Revisiting sneutrino dark matter in natural SUSY scenarios

Joel Jones-Pérez
Pontificia Universidad Católica del Perú (PUCP)

Based on the following works:
N. Cerna, T. Faber, JJP, W. Porod (1705.06583)
T. Faber, Y. Liu, JJP, W. Porod (1909.11686)
N. Cerna, JJP, J. Masias, W. Porod (2102.06236)

SUSY Seesaw

We know neutrinos needs a mass, but the MSSM doesn't care.

Simplest solution: GUT-scale SUSY Seesaw.

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + Y_\nu \left(\hat{\nu}_R^c \, \hat{L} \cdot \hat{H}_u \right) + \tfrac{1}{2} M_R \left(\hat{\nu}_R^c \, \hat{\nu}_R^c \right)$$

First question: what does the LHC has to say about a low-scale SUSY Seesaw?

Second question: in this case, can the correct dark matter relic density be obtained if the LSP is a $\tilde{\nu}_R$?

Our setup

- Set the R-sneutrino as the LSP.
- Keep μ as low as possible → Higgsino-like electroweakinos.
- Ignore squarks and gluinos.
- Objective: Explore LHC bounds on sleptons and understand R-sneutrino dark matter

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Possible hierarchy:

$$m^2_{\tilde{\nu}_R} < \mu < m^2_{\tilde{L}},\, m^2_{\tilde{E}}$$

$$m^2_{\tilde{\nu}_R} < m^2_{\tilde{L}},\, m^2_{\tilde{E}} < \mu$$

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Strong constraints (2017, 13.3 fb^{-1}):

$$\mu \gtrsim 400\,\mathrm{GeV}$$

$$m_{\tilde{L}} \gtrsim 600\,\mathrm{GeV}$$

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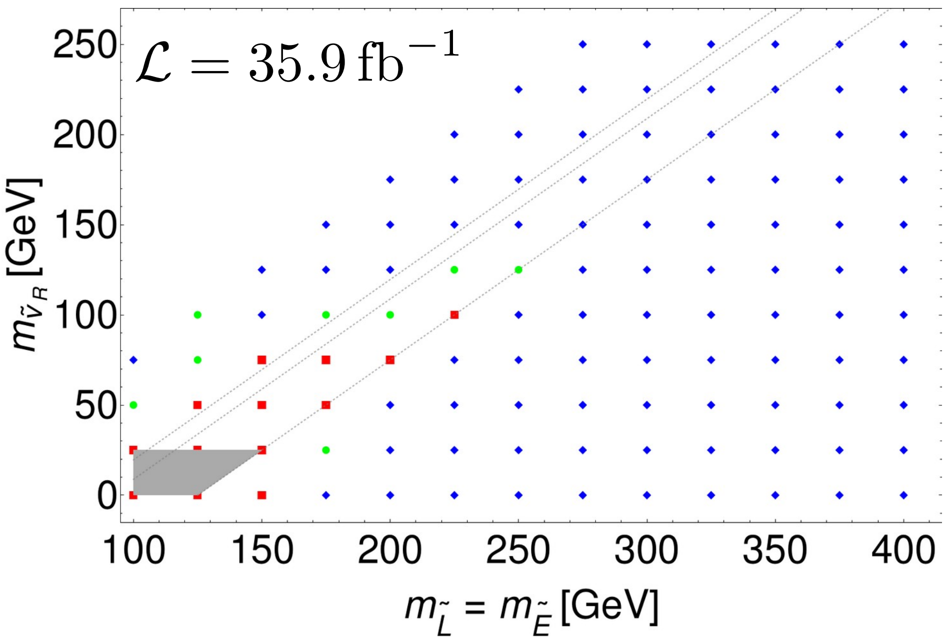
Degenerate scenario at LHC:



Constrained mainly by multi-lepton searches

Ruled out | Allowed | Ambiguous

CMS Collaboration (1709.05406)

CheckMATE (1709.05406 [hep-ph])

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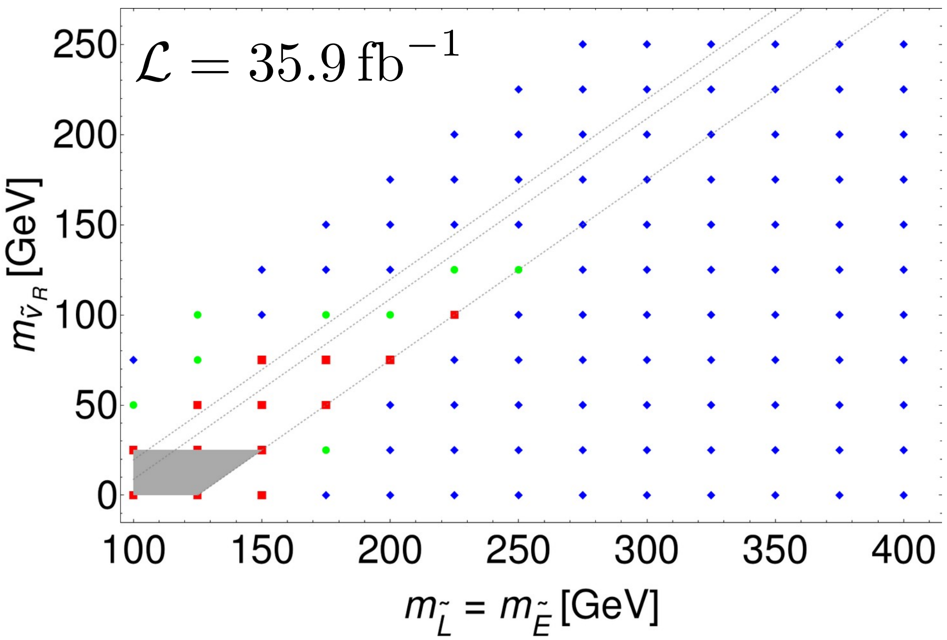

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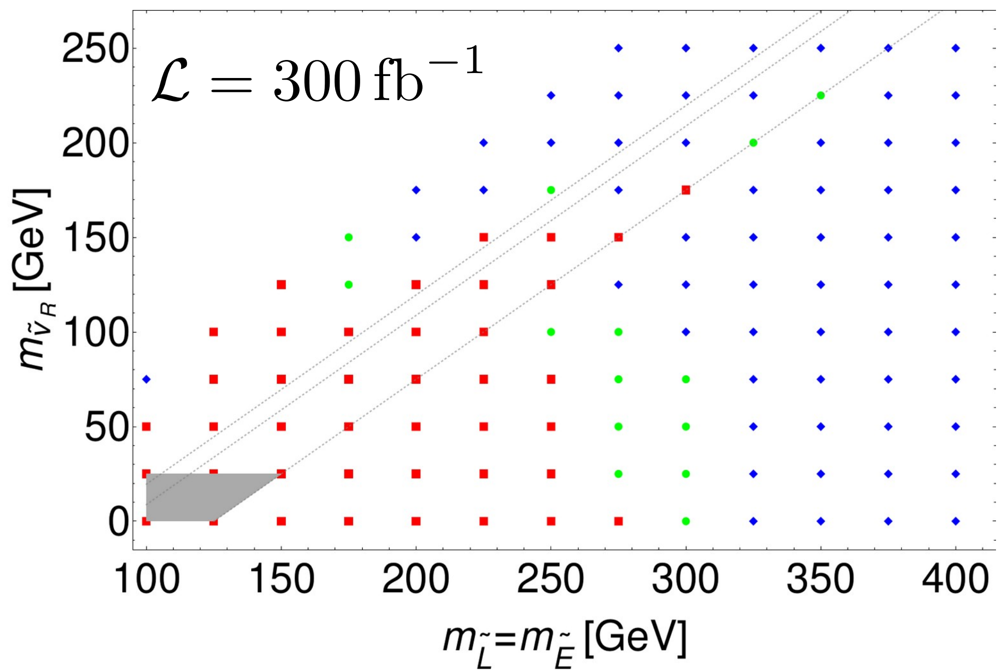

Projection at the end of LHC lifetime has a hard time extending the reach above 250 GeV.

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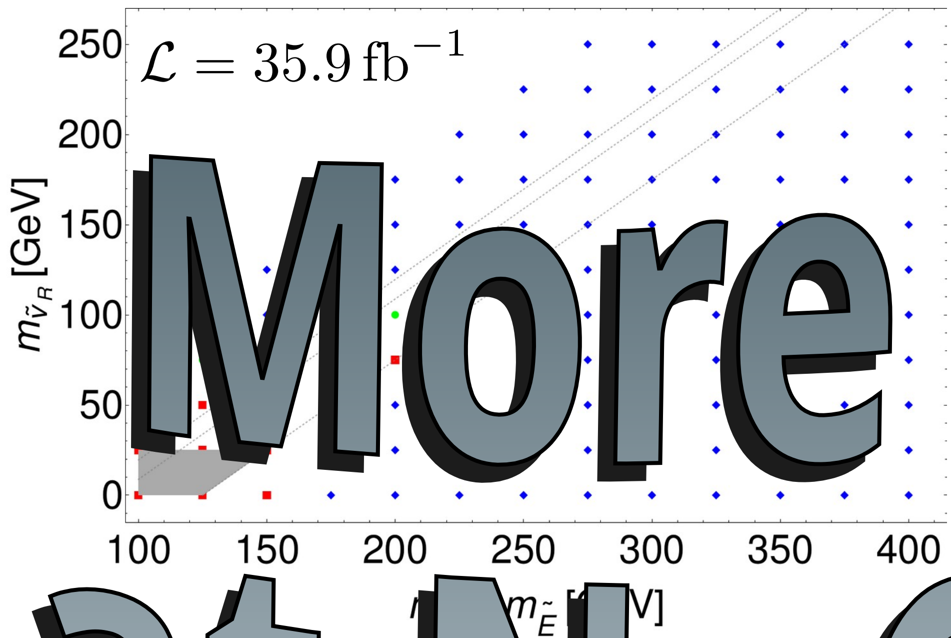

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More details at NuCo 2021!

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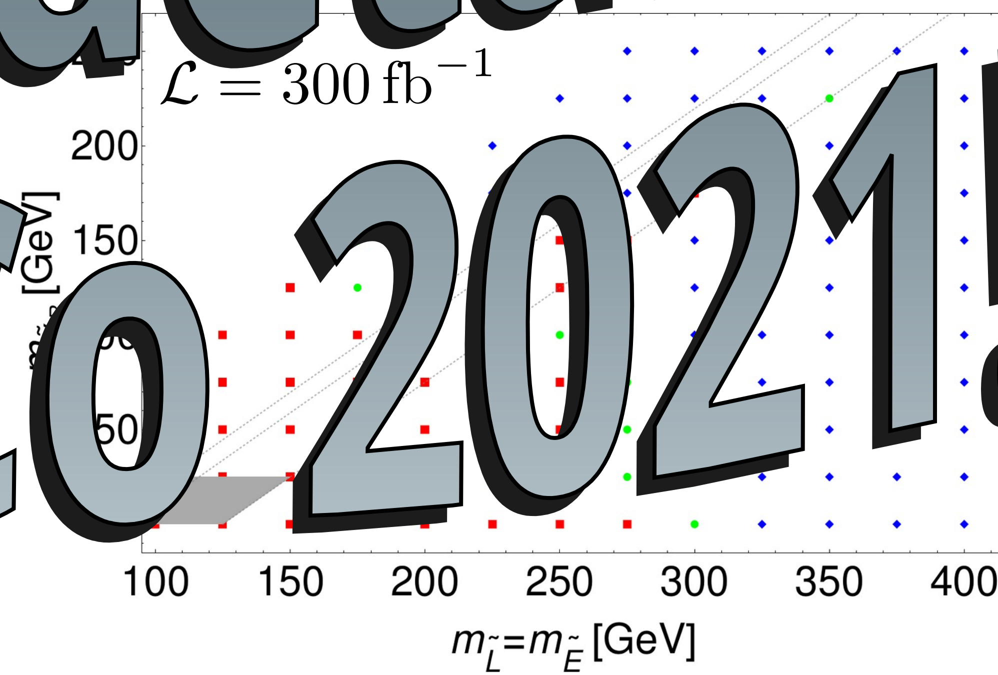

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R-Sneutrino Dark Matter (aka playing with MicrOMEGAs)

Dark Matter Candidates

ν_R $\tilde{\nu}_R$

- We assume three generations of R - (s)neutrinos.
- R - (s)neutrinos share Majorana mass term, M_R.
- R - (s)neutrinos interact via Yukawa Y_ν couplings.

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- R - sneutrino is expected to be heavier due to soft SUSY-breaking mass, $m^2_{\tilde{\nu}_R}$
- R - sneutrino sector includes an extra LNV term, which we neglect.
- R - sneutrino could also interact via trilinear A_ν term, which we also neglect.

Conclusions (preview)

- What did we assume?

$$m^2_{\tilde{\nu}_{R_4}} < m^2_{\tilde{\nu}_{R_{5,6}}} < m^2_{\tilde{L}} = m^2_{\tilde{E}} < \mu$$

$$(Y_\nu)_{a4} \ll (Y_\nu)_{a5,6}$$

$$M_4 = 700\,\mathrm{MeV}$$

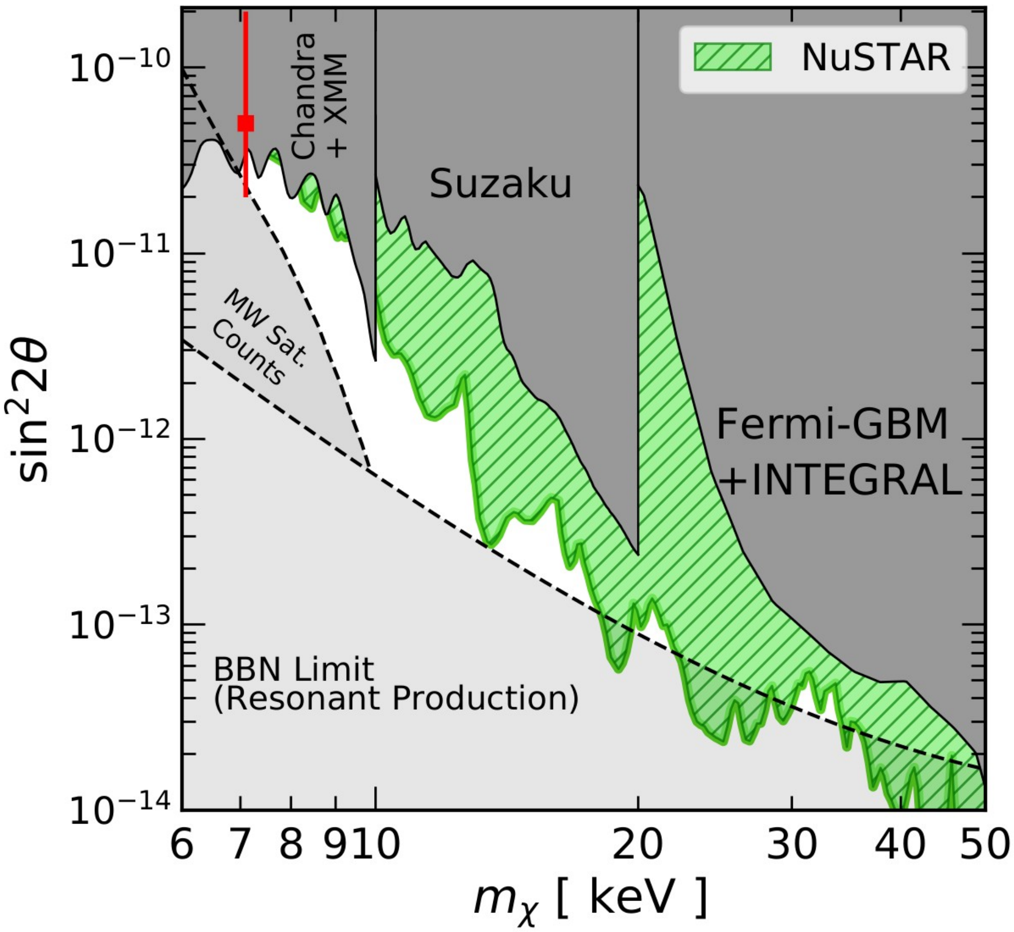
$$M_{5,6} \sim \mathcal{O}(10\,\mathrm{GeV})$$

- What did we get?
  - Freeze-in produced R-sneutrino dark matter, that can reproduce the correct relic density.
  - A neutral NLSP with a way too long lifetime.

Heavy Neutrino Dark Matter

Not in this work.

Heavy neutrino dark matter produced via non-resonant process is disfavoured.



NuSTAR (1908.09037, and references within)

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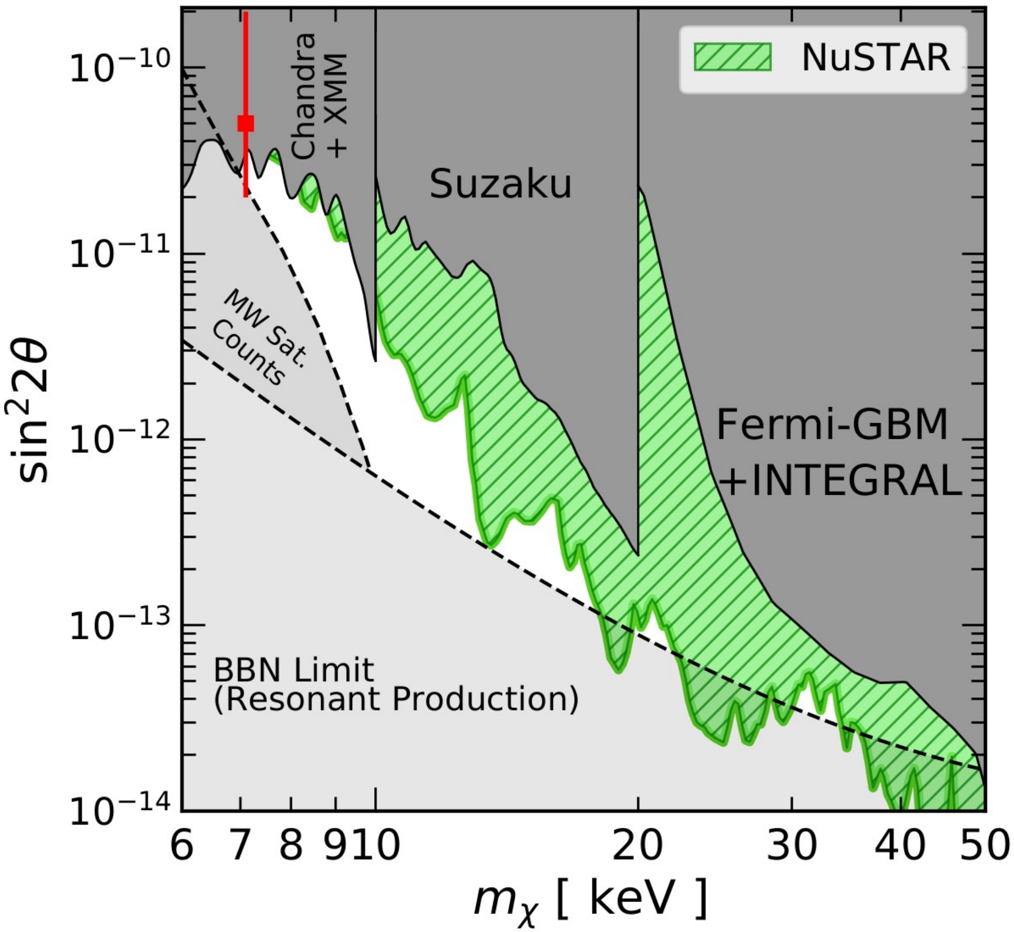
We checked that SUSY loops do not modify $N_4 \to \nu\gamma$ partial width, so constraints apply here, too.

$$\Rightarrow m_{N_4} = 700\,\mathrm{MeV}$$



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Thermal R-Sneutrino Dark Matter

First: determine if they are thermal or not: check $H(T) < \langle \sigma v \rangle_T \, n(T)$

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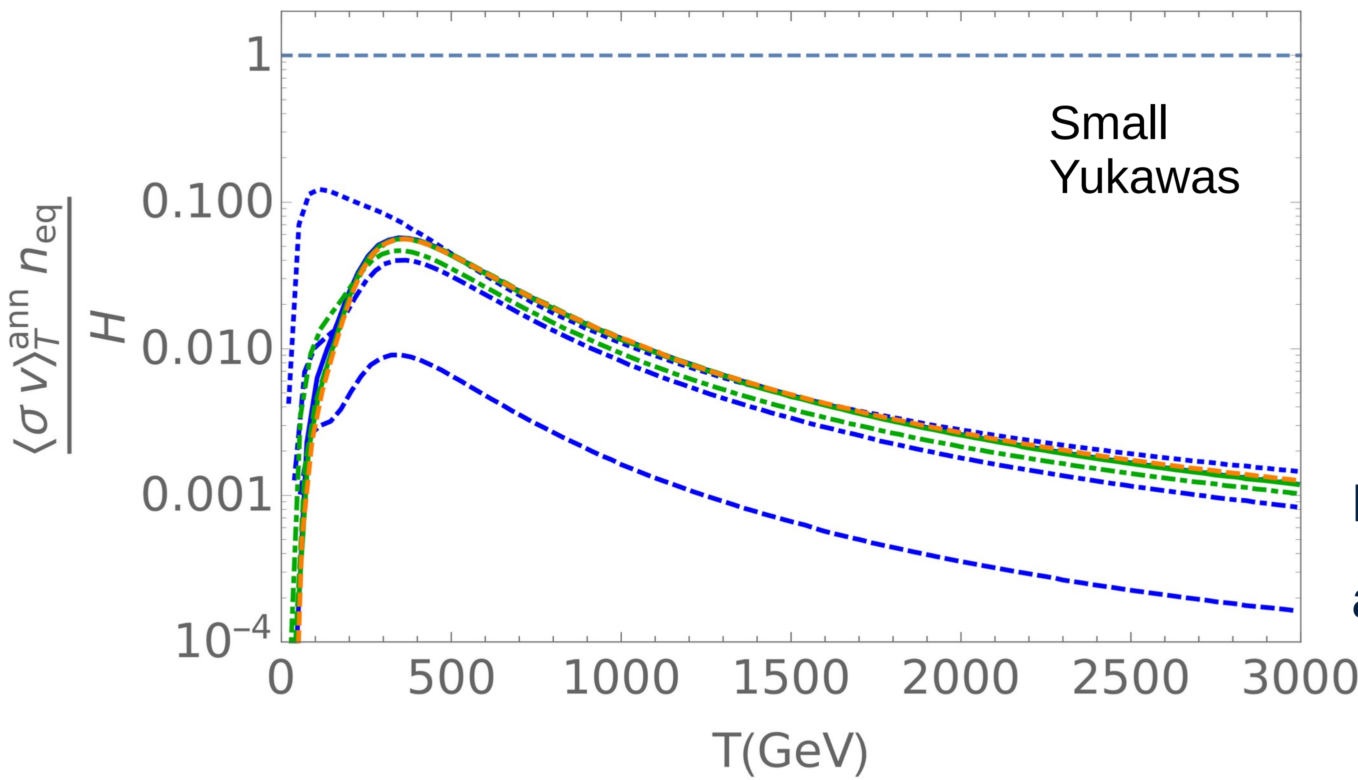

Lines: different R-sneutrino and Slepton soft masses.

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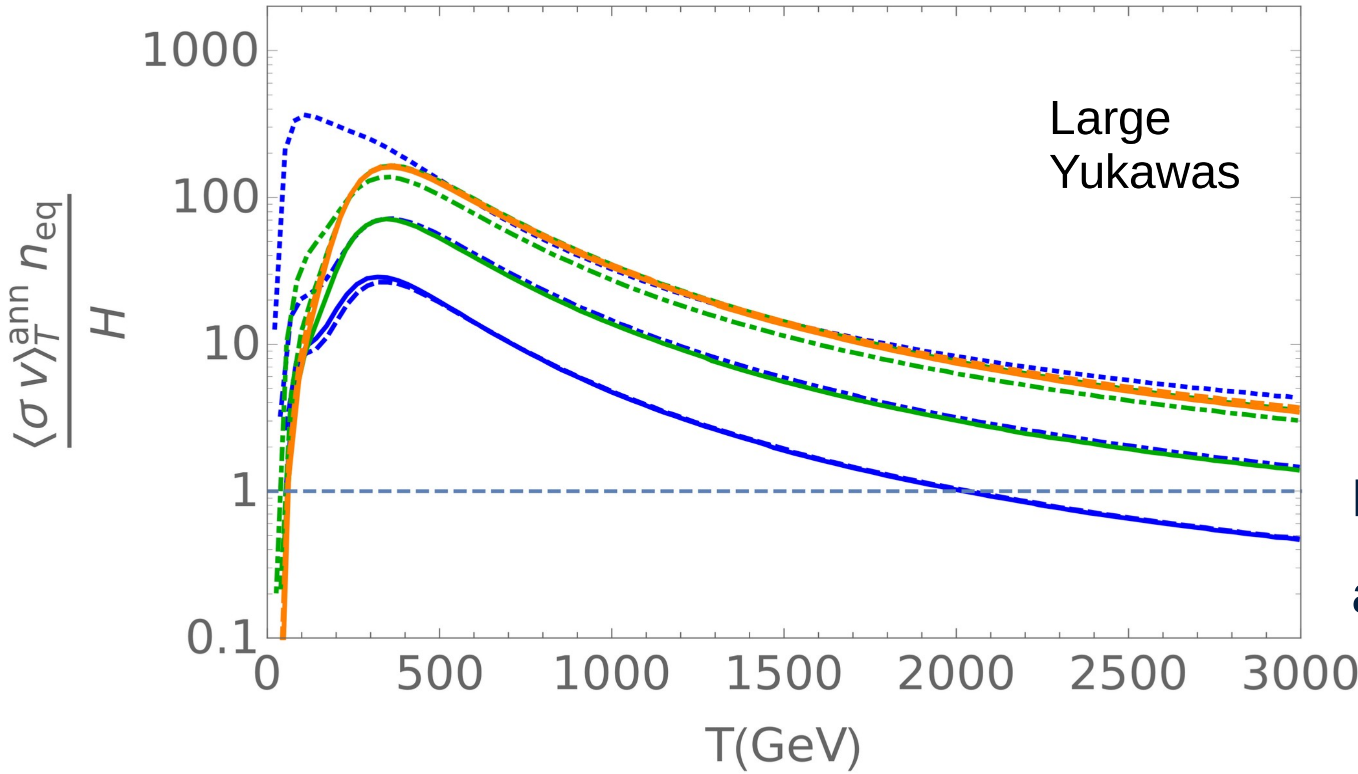

Lines: different R-sneutrino and Slepton soft masses.

SARAH, SPheno, micrOMEGAs

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Thermal sneutrino dark matter: not good. Huge (I mean, REALLY huge) relic density.

So why bother enhancing Yukawas?

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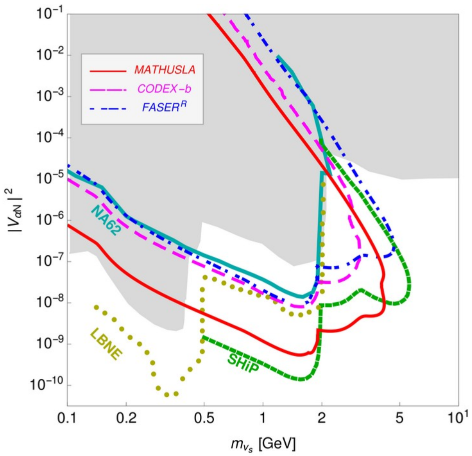
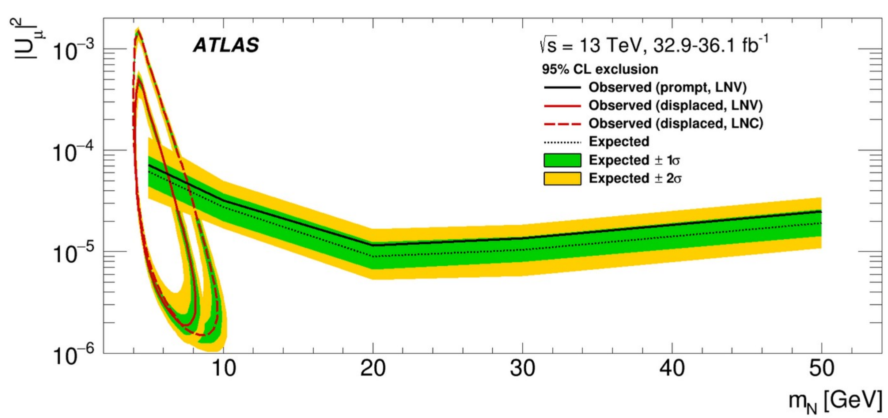
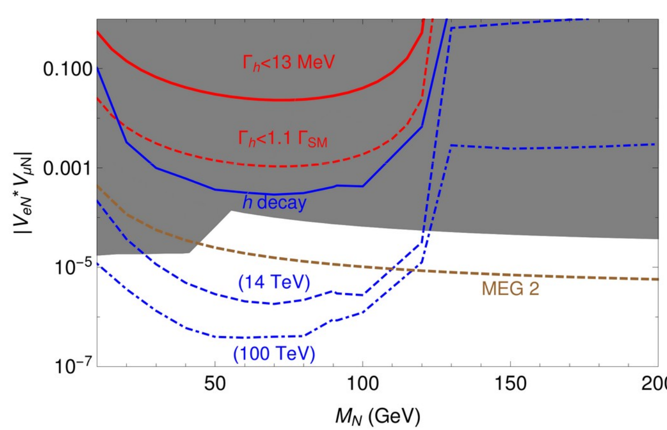
So why bother enhancing Yukawas?

Main Reason: Could lead to future heavy neutrino signals at colliders and precision experiments.







Helo, Hirsch, Wang: 1803.02212 [hep-ph]; ATLAS: 1905.09787 [hep-ex]
Das, Dev, Kim: 1704.00880 [hep-ph]

Choice of Yukawas

Two Yukawa couplings can be enhanced by taking a large γ_{56} in Casas-Ibarra parametrization:

$$(Y_\nu)_{a4} \sim \sqrt{\frac{2m_1 M_4}{v_u^2}}$$

$$(Y_\nu)_{a5} \sim \sqrt{\frac{2m_3 M_5}{v_u^2}} \cosh\gamma_{56} \qquad (Y_\nu)_{a6} \sim \sqrt{\frac{2m_3 M_6}{v_u^2}} \cosh\gamma_{56}$$

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Dark matter will be $\tilde{\nu}_{R_4}$, interacting via small Yukawa, so not thermal.

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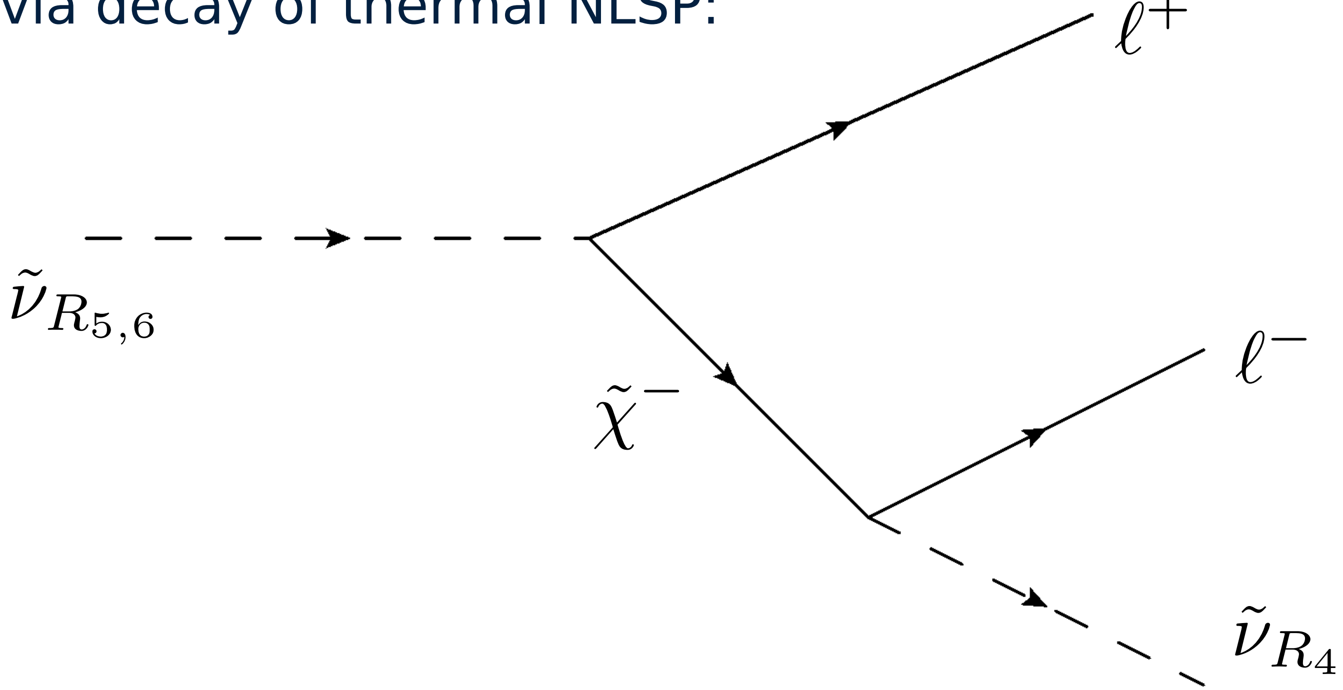
Non-thermal R-Sneutrino Dark Matter

Production via decay of thermal NLSP:

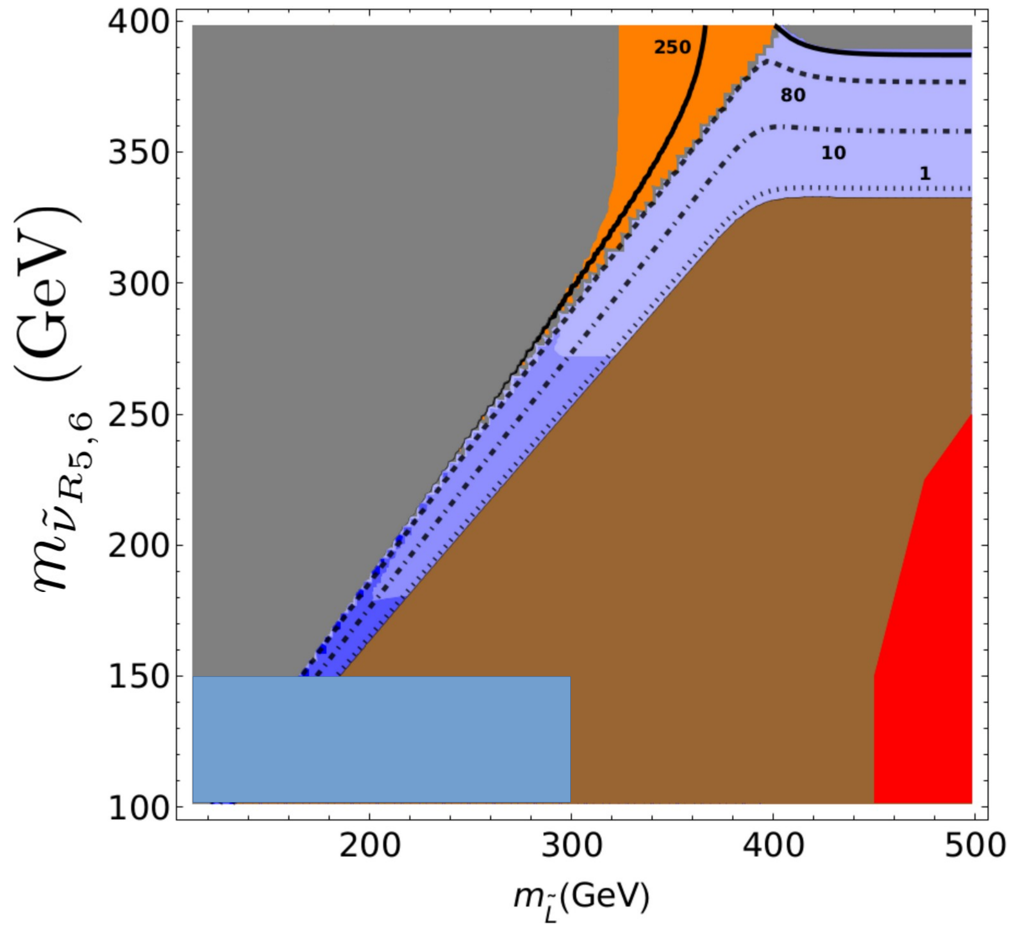


$$(\Omega h^2)^{\rm dec} = (\Omega h^2)^{\rm th} \frac{m_{\tilde{\nu}_{R_4}}}{m^{\rm th}_{NLSP}}$$

Sets upper limit on dark matter mass!

Non-thermal R-Sneutrino Dark Matter

Maximum dark matter mass: 0.7 – 250 GeV



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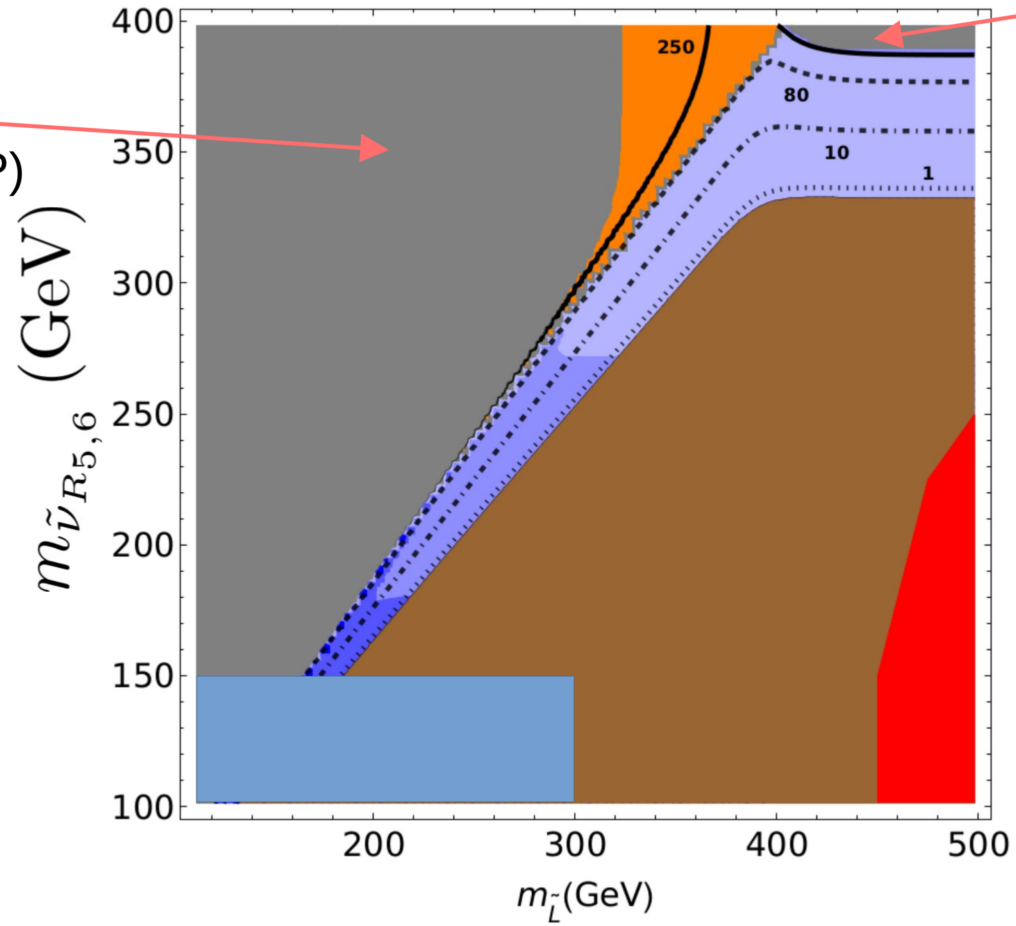
Too small thermal relic density (L-sneutrino NLSP)

Too small thermal relic density (Higgsino NLSP)



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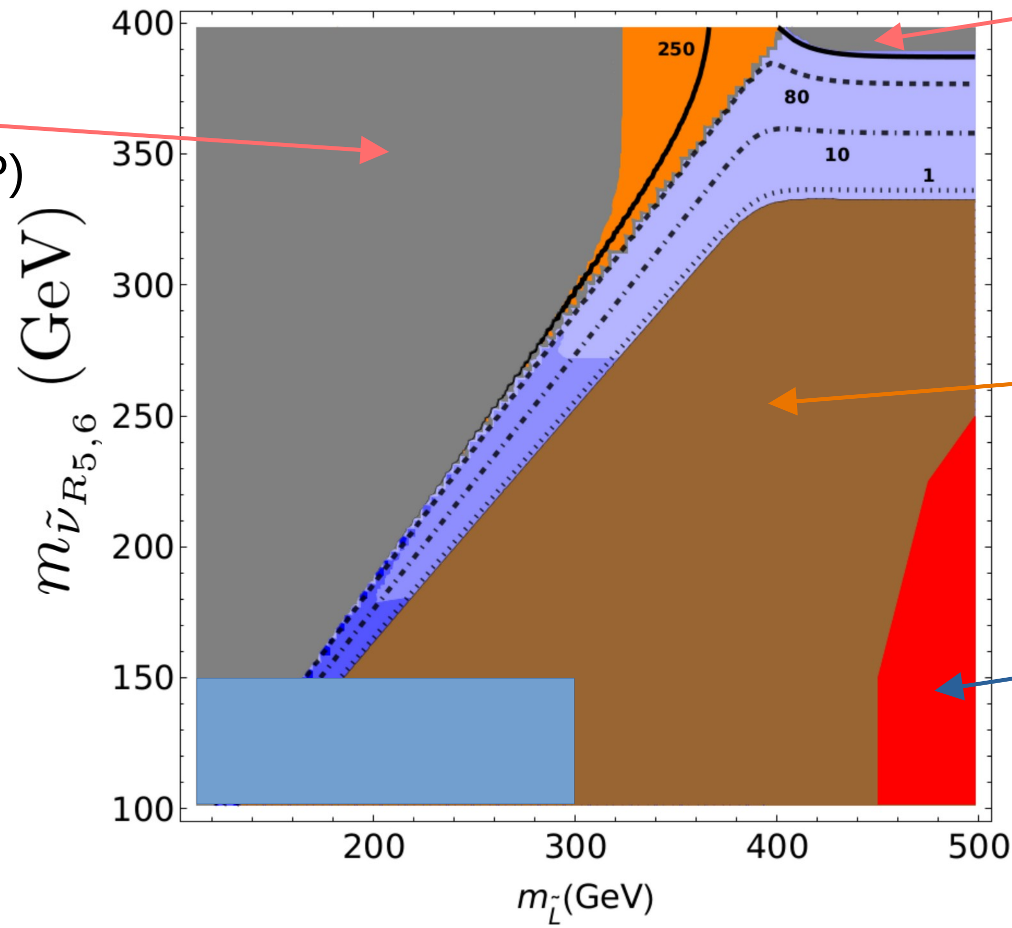

Too small thermal relic density (Higgsino NLSP)

Would require a negative soft mass

Ruled out by LHC (Higgsino lighter than L-slepton)

SARAH, SPheno, micrOMEGAs

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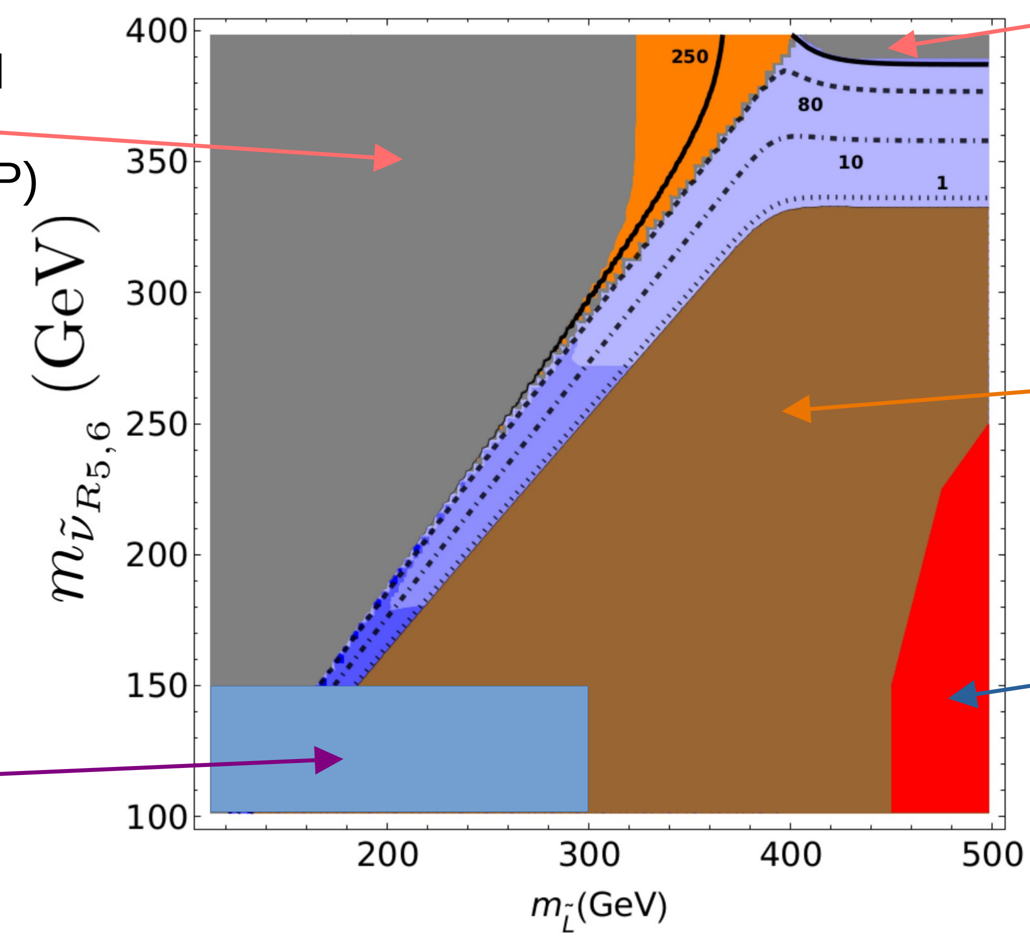

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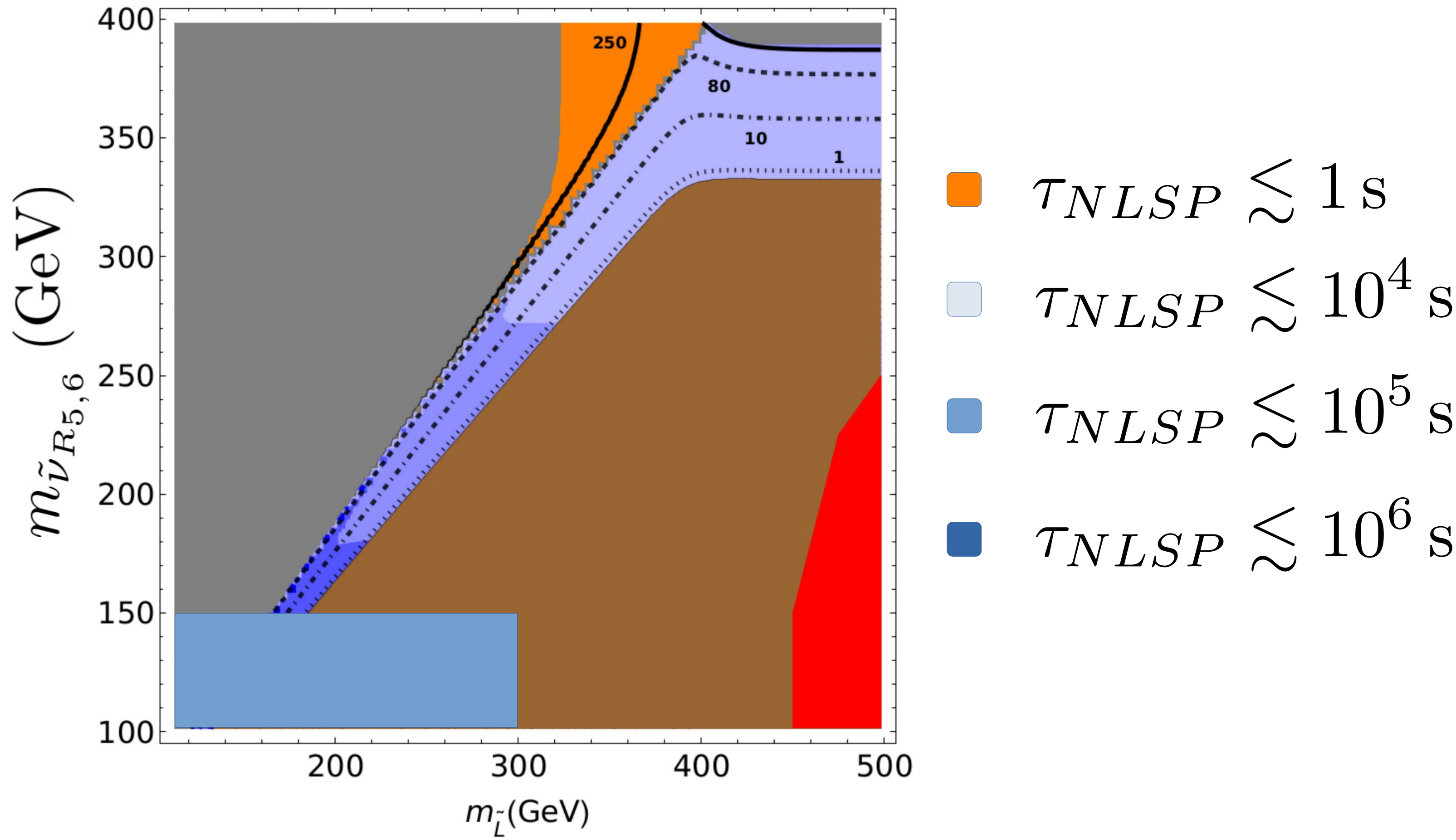

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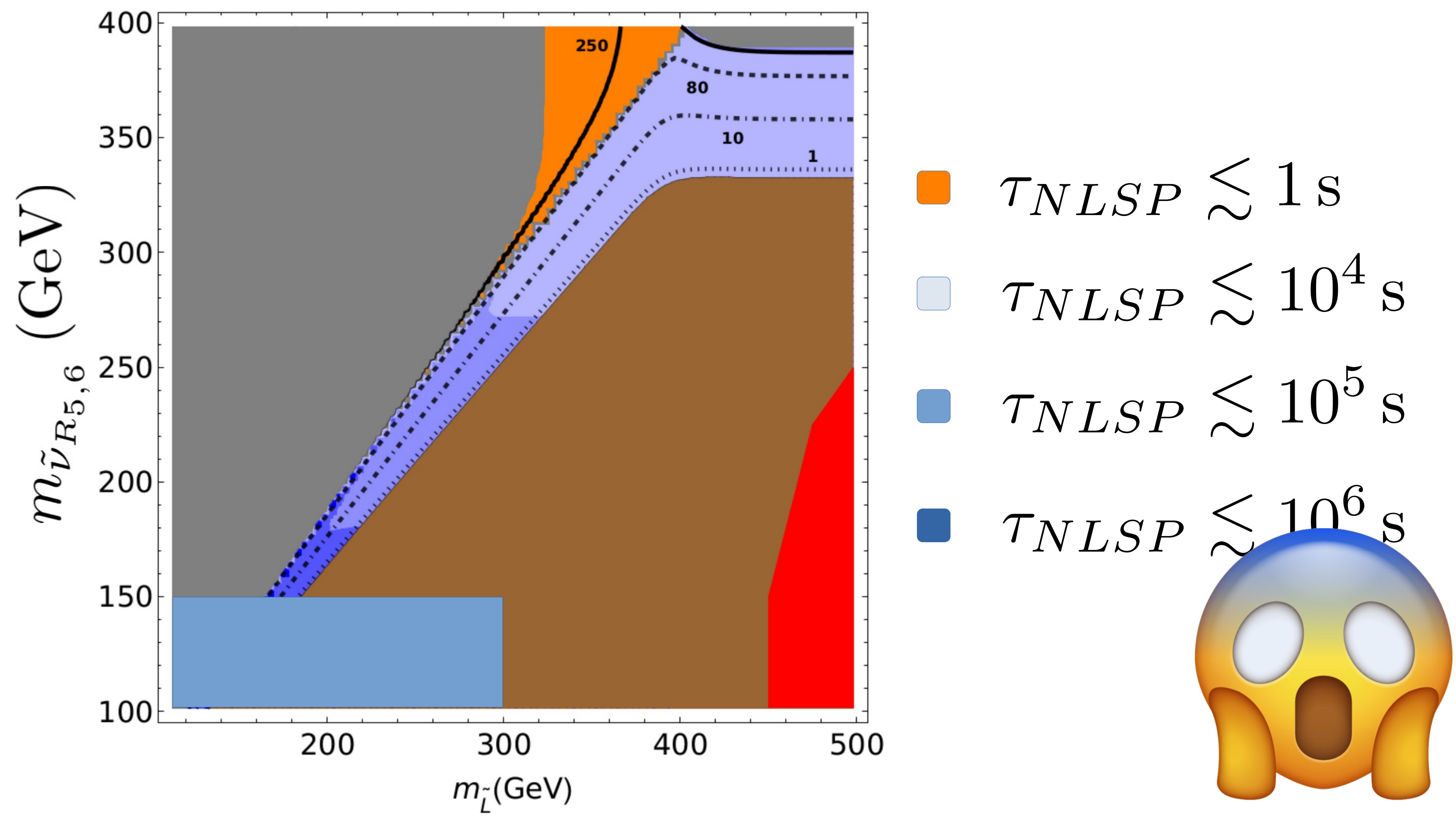
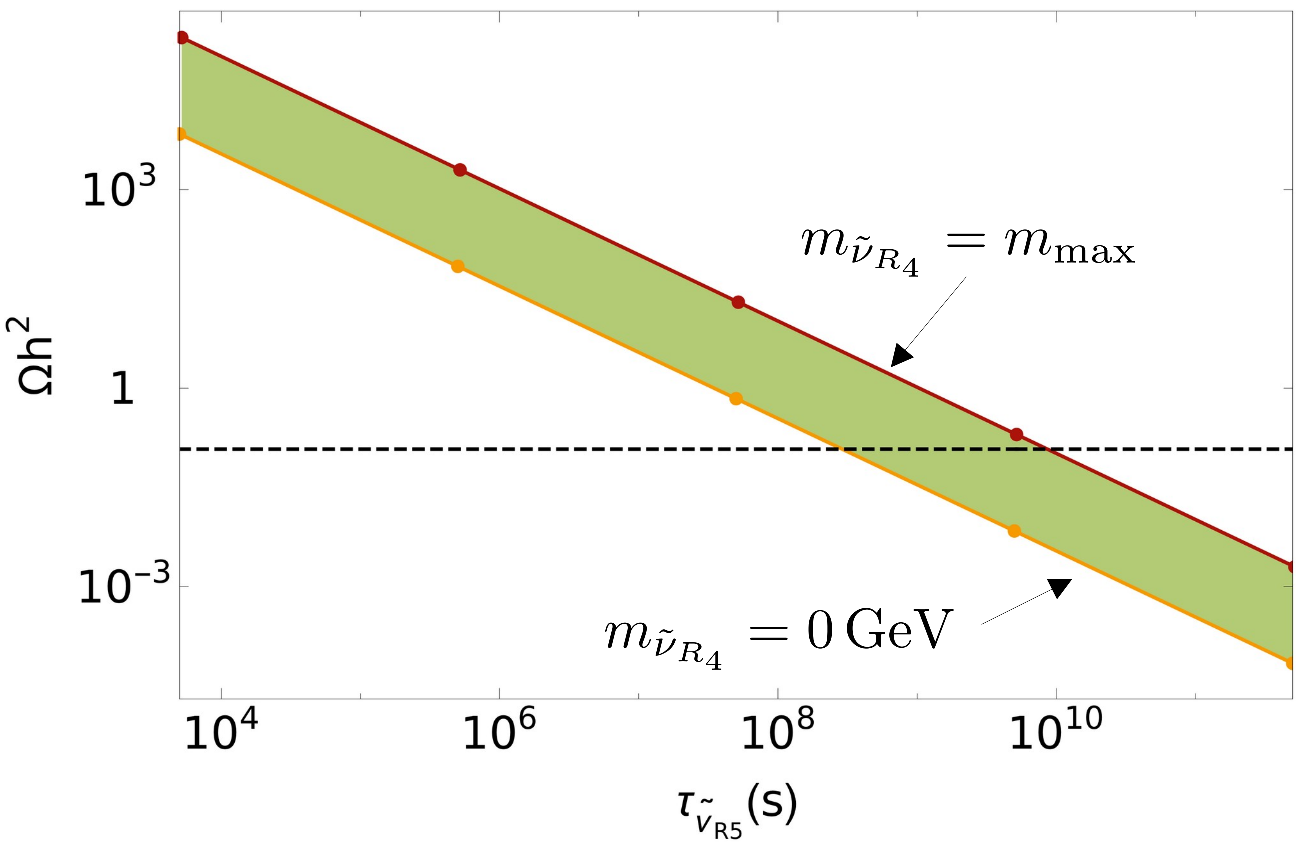


Non-thermal R-Sneutrino Dark Matter

Gets worse when adding annihilation in plasma:



$$(Y_\nu)_{a4} \sim \sqrt{\frac{2 m_1 M_4}{v_u^2}}$$

$$m_{\tilde{L}} = 323\,\mathrm{GeV}$$

$$m_{\tilde{\nu}_{R_{5,6}}} = 302\,\mathrm{GeV}$$

Conclusions

- What did we assume?

$$m^2_{\tilde{\nu}_{R_4}} < m^2_{\tilde{\nu}_{R_{5,6}}} < m^2_{\tilde{L}} = m^2_{\tilde{E}} < \mu$$

$$(Y_\nu)_{a4} \ll (Y_\nu)_{a5,6}$$

$$M_4 = 700\,\mathrm{MeV}$$

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Thanks!

Backup

Neutrino Sector

After diagonalizing the neutrino mass matrix:

3 active ν_L ⟷ 3 light ν_l

3 sterile ν_R ⟷ 3 heavy ν_h

$$U = \begin{pmatrix} U_{a\ell} & U_{ah} \\ U_{s\ell} & U_{sh} \end{pmatrix}$$

Using a Casas-Ibarra parametrization, we can reconstruct the Yukawa matrices:

$$Y_\nu = -i\frac{\sqrt{2}}{v_u} U^*_{\rm PMNS} H^* m_\ell^{1/2} \left(m_\ell R^\dagger + R^T M_h\right) M_h^{-1/2} \bar{H}$$

$$H \sim I \qquad \bar{H} \sim I$$

Complex orthogonal matrix

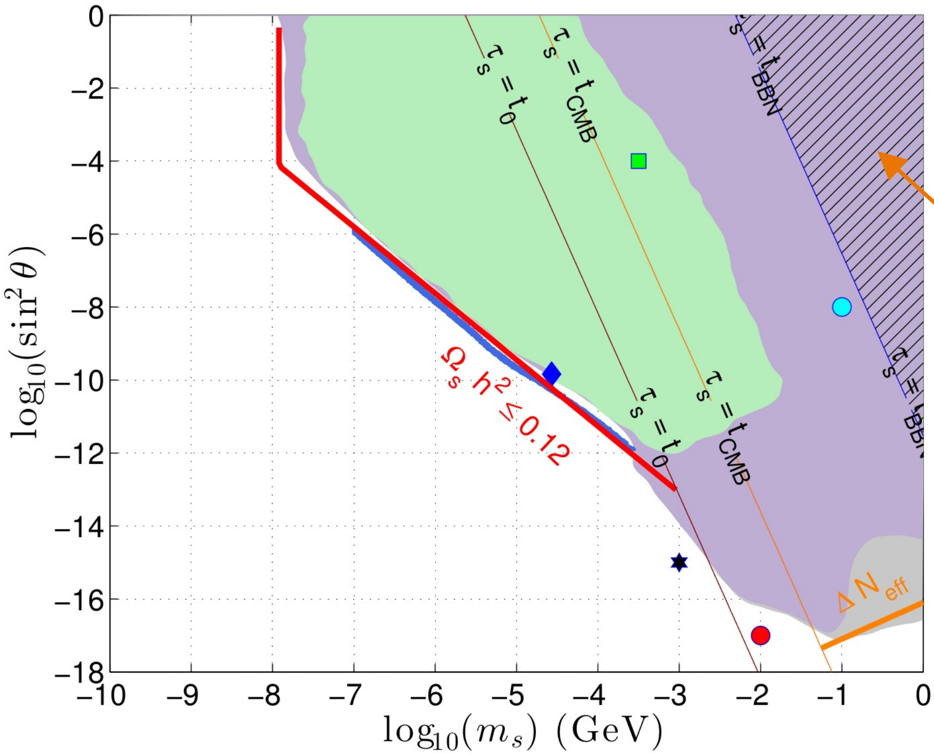
Heavy Neutrino Dark Matter

How do we avoid NuStar bounds?

Our choice: make heavy neutrinos heavier!

Not trivial!

Cosmological bounds appear.



Solution:

Have heavy neutrinos decaying before BBN.

This region!

$$m_{N_4} = 700\,\text{MeV}$$

Vincent, Fernandez-Martinez, Hernández, Lattanzi, Mena (1408.1956)

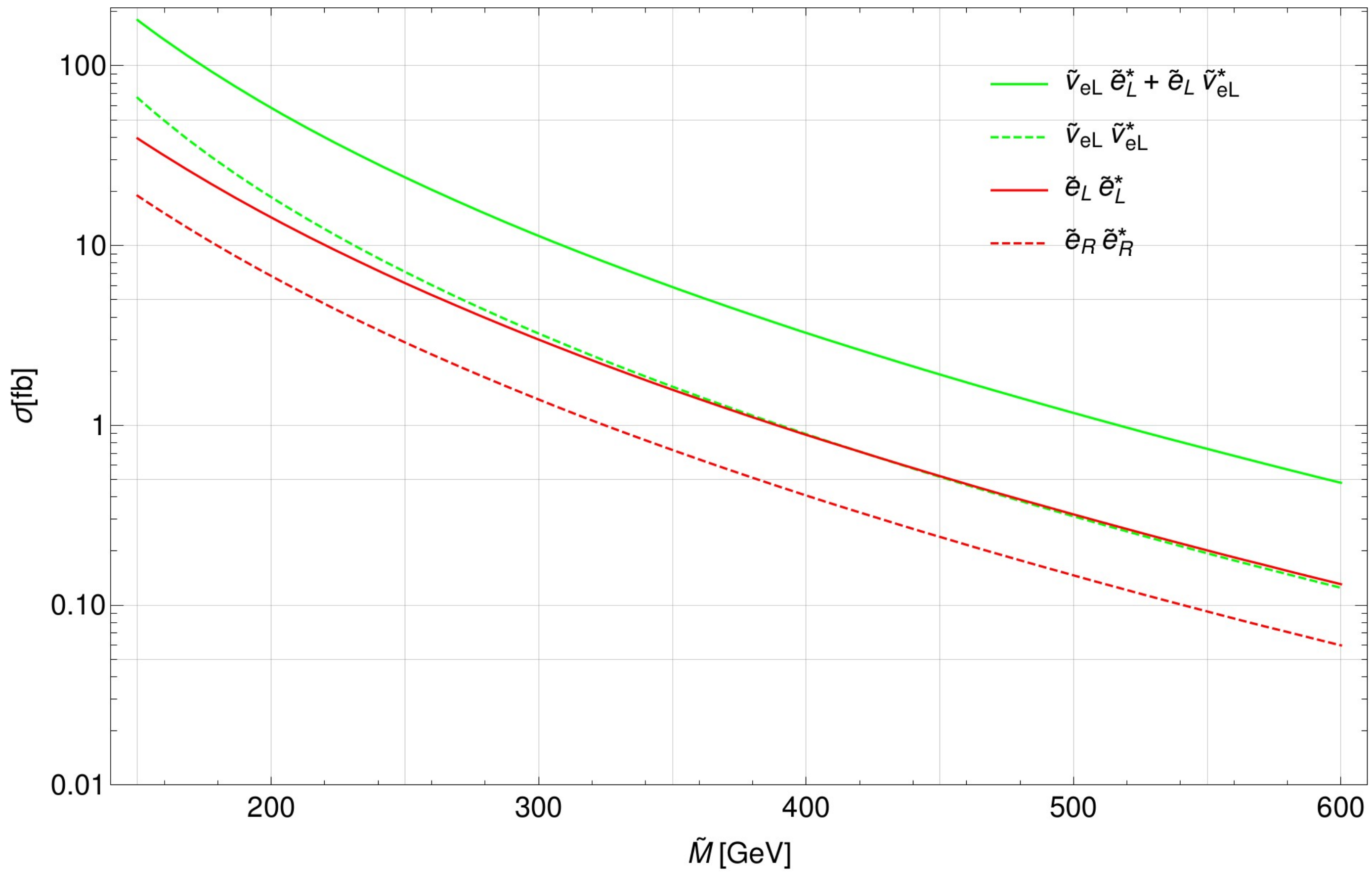
See also Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap (2008.00749)

Sleptons at the LHC

$$m^2_{\tilde{\nu}_R} < m^2_{\tilde{L}} = m^2_{\tilde{E}} < \mu$$

We will concentrate on slepton pair production:

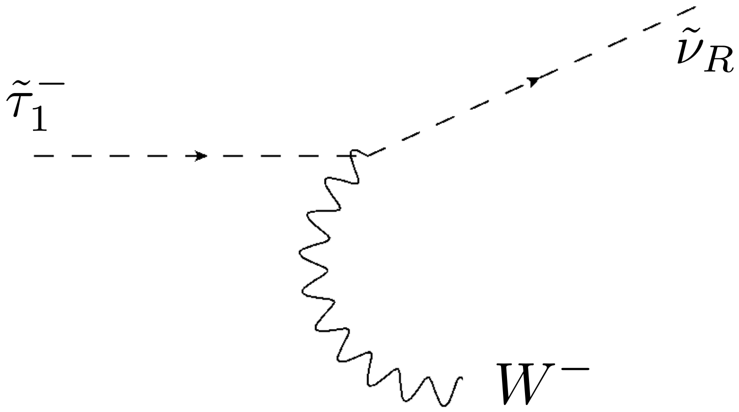
Cross-section at the LHC (13 TeV), according to MadGraph.



Slepton Decay modes:

Staus:

$$(m_{\tilde{\tau}_1} - m_{\tilde{\ell}})_{LR} \sim -\frac{m_\tau\, \mu \tan\beta}{2 m_{\tilde{L}}} < 0$$

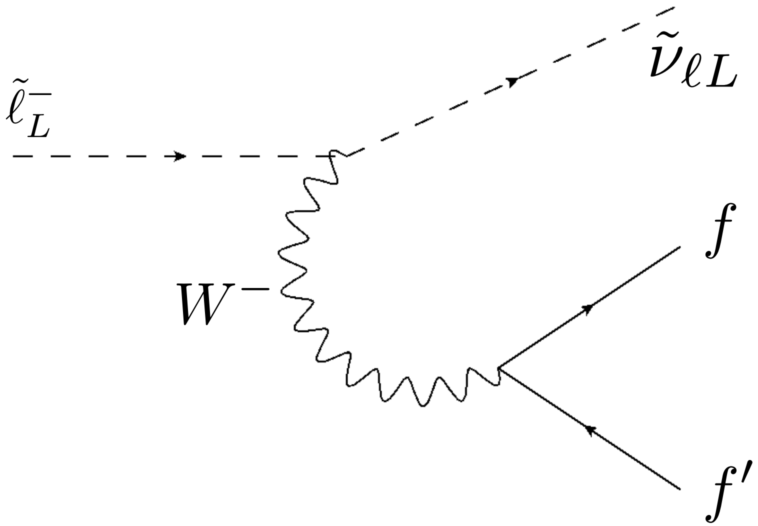


In this work, we only considered cases where L-sneutrinos would not decay into staus.

The μ parameter plays an important role in determining the physical mass.

Slepton Decay modes:

Selectrons, smuons: $$(m_{\tilde{\ell}_L} - m_{\tilde{\nu}_L})_D \approx \frac{(\sin^2\theta_W - 1)m_Z^2 \cos 2\beta}{2m_{\tilde{L}}} > 0$$



We end up with two L-sneutrinos

and very soft fermions

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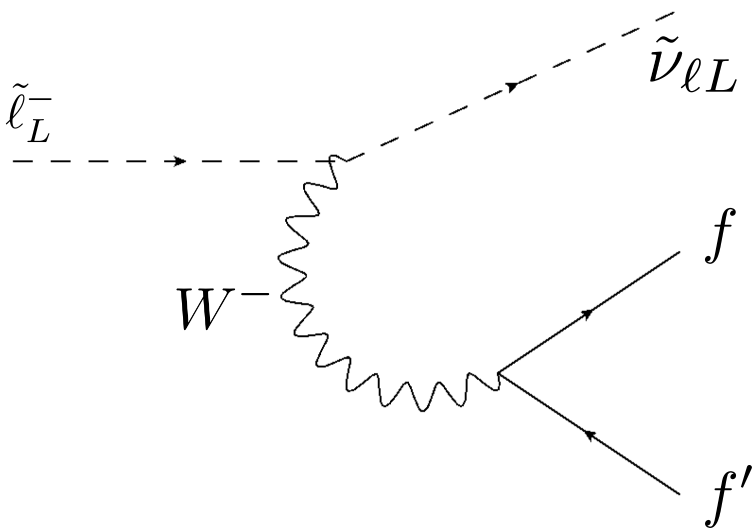
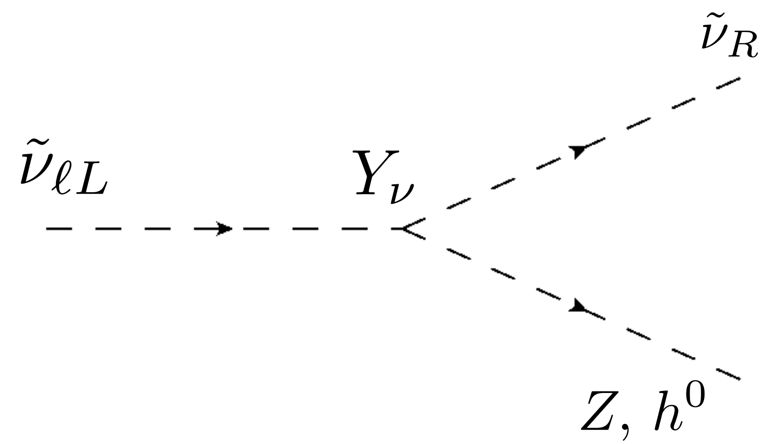


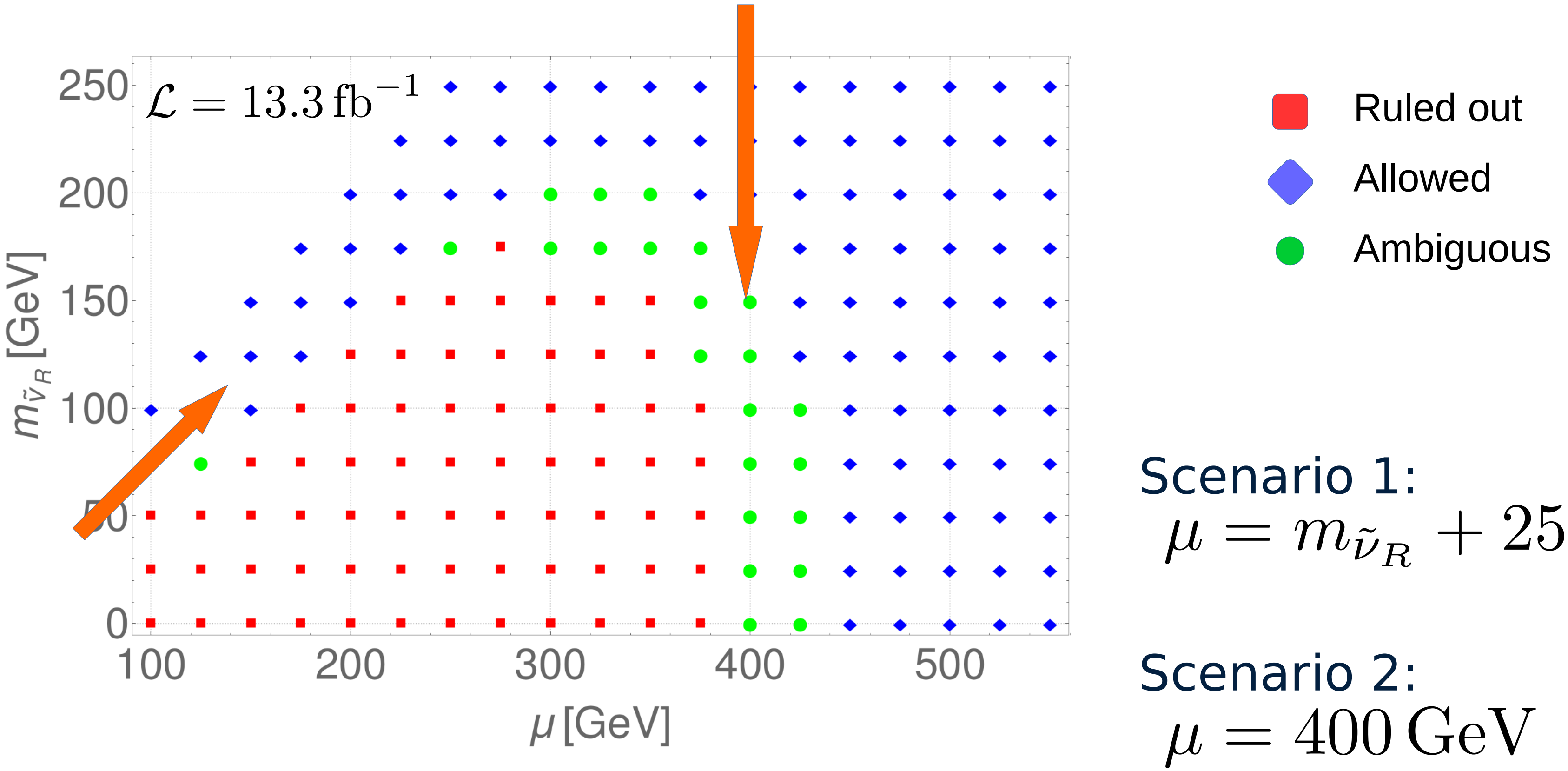


We end up with two L-sneutrinos and very soft fermions

Final states have SM bosons and missing energy

$$m^2_{\tilde{\nu}_R} < \mu < m^2_{\tilde{L}} = m^2_{\tilde{E}}$$

Chargino production: $pp \to \tilde{\chi}^+\tilde{\chi}^- \to \ell^+\ell^-\tilde{\nu}_R\tilde{\nu}^*_R$



Scenario 1:
$\mu = m_{\tilde{\nu}_R} + 25\,\mathrm{GeV}$

Scenario 2:
$\mu = 400\,\mathrm{GeV}$

ATLAS Collaboration (ATLAS-CONF-2016-096)
CheckMATE (1611.09856 [hep-ph])

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Scenario 1

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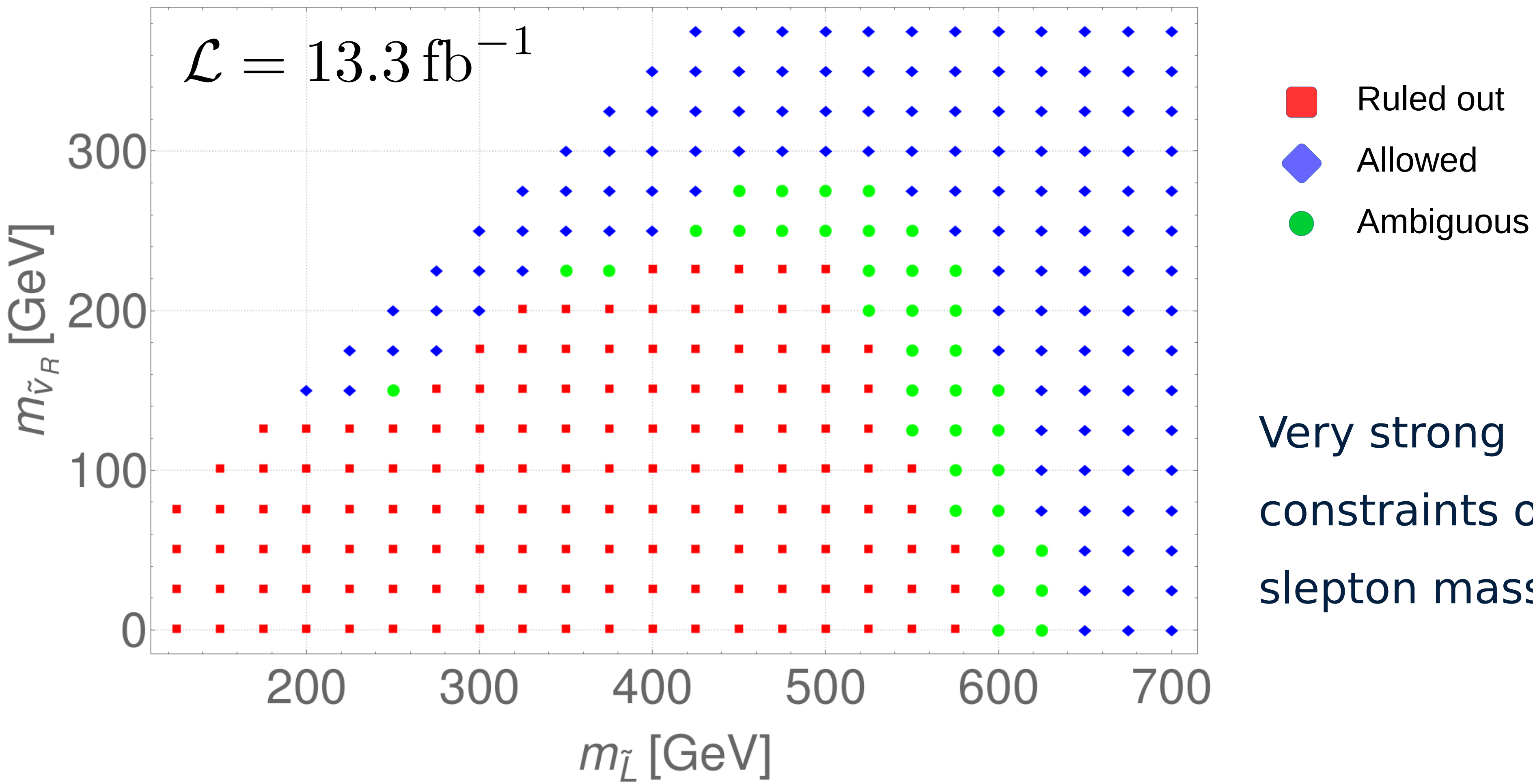
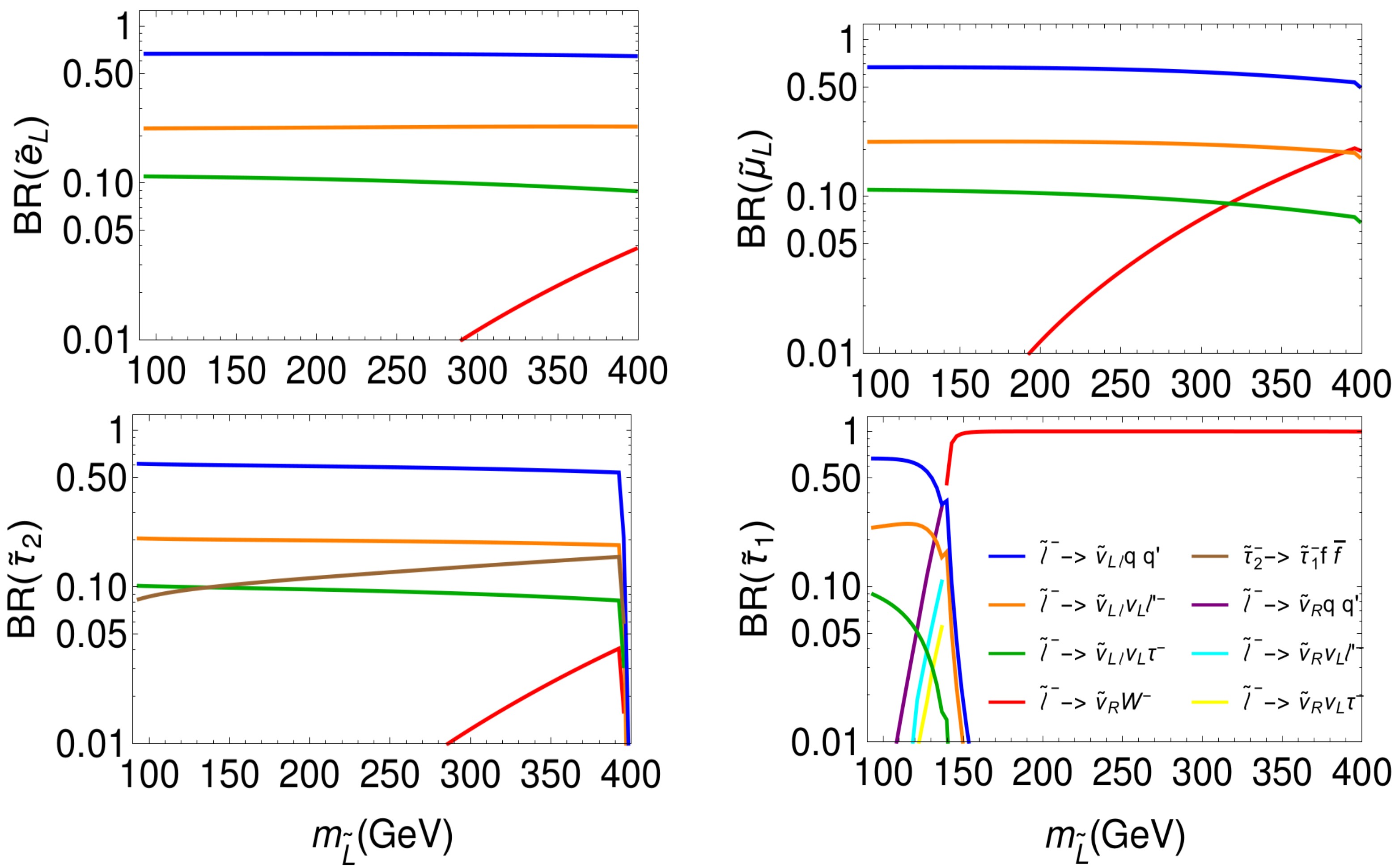


Very strong constraints on slepton mass!

ATLAS Collaboration (ATLAS-CONF-2016-096)

CheckMATE (1611.09856 [hep-ph])

Branching Ratios $m_{\tilde{\nu}_R} < m_{\tilde{\ell}} < \mu$



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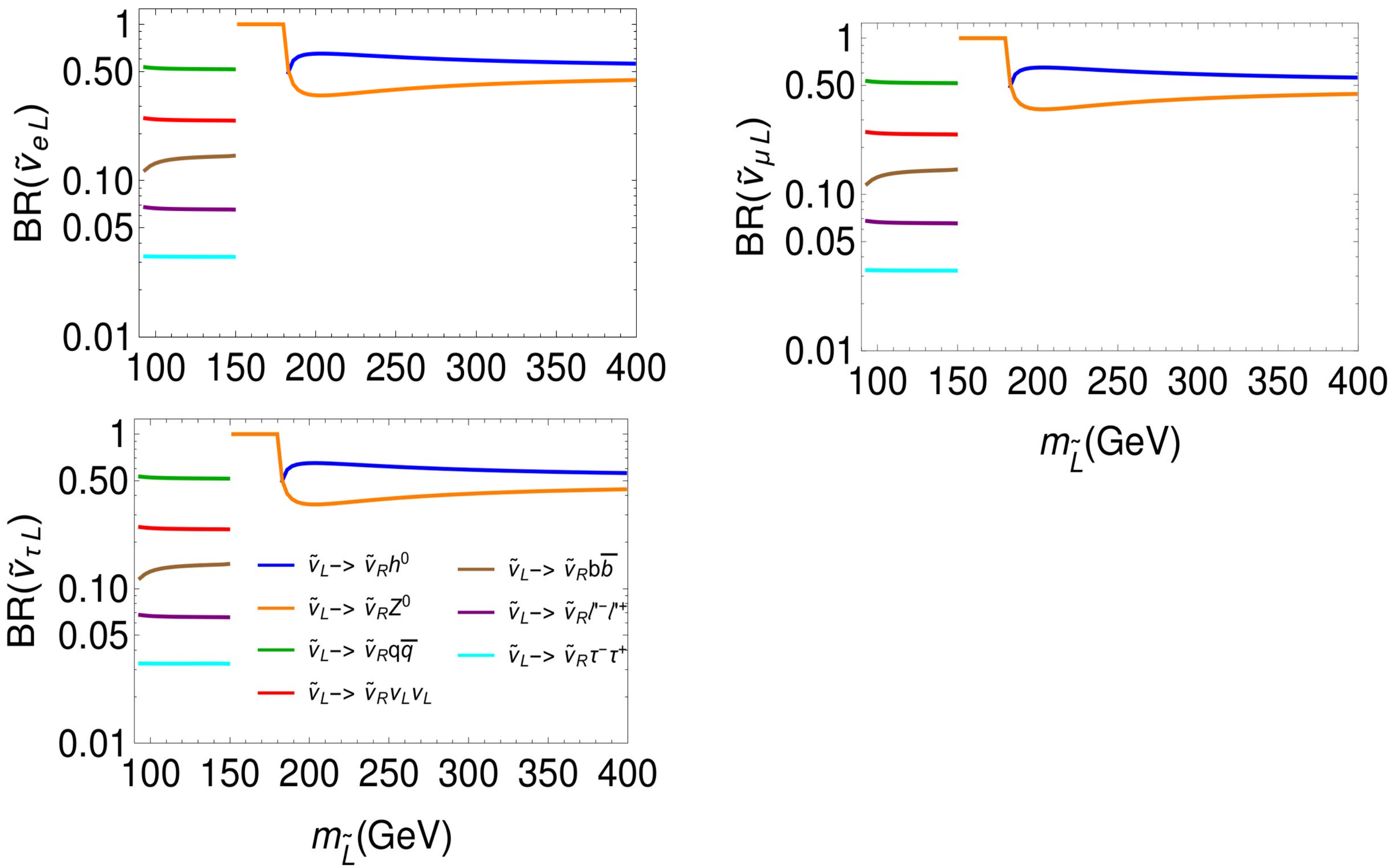

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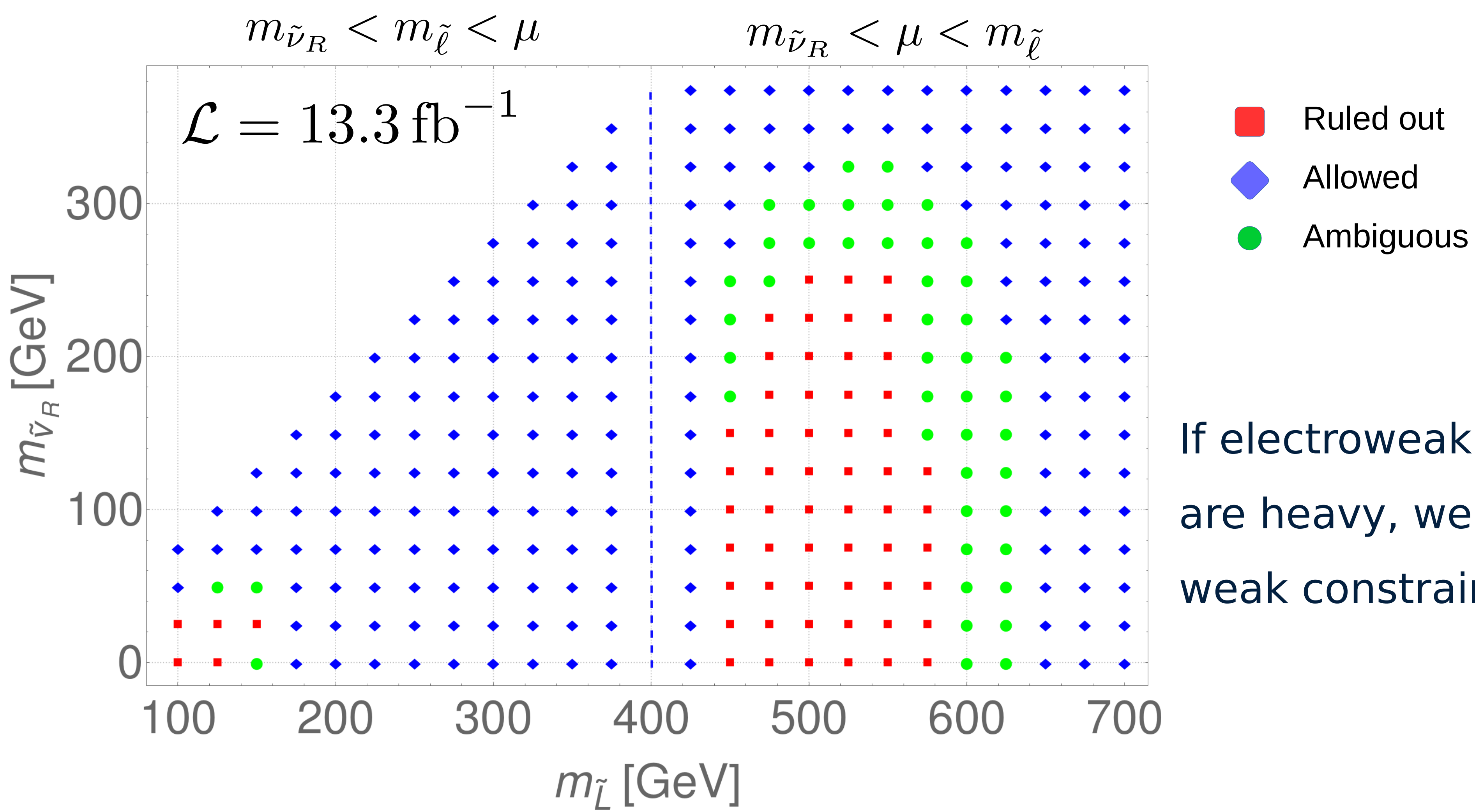

If electroweakinos are heavy, we have weak constraint!

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