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Acad. Prof. Matey Mateev

# New Improved Operational Model for Cosmic Ray Effects in Space Physics

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# Abstract

The influences of galactic and solar cosmic rays (CR) in the middle atmosphere and lower ionosphere are mainly related to ionization and excitation. In this way, CR modify the electric conductivity in the middle atmosphere and the electric processes in it. One fundamental problem in the understanding of interaction between CR and the neutral components in the atmosphere is precisely determination of the electron production rate profiles.

The effects of galactic and solar cosmic rays in the middle atmosphere can be computed with our model CRIMA. We take into account the CR modulation by solar wind and the anomalous CR component also. A new analytical approach for CR ionization by protons and nuclei with charge Z in the lower ionosphere and the middle atmosphere is developed. For this purpose, the ionization losses *(dE/dh)* for the energetic charged particles according to the Bohr-Bethe-Bloch formula are approximated in different energy intervals (two ionization losses intervals, one charge Z decrease interval and intermediate coupling intervals).

Electron production rate profiles *q(h)* are determined by the numerical evaluation of a 3D integral with account of cut-off rigidities. For calculations are used computer algebra systems Wolfram Mathematica 7 and Maple 14, and Pascal procedures.

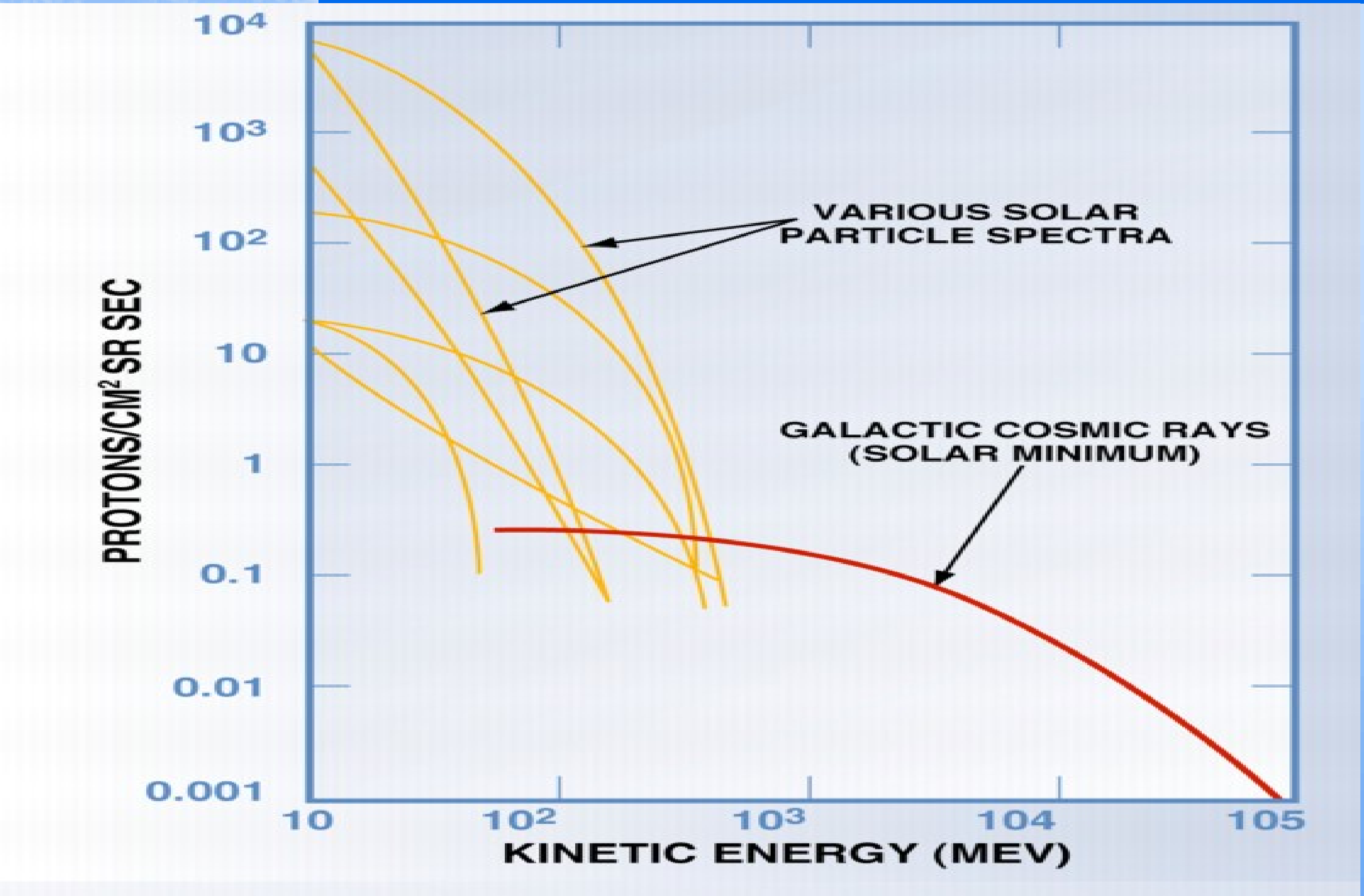
# Contents of the presentation

- An introduction in Cosmic Ray Ionization Model for the Atmosphere (CRIMA)
- Reviews of the main results and computer simulations made by CRIMA
- Some results by CORSIKA simulations in middle and lower atmosphere
- Future development and conclusions

# Introduction

- CR are main ionization agent in middle atmosphere and lower ionosphere
- The influence of CR penetration in the Earth's atmosphere is important for understanding of the solar-terrestrial relationships and space weather
- The presented model is developed on the base of Bohr-Bethe-Bloch theory for ionization losses due to charged particles penetration through substance
- This new generalized model contributes to the better accuracy of the problem solution towards the experimental data
- An intermediate transition region between neighbouring energy intervals is introduced and the charge decrease interval is taken into account

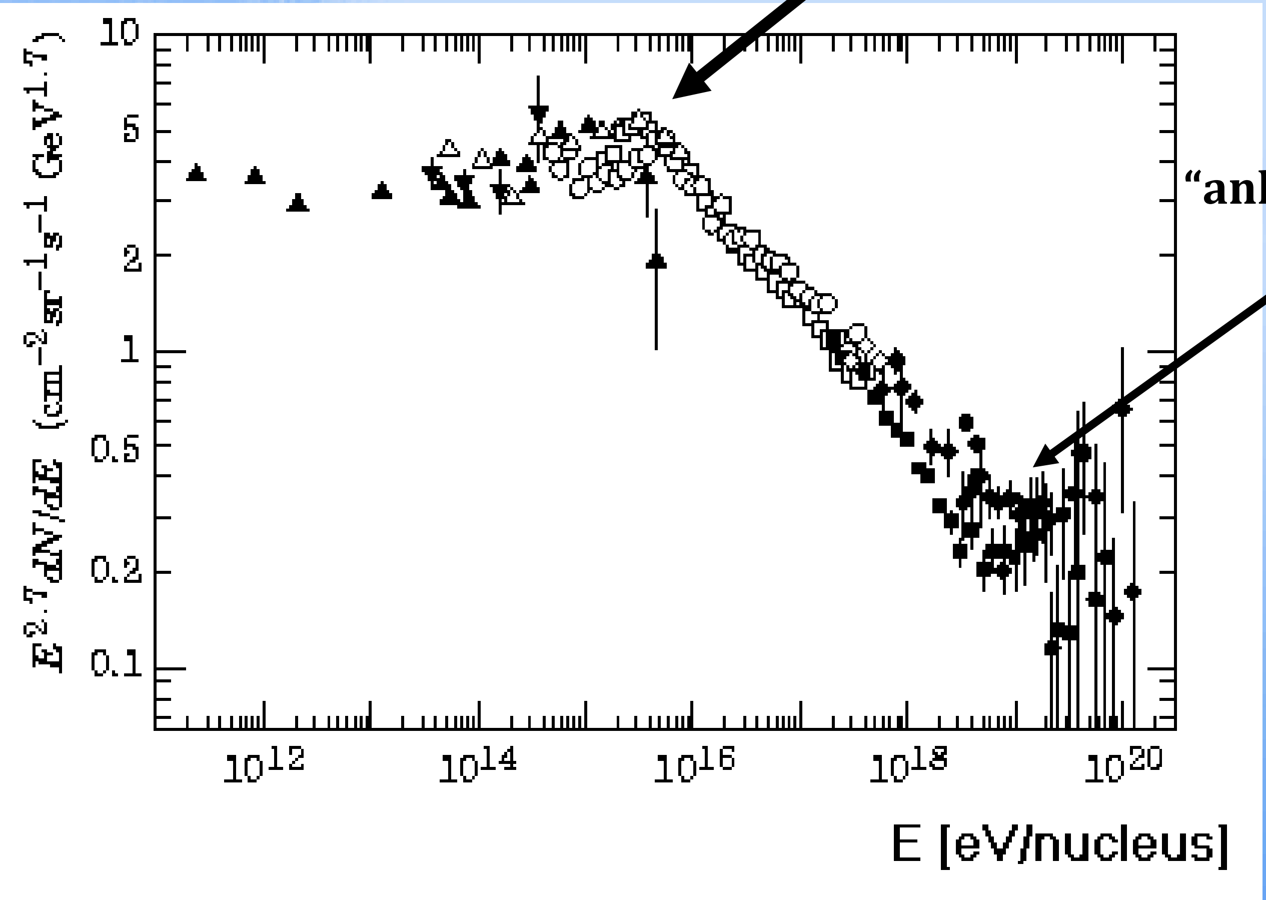
# Cosmic ray spectra



# Cosmic ray spectrum

$10^4$ m$^{-2}$ s$^{-1}$ ~ $10^9$ eV      $10^{-2}$ km$^{-2}$ yr$^{-1}$ ~$10^{21}$ eV

**“knee”**




**“ankle”**

# Mathematical background

Energy intervals approximation in six steps of the ionization losses function according to Bohr-Bethe-Bloch theory and with account of experimental data :

$$-\frac{1}{\rho}\frac{dE}{dh} = \begin{cases} 2.57\times 10^{3} E^{0.5} & \text{if } kT \le E \le 0.15 \text{ MeV/n} & \text{, interval } 1 \\ 1540\ E^{0.23} & \text{if } 0.15 \le E \le E_a = 0.15\ Z^2 \text{ MeV/n} & \text{, interval } 2 \\ 231\times Z^2 E^{-0.77} & \text{if } E_a \le E \le 200 \text{ MeV/n} & \text{, interval } 3 \\ 68\times Z^2 E^{-0.53} & \text{if } 200 \le E \le 850 \text{ MeV/n} & \text{, interval } 4 \\ 1.91\times Z^2 & \text{if } 850 \le E \le 5\times 10^{3} \text{ MeV/n} & \text{, interval } 5 \\ 0.66\times Z^2 E^{0.123} & \text{if } 5\times 10^{3} \le E \le 5\times 10^{6} \text{ MeV/n} & \text{, interval } 6 \end{cases} \qquad (1)$$

$E$ – kinetic energy of particles

$kT$ – thermal energy

Interval 2 – charge decrease interval

$Z$ – charge of the penetrating particle

# Atmospheric cut-offs

- **The energy cut-offs (atmospheric and geomagnetic) determined the starting point of CR differential spectrum at the top of the atmosphere**
- The atmospheric cut-offs are derived for those values of the traveling substance path, which correspond to the actual energy interval of the ionization losses function

$$\tilde{h} = \int_{E_{\min}}^{E} \frac{dE}{\frac{1}{\rho}\left(\frac{dE}{dh}\right)} = \int_{h_1}^{h_\infty} \rho(h)\,dh \approx \rho(h)H(h) \qquad (2)$$

where:

$\tilde{h}$ - traveling substance path

$\rho(h)$ - neutral density in the atmosphere at altitude $h$

$H(h)$ – scale height

# Energy cut offs in Intervals 1-3

- Interval 1

$$E_{A1}(h) = \left[\frac{1285}{A}\tilde{h} + (kT)^{0.5}\right]^2 \qquad (3)$$

- Interval 2 (charge decrease interval)

$$E_{A2}(h) = \left[0.15^{0.77} - 0.9228\left(0.15^{0.5} - (kT)^{0.5}\right) + \frac{1185.8}{A}\tilde{h}\right]^{1/0.77} \qquad (4)$$

- Interval 3

$$E_{A3}(h) = \left[E_a^{1.77} - 0.3182 \times Z^2\left(0.15^{0.5} - (kT)^{0.5}\right) -\right.$$

$$\left. - 0.345 \times Z^2\left(E_a^{0.77} - 0.15^{0.77}\right) + 408.87\left(Z^2 / A\right)\tilde{h}\right]^{1/1.77} \qquad (5)$$

# Energy cut offs in Intervals 4-6

- Interval 4

$$E_{A4}(h) = \Big[200^{1.53} + 104.04\frac{Z^2}{A}\tilde{h} - 0.081 \times Z^2\left(0.15^{0.5} - (kT)^{0.5}\right) -$$

$$- 0.088 \times Z^2\left(E_a^{0.77} - 0.15^{0.77}\right) - 0.254 \times \left(200^{1.77} - E_a^{1.77}\right)\Big]^{1/1.53} \qquad (6)$$

- Interval 5

$$E_{A5}(h) = \frac{1.91 \times Z^2}{A}\tilde{h} + 850 - 1.49 \times 10^{-3} \times Z^2\left(0.15^{0.5} - (kT)^{0.5}\right) -$$

$$-1.6 \times 10^{-3} \times Z^2\left(E_a^{0.77} - 0.15^{0.77}\right) - 4.67 \times 10^{-3}\left(200^{1.77} - E_a^{1.77}\right) - 0.018 \times \left(850^{1.53} - 200^{1.53}\right) \qquad (7)$$

- Interval 6

$$E_{A6}(h) = \Big[5000^{0.877} + 0.579\frac{Z^2}{A}\tilde{h} - 4.5 \times 10^{-4} \times Z^2 \times \left(0.15^{0.5} - (kT)^{0.5}\right) - 4.88 \times 10^{-4} \times Z^2\left(E_a^{0.77} - 0.15^{0.77}\right) -$$

$$-1.41 \times 10^{-3}\left(200^{1.77} - E_a^{1.77}\right) - 5.56 \times 10^{-3}\left(850^{1.53} - 200^{1.53}\right) - 1257{,}45\Big]^{1/0{,}877} \qquad (8)$$

# Boundary crossing between the different energy intervals

- **The boundary crossing defines the energy transfer over the interval limits**

- Boundary crossing between intervals 1 and 2

$$E_{21}(h) = \left[ 0.15^{0.5} + 1.08\left(E_k^{0.77} - 0.15^{0.77}\right) - \frac{1285}{A}\tilde{h} \right]^2 \qquad (9)$$

- Boundary crossing between intervals 2 and 3

$$E_{32}(h) = \left[ E_a^{0.77} + \frac{2.9}{Z^2}\left(E_k^{1.77} - E_a^{1.77}\right) - \frac{1185.8}{A}\tilde{h} \right]^{1/0.77} \qquad (10)$$

# Boundary crossing between the different energy intervals

- Boundary crossing between intervals 3 and 4

$$E_{43}(h) = \left[ 200^{1.77} + 3.93\left(E_k^{1.53} - 200^{1.53}\right) - \frac{408.87 \times Z^2}{A}\tilde{h} \right]^{1/1.77} \qquad (11)$$

- Boundary crossing between intervals 4 and 5

$$E_{54}(h) = \left[850^{1.53} + 54.47\left(E_k - 850\right) - 104.04\left(Z^2 / A\right)\tilde{h}\right]^{1/1.53} \qquad (12)$$

- Boundary crossing between intervals 5 and 6

$$E_{65}(h) = 5000 - 1.91\left(Z^2 / A\right)\tilde{h} + 3.3\left(E_k^{0.877} - 5000^{0.877}\right) \qquad (13)$$

# Initial energies for interval boundaries

- **They define the starting energy values of the interval limits before entering of charged particles in the atmosphere**

- Initial energy of boundary between intervals 1 and 2

$$E_{0.15;2}(h) = \left[0.15^{0.77} + \frac{1185.8}{A}\tilde{h}\right]^{1/0.77} \qquad (14)$$

- Initial energy of boundary between intervals 2 and 3

$$E_{E_a,3}(h) = \left[E_a^{1.77} + 408.87\left(Z^2/A\right)\times\tilde{h}\right]^{1/1.77} \qquad (15)$$

# Initial energies for interval boundaries

- Initial energy of boundary between intervals 3 and 4

$$E_{200,4}(h) = \left[200^{1.53} + 104.04 \times \left(Z^2 / A\right) \times \tilde{h}\right]^{1/1.53} \qquad (16)$$

- Initial energy of boundary between intervals 4 and 5

$$E_{850,5}(h) = 850 + 1.91\left(Z^2 / A\right)\tilde{h} \qquad (17)$$

- Initial energy of boundary between intervals 5 and 6

$$E_{5000,6}(h) = \left[5000^{0.877} + 0.579 \times \left(Z^2 / A\right) \times \tilde{h}\right]^{1/0.877} \qquad (18)$$

# Energy decrease laws in internal regions

- **They define the energy decrease in the energy intervals without boundary crossings**

- Energy decrease law in interval 1

$$E_1(h) = \left[ E_k^{0.5} - \frac{1285}{A} \tilde{h} \right]^2 \qquad (19)$$

- Energy decrease law in interval 2

$$E_2(h) = \left[ E_k^{0.77} - \frac{1185.8}{A} \times \tilde{h} \right]^{1/0.77} \qquad (20)$$

# Energy decrease laws in internal regions

- Energy decrease law in interval 3

$$E_3(h) = \left[E_k^{1.77} - 408.87\left(Z^2 / A\right)\times \tilde{h}\right]^{1/1.77} \qquad (21)$$

- Energy decrease law in interval 4

$$E_4(h) = \left[E_k^{1.53} - 104.04 \times \left(Z^2 / A\right)\times \tilde{h}\right]^{1/1.53} \qquad (22)$$

- Energy decrease law in interval 5

$$E_5(h) = E_k - 1.91 \times \left(Z^2 / A\right)\times \tilde{h} \qquad (23)$$

- Energy decrease law in interval 6

$$E_6(h) = \left[E_k^{0.877} - 0.579 \times \left(Z^2 / A\right)\times \tilde{h}\right]^{1/0.877} \qquad (24)$$

# Electron production rate in 6 energy intervals with CR charge decrease

- **The improved CR ionization model includes the electron production rate terms in 6 energy intervals of the ionization losses function and 5 intermediate transition region terms between the basic intervals**

- ***Lower boundary of integration $E_{min}$*.** The following case of lower integration boundary is assumed:

$$kT \leq E_{A1}(h) \leq E_{\min} \leq 0.15 < E_{\mathrm{a}} \ \mathrm{MeV/n} \qquad (25)$$

- The lower bound of integration $E_{\min}$ is chosen as the maximum of the atmospheric cut-off and the geomagnetic cut-off rigidity
- The case of vertical penetration of cosmic rays is considered
- This model can be extended to the 3-dimensional case in the Earth environment with introduction of the Chapman function

# Electron production rate in 6 energy intervals with CR charge decrease

$$
\begin{aligned}
q(h) = \frac{\rho(h)}{Q} \Bigg\{ & 2570 \left[ \int_{E_{\min}}^{0.15} D(E)[E_1(h)]^{0.5}\, dE + \int_{0.15}^{E_{0.15;2}(h)} D(E)[E_{21}(h)]^{0.5}\, dE \right] + \\
& 1540 \left[ \int_{E_{0.15;2}(h)}^{E_a} D(E)[E_2(h)]^{0.23}\, dE + \int_{E_a}^{E_{E_a,3}(h)} D(E)[E_{32}(h)]^{0.23}\, dE \right] + \\
& 231 \times Z^2 \left[ \int_{E_{E_a,3}(h)}^{200} D(E)[E_3(h)]^{-0.77}\, dE + \int_{200}^{E_{200,4}(h)} D(E)[E_{43}(h)]^{-0.77}\, dE \right] + \\
& 68 \times Z^2 \left[ \int_{E_{200,4}(h)}^{850} D(E)[E_4(h)]^{-0.53}\, dE + \int_{850}^{E_{850,5}(h)} D(E)[E_{54}(h)]^{-0.53}\, dE \right] + \\
& \int_{E_{850,5}(h)}^{5000} D(E)\frac{dE}{dh}[E_5(h)]dE + \int_{5000}^{E_{5000,6}(h)} D(E)\frac{dE}{dh}[E_{65}(h)]dE + 0.66 \times Z^2 \int_{E_{5000,6}(h)}^{\infty} D(E)[E_6(h)]^{0.123}\, dE \Bigg\}
\end{aligned}
$$

# Results

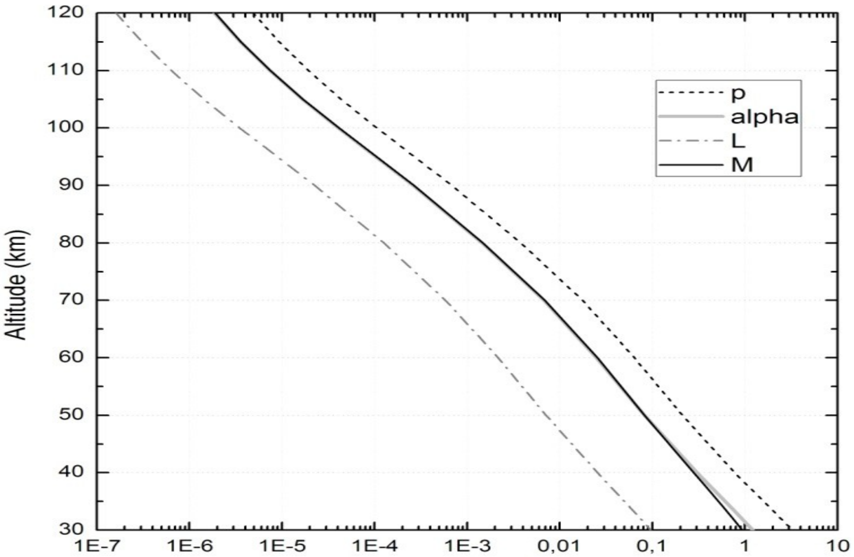



Fig. 1 Electron production rate profiles for the indicated groups of CR nuclei

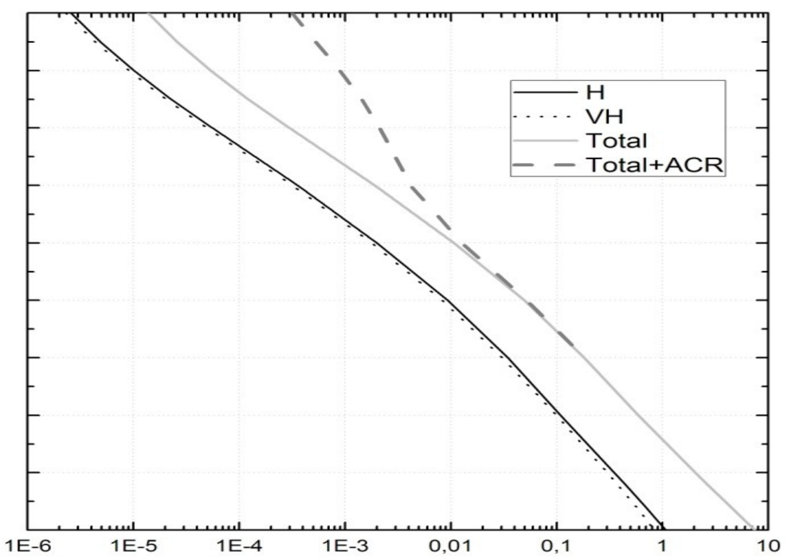



Fig. 2 Electron production rate profiles for the indicated groups of CR nuclei, total ionization rate and ACR contribution

- The electron production rate values are proportional to the square of the charge ($Z^2$), flux intensity in the different energies and the neutral density in middle atmosphere

- Above 90 km ACR ionization dominates over GCR ionization

# Results

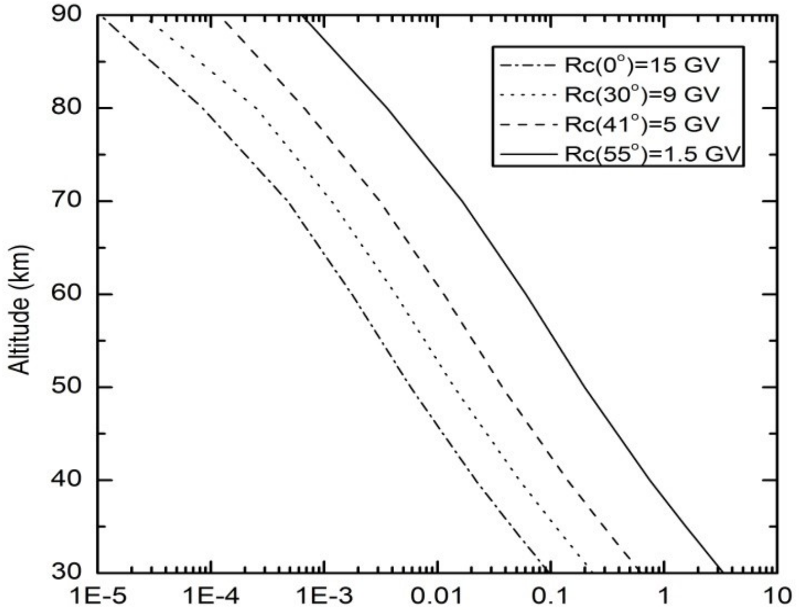



Figure 3. Total electron production rate ($cm^3 . s^{-1}$) for different geomagnetic cut offs.

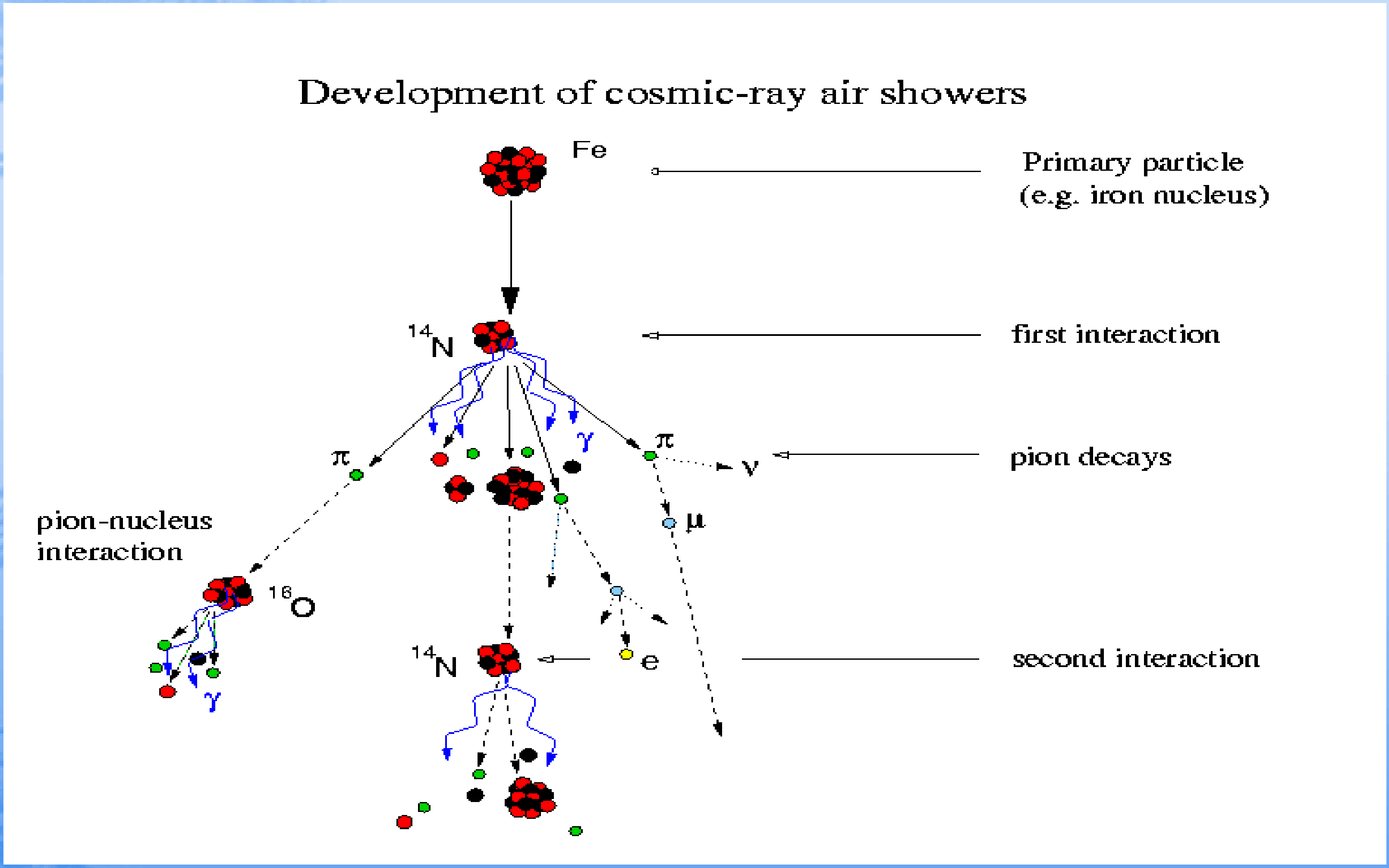
- The geomagnetic cut offs reflect the influence of the geomagnetic field on the CR penetration in the middle atmosphere of the Earth.

- For the higher $R_c$ are obtained the profiles with smaller values.

# CORSIKA

- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles
- Hadronic interactions at lower energies are described either by the GHEISHA interaction routines, by a link to FLUKA
- Version CORSIKA 6.970 from July 19, 2010 (D. Heck et al.)

# Atmospheric cascade

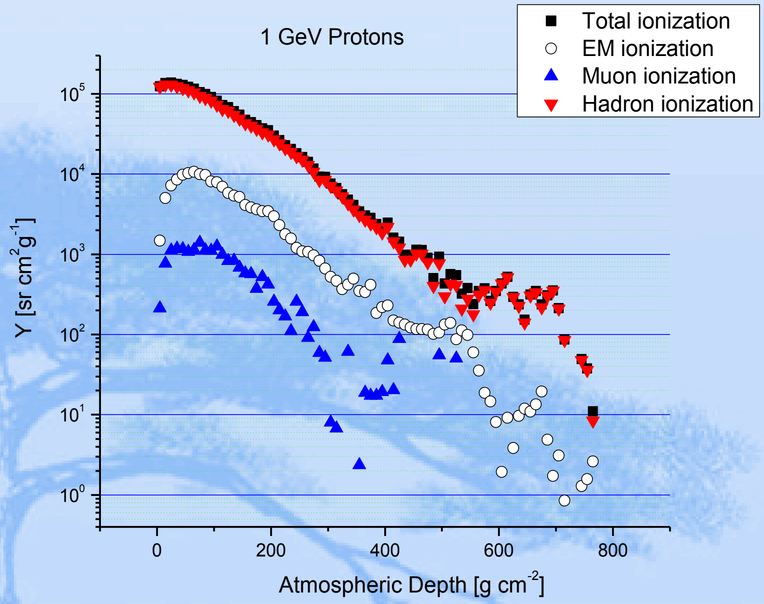


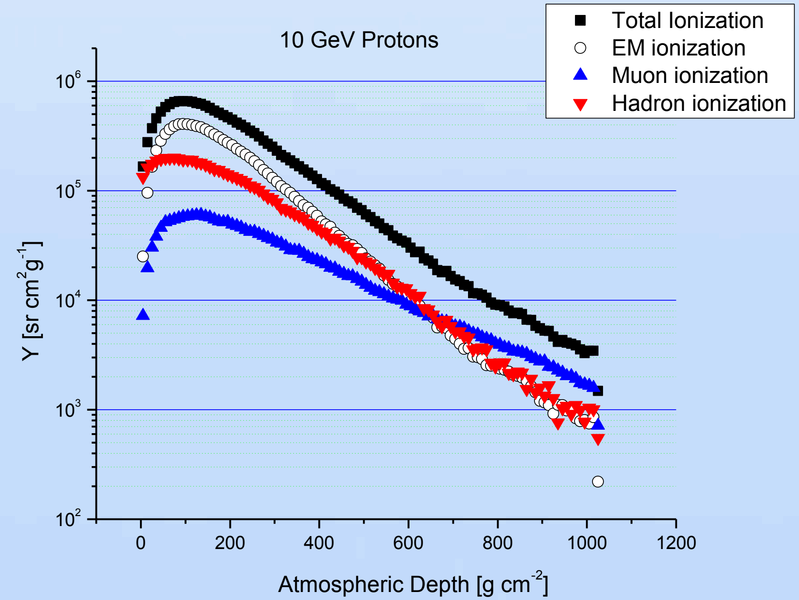
# Ionization yield function *Y, Oulu model*

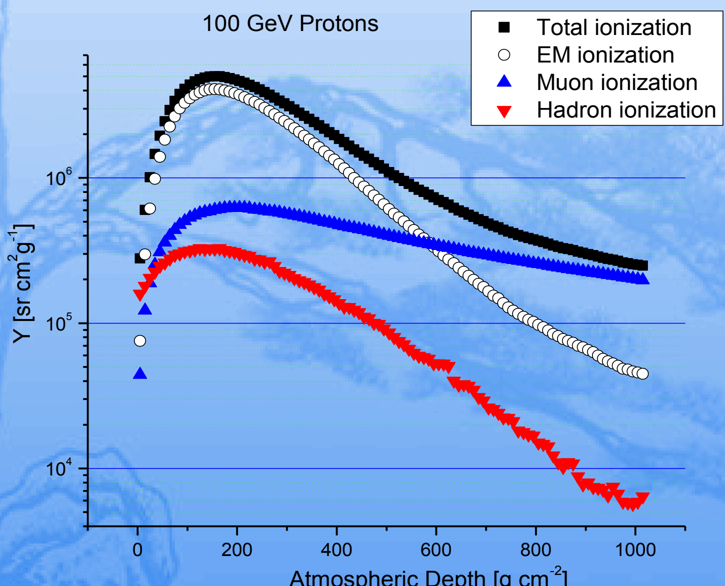
$$Y(x,E) = \Delta E(x,E)\frac{1}{\Delta x}\cdot\frac{1}{E_{ion}}\cdot\Omega$$

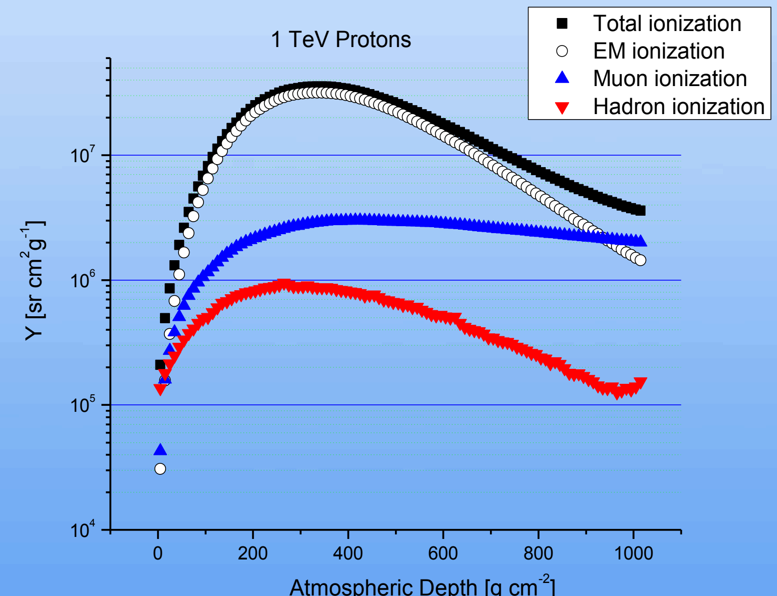
**Ion rate**

$$q(h,\lambda_m) = \int_{E_0}^{\infty} D(E,\lambda_m)Y(h,E)\cdot\rho(h)dE$$

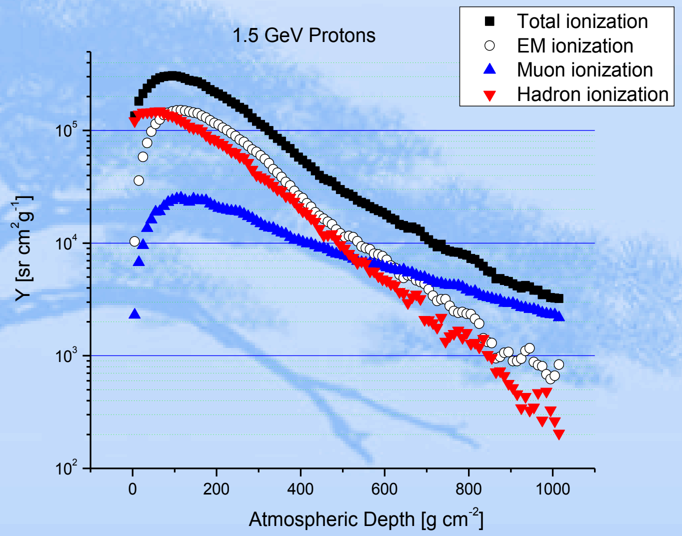

1 GeV Protons
Total ionization
EM ionization
Muon ionization
Hadron ionization
Y [sr cm²g⁻¹]
Atmospheric Depth [g cm⁻²]
0
200
400
600
800

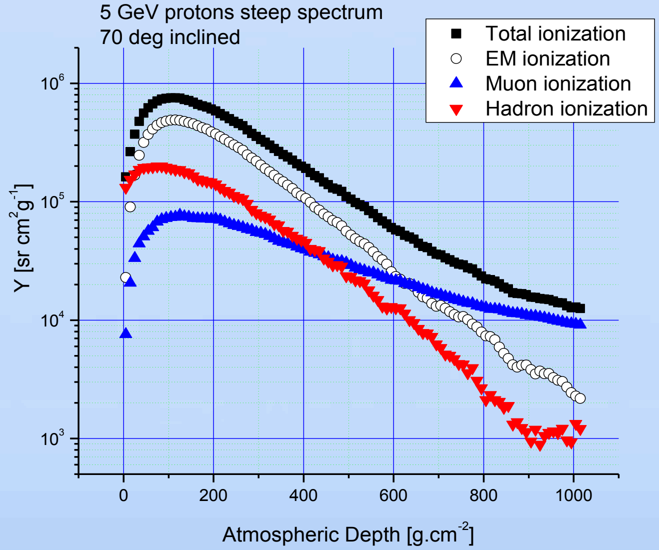

10 GeV Protons
Total Ionization
EM ionization
Muon ionization
Hadron ionization
Y [sr cm²g⁻¹]
Atmospheric Depth [g cm⁻²]
0
200
400
600
800
1000
1200

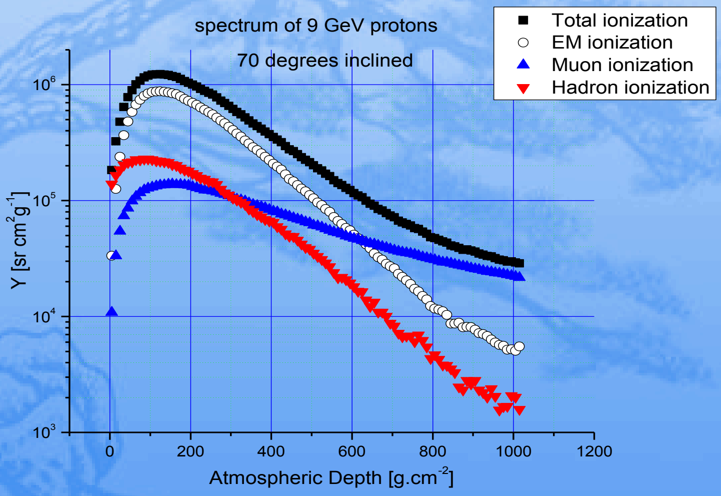

100 GeV Protons
Total ionization
EM ionization
Muon ionization
Hadron ionization
Y [sr cm²g⁻¹]
Atmospheric Depth [g cm⁻²]
0
200
400
600
800
1000

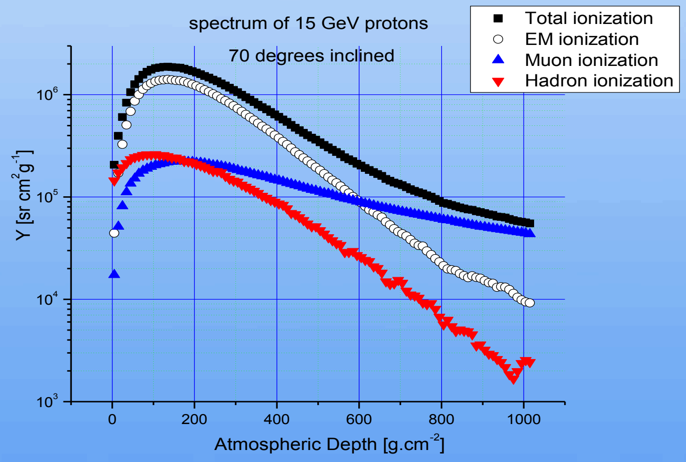

1 TeV Protons
Total ionization
EM ionization
Muon ionization
Hadron ionization
Y [sr cm²g⁻¹]
Atmospheric Depth [g cm⁻²]
0
200
400
600
800
1000

# $Y \sim$ spectrum

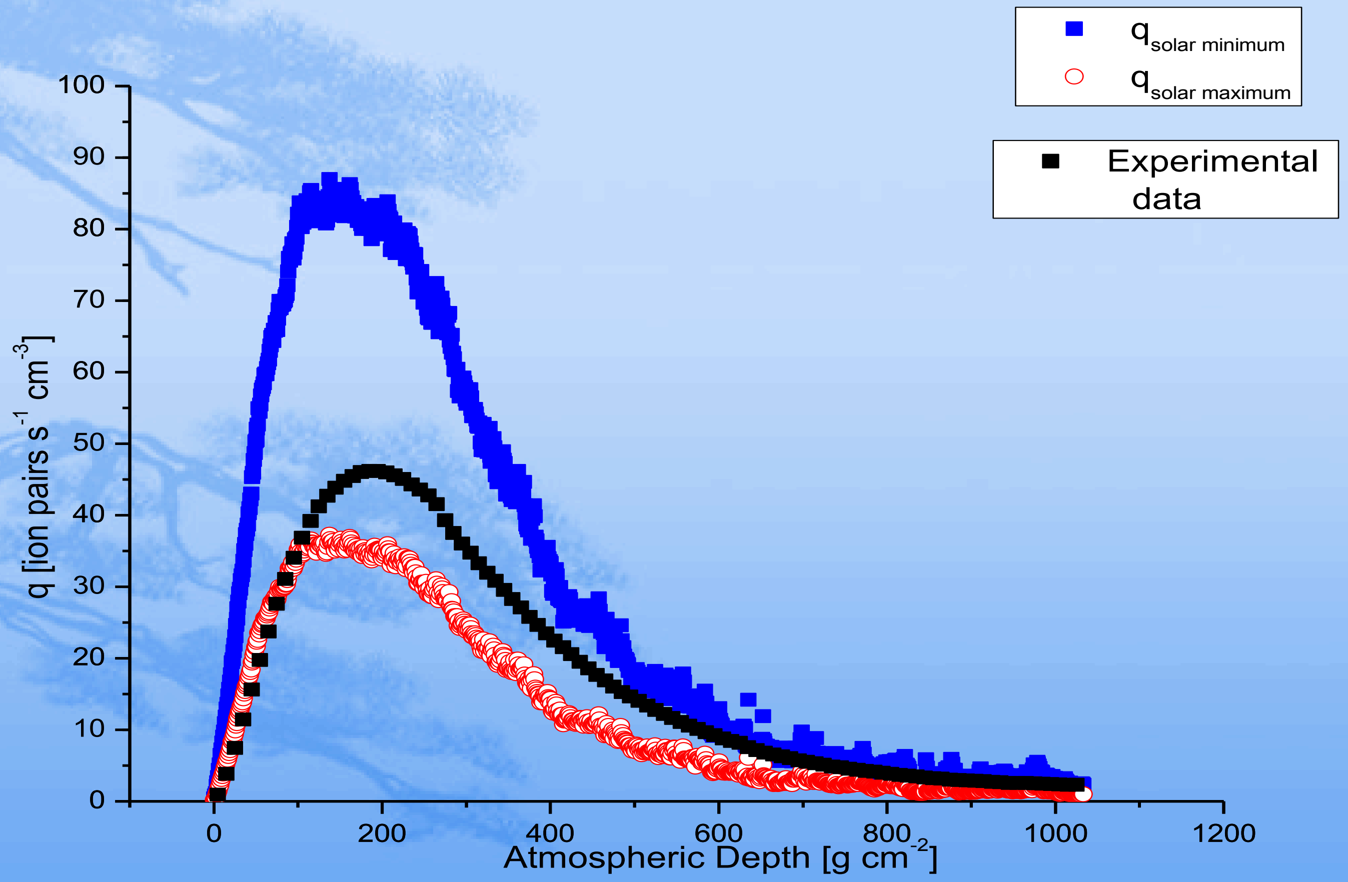


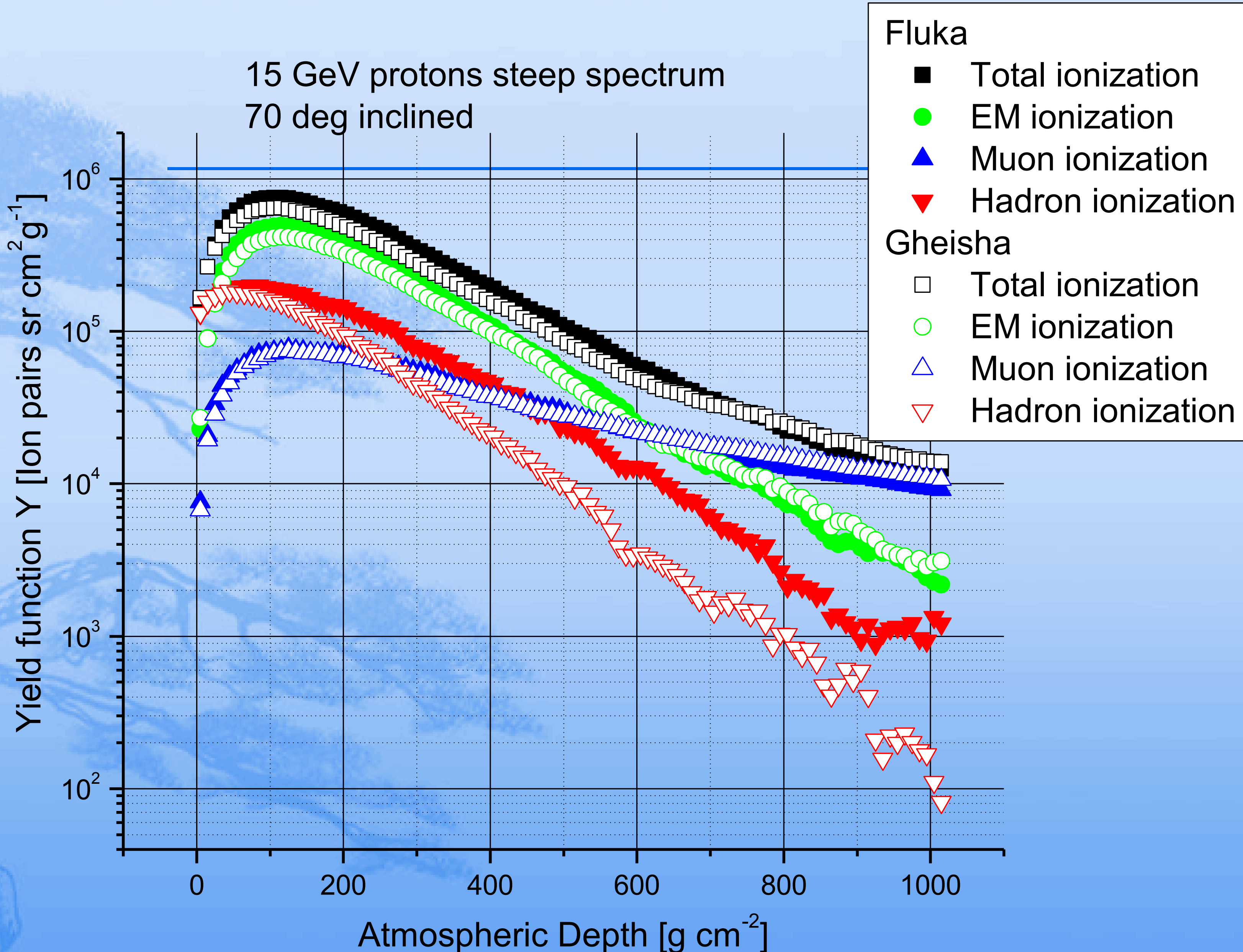



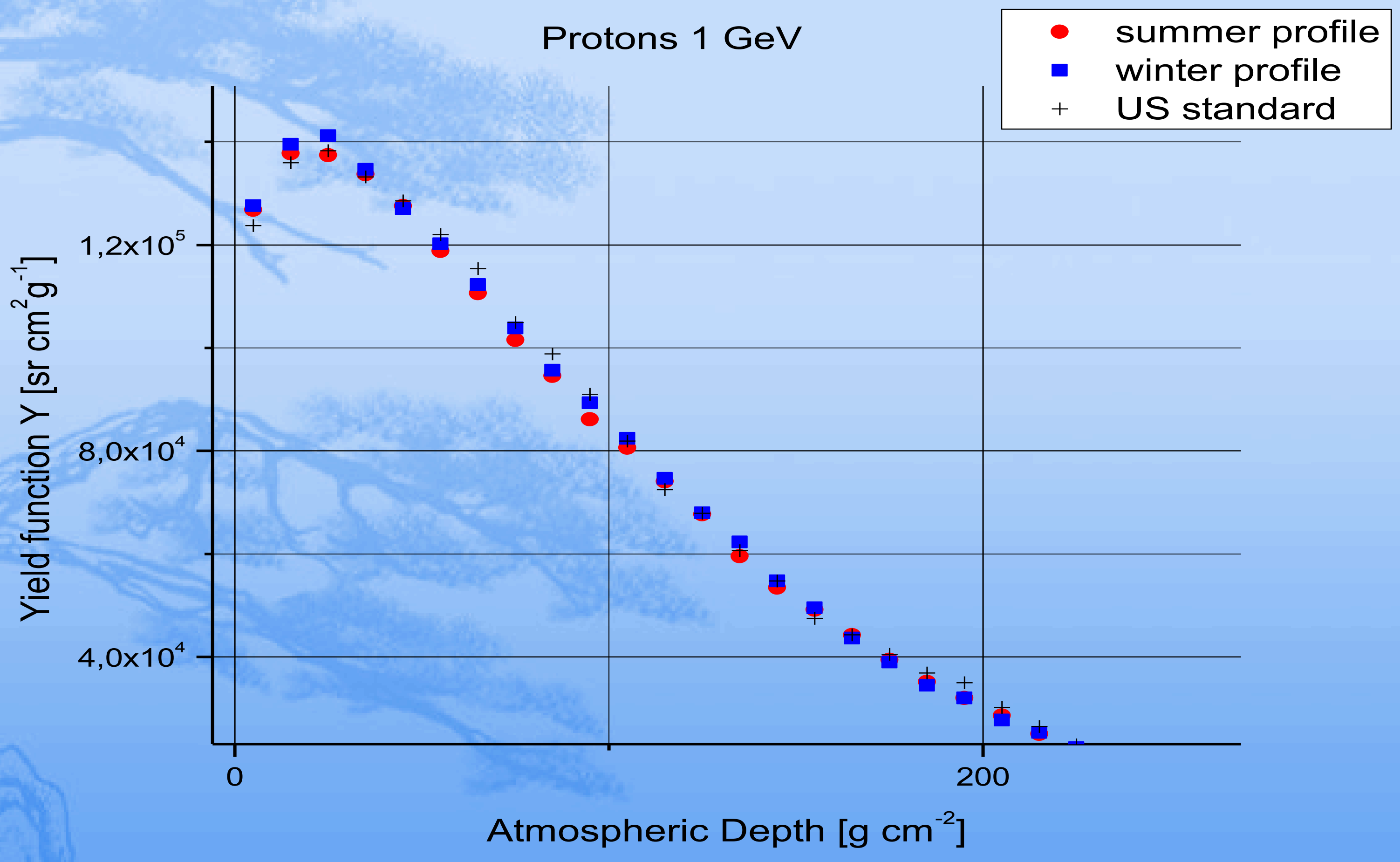



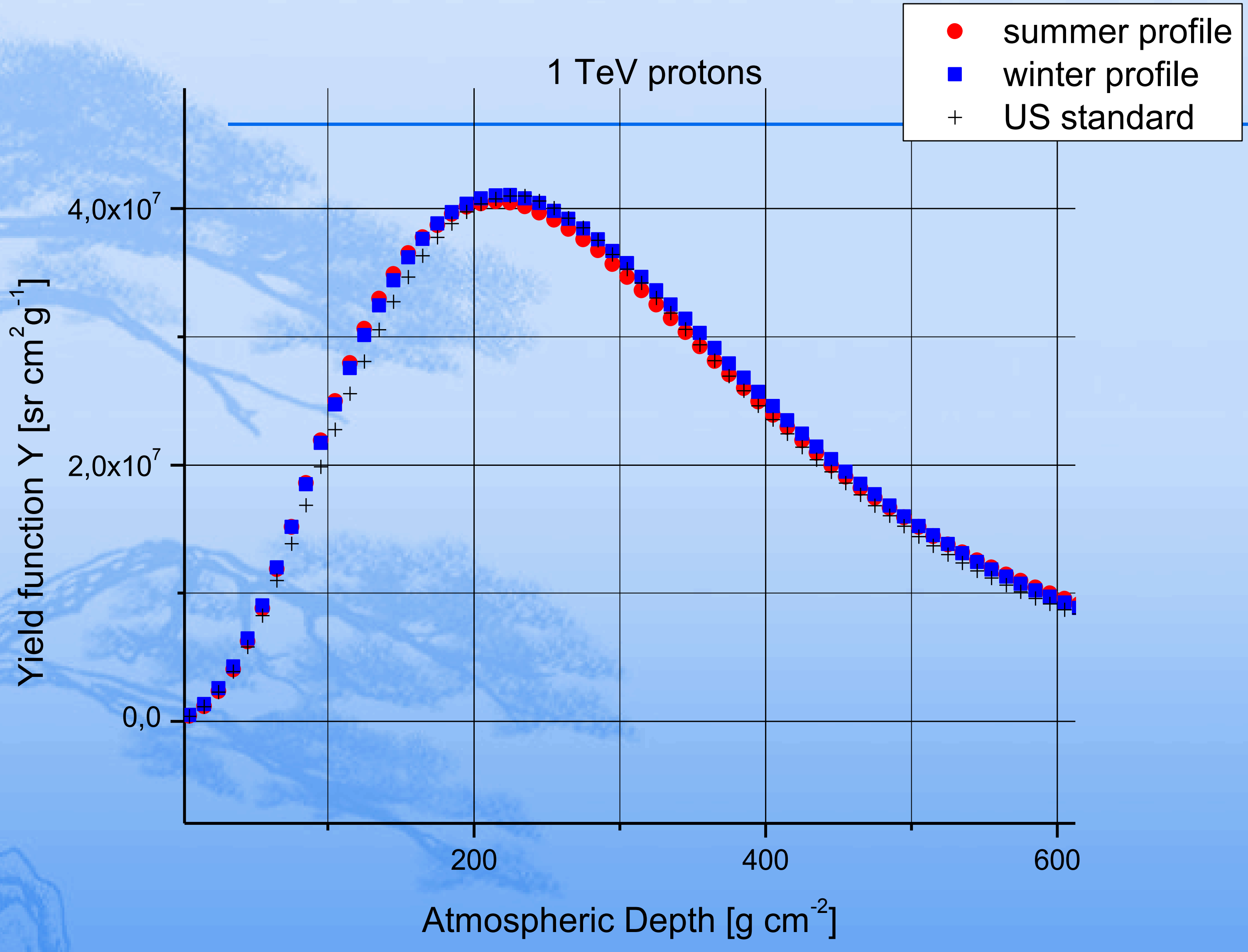
# Comparison with experimental data



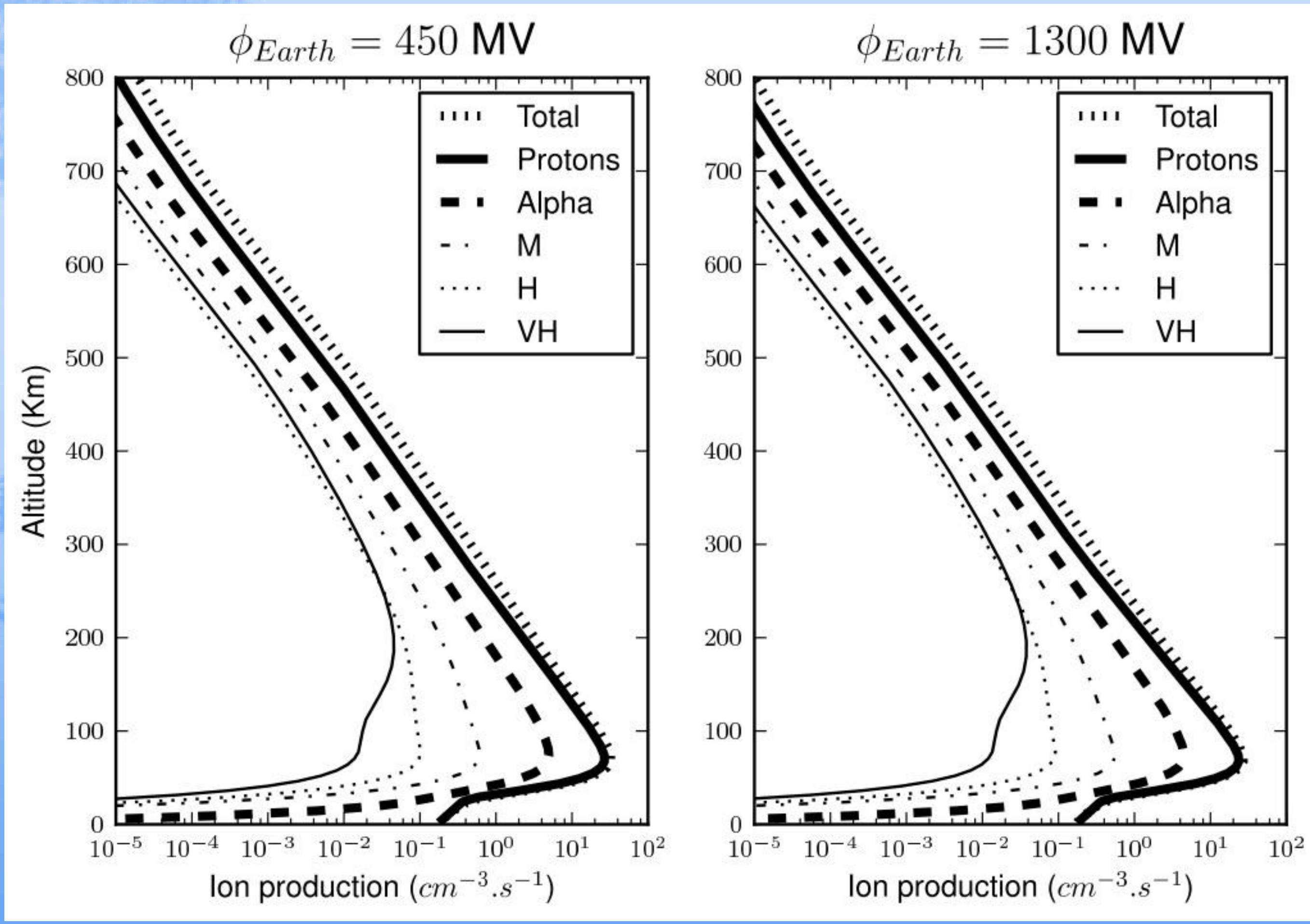

15 GeV protons steep spectrum
70 deg inclined
Fluka
Total ionization
EM ionization
Muon ionization
Hadron ionization
Gheisha
Total ionization
EM ionization
Muon ionization
Hadron ionization
Yield function Y [Ion pairs sr cm$^2$g$^{-1}$]
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
0
200
400
600
800
1000
Atmospheric Depth [g cm$^{-2}$]

# Impact of atmospheric models

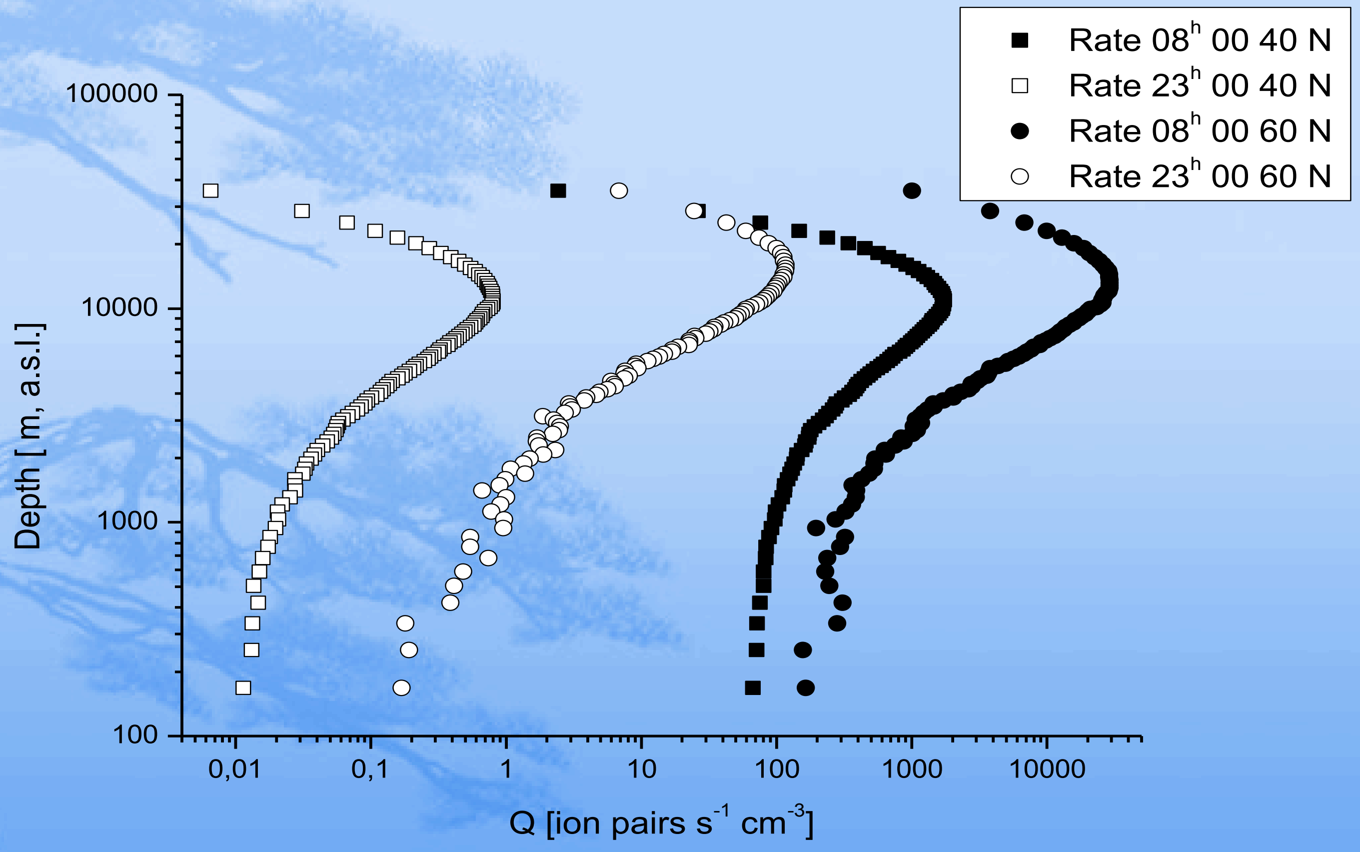


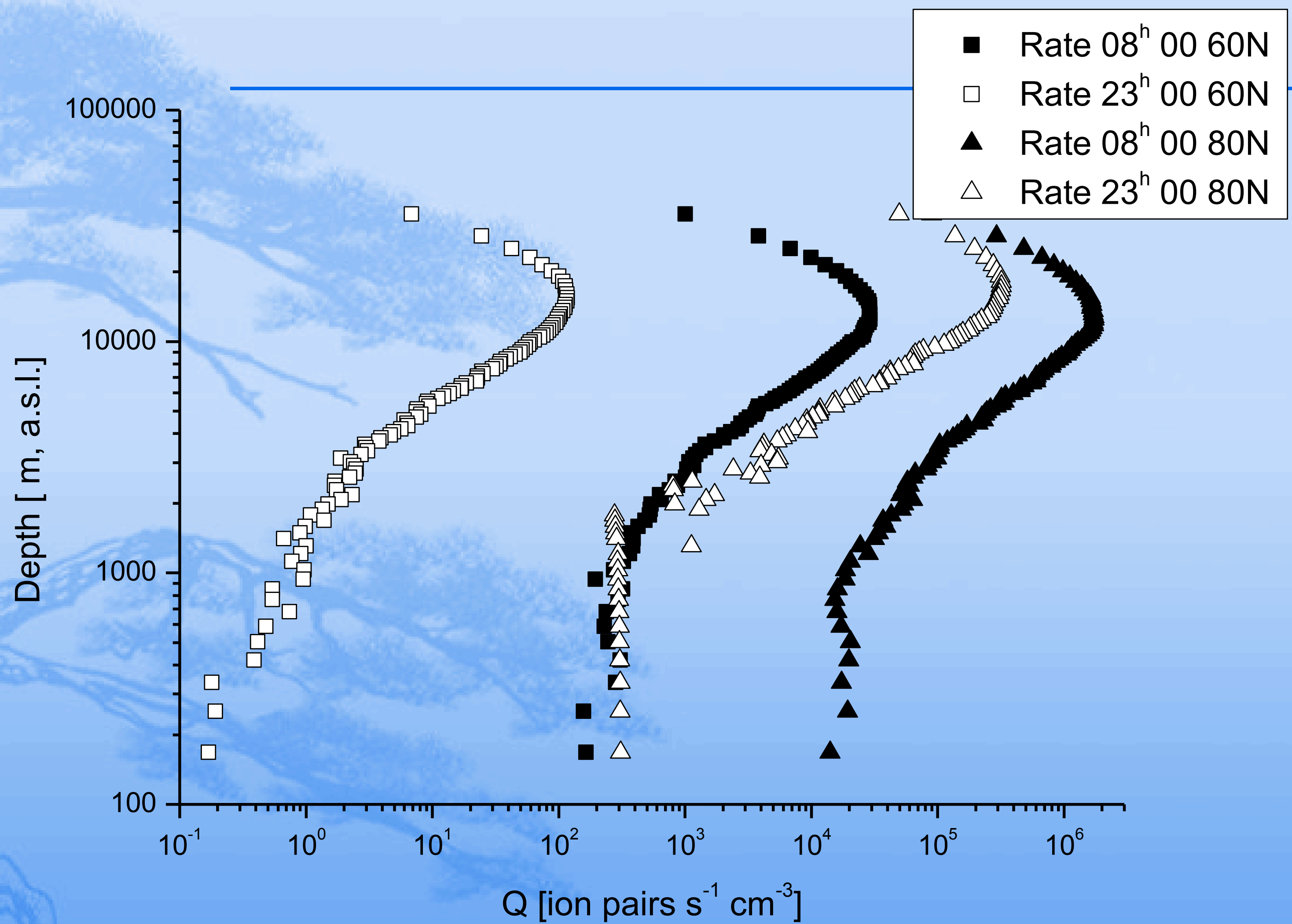

1 TeV protons
summer profile
winter profile
US standard
4,0x10^7
2,0x10^7
0,0
Yield function Y [sr cm^2 g^-1]
200
400
600
Atmospheric Depth [g cm^-2]

# Electron production rate in Titan's atmosphere



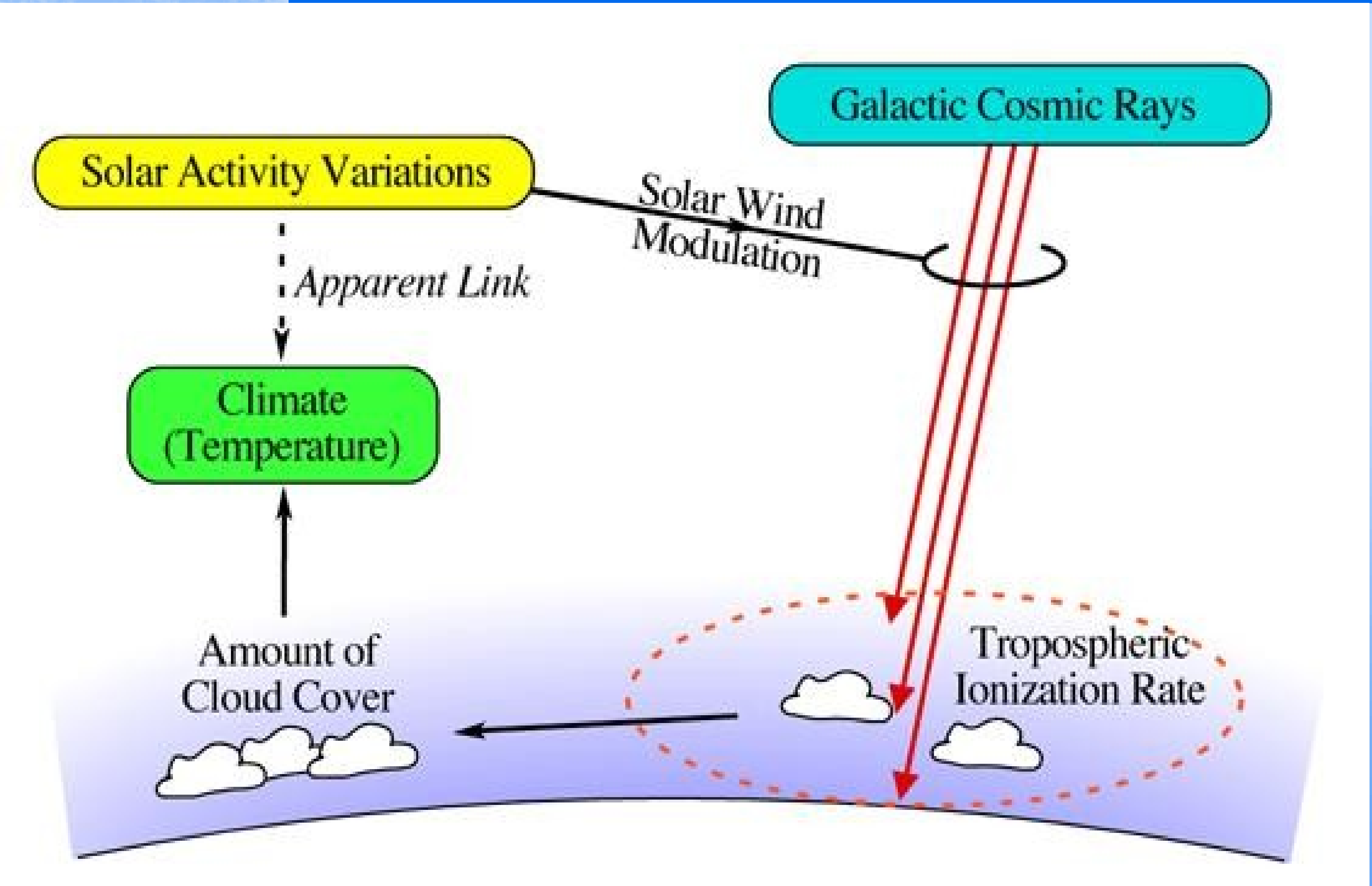
# SEP on 20 January 2005

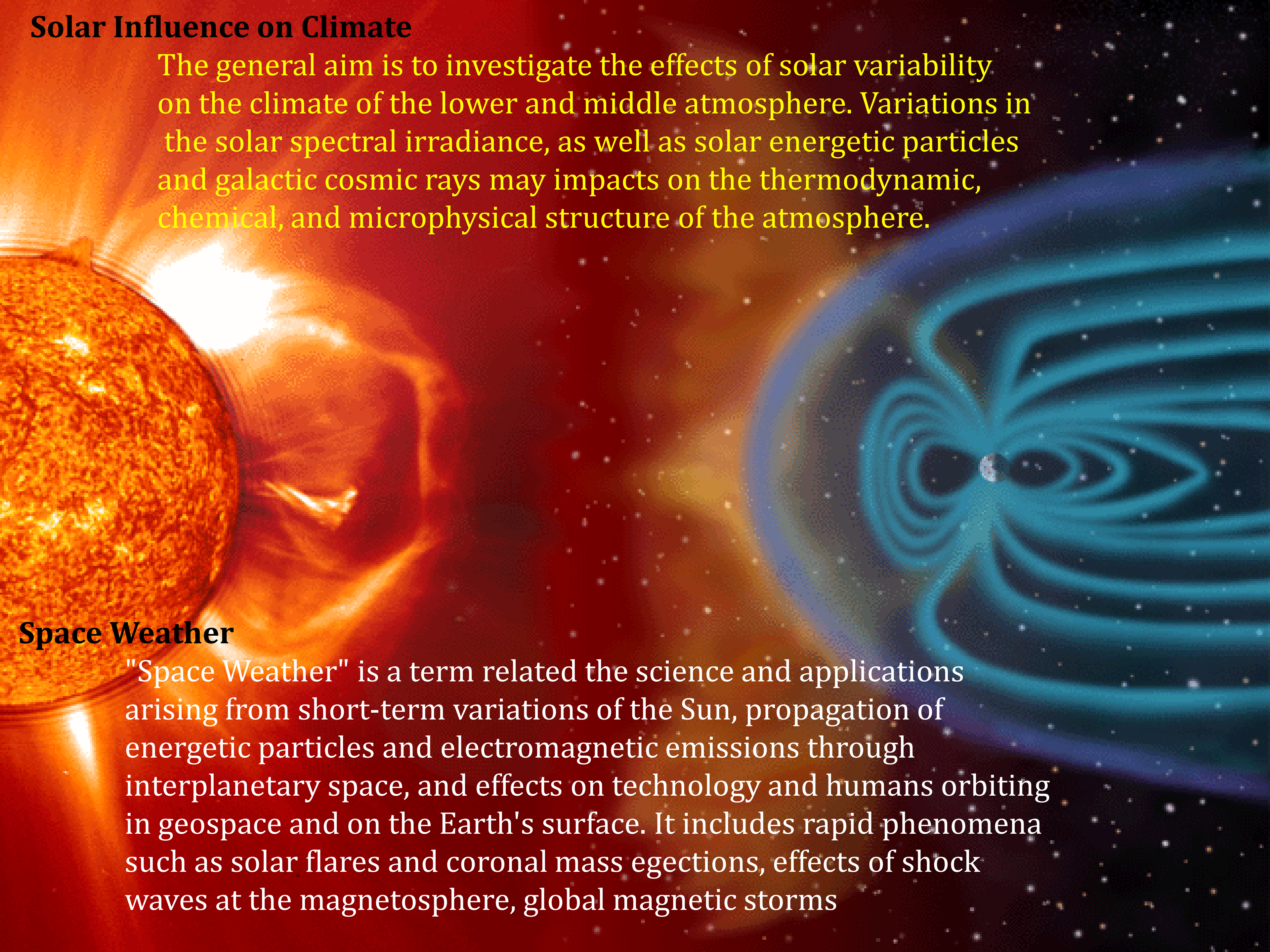




Rate 08h 00 60N
Rate 23h 00 60N
Rate 08h 00 80N
Rate 23h 00 80N
100000
10000
1000
100
Depth [ m, a.s.l.]
10-1
100
101
102
103
104
105
106
Q [ion pairs s-1 cm-3]

# Cosmic ray induced ionization





## Solar Influence on Climate

The general aim is to investigate the effects of solar variability on the climate of the lower and middle atmosphere. Variations in the solar spectral irradiance, as well as solar energetic particles and galactic cosmic rays may impacts on the thermodynamic, chemical, and microphysical structure of the atmosphere.

## Space Weather

"Space Weather" is a term related the science and applications arising from short-term variations of the Sun, propagation of energetic particles and electromagnetic emissions through interplanetary space, and effects on technology and humans orbiting in geospace and on the Earth's surface. It includes rapid phenomena such as solar flares and coronal mass egections, effects of shock waves at the magnetosphere, global magnetic storms

# Future plans

Improvement of CRIMA

Operational CRIMA model for computer simulations and visualization

Determination of basic parameters in heliophysics and space physics

Application of CRIMA model

Ionization rate

Atmospheric chemistry

Comparison with experimental data

# THANK YOU FOR YOUR ATTENTION!