Neutralino Dark Matter in the BMSSM

Nicolás Bernal

CFTP - IST, Lisbon

March 11$^{\text{th}}$ 2010
XLVth Rencontres de Moriond

JCAP 03(2010)007 NB, A. Goudelis
JHEP 08(2009)053 NB, K. Blum, M. Losada, Y. Nir

MSSM: Lightest Higgs boson mass

In terms of M_A and $\tan\beta$ the tree level mass for the lightest Higgs is

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

Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114$ GeV is already violated!

MSSM: Lightest Higgs boson mass

In terms of M_A and $\tan\beta$ the tree level mass for the lightest Higgs is

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

Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114$ GeV is already violated!

➜ To avoid a contradiction we need both

large $\tan\beta$ and large radiative corrections

MSSM: Lightest Higgs boson mass

In terms of M_A and $\tan\beta$ the tree level mass for the lightest Higgs is

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

Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114$ GeV is already violated!

➜ To avoid a contradiction we need both

large $\tan\beta$ and large radiative corrections

Most important RC comes from loops of tops and stops:

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

MSSM: Lightest Higgs boson mass

In terms of M_A and $\tan\beta$ the tree level mass for the lightest Higgs is

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

Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114$ GeV is already violated!

➜ To avoid a contradiction we need both

large $\tan\beta$ and large radiative corrections

Most important RC comes from loops of tops and stops:

Consistency with LEP II achieved with

- Heavy stops $m_{\tilde{t}} \sim 600$ GeV to few TeV
- Large stop mixing

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

MSSM: Lightest Higgs boson mass

In terms of M_A and $\tan\beta$ the tree level mass for the lightest Higgs is

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

Important constraint: $m_h \leq \mathrm{Min}(m_A,\, m_Z)\,|\cos 2\beta| \leq m_Z$

The LEP II bound $m_h \gtrsim 114$ GeV is already violated!

➜ To avoid a contradiction we need both

large $\tan\beta$ and large radiative corrections

Most important RC comes from loops of tops and stops:

Consistency with LEP II achieved with

- Heavy stops $m_{\tilde{t}} \sim 600$ GeV to few TeV
- Large stop mixing

✘ SUSY Little Hierarchy Problem

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.

➜ 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

Antoniadis, Dudas, Ghilencea, Tziveloglou, 08 & 09

Non-renormalizable operators

Remember the ordinary MSSM superpotential:

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

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

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

$Z \equiv \theta^2\, m_{\rm susy}$: spurion field
O_1: is a dimension 5 SUSY operator
O_2: represents SUSY breaking

Remember Antoniadis' talk on Tuesday!
➜ Both operators can lead to CP violation

BMSSM Higgs potential

Corrections to the MSSM Higgs potential

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

where

$$\epsilon_1 \equiv \frac{\mu\,\lambda_1}{M} \qquad \epsilon_2 \equiv -\frac{m_{\text{susy}}\,\lambda_2}{M}$$

- New contributions for Higgs boson masses
- New contributions for higgsino (χ^0 and $\chi^\pm$) masses
- New contributions for Higgs-higgsino couplings

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

Higgs spectrum

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

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

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

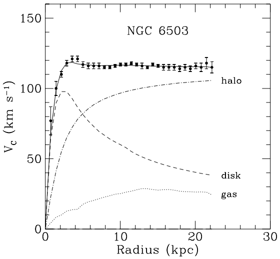
$\delta_\epsilon m_h^2 \quad \sim \quad$ few dozens of GeVs!

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!

➜ The SUSY little hierarchy problem can be avoided

Why Dark Matter?

Galactic Rotation Curves



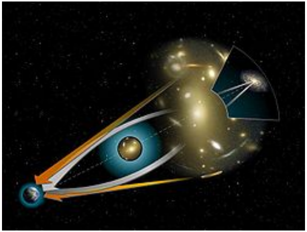
Normally, for $r > r_{vis}$ one would expect

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

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:

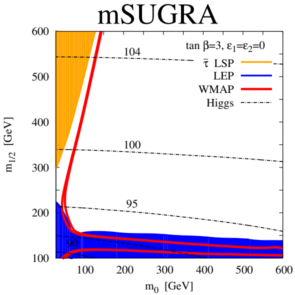
- $\tan\beta$: ratio of the Higgs vevs
- $m_{1/2}$: common mass for the gauginos (bino, wino and gluino)
- m_0: universal scalar mass (sfermions and Higgs bosons)
- A_0: universal trilinear coupling
- sign μ: sign of the μ parameter

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: mSUGRA-like

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

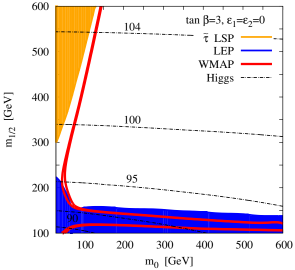


- Regions excluded: $\tilde{\tau}$ LSP
- Bulk region: LSP is mainly bino-like. DM relic density too high
- Regions fulfilling WMAP measurements:
  - ✔ Coannihilation with $\tilde{\tau}$
  - ✔ Higgs- and Z-poles: $m_h \sim m_Z \sim 2m_\chi$ s-channel exchange
- ✘ However $m_h \lesssim 105$ GeV: The whole region is excluded!

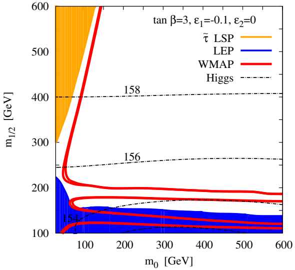
Correlated stop-slepton masses: mSUGRA-like

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

mSUGRA



BMSSM mSUGRA-like



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

✔ 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

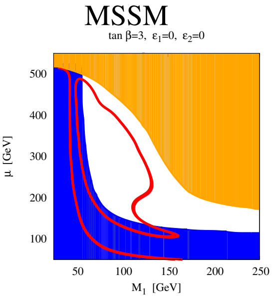
- $\tan\beta$: ratio of the Higgs vevs
- μ: higgsino mass parameter
- m_A: pseudoscalar Higgs mass parameter
- X_t: trilinear coupling for stops, $X_t = A_t - \mu/\tan\beta$
- M_2: wino mass parameter, $M_1 \sim \frac{1}{2}M_2$
- m_U: stop right mass parameter
- m_Q: 3rd generation squarks left mass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

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

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

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

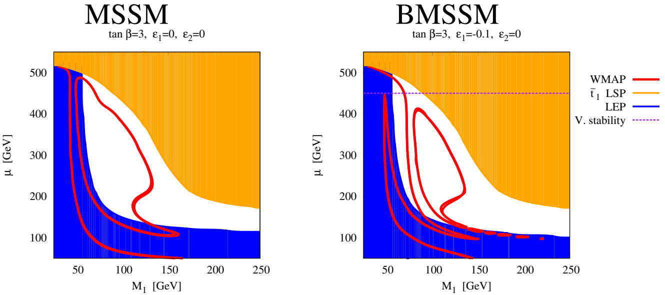
Light stops, heavy sleptons



- Regions excluded: $\tilde{t}$ LSP
- Regions fulfilling WMAP measurements:
  - ✔ Coannihilation with $\tilde{t}$: $\chi\tilde{t} \to Wb, tg$ $\tilde{t}\tilde{t} \to gg$
  - ✔ Higgs- and Z-poles: $m_h \sim m_Z \sim 2m_\chi$ s-channel exchange

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

Light stops, heavy sleptons

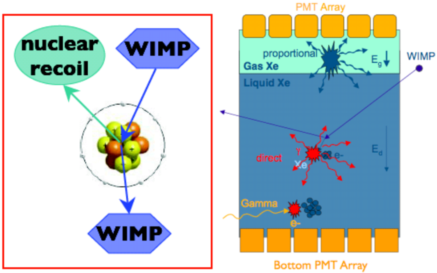


- ✔ important uplift of the Higgs mass: $m_h \sim 122$ GeV
- ✘ NR operators destabilize scalar potential: vacuum metastable
- new region fulfilling DM constraint: Higgs-funnel
- sizable impact on m_χ and ann. cross section when χ_1^0 is higgsino-like

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

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:

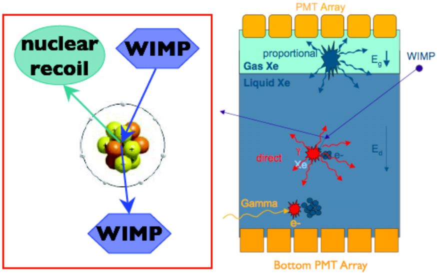
$$\chi_i^2 = \frac{\left(N_i^{\text{tot}} - N_i^{\text{bkg}}\right)^2}{N_i^{\text{tot}}}$$

More on DM DD: Anne Green's talk

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

Recoil rates

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

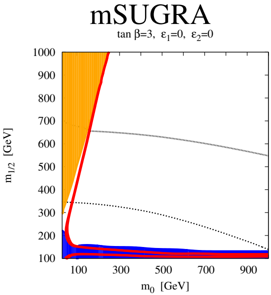
Reduced mass $M_r = \frac{m_\chi\, m_N}{m_\chi + m_N}$

N: number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
E_r: nuclear recoil energy ~few keV
m_χ: WIMP mass
$\sigma_{\chi-p}$: WIMP-proton scattering cross-section
➜ Assume pure spin-independent coupling

ρ_0: local WIMP density 0.38 GeV cm^{-3}
F: nuclear form factor Woods-Saxon
$f(v)$: WIMP local vel. distribution M.B.

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

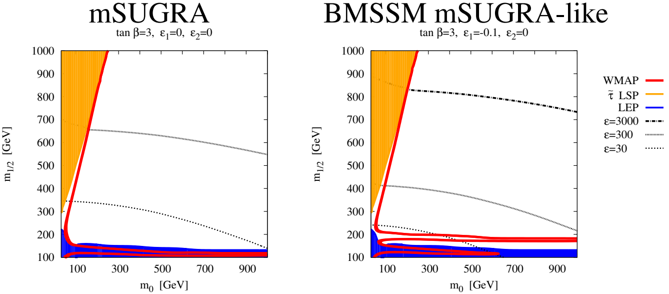
Correlated stop-slepton masses



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

- Detection prospects maximised for low m_0 and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)
- Detection maximised for low $\tan\beta$, $C_{\chi\chi h} \propto \sin 2\beta \quad (|\mu| \gg M_1)$
- ✔ Sizable amount of the parameter space can be probed

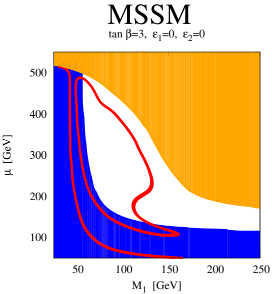
Correlated stop-slepton masses



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

- Detection prospects maximised for low m_0 and $m_{1/2}$ values
- For low $m_{1/2}$, LSP tends to be a higgsino-bino mixed state ($C_{\chi\chi h}$)
- Detection maximised for low $\tan\beta$, $C_{\chi\chi h} \propto \sin 2\beta$ $\quad (|\mu| \gg M_1)$
- ✔ 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!

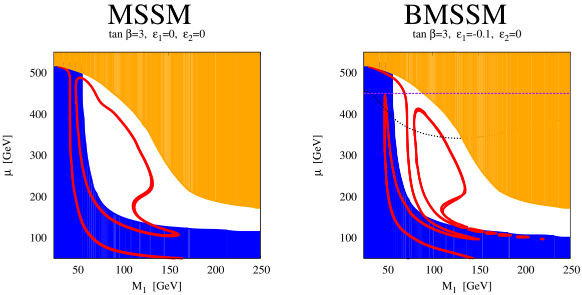
Light stops, heavy sleptons



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

- ✘ 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 $\mu \sim M_1$ $\quad (C_{\chi\chi h}, C_{\chi\chi H})$

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 $\mu \sim M_1$ $(C_{\chi\chi h}, C_{\chi\chi H})$
- ➜ NR operators deteriorates DD: increase m_h and suppression $C_{\chi\chi h}$
- Neither Z- nor h-funnel enhance SI direct detection
- ✔ BMSSM satisfies all DD measurements!

Dark matter indirect detection (γ-rays)

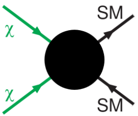
We study the ability of **Fermi** to identify
Gamma-rays generated in
DM annihilation in the galactic center

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

Dark matter indirect detection (γ-rays)

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

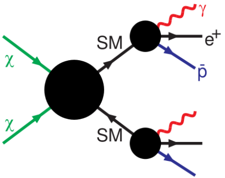
$$\chi\bar{\chi} \rightarrow b\bar{b},\, WW \cdots \rightarrow \gamma + \ldots$$



Dark matter indirect detection (γ-rays)

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

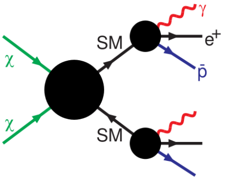
$$\chi\bar{\chi} \to b\bar{b},\, WW \cdots \to \gamma + \ldots$$

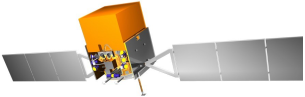


Dark matter indirect detection (γ-rays)

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

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



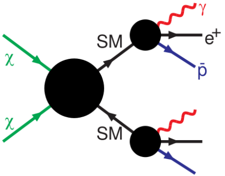


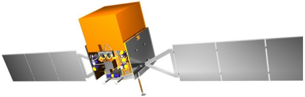
Fermi/GLAST telescope (Launched '08)

Dark matter indirect detection (γ-rays)

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

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





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_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

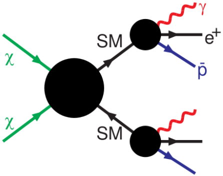
Background: HESS measurements
(Diffuse and point source at SgrA*)

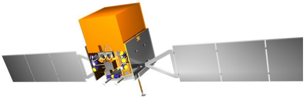
Tomorrow Tomi Ylinen will present FERMI!

Dark matter indirect detection (γ-rays)

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

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



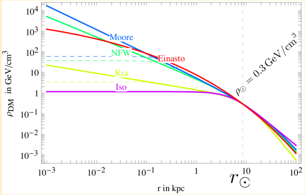


Fermi/GLAST telescope (Launched '08)

Differential event rate

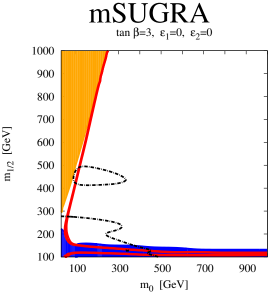
$$\Phi_\gamma(E_\gamma, \psi) = \sum_i \frac{dN_\gamma^i}{dE_\gamma} \langle \sigma_i v \rangle \frac{1}{8\pi\, m_\chi{}^2} \int_{los} \rho(r)^2 dl$$

$\frac{dN}{dE}$: spectrum of secondary particles
E_γ: 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$_c$ (adiabatic compression due to baryons)

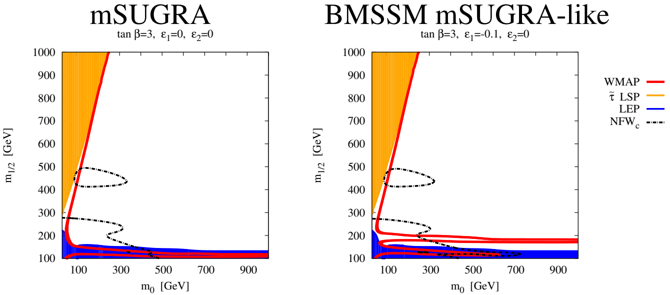
Correlated stop-slepton masses



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

- Detection prospects maximised for low m_0 and $m_{1/2}$
- Thresholds: $\chi\chi \to W^+W^-$, $\chi\chi \to t\bar{t}$
- Detection maximised for high $\tan\beta$ $\chi\chi \to b\bar{b}$ and $\tau\tau \propto \tan\beta$ and $1/\cos\beta$
- For large $\tan\beta$ thresholds weaken
- Only scenarios with highly cusped inner regions could be probed

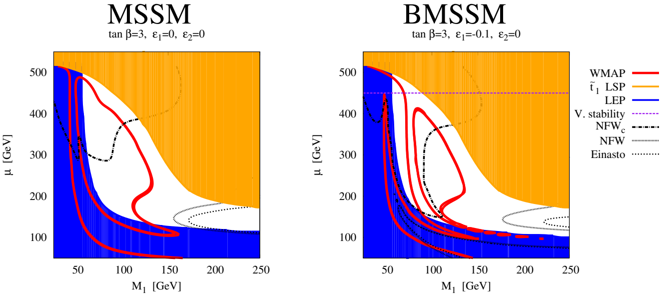
Correlated stop-slepton masses



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

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

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 $\tan\beta$ ($\chi\chi \to b\bar{b}, WW$)
- 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 by present machines!
- Dark matter direct detection and gamma-rays detection could probe a sizeable portion of the chosen benchmarks
- Complementarity between direct and indirect detection modes.
- Also other possibilities: Positrons & antiprotons indirect detection.