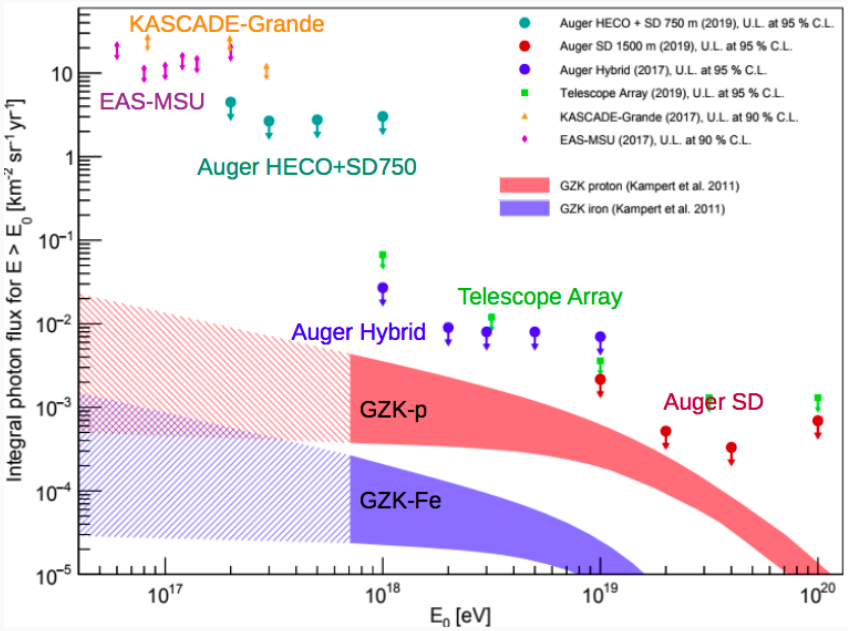
Searching for super heavy dark matter with UHE photons

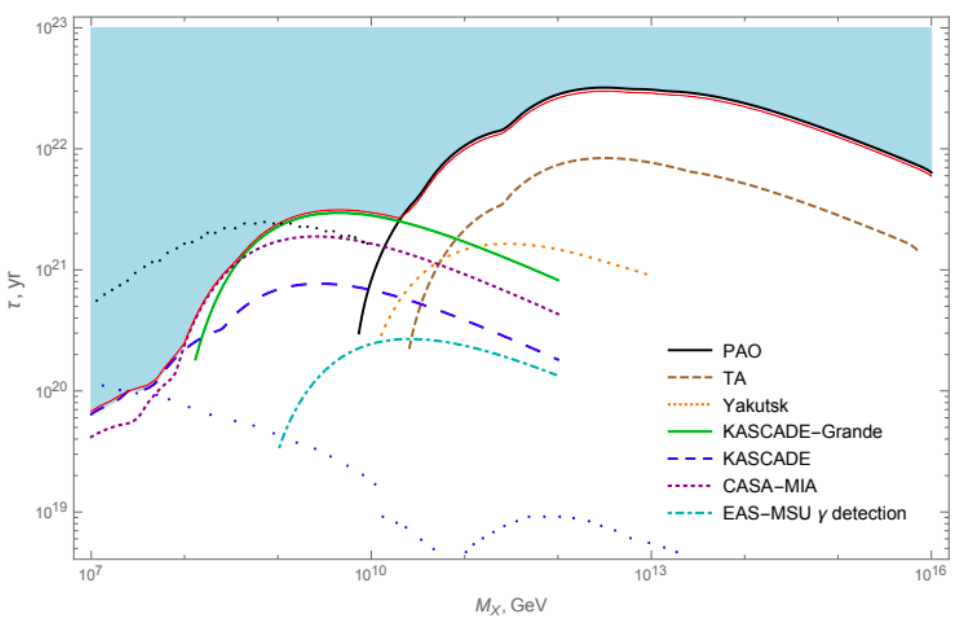
O. Deligny, CNRS/IN2P3 – IJCLab Orsay

Searches for UHE photons

J. Rautenberg for the Auger Collab., ICRC19



O. Kalashev and M. Kuznetsov Phys. Rev. D 94, 063535 (2016)



- Upper limits in photon fluxes can translate into constraints on SHDM particles, which can still have a subdominant contribution to the UHECR intensity **R. Aloisio, V. Berezinsky, M. Kachelriess, Phys. Rev. D74 023516 (2006)**
- Are there connections between these constraints and cosmology?

Naturalness of the SM and WIMPs

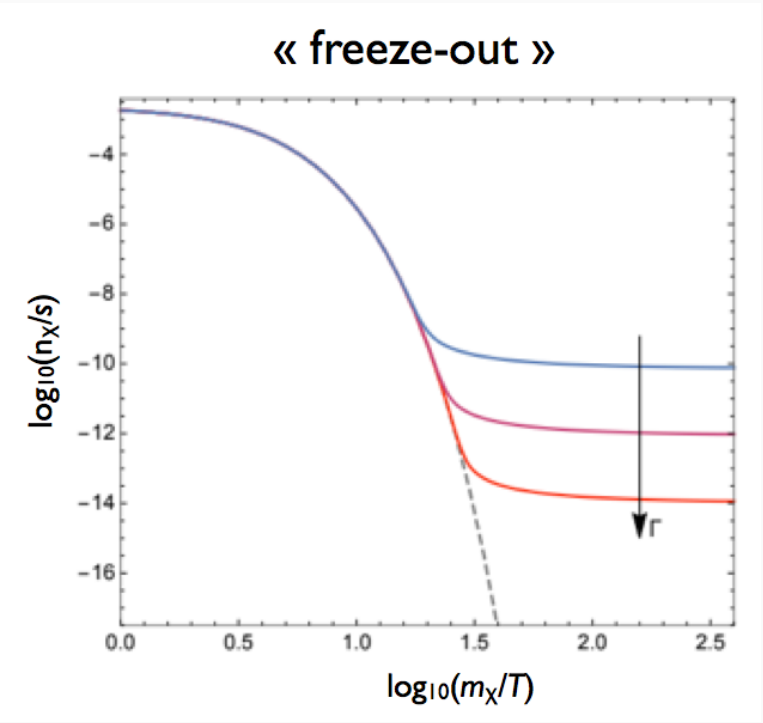
- In the 1980s, electroweak physics little tested and thought to offer a more complex phenomenology than that of the SM
- Problem of the Higgs mass: as a scalar field, can be destabilized by one-loop radiative corrections through its coupling to the top quark (quadratic divergences)

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

- Naturalness: prejudice that stability of observables prevails under small variations of the fundamental parameters (the bare parameters)
- $\delta m_h^2 < m_h^2 \implies \Lambda < 1$ TeV – scale of new physics to respect naturalness
- 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

WIMP paradigm

- At equilibrium with the primordial plasma
- Evolution as exp $(-M_X/T)$: sharp decrease of the population of WIMPs when $T < M_X$
- Eventually, level of density such that the annihilation reaction of WIMPs is kinetically frozen under the effect of dilution

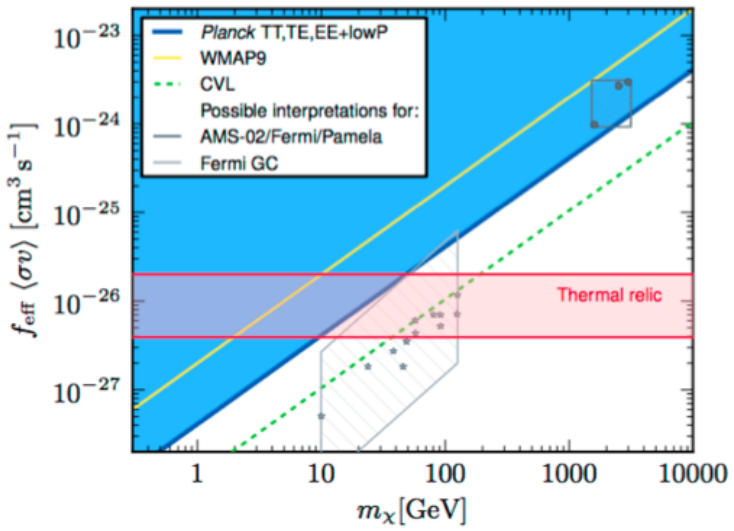


- Freezing time estimated by equating the annihilation rate with the Hubble parameter $\Longrightarrow \Omega_{\mathrm{WIMP}} \sim \frac{10^{-25}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$
- Of the order of unity by taking, as expected for WIMPs, $\langle \sigma v \rangle \sim G_F^2 M_X^2$ $\rightarrow$ the WIMP "miracle"

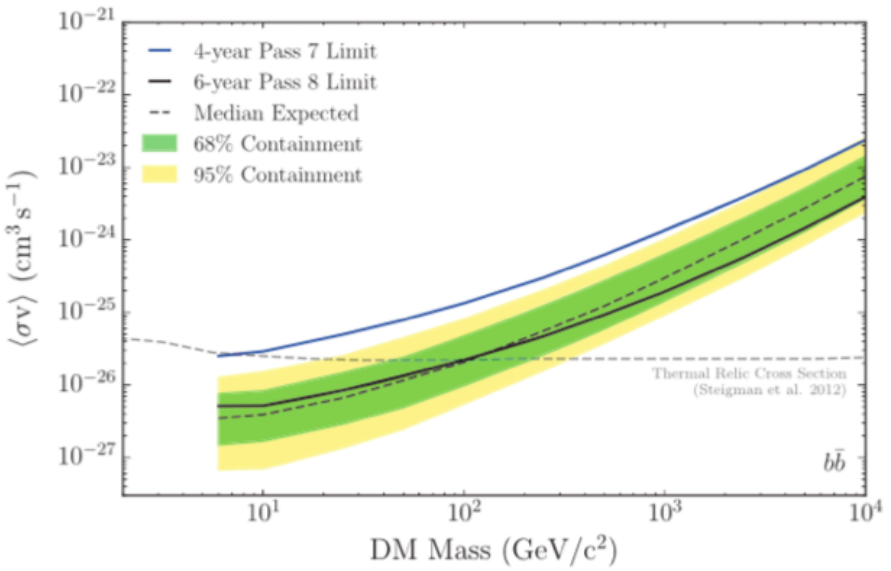
WIMPs? Indirect detection

→ Indirect detection based on the WIMP annihilation in SM particles

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



Fermi-LAT Collab., PRL 231301 (2015)

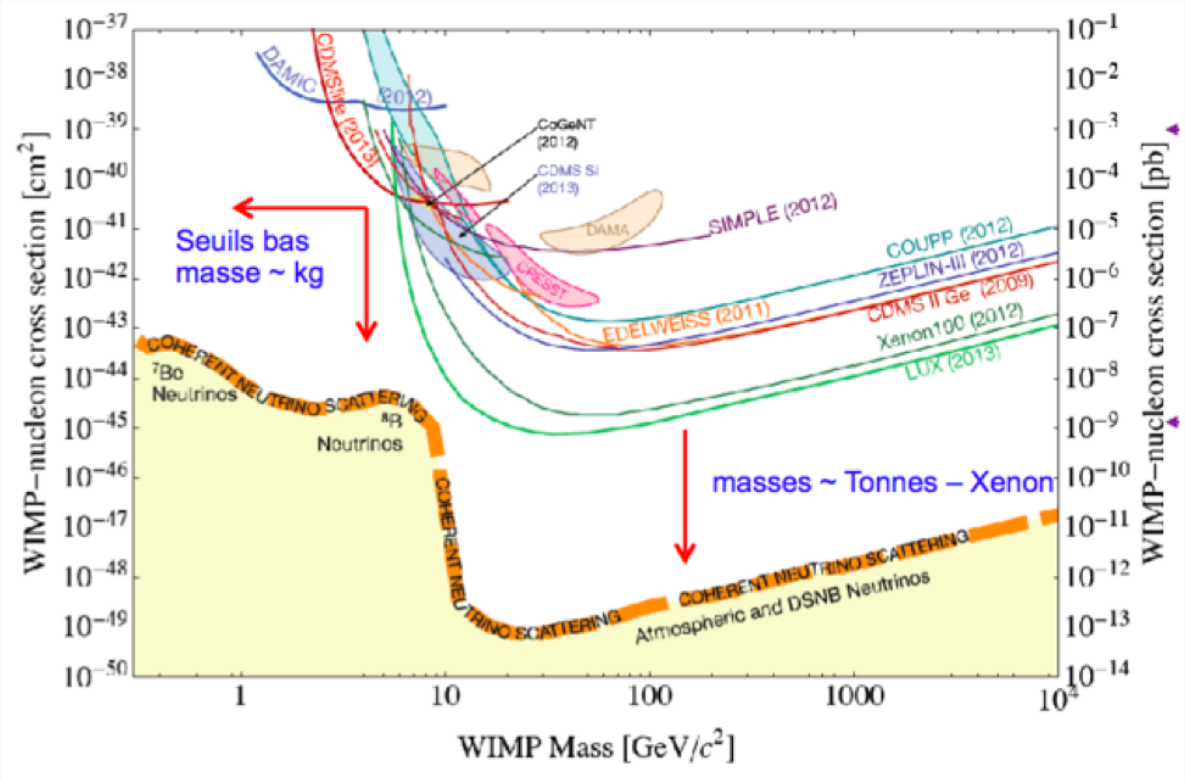


- Searches subject to many uncertainties, in particular possible backgrounds of astrophysical origin or modeling of dark matter halo profiles. Several indications of positive signals but none of them with consensus

WIMPs? Direct detection

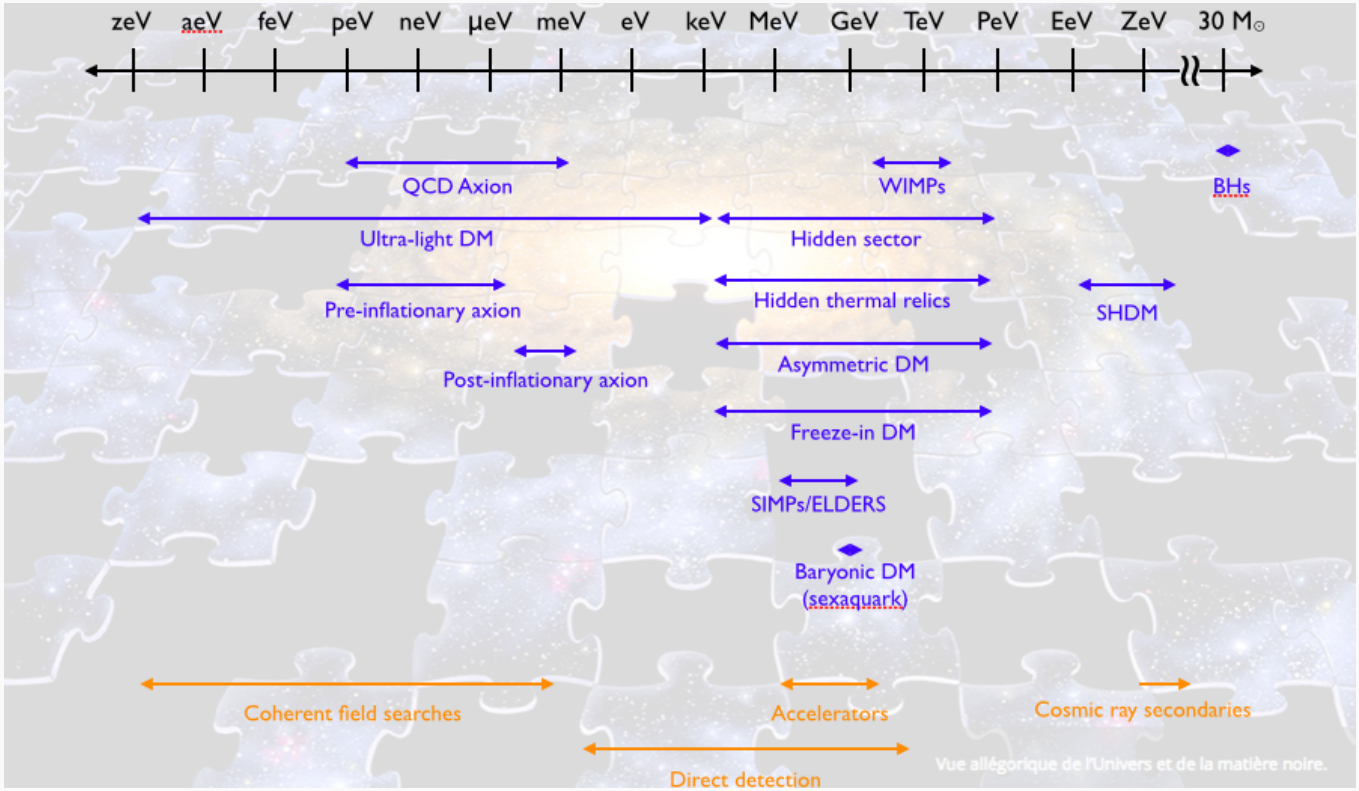
- Search for the interaction of WIMPs from the galactic halo with the nuclei of a terrestrial detector
- Measurement of nuclear recoil

Credits: F. Combes, Reflets de Physique 51, 4



Beyond WIMPs

- "Generalisation of WIMPs": light WIMPs ($M_X \sim 1$ GeV, "asymmetric" DM), $M_X > 100$ GeV with other SUSY particles much heavier, $\Lambda \sim 1$ PeV not related to the electroweak interaction
- Much broader panorama beyond these scenarios



inspired from arXiv:1707.04591

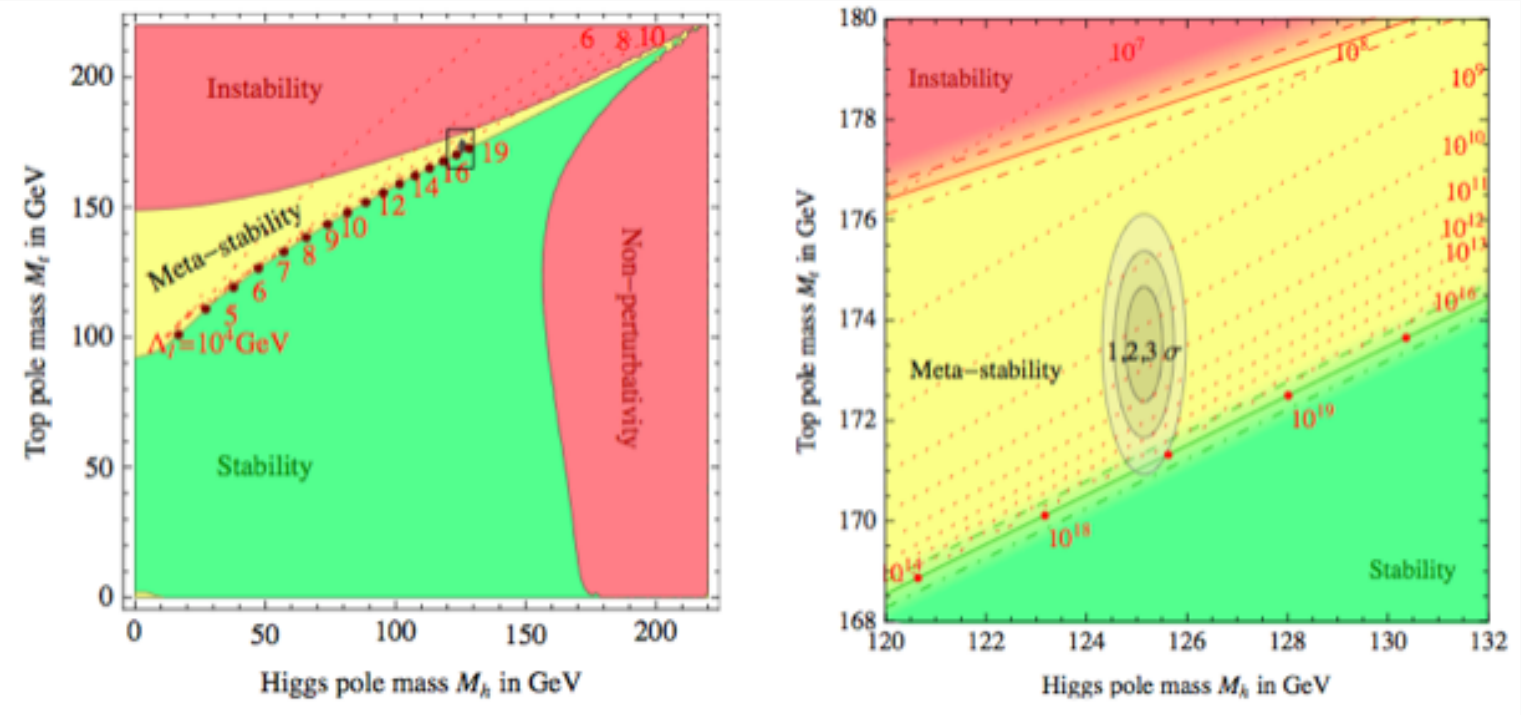
SM vacuum (in)stability

- 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: $m_h^2 > \frac{3m_t^4}{\pi^2 v^2} \log \frac{\Lambda}{v}$
- Very simplified calculation, 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

Post-LHC SM phase diagrams

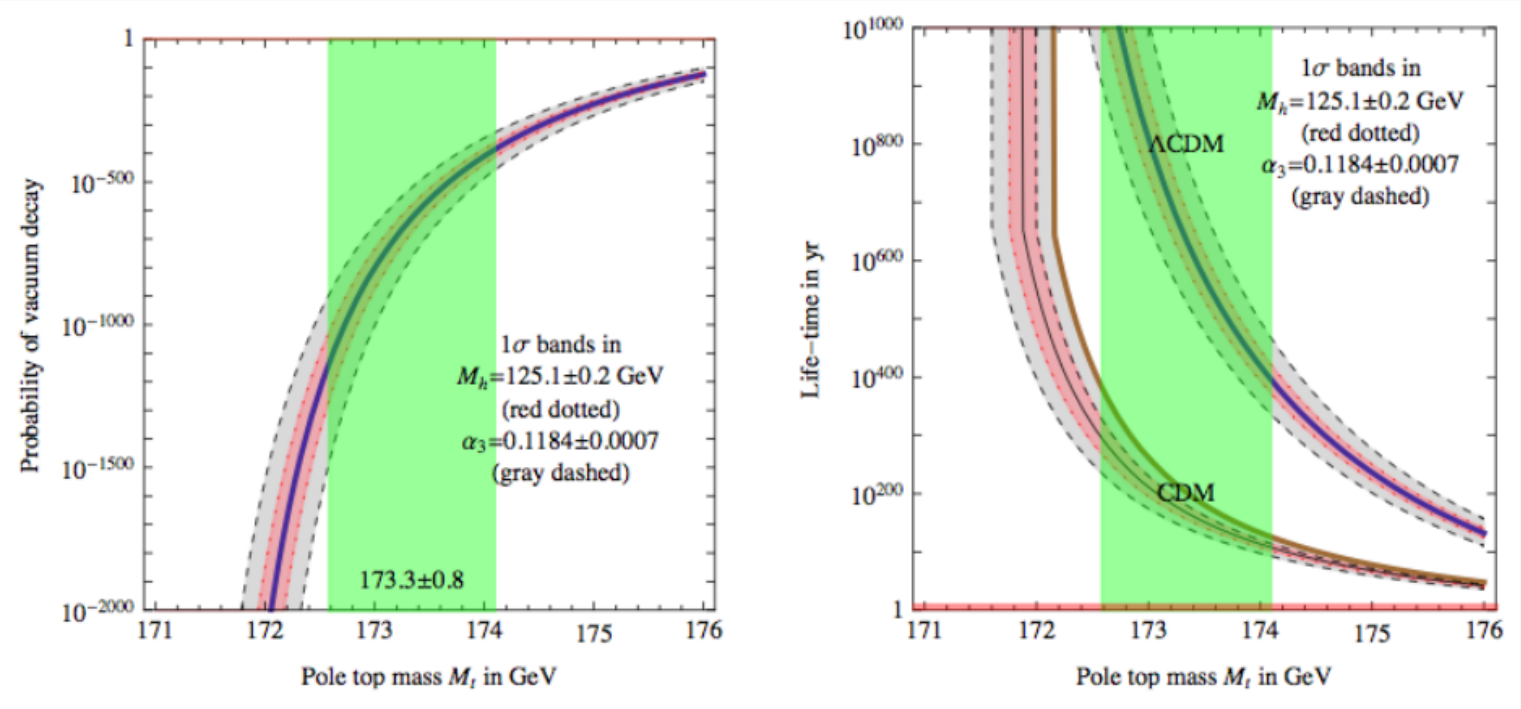
- Extrapolation of the SM parameters up to large energies with full 3-loop NNLO precision

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



Post-LHC SM phase diagrams

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



- Precise values of Higgs boson mass + top Yukawa coupling $\Longrightarrow$ SM vacuum meta-stable
- Absence of new physics at LHC up to now

$\Longrightarrow$ Naturalness not the solution to the hierarchy problem?

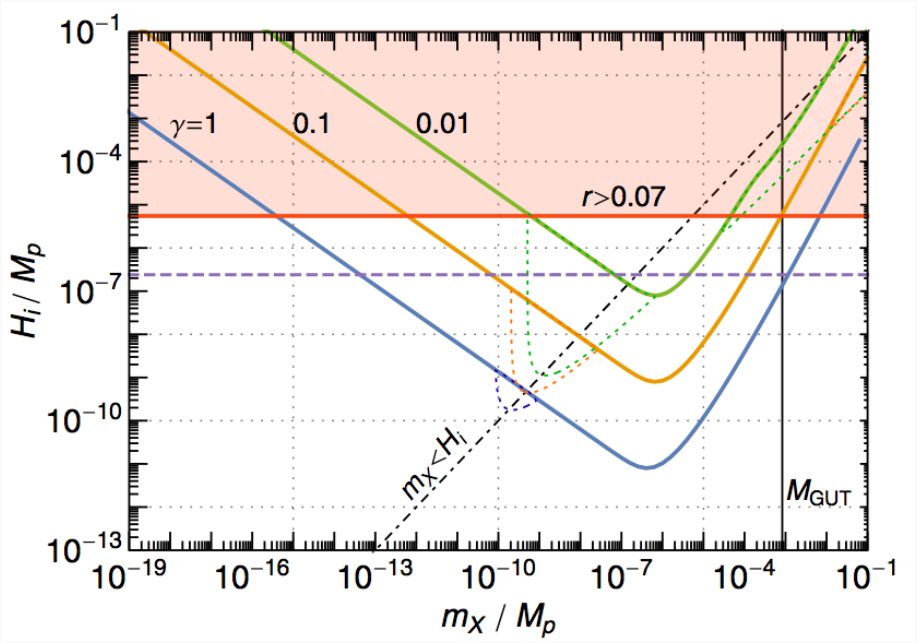
Non-thermal SHDM production

→ M. Garny, M. Sandora, M. Sloth, PRL 116 (2016) 101302

→ 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

- Hidden sector as natural as possible if related to the Planck or to the GUT scale
- SHDM particles that are only gravitationally coupled produced during reheating/at the end of inflation through annihilations of the SM particles ("freeze-in" mechanism)

M. Garny, M. Sandora, M. Sloth, PRL 116 (2016) 101302



- Reheating temperature relatively high so as to produce enough such very feebly coupled heavy particles $\Longrightarrow$ tensor/scalar ratio r of the primordial modes possibly detectable in the power spectrum of the CMB

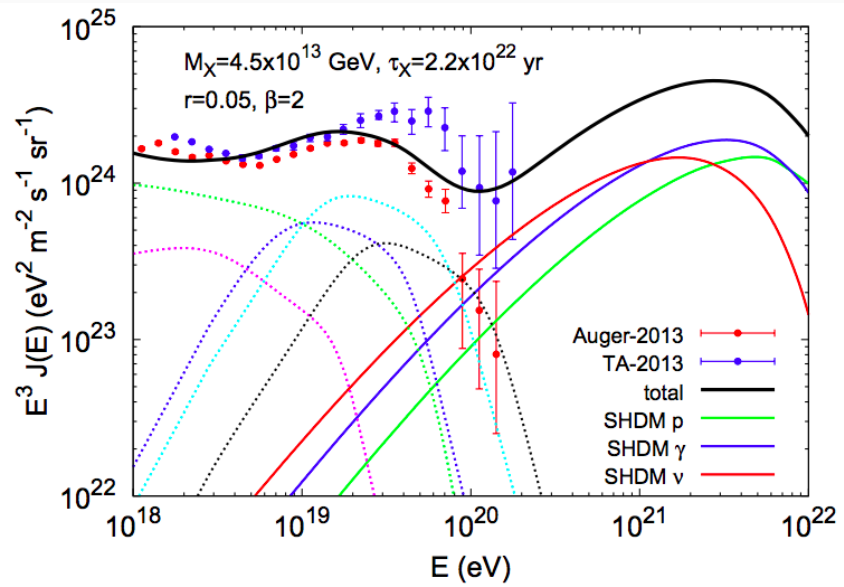
UHE particles as secondaries of metastable SHDM particles

→ V. A. Kuzmin & V. A. Rubakov, Phys. At. Nucl. 61 (1998) 1028, also V. Berezinsky, M. Kachelriess, A. Vilenkin, PRL 79, 4302 (1997)

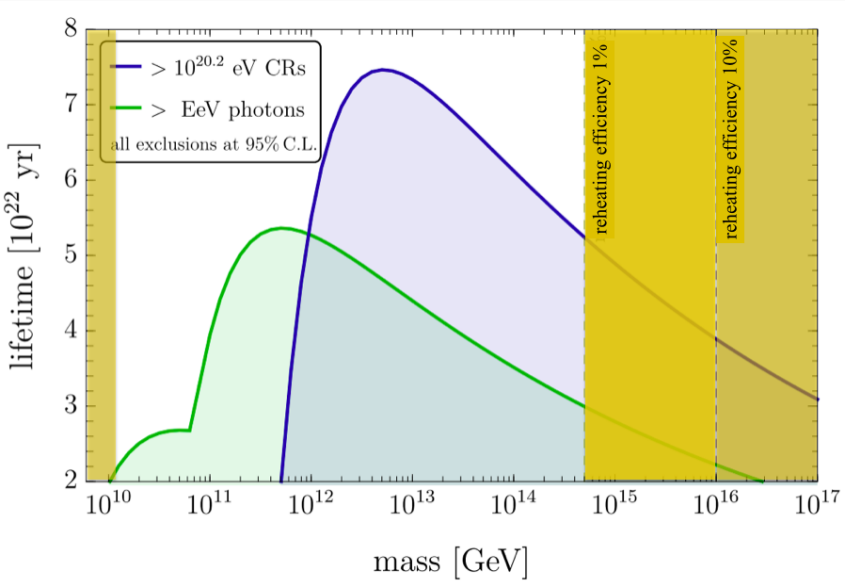
- Heavy DM particles protected from standard decay by perturbative effects through a new quantum number
- But non-perturbative effects can lead to decays through “instantons” in non-commutative gauge theories
- Additional term in the Lagrangian: $\frac{\theta}{64\pi^2}\mathrm{Tr}(F_{\mu\nu}F_{\rho\sigma})$
- For currents not associated to gauge interactions, anomalies not cancelled after renormalisation: possibility to exchange quantum numbers through an anomaly of the type of that allowing π^0 decay in the SM
- Prob. to excite topological field config. from local charges: $\exp\left(-4\pi/\alpha_X\right)$ (t’Hooft, PRL 37 (1976) 8)
- Lifetime of metastable X particles: $\tau_X \simeq \frac{\hbar}{m_X c^2}\exp\left(4\pi/\alpha_X\right)$

UHE particles from non-thermal SHDM

R. Aloisio., S. Matarrese, A. Olinto, JCAP 08 (2015) 024



Snowmass2021 LoI, arXiv:1903.05429

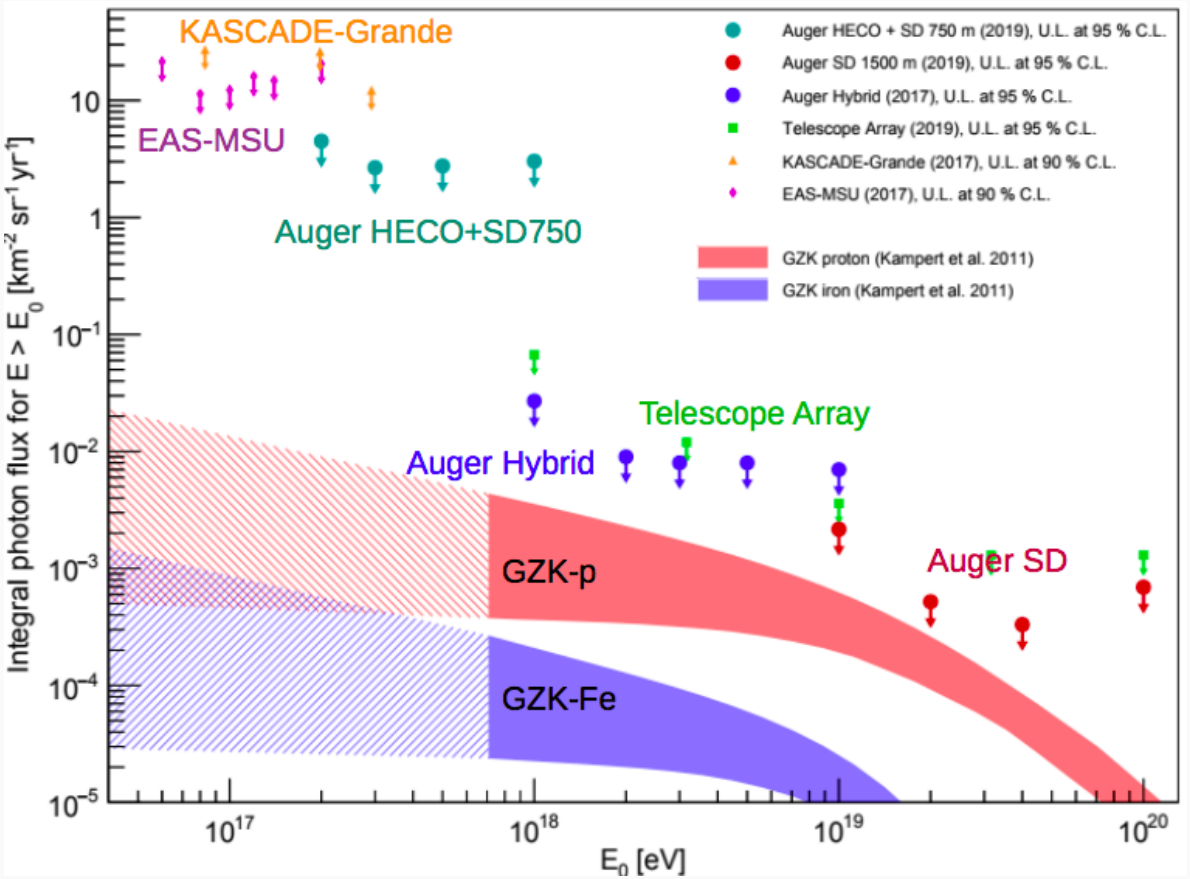


- Constraints from the upper limits on the all-particle UHECR intensity

  E. Alcantara, L. Anchordoqui, J. Soriano, Phys. Rev. D 99 (2019) 103016

- For *r* large enough, non-thermal SHDM tested by UHECR observatories

Larger exposure to UHE photons



- Larger collection area
- Current discrimination power:
  - $\mathcal{E}_{\text{photons}} \simeq 1.5\%\ \mathcal{E}_{\text{CR}}$ above 3 EeV
  - $\mathcal{E}_{\text{photons}} \simeq 10\%\ \mathcal{E}_{\text{CR}}$ above 10 EeV

Summary

- SHDM models constrained by the current UHECR picture, not excluded
- Excess of UHE photons from the GC direction as the main signature
- Some arguments for non-thermal SHDM that motivate a serendipitous discovery
- Better CR/photon discrimination needed

Snowmass2021 - Letter of Interest

Hunting super-heavy dark matter with ultra-high energy photons

Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Collaboration: Pierre Auger

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doi:10.5281/zenodo.4009881

- NB: Other possible scenarios, including thermal SHDM **(K. Dienes, B. Thomas, Phys. Rev. D 85 (2012) 083523 & 083524, A. Berlin, PRL 119 (2017) 121801, etc.)**