RH sneutrino dark matter in U(1)' seesaw model

arXiv: 1105.1652 & work in progress,
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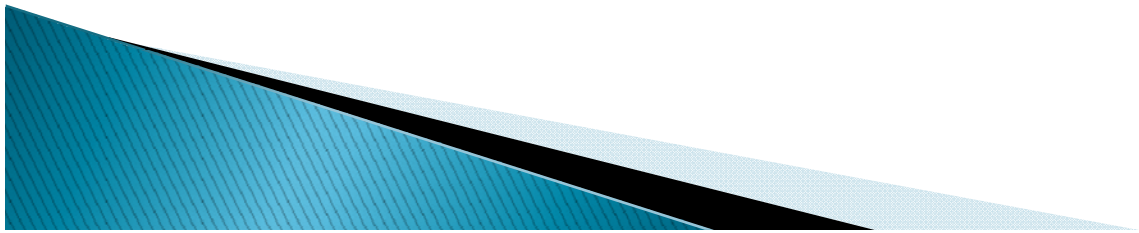
LAPTH, France

Outline

- Motivation
- Sneutrino dark matter models
- RH sneutrino DM model with $U(1)_\chi$
  - Relic density of DM
  - Collider signatures
- Conclusion



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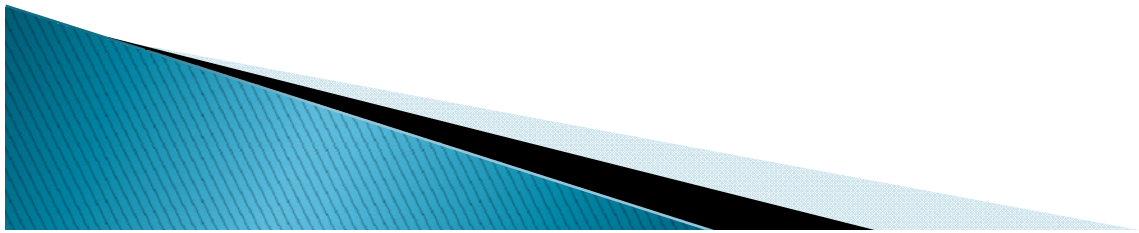
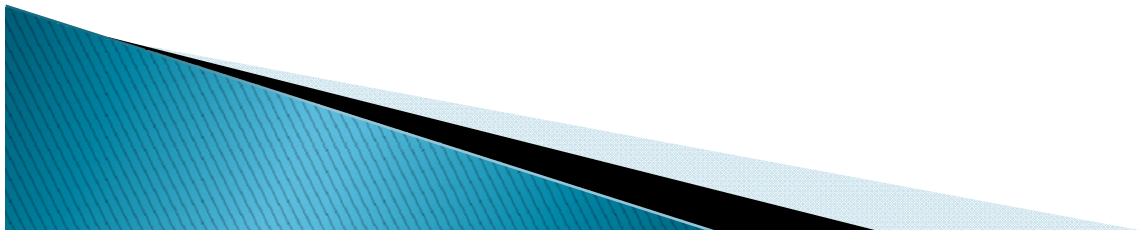
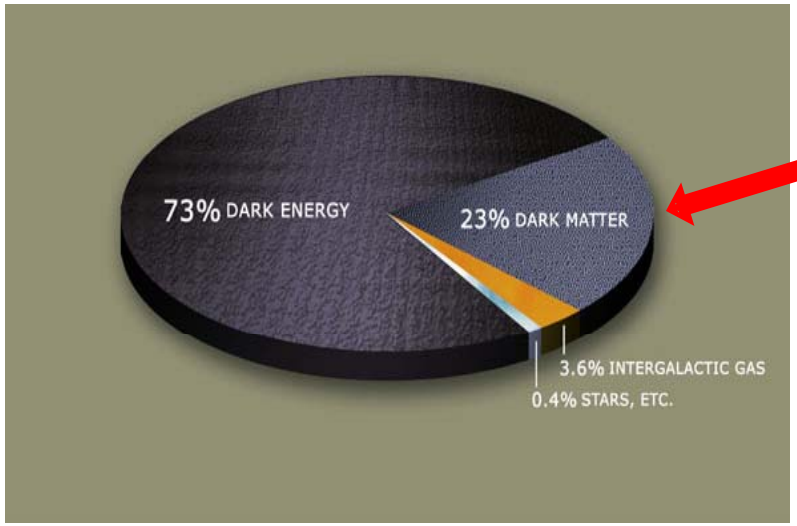


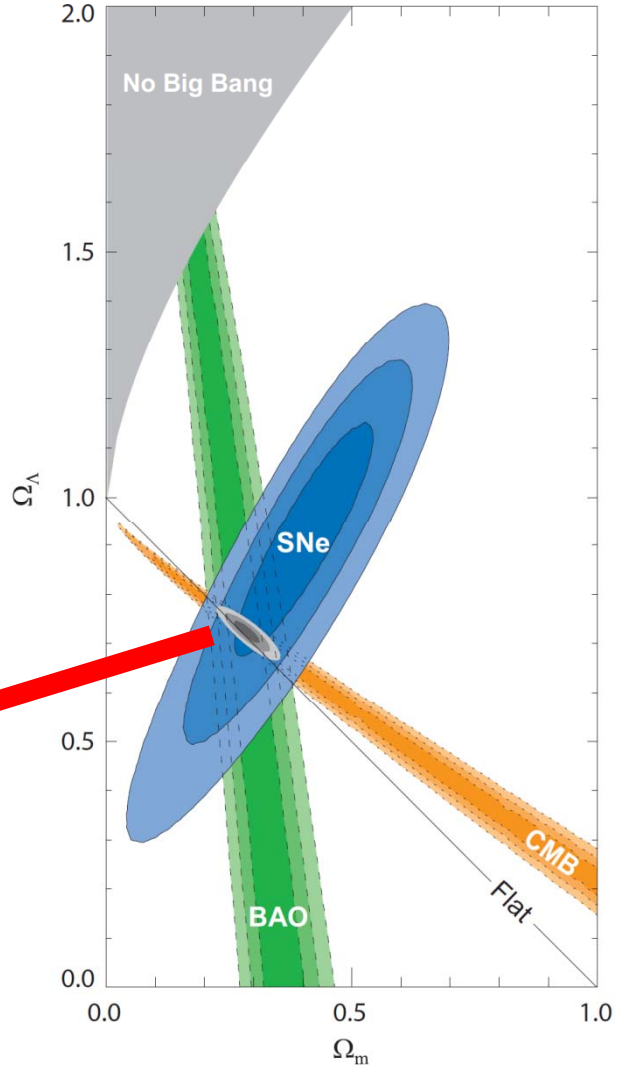
Why dark matter?



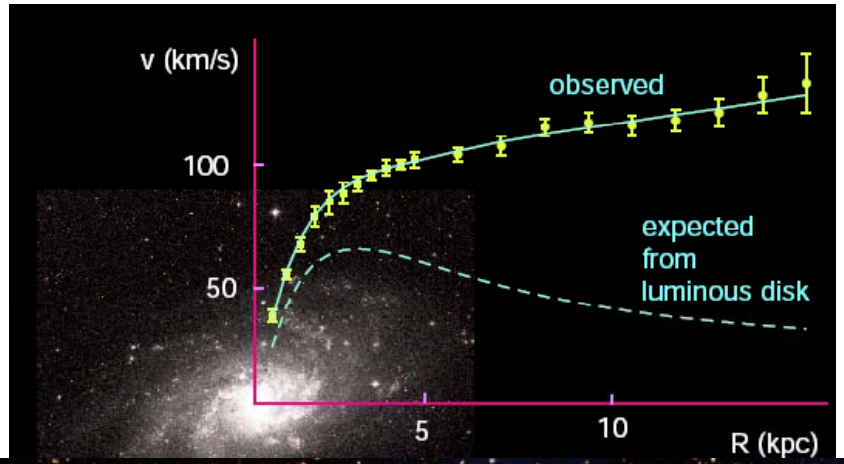
Dark matter

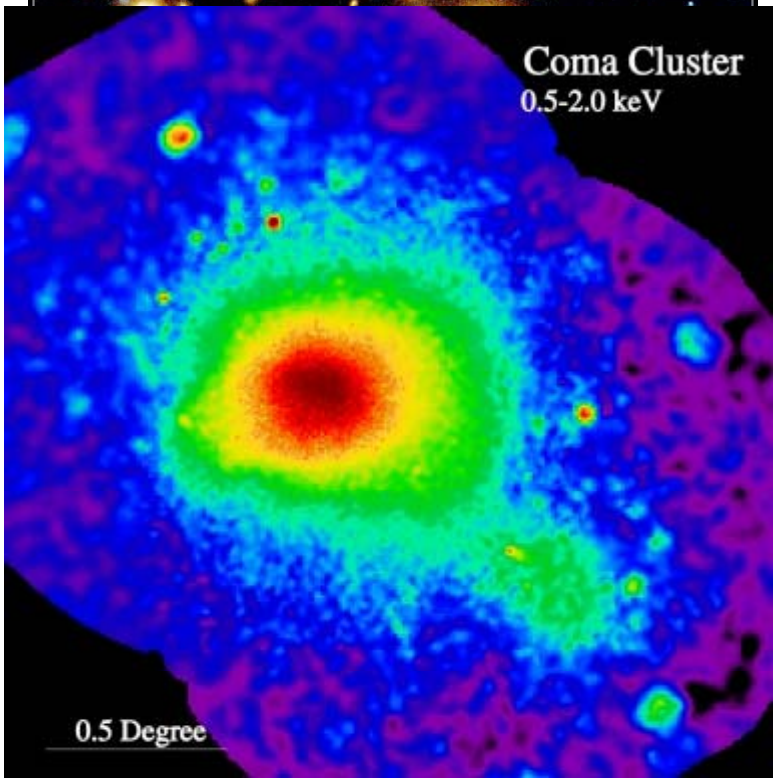
- postulated by Fritz Zwicky in 1930's
  to explain missing mass of the Coma cluster
- a conjectured form of matter:
  undetectable by electromagnetic radiation
  presence can be inferred from gravitational effects
- accounts for 23% of the total mass-energy of the Universe





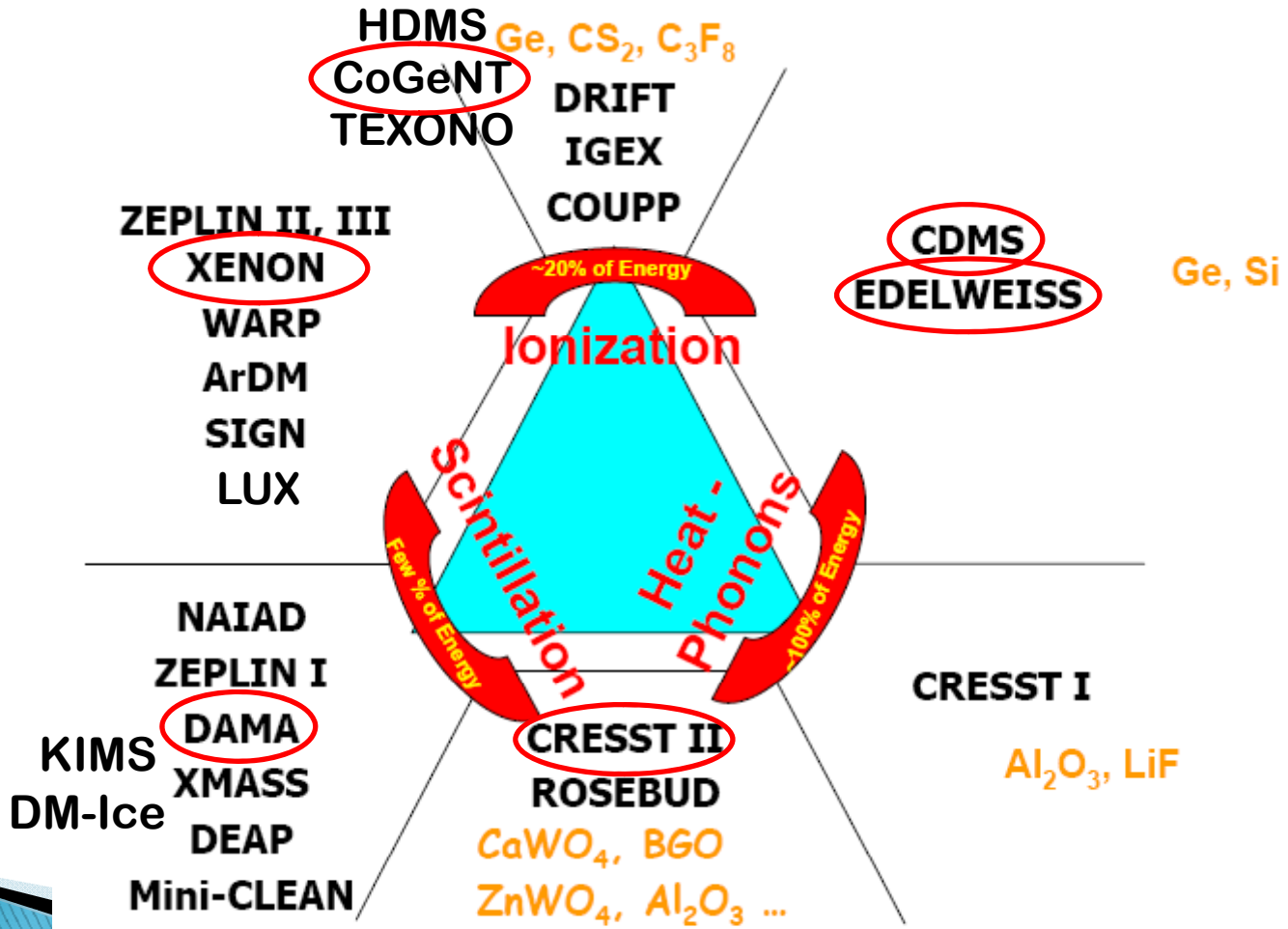
Observational evidence of DM



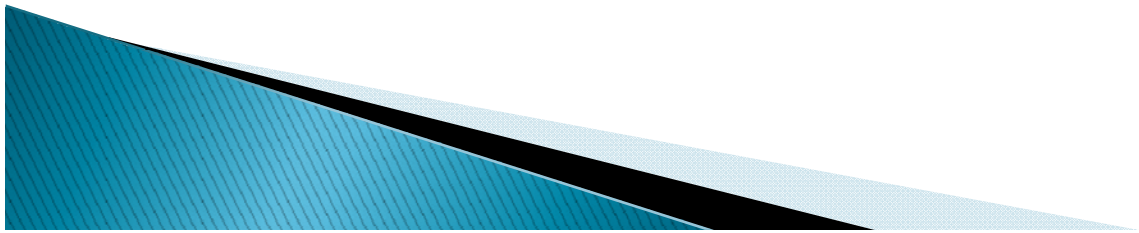


DM direct detection

❖ Recently, some direct detection experiments reported **interesting results**.



Seesaw?



Massive neutrino

arXiv:1103.0734

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

The T2K experiment observes indications of $\nu_\mu \rightarrow \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{13} = 0$, the expected number of such events is 1.5±0.3(syst.). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{CP} = 0$ and normal (inverted) hierarchy.

arXiv:1106.2822

Seesaw mechanism

Minkowski, PLB **67** (1977),
Yanagida (1979),
Gell-Mann, Ramond & Slansky (1980)

- To explain smallness of ν masses → heavy RH neutrinos, N

$$\mathcal{L}_\nu = y_\nu \bar{l} \widetilde{\phi} N + M_N N N + h.c.$$

- In (ν, N) basis, with $M_D = y_\nu \langle \phi \rangle$

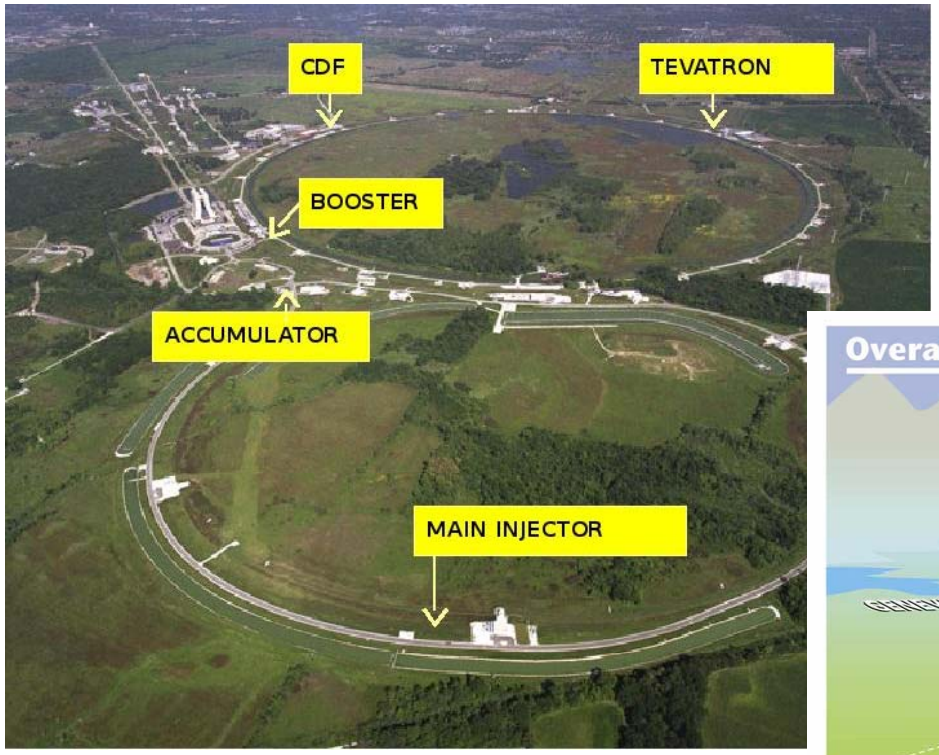
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix}$$

- If $M_N \gg M_D$, mass matrix for light ν's:

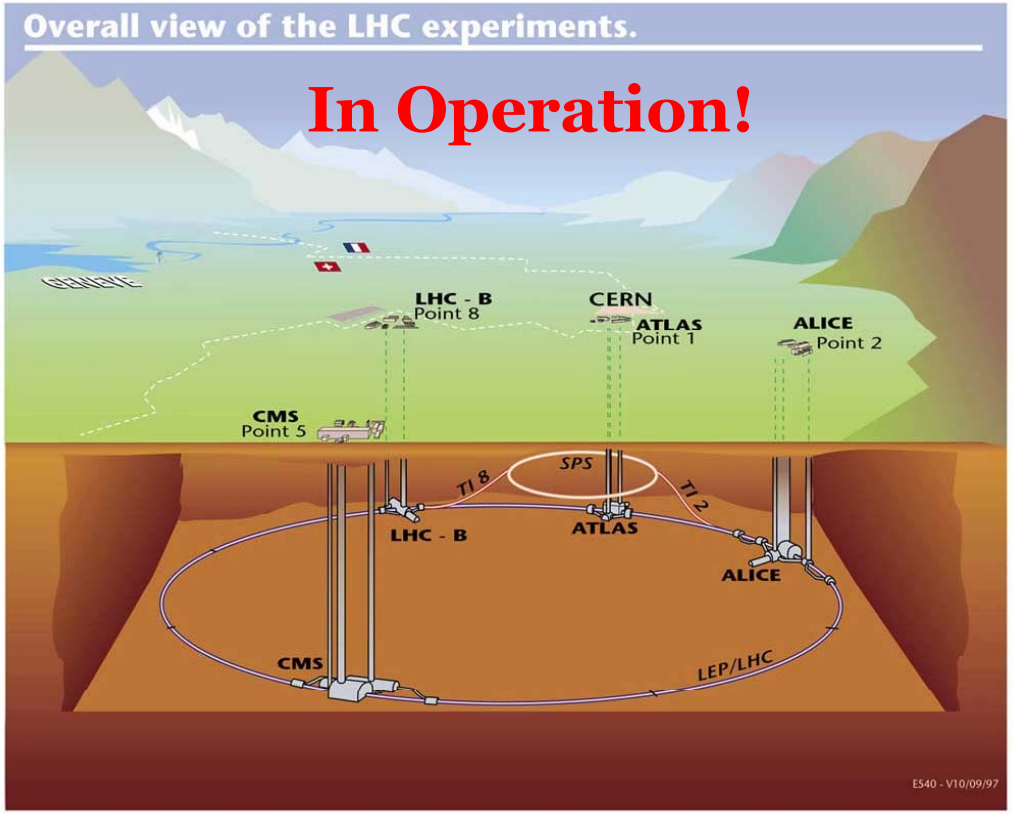
$$M_\nu \simeq M_D^T M_N^{-1} M_D \sim (y_\nu v)^2 M_N^{-1}$$

→ A explanation for small neutrino masses

Colliders



Higgs, SUSY particles, Z', etc



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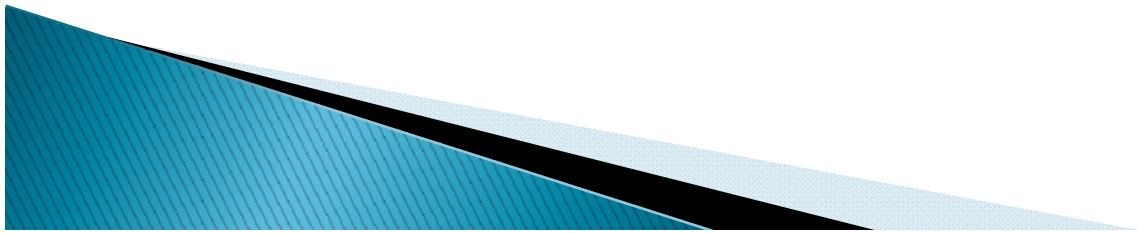


LH sneutrino DM

- LH sneutrinos: annihilate too rapidly via Z-exchange

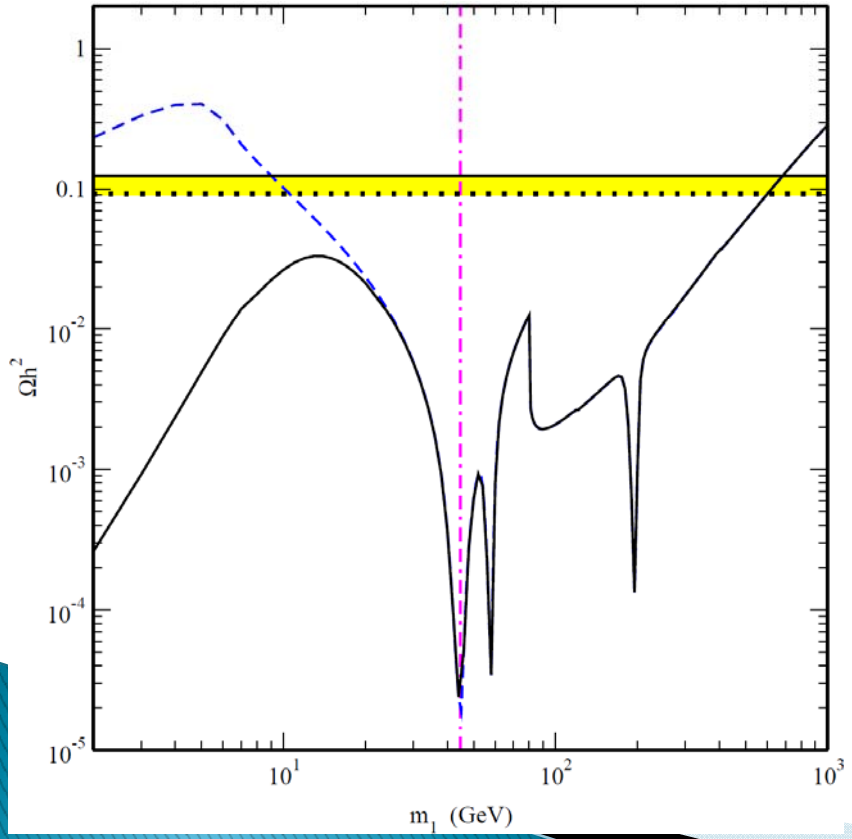
  → too small relic density

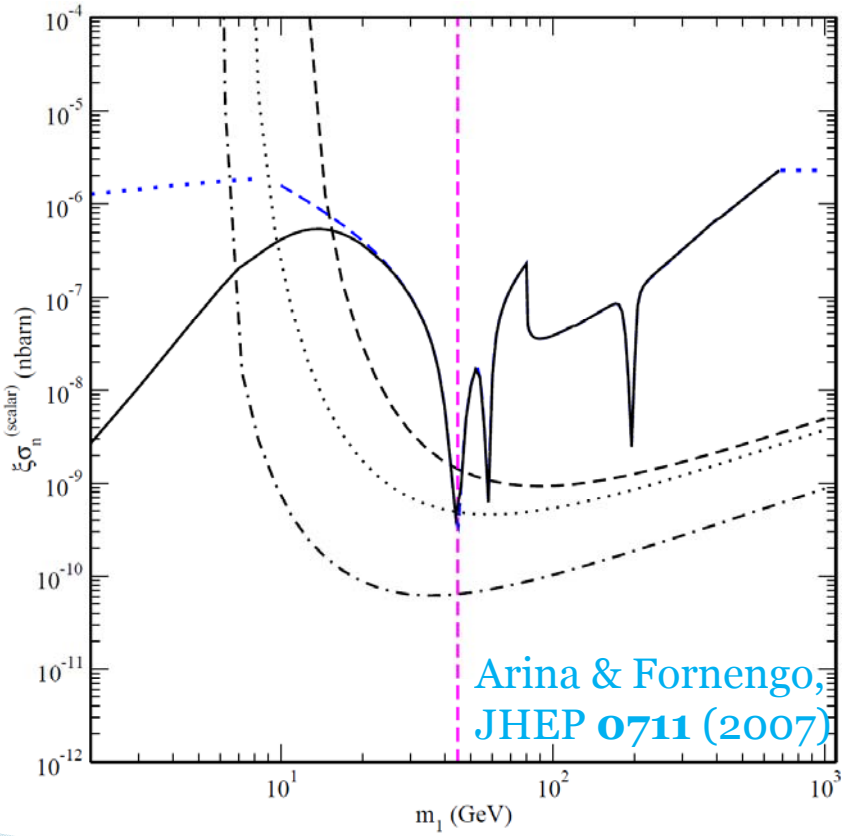
  - Very light ($\mathcal{O}$(GeV)): invisible width of the Z gauge boson

    Hagelin, Kane & Raby, NPB **241** (1984); Ibanez, PLB **137** (1984)

  - Very heavy ($\mathcal{O}$(TeV)): excluded by direct DM searches

    Falk, Olive & Srednicki, PLB **339** (1994)





RH sneutrino DM

- RH sneutrino: a SM singlet

  → cannot be thermalized in the early universe through SM gauge interactions

  - Non-thermal production

    Asaka, Ishiwata & Moroi, PRD **73** (2006)
    Gopalakrishna, Gouvea & Porod, JCAP **0605** (2006)

    → The scenario is possible, but less predictive.

  - Mixed sneutrinos: large mixing angle between LH & RH sneutrinos

    Arkani-Hamed, Hall, Murayama, Smith & Weiner, PRD **64** (2001)
    Borzumati & Nomura, PRD **64** (2001)
    Belanger, Kakizaki, Park, Kraml & Pukov, JCAP **1011** (2010)
    Belanger, Kraml & Lessa, arXiv:1105.4878

  - An extra singlet field (~NMSSM)

    Deppisch & Pilaftsis, JHEP **0810** (2008)
    Cerdeno & Seto, JCAP **0908** (2009)

  - Additional gauge symmetry (Z' resonance)

    Lee, Matchev & Nasri, PRD **76** (2007)

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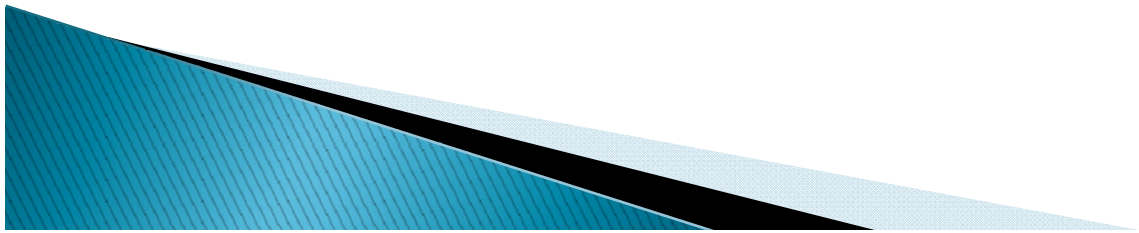


Type 1 seesaw with $U(1)_\chi$

- Particle content

27 of E_6

$SU(5)$	10_F	$\bar{5}_F$	$1(N)$	5_H	$\bar{5}_H$	$1(X)$	$1(S_1)$	$1(S_2)$
$2\sqrt{10}Q'$	-1	3	-5	2	-2	0	10	-10

- Superpotential of the neutrino sector

$$W_{seesaw} = y_{ij} L_i H_u N_j + \frac{\lambda_{N_i}}{2} S_1 N_i N_i \longrightarrow \widetilde{m}^{\nu}_{ij} = -y_{ik} y_{jk} \frac{\langle H_u^0 \rangle^2}{m_{N_k}}$$

$$W' = \lambda X S_1 S_2 + \frac{\kappa}{3} X^3 \qquad \theta_{N\nu} \approx \frac{y_\nu v_u}{\sqrt{2} m_N}$$

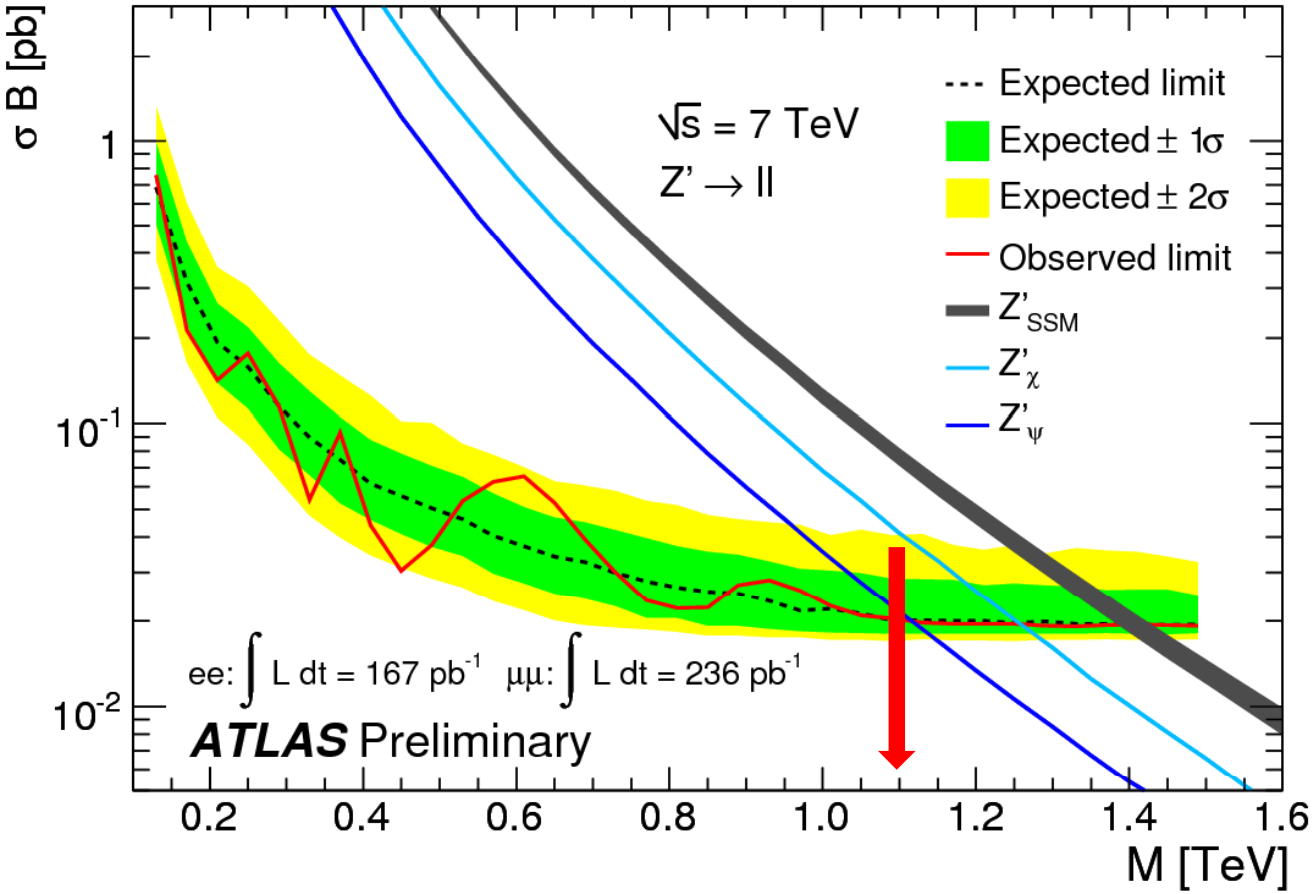
- Current limit on Z' mass (EWPD)

$M_{Z'} > 1.14$ TeV for $g' = \sqrt{5/3} g_2 \tan\theta_W \approx 0.46$

Erler, Langacker, Munir & Pena, JHEP **0908** (2009)

New LHC limit

ATLAS public results



RH sneutrino DM

- Scalar potential $V = V_{\rm susy} + V_{\rm soft} + V_D$

$$V_{\rm susy} = \sum_{\phi=X,S_1,S_2,N_i,H_u,L_i} \left|\frac{\partial W}{\partial \phi}\right|^2$$

$$V_{\rm soft} = \left[y_\nu A_\nu \tilde{L} H_u \tilde{N} + \frac{\lambda_N}{2} A_N S_1 \tilde{N}\tilde{N} + \lambda A_S X S_1 S_2 + \frac{\kappa}{3} A_\kappa X^3 + h.c.\right]$$
$$+ m_X^2 |X|^2 + m_S^2 \left[|S_1|^2 + |S_2|^2\right] + m_{\widetilde{N}}^2 |\widetilde{N}|^2$$

$$V_D = \frac{g'^2}{2}\left[Q'_{S_1}|S_1|^2 + Q'_{S_2}|S_2|^2 + Q'_N|\widetilde{N}|^2 + \cdots\right]^2$$

- RH sneutrino mass

$$V_{mass} = (m_N^2 + m_{\tilde{N}}^2 - \frac{1}{4} m_{Z'}^2 c_{2\beta'})|\tilde{N}|^2 - \frac{1}{2} B_N m_N (\tilde{N}\tilde{N} + \tilde{N}^*\tilde{N}^*)$$

$$\tilde{N} = (\tilde{N}_1 + i\tilde{N}_2)/\sqrt{2}$$

Real & imaginary components get a mass splitting $\because B_N m_N$ term.

→ Lighter scalar field $\widetilde{N}_1$ is taken to be the LSP.

Couplings with U(1)'

$\bar{f}fZ'$	$ig'(Q'_{f_L}P_L - Q'_{f_R^\dagger}P_R)\gamma^\mu$	hAZ'	$-ig'Q'_{H_u}\sin(\alpha+\beta)q^\mu$
$\tilde{f}\tilde{f}^*Z'$	$ig'Q'_f q^\mu$	HAZ'	$ig'Q'_{H_u}\cos(\alpha+\beta)q^\mu$
$\tilde{f}_L\bar{f}\tilde{Z}'$	$-i\sqrt{2}g'Q'_{f_L}P_R$	H^+H^-Z'	$ig'Q'_{H_u}q^\mu$
$\tilde{f}_R\bar{f}\tilde{Z}'$	$-i\sqrt{2}g'Q'_{f_R^\dagger}P_L$	hZZ'	$-i\sqrt{2}g'M_Z Q'_{H_u}\cos(\alpha+\beta)g^{\mu\nu}$
$\tilde{N}_1\tilde{N}_2Z'$	$ig'Q'_N q^\mu$	HZZ'	$-i\sqrt{2}g'M_Z Q'_{H_u}\sin(\alpha+\beta)g^{\mu\nu}$
$\bar{N}\tilde{N}_1\tilde{Z}'$	$-ig'Q'_N P_R$	$h\bar{\chi}_i^0\tilde{Z}'$	$-ig'Q'_{H_u}(N_{4i}\cos\alpha + N_{3i}\sin\alpha)P_R$
$\bar{N}\tilde{N}_2\tilde{Z}'$	$g'Q'_N P_R$	$H\bar{\chi}_i^0\tilde{Z}'$	$-ig'Q'_{H_u}(N_{4i}\sin\alpha - N_{3i}\cos\alpha)P_R$
$S_{1,2}S^*_{1,2}Z'$	$ig'Q'_{S_{1,2}}q^\mu$	$A\bar{\chi}_i^0\tilde{Z}'$	$g'Q'_{H_u}(N_{4i}\cos\beta - N_{3i}\sin\beta)P_R$
$\bar{\tilde{S}}_{1,2}\tilde{S}_{1,2}Z'$	$ig'Q'_{S_{1,2}}\gamma^\mu$	$H^+\bar{\chi}_i^+\tilde{Z}'$	$-i\sqrt{2}g'Q'_{H_u}(V^*_{2i}\cos\beta\,P_R - U_{2i}\sin\beta\,P_L)$
$S_{1,2}\bar{\tilde{S}}_{1,2}\tilde{Z}'$	$-i\sqrt{2}g'Q'_{S_{1,2}}P_R$		

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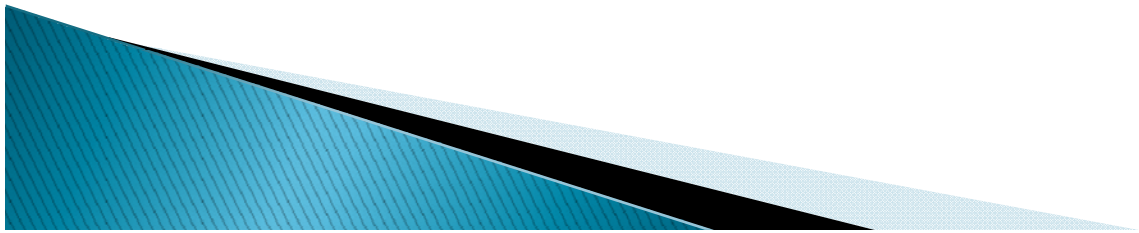
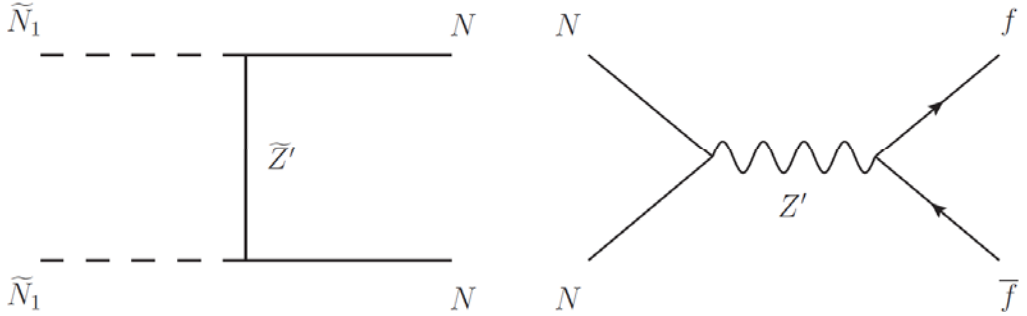


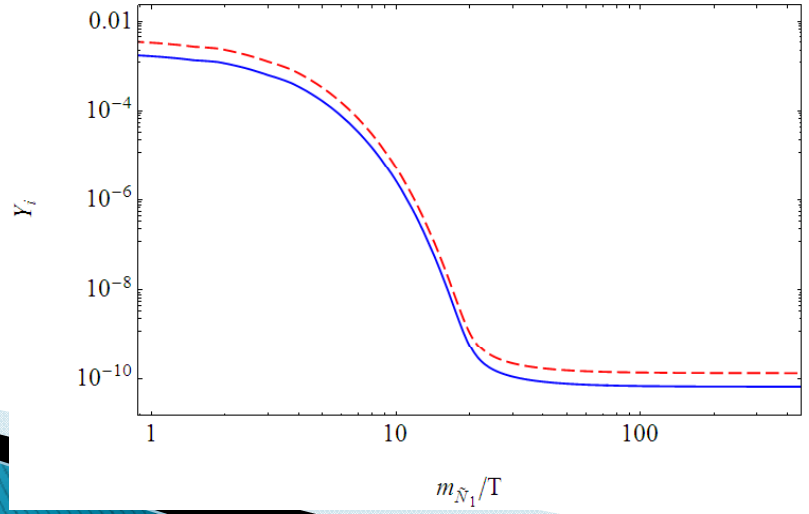
Freeze out of DM



- Boltzmann equations

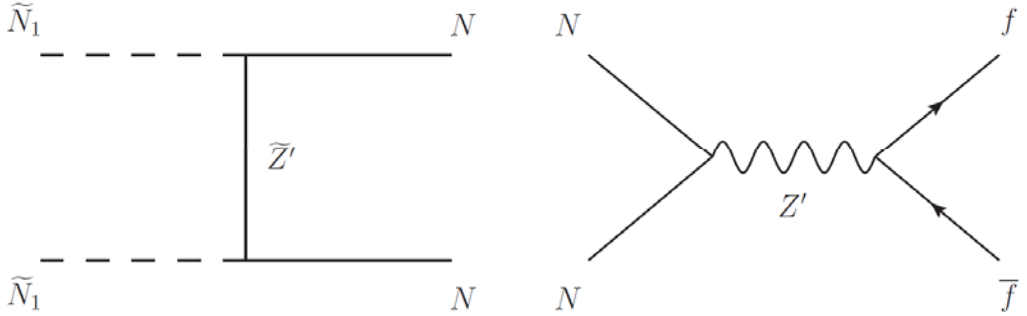
$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle\sigma_{\widetilde{N}_1} v_{\widetilde{N}_1}\rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N\right)^2\right]$$

$$\frac{dn_N}{dt} = -3Hn_N - \langle\sigma_N v_N\rangle \left[(n_N)^2 - (n_N^{\rm eq})^2\right] + \langle\sigma_{\widetilde{N}_1} v_{\widetilde{N}_1}\rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N\right)^2\right]$$



m_{DM}=300 GeV, m_N=260 GeV,
$M_{Z'}$=1.2 TeV, $m_{\widetilde{Z}'}$=600 GeV

Freeze out of DM



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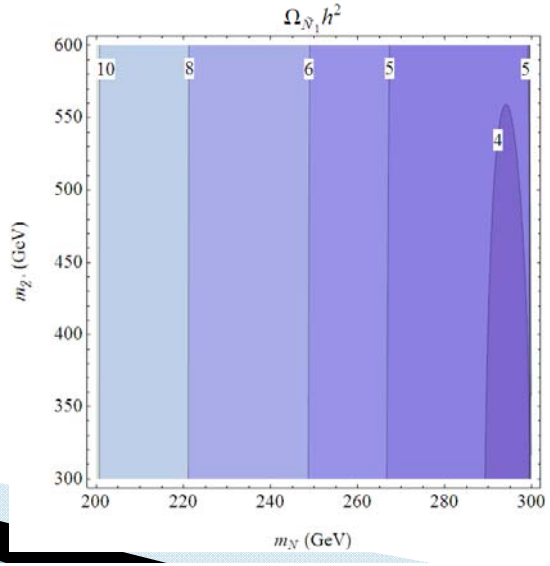

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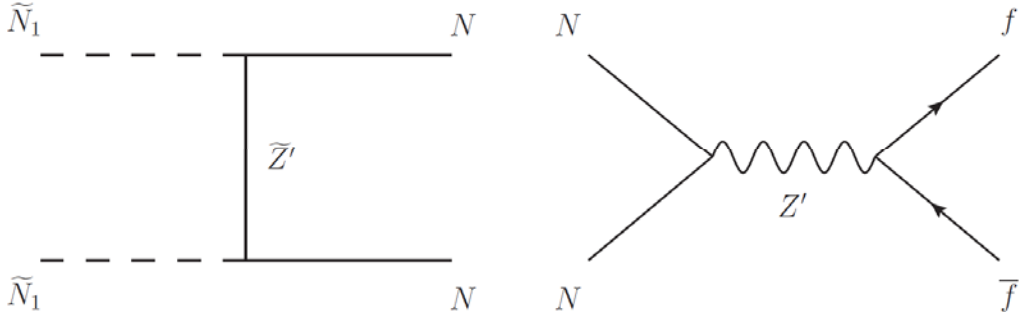
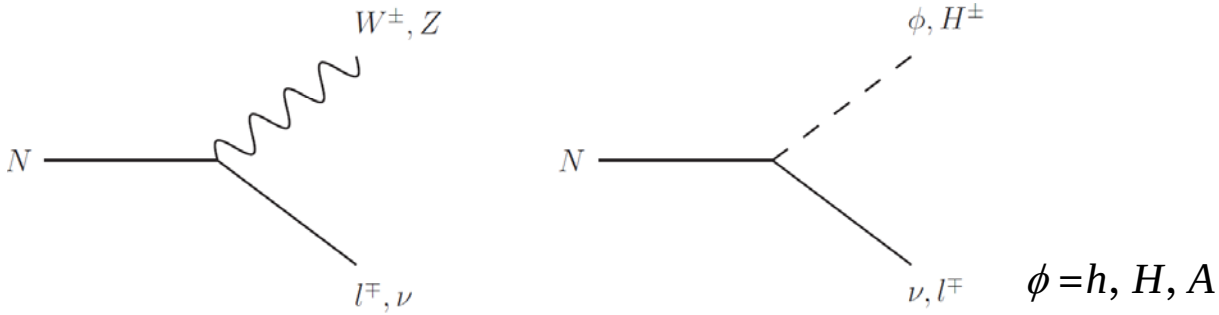


- Boltzmann equations

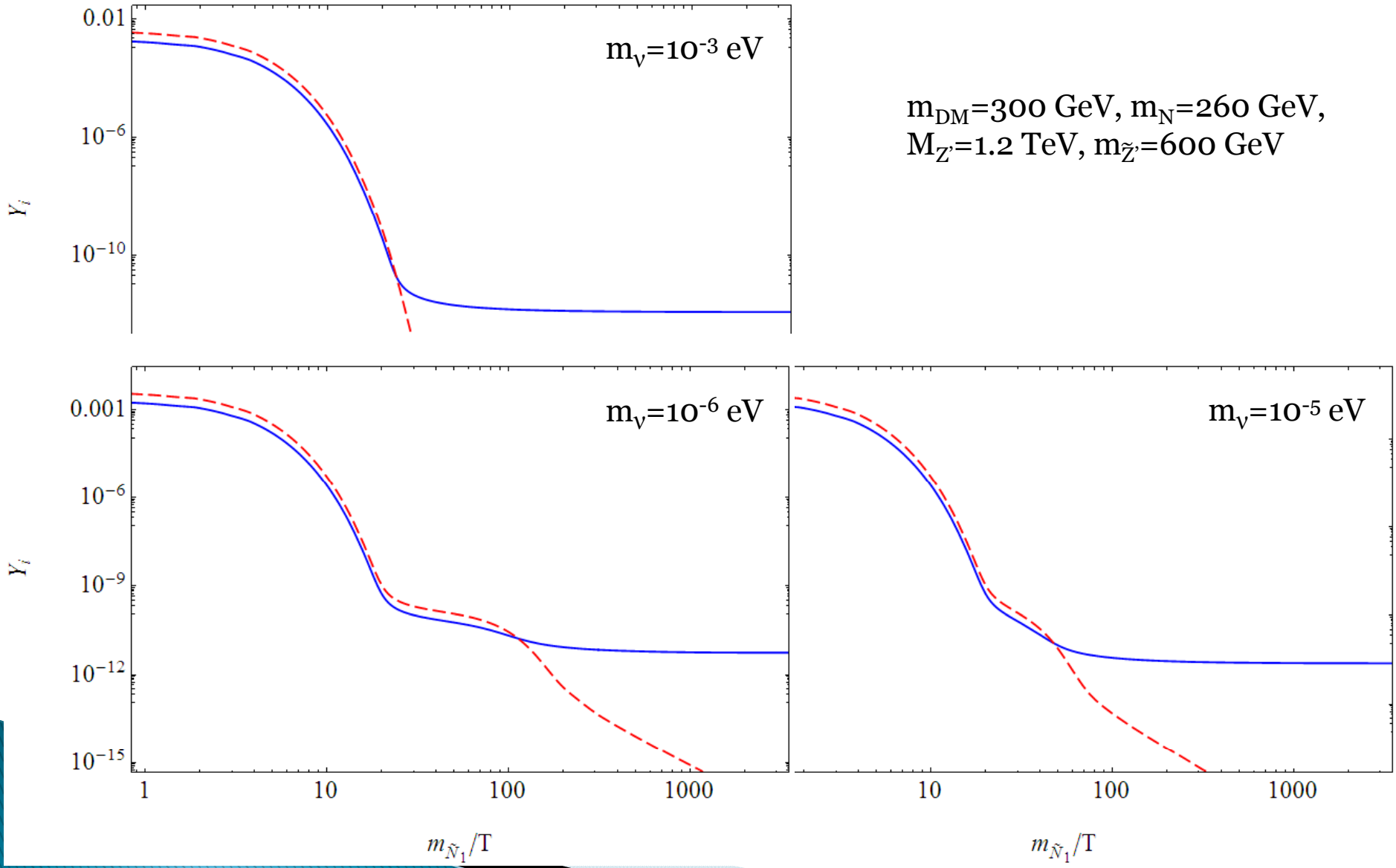
$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle\sigma_{\widetilde{N}_1} v_{\widetilde{N}_1}\rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N\right)^2\right]$$

$$\frac{dn_N}{dt} = -3Hn_N - \langle\sigma_N v_N\rangle \left[(n_N)^2 - (n_N^{\rm eq})^2\right] + \langle\sigma_{\widetilde{N}_1} v_{\widetilde{N}_1}\rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N\right)^2\right] - \Gamma_N (n_N - n_N^{\rm eq})$$



$\phi = h, H, A$

Freeze out



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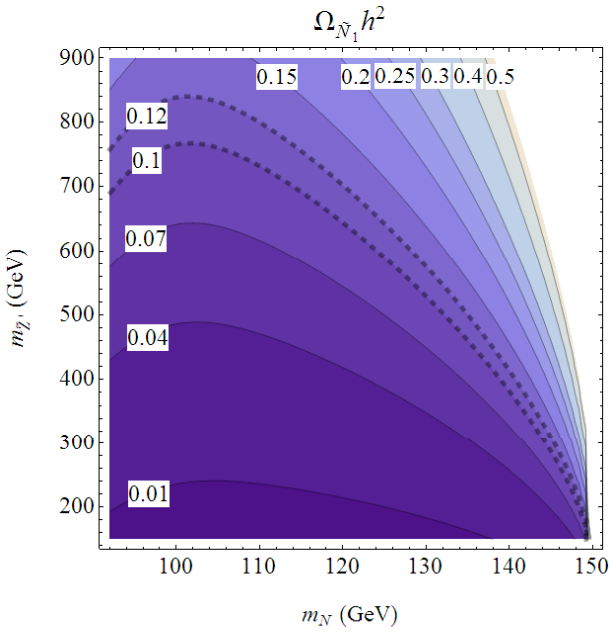
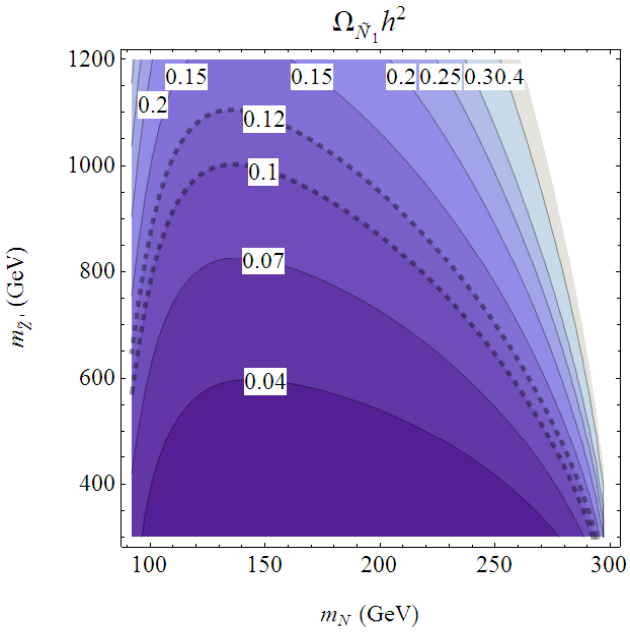
$M_{Z'}$=1.2 TeV, $m_{\tilde{Z}'}$=600 GeV

Relic density (m_{DM}) 1

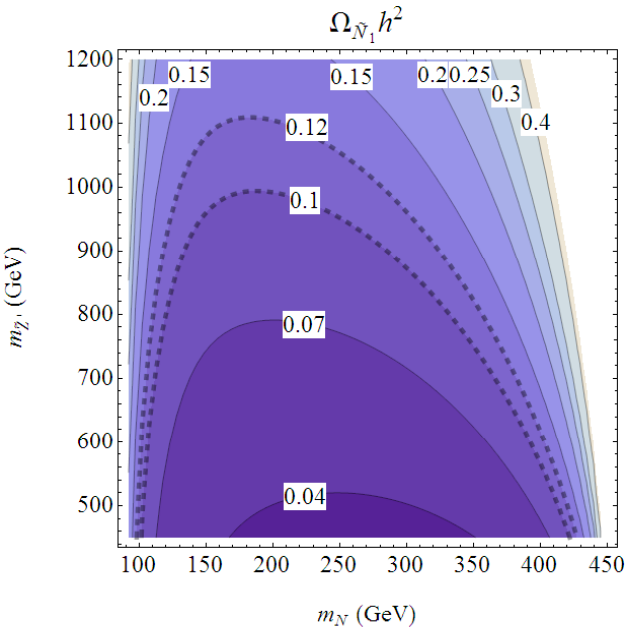
$M_{Z'}$=1.2 TeV, m_ν=10^{-3} eV



m_{DM}=150 GeV



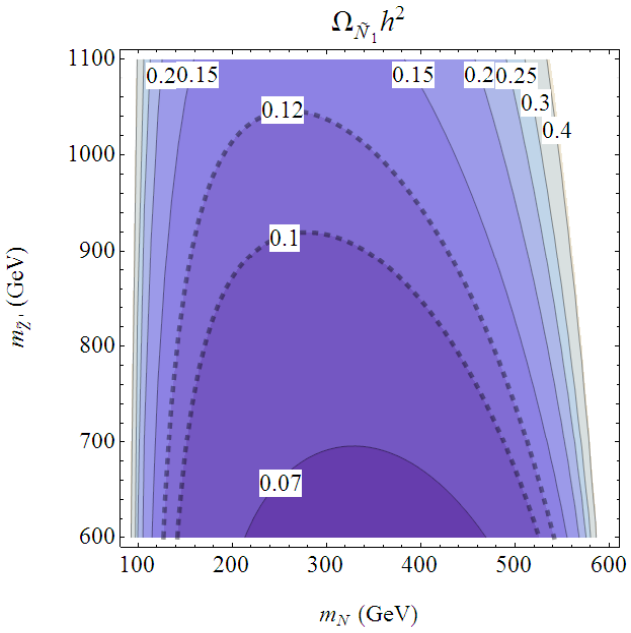
m_{DM}=300 GeV



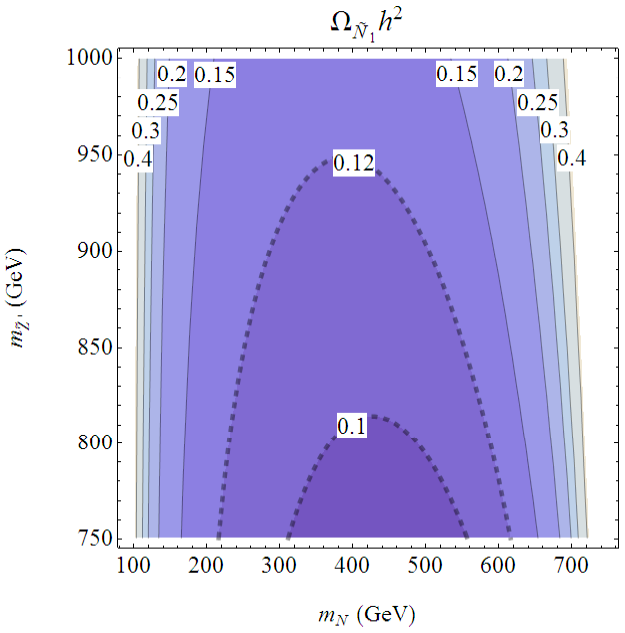
m_{DM}=450 GeV

Relic density (m_{DM}) 2

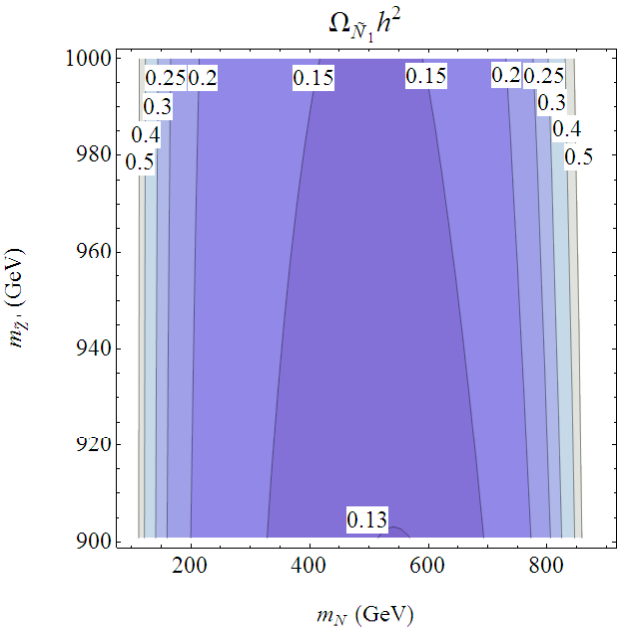
$M_{Z'}$=1.2 TeV, m_ν=10^{-3} eV



m_{DM}=600 GeV



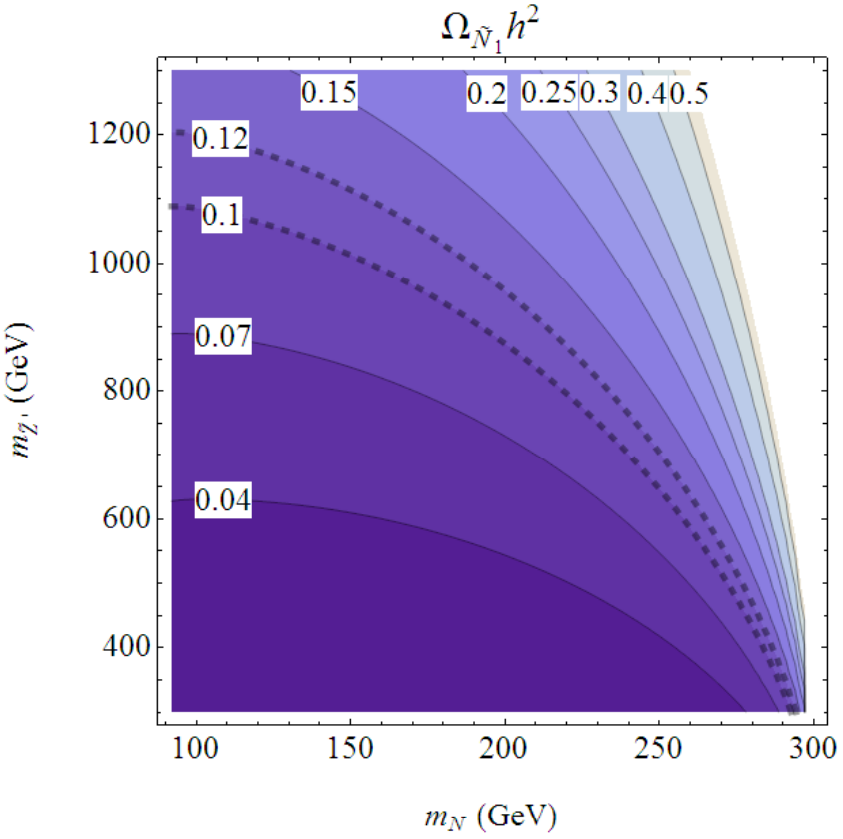
m_{DM}=750 GeV



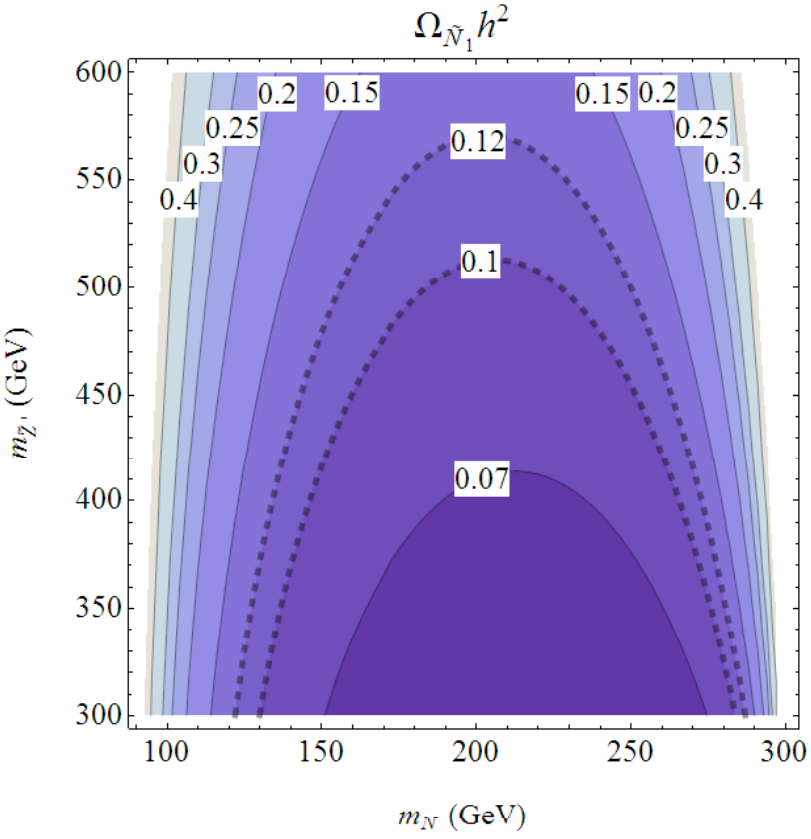
m_{DM}=900 GeV

Relic density (m_ν)

m_{DM}=300 GeV, $M_{Z'}$=1.2 TeV



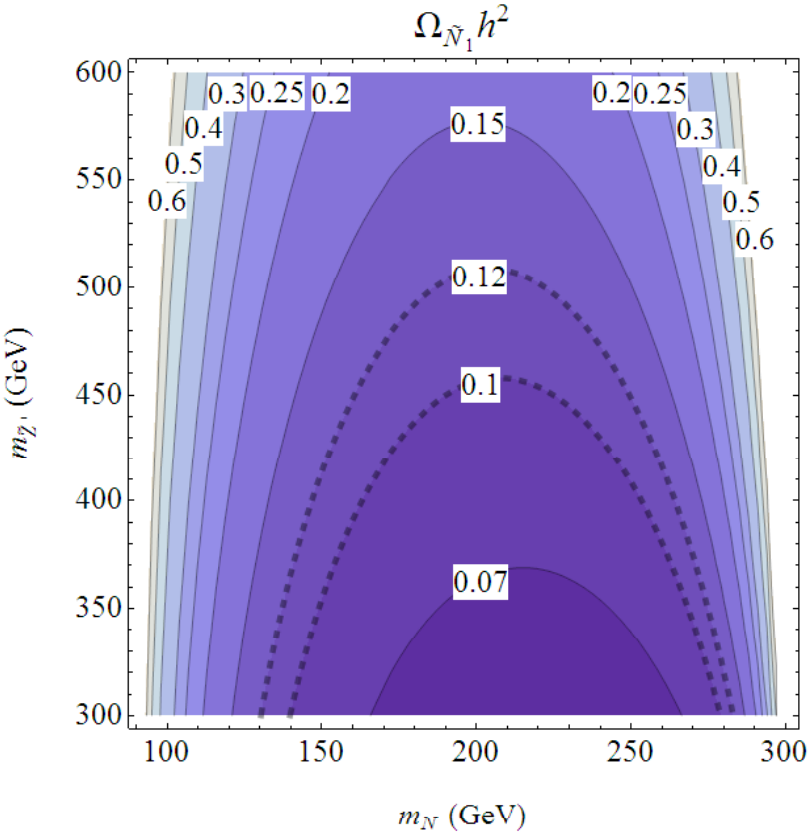
$m_\nu=10^{-1}$ eV



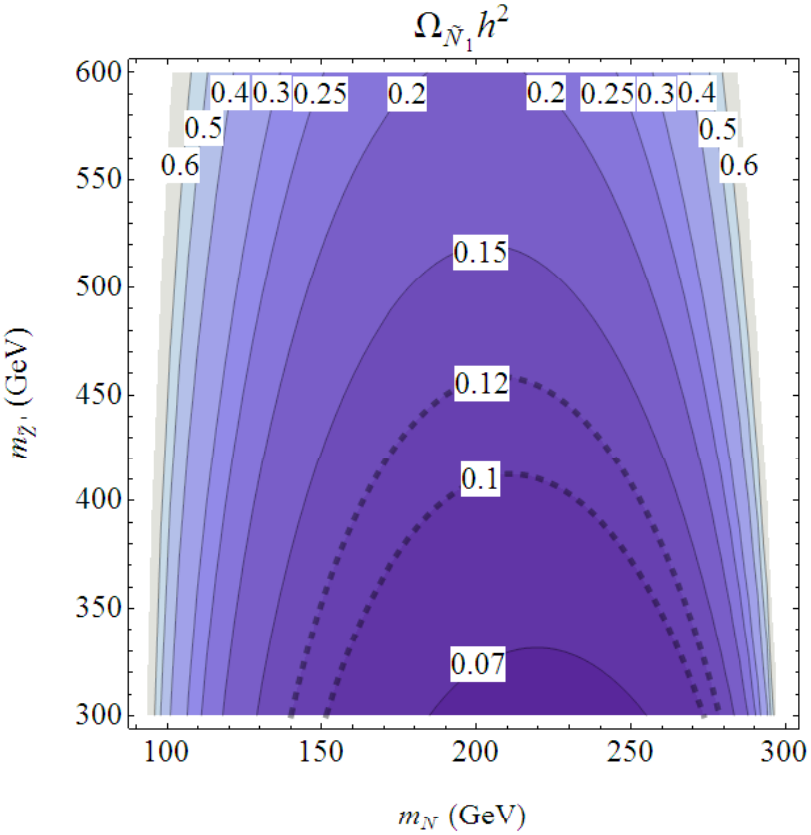
$m_\nu=10^{-5}$ eV

Relic density ($M_{Z'}$)

m_{DM}=300 GeV, m_ν=10^{-3} eV



$M_{Z'}$=2 TeV

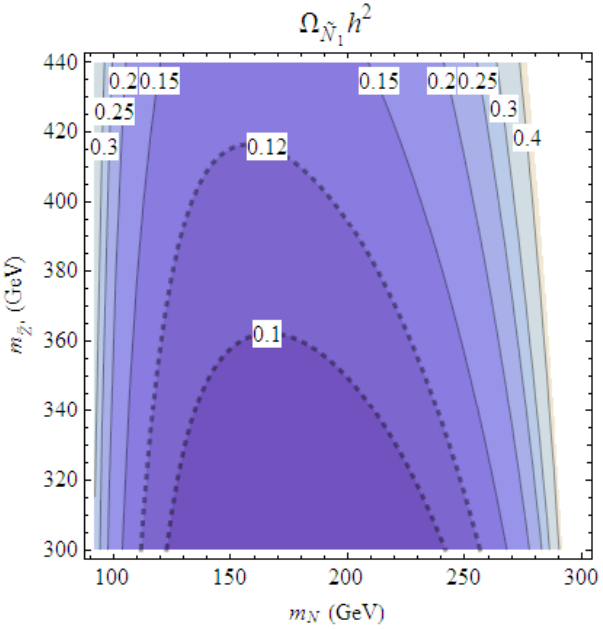


$M_{Z'}$=4 TeV

Relic density (g')

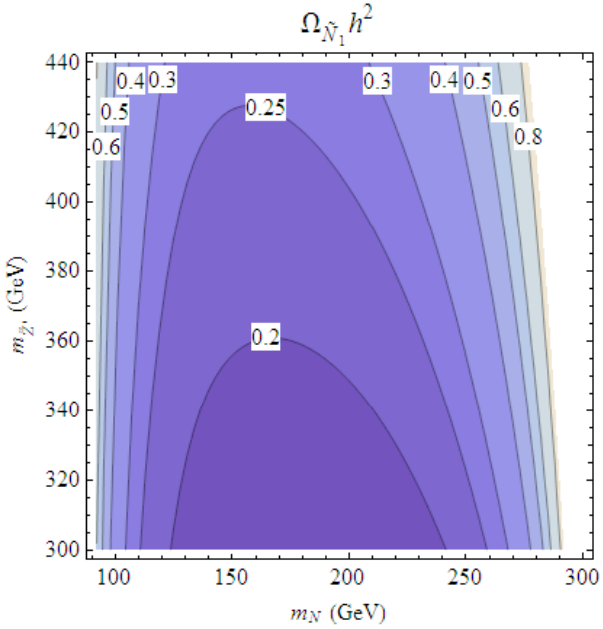
$M_{Z'}$=1.2 TeV, $m_\nu=10^{-3}$ eV

m_{DM}=300 GeV



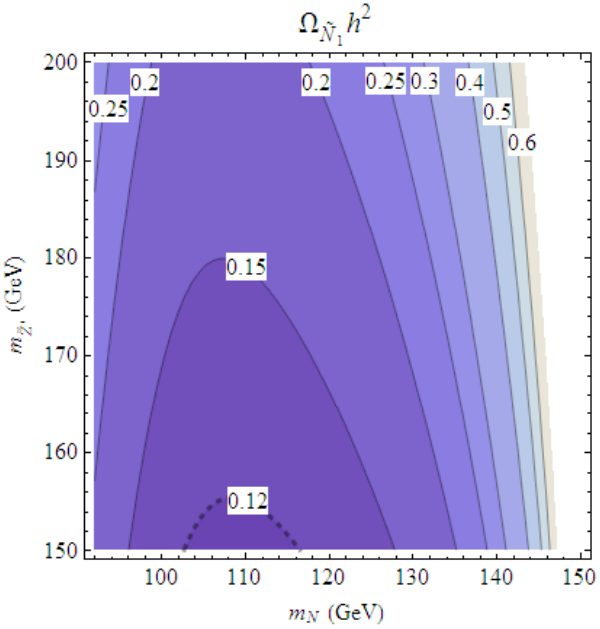
g'=0.3

m_{DM}=300 GeV



g'=0.25

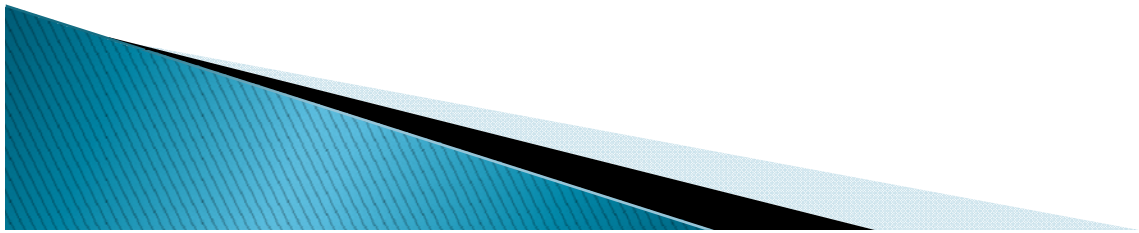
m_{DM}=150 GeV



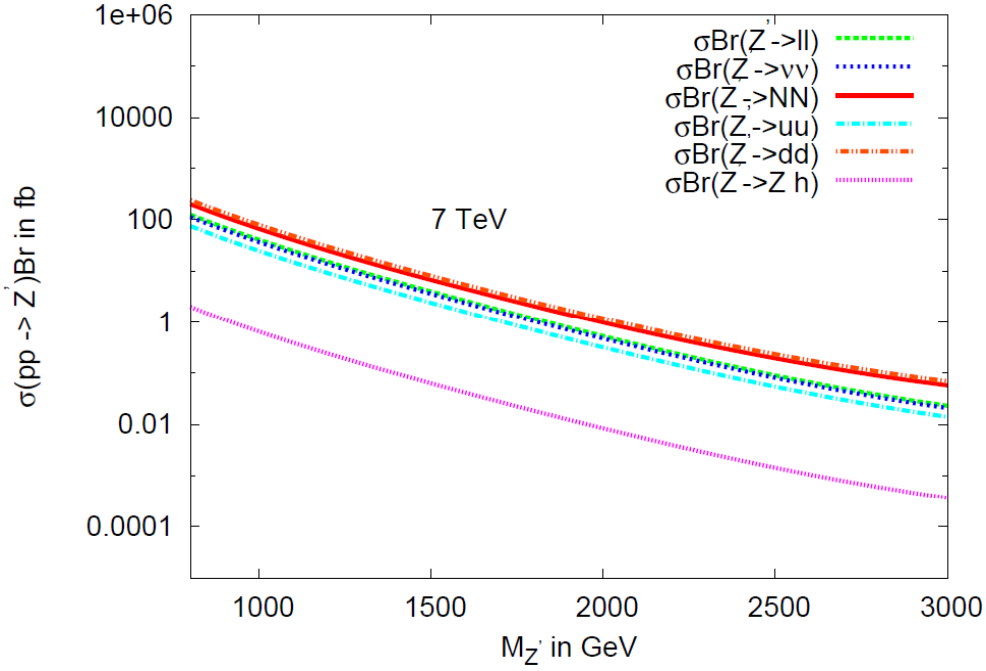
g'=0.2

Outline

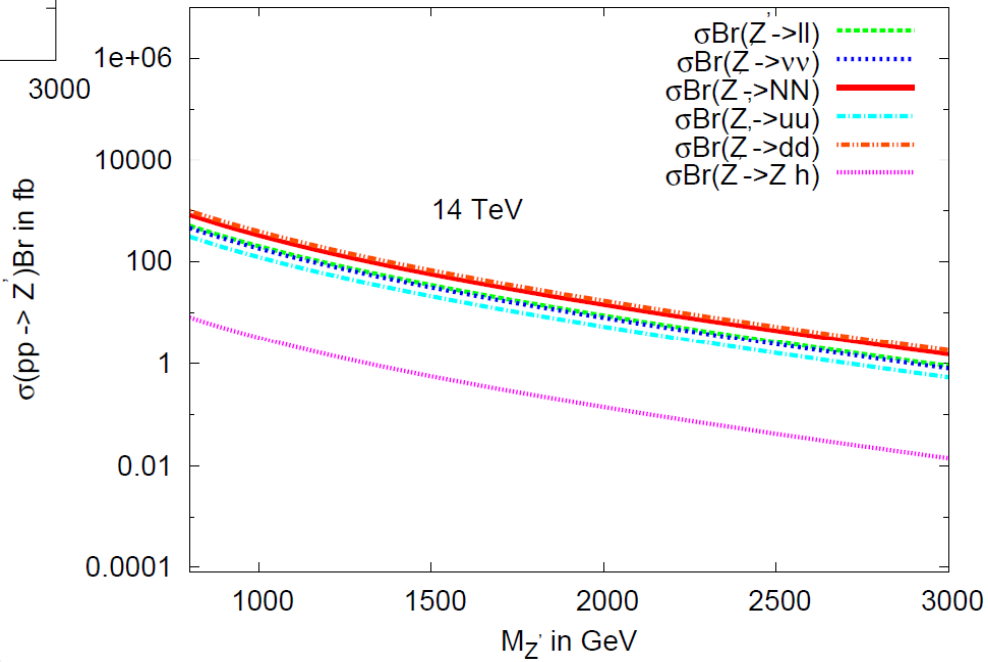
- Motivation
- Sneutrino dark matter models
- RH sneutrino DM model with $U(1)_\chi$
  - Relic density of DM
  - Collider signatures
- Conclusion



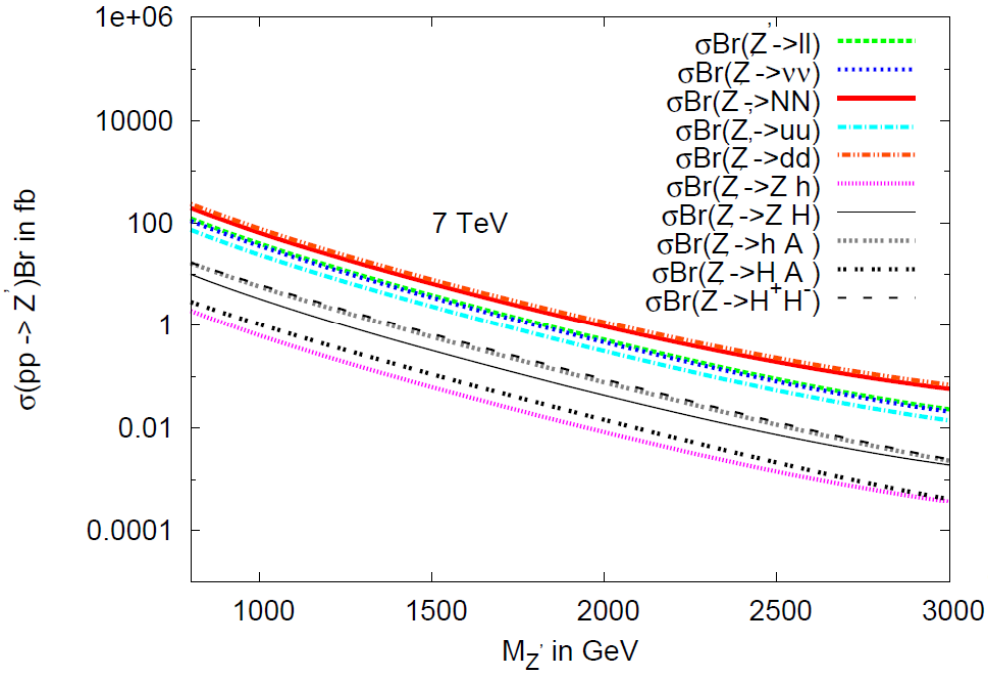
Production & decay of Z' I



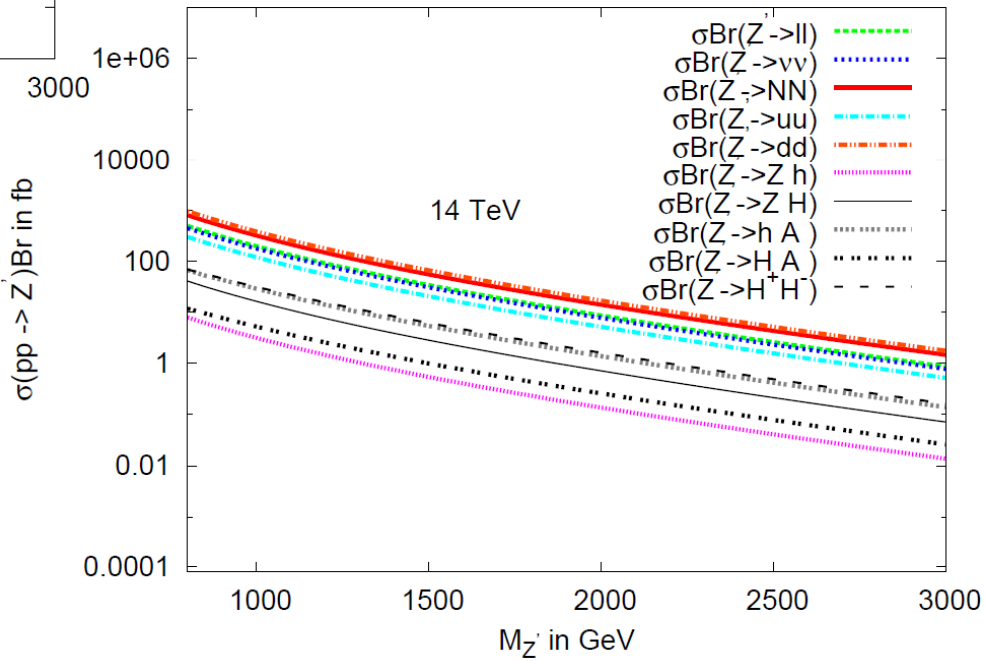
m_N=300 GeV, tan β=10



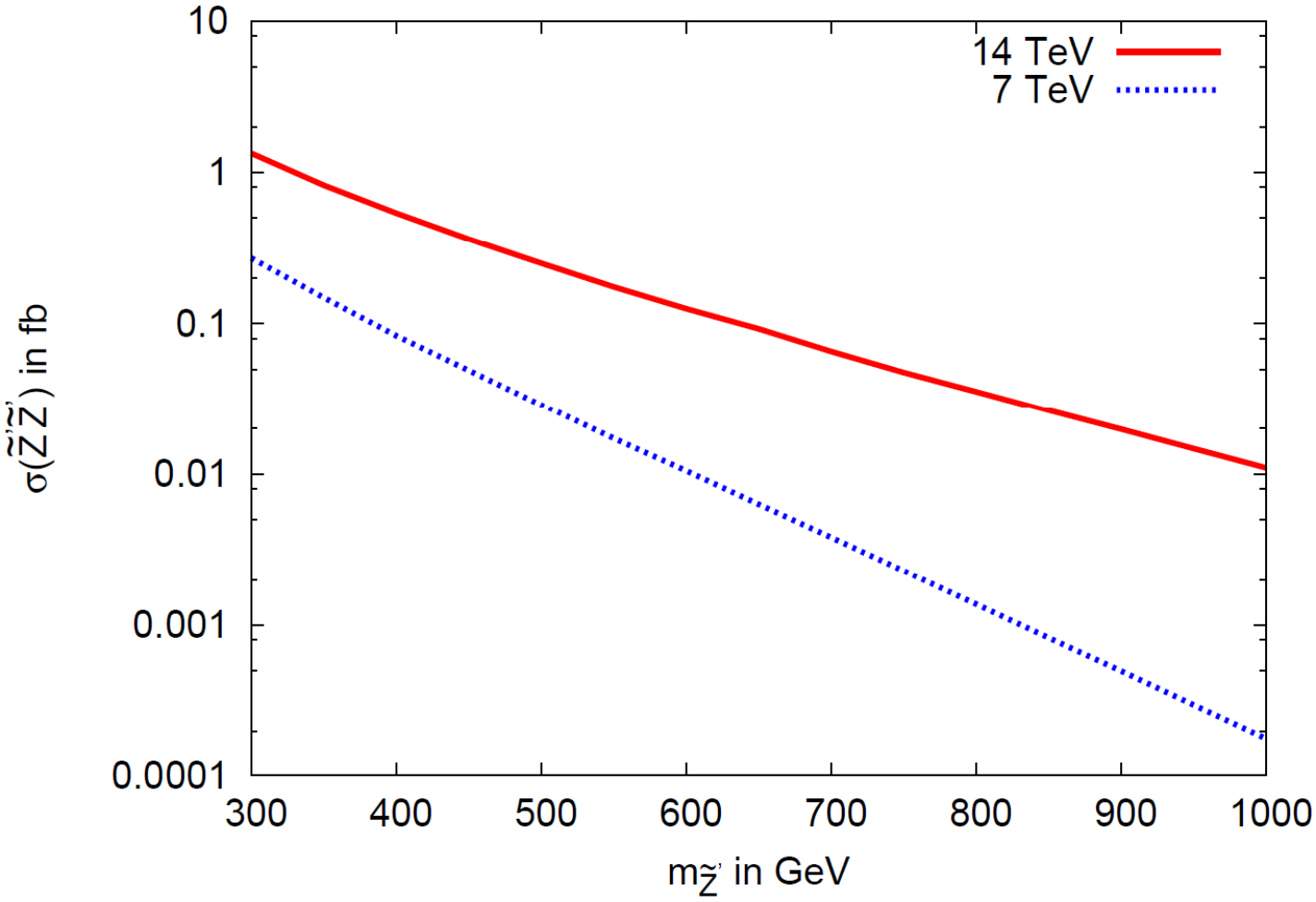
Production & decay of Z' II



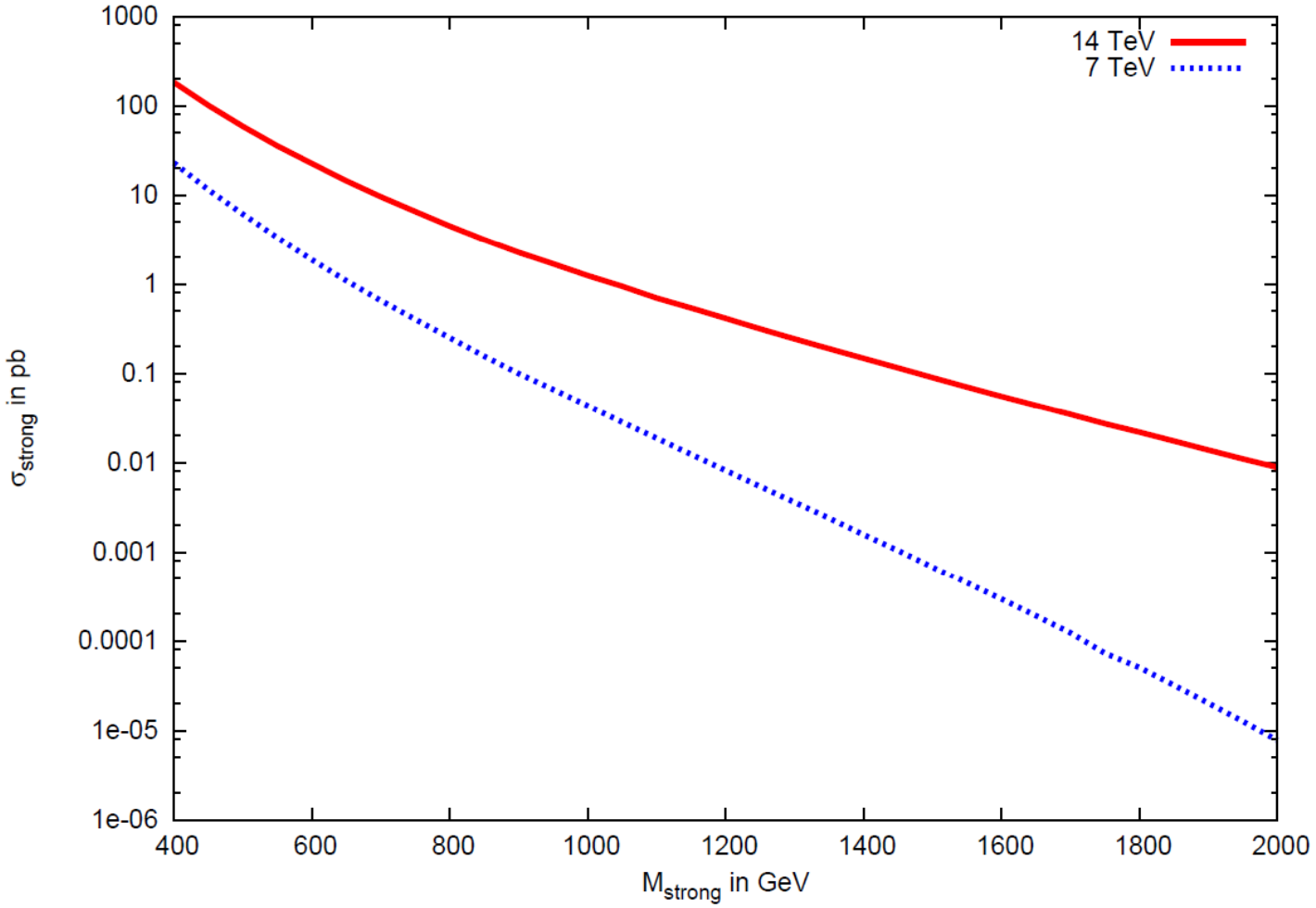
m_N=300 GeV, tan β=10,
m_A=162.2 GeV



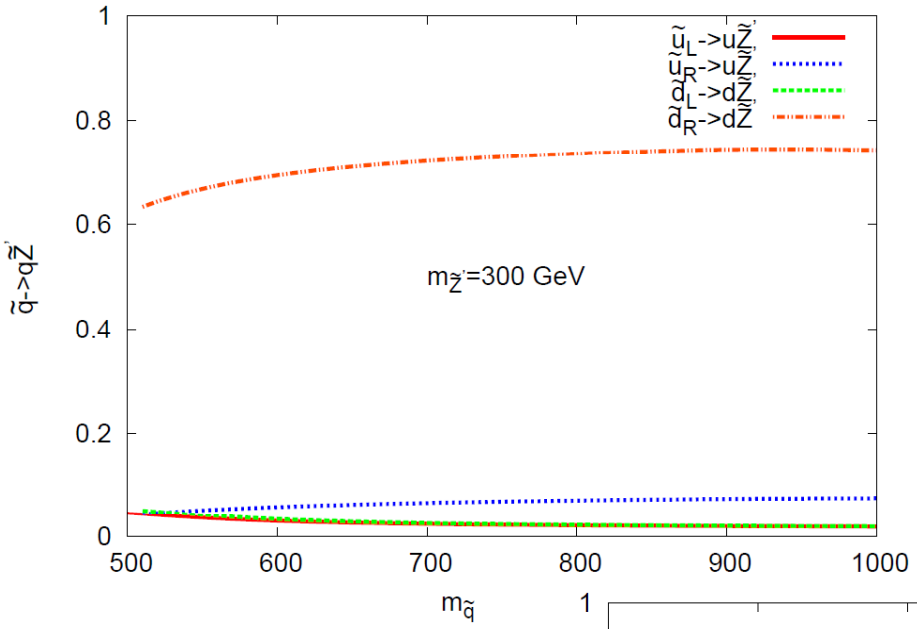
Z' gaugino pair production

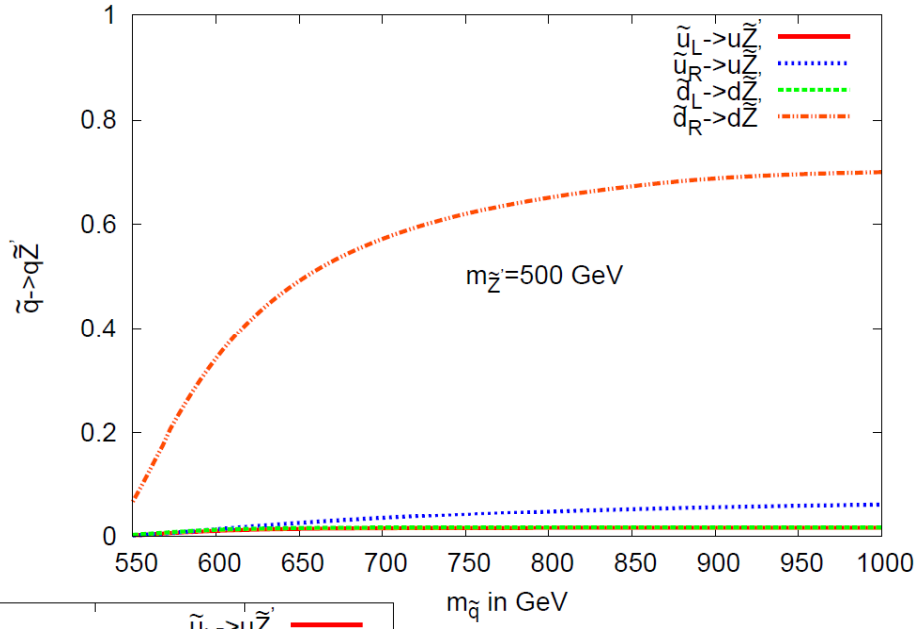


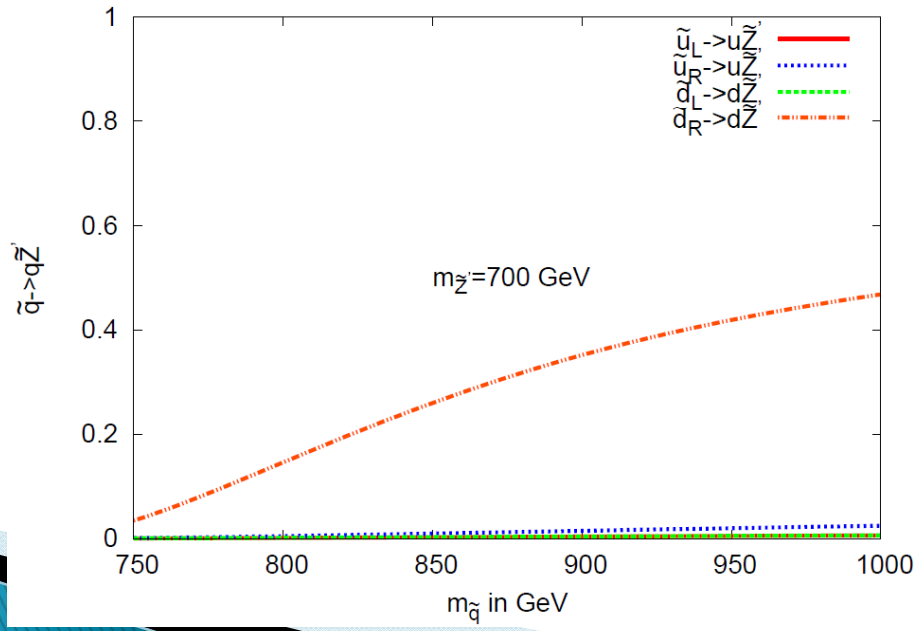
Strong production



Z' gaugino from cascade







Signatures of N

- Pair production of N: $pp \to Z' \to NN$

  $pp \to \tilde{Z}'\tilde{Z}' \to NN\tilde{N}_1\tilde{N}_1$

- Decays of N: $N \to lW, \nu Z, \nu h, \nu H, \nu A, lH^+$

- Multi-lepton signals: $pp \to Z'\ (\tilde{Z}'\tilde{Z}') \to l^{\pm}l^{\pm}W^{\mp}W^{\mp}\ (+\not{p}_T)$

  → 3*l*+j or 4*l* or SSD+4j

- Higgs signal from N: displaced production ($\because y_\nu$) & decay to $b\bar{b}$

  $pp \to Z'\ ,\ \tilde{Z}'\tilde{Z}' \to h\,l^{\pm}W^{\mp}/Z + \not{p}_T \qquad Br(NN \to h\nu l^{\pm}W^{\mp}) \approx 10\%$

- 7 Tev LHC:

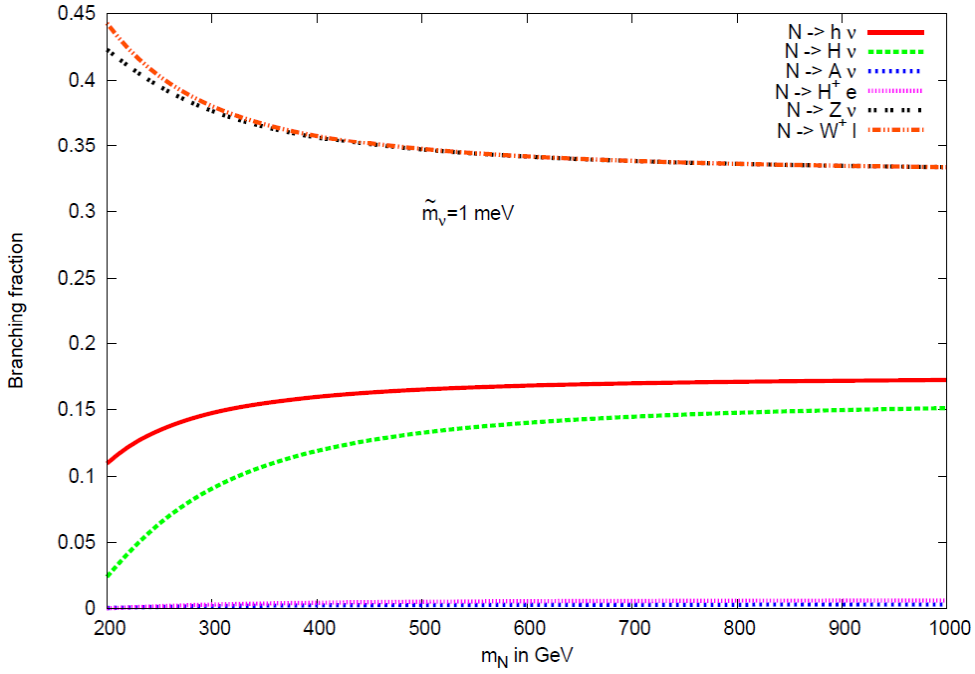
  $\sigma(pp \to Z' \to NN) \simeq 70$ fb for $M_{Z'} = 1$ TeV

  $\sigma(pp \to \tilde{Z}'\tilde{Z}' \to NN) \simeq 43$ fb for $M_{strong} = 1$ TeV

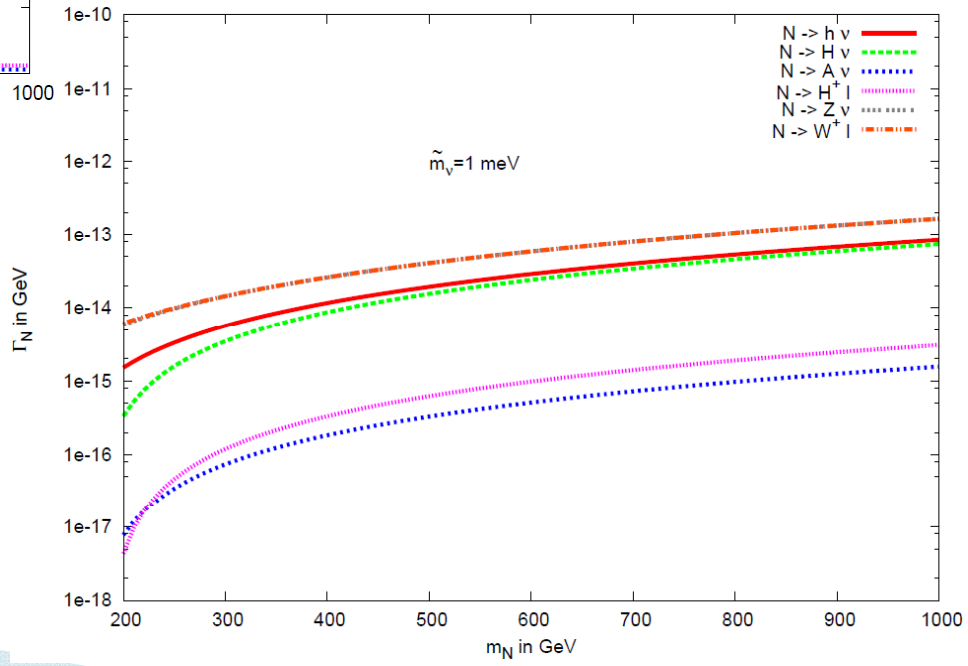
  $\sigma(hl^{\pm}W^{\mp}) \approx$ 21 or 4.3 fb

- 14 Tev LHC: $\sigma(hl^{\pm}W^{\mp}) \approx$ 105 or 130 fb

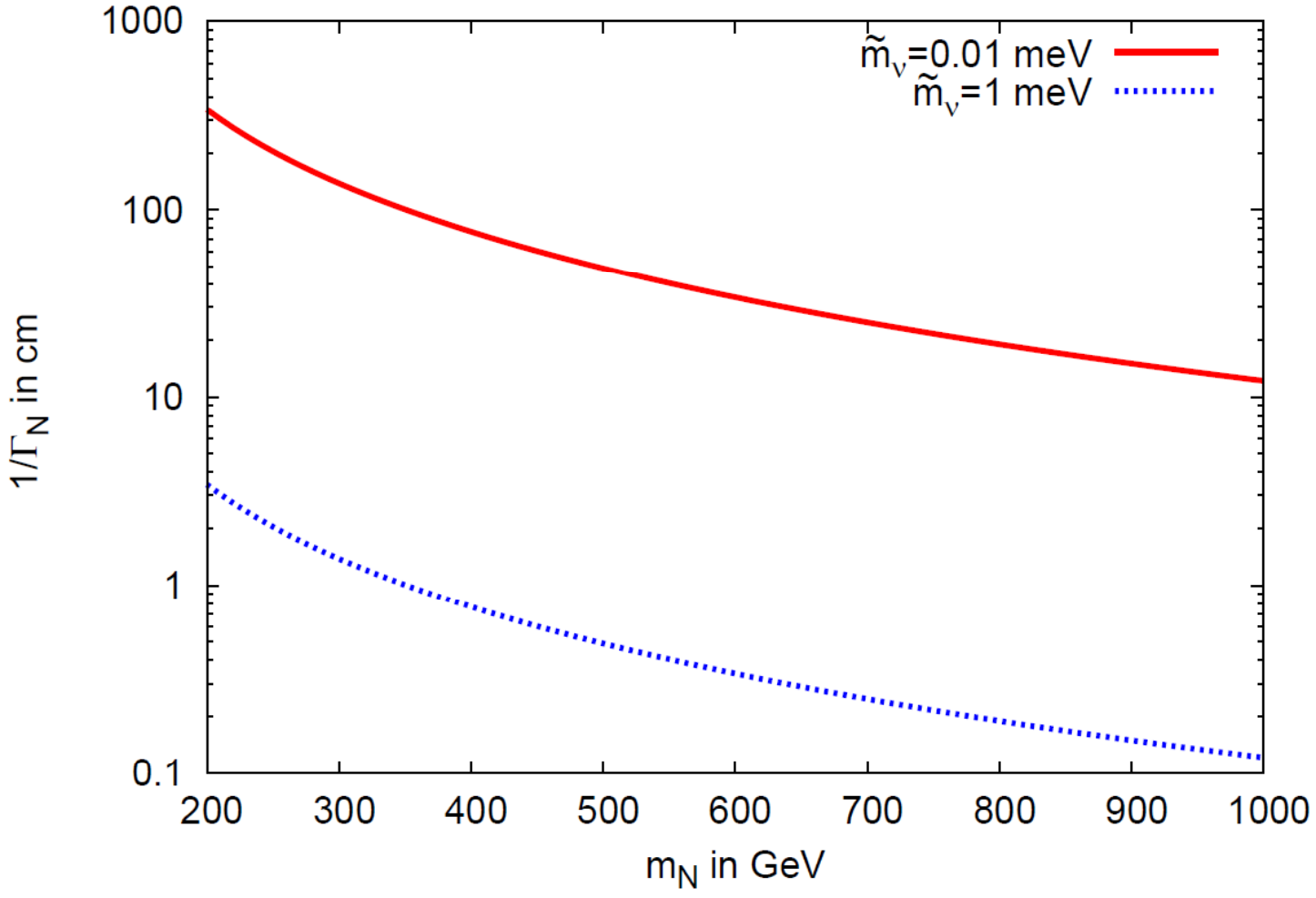
Decays of N



$m_\nu = 10^{-3}$ eV, $\tan\beta = 10$,
$m_A = 162.2$ GeV



Decay length of N



More signatures

- Small tanβ: large Br(N → H$^{\pm}$*l*)

$$pp \to Z' \ (\tilde{Z}'\tilde{Z}') \to H^{\pm}W^{\pm}l^{\mp}l^{\mp} \ (+ \not{p}_T)$$

→ displaced multi-jet (τ or b) & multi-*l*

- Slepton NLSP: one displaced & one prompt vertex

$$pp \to \tilde{Z}'\tilde{Z}' \to \begin{cases} W^{\pm}l^{\mp}l^{\pm}l^{\mp} + \not{p}_T \\ Z^0 l^{\pm}l^{\mp} + \not{p}_T \\ h l^{\pm}l^{\mp} + \not{p}_T \\ H^{\pm}l^{\mp}l^{\pm}l^{\mp} + \not{p}_T \end{cases}$$

- … NLSP: work in progress
- **Displaced decay of N can remove the SM background.**

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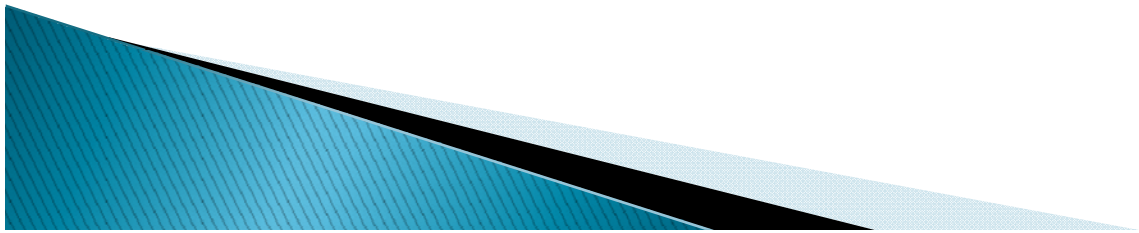

Conclusion

- RH sneutrino in supersymmetric $U(1)_\chi$ seesaw can be a good thermal DM candidate.
- New type of freeze out.
- In LHC, interesting signals from $U(1)_\chi$ gauge boson & gaugino production and decay to N.
- Displaced decay of N → low SM background.
- More analysis on collider signatures is in progress.


Thank you