

DM @IJCLab

Superheavy dark matter: Constraints from TeV γ rays?

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Superheavy dark matter?



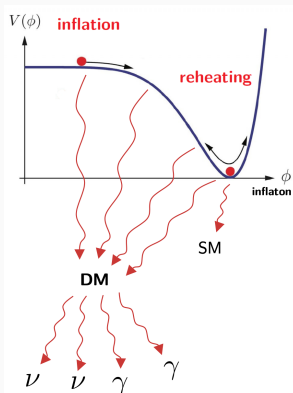
- ☛ Superheavy particles?
 - Inflationary sector:
 $M_\phi \sim 10^{13}$ GeV for vanilla inflaton potentials
 - Sterile neutrinos
 - New degrees of freedom N_R
 - BSM scale at $\sim 10^{13}$ GeV in vanilla seesaw
 - GUT

- Instability energy scale of SM: $\Lambda \sim 10^{[10-12]}$ GeV

- ☛ Hidden/Dark sector at high scale? (ie. superheavy particles interacting feebly with SM *not* through SM gauge interactions)
 - Additional portal? e.g. axion (pseudo-scalar), Higgs (scalar), sterile neutrino (spin 1/2), vector (spin 1), etc.
 - Gravitational SM/DS interactions

Non-thermal production of SHDM particles

- Minimalism: No coupling between SM and DM sectors but gravitational



- Production during inflation by rapid changes of the metric (overabundance for scalars unless $M_X \gtrsim 10^{12}$ GeV)
 - Production by “freeze-in” mechanism through s-channel $\text{SM}+\text{SM} \rightarrow \text{DM}+\text{DM}$ or $\phi + \phi \rightarrow \text{DM}+\text{DM}$ between end of inflation $t = H_{\text{inf}}^{-1}$ and Reheating between $t = \Gamma_{\phi}^{-1}$ at T_{rh}
 - Production by Schwinger effect if dark photon produced gravitationally
- Viable regions in the (H_{inf}, M_X) plane to match the DM relic density for various Reheating efficiency ($\epsilon \simeq 4T_{\text{rh}}(M_{\text{Pl}}H_{\text{inf}})^{-1/2}$ defined between 0 and 1, characterizing the duration of the Reheating duration)
 - Even $M_X \sim M_{\text{GUT}}$ still viable for $H_{\text{inf}} \sim 10^{13}$ GeV

Prompt flux of cosmic particles from DM

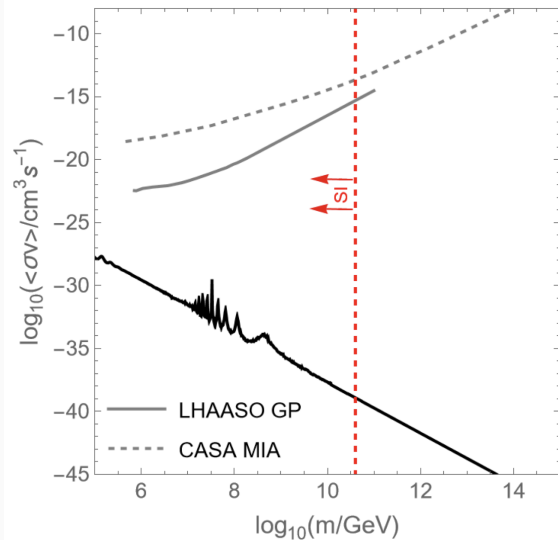
- Diffuse flux (per steradian) of any particle of type i and of high energy E (gamma-rays, (anti-)nucleons, neutrinos) from the prompt emission of annihilating/decaying superheavy particles:

$$\phi_i(E, \mathbf{n}) = \frac{1}{4\pi} \int_0^\infty ds q_i(E, \mathbf{x}(s, \mathbf{n})) e^{-\tau(E, \mathbf{n}, s)s}$$

- Integration of the position-dependent emission rate per unit volume and unit energy along the “lookback position” in the direction \mathbf{n}
- For neutral particles, lookback position = position along the line of sight, $\mathbf{x}(s, \mathbf{n}) = \mathbf{x}_\odot + s\mathbf{n}$, with \mathbf{x}_\odot the position of the Solar system in the Galaxy and $\mathbf{n} \equiv \mathbf{n}(\ell, b)$ a unit vector on the sphere pointing to the longitude ℓ and latitude b
- $\tau(E, \mathbf{n}, s)$: optical depth for photons, galactic scale for $E \gtrsim 10^8$ GeV

Prompt flux – Emission rate from annihilation

• Bounds not competitive



Prompt flux – Emission rate from decay

- Shaped by DM density n_{DM} , more conveniently expressed in terms of energy density $\rho_{\text{DM}} = M_X n_{\text{DM}}$, and by the differential decay width into the particle species i as

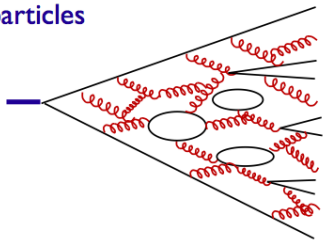
$$q_i(E, \mathbf{x}) = \frac{\rho_{\text{DM}}(\mathbf{x})}{M_X \tau_X} \sum_k \text{BR}_k \frac{dN_{k,i}(E; M_X)}{dE}$$

- BR_k : branching ratio into the channel k
- $\rho_{\text{DM}}(\mathbf{x})$: DM profile
- $\frac{dN_{k,i}(E; M_X)}{dE}$: Energy spectrum of secondaries i from channel k

Fragmentation of final states

- Soft or collinear (real) radiative corrections enhanced by large logarithmic factors $\log^2 (\Lambda/\Lambda_{EW})$ at high scale

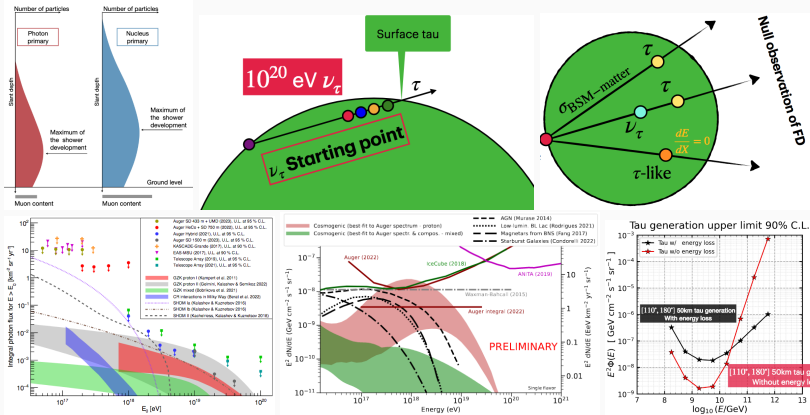
Super-heavy particles



large fluxes of photons and neutrinos

- Fragmentation effects similar to QCD cascades
- “EW cascades”
- Whatever decay channels, large fluxes of UHE γ , ν , e, p, n
- HDMSpectra public tool providing energy spectra of final states for any decay-channel model

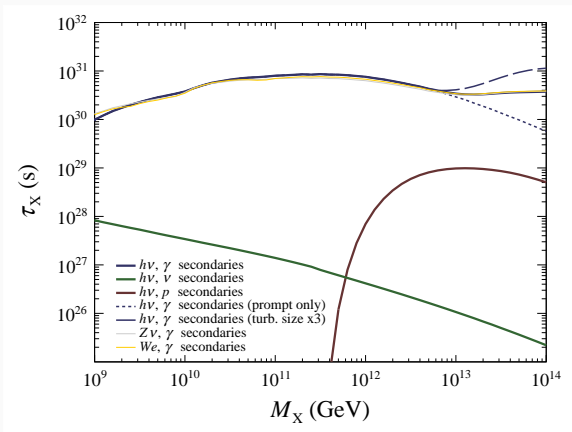
Potential observations at UHE



- γ : Horizon limited to Galactic scale
- Neutrinos : Cosmological horizon
- “BSM” τ channel: specific models invoking sterile neutrinos or SUSY sphaleron transitions

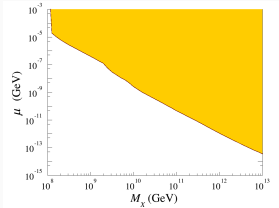
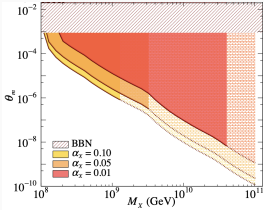
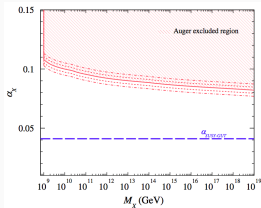
Benchmark constraints

- Best constraints on τ_X from sensitivity to UHE γ s for $M_X \gtrsim 10^9$ GeV



☛ $\tau_X > 10^{30}$ s viable in concrete models?

Metastability through several scenarios



- Secluded sector: decay by instantons [Kuzmin/Rubakov Phys. At. Nucl. 61, 1028 (1998); PRL 130 (2023) 061001 ; PRD 107 (2023) 042002]
- Extended seesaw frameworks [Dudas et al. PRD 101, 115029 (2020); Phys. Rev. D 109 (2024) L081101; EPJC 85, 985 (2025)]
- SUSY broken at high scale with RPV [Dudas et al. PRD 98 (2018) 015030;]

Secondary emission of γ -rays

- Secondary electrons \implies Secondary fluxes of γ -rays from:
 - ICS on low-energy photons (CMB, IR or star-light backgrounds)
 - Synchrotron emission
- To a good approximation, dn/dE_e results from a transport equation that retains only energy-loss and source terms,

$$\frac{\partial}{\partial E_e} \left(b(E_e, \mathbf{x}) \frac{dn(E_e, \mathbf{x})}{dE_e} \right) = \frac{\rho_{\text{DM}}(\mathbf{x})}{M_X \tau_X} \frac{dN_e(E_e; M_X)}{dE_e},$$

with $b(E_e, \mathbf{x})$ the energy-loss rate due to synchrotron emission and ICS, ρ_r the radiation energy density of backgrounds and ρ_B that of the GMF

- Solution:

$$\frac{dn(E_e, \mathbf{x})}{dE_e} = \frac{\rho_{\text{DM}}(\mathbf{x})}{M_X \tau_X b(E_e, \mathbf{x})} Y_e(E_e),$$

with $Y_e(E_e) = \int_{E_e}^{M_X/2} dE'_e dN_e(E'_e; M_X)/dE'_e$ the yield of electrons with energy $\geq E_e$

Inverse Compton Scattering

- Emission rate shaped by the (differential) power $dP_{\text{ICS}}(E_e, E, \mathbf{x})/dE$ of electrons with energy E_e (and mass m_e) emitting photons in the band between E and $E + dE$ weighted by the (differential) density of electrons:

$$q_\gamma(E, \mathbf{x}) = \frac{1}{E} \int_{m_e}^{M_\chi/2} dE_e \frac{dn(E_e, \mathbf{x})}{dE_e} \frac{dP_{\text{ICS}}(E_e, E, \mathbf{x})}{dE}.$$

- In the Thomson limit,

$$\frac{dP_{\text{ICS}}(E_e, E, \mathbf{x})}{dE} = \frac{3\sigma_T m_e^2 E}{4E_e^2} \int_0^1 dy \frac{n(E^0(y), \mathbf{x})}{y} (2y \ln y + y + 1 - 2y^2)$$

with $E^0(y) = Em_e^2/(4E_e^2 y)$

- Emission negligible for $m_\chi \gtrsim 10^6$ GeV...

Synchrotron radiation

- Emission rate shaped by the (differential) synchrotron power of electrons with energy E_e emitting photons in the band between E and $E + dE$ weighted by dn/dE_e :

$$q_\gamma(E, \mathbf{x}) = \frac{1}{E} \int_{m_e}^{M_x/2} dE_e \frac{dn(E_e, \mathbf{x})}{dE_e} \frac{dP_{\text{syn}}(E_e, E, \mathbf{x})}{dE}.$$

- Synchrotron power:

$$\frac{dP_{\text{syn}}(E_e, E, \mathbf{x})}{dE} = \frac{b_B(E_e, \mathbf{x})}{E_c(E_e, \mathbf{x})} \tilde{F}\left(\frac{E}{E_c(E_e, \mathbf{x})}\right), \text{ with}$$

- $b_B(E_e, \mathbf{x})$ the energy-loss rate due to synchrotron emission only
- $\tilde{F}(x) = \frac{9\sqrt{3}}{8\pi} x \int_x^\infty dx' K_{5/3}(x')$ a cutoff function
- E_c a cutoff energy defined as

$$E_c(E_e, \mathbf{x}) \simeq 6.6 \times 10^1 \left(\frac{E_e}{10^9 \text{ GeV}}\right)^2 \left(\frac{B_\perp(\mathbf{x})}{\mu\text{G}}\right) \text{ GeV}$$

- ☛ TeV γ -rays more constraining than UHE ones?

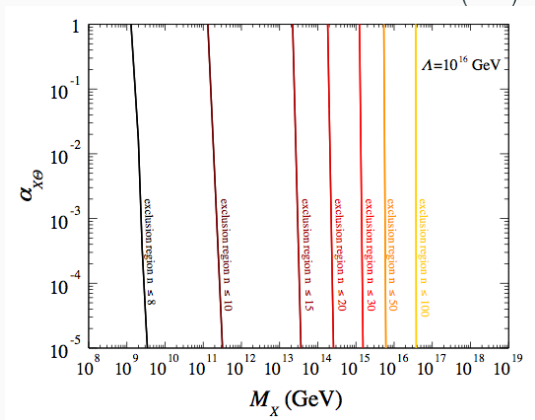
Conclusions

- Continuous searches of UHE gamma rays and neutrinos at the Pierre Auger Observatory
- Upper limits on fluxes of considerable interest for UHECR astrophysics *and* BSM physics, in particular SHDM
- Best constraints on τ_χ from UHE γ -ray flux limits (in general) for $M_\chi \gtrsim 10^9$ GeV
- ☛ Better constrain SHDM models using TeV γ rays by scrutinizing synchrotron emission from electron decay byproducts from the GC?
- ☛ Better constrain TeV DM models using radio fluxes (from synchrotron emission) and GeV γ rays from ICS?

Superheavy and metastable particles?

- Decay rate for an effective interaction term containing a monomial of dimension n in mass unit:

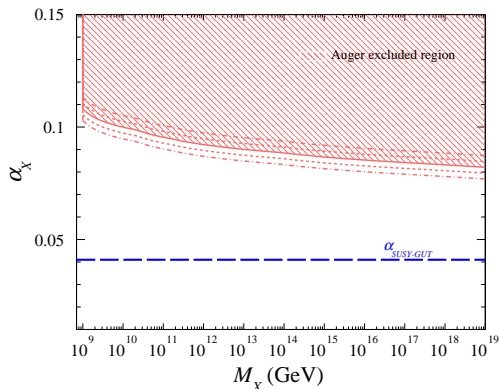
$$\Gamma_X \propto \alpha_{X\Theta} M_X \left(\frac{M_X}{\Lambda} \right)^{2n-8}$$



- Fine tuning between $\alpha_{X\Theta}$ and n ...
- Difficult to justify from a theoretical perspective
- [Pierre Auger Collab., Phys. Rev. D 107 (2023) 042002]**

Metastability by symmetry protection

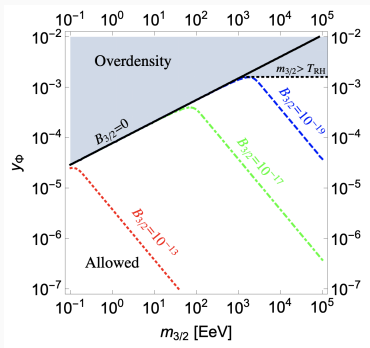
- SHDM particles protected from standard decay by perturbative effects through a new quantum number
- Still, non-perturbative effects can lead to decays through “instantons” in non-commutative gauge theories
- For B , L and X currents not associated to gauge interactions, possibility to exchange quantum numbers through an anomaly



- Lifetime of metastable X particles: $\tau_X \simeq M_X^{-1} \exp(4\pi/\alpha_X)$
[t'Hooft, PRL 37 (1976) 8]
- [Pierre Auger Collab., Phys. Rev. Lett. 130 (2023) 061001]

High scale supergravity – The case of the EeV gravitino

- Supersymmetry broken at high scale \tilde{m}^2 above the inflationary scale ($M_\phi \sim 3 \times 10^{13}$ GeV from density-perturbation amplitude in CMB)?
- SUSY particles never being produced by either thermal processes during reheating or by the decay of the inflaton



☛ Gravitino exception:

$$M_{3/2} > M_\phi^2 / \sqrt{3} M_{\text{Pl}} \sim 10^8 \text{ GeV}$$

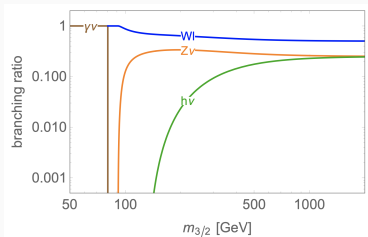
- Production from thermal bath (gluons): $T_{\text{th}} \sim [10^{10} - 10^{12}] \text{ GeV}$
- Linear increase of y_ϕ with $M_{3/2}$ to counterbalance $1/\tilde{m}^2$ couplings
- Alternative: $B_{3/2} \neq 0$:

$$y_\phi < \left(\frac{B_{3/2}}{10^{-18}} \right)^{-1} \left(\frac{M_{3/2}}{10^8 \text{ GeV}} \right)^{-1}$$

Cf. [Dudas et al. PRL 119 (2017) 051801]

R -parity violation operators

- R -parity (stability of the proton) \implies LSP stable DM candidate
- Limits on RPV couplings: baryon- and lepton-number violating interactions out-of-equilibrium in the early universe to preserve the baryon asymmetry
- High-scale SUSY: sparticles never in the thermal bath to mediate interactions washing out the baryon asymmetry



- Bilinear RPV operator:

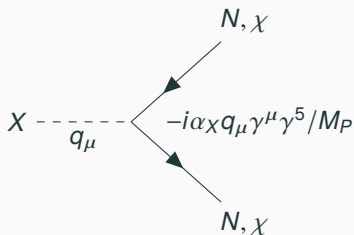
$$W = W_{\text{MSSM}} + \mu' LH_u$$

- Lepton number not conserved
- Baryon number conserved

Cf. [Dudas et al. PRD 98 (2018) 015030], [Allahverdi et al. JHEP 02 (2024) 192]

- $\mu' < 10^{-5} \left(\frac{M_{3/2}}{10^8 \text{ GeV}} \right)^{-2} \text{ GeV}$ (Weak-scale SUSY: $\mu' < 20 \text{ keV}$ from the preservation of the baryon asymmetry)

- Pseudo-scalar X interacting with sterile-neutrinos sector:



(motivated by several UV models with string or higher-dimensional inspired moduli fields)

- Extended Seesaw framework:

$$\begin{pmatrix} \bar{\nu}_L & \bar{\chi}_R^c & \bar{N}_R^c \end{pmatrix} \begin{pmatrix} 0 & \delta m & m_D \\ \delta m & m_\chi & 0 \\ m_D & 0 & M_N \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \chi_R \\ N_R \end{pmatrix}$$

with $\delta m \ll m_\chi \ll m_D \ll M_N$

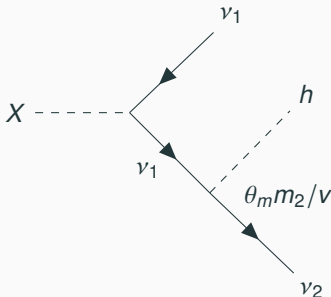
- Mass eigenstates controlled by mixing angle $\theta_m = \delta m / m_\nu \ll 1$:

$$\nu_1 \simeq (\chi_R + \chi_R^c) + \theta_m (\nu_L + \nu_L^c)$$

$$\nu_2 \simeq (\nu_L + \nu_L^c) - \theta_m (\chi_R + \chi_R^c)$$

$$\nu_3 \simeq N_R$$

☛ $X \rightarrow h\nu_1\nu_2$ decay channel:

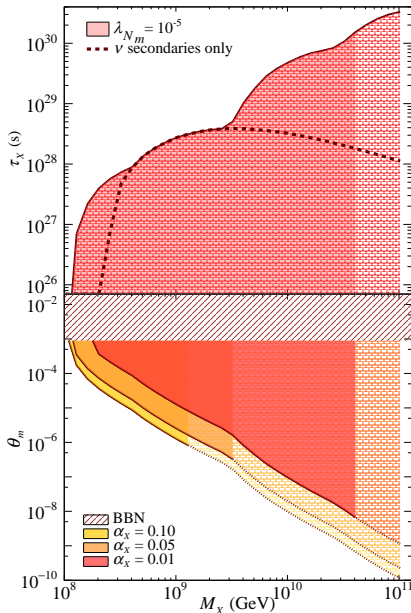
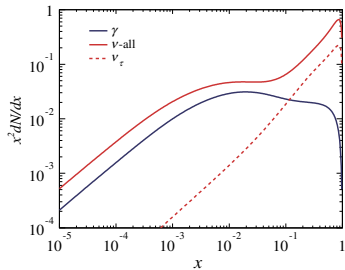


☛ Decay width controlled by $(m_2/v)^2$ and θ_m^2 :

$$\Gamma_{h\nu_1\nu_2}^X = \frac{\alpha_X^2 \theta_m^2}{192\pi^3} \left(\frac{M_X}{M_P}\right)^2 \left(\frac{m_2}{v}\right)^2 M_X$$

Metastability through sterile-neutrino portal

- End-to-end calculation of expected number of UHE gamma rays/neutrinos
- [Pierre Auger Collab., Phys. Rev. D 109 (2024) L081101]



- Extended Seesaw framework:

$$\begin{pmatrix} \overline{\nu}_L & \overline{\chi}_R^c & \overline{N}_R^c \end{pmatrix} \begin{pmatrix} 0 & \delta m & m_D \\ \delta m & M_\chi & \delta M \\ m_D & \delta M & M_N \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \chi_R \\ N_R \end{pmatrix}$$

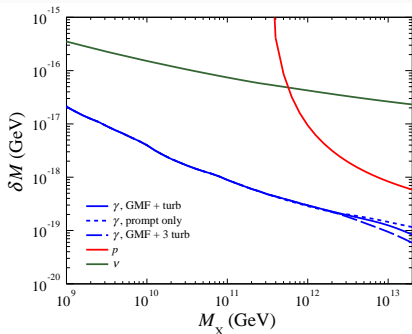
with $\delta m \ll \delta M \ll m_D \ll M_\chi < M_N$

- Mass eigenstates controlled by $\theta_N = \delta m/M_N$ and $\theta_\chi = \delta M/(M_N - M_\chi)$:

$$\begin{aligned} \tilde{\nu} &\simeq (\nu_L + \nu_L^c) + \theta_N(N_R + N_R^c), \\ \tilde{\chi} &\simeq (\chi_R + \chi_R^c) - \theta_\chi(N_R + N_R^c), \\ \tilde{N} &\simeq (N_R + N_R^c) + \theta_N(\nu_L + \nu_L^c) + \theta_\chi(\chi_R + \chi_R^c), \end{aligned}$$

- $\tilde{\chi} \rightarrow h\tilde{\nu}$ decay channel:

$$\begin{aligned} \frac{y_N}{\sqrt{2}} h \left(\overline{\nu}_L N_R + \overline{N}_R \nu_L \right) &= \dots + \frac{iy_N \theta_\chi}{2\sqrt{2}} h \left(\overline{\tilde{\nu}} \tilde{\chi} + \overline{\tilde{\chi}} \tilde{\nu} \right) + \dots \\ \Gamma_{\tilde{\chi} \rightarrow h\tilde{\nu}} &= \frac{|y_N|^2 \theta_\chi^2}{256\pi} M_{\tilde{\chi}} \end{aligned} \tag{1}$$



- End-to-end calculation of expected number of UHE nucleons, gamma rays and neutrinos
- Secondary UHE gamma rays from ICS negligible
- Secondary UHE gamma rays from synchrotron important only for $M_X \gtrsim 10^{13}$ GeV

Justification of the mass hierarchies?

- ➔ High-scale U(1) global symmetry, with sector of superheavy Weyl $\{\psi, \tilde{\psi}\}$ fermions with mass M_P and scalars with vevs $\sim 10^{12-13}$ GeV

X	L	χ_R	N_R	ϕ_X	ϕ_N	ψ_1	$\tilde{\psi}_1$	ψ_2	$\tilde{\psi}_2$	ψ_3	$\tilde{\psi}_3$	ψ_4	$\tilde{\psi}_4$
0	-1	+5	+1	-	-2	-3	+3	-1	+1	+1	-1	+3	-3
-	-1	-7	+1	+14	-2	+1	-1	-13	+13	-11	+11	-9	+9

- ➔ After spontaneous symmetry breaking, seesaw framework as a low-energy effective theory with:

$$\bullet m_\chi = \frac{2\lambda_{S4}\lambda_{43}\lambda_{32}\lambda_{21}\lambda_{15}\langle\phi_N\rangle^5}{M_P^4}$$

$$\bullet M_N = 2\lambda_N\langle\phi_N\rangle$$

$$\bullet \theta_m = \frac{\lambda_{3L}\lambda_{43}\lambda_{S4V}\langle\phi_N\rangle^2}{m_\nu M_P^2}$$

$$\bullet M_\chi = 2\lambda_\chi\langle\phi_\chi\rangle$$

$$\bullet M_N = 2\lambda_N\langle\phi_N\rangle$$

$$\bullet \delta M = \frac{\lambda_{1N}\lambda_{12\chi}\lambda_{23N}\lambda_{34N}\lambda_{4\chi}\langle\phi_N\rangle^4\langle\phi_\chi\rangle}{M_P^4}$$

- ➔ Benchmark target:

$$\theta_m \sim 10^{-6} \text{ for } M_\chi = 10^9 \text{ GeV}$$

- ➔ Benchmark target:

$$\delta M \sim 10^{-18} \text{ for } M_\chi = 10^{10} \text{ GeV}$$