# Dark Matter in Models with Seesaw Mechanisms for Neutrino Masses

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# Summary

- Motivation
- The Setup
- Results
- Conclusions

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Articles: arXiv:0903.1408, arXiv:0907.5090 & arXiv:10xx.xxxx (in preparation)

# 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 $\sigma$ c.l.

$$\boxed{\Omega_{DM} h^2 = 0.110 \pm 0.006}$$

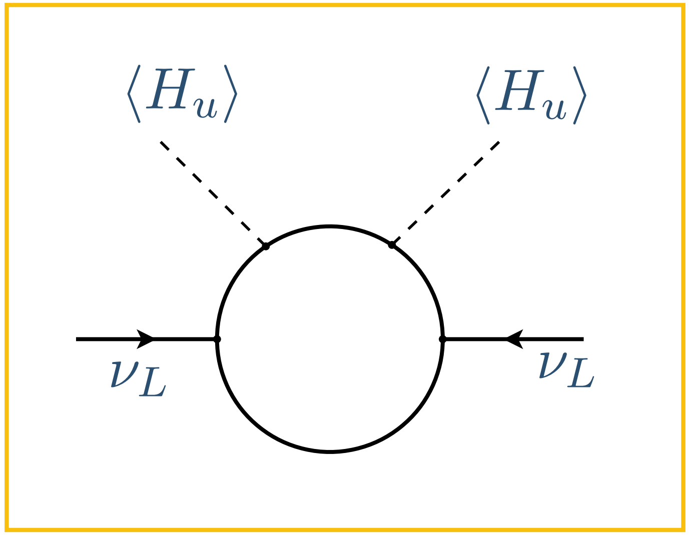
- Since the data from the WMAP satellite and large scale structure formation is best fitted if the DM is cold, weakly interacting mass particles (WIMP) are currently the preferred explanation. While there is certainly no shortage of WIMP candidates, the literature is completely dominated by studies of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

# Seesaw Models for Neutrino Mass

In 1980 Weinberg noticed that the dimension-five operator

$$\mathcal{L}_{\rm Dim5} = L H_u \, L H_u$$

could induce neutrino masses:



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

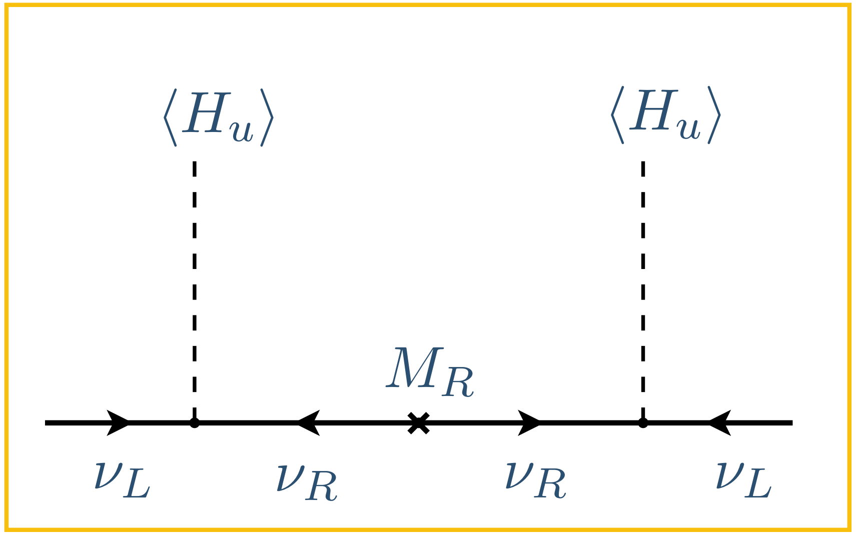
# Type I mechanism

In models with singlet RH neutrinos

$$\mathcal{L} = H_u \, \overline{\nu_L} \, Y_\nu \, \nu_R - \frac{1}{2} \nu_R^T \, C^{-1} \, M_R \, \nu_R$$

we obtain

$$m_{\text{eff}}^{\text{I}} = -(vY_\nu) M_R^{-1} (vY_\nu)^T$$



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

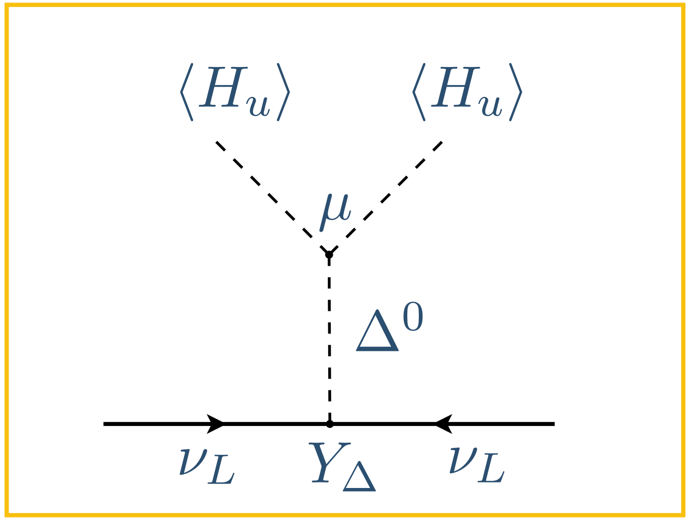
# Type II mechanism

In models with scalar Higgs Triplets

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

we obtain

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



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

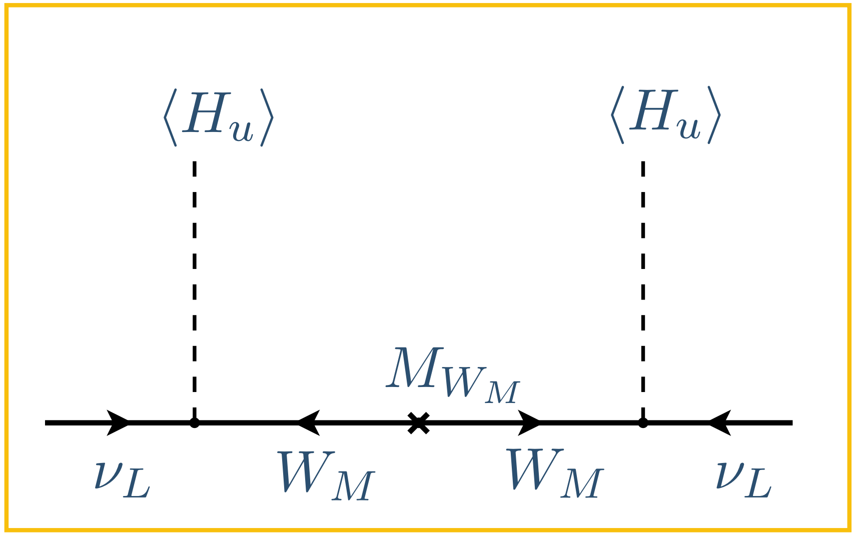
# Type III mechanism

In models with triplet fermions

$$\mathcal{L} = H_u \overline{W_M} Y_\nu^{\mathrm{III}} \nu_L - \frac{1}{2} W_M^T C^{-1} M_{W_M} W_M$$

we obtain

$$m_{\mathrm{eff}}^{\mathrm{III}} = -(v Y_\nu^{\mathrm{III}}) M_{W_M}^{-1} (v Y_\nu^{\mathrm{III}})^T$$

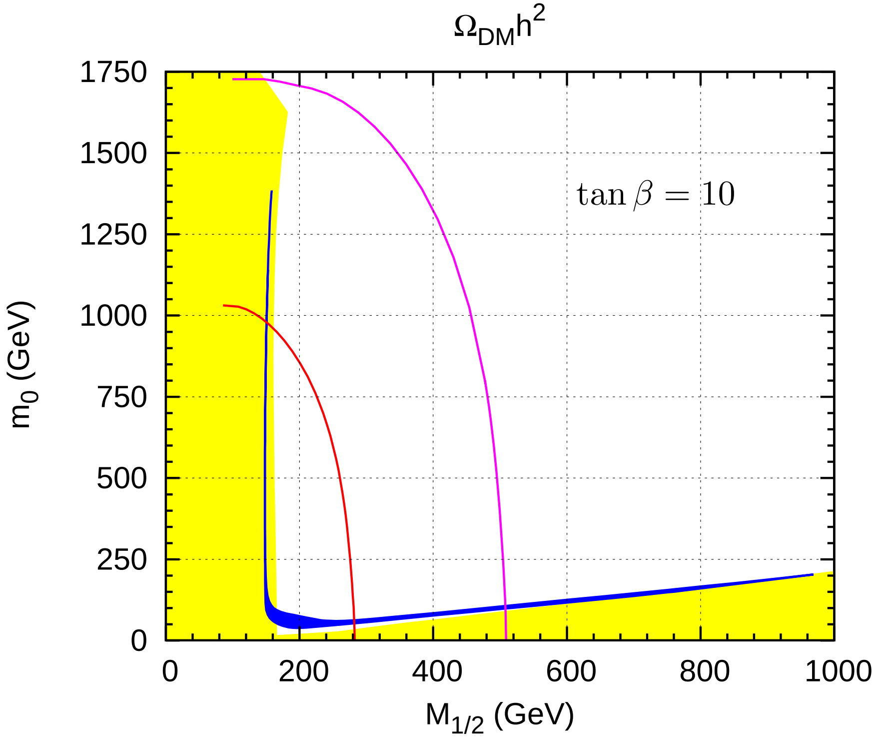


Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Mohapatra, Senjanovic

# Neutralino Dark Matter

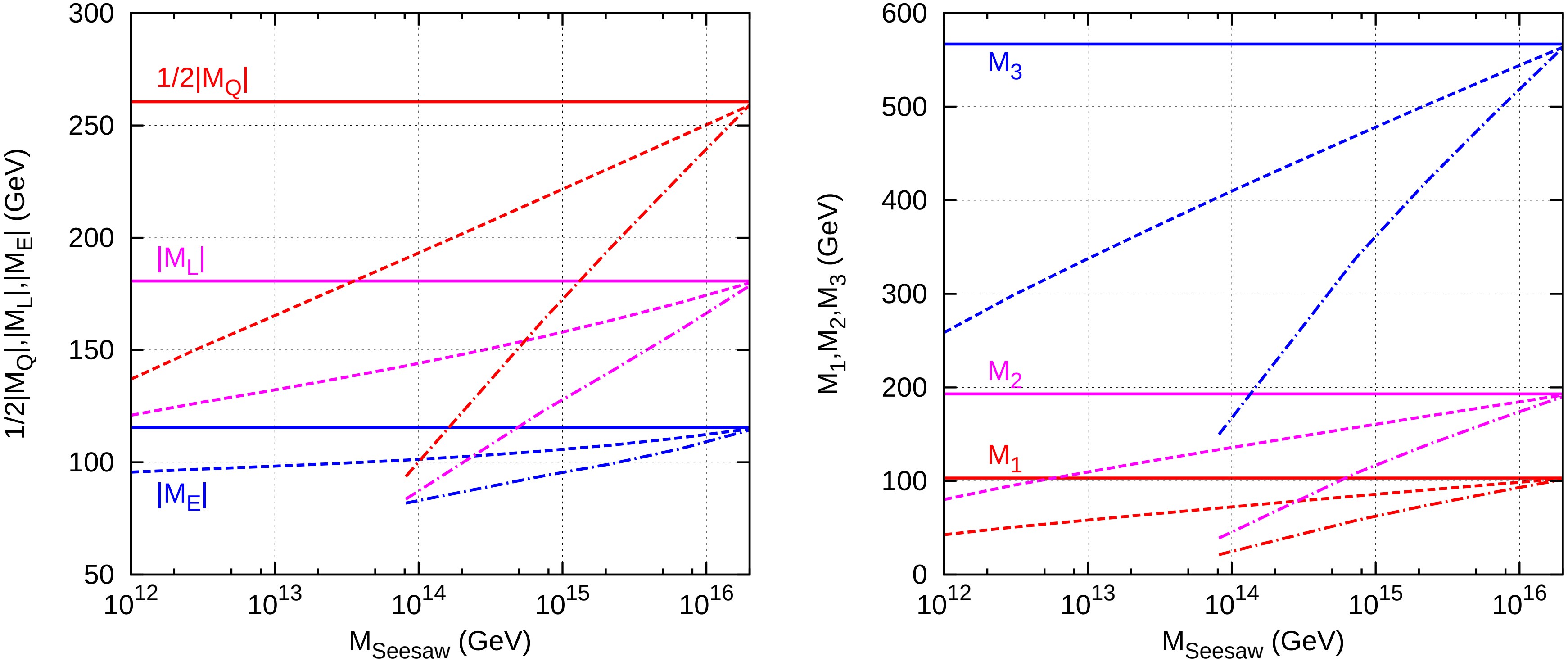
In mSugra only four very specific regions can explain the WMAP data:

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



We will consider neutralino dark matter within a supersymmetric type-I, type-II and type-III seesaw models with mSugra boundary conditions. For type-II and III, 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.

# Running of the soft parameters



Numerically calculated running of scalar (to the left) and gaugino mass parameters (to the right), at two-loop level. The mass parameters are calculated as a function of $M_{\rm Seesaw}$ for the mSugra parameters $m_0 = 70$ GeV and $M_{1/2} = 250$ GeV for seesaw type-I (solid line), type-II (dashed line) and type-III (dot-dashed line). For $M_{\rm Seesaw} \simeq 2 \times 10^{16}$ GeV the mSugra values are recovered. Smaller $M_{\rm Seesaw}$ 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 Setup: GUT scale

At GUT scale the SU(5) invariant superpotentials are

- Type-I

$$W_{\rm RHN} = -\mathbf{Y}_N^{\rm I}\ N^c\ \bar{5}\cdot 5_H + \frac{1}{2}\ M_R\ N^c N^c$$

- Type-II

$$W_{\rm 15H} = \frac{1}{\sqrt{2}}\mathbf{Y}_N^{\rm II}\ \bar{5}\cdot 15\cdot\bar{5} + \frac{1}{\sqrt{2}}\lambda_1\bar{5}_H\cdot 15\cdot\bar{5}_H + \frac{1}{\sqrt{2}}\lambda_2 5_H\cdot\overline{15}\cdot 5_H$$
$$+\mathbf{Y}_5 10\cdot\bar{5}\cdot\bar{5}_H + \mathbf{Y}_{10}10\cdot 10\cdot 5_H + M_{15}15\cdot\overline{15} + M_5\bar{5}_H\cdot 5_H$$

- Type-III

$$W_{\rm 24H} = \mathbf{Y}_N^{\rm III}\ 5_H\cdot 24\cdot\bar{5} + \frac{1}{2}M_{24}\ 24\cdot 24$$

# The $SU(5)$-broken phase

Under $SU(3) \times SU_L(2) \times U(1)_Y$

- The **5**, **10** and $\mathbf{5}_H$ contain

$$\bar{5} = (d^c, L),\ \ 10 = (u^c, e^c, Q),\ \ 5_H = (t, H_u),\ \ \bar{5}_H = (\bar{t}, H_d)$$

- The **15** decomposes as

$$\mathbf{15} = S(6, 1, -\frac{2}{3}) + T(1, 3, 1) + Z(3, 2, \frac{1}{6})$$

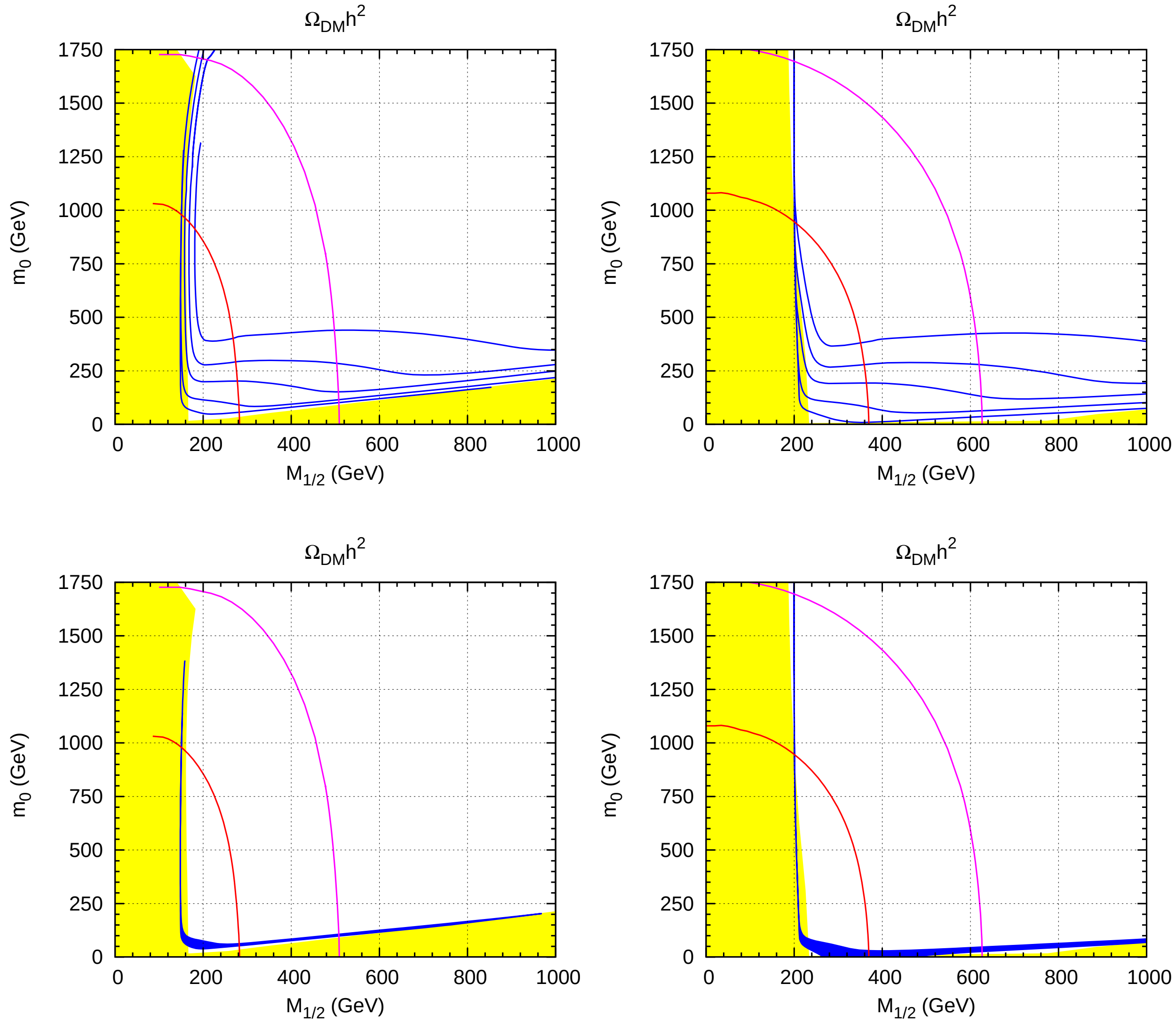
- The **24** decomposes as

$$\mathbf{24} = W_M(1, 3, 0) + B_M(1, 1, 0) + \overline{X}_M(3, 2, -\frac{5}{6}) + X_M(\bar{3}, 2, \frac{5}{6}) + G_M(8, 1, 0)$$

# The Numerical Procedure

- All the plots shown below are based on the program packages `SPheno` and `micrOMEGAs`.
- We use `SPheno` version 3, including the RGEs for Seesaw Type I, II and III at the 2-loop level (calculated with `Sarah`).
- For any given set of mSugra and type-I, type-II or type-III 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, $\Omega_{\chi_1^0} h^2$. All points satisfy neutrino data.
- 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 $\sigma$ c.l. boundaries, i.e. $\Omega_{DM} h^2 = [0.081, 0.12.69]$. Note, however that the use of 1 $\sigma$ 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 $\sigma$ c.l. Left: mSugra; Right: $M_T = 10^{14}$ GeV.

# Variation with the Triplet Mass

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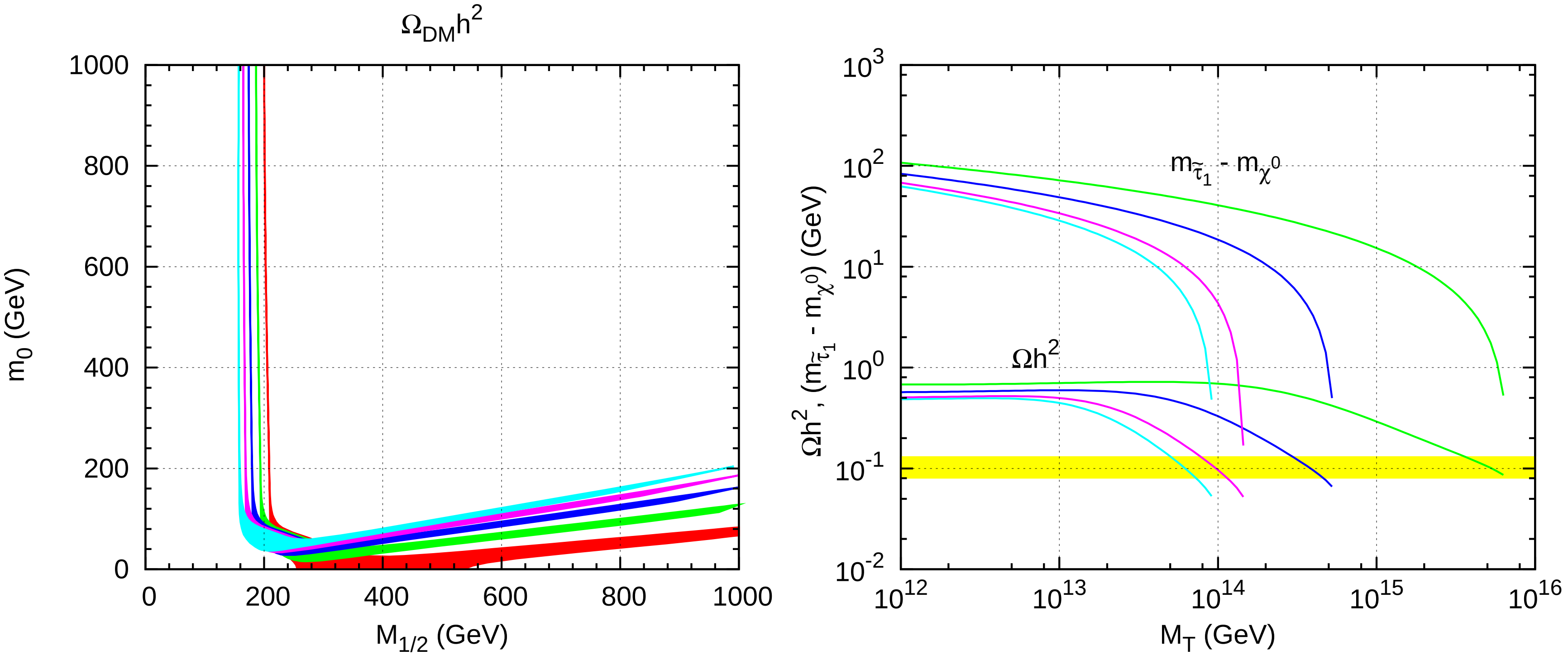
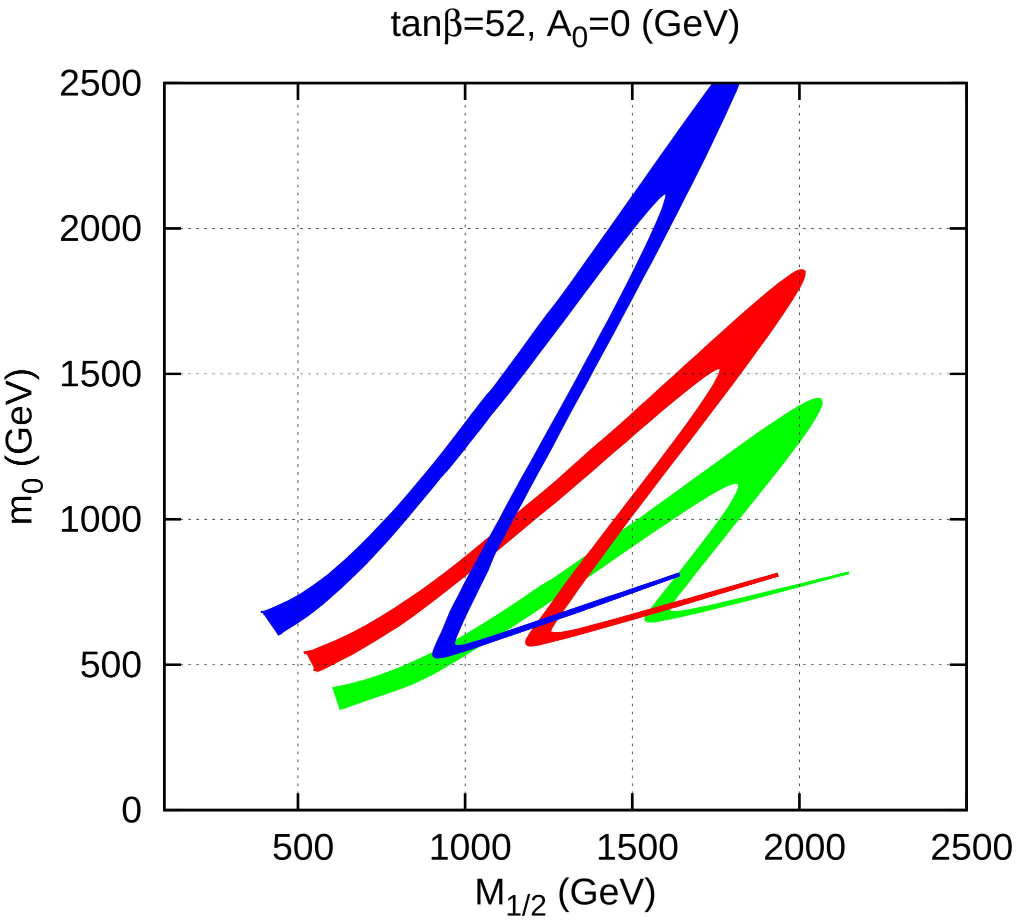
- DM Contours
- MT Variation
- Funnel & MT
- Funnel &mt mb
- DM & LFV
- Type-III

Conclusions



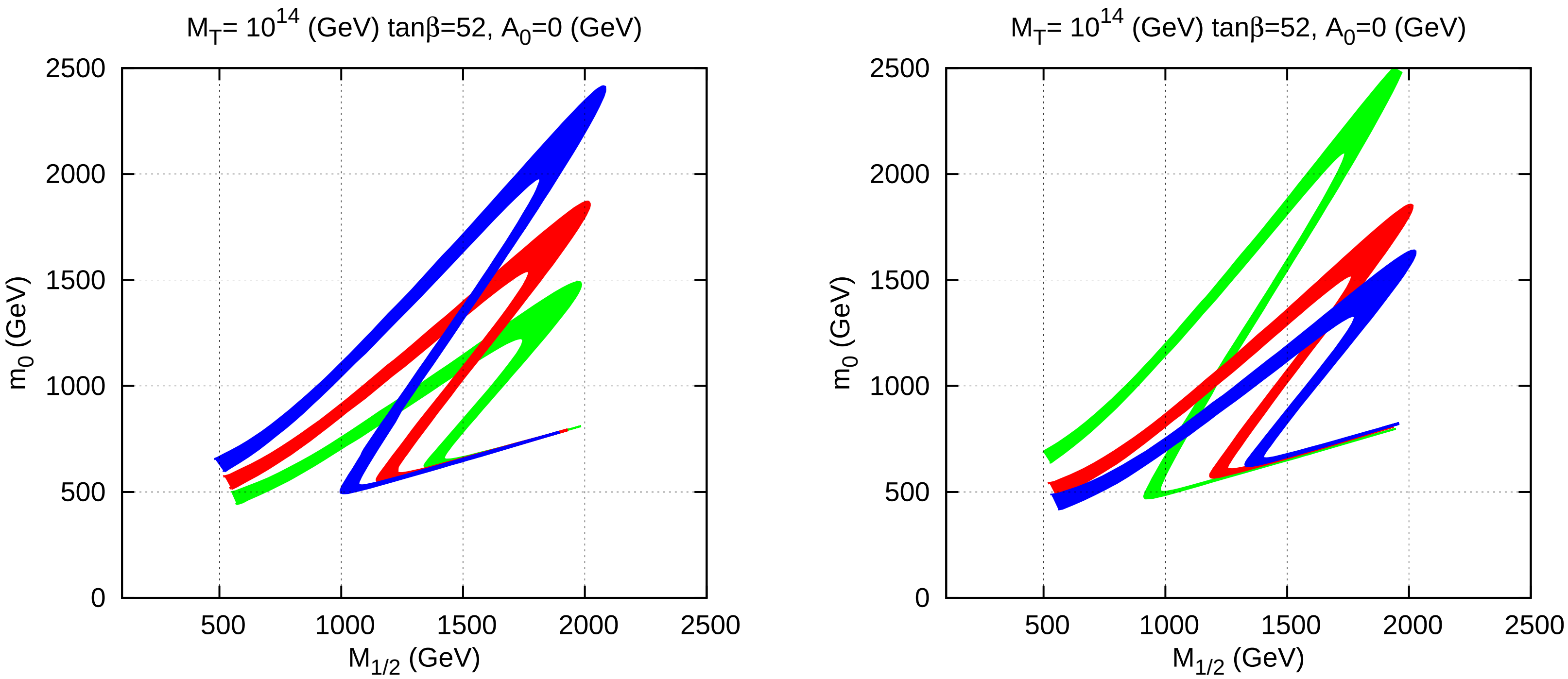
Allowed region for dark matter density ($0.081 < \Omega_{\chi_1^0} h^2 < 0.129$) in the ($m_0, M_{1/2}$) plane for the "standard choice" $\tan\beta = 10$, $A_0 = 0$ and $\mu \geq 0$, for five values from $M_T$, $M_T = 10^{14}$ GeV (red), to $M_T = 10^{16}$ GeV (cyan), to the left. To the right: Variation of the mass difference $m_{\tilde{\tau}_1} - m_{\chi 0}$ (top lines) and of $\Omega h^2$ (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.

# Variation of the Higgs Funnel with $M_T$



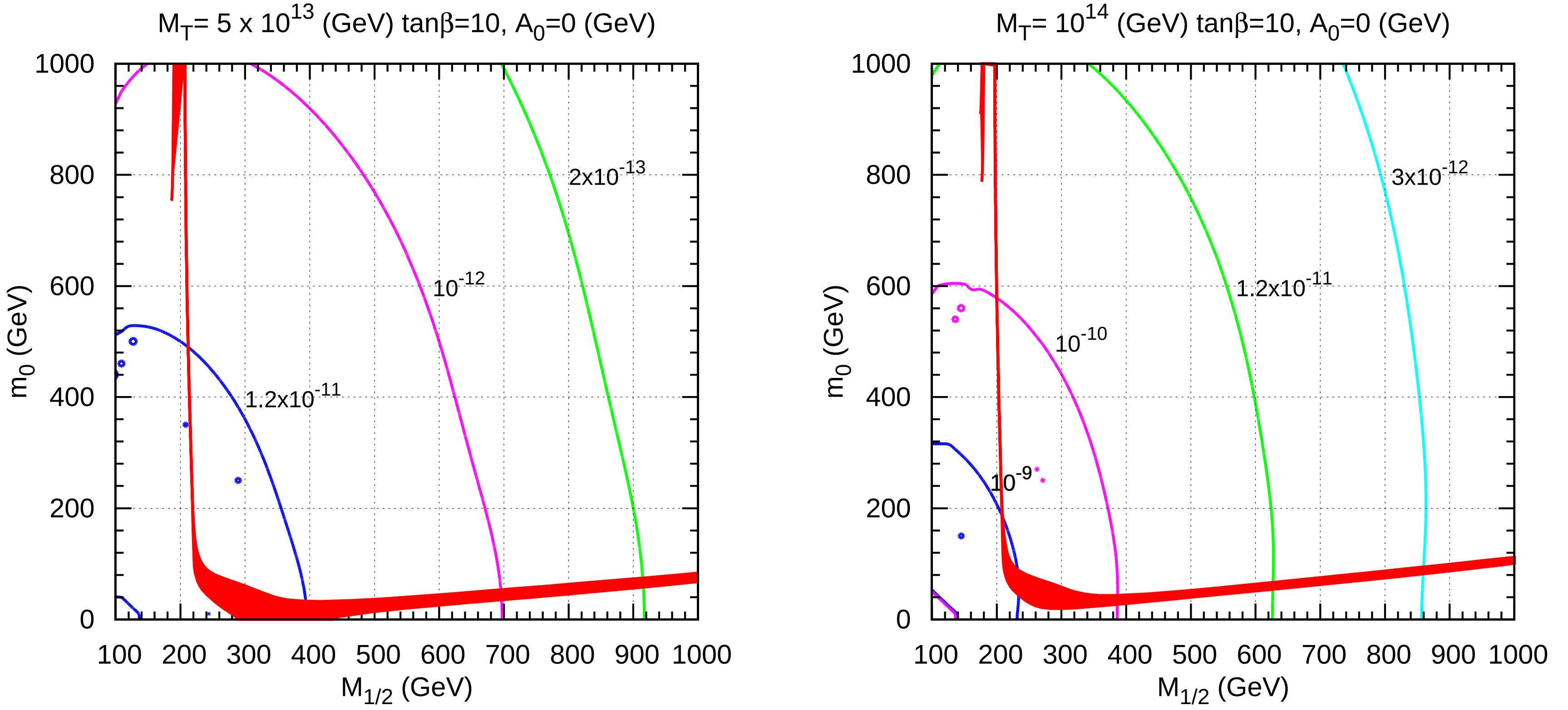
Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 45$, for (from top to bottom) $M_T = 5 \times 10^{13}$ GeV (red), $M_T = 10^{14}$(green) and $M_T = 10^{15}$ GeV (blue).

# Variation of the Higgs Funnel with $m_{\text{top}}$ & $m_b$



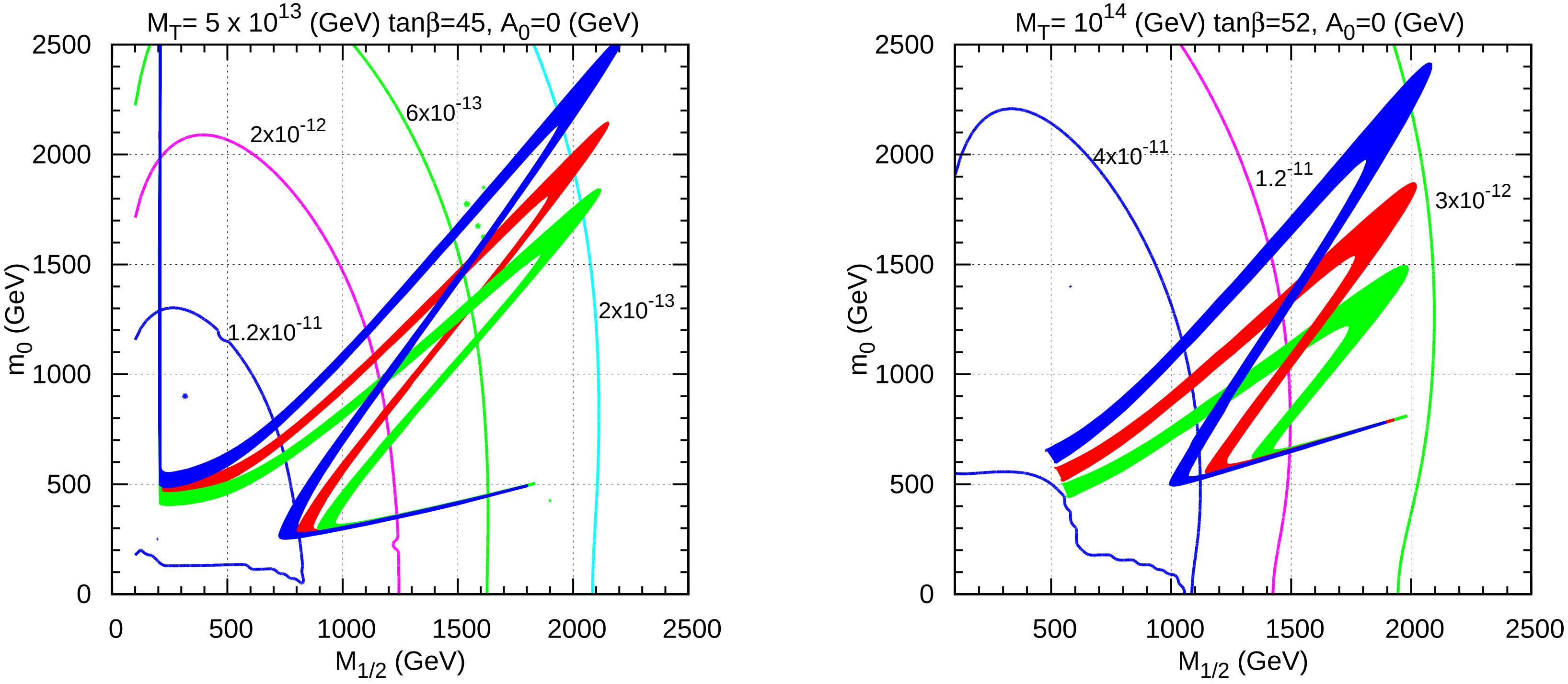
Allowed region for the dark matter density in the $(m_0, M_{1/2})$ plane for $A_0 = 0$, $\mu \geq 0$ and $\tan\beta = 52$, for $M_T = 10^{14}$ GeV and (to the left) for three values of $m_{top} = 169.1$GeV (blue), $m_{top} = 171.2$ GeV (red) and $m_{top} = 173.3$ GeV (green). To the right: The same, but varying $m_b$. $m_{bot} = 4.13$ GeV (blue), $m_{bot} = 4.2$ GeV (red) and $m_{bot} = 4.37$ GeV (green).

# Dark Matter and Lepton Flavour Violation



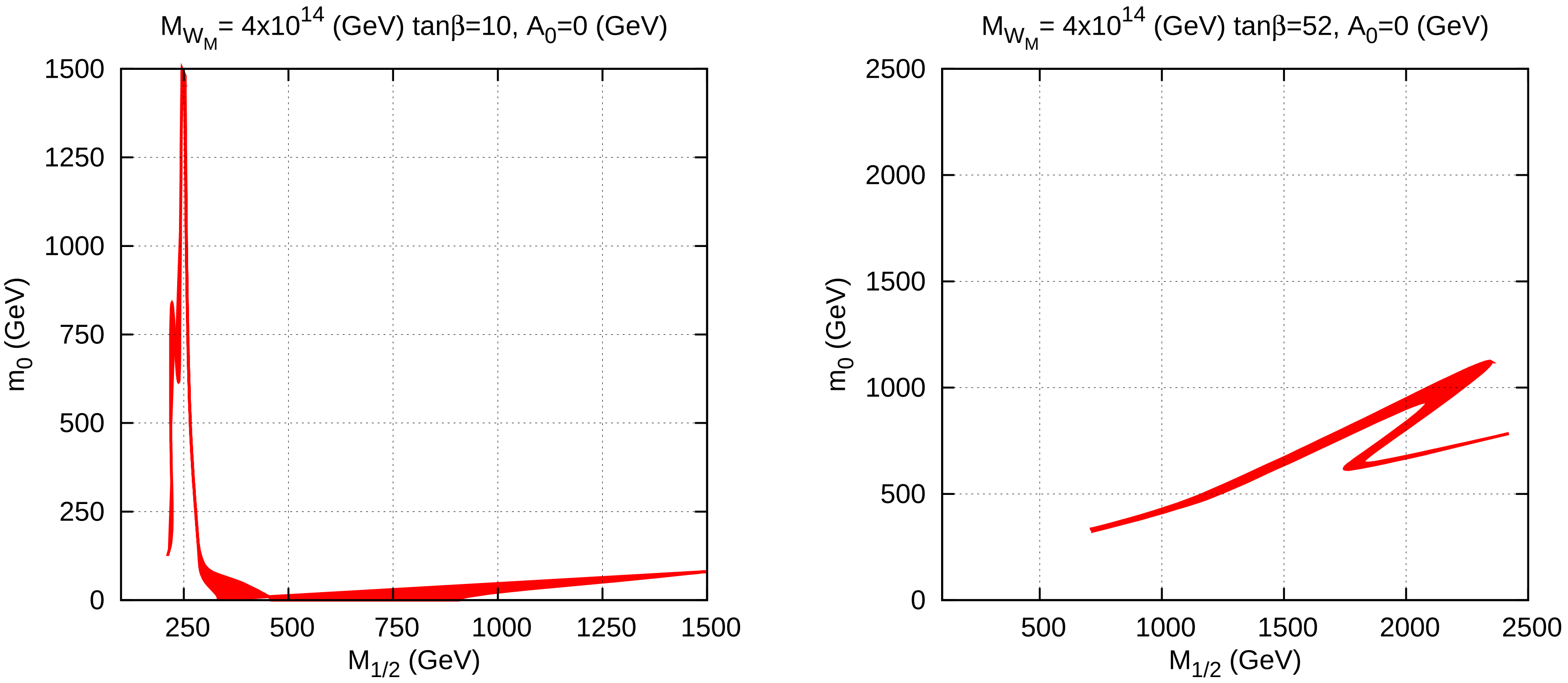
Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for our "standard choice" of mSugra parameters and for two values of $M_T$: $M_T = 5 \times 10^{13}$ (left panel) and for $M_T = 10^{14}$ (right panel). Superimposed are the contour lines for the $Br(\mu \to e\gamma)$.

# 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 $\tan\beta = 52$, 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 $Br(\mu \to e\gamma)$.

# Preliminary: Type-III



Allowed region for dark matter density in the $(m_0, M_{1/2})$ plane for our "standard choice" of mSugra parameters and type-III with $M_{W_M} = 4 \times 10^{14}$ for $\tan\beta = 10$ (left panel) and for $\tan\beta = 52$ (right panel).

# Conclusions

- We have calculated the neutralino relic density in a supersymmetric model with mSugra boundary conditions including type-I, type-II or type-III seesaw mechanisms 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 $M_T$, $M_{W_M}$ 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 $M_T$ or $M_{W_M}$ 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 is realized in nature.