

# Pierre Auger Observatory and Physics Beyond the Standard Model

**Roberto Aloisio**

*(on behalf the Auger Collaboration)*

*Gran Sasso Science Institute*

*INFN – Laboratori Nazionali del Gran Sasso*



**7th International Symposium on Ultra High Energy Cosmic Ray (UHECR24)  
17-21 Nov 2024, Malargüe, Argentina, site of the Pierre Auger Observatory**

# 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

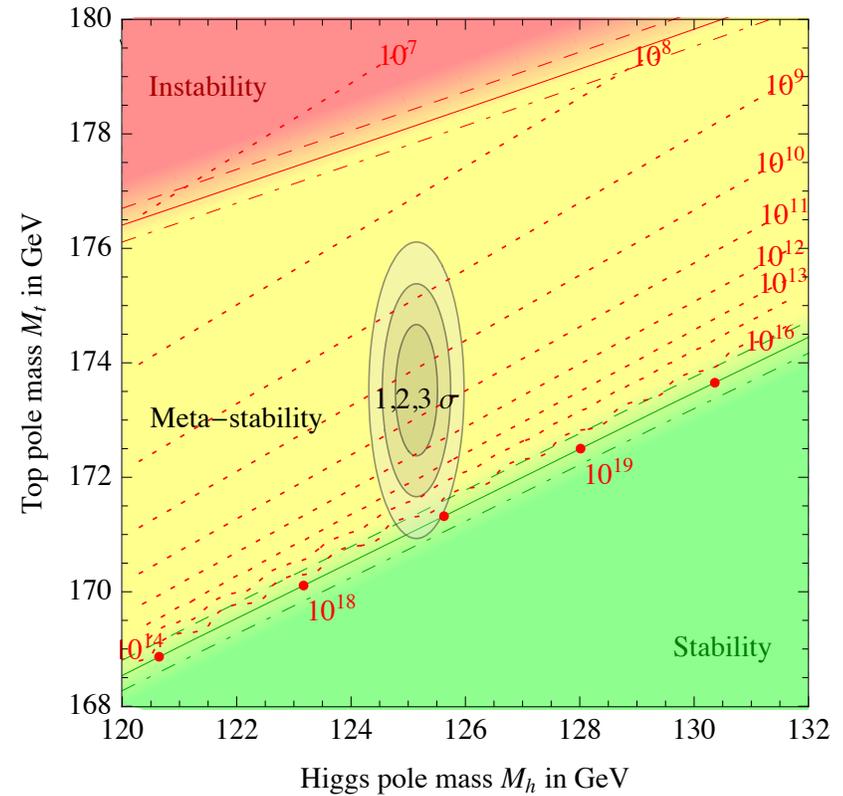
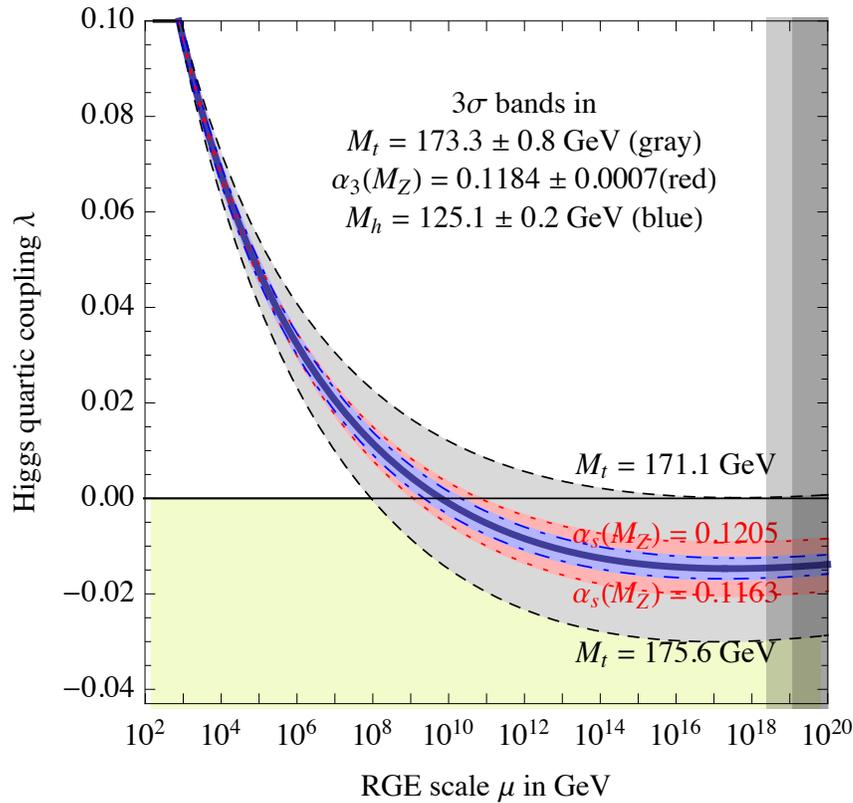
- ✓ Supermassive particles, with mass  $M > 10^8$  GeV, can be easily generated in the early universe by time-dependent gravitational fields and through gravitational (direct) coupling to the inflaton field and/or to SM fields.  
[Schrodinger (1939), Zeldovich & Starobinsky (1972), Kofman, Linde & Starobinsky (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  $\lambda$  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  $\Lambda_I$ .

# Primordial gravitational waves

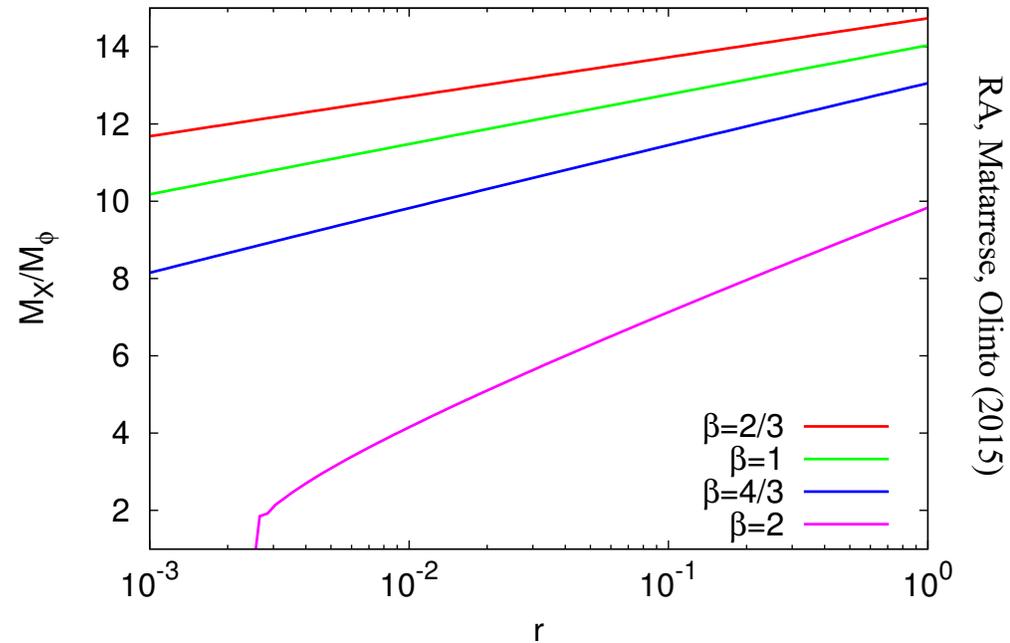
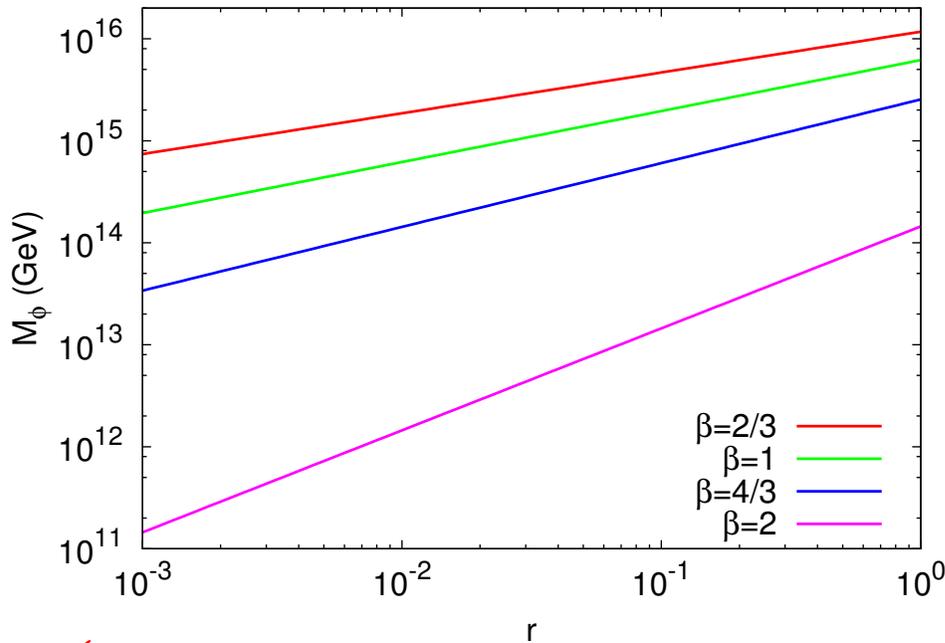
✓ Being out of local thermal equilibrium SHDM naturally produces primordial gravitational waves, imprinted in the CMB.

✓ 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.

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

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

$$\Omega_X(t_0) \simeq 10^{-3} \Omega_R \frac{8\pi}{3} \left( \frac{T_{RH}}{T_0} \right) \times \\ \times \beta^{\frac{2}{4-\beta}} \left( \frac{M_{GUT}}{M_{Pl}} \right)^{\frac{8}{4-\beta}} \left( \frac{\sqrt{4\pi r_0}}{\beta} \right)^{\frac{2\beta}{4-\beta}} \left( \frac{r}{r_0} \right)^{\frac{2+\beta}{4-\beta}} \left( \frac{M_X}{M_\phi} \right)^{5/2} e^{-2M_X/M_\phi}$$



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

$$X \rightarrow q\bar{q} \rightarrow N, \gamma, \nu, \bar{\nu} \quad X \rightarrow \nu\bar{\nu}$$

- ✓ Super-weak coupling between SHDM and the SM sectors

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

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

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

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.

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

# SHDM contribution to UHECR

- ✓ SHDM accumulates in the halo of our own galaxy with an over-density  $\delta$  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  $H_I, \epsilon, r, \alpha_X, \alpha_{X\oplus}$ .

**signature of the model**

## Astrophysics

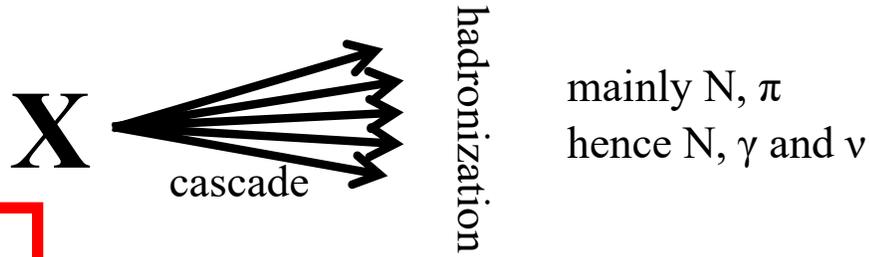
Galactic DM halo fixes the geometrical  
behavior of the SHDM emission, (increased  
emission from the GC direction)

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

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

**signature of the model**

# From SHDM to UHECR – hadrons

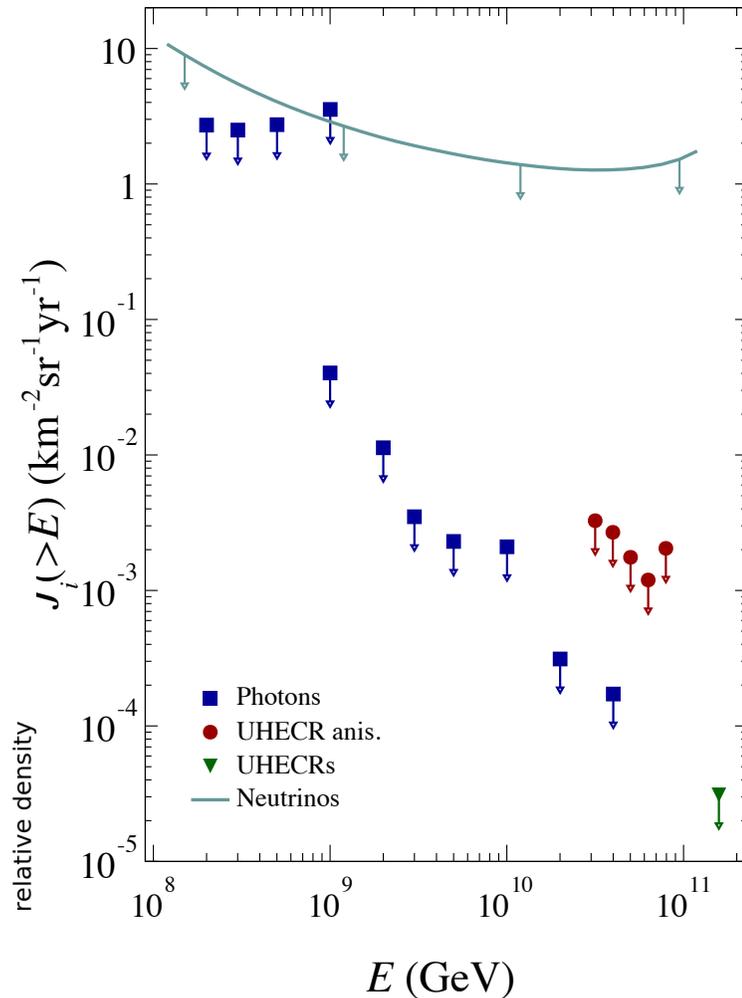
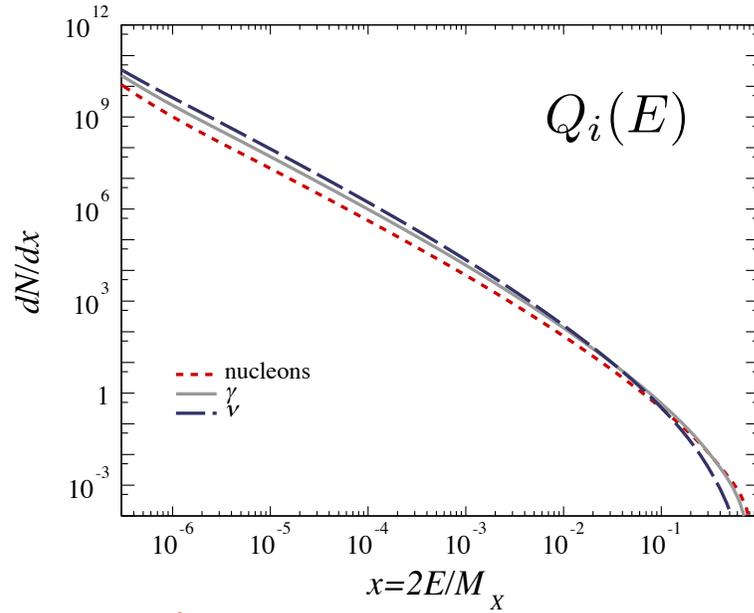


$$Q_{\nu, \gamma, p} \propto E^{-1.9}$$

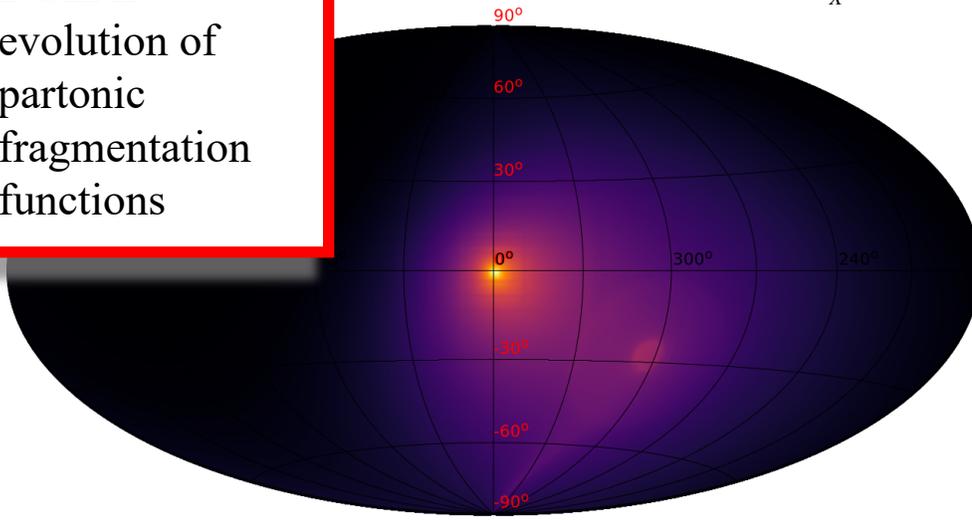
$$J_{\nu, \gamma, p} \propto \frac{1}{M_X \tau_X}$$

RA, et al (2004-2007)

- ✓ SHDM lifetime  $\tau_X$  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



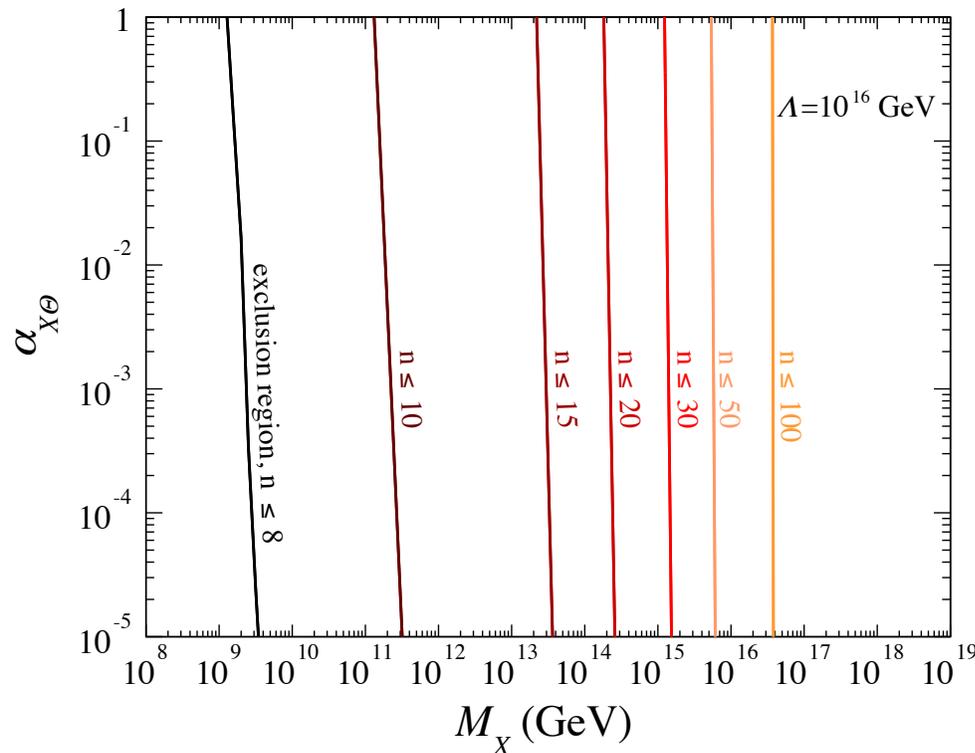
Auger Collaboration PRD 107 (2023) 4, 042002



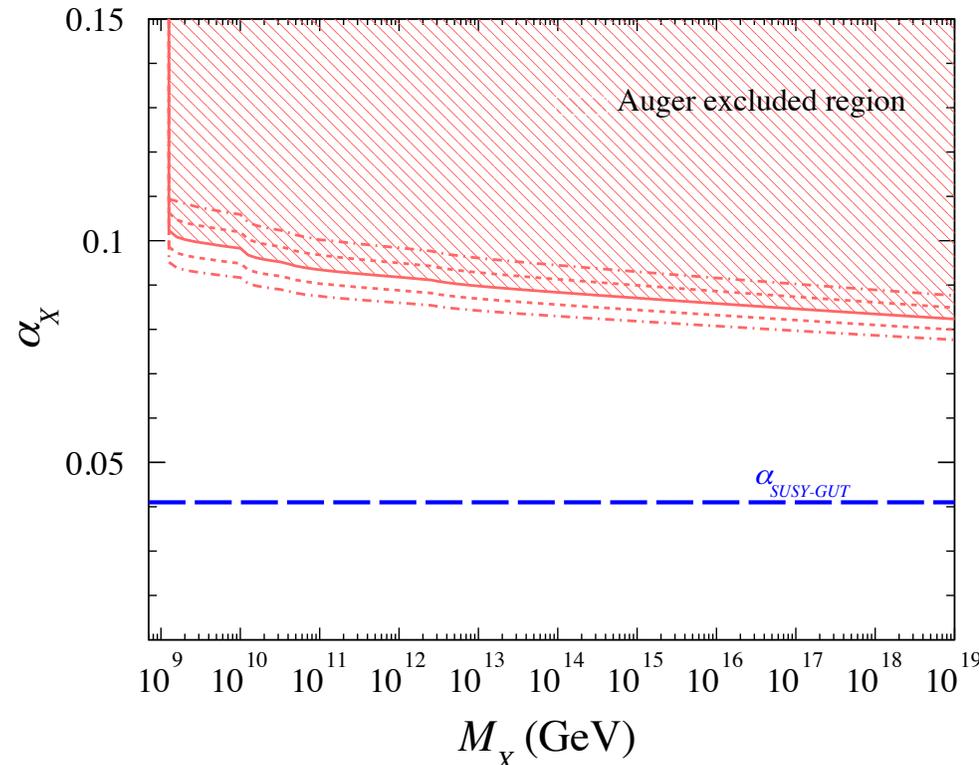
# Auger data constrains on $M_X$ and $\tau_X$

- ✓ By imposing the Auger observational limits on the fluxes of  $N$ ,  $\gamma$ ,  $\nu$  it is possible to place stringent limits on  $M_X$  and  $\tau_X$ .
- ✓ Depending on the assumptions on the decaying mechanism (perturbative or instanton), the limits are on the mass dimension and coupling  $n$ ,  $\alpha_{X\Theta}$  of the perturbative coupling or to the non-abelian gauge coupling  $\alpha_X$  in the dark sector (instanton decay).

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



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

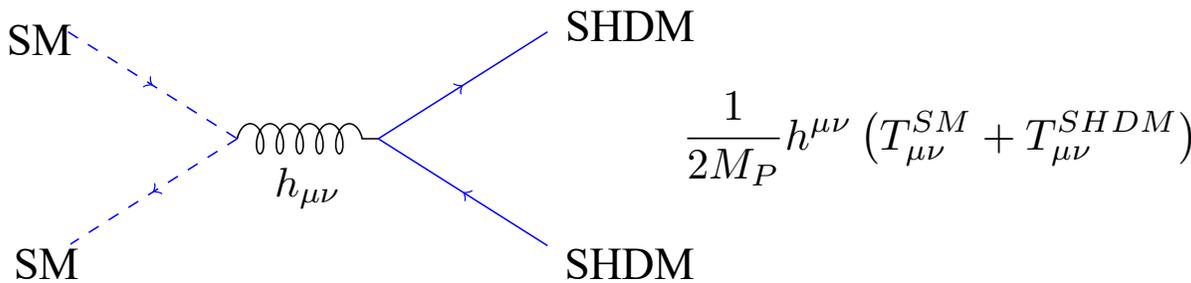


$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X} \quad \alpha_X = \frac{g_X^2}{4\pi}$$

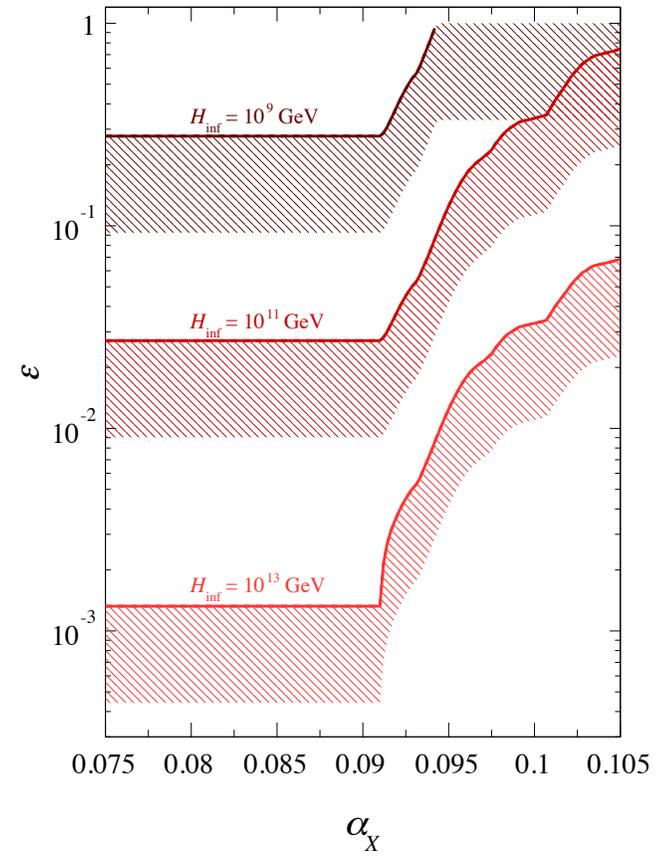
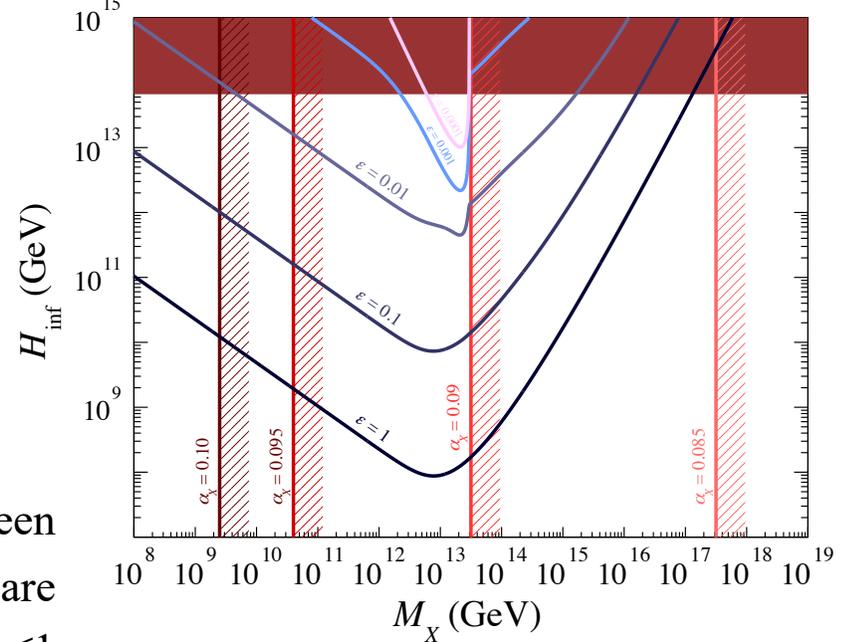
# Cosmology parameters

- 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  $0 < \epsilon \leq 1$  the reheating efficiency, connected with the inflaton decay amplitude  $\Gamma_\phi$ :

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



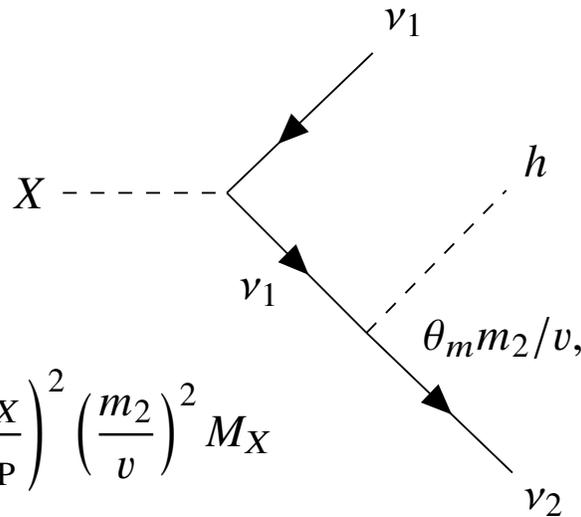
$$\Omega_{CDM} = 9.2 \times 10^{24} \frac{\epsilon^4 M_X}{M_P} Y_{X,0}(M_X, \epsilon, H_I)$$



# Coupling with a sterile neutrino sector

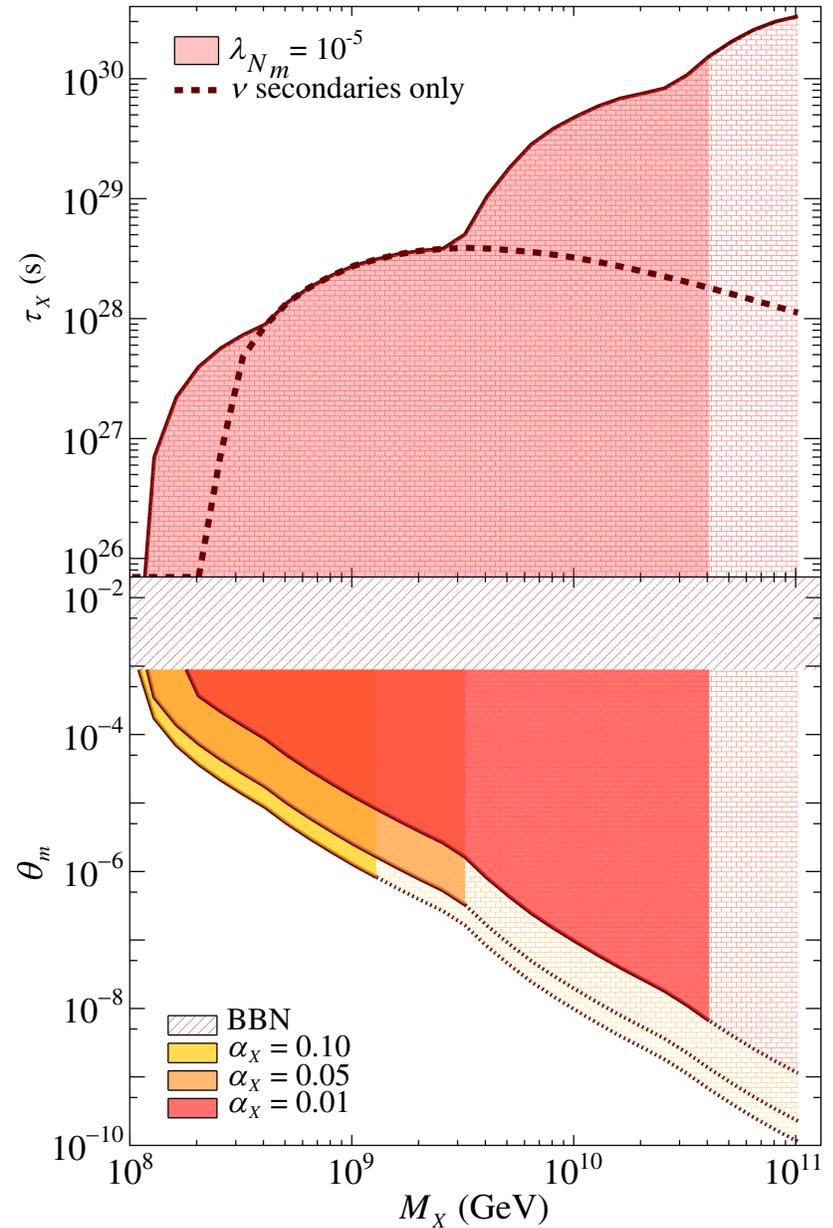
- ✓ A particular class of models meet the lifetime requirements of SHDM by coupling it to a sector of sterile neutrinos [reference model: Dudas, Heurtier, Mambrini, Olive, Pierre (2020)].

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



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

- ✓ 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.



# Lorentz Invariance Violations and the Quantum Gravity Regime



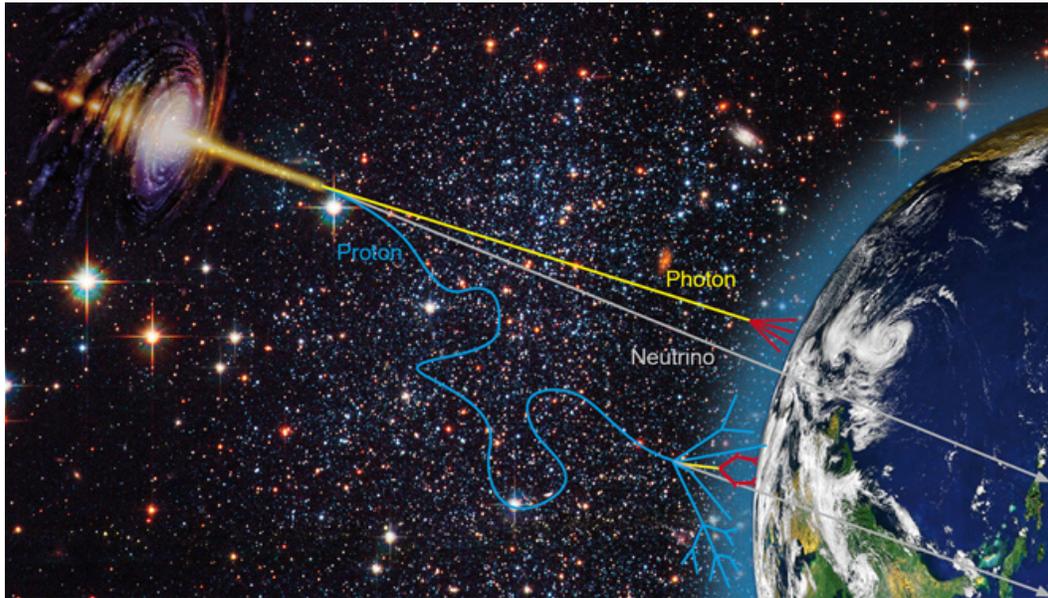
The idea of testing Lorentz Invariance (LI) through UHE CR and gamma ray data was inspired by A.F. Grillo, who suggested many of the analysis presented here.

- ✓ Different approaches to Quantum Gravity (QG) predict departures from Lorentz Invariance (LI) at extreme energy scales (above Planck mass  $M_p \approx 1.2 \times 10^{19}$  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  $l_p \approx 1.6 \times 10^{-33}$  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  $\eta$  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

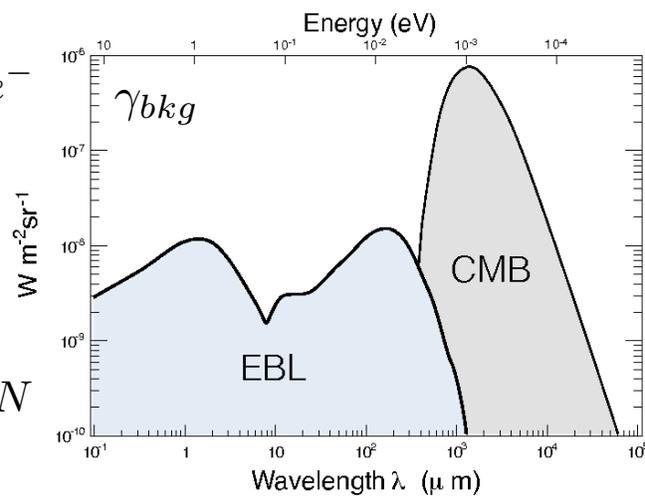
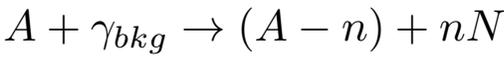
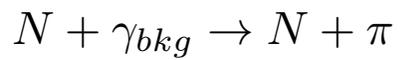
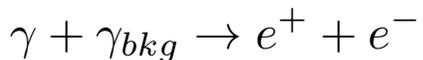
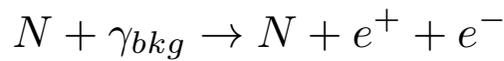


- ✓ Using modified dispersion relations with energy-momentum conservation, only kinematical thresholds are affected.
- ✓ Violations can be particle dependent, i.e. the LIV parameter is  $\eta_i$  with  $i=\gamma, N, \pi^\pm, \pi^0$
- ✓ Most relevant LIV effects are on threshold processes

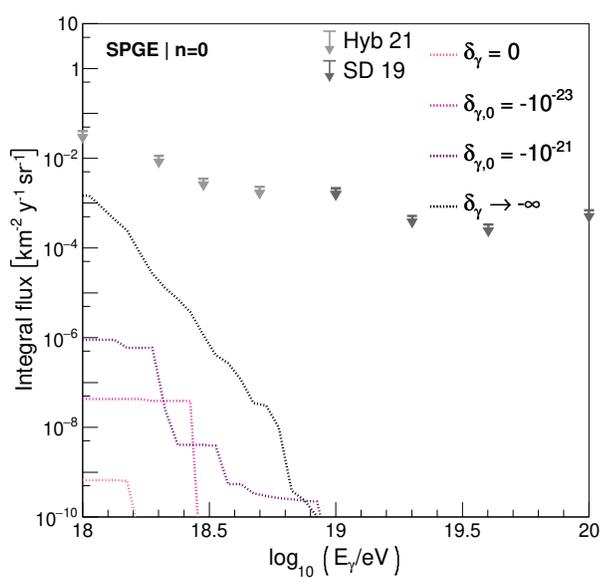
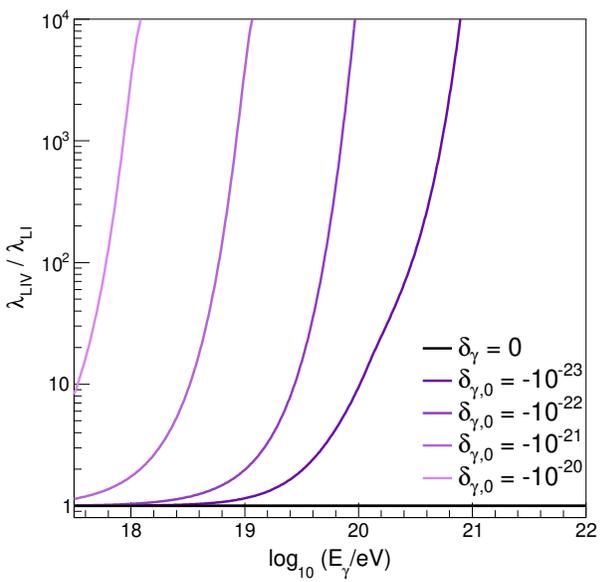
By expanding  $f(E/\Lambda)$

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

- ✓ Depending on the parameter  $\delta$  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.

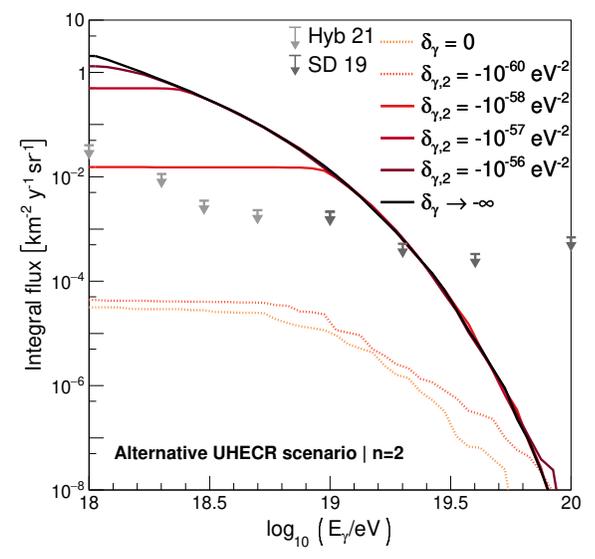
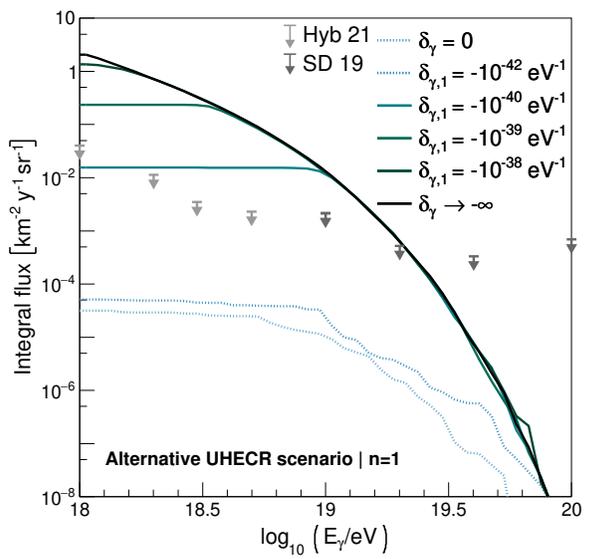
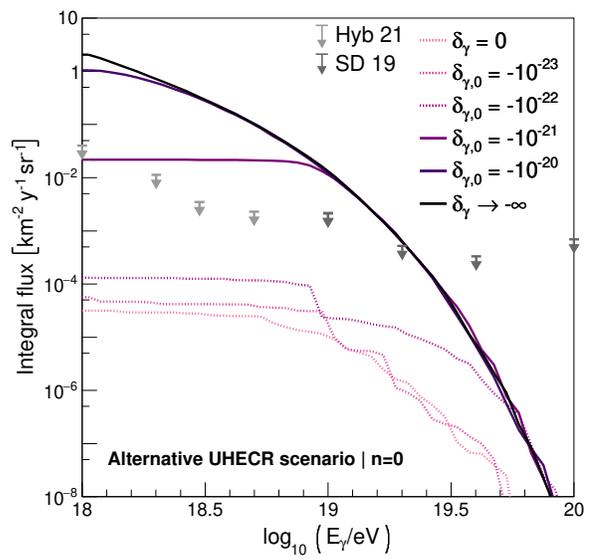


# Electromagnetic sector Photons propagation



- ✓ Relevant LIV scenarios with  $\delta < 0$ .
- ✓ 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.

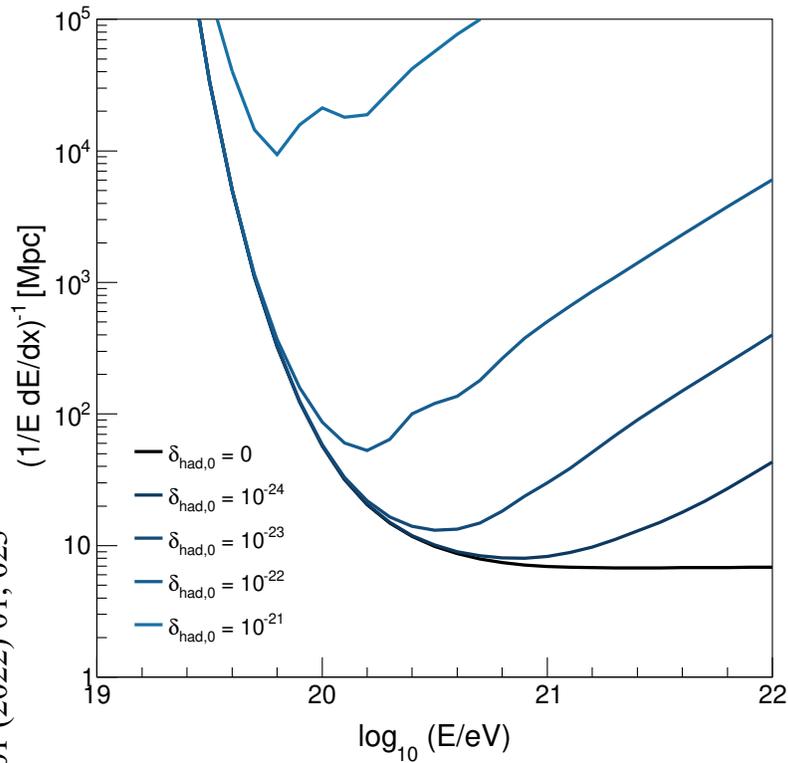
Auger Collaboration JCAP 01 (2022) 01, 023



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

# Hadronic sector UHECR propagation

Auger Collaboration JCAP 01 (2022) 01, 023



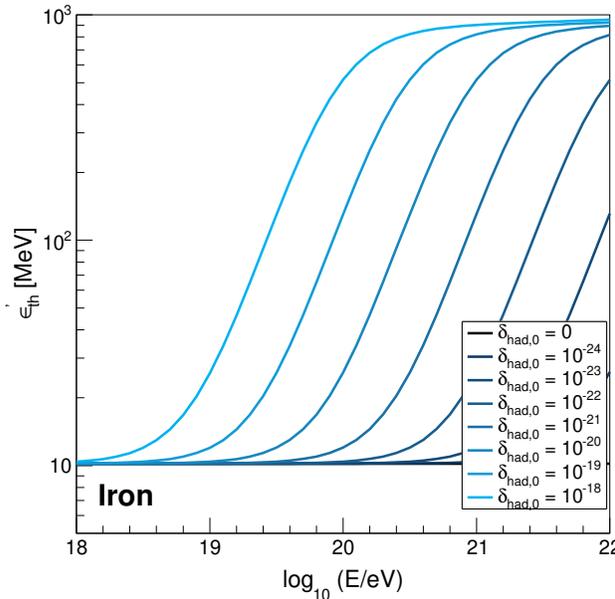
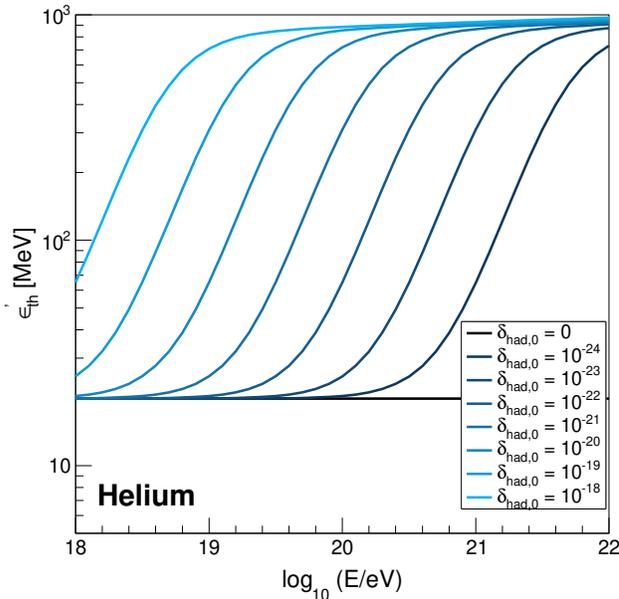
- ✓ Relevant LIV scenarios for UHECR are those with  $\delta > 0$ . Thresholds for photopion production and photodisintegration move to higher energies.
- ✓ To have the same LIV order for all hadrons, using the superposition principle we can write

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

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

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

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



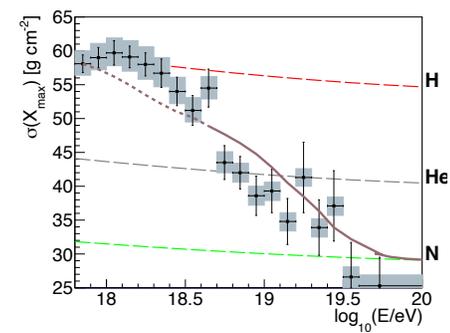
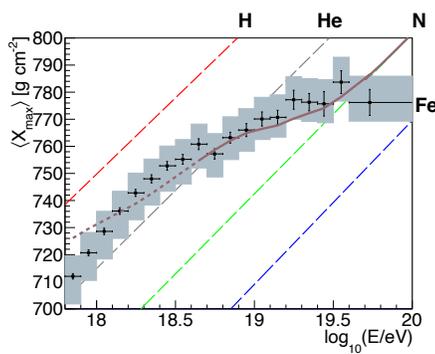
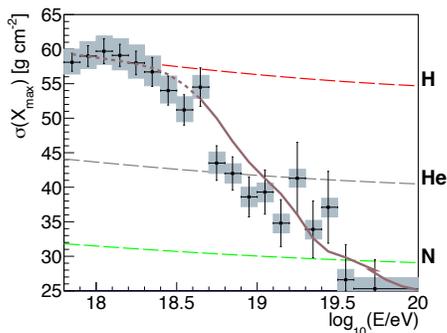
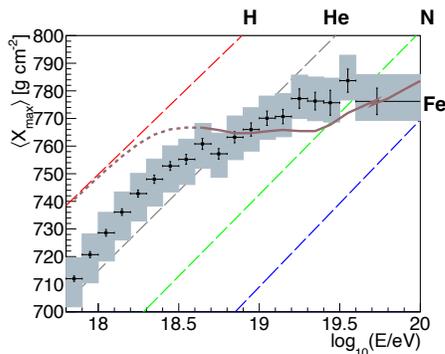
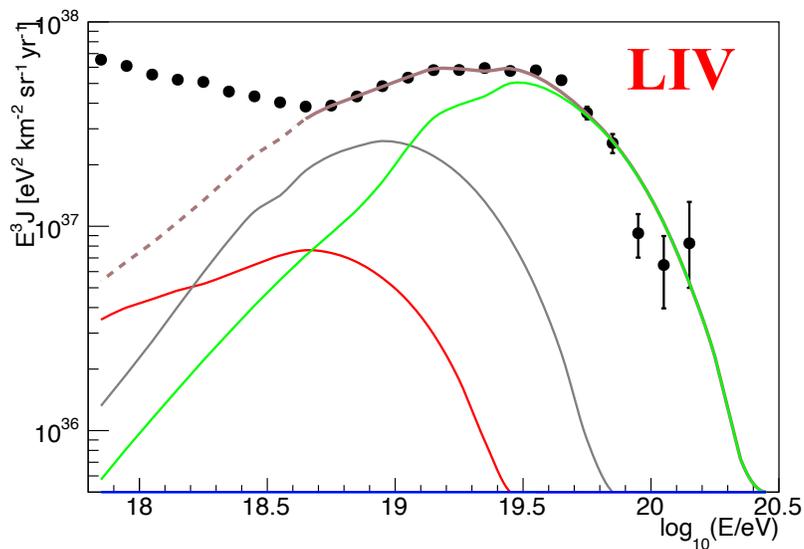
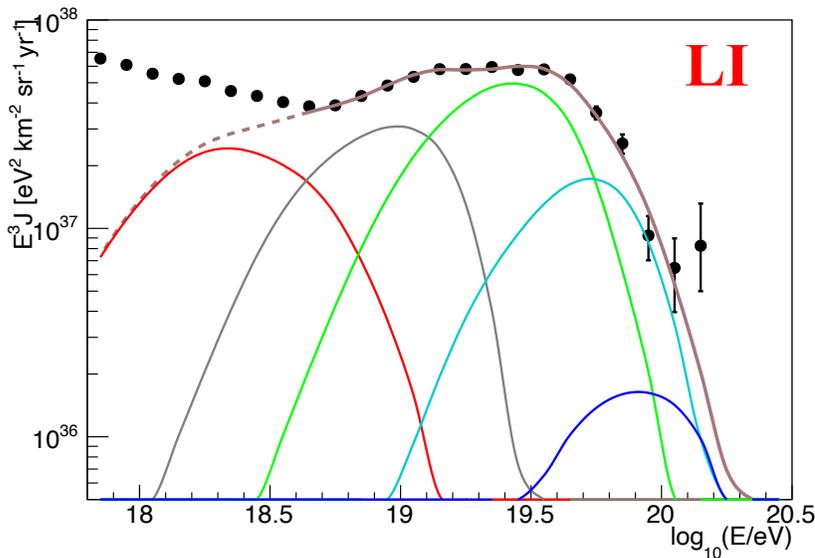
- ✓ In the LIV scenario the interaction length for nucleons and nuclei becomes sensibly larger.
- ✓ Limits on the LIV parameter from the combined fit of the Auger data on spectrum and mass composition.

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

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

✓ Fit parameters  $J_0, f_A, \Gamma, R_{\text{cut}}, \delta_{\text{had},0}$

✓ Standard LI combined fit: Talys cross-sections, EBL by Dominquez+ (MNRAS 2011), hadronic interactions EPOS-LHC



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

# Conclusions

- ✓ The Auger observations have an unprecedented potential to test new physics BSM: stringent limits on the SHDM parameters  $M_X$  and  $\tau_X$  and the LIV parameter  $\delta$ .
- ✓ The SHDM hypothesis connects UHECR observations with cosmological models ( $M_X$ ) and models BSM of particle physics ( $\tau_X$ ).
- ✓ 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.

More on BSM physics with UHECR in the Olivier review talk  
this afternoon

*Thank you*