Astrophysical interpretation of the UHECR data measured by the Pierre Auger Observatory and tests of Lorentz symmetry

CTAO Symposium, 15-18 April 2024

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PIERRE AUGER OBSERVATORY

Lorentz Invariance Violation

The need to study a possible violation of Lorentz invariance arises from the desire to unify **quantum mechanics** and **general relativity**

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General Relativity is a classical theory, but quantum effects are not negligible when energy is of the order of the **Planck scale**

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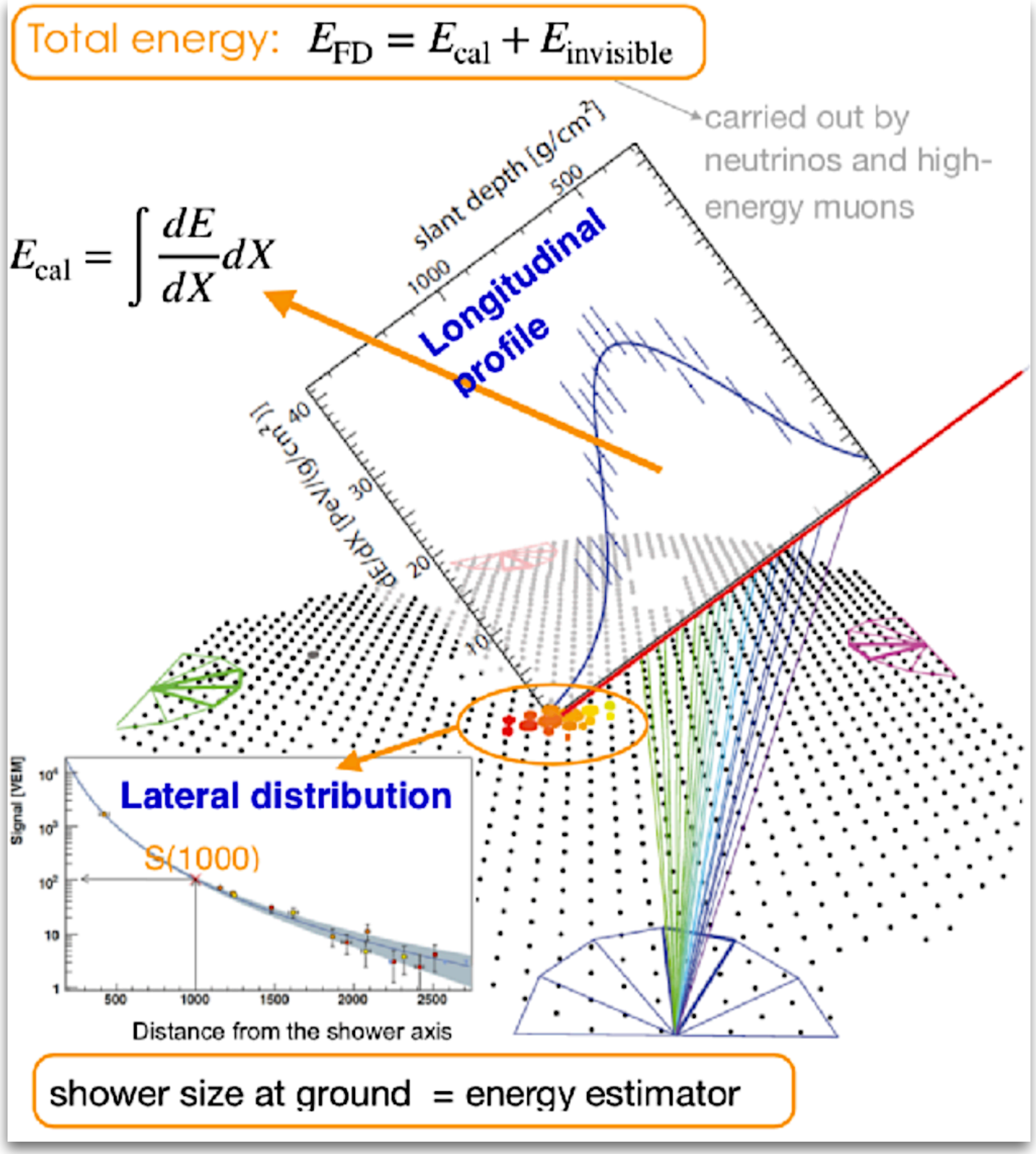
Possible **signatures** of Lorentz Invariance violation could be observed considering **physical phenomena** at the highest energies

Ultra High Energy Cosmic rays

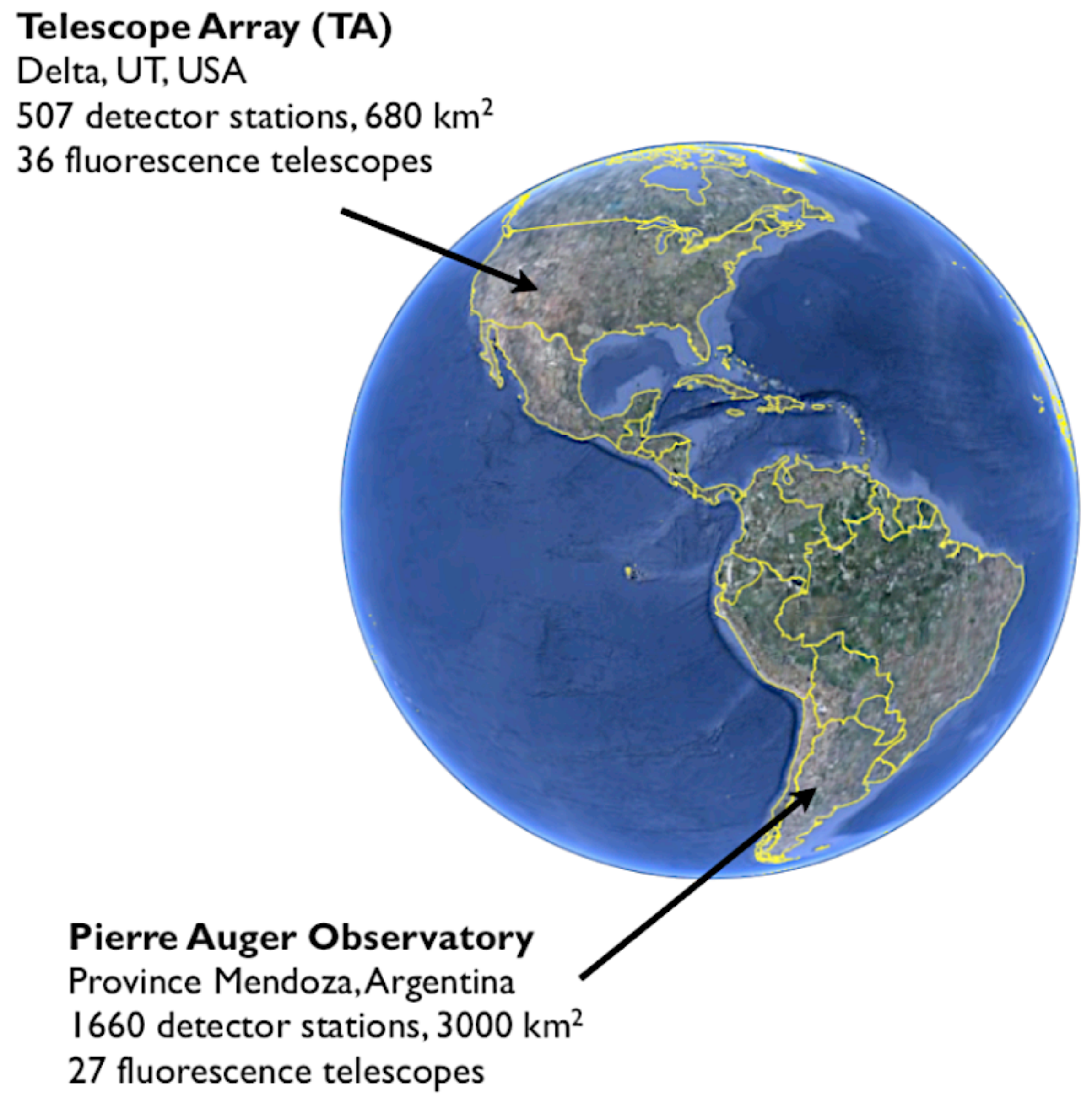
Extragalactic propagation

Extensive Air Showers

The Pierre Auger Observatory



The Pierre Auger Observatory has been designed to investigate the highest energy cosmic rays with energy exceeding 10^{19} eV, combining a surface array of particle detectors with fluorescence telescopes for **hybrid detection**



- **The SDs measure photons and charged particles at ground level**
- **The FDs observe longitudinal development of air showers in the atmosphere**
- **The RDs complement this setup studying radio emission from air showers**

How to break Lorentz Invariance

Lorentz Invariance Violation effects and signatures can be observed changing the kinematics and energy threshold of interactions

Modified dispersion relation

$$E_i^2 - p_i^2 = m_i^2 + \epsilon_i s_i^2$$

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_{i,n} E_i^{2+n}$$

- n is the order of the perturbation
- $\delta_{i,n}$ define the energy scale associated with the violation

LIV is often associated with quantum gravity theories → expansion in terms of the Planck scale

$$\delta_{i,n} = \frac{\eta_{i,n}}{M_{\mathrm{Pl}}^n}$$

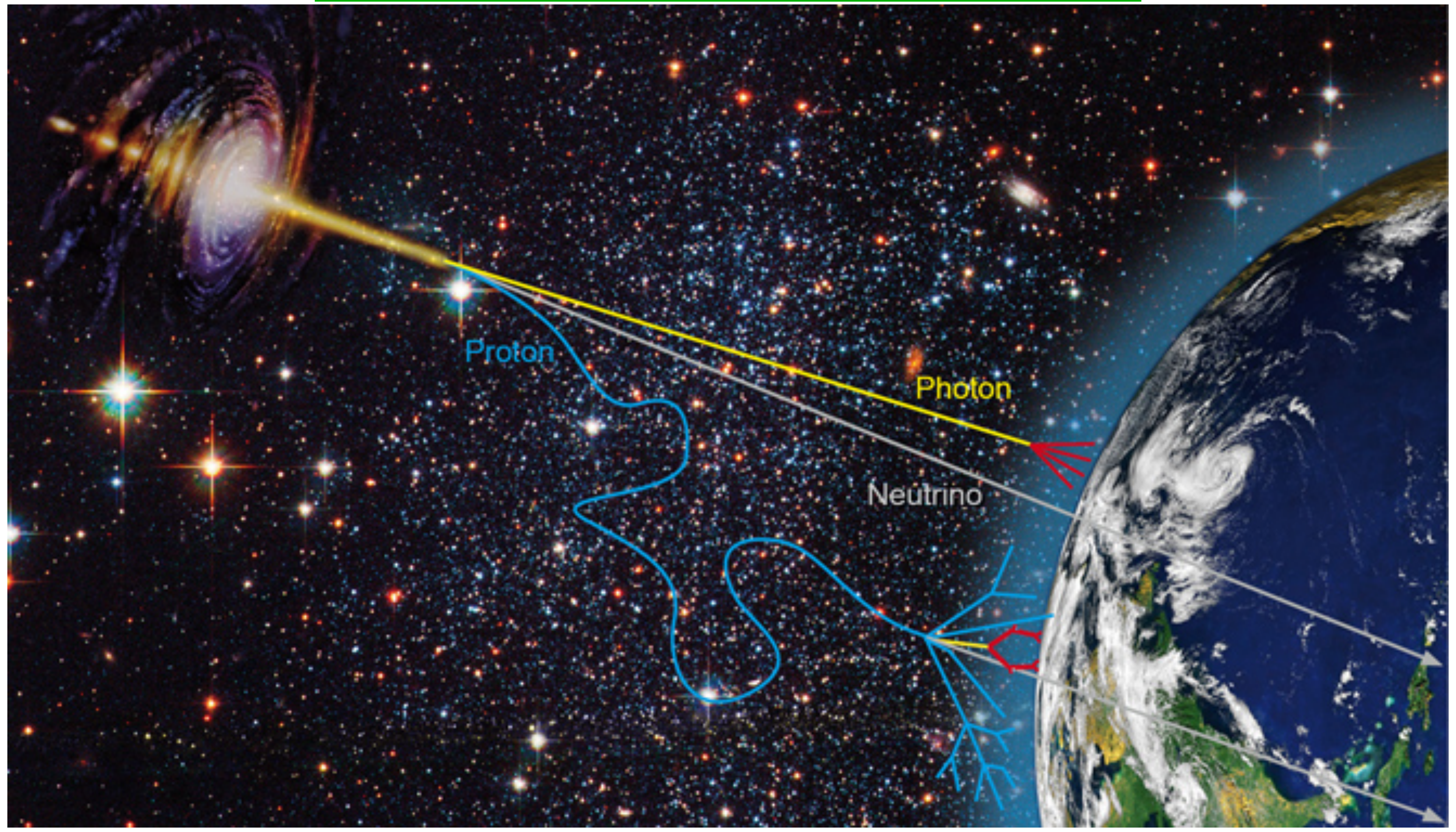
Assumption: only the lowest-order non-vanishing term has a non-negligible effect → **Individual limits on $\delta_{i,n}$**

The Pierre Auger Collaboration, **“Testing effects of Lorentz invariance violation in the propagation of astroparticles with the Pierre Auger Observatory”**, JCAP 2022

LIV searches in the Observatory

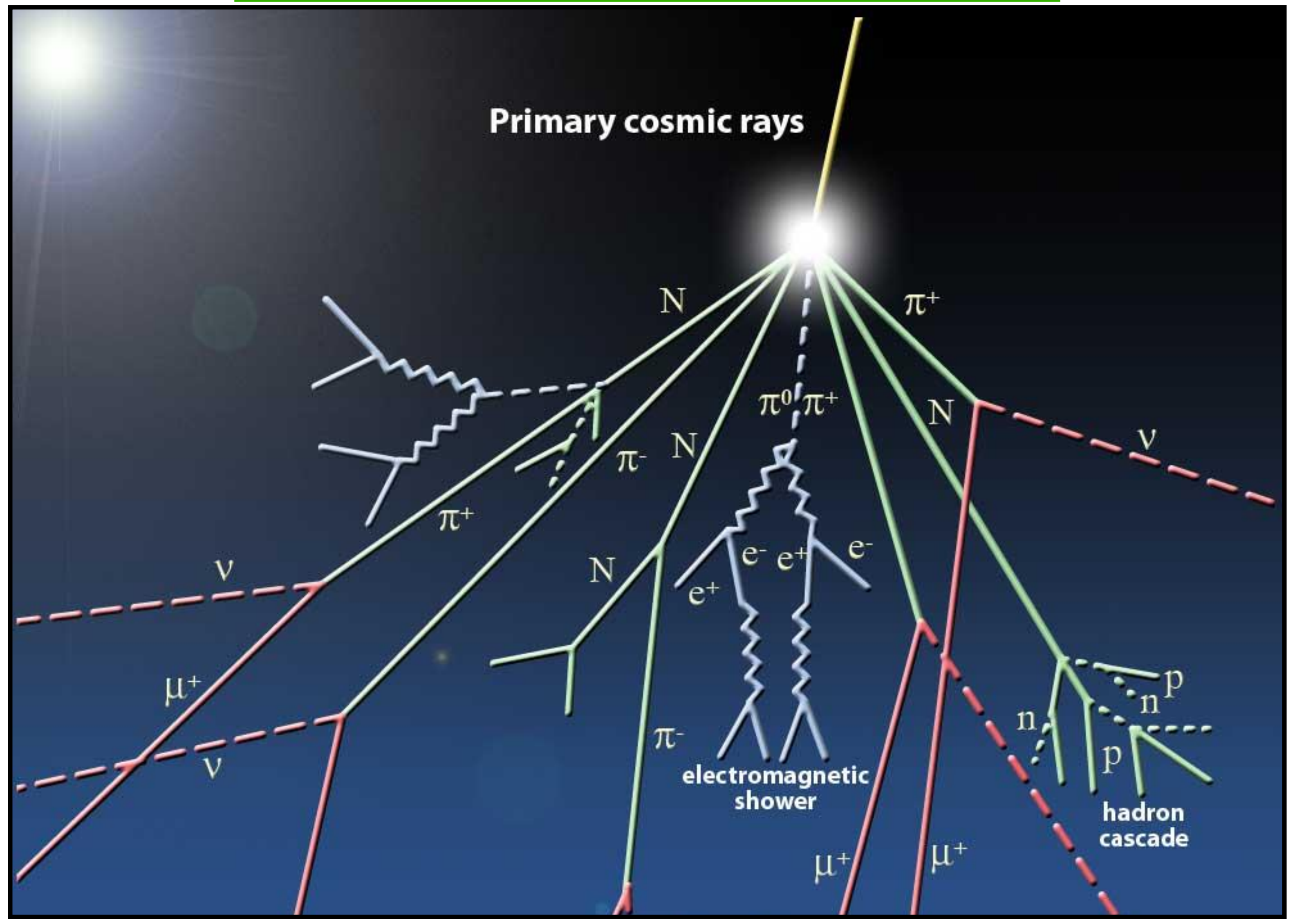
The **extragalactic propagation** of UHECRs as well as the **development of the cascade in the atmosphere** can be modified by violation of Lorentz invariance

Extragalactic propagation



- **Electromagnetic sector:**
  - Suppression of UHE photon absorption by photons of the background
- **Hadronic sector:**
  - Suppression of the nuclear disintegration
  - Suppression of the pion production

Extensive Air Showers



- **Electromagnetic sector:**
  - Modification of the BH cross sections
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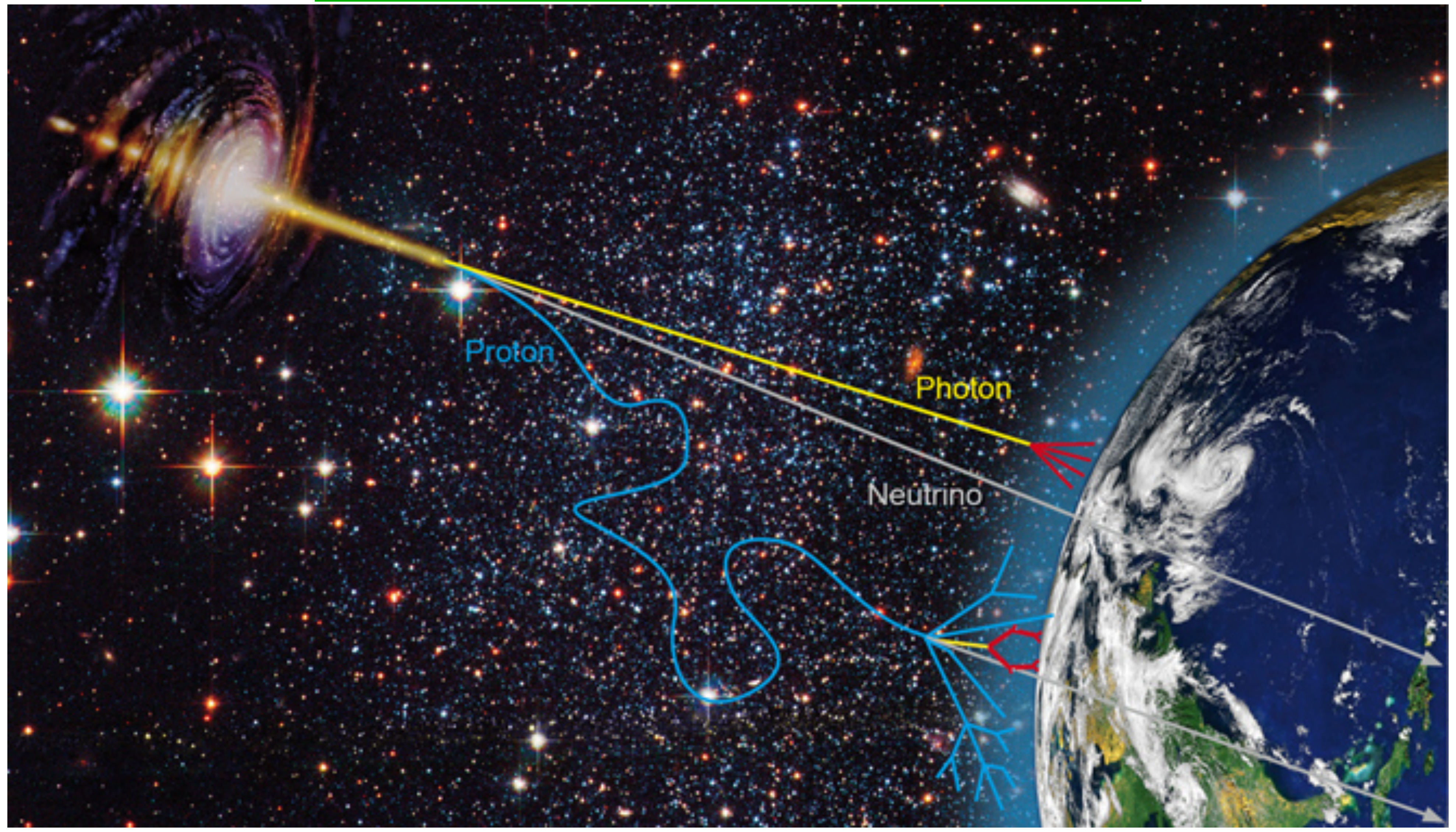

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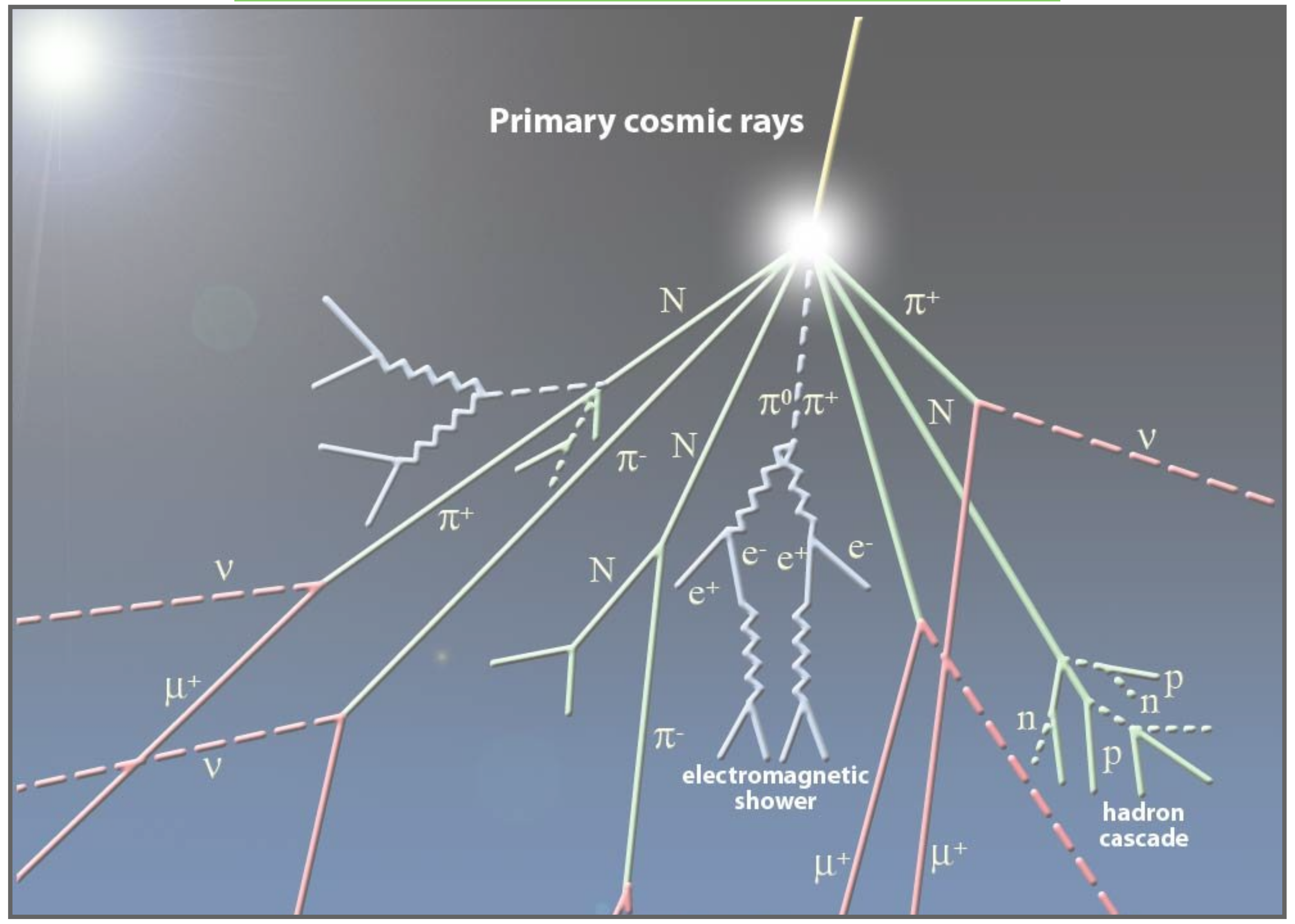

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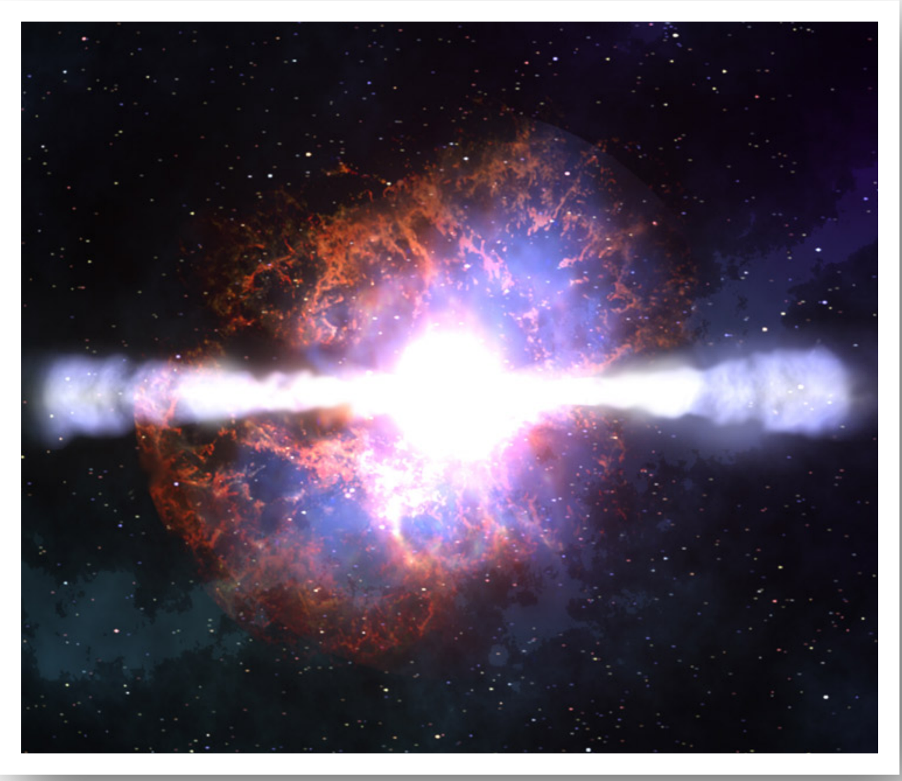
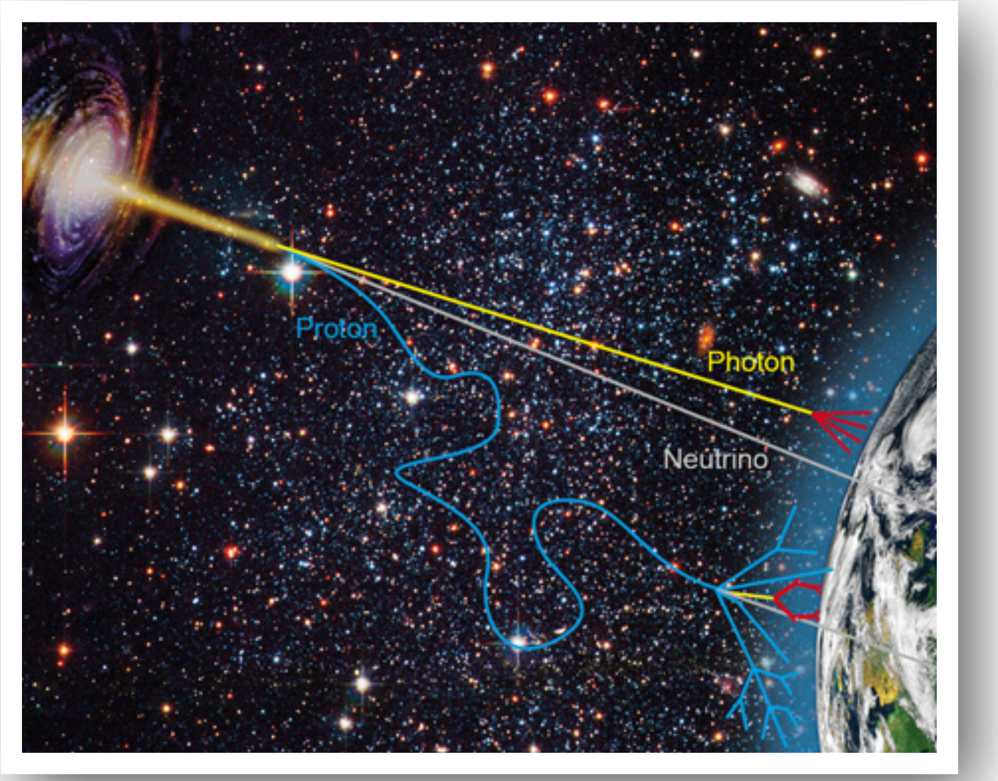
Combined spectrum and composition fit

CRs ejected by EG accelerators

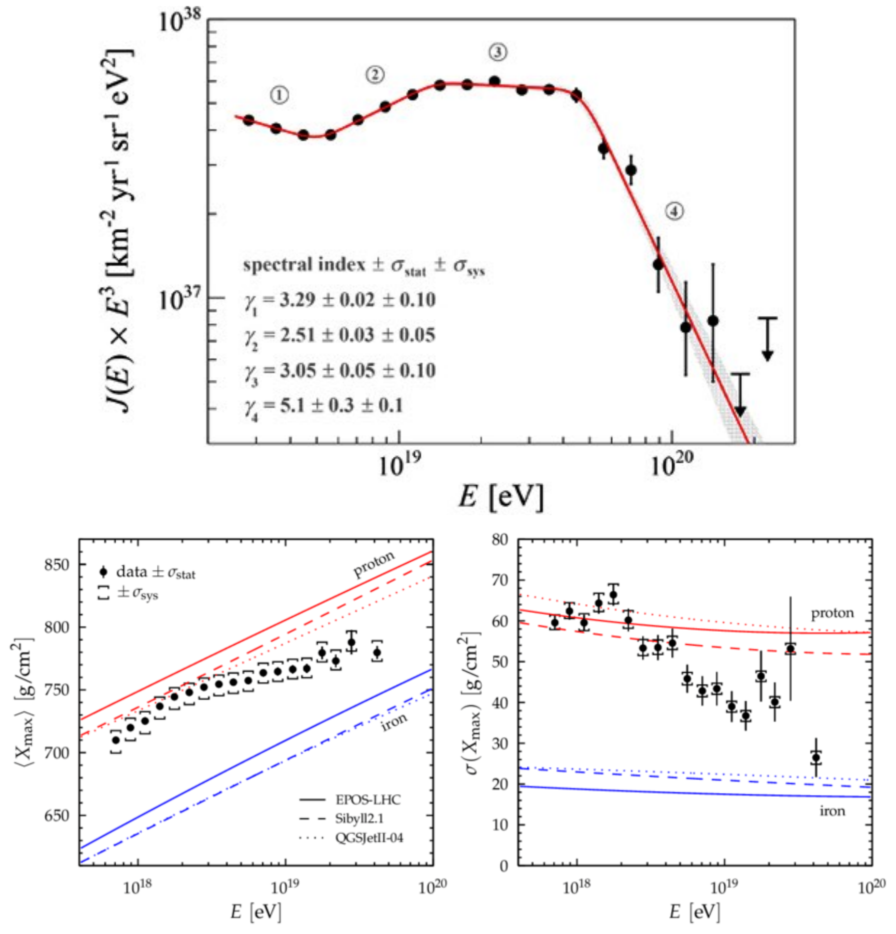


Propagation through the intergalactic medium



Production of showers in the atmosphere

Comparison with the data



Assumptions on a simple astrophysical model:

- Identical sources, uniformly distributed in co-moving volume
- Power-law spectra at escape, up to max energy, rigidity dependence assumption

Choice of propagation and hadronic interaction models for uncertain quantities:

- Extragalactic background light
- Photo-disintegration cross sections
- Hadronic interaction model

Estimation of free parameters

↓

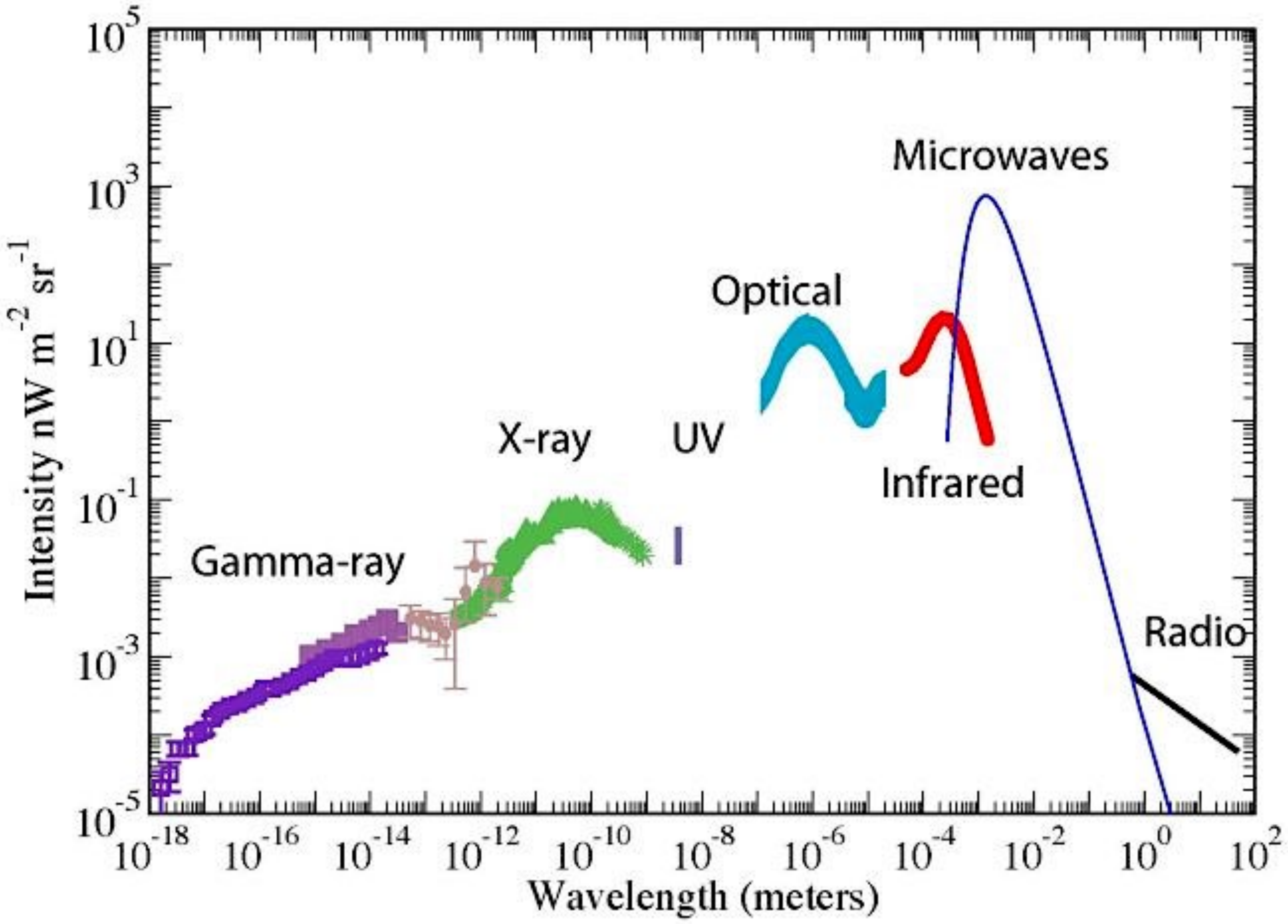
Characterization of the fluxes at the sources (energy spectrum and mass composition)

$$\frac{dN_A}{dE} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

UHECRs Propagation

UHECRs undergo **energy losses** during their propagation caused by both of the **expansion of the Universe** and the **interactions with the background radiation fields**

- For the energies of the UHECRs, relevant photon fields are:
  - Cosmic Microwave Background (**CMB**)
  - UV-optical-IR (Extragalactic Background Light, **EBL**)



- Processes due to the UHECRs interactions with astrophysical background photons:
  - **Pair production:** $\varepsilon' > 1\,\mathrm{MeV}$

    $p + \gamma \rightarrow p + e^+ + e^-$

  - **Pion production:** $\varepsilon' > 150\,\mathrm{MeV}$

    source of cosmogenic neutrinos:

    $p + \gamma \rightarrow n + \pi^+$

    $\pi^+ \rightarrow \mu^+ + \nu_\mu$

    $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

    source of cosmogenic photons:

    $p + \gamma \rightarrow p + \pi^0$

    $\pi^0 \rightarrow \gamma + \gamma$

  - **Disintegration of nuclei:** $\varepsilon' > 8\,\mathrm{MeV}$

    $A + \gamma \rightarrow (A - n) + nN$

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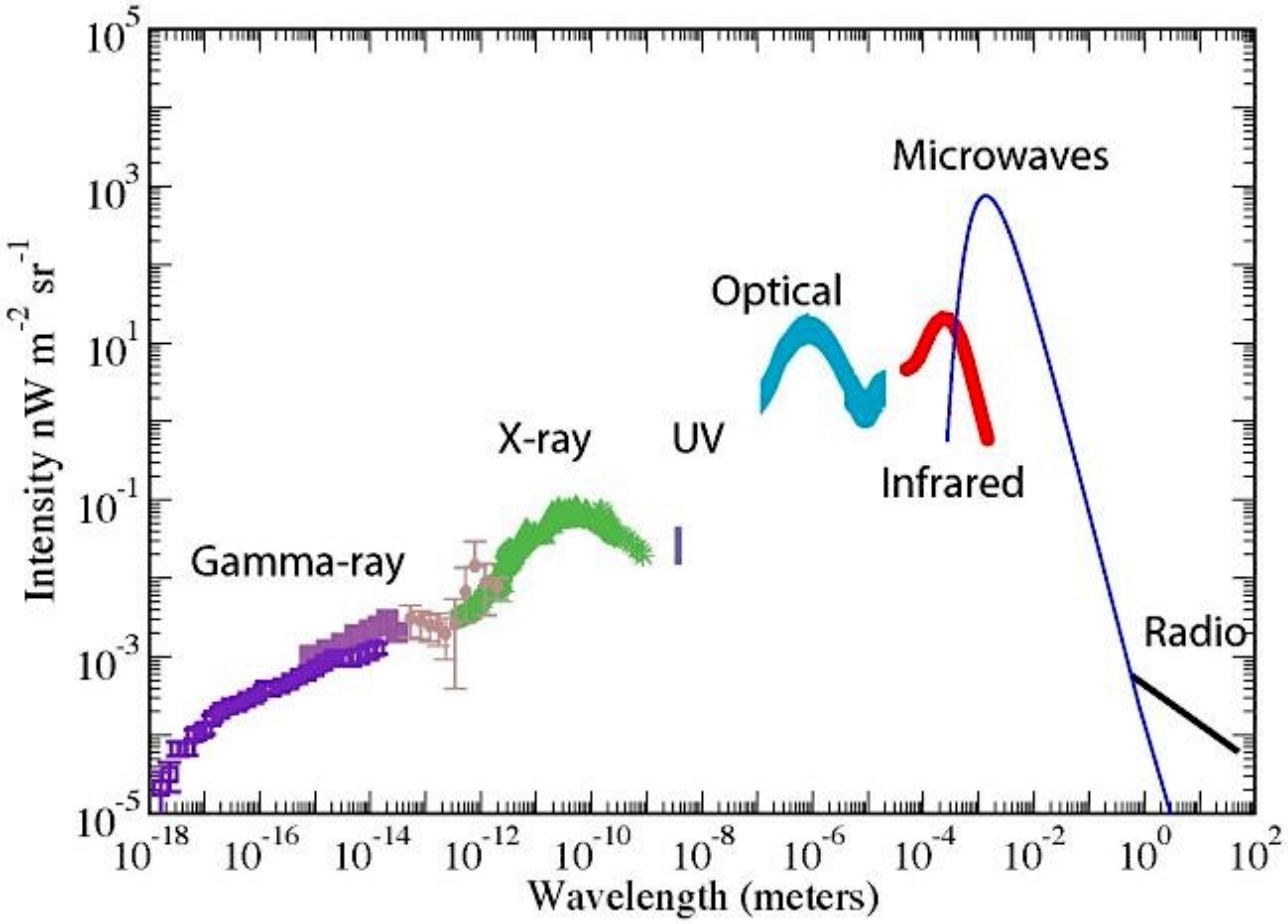

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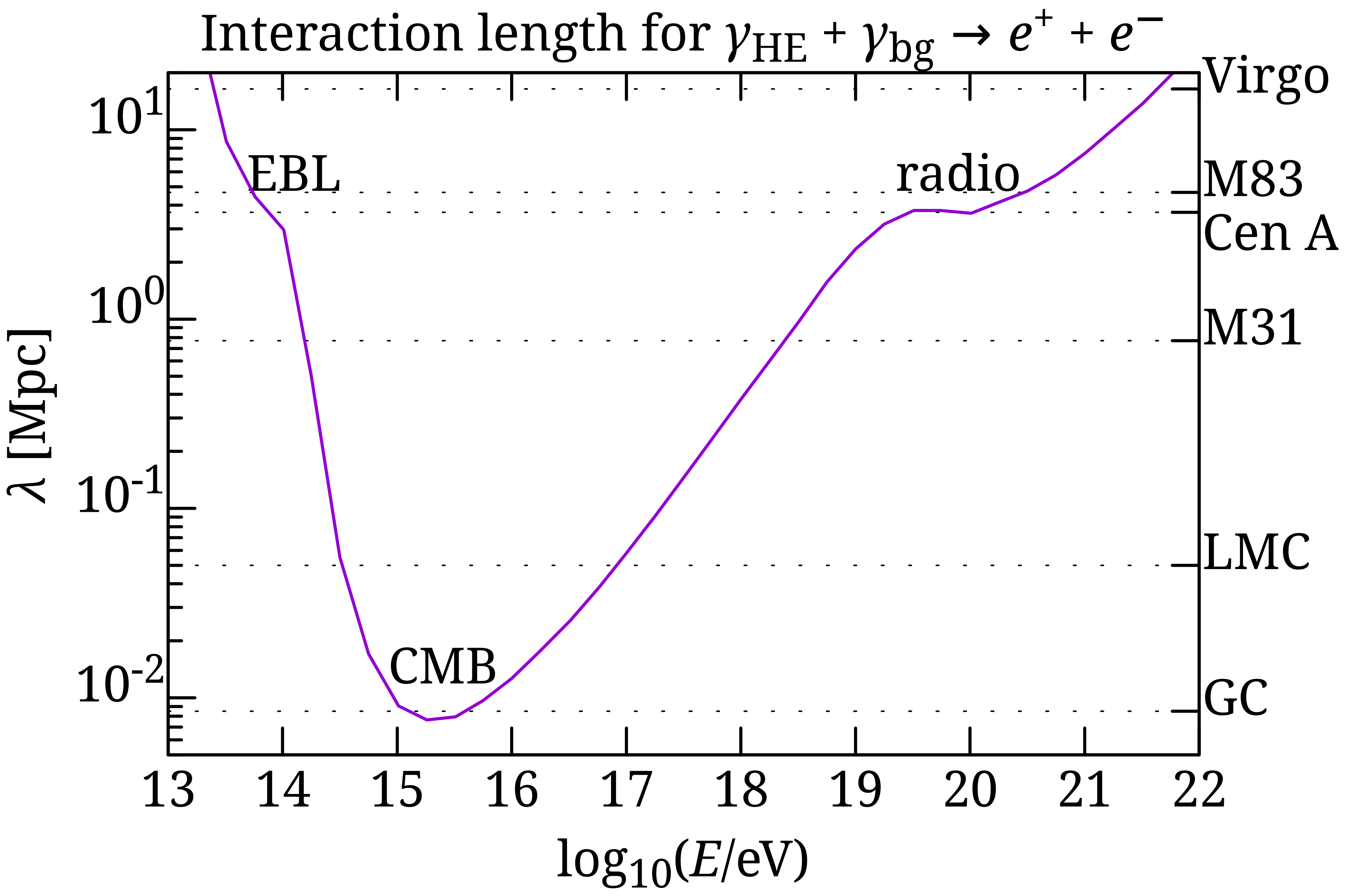
Electromagnetic sector: photon propagation



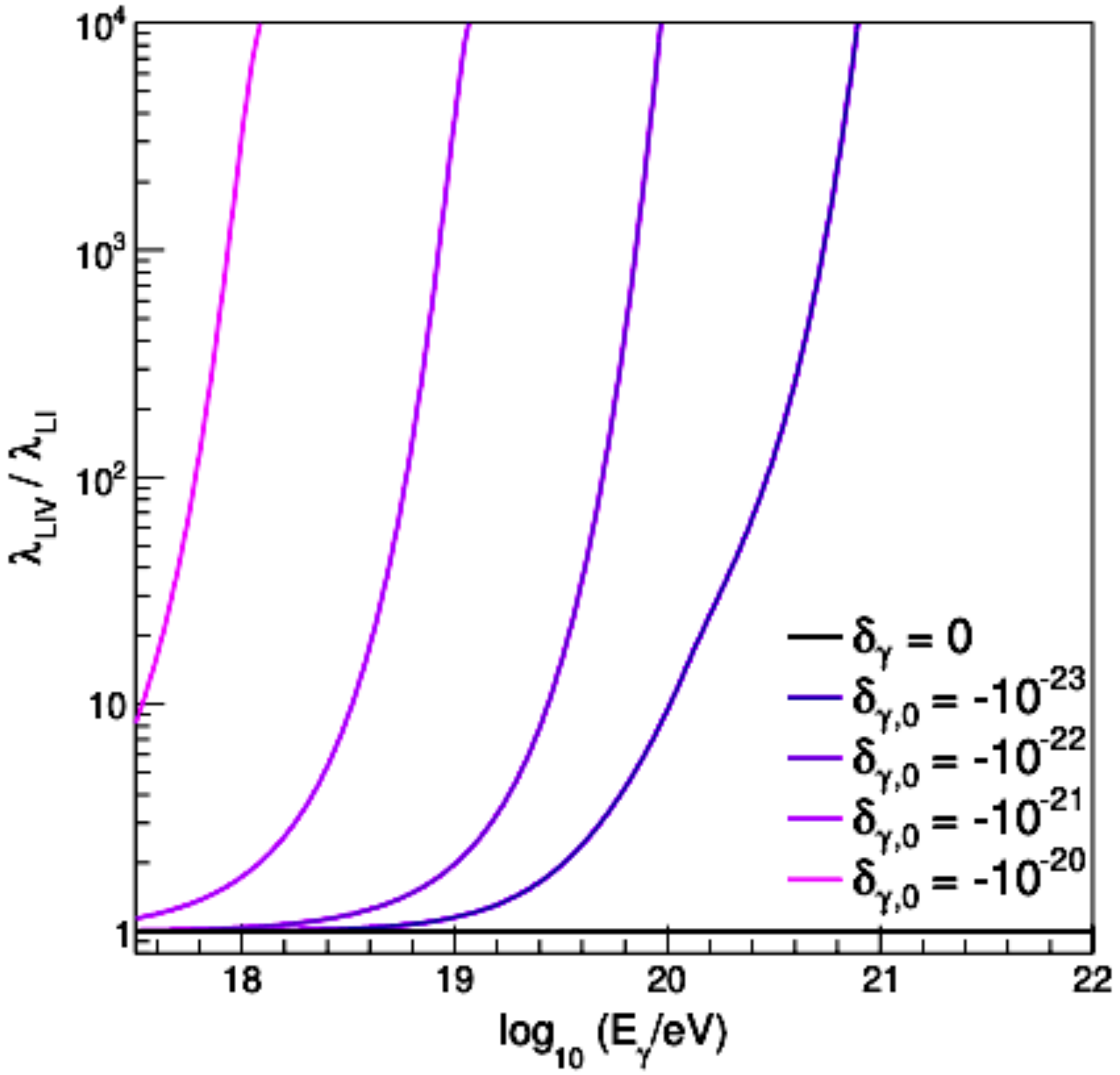
How LIV affects the interaction during propagation?

Simulation of GZK photons for both LIV and LI scenarios

The LIV-modified mean free path was implemented in the software packages CRropa3/EleCa

Expected effects on photon propagation:

- LIV can inhibit pair production at the highest energies
- More photons could reach the Earth



ORDER OF LIV
n=0,1, 2
$\delta<0$
Subluminal LIV

- Photons produced from pion decay, propagating In the extragalactic space under LIV assumptions
- Modifications in pair-production cross section → increase of the mean free path → less interactions → more photons expected

R. G. Lang, H. Martínez-Huerta, and V. de Souza, **"Limits on the Lorentz Invariance Violation from UHECR astrophysics. Astrophys"**, J., 853(1):23, 2018

Electromagnetic sector: photon propagation

Comparing the predicted LIV flux arriving at earth with the upper limits on the photons flux measured by the Pierre Auger Observatory

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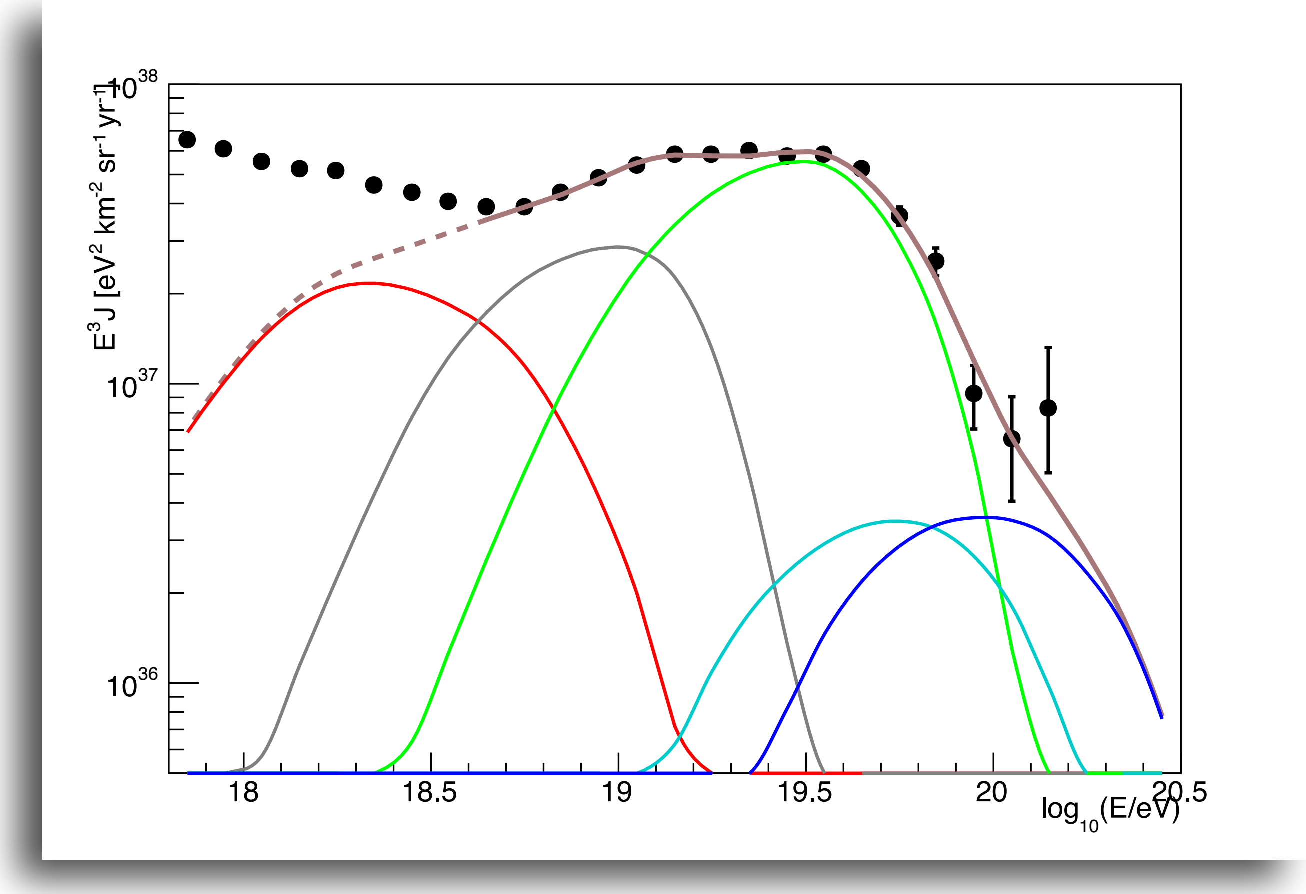
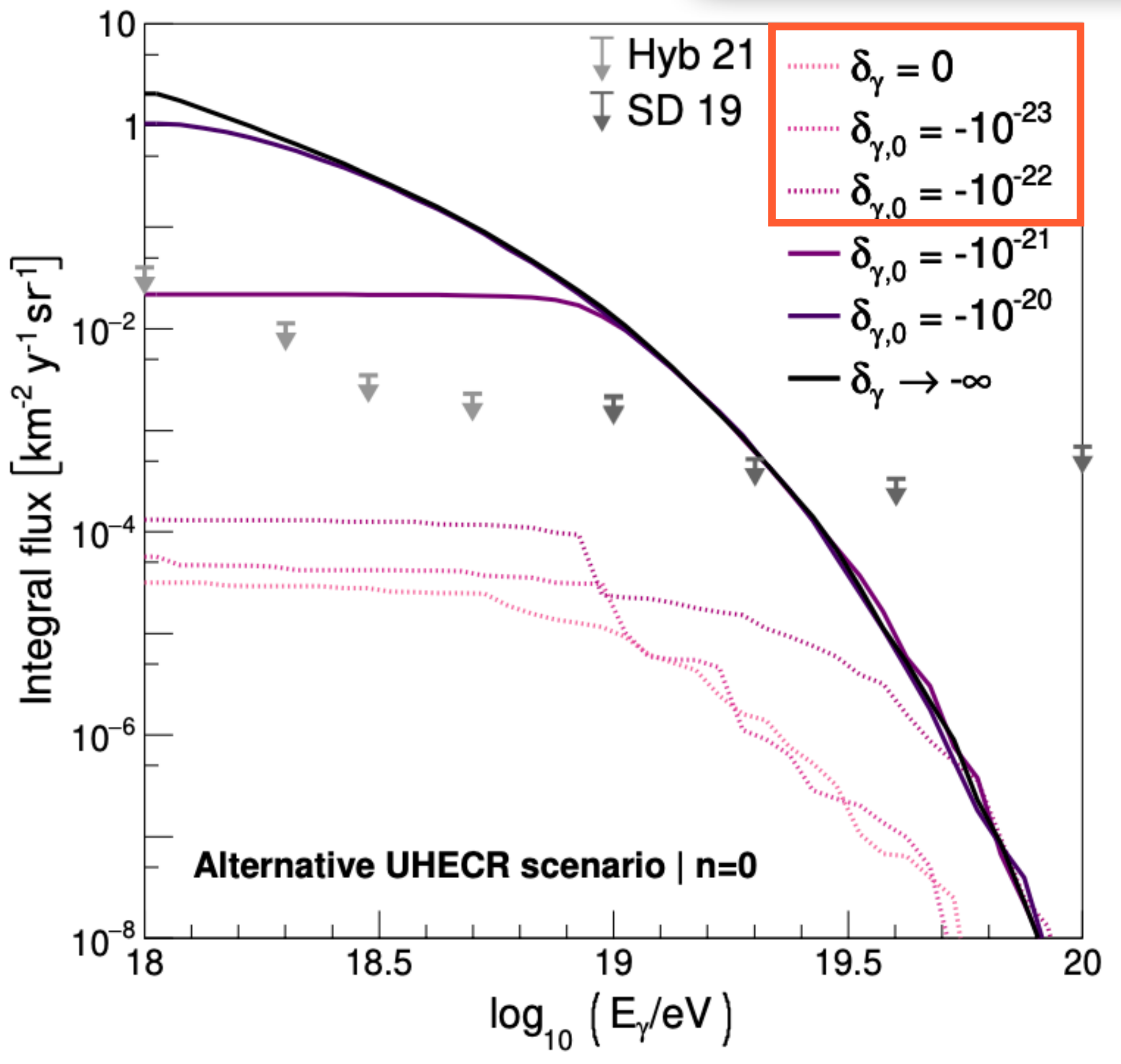
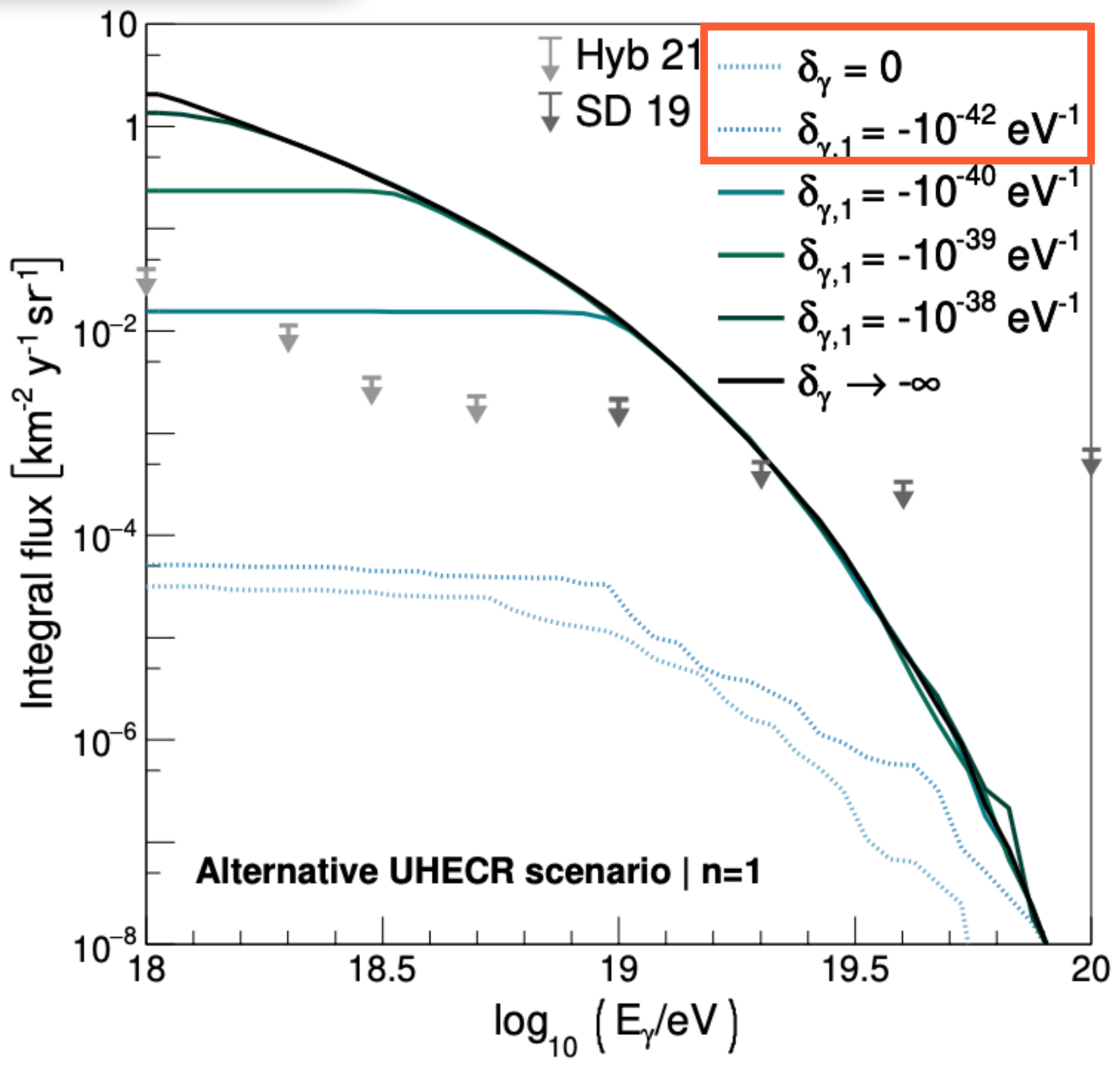
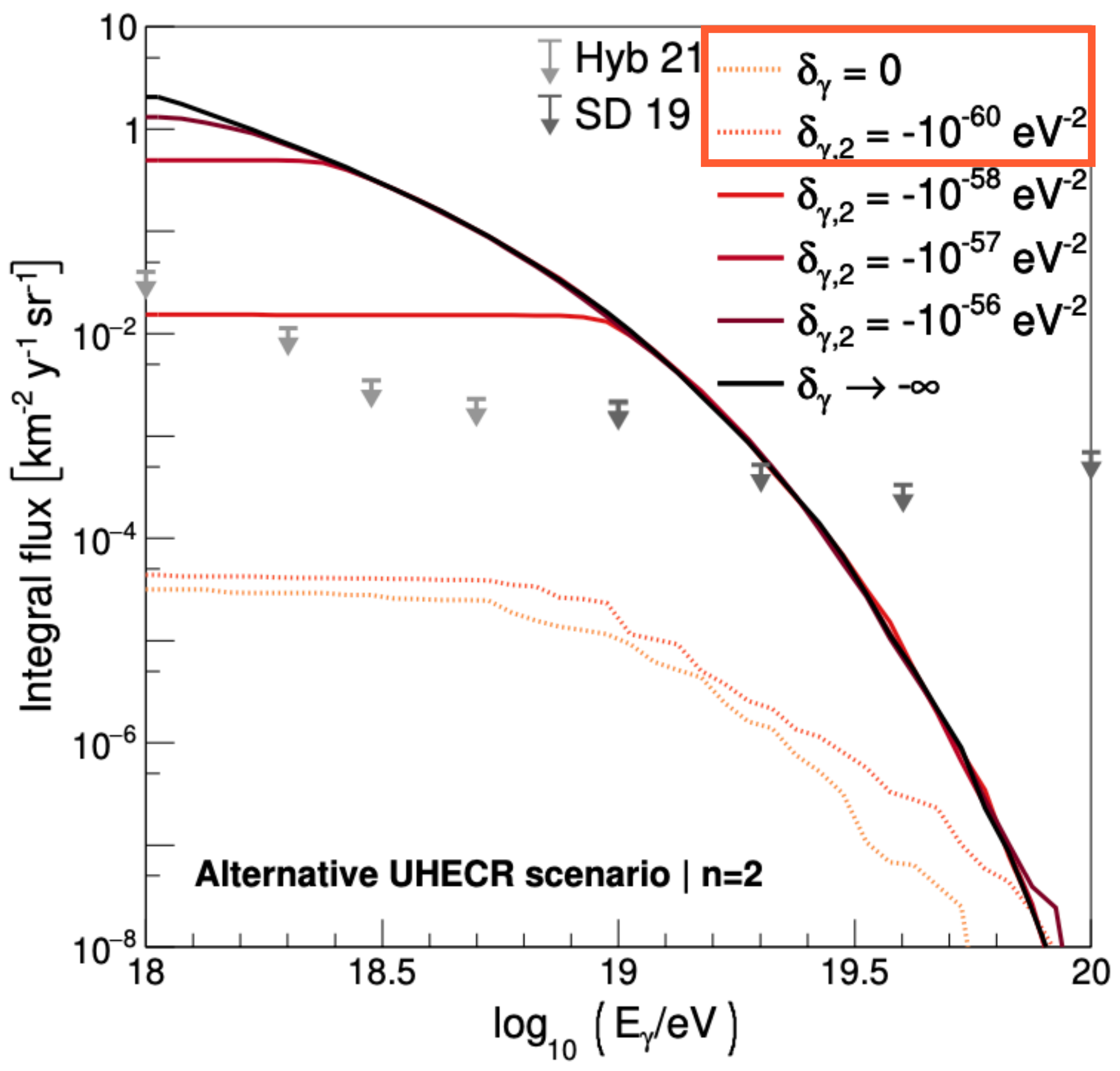


CONSIDERED SCENARIOS:

1. UHECRs (scenarios taken from **best fit of spectrum and composition** at escape from sources) propagating in extragalactic space (standard propagation)
2. **Photons** produced in extragalactic propagation by UHECRs with **additional proton component** at high energy







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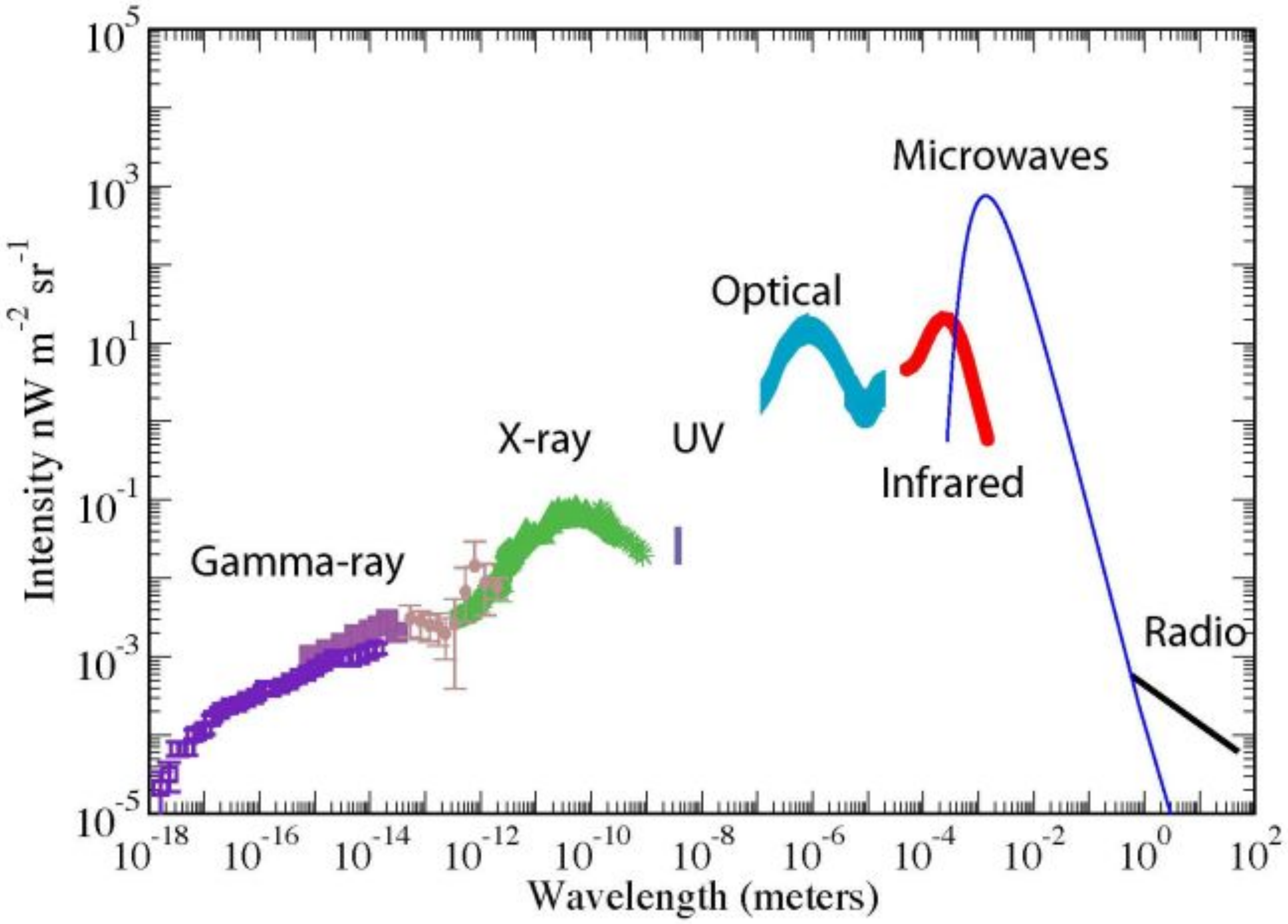

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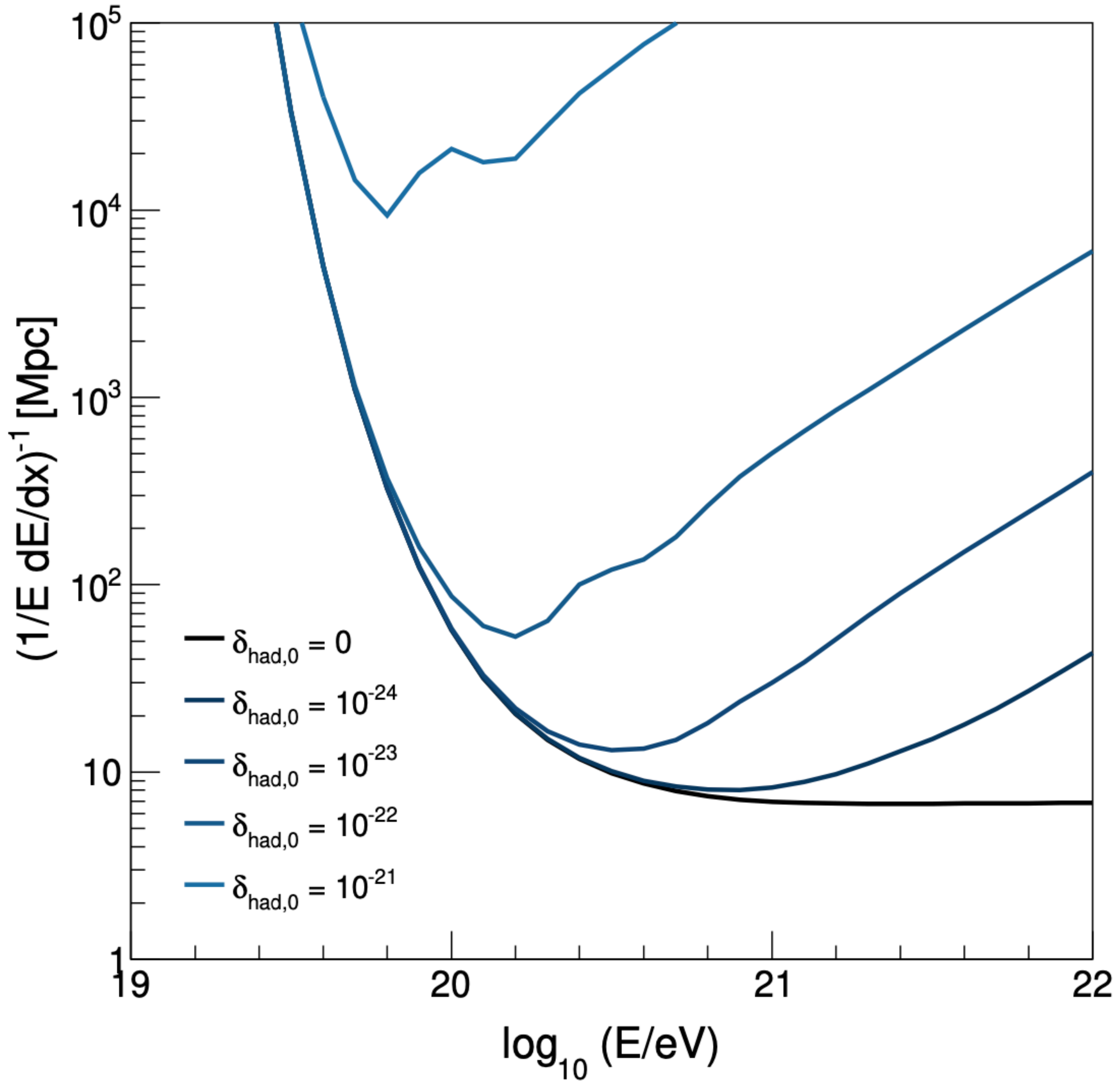
Hadronic sector: UHECRs propagation

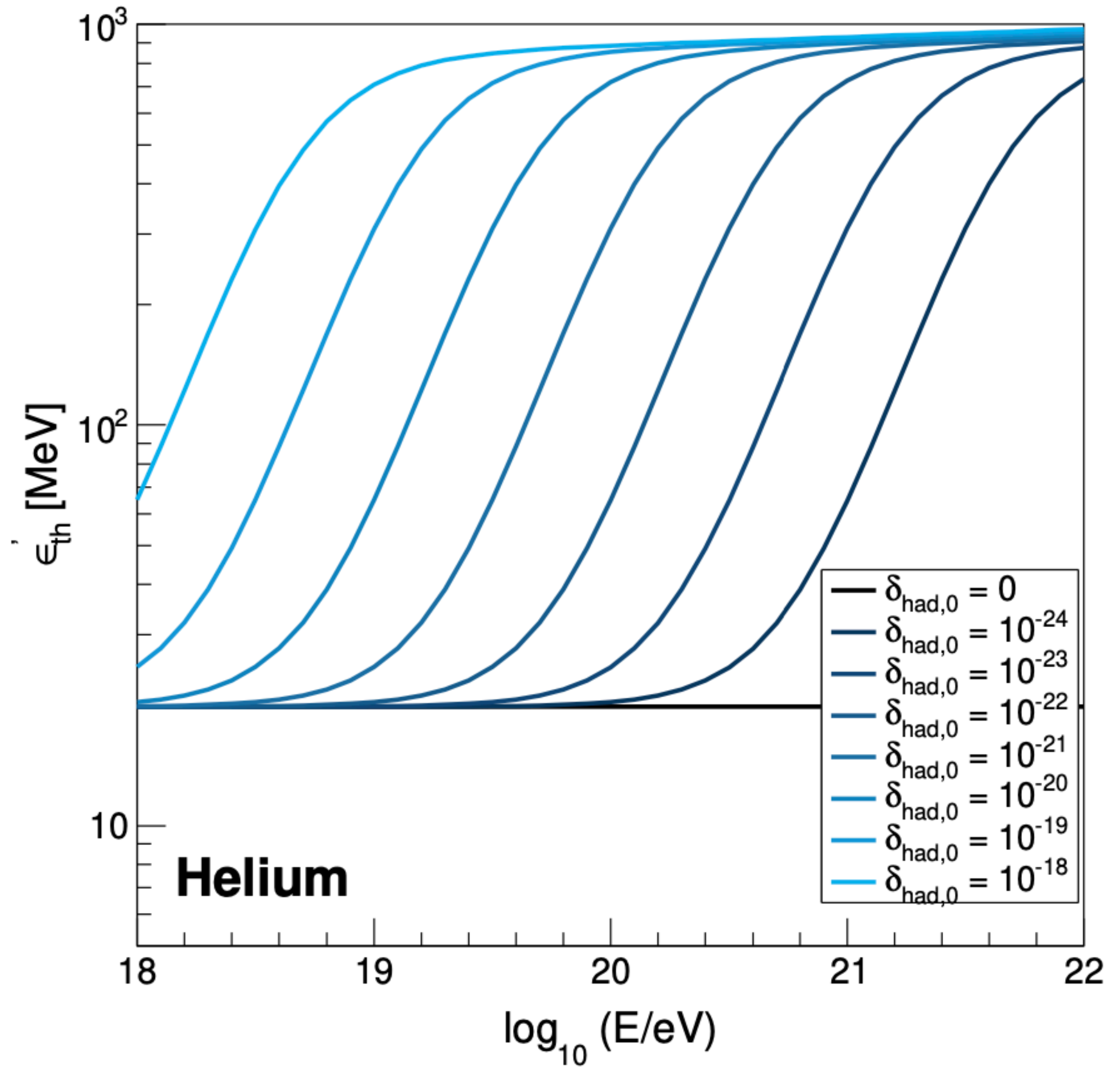


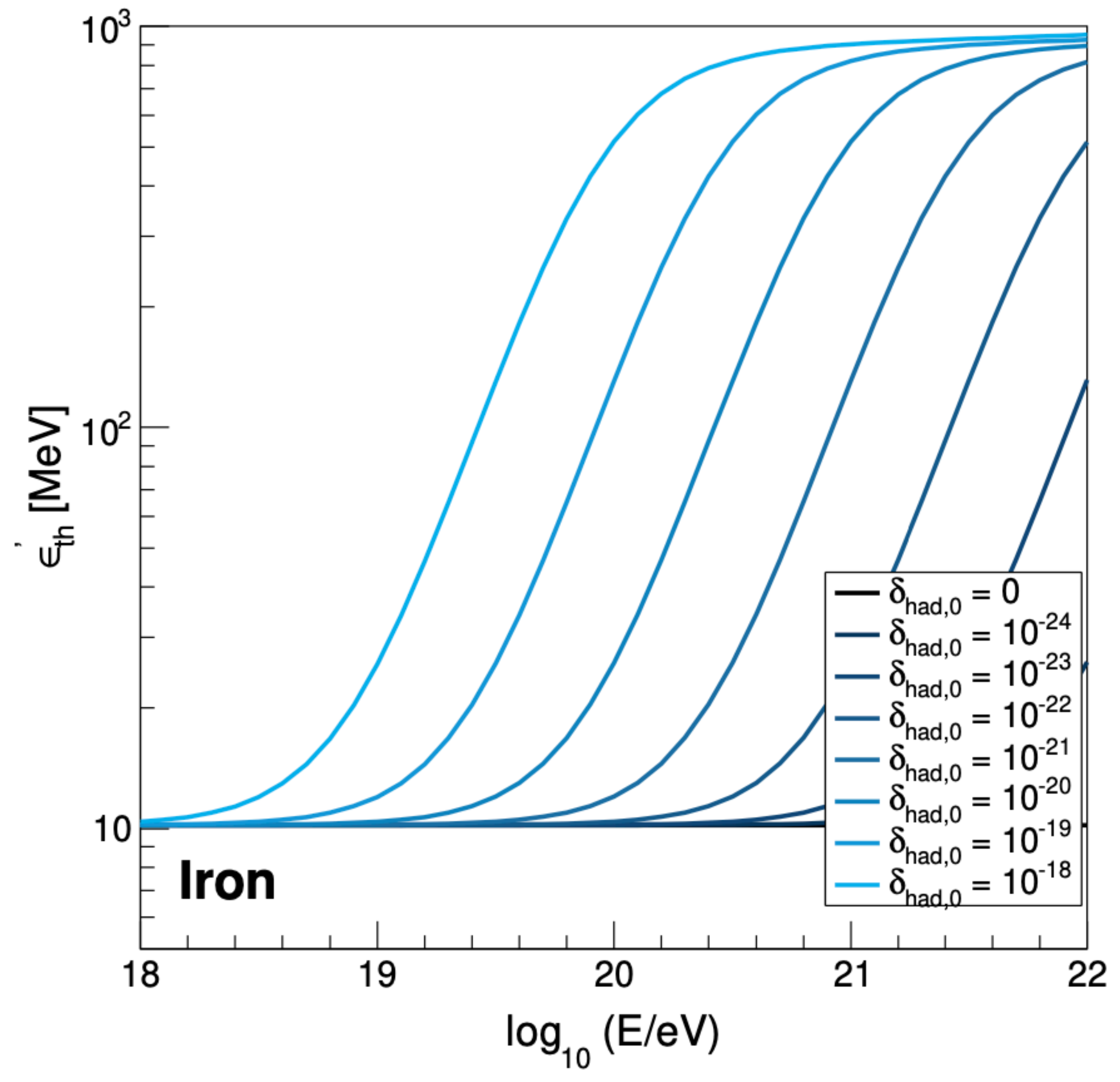
ORDER OF LIV
n=0,1, 2
δ>0
Superluminal LIV

How LIV affects the interaction during propagation?

- Above critical energy, number of interactions during propagation is reduced → the UHECRs interact less
- The cosmic ray can travel farther than LI scenario

The LIV-modified attenuation length for pion production and the LIV- modified energy threshold for photo disintegration were implemented in SimProp





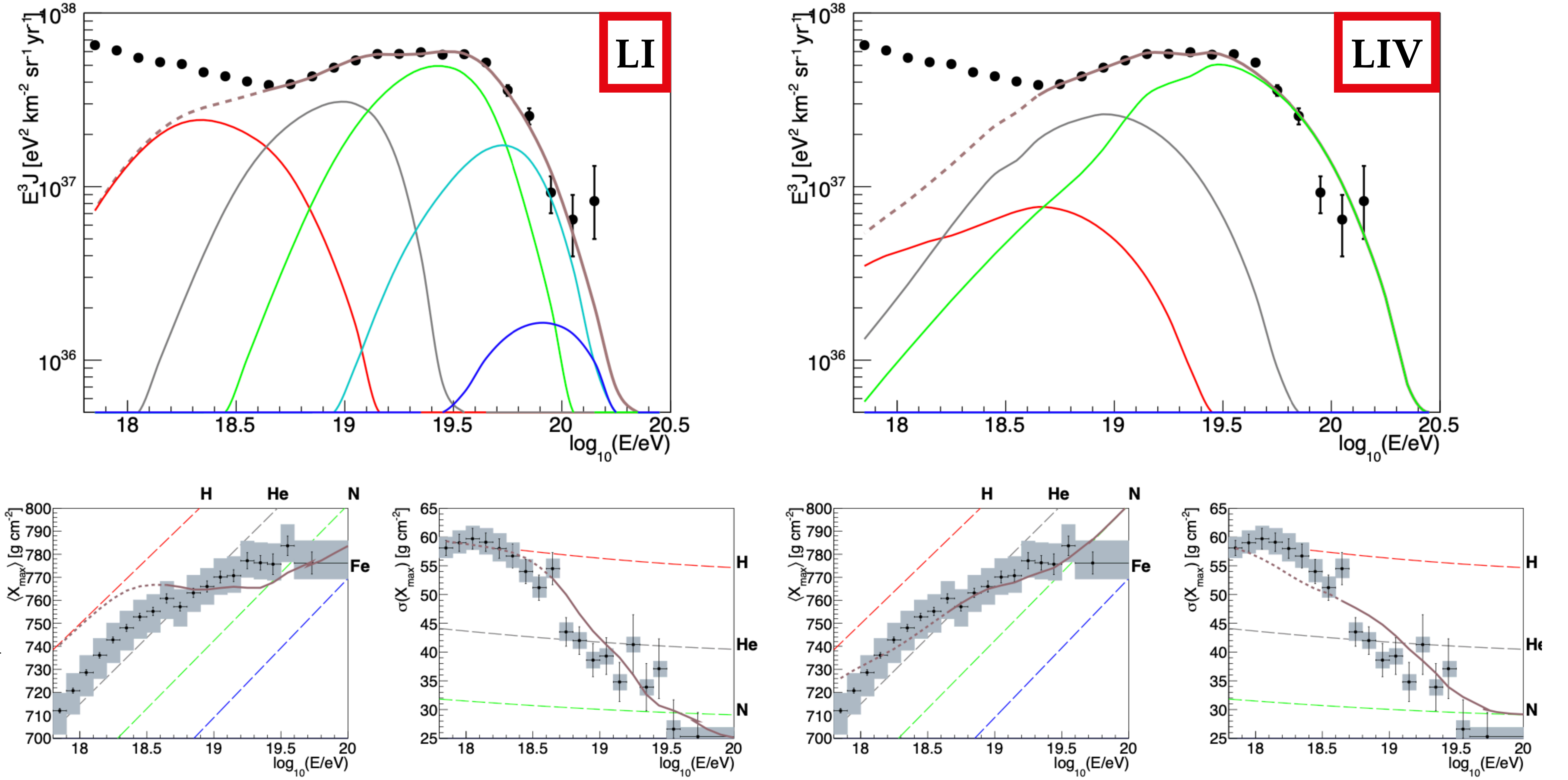
Effects on propagation:

- Interactions of nuclei → modified photo-disintegration
- Consider a nucleus as composed by A nucleons
- LI case: the photo-disintegration threshold depends only on the nuclear species
- LIV case: a dependence of the photo-disintegration threshold on the energy appears

Expected CR spectrum and mass composition

Fitting the data measured by the Pierre Auger Observatory with the expected spectrum and composition at ground for both LIV and LI scenarios (combined fit)

ORDER OF LIV
n=0,1, 2
δ>0
Superluminal LIV



- For each UHECR scenario the free parameters of the fit are:

  The nuclei fractions, the index of the energy spectrum, the maximum rigidity, the normalization factor of the flux, the LIV parameter δ

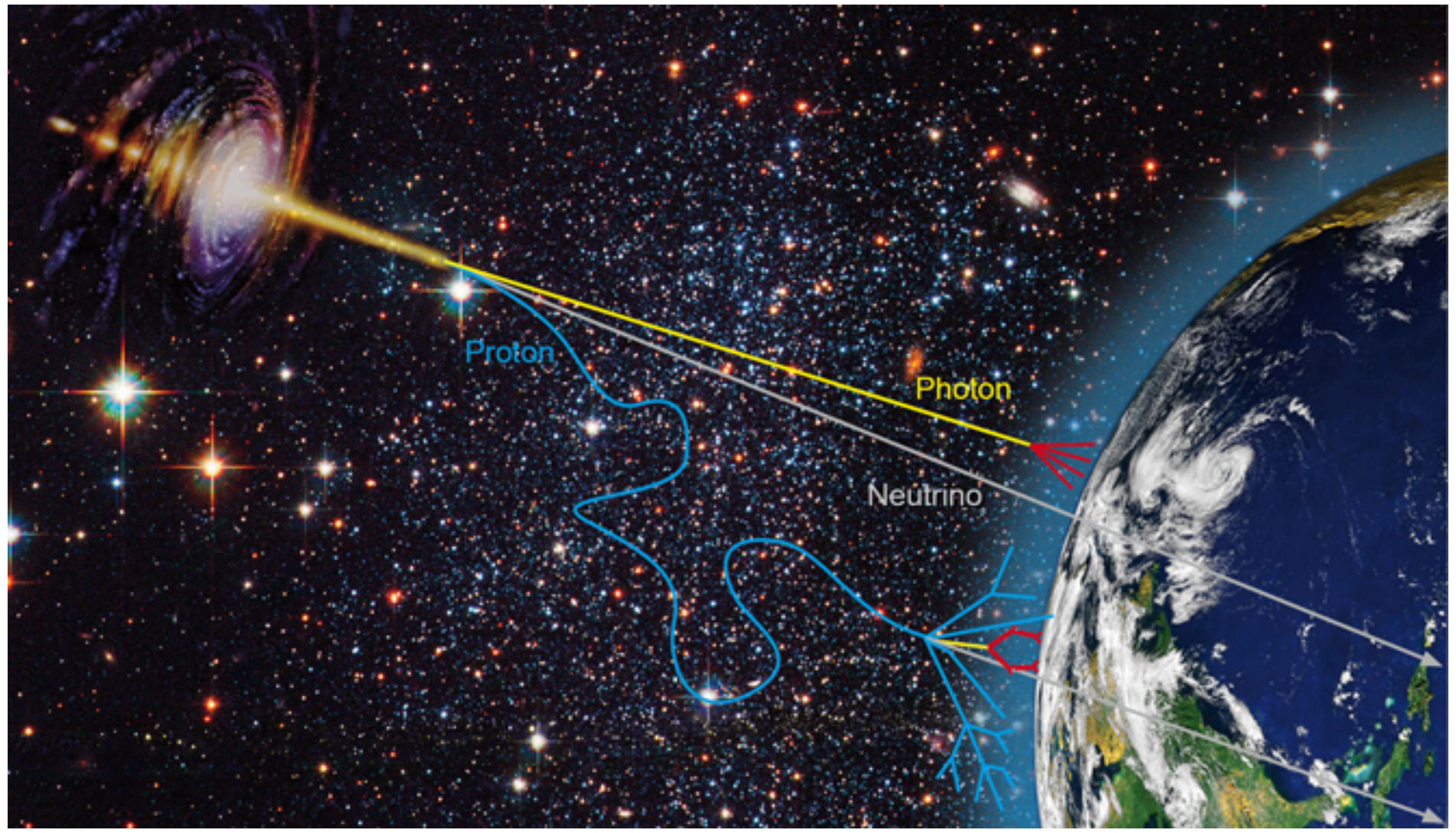
- A log-likelihood fit gives the combination of the parameters that best describes data

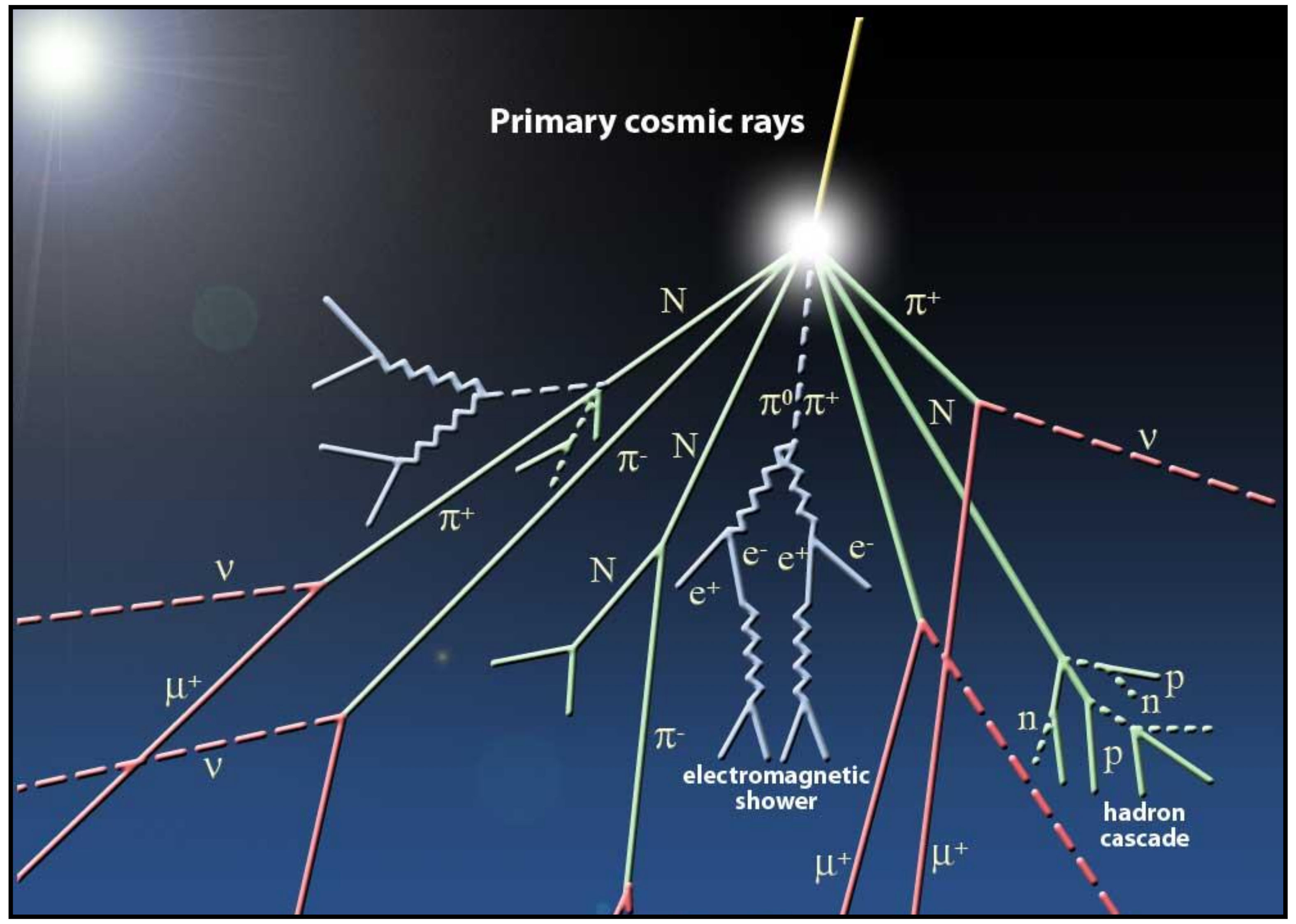
Effect on CR propagation:

- Threshold energy increases → less interactions → if LIV, lighter nuclear species are needed at the sources in order to reproduce the observed composition

Conclusions

- LIV can be tested with **UHECRs**
- **Extragalactic propagation** of UHECRs
  - Searches signatures in **electromagnetic sector**
    → strong constraints on the LIV coefficients
  - Searches signatures in **hadronic sector**
- Constraints of LIV coefficients depend on the composition of the cosmic rays at the source
  → **AugerPrime** will improve the knowledge on the composition of the cosmic rays at Earth
  → LIV searches will profit
- Development of **cascade of particles in atmosphere**
  - Fluctuations of number of muons used for the first time to constrain LIV





Thank you for the attention!

CTAO Symposium, 15-18 April 2024

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Main References

- The Pierre Auger Collaboration, "**Testing effects of Lorentz invariance violation in the propagation of astroparticles with the Pierre Auger Observatory**", JCAP 2022
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- S. Coleman and S. L. Glashow, "**High-energy tests of Lorentz invariance**", Phys. Rev. D, 59:116008, Apr 1999
- S. Coleman and S. L. Glashow, "**Cosmic ray and neutrino tests of special relativity**", Physics Letters B, 405(3):249–252, 1997
- R. G. Lang, H. Martínez-Huerta, and V. de Souza, **"Limits on the Lorentz Invariance Violation from UHECR astrophysics. Astrophys"**, J., 853(1):23, 2018