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

JHEP**1106**:129(2011) & work in progress,
P. Bandyopadhyay & E.J. Chun

Jong-Chul Park

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GDR Terascale
CPPM Marseille, France

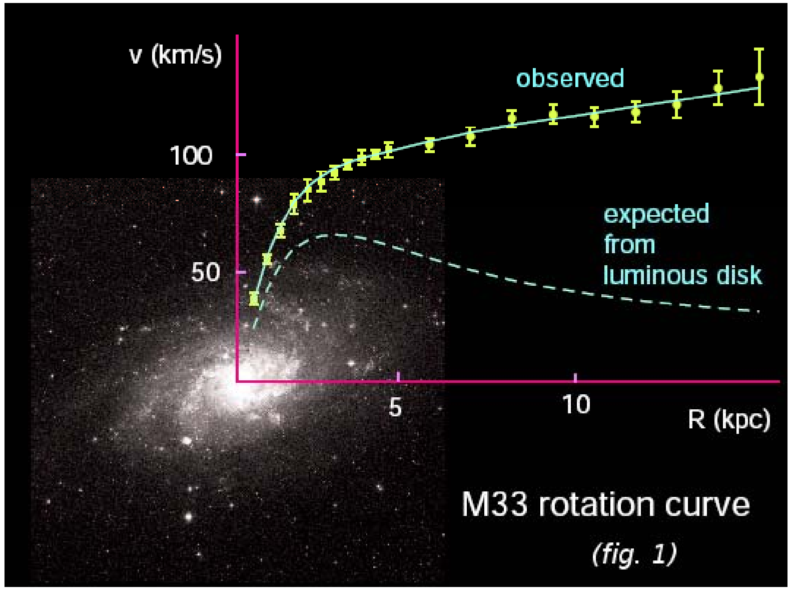
Outline

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

Dark matter

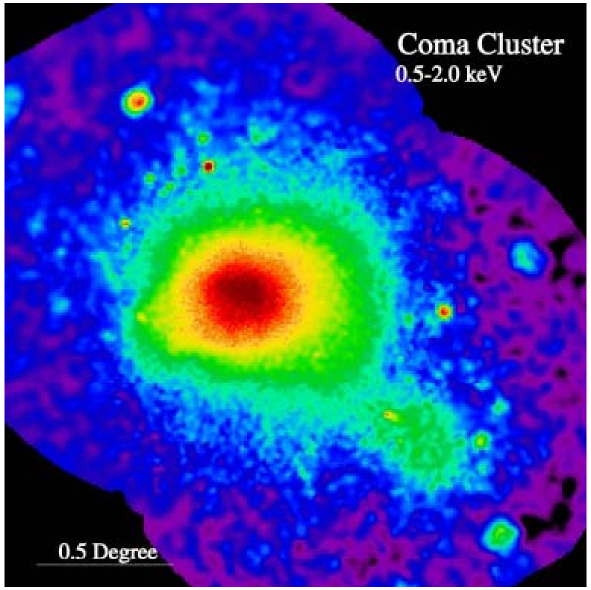
- discovered via gravity

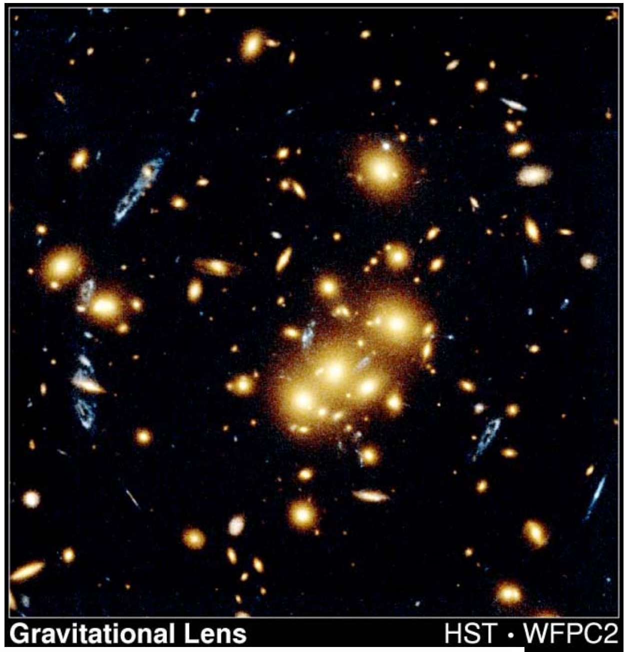
  by Fritz Zwicky (1933) & Vera Rubin (1970)

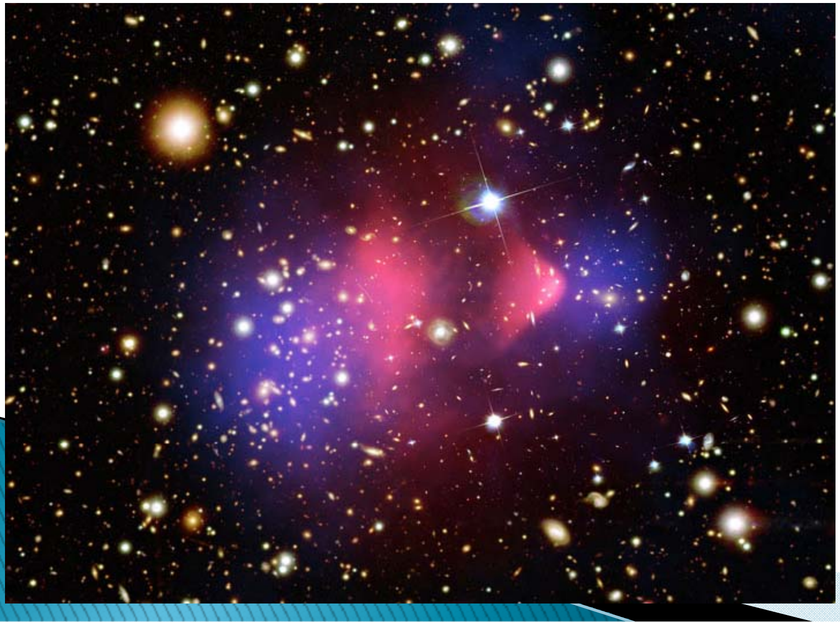


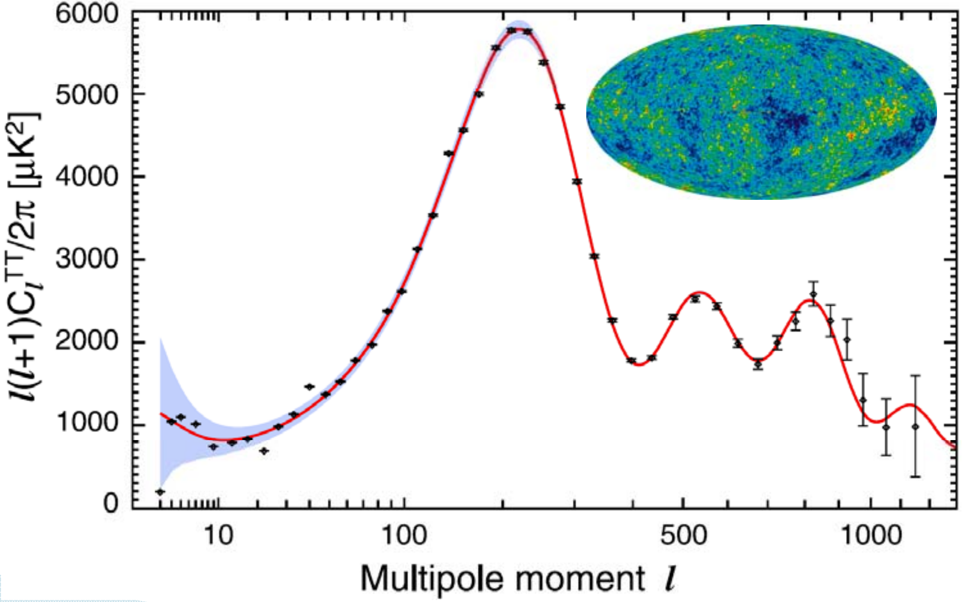
M33 rotation curve

(fig. 1)



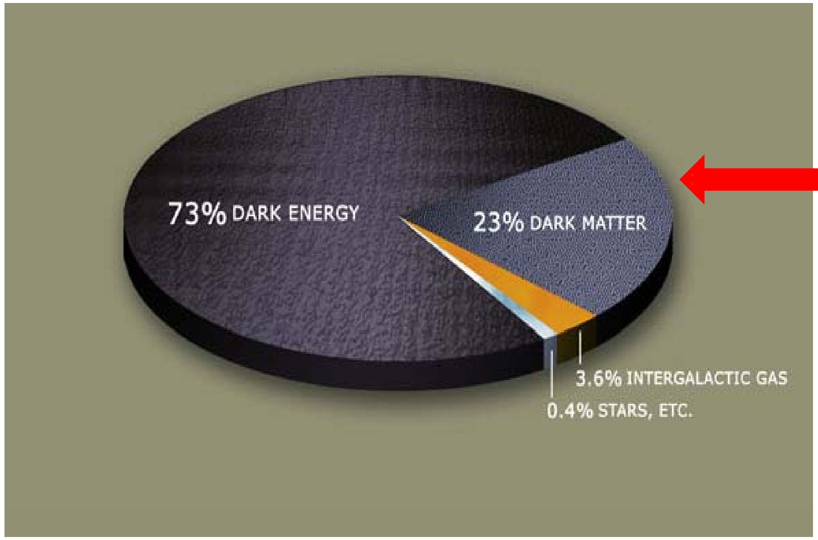


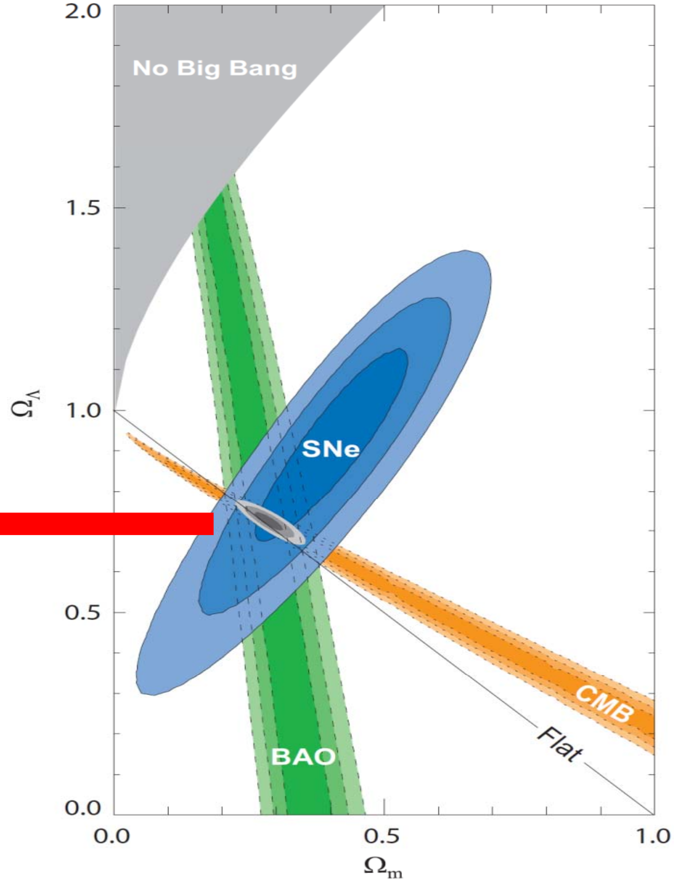




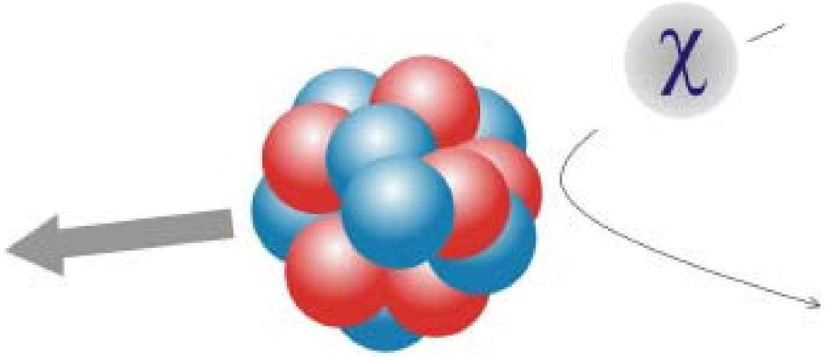
And …

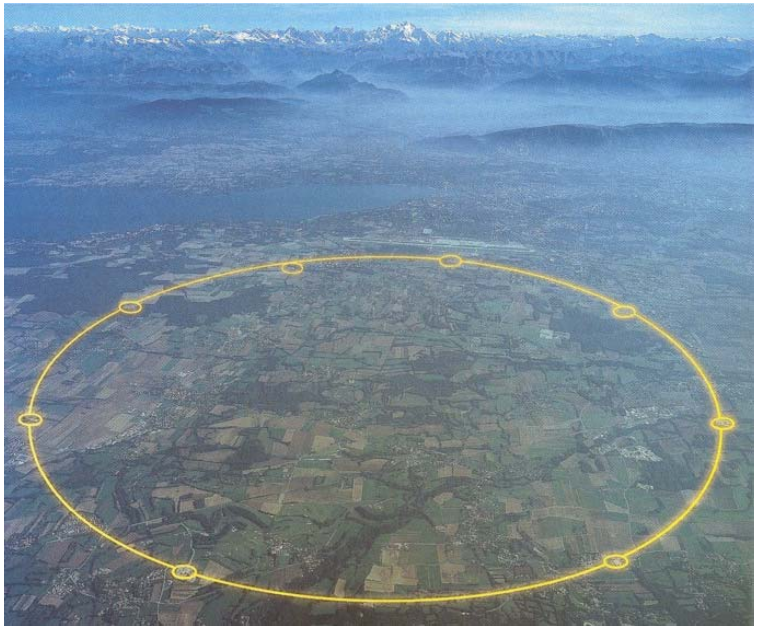
- DM accounts for 23% of the total mass-energy of the Universe





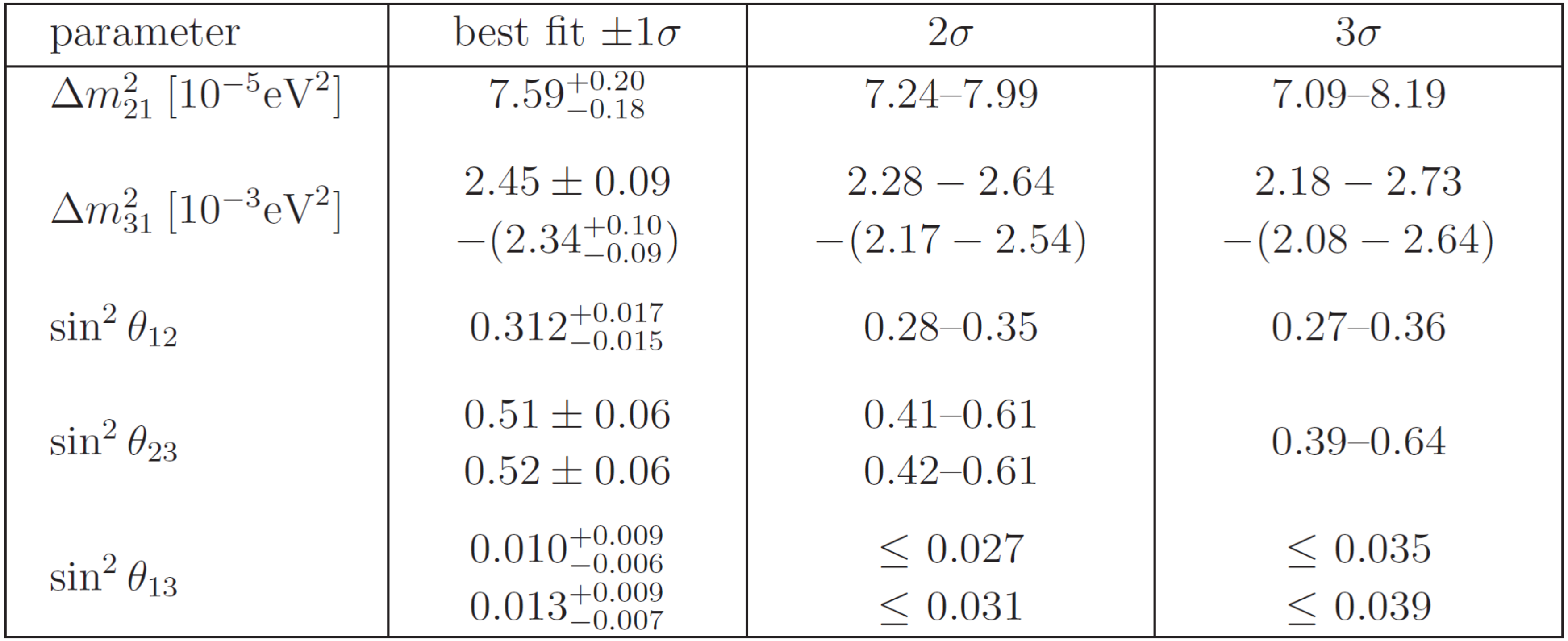
- For the particle identification, a discovery via EM, strong or weak probes is needed: e.g. DM direct detection, production, etc



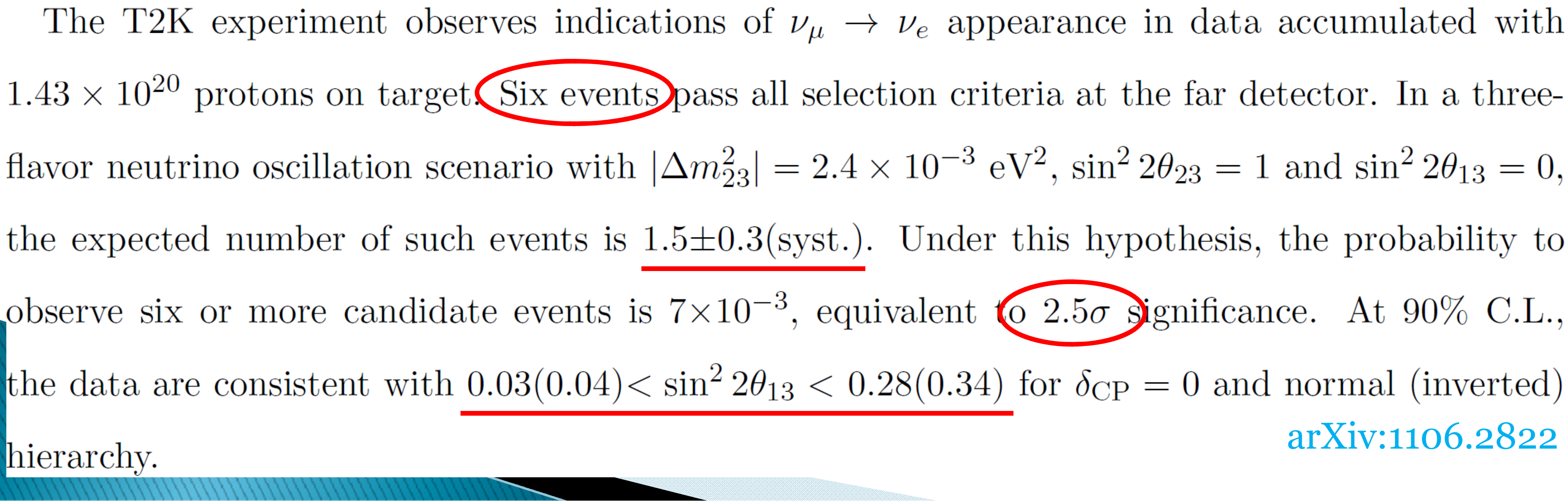


Massive but light neutrino

arXiv:1103.0734



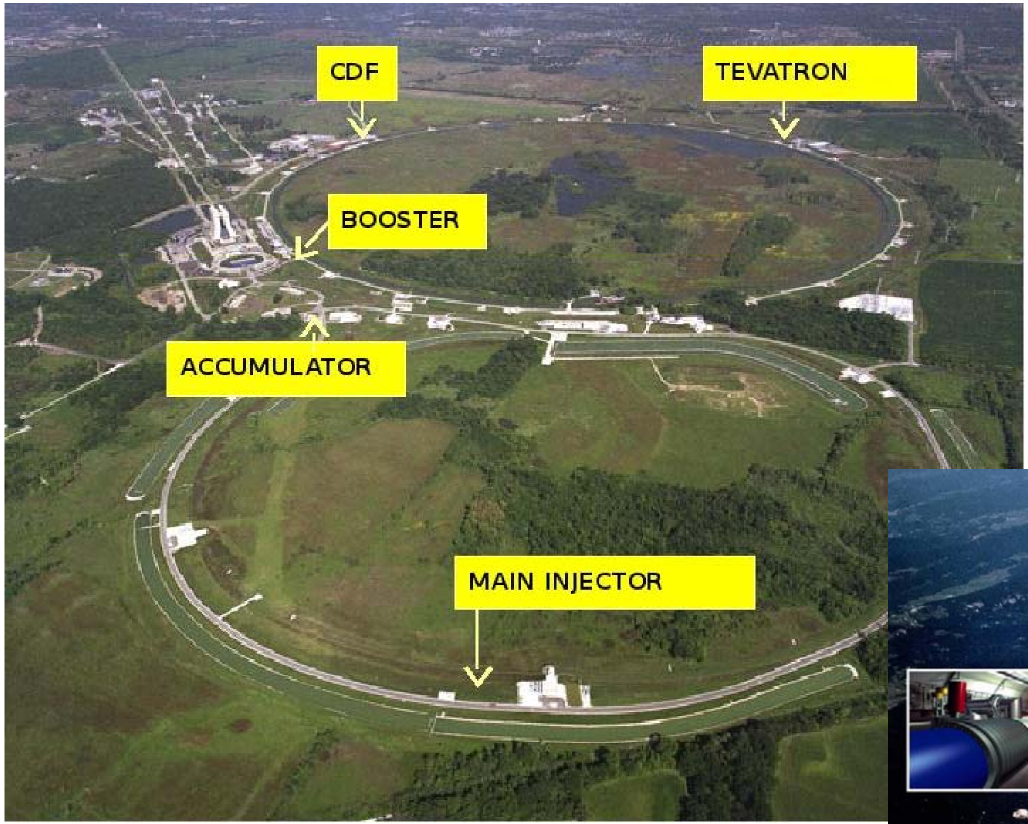
parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	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



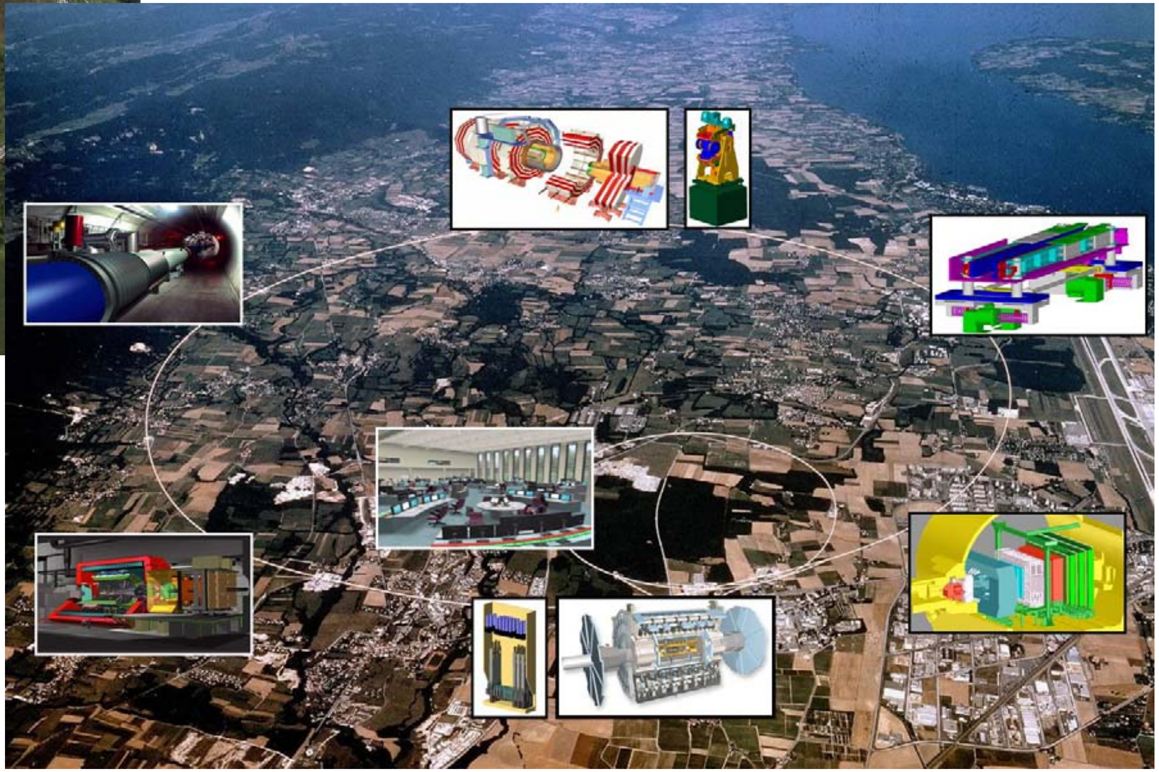
The T2K experiment observes indications of $\nu_\mu \to \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ 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 $7{\times}10^{-3}$, 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 $\delta_{\rm CP} = 0$ and normal (inverted) hierarchy.

arXiv:1106.2822

Colliders



Higgs, SUSY particles, Z', etc



LH sneutrino DM

- ❖ LH sneutrinos: annihilate too rapidly via Z-exchange

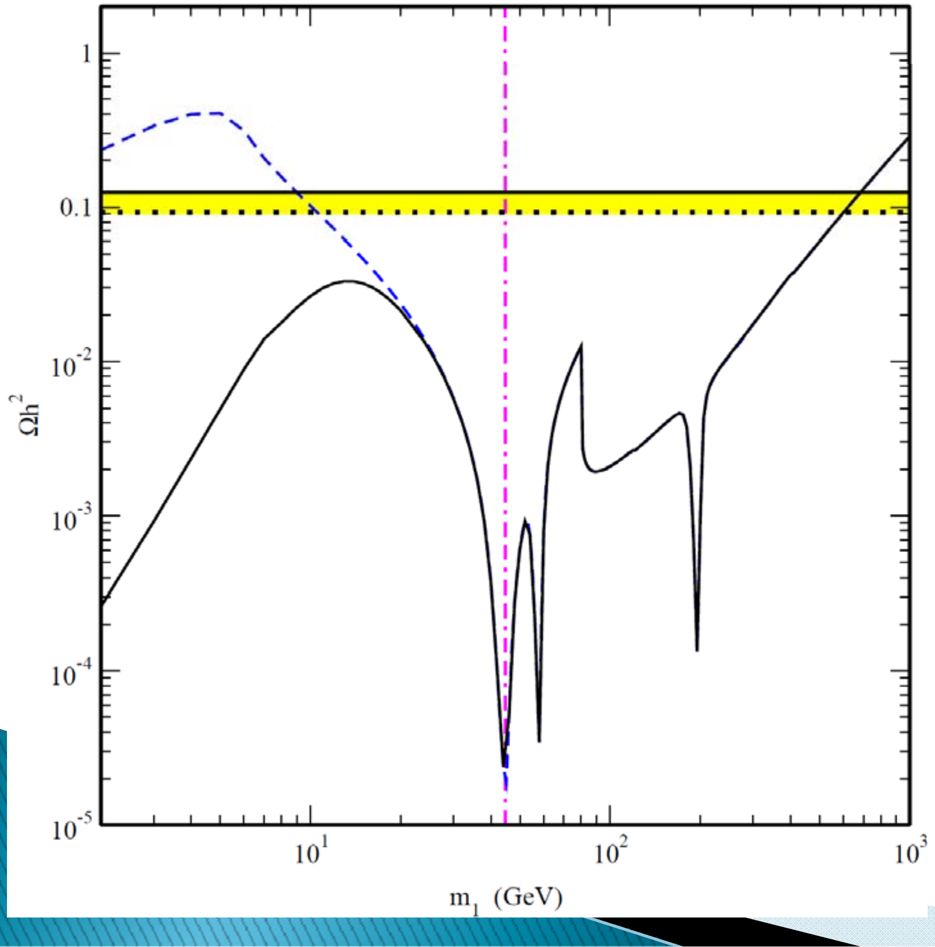
  → too small relic density

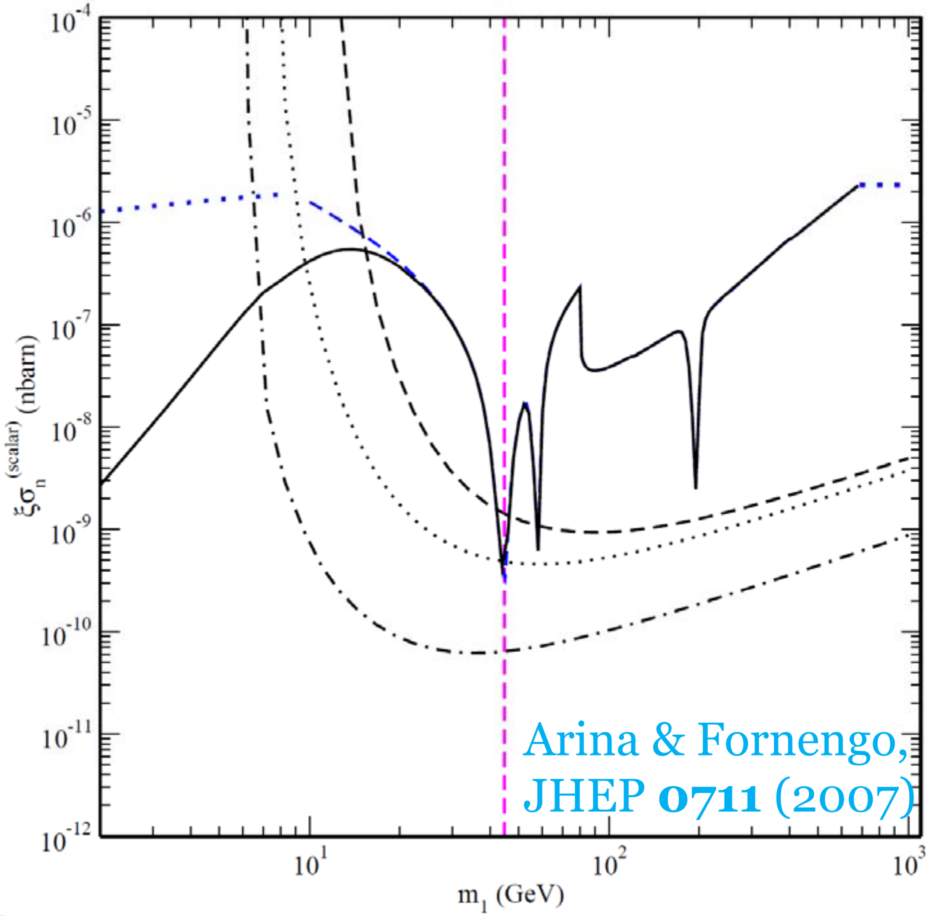
  - ➢ Very light ($\mathcal{O}$(GeV)): invisible width of the Z gauge boson

    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)





Arina & Fornengo, JHEP **0711** (2007)

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, JHEP **1107** (2011)

  - 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)

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'$_\chi$ mass from 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 limit on Z'$_\chi$ mass from LHC: Laisne & Mine's talks

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

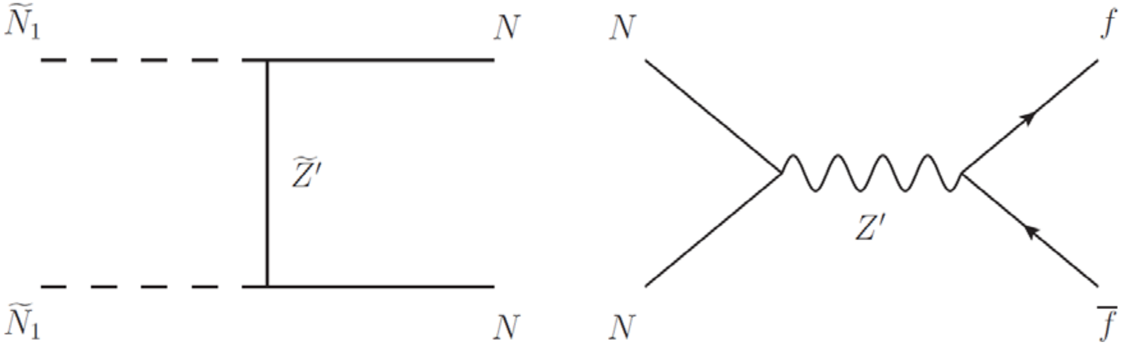
$$V_{mass} = (m_N^2 + m_{\tilde{N}}^2 - \frac{1}{4} m_{Z'}^2 c_{2\beta'}) |\tilde{N}|^2 - \frac{1}{2} B_N m_N (\tilde{N} \tilde{N} + \tilde{N}^* \tilde{N}^*)$$

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

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.

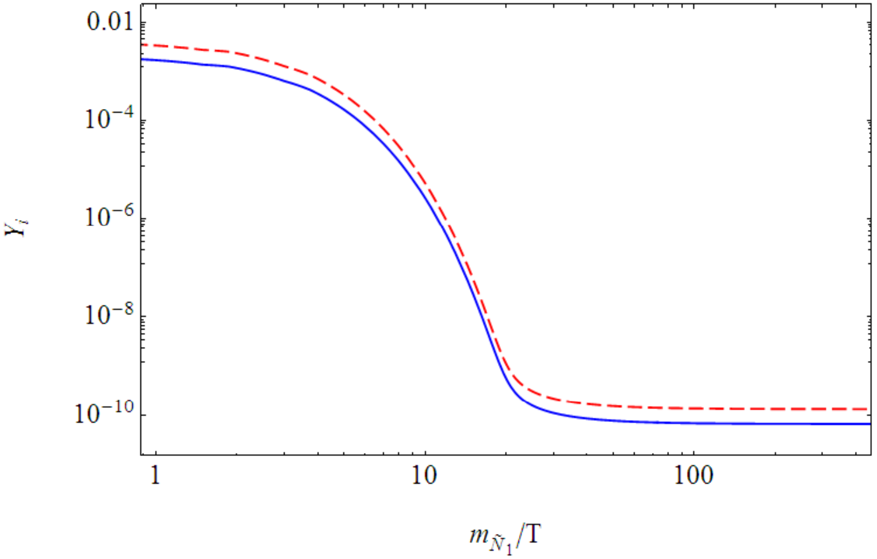
Freeze out of DM



- Boltzmann equations

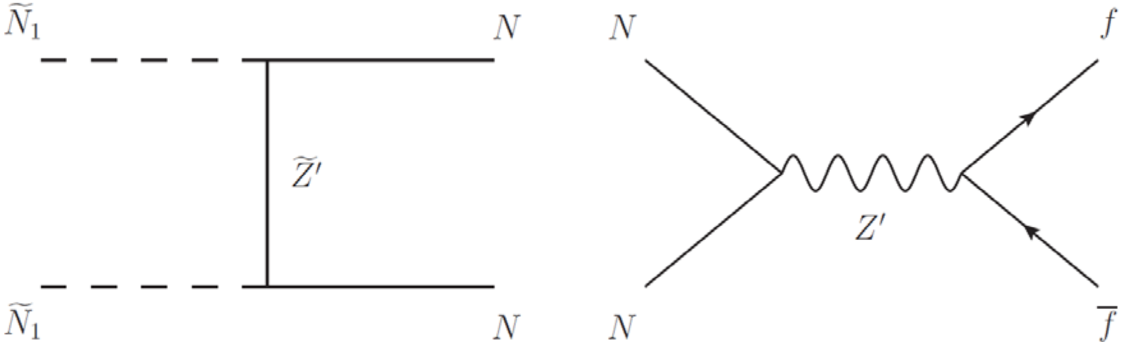
$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle\sigma_{\widetilde{N}_1} v_{\widetilde{N}_1}\rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N\right)^2\right]$$

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



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

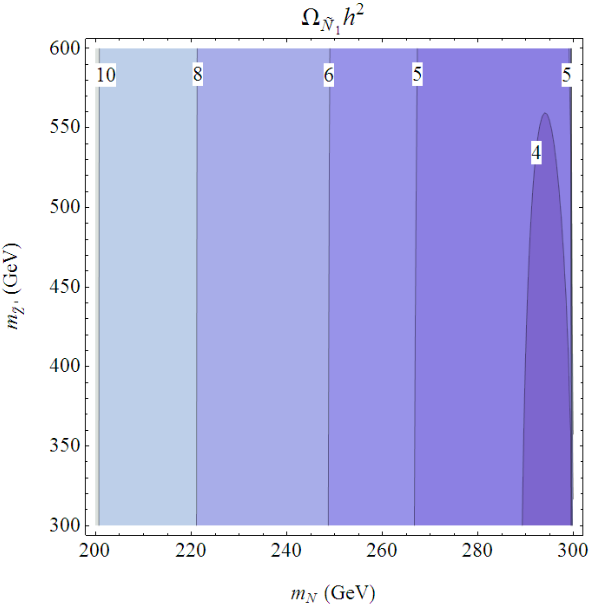
Freeze out of DM



- Boltzmann equations

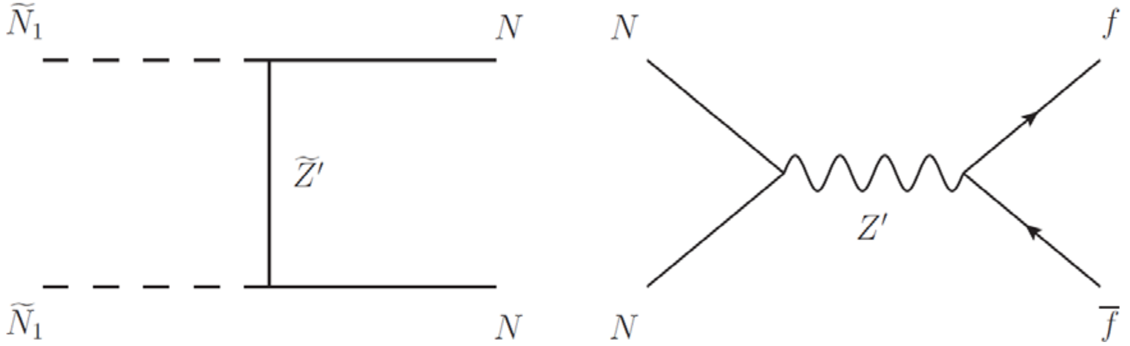
$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle \sigma_{\widetilde{N}_1} v_{\widetilde{N}_1} \rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N \right)^2 \right]$$

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



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

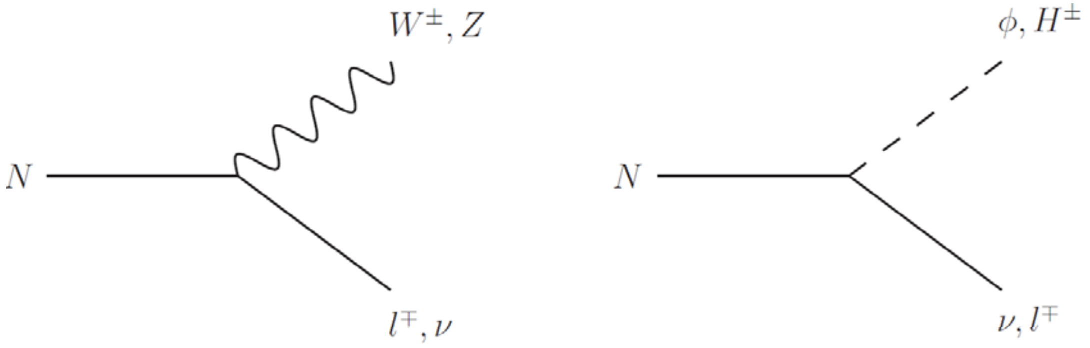
Freeze out of DM



- Boltzmann equations

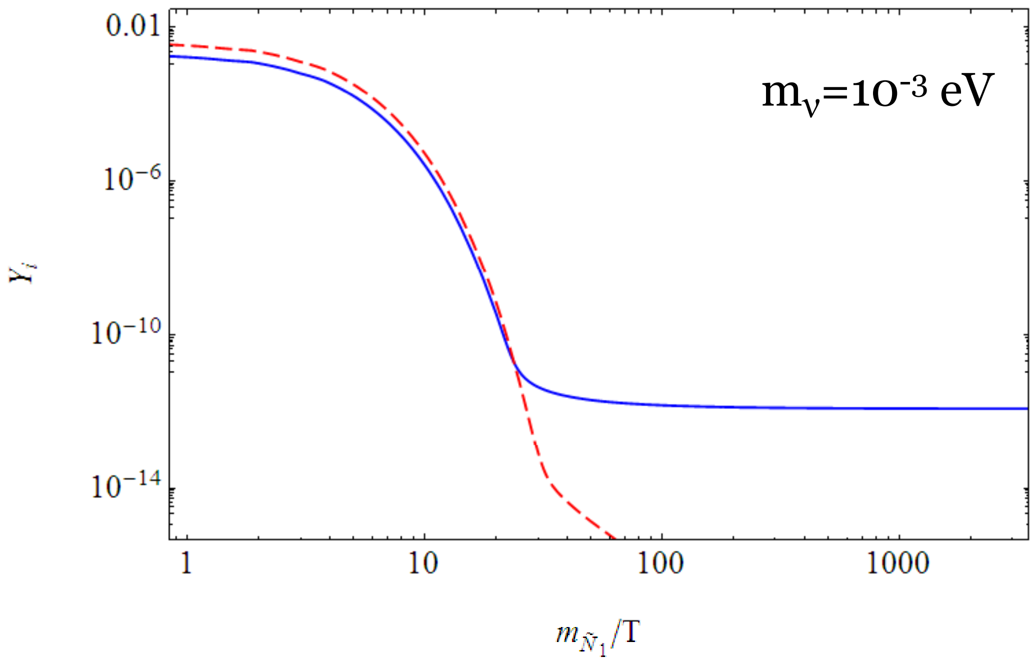
$$\frac{dn_{\widetilde{N}_1}}{dt} = -3Hn_{\widetilde{N}_1} - \langle \sigma_{\widetilde{N}_1} v_{\widetilde{N}_1} \rangle \left[(n_{\widetilde{N}_1})^2 - \left(\frac{g_{\widetilde{N}_1}}{g_N} n_N \right)^2 \right]$$

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

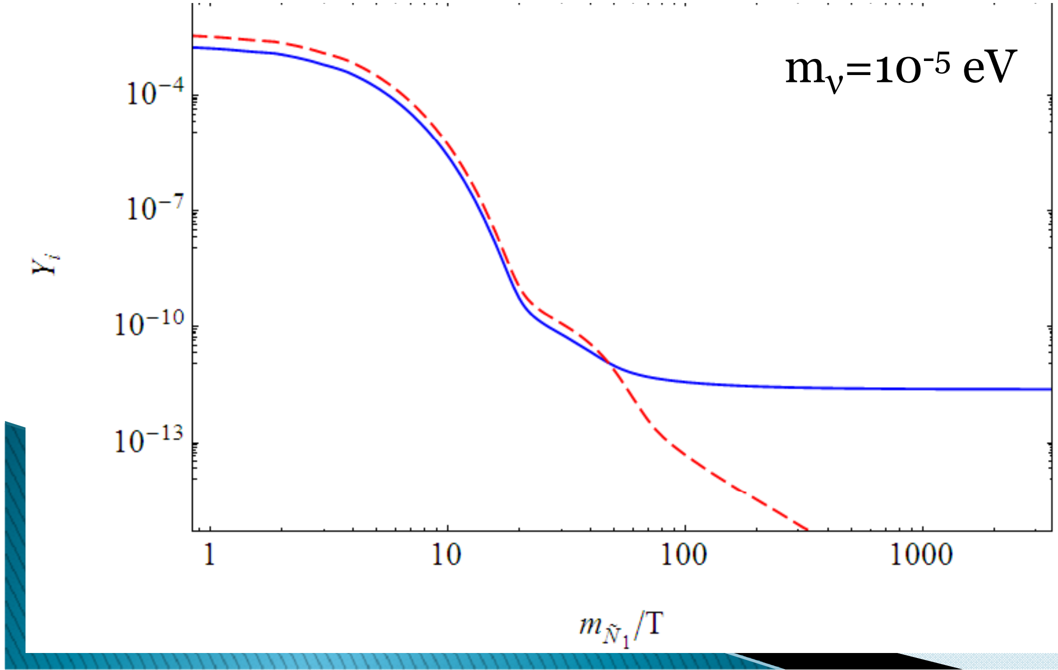


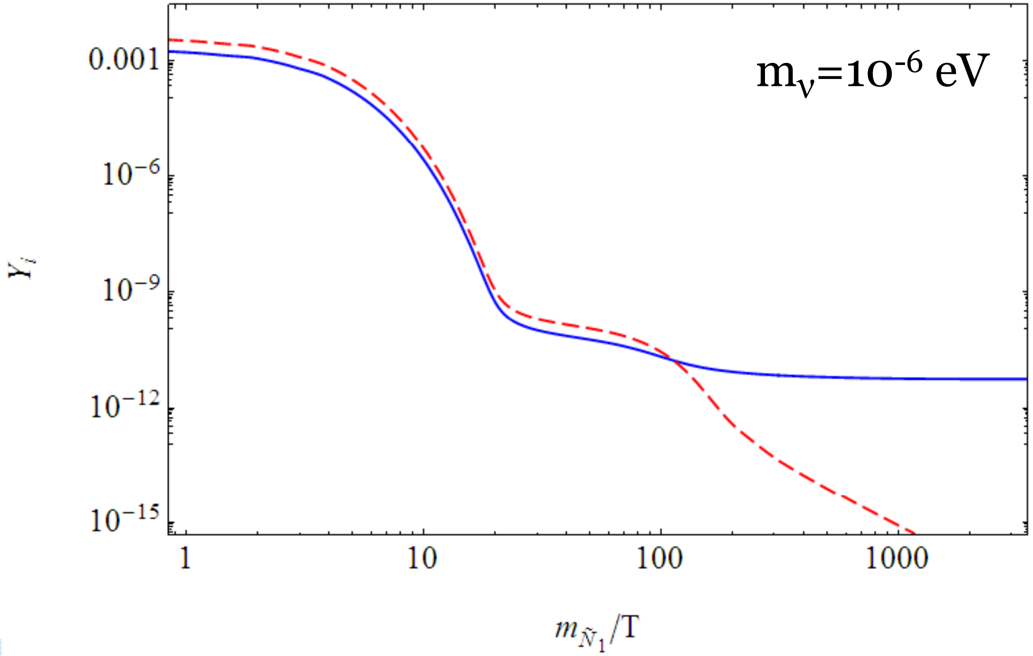
$\phi = h, H, A$

Freeze out



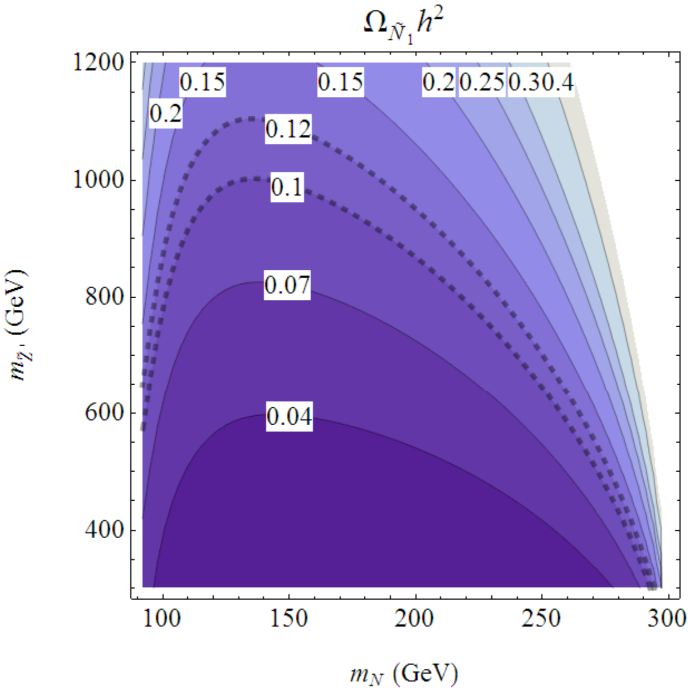
m_{DM}=300 GeV, m_N=260 GeV,
$M_{Z'}$=1.2 TeV, $m_{\tilde{Z}'}$=600 GeV



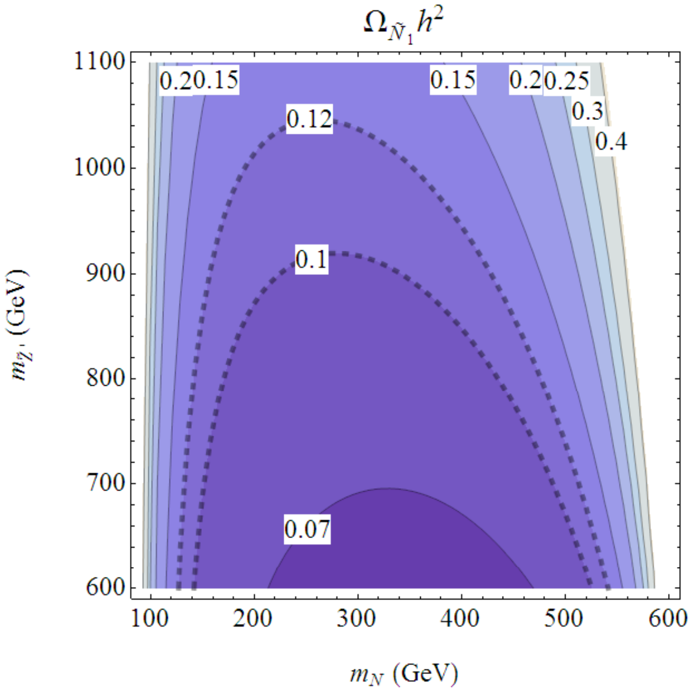


Relic density (m_{DM})

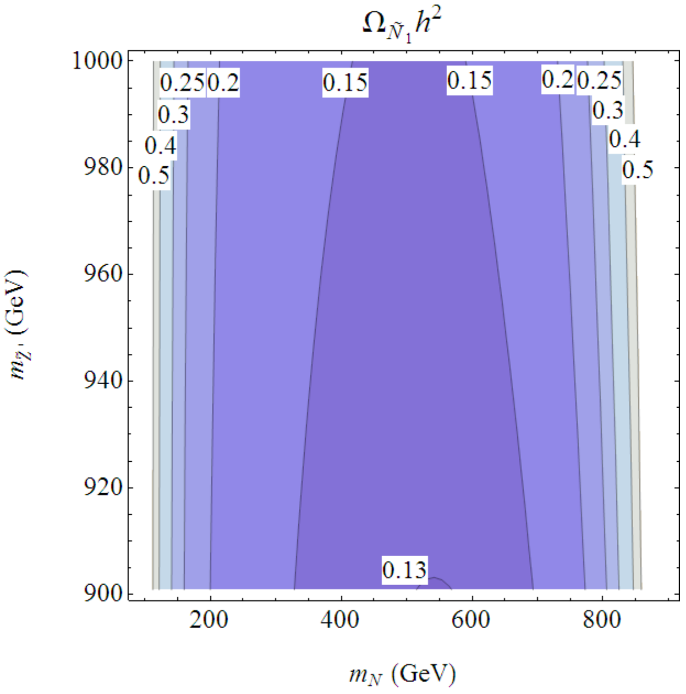
$M_{Z'}$=1.2 TeV, m_ν=10^{-3} eV



m_{DM}=300 GeV



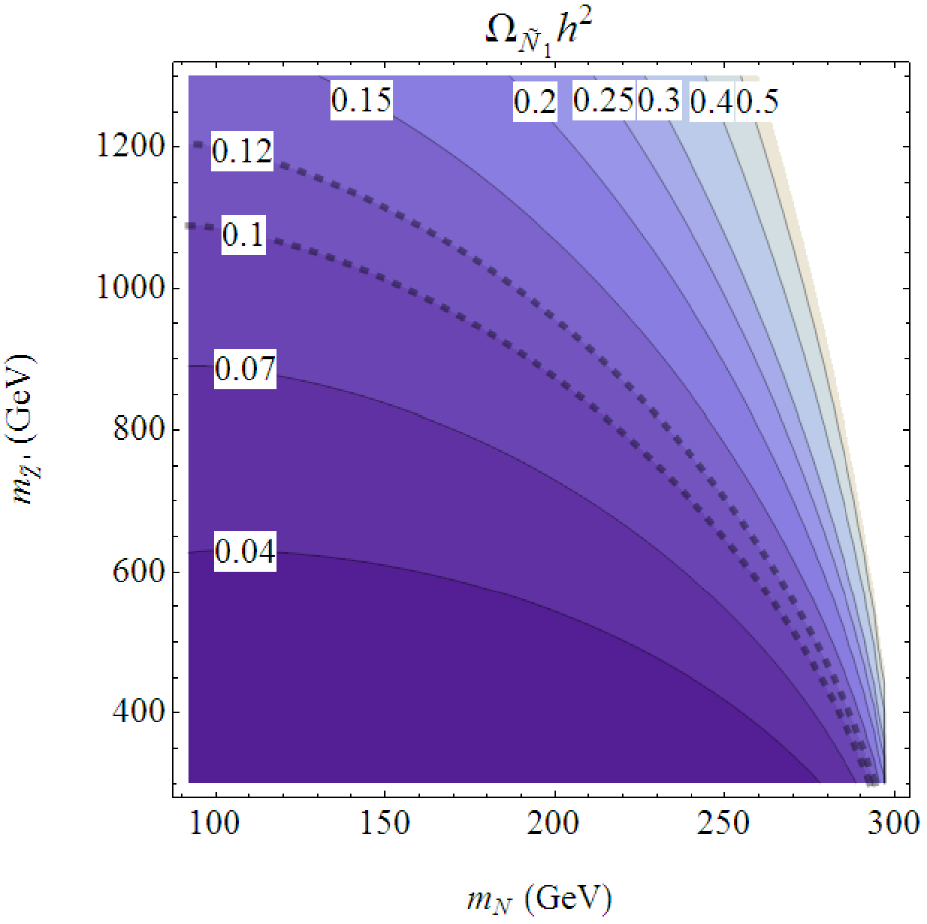
m_{DM}=600 GeV



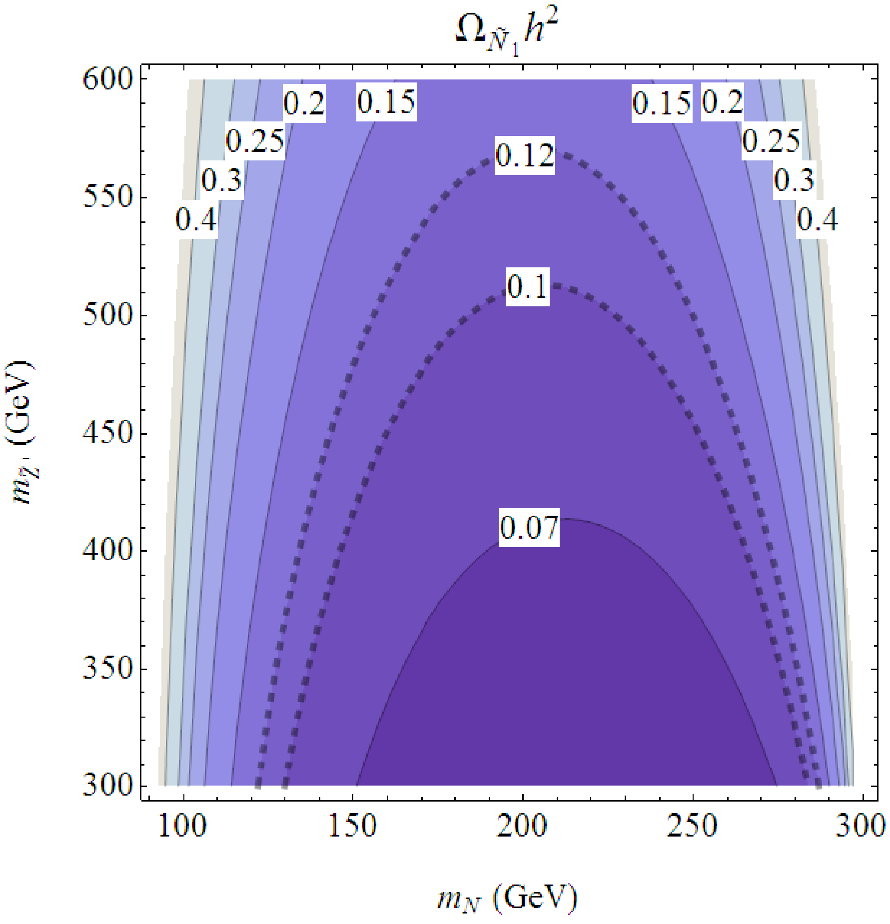
m_{DM}=900 GeV

Relic density (m_ν)

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



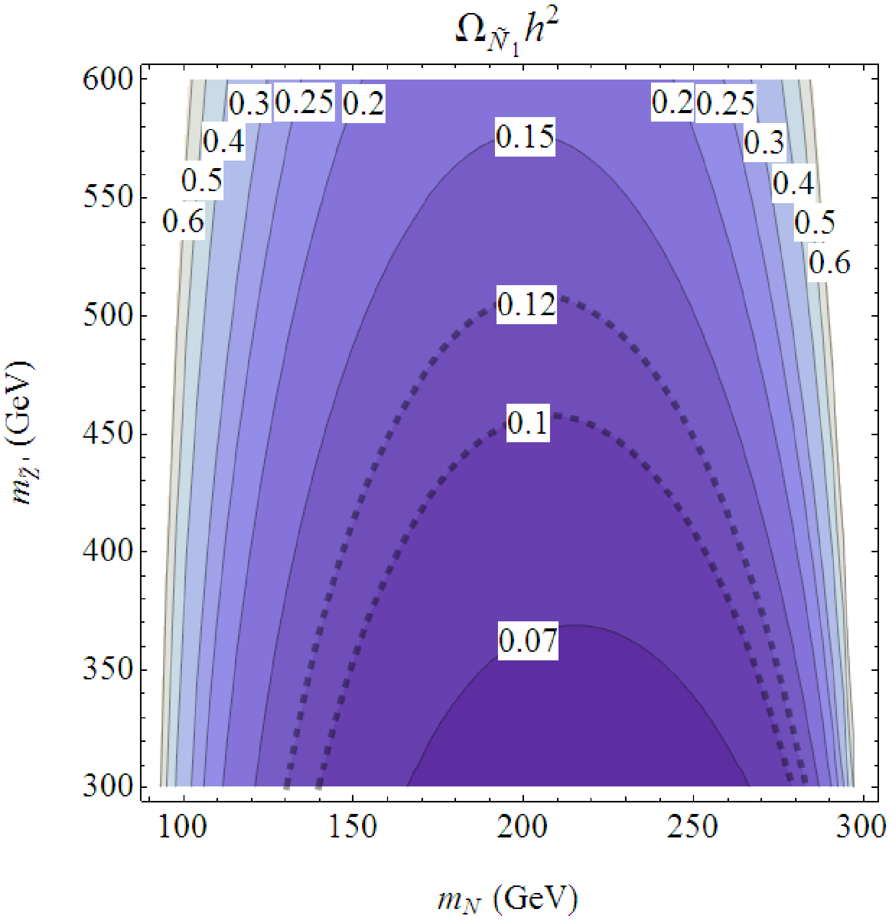
m_ν=10^{-1} eV



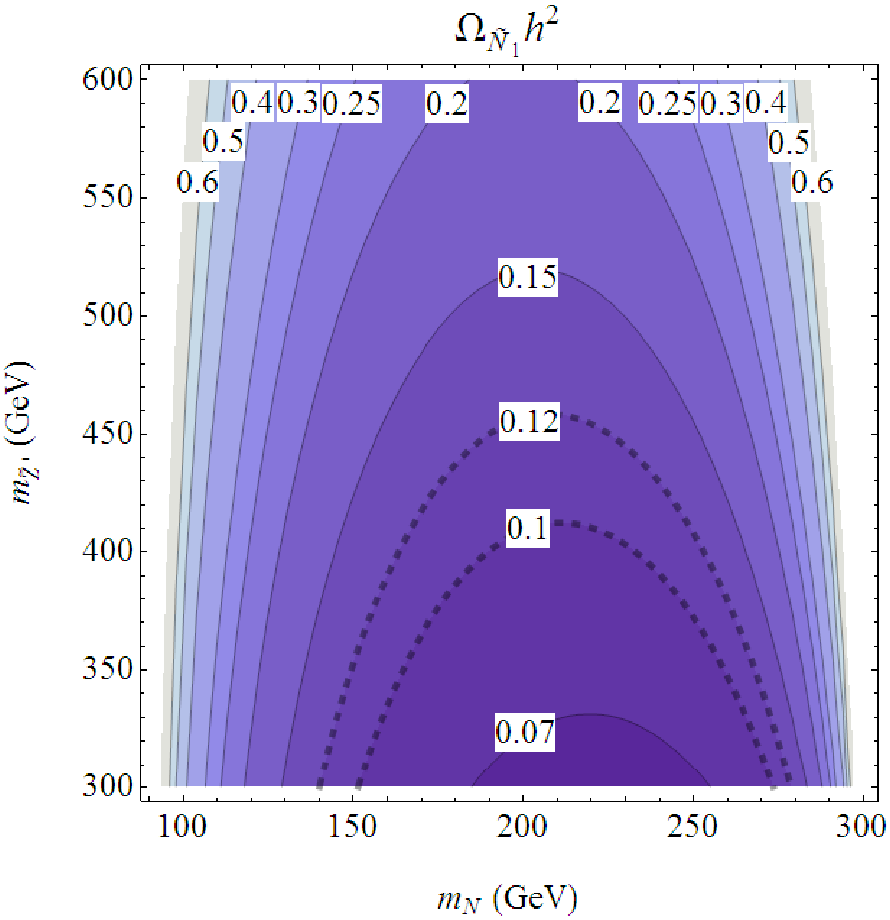
m_ν=10^{-5} eV

Relic density ($M_{Z'}$)

m_{DM}=300 GeV, m_ν=10^{-3} eV



$M_{Z'}$=2 TeV

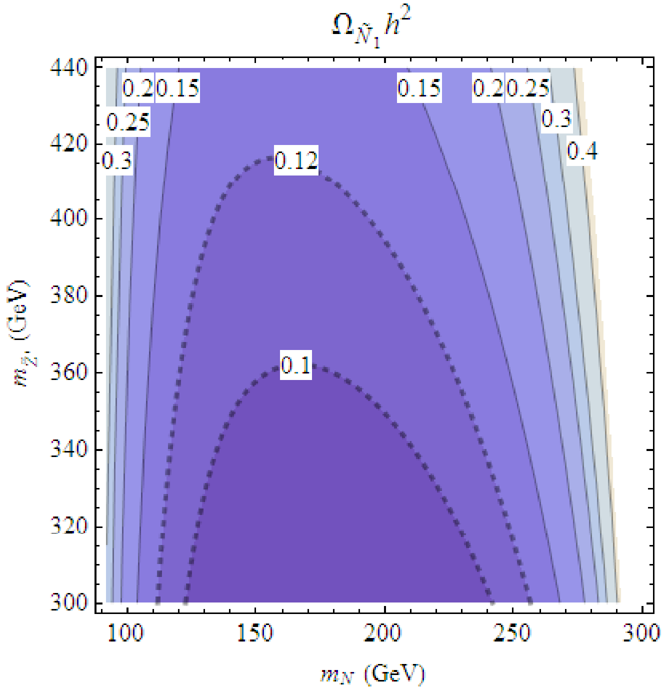


$M_{Z'}$=4 TeV

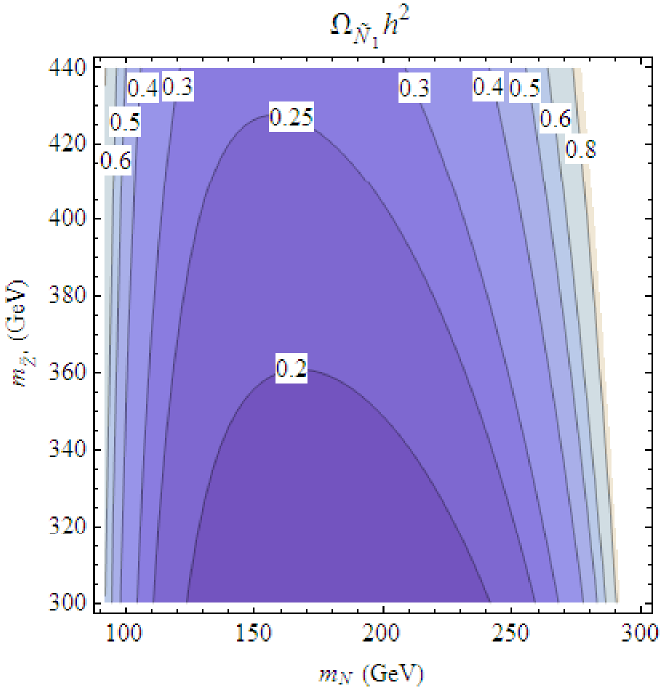
Relic density (g')

$M_{Z'}$=1.2 TeV, m_ν=10^{-3} eV

m_{DM}=300 GeV

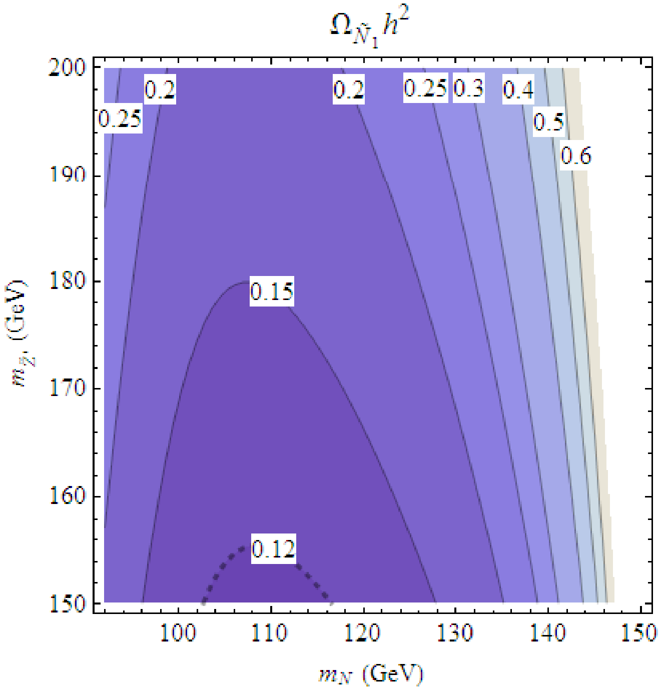


g'=0.3



g'=0.25

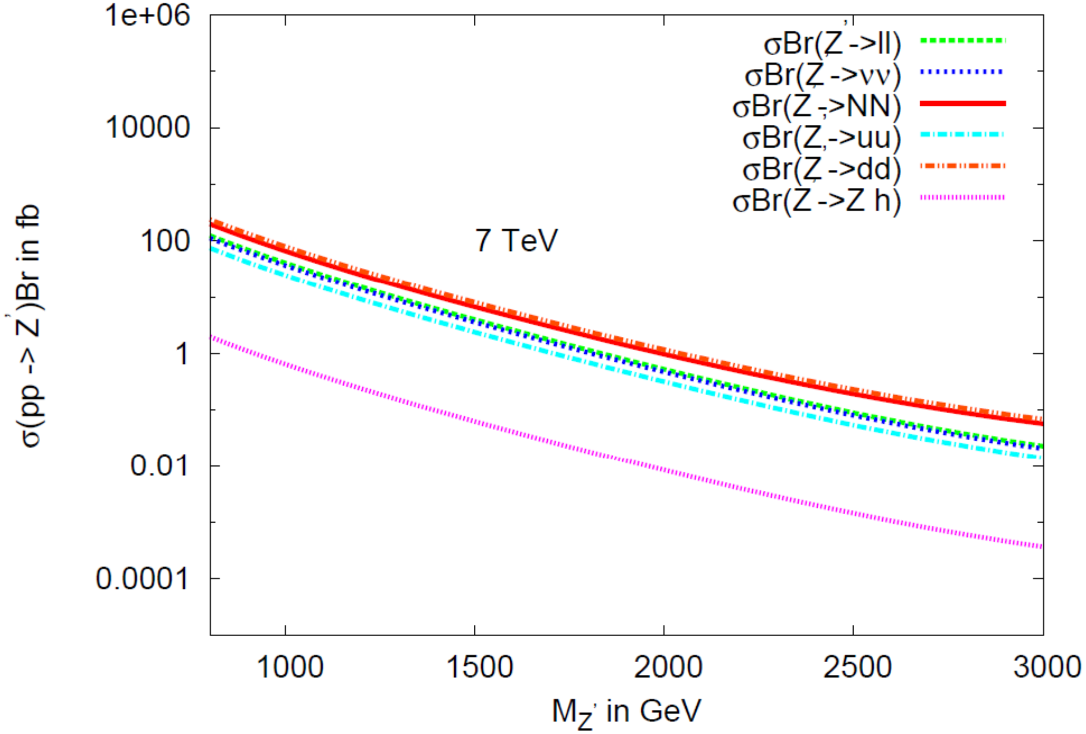
m_{DM}=150 GeV



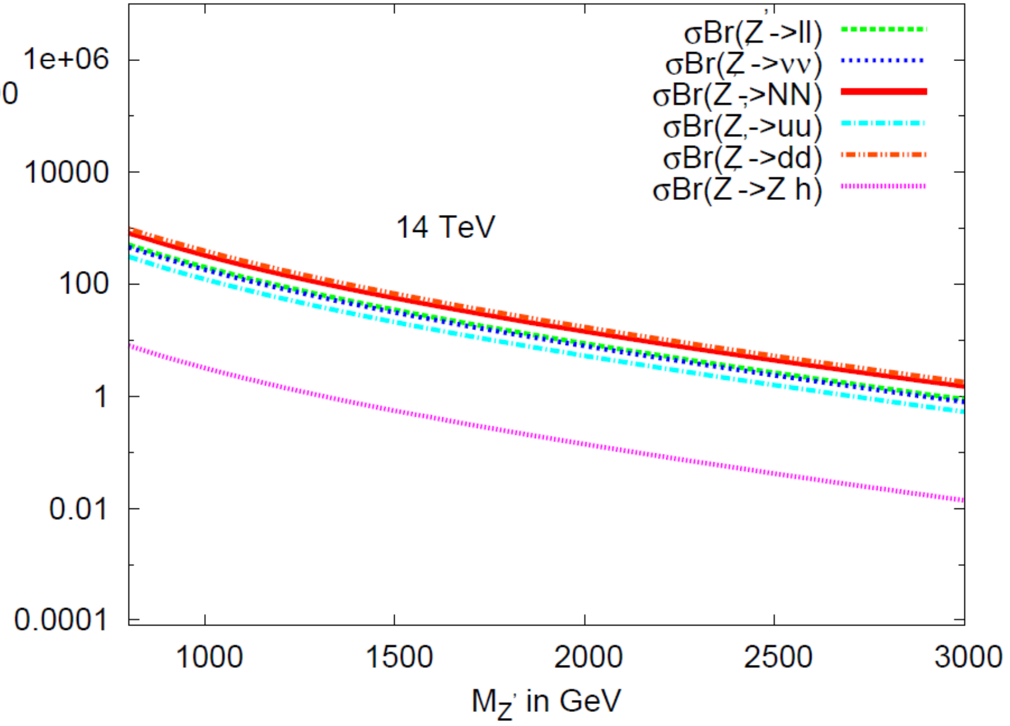
g'=0.2

Reference value: g'=0.46

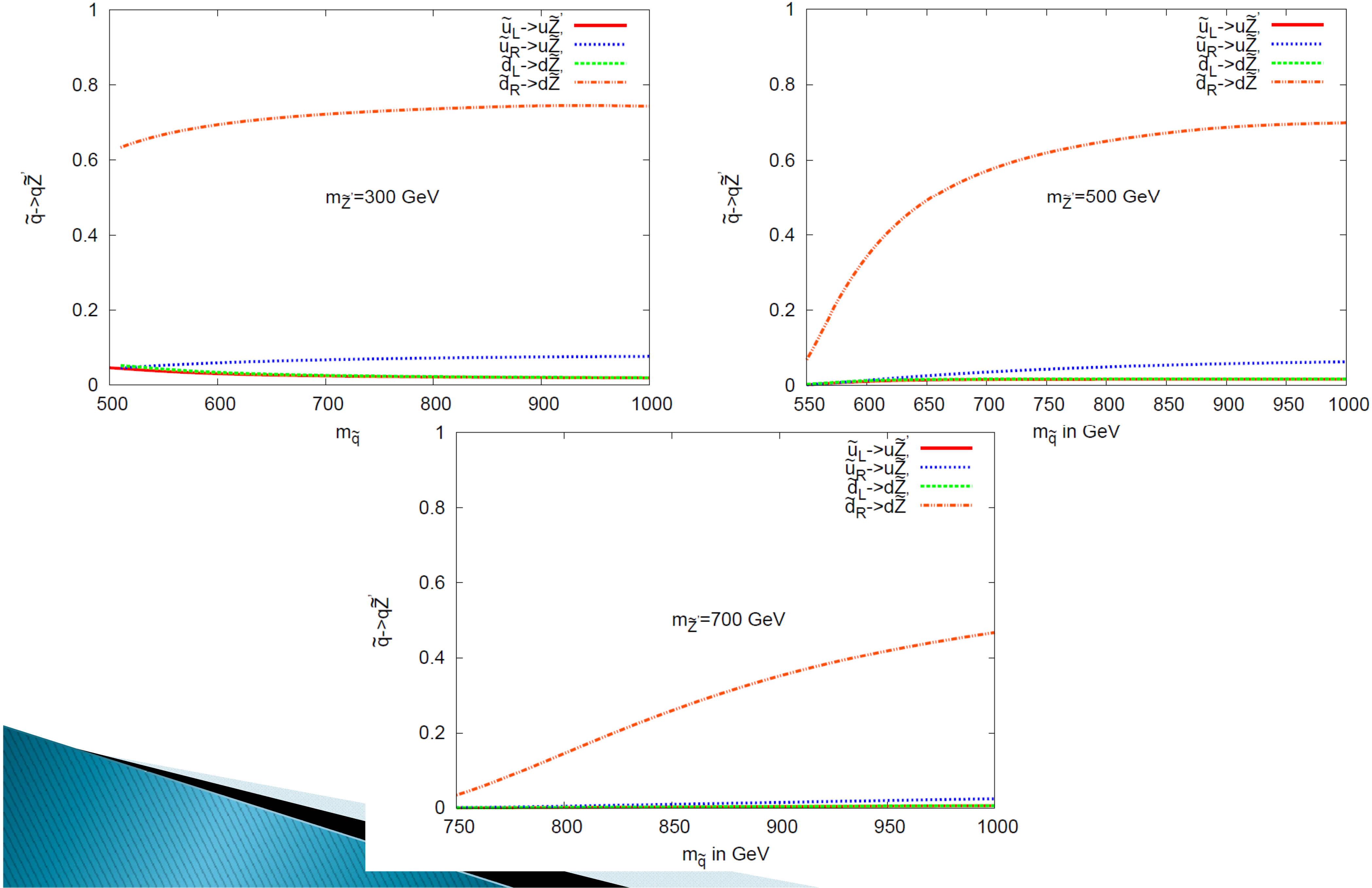
Production & decay of Z'



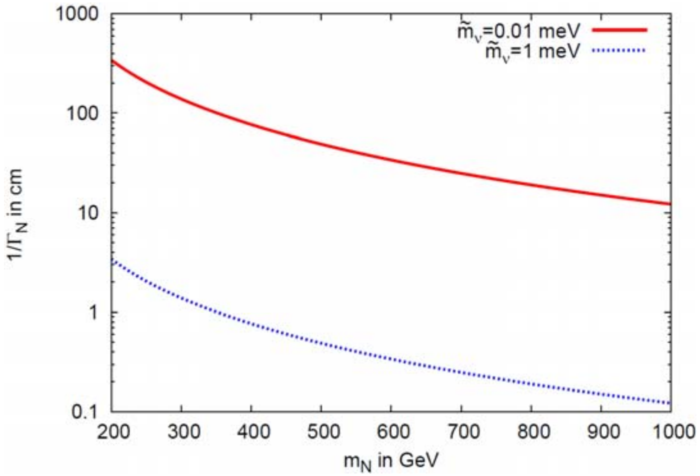
m_N=300 GeV, tan β=10



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 (∵ y_ν) & 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:

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

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

  $\sigma(hl^\pm W^\mp) \approx$ 21 or 4.3 fb
- 14 Tev LHC: $\sigma(hl^\pm W^\mp) \approx$ 105 or 130 fb

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.**

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.