Dark Matter in Models with Seesaw Type-II mechanism for Neutrino Masses

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Summary

- Motivation
- The Model
- Results
- Conclusions

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Dark Matter

- Standard cosmology requires the existence of a non-baryonic dark matter (DM) contribution to the total energy budget of the universe.
- In the past few years estimates of the DM abundance have become increasingly precise. The Particle Data Group now quotes at 1 σ c.l.

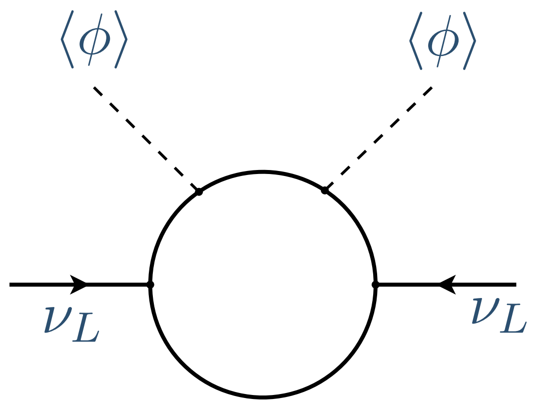
$$\boxed{\Omega_{DM} h^2 = 0.105 \pm 0.008}$$

- Since the data from the WMAP satellite and large scale structure formation is best fitted if the DM is cold, weakly interacting mass particles (WIMP) are currently the preferred explanation. While there is certainly no shortage of WIMP candidates, the literature is completely dominated by studies of the lightest neutralino.

In 1980 Weinberg noticed that the dimension-five operator

$$\mathcal{L}_{\text{Dim5}} = L\phi\, L\phi$$

could induce neutrino masses:



S. Weinberg, Phys. Rev. D **22**, 1694 (1980)

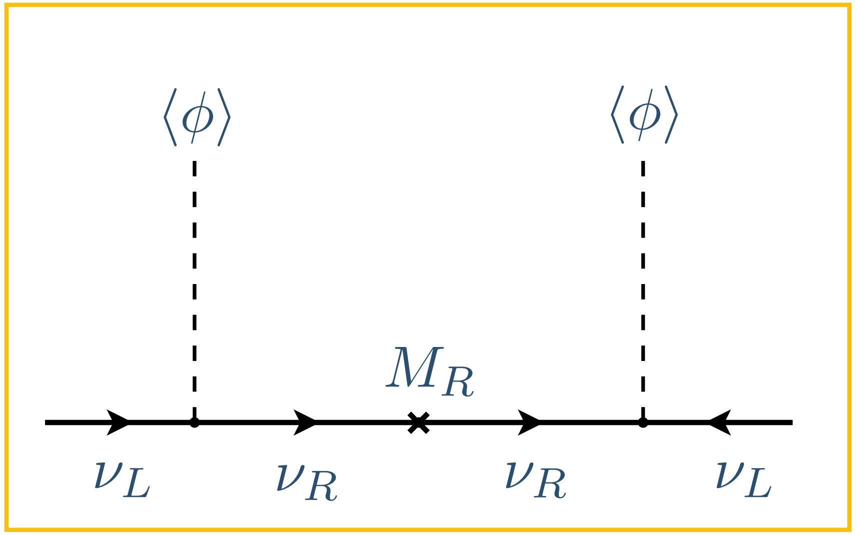
Type I mechanism

In models with RH neutrinos

$-\mathcal{L} = \overline{\nu_L} m_D \nu_R + \frac{1}{2}\overline{\nu^c_L} M_R \nu_R$ where $m_D = Y_\nu v$

we obtain

$$m^{\rm I}_{\rm eff} = -(vY) M_R^{-1} (vY)^T$$



Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Mohapatra, Senjanovic

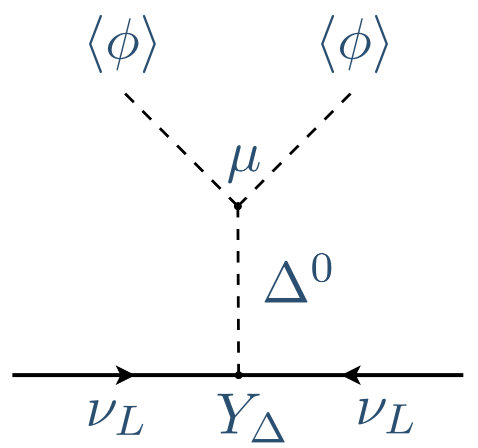
Type II mechanism

In models with Higgs Triplets

$$-\mathcal{L} = \frac{1}{2} Y_\Delta \overline{\nu_L^c} i\tau_2 \Delta_L \nu_L + \mu \phi^T \Delta_L \phi + M_\Delta^2 \Delta_L^\dagger \Delta_L + \cdots$$

we obtain

$$m_{\text{eff}}^{\text{II}} = \frac{v^2 \mu Y_\Delta}{M_\Delta^2}$$

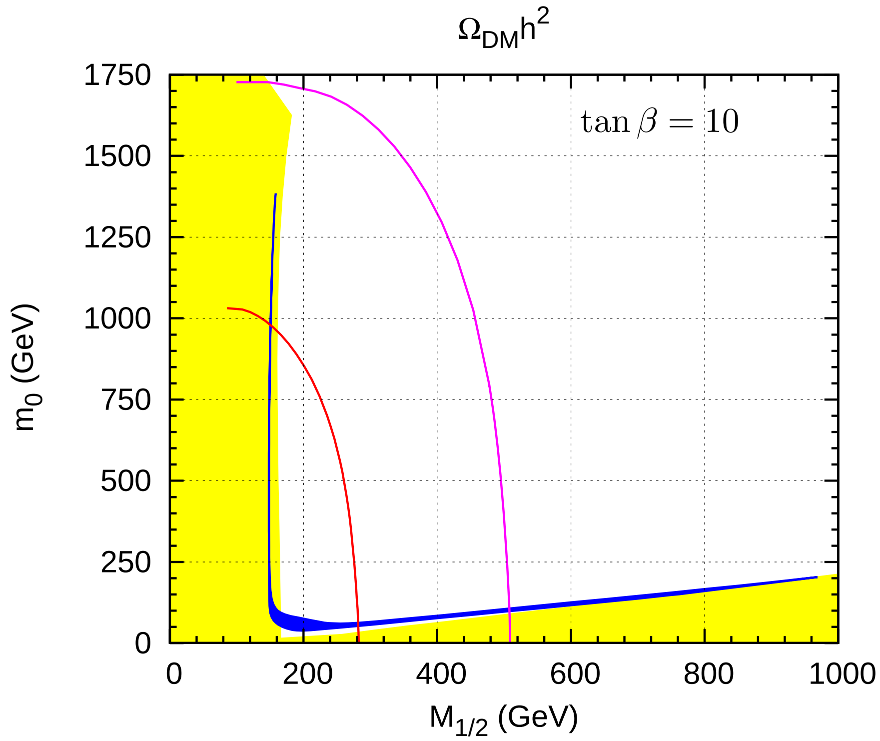


Schechter, Valle, Mohapatra, Senjanovic, Lazarides, Shafi, Wetterich

Neutralino Dark Matter

In mSugra only four very specific regions can explain the WMAP data:

- The bulk region
- The co-annihilation line
- The "focus point" line
- The "higgs funnel" region (large $\tan\beta$)



We considered neutralino dark matter within a supersymmetric type-II seesaw model with mSugra boundary conditions. For definiteness, the model we consider consists of the MSSM particle spectrum to which we add a single pair of $\mathbf{15}$- and $\overline{\mathbf{15}}$-plets. The deformed sparticle spectrum with respect to mSugra expectations leads to characteristic changes in the allowed regions as a function of the unknown seesaw scale.

- The model consists in extending the MSSM particle spectrum by a pair of $\mathbf{15}$ and $\overline{\mathbf{15}}$. It is the minimal supersymmetric seesaw type-II model which maintains gauge coupling unification.
- `mSugra` is the "standard" against which we compare all our results. It is specified by m_0, $M_{1/2}$, A_0, $\tan\beta = \frac{v_2}{v_1}$ and the sign of μ. They are defined at the GUT scale, the RGEs are known at the 2-loop level.
- Under $SU(3) \times SU_L(2) \times U(1)_Y$ the $\mathbf{15}$ decomposes as

$$\begin{aligned} \mathbf{15} =& S + T + Z \\ S \sim& (6,1,-\frac{2}{3}), \qquad T \sim (1,3,1), \qquad Z \sim (3,2,\frac{1}{6}) \end{aligned}$$

- The $SU(5)$ invariant superpotential reads as

$$\begin{aligned} W =& \frac{1}{\sqrt{2}} \mathbf{Y}_{15} \bar{5} \cdot 15 \cdot \bar{5} + \frac{1}{\sqrt{2}} \lambda_1 \bar{5}_H \cdot 15 \cdot \bar{5}_H + \frac{1}{\sqrt{2}} \lambda_2 5_H \cdot \overline{15} \cdot 5_H \\ &+ \mathbf{Y}_5 10 \cdot \bar{5} \cdot \bar{5}_H + \mathbf{Y}_{10} 10 \cdot 10 \cdot 5_H + M_{15} 15 \cdot \overline{15} + M_5 \bar{5}_H \cdot 5_H \end{aligned}$$

Here, $\bar{5} = (d^c, L)$, $10 = (u^c, e^c, Q)$, $5_H = (t, H_2)$ and $\bar{5}_H = (\bar{t}, H_1)$.

The $SU(5)$-broken phase

Below the GUT scale in the $SU(5)$-broken phase the superpotential contains the terms

$$W = \ldots + \frac{1}{\sqrt{2}}(Y_T L T_1 L + Y_S d^c S d^c) + Y_Z d^c Z L + Y_d d^c Q H_1 + Y_u u^c Q H_2 + Y_e e^c L H_1$$
$$+ \frac{1}{\sqrt{2}}(\lambda_1 H_1 T_1 H_1 + \lambda_2 H_2 T_2 H_2) + M_T T_1 T_2 + M_Z Z_1 Z_2 + M_S S_1 S_2 + \mu H_1 H_2$$

- Y_d, Y_u and Y_e generate quark and charged lepton masses as in MSSM
- For the case of a complete $\mathbf{15}$, $Y_T = Y_S = Y_Z$ and M_T, M_S and M_Z are determined from M_{15} by the RGEs. If $M_Z \sim M_S \sim M_T \sim M_{15}$ gauge coupling unification will be maintained.
- The triplet T_1 has the correct quantum numbers to generate neutrino masses. The resulting neutrino mass matrix can be written as

$$m_\nu = \frac{v_2^2}{2}\frac{\lambda_2}{M_T} Y_T \quad \Rightarrow \quad \frac{M_T}{\lambda_2} \simeq 10^{15}\text{GeV} \left(\frac{0.05 \text{ eV}}{m_\nu}\right)$$

Thus, current neutrino data requires M_T to be lower than the GUT scale by (at least) an order or magnitude.

Running of the soft parameters

- For the gaugino masses one finds in leading order

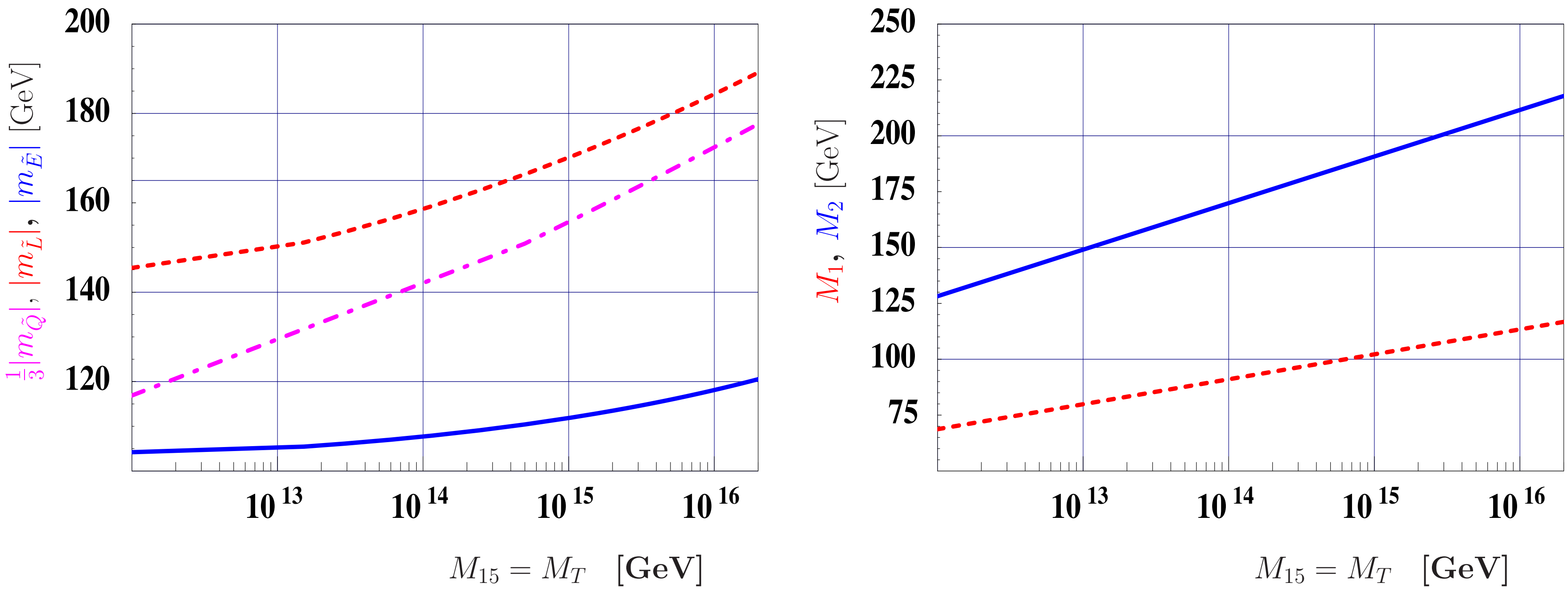
$$M_i(m_{SUSY}) = \frac{\alpha_i(m_{SUSY})}{\alpha(M_G)} M_{1/2}$$

- For the soft mass parameters of the first two generations one gets

$$m_{\tilde{f}}^2 = M_0^2 + \sum_{i=1}^{3} c_i^{\tilde{f}} \left[\left(\frac{\alpha_i(M_T)}{\alpha(M_G)} \right)^2 f_i + f_i' \right] M_{1/2}^2$$

where the coefficients $c_i^{\tilde{f}}$, f_i and f_i' are known functions of the parameters.

Running . . .

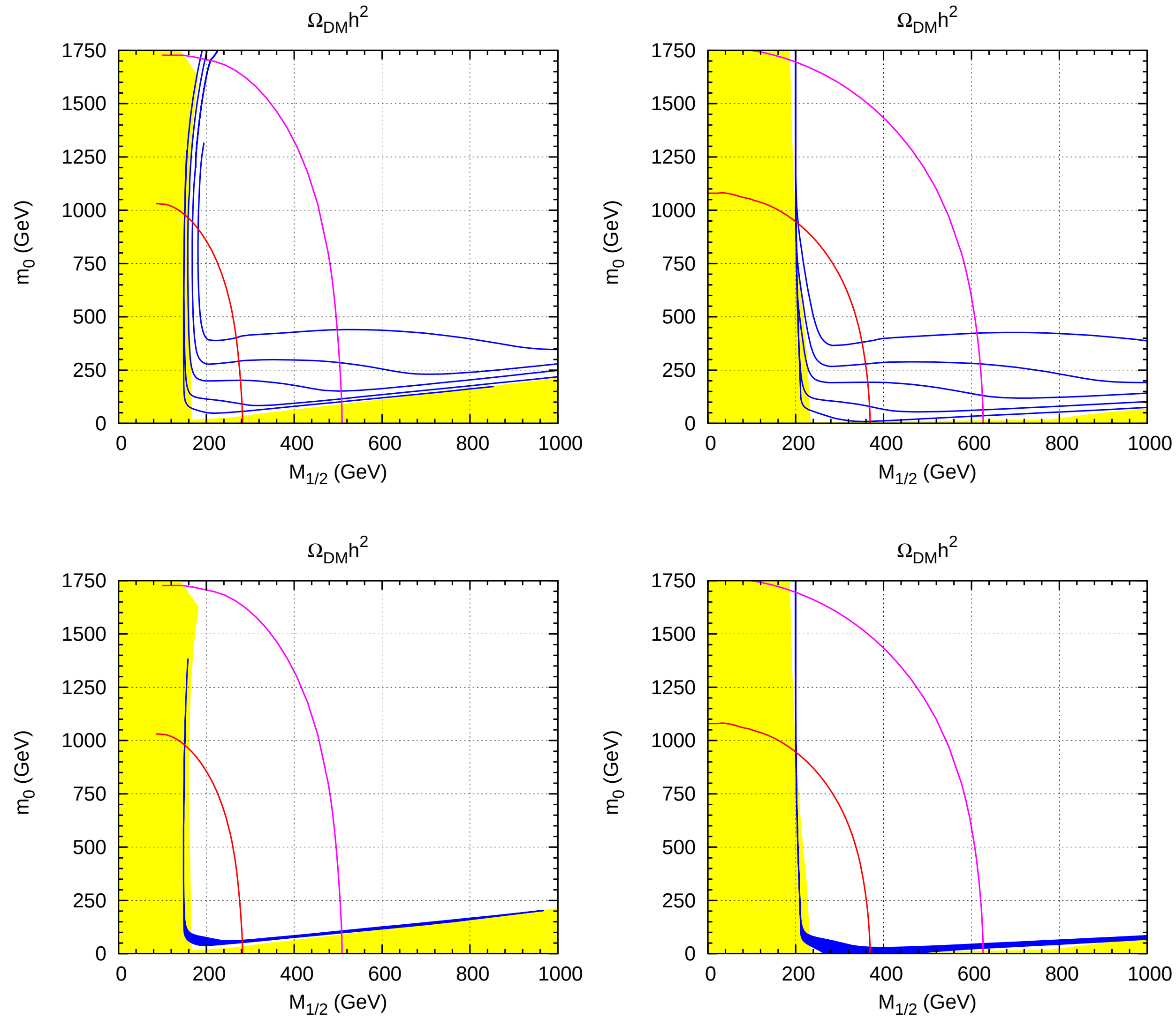


Analytically calculated running of scalar (to the left) and gaugino mass parameters (to the right), leading order only. The mass parameters are calculated as a function of $M_{\mathbf{15}}$ for the mSugra parameters $m_0 = 70$ GeV and $M_{1/2} = 250$ GeV. For $M_{\mathbf{15}} \simeq 2 \times 10^{16}$ GeV the mSugra values are recovered. Smaller $M_{\mathbf{15}}$ lead to smaller soft masses in all cases. Note that the running is different for the different mass parameters with gaugino masses running faster than slepton mass parameters.

The Numerical Procedure

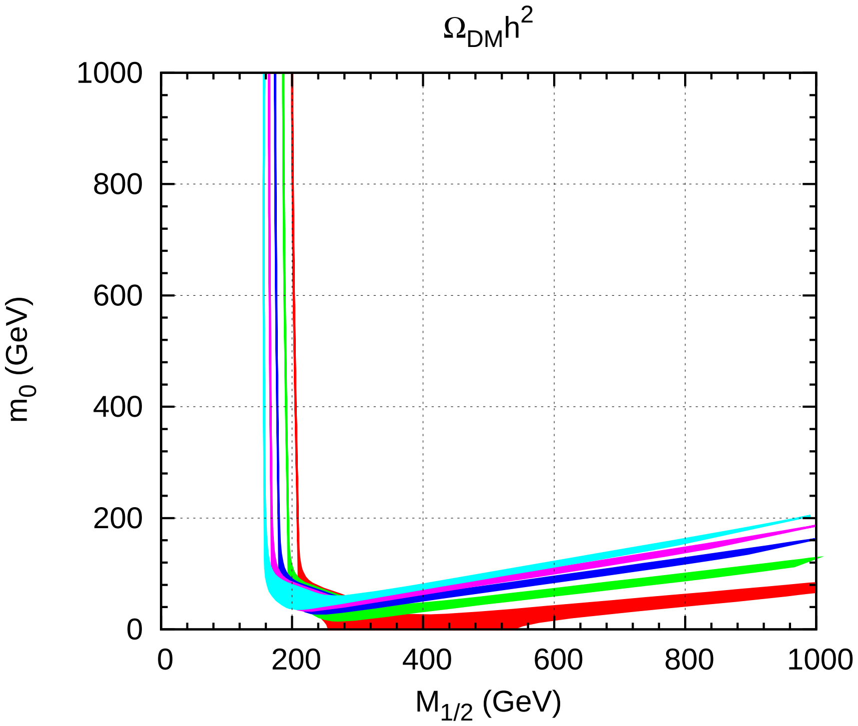
- All the plots shown below are based on the program packages SPheno and micrOMEGAs.
- We use SPheno V3, including the RGEs for the $\mathbf{15}+\overline{\mathbf{15}}$ case at the 2-loop level for gauge couplings and gaugino masses and at one-loop level for the remaining MSSM parameters and the 15-plet parameters.
- For any given set of mSugra and 15-plet parameters SPheno calculates the supersymmetric particle spectrum at the electro-weak scale, which is then interfaced with micrOMEGAs2.2 to calculate the relic density of the lightest neutralino, $\Omega_{\chi_1^0} h^2$.
- For the standard model parameters we use the PDG 2008 values. As discussed below, especially important are the values (and errors) of the bottom and top quark masses, $m_b = 4.2 + 0.17 - 0.07$ GeV and $m_t = 171.2 \pm 2.1$ GeV. Note, the m_t is understood to be the pole-mass and $m_b(m_b)$ is the $\overline{MS}$ mass.
- For the allowed range for $\Omega_{DM} h^2$ we always use the 3 σ c.l. boundaries, i.e. $\Omega_{DM} h^2 = [0.081, 0.12.69]$. Note, however that the use of 1 σ contours results in very similar plots, due to the small error bars.
- We define our "standard choice" of mSugra parameters as $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ and use these values in all plots, unless specified otherwise.

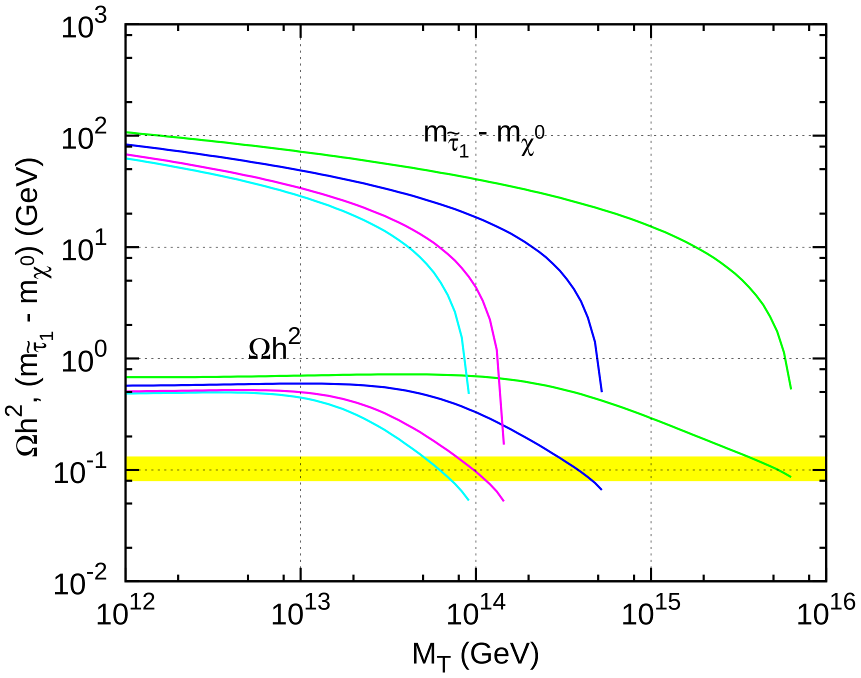
Contours of Equal Dark Matter Density ($\Omega_{\chi_1^0} h^2$)



Top: Contours of $\Omega_{\chi_1^0} h^2$ in the $(m_0, M_{1/2})$ plane for $\tan\beta = 10$, $A_0 = 0$ and $\mu \geq 0$, for mSugra (left) and type-II seesaw with $M_T = 10^{14}$ GeV (right). The lines are constant $\Omega_{\chi_1^0} h^2 = 0.1, 0.2, 0.5, 1, 2$. Bottom: Range allowed by the DM constraint at 3 σ c.l. Left: mSugra; Right: $M_T = 10^{14}$ GeV.

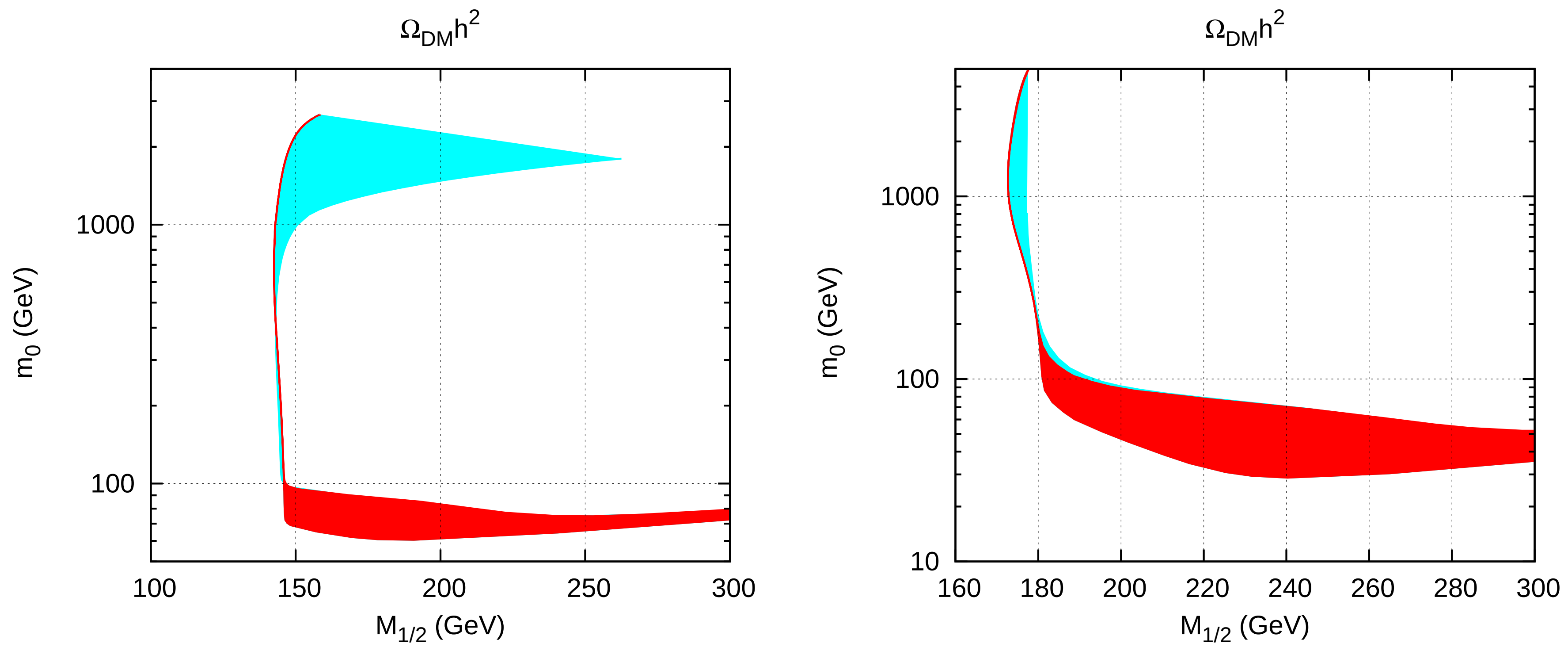
Variation with the Triplet Mass





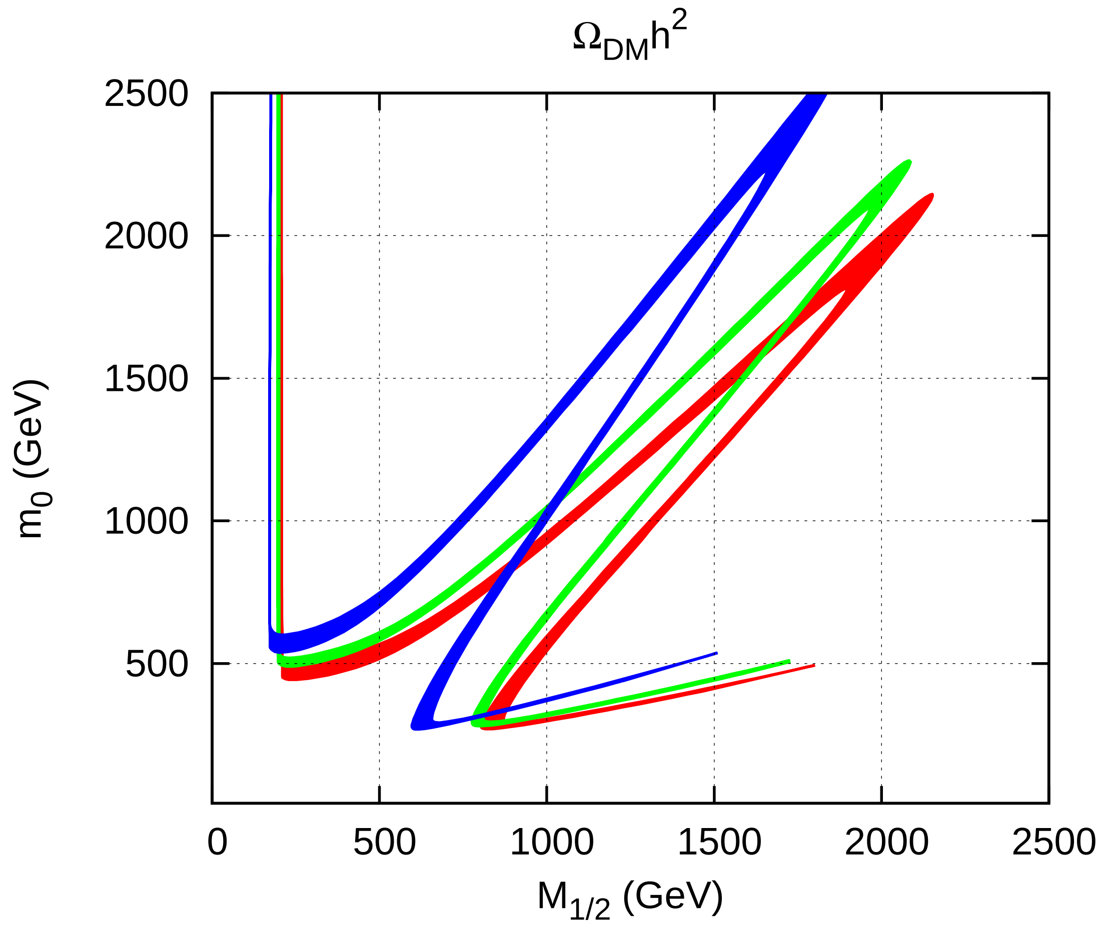
Allowed region for dark matter density $(0.081 < \Omega_{\chi_1^0} h^2 < 0.129)$ in the $(m_0, M_{1/2})$ plane for the "standard choice" $\tan\beta = 10$, $A_0 = 0$ and $\mu \geq 0$, for five values from M_T, $M_T = 10^{14}$ GeV (red), to $M_T = 10^{16}$ GeV (cyan), to the left. To the right: Variation of the mass difference $m_{\tilde{\tau}_1} - m_{\chi_0}$ (top lines) and of Ωh^2 (bottom lines), as a function of M_T for four different values of m_0: 0 (cyan), 50 (magenta), 100 (blue) and 150 GeV (green) for one fixed value of $M_{1/2} = 800$ GeV. The yellow region corresponds to the experimentally allowed DM region.

Dependence on m_{top} in the Focus Point Region



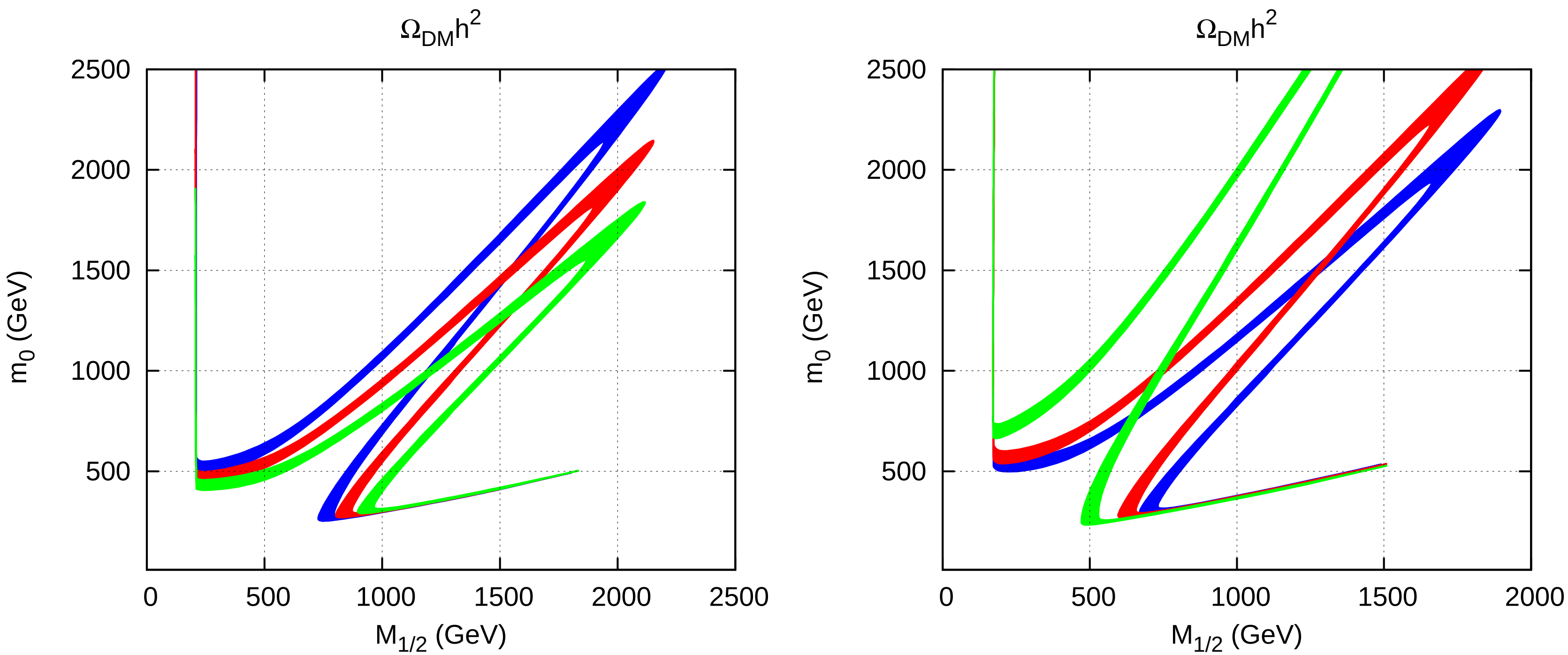
Logarithmically scaled zoom into the focus point region. In red the allowed region for $0.081 < \Omega h^2 < 0.129$ and in cyan the allowed region due the variation of $m_{\text{top}} = 171.2 \pm 2.1$ GeV. The left panel is for mSugra case and the right panel for $M_T = 10^{15}$ GeV. The other parameters are taken at our "standard" values.

Variation of the Higgs Funnel with M_T

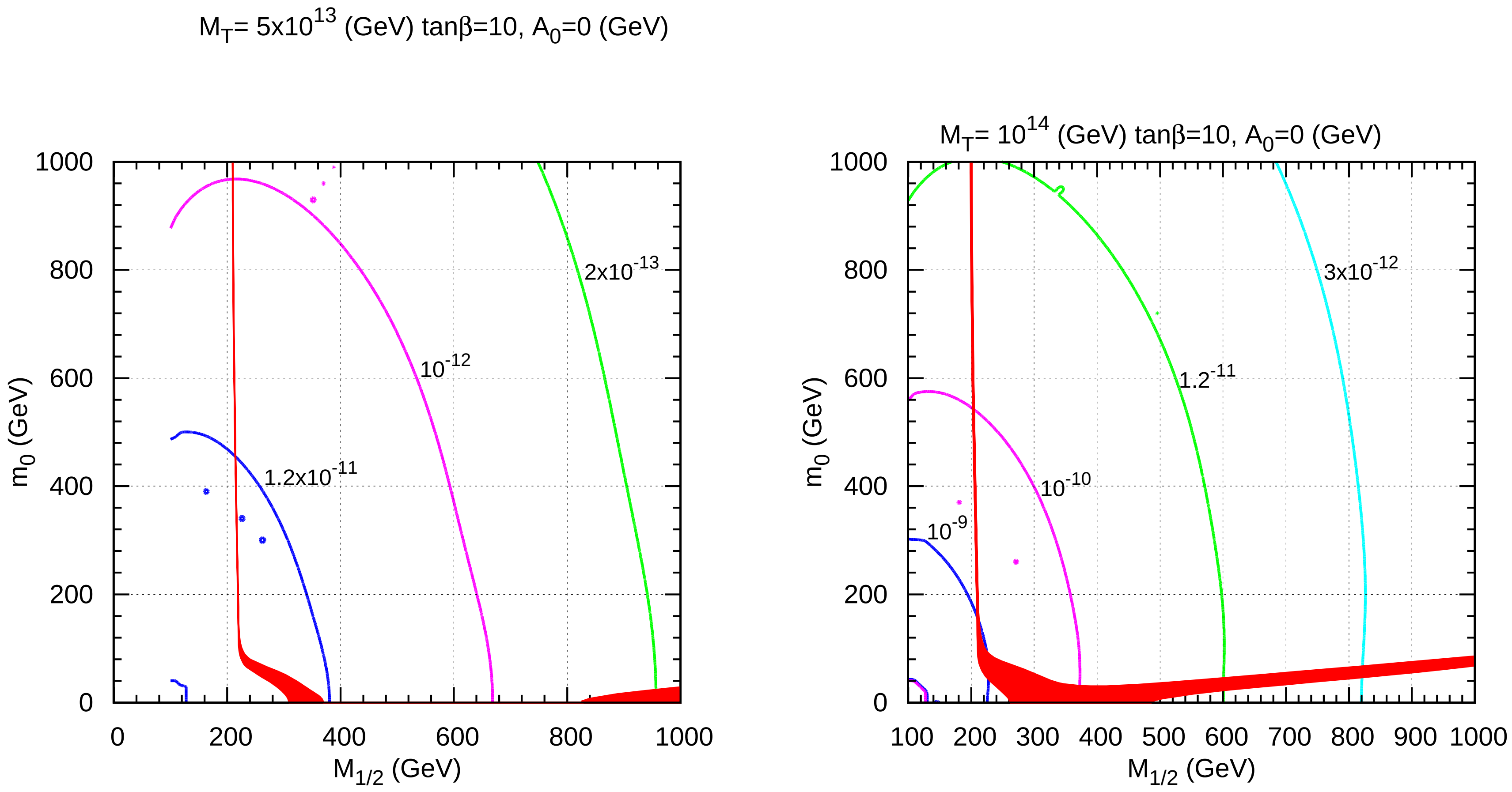


Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 45$, for (from top to bottom) $M_T = 5 \times 10^{13}$ GeV (red), $M_T = 10^{14}$(green) and $M_T = 10^{15}$ GeV (blue).

Variation of the Higgs Funnel with m_{top} & m_b

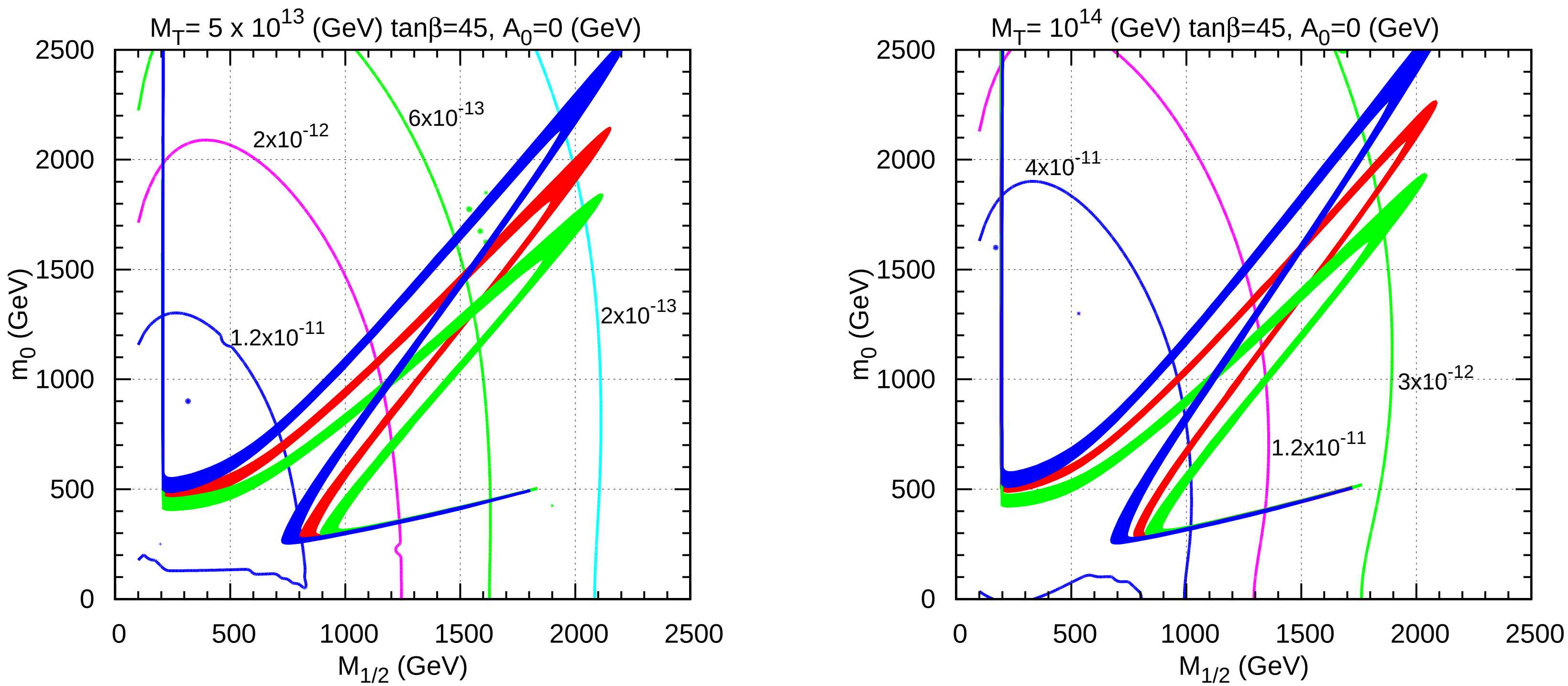


Allowed region for the dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 45$, for $M_T = 5 \times 10^{13}$ GeV and (to the left) for three values of $m_{top} = 169.1$GeV (blue), $m_{top} = 171.2$ GeV (red) and $m_{top} = 173.3$ GeV (green). To the right: The same, but varying m_b. $m_{bot} = 4.13$ GeV (blue), $m_{bot} = 4.2$ GeV (red) and $m_{bot} = 4.37$ GeV (green).



Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for our "standard choice" of mSugra parameters and for two values of M_T: $M_T = 5 \times 10^{13}$ (left panel) and for $M_T = 10^{14}$ (right panel). Superimposed are the contour lines for the $Br(\mu \to e\gamma)$.

DM & LFV . . .



Allowed region for dark matter density ($0.081 < \Omega_{\chi_1^0} h^2 < 0.129$) in the ($m_0, M_{1/2}$) plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 45$, for three values of $m_{top} = 169.1$ GeV (blue), $m_{top} = 171.2$ GeV (red) and $m_{top} = 173.3$ GeV (green) for $M_T = 5 \times 10^{13}$ (left panel) and for $M_T = 10^{14}$ (right panel). Superimposed are the contour lines for the $Br(\mu \to e\gamma)$.

Conclusions

- We have calculated the neutralino relic density in a supersymmetric model with mSugra boundary conditions including a type-II seesaw mechanism to explain current neutrino data.
- We have discussed how the allowed ranges in mSugra parameter space change as a function of the seesaw scale.
- The neutrino data put an upper bound on M_T of the order of $\mathcal{O}(10^{15})$ GeV. Therefore the shifts in the DM regions are necessarily non-zero if our setup is the correct explanation of the observed neutrino data.
- Even more stringent upper limits on M_T follow, in principle, from the non-observation of LFV decays. A smaller M_T implies larger shifts of the DM region.
- The DM calculation suffers from a number of uncertainties, even if we assume the soft masses to be perfectly known. The most important SM parameters turn out to be the bottom and the top quark mass.
- Nevertheless, DM provides in principle an interesting constraint on the (supersymmetric) seesaw explanation of neutrino masses, if seesaw type-II is realized in nature.

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