Pierre Auger Observatory and Physics Beyond the Standard Model

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(on behalf the Auger Collaboration)

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Meeting of the Auger Italian Collaboration
3-5 Feb 2025, Torino, Italy

Outline of the talk

1. Super Heavy Dark Matter
2. An emerging UV scale in the SM
3. Primordial Gravitational Waves
4. SHDM Decay and constrains from Auger data
5. Lorentz Invariance Violations and Quantum Gravity
6. UHECR propagation and LIV models
7. LIV constrains from Auger data
8. 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)]

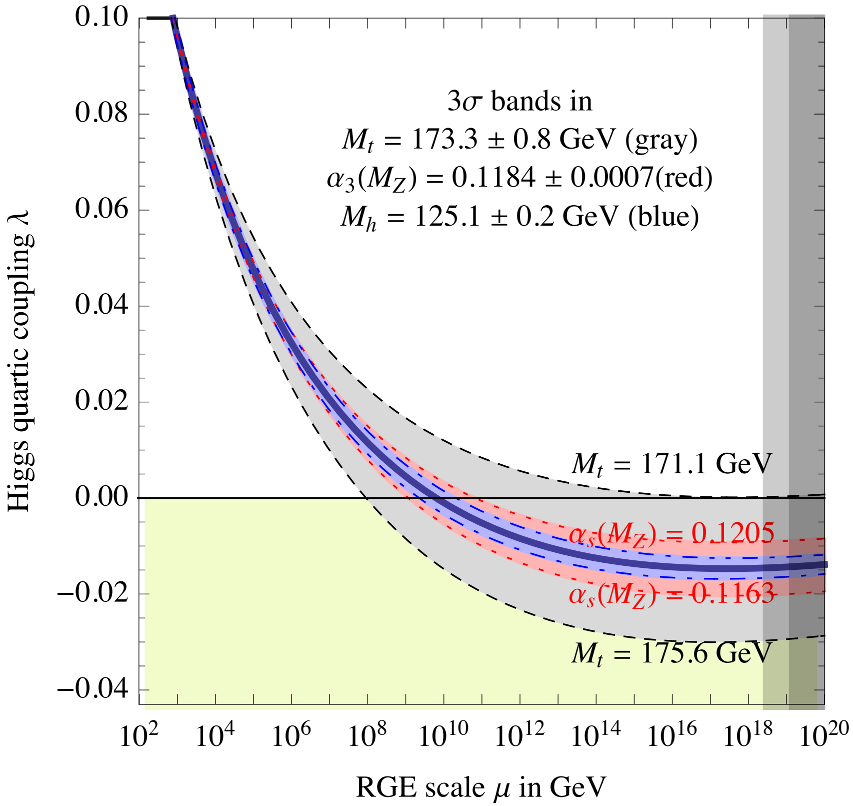
- ✓ They can be long-lived if their decay is inhibited by some discrete symmetry (such as R-parity for SUSY neutralinos) weakly broken or through non-perturbative instanton effect.
  [Berezinsky, Kachelriess & Vilenkin (1997), Kuzmin & Rubakov (1997)]

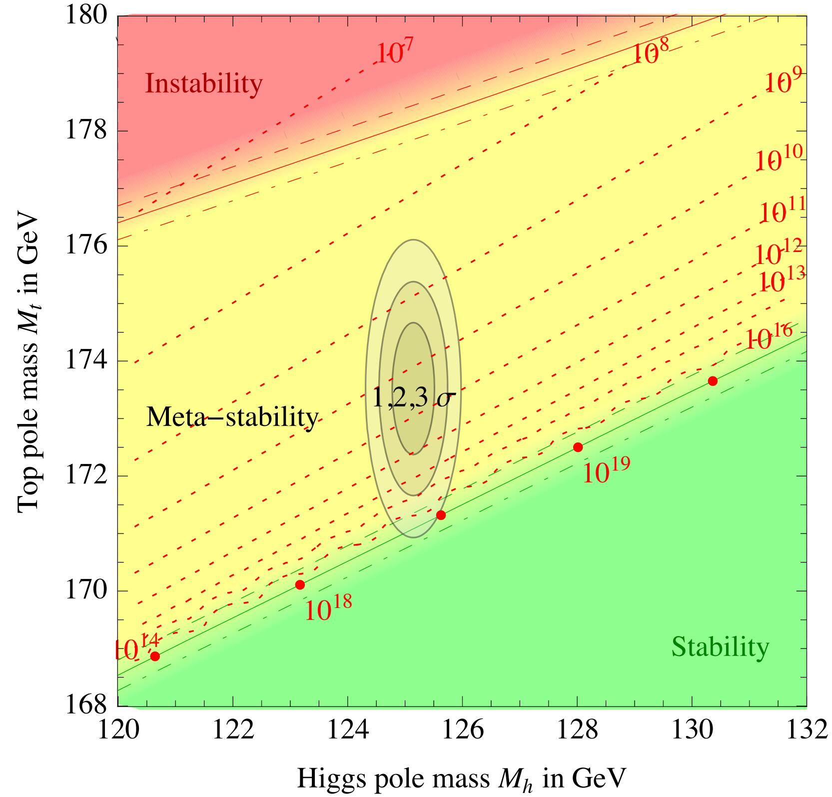
In this case SH relics can be dark matter candidates (SHDM)

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 λ(μ) 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

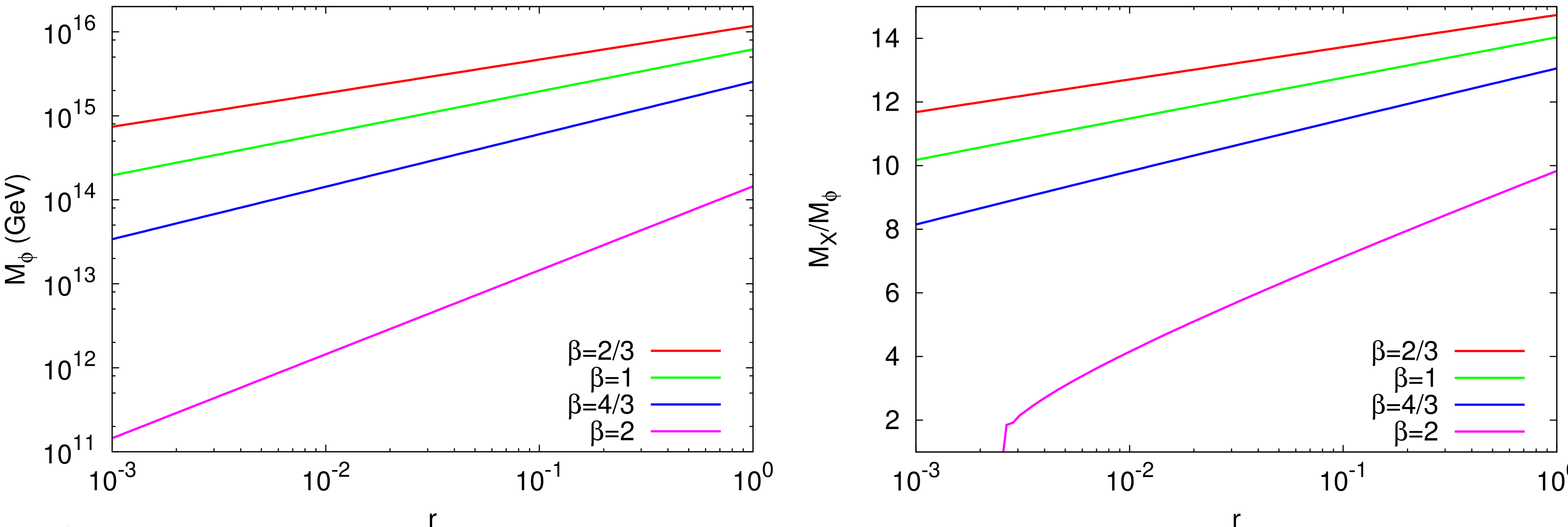
✓ Being out of local thermal equilibrium SHDM naturally produces primordial gravitational waves, imprinted in the CMB.

✓ 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 $X\Theta$

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

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, ε, r, α_X , $\alpha_{X\Theta}$.

signature of the model

Astrophysics

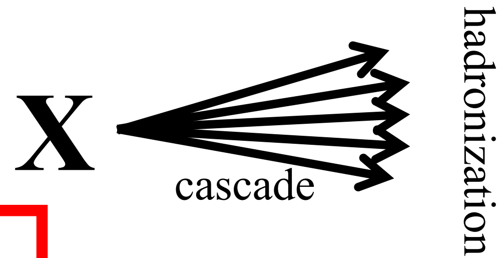
Galactic DM halo fixes the geometrical behavior of the SHDM emission, (increased emission from the GC direction)

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

α=1 NFW, α=3/2 Moore density profile

signature of the model

From SHDM to UHECR – hadrons

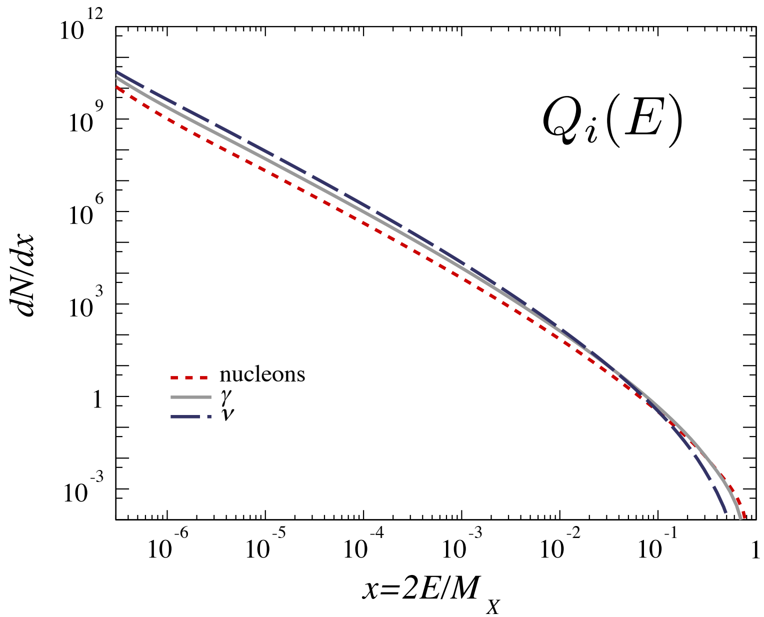


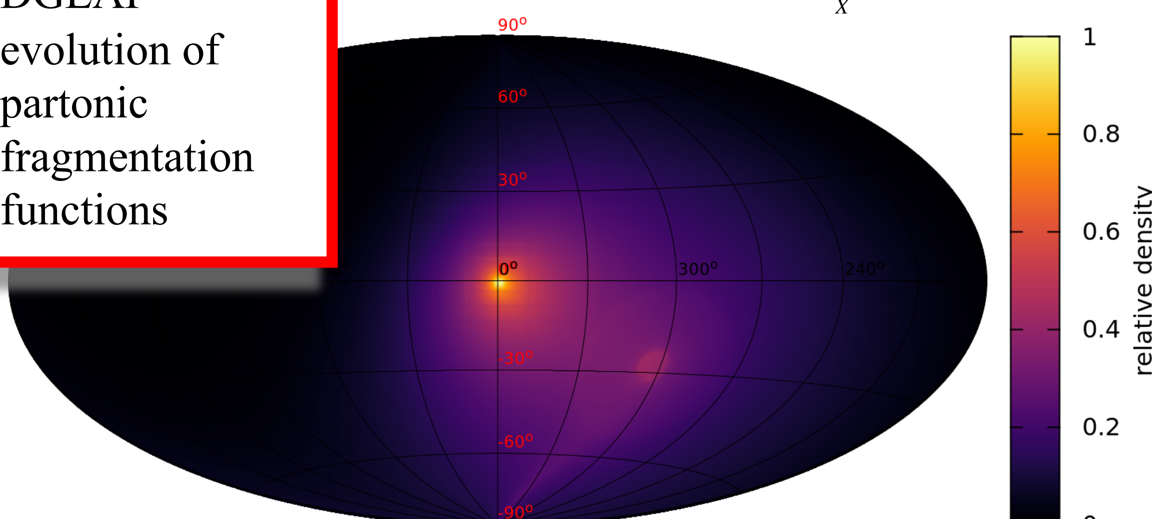
mainly N, π
hence N, γ and ν

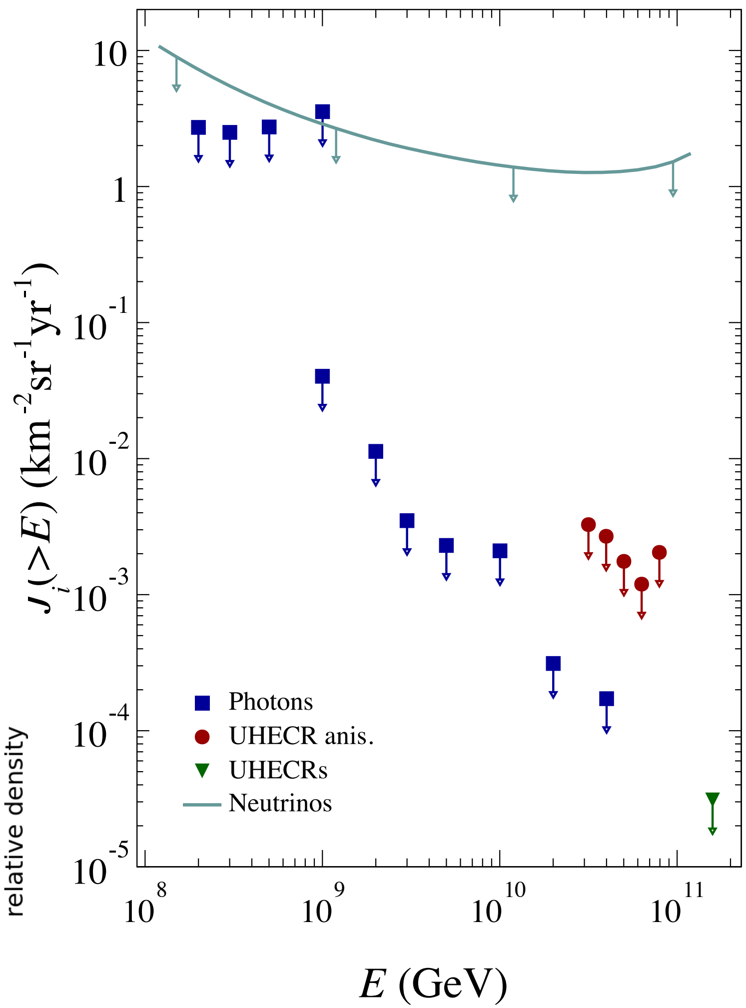
$$Q_{\nu,\gamma,p} \propto E^{-1.9}$$
$$J_{\nu,\gamma,p} \propto \frac{1}{M_X \tau_X}$$

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







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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 and coupling n, $\alpha_{\Theta X}$ of the perturbative coupling or to the non-abelian gauge coupling α_X in the dark sector (instanton decay).

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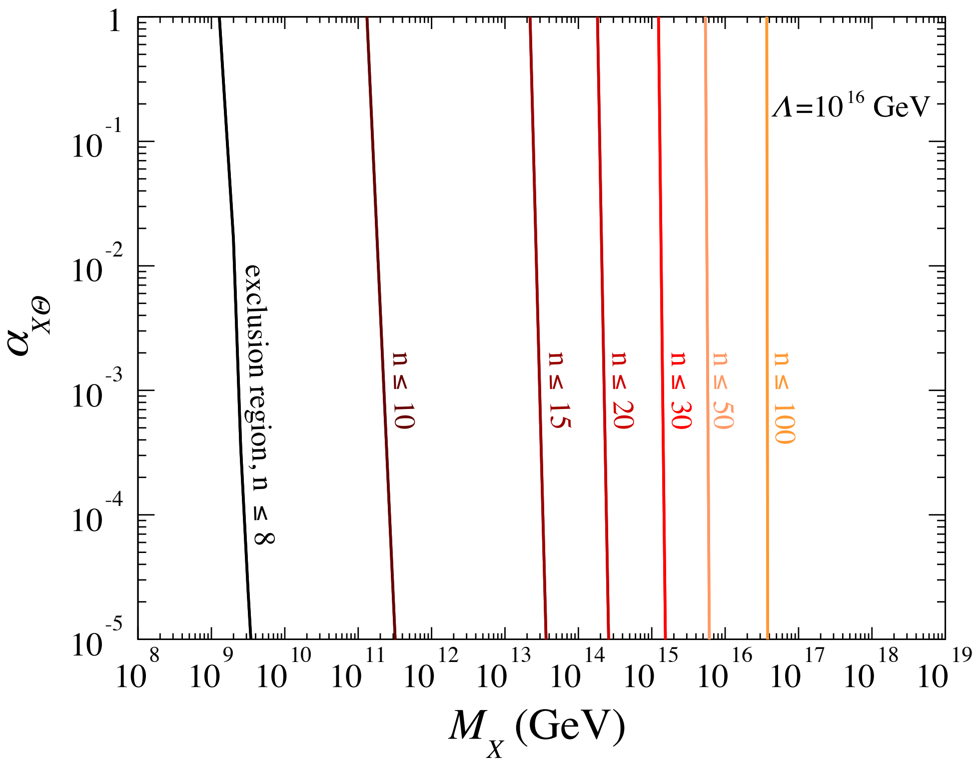
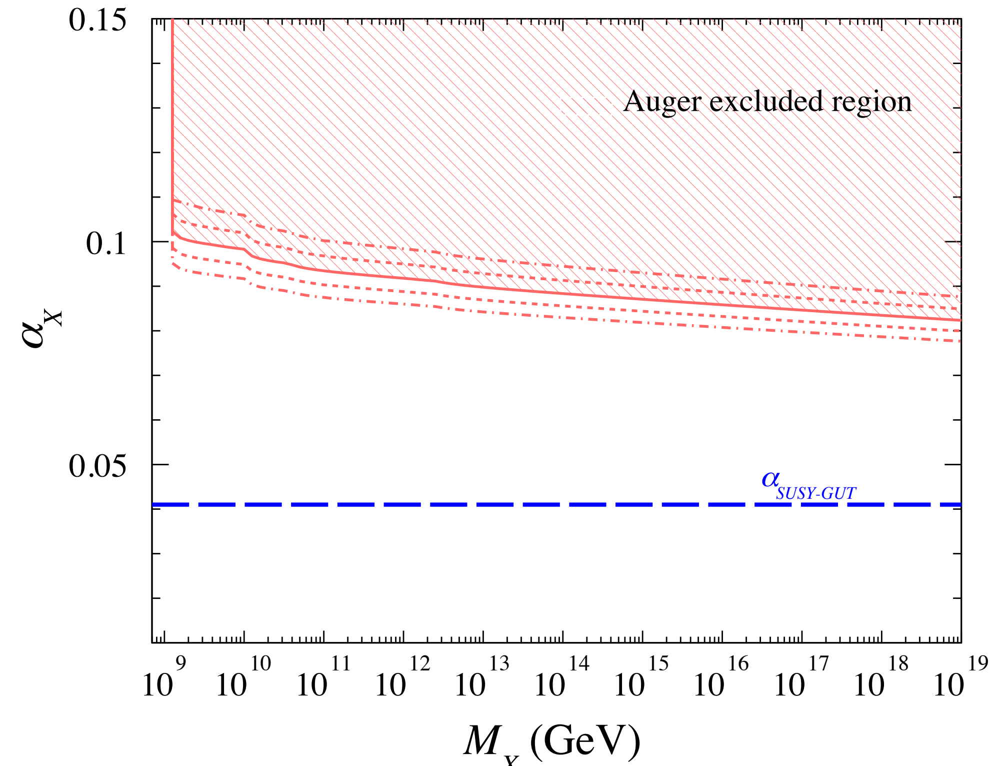


$$\tau_{X\Theta} = \frac{V_n}{4\pi M_X \alpha_{X\Theta}} \left(\frac{\Lambda}{M_X}\right)^{2n-8} \qquad \alpha_{X\Theta} = \frac{g_{X\Theta}^2}{4\pi}$$



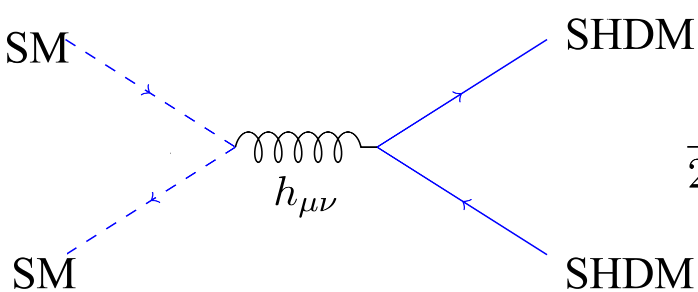
$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X} \qquad \alpha_X = \frac{g_X^2}{4\pi}$$

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.

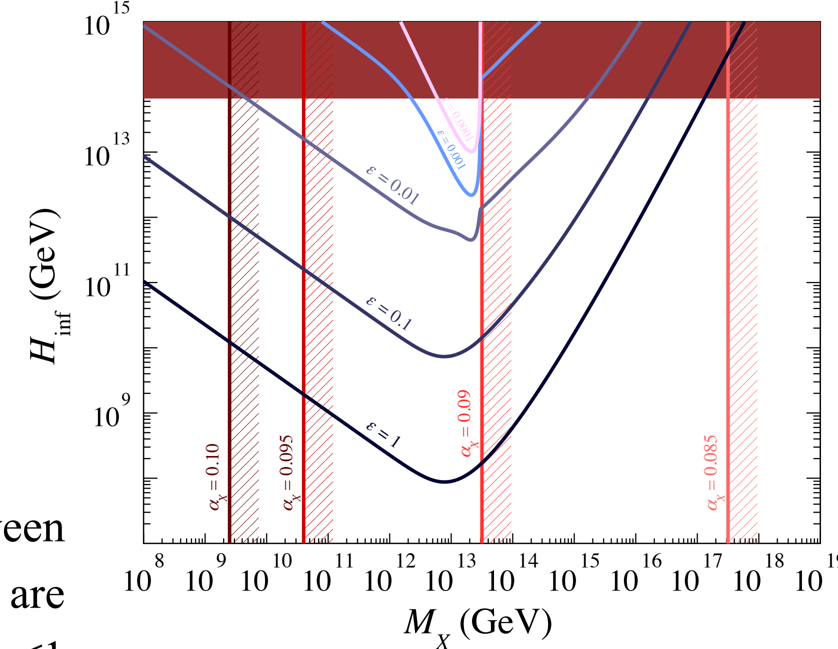
- Taking the model of gravitational interaction between SHDM and SM the relevant cosmological parameters are H_I the Hubble parameter at the end of inflation and $0<\varepsilon\leq 1$ the reheating efficiency, connected with the inflaton decay amplitude Γ_φ :

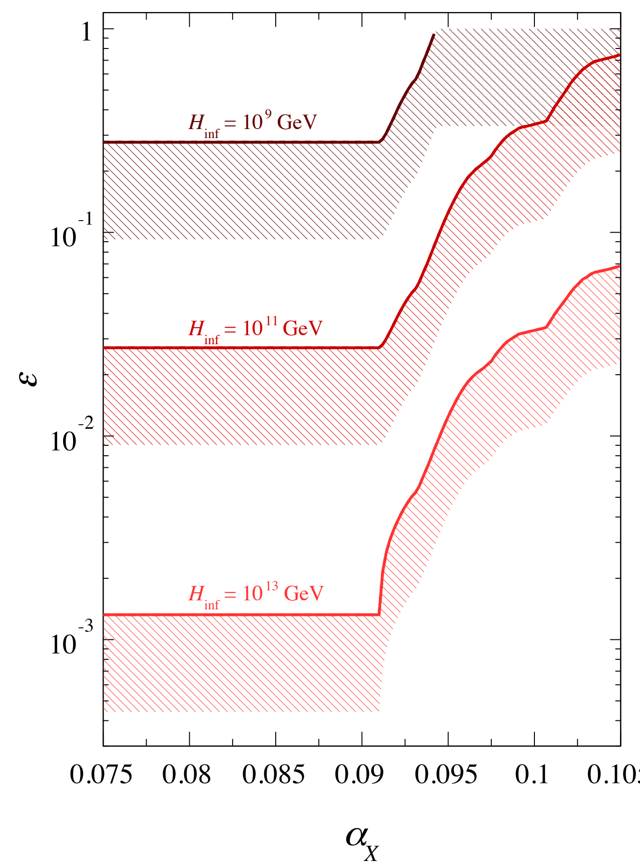
$$\epsilon = \sqrt{\frac{\Gamma_\phi}{H_I}}$$



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

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





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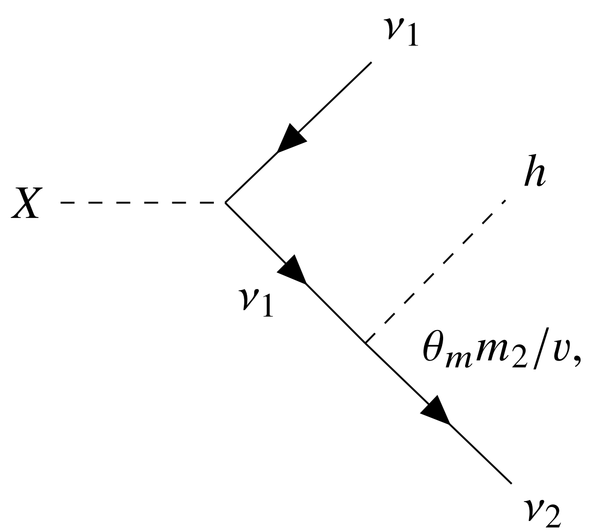
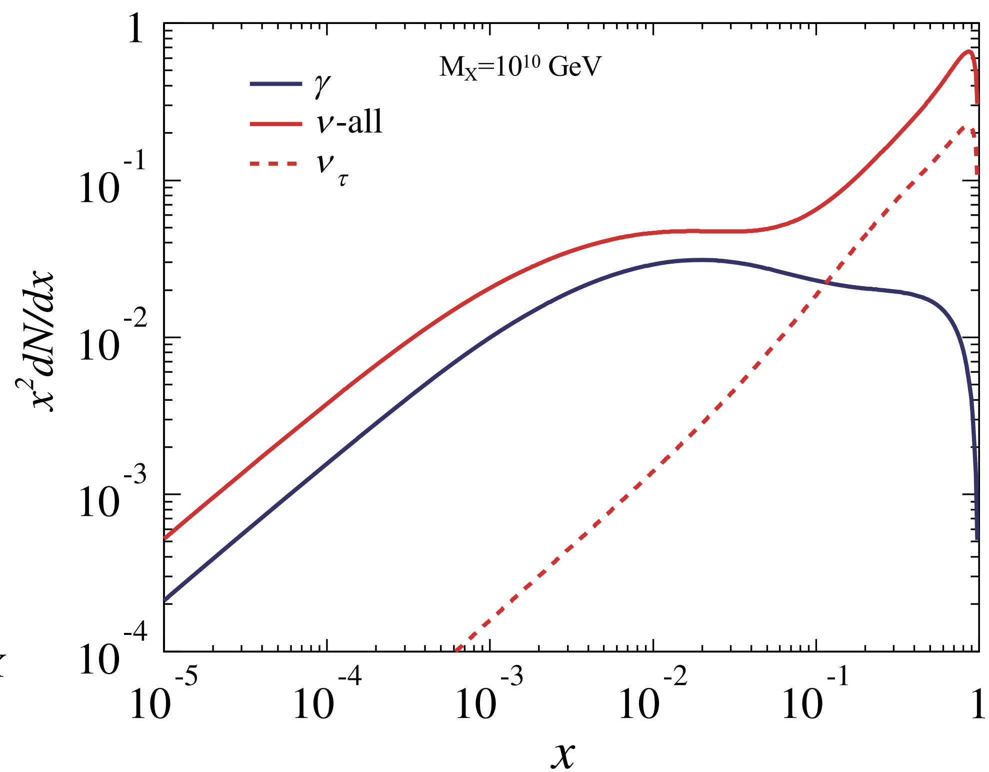
Coupling with a sterile neutrino sector

- A particular class of models meet the lifetime requirements of SHDM by coupling it to a sector of sterile neutrinos [reference model: Dudas, Heurtier, Mambrini, Olive, Pierre (2020)].

- In the reference model the dominant decay channel is a three-body decay



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



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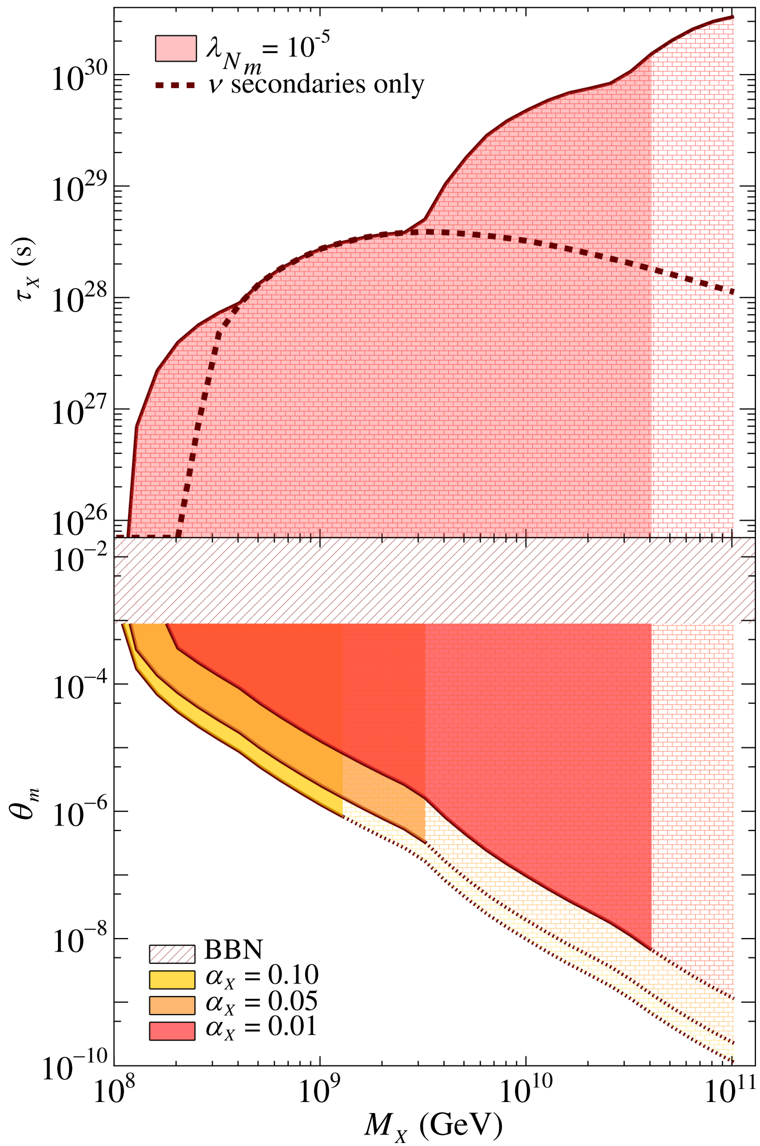
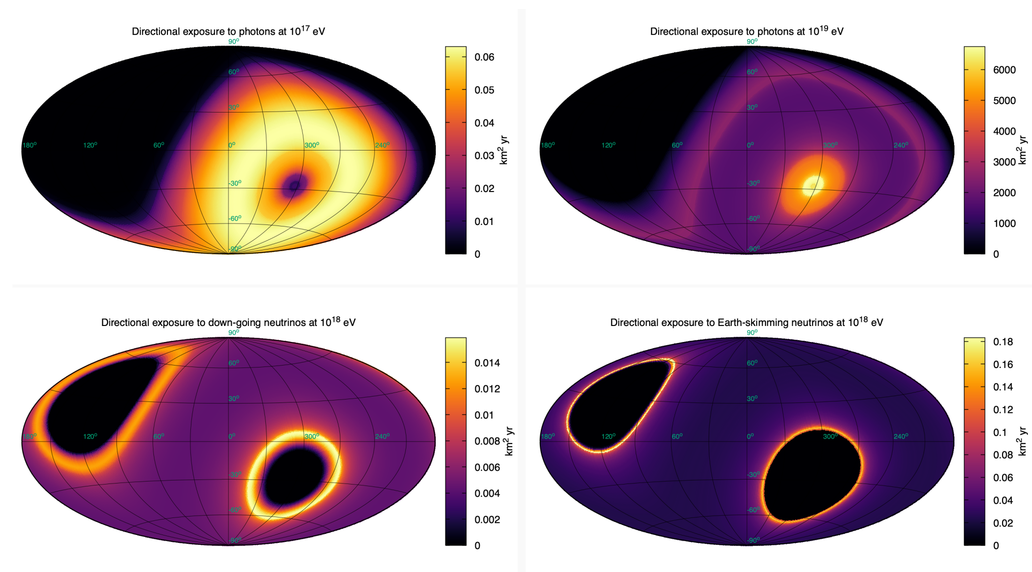
- UHE SM neutrinos and photons are expected to be the final products of the decay. Using the sensitivity of Auger to these particles it is possible to constrain the model.

✓ Auger neutrino/gamma sensitivity over 3.5 decades in energy





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SHDM contribution to UHECR anisotropy

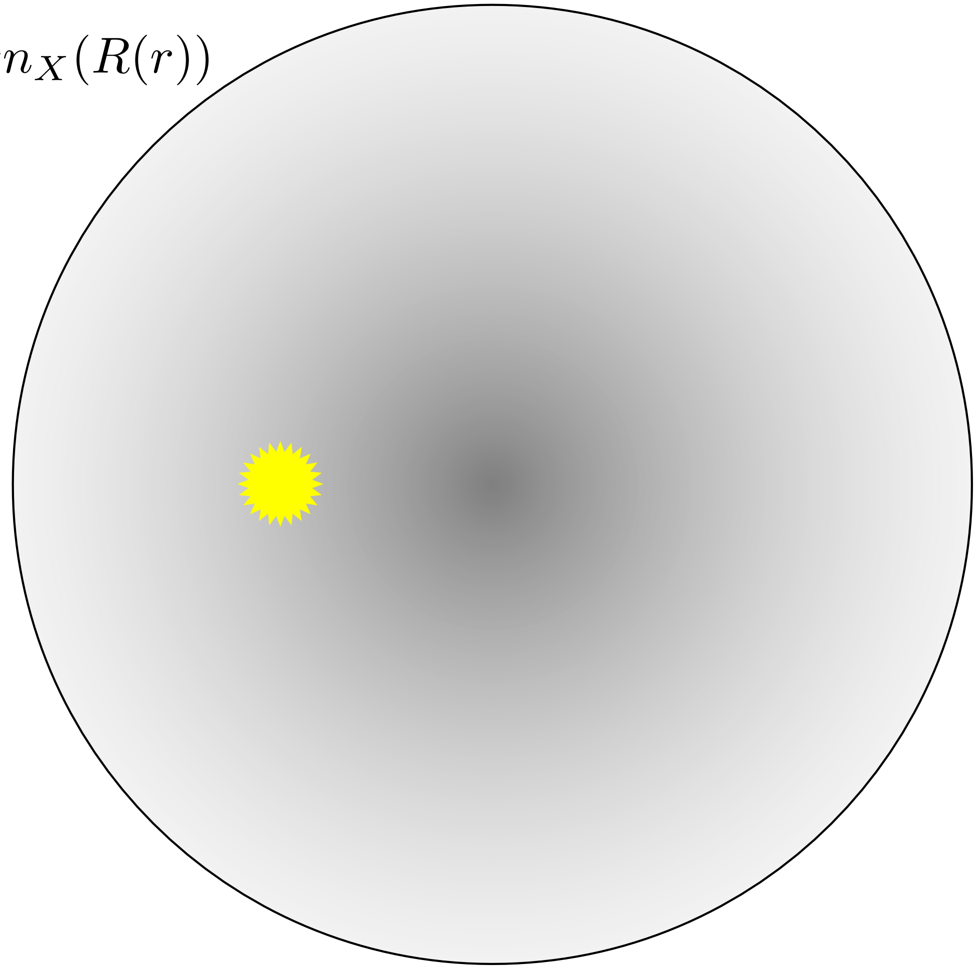
The observed UHECR events are distributed in the sky depending on both real celestial anisotropy and the detector relative acceptance ω(α,δ) (terrestrial equatorial coordinates: α right ascension and δ declination).

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

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

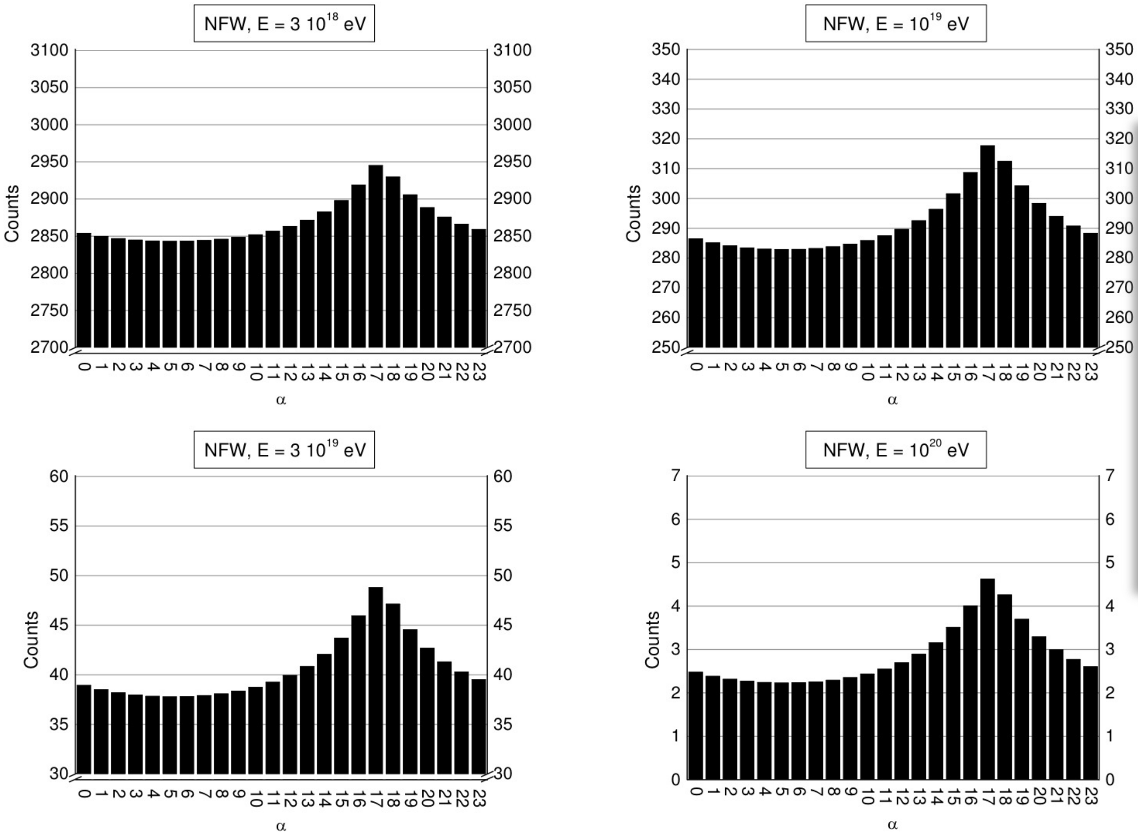
$$r_{max}(\theta) = R_\odot \cos\theta + \sqrt{R_h^2 + R_\odot^2 \sin^2\theta}$$

RA, Tortorici (2008)



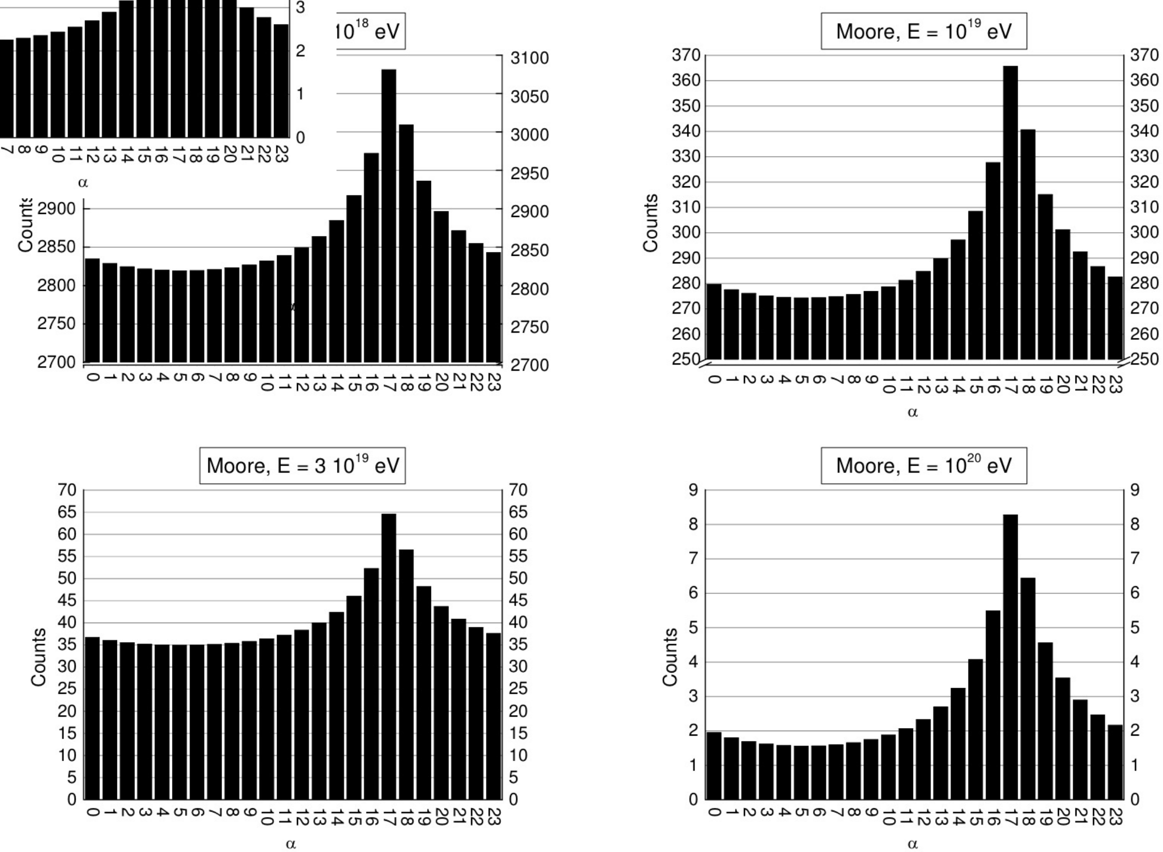
Being the SHDM distributed in our galactic halo with $n_X(R)$ spherically symmetric around the GC, a pure dipole deviation from isotropy is expected with the dipole vector pointing toward the GC itself.

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)



We started an analysis of the Auger data on UHECR anisotropy at EeV energies, with a particular focus on the new data about neutrons limits at EeV energies.

Lorentz Invariance Violations and the Quantum Gravity Regime

The idea of testing Lorentz Invariance (LI) through UHE CR and gamma ray data was inspired by A.F. Grillo, who suggested many of the analysis presented here.

- Different approaches to Quantum Gravity (QG) predict departures from Lorentz Invariance (LI) at extreme energy scales (above Planck mass $M_P \approx 1.2\times10^{19}$ GeV) .

  [For a review see Addazzi+ Progress in Particle and Nuclear Physics, Volume 125, July 2022, 103948, arXiv:2111.05659v2]

- LI Violations (LIV) may seem hard to accept but LI is a property of Space-Time and Space-Time in QG is a derived concept. At some very small scales (above the Plack length $l_P \approx 1.6\times10^{-33}$ cm) the structure of Space-Time becomes undefined.

- Effective field theories in which the relativity principle is violated, i.e. a preferred reference frame arises, at scales $\Lambda = M_P/\eta$ (with η LIV parameter).

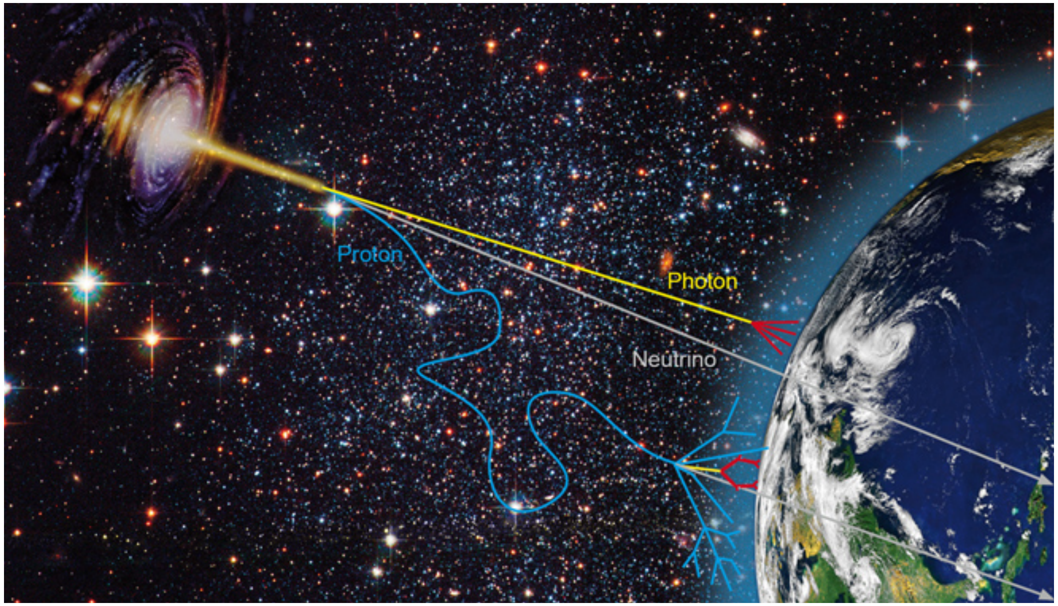
$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{eff}(\Lambda)$$

- Energy momentum conservation, with modified dispersion relations:

$$E^2 - p^2 = m^2[1 + g(E/\Lambda)] + E^2 f(E/\Lambda)$$

  - g terms (conformal LIV), renormalizable, difficult to test experimentally
  - f terms non-renormalizable, experimental tests possible

Lorentz Invariance Violations and UHE particles propagation



- Using modified dispersion relations with energy-momentum conservation, only kinematical thresholds are affected.
- Violations can be particle dependent, i.e. the LIV parameter is η_i with $i=\gamma$, N, $\pi^{\pm}$, π^0
- Most relevant LIV effects are on threshold processes

By expanding f(E/Λ)

$$E^2 - p^2 = m^2 + \sum_{n=0}^{\infty} \delta_n E^{2+n} \qquad \delta_n = \frac{\eta_n}{M_p^n}$$

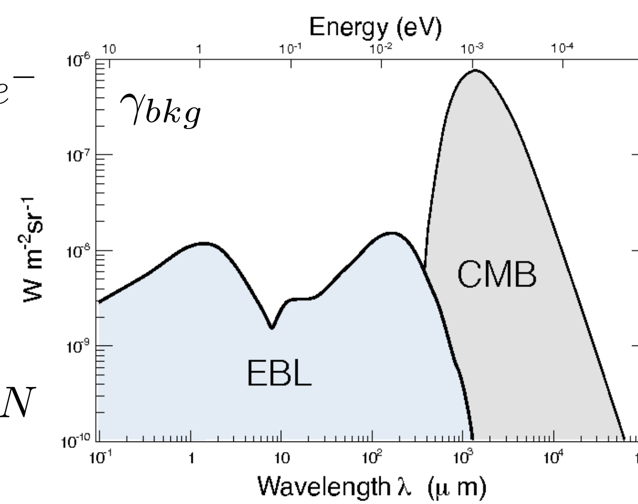
- Depending on the parameter δ the LIV threshold is moved respect to the LI one to lower energies or higher energies up to infinite (process kinematically forbidden).
- LIV with lower thresholds are typically excluded by observations.

$$N + \gamma_{bkg} \rightarrow N + e^+ + e^-$$

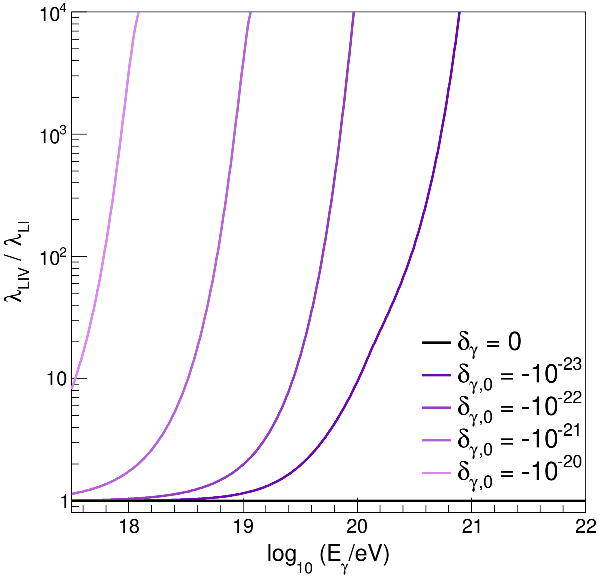
$$\gamma + \gamma_{bkg} \rightarrow e^+ + e^-$$

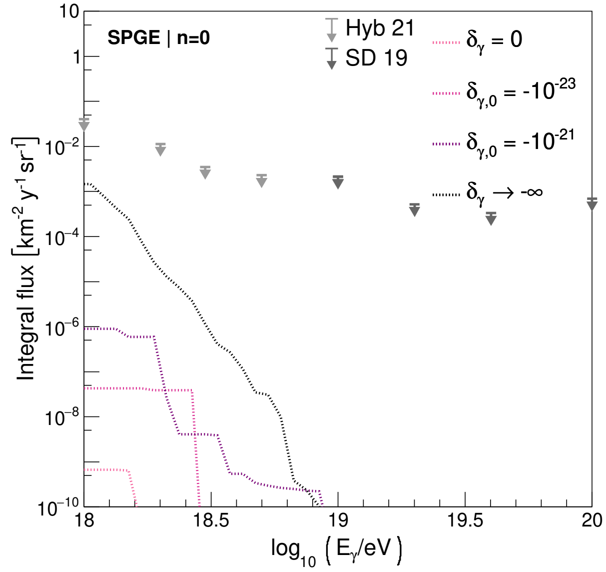
$$N + \gamma_{bkg} \rightarrow N + \pi$$

$$A + \gamma_{bkg} \rightarrow (A-n) + nN$$



Electromagnetic sector Photons propagation





- ✓ Relevant LIV scenarios with δ<0.
- ✓ The Auger combined fit produces a marginal flux of cosmogenic photons at the highest energies.
- ✓ Alternative scenarios with an additional (subdominant) proton component at the highest energies constrains the maximum allowed LIV.

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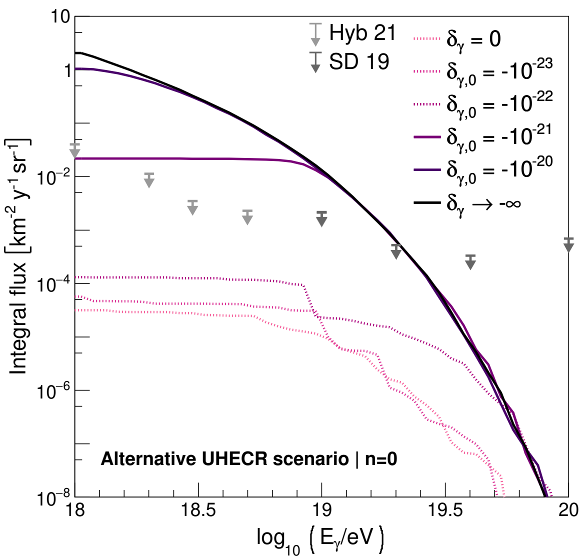
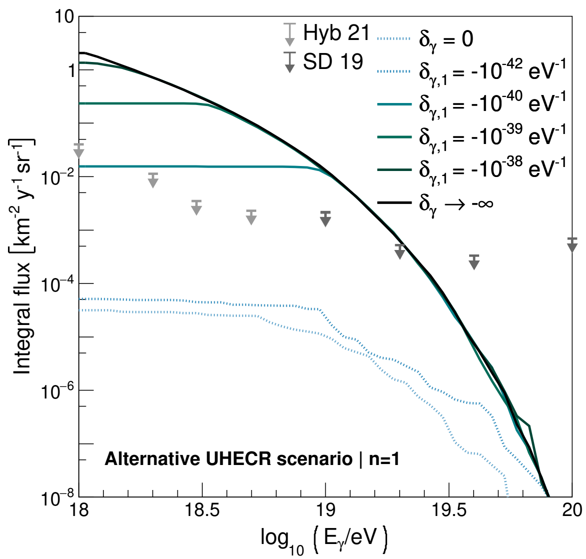
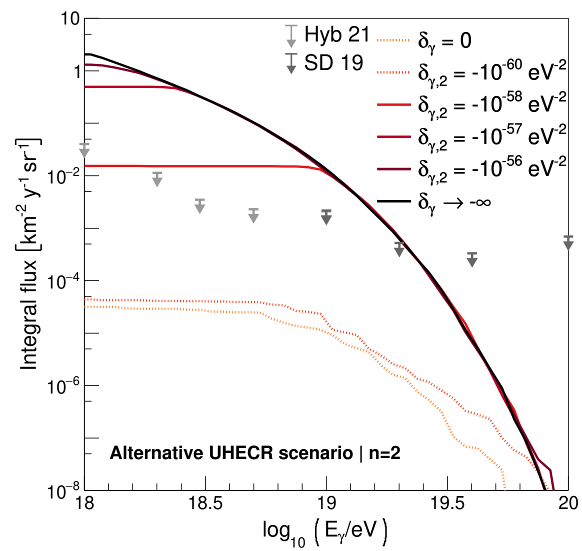
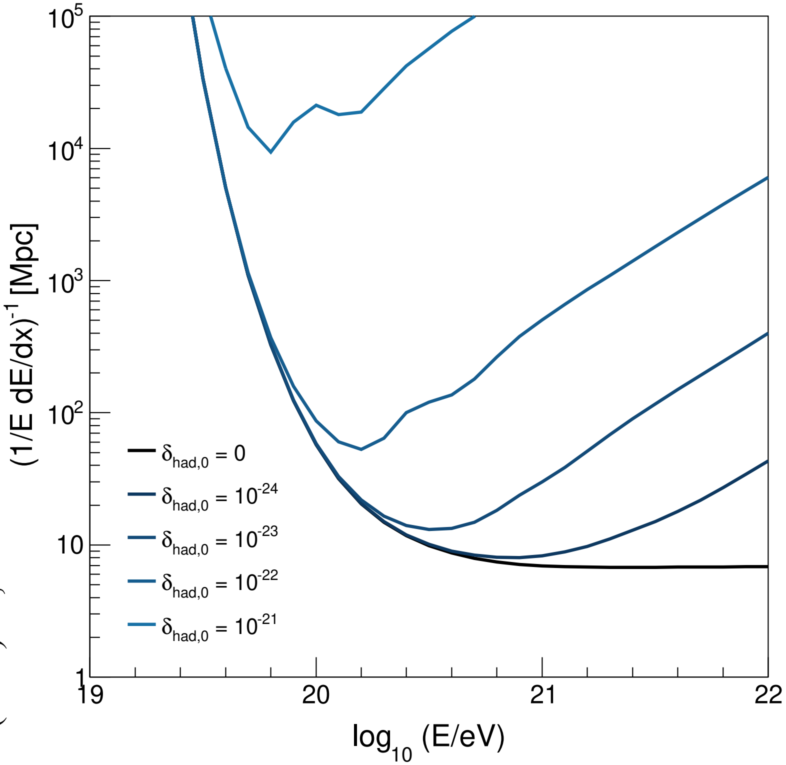






$$-\delta_{\gamma,0} < 10^{-21} \qquad -\delta_{\gamma,1} < 10^{-40}\ eV^{-1} \qquad -\delta_{\gamma,2} < 10^{-58}\ eV^{-2}$$

Hadronic sector UHECR propagation



- Relevant LIV scenarios for UHECR are those with $\delta>0$. Thresholds for photopion production and photodisintegration move to higher energies.
- To have the same LIV order for all hadrons, using the superposition principle we can write

$$E_A^2 = p_A^2 + m_A^2 + \sum \delta_{A,n} E_A^{2+n}$$

$$A^2 E_p^2 = A^2 p_p^2 + A^2 m_p^2 + A^2 \sum \delta_{A,n} A^n E_p^{2+n}$$

$$E_p^2 = p_p^2 + m_p^2 + \sum \delta_{A,n} A^n E_p^{2+n} \qquad \delta_{A,n} = \delta_{p,n}/A^n$$

$$\delta_{had,n} = \delta_{p,n} = \delta_{\pi,n}/2 = A^n \delta_{A,n}$$

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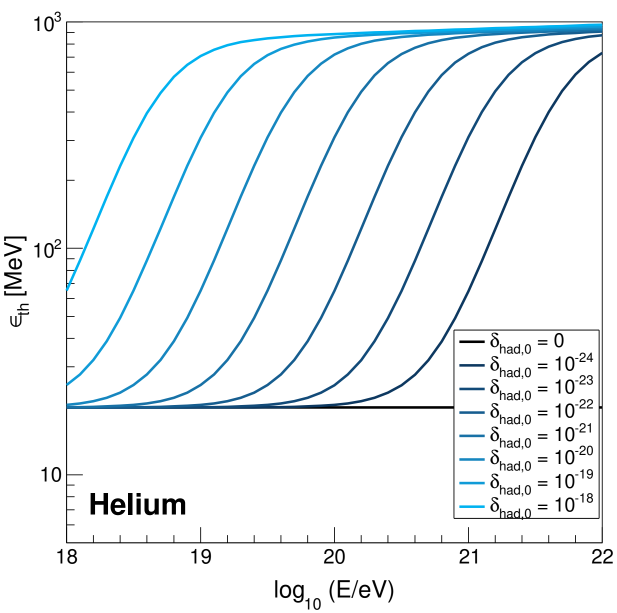
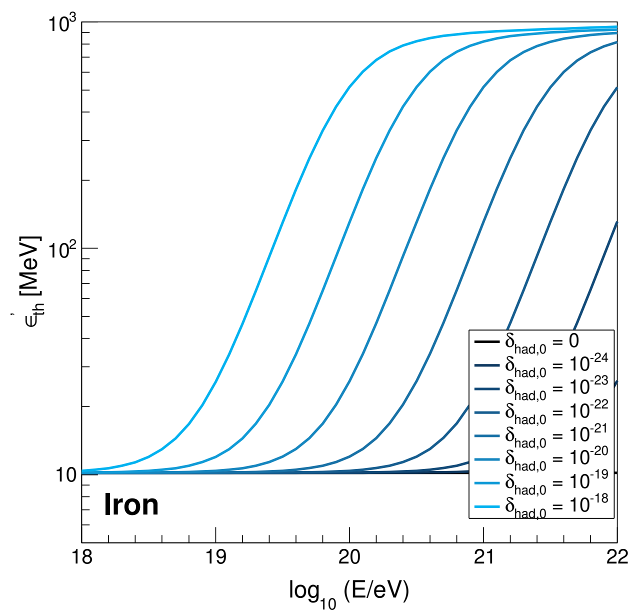


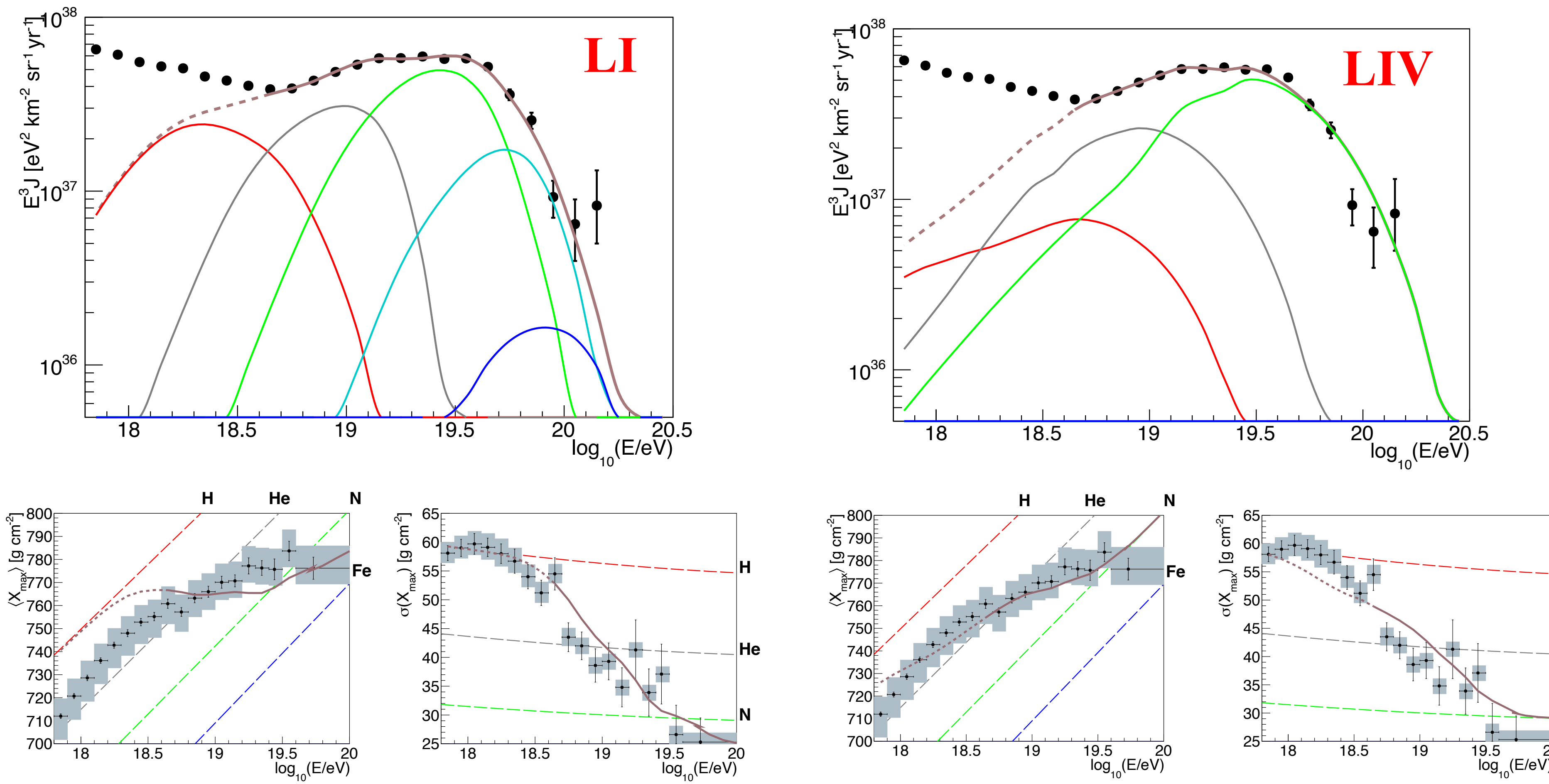


- In the LIV scenario the interaction length for nucleons and nuclei becomes sensibly larger.
- Limits on the LIV parameter from the combined fit of the Auger data on spectrum and mass composition.

$$\frac{dN_A}{dE} = J_0 f_A \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\Gamma} \times \begin{cases} 1, & \text{for } R < R_{\mathrm{cut}} \\ \exp\left(1 - R/R_{\mathrm{cut}}\right), & \text{for } R \geq R_{\mathrm{cut}} \end{cases}$$

$$\delta_{\mathrm{had},0} R_{\mathrm{cut}}^2 Z^2 = \delta_{\mathrm{had},n} R_{\mathrm{cut}}^{(n+2)} Z^{n+2} \implies \delta_{\mathrm{had},n} = \delta_{\mathrm{had},0} R_{\mathrm{cut}}^{-n} Z^{-n}$$

- ✓ Fit parameters J_0, f_A, Γ, R_{cut}, $\delta_{had,0}$
- ✓ Standard LI combined fit: Talys cross-sections, EBL by Dominquez+ (MNRAS 2011), hadronic interactions EPOS-LHC



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$$\delta_{had,0} < 10^{-19} \quad \delta_{had,1} < 10^{-38}\ eV^{-1} \quad \delta_{had,2} < 10^{-57}\ eV^{-2}$$

Conclusions

- The Auger observations have an unprecedented potential to test new physics BSM: stringent limits on the SHDM parameters M_X and τ_X and the LIV parameter δ.
- 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.
- Larger statistics at the highest energies are instrumental to probe the phase space of SHDM and LIV models.

Thank you