Implications of photon-flux upper limits at ultra-high energies in scenarios of superheavy dark matter

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Based on Phys. Rev. Lett. 130 (2023) 061001 & Phys. Rev. D 107 (2023) 042002

Study motivation

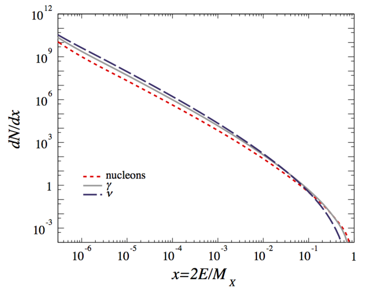
- WIMPs?
  - Problem of the Higgs mass: as a scalar field, can be destabilized by one-loop radiative corrections through its coupling to the top quark (quadratic divergences)
  - Naturalness: stability of observables should prevail under small variations of the fundamental (bare) parameters $\implies \delta m_h^2 < m_h^2 \implies \Lambda < 1$ TeV – scale of new physics
  - Right DM abundance for "heavy protons interacting like neutrinos"
- Various null results for WIMP searches: originally expected masses pushed towards larger values and couplings towards weaker ones
- Post-LHC era: quartic coupling of the Higgs never too negative up to the Planck mass to induce instability $\implies$ SM may be extrapolated up to Planck mass without encountering any inconsistency
- Inflationary cosmologies: SHDM production during reheating possible through minimal coupling (gravitation) or other mechanisms
- Decay byproducts detectable in UHECR data

UHE particles as secondaries of SHDM decays

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

$$\frac{\mathrm{d}N_\gamma(x)}{\mathrm{d}x} = \frac{n(n-1)(n-2)\epsilon_\pi}{3} \int_x^1 \frac{\mathrm{d}z}{z} \frac{x}{z} \left(1 - \frac{x}{z}\right)^{n-3} \frac{D_h(z)}{z},$$

- ϵ_π: “efficiency” of the hadronization process into pions
- $D_h(z)$: fragmentation function (FF) of a parton into a hadron from FFs of partons evolved starting from measurements at the EW scale up to the energy scale fixed by M_X using the DGLAP equation



- EW sector: Electroweak showering for $M_X \gg m_W$ (fragmentation of final-state particles)
- Use of HDMSpectra tool [Bauer et al.]

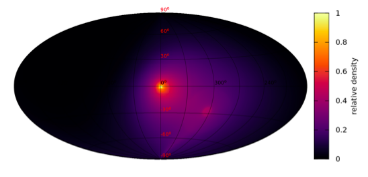
Searches for SHDM decay byproducts

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

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

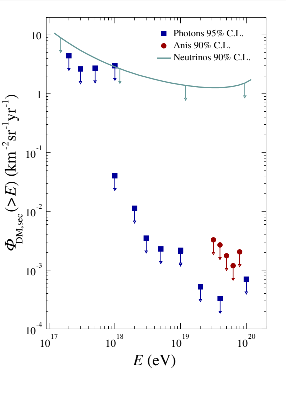
  - ρ_{DM}: DM profile
  - $\frac{\mathrm{d}N_i}{\mathrm{d}E}$: energy spectra of $i = \gamma, \nu, \overline{\nu}, N, \overline{N}$ from fragmentation

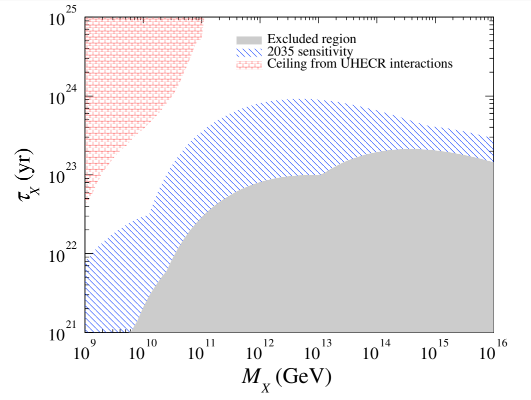
- Free parameters: M_X, τ_X
- Observables:
  - Anisotropies in UHECR arrival directions
  - Searches for photon fluxes
  - Searches for neutrinos



Limits

Photon ceiling: [Bérat et al., ApJ 929 (2022) 55]



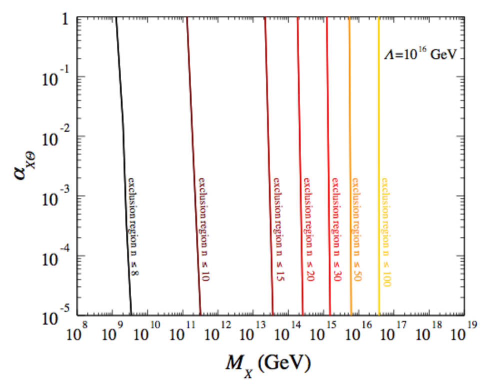


Constraints on perturbative decay

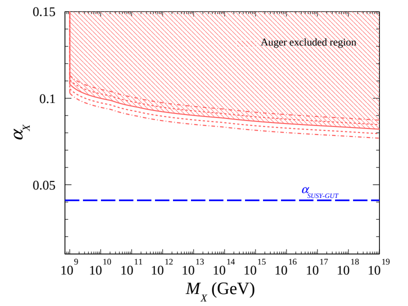
- Decay rate for an effective interaction term containing a monomial of dimension n in mass unit:

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

- Fine tuning between $\alpha_{X\Theta}$ and n



Non-perturbative decay: instantons



- Stability: new quantum number
- Decay through "instantons" in non-commutative gauge theories
- Distinct classes of vacua labeled by a topological quantum number

- For B, L and X currents not associated to gauge interactions, possibility to exchange quantum numbers through an anomaly
- e.g. – Striking $B + L$ violating processes in SM: $\Delta B = \Delta L = 3\Delta n$

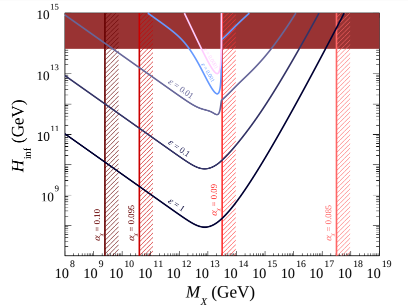
$$\Delta n = -1 : \; qq \to 7\bar{q} + 3\bar{\ell}$$

$$\Delta n = +1 : \; qq \to 11q + 3\ell$$

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→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

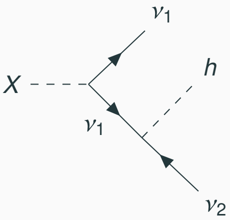
$$\frac{dn_X(t)}{dt} + 3H(t)n_X(t) \simeq \sum_i \overline{n}_i^2 \Gamma_i$$



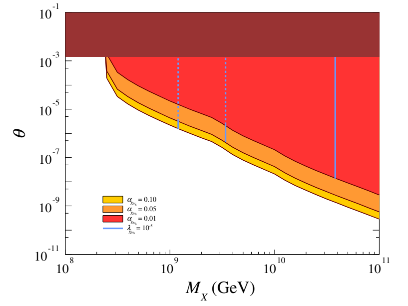
- GUT mass scale viable for $\epsilon \to 1$ ($T_{\rm rh}$ relatively high) $\Longrightarrow$ tensor/scalar ratio r of the primordial modes possibly detectable in the CMB
- For $\epsilon \leq 0.01$, 10^{13} GeV mass scale viable, testable for $\alpha_X \lesssim 0.09$

Metastable SHDM coupled to sub-eV sterile neutrinos

- X: (pseudo-)scalar with interaction $\frac{\alpha_X}{2M_P}(\partial_\mu X)\overline{\nu}_s\gamma^\mu\gamma^5\nu_s$ **[Dudas et al., Phys. Rev. D 101 (2020) 11, 115029]**



$$\Gamma \simeq \frac{\alpha_X^2\theta^2}{192\pi^3}\left(\frac{m_2}{v}\right)^2\left(\frac{M_X}{M_P}\right)^2 M_X$$



- Convert lifetime constraints into mixing-angle ones
- NB: Oscillation parameter space $(\Delta m^2, \sin^2 2\theta)$ not constraining (cf. arXiv:1607.00032 for conversion)

Non-thermal production during reheating

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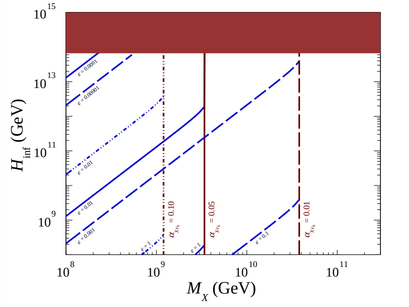
- Radiative production from inflaton decay

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



- Radiative production dominant
- EeV DM

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/neutrinos
- 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 ($H_{\mathrm{inf}} \simeq 10^{13}$ GeV) and T_{rh} is high (so that reheating is quasi-instantaneous)
- Constraints on sub-eV sterile-neutrino mixing if connected to SHDM
- UHECR/cosmology complementarity

Naturalness, WIMPs and Dark Matter

- ☛ Particle physics
  - Problem of the Higgs mass: as a scalar field, can be destabilized by one-loop radiative corrections through its coupling to the top quark (quadratic divergences)

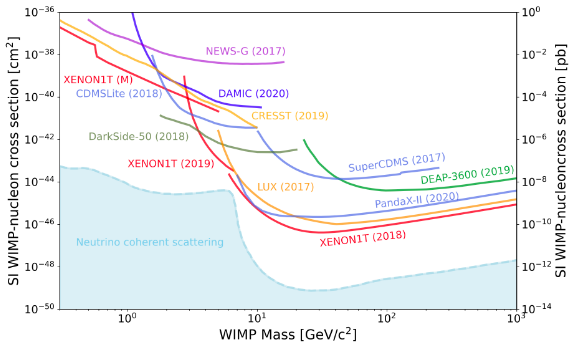
$$\delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[(4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2) + \log\left(\frac{\Lambda}{\mu}\right)\right]$$

  - Naturalness: stability of observables should prevail under small variations of the fundamental (bare) parameters $\implies \delta m_h^2 < m_h^2 \implies \Lambda < 1$ TeV – scale of new physics
  - Supersymmetry or extra dimensions: add through various mechanisms to the spectrum of elementary particles other ones, one of which would be stable with a mass around 100 GeV and weak couplings
- ☛ Cosmology
  - Freezing time estimated by equating the annihilation rate with the Hubble parameter $\implies \Omega_{\rm WIMP} \sim \frac{10^{-25}\ {\rm cm^3 s^{-1}}}{\langle \sigma v \rangle}$
  - Of the order of unity by taking, as (should be) expected for WIMPs, $\langle \sigma v \rangle \sim G_F^2 M_X^2 \rightarrow$ the WIMP “miracle”

Direct-detection of WIMPs?

- Direct-detection searches: measurement of nuclear recoil

PDG, Prog. Theor. Exp. Phys. 2020 (2020) 083C01



- Accelerator-based and indirect-detection searches also unsuccessful
- Neutrino floor at reach with next experiments

SHDM motivations? SM vacuum (in)stability

- ☛ Alternative to naturalness to probe the energy scale Λ: SM vacuum (in)stability $\rightarrow$ very simplified calculation below, just a trend showing the necessity of new physics at scale Λ to avoid instability and the leading role of m_h and m_t

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

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

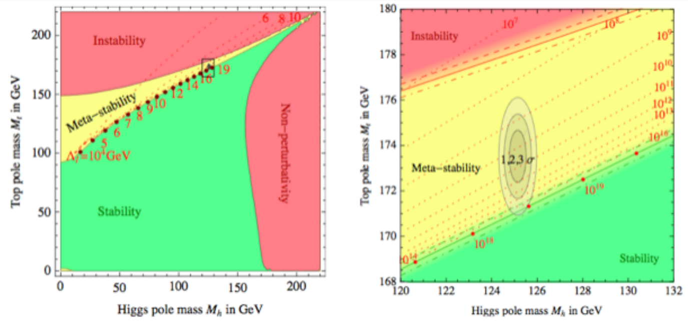
  - As soon as $\lambda(\mu)$ turns negative, the Higgs potential becomes unbounded from below and the vacuum can suffer from instability
  - Neglecting gauge interactions, the solution of the RGE at the instability scale $\lambda(\Lambda) = 0$ relates the Higgs mass with the top Yukawa coupling:

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

LHC SM phase diagrams

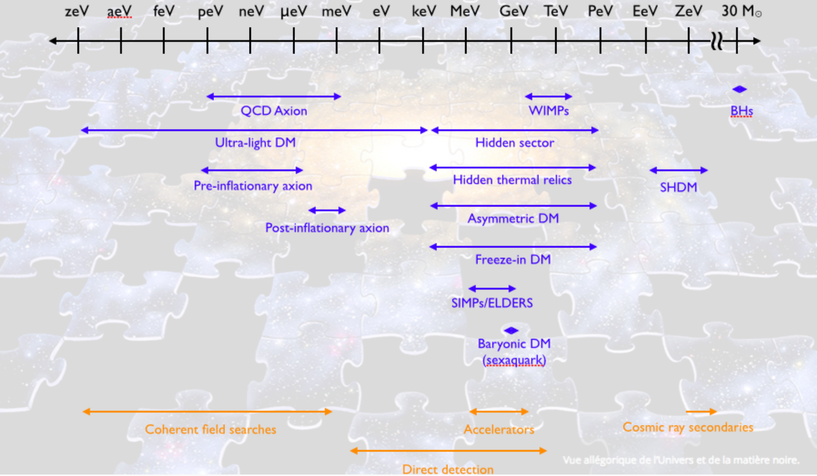
- Extrapolation of the SM parameters up to large energies with full 3-loop NNLO precision

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



- Precise values of m_{H} and y_{top} $\Longrightarrow$ SM vacuum *meta-stable* to high Λ
- No inconsistency that would make the SM vacuum unstable by extrapolating the SM all the way from the mass of the top to M_{P}

Dark Matter?

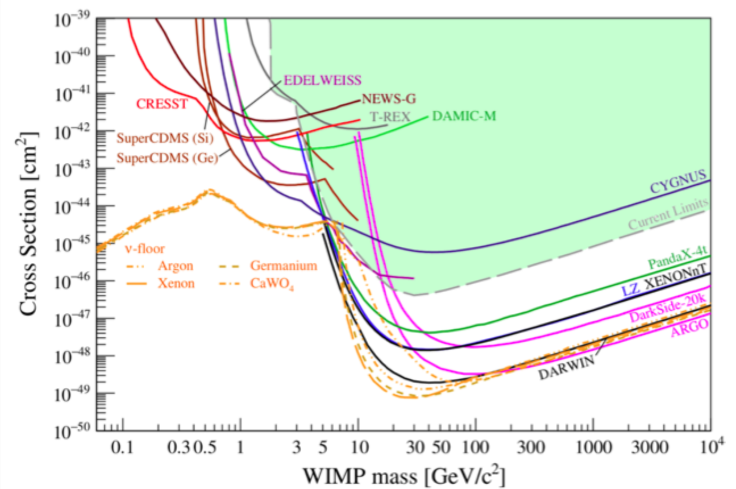


inspired from arXiv:1707.04591

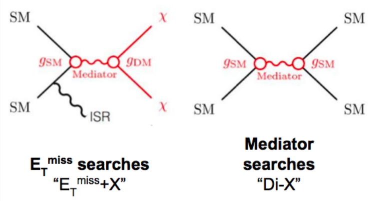
Direct-detection of WIMPs? Next

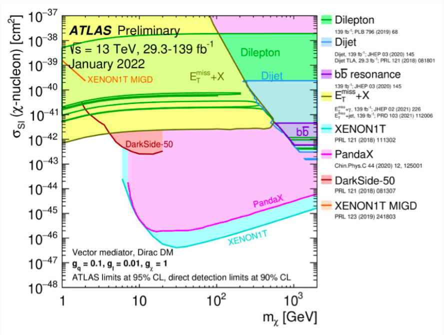
- Neutrino floor at reach

APPEC report, J. Billard et al., (2021) arXiv:2104.07634



- Two ways:



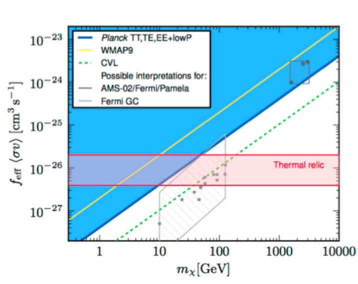


- Search for missing E_T+ jet or Z or top pairs: tail in p_T dist.
- Mass range probed up to 2 TeV
- Mediator searches: probing the rarest final states with two large-radius jets events
- Mass range probed from $O(10)$ GeV to above 3 TeV

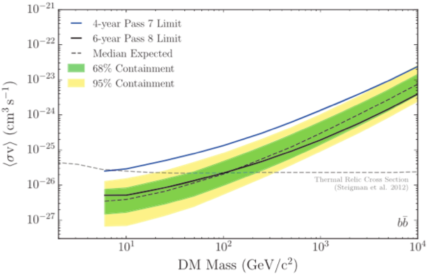
Indirect detection of WIMPs?

→ Indirect detection based on the WIMP annihilation in SM particles

Planck Collab. A&A 594, A13 (2016)



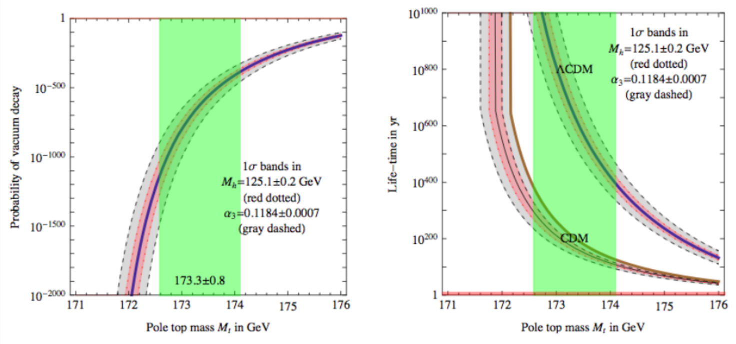
Fermi-LAT Collab., PRL 231301 (2015)



- Modification of the degree of ionization of the primordial plasma through the energy injected by the WIMP annihilations, and thus on the modification of the polarization of the CMB in a manner similar to reionization
- GeV emission from dwarf spheroidal satellite galaxies of the MW, due to their low-baryon content and lack of non-thermal processes

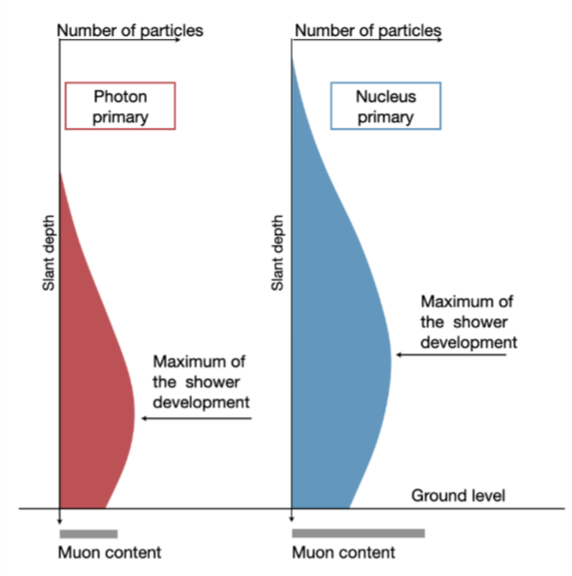
LHC SM phase diagrams

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?

Searches for UHE photons



Searches for UHE neutrinos