Thermal sneutrino dark matter in inverse seesaw model

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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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MSSM+type-I seesaw mechanism

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

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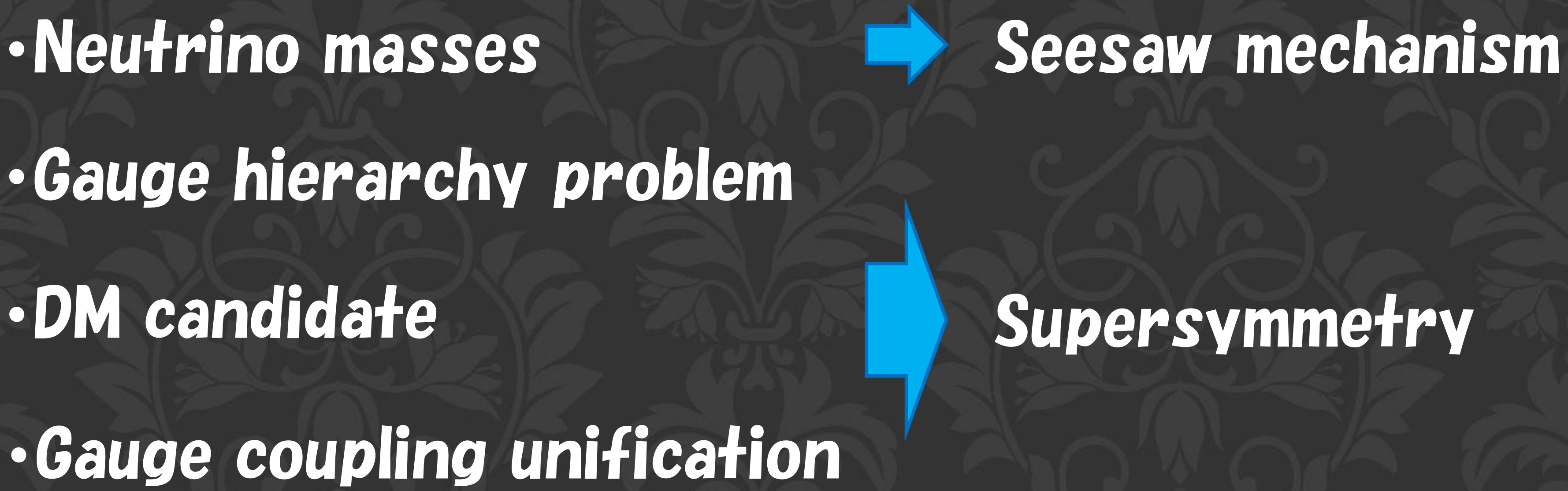

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Above problems can be solved, but type-I seesaw requires Majorana mass scale as $10^{12\text{-}16}\,\mathrm{GeV}$

How small Majorana mass is possible?

Motivation

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

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

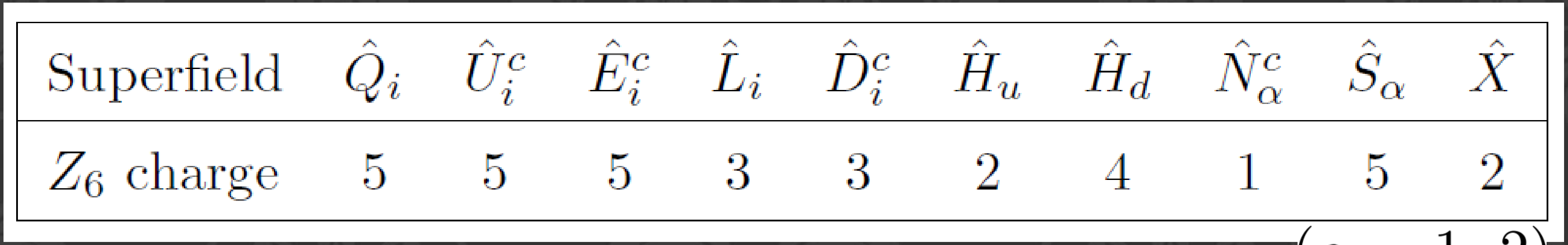
extension at TeV scale with O(1) Yukawa is possible

↳ Rich phenomenology at collider!

Dynamical origin of lepton number violating scale?

Model

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



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_6 charge	5	5	5	3	3	2	4	1	5	2

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

Model

forbid R-parity violating terms

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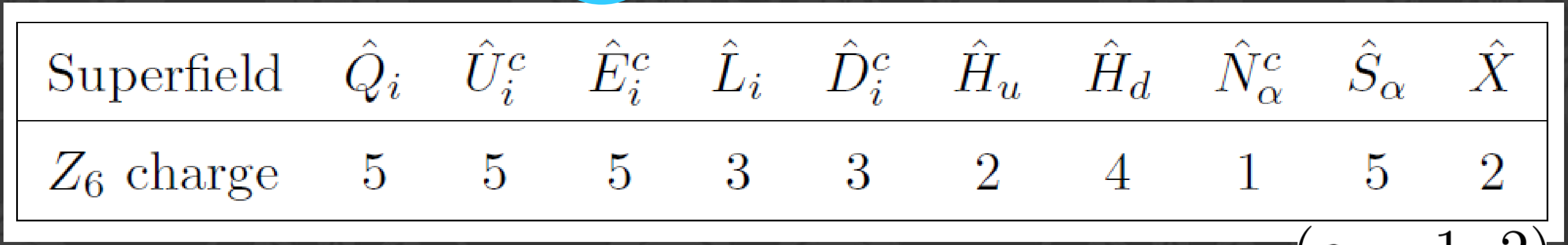

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New super potential in addition to MSSM

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

Lagrangian related to neutrino

$$-\mathcal{L}_\nu = -(Y_e)_{ij}L_iH_dE^c_j + (Y_\nu)_{i\alpha}L_iN^c_\alpha H_u + (\mu_{\mathrm{NS}})_{\alpha\beta}N^c_\alpha S_\beta + \frac{1}{2}\lambda_{\alpha\beta}S_\alpha S_\beta X + \mathrm{H.c.}$$

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

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

Model

Neutrino mass matrix:

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

Model

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

As possibilities,

$$\text{(i)} \;\; \text{ISS type I: } M_S \ll M_D \ll \mu_{\rm NS},$$

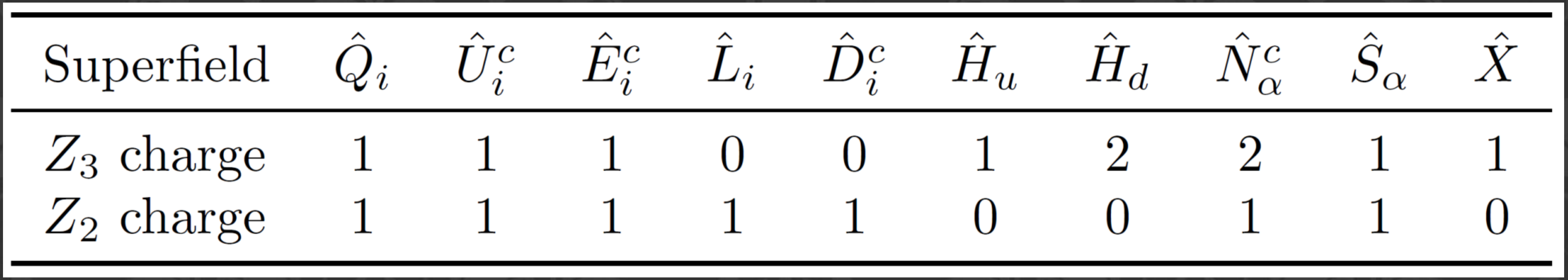
$$\text{(ii)} \;\; \text{ISS type II: } M_S \sim M_D \ll \mu_{\rm NS},$$

$$\text{(iii)} \;\; \text{ISS type III: } M_D \ll M_S \ll \mu_{\rm NS}.$$

Model

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

$$Z_3 \times Z_2$$



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Matter parity is defined

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LSP can be DM candidate!

Gravitino, Sneutrino, Neutralino

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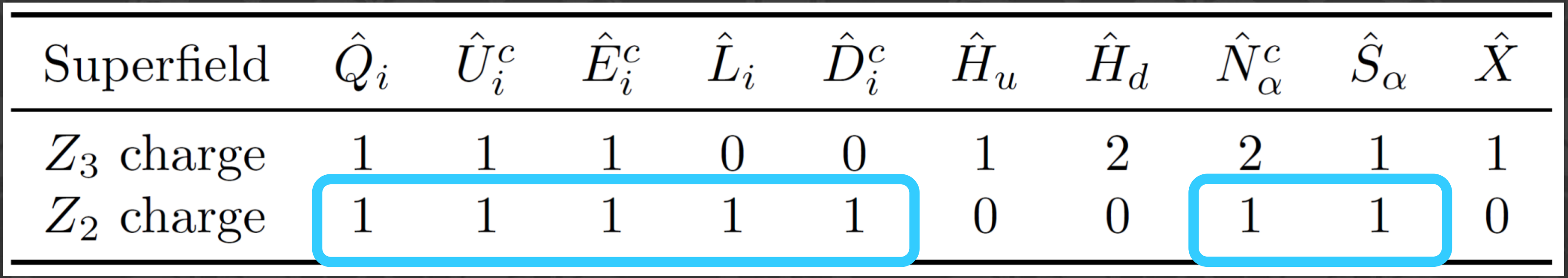

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Model

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

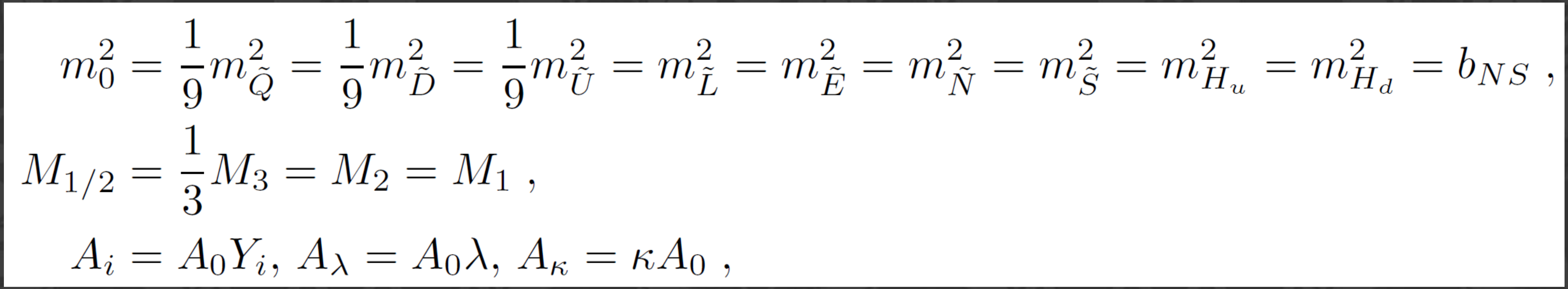
-0νββ decay

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



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

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

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

-Put arbitrary factor to make colored particles heavy enough

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

-v_X a and κ are fixed at low scale

not to worry about running effect

DM estimation

Sneutrino mass matrix

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

-RG corrections to them is small enough

-Physical states

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

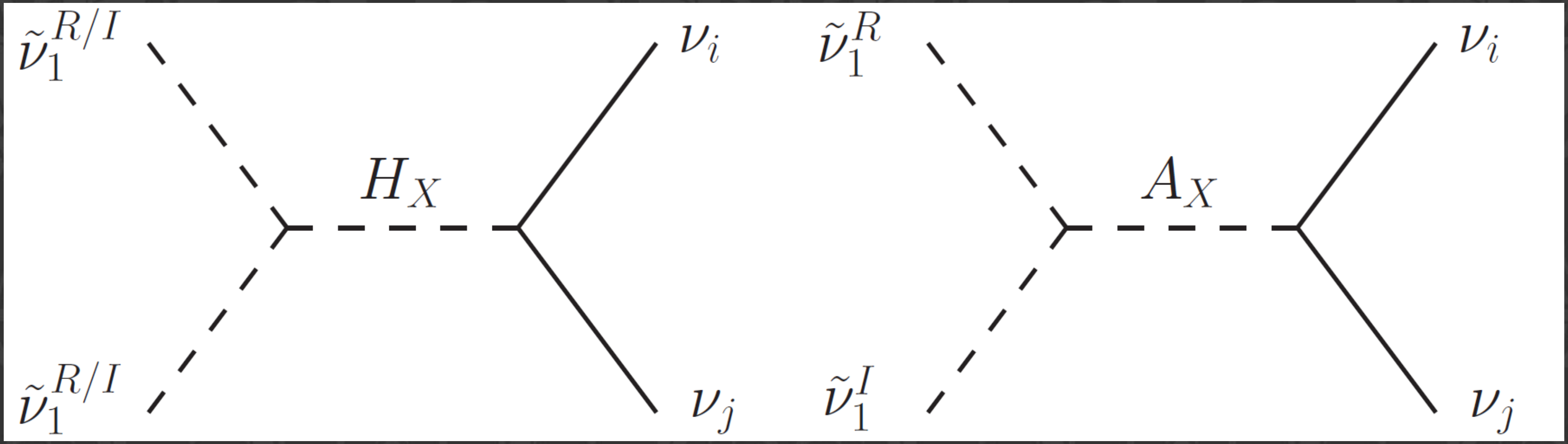
$$m^2_{\tilde{\nu}_1} \approx \mu^2_{NS}$$

-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

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

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

- Approximate masses

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

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

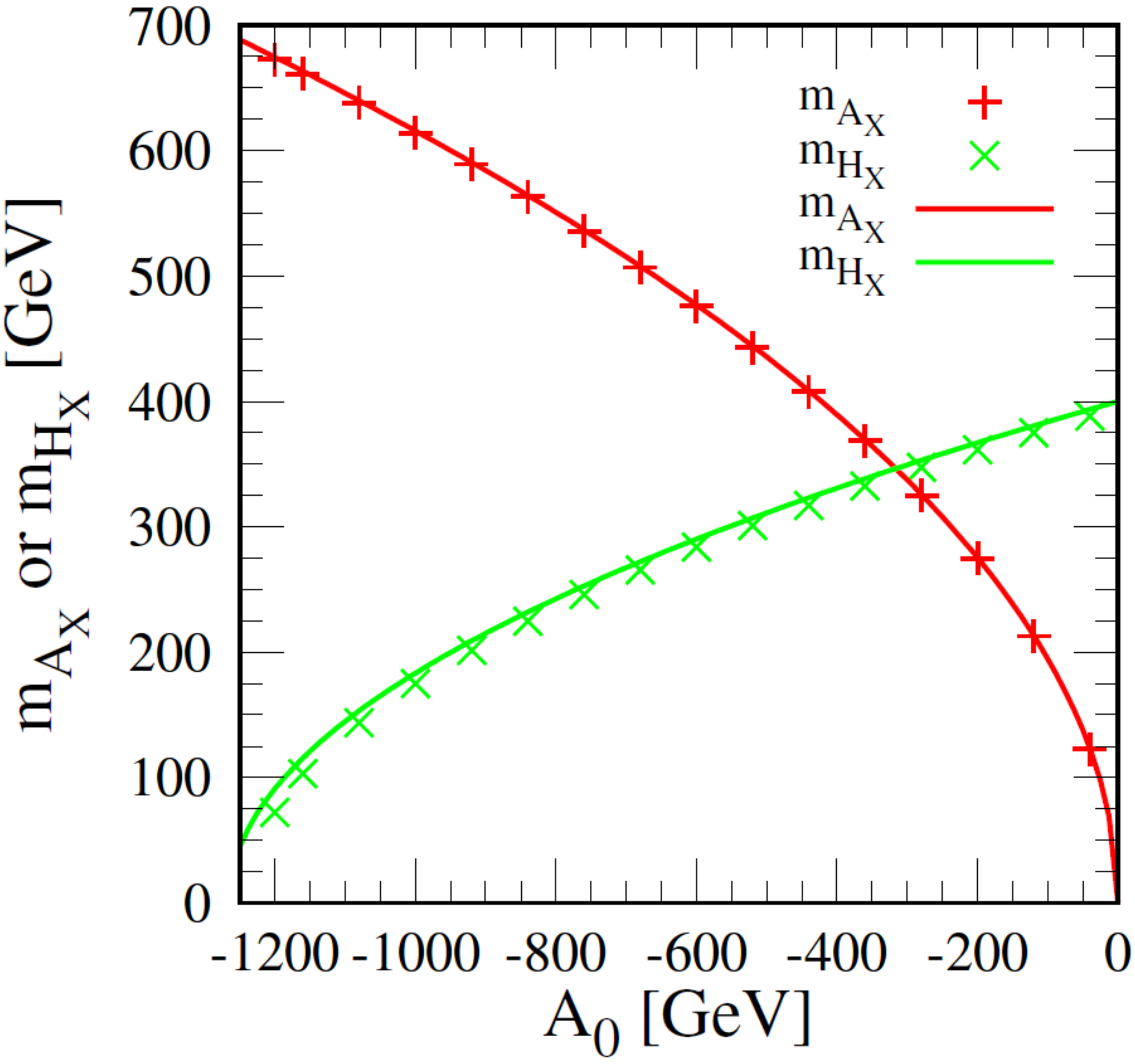
DM estimation

Higgs masses (H_X and A_X)

- Comparison

DM estimation

- Higgs masses (H_X and A_X)
  - -Compa



DM estimation

Features of our analysis

-Three exceptions of thermal abundance 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 abundance calculation

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We have to take into account 1 and 3!

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

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

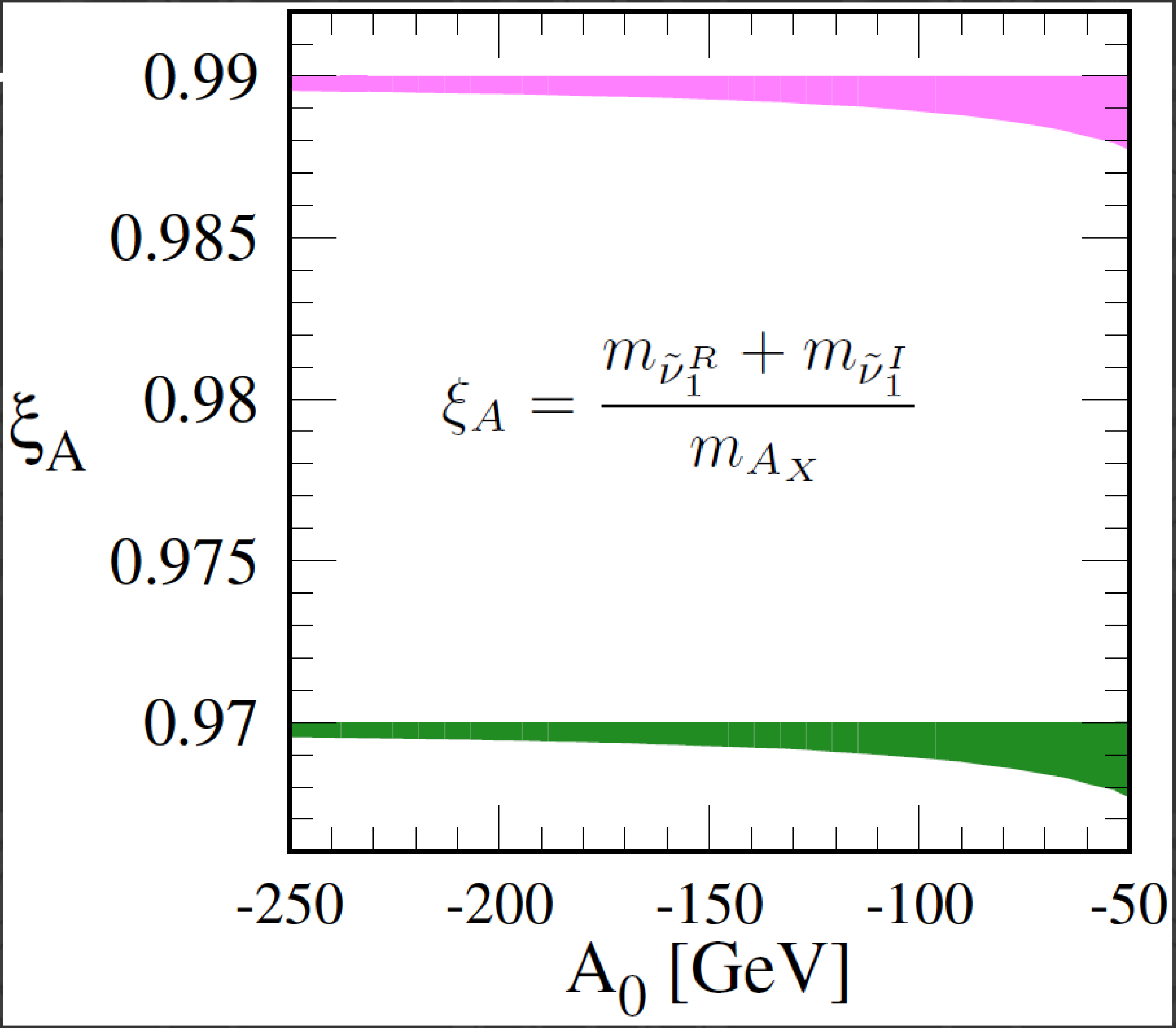
requiring not to deviate more than 2.5×10^{-3}

DM estimation

- How to hit the funnel

DM estimation

How

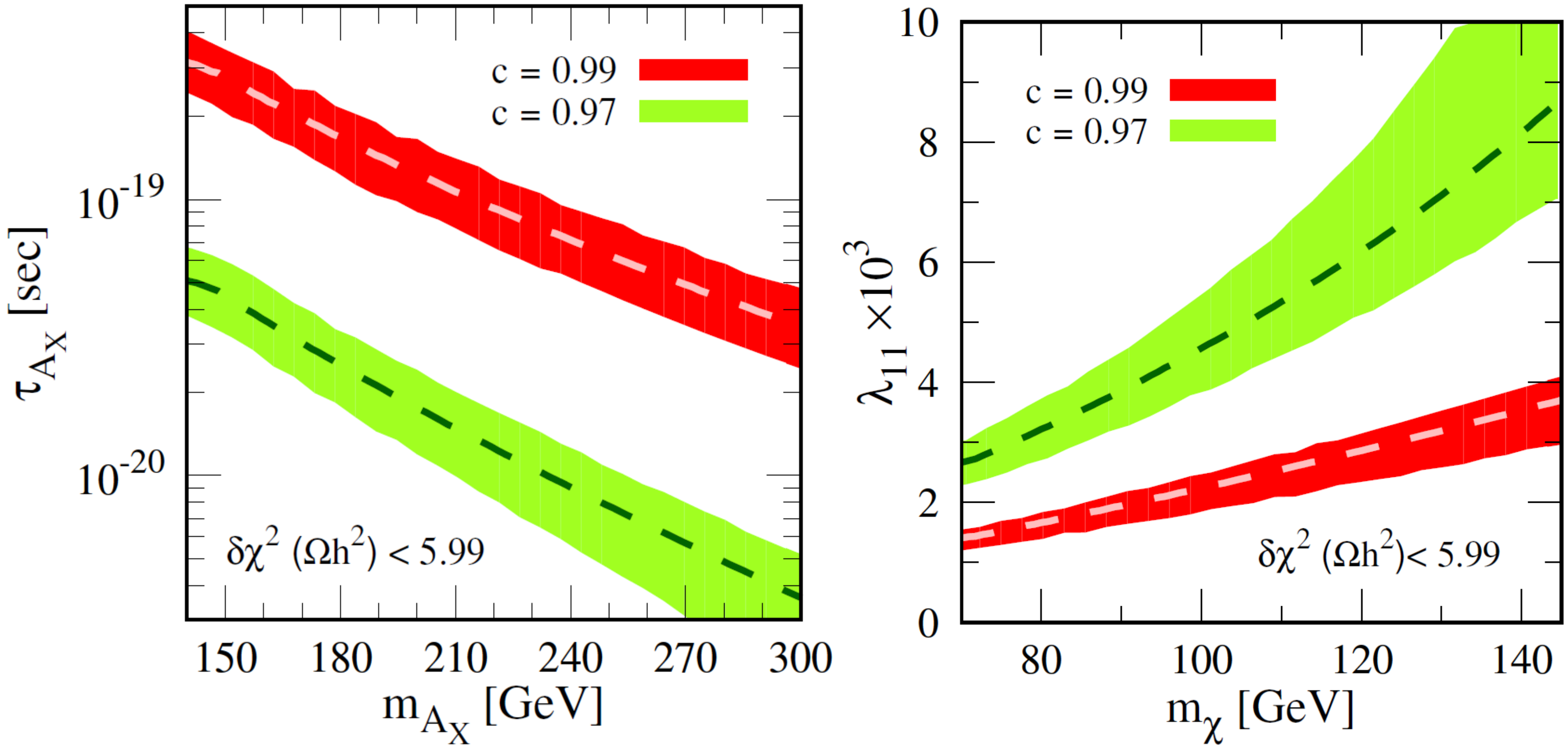


DM estimation

Results in A_χ-funnel scenario

DM estimation

Results in A_X-funnel scenario



DM estimation

How about H_X-funnel?

-H_X-funnel does NOT work because…

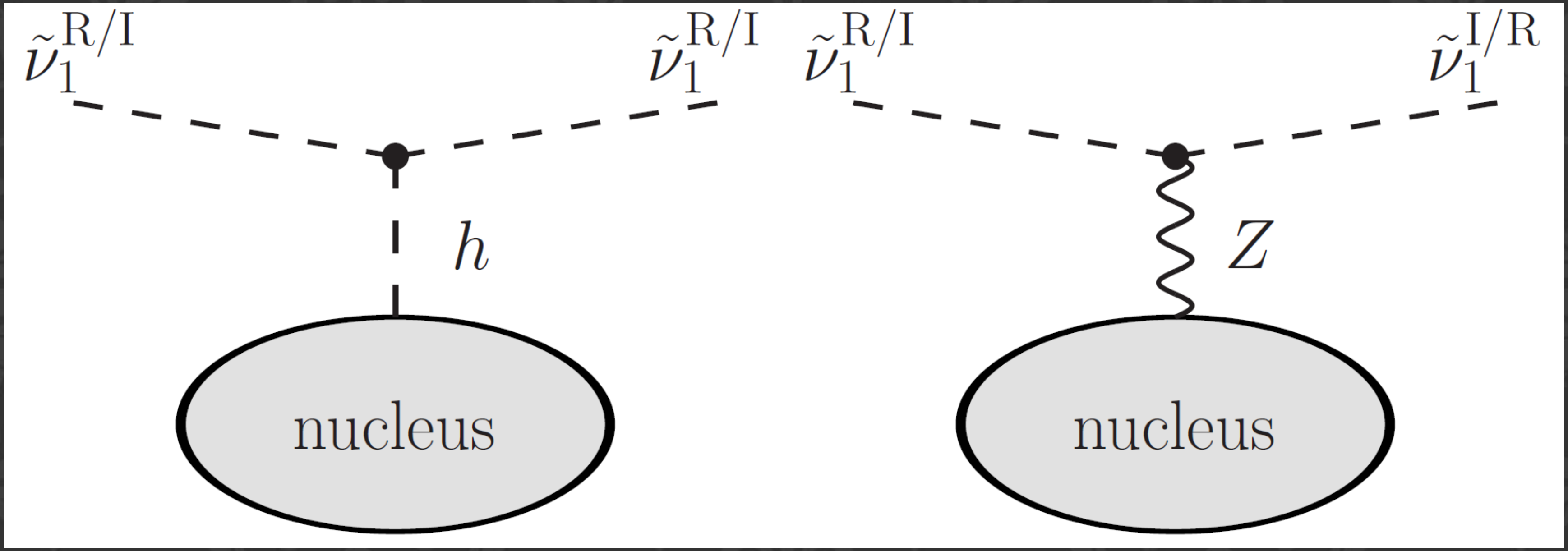
1. H_X-funnel has p-wave suppression
2. To compensate, larger λ is required

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

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

DM properties

Direct detection



DM properties

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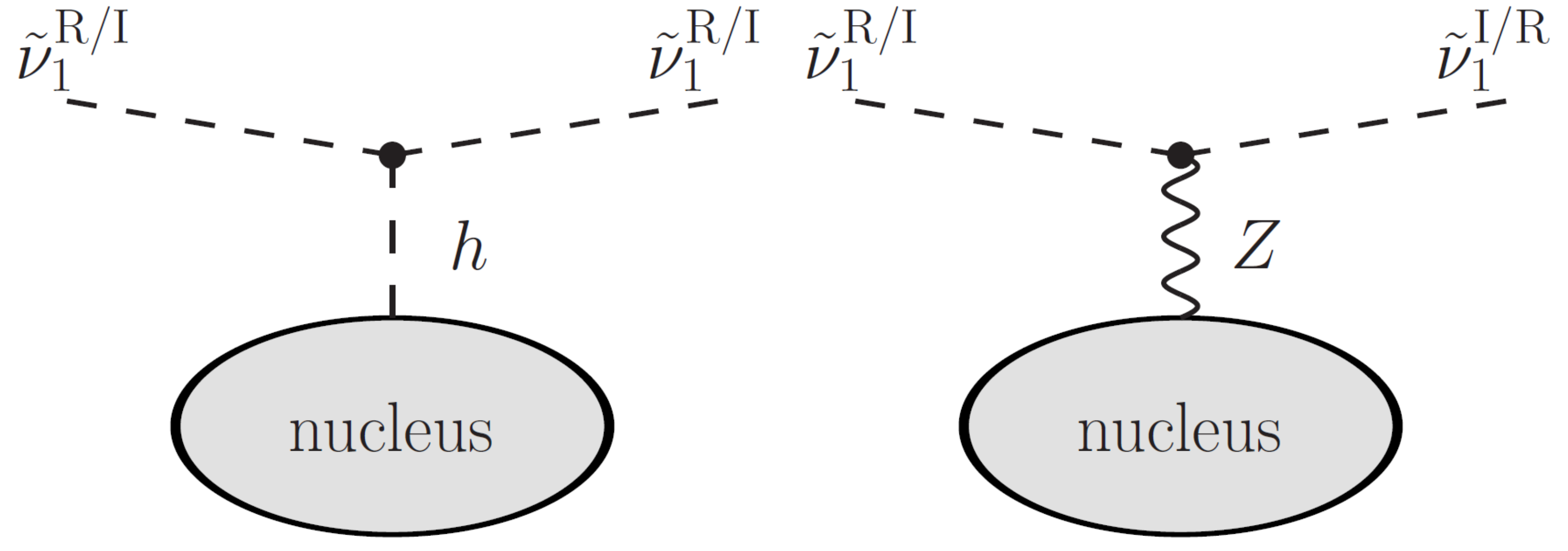

- Using $Y_\nu \sim 10^{-6}$ and M_{SUSY}=1 TeV, Higgs exchange cross section is given as $O(10^{-29})$ pb which is even below neutrino floor

DM properties

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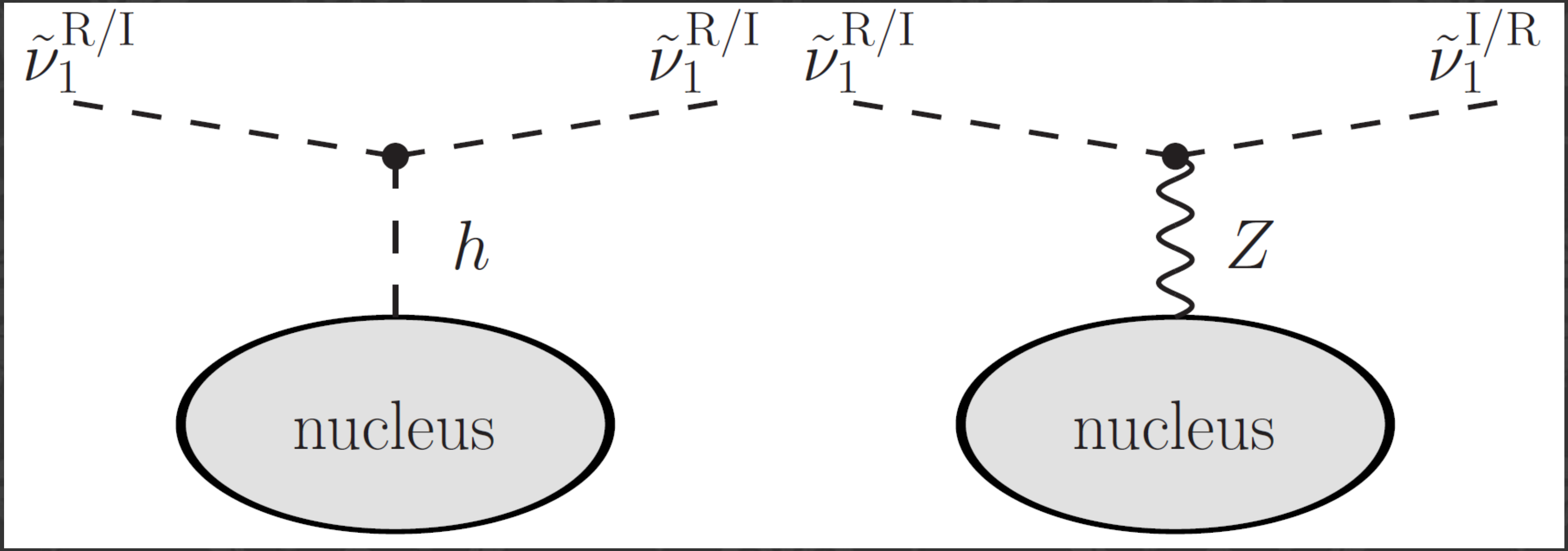
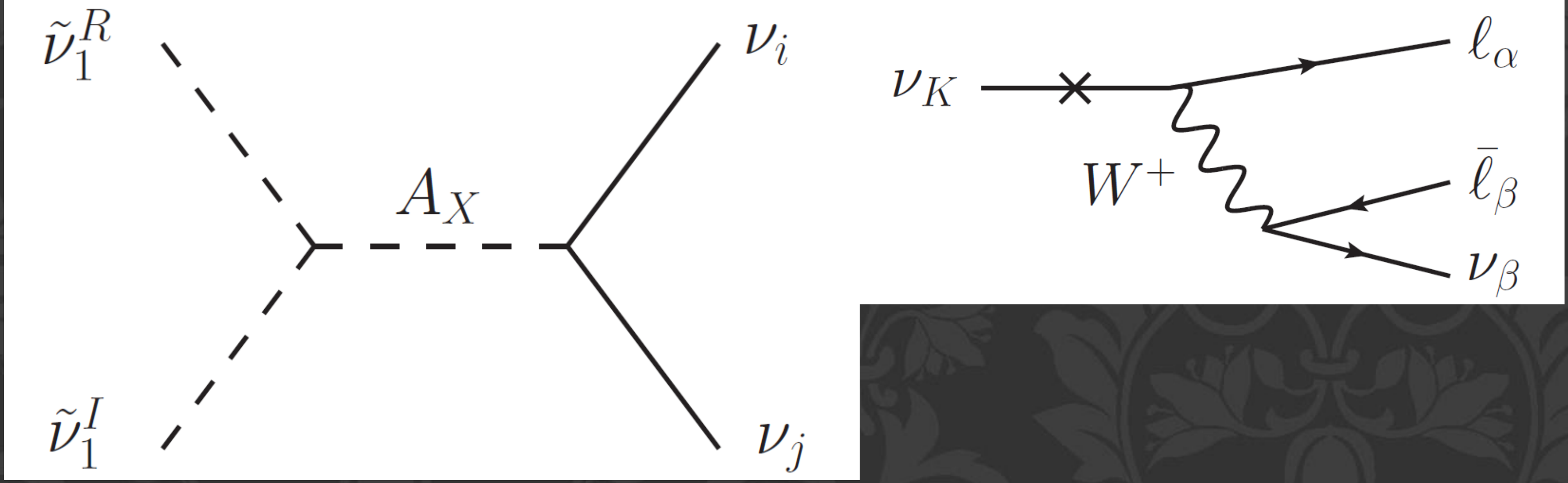


- Using $Y_\nu \sim 10^{-6}$ and $M_{SUSY} = 1$ TeV, Higgs exchange cross section is given as $O(10^{-29})$ pb which is even below neutrino floor
- Z exchange is more suppressed

DM properties

Indirect detection



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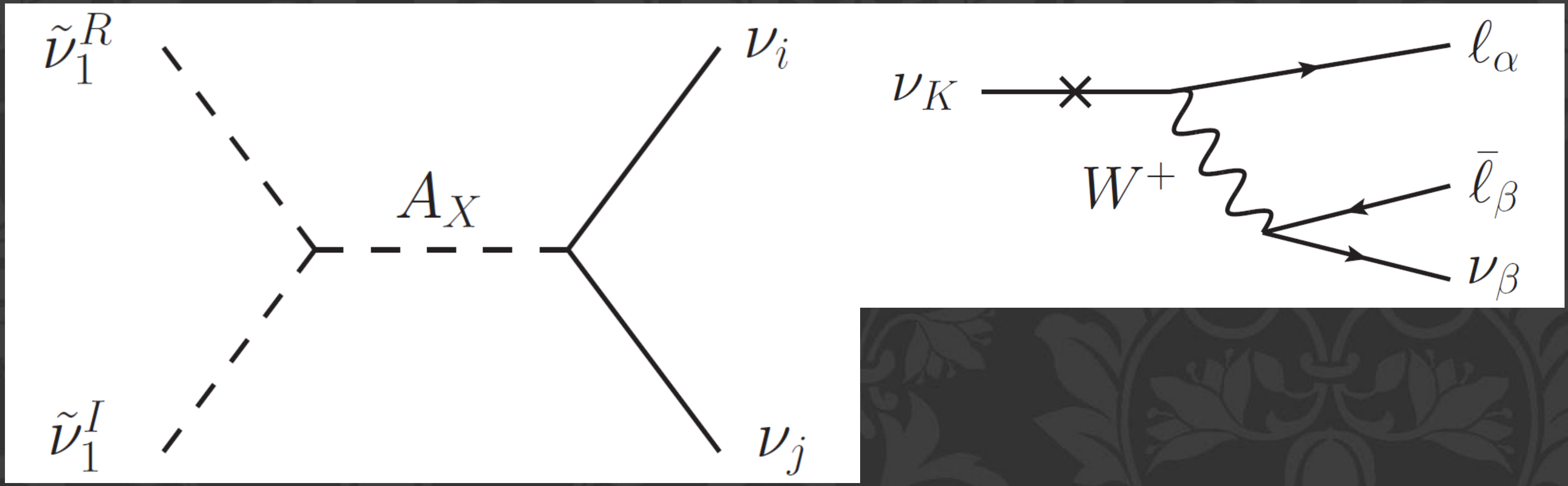

- If DM annihilate into two active neutrinos or one active and one heavy neutrino, we could see line signal of active ν at IceCube

DM properties

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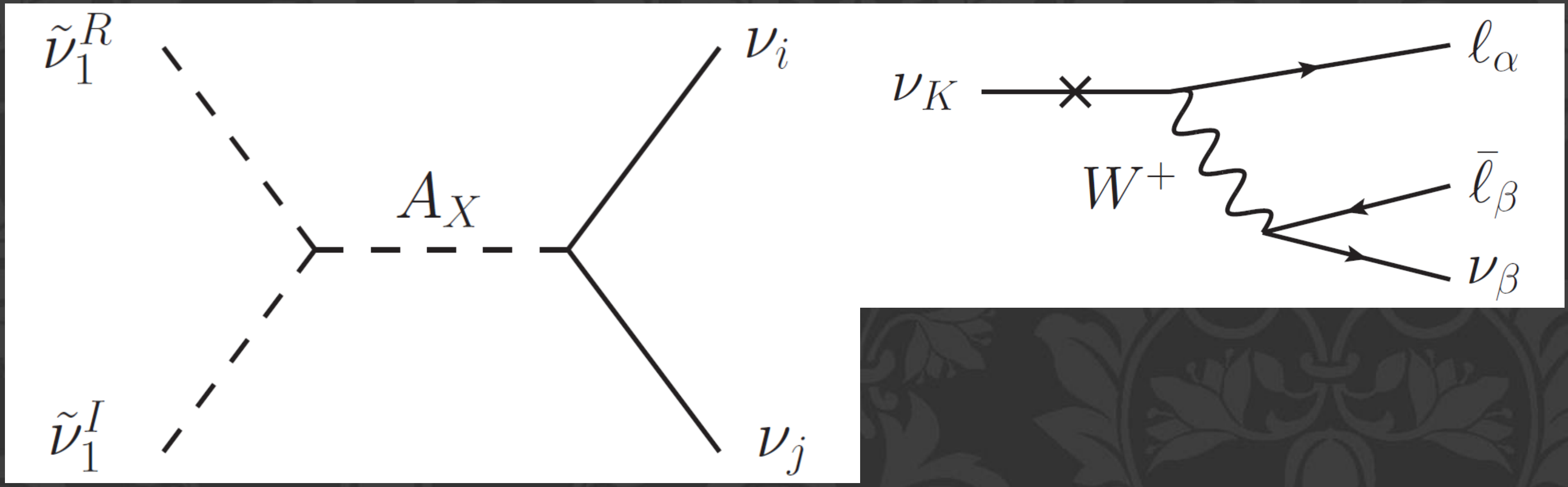

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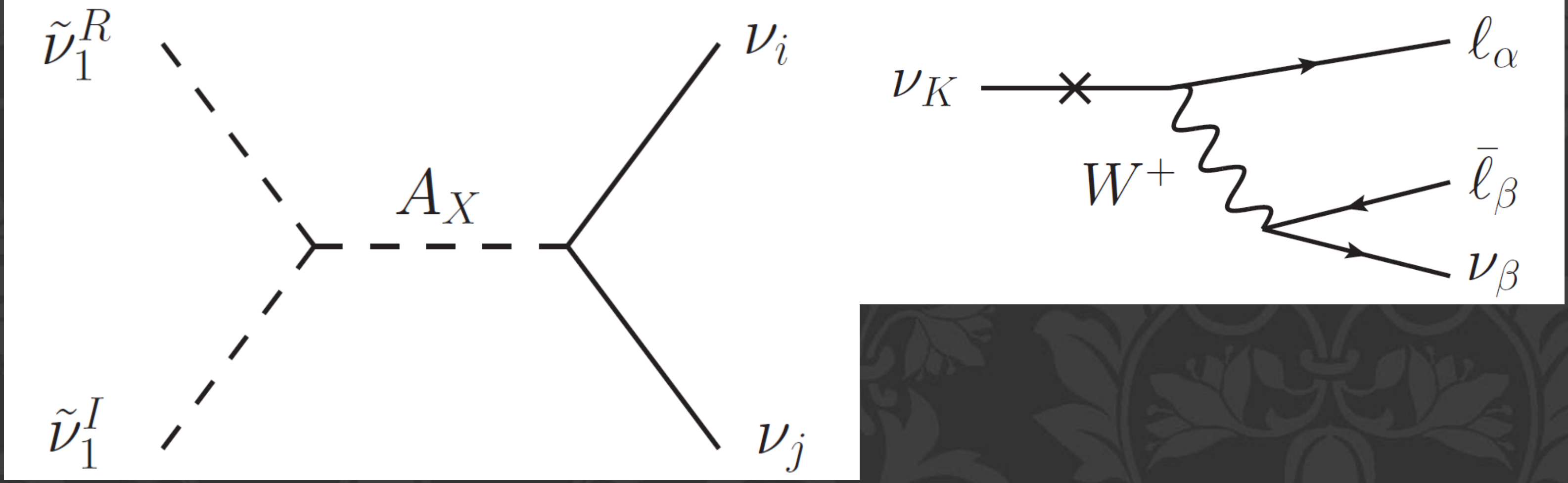
- Since heavy neutrino can decay into SM leptons, we could see some signal from this cascade decay

DM properties

Indirect detection



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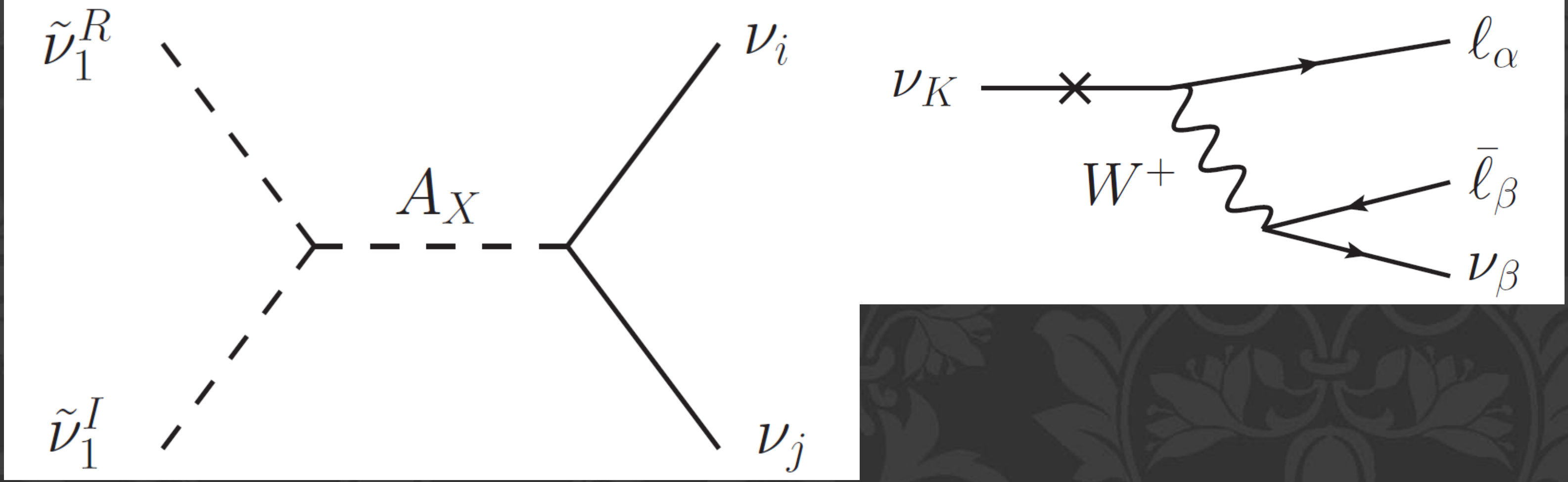

- Since annihilation cross section into one active and one heavy neutrinos is $O(10^{-41})\mathrm{cm}^3\ \mathrm{s}^{-1}$, this signal is not so promising

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

Conclusions

- SUSY inverse seesaw model
  - Lepton number 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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  - 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

Future prospects

- At the moment, our model is playing hide & seek but…
  - Collider phenomenology (See Cédric's lecture)
  - Astrophysical observation
  - Early universe aspects

need to be explored

Thank you for your attention