Effects of Lorentz invariance violation on EHECR propagation and spectrum

(MSc. Project)

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13/04/2019

Malá Skála

OUTLINE

1) Introduction

- Cosmic rays spectrum in general

2) Propagation of proton EHECR

- Energy losses and energy evolution
- Possible origin of EHECR

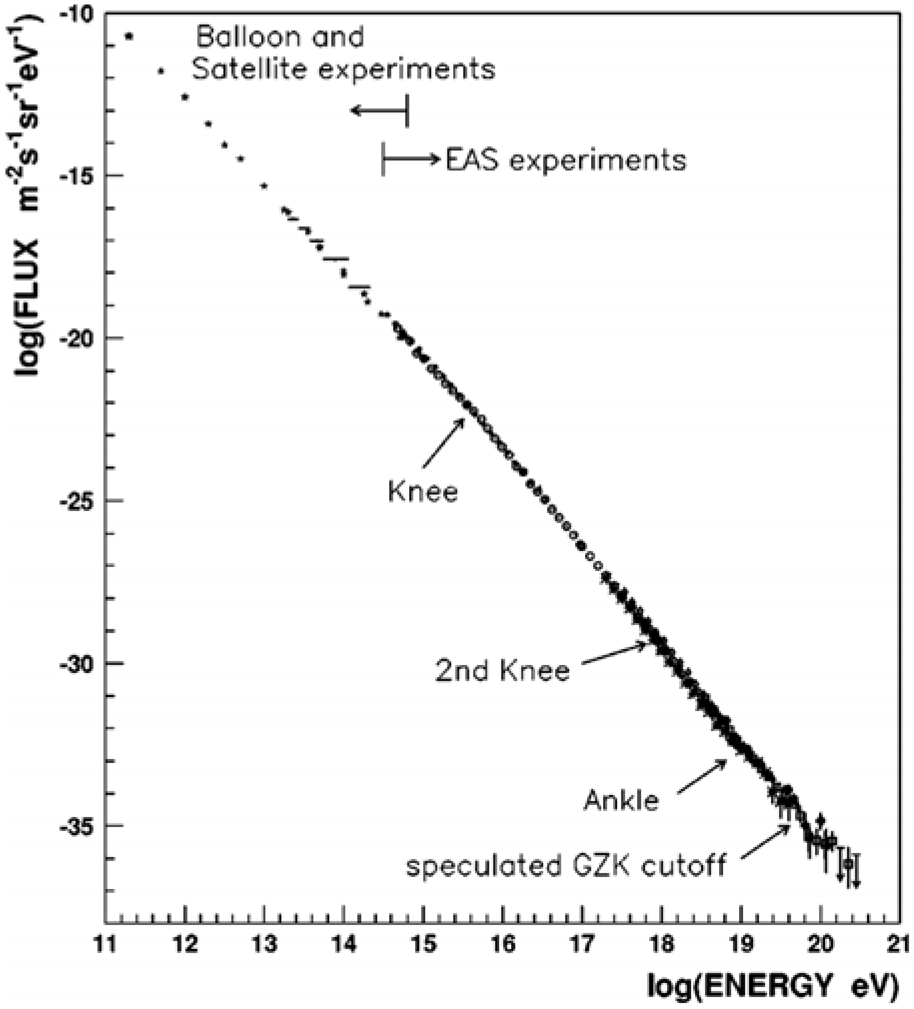
3) LIV effects on the proton propagation

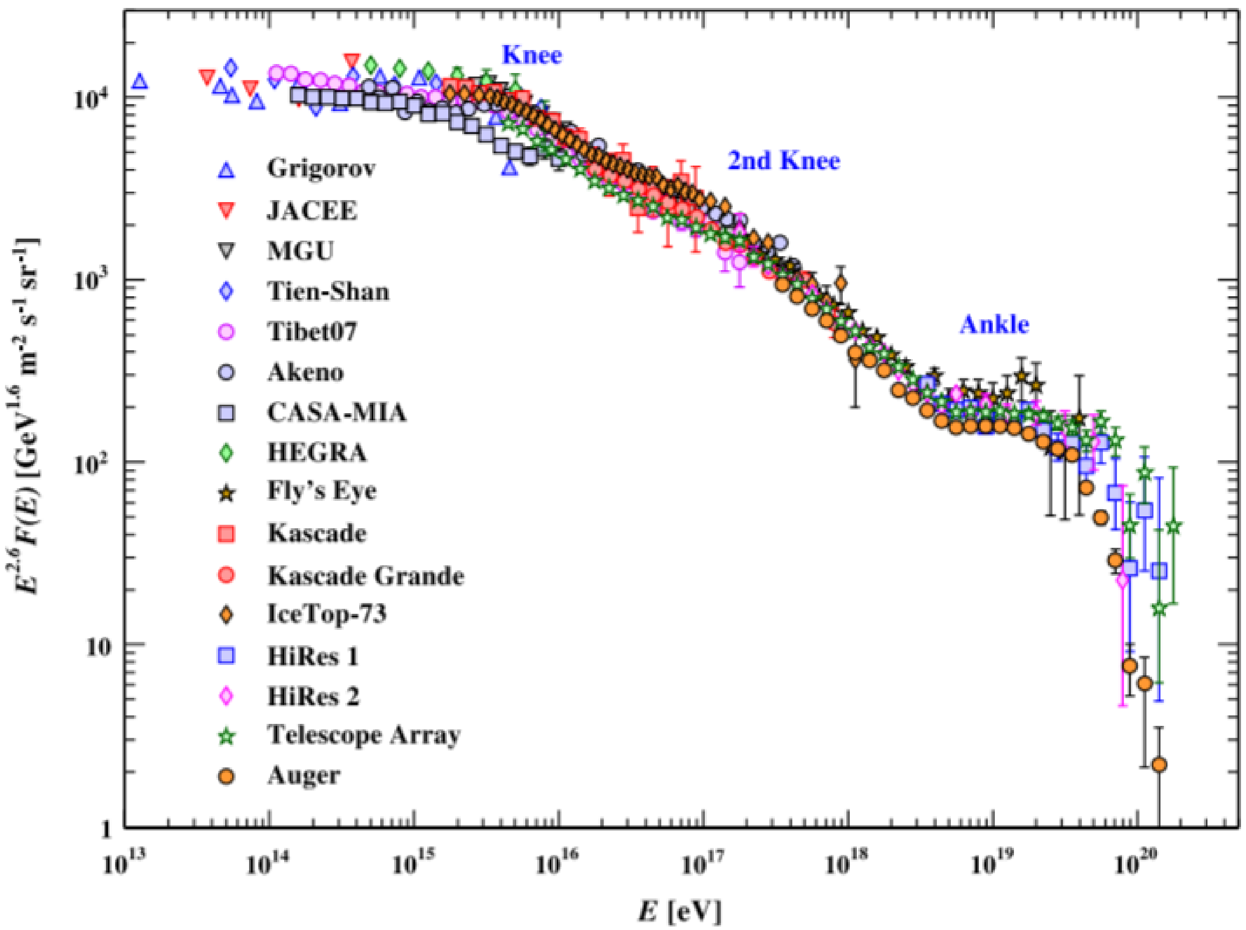
- LIV framework
- Proton modified propagation

3) LIV effects on the proton CR energy spectrum

4) Preliminary Conclusions

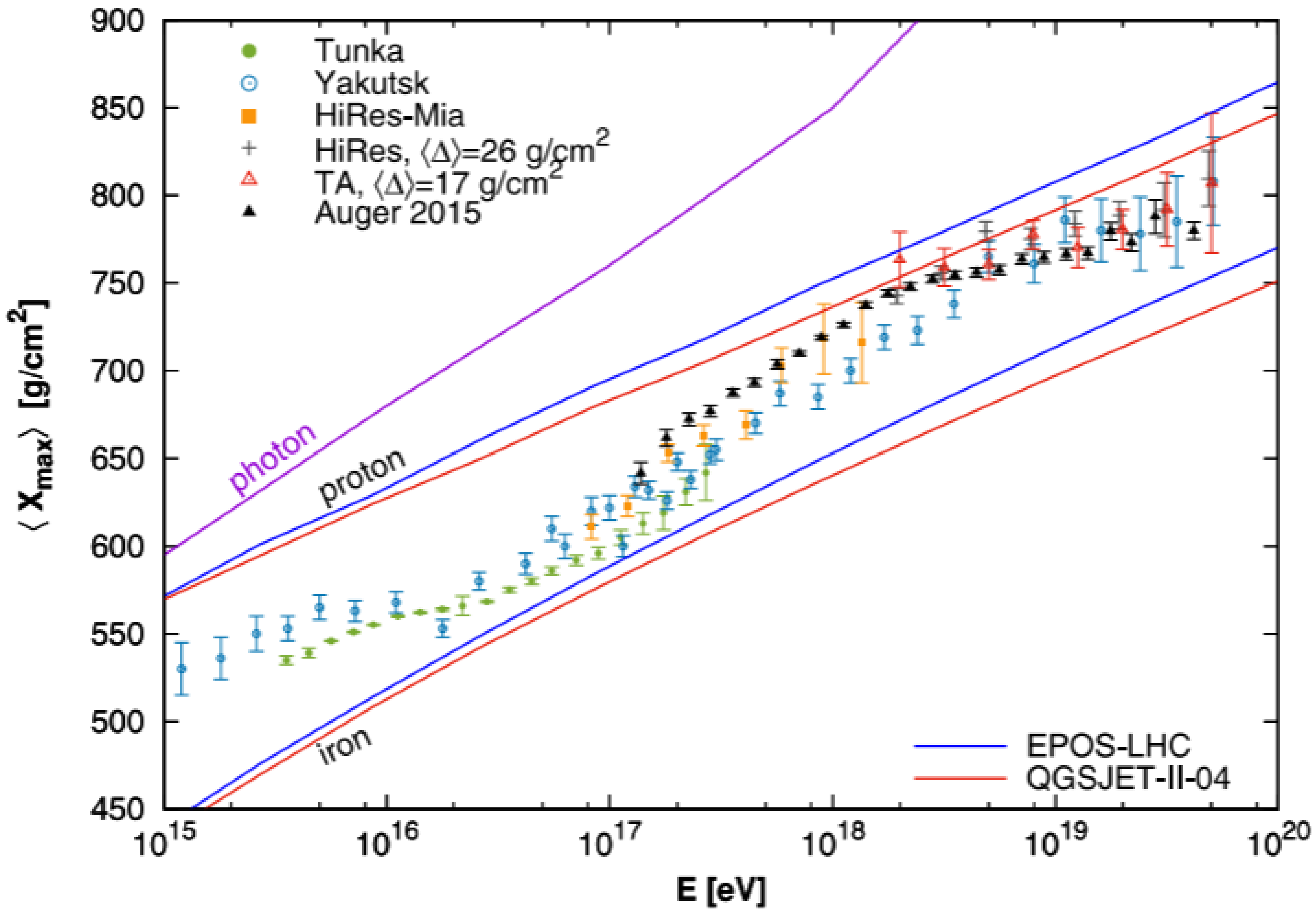
COSMIC RAYS SPECTRUM





Ref.[1],[2].

COMPOSITION OF COSMIC RAYS



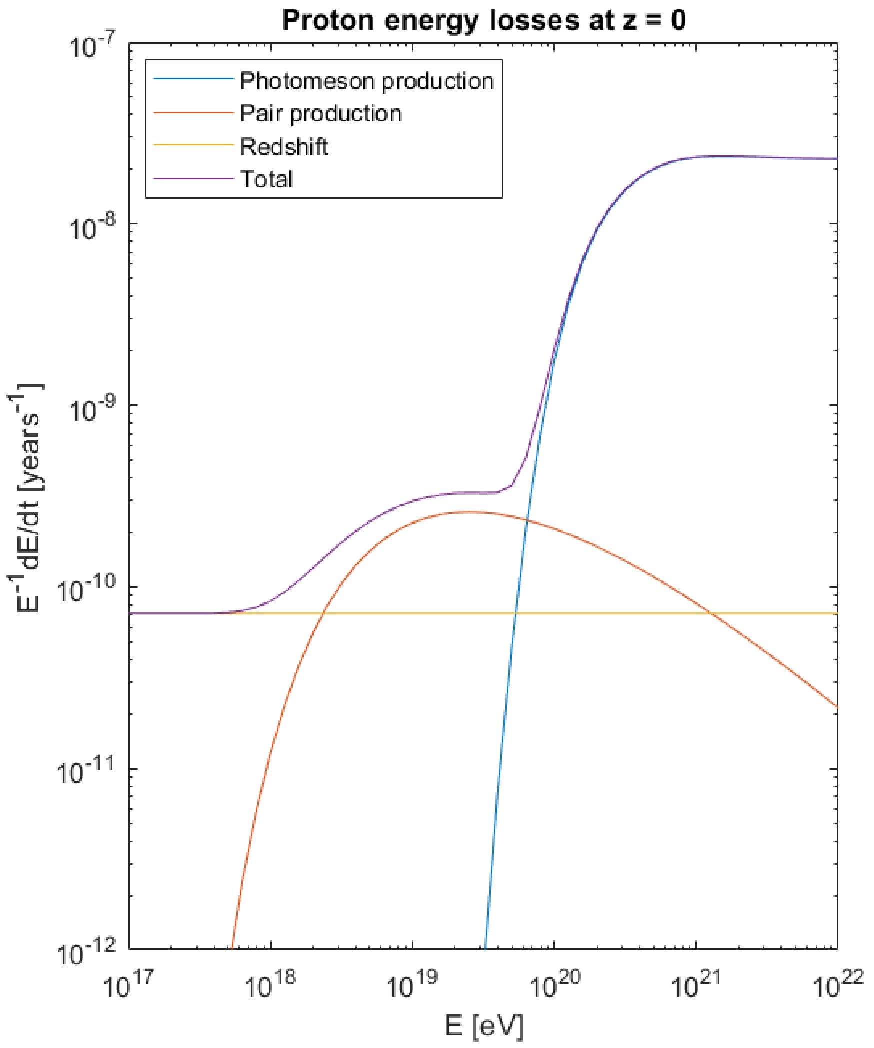
Ref.[2].

PROPAGATION OF PROTON COSMIC RAYS

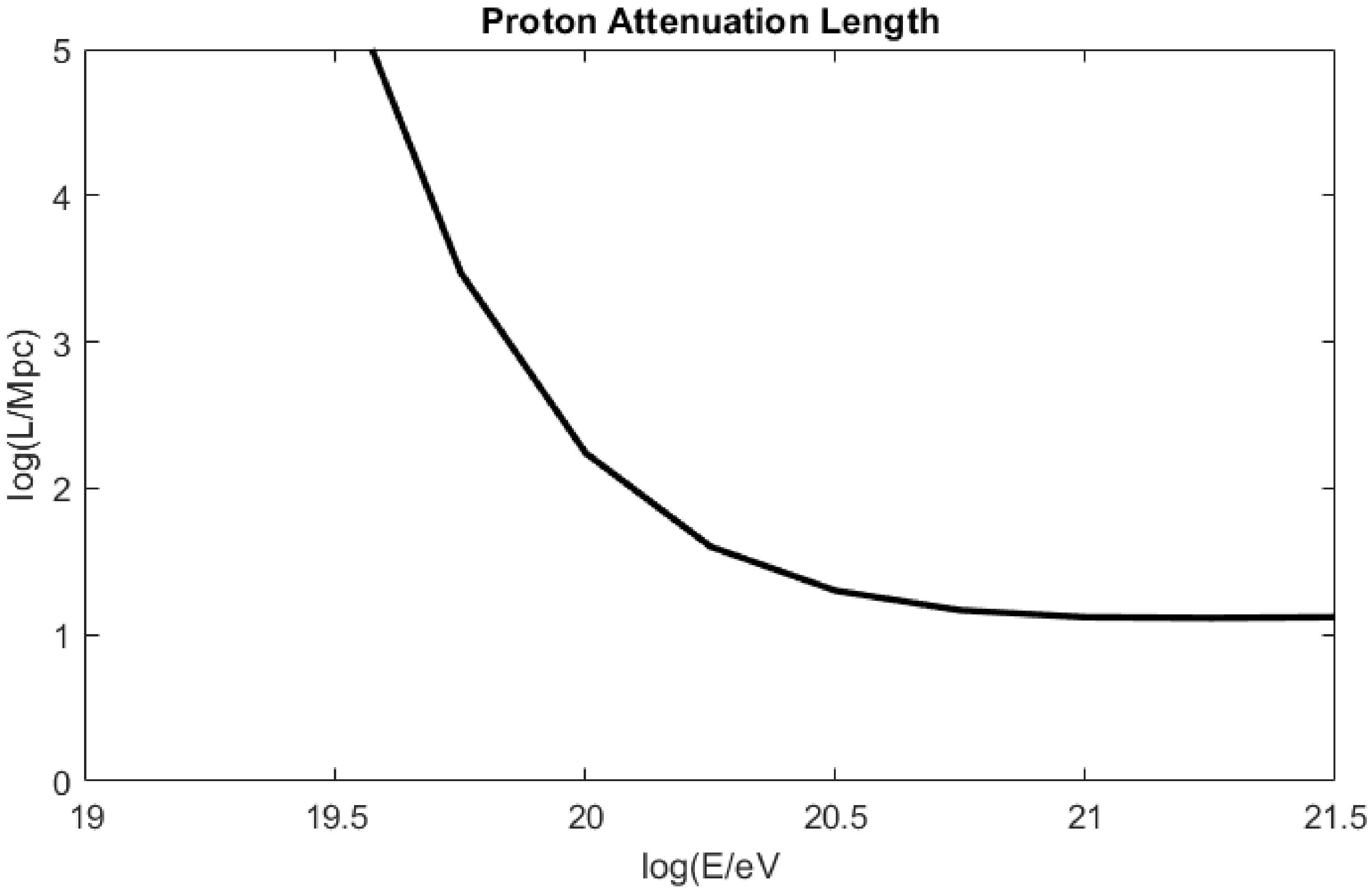
Energy losses:

- **Redshift:** **H(0)**
- **Pair production:** $p + \gamma_{cmb} \rightarrow p + e^{+} + e^{-}$
- **Pion production:** $p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$
  $p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$

GZK cutoff: threshold ~$6\text{x}10^{19}$eV



PROTON ATTENUATION LENGTH



ENERGY LOSS EQUATIONS

REDSHIFT:

$$-\frac{dE}{dt} = EH(z)$$

PAIR PRODUCTION:

$$-\frac{dE}{dt} = \frac{\alpha r_0^2 Z^2 (mc^2 kT)^2}{\pi^2 \hbar^3 c^3} f(\nu)$$

PHOTOMESON PRODUCTION:

$$-\frac{dE}{dt} = E\frac{\omega_0 c}{2\pi^2 \gamma^2 \hbar^3 c^3} \int_{\eta}^{\infty} d\epsilon \; \epsilon\sigma(\epsilon)K(\epsilon)ln(1 - e^{-\frac{\epsilon}{2\gamma\omega_0}})$$

ENERGY EVOLUTION OF COSMIC RAY PROTONS

$$\frac{1}{E}\frac{dE}{dt} = -\tau(E) \quad + \quad dt = -\frac{1}{H(z)(1+z)}dz$$

$$\Downarrow$$

$$\frac{1}{E}\frac{dE}{dz} = H(z)^{-1}(1+z)^{-1}\tau(E = (1+z)E_0, T = (1+z)T_0, \epsilon = (1+z)\epsilon_0)$$

ENERGY EVOLUTION OF COSMIC RAY PROTONS

REDSHIFT:

$$\frac{dE}{dz} = E\frac{1}{(1+z)}$$

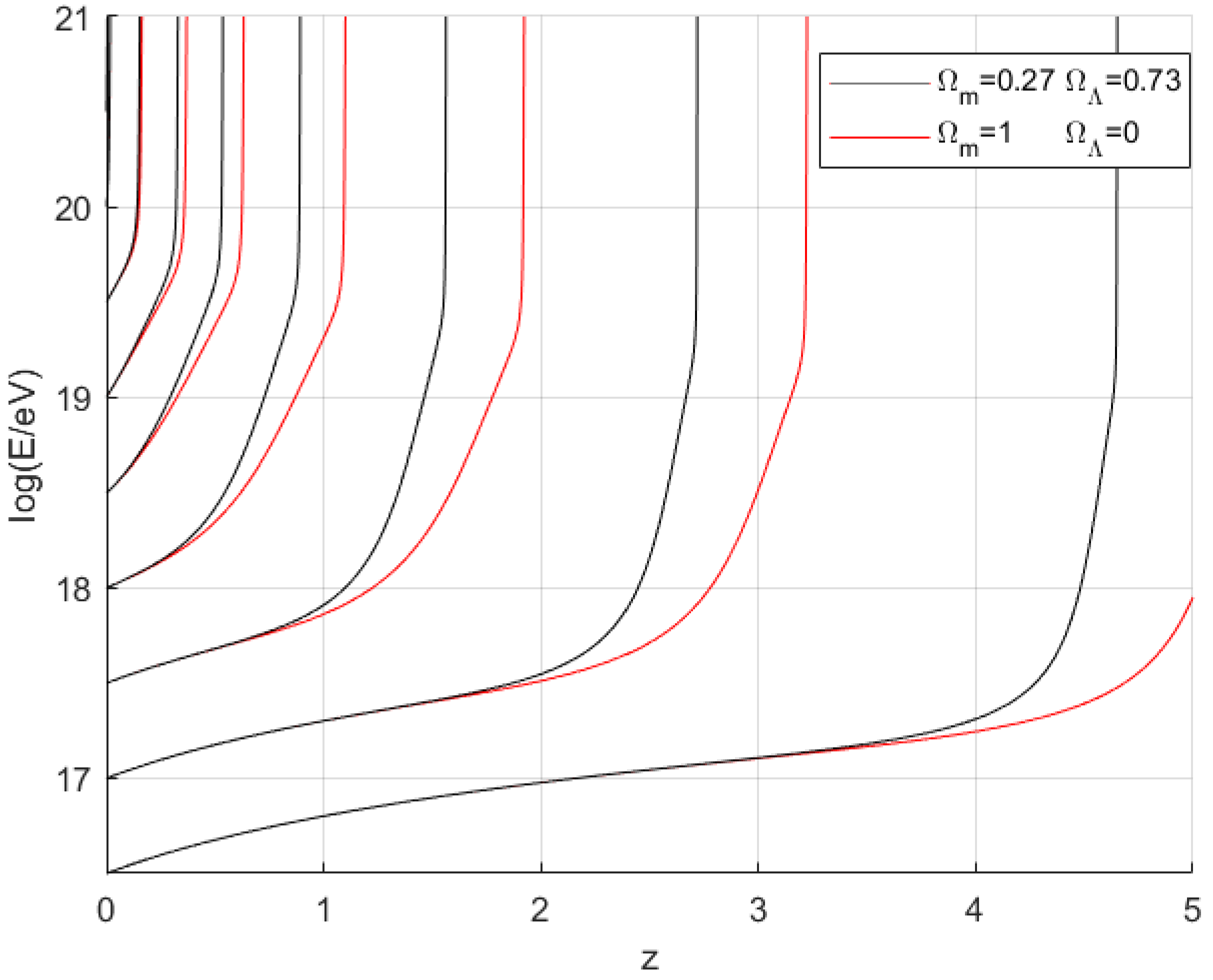
PAIR PRODUCTION:

$$\frac{dE}{dz} = \frac{(1+z)}{H(z)}\frac{\alpha r_0^2 Z^2 (mc^2 kT)^2}{\pi^2 \hbar^3 c^3} f(\nu)$$

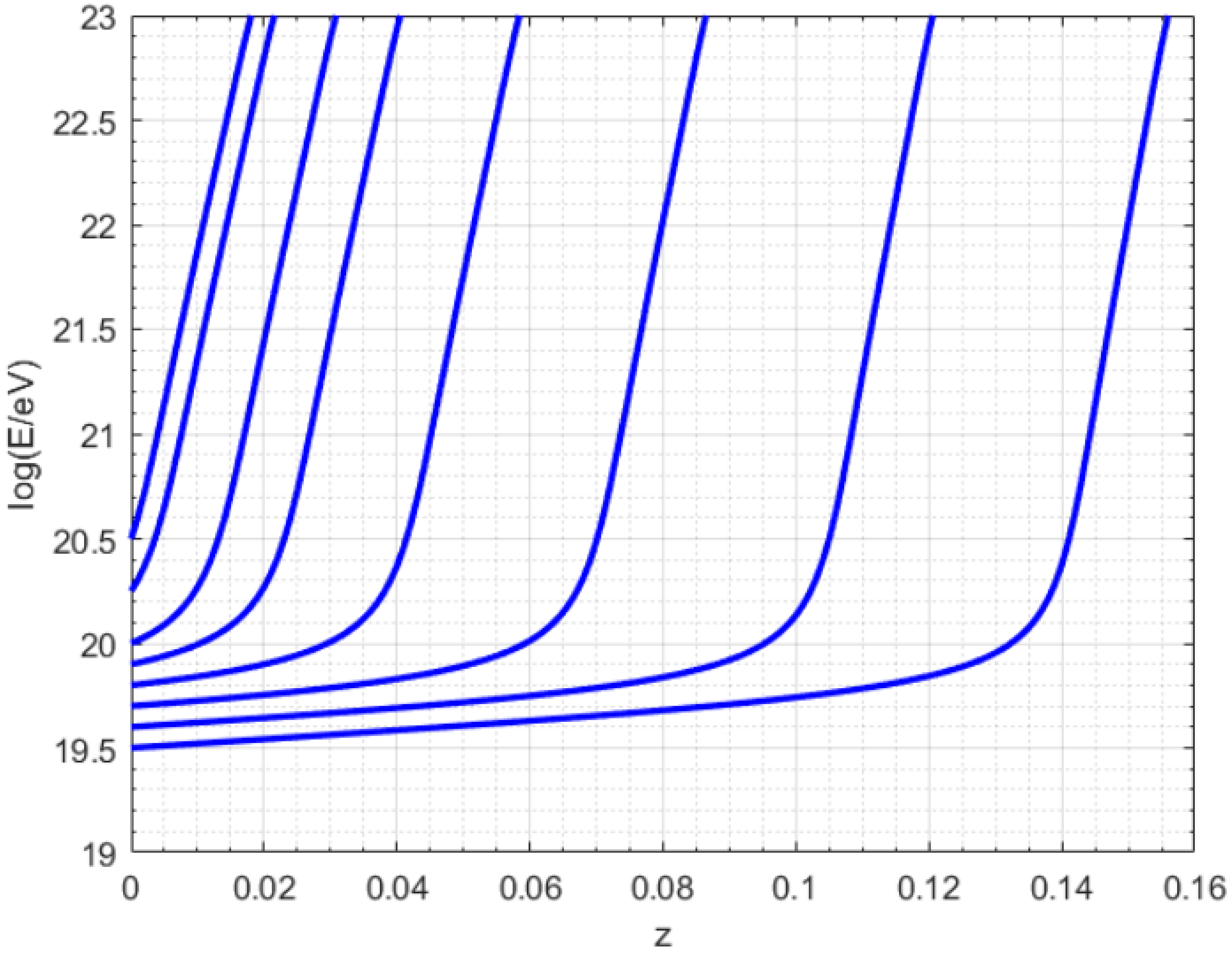
PHOTOMESON PRODUCTION:

$$\frac{dE}{dz} = E\frac{(1+z)^2}{H(z)}\frac{\omega_0 c}{2\pi^2\gamma^2\hbar^3 c^3}\int_\eta^\infty d\epsilon\, \epsilon\sigma(\epsilon)K(\epsilon)ln(1 - e^{-\frac{\epsilon}{2\gamma\omega_0}})$$

ENERGY EVOLUTION OF COSMIC RAY PROTONS



ENERGY EVOLUTION OF EHECR PROTONS

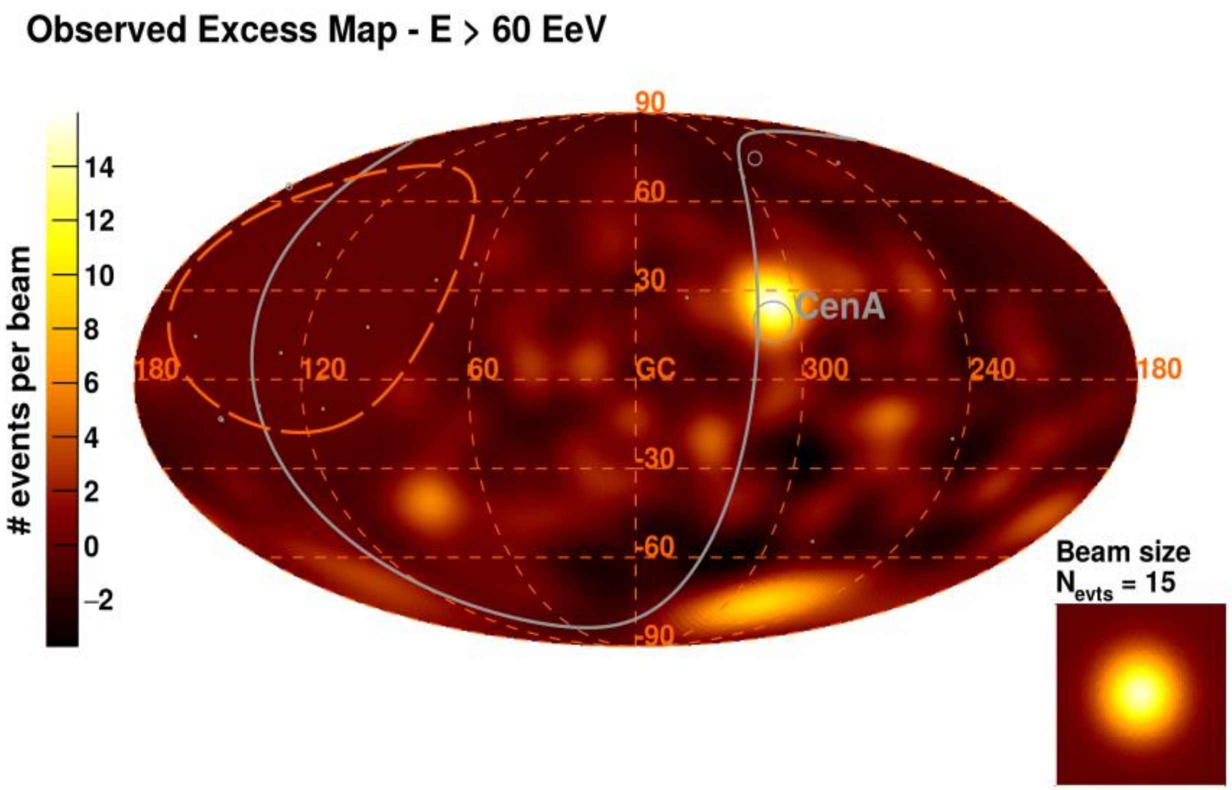


HORIZON OF PROTON EHECR

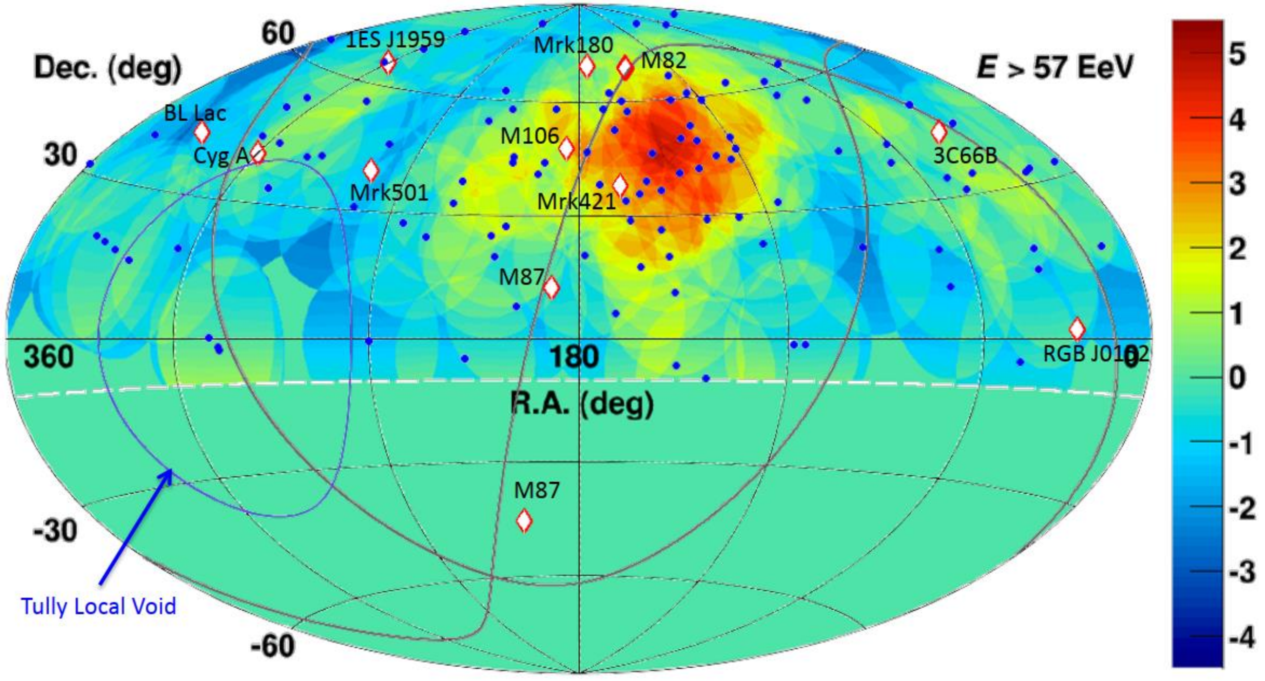
E_{earth}/E_{max}	20.5	21	21.5	22	22.5	23
19.5	603	615	628	640	652	665
19.6	453	468	478	491	506	518
19.7	305	320	332	347	360	375
19.8	182	197	212	225	240	255
19.9	101	119	132	147	162	178
20.0	57	75	90	103	119	136
20.1	35	53	66	82	97	112
20.2	20	38	53	68	84	99
20.3	11	29	44	60	75	90
20.4	4	22	38	53	68	84
20.5	0	18	33	49	64	79

ORIGIN OF EHECR

PAO hotspot



TA hotspot



Ref.[4],[5].

LORENTZ INVARIANCE VIOLATION FRAMEWORK

How this works

$$E^2 = p^2 + m^2 + \Delta_{LIV}(\vec{p})$$

LORENTZ INVARIANCE VIOLATION FRAMEWORK

How this works

$$E^2 = m^2 + p^2 + \eta_1 \frac{\mu^2}{M_{Pl}}|p| + \eta_2 \frac{\mu}{M_{Pl}}|p|^2 + \eta_3 \frac{1}{M_{Pl}}|p|^3 + \eta_4 \frac{1}{M_{Pl}^2}|p|^4 + \ldots$$

$$E^2 - p^2 = m^2 + \Delta \rightarrow s = m^2 + \Delta$$

INELASTICITY

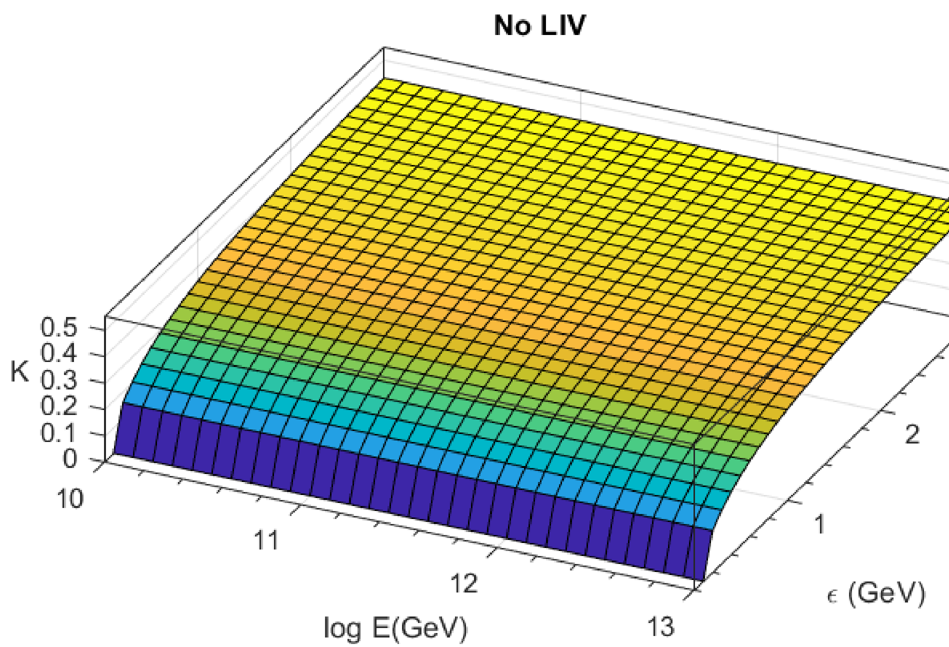
$$K_x = \frac{E_i - E_f}{E_i}$$

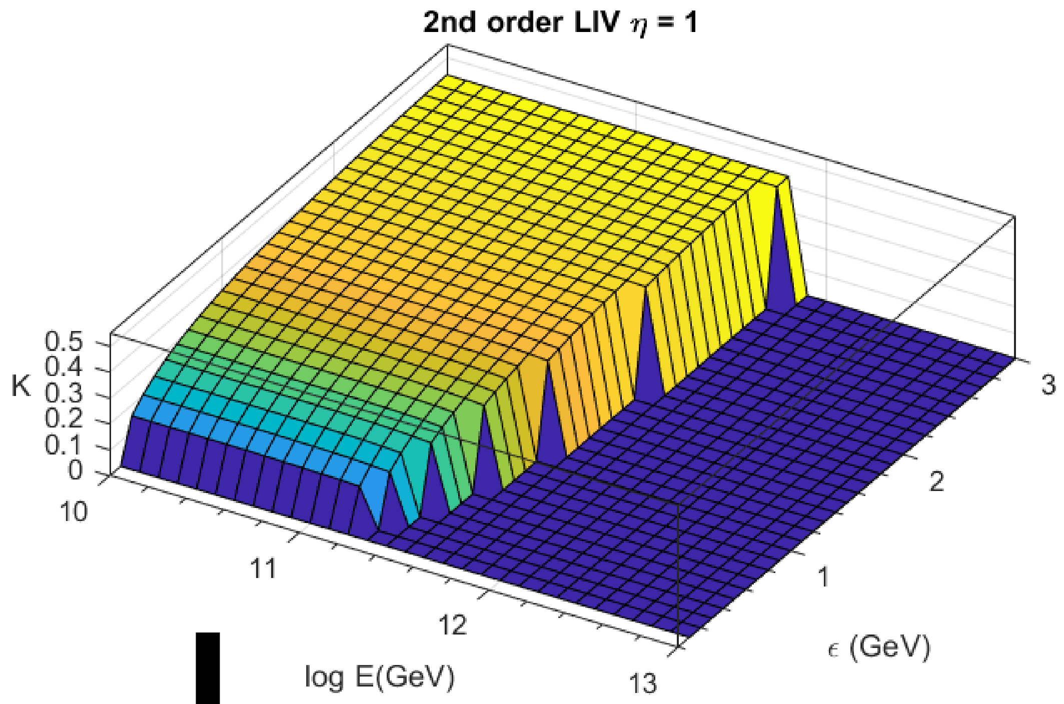
$$K_x = \frac{1}{2}\left(1 + \frac{m_x^2 - m_p^2}{s}\right)$$

+ LIV

$$\begin{aligned}
&(1-K_x)\sqrt{2\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + f_p(1-K_x)^2E^2+m_p^2} \\
&\quad - \frac{2\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + 2f_p(1-K_x)^2E^2+m_p^2 - f_xK_x^2E^2 - m_x^2}{\sqrt{2\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + f_p(1-K_x)^2E^2+m_p^2}} \\
&\quad - \sqrt{1 - \frac{2\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + f_p((1-K_x)E)^2+m_p^2}{E^2}} \\
&\quad \sqrt{\frac{2\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + 2f_p(1-K_x)^2E^2+m_p^2 - f_xK_x^2E^2 - m_x^2}{8\sqrt{f_p(1-K_x)^2E^2+m_p^2}\,\varepsilon + 8f_p(1-K_x)^2E^2 + 8m_p^2} - f_p(1-K_x)^2E^2+m_p^2}\;\cos(\theta) = 0
\end{aligned}$$

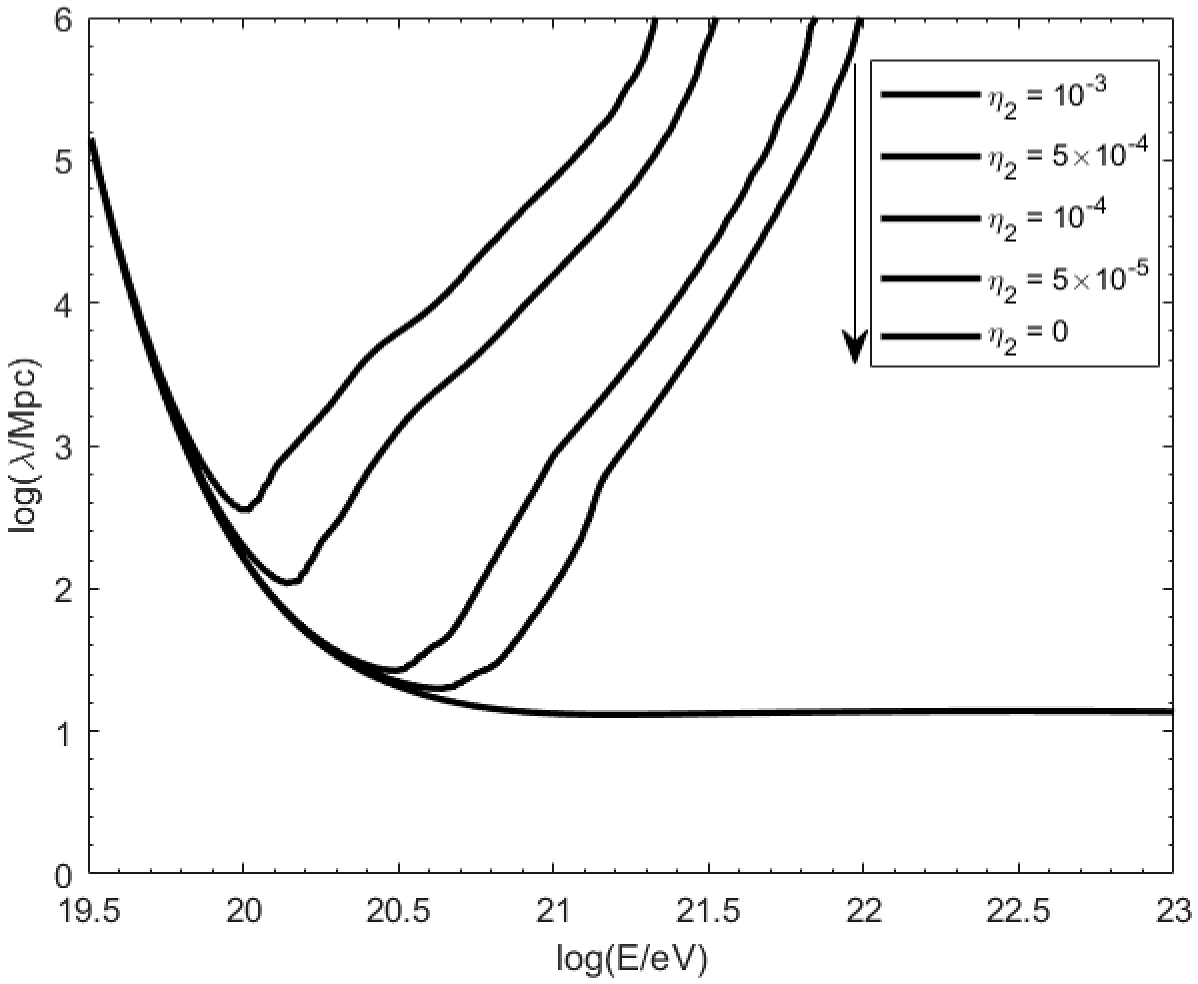
INELASTICITY



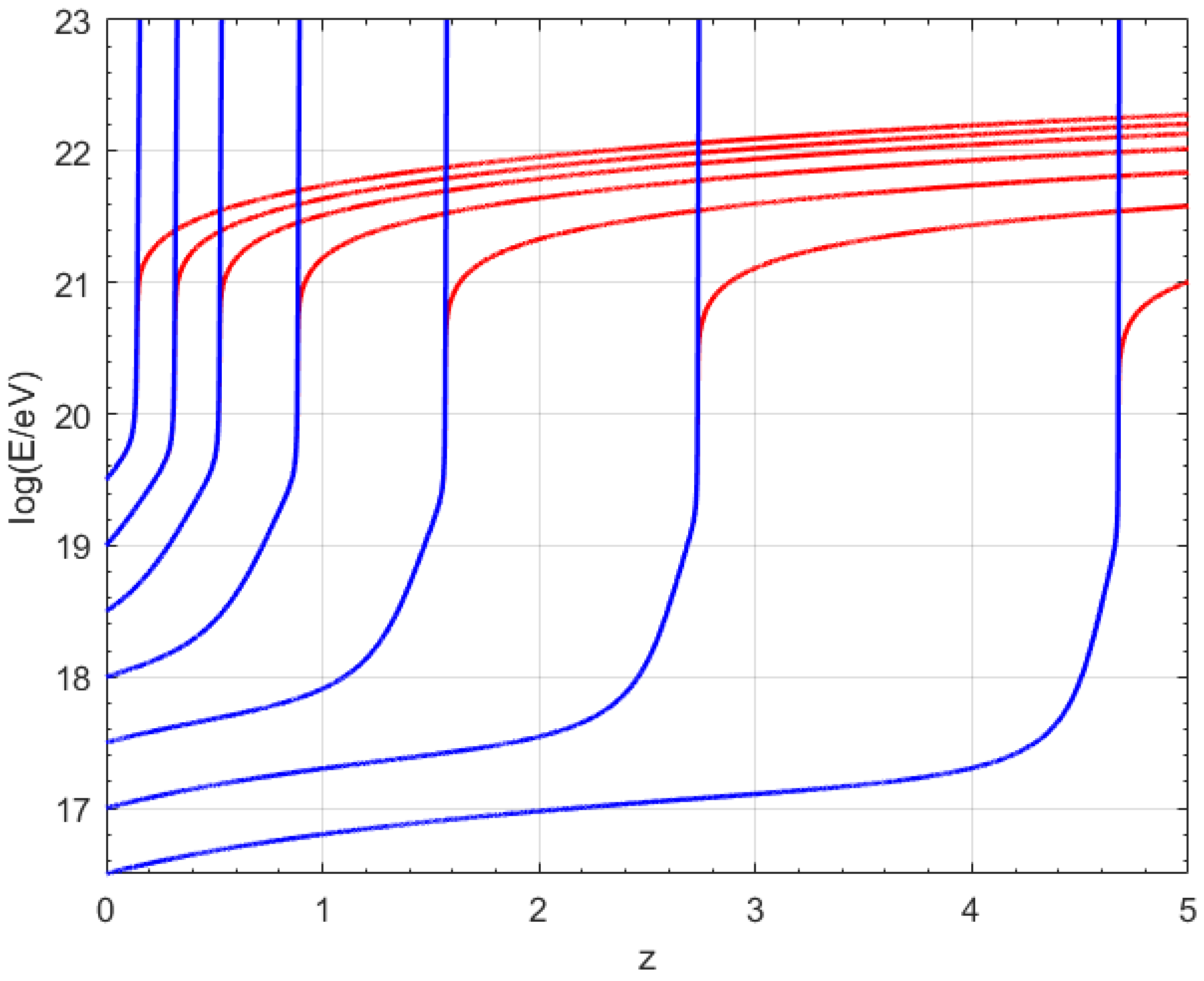


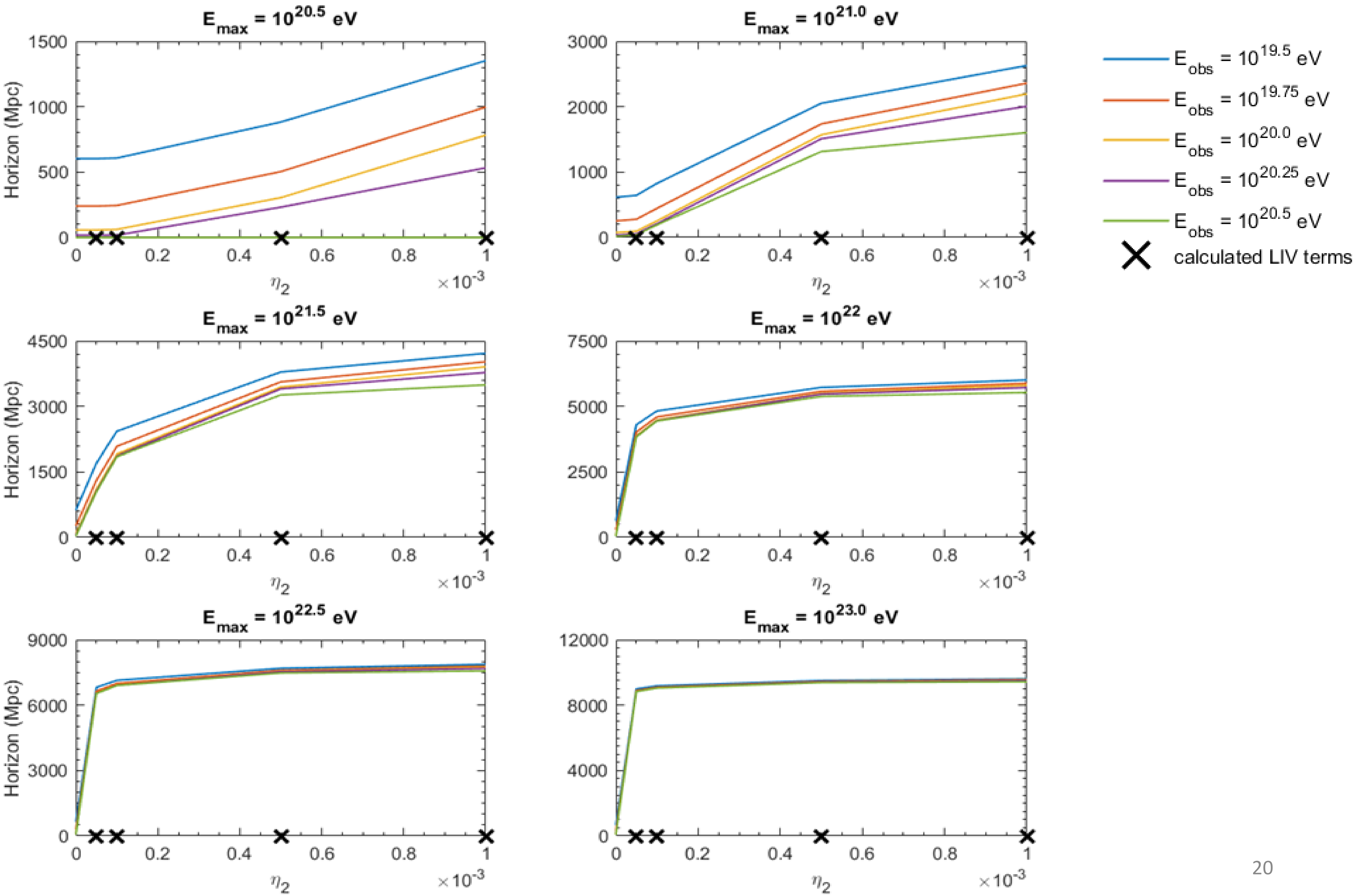
$$\frac{1}{E}\frac{dE}{dt} = -\frac{\omega_0 c}{2\pi^2\gamma^2\hbar^3 c^3}\int_{\eta}^{\infty} d\epsilon\ \epsilon\ \sigma(\epsilon)K(\epsilon)\ln[1 - e^{-\epsilon/2\gamma\omega_0}]$$

PROTON ATTENUATION LENGTH

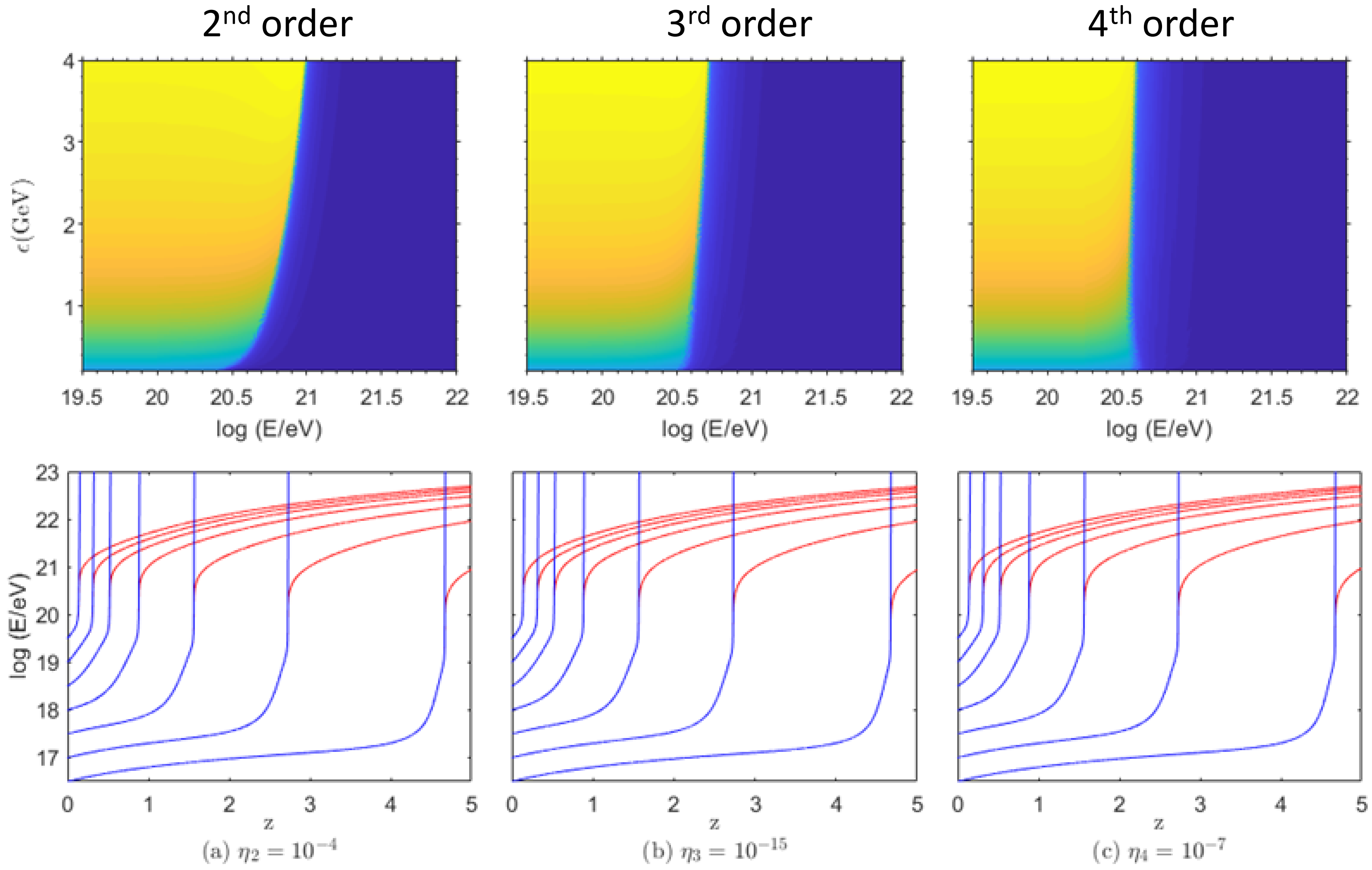


ENERGY EVOLUTION WITH LIV

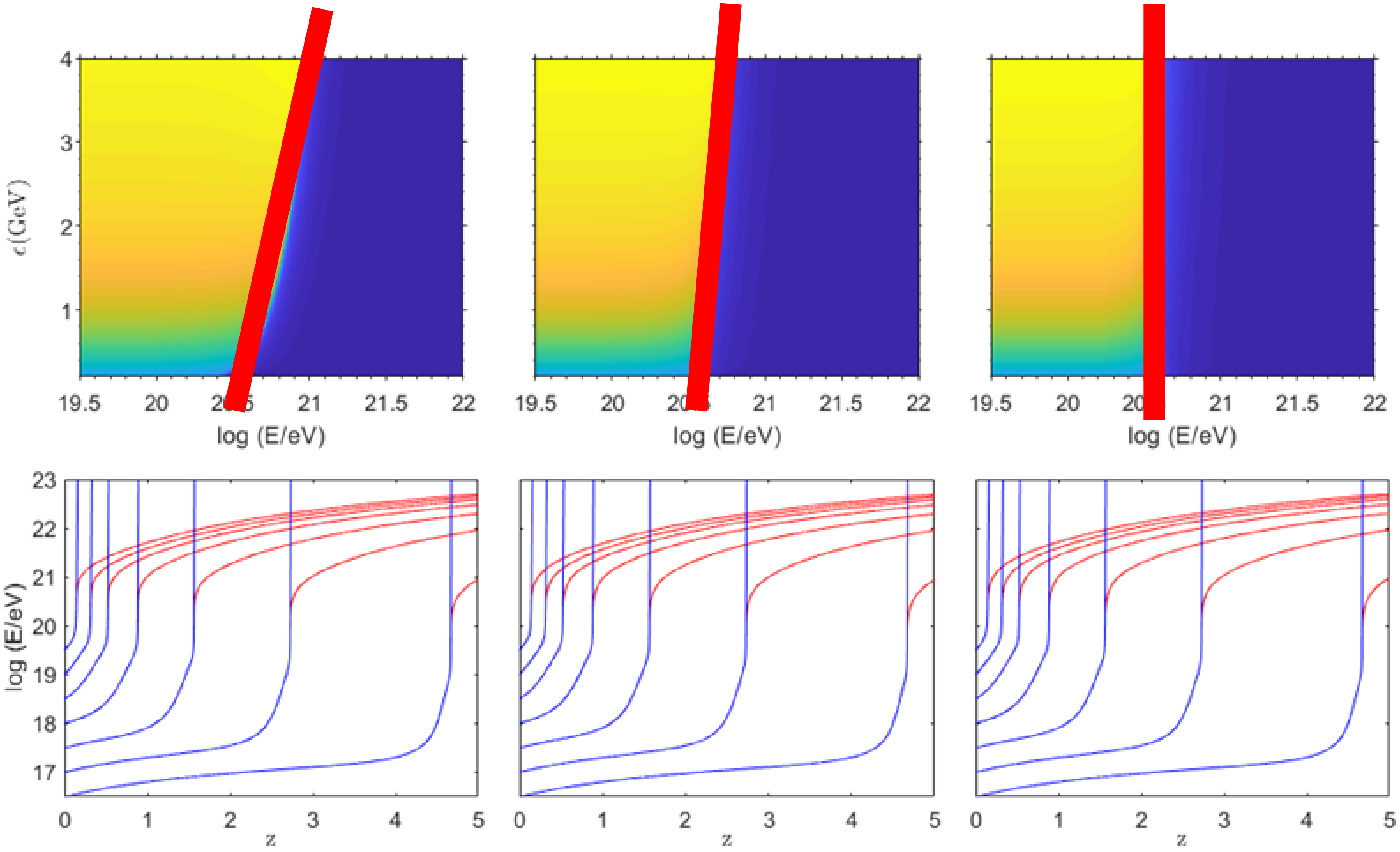



E_max = 10^20.5 eV
E_max = 10^21.0 eV
E_max = 10^21.5 eV
E_max = 10^22 eV
E_max = 10^22.5 eV
E_max = 10^23.0 eV
Horizon (Mpc)
η2
×10^-3
E_obs = 10^19.5 eV
E_obs = 10^19.75 eV
E_obs = 10^20.0 eV
E_obs = 10^20.25 eV
E_obs = 10^20.5 eV
calculated LIV terms

EFFECT OF DIFFERENT LIV ORDER ON INELASTICITY K



EFFECT OF DIFFERENT LIV ORDER ON INELASTICITY K

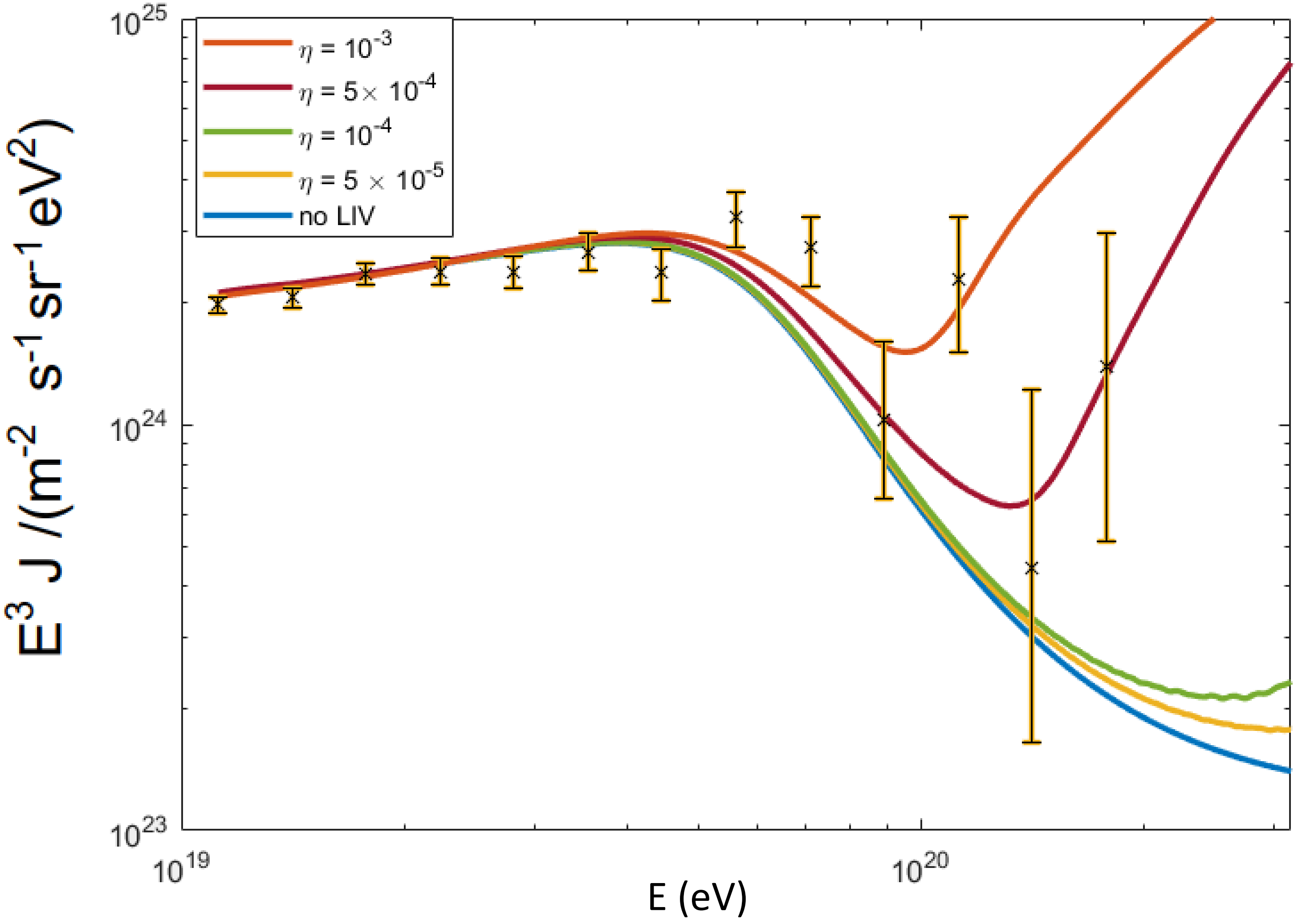


(a) $\eta_2 = 10^{-4}$ (b) $\eta_3 = 10^{-15}$ (c) $\eta_4 = 10^{-7}$

PROTON COSMIC RAY SPECTRUM

$$J(E) = \frac{3cK(0)}{8\pi H_0} \int_0^{Z_{max}} dz \frac{(1+z)^{\xi-1}}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} E_s^{-\Gamma} \frac{dE_s}{dE}$$

PROTON COSMIC RAY SPECTRUM



PRELIMINARY CONCLUSIONS

- Higher order LIV corrections has the same effect on propagation.
- LIV effect on GZK horizon - sources further away are possible.
- LIV recover the “tail” of the cosmic ray spectrum.

Thank you for your attention

REFERENCES

[1] M Nagano. Observations and implications of the ultrahigh-energy cosmic rays. *Moder Physics*, 72(3):689–732, 2000.

[2] Mollerach, S., & Roulet, E. (2018). Progress in high-energy cosmic ray physics. Progress in Particle and Nuclear Physics, 98, 85–118.

[3] D. Harari, S. Mollerach, and E. Roulet. On the ultrahigh energy cosmic ray horizon. *Journal of Cosmology and Astroparticle Physics*, 0611, 2006

[4] The Pierre Auger Observatory: An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources, 2018

[5] Telescope array: Evidence of Intermediate-Scale Energy Spectrum Anisotropy of Cosmic Rays E≥1019.2 eV with the Telescope Array Surface Detector, 2018

FLUX

$$J(E) = \frac{3cK(0)}{8\pi H_0} E^{-\Gamma} \int\limits_0^{z_{max}} \frac{(1+z)^{(\zeta-1)}}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \left(\frac{E_i}{E}\right)^{-\Gamma} \frac{dE_i}{dE} dz$$

$$\frac{dE_g(z)}{dE} = (1+z)\exp\left[\frac{1}{H_0}\int_0^z dz'(1+z')^{1/2}\left(\frac{db_0(E')}{dE'}\right)_{E'=(1+z')E_g(z')}\right]$$

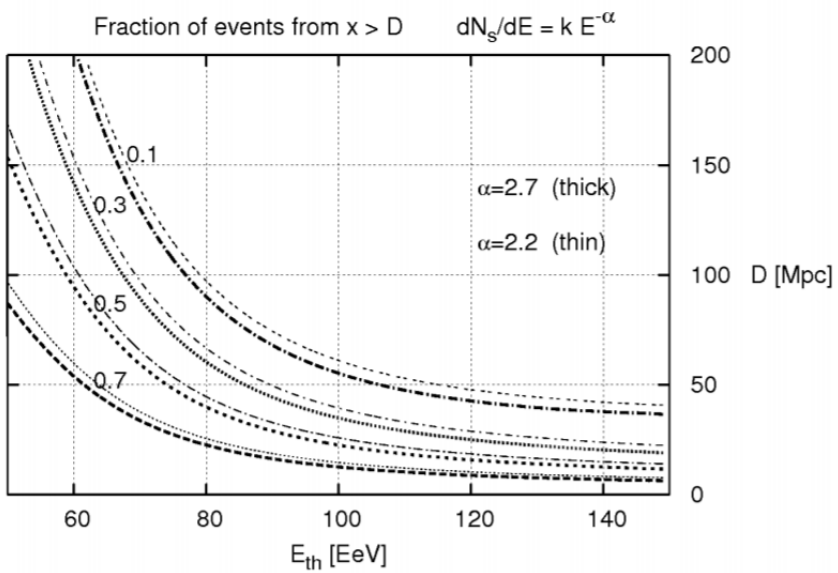
$$\frac{db_0(E)}{dE} = -\beta_0(E) + \frac{c}{4\pi^2\Gamma^3}\int_{\varepsilon_{\rm th}}^{\infty} d\varepsilon_r \sigma(\varepsilon_r) f(\varepsilon_r) \frac{\varepsilon_r^2}{\exp\left(\frac{\varepsilon_r}{2\Gamma T_0}\right) - 1}$$

$$\lambda(E,z) = E_g(z)/E$$

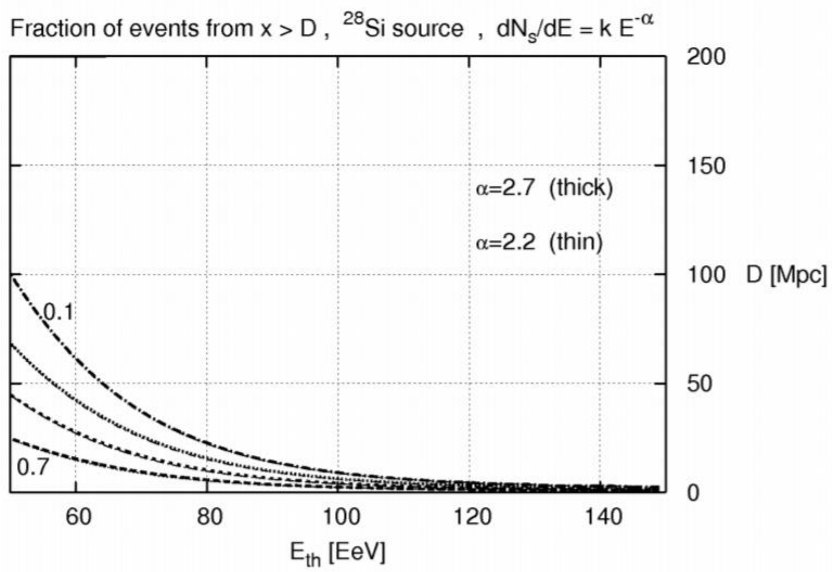
$$\frac{1}{E}\frac{dE}{dt} = -\beta(E,z)$$

HORIZON OF DIFFERENT PARTICLES

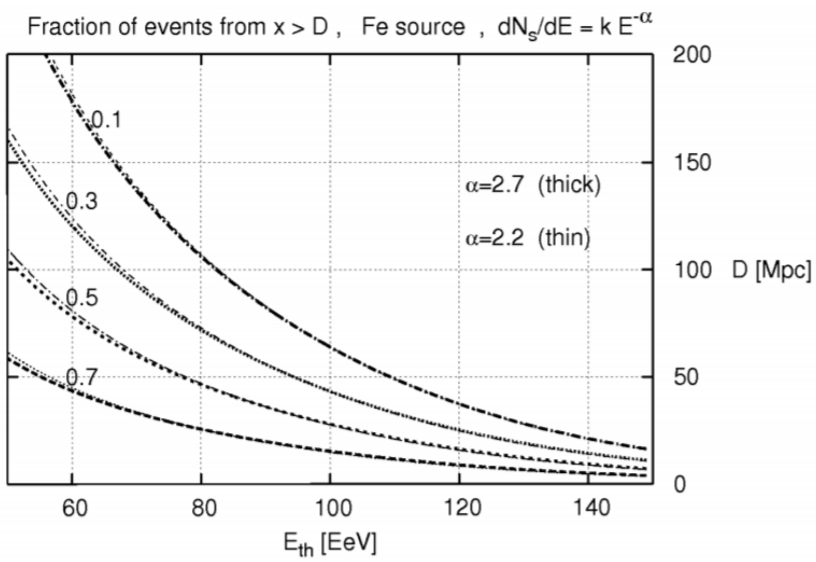
Proton



Si nuclei



Fe nuclei



Ref.[3].

TRANS-GZK EVENTS

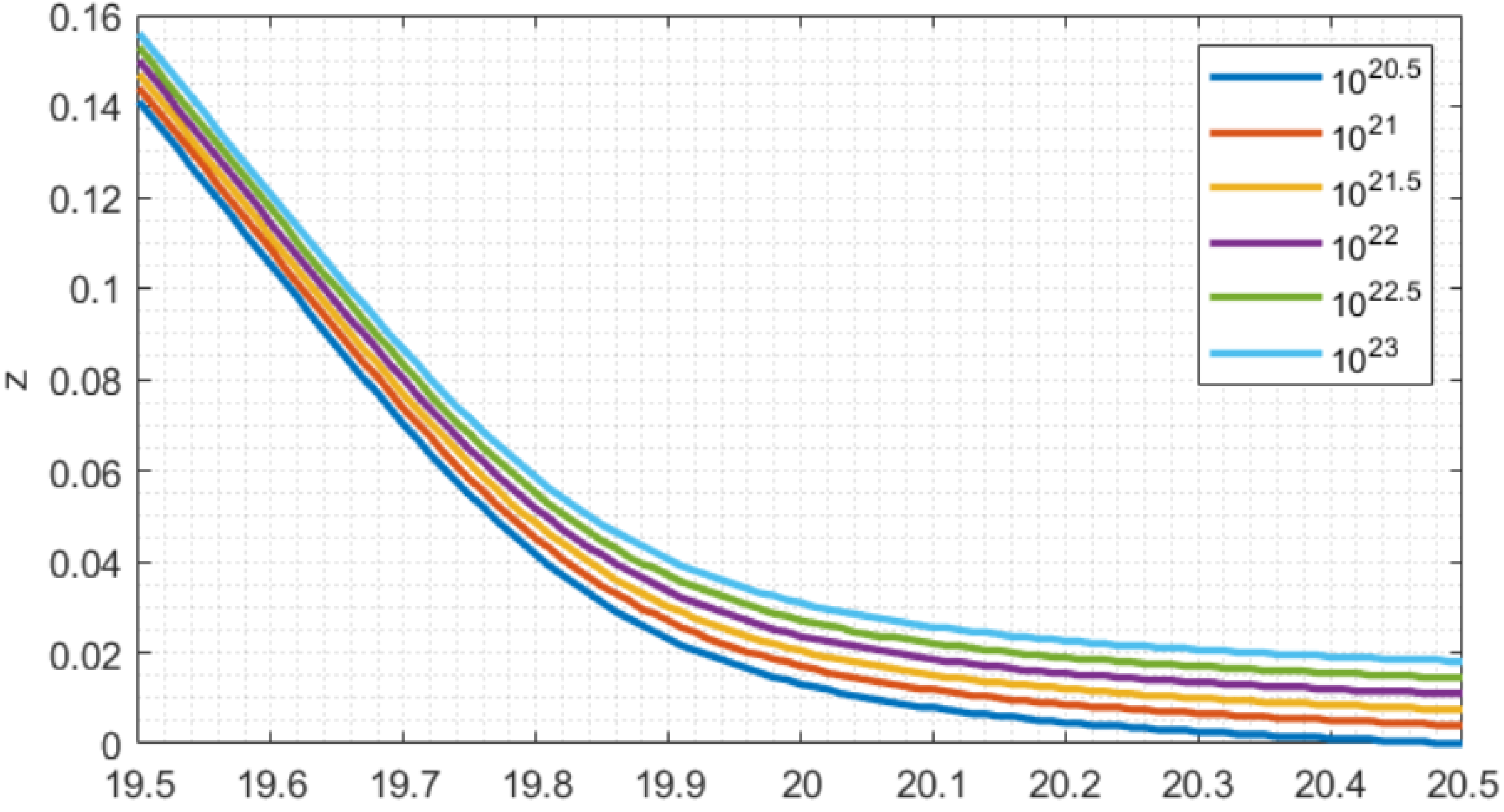
Oh-My-God particle

- Energy = 3.2 ±(0,9) x10^{20} eV (51J)
- 99.99999999999999999999951% of speed of light

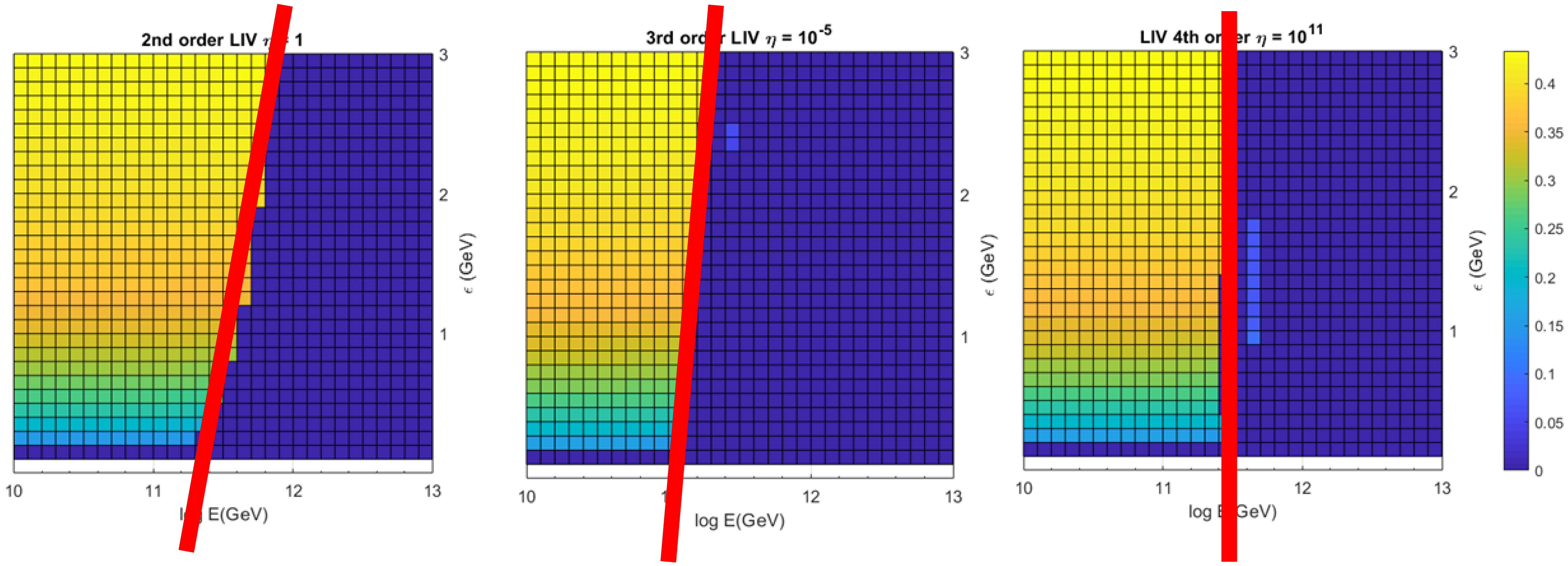
Events with > *5,7* x10^{19} eV

- *Northern Telescope array : 7 years ⇨ 109 events*
- *Southern Pierre Auger Observatory: 10 years ⇨ 157 events*

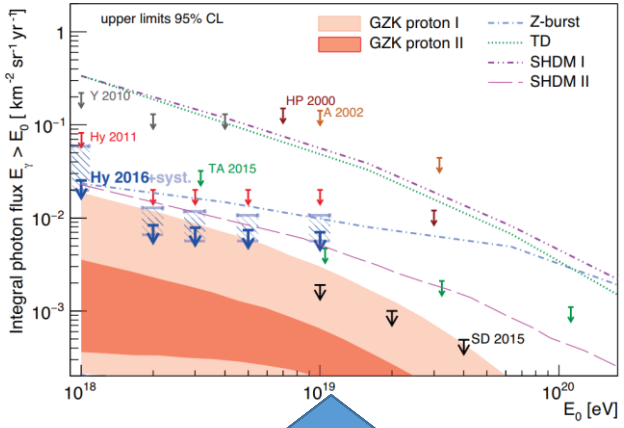
ENERGY EVOLUTION OF COSMIC RAY PROTONS



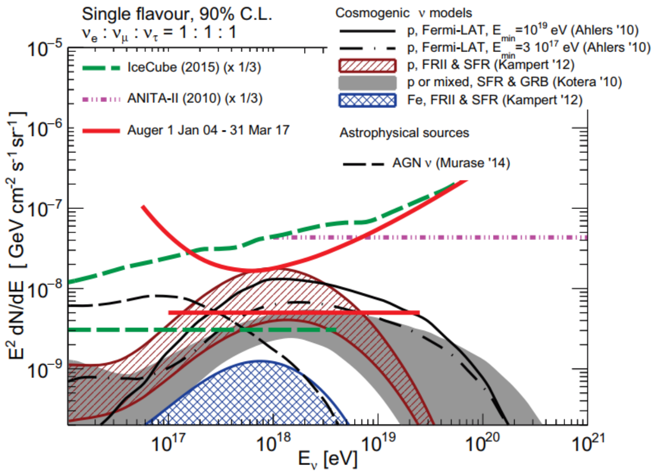
EFFECT OF DIFFERENT LIV ORDER



MY PROJECT



Modified physical quantities → Modified spectrum of CR → Effect on the GZK horizon



My previous and current research

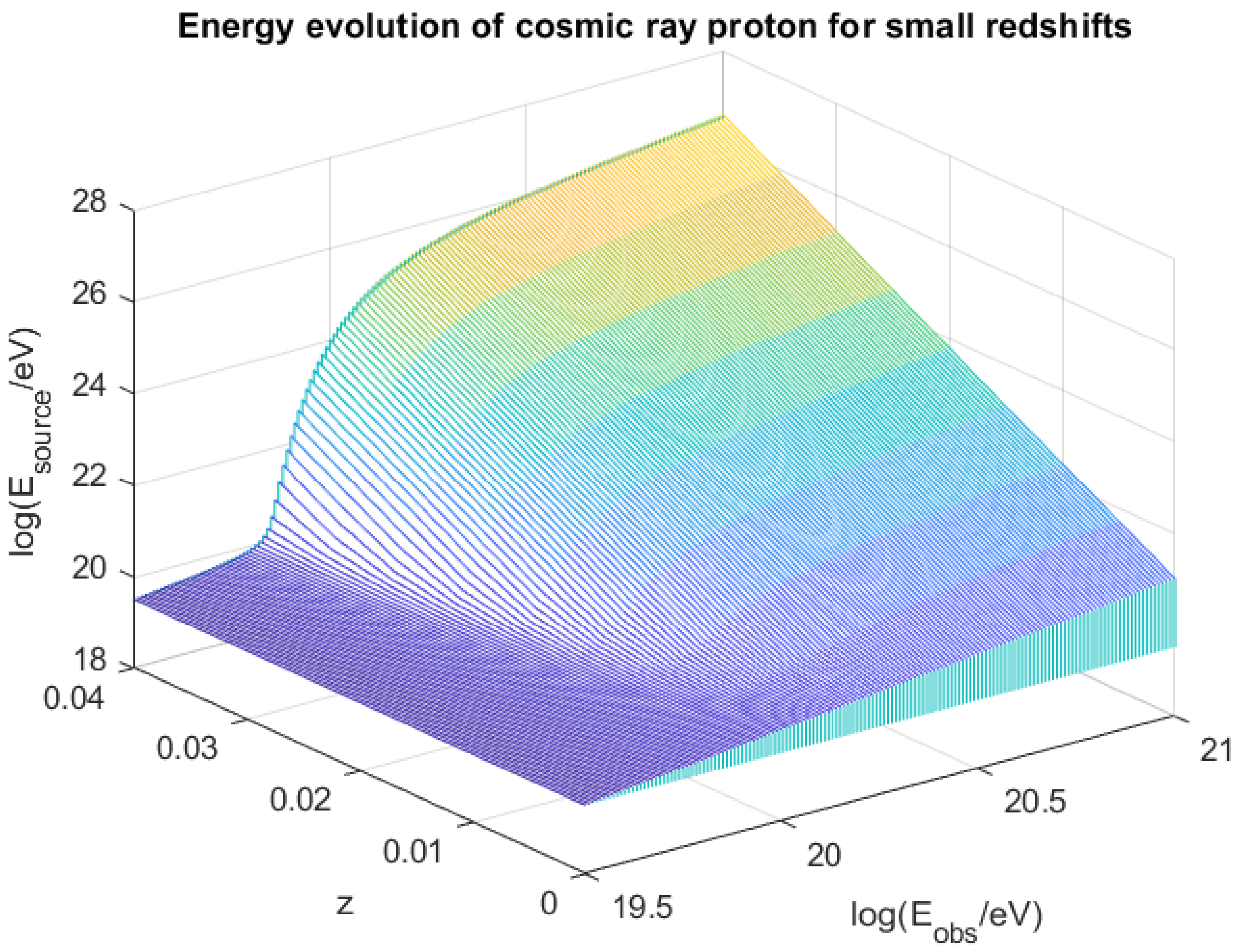
(BSc. Project & MSc. Project)

Tomáš Fodran

27/02/2019

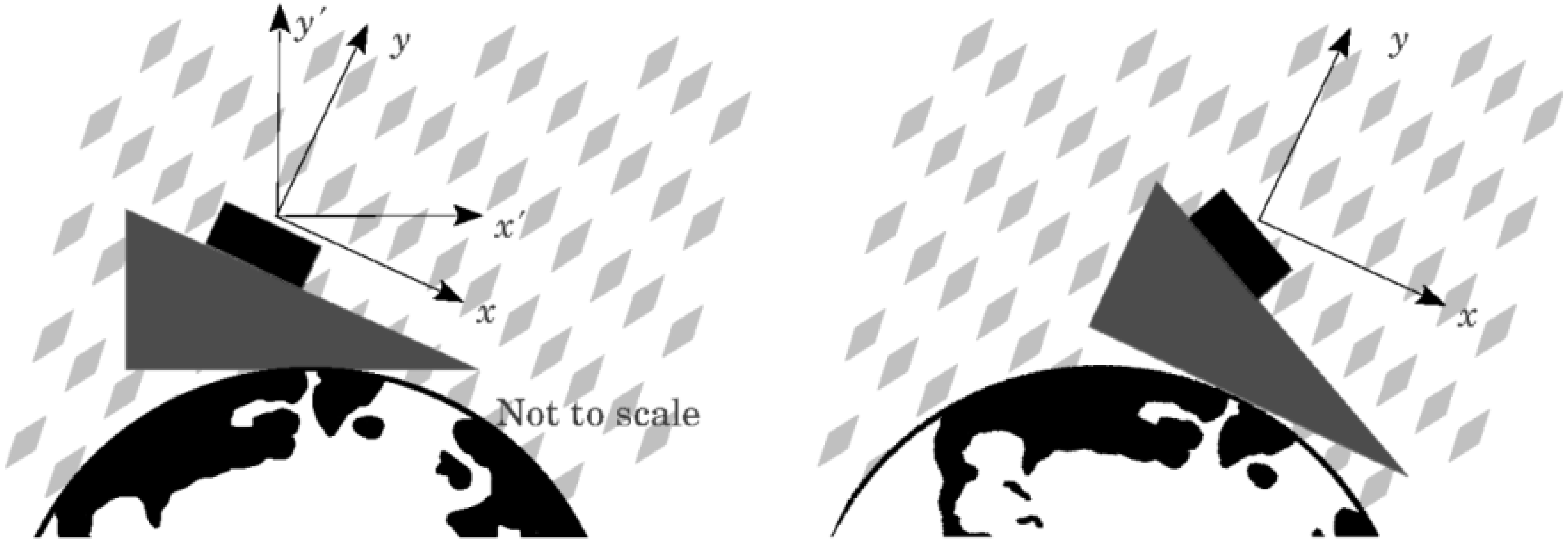
Nijmegen

ENERGY EVOLUTION OF COSMIC RAY PROTONS



LORENTZ INVARIANCE VIOLATION FRAMEWORK

How this works



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