# Neutrino Masses and Dark Matter in a Supersymmetric Inverse Seesaw Model

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**Based on JHEP 1710 (2017) 039 [arXiv:1707.04374] and arXiv:1806.04468 in collaboration with:**
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# Outline

- Introduction
- The Model
- Neutrino Phenomenology
- Dark Matter
- Summary and Outlook

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- **Introduction**
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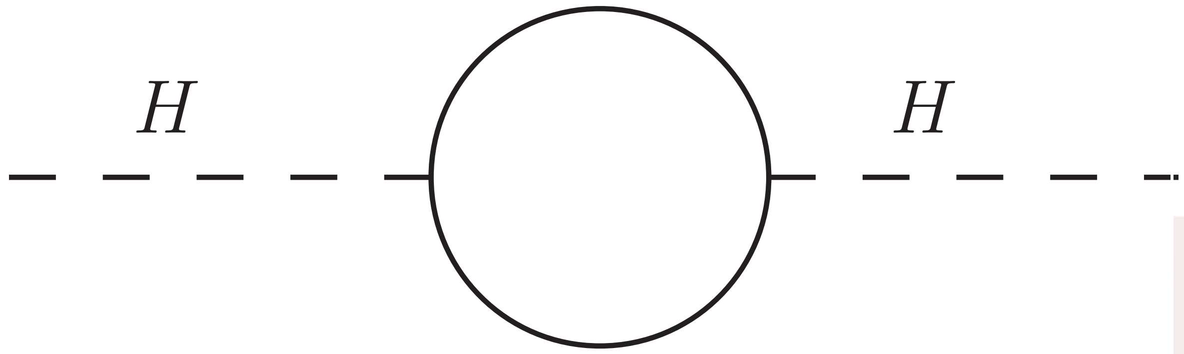
# Motivation

- Hierarchy Problem
- Neutrino Masses
- Dark Matter

# The Notorious Hierarchy Problem

- Why is the Higgs boson so light?
  - Supersymmetry (SUSY)
  - Composite Higgs
  - It just happens to be
  - ???
- We stick with SUSY here

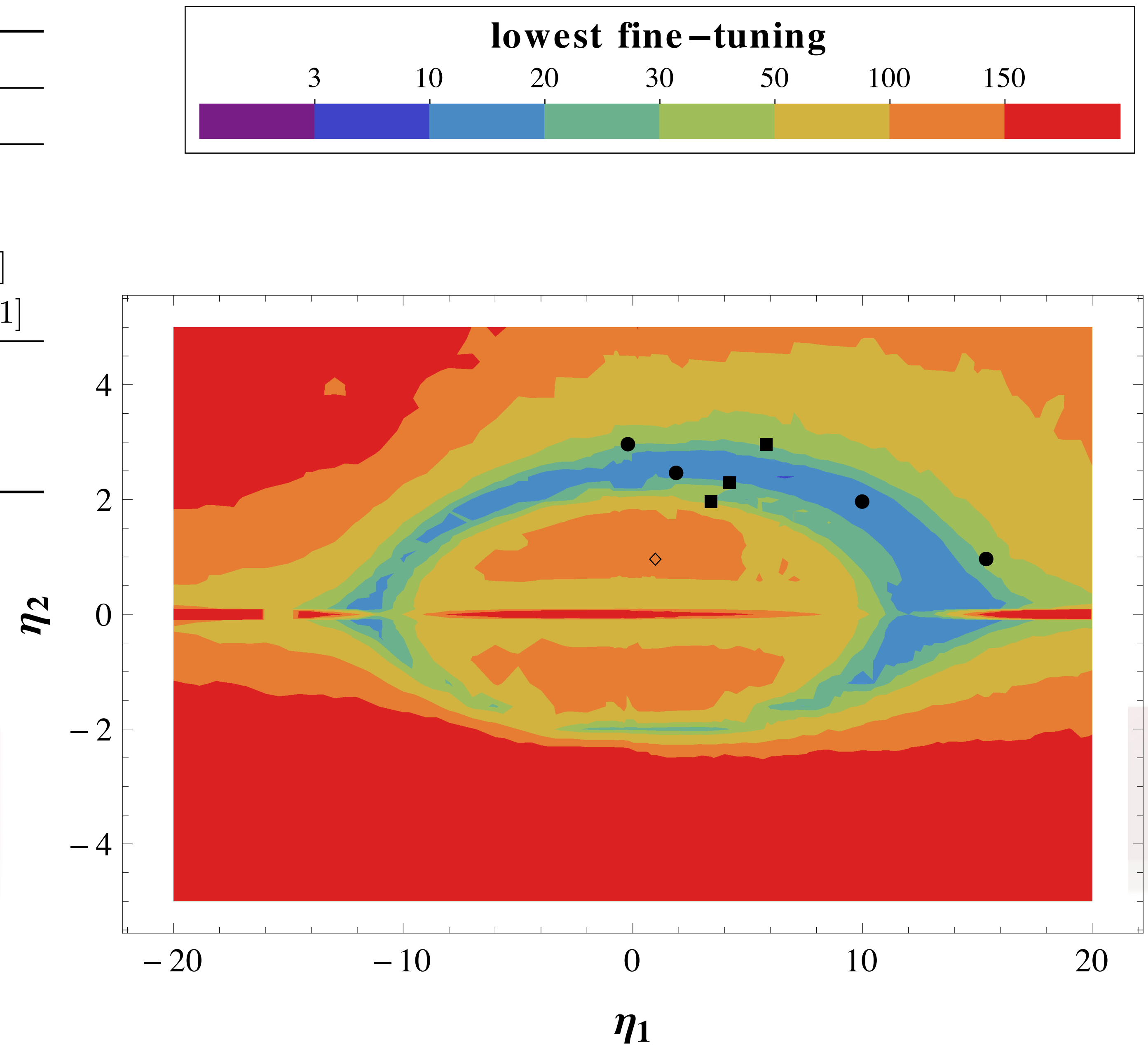


# SUSY Fine-Tuning

| $\eta_1, \eta_2$ | $\Delta_{\rm min}$ | Origin |
|---|---|---|
| 1, 1 | 118 | CMSSM (Gaugino Unification) |
| 10, 2 | 12 | 200 of SU(5) [1] |
| $\frac{19}{10}, \frac{5}{2}$ | 18 | 770 of $SO(10) \to (1,1)$ of $SU(4) \times SU(2)_R$ [1] |
| $\frac{77}{5}, 1$ | 36 | 770 of $SO(10) \to (1,0)$ of $(SU(5)' \times U(1))_{\rm flipped}$ [1] |
| $-\frac{1}{5}, 3$ | 46 | 210 of $SO(10) \to (75,0)$ of $(SU(5)' \times U(1))_{\rm flipped}$ [1] |
| $\frac{21}{5}, \frac{7}{3}$ | 13 | O-II with $\delta_{\rm GS} = -6$ [2] |
| $\frac{17}{5}, 2$ | 28 | O-II with $\delta_{\rm GS} = -7$ [2] |
| $\frac{29}{5}, 3$ | 44 | O-II with $\delta_{\rm GS} = -5$ [2] |

[1] Chakrabortty, Raychaudhuri '09; Martin '09
[2] Brignole, Ibanez, Munoz '94, '95; Horton, Ross '09

**[Antusch, Calibbi, Maurer, Monaco, MS '12]**

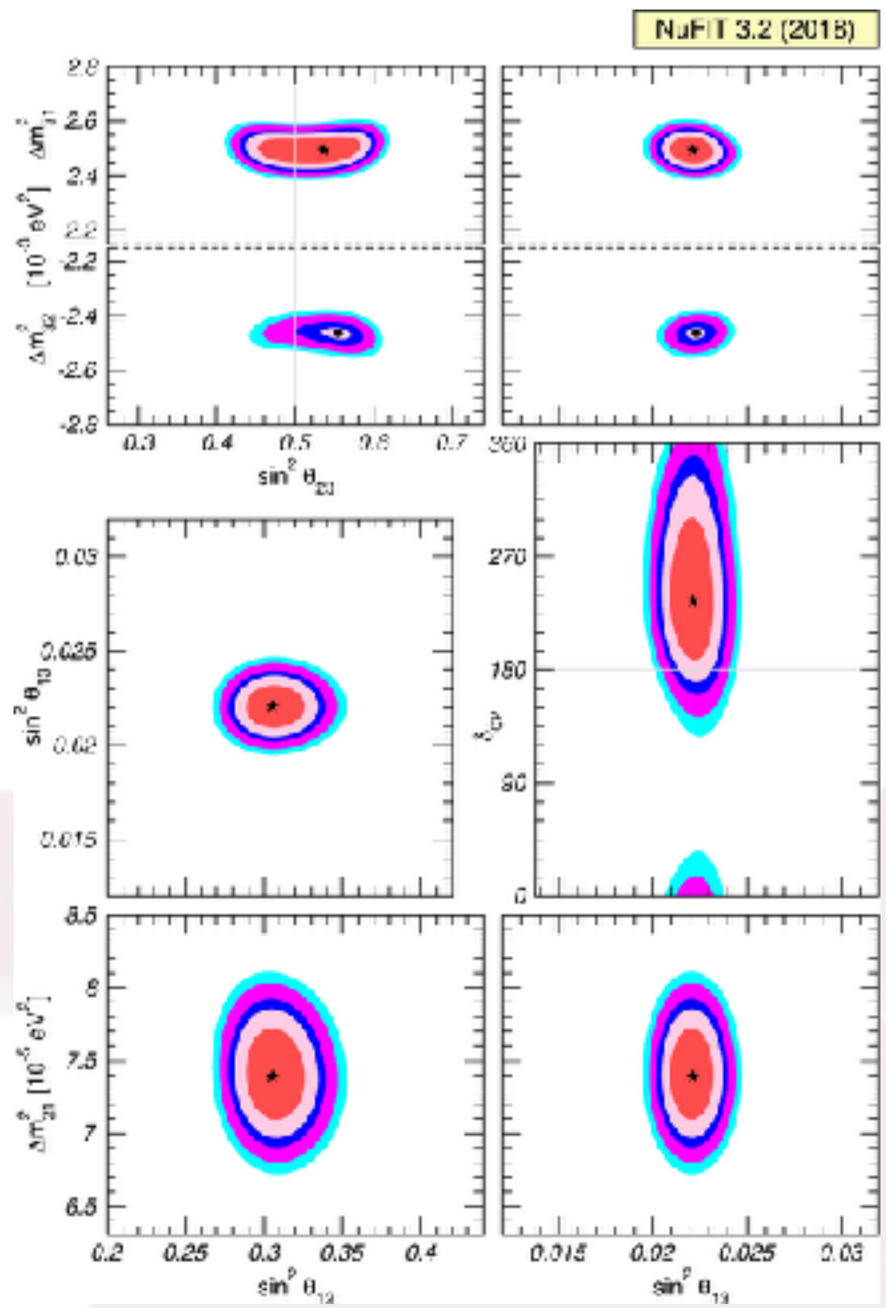



Another gauge mediation example:
$(\eta_1, \eta_2) = (13, 17/7) \approx (13, 2.43)$

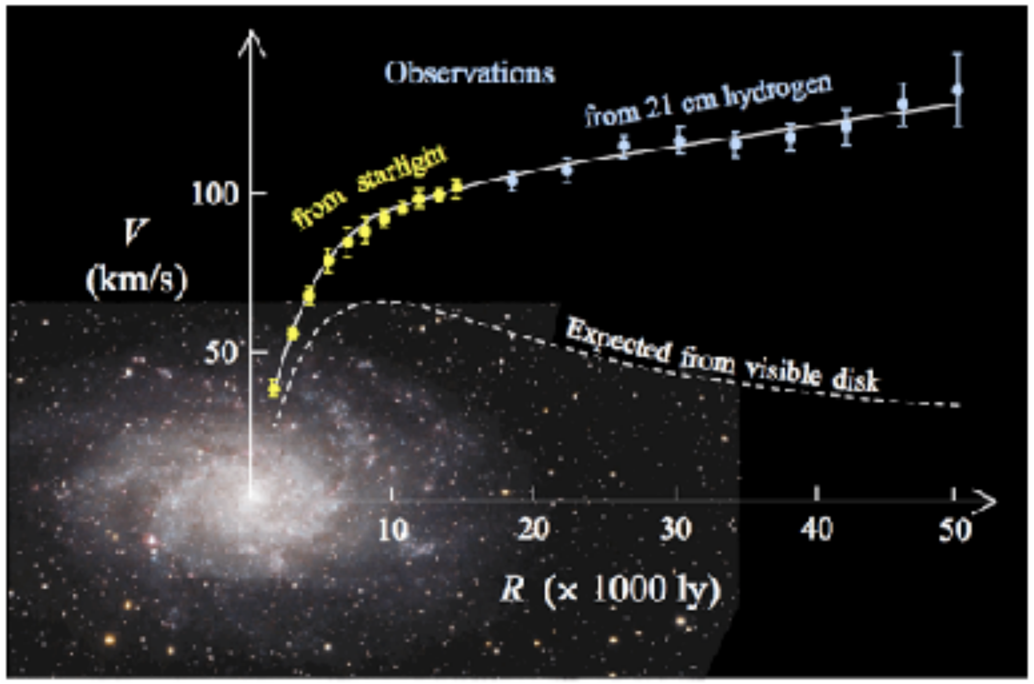
**[Brümmer, Ibe, Yanagida '13]**

# Neutrino Masses

- Neutrino Oscillations well established
- At least two neutrinos must have a mass
- In the Standard Model neutrinos are massless
- Many extensions possible

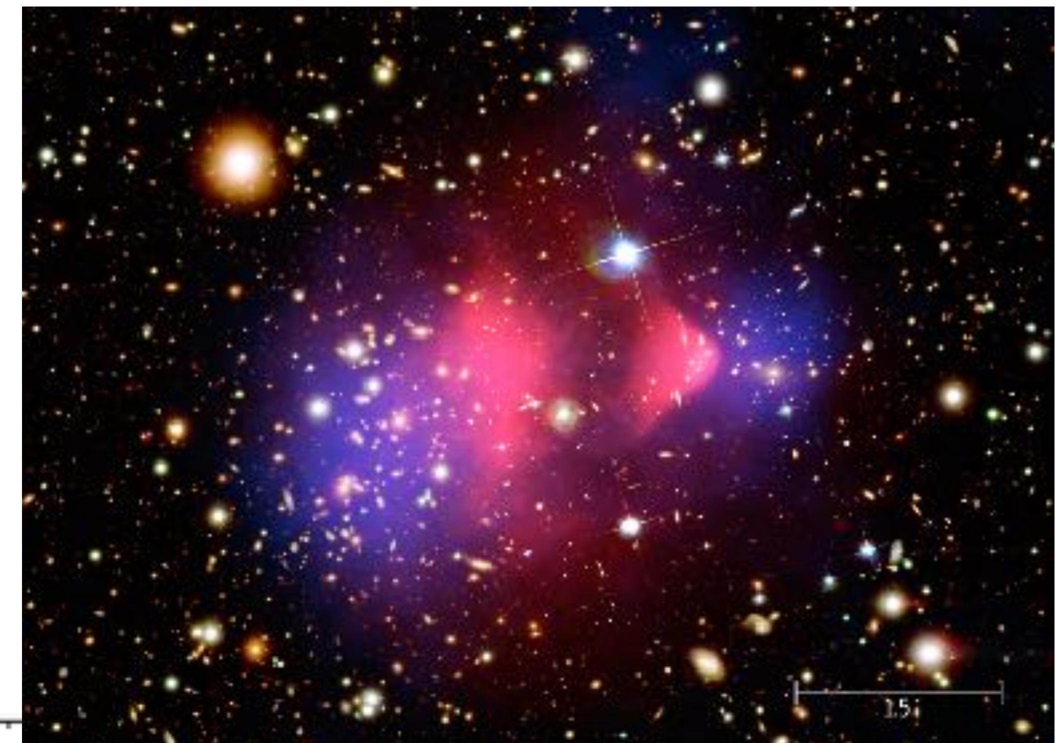


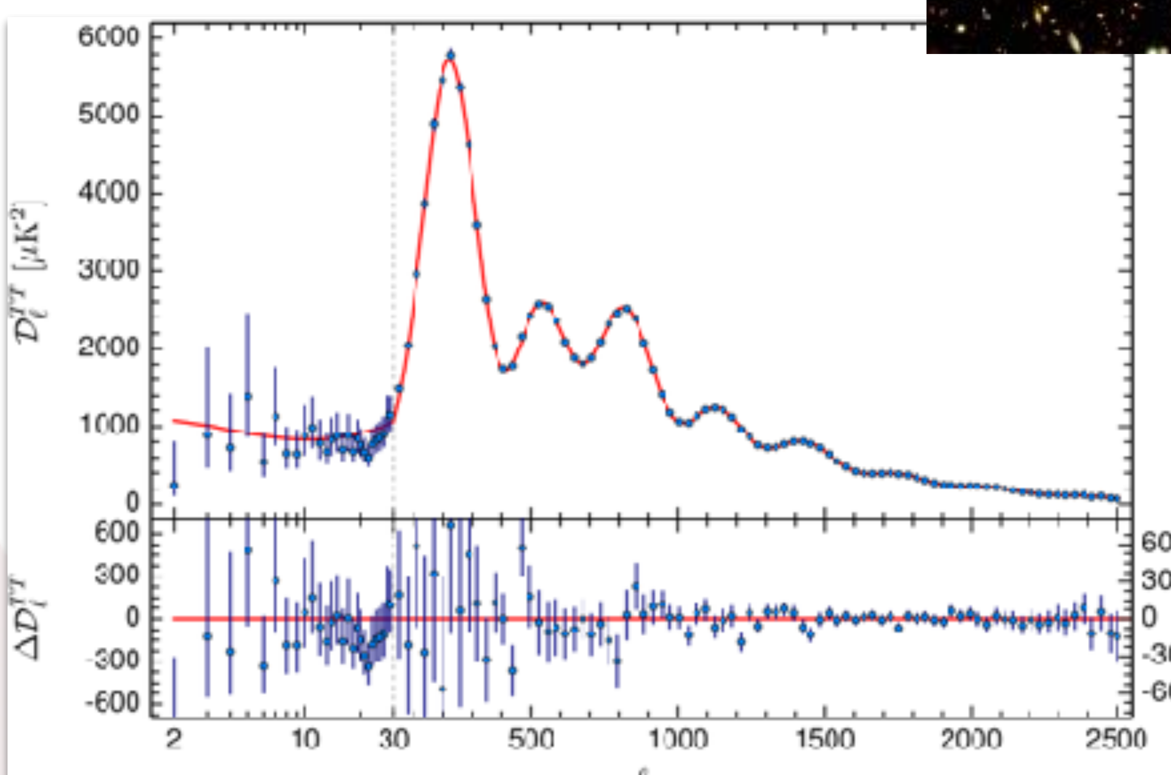
# Dark Matter




[M33 rot. curve, Source: Wikipedia]

[Chandra picture of the bullet cluster]






[https://wiki.cosmos.esa.int/planckpla2015/images/2/2f/]

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# Model Motivation

- Why Supersymmetry?
  - Appealing solution for the hierarchy problem
- Why Electroweak Scale?
  - We can test it now at the LHC and DM experiments
- Why Seesaw?
  - Explanation for the smallness of neutrino masses

➡ A SUSY EW scale seesaw model

# Field content

**[Chang, Cheung, Ishida, Lu, MS, Tsai '17]**

- MSSM fields
- Right-handed neutrinos $N$ (at least 2)
- Lepton-like gauge singlet fields $S$ (at least 2)
- Higgs-like gauge singlet field $X$ (at least 1)

# Symmetries and Superpotential

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

| 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 |

- SM gauge symmetries + $Z_6$ (SU(5) compatible)
- Superpotential

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

- Lepton number broken by last term

# Symmetries and Superpotential

[Chang, Cheung, Ishida, Lu, MS, Tsai '17 & '18]

| 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 |

- Electroweak symmetry broken as in the MSSM
- $Z_3$ x $Z_2$ broken to $Z_2$ by vev of $X$ of O($M_{\text{SUSY}}$)
- Unbroken $Z_2$ stabilizes DM candidates:

➡ Gravitino, Sneutrino, Neutralino

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# ISS Types

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

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

- 3 kinds of Inverse SeeSaw (ISS) mechanism:
  - ISS Type I: $M_S \ll M_D \ll \mu_{NS}$ (conventional ISS)
  - ISS Type II: $M_S \sim M_D \ll \mu_{NS}$
  - ISS Type III: $M_D \ll M_S \ll \mu_{NS}$
- $M_D$ and $M_S$ proportional to EW scale vevs

# Neutrino Masses & Yukawa Couplings

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

- Common leading order light neutrino masses

$$m_\nu = M_D \, \mu_{NS}^{-1} \, M_S \, \mu_{NS}^{-1} \, M_D^T \sim Y_\nu \, \lambda \, Y_\nu^T \, \mathcal{O}(\text{TeV})$$

- Tiny masses due to small Yukawa couplings
- Casas-Ibarra formula in our case

$$Y_\nu = \frac{\mathrm{i}}{v_u} U_{\text{PMNS}} \sqrt{m_i} \, \Omega \, \left( \sqrt{M_S^d} \right)^{-1} V_S$$

# Neutrino Masses & Yukawa Couplings

**[Chang, Cheung, Ishida, Lu, MS, Tsai '17]**

- In minimal case one neutrino massless
- Sizes of the Yukawa couplings
  - ISS Type I: $Y_\nu \sim 10^{-4}$ and $\lambda \sim 10^{-8}$ and $\epsilon_I \sim 10^{-4}$
  - ISS Type II: $Y_\nu \sim 10^{-5}$ and $\lambda \sim 10^{-5}$ and $\epsilon_{II} \sim 10^{-5}$
  - ISS Type III: $Y_\nu \sim 10^{-6}$ and $\lambda \sim 10^{-3}$ and $\epsilon_{III} \sim 10^{-3}$

# Neutrinoless Double Beta Decay

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

- New neutrino states almost Dirac
- Contributions to $m_{\text{eff}}$ small, e.g. ISS Type I:

$$m_{\text{eff}}^{\text{new}} \simeq \sum_{i=4}^{7} (U_{ei})^2 \frac{\langle p^2 \rangle}{\mu_{NS}^2} M_S \approx 8 \times 10^{-9} \ \text{meV} \cdot \left( \frac{\text{TeV}}{\mu_{NS}} \right)$$

- In minimal version $m_{\text{eff}}$ is O(1) meV for NH and O(10) meV for IH

# Non-Unitarity of the PMNS Matrix

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

- The 3x3 PMNS matrix is not unitary anymore
- In this model

$$U_{\mathrm{PMNS}} U^{\dagger}_{\mathrm{PMNS}} = 1 + \mathcal{O}(\epsilon^2)$$

- Current constraints $\epsilon < O(10^{-3} - 10^{-1})$

[Fernandez-Martinez, Hernandez-Garica, Lopez-Pavon 2016]

# Charged Lepton Flavor Violation

- Smoking gun for new physics
- In our model two kind of contributions
  - Non-SUSY contributions from new neutrinos
  - SUSY contributions involving charged sleptons and sneutrinos

# Charged Lepton Flavor Violation

[Chang, Cheung, Ishida, Lu, MS, Tsai '17]

- The non-SUSY part can be written as

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{ie} U^*_{i\mu} \, F(m_i^2/M_W^2) \right|^2$$

- Dominant contribution from non-unitarity of the mixing matrix

$$\mathrm{BR}(\mu \to e\gamma) = \begin{cases} \mathcal{O}(10^{-20}) & \text{for ISS type I,} \\ \mathcal{O}(10^{-24}) & \text{for ISS type II,} \\ \mathcal{O}(10^{-28}) & \text{for ISS type III,} \end{cases}$$

- Experiment: BR($\mu \to e\gamma$) < $4.2\cdot10^{-13}$ @90%CL

[Final MEG result 2016]

# Charged Lepton Flavor Violation

**[Chang, Cheung, Ishida, Lu, MS, Tsai '17]**

- SUSY part very similar to MSSM apart from sneutrinos
- Sneutrinos combination of left-, right-handed sneutrinos and scalar component of extra singlets
- The vev of $X$ induces (small) mass splitting of the real and imaginary part of the sneutrinos
- Minimally 14 (real) sneutrinos

# Charged Lepton Flavor Violation

**[Chang, Cheung, Ishida, Lu, MS, Tsai '17]**

- Neglecting contributions proportional to small Yukawa couplings

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

- Real and imaginary part have same mass
- Small mixing of left-handed sneutrinos with other sneutrinos

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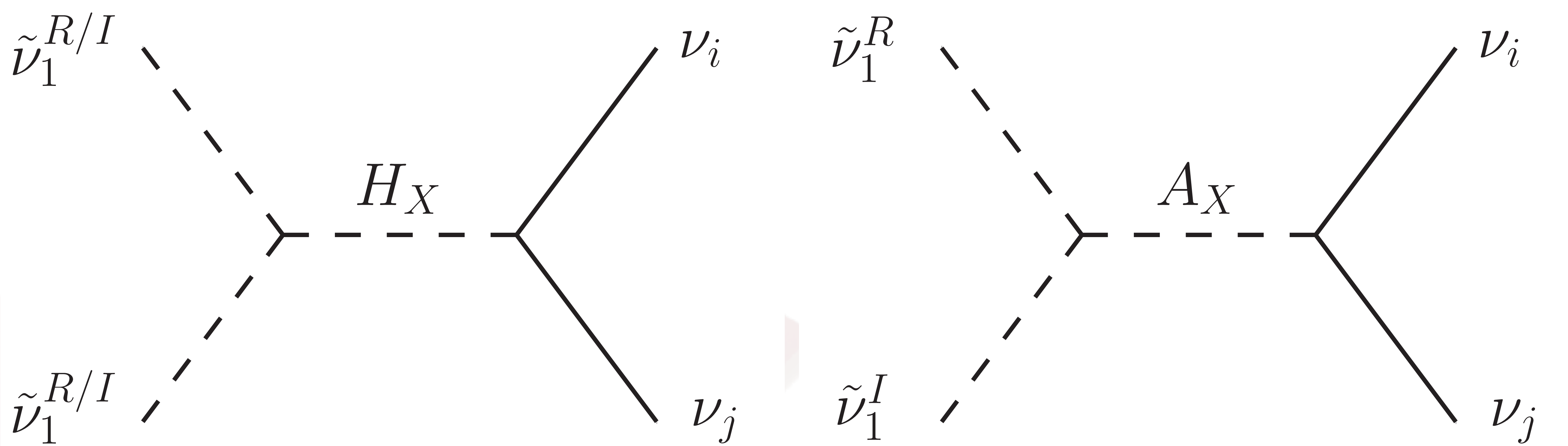
# Three Exceptions

[Griest, Seckel '90]

- Thermally produced DM has to annihilate sufficiently at freeze-out
- Three special cases:
  1. Co-Annihilation
  2. Annihilation near a threshold
  3. Annihilation near a resonance
- We have 1. and 3.

# Dominant (Co-)Annihilation Channels

**[Chang, Cheung, Ishida, Lu, MS, Tsai '18]**




$H_X$-funnel $A_X$-funnel

# Boundary Conditions

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- Inspired by CMSSM

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

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

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

- Arbitrary factor to decouple coloured states
- Fixed $m_0$ and $M_{1/2}$ at the high scale
- Fixed $v_X$ and $\kappa$ at the low scale

# Sneutrino Masses

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- Leading order 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 for the singlets smallish
- Lightest states

$$\tilde{\nu}_1 \approx \frac{1}{\sqrt{2}} \left( \tilde{N}_1^c - \tilde{S}_1 \right) \, , \quad m^2_{\tilde{\nu}_1} \approx \mu^2_{\mathrm{NS}}$$

- Mass difference CP even/CP odd sneutrinos

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

# Higgs Masses

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- Two more real scalars $H_X$ and $A_X$
- Mixing with MSSM scalars O(loop x $m_\nu^2$)
- Approximate Mass Formulas

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

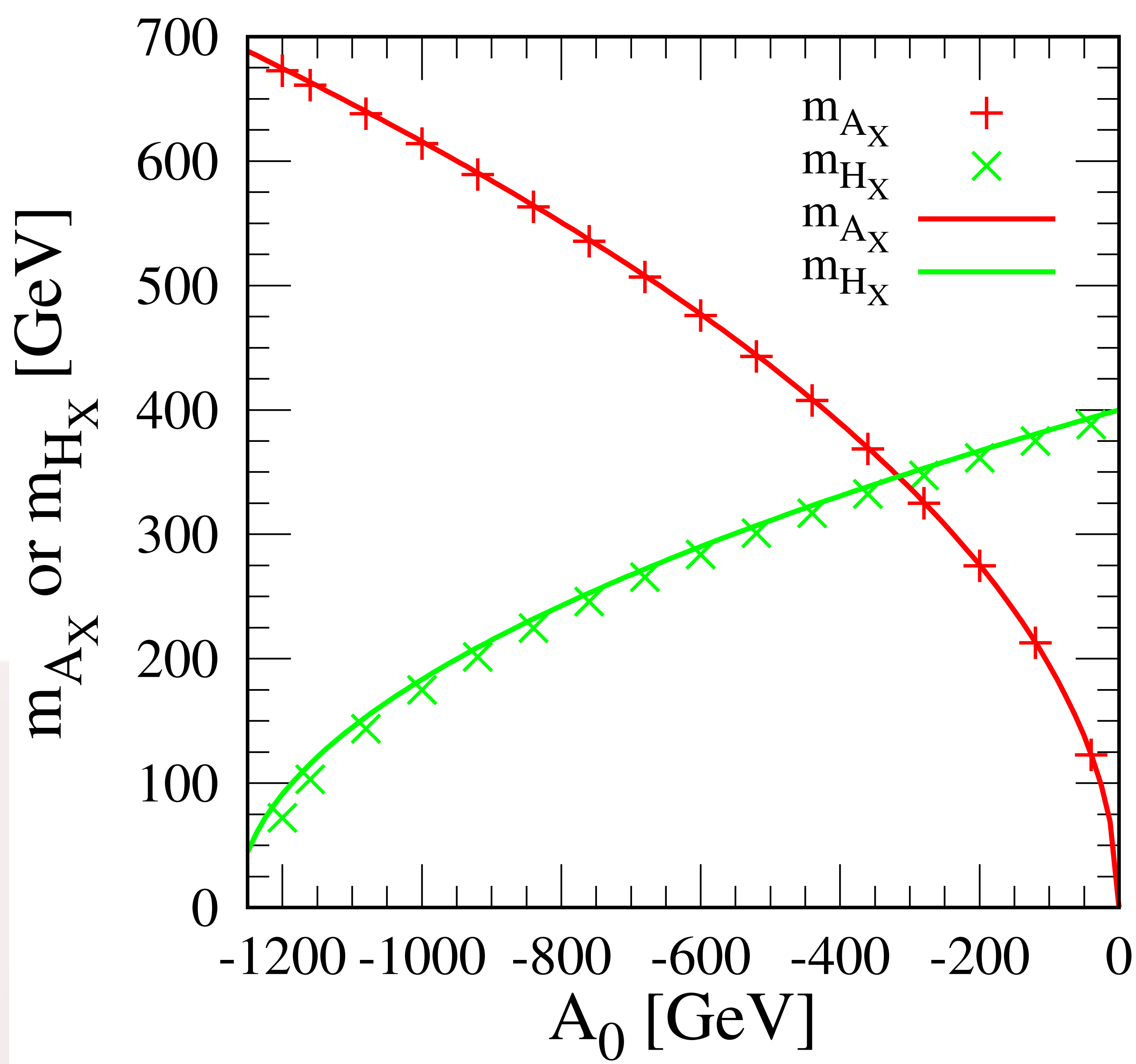
$$m^2_{A_X} \approx -\frac{3\,v_X}{\sqrt{2}}\kappa_0 A_0 \left(1 - 2.3\,\kappa_0^2\right)$$

- Constraint on $A_0$

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

# Higgs Masses

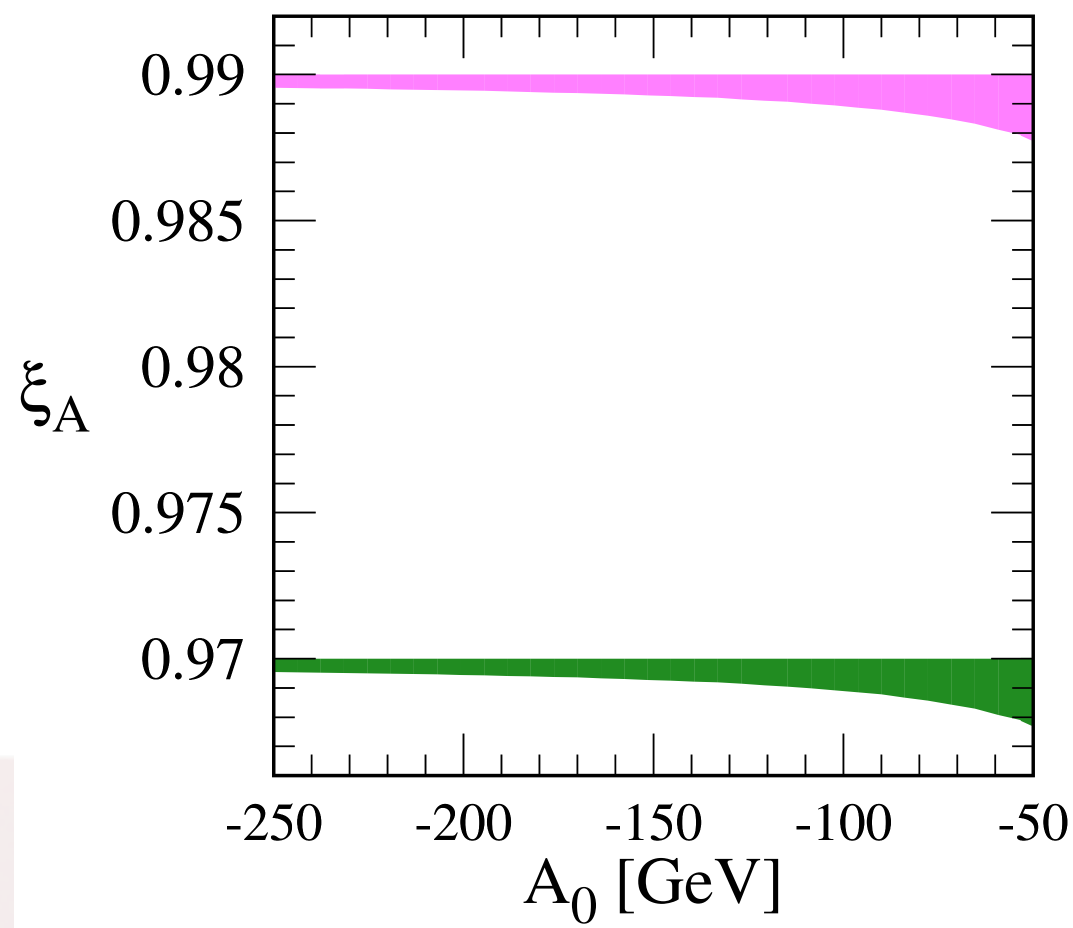
**[Chang, Cheung, Ishida, Lu, MS, Tsai '18]**



# Hitting the Funnel

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- The resonance region is narrow in parameter space
- We can guess very well where it is using the mass formulas
- Fixes $\mu_{NS}$
- The deviation from the input $c$ to the output $\xi_A$ less than 2.5 x $10^{-3}$




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

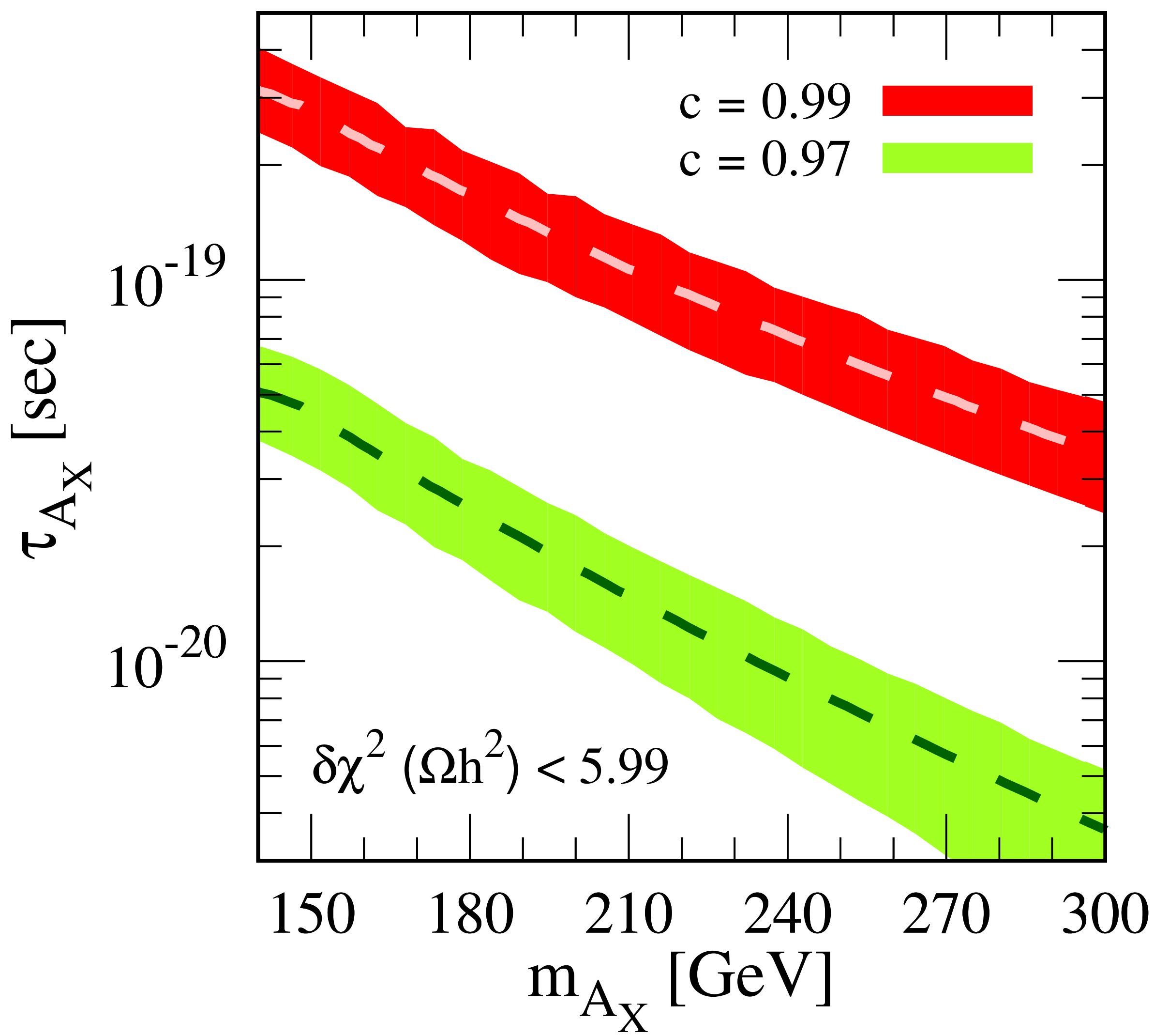
# Parameters

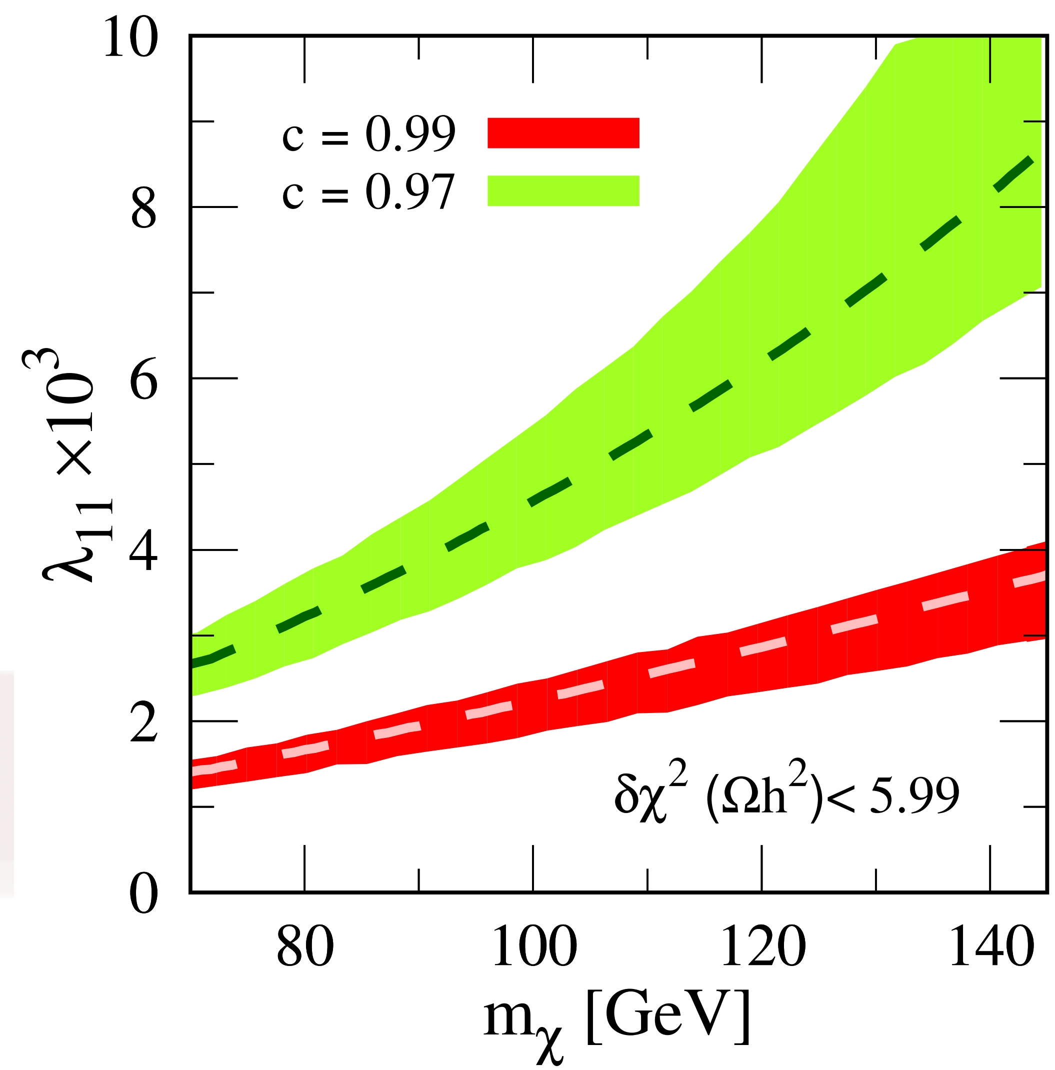
[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

| Parameter | $A_X$-funnel | $H_X$-funnel |
|---|---|---|
| $m_0$ | $1\,\text{TeV}$ | $1\,\text{TeV}$ |
| $M_{1/2}$ | $1.3\,\text{TeV}$ | $1.3\,\text{TeV}$ |
| $A_0$ | $-250 \leq A_0/\,\text{GeV} \leq -50$ | $-1200 < A_0/\,\text{GeV} < -350$ |
| $\tan\beta$ | $10$ | $10$ |
| $v_X$ | $1000/\sqrt{2}\,\text{GeV}$ | $1000/\sqrt{2}\,\text{GeV}$ |
| $\kappa_0$ | $0.4$ | $0.4$ |
| $\lambda_{11} = 0.5\,\lambda_{22}$ | $1 \times 10^{-4} < \lambda_{11} < 0.01$ | $1 \times 10^{-4} < \lambda_{11} < 0.01$ |
| $c$ | $\{0.97,\, 0.99\}$ | $\{0.97,\, 0.99\}$ |

# $A_X$-Funnel Results

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]



# The $H_X$-Funnel

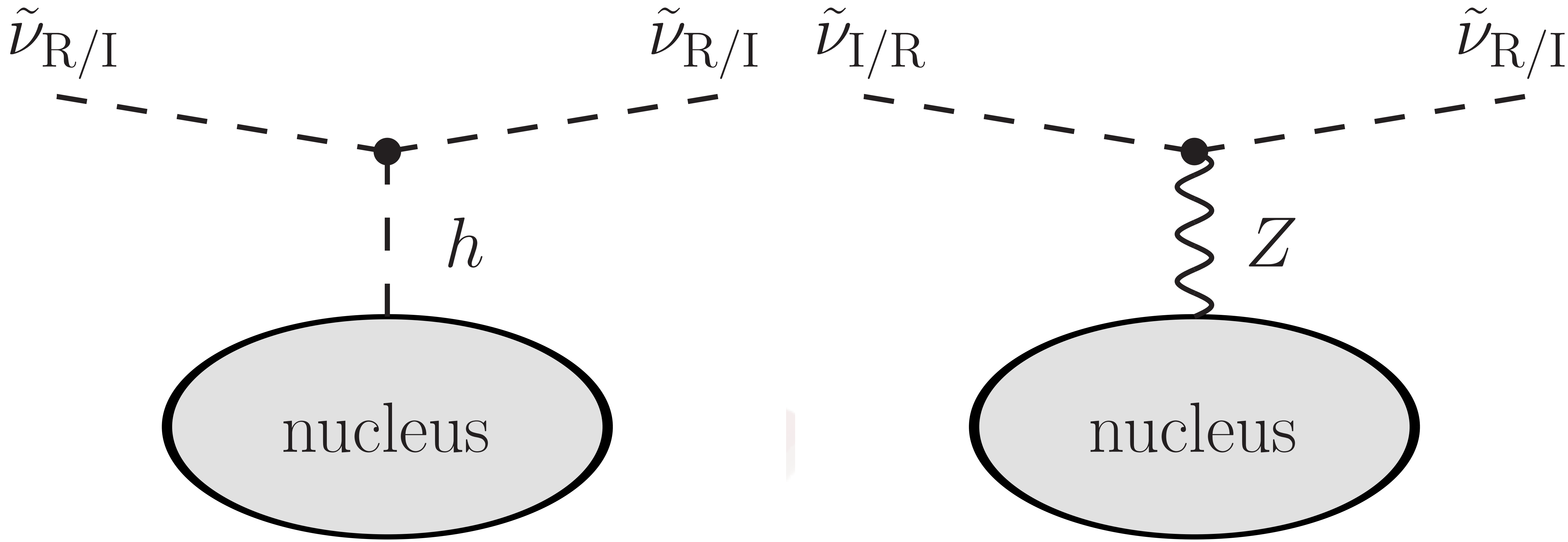
[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- The $H_X$-funnel suffers from p-wave suppression
- Larger $\lambda$ could increase annihilation cross section
- Large $\lambda$ separates the lightest sneutrino from heavy neutrinos, closes channels

▸ $H_X$-funnel does not work

# Direct Detection

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]



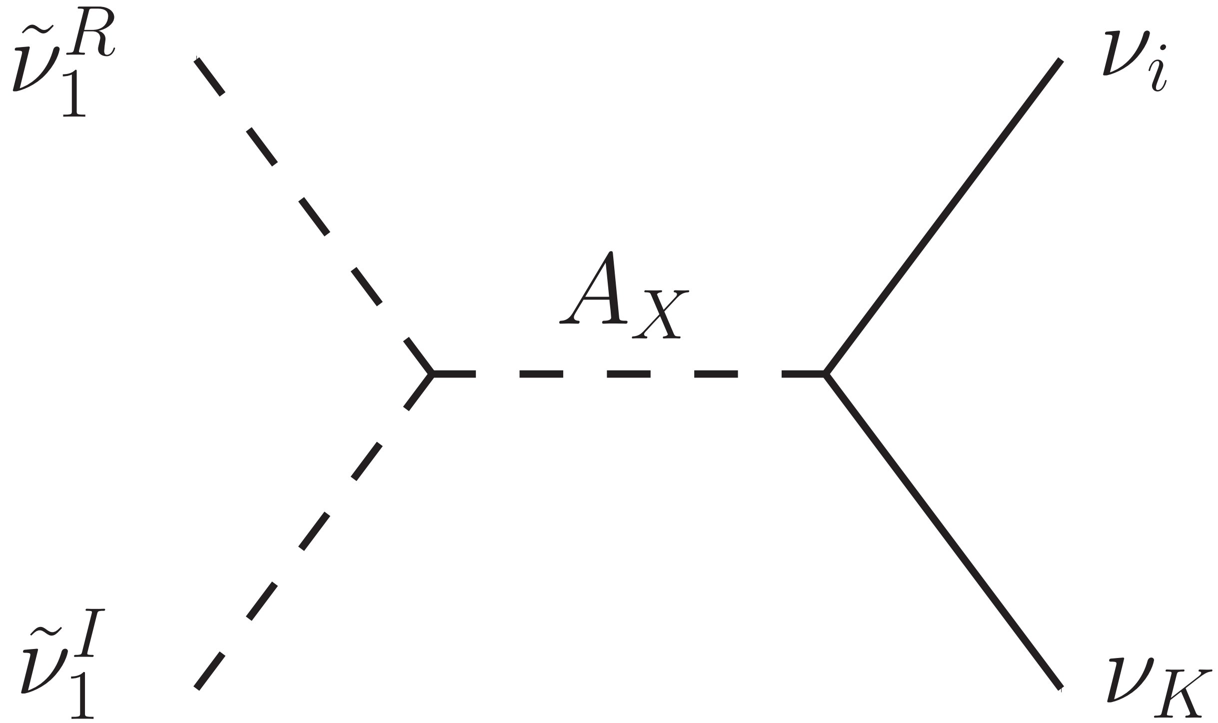
# Direct Detection

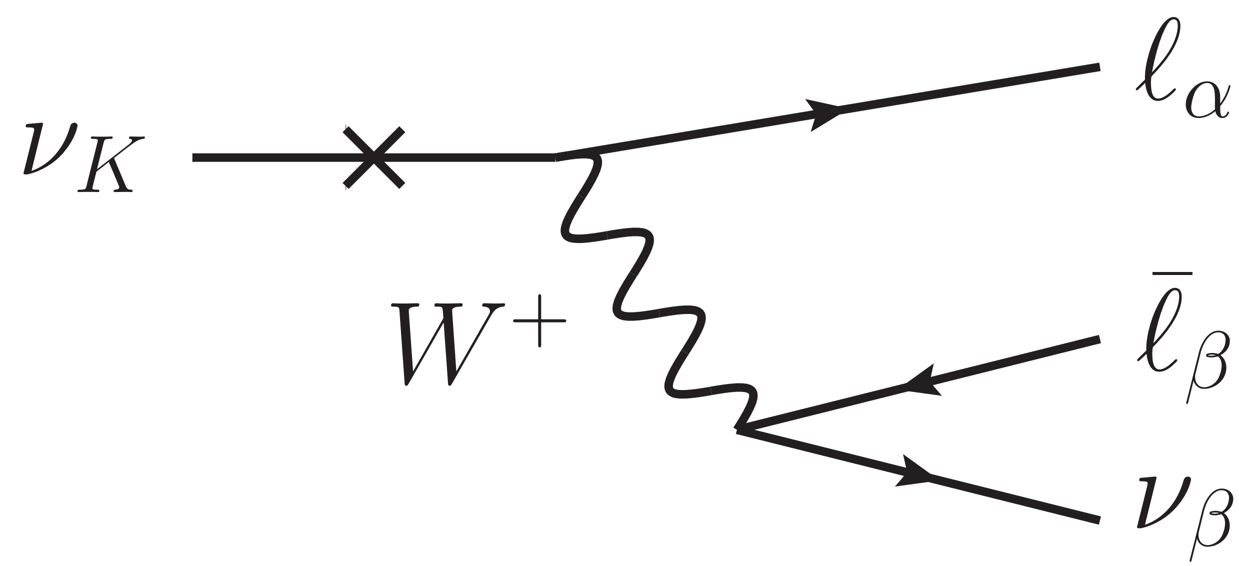
[Chang, Cheung, Ishida, Lu, MS, Tsai '18]

- Higgs exchange cross section O($10^{-29}$) pb
- Even below neutrino floor
- Current XENON1T limit O($10^{-11}$) pb@100 GeV
- Z-exchange is velocity suppressed > $10^{-12}$
- Z-exchange is furthermore inelastic and can be kinematically forbidden

# Indirect Detection

[Chang, Cheung, Ishida, Lu, MS, Tsai '18]



# Indirect Detection

**[Chang, Cheung, Ishida, Lu, MS, Tsai '18]**

- Three possible DM annihilation channels
  - Two heavy neutrinos: Cascade decays, weak constraints on complicated final states
  - Two light neutrinos: Heavily suppressed, below current bounds
  - One heavy, one light neutrino: Monochromatic neutrinos at IceCube? Our model is $10^{18}$ below current bound

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# Summary and Outlook

- Solve three short comings of the SM
  - Naturalness (SUSY)
  - Neutrino Masses (Inverse Seesaw Mechanism)
  - Dark Matter (Sneutrino DM or MSSM DM)
- Many predictions, easy to exclude
- Some features yet to be explored (Collider aspects, Leptogenesis, …)

Thanks a lot for your attention!