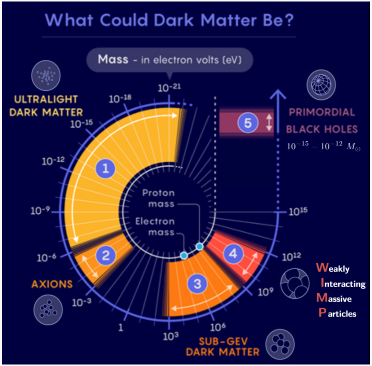
PEPS meeting

Probing superheavy dark matter with PEPS

O. Deligny (CNRS/IN2P3 – IJCLab)

May 26, 2026

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

- ☛ Dark-sector superheavy particles interacting feebly with SM ones (ie. *not* through SM gauge interactions)
  - Additional portal? e.g. axion (pseudo-scalar), Higgs (scalar), sterile neutrino (spin 1/2), vector (spin 1), etc.
  - Tiny symmetry violation

Prompt flux of cosmic particles from DM

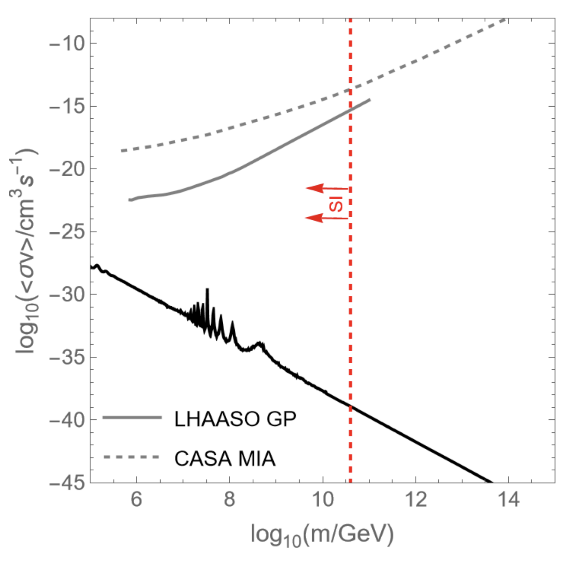
☛ Diffuse flux (per steradian) of any particle of type i and of high energy E (gamma-rays, (anti-)nucleons, neutrinos) from the prompt emission of annihilating/decaying superheavy particles:

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

- 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

☛ Thermal cross section constrained



Prompt flux – Emission rate from decay

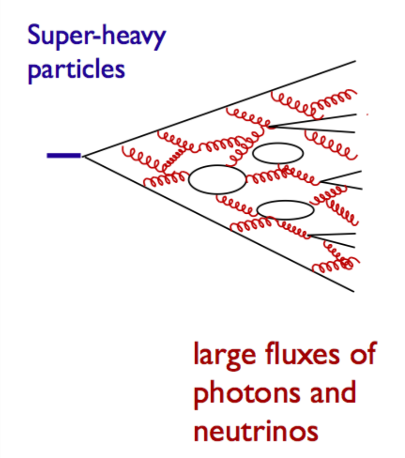
☛ Shaped by DM density n_{DM}, more conveniently expressed in terms of energy density $\rho_{\mathrm{DM}} = M_X\, n_{\mathrm{DM}}$, and by the differential decay width into the particle species i as

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

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

Fragmentation of final states

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



- 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

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 $\geq E_\mathrm{e}$

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

- 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 $E + \mathrm{d}E$ 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:

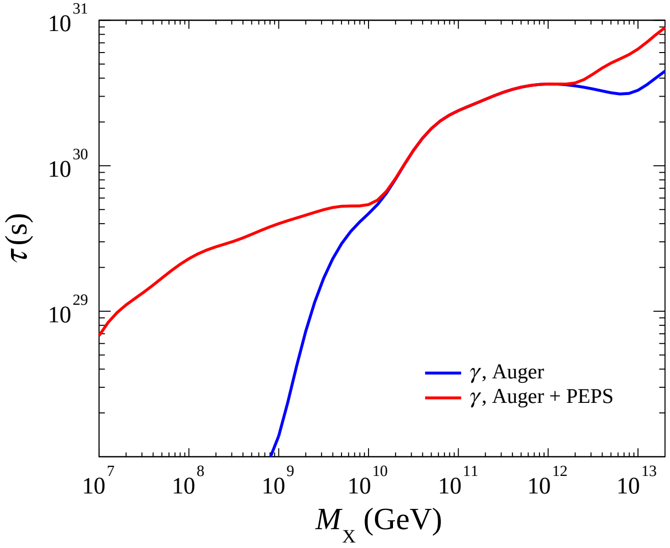
$$\frac{\mathrm{d}P_\mathrm{syn}(E_\mathrm{e},E,\mathbf{x})}{\mathrm{d}E} = \frac{b_B(E_\mathrm{e},\mathbf{x})}{E_\mathrm{c}(E_\mathrm{e},\mathbf{x})}\tilde{F}\left(\frac{E}{E_\mathrm{c}(E_\mathrm{e},\mathbf{x})}\right), \text{ with}$$

  - $b_B(E_\mathrm{e},\mathbf{x})$ 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

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

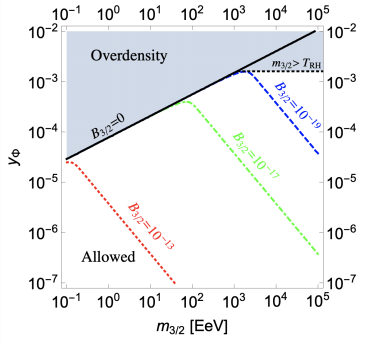
☛ TeV γ-rays more constraining than UHE ones?

Benchmark constraints



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



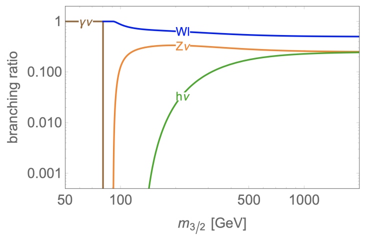
☛ Gravitino exception: $M_{3/2} > M_\phi^2/\sqrt{3}M_{\mathrm{Pl}} \sim 10^8$ GeV

- Production from thermal bath (gluons): $T_{\mathrm{rh}} \sim [10^{10}\text{–}10^{12}]$ GeV
- Linear increase of y_ϕ with $M_{3/2}$ to counterbalance $1/\tilde{m}^2$ couplings
- Alternative: $B_{3/2} \neq 0$: $y_\phi < \left(\frac{B_{3/2}}{10^{-18}}\right)^{-1}\left(\frac{M_{3/2}}{10^8\ \mathrm{GeV}}\right)^{-1}$

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]

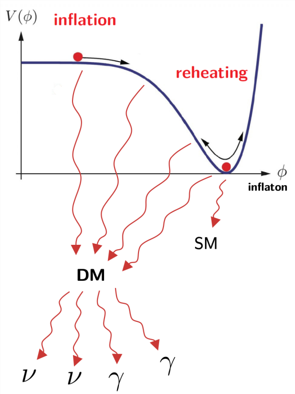
- $\mu' < 10^{-5} \left(\frac{M_{3/2}}{10^8\ \mathrm{GeV}}\right)^{-2}$ GeV (Weak-scale SUSY: $\mu' < 20$ keV from the preservation of the baryon asymmetry)

Conclusions

- Superheavy particles: viable alternative to WIMPs for being DM
- Various viable 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
- Sensitivity to PeV–EeV γs of considerable interest for BSM physics, in particular SHDM

Backups

Non-thermal production of SHDM particles



- 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 SM+SM→DM+DM or $\phi + \phi$ →DM+DM between end of inflation $t = H_{\text{inf}}^{-1}$ and Reheating between $t = \Gamma_\phi^{-1}$ at T_{rh}
- Production by inflaton decay

- 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