Mixed Light Sneutrinos as Thermal Dark Matter

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in collaboration with

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Outline

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2. Framework
3. Constraints on the model
4. Results in parameter space
    4-1. Direct detection
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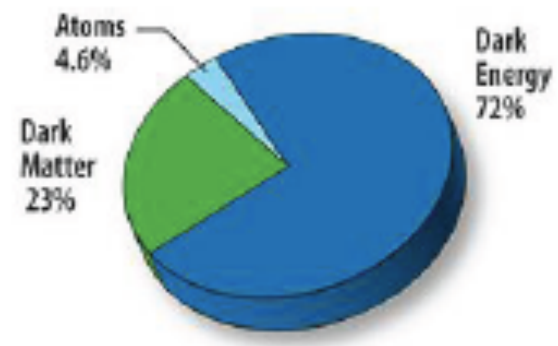
5. Collider signatures
6. Conclusions

1. Motivation

- Neutrino oscillations:
  - Nonzero neutrino masses are required
  - Neutrinos are massless in the SM



[http://map.gsfc.nasa.gov]

- Non-baryonic dark matter (DM)
  - $\Omega_{DM} h^2 = 0.1109 \pm 0.0059$
  - No candidate particle in the SM

- In Supersymmetric (SUSY) models with Dirac neutrinos
  - Right Handed (RH) neutrinos → RH-sneutrino superpartners
  - Non-negligible $A_{\tilde{\nu}}$ induces sizable L-R mixing in sneutrino sector
    → Light sneutrino $\tilde{\nu}_1$ is the LSP
    → Relic density is in desirable range

[Arkani-hamded,Hall,Murayama,Weiner(2001);
Arina,Fornengo(2007);Thomas,Tucker-Smith,Weiner(2008)]

2. Framework

- MSSM is now extended with only Dirac masses for sneutrinos

$$\Delta\mathcal{L}_{\rm soft} = m^2_{\tilde{N}_i}|\tilde{N}_i|^2 + A_{\tilde{\nu}_i}\tilde{L}_i\tilde{N}_i H_u + \text{h.c.}$$

- Sneutrino mass matrix

$$\mathcal{M}^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\tilde{L}} + \frac{1}{2}m^2_Z\cos 2\beta & \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\, v\sin\beta \\ \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\, v\sin\beta & m^2_{\tilde{N}} \end{pmatrix}$$

$$\tilde{\nu}_1 = \cos\theta_{\tilde{\nu}}\,\tilde{\nu}_R - \sin\theta_{\tilde{\nu}}\,\tilde{\nu}_L\,, \quad \theta_{\tilde{\nu}} = \frac{1}{2}\sin^{-1}\left(\frac{\sqrt{2}A_{\tilde{\nu}}\, v\sin\beta}{m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1}}\right) \quad \text{where } m_{\tilde{\nu}_1} < m_{\tilde{\nu}_2}$$

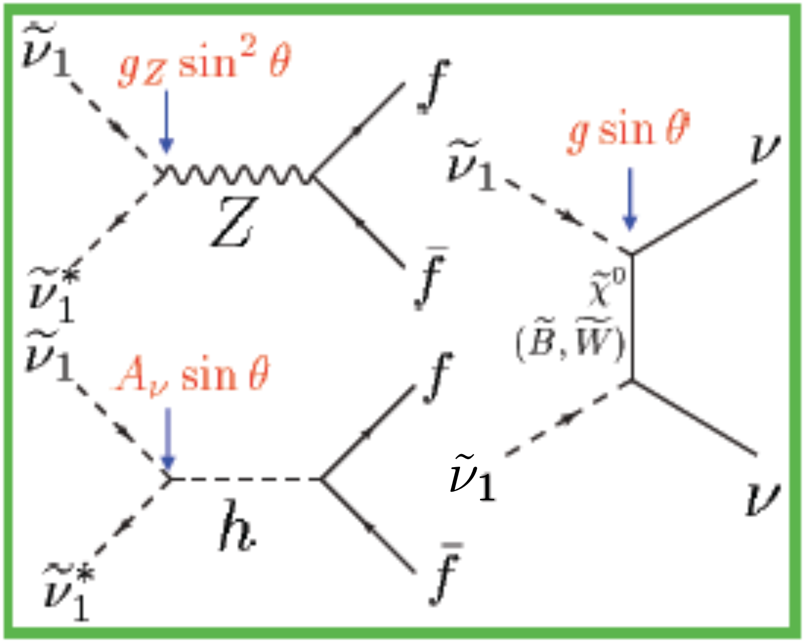
$$\tilde{\nu}_2 = \sin\theta_{\tilde{\nu}}\,\tilde{\nu}_R + \cos\theta_{\tilde{\nu}}\,\tilde{\nu}_L\,,$$

- $A_{\tilde{\nu}}$ is not proportional to small neutrino Yukawa couplings

  → not negligible → RH sneutrino mass term by $A_{\tilde{\nu}}$

- Light sneutrino $\tilde{\nu}_1$ is mostly $\tilde{\nu}_R$ by assuming $m_{\tilde{N}} < m_{\tilde{L}}$

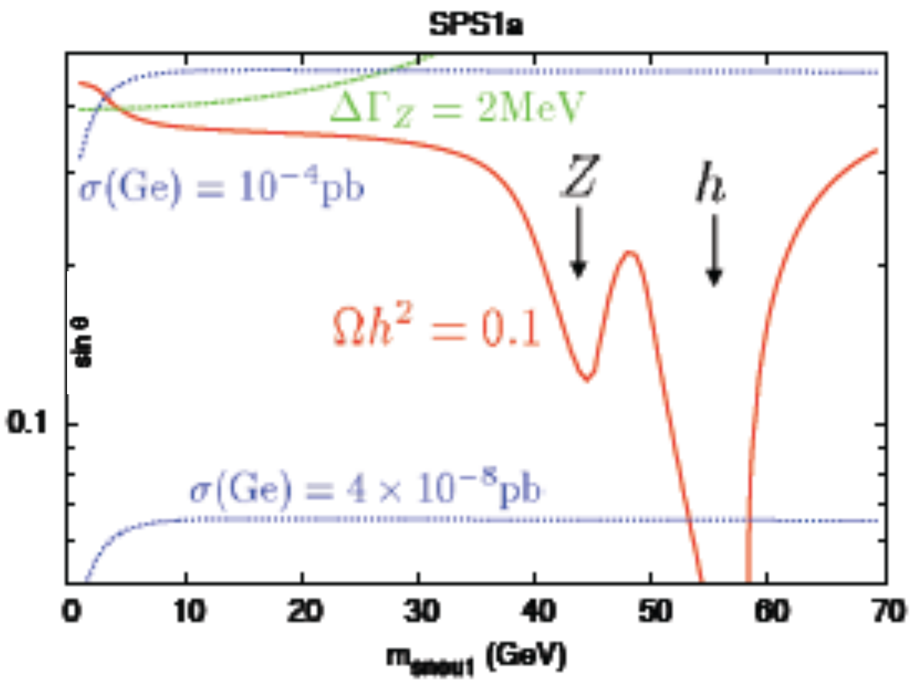
Important processes



- **Computation:**

  LanHEP → CalcHEP → micrOMGEAs

  [Belanger,Boudjema,Pukhov,Semenov]



Particle spectrum

- Assumptions
  - * $M_2 \simeq 2M_1 \simeq M_3/3$ at the weak scale
  - * use $m_{\tilde{\nu}_1}$, $m_{\tilde{\nu}_2}$ and $\theta_{\tilde{\nu}}$, as input parameters,
  - * compute the $m_{\tilde{L}}$, $m_{\tilde{N}}$ and $A_{\tilde{\nu}}$
  - * one-generation case, only the tau-sneutrino is light
  - * three-generation case,
    complete degeneracy between the slepton gen

- Additional radiative corrections to Higgs at 2-loop and sneutrinos at 1-loop
  - Main contribution to radiative corrections to sneutrino masses

$$\Delta M^2_{\tilde{\nu}RR}(Q)|_{\text{app}} = \frac{A^2_{\tilde{\nu}}}{8\pi^2}\left(\log\frac{m^2_{\tilde{\nu}_2}}{Q^2} - 1\right)$$

  - Higgs mass → negative correction

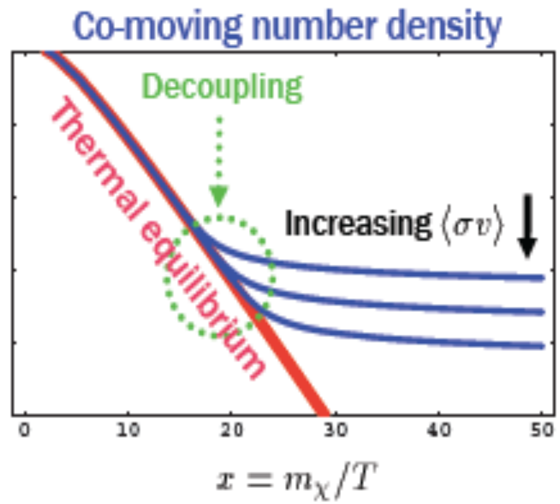
$$\Delta\lambda_2^{(\tilde{\nu})} = -\frac{1}{16\pi^2}\sum_{i=1}^{N_f}\frac{|A_\nu|^4}{(m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1})^2}\left(\frac{m^2_{\tilde{\nu}_2} + m^2_{\tilde{\nu}_1}}{m^2_{\tilde{\nu}_2} - m^2_{\tilde{\nu}_1}}\log\frac{m^2_{\tilde{\nu}_2}}{m^2_{\tilde{\nu}_1}} - 2\right)$$

3. Constraints

- Relic abundance of neutrino:

After annihilation rate dropped below expansion rate, number of density per co-moving volume is almost fixed

$$\Omega_\chi h^2 \simeq 0.04 \times \left(\frac{\langle \sigma v \rangle}{1\ \mathrm{pb}}\right)^{-1} \left(\frac{x_F}{22}\right) \left(\frac{g_*}{90}\right)^{-1/2}$$



Standard freeze-out feature

- Collider constrains:

Invisible width of Z-boson with light sneutrino $m_{\tilde{\nu}} < m_Z/2$, and LEP2 constraints

$$\Delta\Gamma_Z = \sum_{i=1}^{N_f} \Gamma_\nu \frac{\sin^4\theta_{\tilde{\nu}}}{2} \left(1 - \left(\frac{2m_{\tilde{\nu}}}{m_Z}\right)^2\right)^{3/2} < 2\ \mathrm{MeV}$$

- Direct detection (DD):

Spin-independent DD through Z or Higgs exchange assuming point-like nucleus

$$\sigma^{\mathrm{SI}}_{\tilde{\nu}_1 N} = \frac{4\mu_\chi^2}{\pi} \frac{(Zf_p + (A-Z)f_n)^2}{A^2}$$

For Xenon $A = 131, Z = 54$
while for Germanium $A = 76, \dot{Z} = 32$

Annihilation channels

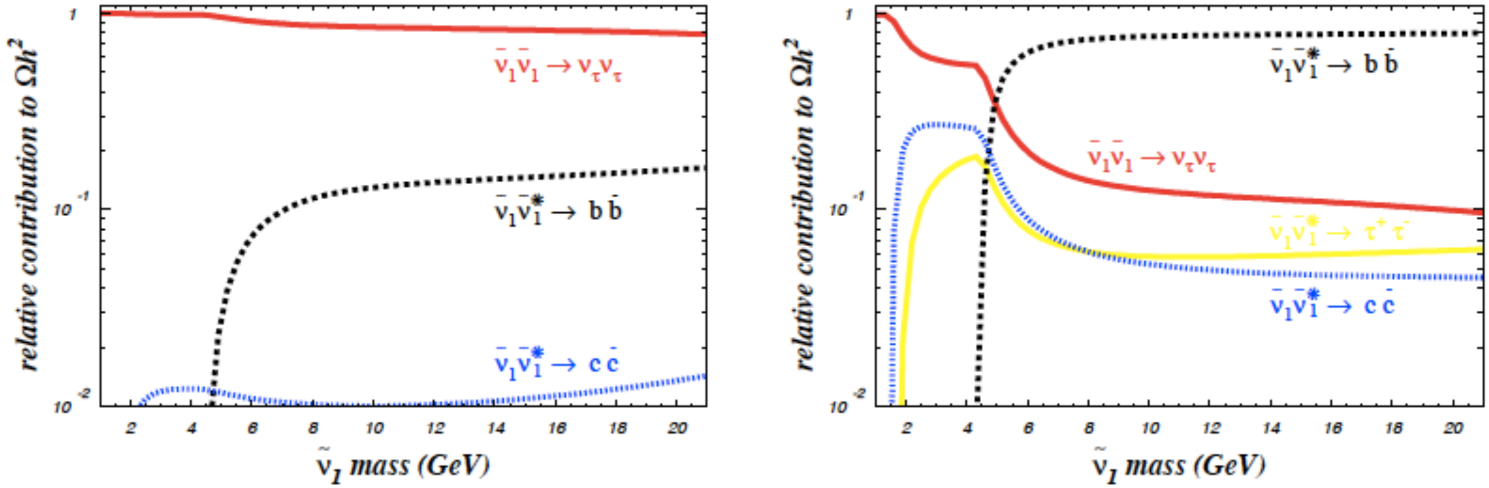
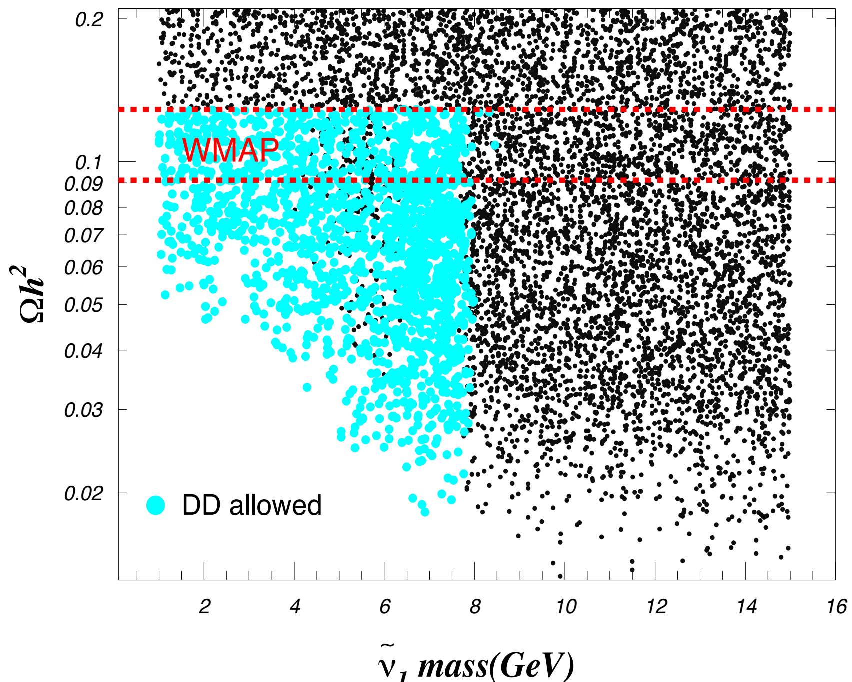
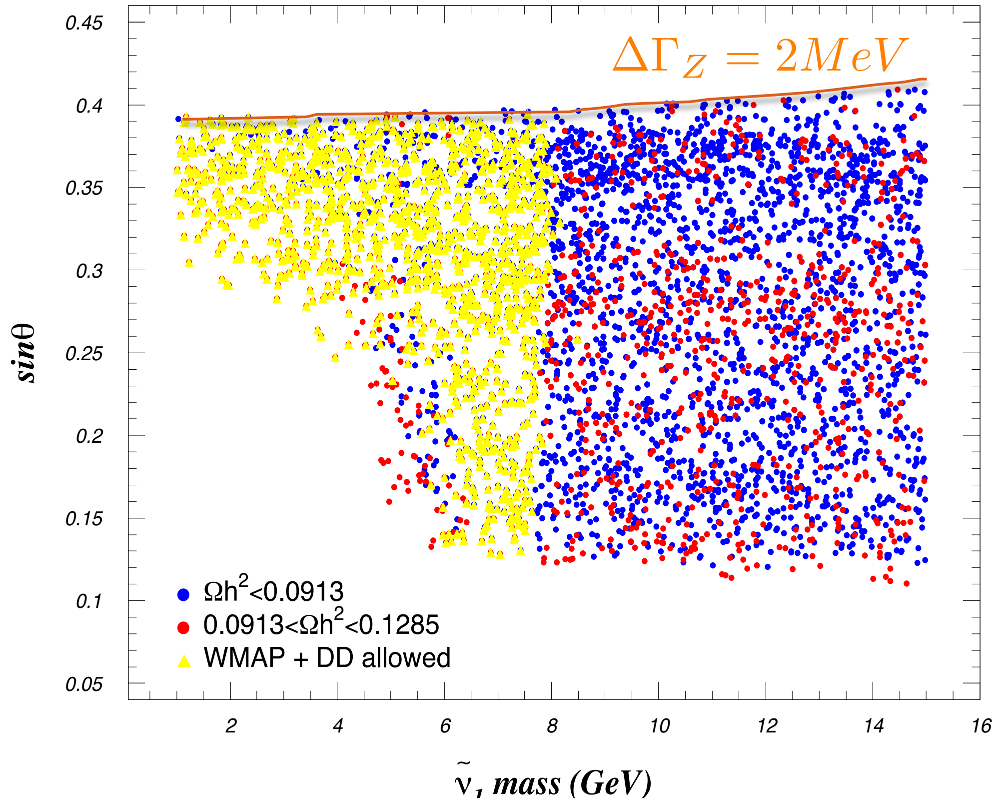


Figure : Relative contributions of different annihilation channels as a function of the $\tilde{\nu}_1$ mass, on the left for $m_{\tilde{\nu}_2} = 200$ GeV and $\sin\theta_{\tilde{\nu}} = 0.35$, on the right for $m_{\tilde{\nu}_2} = 500$ GeV and $\sin\theta_{\tilde{\nu}} = 0.22$

Parameter scan with constraints

- Apply WMAP bound $\Omega h^2 < 0.1285$ and collider constraints
- Scan over $m_{\tilde{\nu}_1}, m_{\tilde{\nu}_2}, sin\theta, M_2$

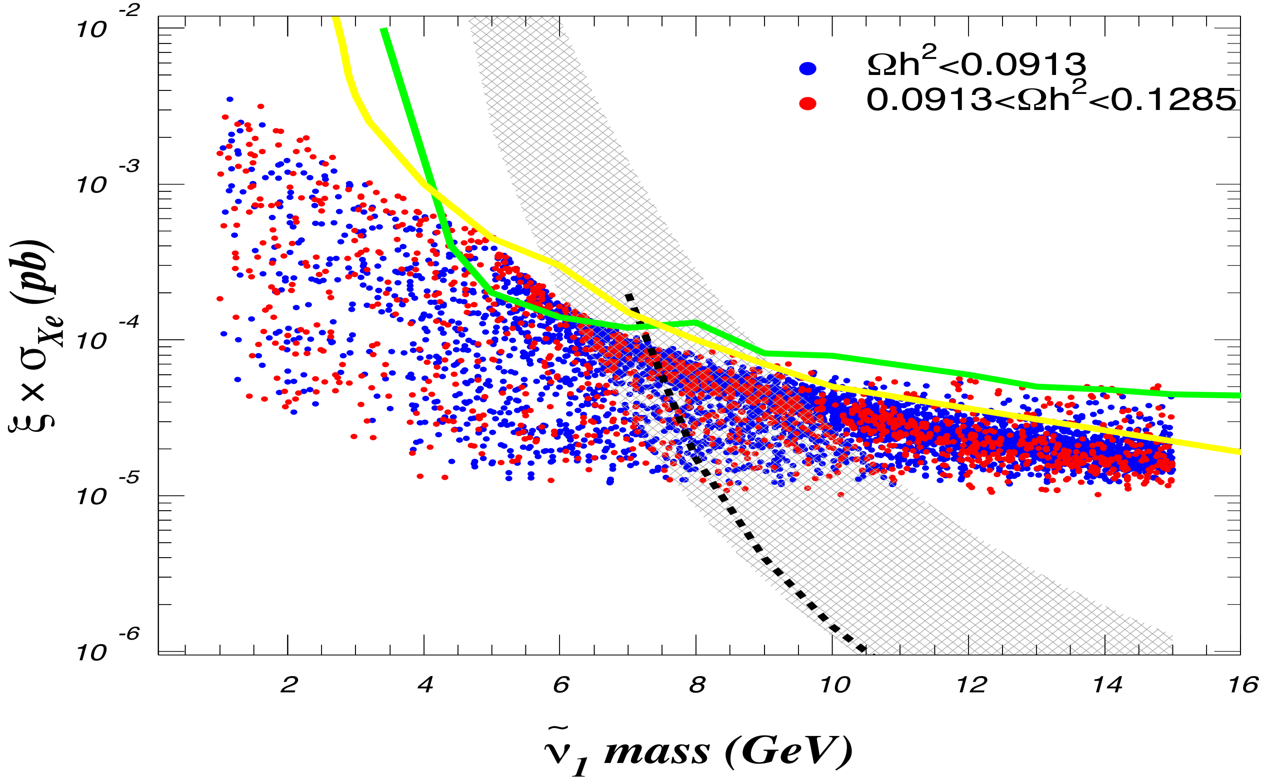




one light sneutrino case

4-1. Direct detection one light sneutrino case

- Apply WMAP bound $\Omega h^2 < 0.1285$ and collider constraints $\Delta\Gamma_Z = 2MeV$, LEP2



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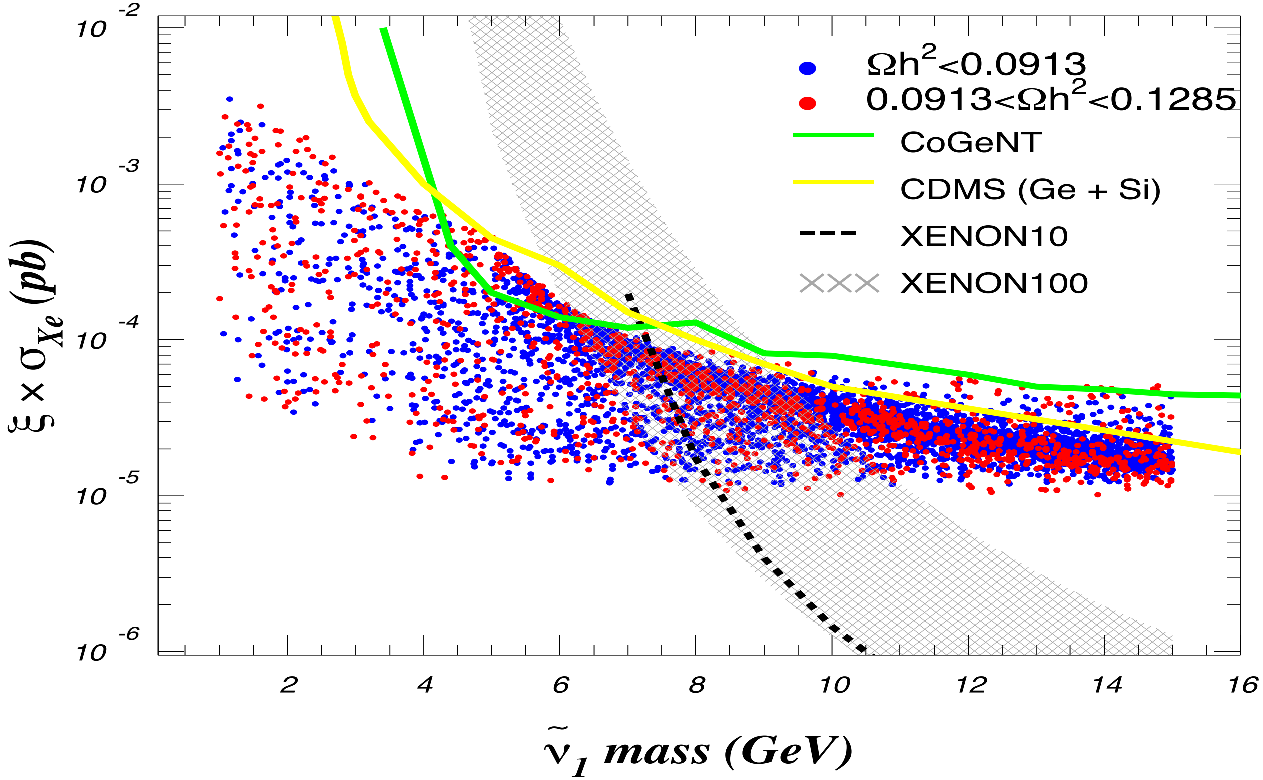

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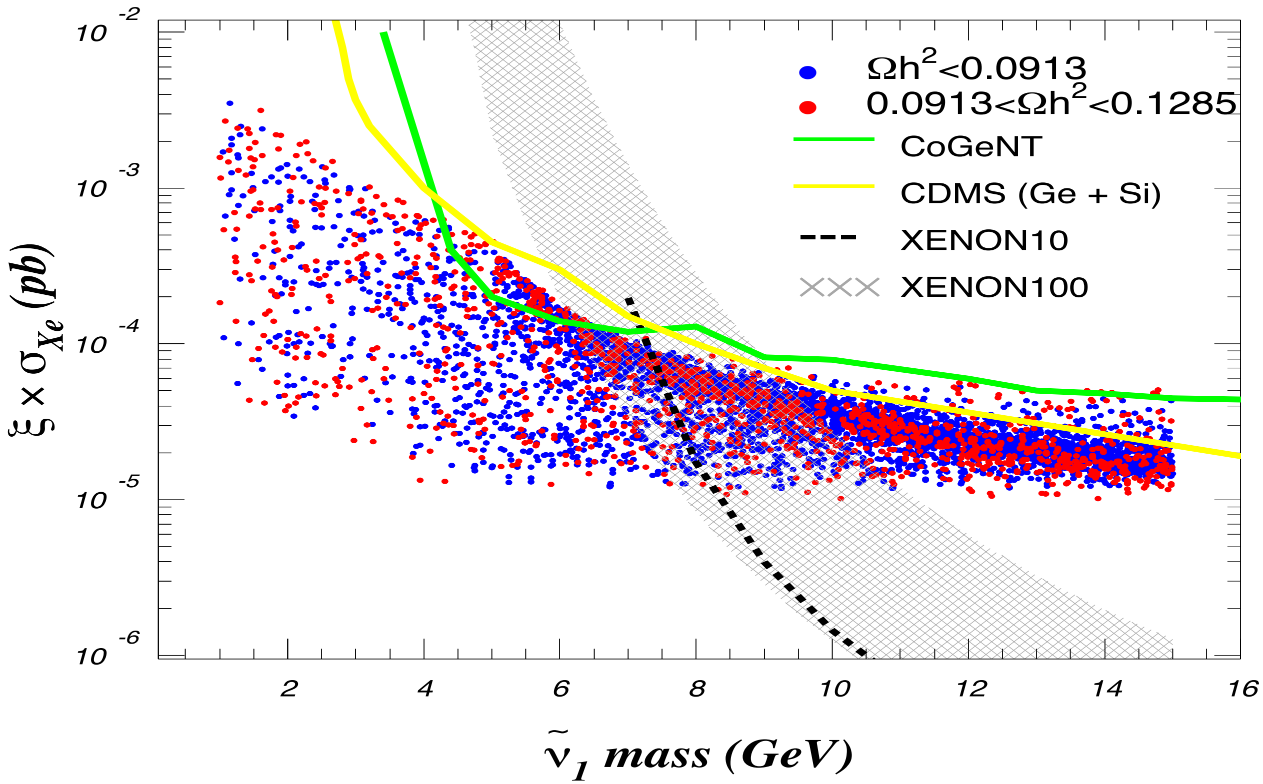
- Apply WMAP bound $\Omega h^2 < 0.1285$ and collider constraints $\Delta\Gamma_Z = 2MeV$
- $\xi = \Omega h^2/0.11$ for $\Omega h^2 < 0.0913$, and 1 otherwise
- $v_0 = 220 \pm 20\text{km/s}$, $500 < v_{esc} < 600\text{km/s}$, $\rho = 0.3\ \text{GeV/cm}^3$



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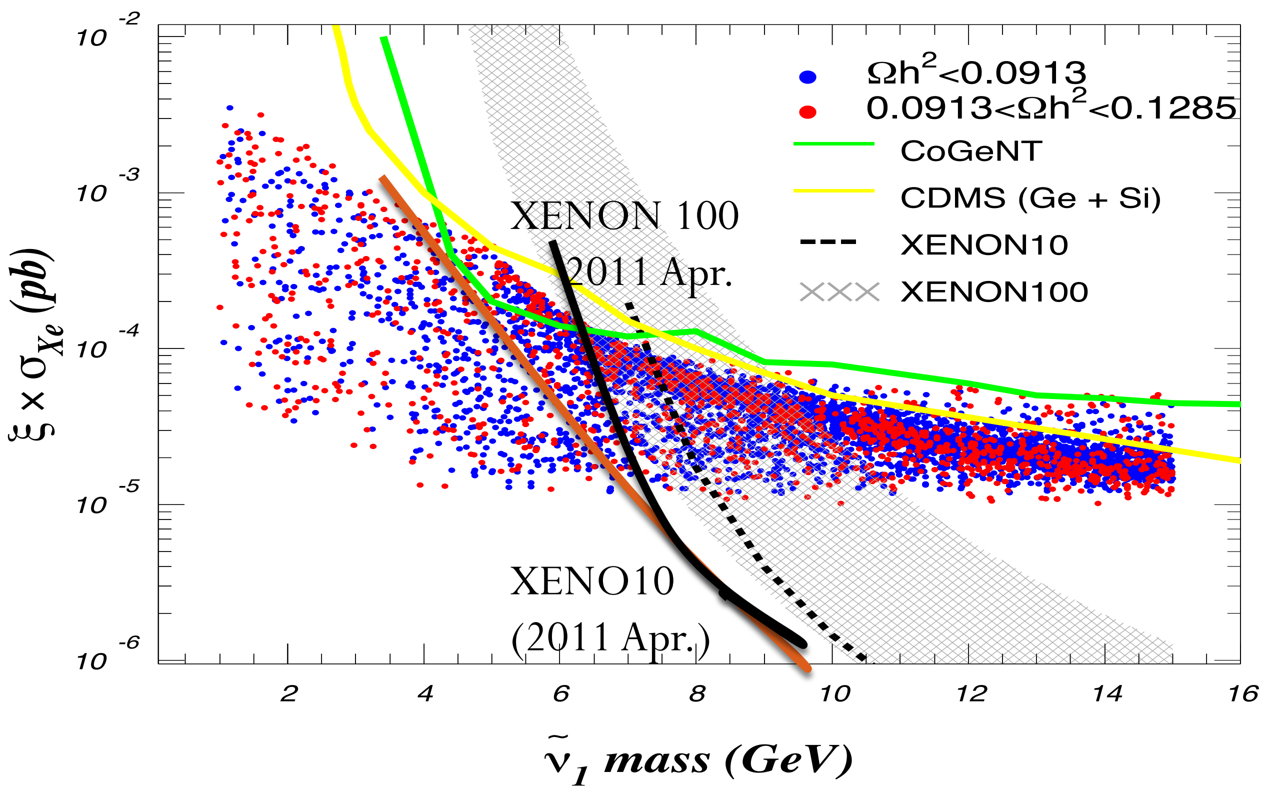
- $v_0 = 220 \pm 20\text{km/s}$, $500 < v_{esc} < 600\text{km/s}$, $\rho = 0.3\ \text{GeV/cm}^3$
- DD exp. favored regions below 8 GeV



4-1.Direct detection three degenerate light sneutrinos

- Relic density can increase by factor up to 3: $\langle \sigma v \rangle \propto (\sum g_i^2 \sigma_{ij}) / \sum g_i^2$
- Z- width on mixing angle is stronger

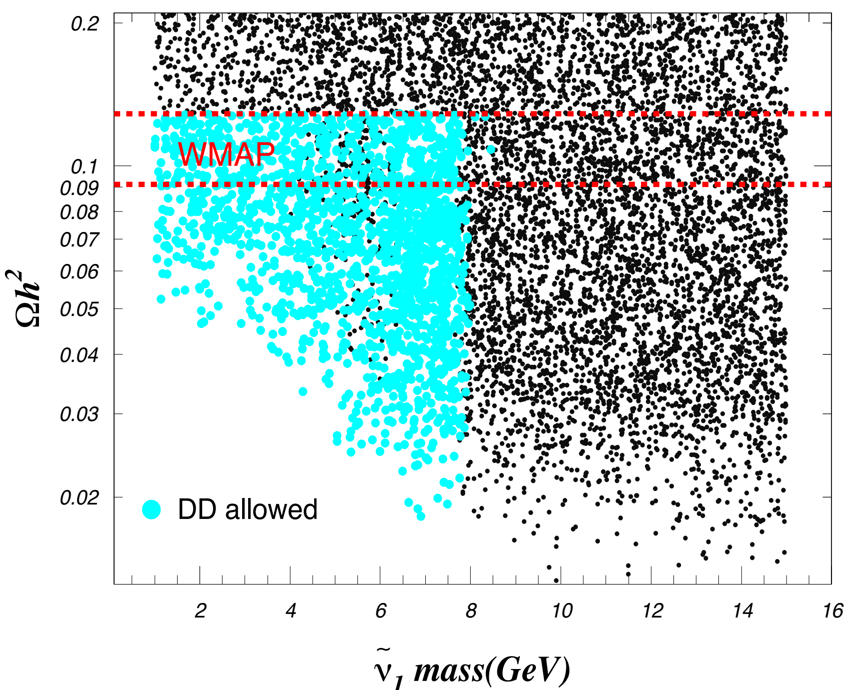
$$\Delta\Gamma_Z = \sum_{i=1}^{N_f} \Gamma_\nu \frac{\sin^4 \theta_{\tilde{\nu}}}{2} \left(1 - \left(\frac{2m_{\tilde{\nu}}}{m_Z}\right)^2\right)^{3/2} < 2 \text{ MeV}$$

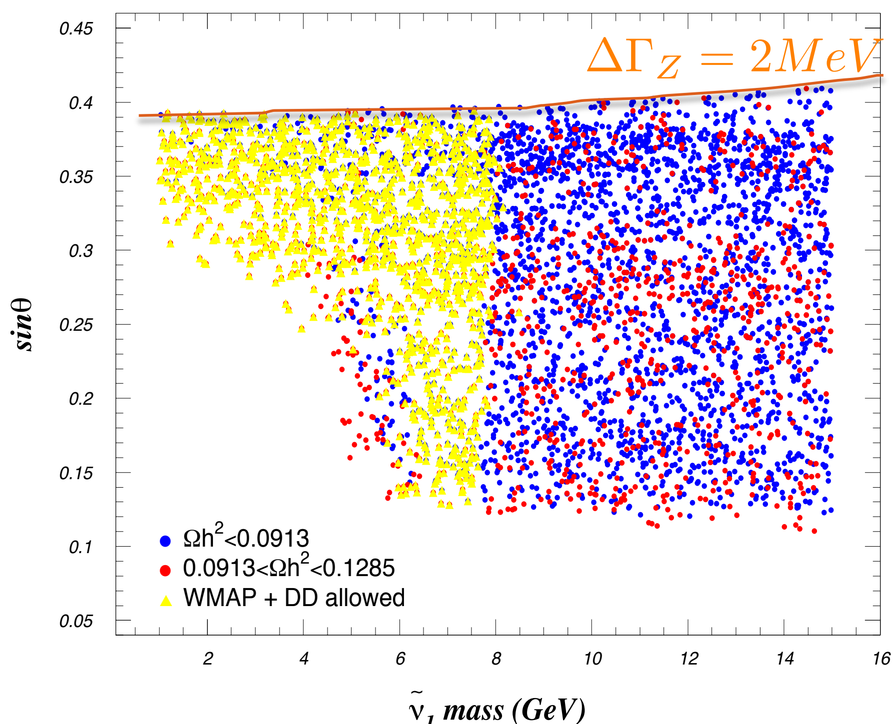
$\Rightarrow$ Tension between these two facts above

three light sneutrinos case

Relic density increases up to 3 times

Z-width constrains mixing angle upper bound to be smaller





one light sneutrino case

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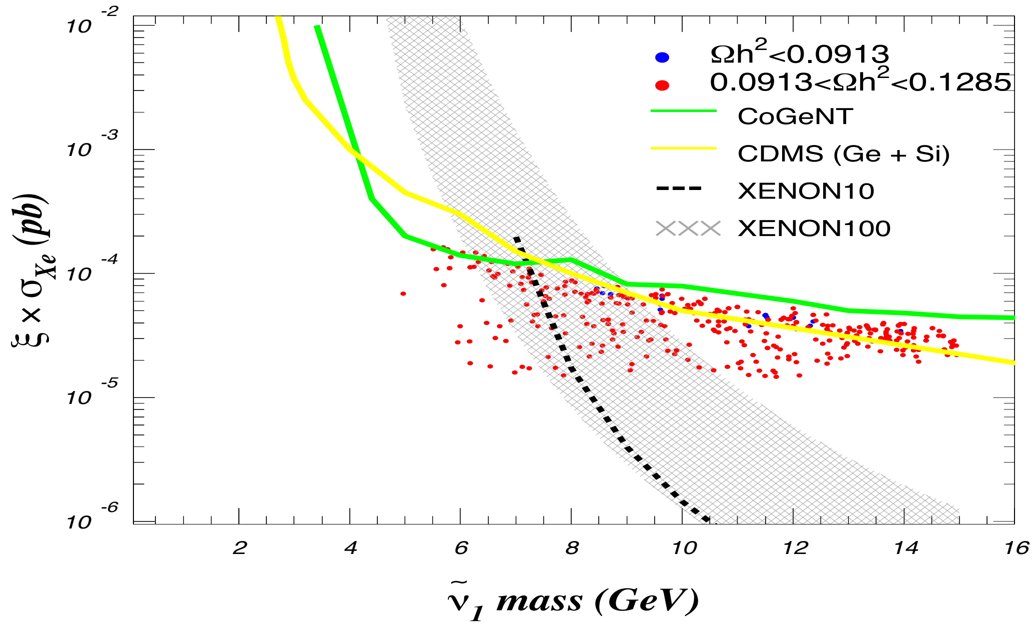

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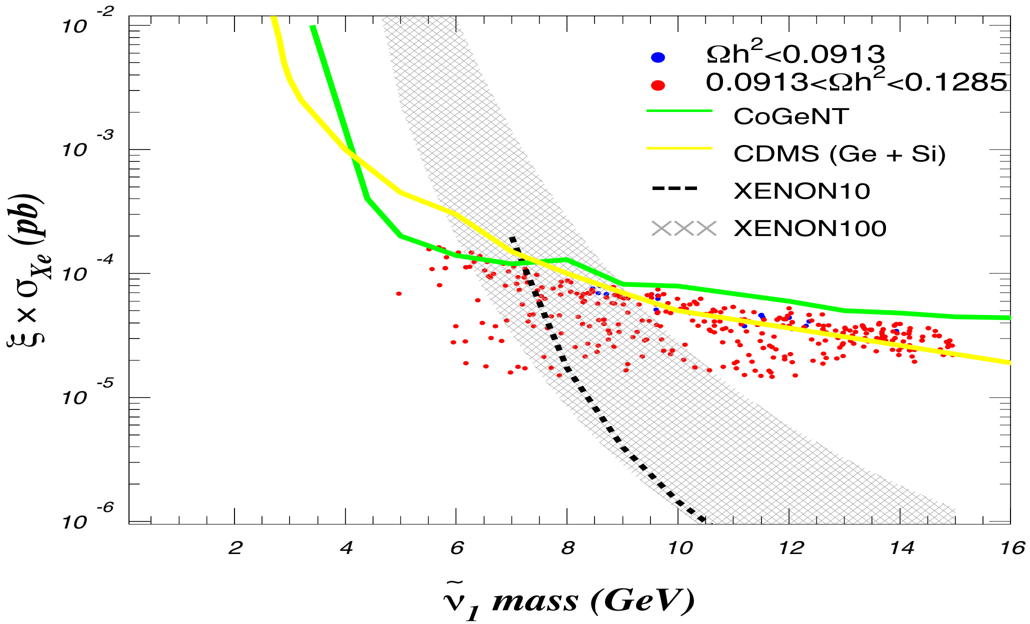
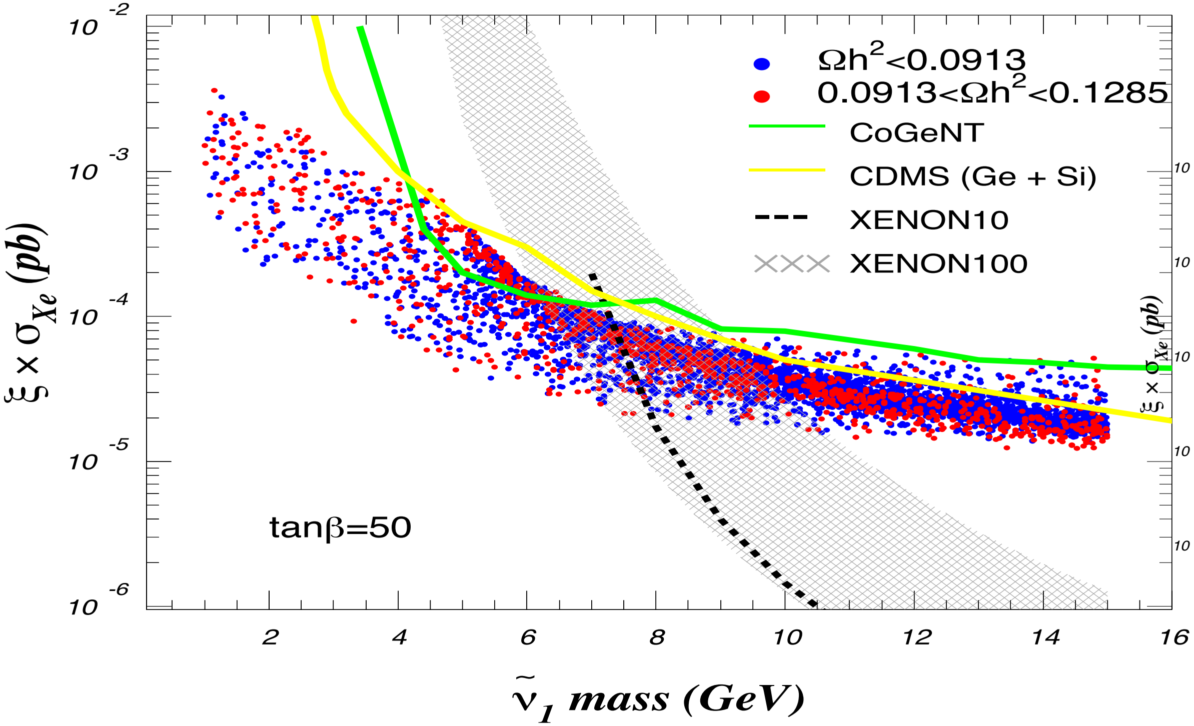


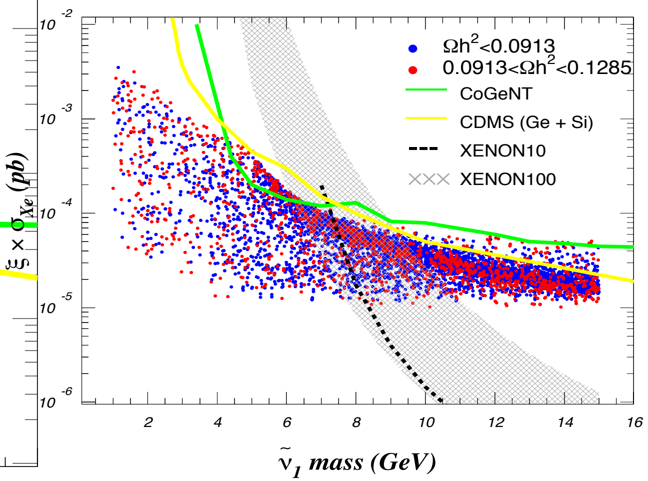
- Mass splitting between different flavours of sneutrinos can be induced by small mass splittings in soft terms → back to the case of one light sneutrino

4-1.Direct detection one light sneutrino with $\tan\beta = 50$

* $\tan\beta = 50$: low $m_{\tilde{\nu}_2}$ removed



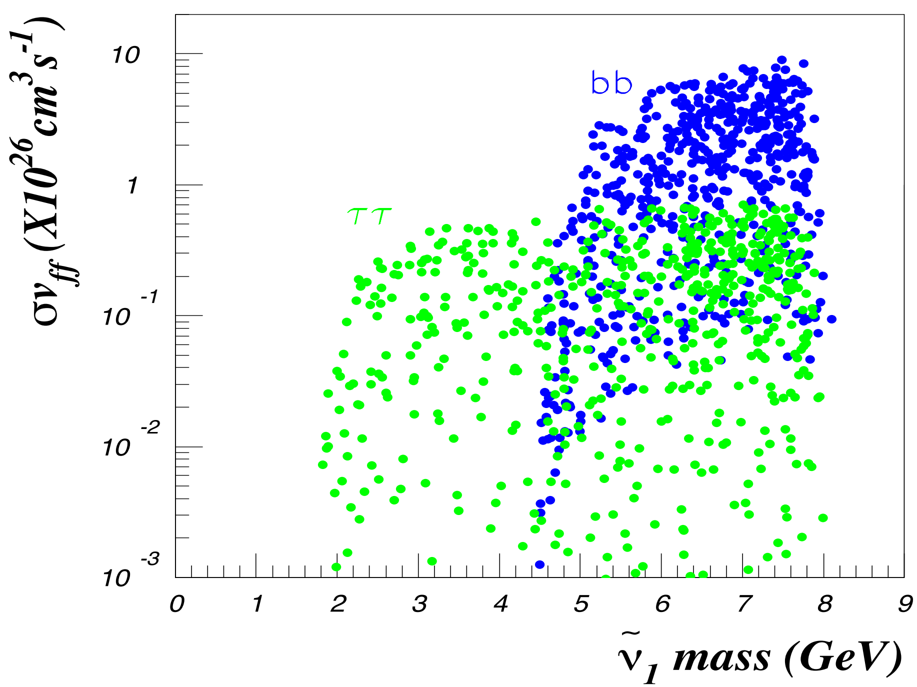
$\tan\beta = 10$

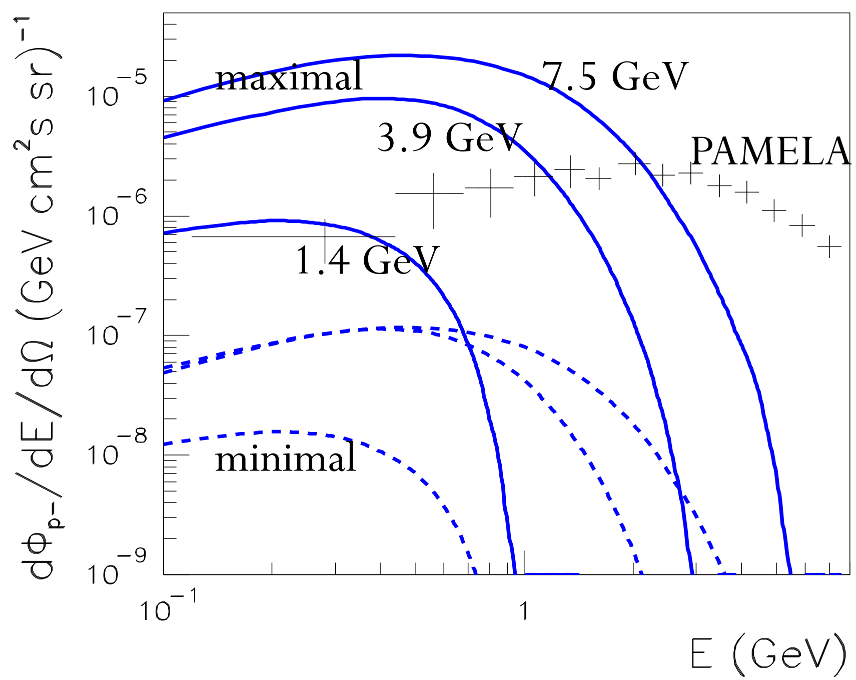


4-2. Indirect detection

Photons, Antiprotons and Positrons

- Annihilation channels into charged fermions leave signature in photons
- NFW DM profile
- Fermi-LAT can probe photon signals
- Room for dark matter contribution to antiproton, positron fluxes detected by PAMELA

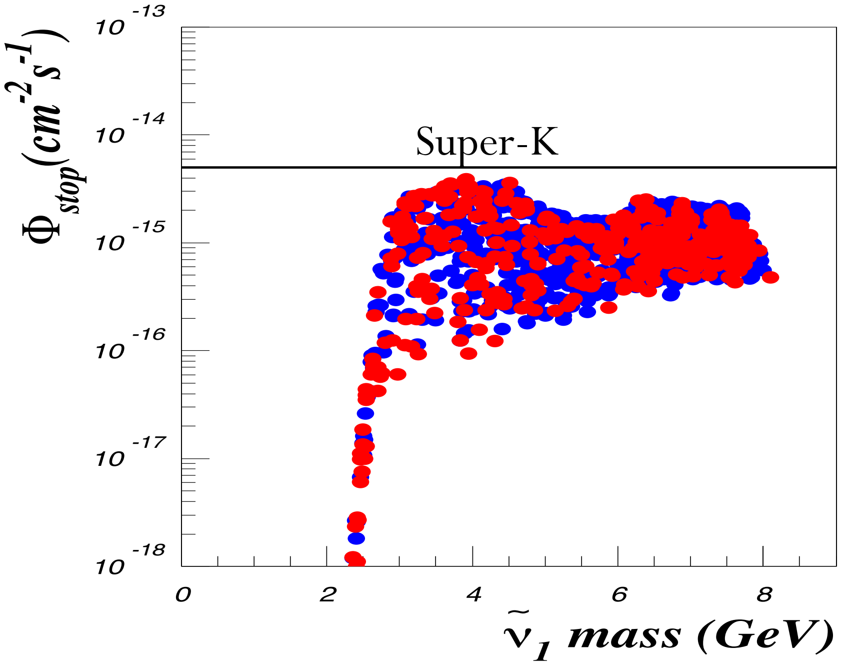


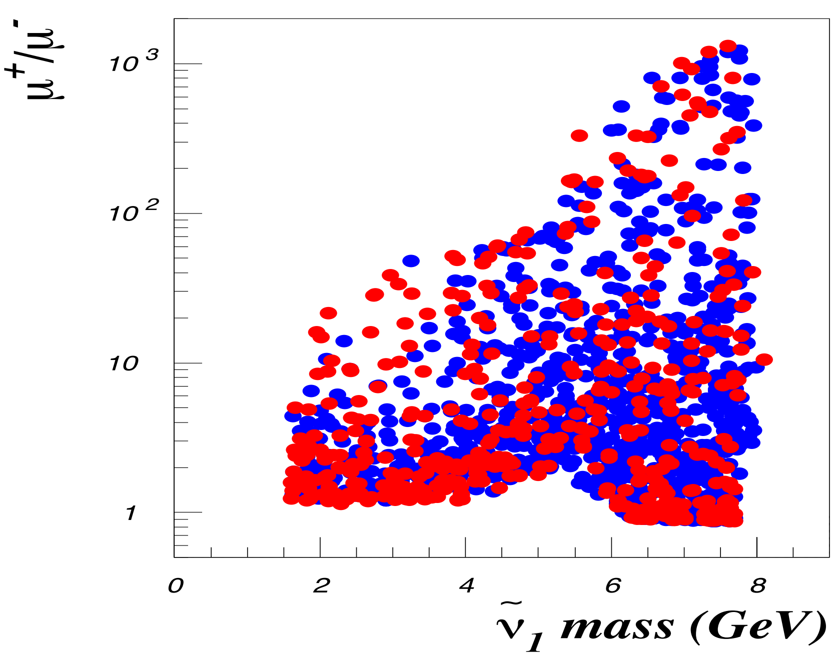


4-2. Indirect detection

Neutrinos from annihilation in the Sun

- Stopped muon flux detectable at Super-K with threshold 1.6 GeV
- Antimuon flux is larger than muon flux in our model
  → additional test

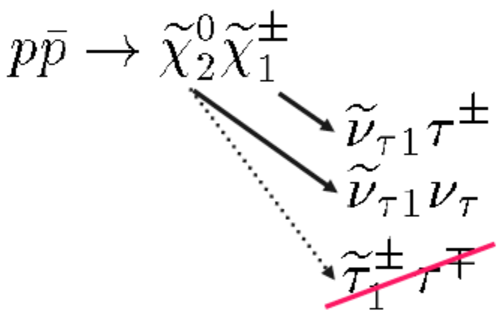




5. Collider signatures

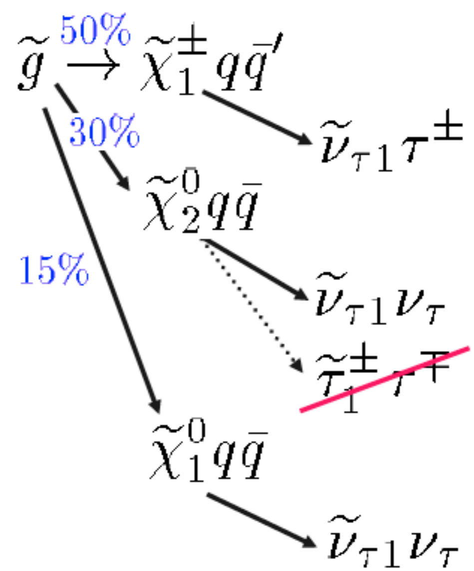
LHC

- To reconcile GeV sneutrino scenario with DD exp.constrains, lighter gauginos and heavier sleptons are desirable

- **Lepton modes**
  - 

- **Higgs decay into invisible modes**

  $\mathrm{Br}(h \to \widetilde{\nu}_1 \widetilde{\nu}_1^*) > 90\%$ in most cases

- 

5. Collider signatures

ILC $\sqrt{s}$ = 500 GeV

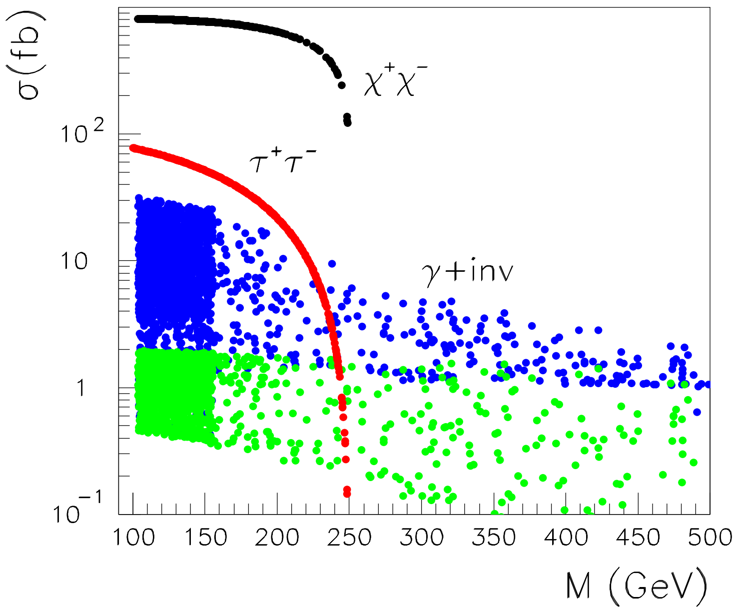
- Main SUSY productions

  $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp},\ \tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_2^0\tilde{\chi}_2^0,\ \tilde{\nu}_1\tilde{\nu}_1^*,\ \tilde{\tau}_1^+\tilde{\tau}_1^-$

- e^+e^- → Zh is main production for light Higgs

- Br ($h \to \tilde{\nu}\tilde{\nu}^*$) ~ 99 %

- Single photon production from $\tilde{\nu}_1\tilde{\nu}_1^*$ (dominant) and $\tilde{\chi}_i^0\tilde{\chi}_j^0$



$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \qquad M = m_{\tilde{\chi}_1^{\pm}}$

$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^- \qquad M = m_{\tilde{\tau}_1}$

Conclusions

- * In SUSY models with Dirac neutrino mass, $A_{\tilde{\nu}}$ induces a sizable mixing between LH-RH sneutrinos → lighter sneutrino dark matter for below ~ 10 GeV

  * Mixing should be large enough to give efficient pair-annihilation but not be too large in order not to exceed DD limits or Z invisible decay width

- Cross-section for the spin-independent elastic scattering on nuclei is predicted to be $\sigma^{\mathrm{SI}} > 10^{-5}$ pb, an order of magnitude of present limits for DM masses around 5-10 GeV, favored region by CoGeNT (perhaps CRESST)

- * Positron and Antiproton fluxes and Photon flux can be probed by PAMELA and FermiLAT respectively, through sneutrino pair annihilations into $b\bar{b}$ and $\tau^+\tau^-$

  * Only Super-K has low enough threshold to have sensitivity to neutrinos from light sneutrino annihilation by detecting stopped muons in it

- At LHC light Higgs and neutralinos decay exclusively and lighter chargino give a single lepton while at ILC SUSY production contribute to single photon x-section