Lorentz Invariance Violation studies in ultra-high energy cosmic rays at the Auger experiment

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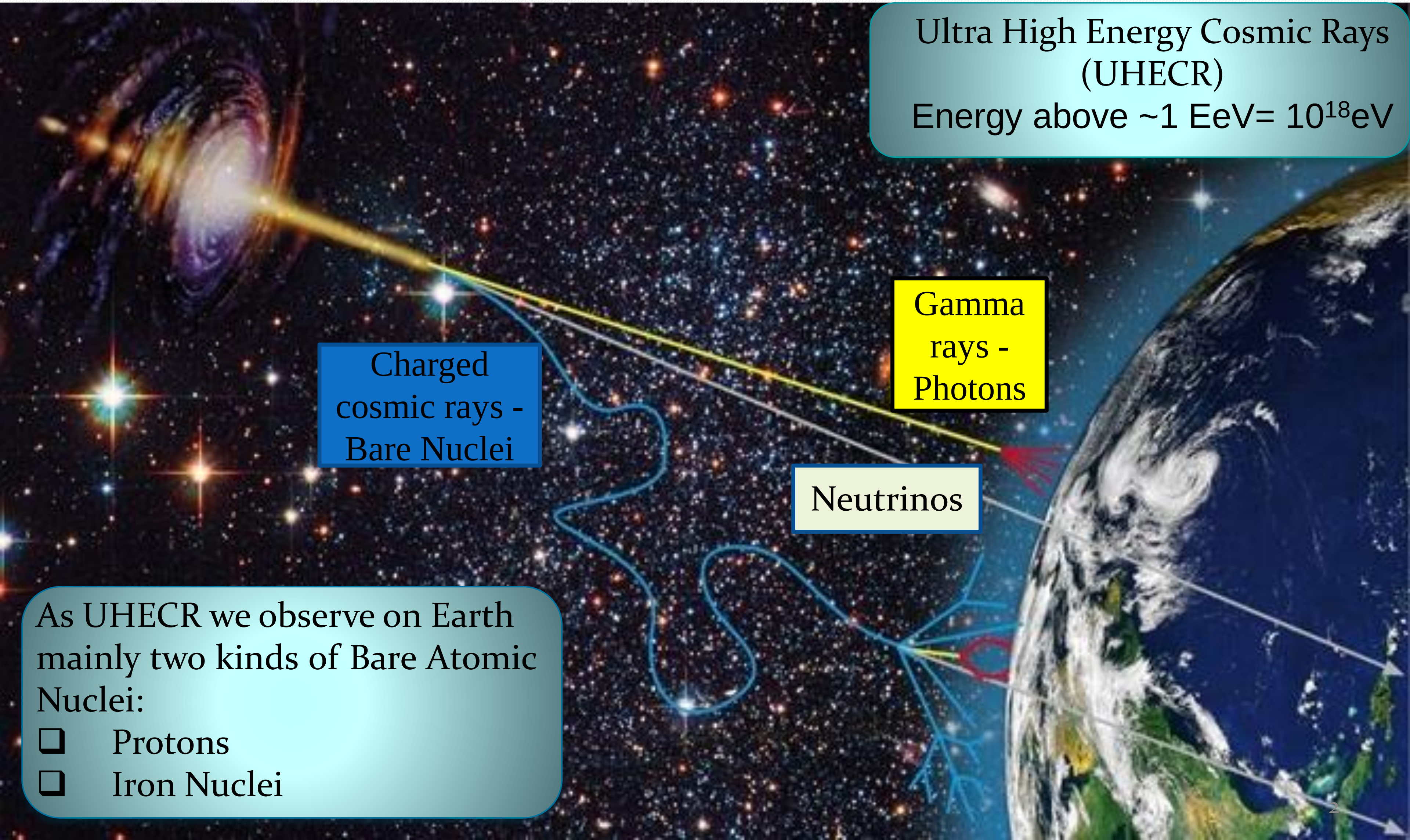
What a cosmic ray is

Cosmic Rays are cosmic messengers, made of:

Ultra High Energy Cosmic Rays (UHECR)
Energy above ~1 EeV= 10^{18}eV

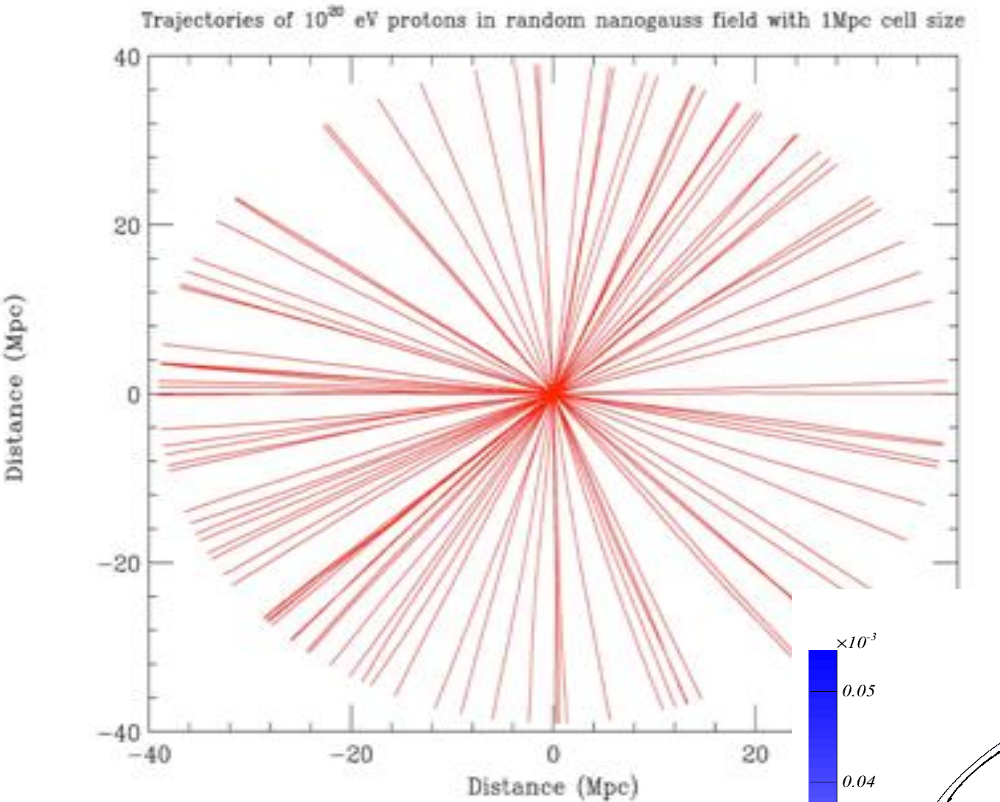


As UHECR we observe on Earth mainly two kinds of Bare Atomic Nuclei:

- ❑ Protons
- ❑ Iron Nuclei

Importance of high energy Protons

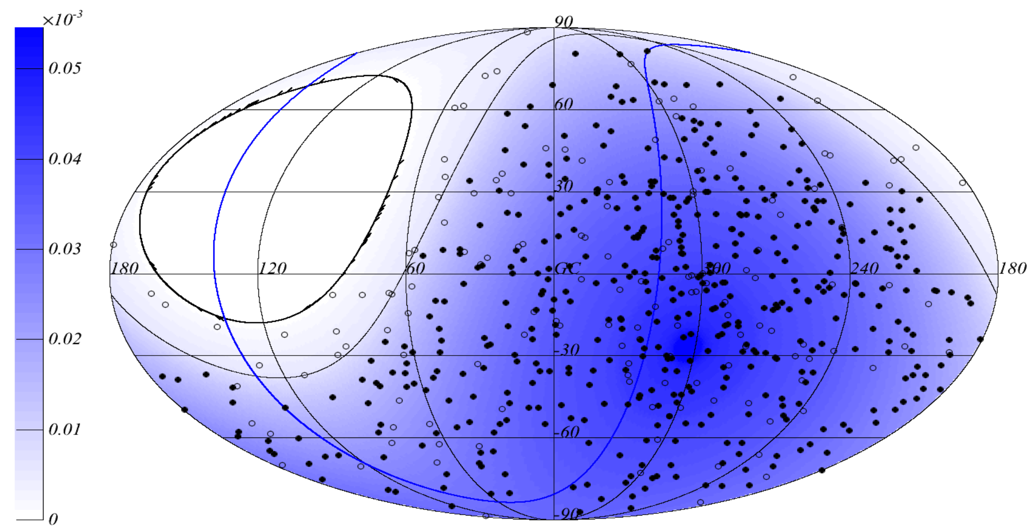
$$E \approx 10^{20}\, eV$$



Simulations show for Protons an average deflection of :

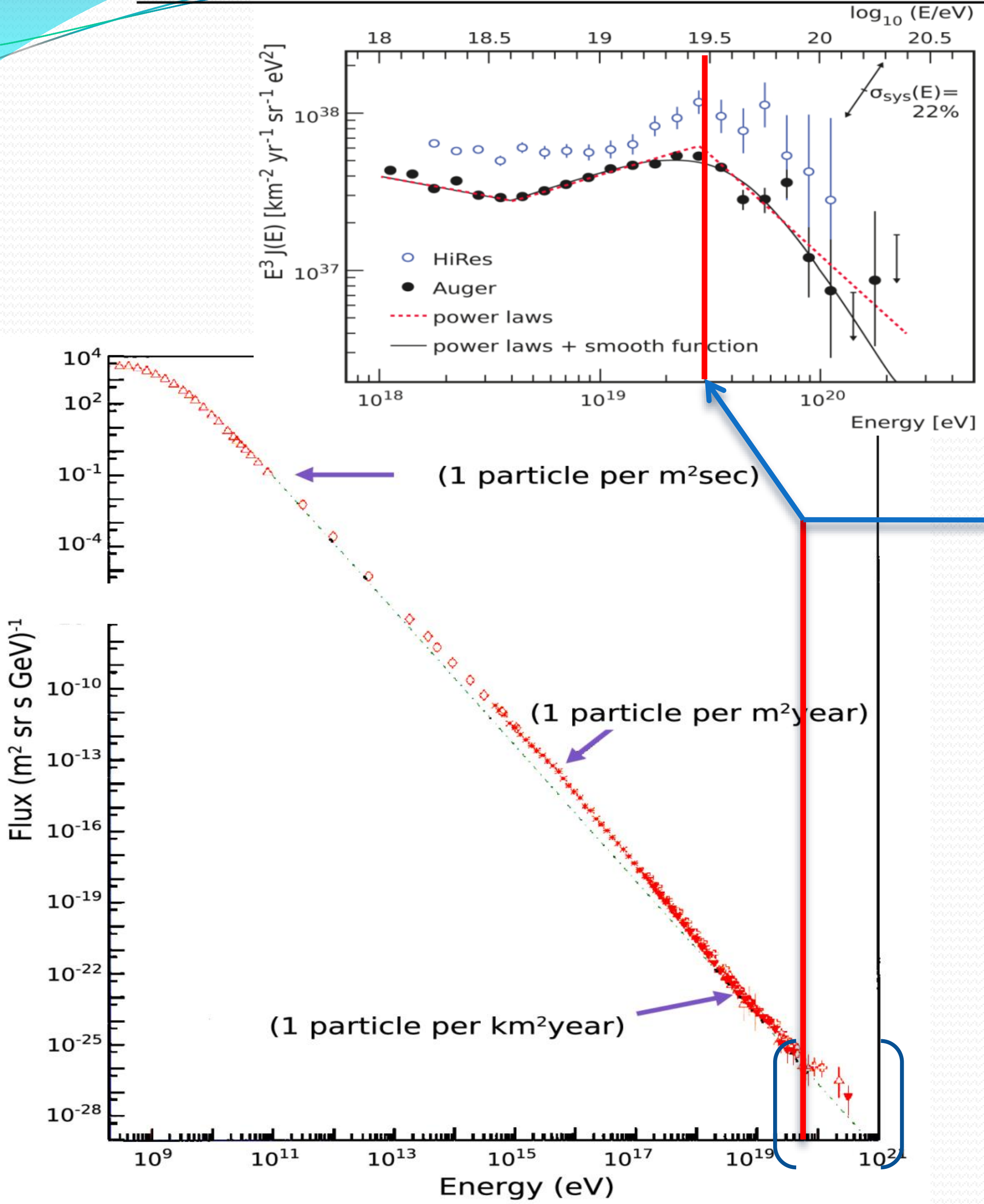
$$\Delta\Phi \approx 1^\circ \div 3^\circ$$

Possibility to use Protons for anisotropy studies :
Using Protons it is possible to aim to the sources



Protons energy $\longrightarrow 10^{20}\ eV$
Extragalactic
Magnetic field $\longrightarrow 1\ nG$

Cosmic rays



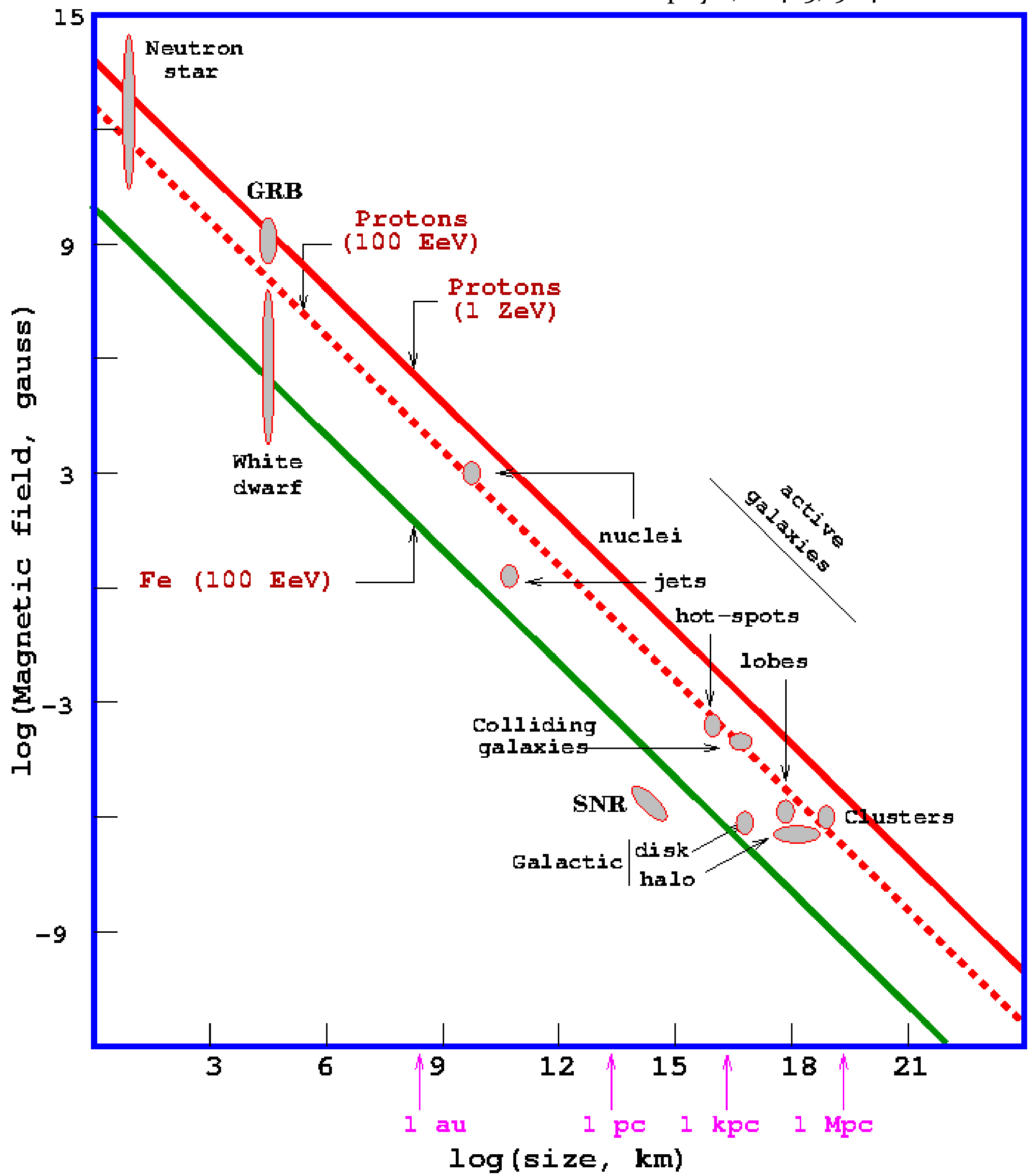
Event suppression at the highest energies:

$$E \approx 5 \cdot 10^{19} eV$$

Necessity to understand this cut-off

Candidate sources

A.M. Hillas Ann.Rev:Astron.Astrophys.,22:425,1984



Acceleration models require cosmic rays (bare nuclei) to be confined into the source.
There must be a limit to the energy of a cosmic ray

Cosmic ray energy — Source magnetic field

$$E_{max} \propto eZ \cdot R \cdot B$$

Cosmic ray charge — Source dimension

Lack of sources as explaination of GZK suppression

Other possible cause of the suppression → GZK effect (Greizen Zapetszin Kuzmin)

The high energy cosmic rays interact with the Cosmic Microwave Background, dissipating energy

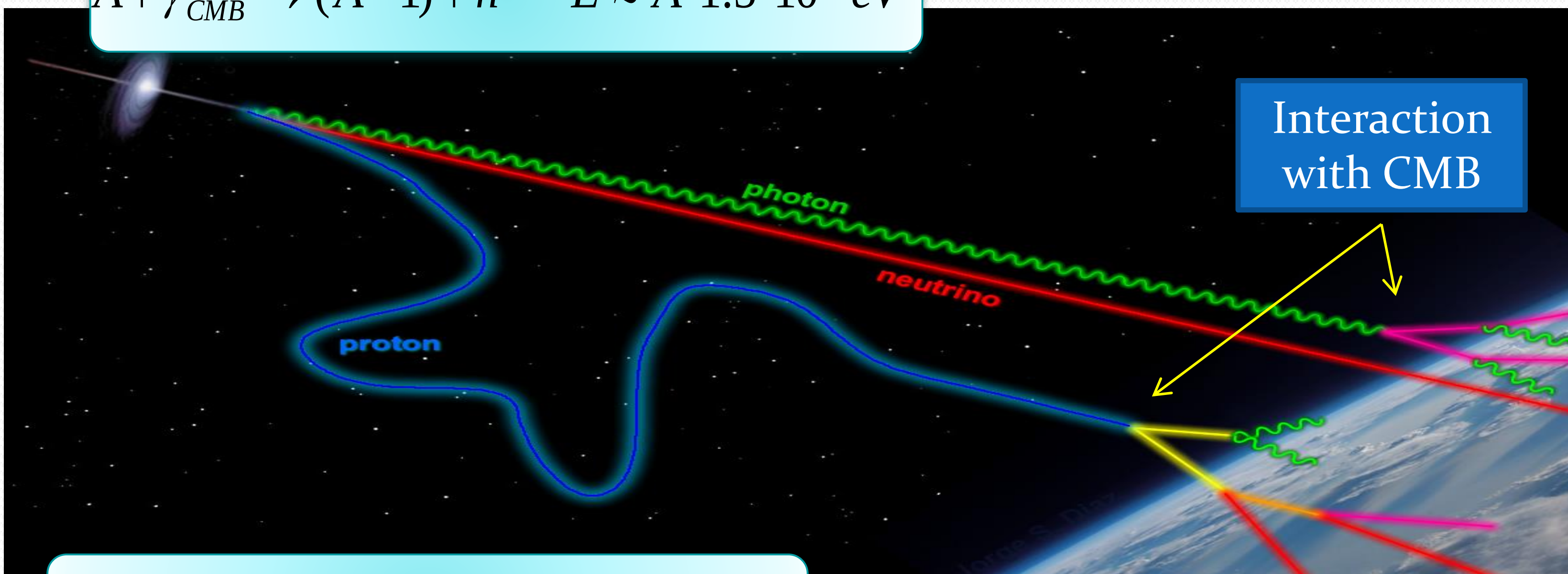
$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p+\pi^{0} \qquad E \approx 5\cdot 10^{19}\, eV$$

$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n+\pi^{+} \qquad E \approx 5\cdot 10^{19}\, eV$$

→ Delta resonance for protons

$$A+\gamma_{CMB} \rightarrow (A-1)+n \qquad E \approx A\cdot 1.5\cdot 10^{19}\, eV$$

→ Photodissociation for bigger nuclei



$$p+\gamma_{CMB} \rightarrow p+e^{+}+e^{-} \qquad E \approx 5\cdot 10^{17}\, eV$$

→ Pair production

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

→ In analogy → couple production for photons

Effect of the interaction with the CMB

Attenuation of **proton** for interaction with the CMB and galactic-extragalactic E.M. radiation through a Δ resonance

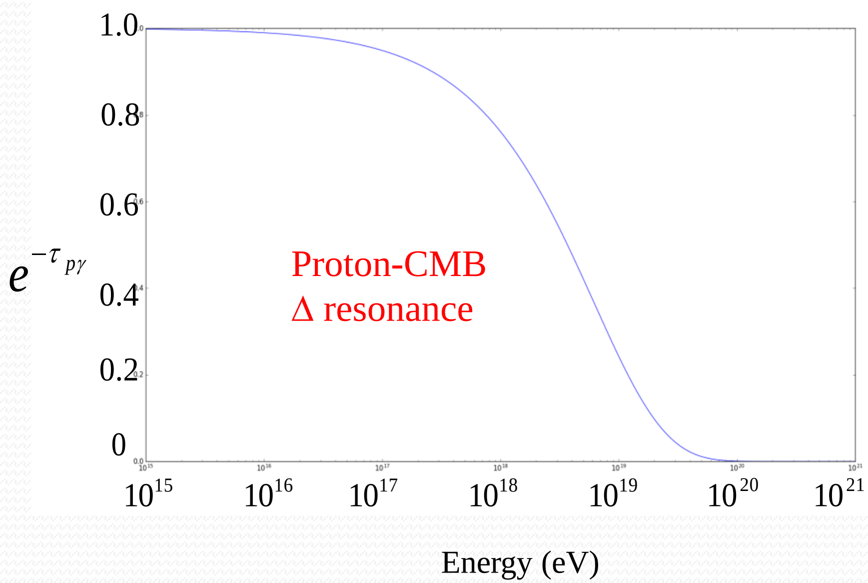
Optical depth:

$$\tau_{p\gamma}(E) = \frac{1}{\lambda_{p\gamma}} \frac{1}{8p^2} \int_L dx \int_{E_{thr}}^{+\infty} \left\{ \left(\frac{1}{e^{\omega/KT} - 1} \right)_{CMB} + \frac{f(\omega, T')}{\omega^2} \right\} d\omega \int_{s_{\min}}^{s_{\max}} K_{in}(s) \, \sigma_{p\gamma}(s) \; s \cdot ds$$

Inelasticity: energy dissipate for every photo-pion production

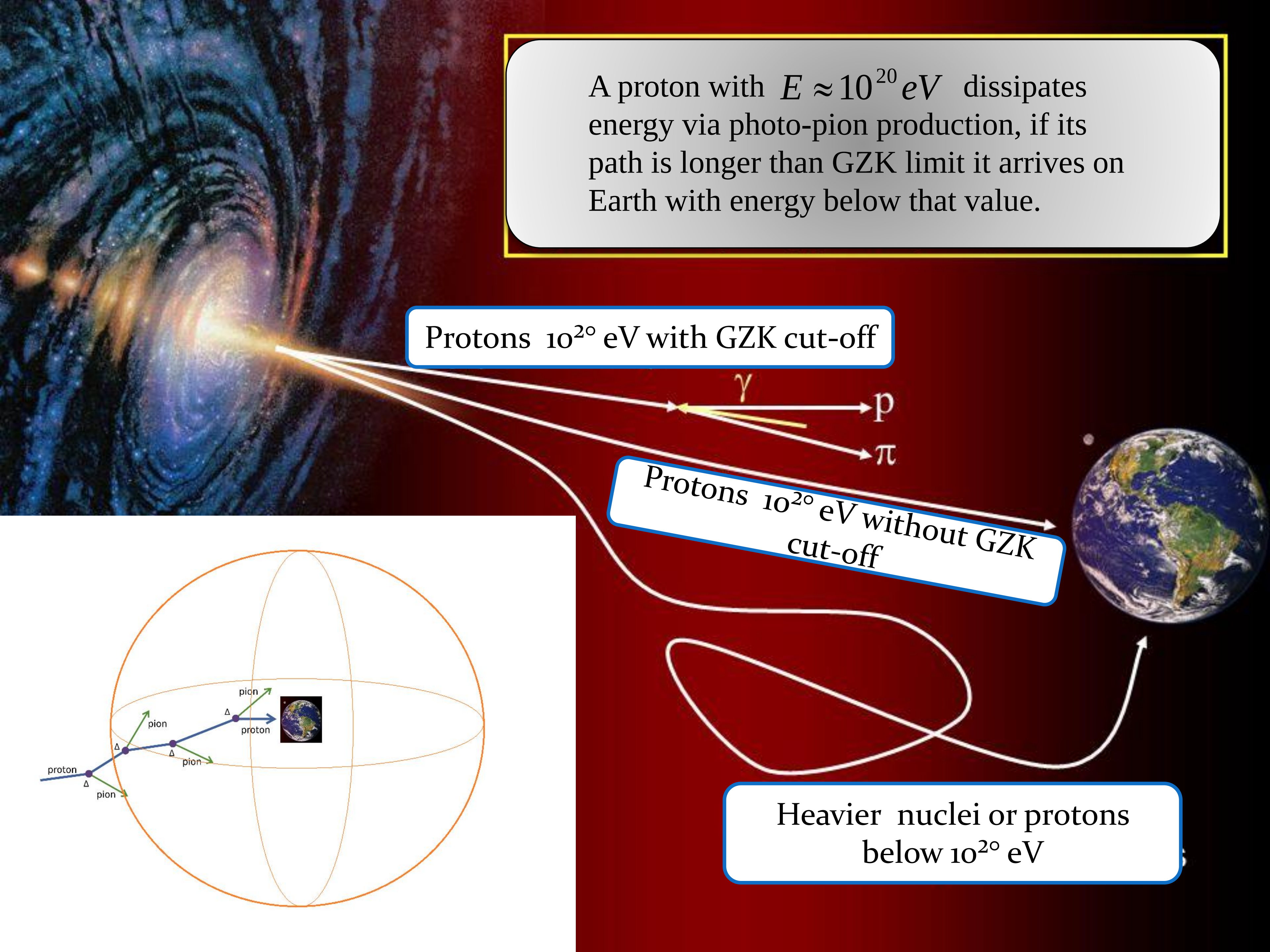
$$K_{in}(s) = \frac{\Delta E_p}{E_p} = \frac{1}{2}\left(1 - \frac{m_p{}^2 - m_\pi{}^2}{s}\right)$$

Attenuation: Fraction of protons with given energy after a given path



In this plot $L \approx 50\,Mpc$

A proton with $E \approx 10^{20} eV$ dissipates energy via photo-pion production, if its path is longer than GZK limit it arrives on Earth with energy below that value.



Lorentz invariance

Special relativity → Lorentz Group

Special Relativity → Teory that describes the change of coordinates from one inertial frame to another one

Linear transformations compatible with the Minkowski metric tensor

$$\eta^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$ → Minkowski metric tensor

Linear coordinate transformation ← $$y^{\mu} = \Lambda^{\mu}{}_{\nu} x^{\nu}$$

Compatibility with the metric tensor ← $$\Lambda^{\mu}{}_{\alpha} \cdot \eta^{\alpha\beta} \cdot \Lambda^{\nu}{}_{\beta} = \eta^{\mu\nu}$$

Relativistic dynamic

For every massive particle the dynamic is governed by the **dispersion relation:**

$$E^2 = c^2 \vec{p}^{\,2} + m^2 c^4$$

$$E^2 - c^2 \vec{p}^{\,2} = m^2 c^4$$

where $c = 1$ is a constant

In natural units

It represents the maximum attainable velocity → the speed of light

Lorentz Invariance Violation (LIV)

In the simpler case of Lorentz Invariance Violation (LIV) every particle 'i' has a different **maximum attainable velocity** (its 'personal' speed of light)

$$c_i = 1 - \varepsilon$$

with

$$\varepsilon << 1$$

Effects of introducing the LIV → Changing the dispersion relation

Effects visible in **ultrarelativistic regime**

$$E^2 = c_i^{\,2} \vec{p}^{\,2} + m^2 c_i^{\,4}$$

$$E^2 = (1-\varepsilon)^2 \vec{p}^{\,2} + (1-\varepsilon)^4 m^2$$

$$m^2 << \vec{p}^{\,2}$$

$$E^2 \approx (1 - 2\varepsilon) \vec{p}^{\,2} + m^2$$

The corrections relative to the mass term have been neglected because of the ultrarelativistic regime.

Effect of LIV on GZK sphere

The violation can modify the GZK limit:

$$\left(E_p + E_\gamma\right)^2 - \left(\vec{p}_p + \vec{p}_\gamma\right)^2 \geq m_\Delta{}^2$$

This relation must be satisfied to obtain a Δ resonance

$$p + \gamma_{CMB} \to \Delta^+ \to p + \pi^0$$
$$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$$

Term modified by the LIV

$$E_p{}^2 + E_\gamma{}^2 + 2E_pE_\gamma - (1-2\varepsilon)\vec{p}_p{}^2 - \vec{p}_\gamma{}^2 - 2\vec{p}_\gamma\vec{p}_p \geq m_\Delta{}^2$$

$$-2\varepsilon E_p{}^2 + 4E_pE_\gamma - (m_\Delta{}^2 - m_p{}^2) \geq 0$$

This inequality is never satisfied if the violation parameter satisfies the relation:

$$\varepsilon > \frac{2E_\gamma{}^2}{\left(m_\Delta{}^2 - m_p{}^2\right)}$$

There is not a unique value for $E\gamma$ the CMB follows a Boltzman distribution.

In first approximation

$$\begin{cases} E\gamma \approx 7.0 \cdot 10^{-4}\, eV \\ m_\Delta \approx 938 MeV \\ m_p \approx 1232 MeV \end{cases}$$

$$\varepsilon > 10^{-23}$$

GZK cut-off starts to be influenced by the LIV

First constrain on LIV intensity

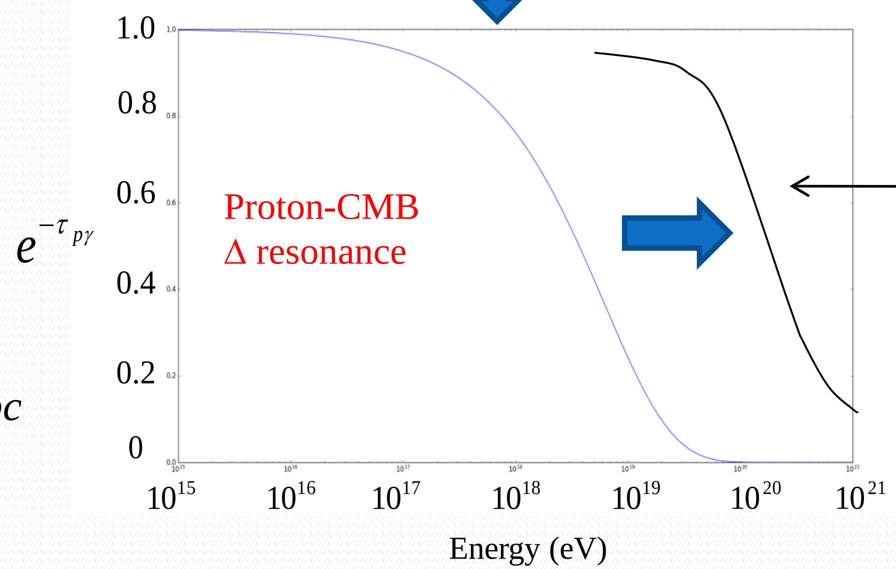
How to compute the GZK spere radius variation

In first approximation the LIV influeneces GZK only if $\varepsilon > 10^{-23}$

In this case the LIV can change the interaction lenght, because of its effect on the proton dynamics.

$$\tau_{p\gamma}(E) = \frac{1}{8p^2}\int_L dx \int_{E_{thr}}^{+\infty}\left\{\left(\frac{1}{e^{\omega/KT}-1}\right)_{CMB} + \frac{f(\omega,T')_{IMB}}{\omega^2}\right\}d\omega \int_{s_{min}}^{s_{max}} K_{in}(s)\sigma_{p\gamma}(s)s\cdot ds$$

Terms modified by LIV



In this plot

$L \approx 50\,Mpc$

The effect is to shift the attenuation curve:
to obtain the same attenuation

a longer path

$$\tau_{p\gamma}(E) = \frac{1}{8p^2}\int_L dx \int_{E_{thr}}^{+\infty}\left\{\left(\frac{1}{e^{\omega/KT}-1}\right)_{CMB} + \frac{f(\omega,T')}{\omega^2}\right\}d\omega \int_{s_{\min}}^{s_{\max}} K_{in}(s)\ \sigma_{p\gamma}(s)\ s\cdot ds$$

This term correction has the same consequences

$$s_{\min} = m_p^{\ 2} - 2\varepsilon\cdot\vec{p}^{\,2} \approx m_p^{\ 2} - 2\varepsilon\cdot E_p^{\ 2}$$

$$s_{\max} = 4E_pE_\gamma - 2\varepsilon\cdot\vec{p}^{\,2} \approx 4E_pE_\gamma - 2\varepsilon\cdot E_p^{\ 2}$$

$$E_{thr} = \left(\frac{m_\Delta^{\ 2} - m_p^{\ 2}}{4E_p}\right) + \frac{1}{2}\varepsilon\cdot E_p$$

Terms introduced by LIV

$$E_p \approx 10^{20}\ eV \qquad \varepsilon \approx 10^{-23}$$

$$\left(\frac{m_\Delta^{\ 2} - m_p^{\ 2}}{4E_p}\right) \approx 10^{-3}\ eV$$

$$\frac{1}{2}\varepsilon\ E_p \approx 10^{-3}\ eV$$

These terms are comparable

This extreme of integration linearly depends on $\varepsilon\cdot E_p$

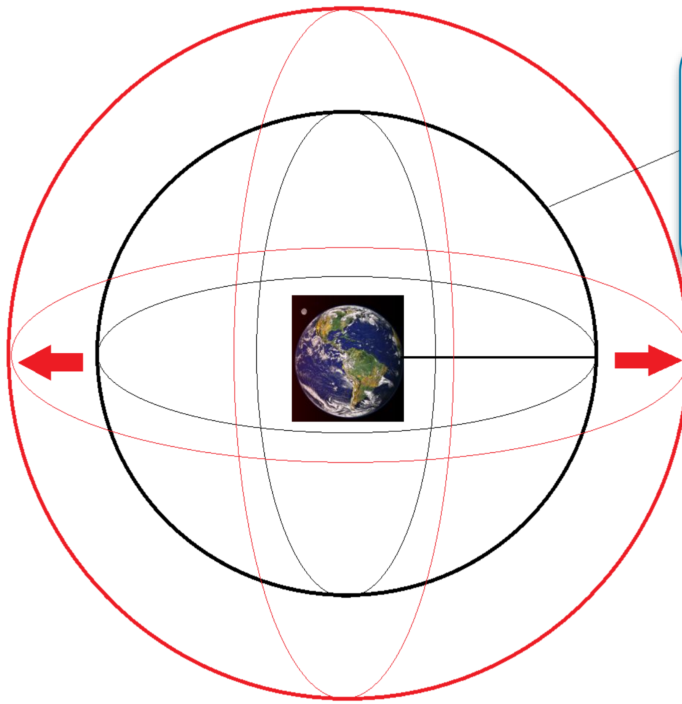
Increasing the LIV parameter, from $\varepsilon \approx 10^{-23}$, for a proton with $E_p \approx 10^{20}\ eV$ attenuation remains the same increasing the path lenght of a not negligible quantity

GZK sphere size is increased by the introduction of LIV

It would be possible to observe protons with energy

$$E \approx 10^{20} eV$$

accelerated farther than the estimated GZK radius



GZK opacity sphere
50 Mpc
160 millions light years

Effect of LIV:
dilatation of the GZK sphere radius

It would be possible to search for correlation between high energy protons and sources collocated outside the GZK sphere

Conclusion

Two cases

$\varepsilon = 0$

GZK effect is present, it is possible to use protons for **anisotropy research**

$\varepsilon > 0$

The GZK sphere increases with ε, asimptotically to infinite

Necessity to compute the GZK sphere expansion magnitude

If the sphere increases, but its radius remains finite

Possible to evaluate constrains to LIV theory, starting from experimental data

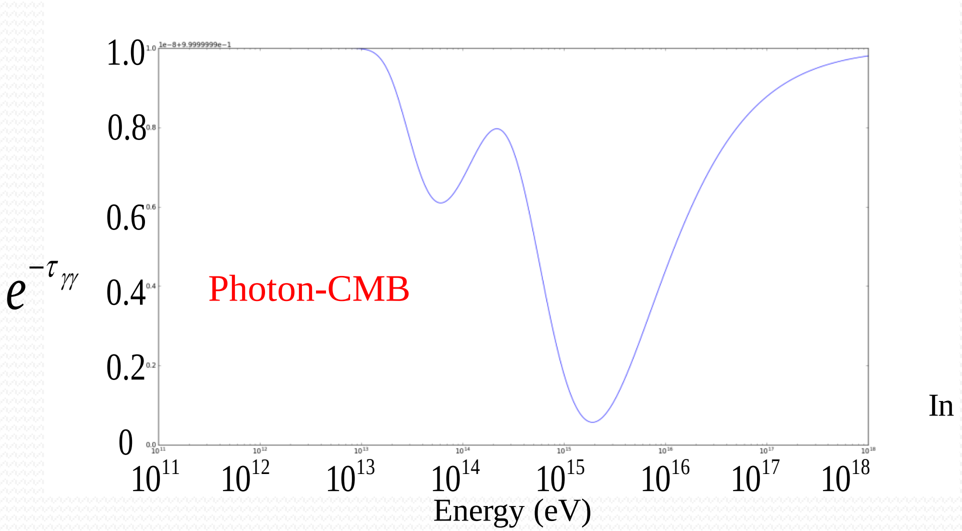
Possible to search correlation with farther sources

Effect of the interaction of photons with the CMB

Attenuation of **photon** for interaction with CMB and galactic-extragalactic E.M. radiation

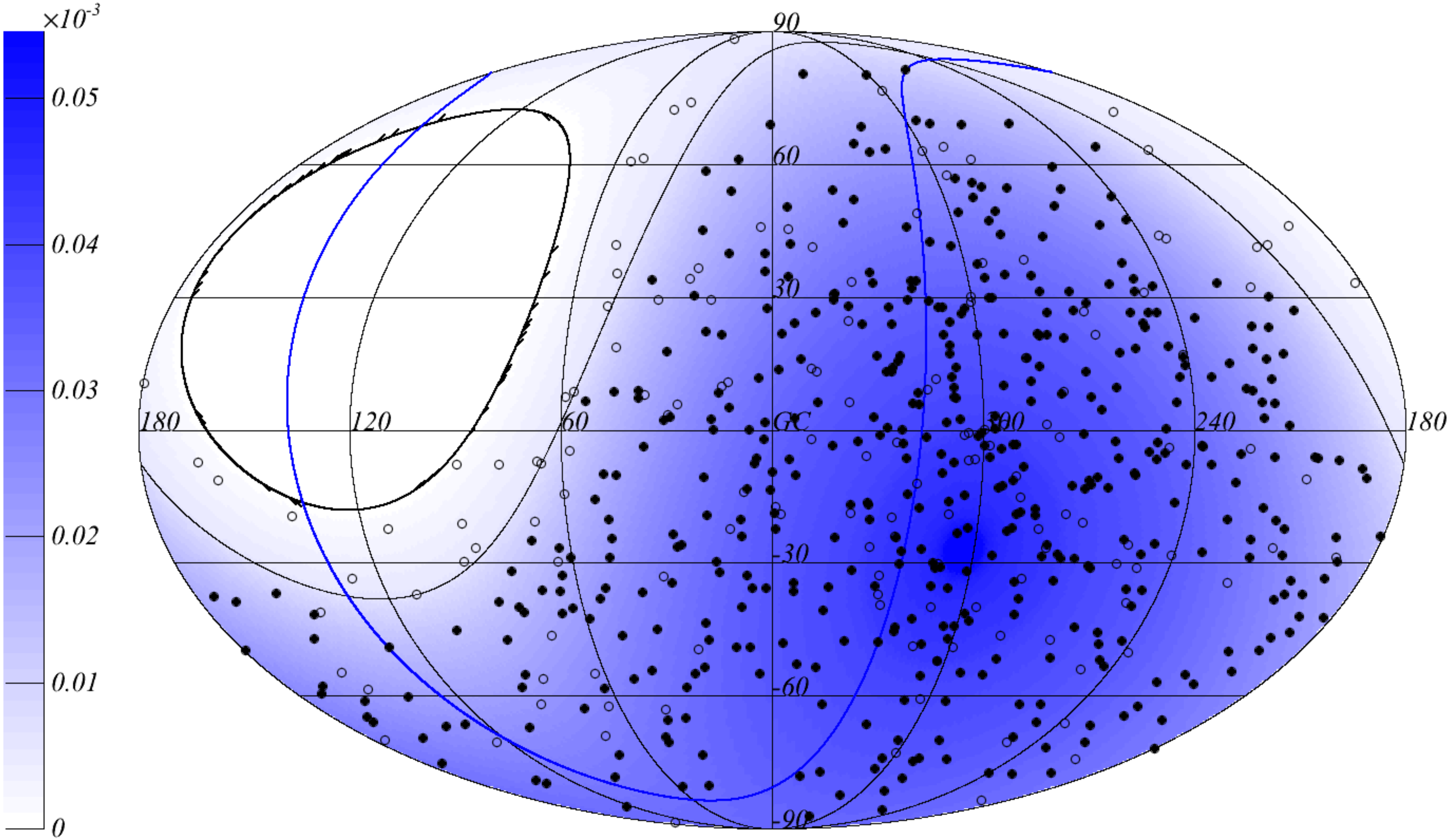
Optical depth:

$$\tau_{\gamma\gamma}(E)=\frac{1}{8E^2}\int_L dx\int_{E_{thr}}^{+\infty}\left\{\left(\frac{1}{e^{\omega/KT}-1}\right)_{CMB}+\frac{f(\omega,T')_{IMB}}{\omega^2}\right\}d\omega\int_{s_{\min}}^{s_{\max}}\sigma_{\gamma\gamma}(s)s\cdot ds$$



In this plot $L\approx 30\,Kpc$

Map of events



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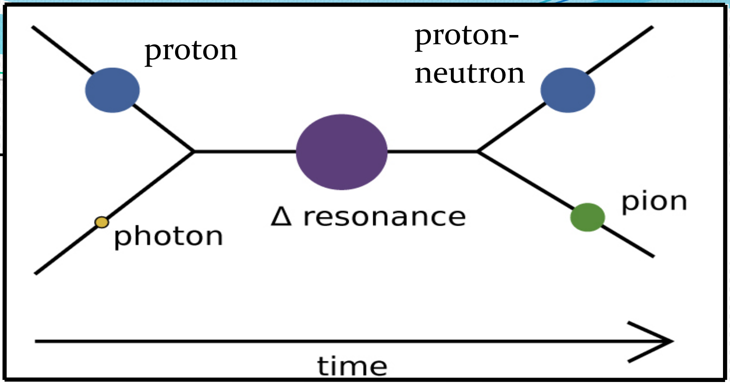
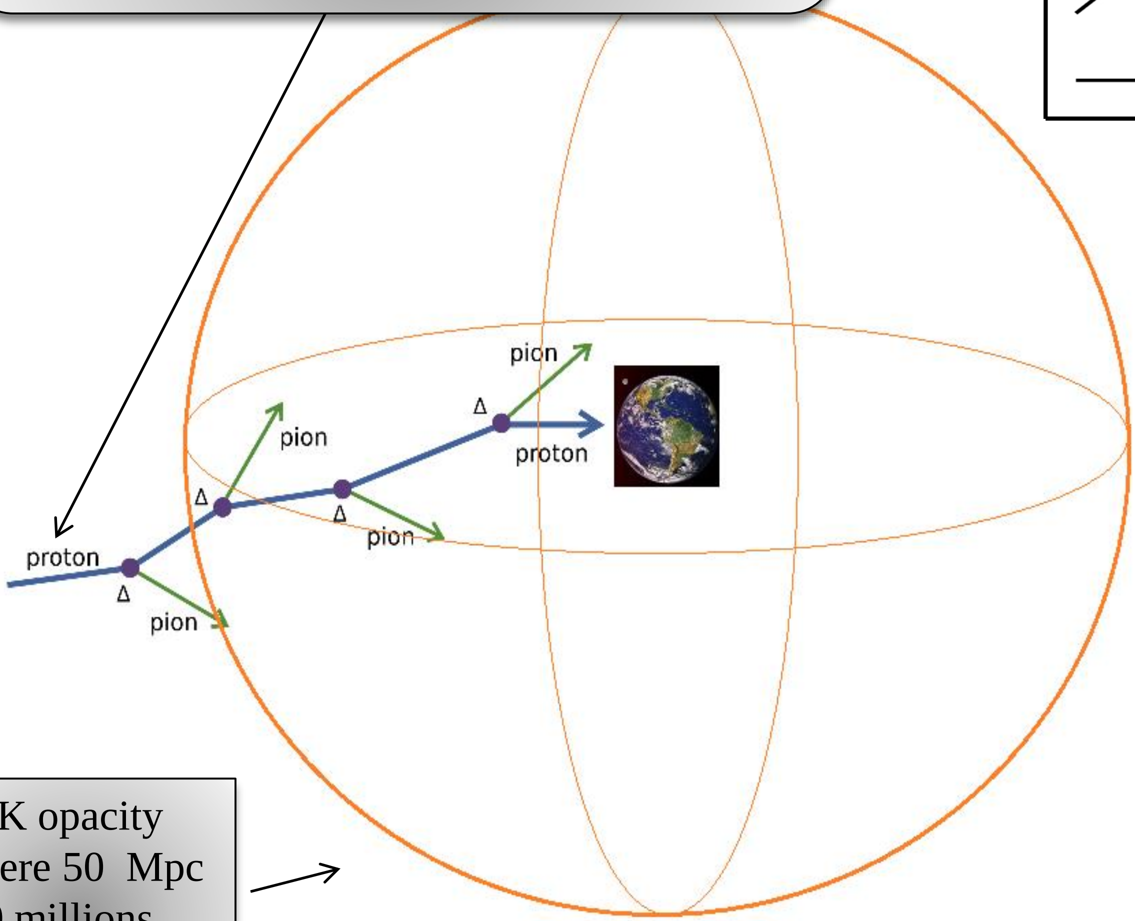




GZK opacity sphere 50 Mpc 160 millions light years

With GZK effect: our universe is opaque to the propagation of protons with energy

$$E \approx 10^{20} eV$$

on distances longer than 50 Mpc

Search for an effective theory

An effective theory has to take into account the modified dispersion relation.

From the modified Dirac equation:

$$\left(\left(i\gamma^{\mu}\partial_{\mu}-m\right)-i\vec{\gamma}\cdot\vec{\nabla}\right)\psi=0$$

follows:

$$\left(\left(i\gamma^{\mu}\partial_{\mu}+m\right)-i\varepsilon\,\vec{\gamma}\cdot\vec{\nabla}\right)\left(\left(i\gamma^{\mu}\partial_{\mu}-m\right)-i\varepsilon\,\vec{\gamma}\cdot\vec{\nabla}\right)\psi=0$$

Substituting in this equation the spinor as: $\psi=u(p)\;e^{-ipx}$ or $\psi=v(p)\;e^{ipx}$ follows:

$$\left(p_0{}^2-(1-\varepsilon)^2\,\vec{p}^2-m^2\right)\begin{cases}u(p)\\v(p)\end{cases}=0$$

the required dispersion relation →

$$E^2\approx(1-2\varepsilon)\vec{p}^2+m^2$$

This equation is compatible with a redefinition of the Dirac matrices: $\Gamma_0'=\gamma_0$ $\vec{\Gamma}=\vec{\gamma}(1-\varepsilon)$

$$\{\Gamma_{\mu}',\Gamma_{\nu}\}=2g_{\mu\nu}$$

The previous implies redefinition of the metric tensor:

$$g_{\mu\nu}=\begin{pmatrix}1&0&0&0\\0&-(1-2\varepsilon)&0&0\\0&0&-(1-2\varepsilon)&0\\0&0&0&-(1-2\varepsilon)\end{pmatrix}$$

This corresponds to a different maximum attainable velocity

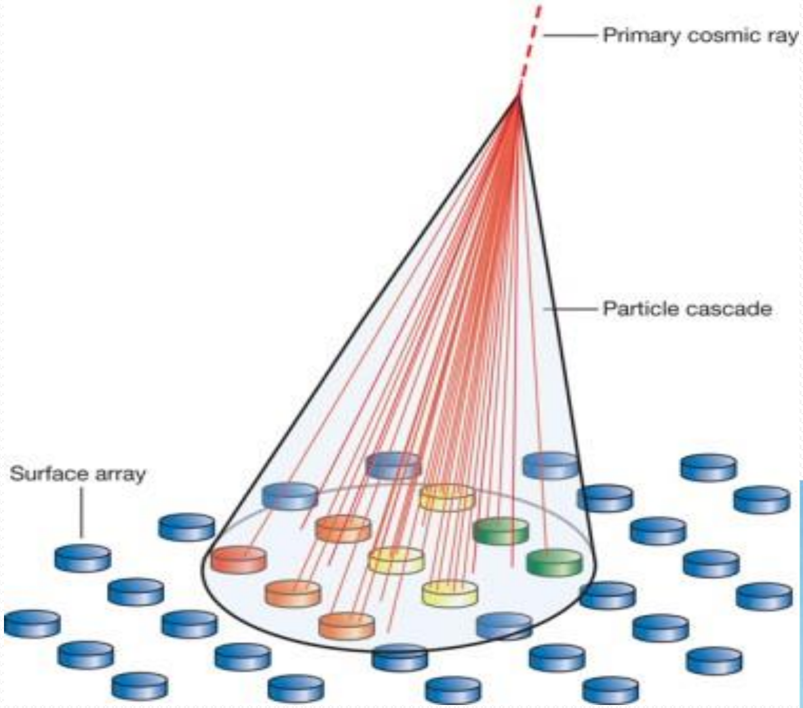
The corresponding effective Lagrangiane for a free fermionic particle is:

$$L = \overline{\psi}\left(i\Gamma^{\mu}\partial_{\mu} - m\right)\psi$$

In the simple model considered here the space-time structure is always isotropic

More generals LIV theory imply the coupling of the fermion with other fields (spurions).
These fields must be equal to zero in the privileged frame of reference where the CBM is isotropic.
This corresponds to have a space-time metric tensor in the form of a Finsler metric.

Collecting a sampling of an Extended Air Shower cascade at ground

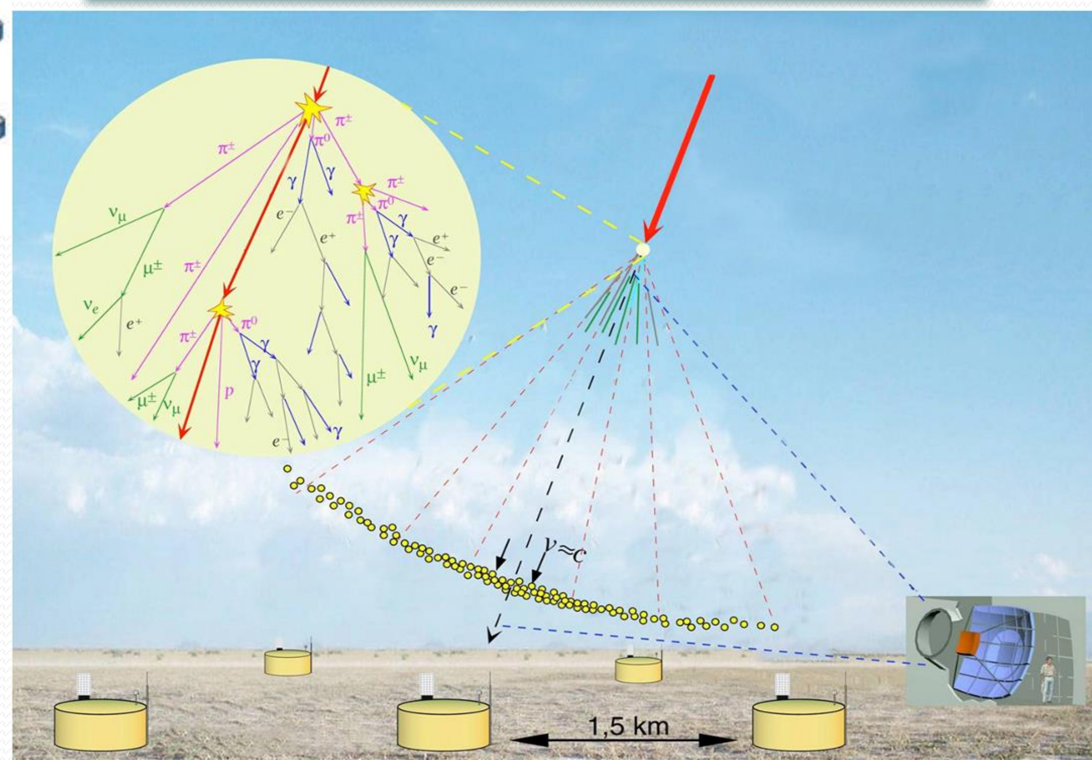


The sampling is collected using Water Cerenkov Tanks (WTD)

Precise timing of arrival at ground is essential to reconstruct the provenience direction of the primary Cosmic Ray

The number of particles at ground at a reference distance from the shower axis is a good **energy** estimator.

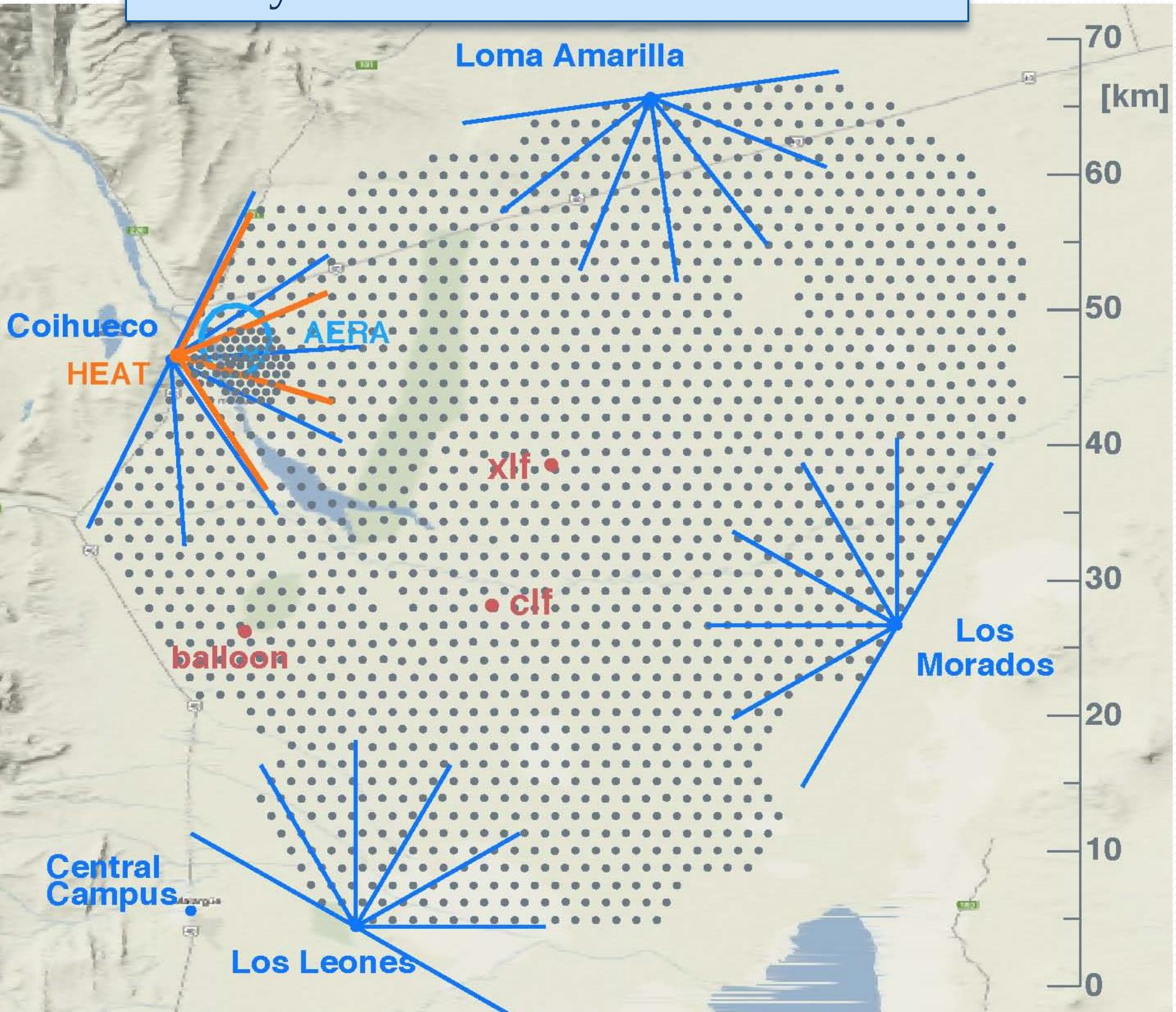
To improve the data collecting Pierre Auger Obsevatory uses even Fluorescence Detector (FD) Telescopes.



The Pierre Auger Observatory

Above ~40 EeV the flux is extremely low: less than one particle per km^2 per century

→ Necessity of a very big apparatus

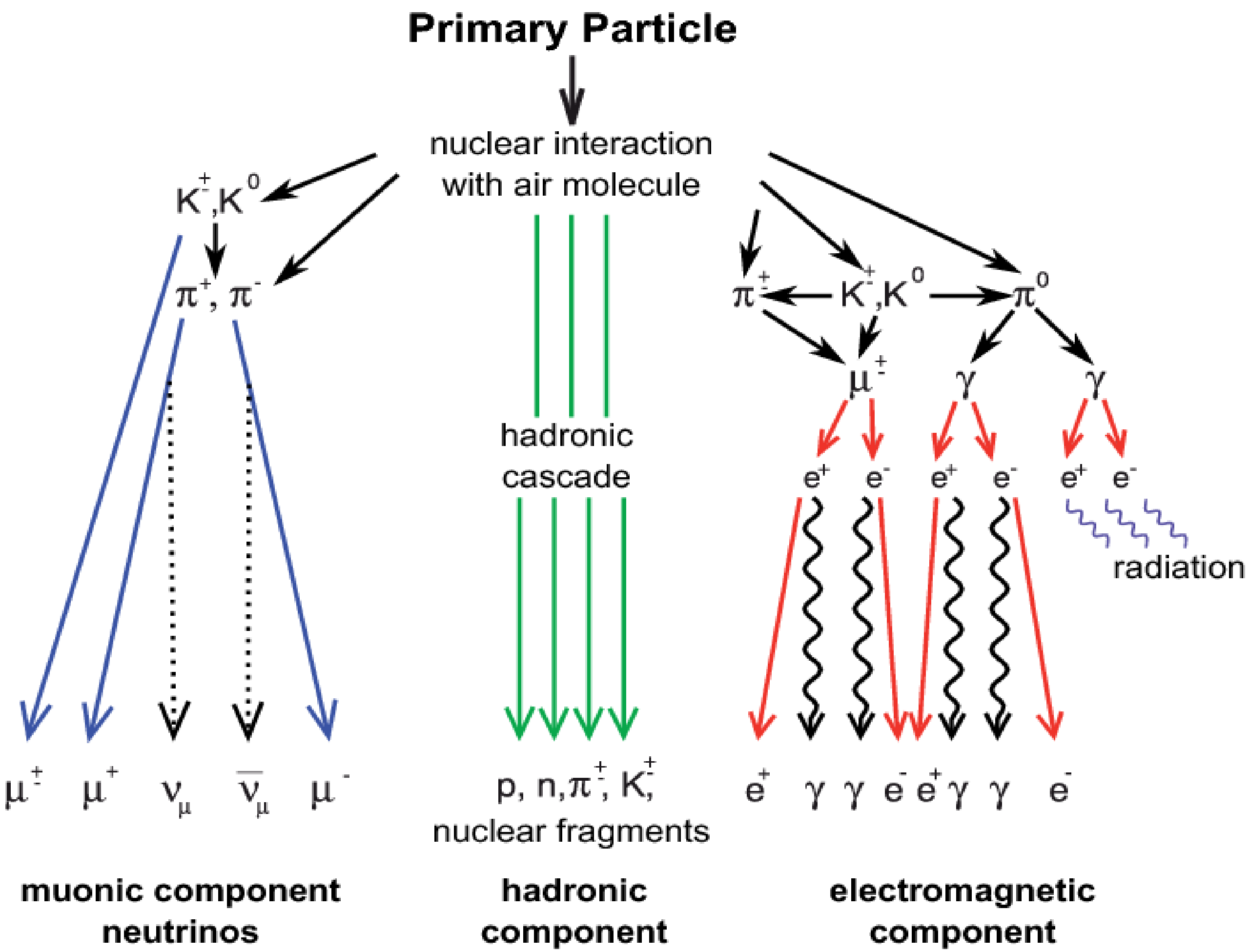


Surface detector (SD)
1600 water Cherenkov detectors
1.5 km spacing
~3000 km^2

Fluorescence detector (FD) 24 UV telescopes

Hadronic cascade

When a UHECR interact with the high atmosphere, it creates a cascade of secondary particles: an extensive air shower (EAS)
The atmosphere operates like a Calorimeter



ENERGY of an EAS at ground revelators

- Muons 10%
- Neutrinos 1%
- Hadronic cascade 4%
- Electromagnetic component 85%