Sneutrino Dark Matter meets EW SUSY inverse seesaw

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Refs: 1707.04374, 1806.04468

Motivation

Why do we need to extend the SM?

- Neutrino masses
- Gauge hierarchy problem
- DM candidate
- Gauge coupling unification

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→ Supersymmetry

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⇨ Supersymmetry

MSSM+type-I seesaw mechanism

Problems above can be solved, but type-I seesaw requires Majorana mass scale as $10^{12\text{-}16}\,\mathrm{GeV}$

How small Majorana mass is possible?

Motivation

Linear scaling of neutrino Yukawa coupling (type-I)

$$\frac{F^2 v_{\rm EW}^2}{M_N} \simeq 0.1\ {\rm eV}$$

Motivation

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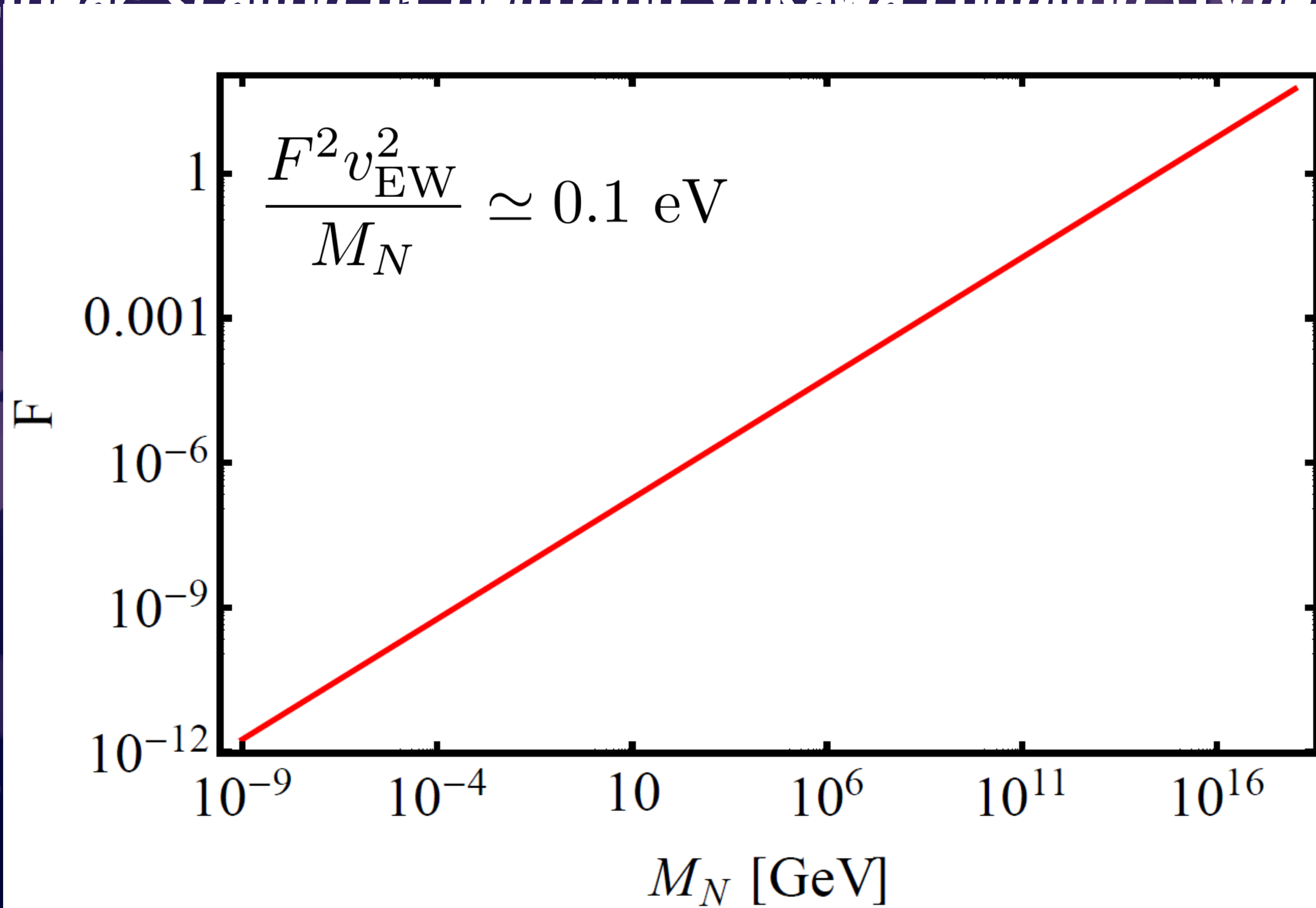

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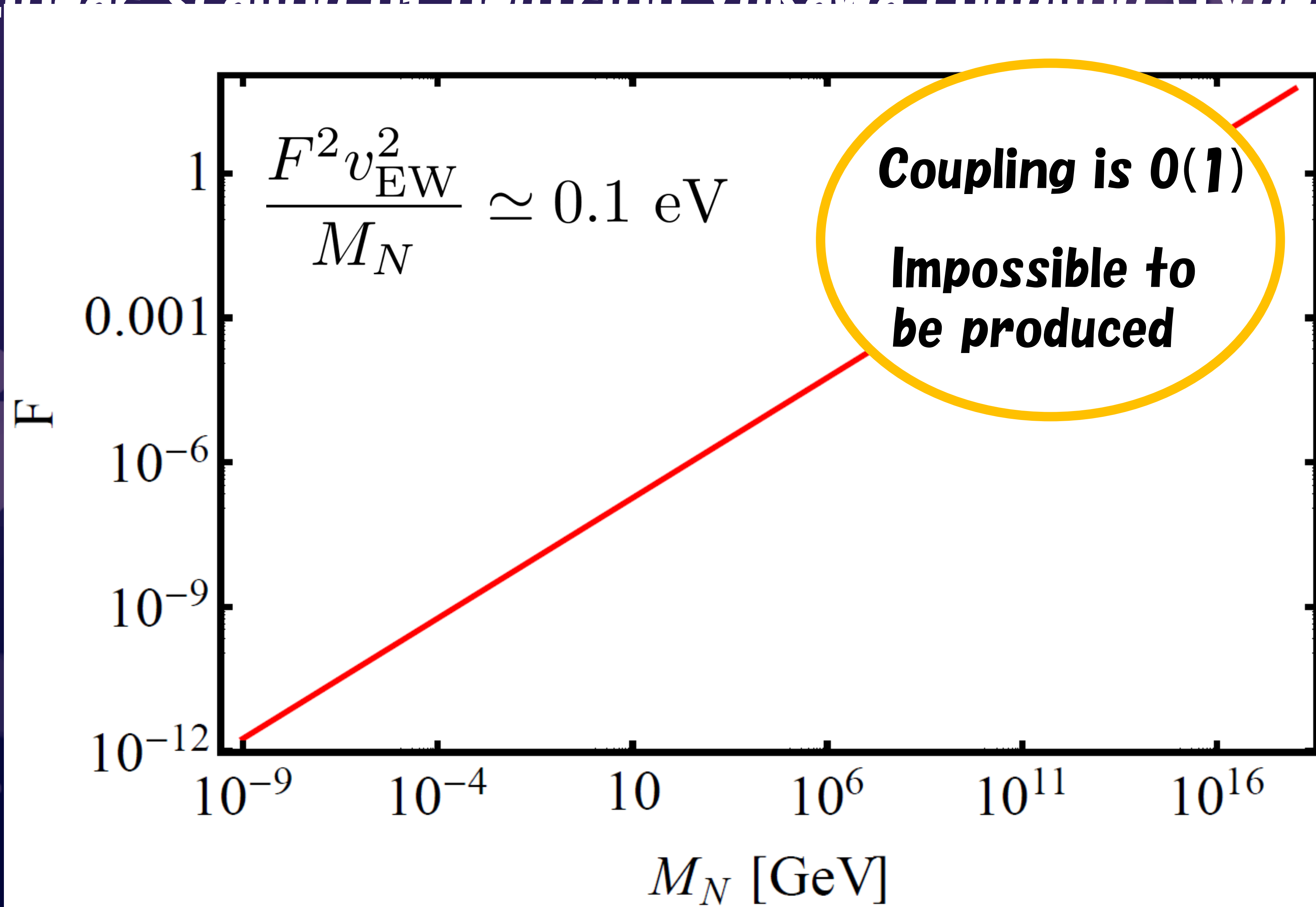

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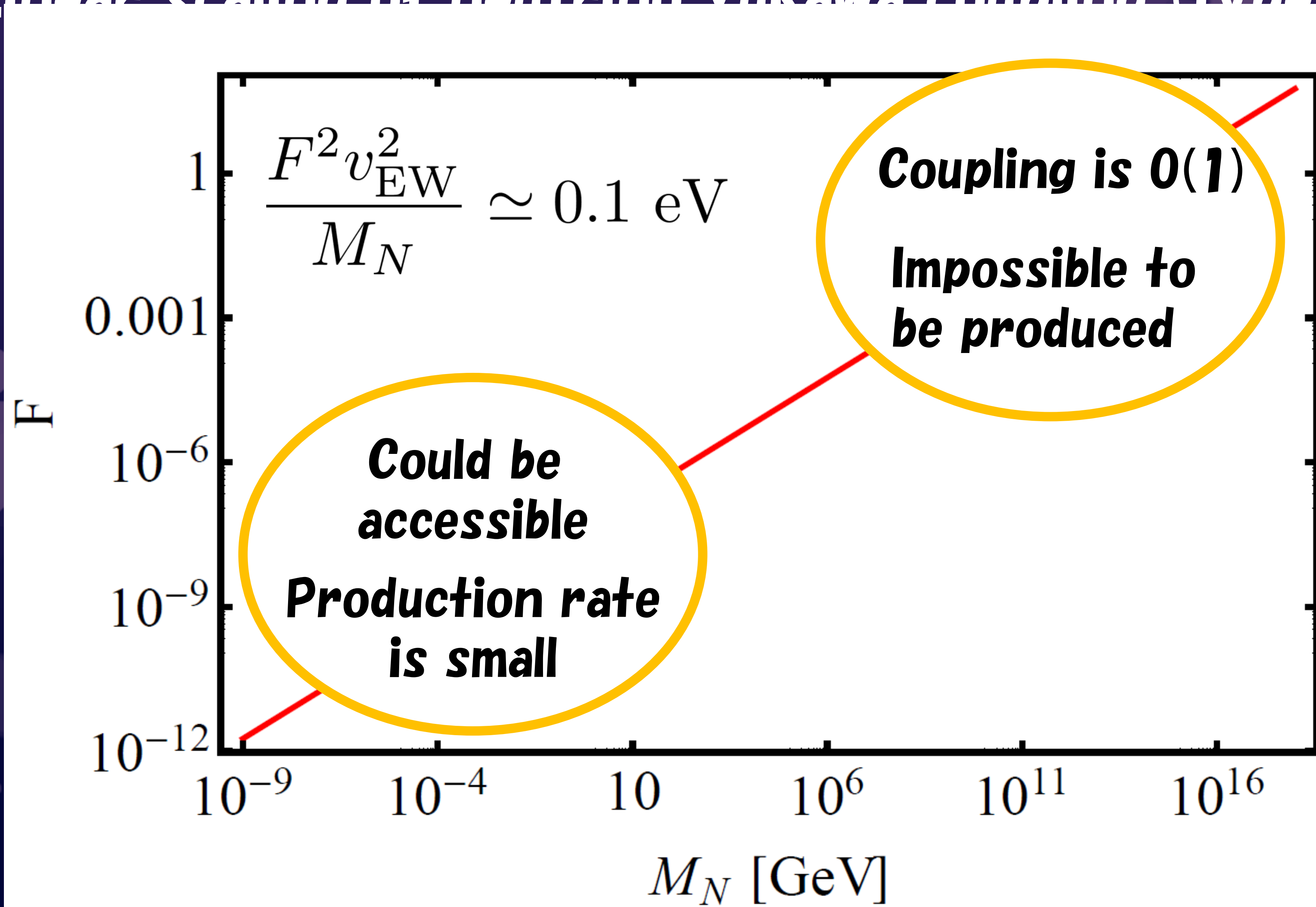

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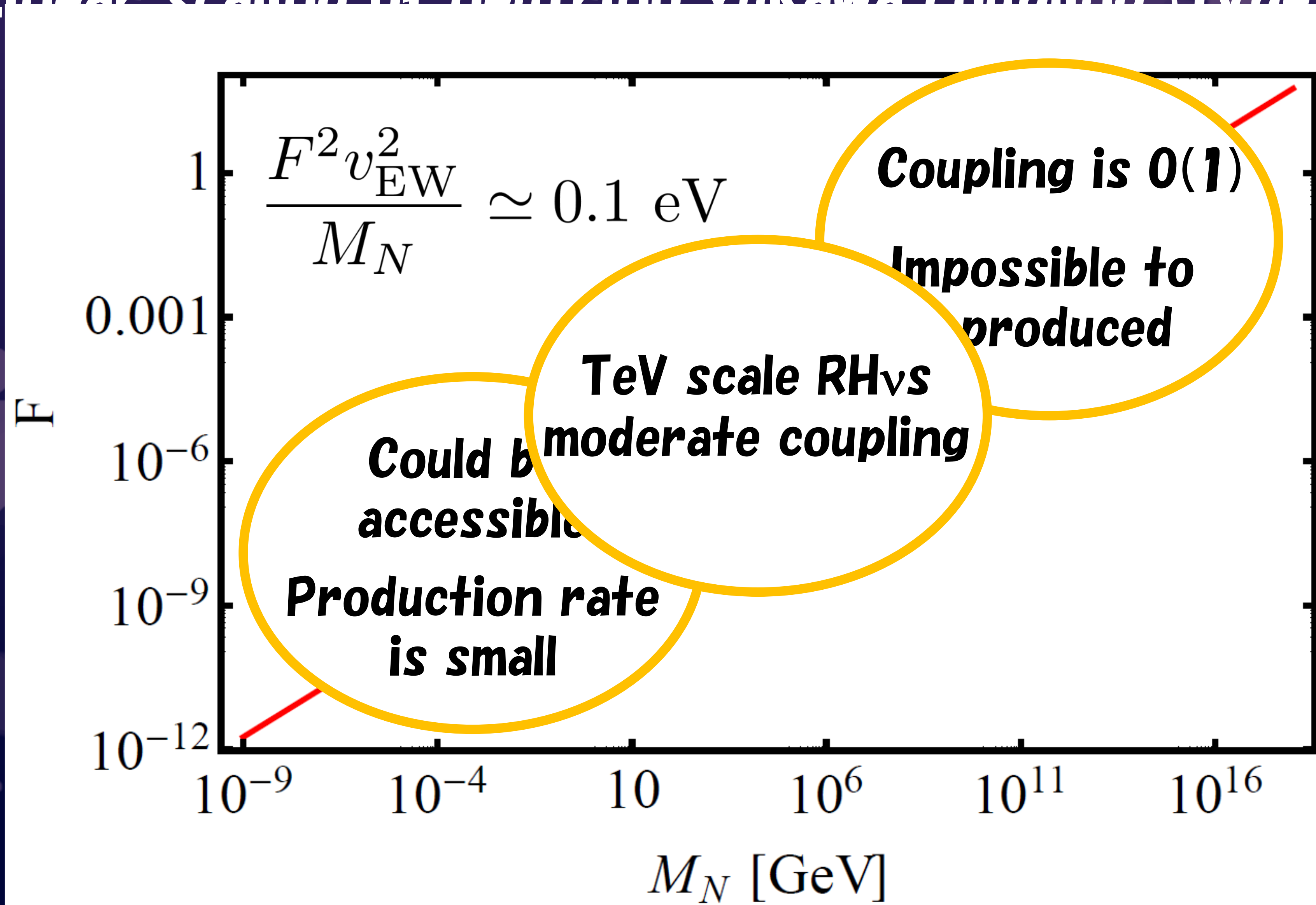

Motivation

There are lots of alternative ideas

- Inverse seesaw (ISS) mechanism

[Mohapatra (1986): Mohapatra and Valle (1986)]

Amplify the model by using another gauge singlet

$$-\mathcal{L} \supset y_\nu \bar{L} H \nu_R + M_N \overline{\nu_R^C} \nu_R + M_S S S + \mu \nu_R S + \mathrm{h.c}$$

Neutrino mass matrix

$$M_\nu = \begin{pmatrix} 0 & y_\nu v_{\mathrm{EW}} & 0 \\ y_\nu^T v_{\mathrm{EW}} & M_N & \mu \\ 0 & \mu & M_S \end{pmatrix} \Rightarrow m_\nu = -\frac{y_\nu v_{\mathrm{EW}} M_S y_\nu^T v_{\mathrm{EW}}}{\mu^2}$$

Small M_S(Lepton # violation) leads tiny m_ν

Motivation

Assumption in most of works

technically naturalness

$$M_\nu = \begin{pmatrix} 0 & y_\nu v_{\rm EW} & 0 \\ y_\nu^T v_{\rm EW} & 0 & \mu \\ 0 & \mu & M_S \end{pmatrix}$$

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$$M_\nu = \begin{pmatrix} 0 & y_\nu v_{\rm EW} & 0 \\ y_\nu^T v_{\rm EW} & 0 & \mu \\ 0 & \mu & M_S \end{pmatrix}$$

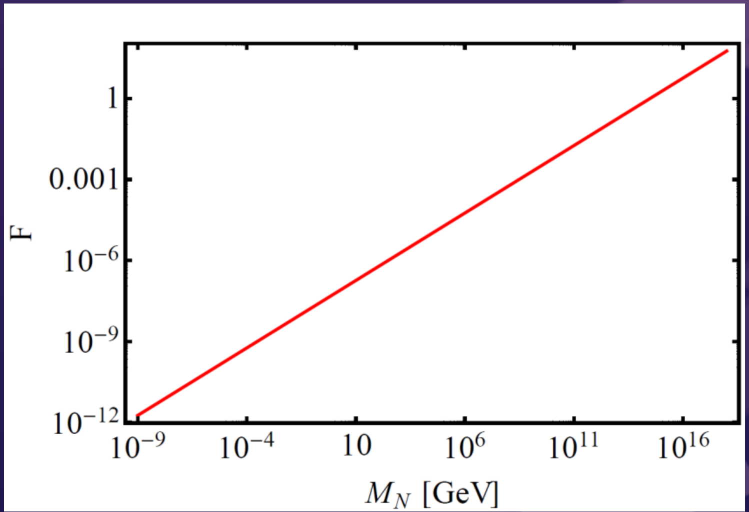
when $M_S \to 0$ lepton # sym. is recovered

↳ smallness of M_S is technically natural

Motivation

Assumption in most of works

benefit of inverse seesaw



$$m_\nu = \left(\frac{y_\nu}{1}\right)^2 \left(\frac{v_{\rm EW}}{10^2{\rm GeV}}\right)^2 \left(\frac{\rm TeV}{\mu}\right)^2 \left(\frac{M_S}{10{\rm eV}}\right)$$

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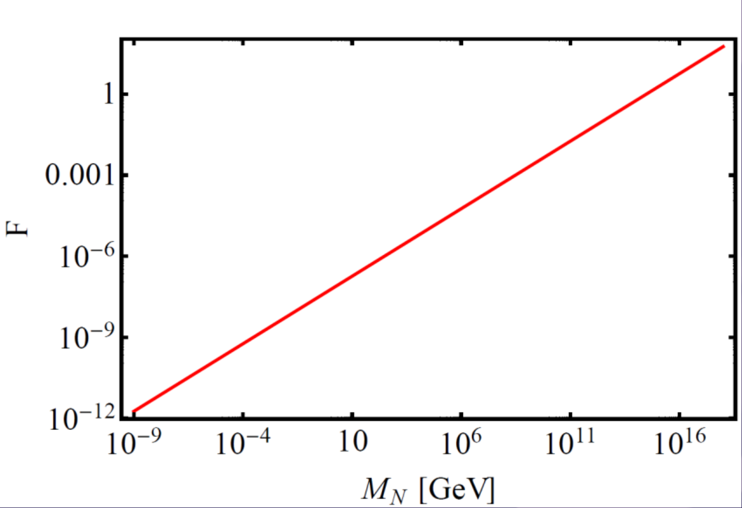

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extension at TeV scale with O(1) Yukawa is possible

Rich phenomenology at collider!

Dynamical origin of lepton number violating scale?

Model (NCTS model)

Symmetry: $\mathcal{G}_{\mathrm{SM}} \times Z_6$

Superfield	$\hat{Q}_i$	$\hat{U}^c_i$	$\hat{E}^c_i$	$\hat{L}_i$	$\hat{D}^c_i$	$\hat{H}_u$	$\hat{H}_d$	$\hat{N}^c_\alpha$	$\hat{S}_\alpha$	$\hat{X}$
Z_6 charge	5	5	5	3	3	2	4	1	5	2

$(\alpha = 1\,, 2)$

Model (NCTS model)

forbid R-parity violating terms
without imposing R-parity

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Z_6 charge	5	5	5	3	3	2	4	1	5	2

$(\alpha = 1\,, 2)$

New super potential in addition to MSSM

$$\mathcal{W}_\nu = Y_\nu \, \hat{L}\hat{H}_u\hat{N}^c + \mu_{\rm NS}\,\hat{N}^c\hat{S} + \frac{\lambda}{2}\,\hat{X}\,\hat{S}^2 + \frac{\kappa}{3}\,\hat{X}^3$$

Lagrangian related to neutrino

$$-\mathcal{L}_\nu = (Y_\nu)_{i\alpha}L_iN_\alpha^cH_u + (\mu_{\rm NS})_{\alpha\beta}N_\alpha^cS_\beta + \frac{1}{2}\lambda_{\alpha\beta}S_\alpha S_\beta X + {\rm H.c.}$$

Model

Phenomenological constraints?

-LFV

1. Non-SUSY contribution: $\mathrm{Br}(\mu \to e + \gamma) \simeq \mathcal{O}(10^{-20})$

2. SUSY contribution: depends on sparticle mixing

-0νββ decay

1. Non-SUSY contribution: $m_{\mathrm{eff}} \simeq 8 \times 10^{-9}\mathrm{meV} \left(\frac{\mu_{NS}}{\mathrm{TeV}}\right)$

2. SUSY contribution: no contribution due to "R-parity" conservation

DM estimation

Boundary conditions

$$m_0^2 = \frac{1}{9} m_{\tilde{Q}}^2 = \frac{1}{9} m_{\tilde{D}}^2 = \frac{1}{9} m_{\tilde{U}}^2 = m_{\tilde{L}}^2 = m_{\tilde{E}}^2 = m_{\tilde{N}}^2 = m_{\tilde{S}}^2 = m_{H_u}^2 = m_{H_d}^2 = b_{NS} \ ,$$

$$M_{1/2} = \frac{1}{3} M_3 = M_2 = M_1 \ ,$$

$$A_i = A_0 Y_i, \ A_\lambda = A_0 \lambda, \ A_\kappa = \kappa A_0 \ ,$$

DM estimation

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- Put arbitrary factor to make colored particles heavy enough

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- Put arbitrary factor to make colored particles heavy enough

- m_0 and $M_{1/2}$ are fixed at high scale

- v_χ a and κ are fixed at low scale

  not to worry about running effect

DM estimation

Sneutrino mass matrix @tree level

$$m^2_{\tilde{\nu}^R} \approx m^2_{\tilde{\nu}^I} \approx \begin{pmatrix} m_0^2 + \frac{1}{2} M_Z^2 \cos(2\beta) & 0 & 0 \\ 0 & m_0^2 + \mu_{NS}^2 & m_0^2 \\ 0 & m_0^2 & m_0^2 + \mu_{NS}^2 \end{pmatrix}$$

-RG corrections to them is small enough

-Physical states

$$\tilde{\nu}_{1,2} \approx \frac{1}{\sqrt{2}} \left(\tilde{N}_1^c \mp \tilde{S}_1 \right) \text{ and } \tilde{\nu}_3 \approx \tilde{L}_1$$

$$m^2_{\tilde{\nu}_1} \approx \mu^2_{NS}$$

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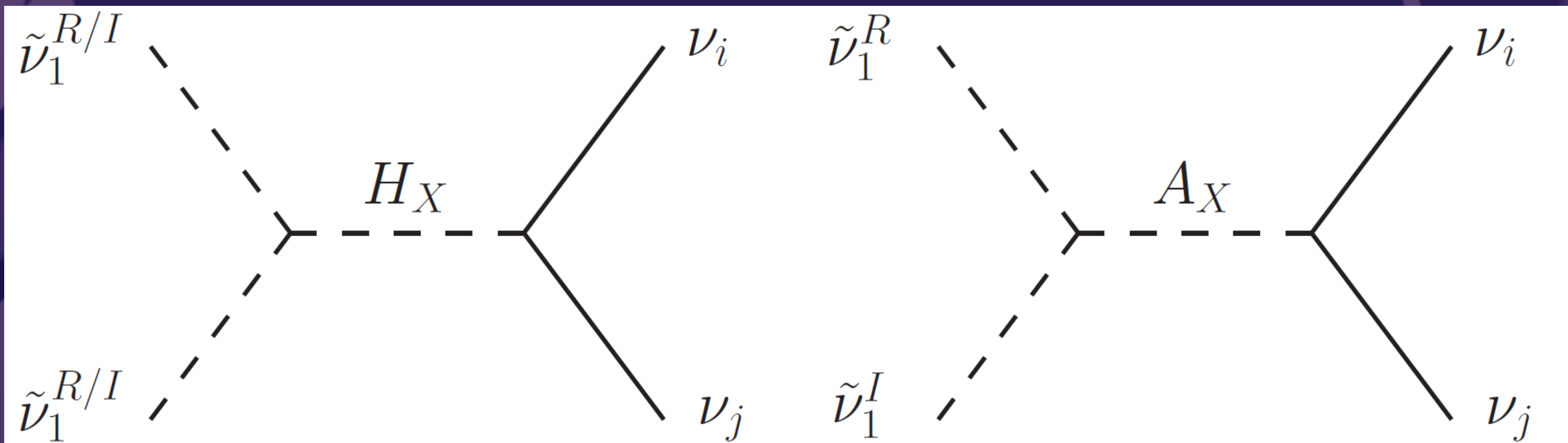
$$m^2_{\tilde{\nu}_1} \approx \mu^2_{NS}$$

- Mass difference between CP-even & -odd states

$$m^2_{\tilde{\nu}_1^R} - m^2_{\tilde{\nu}_1^I} \approx \frac{1}{2}\lambda v_X \left(\sqrt{2}\,A_0 - 2\sqrt{2}\mu_{NS} + \kappa v_X\right)$$

DM estimation

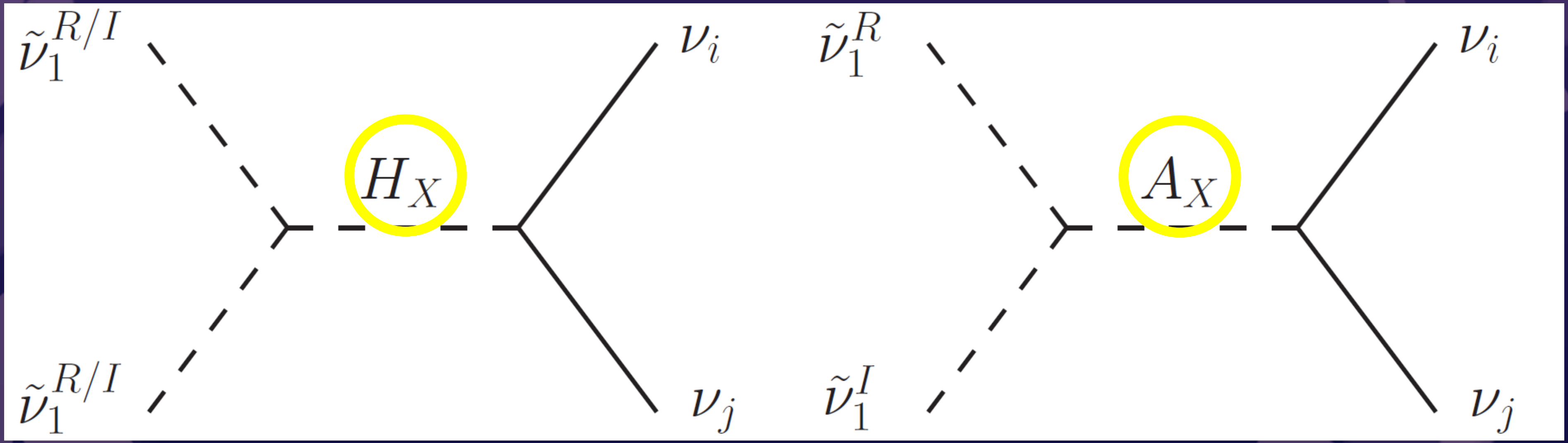
Dominant (co-)annihilation channels



H-funnel A-funnel

DM estimation

Dominant (co-)annihilation channels



H-funnel A-funnel

Origin of #L violation mediates two sectors!

DM estimation

Features of our analysis

- Three exceptions of thermal relic calculation

[Griest and Seckel (1991)]

1. Co-annihilation

2. Annihilation into forbidden channel
   (near threshold)

3. Annihilation near pole (resonance)

DM estimation

Features of our analysis

- Three exceptions of thermal relic calculation

[Griest and Seckel (1991)]

1. Co-annihilation
2. Annihilation into forbidden channel (near threshold)
3. Annihilation near pole (resonance)

We have to take into account 1 and 3!

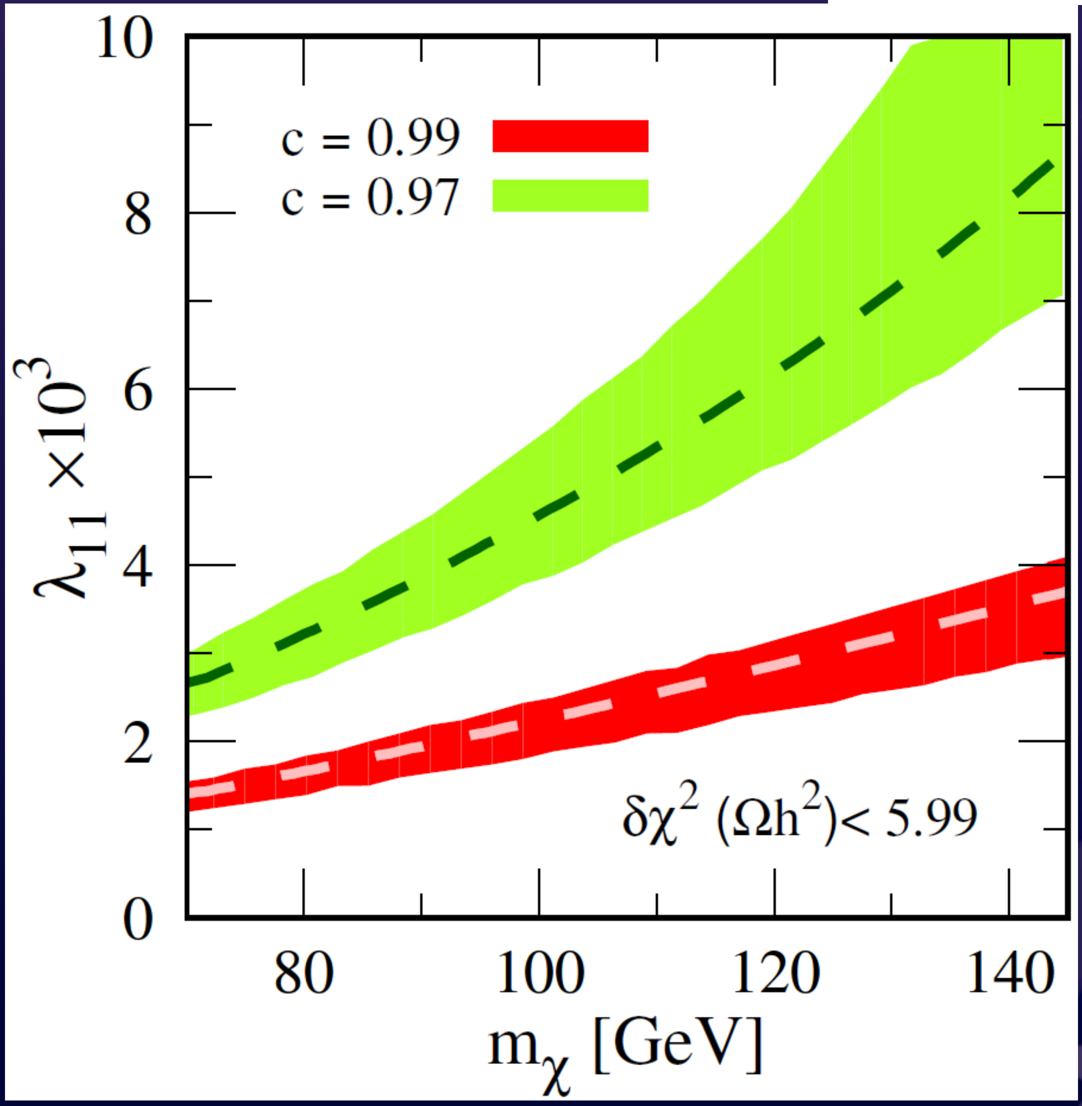
DM estimation

Results in A_X-funnel scenario

DM estimation

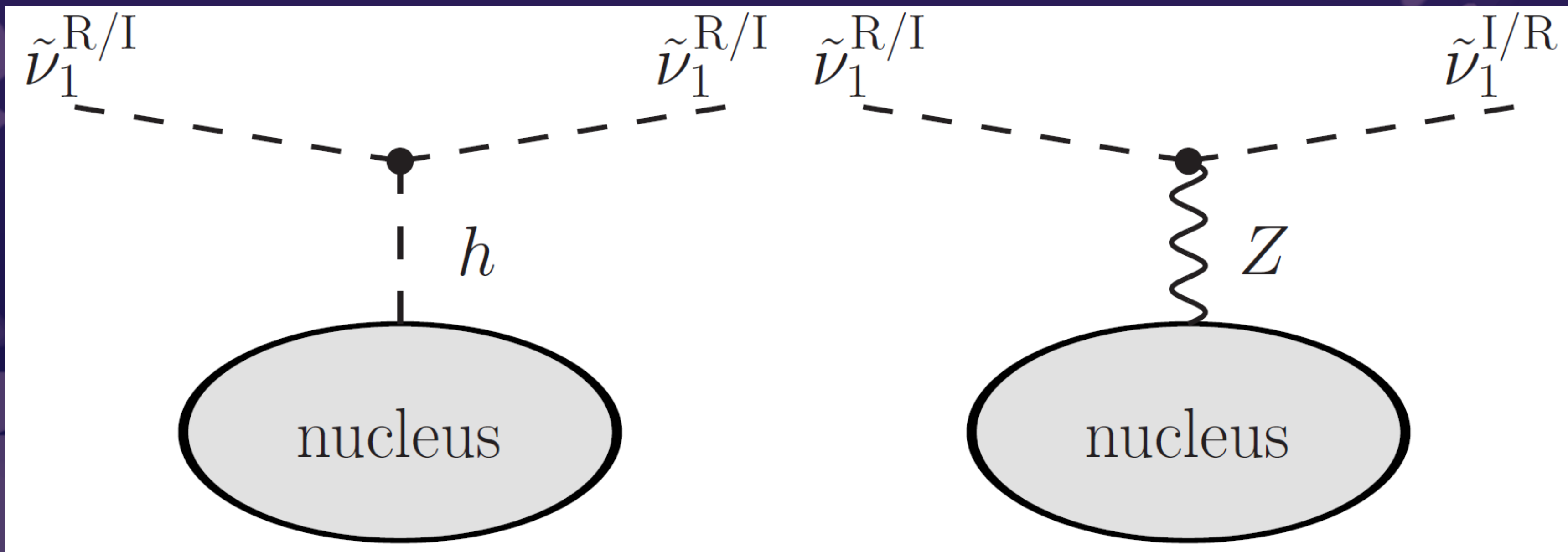
Results in A_X-funnel scenario

$$m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I} = c\, m_{A_X}$$



DM properties

Direct detection



- Z exchange is more suppressed

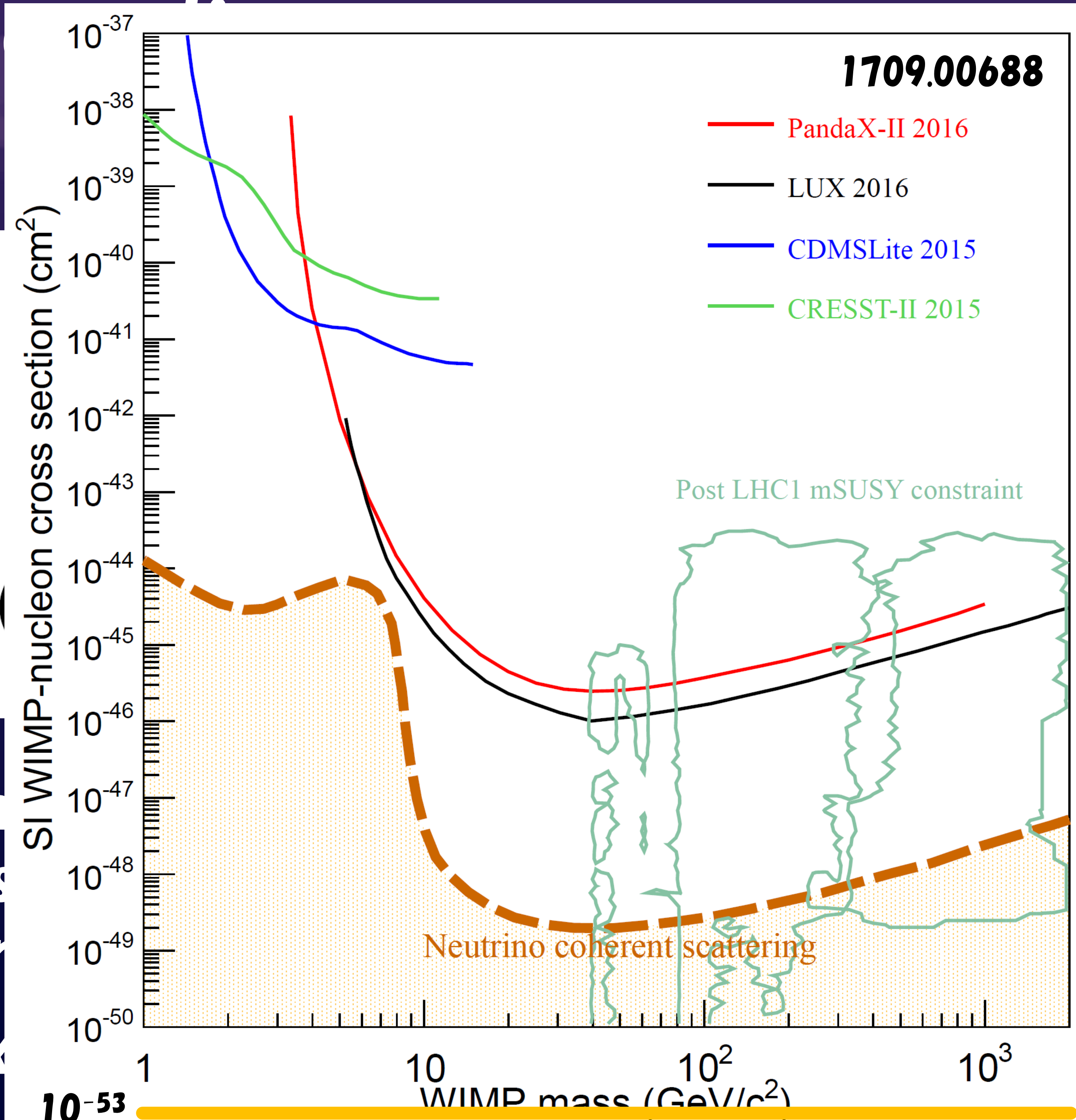
- Using $Y_\nu \sim 10^{-6}$ and $M_{SUSY} = 1$ TeV, Higgs exchange cross section is given as $O(10^{-29})$ pb which is even below neutrino floor

10^{-53}

DM pr

Direct

$\tilde{\nu}_1^{R/I}$ $\tilde{\nu}_1^{I/R}$



10^{-53}

–Usin ... change

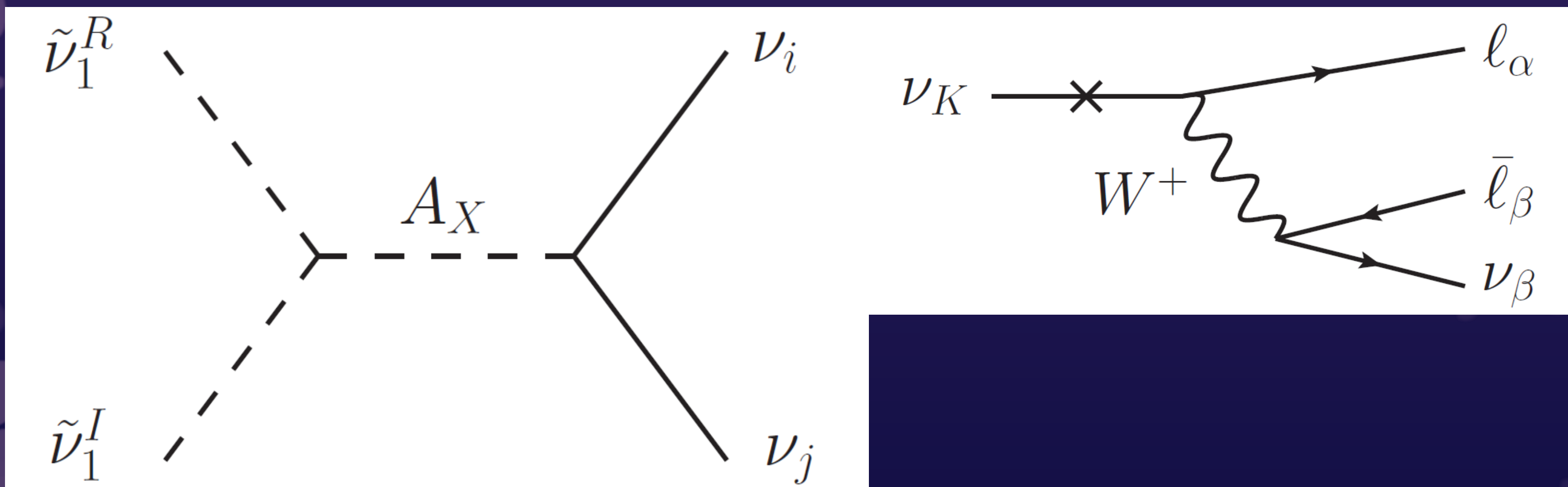
cros ... h is

ever

–Z ex

DM properties

Indirect detection

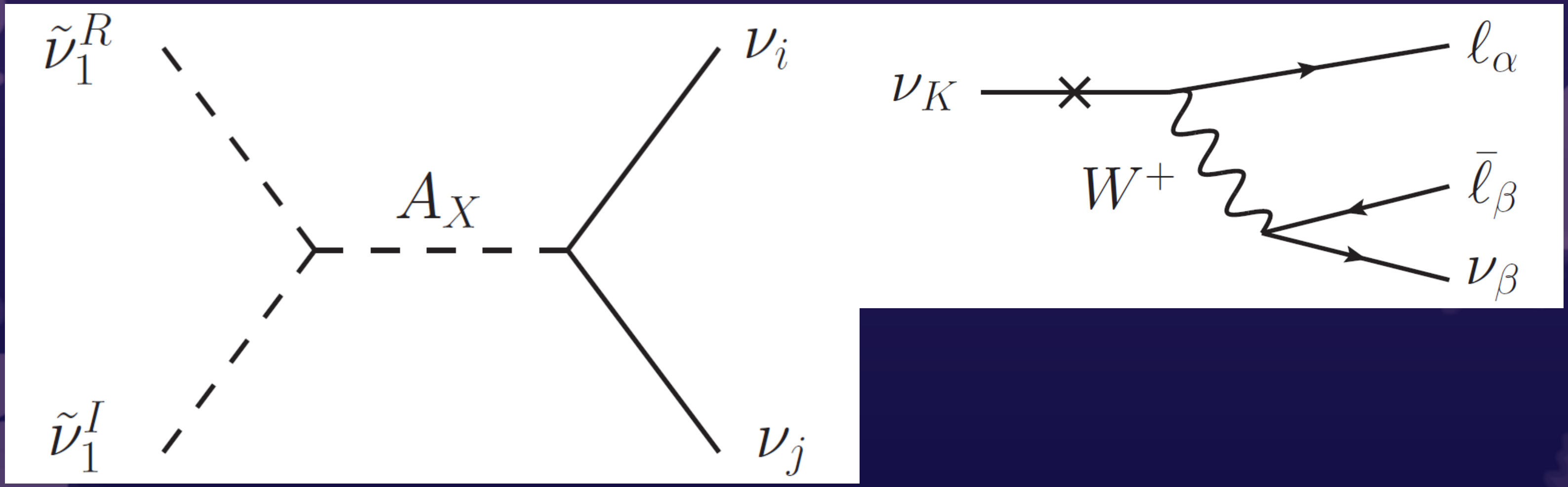


- If DM annihilate into two active neutrinos or one active and one heavy neutrino, we could see line signal of active ν at IceCube

- Since heavy neutrino can decay into SM leptons, we could see some signal from this cascade decay

DM properties

Indirect detection



- Since annihilation cross section into two active neutrinos $O(10^{-41})\text{cm}^3\ \text{s}^{-1}$, this signal seems not to be so promising

- However, this cross section is a few order of magnitude smaller, we could see signal in future

Conclusions

- SUSY inverse seesaw model
  - Majorana mass term is dynamically induced
  - Low scale seesaw mechanism can be realized
  - Thermal relic sneutrino DM is possible thanks to existing the origin of lepton # violation
  - Our extensions to MSSM is really hidden.

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- SUSY inverse seesaw model
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  - Low scale seesaw mechanism can be realized
  - Thermal relic sneutrino DM is possible thanks to existing the origin of lepton # violation
  - Our extensions to MSSM is really hidden,

    in other words,

    our model can be easily excluded by observations

Thank you for your attention

DM estimation

How to hit the funnel

- First, we define a parameter c $m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I} = c\, m_{A_X}$

  c is chosen either 0.97 or 0.99

- Second, we fix μ_{NS} by using mass formulae

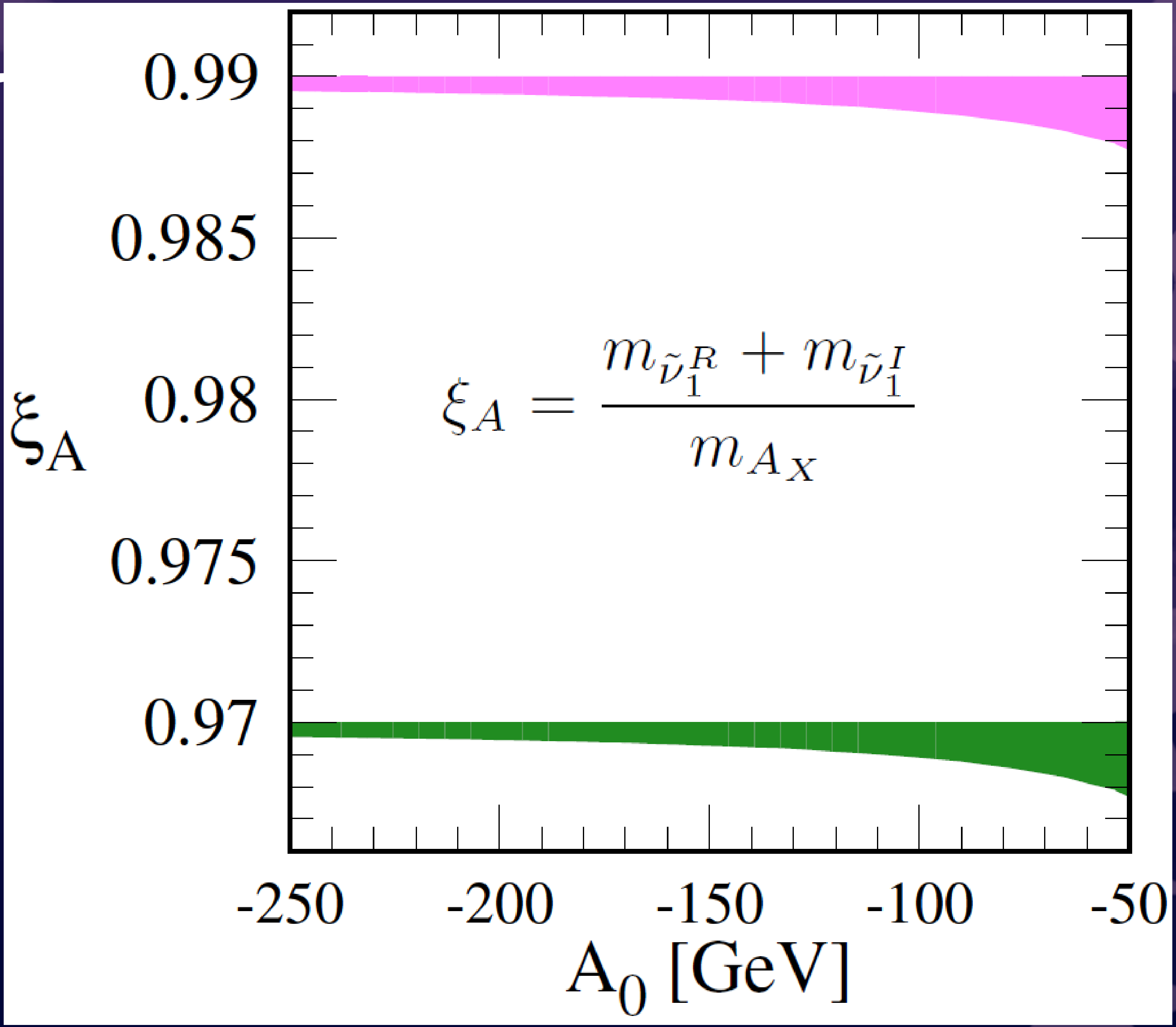
- Third, we run SPheno to calculate mass spectrum, estimate μ_{NS} again and take the ratio

$$\xi_A = \frac{m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I}}{m_{A_X}}$$

requiring not to deviate more than 2.5×10^{-3}

DM estimation

How



WIMP in the model

Definition of WIMP before

"Weakly" interacting massive particle

same magnitude as weak interaction

$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \cdot 10^{-26} \mathrm{cm/s}}{\langle \sigma v (\chi\chi \to SM) \rangle} \right) \approx \left(\frac{\alpha^2 / (200 \mathrm{GeV})^2}{\langle \sigma v (\chi\chi \to SM) \rangle} \right)$$

Definition of WIMP now

"Weakly" interacting massive particle

as weak as you want
as long as you can explain abundance

Model

Symmetry breaking:

Requirement to scalar fields

- No field takes VEV except for Hu, Hd, X

From potential analysis,

$$v_X = -\frac{A_\kappa}{4\,\kappa^2} \pm \frac{\sqrt{A_\kappa^2 - 8\,\kappa^2 M_X^2}}{4\,\kappa^2}$$

Origin of "lepton #" violation

$$\frac{1}{2}\lambda_{\alpha\beta}S_\alpha S_\beta X \Rightarrow \frac{1}{2}\lambda_{\alpha\beta}v_X S_\alpha S_\beta$$

Model

Neutrino mass matrix:

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & \mu_{\rm NS} \\ 0 & \mu_{\rm NS}^T & M_S \end{pmatrix}$$

Smallness of $M_S \equiv \lambda v_X$ is explained by coupling

As possibilities,

(i) ISS type I: $\lambda \ll Y_\nu \ll 1$ NS,

(ii) ISS type II: $\lambda \sim Y_\nu \ll 1$ 'NS,

(iii) ISS type III: $Y_\nu \ll \lambda \ll 1$ $\mu_{\rm NS}$.

Model

Feature of model $\mathcal{G}_{\rm SM} \times Z_6$

$Z_3 \times Z_2$

Superfield	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{E}_i^c$	$\hat{L}_i$	$\hat{D}_i^c$	$\hat{H}_u$	$\hat{H}_d$	$\hat{N}_\alpha^c$	$\hat{S}_\alpha$	$\hat{X}$
Z_3 charge	1	1	1	0	0	1	2	2	1	1
Z_2 charge	1	1	1	1	1	0	0	1	1	0

Matter parity is defined

LSP can be DM candidate!

Gravitino, Sneutrino, Neutralino

Non-MSSM candidate!

DM estimation

Sneutrino mass matrix

$$m^2_{\tilde{\nu}^R} \approx m^2_{\tilde{\nu}^I} \approx \begin{pmatrix} \Re(M^2_{\tilde{L}}) + \frac{1}{2}M_Z^2\cos(2\beta) & 0 & 0 \\ 0 & \Re(M^2_{\tilde{N}^c} + \mu_{NS}\mu^\dagger_{NS}) & \Re(b_{NS}) \\ 0 & \Re(b^T_{NS}) & \Re(M^2_{\tilde{S}} + \mu^\dagger_{NS}\mu_{NS}) \end{pmatrix}$$

boundary conditions

$$m^2_{\tilde{\nu}^R} \approx m^2_{\tilde{\nu}^I} \approx \begin{pmatrix} m_0^2 + \frac{1}{2}M_Z^2\cos(2\beta) & 0 & 0 \\ 0 & m_0^2 + \mu^2_{NS} & m_0^2 \\ 0 & m_0^2 & m_0^2 + \mu^2_{NS} \end{pmatrix}$$

Eigenvalues at tree level

$$m_0^2 + \frac{1}{2}M_Z^2\cos(2\beta)\,,\, \mu^2_{\rm NS}\,,\, 2m_0^2 + \mu^2_{\rm NS}$$

DM estimation

Higgs masses (H_X and A_X)

- We have two more Higgs compared to MSSM which are composed X-scalar

- Mixing with MSSM scalars is extremely suppressed

$$\Rightarrow \mathcal{O}\left(\text{loop factor} \times m_\nu^2\right)$$

- Approximate masses

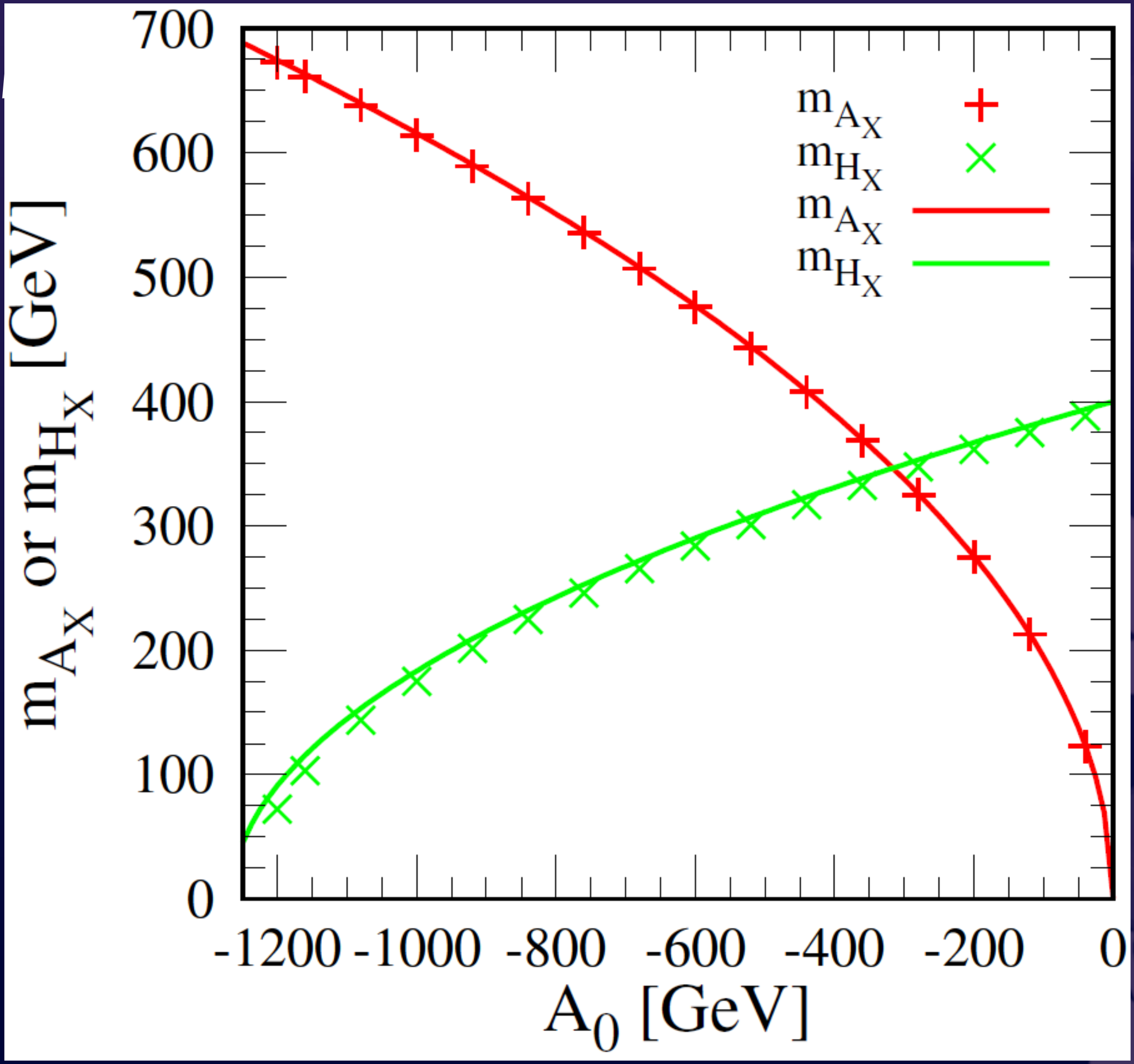
$$m_{H_X}^2 \approx 2\,\kappa_0^2 v_X^2 + \frac{v_X}{\sqrt{2}}\kappa_0 A_0\left(1 - 2.3\,\kappa_0^2\right)\ , m_{A_X}^2 \approx -\frac{3\,v_X}{\sqrt{2}}\kappa_0 A_0\left(1 - 2.3\,\kappa_0^2\right)$$

$$\Rightarrow -\frac{2\sqrt{2}\,\kappa_0}{1 - 2.3\,\kappa_0^2} v_X \lesssim A_0 < 0$$

DM estimation

Higgs masses (H_X and A_X)

- Compa



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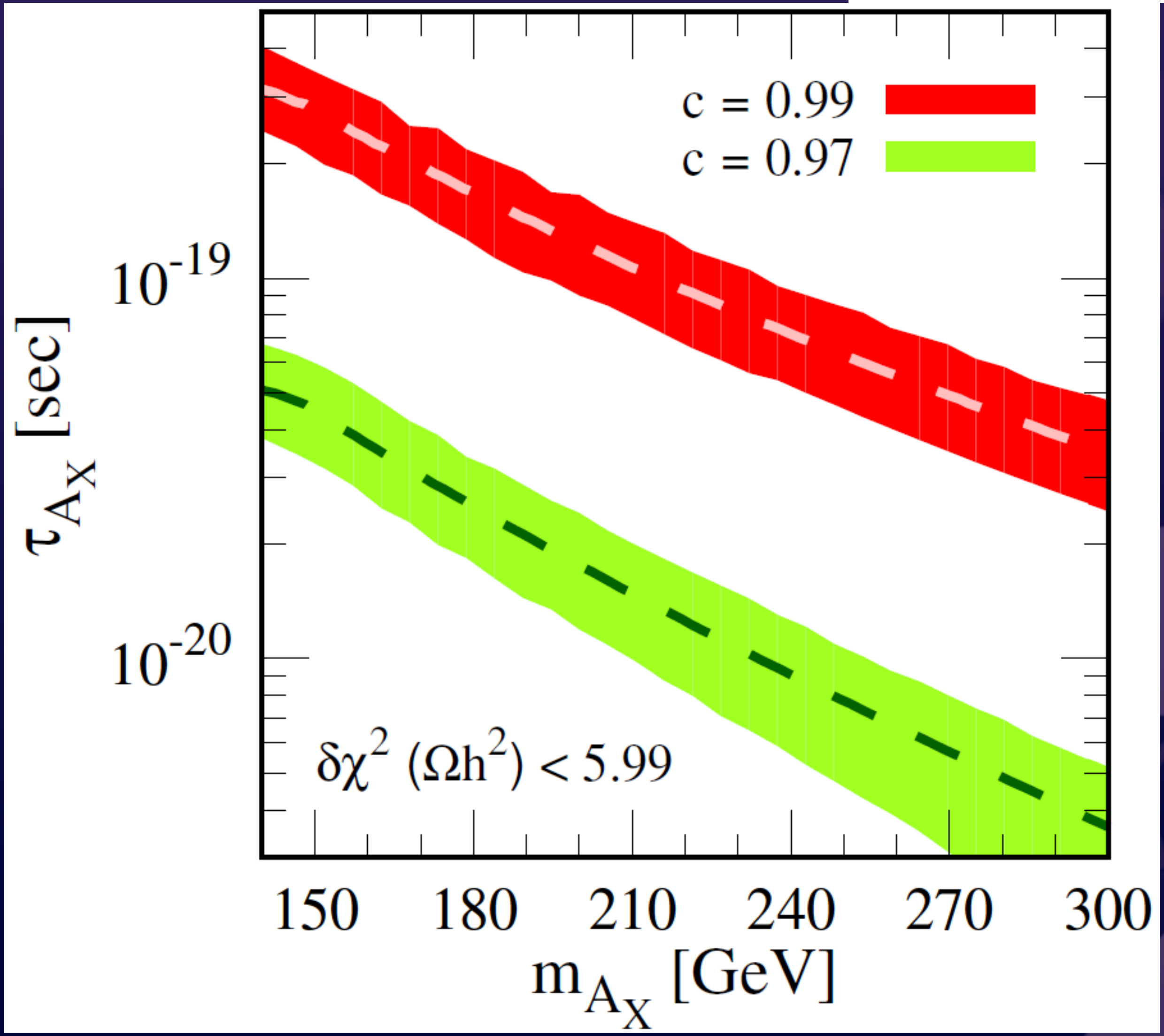

DM estimation

How about H_X-funnel?

-H_X-funnel does NOT work because…

1. H_X-funnel has p-wave suppression
2. To compensate, larger λ is required

$$\mathcal{W}_\nu = Y_\nu \hat{L}\hat{H}_u\hat{N}^c + \mu_{NS}\,\hat{N}^c\hat{S} + \frac{\lambda}{2}\,\hat{X}\,\hat{S}^2 + \frac{\kappa}{3}\,\hat{X}^3$$

3. When λ gets large, it closes the decay channel into heavy neutrinos due to mass splitting

Future prospects

- At the moment, our model is playing hide & seek but…
  - Collider phenomenology
  - Aspects for early universe
  - Astrophysical observation

Any suggestion to study is welcome!

need to be explored