New Physics: Constrains from Ultra High Energy Cosmic Rays

Roberto Aloisio

INFN – Gran Sasso Science Institute - L'Aquila

INAF – Osservatorio Astrofisico Arcetri - Firenze

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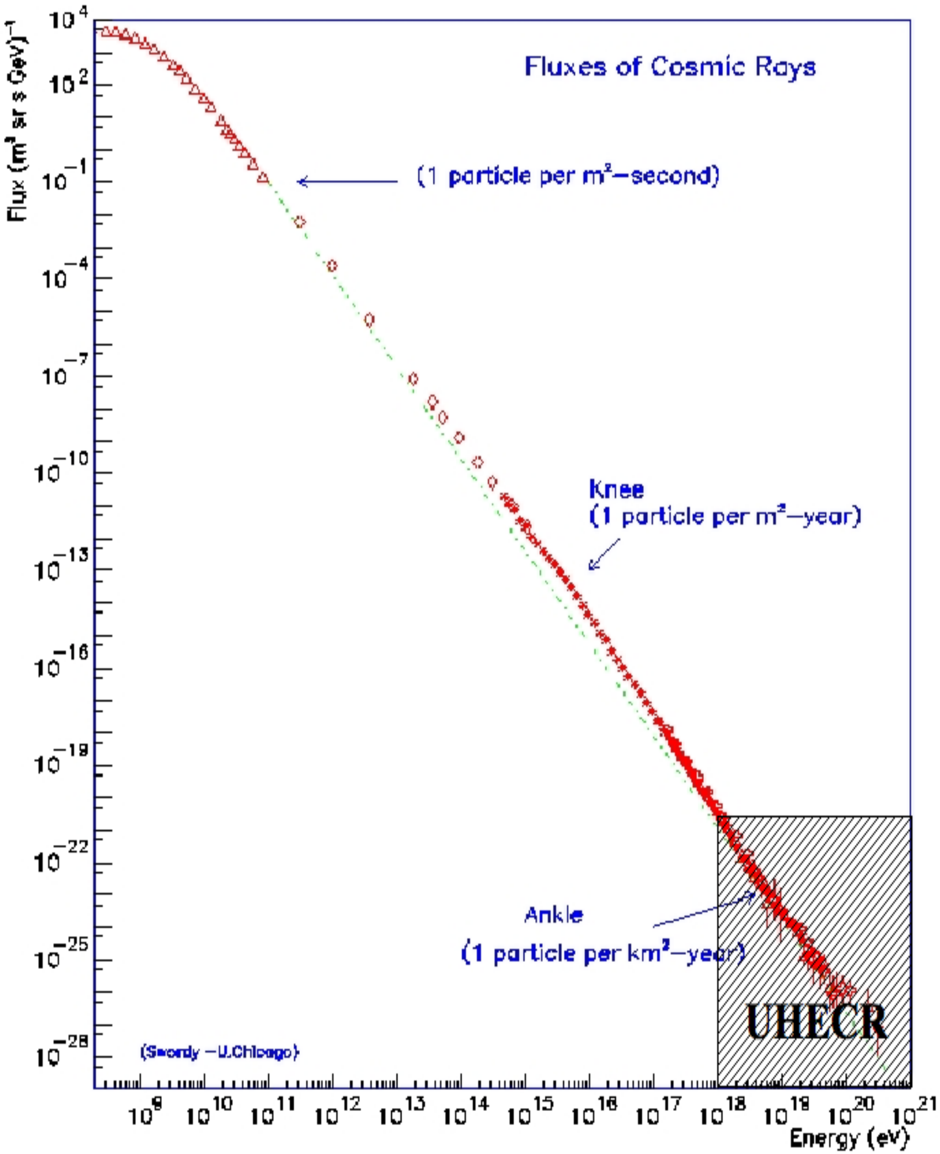
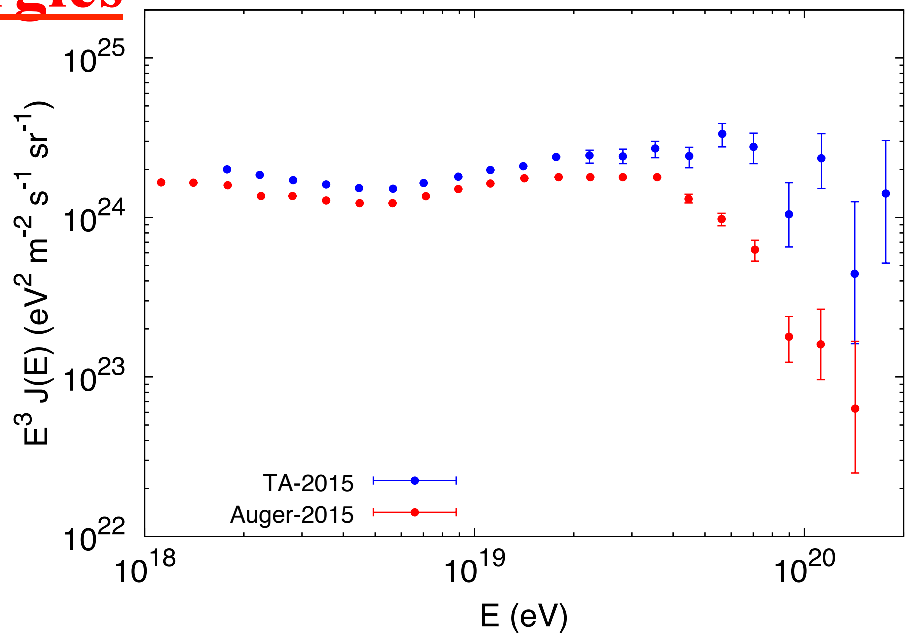
CR spectrum at Ultra High Energies

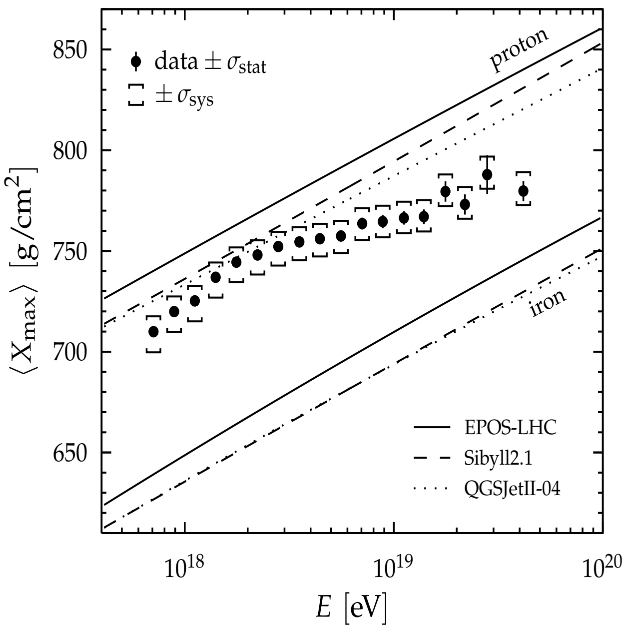


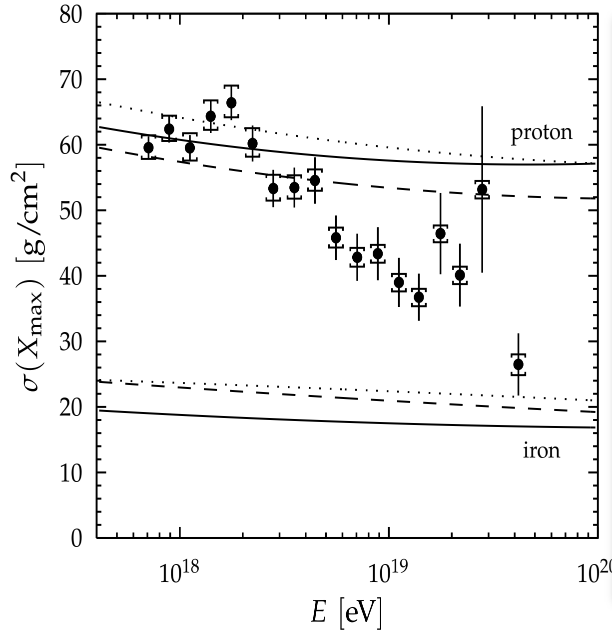


The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & EBL) and possible intergalactic magnetic fields (IMF).

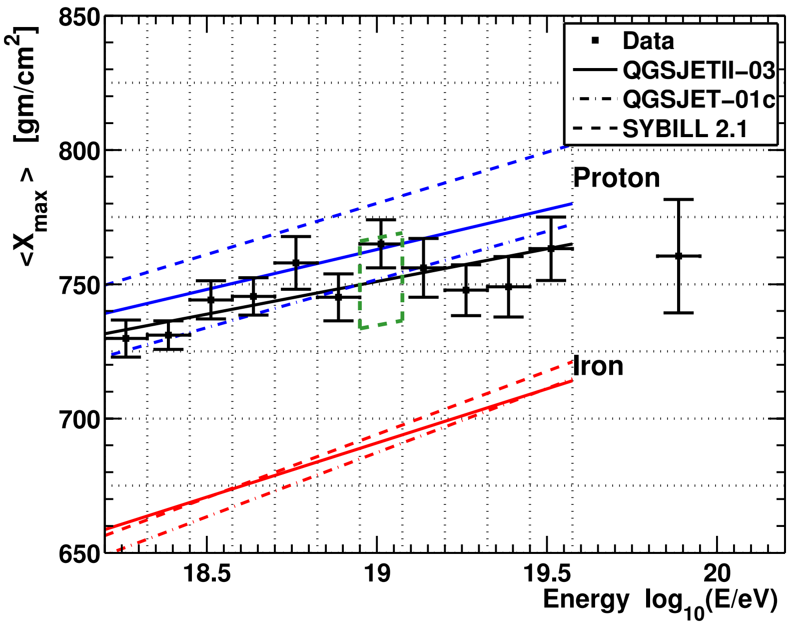
- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy** (astronomy?)
- ✓ **Cosmogenic secondary particles**

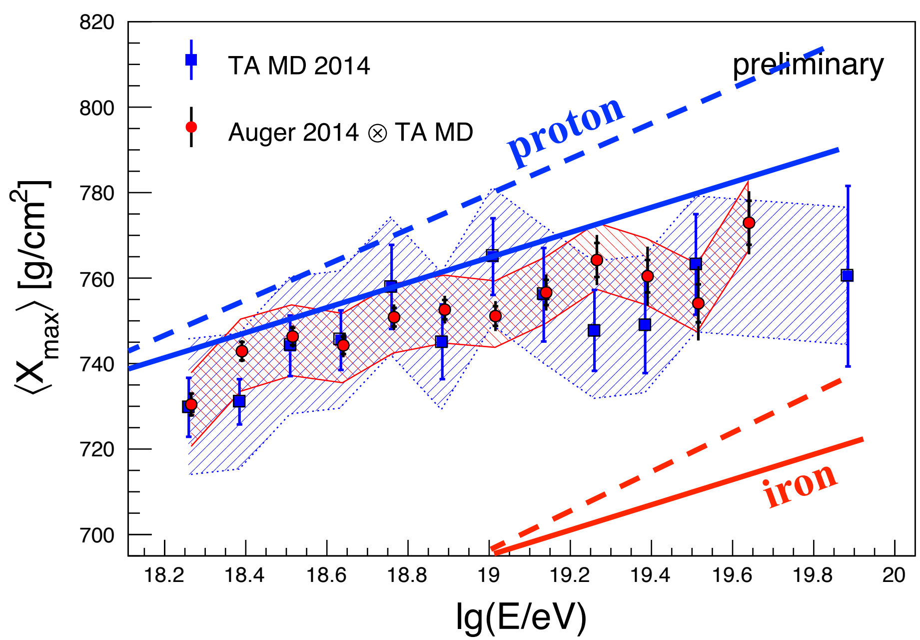
Ultra High Energies Cosmic Rays – Composition





- **Auger**: protons at low energy and heavier nuclei at high energy.
- **TA**: protons only.
- **Strong uncertainties due to the hadronic interaction model.**





Super Heavy Dark Matter

Supermassive particles with mass comparable with the inflaton mass can be generated in the early universe by time-dependent gravitational fields or through direct coupling to the inflaton field.

(Kofman, Linde & Starobinsky (1994), Felder, Kofman & Linde (1998), Zeldovich & Starobinsky (1972), Chung, Kolb & Riotto (1998), Kuzmin & Tkachev (1998))

They can be long-lived if their decay is inhibited by some discrete symmetry (such as R-parity for SUSY neutralinos)

(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 at inflation (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 (SM secondary in Astrophysics observations).
- SHDM can be experimentally tested only indirectly through cosmological observations and UHECR observations.

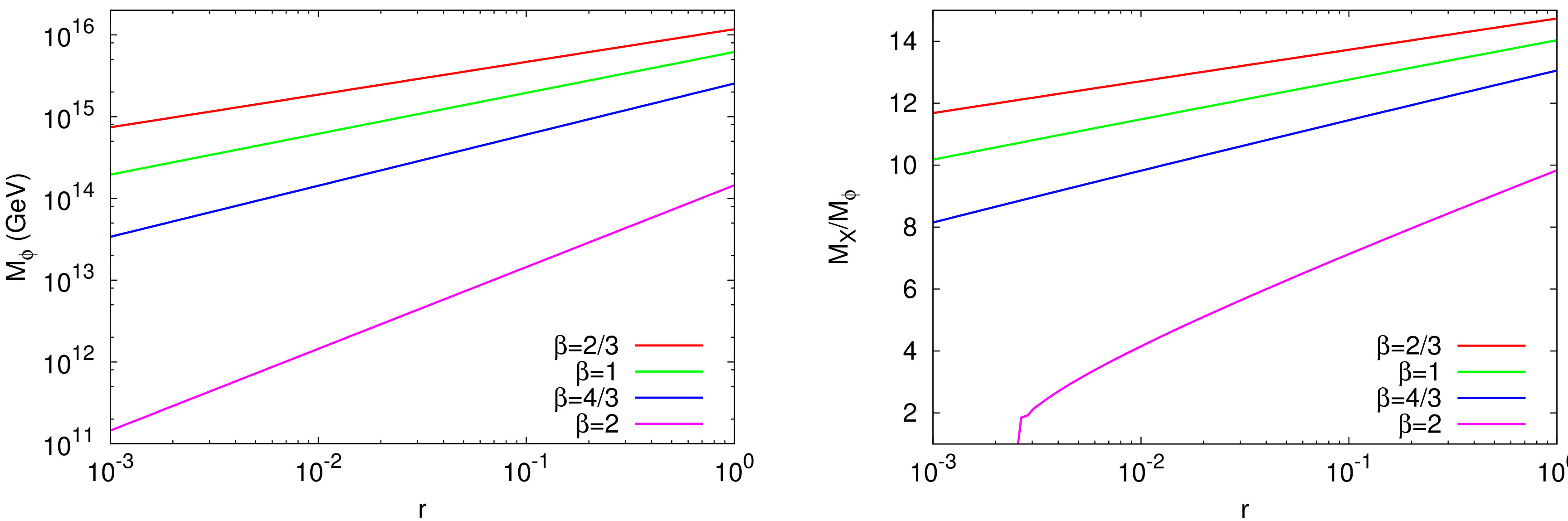
SHDM and Inflation

Being out of local thermal equilibrium SHDM naturally produces tensor modes.

The observed tensor-to-scalar ratio in CMB fluctuations sets the scale for SHDM.

$$\Omega_X(t_0) \simeq 10^{-3}\Omega_R \frac{8\pi}{3}\left(\frac{T_{RH}}{T_0}\right)\left(\frac{M_\phi}{M_{Pl}}\right)^2\left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$

$$V(\phi) = \frac{M_\phi^{4-\beta}}{\beta}\phi^\beta \qquad V_\star \simeq \frac{3\pi^2}{2}A_s r M_{Pl}^4 \simeq M_{GUT}^4\left(\frac{r}{r_0}\right) \qquad \epsilon(\phi) = \frac{M_{Pl}^2}{16\pi}\left[\frac{V'(\phi)}{V(\phi)}\right]^2 = \frac{r}{16}$$



RA, Matarrese, Olinto (2015)

SHDM mass M_X determined assuming $\Omega_X = \Omega_{DM}$ today

SHDM and UHECR

The rare decays of SHDM may generate UHE standard model particles

As CDM SH relics cluster in galactic halos

Decays of X-particles at present epoch could arise in different models

Wormhole effect

(Berezinsky, Kachelriess & Vilenkin (1997))

Quantum Gravity through wormhole effect could violate the discrete symmetry

$$\tau_X \simeq \frac{M_{Pl}^2}{M_X^3} e^{2S}$$

(S wormhole action)

Instanton induced decay

(Kuzmin & Rubakov (1997))

X-particles could decay through an istanton transition

$$\tau_X \simeq \frac{1}{M_X} e^{4\pi/\alpha_X}$$

(α_X gauge coupling)

The basic parameters of the SHDM model are

$M_X \simeq O(10^{14} GeV)$ Particle mass

$\tau_X \simeq O(10^{22} y)$ Particle lifetime

n_X Galactic halo Dark Matter distribution

SHDM flux contribution

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

Fixes the energy behavior and chemical composition. The observed UHECR flux selects a sub-space of the SHDM parameter space, through

$$r_X = \Omega_X \frac{t_0}{\tau_X}$$

signature of the model

Astrophysics

Galactic DM halo fixes the geometrical behavior of the SHDM emission, it gives an increased emission from the GC direction

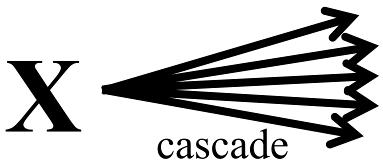
$$n_X(R) = \frac{n_0}{(R/R_s)^\alpha (1 + R/R_s)^{3-\alpha}}$$

α=1 NFW density profile

α=3/2 Moore density profile

signature of the model

From SHDM to UHECR



hadronization

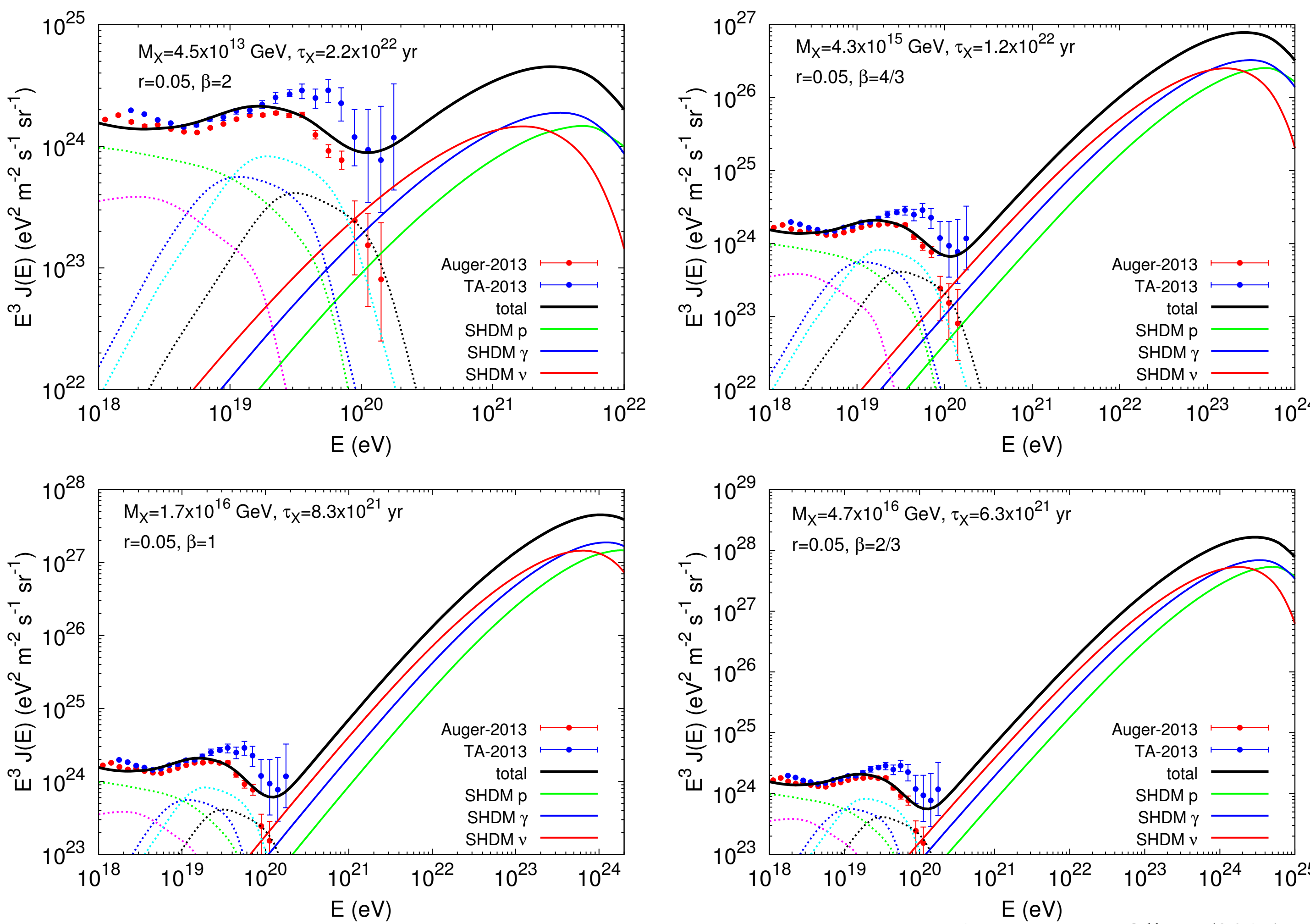
mainly π
therefore γ and ν

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

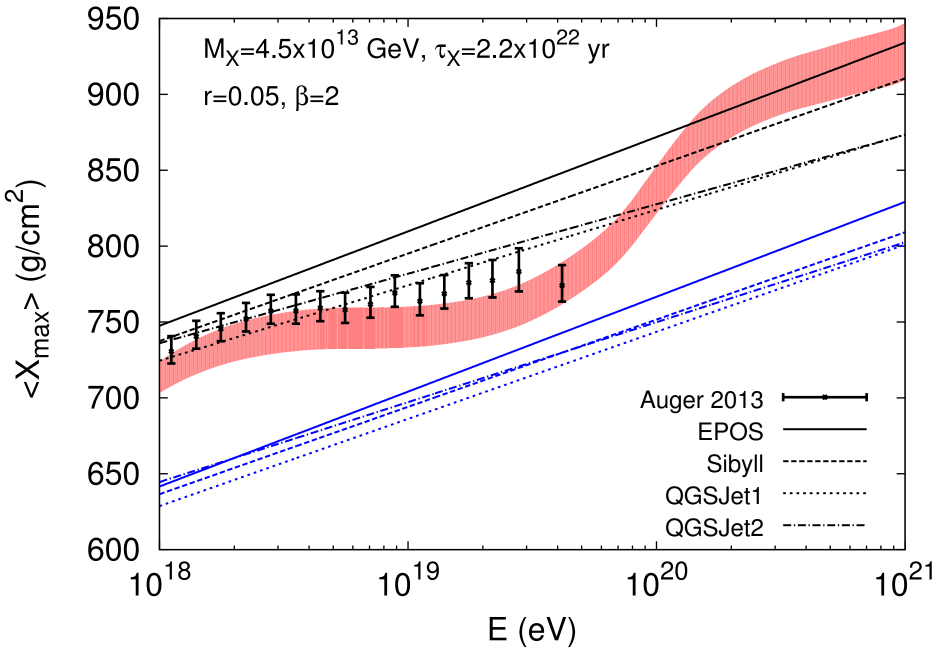
$$J_{\nu,\gamma,p} \propto \frac{1}{M_X \tau_X}$$

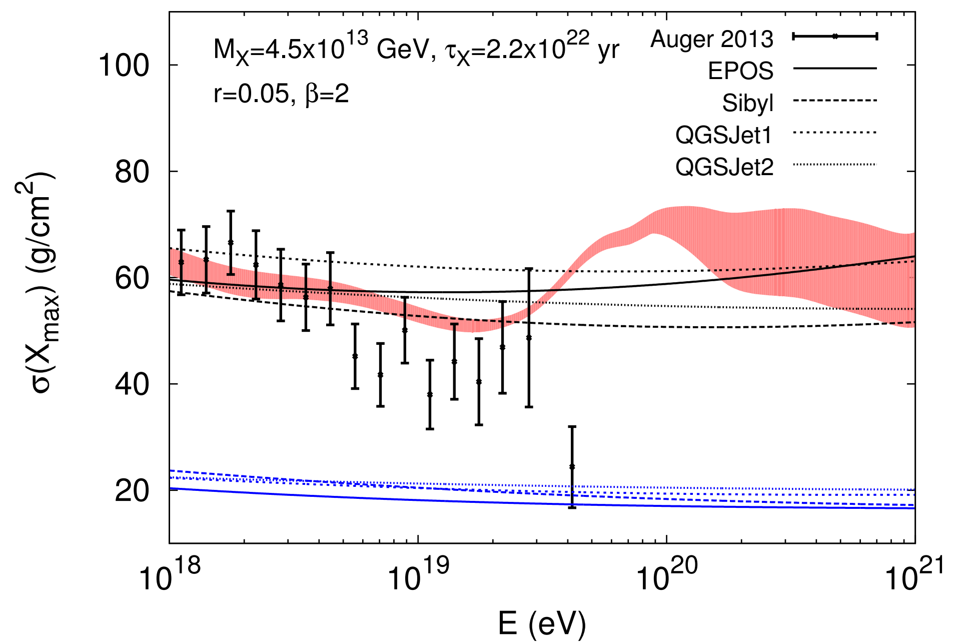
RA, et al (2004-2007)

- ✓ SHDM lifetime τ_X regulates the expected CR flux.
- ✓ SHDM halo density profile (Moore in figs)
- ✓ Integrating over the whole sky.
- ✓ Taking into account the whole universe.



RA, Matarrese, Olinto (2015)

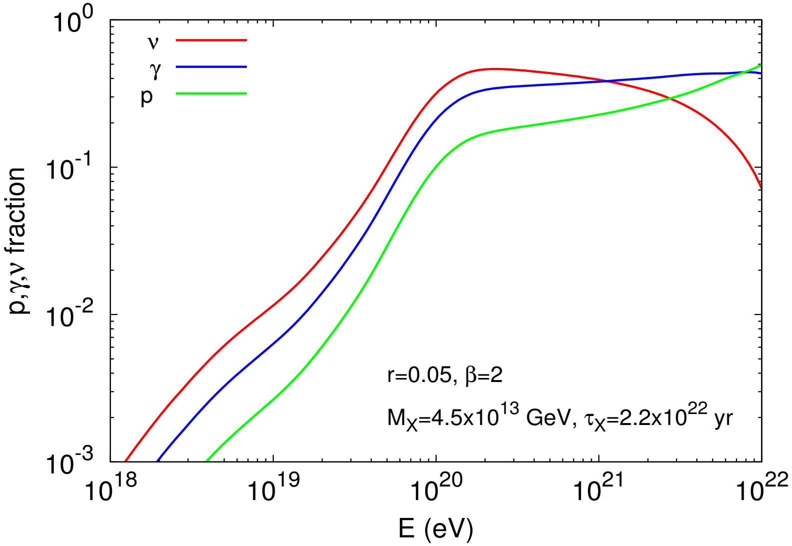


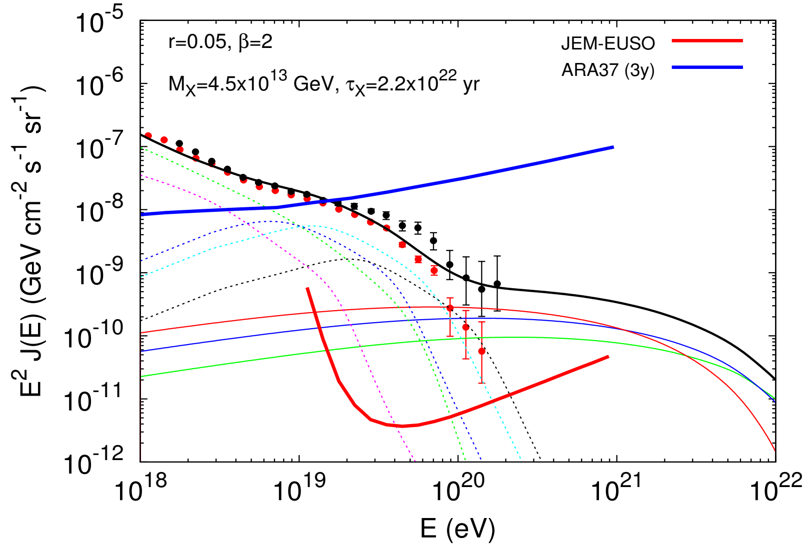


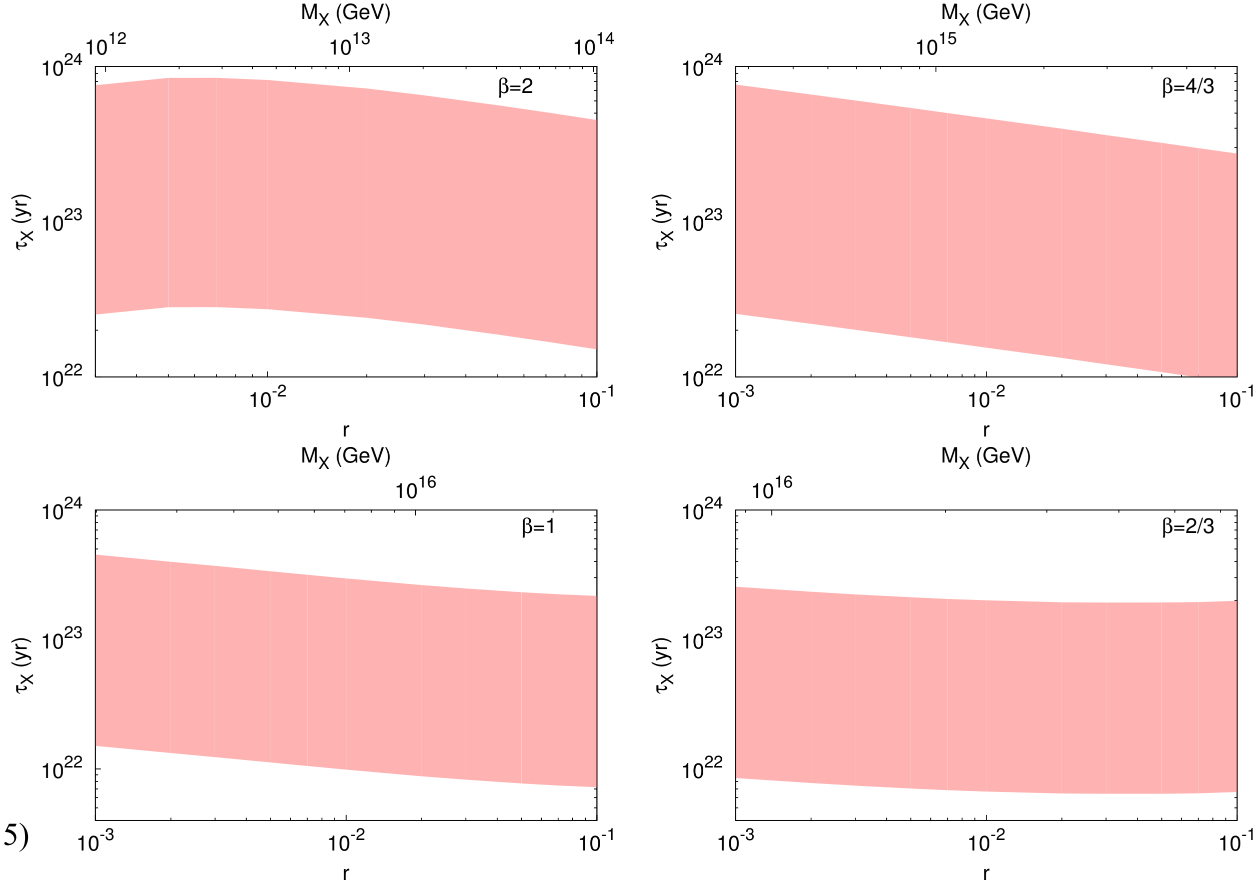
RA, Matarrese, Olinto (2015)

The most constraining observations that limit (from below) τ_X are

- ✓ Chemical composition of UHECR
- ✓ Photons fraction at $E>10^{19}$ eV at the level of 1 %







- ✓ UHECR experiments are more suitable to detect UHE particles produced by SHDM decays.
- ✓ JEM-EUSO has the capability of exploring SHDM till $\tau_X \sim 10^{24}$ yr.

RA, Matarrese, Olinto (2015)

SHDM anisotropy contribution

The observed UHECR events are distributed in the sky depending on both real celestial anisotropy and the detector relative acceptance ω(δ) (terrestrial equatorial coordinates: α right ascension and δ declination). Assuming a superposition of (isotropic) extragalactic astrophysical generated protons and galactic UHECR from SHDM decay, the total flux will be

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

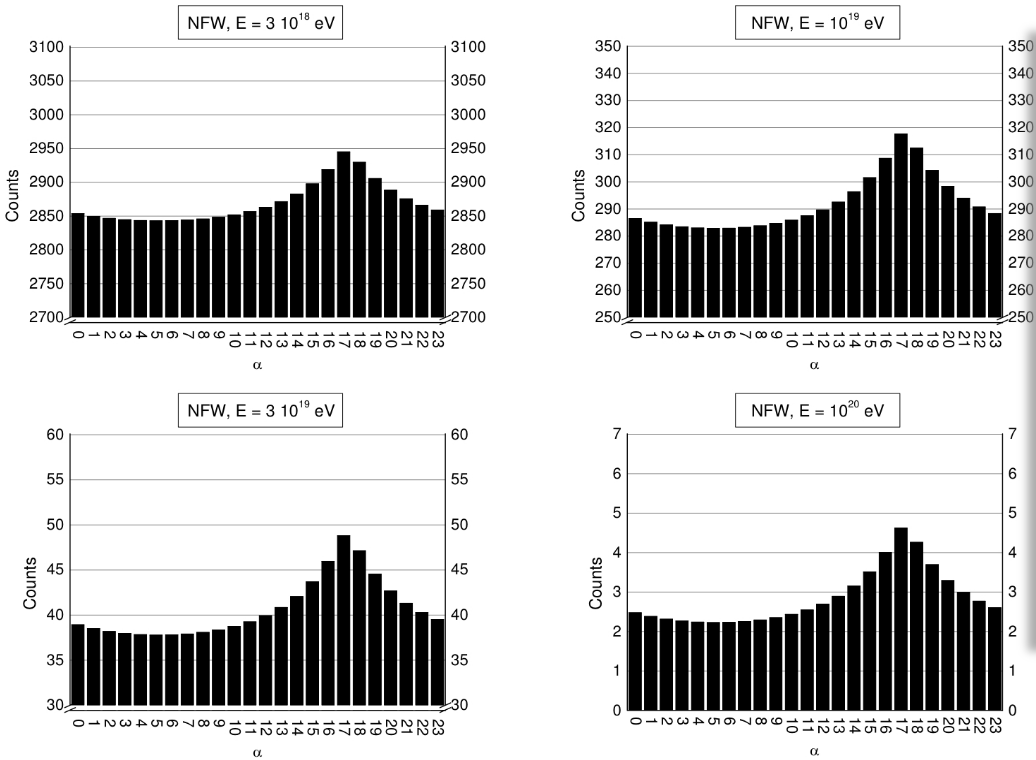
The number of events at energy $E>E_0$ collected during T_0 inside the Auger field of view in declination (with a uniform exposure in right ascension α) is

$$N_{\alpha_i}(\geq E_0) = S_A T_0 \int_{\alpha_i}^{\alpha_i+\Delta\alpha} d\alpha \int_{E_0} \int_{\delta_{min}}^{\delta_{max}} J_{UHECR}(E,\alpha,\delta)\cos(\delta)d\delta$$

The SHDM component is photon dominated and it does not feel the effect of the galactic magnetic field, following the behavior of the galactic DM density distribution with an enhancement in the GC direction. On the other hand the (astrophysical) extragalactic contribution to the flux $J_{EG}(E)$ at the lowest energies is highly isotropic.

Even a very small anisotropy signal at the lowest energies could help in tagging any SHDM contribution to the flux.

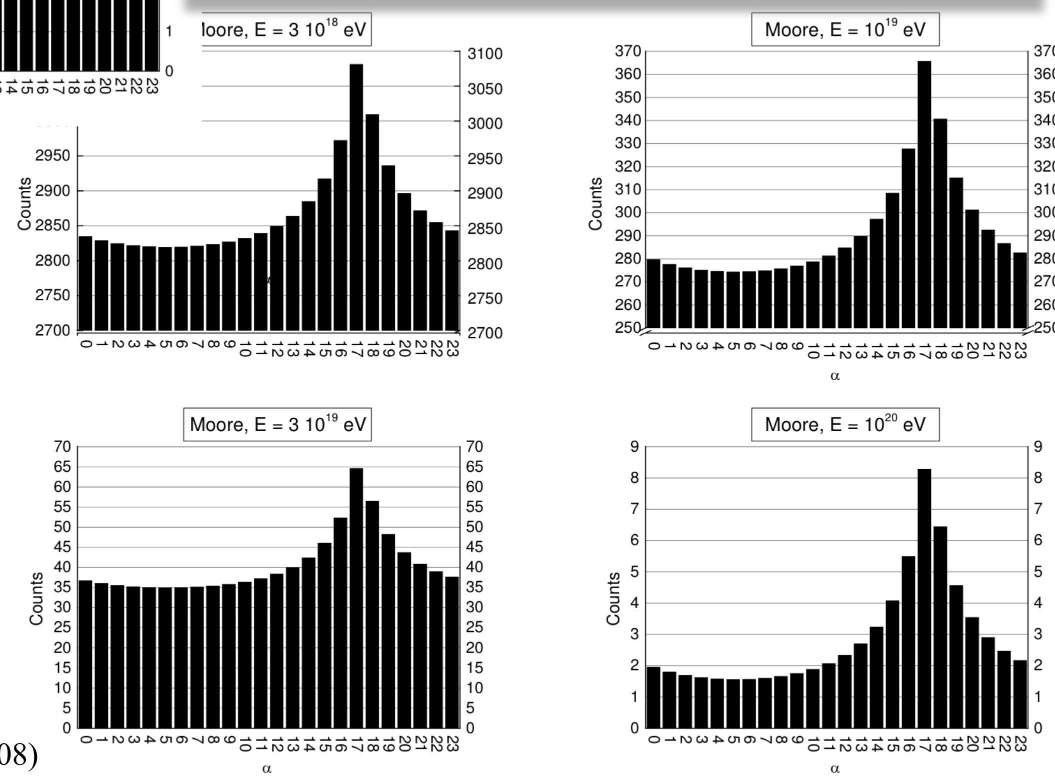
RA, Tortorici (2008)



Energy (EeV)	r (NFW-min)	N(4 s.d.)	r (Moore-min)	N(4 s.d.)
> 3	0.015	150000	0.018	100000
> 10	0.045	16000	0.060	9000
> 30	0.100	3200	0.140	1600
> 100	0.300	350	0.440	150

Energy (EeV)	r (NFW-max)	N(4 s.d.)	r (Moore-max)	N(4 s.d.)
> 3	0.019	90000	0.027	45000
> 10	0.065	7500	0.092	4000
> 30	0.150	1400	0.215	700
> 100	0.480	150	0.690	70

The number of events needed to detect at 4 σ level the expected anisotropy depends on the SHDM density profile. It spans from 2 years (Moore profile) up to 8 years (NFW profile). Already at $3\text{x}10^{18}$ eV the anisotropy could be at the level of few % , within reach Auger capabilities.



RA, Tortorici (2008)

Lorentz Invariance Violations

Quantum Gravity

It is generally believed that the picture of space-time locally modeled as a flat Minkowski space should break down at very short distances of the order of the Planck length:

$$l_P = \left(\frac{G\hbar}{c^3}\right) \simeq 1.6 \times 10^{-33} cm$$

limitations in the possible accuracy of localization of spacetime events should in fact be a feature of a Quantum Theory incorporating gravitation.

Wheeler (1957); Kirzhnits & Checin (1971); Amelino-Camelia, Ellis, Mavromatos, Nanopoulos (1997-1998), Coleman & Glashow (1999); Dvali & Shifman (1999)

Effective field theories

Many different models of QG imply violations of the Lorentz invariance, all result in a modification of the dispersion relation of particles

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

Relativity principle violated with a preferred reference frame (space-time foam, universe co-moving frame).

$$E^2 - p^2 = m^2 \left[1 + g(p/M_P)\right]$$

g-terms renormalizable, extremely weak, no experimental test

$$+p^2 f(p/M_P)$$

f-terms non rinormalizable, experimental test: I and II order in p/M_P

Interactions of UHECR with astrophysical backgrounds test Lorentz invariance up to scales not differently attainable: $\gamma = 10^{11}$.

$$p + \gamma \rightarrow e^+ + e^- + p \qquad p + \gamma \rightarrow \pi + N \qquad \gamma + \gamma \rightarrow e^+ + e^-$$

TABLE I. Values of x that solve the equation for the threshold for pair production in the non-Lorentz invariant approach.

	Infrared	Microwave	Radio
I_+	≈ 0.73	0.06	5×10^{-7}
I_-	No solution	No solution	No solution
II_+	≈ 1	≈ 1	2×10^{-3}
II_-	≈ 1	≈ 1	No solution

TABLE II. Limits on the scale M where the LI is broken.

	Infrared	Microwave	Radio
I_+	$M\gtrsim 0.2M_P$	$M\gtrsim 800M_P$	$M\gtrsim 2.5\times10^{18}M_P$
I_-	$M\gtrsim 6M_P$	$M\gtrsim 3\times10^{4}M_P$	$M\gtrsim 8\times10^{19}M_P$
II_+	$(M\gtrsim 3\times10^{-8}M_P)$	$(M\gtrsim 7\times10^{-6}M_P)$	$M\gtrsim 10^{5}M_P$
II_-	$(M\gtrsim 3\times10^{-7}M_P)$	$(M\gtrsim 10^{-4}M_P)$	$M\gtrsim 10^{6}M_P$

TABLE III. Values of x that solve the equations for the threshold of photopion production on the microwave background (first column) and lower limit on the scale M of breaking of LI (second column).

	x	Limit
I_+	2×10^{-5}	$M\gtrsim 3\times10^{13}M_P$
I_-	No solution	$M\gtrsim 10^{15}M_P$
II_+	0.02	$M\gtrsim 536M_P$
II_-	No solution	$M\gtrsim 6\times10^{3}M_P$

RA, Blasi, Ghia, Grillo (2000)

$$E^2 - p^2 \simeq m_i^2 + f_i \frac{p^{2+n}}{M_P^n}$$

If UHECR are protons with high maximum energy ($>10^{20}$ eV). The observation of GZK cut-off implies stringent limits on LIV.

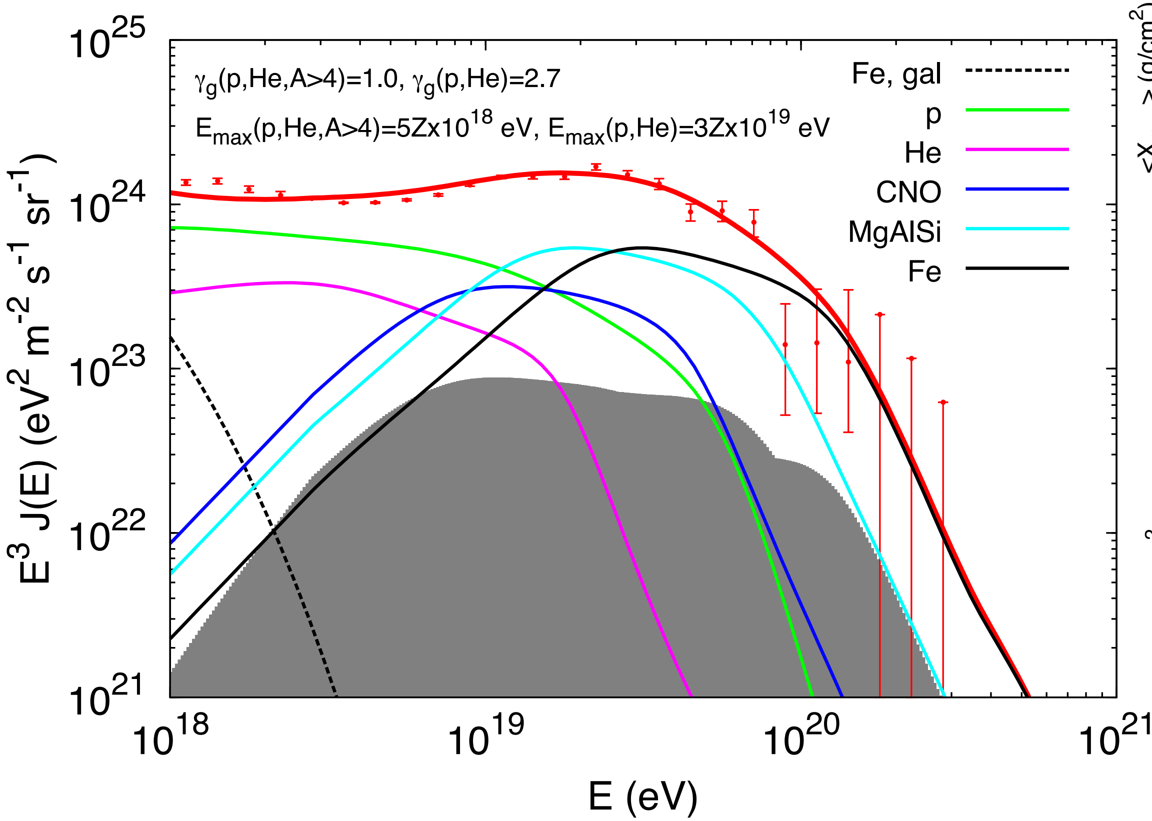
Proton interactions

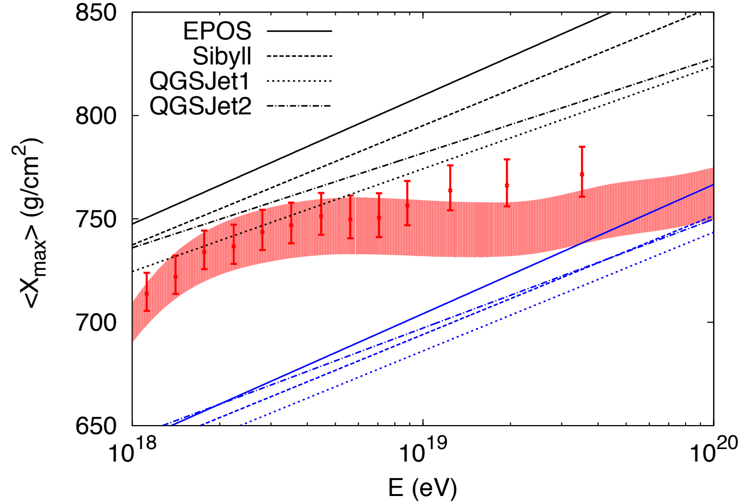
$f_p < 0$ threshold moves to higher energies, LIV limits

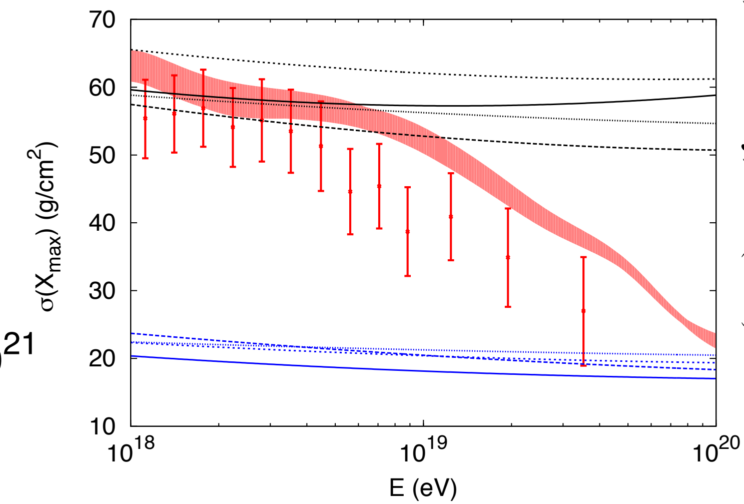
$$n = 1 \rightarrow f_p < -3\times10^{-14}$$
$$n = 2 \rightarrow f_p < -3\times10^{-6}$$

$f_p > 0$ thresholds move to lower energies, exotic processes appear: Cerenkov in vacuum (excluded).

LIV in the Auger era







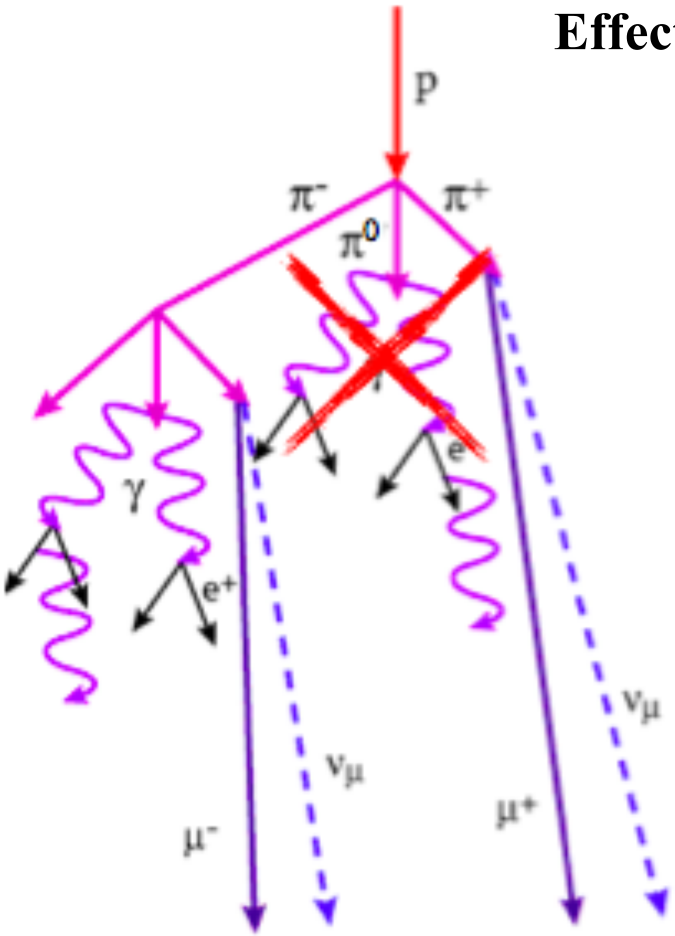
RA, Berezinsky, Blasi (2014)

Auger data imply:

- ✓ Low maximum acceleration energy (E_{max} < few x 10^{19} eV, for protons).
- ✓ Steep injection of light nuclei
- ✓ Flat injection of heavy nuclei

Because of the low maximum energy no effective limits on LIV models from UHECR propagation.

Interactions of UHECR with the earth atmosphere can place other bounds to possible violations of the Lorentz invariance.



Effects on pions decay

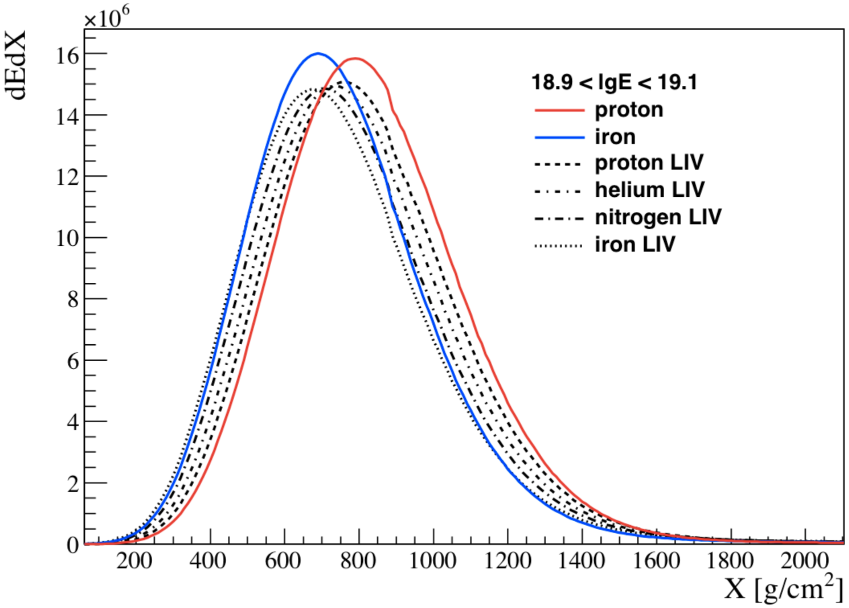
$$\pi^0 \to \gamma\gamma \qquad \pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu)$$

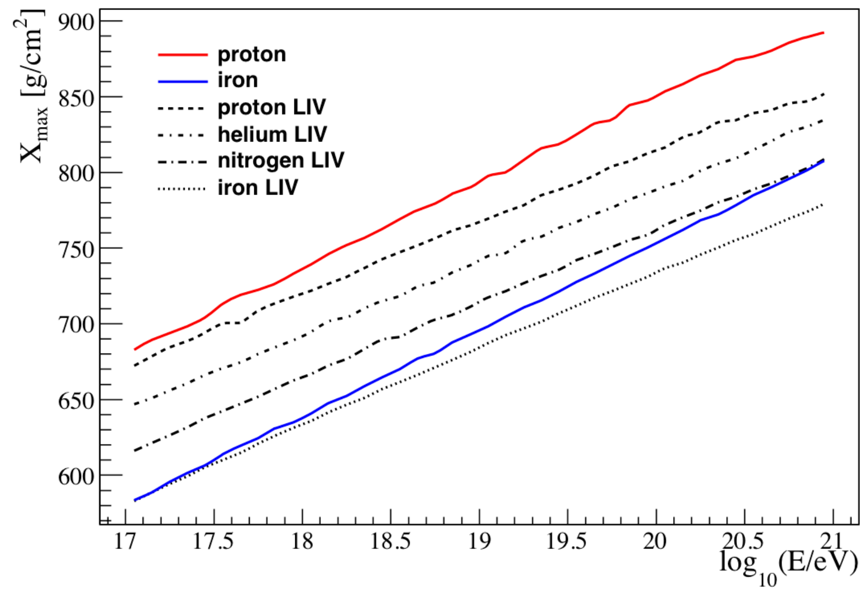
$$E^2 - p^2 = m_i^2 + f_i \frac{p^{2+n}}{M_P^n}$$

$f_\pi < 0$ suppression of the processes at high energies

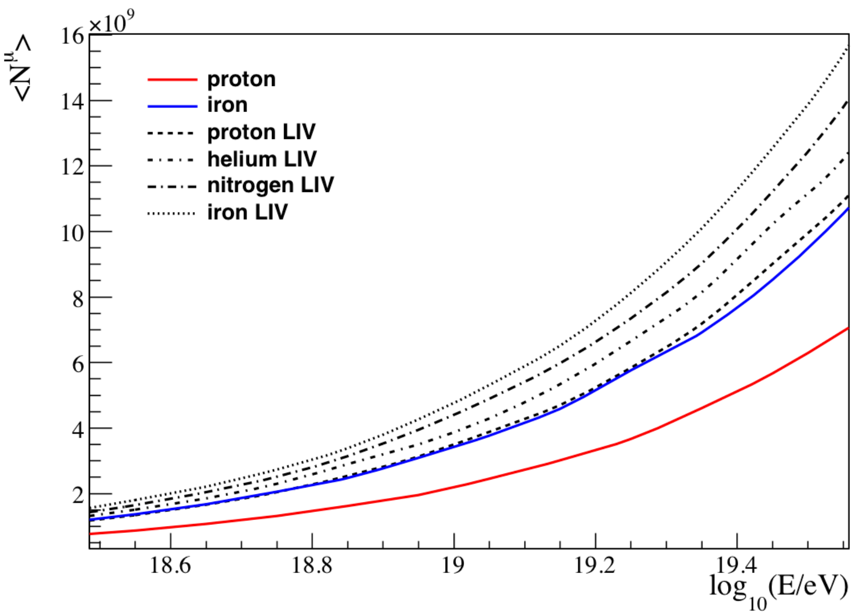
$$E_\pi > \left(\frac{M_P^n m_\pi^2}{|f_\pi|} \right)^{\frac{1}{n+2}}$$

consequences on the observed shower development (position of the maximum, muon content)





Boncioli, di Matteo, Salamida, RA, Blasi, Grillo, Ghia, Petrera, Pierog (2015)



10^5 showers simulated with CONEX, case with n=1 and $-f_\pi$=1, π^0 decay inhibited for

$$E_\pi > \left(\frac{M_P m_\pi^2}{|f_\pi|}\right)^{1/3} \simeq 6 \times 10^{15} eV$$

The overall effect of LIV on the atmospheric shower development is to mimic an heavier composition with lower X_{max} and higher number of muons.

Conclusions

✓ Super Heavy Dark Matter

- ✓ The observation of UHECR at extreme energies ($E>10^{20}$ eV) can set stringent limits on the SHDM lifetime. SHDM can be discovered by future precise cosmological measurements combined with future observations of ultra high energy cosmic rays and neutrinos.

✓ Lorentz invariance violations

- ✓ The observation of UHECR at extreme energies ($E>10^{20}$ eV) can set stringent limits on LIV in the case of pure proton composition. In the case of Auger data, with low maximum energies, reduced capability of UHECR observations to constrain LIV.
- ✓ Interactions of UHECR with earth atmosphere can still provide some limits to LIV models.