Limits on photon fluxes from data of the Pierre Auger Observatory and implications on super-heavy dark matter

O. Deligny for the Pierre Auger Collaboration

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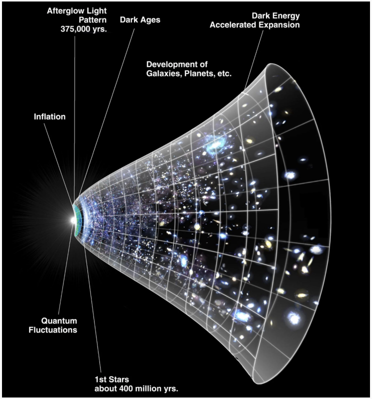
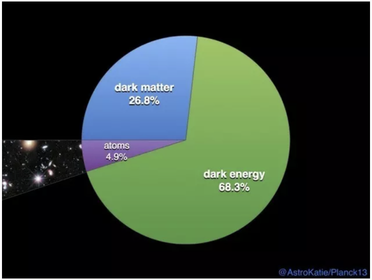
Inflationary cosmology



- CMB: persistent post-luminescence imaging the universe at the time of recombination ($\sim$ 375,000 yr)
- CνB: persistent "post-luminescence" imaging the universe when it became transparent to ν ($\sim$ 1 s)
- DM: requested from several gravitational anomalies, persistent "post-luminescence" from the very early universe

DM searches – Looking under the lamppost

Superheavy dark matter?



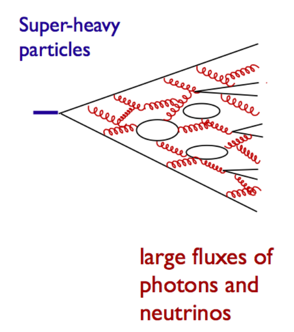
☛ Superheavy particles?

- Inflationary sector: $M_\phi \sim [1-3] \times 10^{13}$ GeV
- Sterile neutrinos
  - New degrees of freedom N_R
  - BSM scale at $\sim 10^{13}$ GeV in "vanilla" seesaw
- 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)

- Gravitational SM/DS interactions
- Additional portal? e.g. axion (pseudo-scalar), Higgs (scalar), sterile neutrino (spin 1/2), vector (spin 1), etc.

Signatures in decay byproducts



- For n pairs of $q\overline{q}$,

$$\frac{dN_{\gamma,\nu}(x)}{dx} = \frac{n(n-1)(n-2)\epsilon_\pi}{3} \times \int_x^1 \frac{dz}{z}\frac{x}{z}\left(1-\frac{x}{z}\right)^{n-3}\frac{D_h(z)}{z}$$

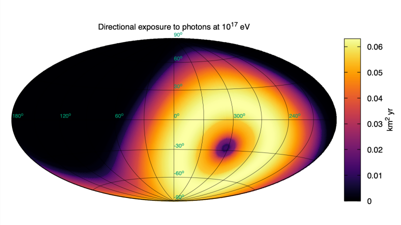
- ϵ_π: "efficiency" of the hadronization process into pions
- $D_h(z)$: fragmentation function of a parton into a hadron (DGLAP)

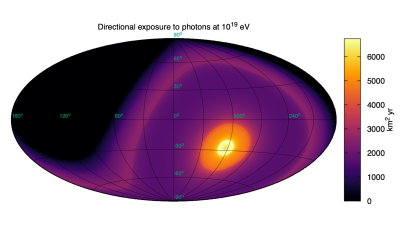
- Fragmentation in the EW sector as well (soft or collinear (real) radiative corrections enhanced by large logarithmic factors at high scale)
- Expected number of (prompt) secondaries from SHDM decay ($i = \gamma, \nu, \overline{\nu}, N, \overline{N}$):

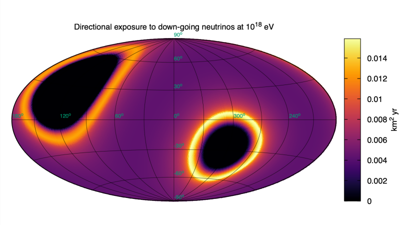
$$n_i(E; M_X\tau_X) = \frac{1}{4\pi M_X\tau_X}\frac{dN_i}{dE}\int d\mathbf{n}\,\omega_i(E,\mathbf{n})\int_0^\infty ds\,\rho_{\mathrm{DM}}(\mathbf{x}_\odot + s\mathbf{n})$$

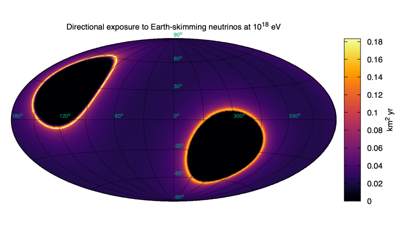
Exposure to UHE gamma rays and neutrinos

☛ Sensitivity over ≃ 3.5 decades in E

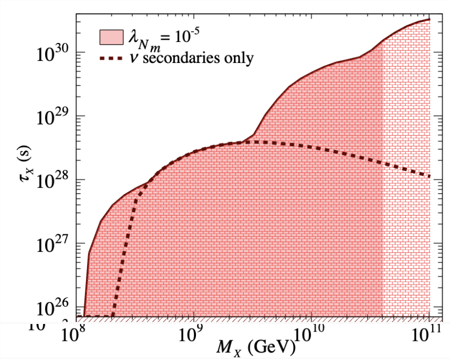








Benchmark constraints



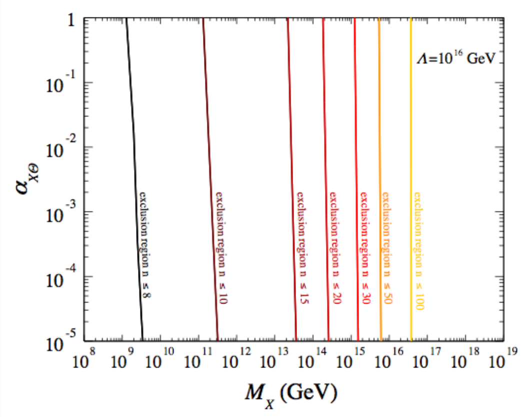
[Pierre Auger Collab., Phys. Rev. D 109 (2024) L081101]

- Best constraints on τ_X from Auger sensitivity to UHE gamma rays for $M_X \gtrsim 10^9$ GeV
- Prompt flux only
- Secondaries from ICS negligible in general
- Secondaries from synchrotron only for $M_X \gtrsim M_{\rm GUT}$

Superheavy and metastable particles?

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

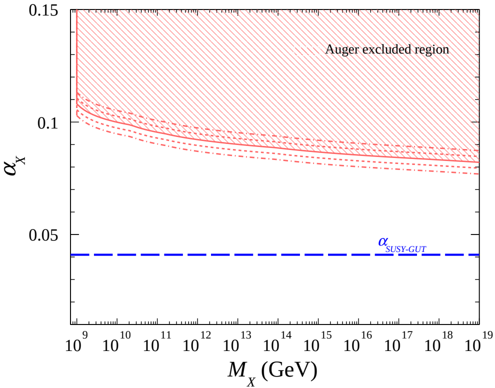
$$\Gamma_X \propto \alpha_{X\Theta} M_X \left(\frac{M_X}{\Lambda}\right)^{2n-8}$$



- 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]**

Metastability through sterile-neutrino portal

☛ Extended Seesaw framework:

$$\begin{pmatrix} \overline{\nu}_{\rm L} & \overline{N}_{\rm s}^{\rm c} & \overline{N_{\rm R}}^{\rm c} \end{pmatrix} \begin{pmatrix} 0 & \delta m & m_{\rm D} \\ \delta m & m_{\rm s} & 0 \\ m_{\rm D} & 0 & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu_{\rm R}^{\rm c} \\ N_{\rm s} \\ N_{\rm R} \end{pmatrix}$$

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

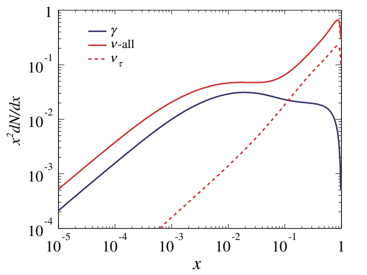
$$\begin{aligned} \nu_1 &\simeq (N_m + N_m) + \theta_m(\nu_{\rm L} + \nu_{\rm L}), \\ \nu_2 &\simeq (\nu_{\rm L} + \nu_{\rm L}) - \theta_m(N_m + N_m), \\ \nu_3 &\simeq N_M, \end{aligned}$$

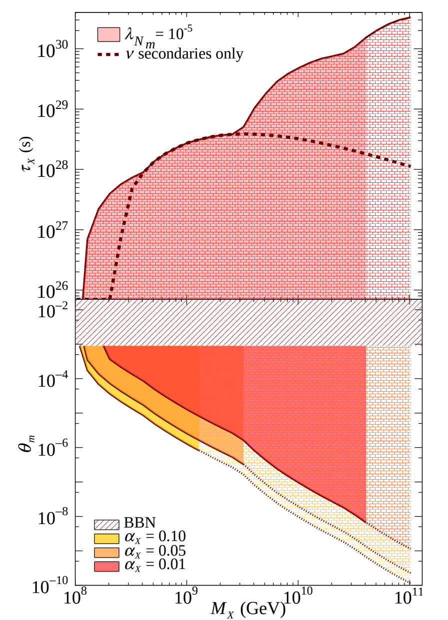
☛ Additional pseudo-scalar coupled to N [Dudas et al., PRD 101 115029 (2020)]:

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

Metastability through sterile-neutrino portal

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





Cosmological implications

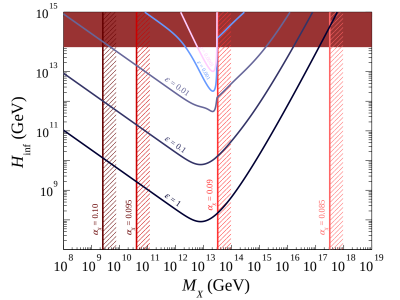
- No coupling between SM and DM sectors except gravitational
- DM production by "freeze-in" mechanism through s-channel SM+SM→DM+DM **[Garny et al. PRL 116 (2016) 101302]** or $\phi + \phi$ →DM+DM **[Mambrini & Olive Phys. Rev. D 103 (2021) 11, 115009]** while inflaton decays into SM particles and reheats the universe after inflation:

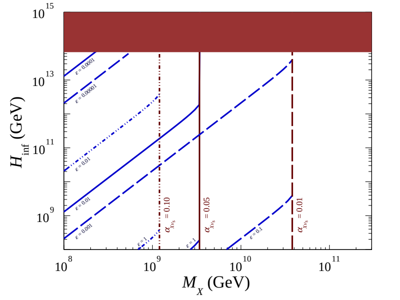
$$\frac{dn_X(t)}{dt} + 3H(t)n_X(t) \simeq \sum_i \bar{n}_i^2 \Gamma_i \text{ (+ infl. radiative decay)}$$

- Reheating dynamics between $t = H_{\rm inf}^{-1}$ and $t = \Gamma_\phi^{-1}$ at $T_{\rm rh}$ **[Chung et al. Phys. Rev.929 D 60, 063504 (1999), Giudice et al., Phys. Rev. D 64, 023508 (2001)]**:
  - $T(a) \simeq 0.2(\epsilon M_{\rm Pl} H_{\rm inf})^{1/2} \left(a^{-3/2} - a^{-4}\right)^{1/4}$
  - $H(a) = H_{\rm inf}(a/a_{\rm inf})^{-3/2}, a \leq a_{\rm rh}$
  - $H(a) = H_{\rm inf}\epsilon^2(a/a_{\rm rh})^{-2}, a > a_{\rm rh}$
- 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)

Viable regions

- Delineating viable regions in the (H_{inf}, M_X) plane for various ϵ values to match the DM relic density

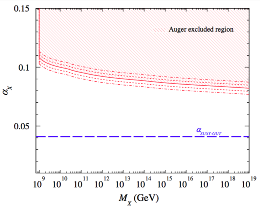


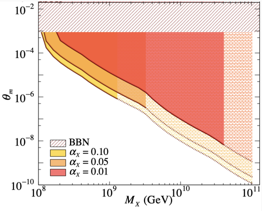


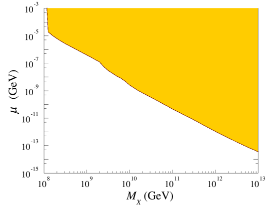
- GUT mass scale viable for $\epsilon \to 1$ (T_{rh} relatively high) $\implies$ tensor/scalar ratio r of the primordial modes possibly detectable in the CMB
- For $\epsilon \leq 0.01$, 10^{13} GeV mass scale viable, testable for $\alpha_X \lesssim 0.09$

Conclusions

- ☛ Best constraints on τ_X from Auger photon limits (in general) for $M_X \gtrsim 10^9$ GeV
- ☛ SHDM with $\tau_X > 10^{22-23}$ yr???
- ☛ Constraints on viable theoretical frameworks:







- Hidden sector interacting with SM via gravitons only
- SHDM coupled to ultra-light sterile neutrinos
- SUSY broken at high scale with tiny RPV [in preparation]