Can neutrinos illuminate the dark matter?

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Based on works: Arghyajit Datta, Rishav Roshan, AS [PRL 127 (2021)]
Soumen Kumar Manna, AS [PRD 108 (2023)]
Stephen F King, Soumen kumar Manna, Rishav Roshan, AS [PRD 111 (2025)]

Plan of the Talk

Origin of neutrino mass and Type-I seesaw

Lightest RHN as Dark Matter within Type-I seesaw

Majorons as dark matter

Conclusion

"Hey everybody -we've discovered the Higgs boson!
It was hidden under this big pile of equations all the time!"

Physics beyond the Standard Model with neutrinos and dark matter

Neutrinos mass can't be accommodated

No SM field can play the role of DM

Type-I seesaw and Neutrino mass

SM + 3 Right-Handed Neutrinos

$$\mathcal{L}_{\mathbf{BSM}} = \mathbf{Y}^{\nu}_{\alpha \mathbf{i}} \bar{\ell}_{L_\alpha} \tilde{H} N_i + \frac{M_N}{2} \bar{N_i}^c N_i + h.c$$

After EWSB

$$\begin{pmatrix} \bar{\nu}_L & \overline{(N_R)^c} \end{pmatrix} \begin{pmatrix} 0_{3\times3} & m^D_{3\times3} \\ m^{D^T}_{3\times3} & M_{N_{3\times3}} \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix}$$

m_{seesaw}

$$\mathbb{L}^\dagger m_{seesaw} \mathbb{L}^* = m^{block}_{diag}$$

Active-sterile mixing

$$\begin{pmatrix} m_{\nu_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & M_{N_{3\times3}} \end{pmatrix}$$

$$m_\nu = -m_D M_N^{-1} m_D^T$$

$$U^\dagger m_\nu U^* = D_m$$

$$\nu_L = U\nu + VN$$

$$\mathbf{V = m_D M_N^{-1}}$$

$$\begin{pmatrix} D_{m_{3\times3}} & 0_{3\times3} \\ 0_{3\times3} & D_{M_{3\times3}} \end{pmatrix}$$

$$\mathbf{D_m} = \mathrm{diag}(\mathrm{m_1, m_2, m_3})$$

$$D_M = \mathrm{diag}(\mathrm{M_1, M_2, M_3})$$

[A] RHNs as dark matter

Minimal framework: with 2 RHNs which can account for neutrino mass and BAU

With three RHNs framework of seesaw: N_1 can then be the DM while $N_{2,3}$ can take care of neutrino mass + BAU

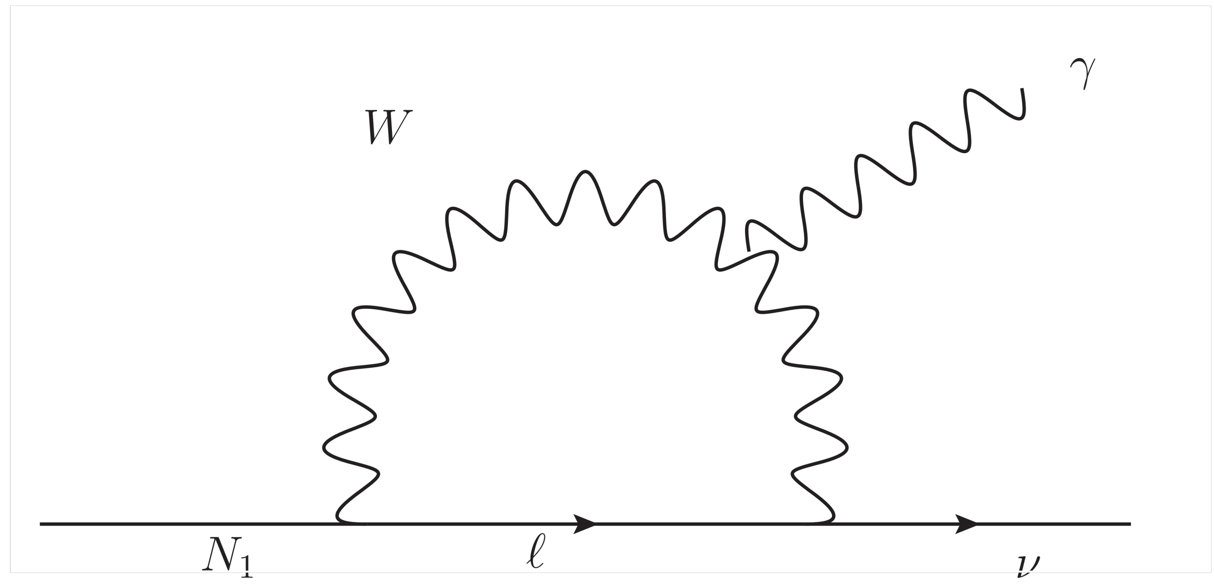
↓

Yukawa interaction of N_1: can be problematic from stability point of view

- **Via offshell W/Z:**

$$\mathrm{N}_1 \to l_1^- l_2^+ \nu_{l_2},\; N_1 \to l^- q_1 \bar{q}_2,\; N_1 \to l^- l^+ \nu_l,\; N_1 \to \nu_l \bar{l}' l',\; N_1 \to \nu_l q \bar{q},\; N_1 \to \nu_l \nu_{l'} \bar{\nu}_{l'},\; N_1 \to \nu_l \nu_l \bar{\nu}_l$$

- **Radiative decay:**



$$\Gamma_{N_1 \to \gamma\nu} = \frac{9\alpha G_F^2}{1024\pi^4} \sin^2 2\theta_1 M_1^5$$

$$\theta_1^2 = \sum_{i=1,2,3} \frac{|(m_D)_{i1}|^2}{M_1^2} \equiv \sum_{i=1,2,3} |V_{i1}|^2$$

expected lifetime of N_1 must be greater than the age of the universe

$$\theta_1^2 \leq 2.8 \times 10^{-18} \left(\frac{\mathrm{MeV}}{M_1}\right)^5$$

A1: From the decay of SM gauge bosons and Higgs (without temperature effect)

Arghyajit Datta, Rishav Roshan, AS [PRL 127 (2021)]

$$Y^\nu = \begin{pmatrix} 0 & y_{e2} & y_{e3} \\ 0 & y_{\mu 2} & y_{\mu 3} \\ 0 & y_{\tau 2} & y_{\tau 3} \end{pmatrix} \longrightarrow \begin{pmatrix} \epsilon_1 & y_{e2} & y_{e3} \\ \epsilon_2 & y_{\mu 2} & y_{\mu 3} \\ \epsilon_3 & y_{\tau 2} & y_{\tau 3} \end{pmatrix}$$

$$V_{i1} = m_{D_{i1}}/M_1 = \epsilon_i \frac{v}{\sqrt{2} M_1} \propto \sqrt{\frac{m_1}{M_1}}$$

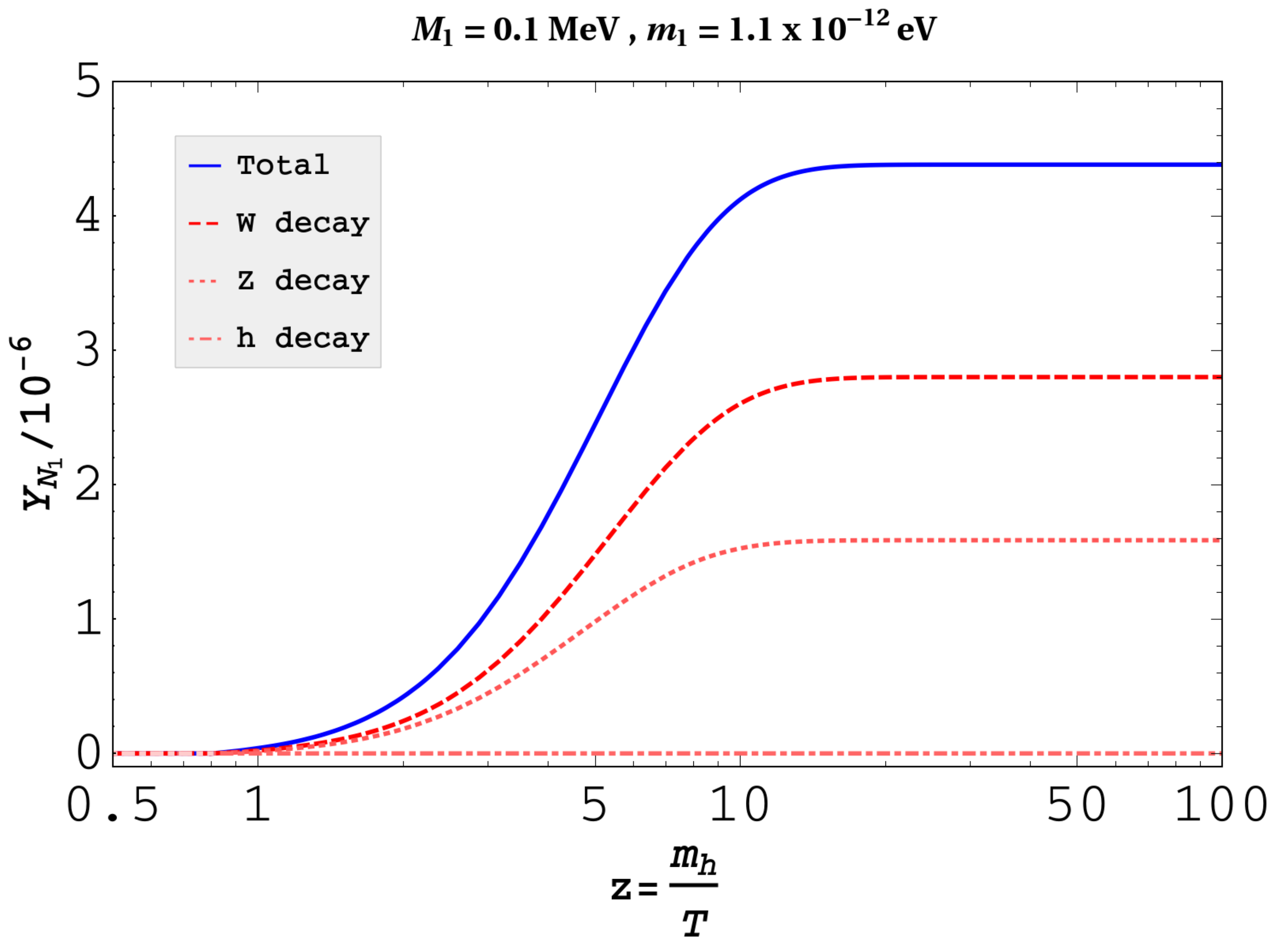
N_1 is absolutely stable, but production is NOT possible

Perturbed slightly N_1 **not in thermal equilibrium, freeze-in production possible**

$$\mathcal{L}_{\mathcal{G}} \subset \frac{g}{\sqrt{2}} W^+_\mu \sum_{i,j=1}^{3} \left[\bar{N}^c_i (V^\dagger)_{ij} \gamma^\mu P_L \ell_j\right] + \frac{g}{2C_{\theta_w}} Z_\mu \times \sum_{i,j\ 1}^{3} \left[\bar{\nu}_i (U^\dagger V)_{ij} \gamma^\mu P_L N^c_j + \bar{N}^c_i (V^\dagger V)_{ij} \gamma^\mu P_L N^c_j\right],$$

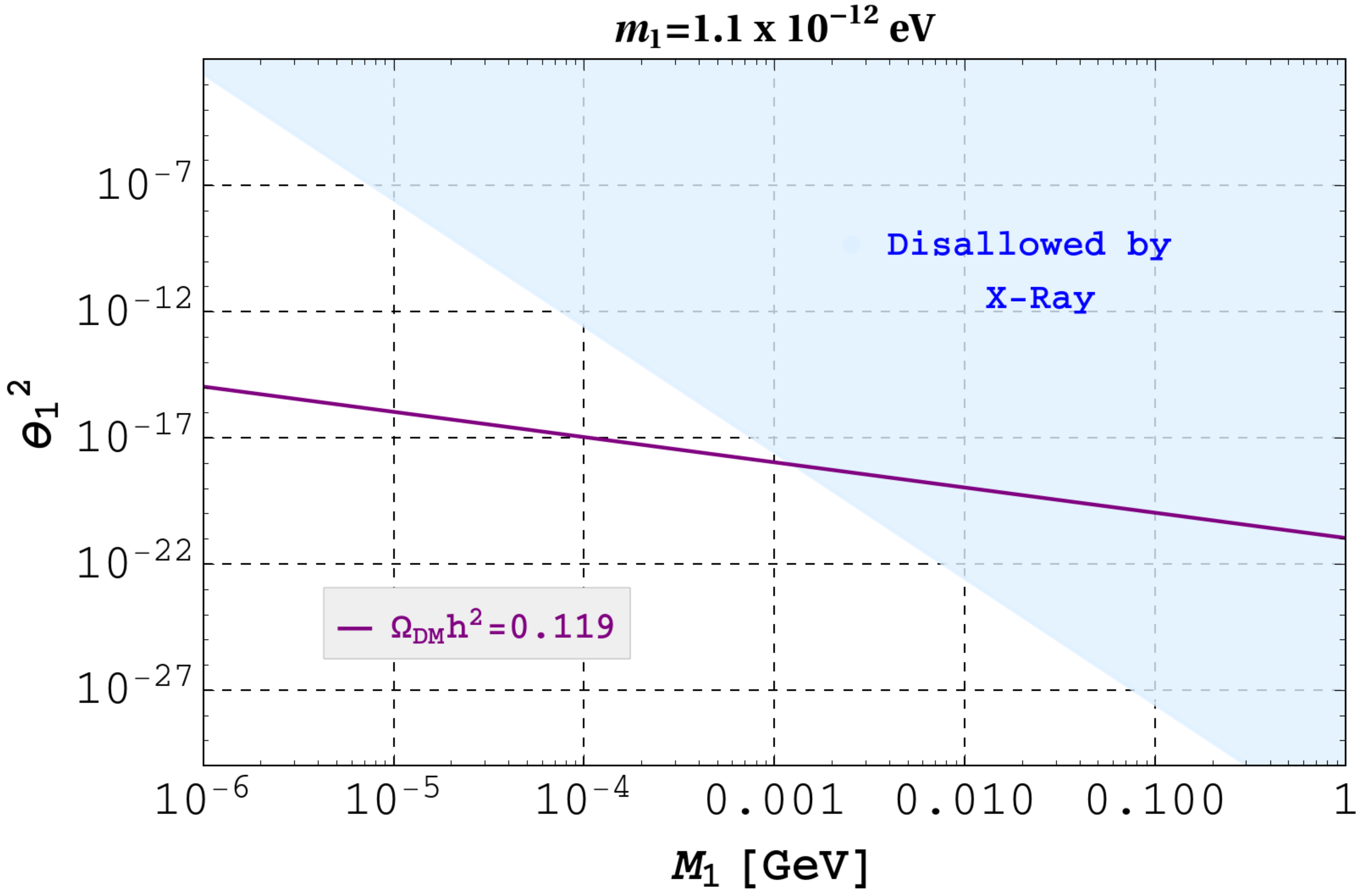
$$\epsilon_i << 1$$

$$\mathcal{L}_{\mathcal{Y}} \subset \frac{\sqrt{2}}{v} h \sum_{i,j=1}^{3} \left[\bar{\nu}_i (U^\dagger V)_{ij} M_j N_j + \bar{N}^c_i (V^\dagger V)_{ij} M_j N_j\right],$$



$$\Omega_{N_1} h^2 = 2.755 \times 10^5 \left(\frac{M_1}{\text{MeV}}\right) Y_{N_1}(z_\infty)$$

- DM relic only depends on lightest active neutrino mass m_1. $\Omega_{N_1} h^2 \propto M_1 Y_{N_1}(Z_\infty) \sim M_1 \Gamma_{W/Z} \sim M_1 \frac{m_1}{M_1}$
- Correct relic can be observed for $m_1 \sim 10^{-12}$ eV



→ **1 MeV to 1 KeV** mass of N_1 as **FIMP dark matter**

[A2] Taking temperature effect into consideration

See Talk by Salvador Rosauro-Alcaraz

[B] Majorons as DM

Type-I seesaw and Origin of Majoron

$y^{\nu}_{\alpha i}\,\overline{L}_{\alpha}\tilde{H}\mathcal{N}_{R_i}$ + Majorana mass of the RHN in type-I seesaw $\frac{M_N}{2}\overline{\mathcal{N}^c_{R_i}}\mathcal{N}_{R_i}$

↓

(Together) Lepton Number Symmetry (LNS) breaking term

One can embed the Type-I seesaw in a global $U(1)_L$ framework with a SM singlet Scalar Φ having Lepton charge and replace the mass term with

$$-\mathscr{L} \supset \frac{f_i}{2}\Phi\overline{\mathcal{N}^c_{R_i}}\mathcal{N}_{R_i}$$

LNS conserving term

↓

$$\langle\Phi\rangle = \frac{v_\phi}{\sqrt{2}} \to M_N = f\frac{v_\phi}{\sqrt{2}}$$

↓

Spontaneous breaking of global $U(1)_L$

↓

$$\Phi = (v_\phi + \phi + i\chi)/\sqrt{2}$$

→ Massless Nambu Goldstone boson (Majoron)

Global symmetry breaking (explicit and spontaneous) and properties of Majoron

↓

Possible origin: any global symmetry is expected to be broken by gravity effect

$$-\mathscr{L}_{\rm LNB} = -\frac{m^2}{4}(\Phi^2 + \Phi^{*2})$$

Mass of Majoron (becomes **pseudo NGB)**

$$m_\chi^2 = m^2$$

Interaction of Majoron: its pNGB nature indicates that its interaction be **suppressed by the SSB scale** of $U(1)_L$

↓

A natural candidate for **dark matter**

Rothstein, Babu, and Seckel (1993)
Berezinsky and Valle (1993)

Majoron as Freeze out type of DM

In order to keep Majoron in thermal equilibrium: additional interaction required, e.g. Higgs portal interaction

$$\mathcal{L} = \lambda_{h\chi}\Phi^2|H|^2 + h.c. = -\lambda_{h\chi}\chi^2|H|^2 + \ldots = \frac{1}{2}m_\chi^2\chi^2\left(1+\frac{h}{v}\right)^2 + \ldots$$

$\downarrow$ $\Phi = (v_\phi + \phi + i\chi)/\sqrt{2}$

An explicit symmetry breaking term

It provides a mass term too…

Frigerio, Hambye, and Masso (2011);
Queiroz and Sinha (2014)

$\chi\chi \to \mathrm{SM\ SM}$ processes are possible via Higgs mediation

With $\lambda_{\chi h} \sim \mathcal{O}(0.1)$, $m_\chi \gtrsim 1$ TeV is allowed (similar to singlet scalar WIMP scenario)

$\downarrow$

Contrary to Natural expectation:
Coefficients of these explicit breaking terms should be small

Majoron as Freeze-in DM (Simplest possibility: production from RHN decay)

Gu, Ma, and Sarkar (2010);
Frigerio, Hambye, and Masso, (2011);
Garcia-Cely and Heeck (2017);
Brune and Pas (2019);
Abe et al. (2020)

$$-\mathscr{L}_{int} \supset \frac{if_i}{2\sqrt{2}} \chi \overline{\mathcal{N}^c_{R_i}} \mathcal{N}_{R_i} + h.c..$$

$$V_m = V_{as}^\dagger U, \quad V_{as} = m_D^* M_N^{-1}$$

$$-\mathscr{L}_{\chi N\nu} = \frac{\chi}{2\sqrt{2}} \sum_{i,j} f_i \left(\overline{\nu_j} P_R N_i V^T_{m_{ji}} + \overline{N_i} P_R \nu_j V_m ij \right) + h.c.,$$

Production of Majoron

$N \to \chi\nu$

$$\Gamma_{N_i \to \chi\nu} = \frac{M_i^3}{32\pi v_\phi^2} \sum_{j=1,2,3} |V_{m_{ij}}|^2 .$$

$$\Omega_\chi h^2 \approx \frac{1.09 \times 10^{27}}{g_\star^{\mathcal{S}} \sqrt{g_\star^\rho}} m_\chi \sum_i \frac{g_i \Gamma_{N_i \to \chi\nu}}{M_i^2}$$

$$-\mathscr{L}_{\chi\nu\nu} = -\frac{\chi}{2\sqrt{2}} \sum_{j,k} \left(\sum_i i f_i \overline{\nu_j} P_R \nu_k V_m{}^T_{ji} V_{m_{ik}} + h.c. \right)$$

Decay of Majoron: $\chi \to \nu\nu$

$$\Gamma_{\chi \to \nu\nu} = \frac{m_\chi}{16\pi v_\phi^2} \sum_j m_{\nu_j}^2$$

$$\Gamma^{-1}_{\chi \to \nu\nu} > \tau_U$$

$$\Omega_\chi h^2 < 1.28 \times 10^{-9} \left(\frac{10^{19}\ \text{sec}}{\tau_U} \right)$$

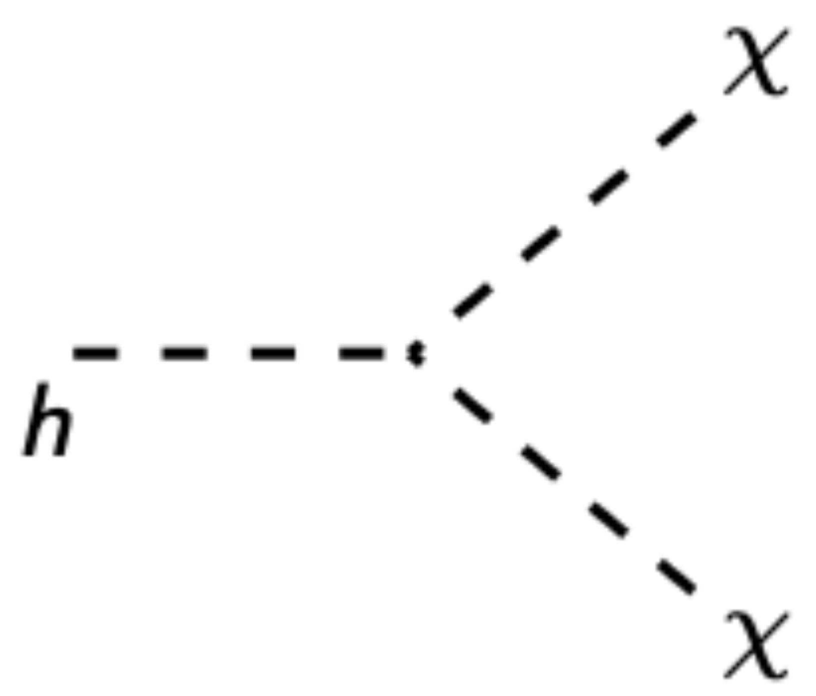
Hence Majoron production via $N \to \chi\nu$ is not sufficient to produce correct DM abundance once combined with the stability criteria

Majoron as FIMP via Higgs portal

Gu, Ma, and Sarkar (2010);
Frigerio, Hambye, and Masso, (2011);
Garcia-Cely and Heeck (2017);
Brune and Pas (2019);
Abe et al. (2020)

Re-looking at the explicit LNS breaking Higgs portal interaction: $\mathscr{L} = -\lambda_{h\chi}\chi^2 H^\dagger H$

Contrary to the Freeze-out possibility, this $\lambda_{h\chi}$ is not required to be small (consistent with naturalness criteria)



- After EWSB: $\Omega_\chi h^2 \propto m_\chi \Gamma(h \to \chi\chi)$
- $\lambda_{h\chi}$ remains as the sole parameter
- $\Omega_\chi h^2 \simeq 0.12$ fixes $\lambda_{h\chi} \sim \mathcal{O}(10^{-10})$
- m_χ then turns out to be 2.8 MeV

Plausible, but a fine tuned situation....

Majorons Revisited: broadening the parameter space of Majoron as DM

Soumen Kumar Manna, AS [PRD 108 (2023)]

- $U(1)_L$ symmetry remains intact at renormalizable level

- All the explicit breaking terms are of higher orders

Kallosh, Linde, Linde, Susskind (1995).....

Draper, Garcia, Reece (2022)
Cordova, Ohmori, Rudelius (2022)

$$-\mathscr{L} = \mathscr{L}_{\text{seesaw}} + \mathscr{L}_{\text{LNB}} + \mathscr{L}_{d_5}$$

$$-\mathscr{L}_{\text{LNB}} = \frac{m^2}{4}(\Phi^2 + \Phi^{*2})$$

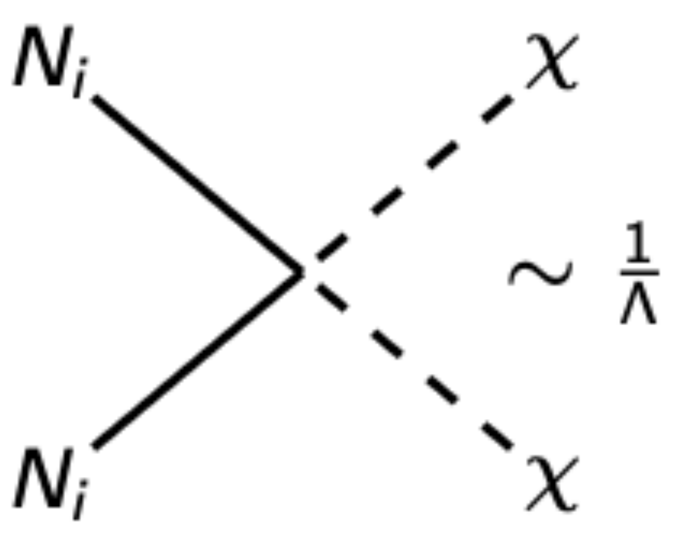
: can be realised also to be emerged from higher order explicit symmetry breaking terms

(Such as, $k\frac{|\Phi|^4}{\Lambda^2}(\Phi^2 + \Phi^{*2})$]

$$-\mathscr{L}_{\text{d}_5} = \frac{\alpha_i}{2\Lambda}\left[\Phi^2 + (\Phi^*)^2\right]\overline{\mathscr{N}^c_{R_i}}\mathscr{N}_{R_i} + h.c.$$

This explicit $U(1)_L$ breaking operator introduces new Majoron production chanel:

$$-\mathscr{L}_{d_5} = \frac{\alpha_i}{2\Lambda}\left[\Phi^2 + (\Phi^*)^2\right]\overline{\mathcal{N}^c_{R_i}}\mathcal{N}_{R_i} + h.c. \supset \frac{1}{2\Lambda}\chi^2\overline{N^c_i}N_i,$$ with $\alpha_i = 1$



- **It also contributes to the RHN mass:** $$M_i = v_\phi\left(\frac{f_i}{\sqrt{2}} + \frac{v_\phi}{\Lambda}\right)$$

- **Majoron production may begin at much earlier time** (contrary to $N \to \nu\chi$ production being effective after EWSB)

[Suggestive of UV Freeze-in]

Our considerations:

SSB of $U(1)_L$ takes place at a temperature $T = T_L(\sim v_\phi) < T_{\rm RH}$

The CP-even component ϕ being very heavy essentially decoupled from the plasma [equivalent of setting $\phi = 0$ in the Lagrangian]

Evolution of DM

[Case: A]: RHNs are present in thermal bath at $T \sim T_L$ (when $U(1)_L$ symmetry is spontaneously broken, < $T_{\rm RH}$)

[Case: B]: RHNs are NOT in thermal bath at $T \sim T_L$

Case: A

$$\frac{dY_\chi}{dT} \simeq -\frac{2\mathcal{S}}{\mathcal{H}T}\sum_i \langle \sigma v \rangle_{N_i N_i \to \chi\chi} {Y^{eq}_{N_i}}^2 \left[1 - \frac{Y_\chi^2}{{Y^{eq}_\chi}^2}\right]$$

Case: B

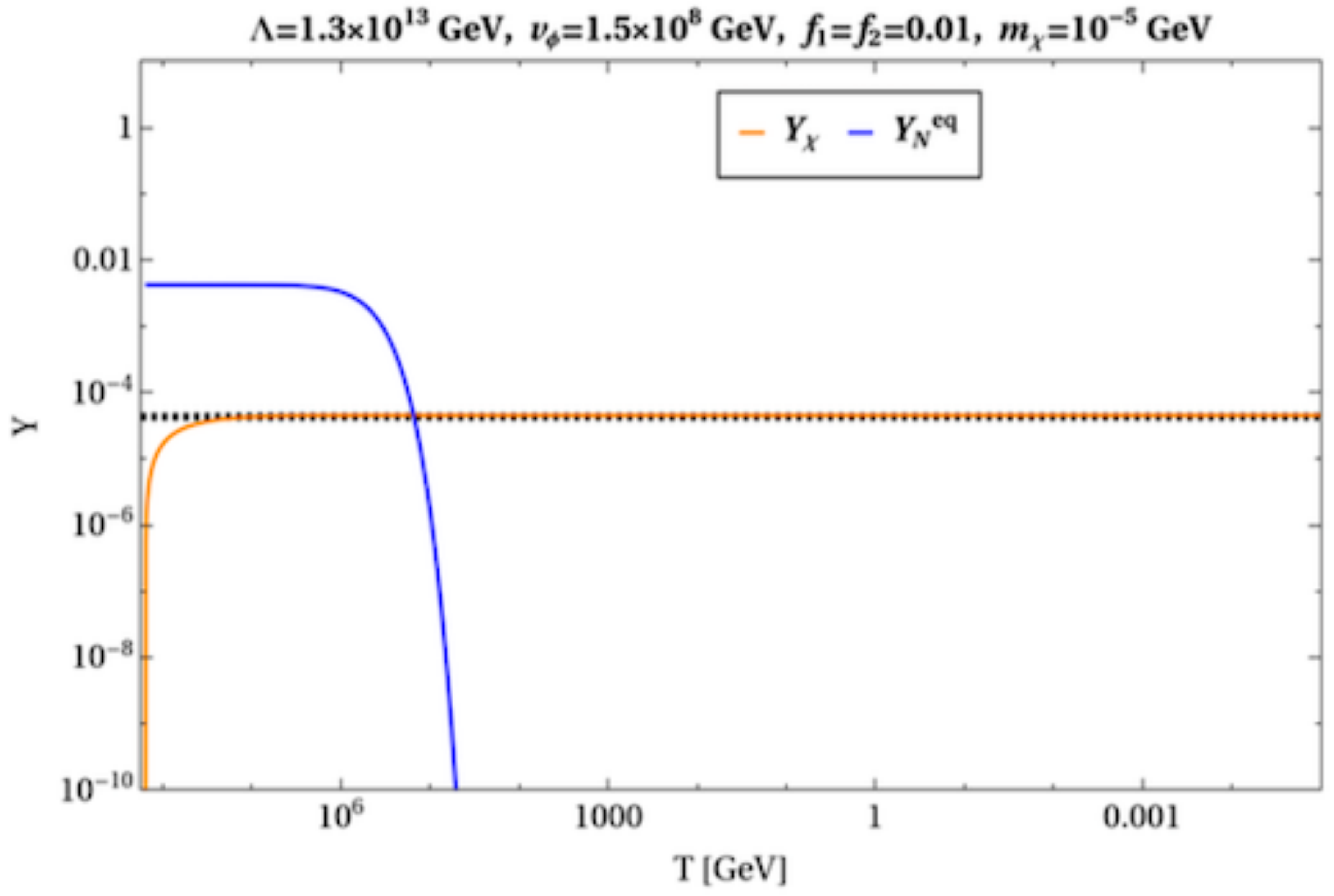
$$\frac{dY_{N_i}}{dT} = \frac{1}{\mathcal{H}T}\langle \Gamma_{N_i \to LH}\rangle \left(Y_{N_i} - Y^{eq}_{N_i}\right) + \frac{2\mathcal{S}}{\mathcal{H}T}\langle \sigma v \rangle_{N_i N_i \to \chi\chi}\left(Y^2_{N_i} - \frac{(Y^{eq}_{N_i})^2}{(Y^{eq}_\chi)^2} Y_\chi^2\right)$$

$$\frac{dY_\chi}{dT} = -\frac{2\mathcal{S}}{\mathcal{H}T}\sum_i \langle \sigma v \rangle_{N_i N_i \to \chi\chi}\left(Y^2_{N_i} - \frac{(Y^{eq}_{N_i})^2}{(Y^{eq}_\chi)^2} Y_\chi^2\right)$$

Freeze in production of Majorons by $NN \to \chi\chi$

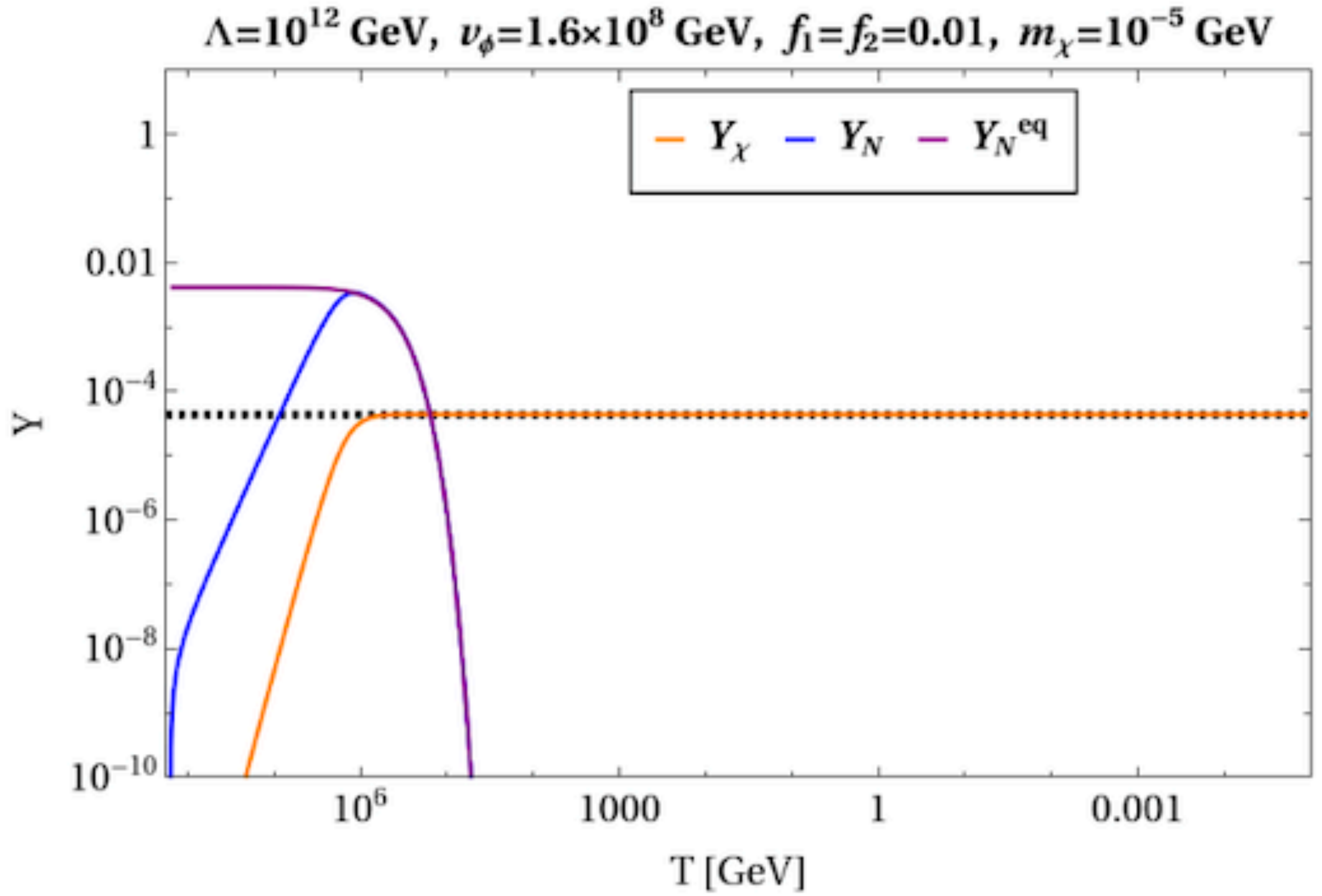
BP	Λ (GeV)	v_ϕ (GeV)	m_χ (GeV)
case A	1.3×10^{13}	1.5×10^{8}	10^{-5}
case B.1	10^{12}	1.6×10^{8}	10^{-5}

[Case **A**: RHN in bath at T_L] Degenerate RHNs



Production happens near T_L

[Case **B**: RHNs absent in bath at T_L] Degenerate RHNs

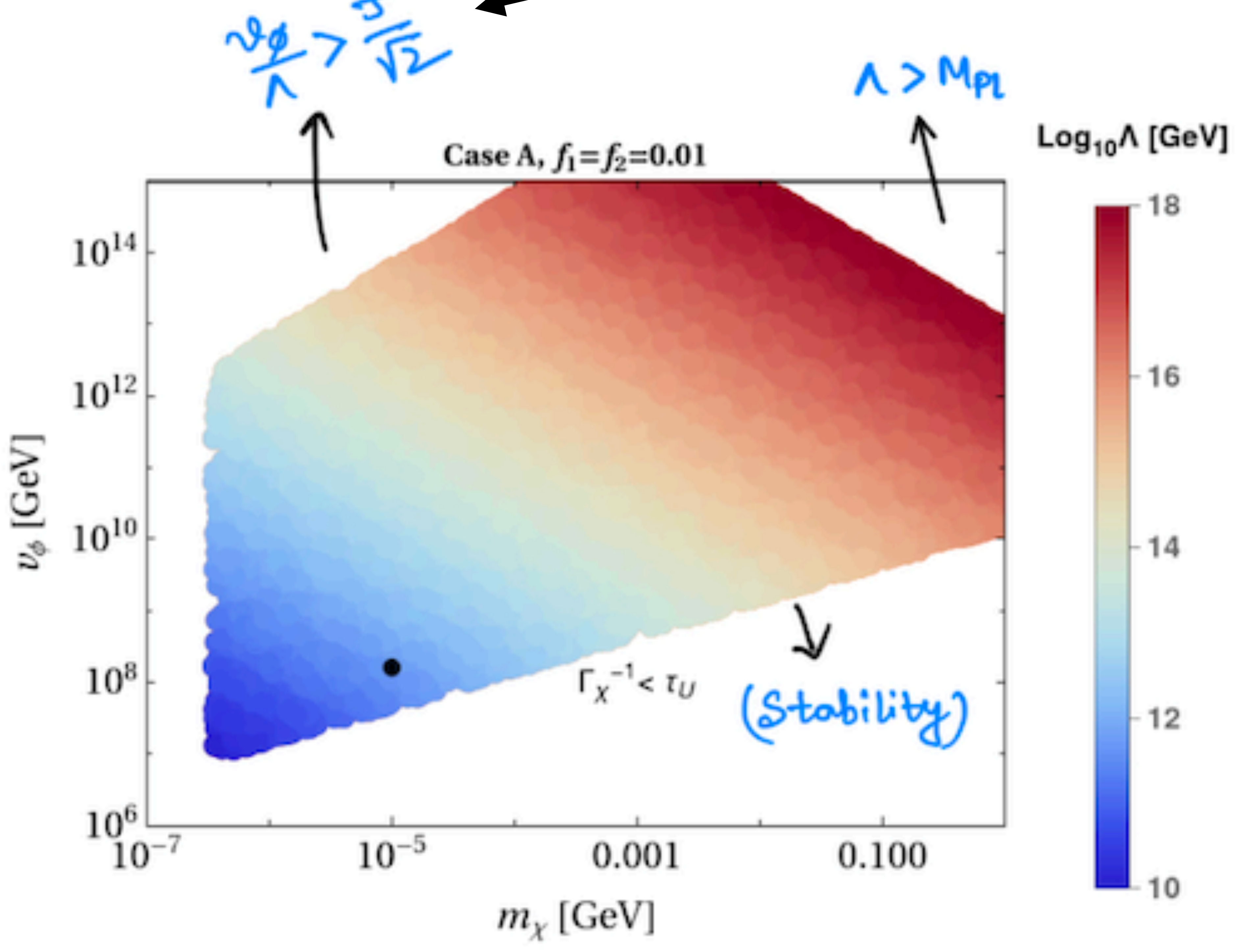


Production happens from T_L to a later stage

- For both case, the degenerate RHN masses: $M_i = 1.5 \times 10^6$ GeV (with $f_1 = f_2 = 0.01$)
- The DM yield satisfies $\Omega_\chi h^2 = 2.755 \times 10^8 \left(\frac{m_\chi}{\mathrm{GeV}}\right) Y_\chi(T_0)$ where T_0 is the present temperature

Relic Satisfied Parameter space for [Case A and B for Degenerate RHNs)

Tree-level mass of RHN < contribution from explicit breaking



[Case A: (RHN in bath at T_L] Degenerate RHNs

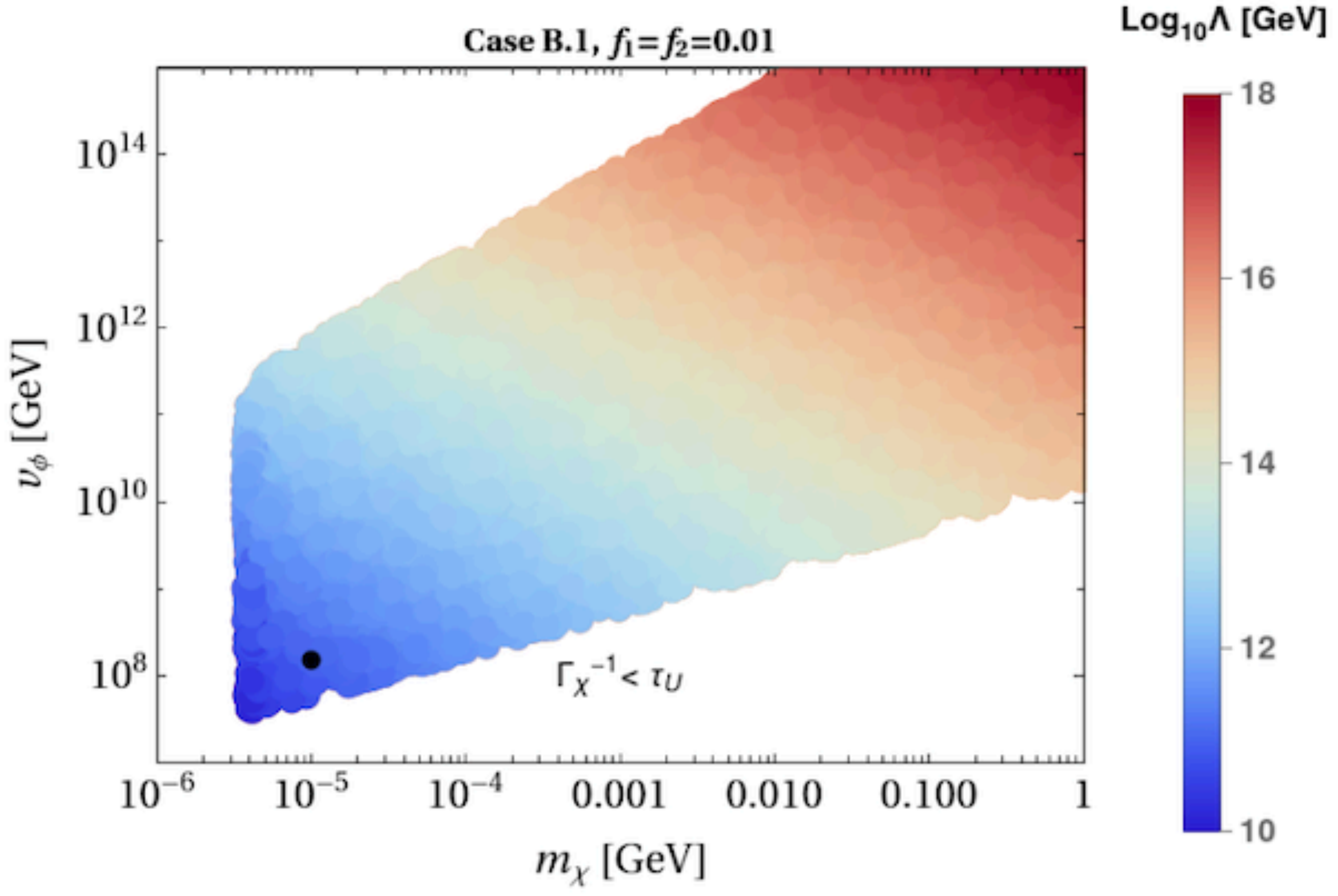
Parameter ranges for scan

m_χ: 0.4 (3) keV — 1 GeV

v_ϕ : 10^6 GeV – 10^{15} GeV

Λ : 10^{10} GeV – 10^{18} GeV

$[\Lambda \leq M_P]$



[Case B: RHNs absent in thermal bath at T_L] Degenerate RHNs

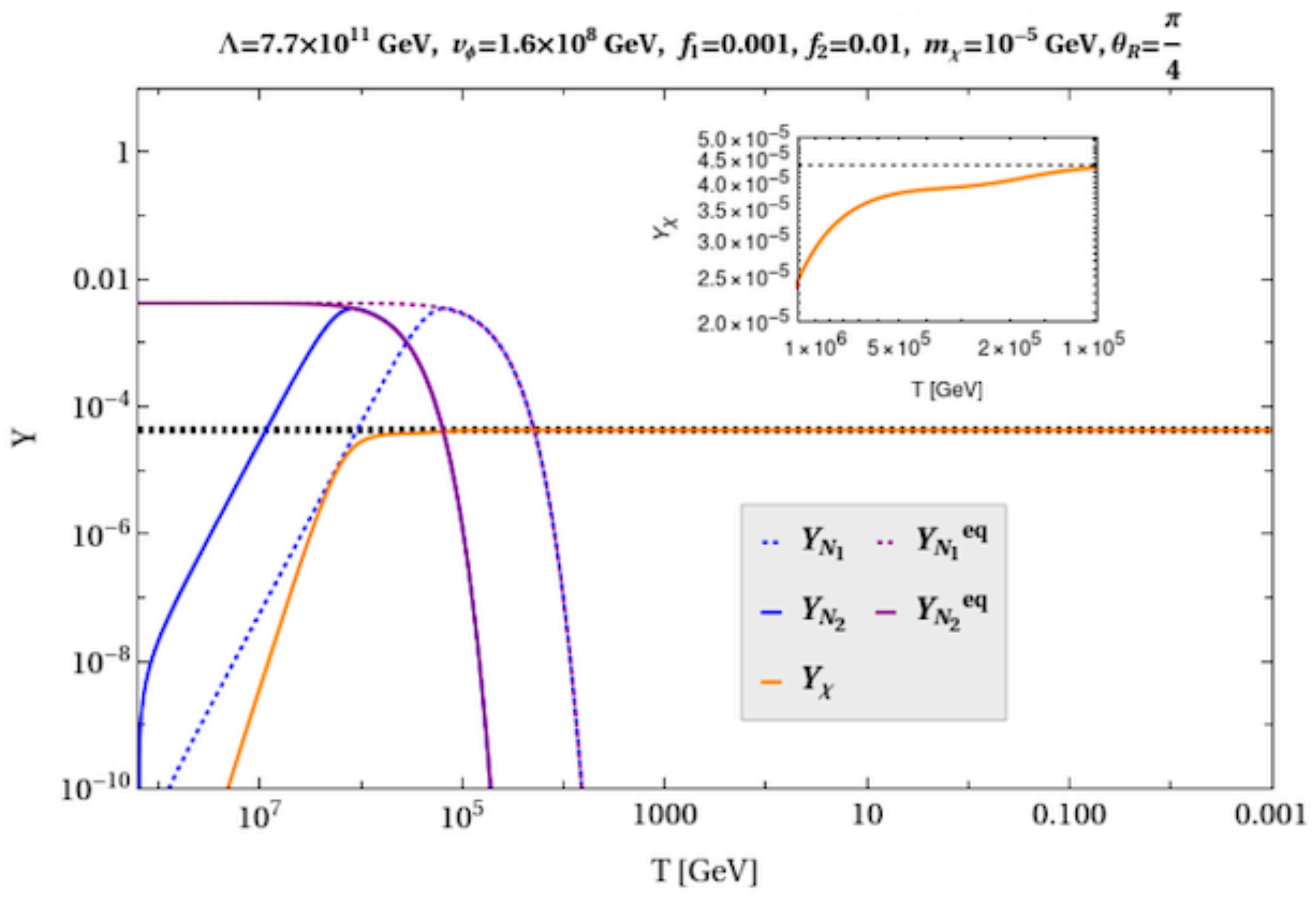
Smaller values of Λ seems realisable with Case B

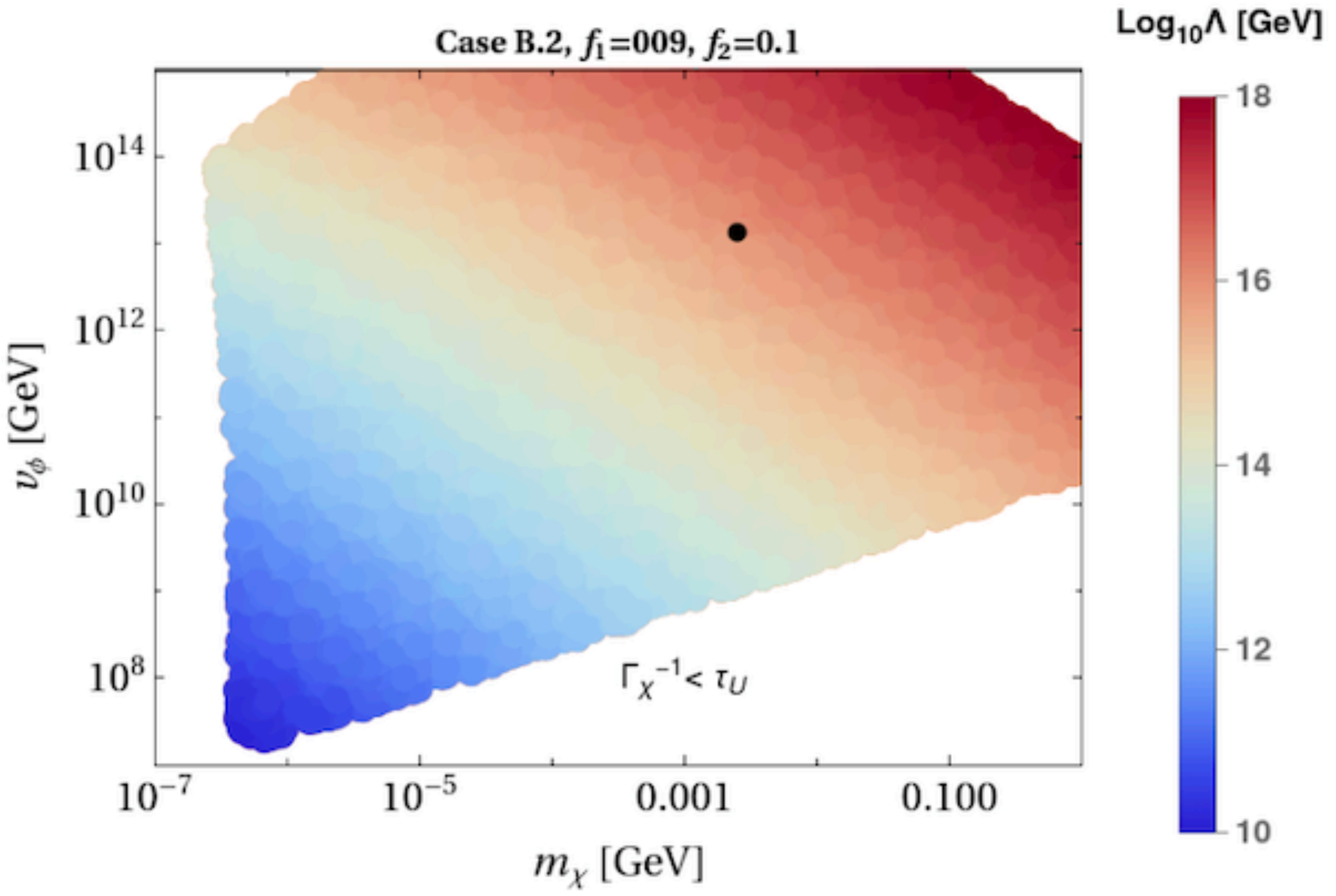
RHNs needs to be produced initially, hence information on neutrino Yukawa coupling y_ν is important

Relic Satisfied Parameter space for [for NON-Degenerate RHNs)

Case A: parameter space remains identical as degenerate case

[Case B: RHNs absent in thermal bath at T_L]





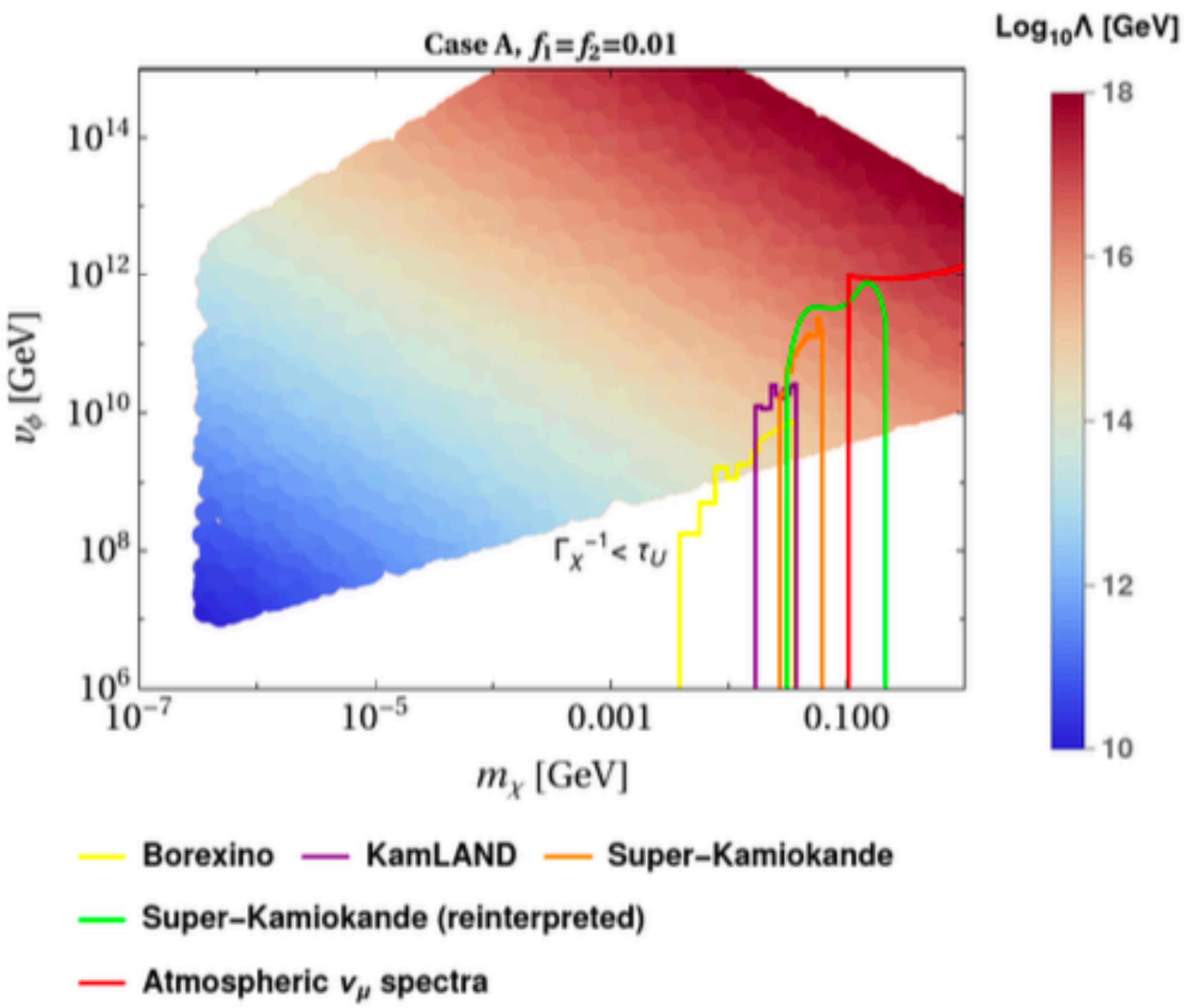
v_ϕ (GeV)	m_χ (GeV)	f_1	f_2	θ_R	Λ (GeV)
1.6×10^8	10^{-5}	0.001	0.01	$\frac{\pi}{4}$	7.7×10^{11}

A delayed Freeze-in can be noticed: as the lighter RHN catches equilibrium at a later stage

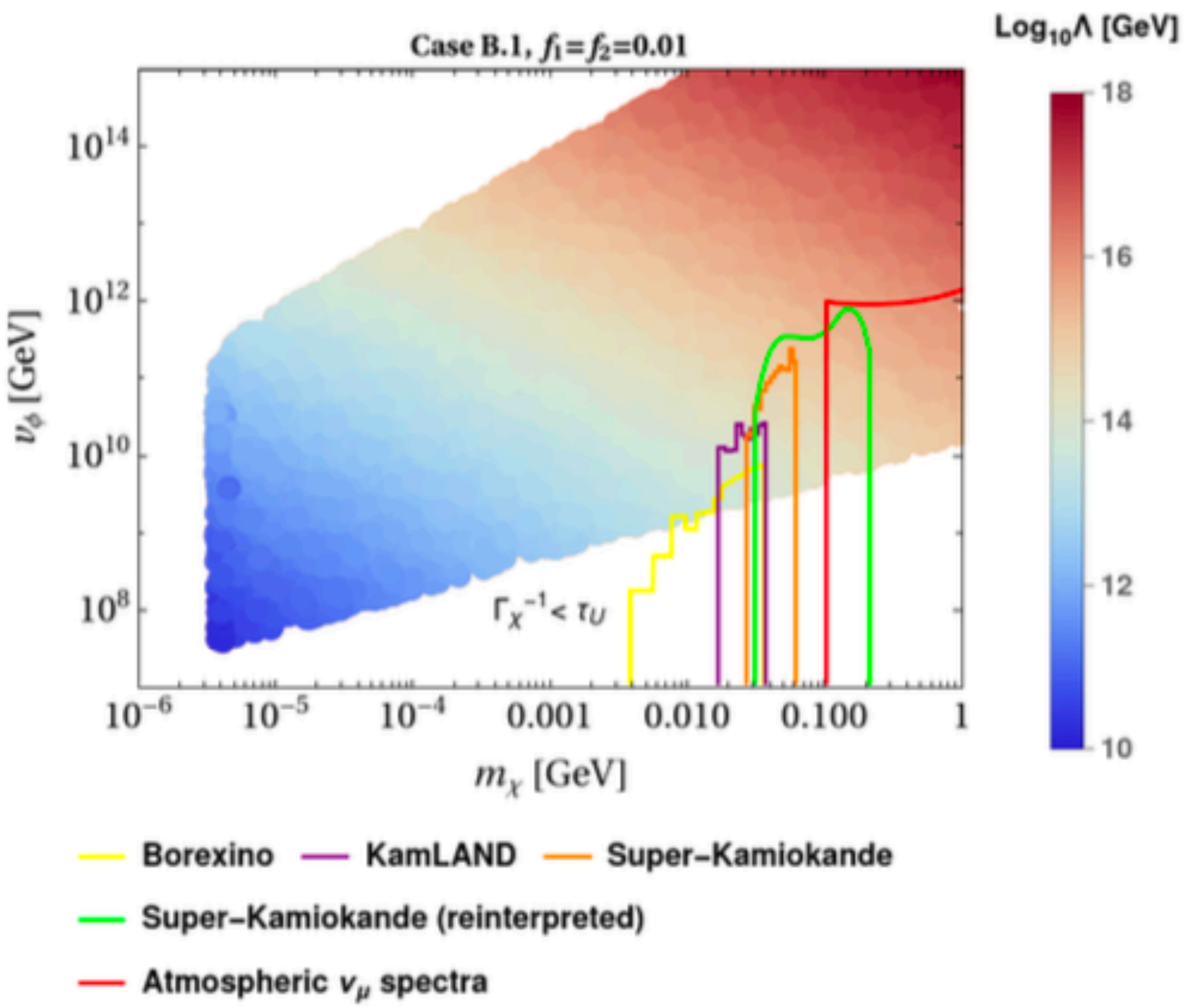
Indirect search: $\chi \to \nu\nu$ (Heeck et. al. 2017)

- $\chi \to \nu\nu$ is possible due to **active-sterile mixing**, where the tree-level coupling is $\propto m_\nu$.
- **Majoron mass $\gtrsim$ 4 MeV** can be testified via **monochromatic neutrino-flux** in experiments such as, **Borexino, KamLAND, Super-Kamiokande, Icecube** etc.
- $\chi \to \nu\nu$ searches are **independent** to any other visible channel search.

case-A (degenerate RHNs):



case-B (degenerate RHNs):



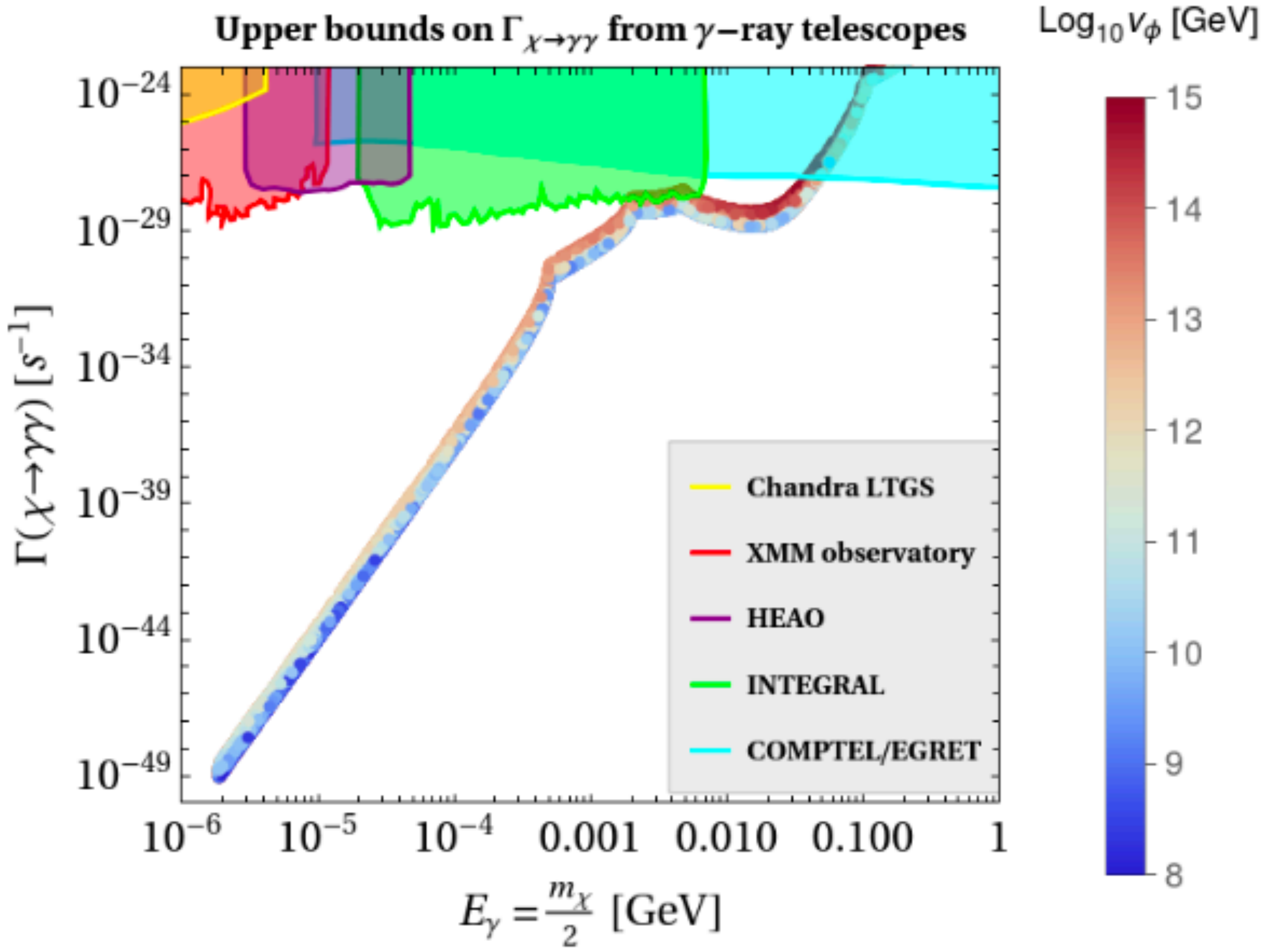
Indirect search: $\chi \to \gamma\gamma$ (Lattanzi et. al. 2013, Heeck et. al. 2017)

⋆ $\chi \to \gamma\gamma$ is possible via 2-loops.

⋆ For **Majoron mass < MeV**, $\chi \to \gamma\gamma$ various γ-ray telescope observatory such as **INTEGRAL, COMPTEL/EGRET, Fermi-LAT, Chandra and XMM telescope** etc. are possible.

⋆ However, $\chi \to \gamma\gamma$ channel is model dependent and thus **less robust**.

case-B (degenerate RHNs, $f = 0.01$):



Other constraints (Escudero et. al. 2020, Bae et. al. 2018)

⋆ **From Supernova:**

- Excess energy emission from SN provides a **disallowed** range of the coupling $g_{\chi\nu\nu}$: $(10^{-7} - 10^{-5})$ for $m_\chi < 10$ MeV and $(10^{-9} - 10^{-6})$ for $m_\chi < 200$ MeV.

$$g_{\chi\nu\nu} = \frac{\Sigma_i m_{\nu_i}}{2 v_\phi}$$

- In our parameter scan, $\Longrightarrow$ $g_{\chi\nu\nu} \lesssim 2.5 \times 10^{-18}$.

→ **SN constraints are easily evaded in our case.**

⋆ **From Lyman-α observations:**

- Important for DM mass at **keV scale**.
- Constraint on thermal warm dark matter (WDM) mass can be translated into an **approximate lower bound** on Majoron mass, $m_\chi \gtrsim 5.3$ keV.

The case with **Degenerate** RHNs: can it be further connected to **resonant** leptogenesis ?

Stephen F King, Soumen kumar Manna, Rishav Roshan, AS [PRD 111 (2025)]

Earlier we noticed: the additional explicit LNV term contributes to Majoron production as well as RHN mass

↓

Can this be used to split the degeneracy of the TWO RHNs?

↓

Then the same term can used for resonant leptogenesis

A typical construction for exactly degenerate RHNs

Symmetries	Φ	$\mathcal{N}_1$	$\mathcal{N}_2$
$U(1)_L$	-2	1	1
Z_2	$-$	$+$	$-$

$$-\mathscr{L}_{\rm SC} \supset \frac{f}{2}\Phi\overline{\mathcal{N}_1^C}\mathcal{N}_2 + y_{\alpha 1}\overline{L_\alpha}\tilde{H}\mathcal{N}_1 + h.c. \longrightarrow M_R = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix},$$

With $M = f v_\phi/\sqrt{2}$

$$-\mathscr{L}_{\rm LNV} = \frac{c_1}{2\Lambda}\left[\Phi^2 + (\Phi^*)^2\right] \overline{\mathcal{N}_1^C}\mathcal{N}_1 + \frac{c_2}{2\Lambda}\left[\Phi^2 + (\Phi^*)^2\right] \overline{\mathcal{N}_2^C}\mathcal{N}_2 + \frac{y_{\alpha 2}}{\Lambda}\overline{L_\alpha}\tilde{H}\mathcal{N}_2(\Phi + \Phi^*) + h.c..$$

↓ diagonal entries of M_R ↓

↓ Yukawa interaction of second RHN

Results into RHN masses a after seesawing:

$$M_{1,2} = \frac{f v_\phi}{\sqrt{2}} \pm \frac{v_\phi^2}{\Lambda}$$

Determination of neutrino mass requires estimating neutrino Yukawa coupling via CI parametrisation:

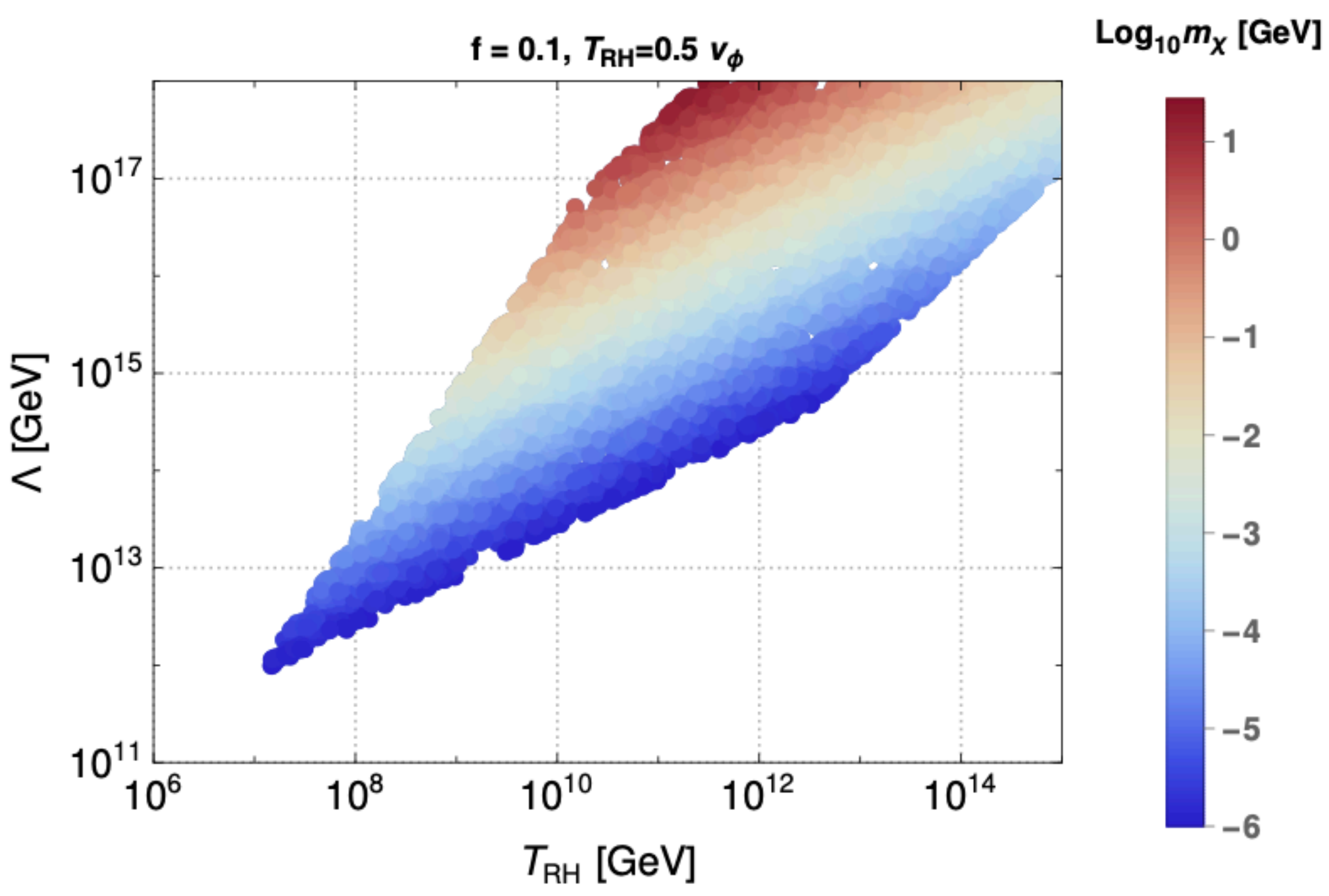
$$y^\nu = \frac{\sqrt{2}}{v} U^\dagger D_{\sqrt{m_\nu}} R D_{\sqrt{M_R^d}}$$

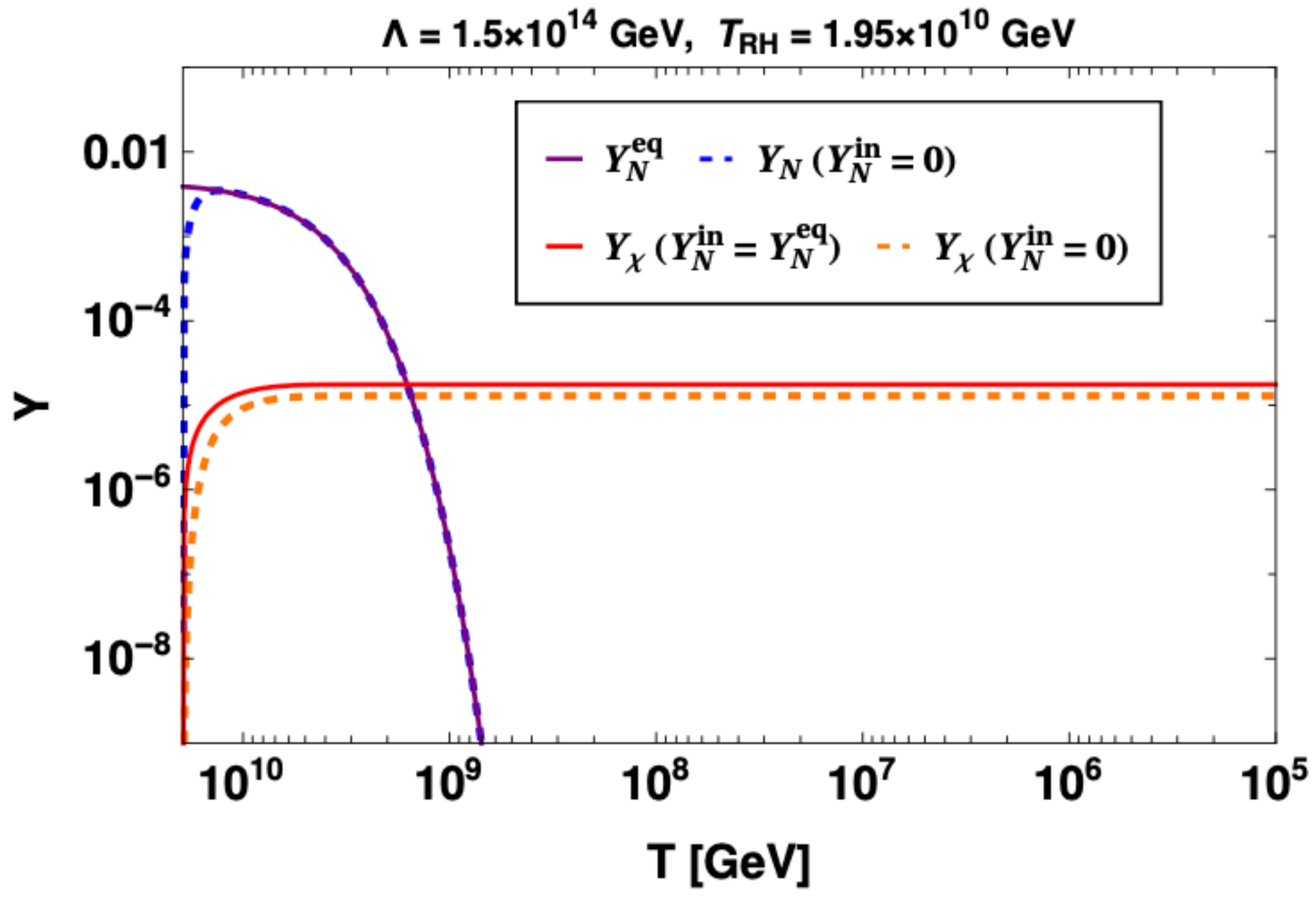
DM phenomenology

$U(1)_L$ symmetry breaking to take place prior to the reheating temperature $T_{\rm RH}$ of the Universe

A typical hierarchy $v_\phi > T_{\rm RH} > M_i$ is in place

dark matter production is sensitive to $T_{\rm RH}$, which is considered as a free parameter in the study





Resonant Leptogenesis

- Below the $T_{\rm RH}$, the RHNs are produced from inverse decay (with zero initial abundance) via neutrino Yukawa interaction.

- The dynamical generation of lepton asymmetry takes place in an the era of radiation dominated Universe, below $T_{\rm RH}$ $(M_i < T_{\rm RH})$ when the RHNs start decaying in out of equilibrium:

$$\Gamma_{N_i \to LH} = \frac{|y^{\nu}_{ii}|^2}{8\pi} M_i.$$

abundance of the RHNs and evolution of L-asymmetry are guided by

$$\frac{dY_{N_i}}{dx} = -\frac{1}{\mathcal{H}x\mathcal{S}}\left[\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right](\gamma_{N_i} + 2\gamma_{h_s} + 4\gamma_{h_t}),$$

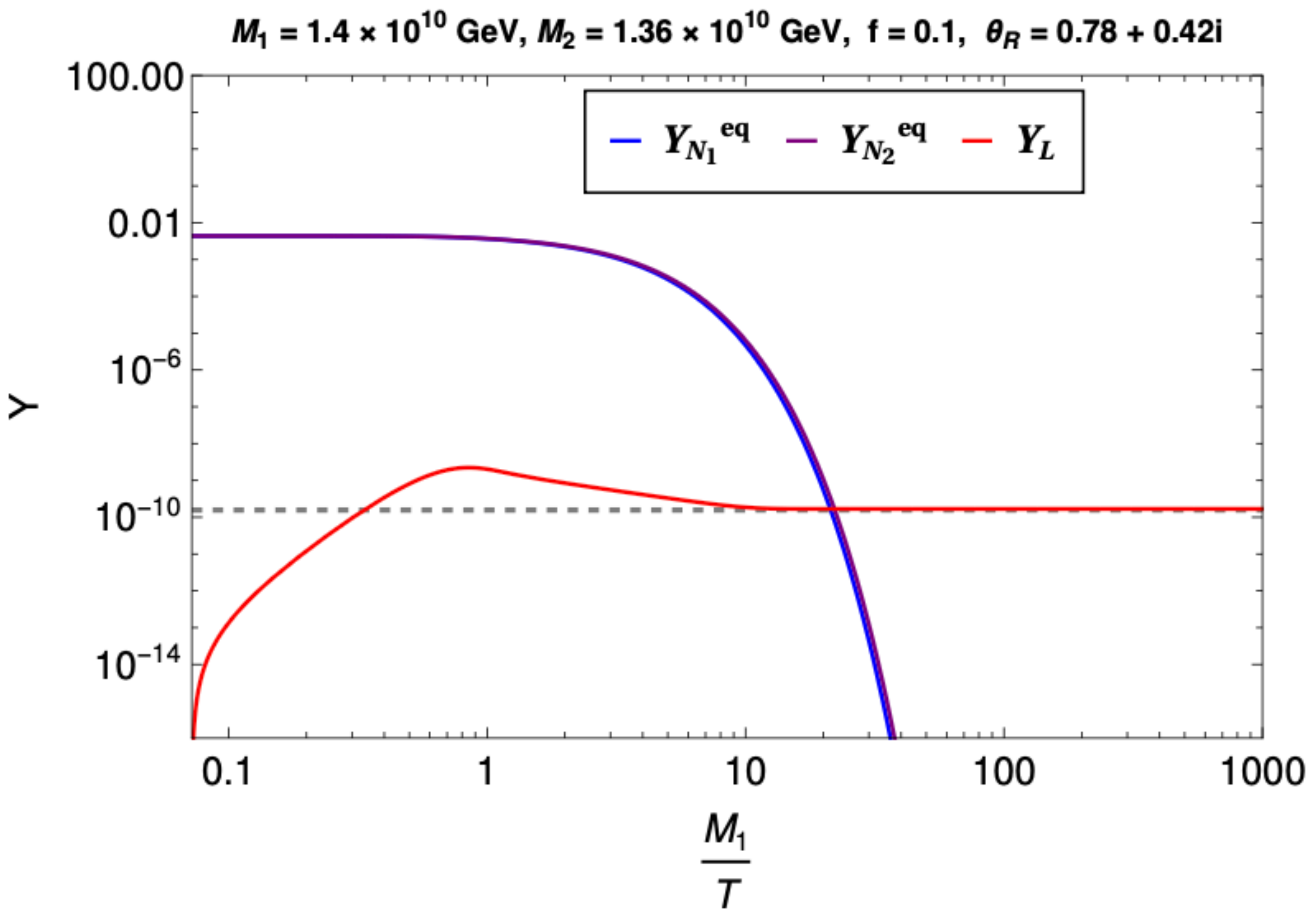
$$\frac{dY_L}{dx} = \sum_i \frac{1}{\mathcal{H}x\mathcal{S}}\left[\epsilon_{N_i}\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right) - \frac{Y_L}{2Y^{eq}_l}\right]\gamma_{N_i} - \frac{Y_L}{Y^{eq}_l}\gamma_\sigma$$

CP asymmetry

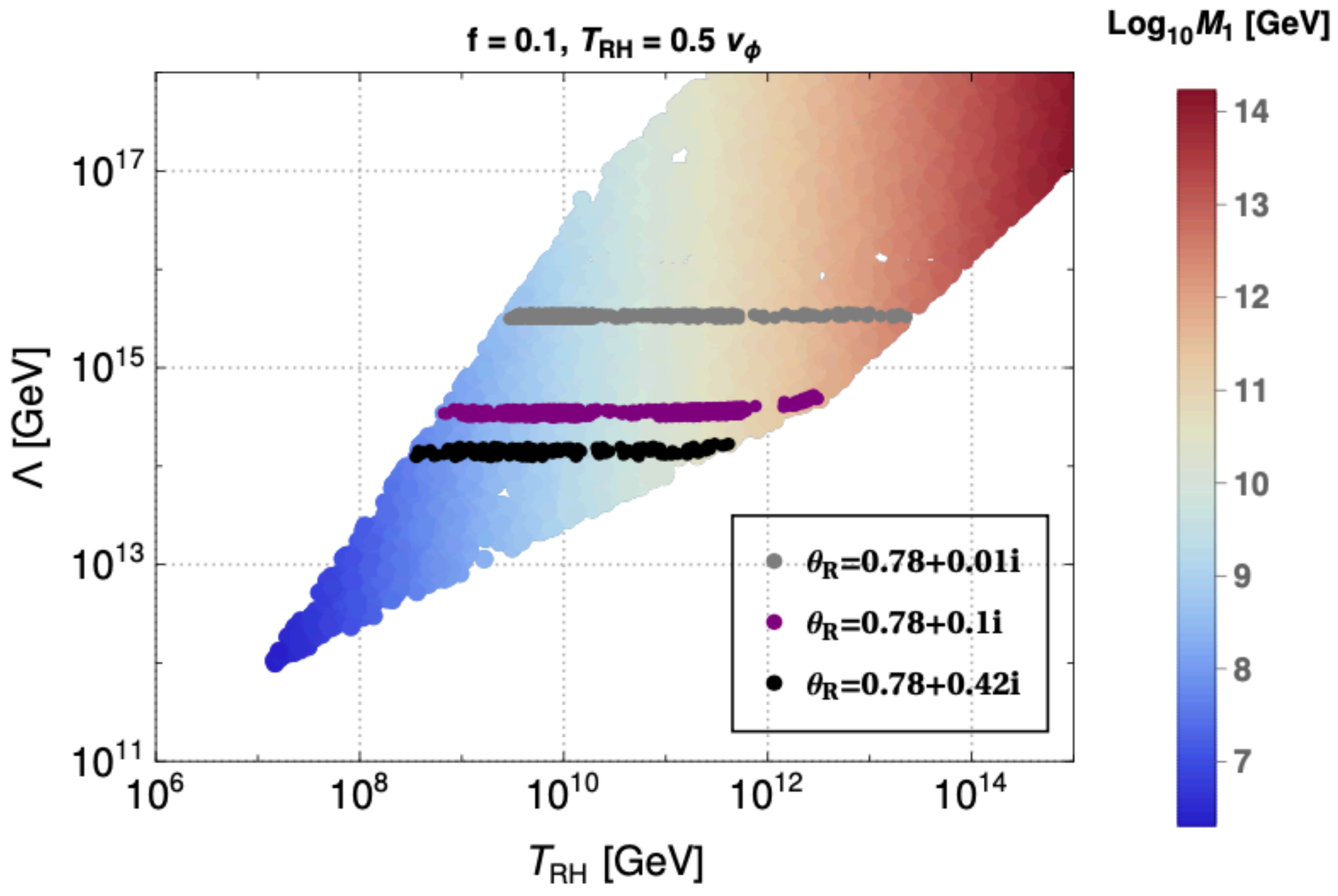
$$\epsilon_{N_i} = -\sum_{j\neq i} \frac{M_i \Gamma_{N_j}}{M_j^2}\left(\frac{V_{ij}}{2} + S_{ij}\right)\frac{\mathrm{Im}(y^{\nu\dagger} y^{\nu})^2_{ij}}{(y^{\nu\dagger} y^{\nu})_{ii}(y^{\nu\dagger} y^{\nu})_{jj}}$$

$$V_{ij} = 2\frac{M_j^2}{M_i^2}\left[\left(1 + \frac{M_j^2}{M_i^2}\right)\ln\left(1 + \frac{M_i^2}{M_j^2}\right) - 1\right]$$

$$\text{and} \quad S_{ij} = \frac{M_j^2(M_j^2 - M_i^2)}{(M_j^2 - M_i^2)^2 + M_i^2 \Gamma^2_{N_j}},$$



Evolution of the yields of RHNs and lepton asymmetry



The BAU satisfied parameter space

Conclusions

- Lightest right handed neutrino can be the dark matter in the context of Type-I seesaw, in its simplest version where their production is governed by the decay of SM gauges bosons.

- Majorons as dark matter (may as well be connected to BAU) within the type-I seesaw turns out to be viable in a broad range of parameter space for Majoron mass

Neutrinos have the potential of shedding light on the nature of dark matter.