The Multimessenger Sky at Extreme Energies:
From Sources to Fundamental Physics
Trieste, 7-11 September 2026

Hunting super-heavy dark matter

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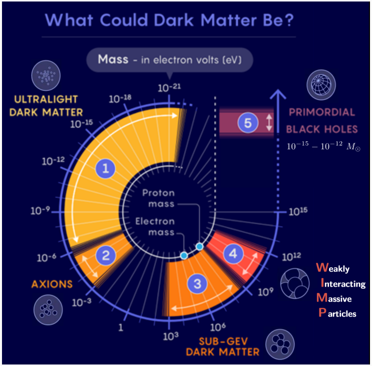
Superheavy dark matter



☛ SM vacuum instability scale:

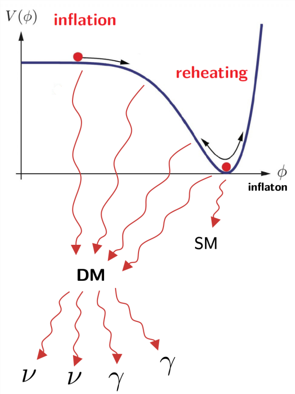
$$\Lambda_{\rm SM} \sim 10^{10-12}\ \text{GeV}$$

☛ BSM energy scales?

inflation:	$M_\phi \sim 10^{13}$ GeV
seesaw:	$M_N \sim 10^{10-15}$ GeV
GUT:	$M_{\rm GUT} \sim 10^{16}$ GeV

☛ Dark-sector superheavy particles: Production? Lifetime?

Production of SHDM particles in the early Universe



- Production solely through DM coupling to the rapidly-evolving gravitational background during inflation and especially at the transition to the post-inflationary era
- Freeze-in production SM+SM$\rightarrow$DM+DM or $\phi + \phi$ $\rightarrow$DM+DM via graviton exchanges during Reheating
- Production by inflaton decay

- Over-/Under-production (spin-dependent) for $M_X \lesssim H_{\text{end}}$, then over-production exponentially suppressed with $M_X/H_{\text{end}} > 1$
- Viable cosmological parameters to match the DM relic density

$$\Omega_X h^2 \leftrightarrow (M_X, H_{\text{end}}, T_{\text{rh}})$$

Scotogenic fluxes of cosmic particles

☛ Diffuse flux (per steradian) of particle of type i and of energy E from superheavy DM particles:

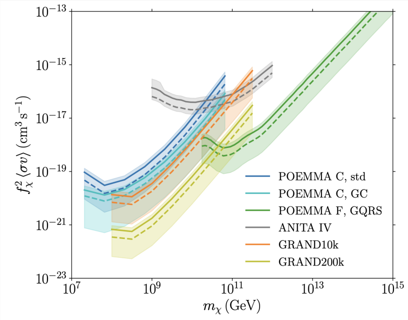
$$\phi_i(E,\mathbf{n}) = \frac{1}{4\pi}\int_0^\infty \mathrm{d}s\, q_i(E,\mathbf{x}(s,\mathbf{n}))$$

- $q_i(E,\mathbf{x}(s,\mathbf{n}))$: emission rate per unit volume and unit energy
  - Prompt emission:
    - Annihilation
    - Decay
  - Secondary emission from electrons (resulting from annihilation/decay or fragmentation byproducts):
    - ICS
    - Synchrotron

Emission rate from annihilation

- Indirect detection quite insensitive to annihilating SHDM...

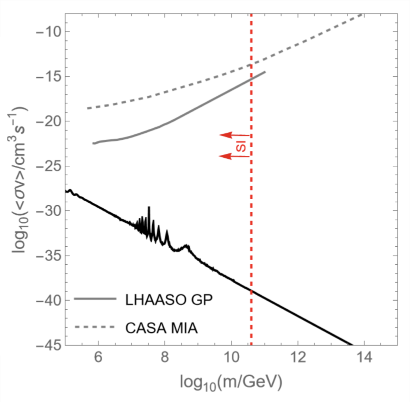
[C. Guépin et al., Phys Rev D 104 (2021) 8, 083002]



- $\langle \sigma v \rangle_{\rm exp} \sim \frac{10^{-35}}{(M_X/10^9 {\rm GeV})^2}$ cm^3 s^{-1}

- Ex: Minimal freeze-in DM: single new Weyl fermion pair

[N. Bernal et al., Phys Rev D 113 (2026) 11, 115065]



- EW doublet with $M_X > T_{\rm RH}$

Prompt flux – Emission rate from decay

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

$$q_i(E, \mathbf{x}) = \frac{\rho_{\rm DM}(\mathbf{x})}{M_X} \times \frac{1}{\tau_X} \sum_k {\rm BR}_k \frac{{\rm d}N_{k,i}(E; M_X)}{{\rm d}E}$$

- ${\rm BR}_k$: branching ratio into the channel k
- $\rho_{\rm DM}(\mathbf{x})$: DM profile
- $\frac{{\rm d}N_{k,i}(E;M_X)}{{\rm d}E}$: Energy spectrum of secondaries i from channel k
  - Soft or collinear (real) radiative corrections enhanced by large logarithmic factors $\log^2(\Lambda/\Lambda_{\rm EW})$ at high scale
  - HDMSpectra public tool providing energy spectra of final states for any decay-channel model

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, $\mathrm{d}n/\mathrm{d}E_\mathrm{e}$ results from a transport equation that retains only energy-loss and source terms,

$$\frac{\partial}{\partial E_\mathrm{e}}\left(b(E_\mathrm{e},\mathbf{x})\frac{\mathrm{d}n(E_\mathrm{e},\mathbf{x})}{\mathrm{d}E_\mathrm{e}}\right) = \frac{\rho_\mathrm{DM}(\mathbf{x})}{M_X\tau_X}\frac{\mathrm{d}N_\mathrm{e}(E_\mathrm{e};M_X)}{\mathrm{d}E_\mathrm{e}},$$

  with $b(E_\mathrm{e},\mathbf{x})$ 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:

$$\frac{\mathrm{d}n(E_\mathrm{e},\mathbf{x})}{\mathrm{d}E_\mathrm{e}} = \frac{\rho_\mathrm{DM}(\mathbf{x})}{M_X\tau_X b(E_\mathrm{e},\mathbf{x})}Y_\mathrm{e}(E_\mathrm{e}),$$

  with $Y_\mathrm{e}(E_\mathrm{e}) = \int_{E_\mathrm{e}}^{M_X/2}\mathrm{d}E'_\mathrm{e}\,\mathrm{d}N_\mathrm{e}(E'_\mathrm{e};M_X)/\mathrm{d}E'_\mathrm{e}$ the yield of electrons with energy $\geq E_\mathrm{e}$

Inverse Compton Scattering

- Emission rate shaped by the (differential) power $\mathrm{d}P_{\mathrm{ICS}}(E_{\mathrm{e}}, E, \mathbf{x})/\mathrm{d}E$ of electrons with energy E_{e} (and mass m_{e}) emitting photons in the band between E and $E + \mathrm{d}E$ weighted by the (differential) density of electrons:

$$q_{\gamma}(E, \mathbf{x}) = \frac{1}{E} \int_{m_{\mathrm{e}}}^{M_X/2} \mathrm{d}E_{\mathrm{e}} \frac{\mathrm{d}n(E_{\mathrm{e}}, \mathbf{x})}{\mathrm{d}E_{\mathrm{e}}} \frac{\mathrm{d}P_{\mathrm{ICS}}(E_{\mathrm{e}}, E, \mathbf{x})}{\mathrm{d}E}.$$

- In the Thomson limit,

$$\frac{\mathrm{d}P_{\mathrm{ICS}}(E_{\mathrm{e}}, E, \mathbf{x})}{\mathrm{d}E} = \frac{3\sigma_{\mathrm{T}} m_{\mathrm{e}}^2 E}{4E_{\mathrm{e}}^2} \int_0^1 dy \, \frac{n(E^0(y), \mathbf{x})}{y} (2y \ln y + y + 1 - 2y^2)$$

with $E^0(y) = E m_{\mathrm{e}}^2 / (4E_{\mathrm{e}}^2 y)$

- Emission negligible for $M_X \gtrsim 10^6$ 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 $E + \mathrm{d}E$ weighted by dn/dE_e:

$$q_\gamma(E, \mathbf{x}) = \frac{1}{E} \int_{m_\mathrm{e}}^{M_X/2} \mathrm{d}E_\mathrm{e} \frac{\mathrm{d}n(E_\mathrm{e}, \mathbf{x})}{\mathrm{d}E_\mathrm{e}} \frac{\mathrm{d}P_\mathrm{syn}(E_\mathrm{e}, E, \mathbf{x})}{\mathrm{d}E}.$$

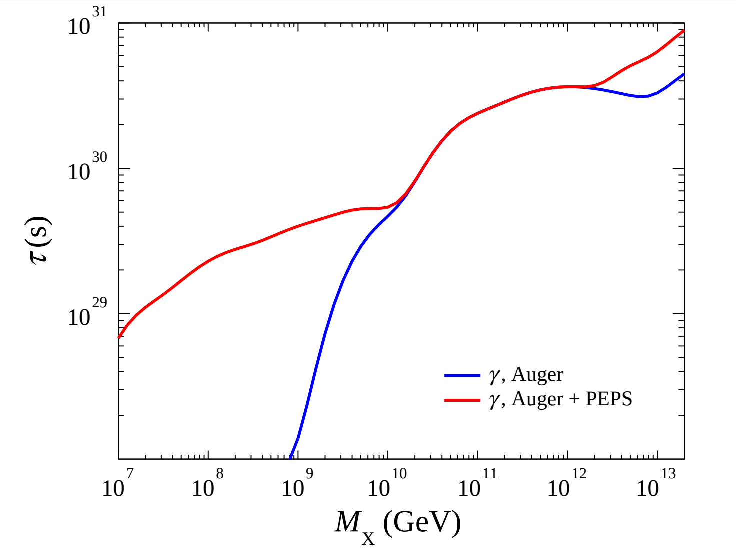
- Synchrotron power:

$$\frac{\mathrm{d}P_\mathrm{syn}(E_\mathrm{e}, E, \mathbf{x})}{\mathrm{d}E} = \frac{b_B(E_\mathrm{e}, \mathbf{x})}{E_\mathrm{c}(E_\mathrm{e}, \mathbf{x})} \tilde{F}\left(\frac{E}{E_\mathrm{c}(E_\mathrm{e}, \mathbf{x})}\right), \text{ with}$$

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

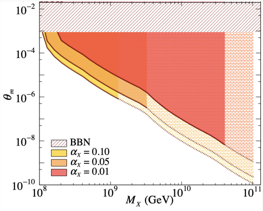
$$E_\mathrm{c}(E_\mathrm{e}, \mathbf{x}) \simeq 6.6 \times 10^1 \left(\frac{E_\mathrm{e}}{10^9\ \mathrm{GeV}}\right)^2 \left(\frac{B_\perp(\mathbf{x})}{\mu\mathrm{G}}\right)\ \mathrm{GeV}$$

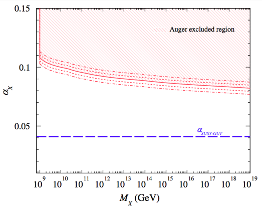
Benchmark constraints for $h\nu/W\ell$ channels

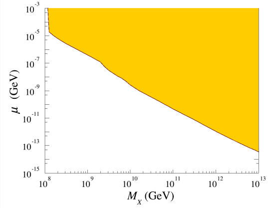


Explicit models

☛ Constraints on viable models realizing SHDM with $\tau_X > 10^{23}$ yr:







- Extended type-I seesaw frameworks
- Extended type-II seesaw frameworks
- Totally secluded sector with dark instantons
- Hidden-sector gauge boson
- EeV gravitino with RPV
- EeV raritons
- Split seesaw

Metastability through sterile-neutrino portal [Dudas et al., PRD 101 115029 (2020)]

- Extended Seesaw framework:

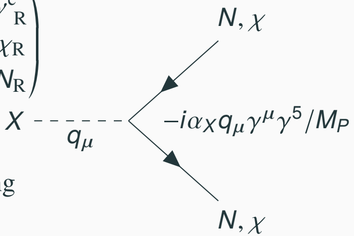
$$\begin{pmatrix} \overline{\nu}_L & \overline{\chi_R^c} & \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & \delta m & m_D \\ \delta m & m_\chi & 0 \\ m_D & 0 & M_N \end{pmatrix} \begin{pmatrix} \nu^c_R \\ \chi_R \\ N_R \end{pmatrix}$$

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

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

$$\begin{aligned} \nu_1 &\simeq (\chi_R + \chi_R^c) + \theta_m(\nu_L + \nu_L^c) \\ \nu_2 &\simeq (\nu_L + \nu_L^c) - \theta_m(\chi_R + \chi_R^c) \\ \nu_3 &\simeq N_R \end{aligned}$$

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

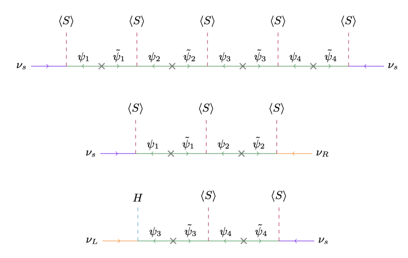


(motivated by several UV models with string or higher-dimensional inspired moduli fields)

Justification of the mass hierarchy

➥ 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_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



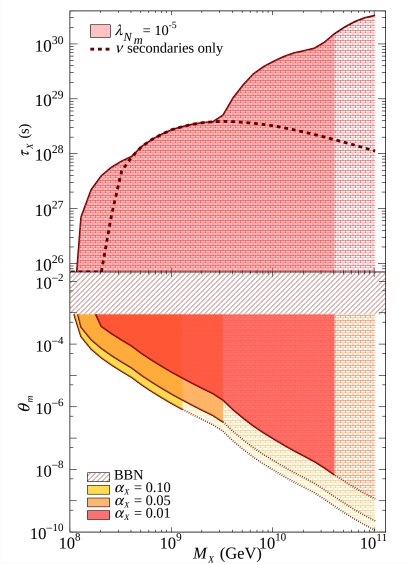
☛ After spontaneous symmetry breaking, seesaw framework as a low-energy effective theory with:

- $m_\chi = \dfrac{2\lambda_{S4}\lambda_{43}\lambda_{32}\lambda_{21}\lambda_{1S}\langle\phi_N\rangle^5}{M_\mathrm{P}^4}$
- $M_N = 2\lambda_R\langle\phi_N\rangle$
- $\theta_m = \dfrac{\lambda_{3L}\lambda_{43}\lambda_{S4}v\langle\phi_N\rangle^2}{m_\nu M_\mathrm{P}^2}$

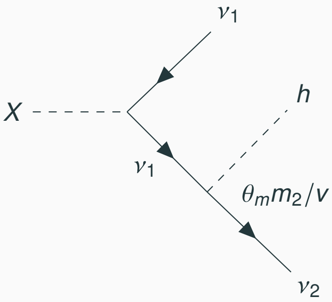
➥ Benchmark target: $\theta_m \sim 10^{-6}$ for $M_X = 10^9$ GeV

Metastability through sterile-neutrino portal

[Pierre Auger Collab., Phys. Rev. D 109 (2024) L081101]



☛ $X \to h\nu_1\nu_2$ decay chanel:



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

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

Metastability through mixing in superheavy sector [OD, EPJC 85, 985 (2025)]

- Extended Seesaw framework:

$$\begin{pmatrix}\overline{\nu_L} & \overline{\chi_R^{\ c}} & \overline{N_R^{\ c}}\end{pmatrix}\begin{pmatrix}0 & \delta m & m_D\\ \delta m & M_\chi & \delta M\\ m_D & \delta M & M_N\end{pmatrix}\begin{pmatrix}\nu^c_{\ R}\\ \chi_R\\ N_R\end{pmatrix}$$

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 $\theta_\chi = \delta M/(M_N - M_\chi)$:

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

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

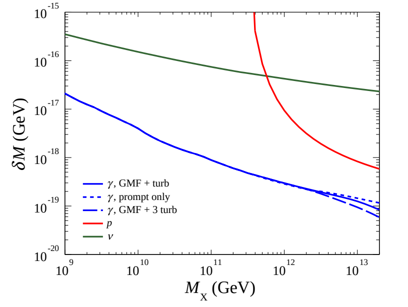
$$\frac{y_N}{\sqrt{2}}h\left(\overline{\nu_L}N_R + \overline{N_R}\nu_L\right) = \cdots + \frac{\mathrm{i}y_N\theta_\chi}{2\sqrt{2}}h\left(\bar{\tilde{\nu}}\tilde{\chi} + \bar{\tilde{\chi}}\tilde{\nu}\right) + \ldots$$

$$\Gamma_{\tilde{\chi}\to h\tilde{\nu}} = \frac{|y_N|^2\,\theta_\chi^2}{256\pi}M_{\tilde{\chi}} \qquad (1)$$

Justification of the mass hierarchies?

L	χ_R	N_R	ϕ_χ	ϕ_N	ψ_1	$\tilde{\psi}_1$	ψ_2	$\tilde{\psi}_2$	ψ_3	$\tilde{\psi}_3$	ψ_4	$\tilde{\psi}_4$
−1	−7	+1	+14	−2	+1	−1	−13	+13	−11	+11	−9	+9

[OD, EPJC 85, 985 (2025)]



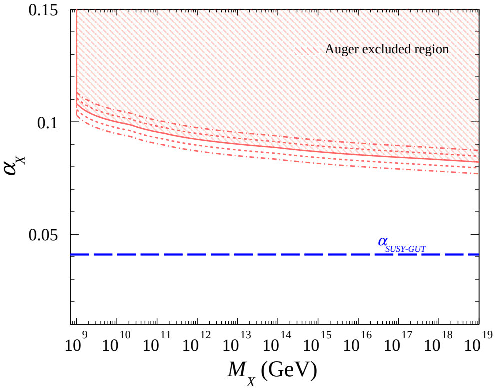
☛ After spontaneous symmetry breaking, seesaw framework as a low-energy effective theory with:

- $M_\chi = 2\lambda_\chi \langle \phi_\chi \rangle$
- $M_N = 2\lambda_N \langle \phi_N \rangle$
- $\delta M = \dfrac{\lambda_{1N}\lambda_{12\chi}\lambda_{23N}\lambda_{34N}\lambda_{4\chi}\langle \phi_N \rangle^4 \langle \phi_\chi \rangle}{M_\mathrm{P}^4}$

➥ Benchmark target: $\delta M \sim 10^{-18}$ for $M_X = 10^{10}$ GeV

Dark instantons

- 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, exchange of quantum numbers through an anomaly **[Kuzmin & Rubakov, Phys. Atom. Nucl. 61, 1028 (1998)]**



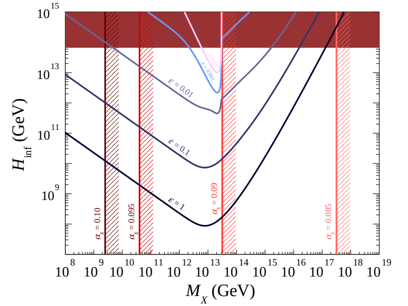
- Lifetime of metastable X particles: $\tau_X \simeq M_X^{-1} \exp(4\pi/\alpha_X)$

  [t'Hooft, PRL 37 (1976) 8]
- **[Pierre Auger Collab., Phys. Rev. Lett. 130 (2023) 061001]**

Cosmological implications

- No coupling between SM and DM sectors except gravitational
- Gravitational production of DM from rapid change of the metrics or by freeze-in through thermal bath
- Reheating efficiency $\epsilon \simeq 4T_{\rm rh}(M_{\rm Pl}H_{\rm inf})^{-1/2}$ defined between 0 and 1, characterizing the duration of the reheating period ($\epsilon \simeq 1 \implies$ instantaneous reheating)

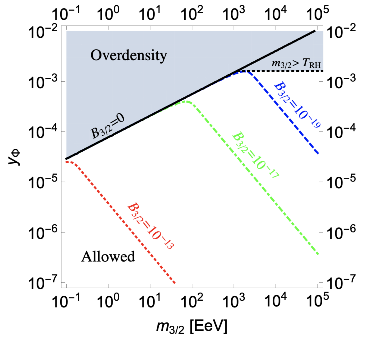
[Pierre Auger Collab., Phys. Rev. Lett. 130 (2023) 061001]



- GUT mass scale viable for $\epsilon \to 1$ (high $T_{\rm rh}$) $\implies$ tensor/scalar ratio r of the primordial modes possibly detectable in the CMB

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



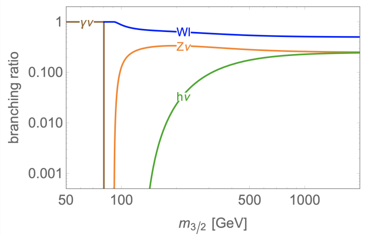
☛ Gravitino exception: $M_{3/2} > M_\phi^2/\sqrt{3}M_{\rm Pl} \sim 10^8$ GeV

- Production from thermal bath (gluons): $T_{\rm rh} \sim [10^{10}–10^{12}]$ 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:

$$W = W_{\mathrm{MSSM}} + \mu' L H_u$$

- Lepton number not conserved
- Baryon number conserved

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

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

Conclusions

- Superheavy particles: viable alternative to WIMPs for being DM
- Gravitational/Inflaton-seeded production mechanisms
- Several viable mechanisms to generate long-lived superheavy particles, avoiding fine tuning or *ad hoc* global symmetry
- Best constraints on τ_X from UHE γ-ray flux limits in general