Sneutrino dark matter in a SUSY 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

Neutrino masses → Seesaw mechanism by adding RHνs

Gauge hierarchy problem, DM candidate, Gauge coupling unification → Supersymmetry

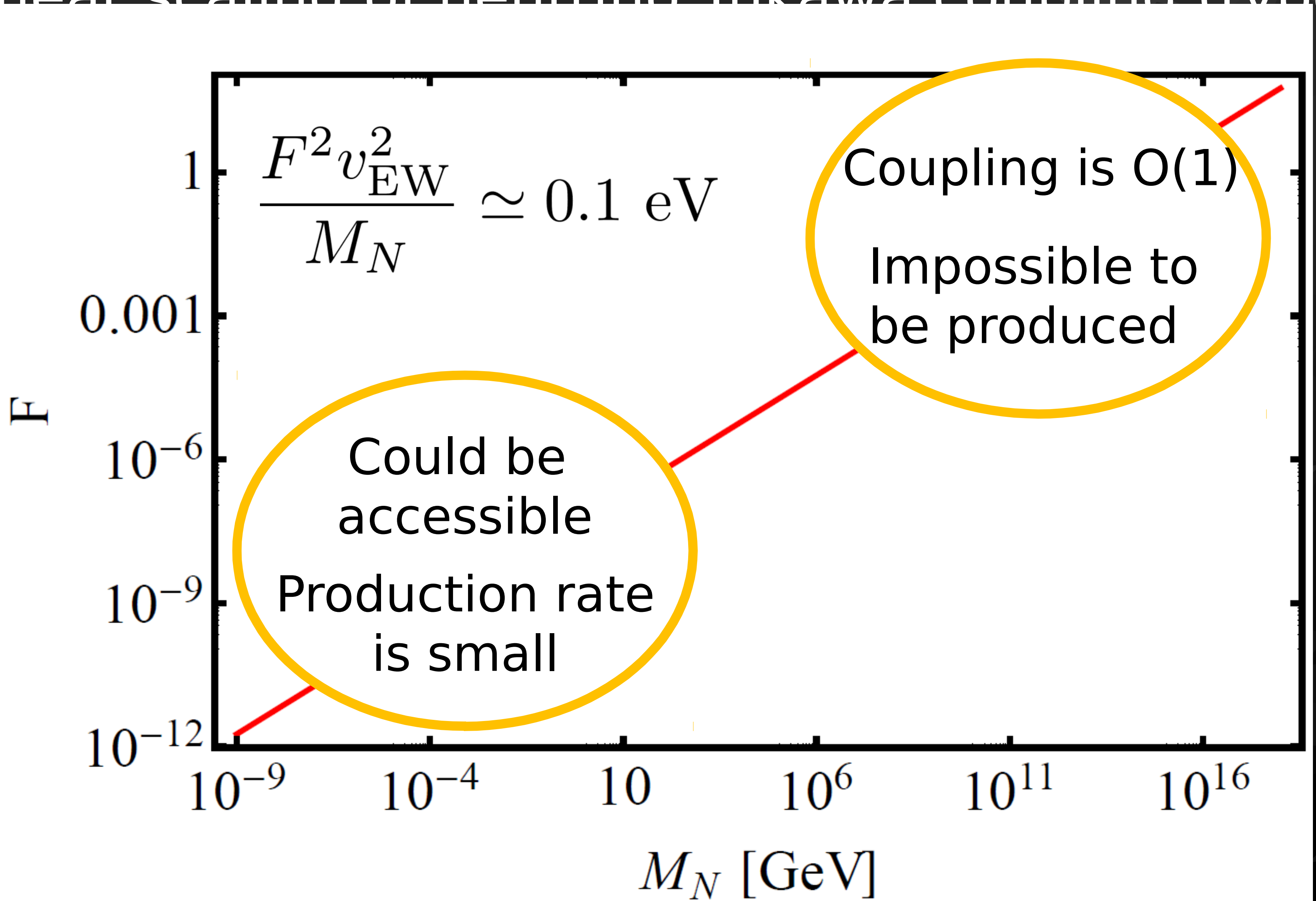
MSSM+type-I seesaw mechanism

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)



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

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

Neutrino mass matrix

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

Small M_S(Lepton # violation) leads tiny m_ν

Motivation

Assumption in most of works

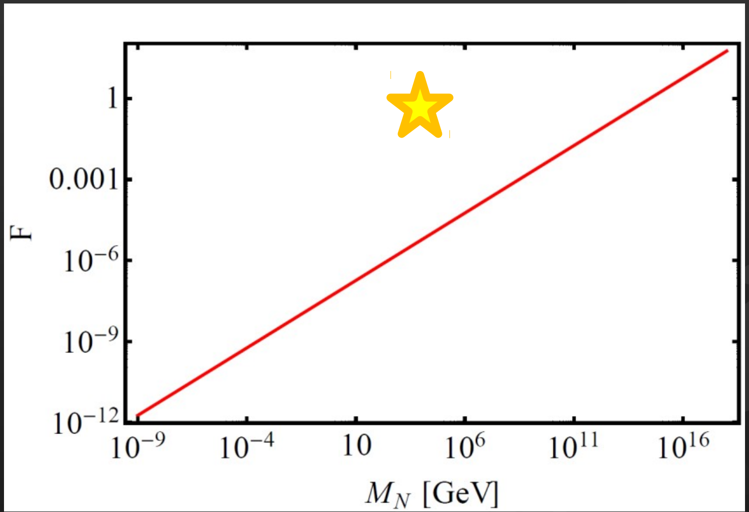
technically naturalness

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

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

smallness of M_s is technically natural

Motivation



Assumption in most of works

benefit of ISS

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

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

Rich phenomenology at collider!

Dynamical origin of lepton number violating scale

Contents

Model

arXiv:1707.04374

Model (NCTS model)

forbid R-parity violating terms
without imposing R-parity

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

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

$(\alpha = 1, 2)$

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

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

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

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

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: $\lambda \ll Y_\nu \ll 1$ $_{\rm NS}$,

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

(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!

Neutralino, Sneutrino, Gravitino

Non-MSSM candidate!

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

arXiv:1806.04468

WIMP in the model

Definition of WIMP before

"Weakly" interacting massive particle

same magnitude as weak interaction

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

Definition of WIMP now

"Weakly" interacting massive particle

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

DM estimation

Boundary conditions

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

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

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

-Put arbitrary factor to make colored particles heavy enough

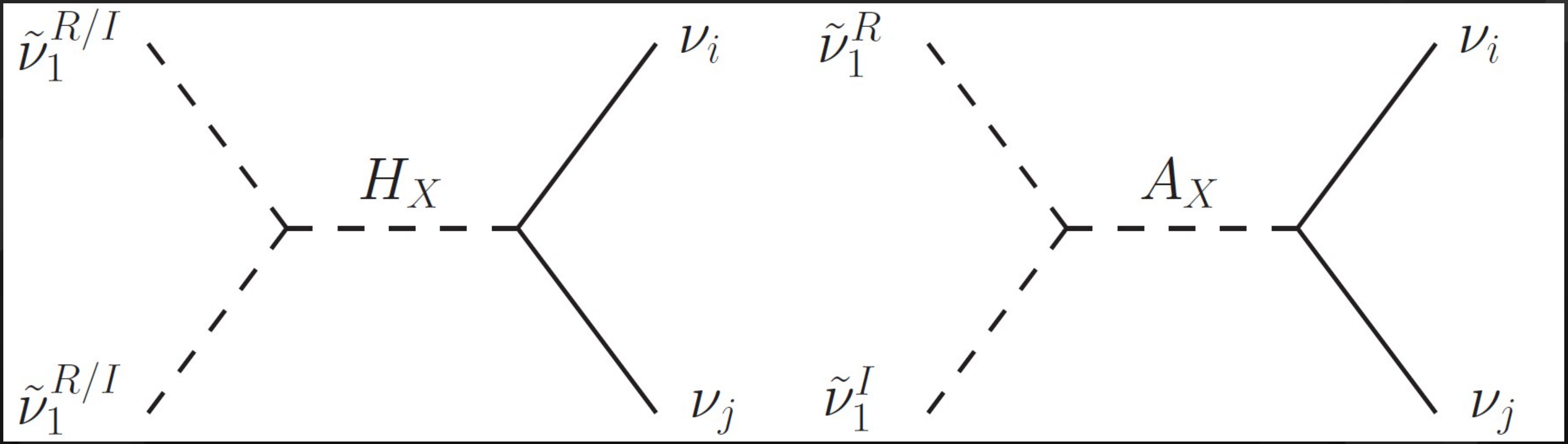
-m_0 and $M_{1/2}$ are fixed at high scale

-v_X, μ_{NS}, λ and κ are fixed at low scale

not to worry about running effect

DM estimation

Dominant (co-)annihilation channels



H-funnel A-funnel

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

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

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 are small enough

-Physical states

$$\mu_{\mathrm{NS}} \ll m_0$$

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

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

-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

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 suppresse

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

-Approximate masses

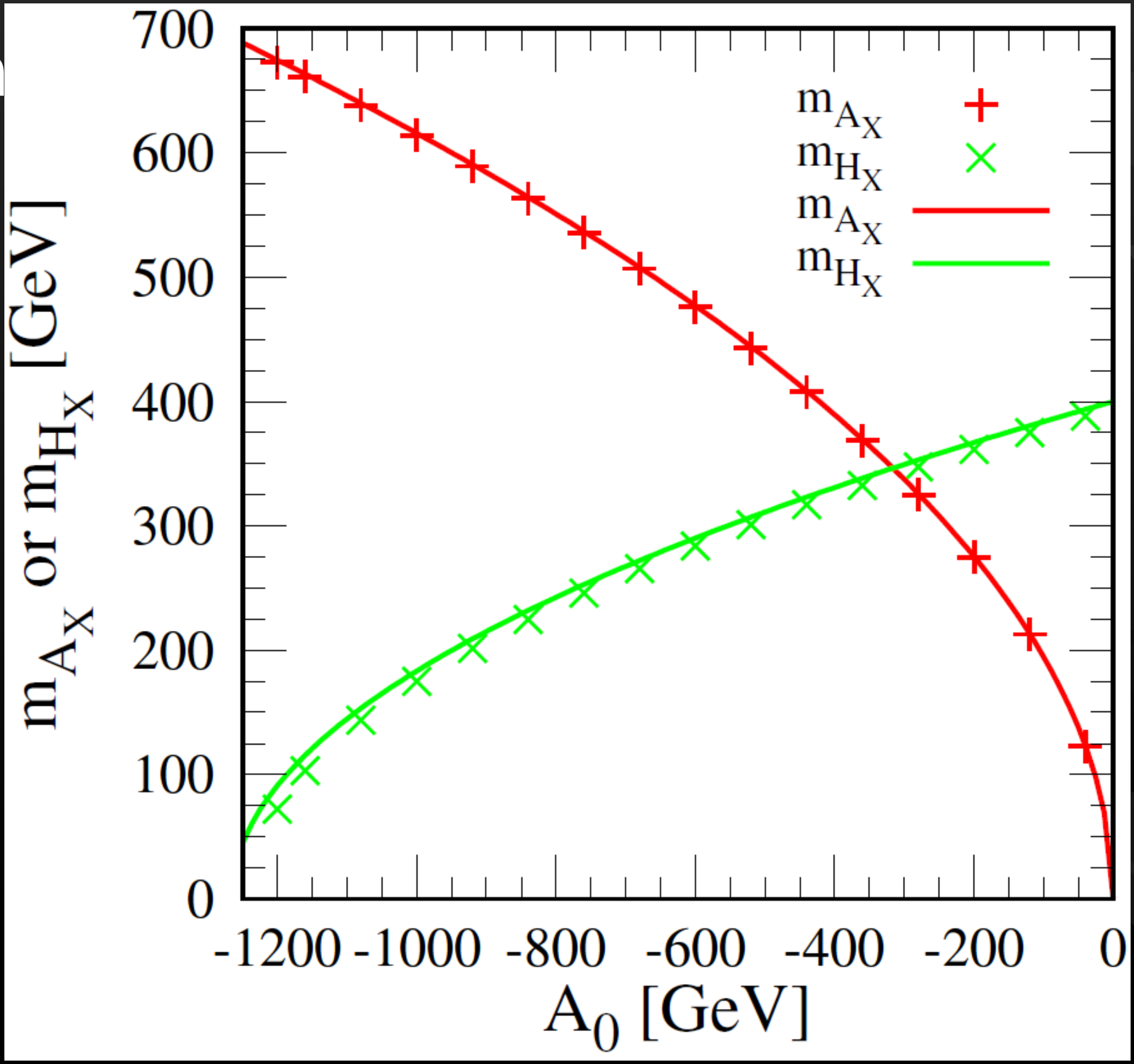
$$m_{H_X}^2 \approx 2\,\kappa_0^2 v_X^2 + \frac{v_X}{\sqrt{2}}\kappa_0 A_0\left(1 - 2.3\,\kappa_0^2\right)\ ,\, m_{A_X}^2 \approx -\frac{3\,v_X}{\sqrt{2}}\kappa_0 A_0\left(1 - 2.3\,\kappa_0^2\right)$$

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

DM estimation

Higgs masses (H_X and A_X)

-Compa



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)

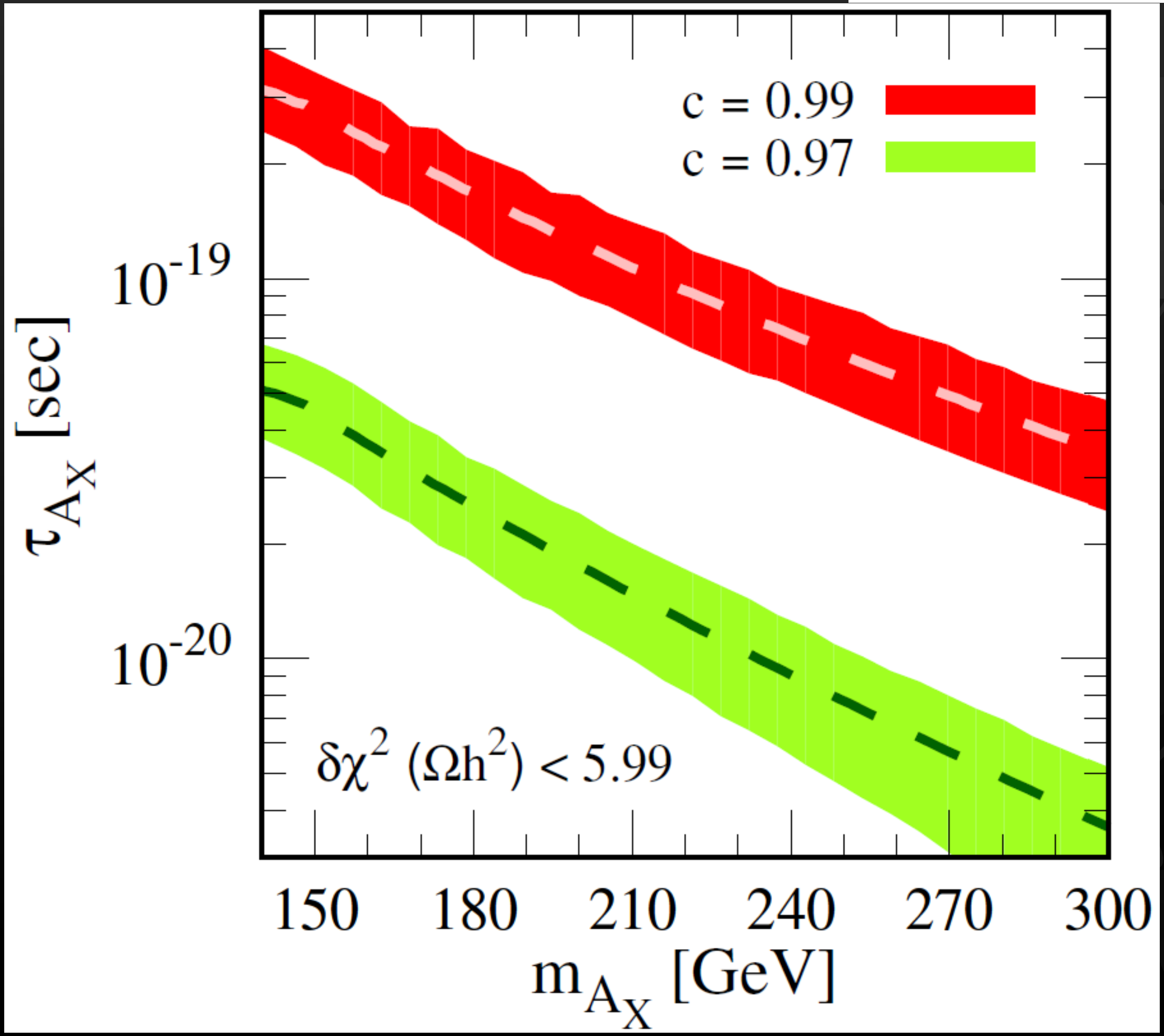
3. Annihilation near pole (resonance)

We have to take into account 1 and 3!

DM estimation

Results in A_X-funnel scenario

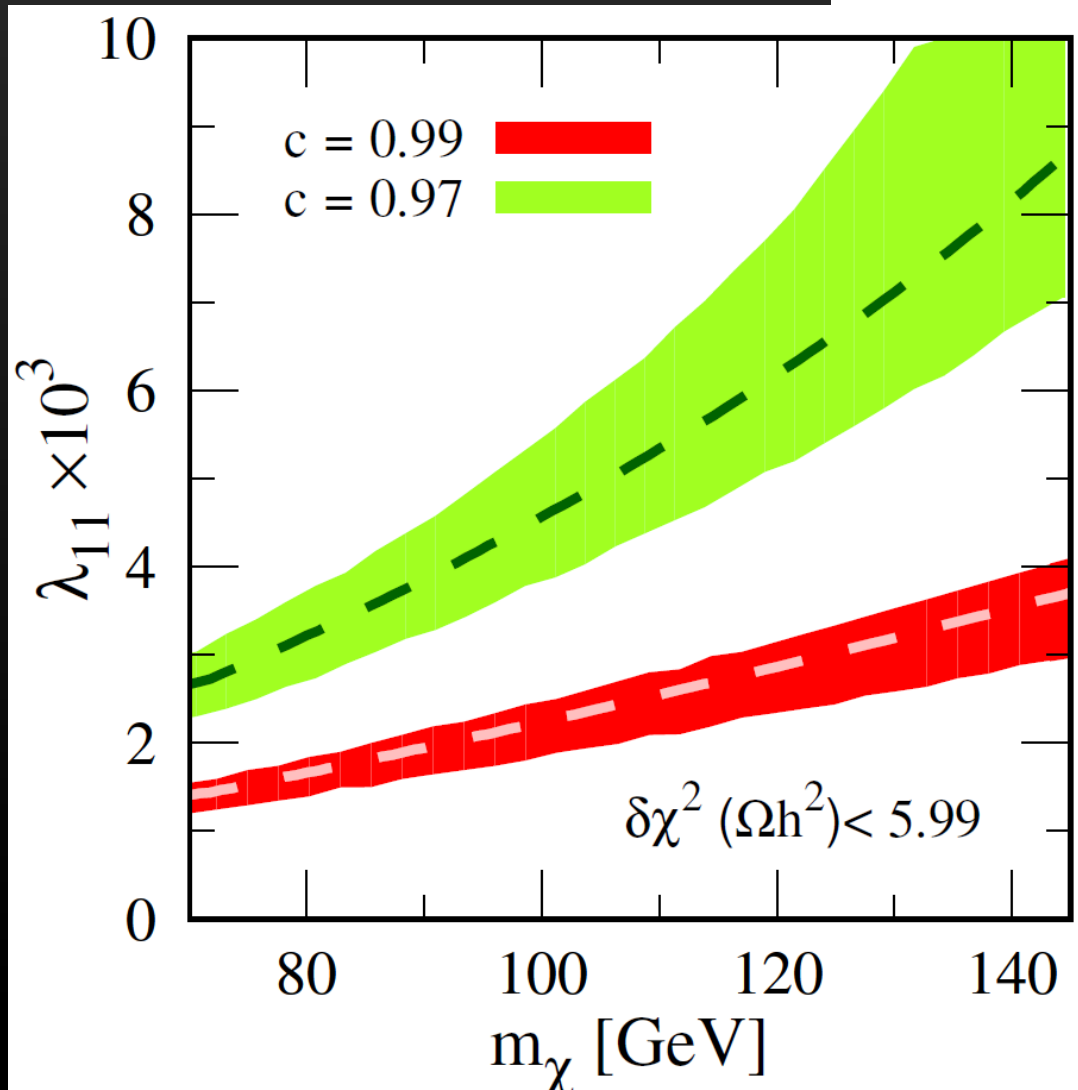
$$m_{\tilde{\nu}_1^R} + m_{\tilde{\nu}_1^I} = c\, m_{A_X}$$



DM estimation

Results in A_X-funnel scenario

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



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

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

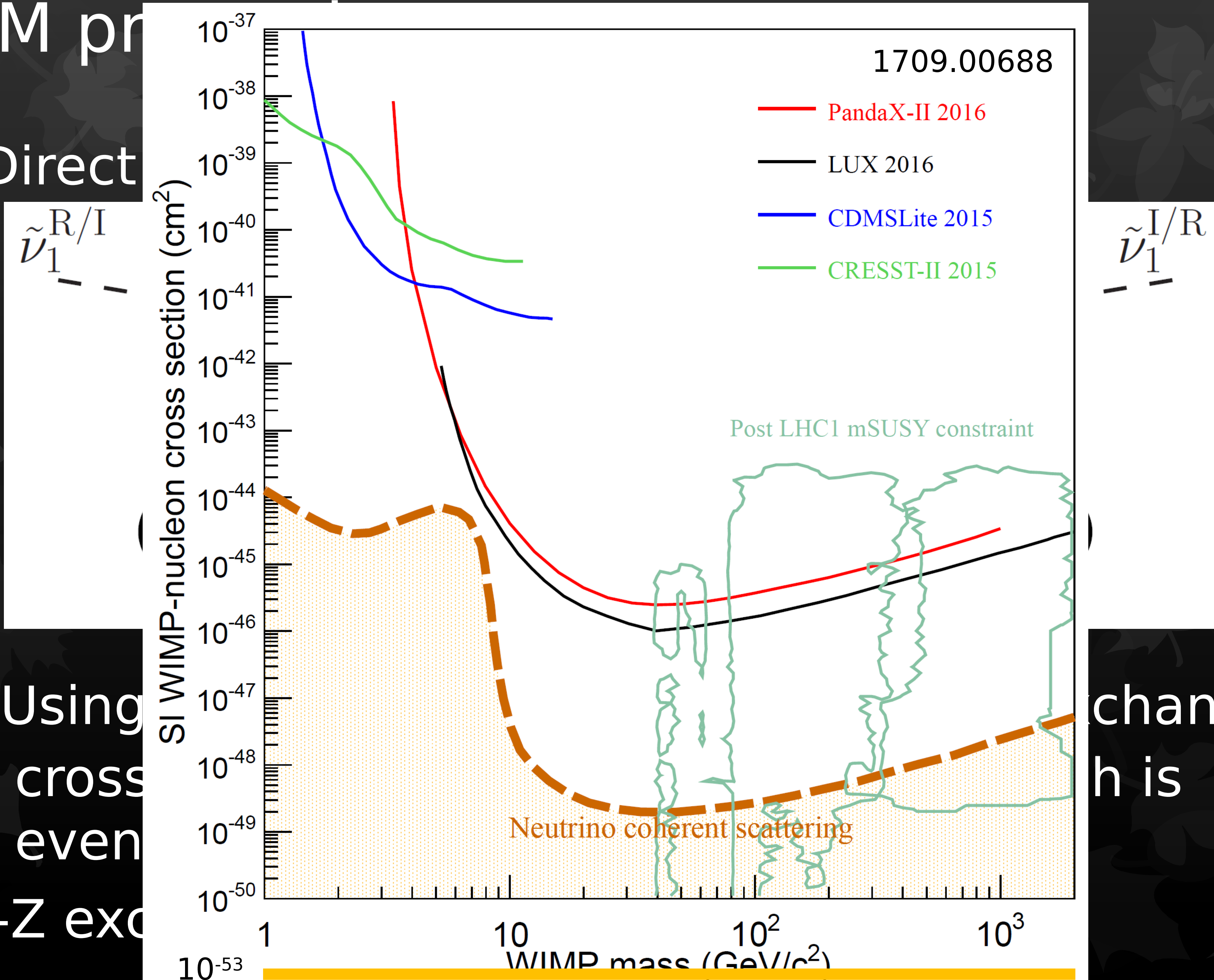
3. When λ **gets large, it closes the decay chan**
into heavy neutrinos due to mass splitting

DM properties

arXiv:1806.04468

DM pr

Direct



-Using ... change

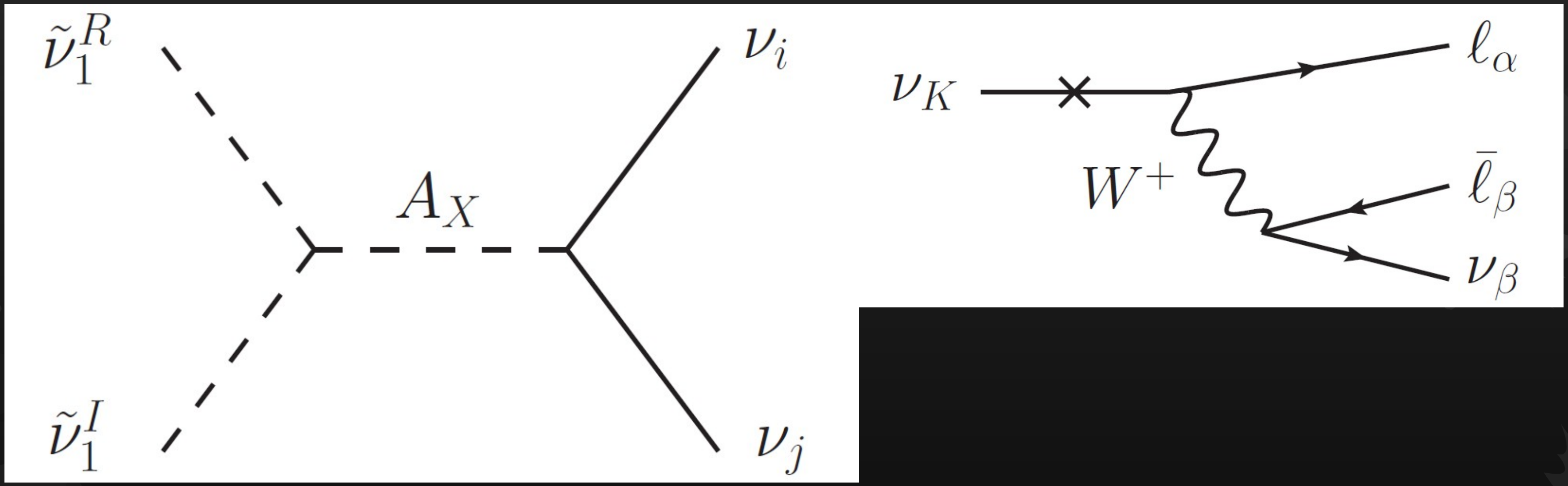
cross ... h is

even

-Z exc

DM properties

Indirect detection

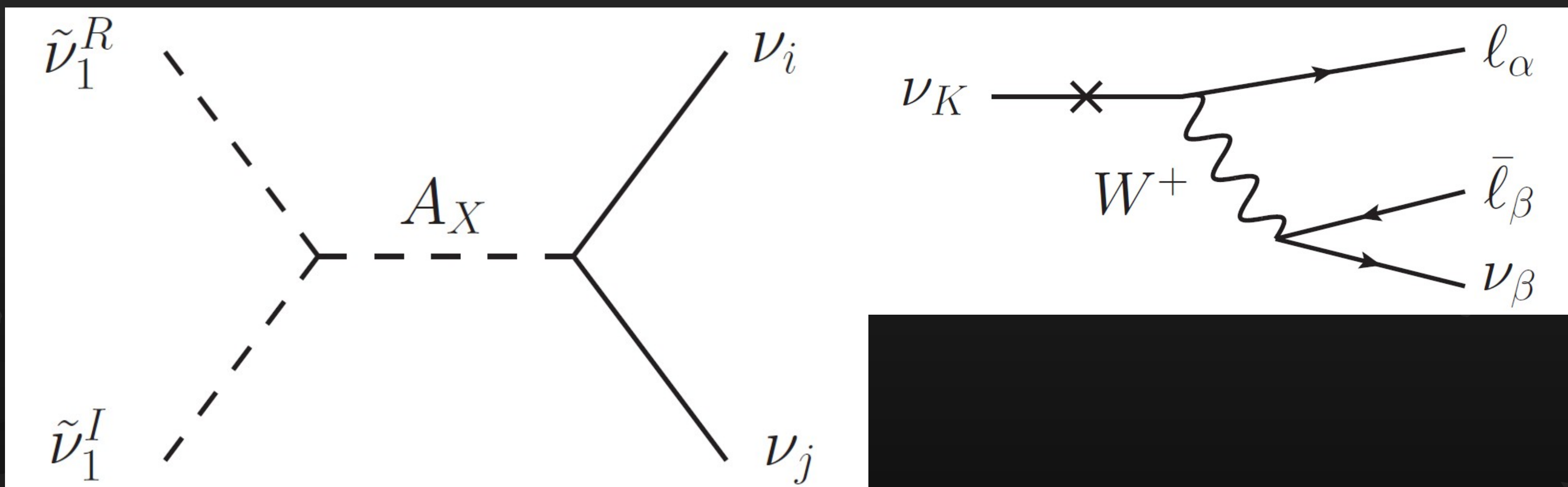


-If DM annihilate into two active neutrinos or one active and one heavy neutrino, we could see line signal of active ν at IceCube

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

DM properties

Indirect detection

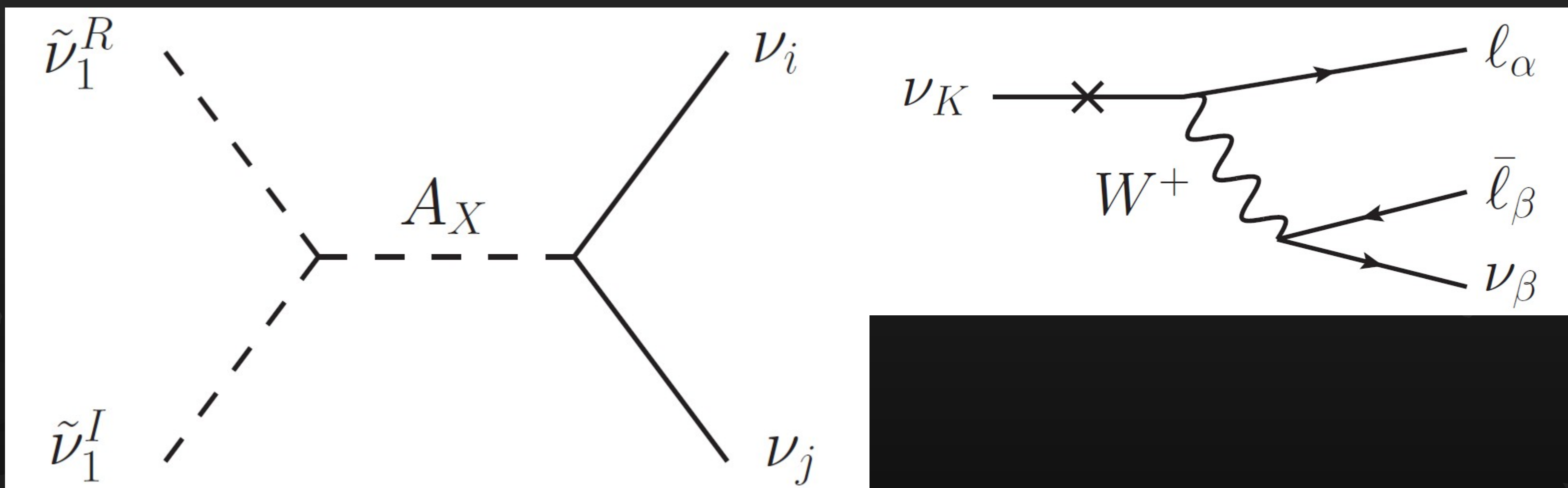


-Since annihilation cross section into two active neutrinos is $O(10^{-41})\text{cm}^3\ \text{s}^{-1}$,
this signal seems not to be so promising

Current limit by IceCube: $2\times10^{-23}\text{cm}^3\ \text{s}^{-1}$
$(m_{DM} \sim 100\text{GeV})$

DM properties

Indirect detection



-The most plausible cross section would be channel into two heavy neutrinos: $O(10^{-29})\text{cm}^3$ s

-This cross section is a few order of magnitude smaller than current limit, we could see signal in future!

Conclusions

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 the MSSM are really hidden,

in other words,
our model can be easily excluded by observations
⟺ draw a line to "signalism"

Future prospects

- At the moment, our model is playing hide & seek but we are trying to think...

  -Collider phenomenology

  -Aspects for early universe

  -Astrophysical observations

Open questions

- So far so good as one of the models, but…

-How to find our DM as a signal?

-How to discriminate our model from others?

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