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

Outline

MSSM Higgs potential

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

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

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Full tree-level scalar Higgs potential:

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

- Quadratic terms comes from F term in the superpotential

μ: higgsino mass parameter

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- Quadratic terms comes from F term in the superpotential and SUSY-breaking terms

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  m_H and B: SUSY-breaking mass parameters

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  - μ: higgsino mass parameter
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➜ 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:

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

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

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

$$
\begin{aligned}
m_h^2 &= \frac{1}{2}\left[m_Z^2 + m_A^2 - \sqrt{\left(m_A^2 - m_Z^2\right)^2 + 4\, m_A^2\, m_Z^2\, \sin^2 2\beta}\right] \\
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Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

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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:

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

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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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✘ However, large A_t-terms are hard to achieve in specific models of SUSY breaking

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✘ SUSY Little Hierarchy Problem

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
   - γ-rays
6. Conclusions and prospects

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 $m_{\rm susy}$.

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

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

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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.

Brignole, Casas, Espinosa, Navarro, 03

Dine, Seiberg, Thomas, 07

Non-renormalizable operators

Remember the ordinary MSSM superpotential:

$$W_{\text{MSSM}} \supset \int d^2\theta \, \mu \, H_u \, H_d$$

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

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

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

$Z \equiv \theta^2 \, m_{\mathrm{susy}}$: 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.} \\
&\quad + \frac{\epsilon_1}{\mu^*}\Big[2(H_u H_d)(\tilde{H}_u \tilde{H}_d) + 2(\tilde{H}_u H_d)(H_u \tilde{H}_d) \\
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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:

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

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

$\delta_\epsilon m_h^2 \quad \sim \quad$ few dozens of GeVs!

The $\delta_\epsilon m_h^2$ relaxes the constraint in a significant way:
for $\epsilon_1 \lesssim -0.1$ and $\tan\beta \lesssim 5$, light and unmixed stops allowed!

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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 χ_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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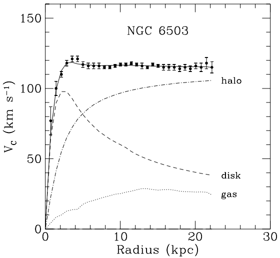
➜ Spectrum, dark matter relic density and DM detection rates are calculated using modified versions of `SuSpect` and `micrOMEGAs`

Outline

Why Dark Matter?

Galactic Rotation Curves



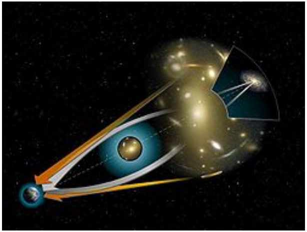
Normally, for $r > r_{vis}$ one would expect

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

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: ΛCDM

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

WMAP 5-year results give

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

whereas

$$\Omega_b h^2 - = 0.02267 \pm 0.00058$$

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
- sign μ: sign of the μ parameter

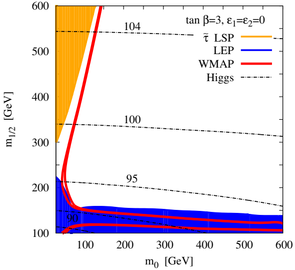
In mSUGRA scenarios usually the lightest neutralino is the LSP

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 $\tan\beta = 3$

mSUGRA



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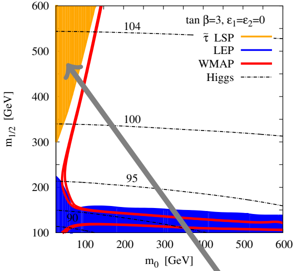
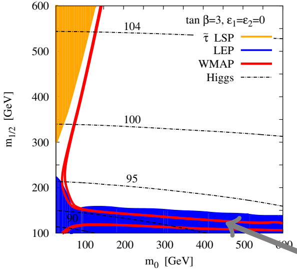


- Regions excluded: $\tilde{\tau}$ LSP

Correlated stop-slepton masses

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

mSUGRA



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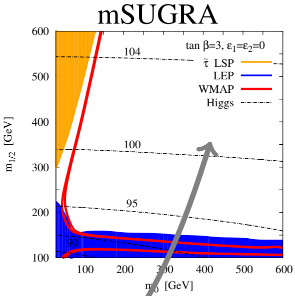

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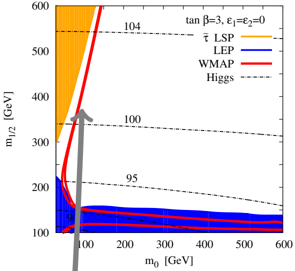

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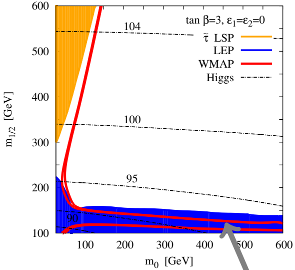

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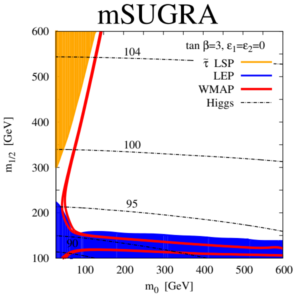

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✘ However $m_h \lesssim 105$ GeV: The whole region is excluded!

Correlated stop-slepton masses

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

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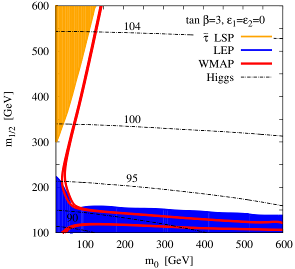
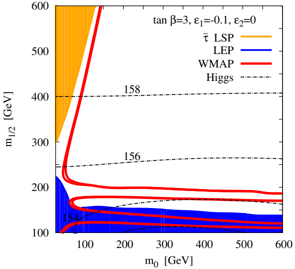


BMSSM mSUGRA-like



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

Correlated stop-slepton masses

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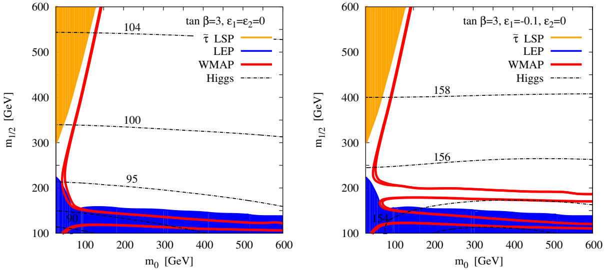

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✔ Important uplift of the Higgs mass → 'bulk region' re-opened

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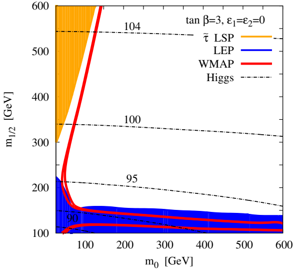

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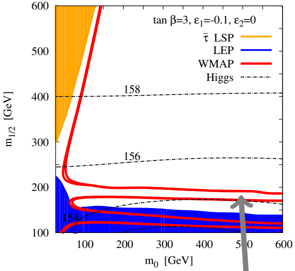

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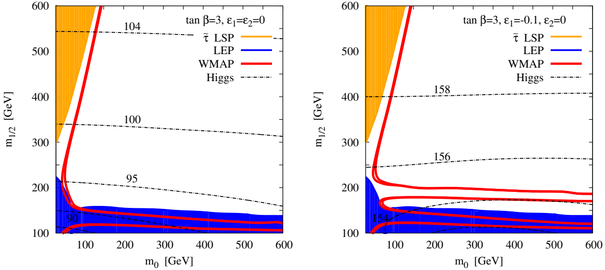

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- ✔ Important uplift of the Higgs mass → 'bulk region' re-opened
- New region fulfilling DM constraint: Higgs-funnel
- χ_1^0 bino-like: marginal impact on m_χ and ann. cross section

Light stops, heavy sleptons

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

- $\tan\beta$: ratio of the Higgs vevs
- μ: 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$^{\text{rd}}$ generation squarks left mass parameter
- $m_{\tilde{f}}$: mass for sleptons, 1$^{\text{st}}$ and 2$^{\text{nd}}$ gen. squarks and $\tilde{b}_R$

$$m_U = 210\ \text{GeV}, \quad X_t = 0\ \text{GeV}, \quad m_Q = m_{\tilde{f}} = m_A = 500\ \text{GeV}$$

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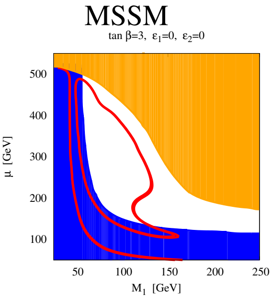
$$m_U = 210\text{ GeV},\quad X_t = 0\text{ GeV},\quad m_Q = m_{\tilde{f}} = m_A = 500\text{ GeV}$$

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

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

Light stops, heavy sleptons



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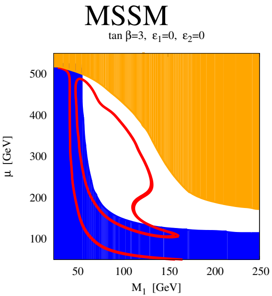

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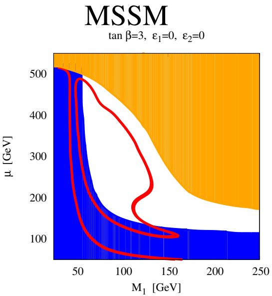
Light stops, heavy sleptons



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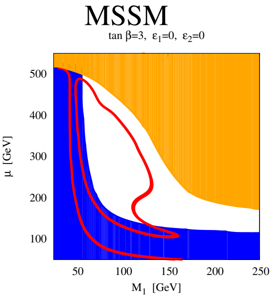

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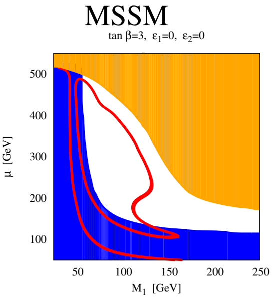

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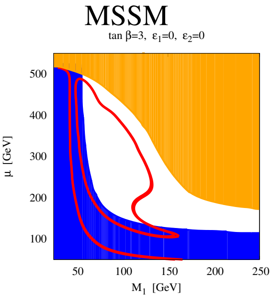

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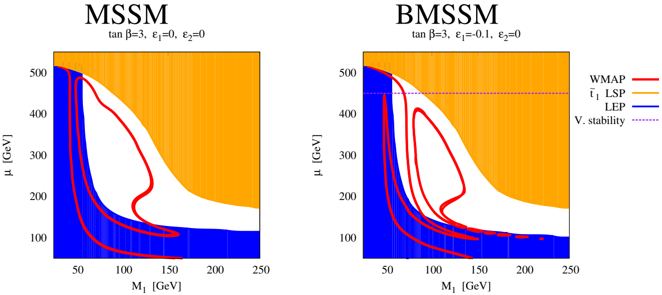
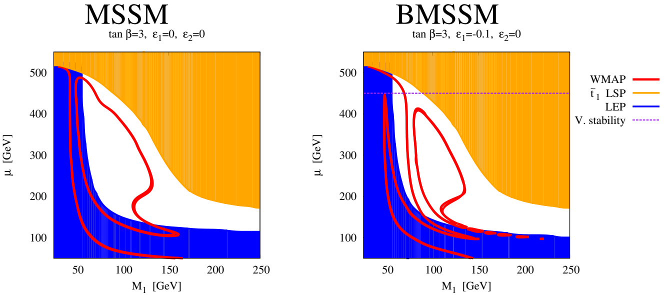
✘ However $m_h \lesssim 85$ GeV: The whole region is excluded!

Light stops, heavy sleptons



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

Light stops, heavy sleptons



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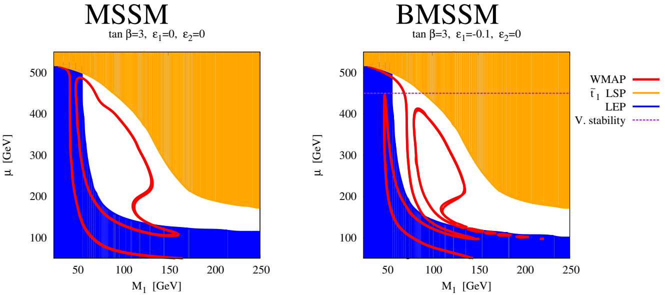

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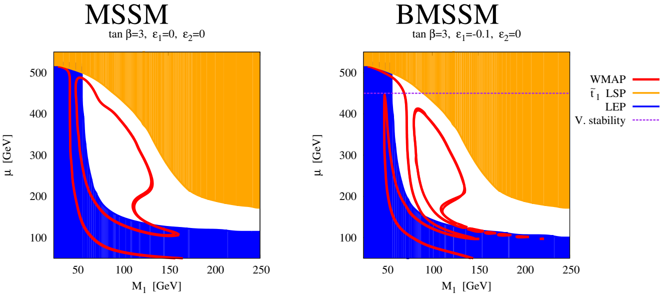

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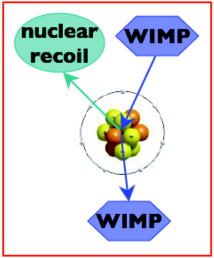
- sizable impact on m_χ and ann. cross section when χ_1^0 is higgsino-like

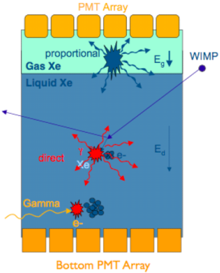
Outline

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: ε = 30, 300, 3000 kg· year
Xenon1T and 11 days, 4 months or 3 years

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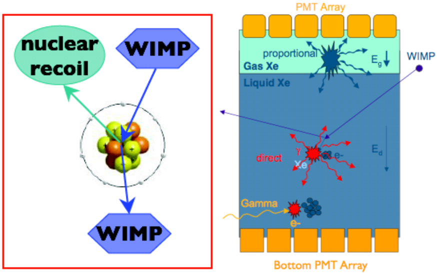

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Xenon discriminates signal from background by simultaneous measurements of:

- scintillation
- ionization

The collaboration expects to have a negligible background.

➜ 7 energy bins between [4, 30] keV

Detectability definition:

$$\chi_i^2 = \frac{\left(N_i^{\rm tot} - N_i^{\rm bkg}\right)^2}{N_i^{\rm tot}}$$

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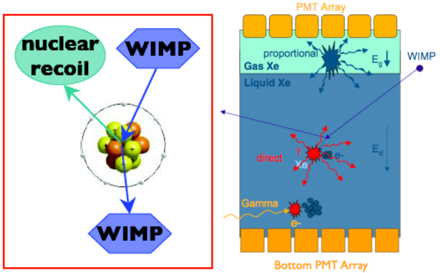

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Recoil rates

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

Reduced mass $\quad M_r = \dfrac{m_\chi\, m_N}{m_\chi + m_N}$

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

E_r: nuclear recoil energy $\quad\sim$few keV

m_χ: WIMP mass

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

➜ Assume pure spin-independent coupling

ρ_0: local WIMP density $\quad 0.38$ GeV cm^{-3}

F: nuclear form factor Woods-Saxon

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

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

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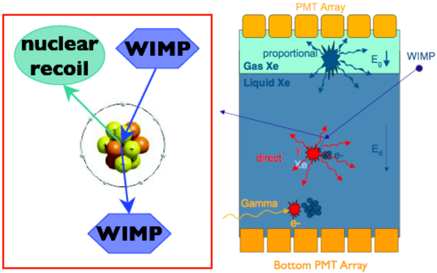

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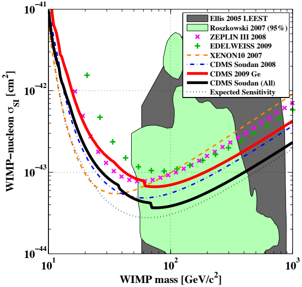
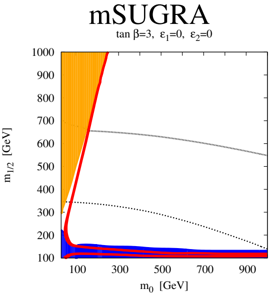
Exclusion lines



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

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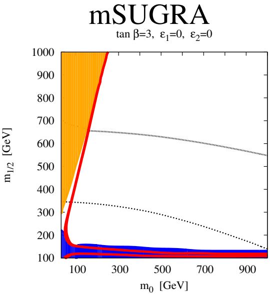
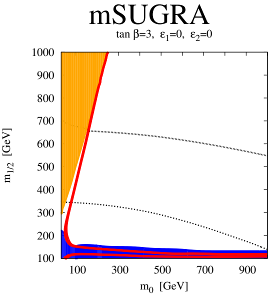


Exclusion lines: ability to test and exclude at 95% CL

- 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)

Correlated stop-slepton masses



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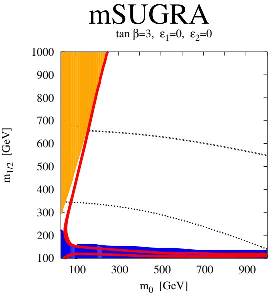
- Detection prospects maximised for low m_0 and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)

Correlated stop-slepton masses



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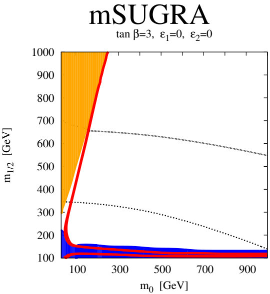

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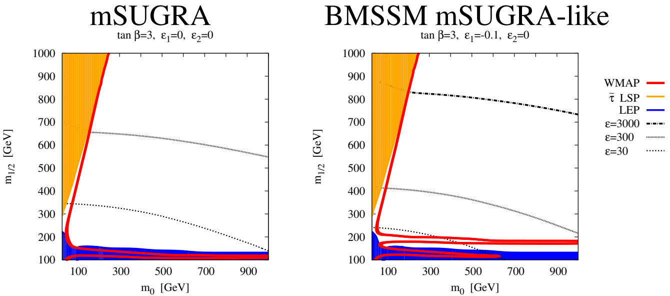
✔ Sizable amount of the parameter space can be probed

Correlated stop-slepton masses



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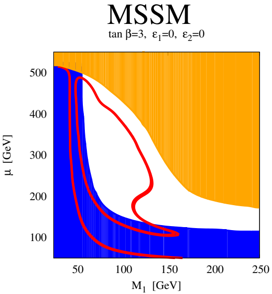
➜ NR operators → deterioration of the detection: m_h

✔ But without NR operators, the parameter space was excluded!

Light stops, heavy sleptons



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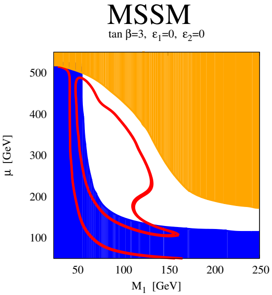

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✘ Partially ruled out by Xenon10 and CDMS-II results!

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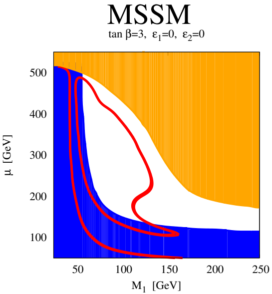

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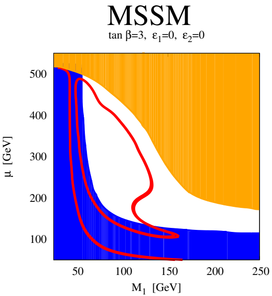

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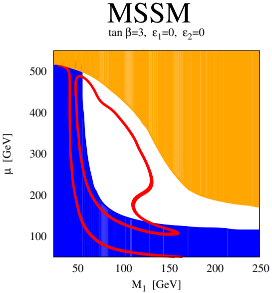

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- Scattering cross section enhanced near $\mu \sim M_1$ $(C_{\chi\chi h}, C_{\chi\chi H})$
- Neither Z- nor h-funnel enhance SI direct detection

  Spin-dependent detection sensible to the Z-peak (non-universality)

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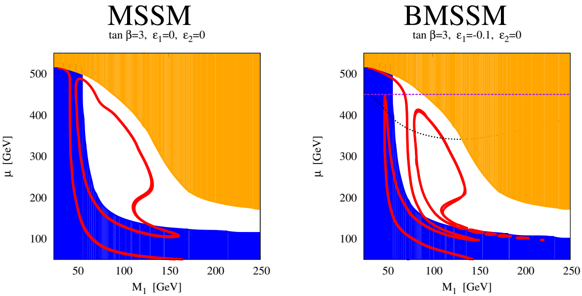

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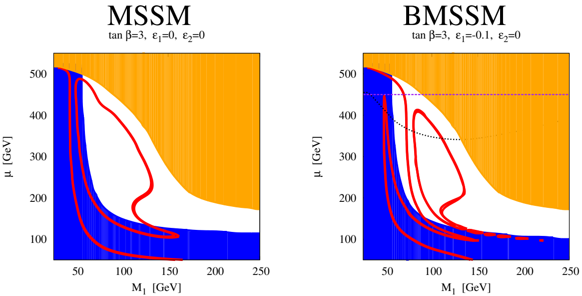
- Neither Z- nor h-funnel enhance SI direct detection
- ➜ NR operators deteriorates DD: increase m_h and suppression $C_{\chi\chi h}$

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 μ 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
- ➜ NR operators deteriorates DD: increase m_h and suppression $C_{\chi\chi h}$
- ✔ BMSSM satisfies all DD measurements!

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**
   - γ-rays
6. Conclusions and prospects

Dark matter indirect detection (γ-rays)

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

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

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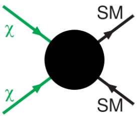

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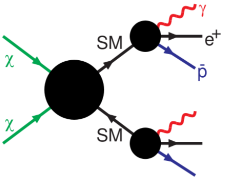

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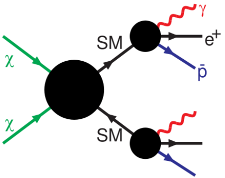

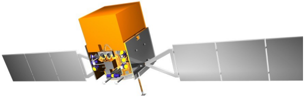

Fermi/GLAST telescope (Launched '08)

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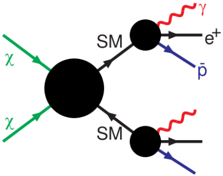

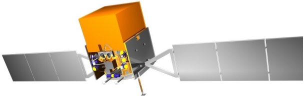

Fermi/GLAST telescope (Launched '08)

Differential event rate

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

$\frac{dN}{dE}$: spectrum of secondary particles
E_γ: 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 (γ-rays)

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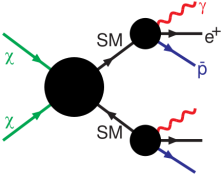

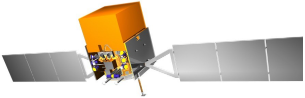

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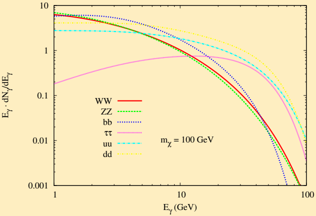

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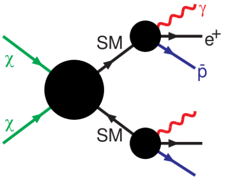

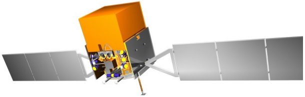

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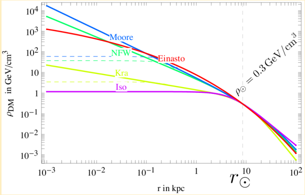
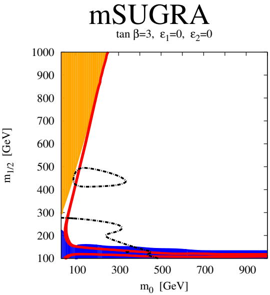


3 halo profiles: Einasto, NFW and NFW$_c$ (adiabatic compression due to baryons)

Correlated stop-slepton masses



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

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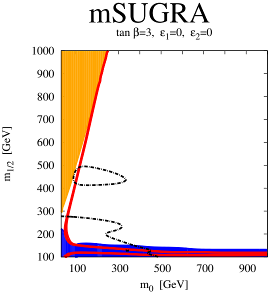

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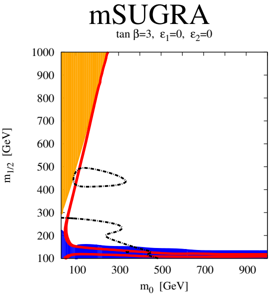

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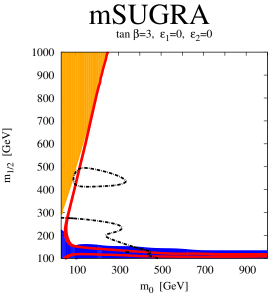

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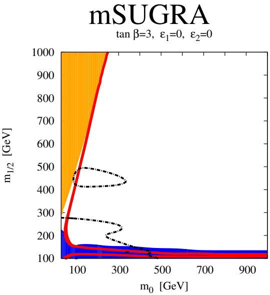

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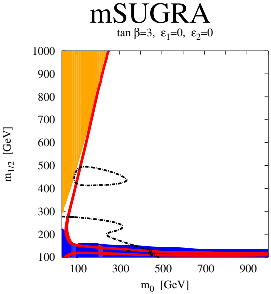

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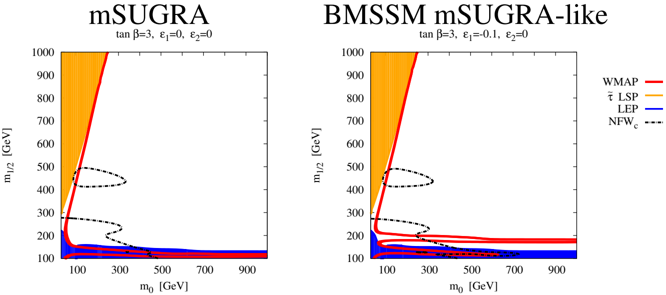

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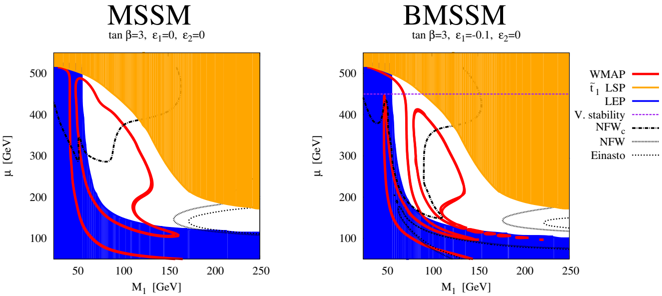
- NR operators: Higgs pole ‘invisible’ ($v \to 0$)

Light stops, heavy sleptons



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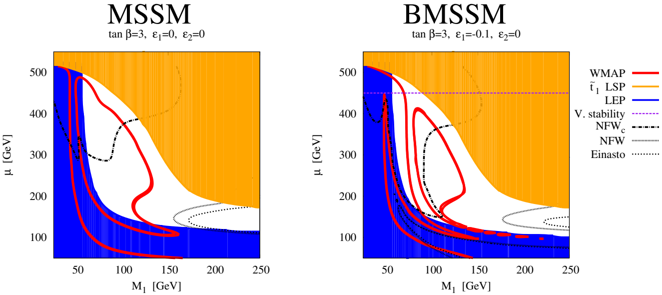

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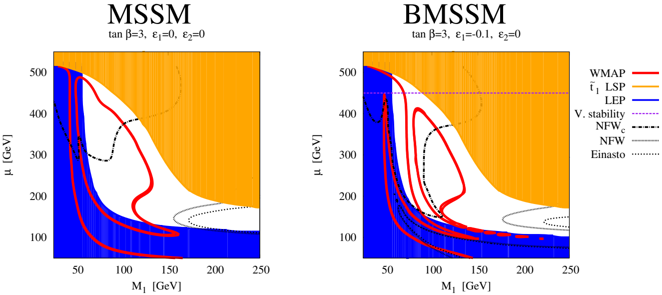

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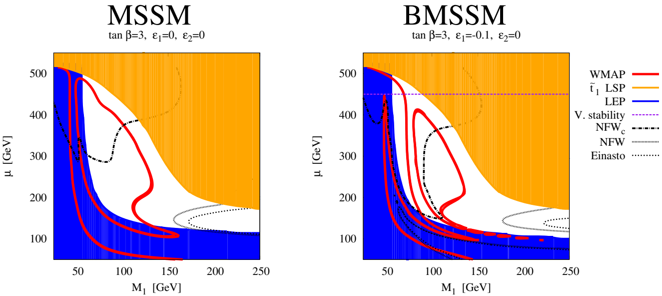

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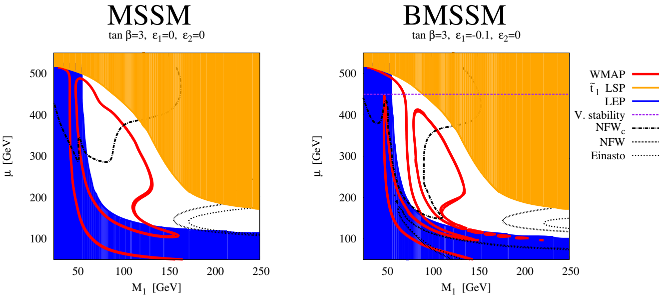

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- h-funnel could not be tested (no s-wave contribution)
- NFW and Einasto could test some regions, but not relevant

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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)

Outline

Antimatter propagation

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

➜ Diffusion equation

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

Propagation parameters K_0 and α fixed by N-body simulations

Antimatter propagation

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

➜ Source term due to DM DM annihilation

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

Antimatter propagation

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

➜ Energy loss term

$$b(E) = \frac{E^2_{\rm GeV}}{\tau_E} \qquad \text{Energy loss rate}$$

For antiprotons energy losses can be ignored

Antimatter propagation

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

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

$$\Gamma_{\rm ann} = \left(n_H + 4^{2/3}\,n_{He}\right)\sigma^{p\bar{p}}_{\rm ann}\,v_{\bar{p}} \qquad \text{Annihilation rate}$$

Annihilation only relevant for antiprotons

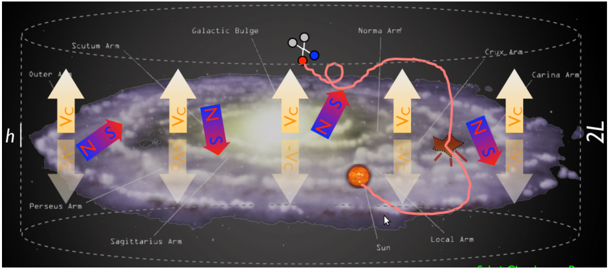
Antimatter propagation

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

➜ Final Diffusion equation

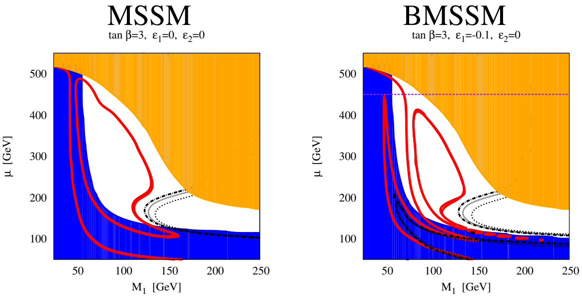
Semi-analytical 2D diffusion equation

Baltz & Edsjo ’98; Lavalle, Pochon, Salati & Taillet ’06



picture snatched to M. Cirelli

Light stops, heavy sleptons - Positrons



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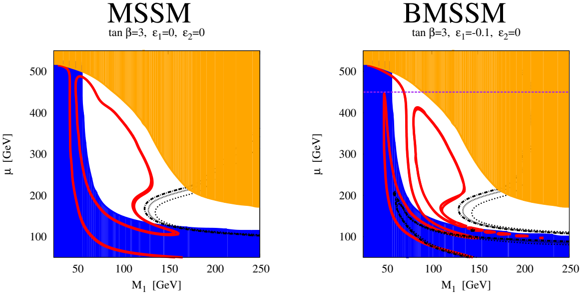
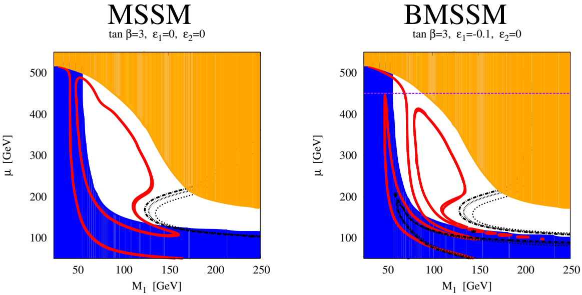


➜ Perspectives for the oncoming AMS-02 satellite
background: Fermi & PAMELA measurements.
PAMELA's 'heritage': A quite large background that is difficult to overcome.

Light stops, heavy sleptons - Positrons



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✘ PAMELA excess buries all signals

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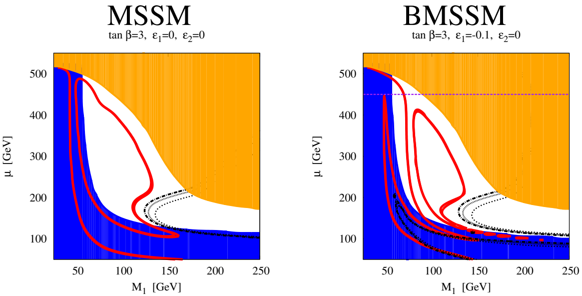
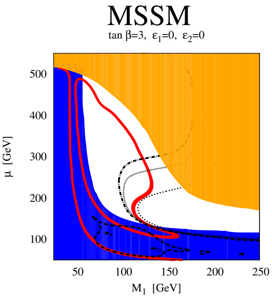


➜ Perspectives for the oncoming AMS-02 satellite background: Fermi & PAMELA measurements. PAMELA's 'heritage': A quite large background that is difficult to overcome.

✘ 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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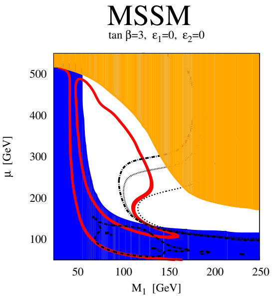

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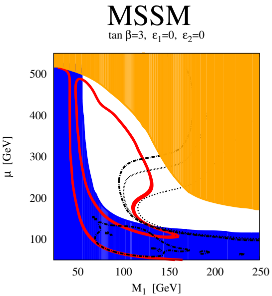

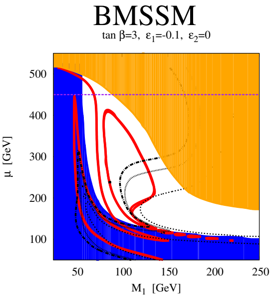

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- The background is not very high, but the signal is quite low!

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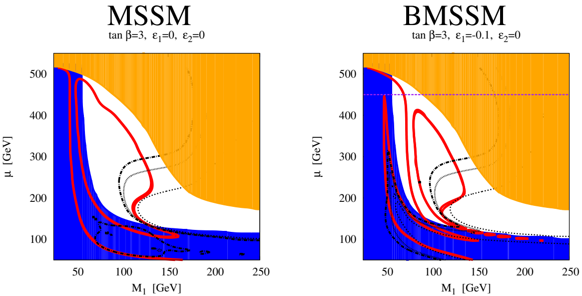

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- Much better that positrons!