Pierre Auger Observatory and Super Heavy Dark Matter

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Outline of the talk

1. Super Heavy Dark Matter
2. An emerging UV scale in the SM
3. Primordial Gravitational Waves
4. SHDM decay
5. Model constrains from Auger data
6. Conclusions

Super Heavy Dark Matter

- ✓ Supermassive particles, with mass $M>10^8$ GeV, can be easily generated in the early universe by time-dependent gravitational fields and through gravitational (direct) coupling to the inflaton field and/or to SM fields.
  [Schrodinger (1939), Zeldovich & Starobinsky (1972), Kofman, Linde & Starobinsky (1994), Felder, Kofman & Linde (1998), Chung, Kolb & Riotto (1998), Kuzmin & Tkachev (1998), M. Garny, M. Sandora, and M. S. Sloth (2015), E. W. Kolb and A. J. Long (2017), Y. Mambrini and K. A. Olive (2021)]

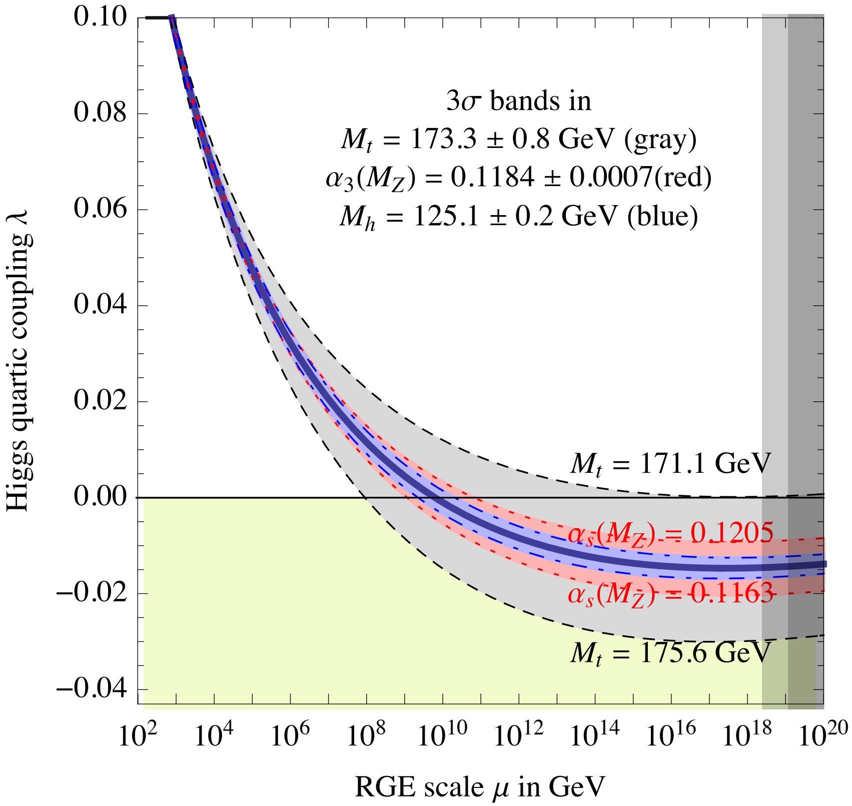
- ✓ They can be long-lived if their decay is inhibited by some discrete symmetry (such as R-parity for SUSY neutralinos) weakly broken or through non-perturbative instanton effect.
  [Berezinsky, Kachelriess & Vilenkin (1997), Kuzmin & Rubakov (1997)]

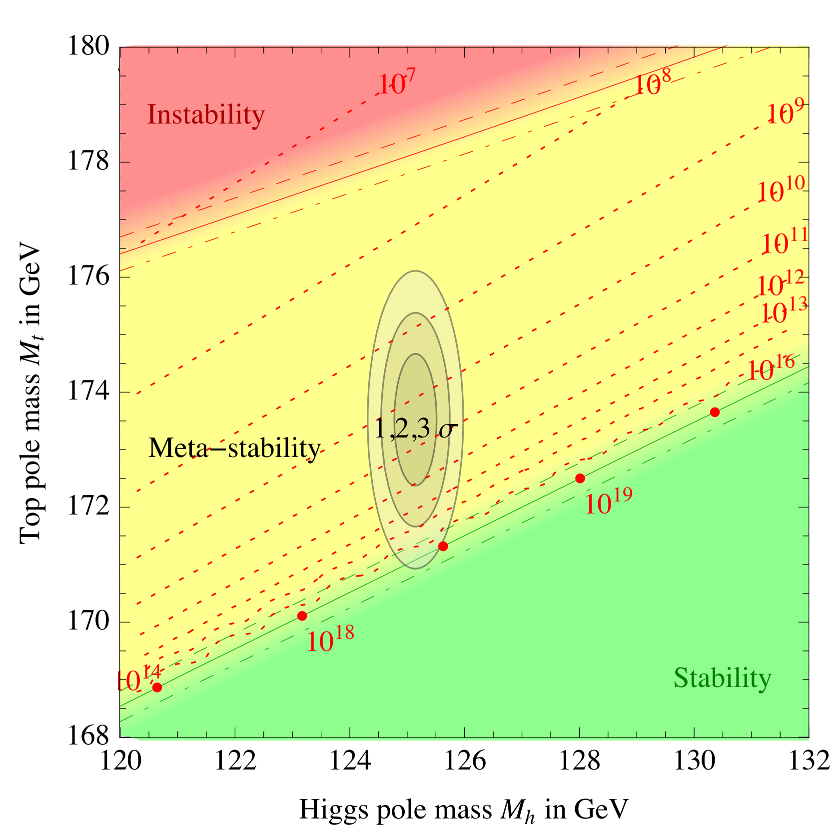
In this case SH relics can be dark matter candidates (SHDM)

WIMP vs SHDM

- WIMP naturally produced in SUSY models (new physics supra-TeV, naturalness).
- SHDM naturally produced during inflation/reheating, always out of local thermal equilibrium.
- Both require additional (weakly broken) symmetries to prevent fast decays.
- WIMP can be experimentally tested through: production (LHC), direct detection (underground labs), indirectly (astrophysical observations).
- SHDM can be experimentally tested only indirectly through cosmological (CMB) observations and UHECR observations.

An emerging UV scale in the SM





Buttazzo, De Grassi, Giardino, Giudice, et al. (2014)

- ✓ Given the LHC measured masses of Higgs boson and Top quark, the running Higgs quartic coupling λ approaches zero at a scale $\Lambda_I = 10^{10}$-10^{12} GeV signaling a new UV scale where a possible instability of the Higgs potential arises.
- ✓ This evidence can be the first sign of new physics beyond the SM at the LHC, however the extremely slow evolution of $\lambda(\mu)$ does not exclude the possible SM extension until the Plank mass $M_{Pl}=10^{19}$ GeV.
- ✓ Neglecting the naturalness problem, the DM problem can be solved in the framework of the SHDM approach with the dark sector scale corresponding to Λ_I.

Primordial gravitational waves

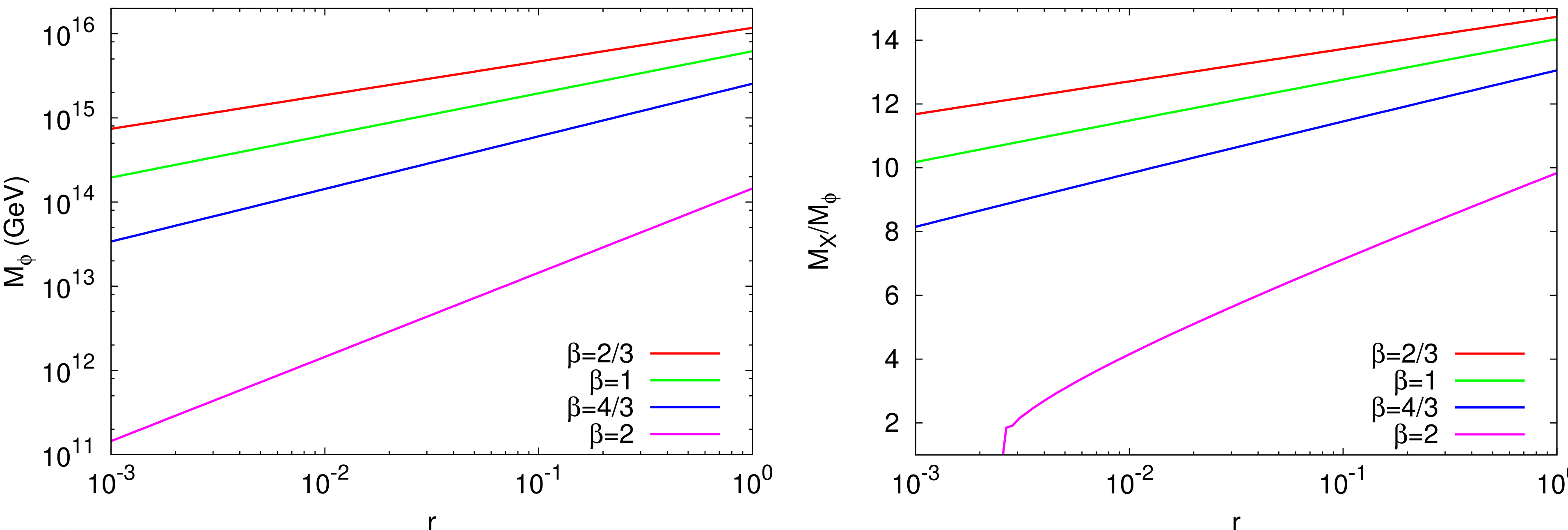
- ✓ Being out of local thermal equilibrium SHDM naturally produces primordial gravitational waves, imprinted in the CMB.
- ✓ In the case of SHDM generation by time dependent gravitational fields. The tensor-to-scalar ratio in the CMB fluctuations sets the scale for SHDM.

$$V(\phi) = \frac{M_\phi^{4-\beta}}{\beta}\phi^\beta \qquad V_\star \simeq \frac{3\pi^2}{2} A_s r M_{Pl}^4 \simeq M_{GUT}^4 \left(\frac{r}{r_0}\right)$$

$$M_\phi = M_{GUT}\left[\beta\left(\frac{M_{GUT}}{M_{Pl}}\right)^\beta \left(\frac{\sqrt{\pi r_0}}{\beta}\right)^\beta \left(\frac{r}{r_0}\right)^{1+\beta/2}\right]^{\frac{1}{4-\beta}}$$

$$\Omega_X(t_0) \simeq 10^{-3}\Omega_R \frac{8\pi}{3}\left(\frac{T_{RH}}{T_0}\right) \times$$

$$\times\, \beta^{\frac{2}{4-\beta}} \left(\frac{M_{GUT}}{M_{Pl}}\right)^{\frac{8}{4-\beta}} \left(\frac{\sqrt{4\pi r_0}}{\beta}\right)^{\frac{2\beta}{4-\beta}} \left(\frac{r}{r_0}\right)^{\frac{2+\beta}{4-\beta}} \left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$



RA, Matarrese, Olinto (2015)

- ✓ the observation of a non-zero fraction of tensor modes in the CMB fluctuations pattern, already at the level of 10^{-3}, would confirm that the production of SHDM particles in the early universe is a viable mechanism to explain the DM problem, assuring a density of SHDM today at the observed level.

SHDM decay

$$X \to q\bar{q} \to N, \gamma, \nu, \bar{\nu} \qquad X \to \nu\bar{\nu}$$

✓ Super-weak coupling between SHDM and the SM sectors

$$\mathcal{L}_{int} = \frac{g_{X\Theta}}{\Lambda^{n-4}} X\Theta$$

Λ energy scale of the dark sector (typically $\lesssim 10^{16}$ GeV, GUT), with n the mass dimension of the SHDM-SM interaction operator XΘ

$$\tau_{X\Theta} = \frac{V_n}{4\pi M_X \alpha_{X\Theta}} \left(\frac{\Lambda}{M_X}\right)^{2n-8} \qquad \alpha_{X\Theta} = \frac{g_{X\Theta}^2}{4\pi}$$

being V_n a phase space factor.

✓ Instanton induced decay

Retaining the hypothesis that the only interaction between SHDM and SM sectors is gravitational. In non-abelian gauge theories (in the dark sector) even stable particles in the perturbative domain will in general eventually decay due to non-perturbative effects. Such effects, known as instantons, provide the occurrence of quantum tunneling between distinct classes of vacua, forcing the fermion fields to evolve during the transitions and leading to the generation of particles depending on the associated anomalous symmetries.

$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X} \qquad \alpha_X = \frac{g_X^2}{4\pi}$$

SHDM contribution to UHECR

✓ SHDM accumulates in the halo of our own galaxy with an over-density δ given by:

$$\delta = \frac{\delta_X^{halo}}{\rho_X^{extr}} = \frac{\rho_{DM}^{halo}}{\Omega_{DM}\rho_c} \simeq 2 \times 10^5$$

Berezinsky, Kachelriess, Vilenkin (1997)

UHECR flux

$$J_{SHDM}(E,\theta) = \frac{1}{4\pi M_X \tau_X} Q(E) \int_0^{r_{max}(\theta)} dr\, n_X(R(r))$$

Particle Physics and Cosmology

Fix the spectrum and mass composition. The observed flux selects a sub-space of the SHDM parameter space, through

$$(M_X, \tau_X)$$

connected to cosmology and particle physics through H_I, α_X and ε.

signature of the model

Astrophysics

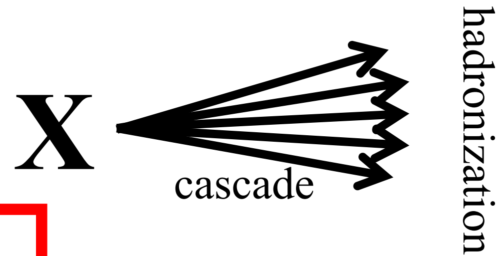
Galactic DM halo fixes the geometrical behavior of the SHDM emission, (increased emission from the GC direction)

$$n_X(R) = \frac{n_0}{(R/R_s)^{\alpha}(1+R/R_s)^{3-\alpha}}$$

$\alpha=1$ NFW, $\alpha=3/2$ Moore density profile

signature of the model

From SHDM to UHECR – hadrons

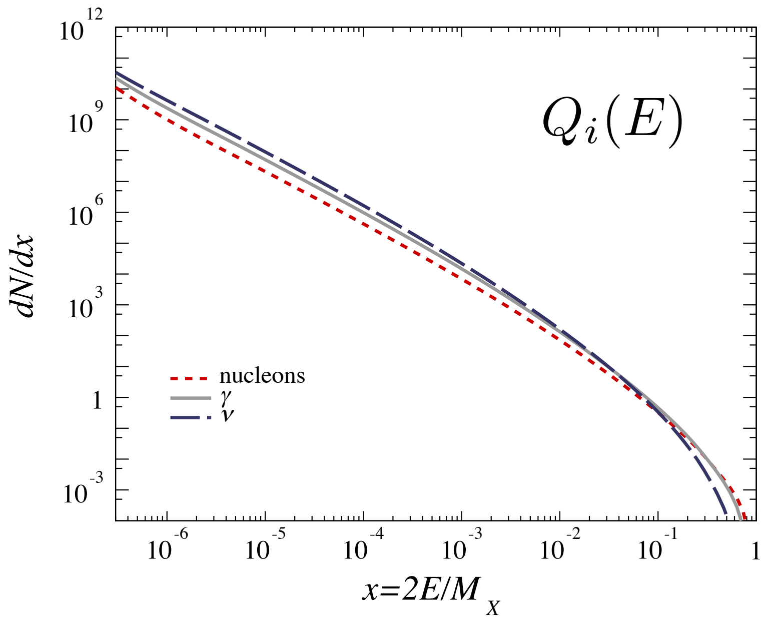


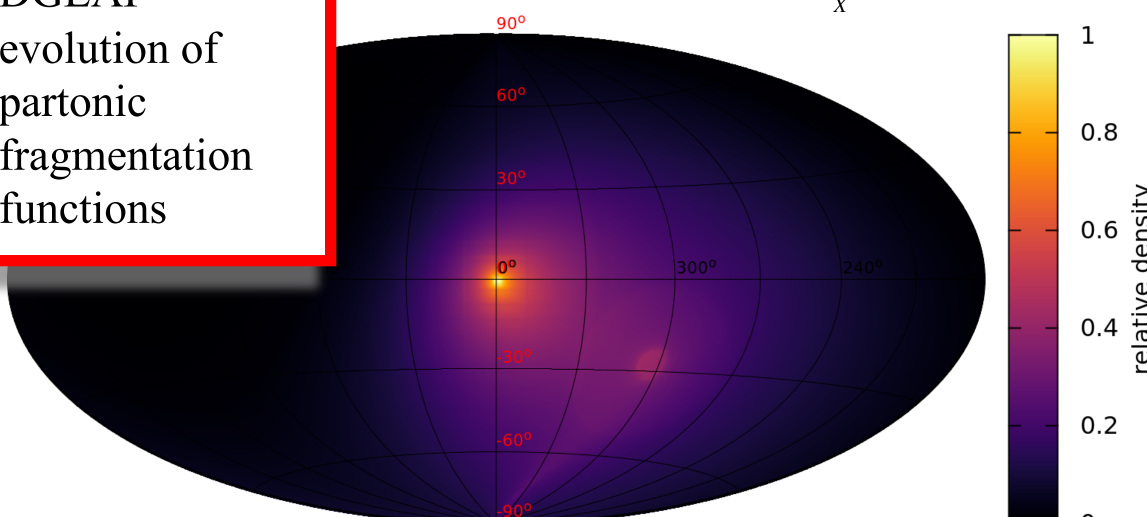
mainly N, π
hence N, γ and ν

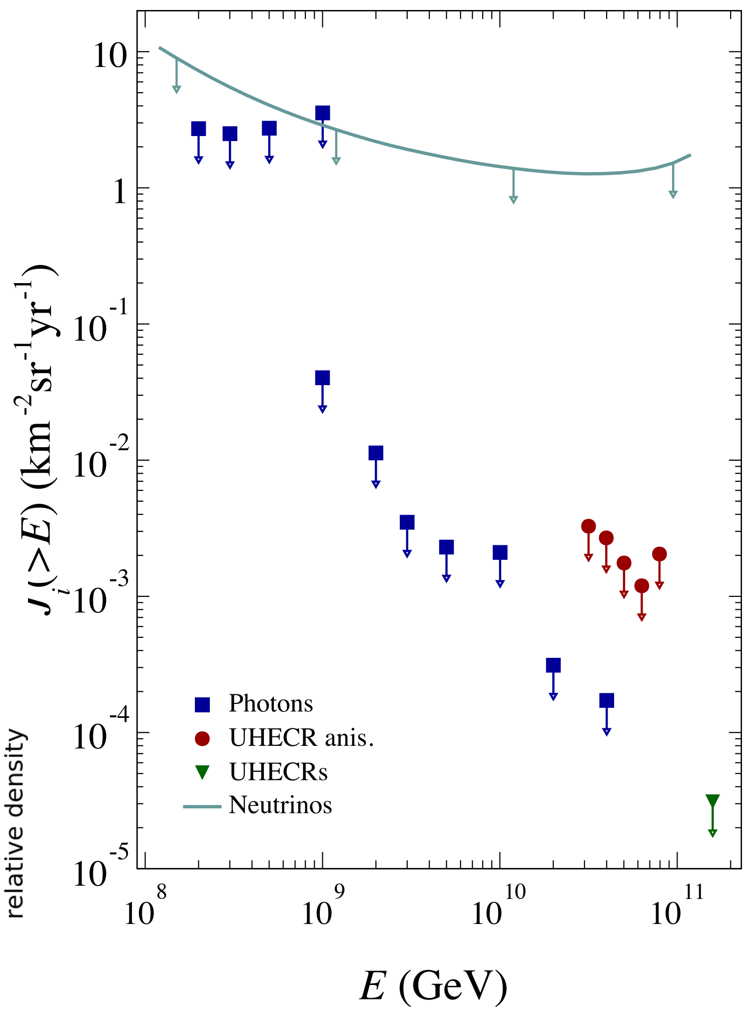
$$Q_{\nu,\gamma,p} \propto E^{-1.9}$$
$$J_{\nu,\gamma,p} \propto \frac{1}{M_X \tau_X}$$

RA, et al (2004-2007)

- ✓ SHDM lifetime τ_X and mass M_X fix the CR flux.
- ✓ SHDM halo density profile
- ✓ Integrating over the whole sky (and universe).
- ✓ DGLAP evolution of partonic fragmentation functions







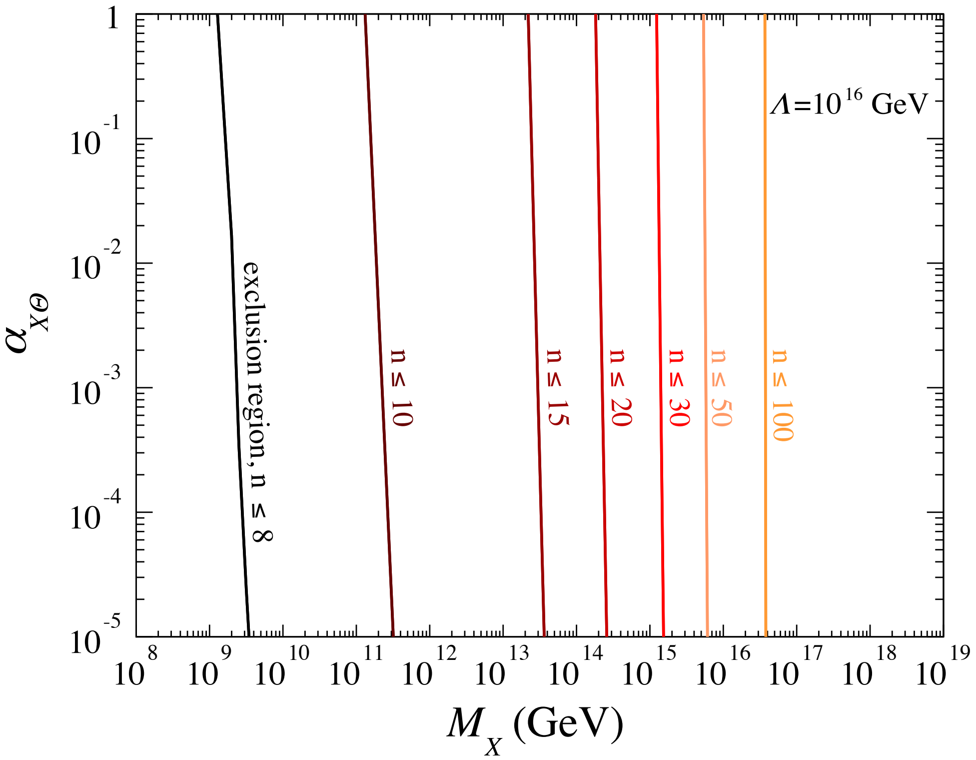
Auger Collaboration PRD 107 (2023) 4, 042002

Auger data constrains on M_X and τ_X

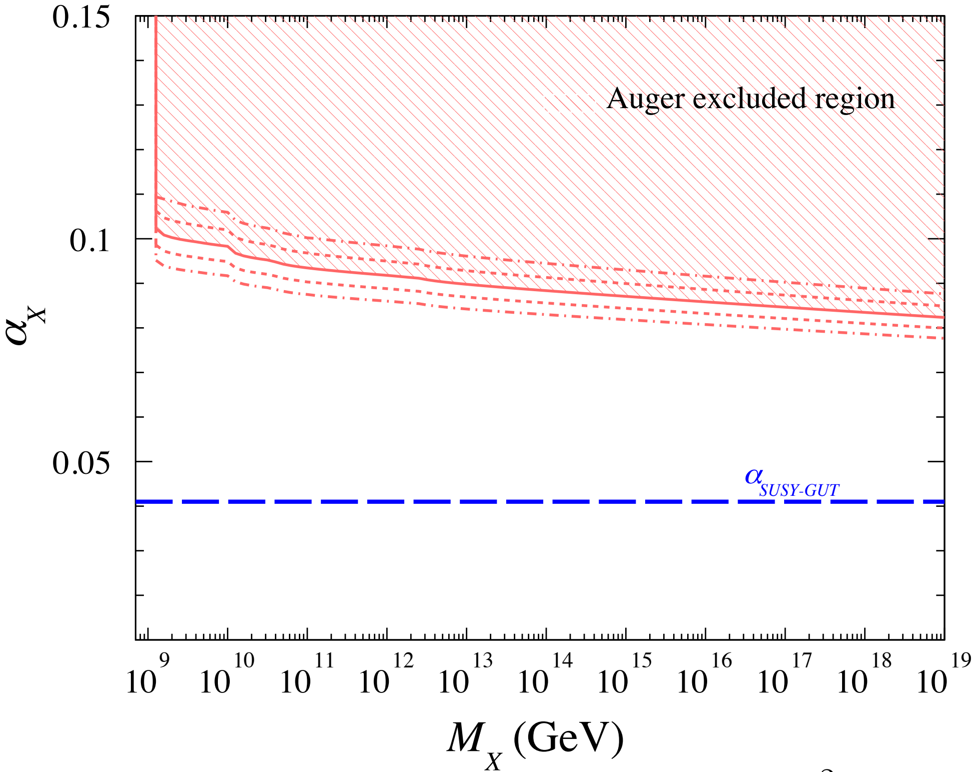
- By imposing the Auger observational limits on the fluxes of N, γ, ν it is possible to place stringent limits on M_X and τ_X.

- Depending on the assumptions on the decaying mechanism (perturbative or instanton), the limits are on the mass dimension n of the perturbative coupling or to the non-abelian gauge coupling α_X in the dark sector (instanton decay).

Auger Collaboration PRL 130 (2023) 6, 061001, PRD 107 (2023) 4, 042002



$$\tau_{X\Theta} = \frac{V_n}{4\pi M_X \alpha_{X\Theta}} \left(\frac{\Lambda}{M_X}\right)^{2n-8} \qquad \alpha_{X\Theta} = \frac{g_{X\Theta}^2}{4\pi}$$

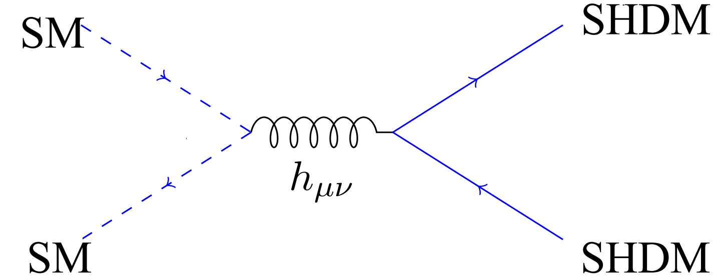


$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X} \qquad \alpha_X = \frac{g_X^2}{4\pi}$$

Cosmology parameters

- Combining the limits from Auger data with the requirement of the correct abundance of SHDM today it is possible to constrain cosmological parameters

$$\frac{1}{2M_P}h^{\mu\nu}\left(T^{SM}_{\mu\nu}+T^{SHDM}_{\mu\nu}\right)$$



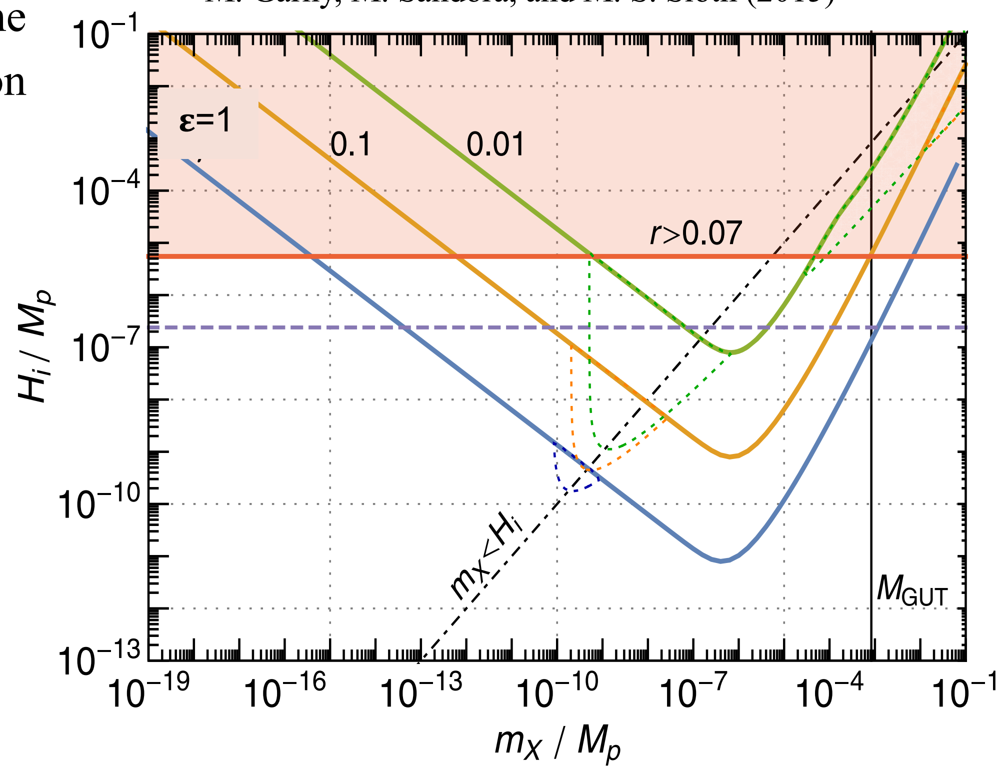
- Taking the reference model of a pure gravitational interaction between SHDM and SM (Plank Interacting Dark Matter, PIDM) the relevant cosmological parameters are H_I the Hubble parameter at the end of inflation and $0<\varepsilon\leq 1$ the reheating efficiency, connected with the inflaton decay amplitude Γ_φ :

$$\epsilon = \sqrt{\frac{\Gamma_\phi}{H_I}}$$

$$\Omega_{CDM} = 9.2\times 10^{24}\frac{\epsilon^4 M_X}{M_P}Y_{X,0}(M_X,\epsilon,H_I)$$

- The evolution of the SHDM density can be determined through a Boltzman equation considering the cross section $\langle\sigma v\rangle \lesssim 1/M_X^2$ for the annihilation of SHDM into SM particles and their equilibrium distribution.

M. Garny, M. Sandora, and M. S. Sloth (2015)

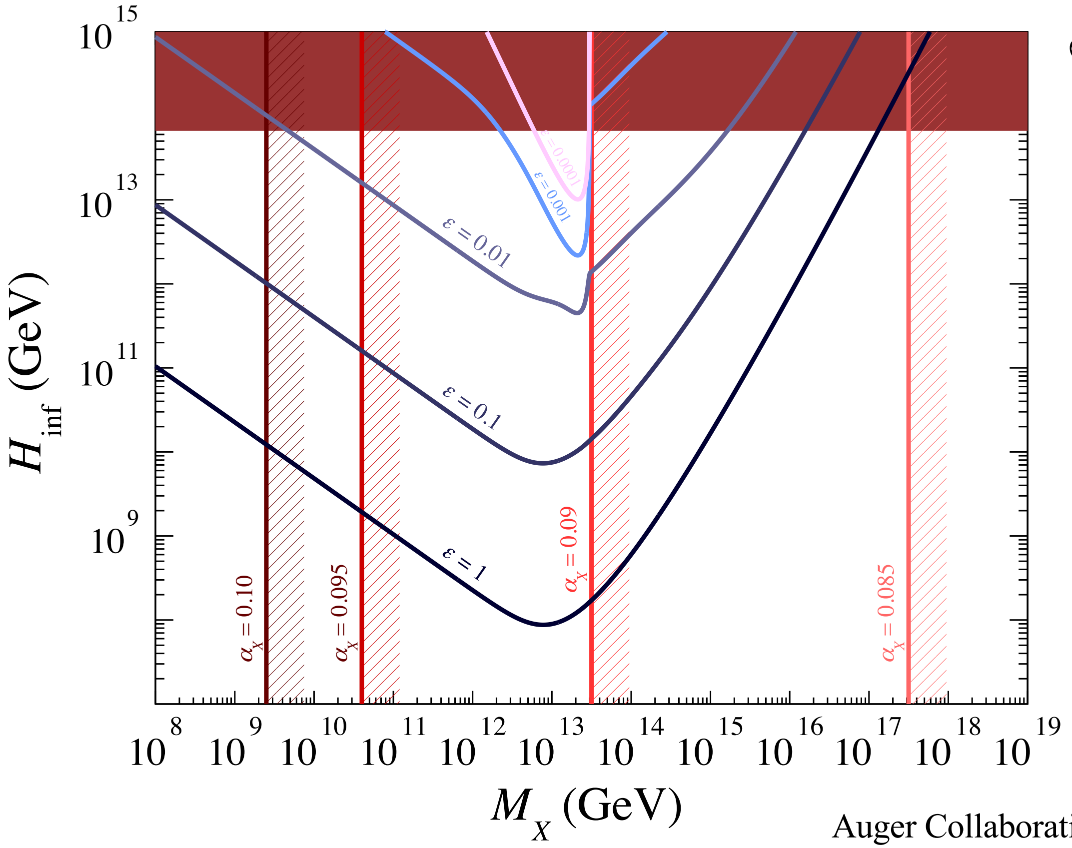


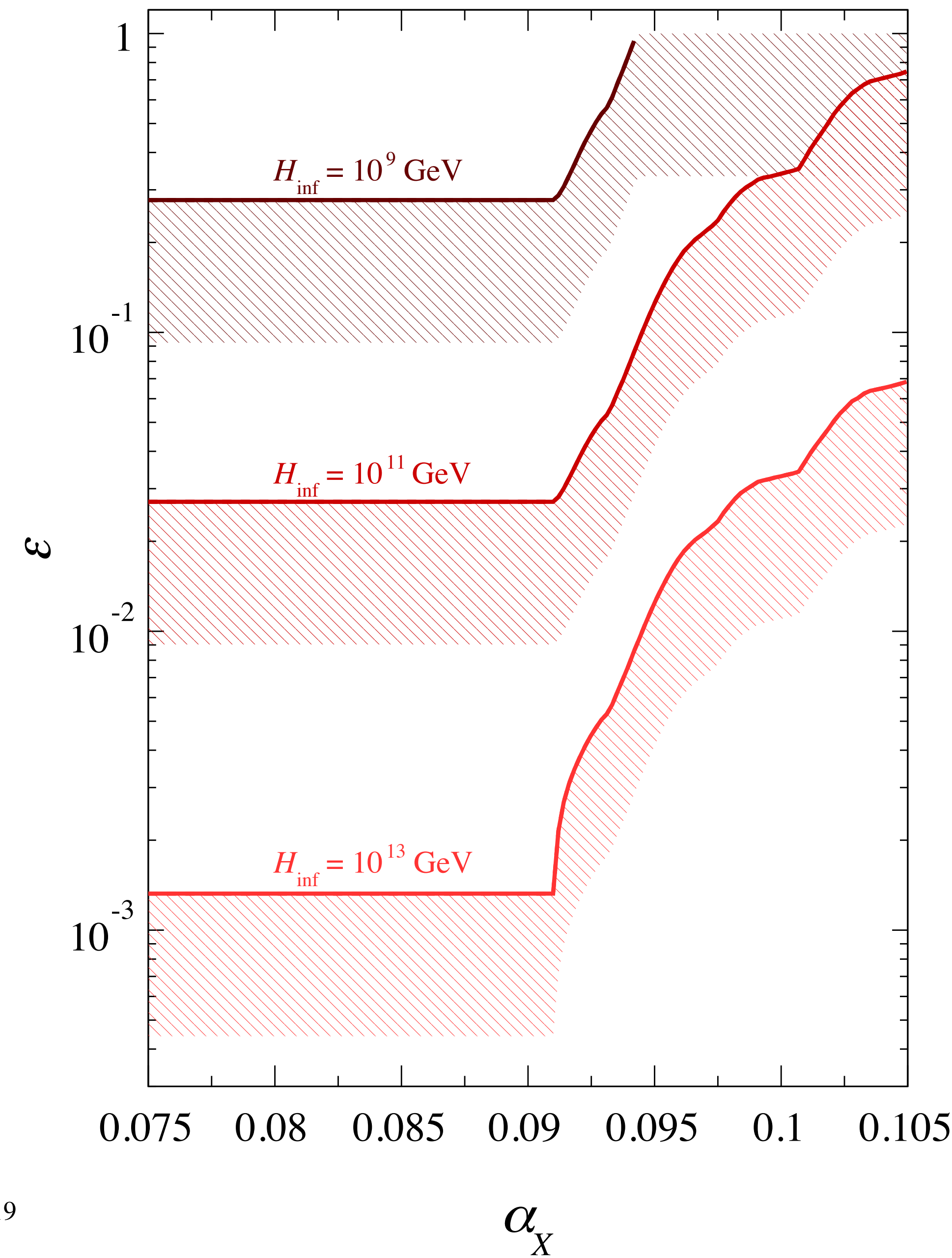
Auger data constrains on cosmology

- Requiring that the X particles density today is the observed CDM density.

- The limits on M_x and $\boldsymbol{\tau}_X$ can be rewritten in terms of the cosmology parameters H_I and $\boldsymbol{\varepsilon}$.

$$H_{inf} \lesssim 6.6 \times 10^{-6} M_P \left(\frac{r}{0.1}\right)^{1/2}$$





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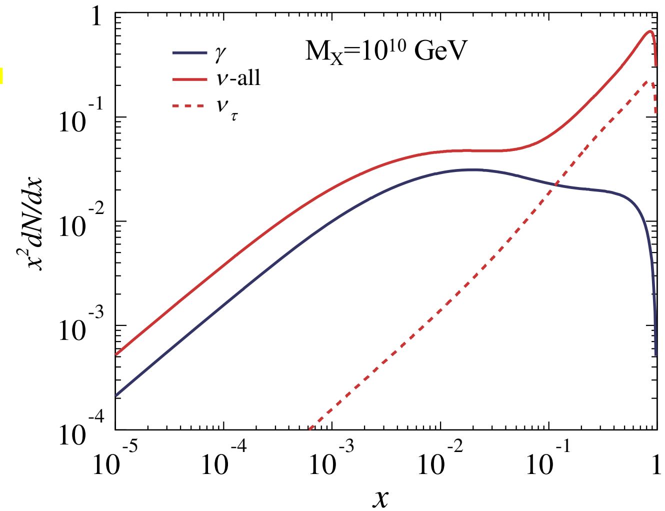
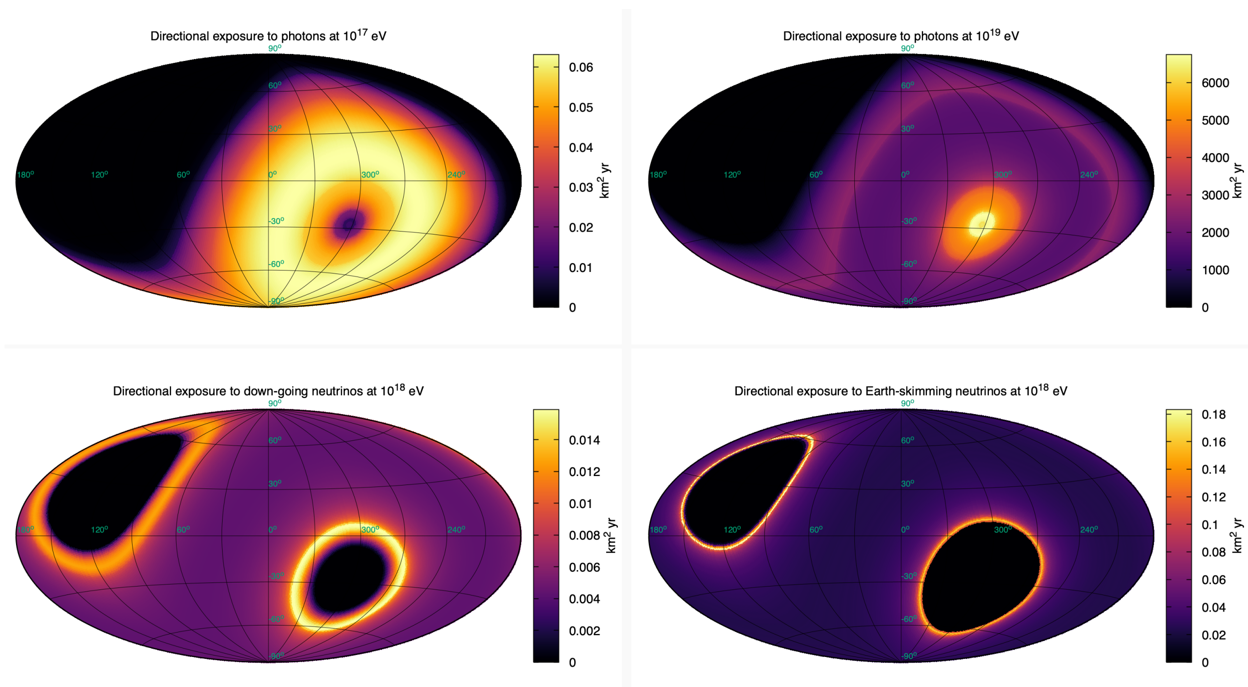
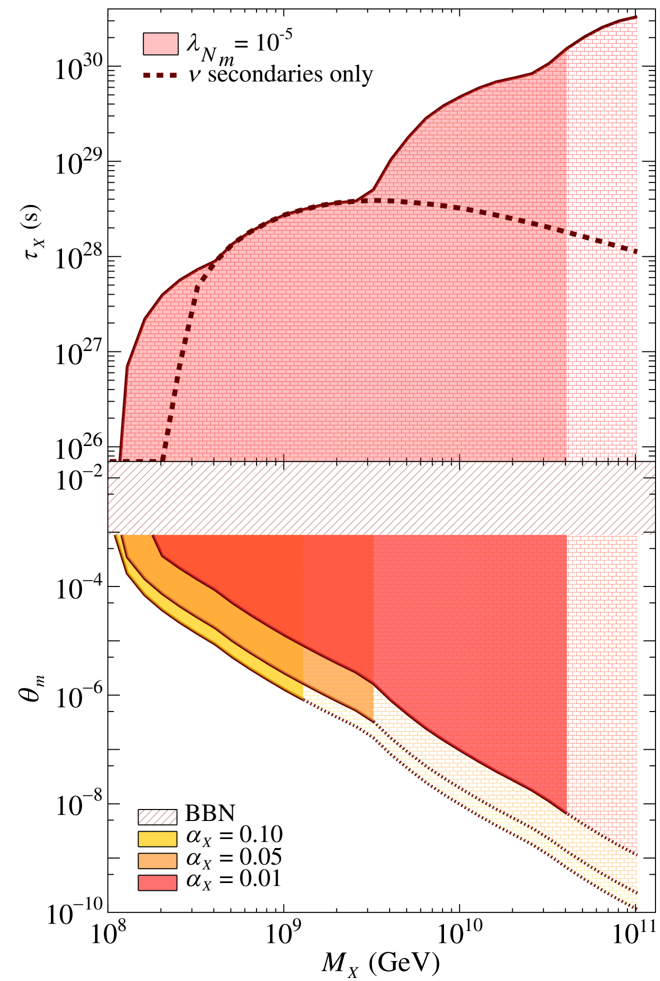
Coupling with a sterile neutrino sector

- Using the sensitivity of Auger to ultra-high energy neutrinos and photons, it is possible to constrain a wide class of models, that meet the lifetime requirements of SHDM by coupling it to a sector of light sterile neutrinos [Reference model: Dudas, Heurtier, Mambrini, Olive, Pierre (2020)].



- Auger neutrino/gamma sensitivity over 3.5 decades in energy





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SHDM contribution to UHECR anisotropy

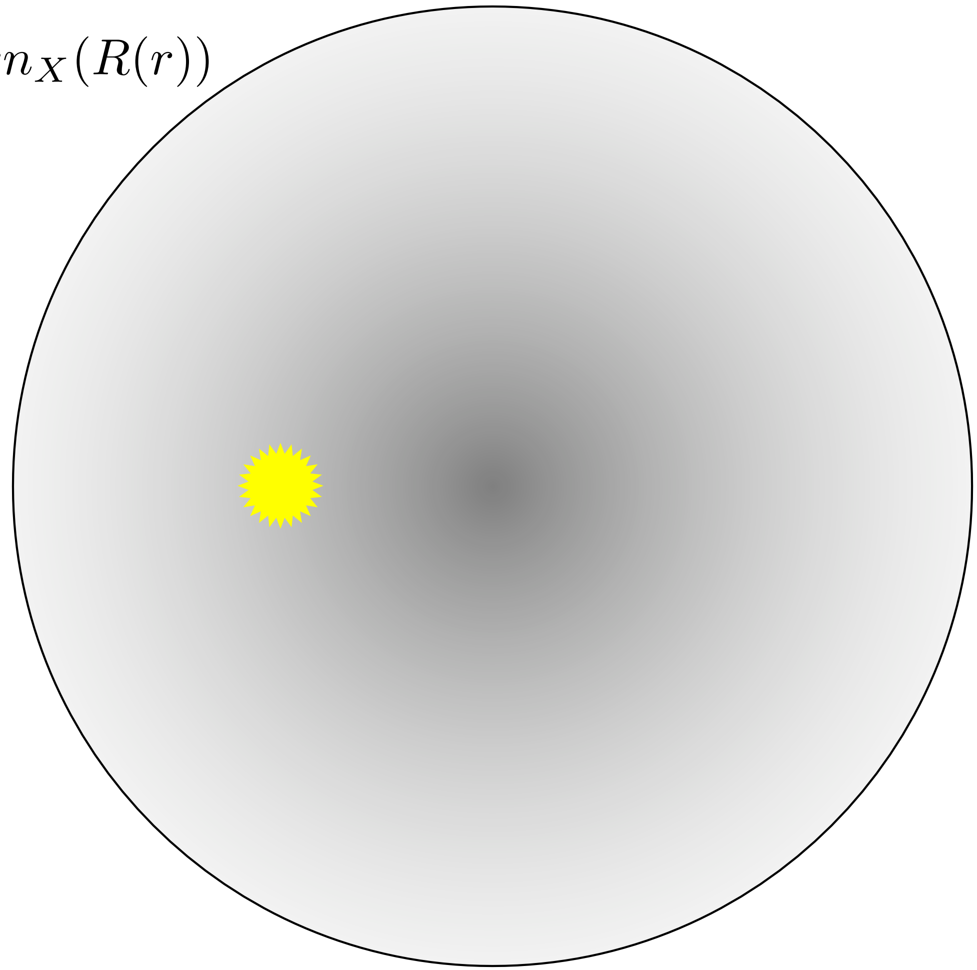
The observed UHECR events are distributed in the sky depending on both real celestial anisotropy and the detector relative acceptance $\omega(\alpha,\delta)$ (terrestrial equatorial coordinates: α right ascension and δ declination).

$$J_{UHECR}(E,\alpha,\delta) = J_{EG}(E,\alpha,\delta)\omega(\alpha,\delta) + J_{SHDM}(E,\alpha,\delta)\omega(\alpha,\delta)$$

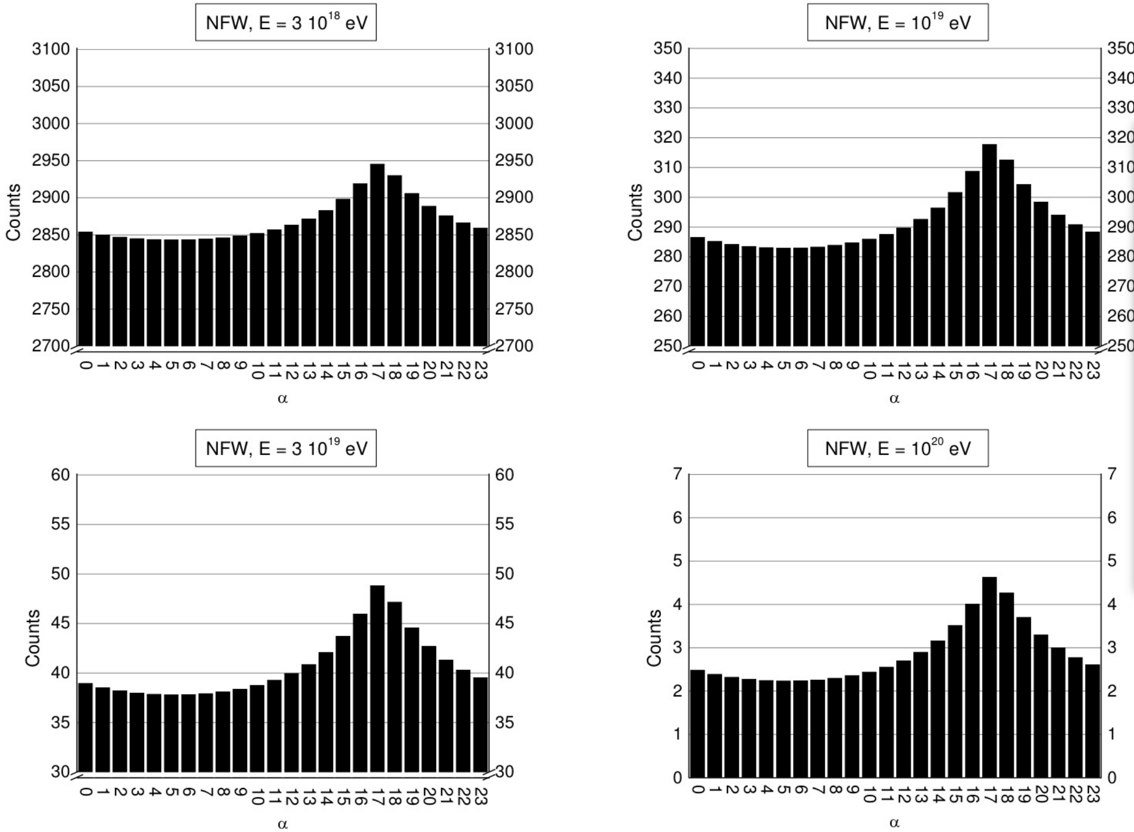
$$J_{SHDM}(E,\theta) = \frac{1}{4\pi M_X \tau_X} Q(E) \int_0^{r_{max}(\theta)} dr n_X(R(r))$$

$$r_{max}(\theta) = R_\odot \cos\theta + \sqrt{R_h^2 + R_\odot^2 \sin^2\theta}$$

RA, Tortorici (2008)

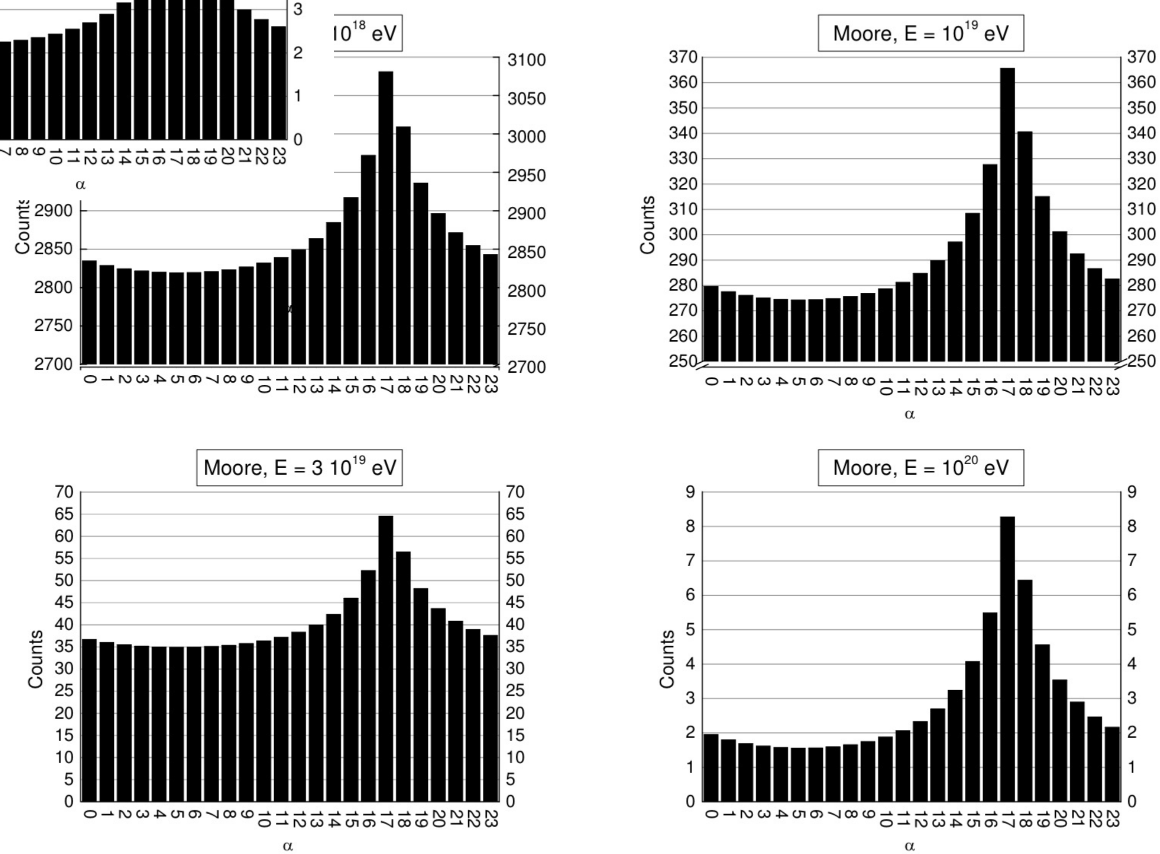


Being the SHDM distributed in our galactic halo with $n_X(R)$ spherically symmetric around the GC, a pure dipole deviation from isotropy is expected with the dipole vector pointing toward the GC itself.



RA, Tortorici (2008)

The number of events needed to detect at 4 σ level the expected anisotropy depends on the SHDM density profile. With more spiky densities (as the Moore profile) the Auger statistics enables to probe the SHDM contributions to UHECR fluxes down to EeV energies.



RA, Tortorici (2008)

A future analysis of the Auger data on UHECR anisotropy could provide very stringent limits on the SHDM models, already at intermediate (EeV) energies.

Conclusions

- ✓ The Auger observation of UHECR set very stringent limits on the SHDM parameters M_X and τ_X.
- ✓ The SHDM hypothesis connects UHECR observations with cosmological models (M_X) and models BSM of particle physics (τ_X).
- ✓ SHDM can be discovered by future precise cosmological measurements (CMB tensor modes) combined with the Auger observation of UHECR.
- ✓ The large statistics accumulated by the Auger observatory in the energy range 1 EeV $<E<$ 10 EeV represent a unique opportunity to test the faint anisotropy signals expected by the SHDM decay.
- ✓ Larger statistics at the highest energies $E>100$ EeV are instrumental to probe the phase space of the SHDM models.

Thank you