Limits to gauge coupling in the dark sector set by the non-observation of instanton-induced decay of Super-Heavy Dark Matter in the Pierre Auger Observatory data

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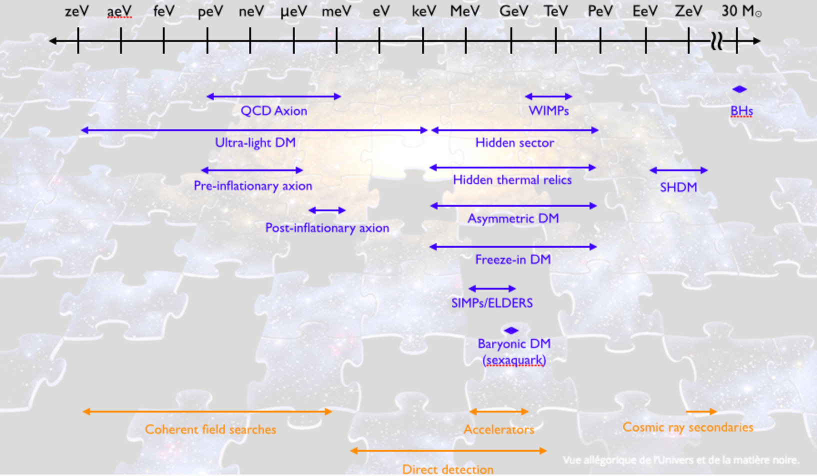
Dark Matter?



inspired from arXiv:1707.04591

SHDM motivations?

☛ Energy scale of new physics?

- Naturalness and DM: WIMP paradigm
- SM vacuum (in)stability: SHDM?

☛ Energy instability scale? Simplified trend at tree level:

- To lowest order in the Higgs self-coupling λ, $\lambda(\mu)$ evolution dominated by the term from the top coupling (one-loop radiative correction):

$$\frac{\mu \mathrm{d}\lambda}{\mathrm{d}\mu} = -\frac{3\lambda_t^4}{8\pi^2} + \dots$$

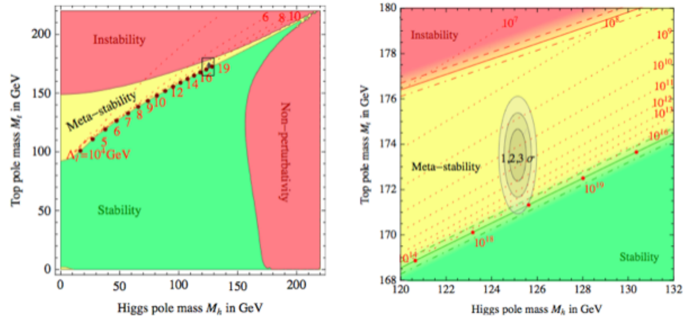
- As soon as $\lambda(\mu)$ turns negative, the Higgs potential becomes unbounded from below and the vacuum can suffer from instability
- Neglecting gauge interactions, the solution of the RGE at the instability scale $\lambda(\Lambda) = 0$ relates the Higgs mass with the top Yukawa coupling:

$$m_h^2 > \frac{3m_t^4}{\pi^2 v^2} \log \frac{\Lambda}{v}$$

LHC SM phase diagrams

- Extrapolation of the SM parameters up to large energies with full 3-loop NNLO precision

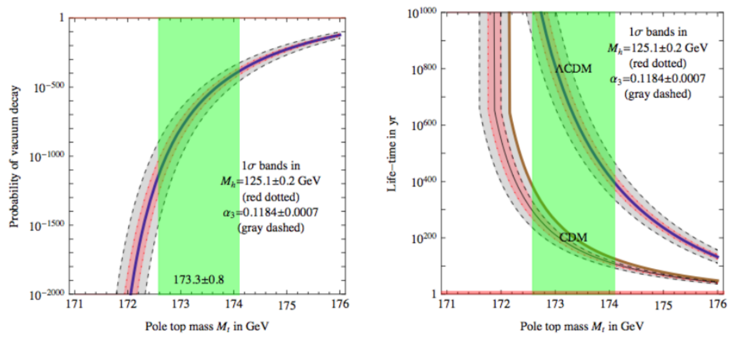
D. Buttazzo et al., JHEP vol 2013, 89 (2013)



- Precise values of Higgs boson mass + top Yukawa coupling $\Longrightarrow$ SM vacuum *meta-stable* up to high Λ

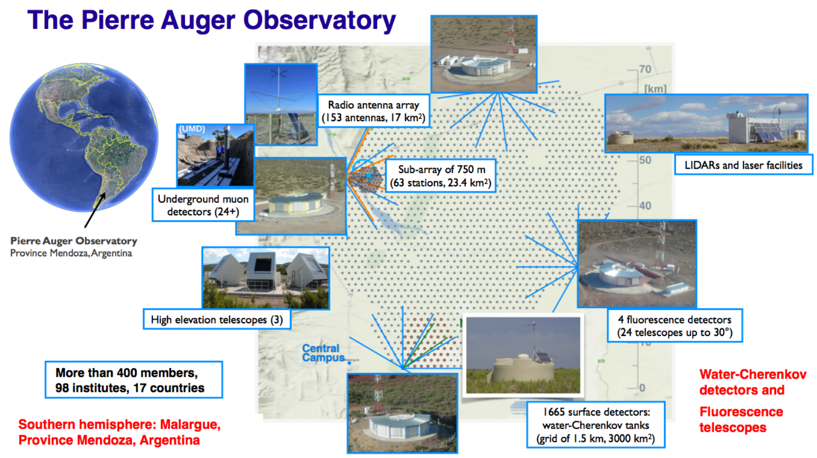
LHC SM phase diagrams

D. Buttazzo et al., JHEP vol 2013, 89 (2013)



- No inconsistency that would make the SM vacuum unstable by extrapolating the SM all the way from the mass of the top to the Planck mass
- Dark sector of super-heavy particles?

The Pierre Auger Observatory



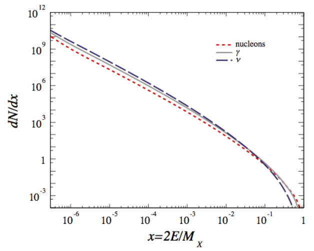
see review talk by A. Castellina on Friday

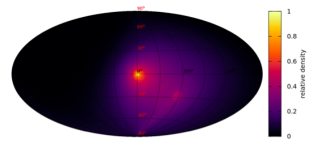
Secondary by-product fluxes from SDHM decay

- Flux of secondaries from SHDM decay ($i = \gamma, \nu, \overline{\nu}, N, \overline{N}$):

$$J_i^{\mathrm{gal}}(E) = \frac{1}{4\pi M_X c^2 \tau_X} \frac{\mathrm{d}N_i}{\mathrm{d}E} \int_0^\infty \mathrm{d}s \; \rho_{\mathrm{DM}}(\mathbf{x}_\odot + \mathbf{x}_i(s;\mathbf{n})).$$

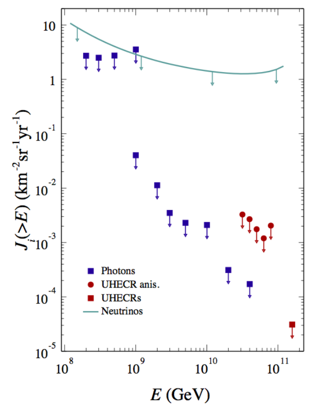
- ρ_{DM}: DM profile
- $\frac{\mathrm{d}N_i}{\mathrm{d}E}$: energy spectra of $i = \gamma, \nu, \overline{\nu}, N, \overline{N}$ from hadronization processes, evolving the fragmentation functions from EW scale up to M_X using DGLAP [Aloisio et al., Phys. Rev. D 69 094023 (2004)] here, see also Sarkar & Toldra (2002), Barbot & Drees (2003), Kachelriess et al. (2018), Alcantara, et al. (2019)
- Free parameters: M_X, τ_X

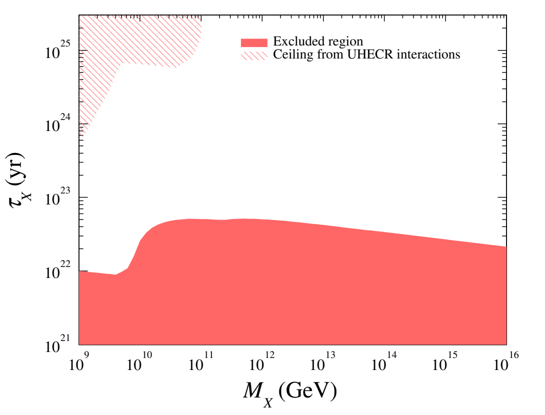




Sensitivity of the Observatory to SDHM decay

Pierre Auger Collaboration, arXiv:2203.08854, accompanying long paper soon



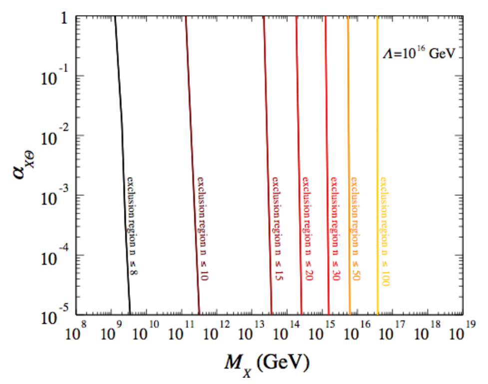


Constraints on perturbative decay

- 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 **[Pierre Auger Collaboration, arXiv:2203.08854, long paper soon]**

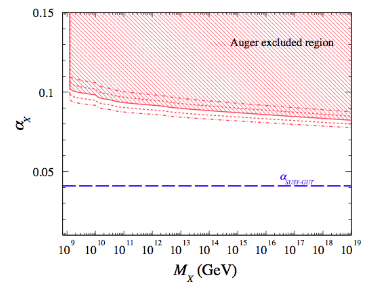


Constraints on non-perturbative decay

[Kuzmin & Rubakov, Phys. Atom. Nucl.979 61, 1028 (1998)]

- 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: $\tau_X \simeq M_X^{-1} \exp\left(4\pi/\alpha_X\right)$ [t’Hooft, PRL 37 (1976) 8]



[Pierre Auger Collaboration, arXiv:2203.08854, long paper soon]

Non-thermal SHDM production during reheating

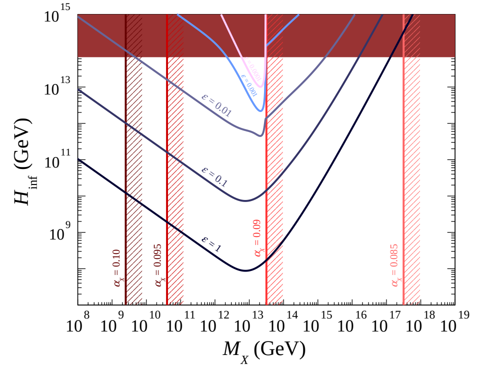
- No coupling between SM and DM sectors except gravitational
- DM production by "freeze-in" mechanism through s-channel SM+SM$\rightarrow$DM+DM [Garny et al. PRL 116 (2016) 101302] or $\phi + \phi \rightarrow$DM+DM [Mambrini & Olive Phys. Rev. D 103 (2021) 11, 115009] while inflaton decays into SM particles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

$$\frac{dn_X(t)}{dt} + 3H(t)n_X(t) \simeq \sum_i \overline{n}_i^2 \Gamma_i$$

- 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 $(H_{\rm inf}, M_X)$ plane for various ϵ values to match the DM relic density



- GUT mass scale viable for $\epsilon \to 1$ ($T_{\rm rh}$ 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 $\alpha_X \lesssim 0.09$

Summary

- Assuming no new physics up to high energy scales, several constraints on the properties of a dark sector of SH particles brought by the absence of UHE photons
- X particles with masses as large as the GUT energy scale could be sufficiently abundant to match the DM relic density, provided that the inflationary energy scale is high ($H_{\rm inf} \simeq 10^{13}$ GeV) and $T_{\rm rh}$ is high (so that reheating is quasi-instantaneous)
- UHECR/CMB complementarity