GCR+SEP induced ionization

Ilya G. Usoskin
University of Oulu, Finland

Modelling of atmospheric ionization

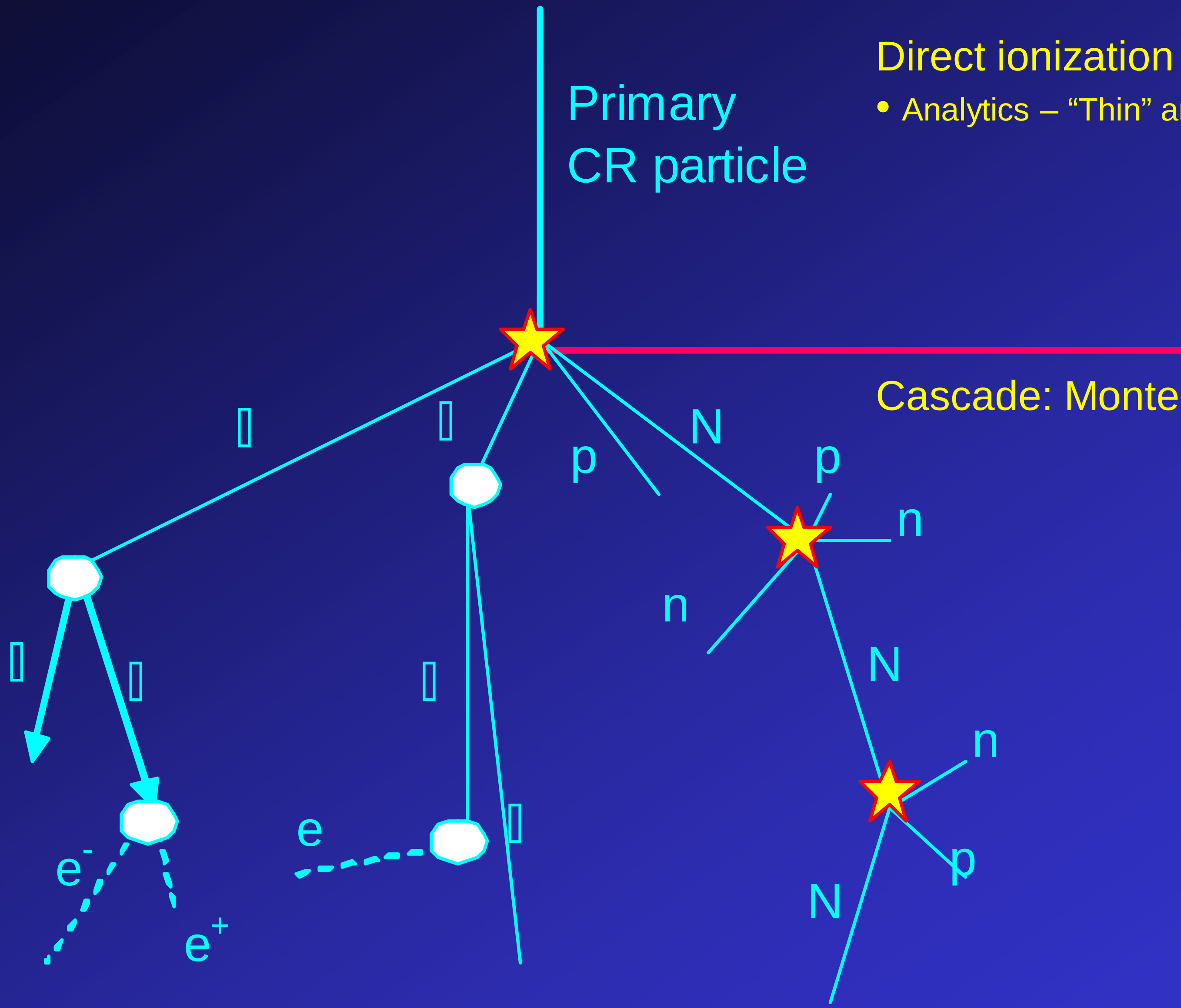
Source	Understanding	Modelling	Data
UVI	Good	Good	Good
GCR	Good	Good	Good
SEP	Good	Good	Fair
EPP	Good	Good	Poor
soil	Good	Good	No

Modelling

Direct ionization by primaries:

- Analytics – “Thin” and “thick” target model.

Cascade: Monte-Carlo



CRII models: basic information

Monte-Carlo:

Oulu CRAC:CRII (CORSIKA+FLUKA)

Usoskin et al., *J. Atm. Solar-Terr. Phys*, 66 (2004).
Usoskin, Kovaltsov, *J. Geophys. Res.*, (2006, 2010).

Bern model ATMOCOSMIC (GEANT-4):

Desorgher et al., *Int. J. Mod. Phys. A,* 20, 6802 (2005)
Scherer et al. *Space Sci. Rev*., (2006).

Physics: Monte-Carlo simulation of the cascade, all species and processes included

Accuracy: - below 1 g/cm^2 (~50 km) -10%

AIMOS (GEANT-4) (Wissing & Kallenrode 2009)

Targeted to the EPP/SEP effect in the middle-upper atmosphere (E<500 MeV)

Analytical parameterization O'Brien, K. (2005)

Physics: Analytical solution of Boltzman equation describing particle transport in the atmosphere;
Validity: good in the upper atmosphere (thin/thick target) and gets progressively worse downwards.

Thin/thick target analytical model Jackman & Vitt (1996):

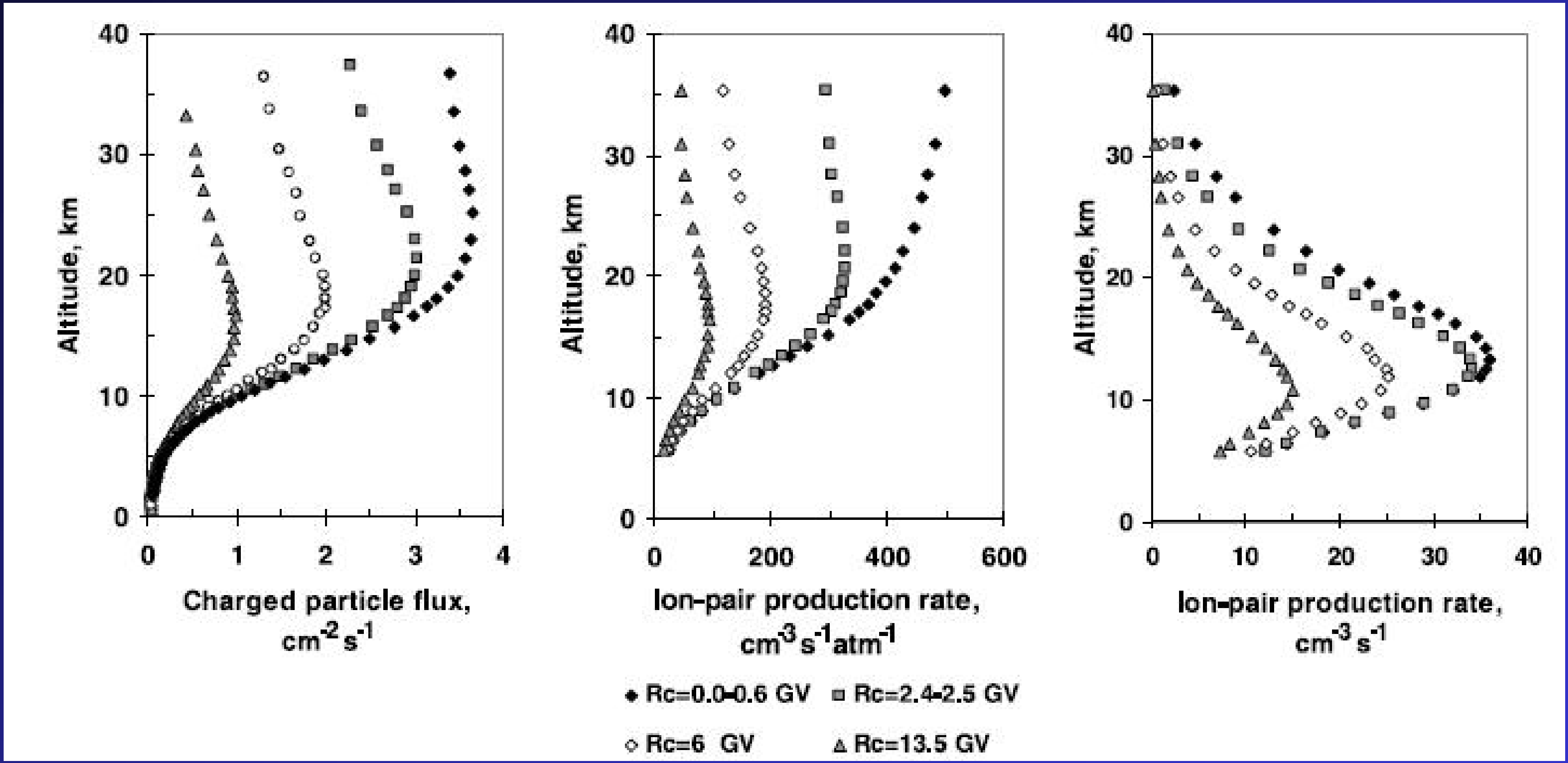
Physics: Analytical straightforward computations of ionization losses, no nuclear reaction,
Validity: Only upper atmosphere, usually considers particles (< 500 MeV)

Output of the models

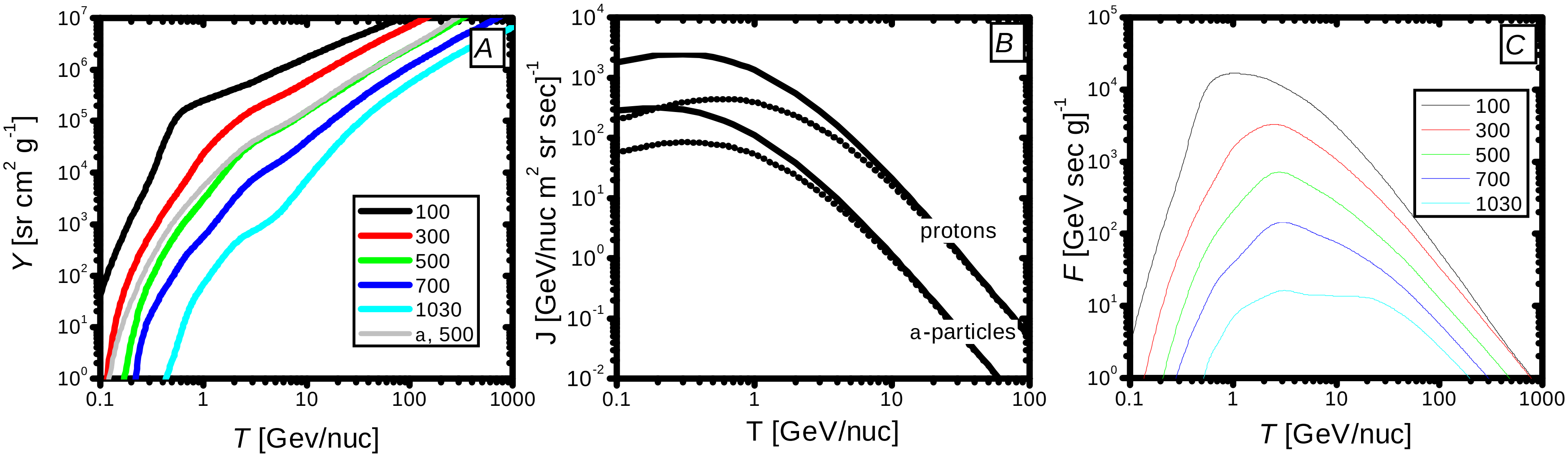
Cosmic ray induced ionization (CRII) rate, i.e. the number of ion pairs produced in 1 cm^3 (g) per second.
Equilibrium concentration depends on the recombination processes and ion mobility and forms an independent task.

Galactic Cosmic Rays

Ionization measurements



CRII: ionization function

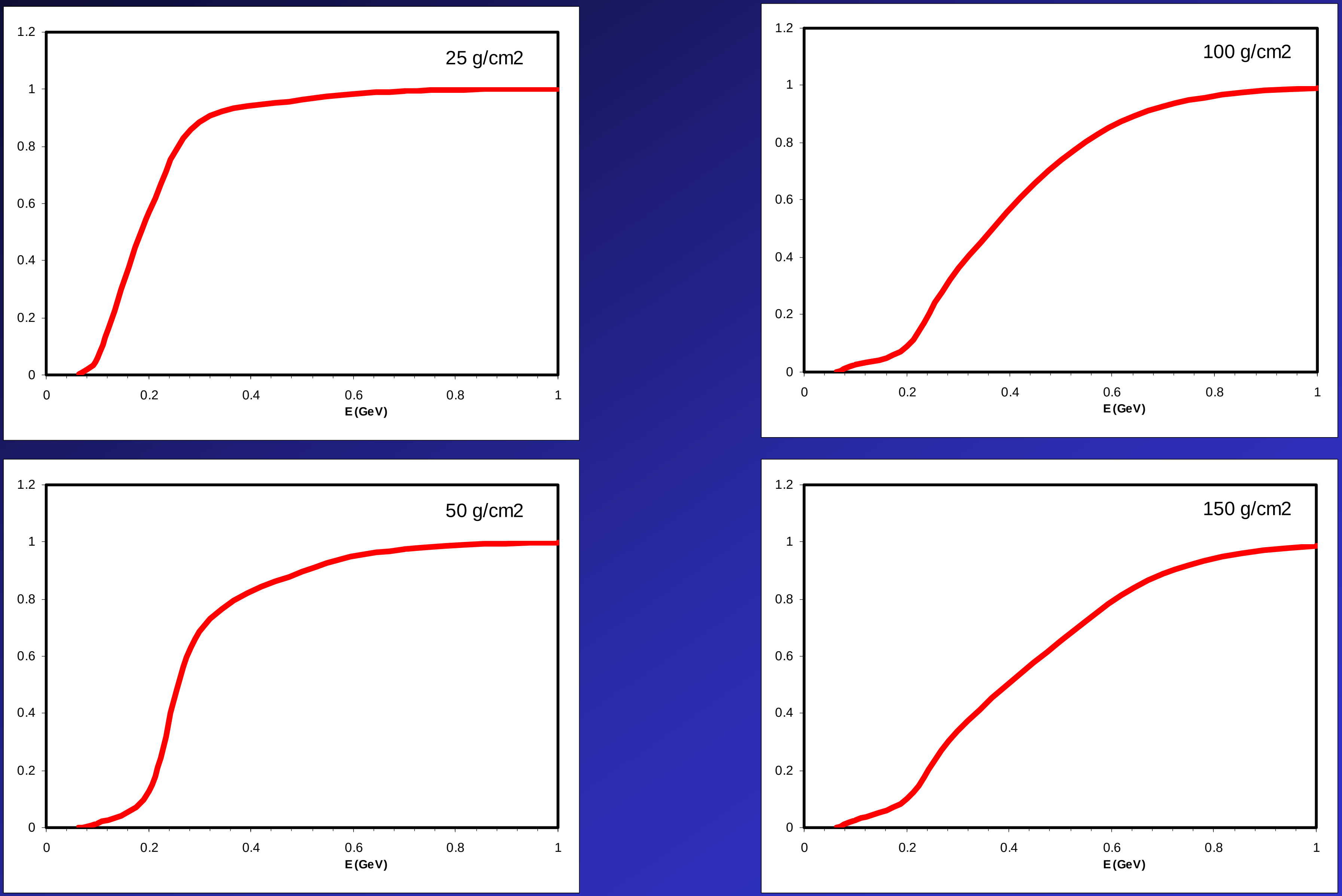


CRII is defined as an integral product of the ionization yield function *Y* and the energy spectrum of GCR *J*.

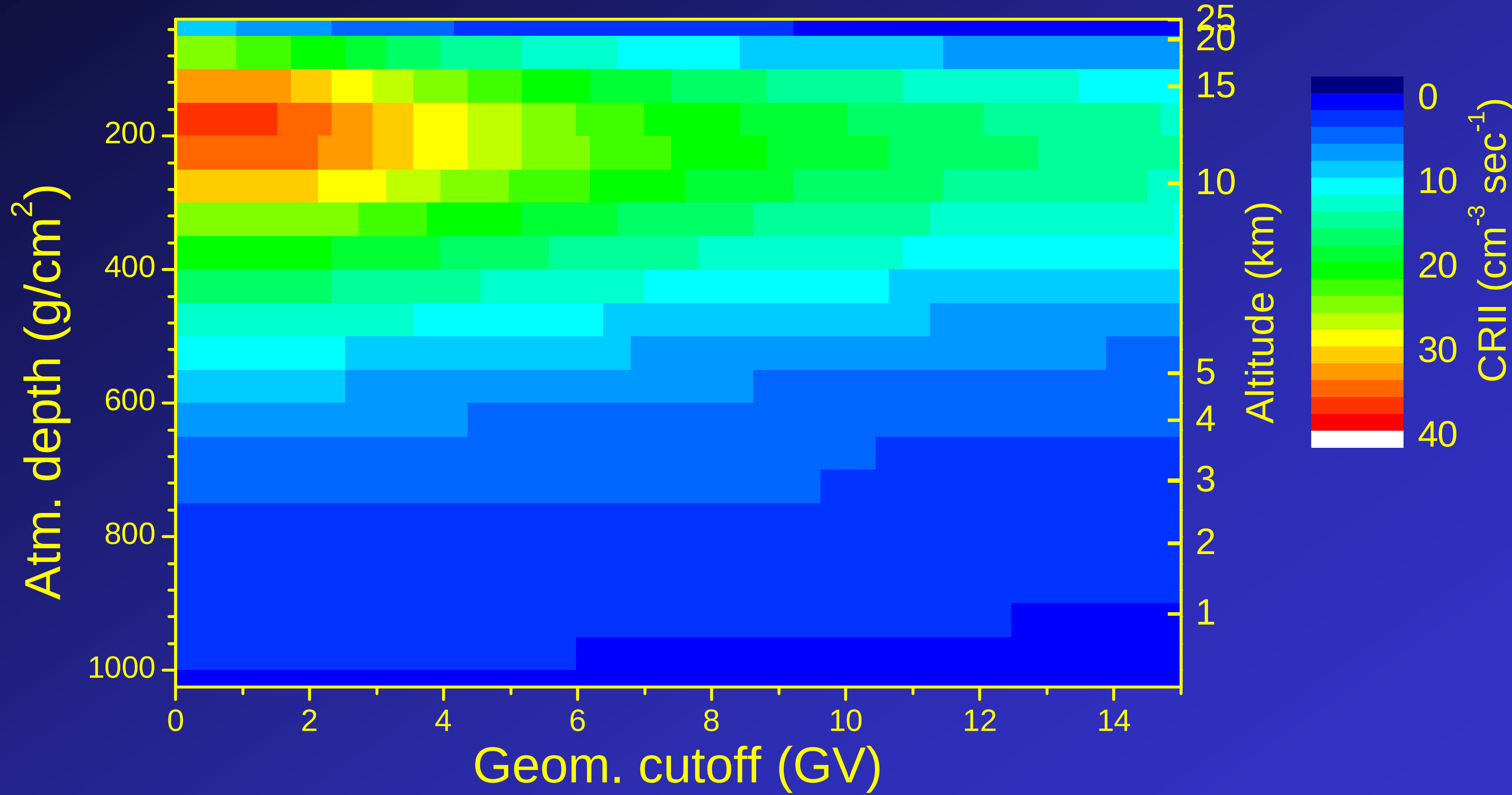
$$Q(x,\phi) = \sum Q_i = \sum \int_{T_C}^{\infty} J_i(T,\phi) \cdot Y_i(x,T) \cdot dT$$

The most effective energy of CRII depends on the atmospheric depth – from ≈1 GeV/nuc in the stratosphere to about 10 GeV/nuc at the sea-level.

Cumulative ionization function



CRII: altitude vs. latitude



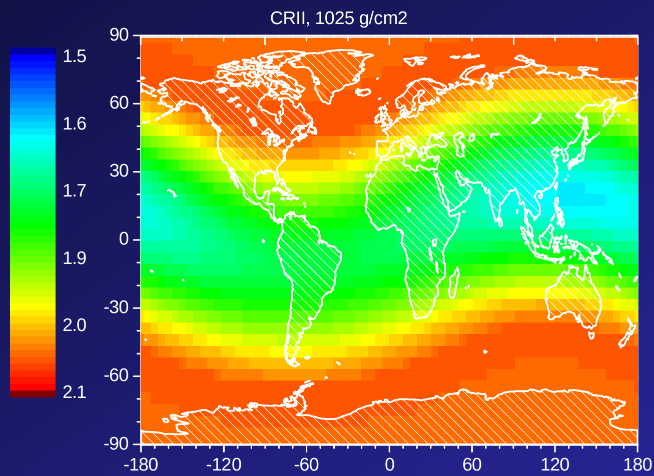
ξ of the order of 10^{-19} -- 10^{-18} s^{-1}.

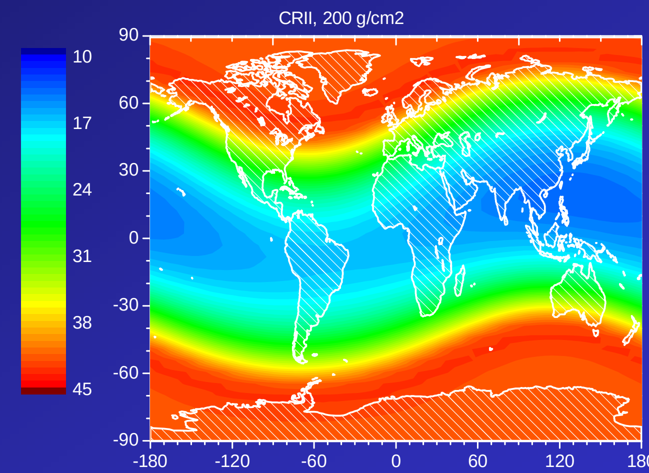
Spatial distribution of CRII (cm^{-3} sec^{-1})

Ground level

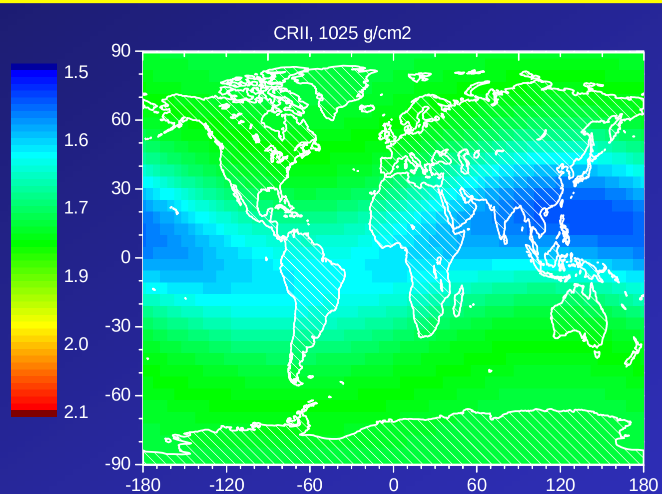
12 km altitude

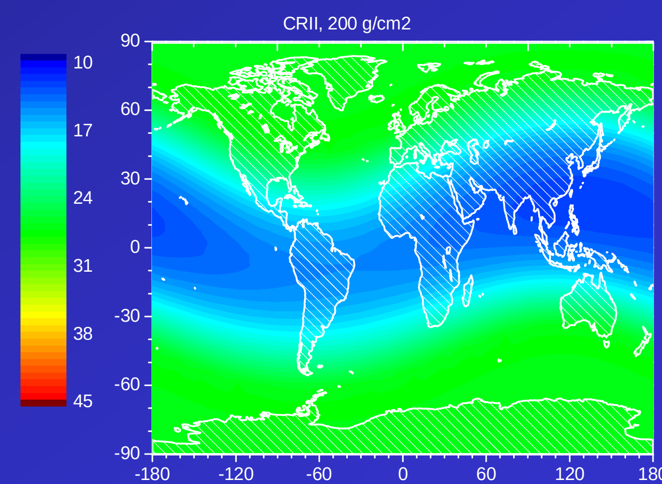
Solar minimum



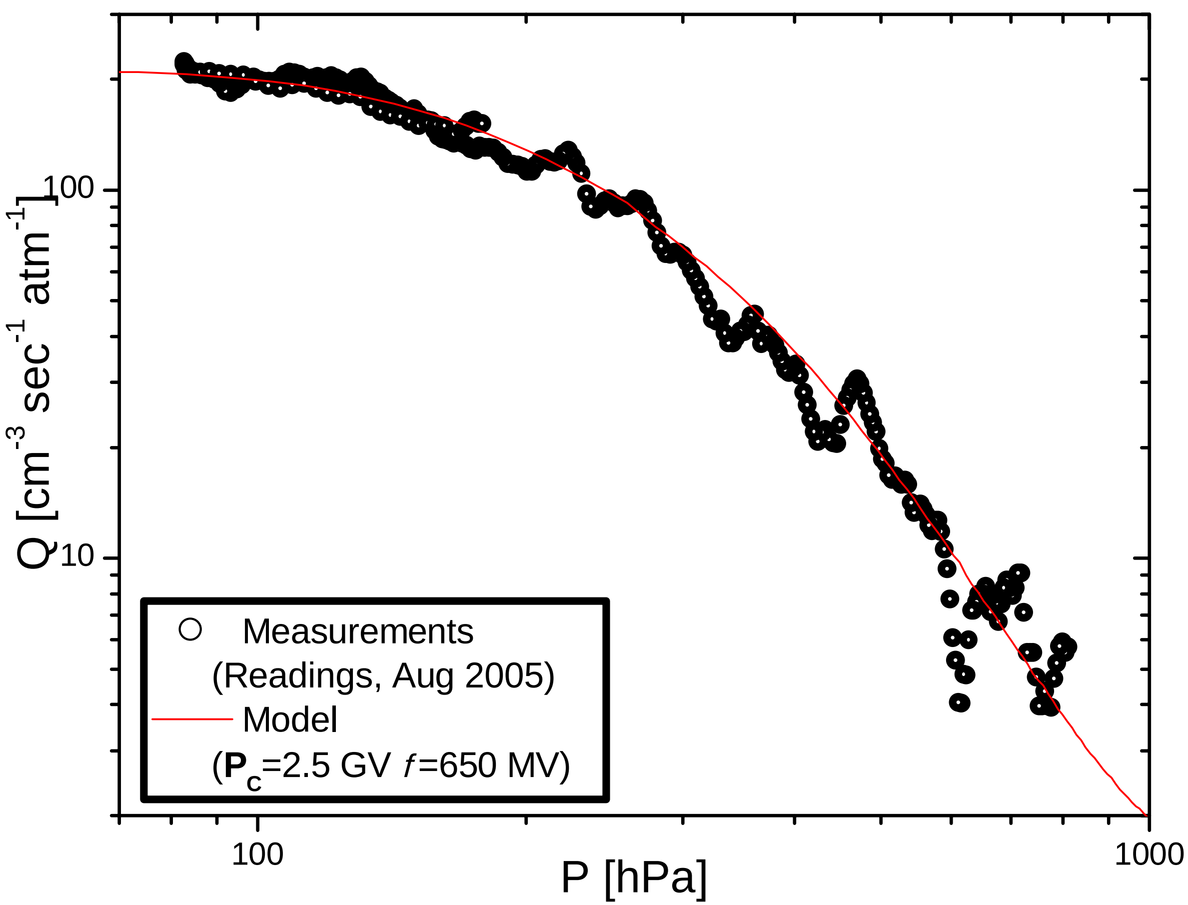


Solar maximum



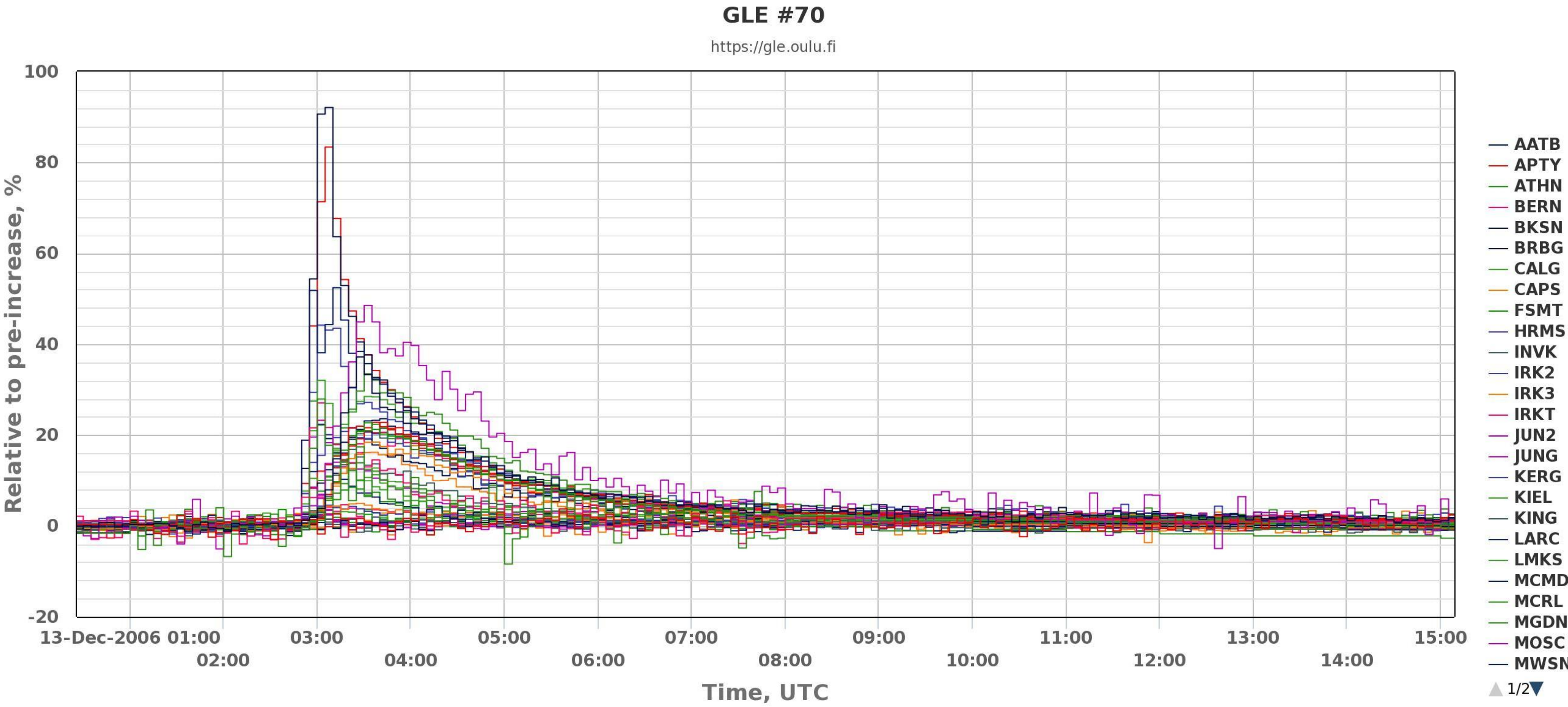


Comparison with measurements

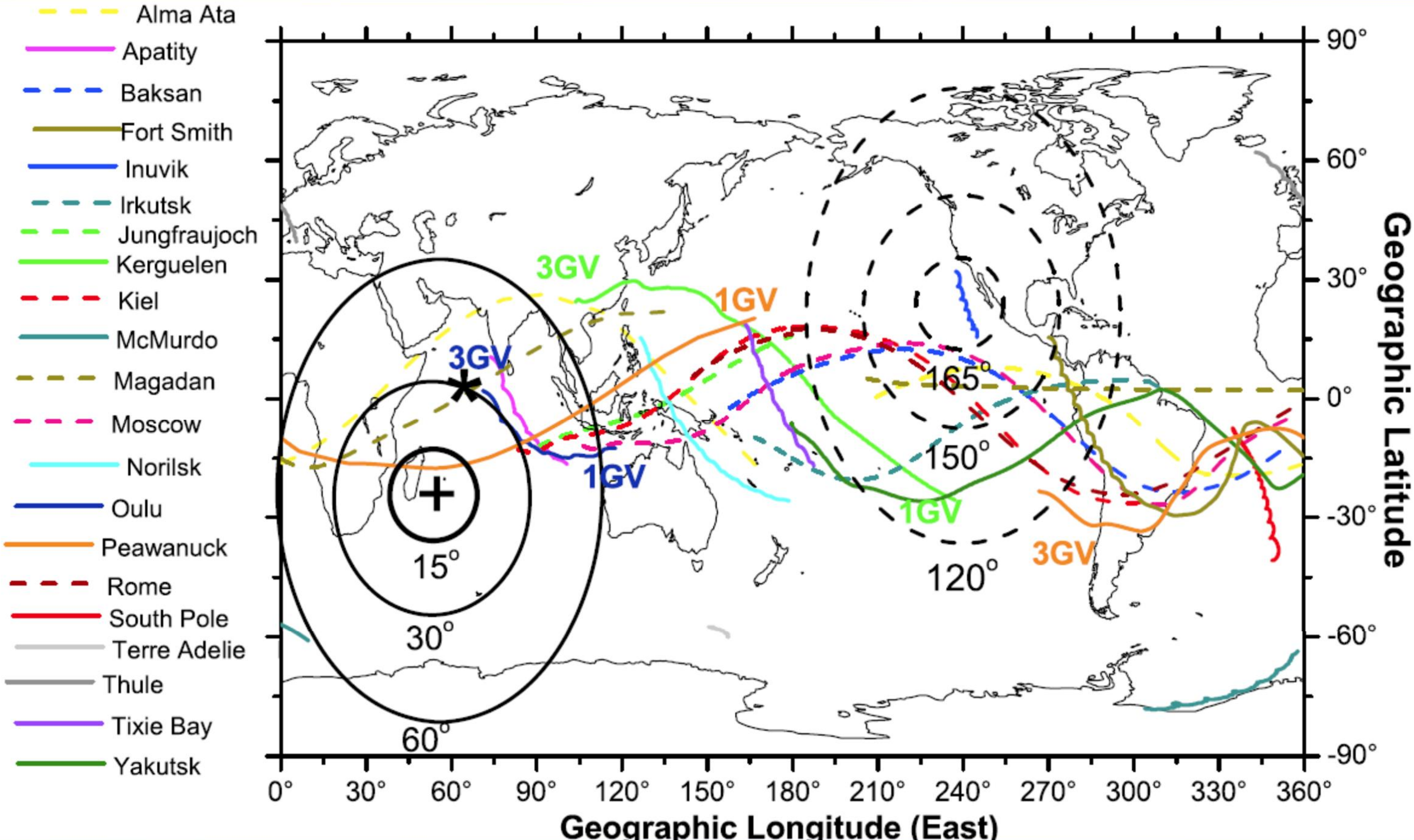


Solar Energetic Particles

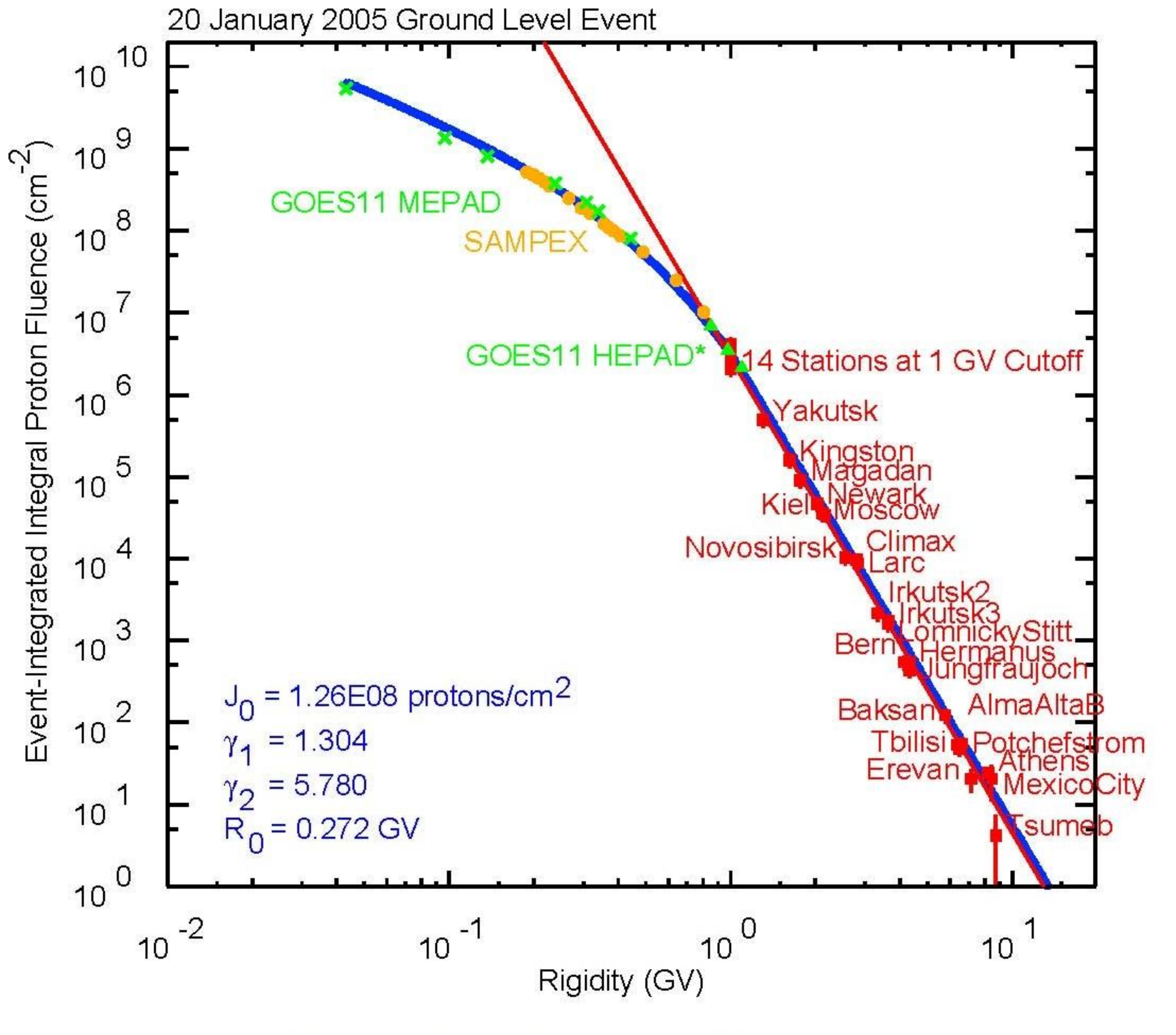
GLE 13.12.2006



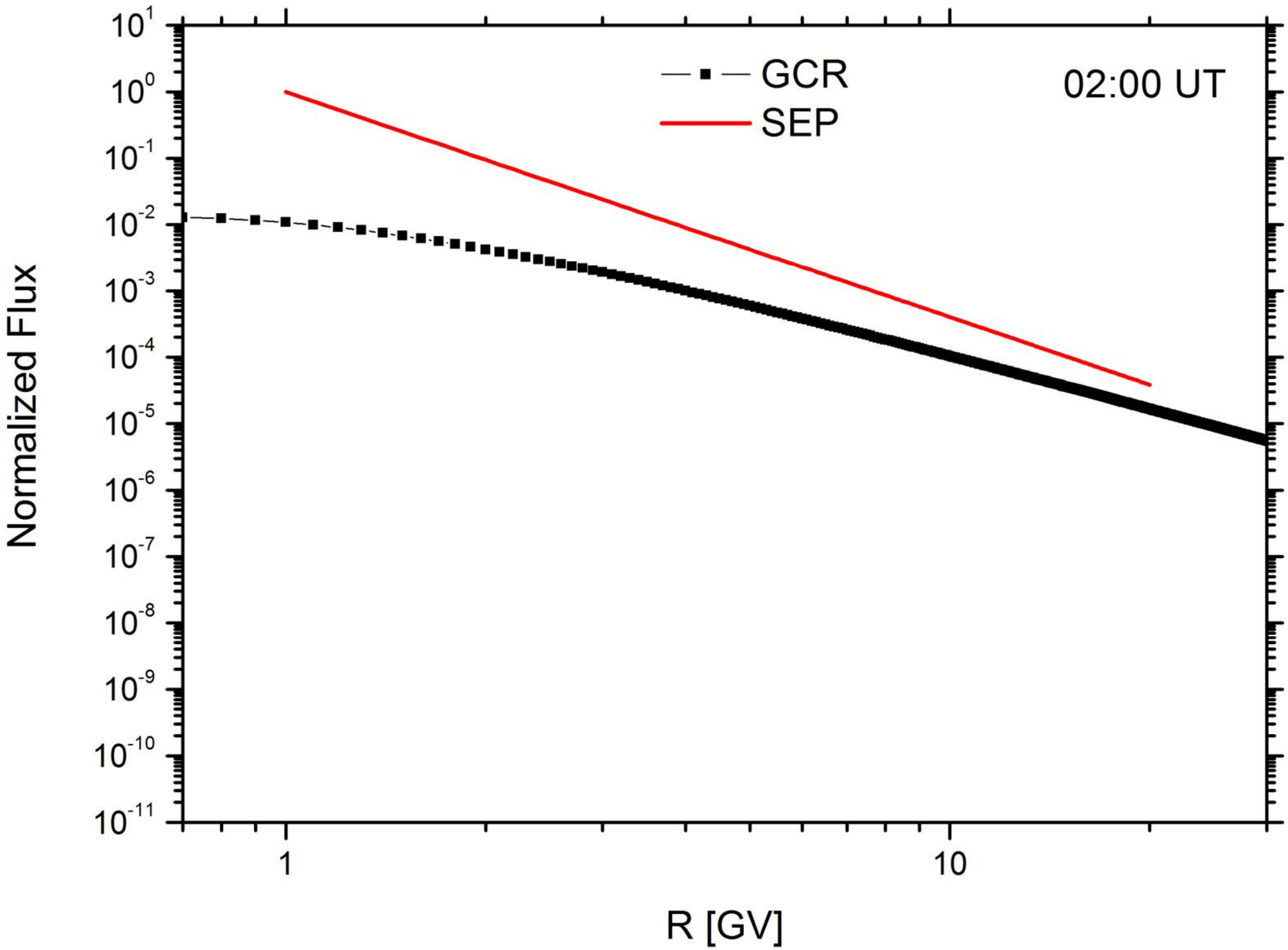
Asyptotic viewing directions of NM



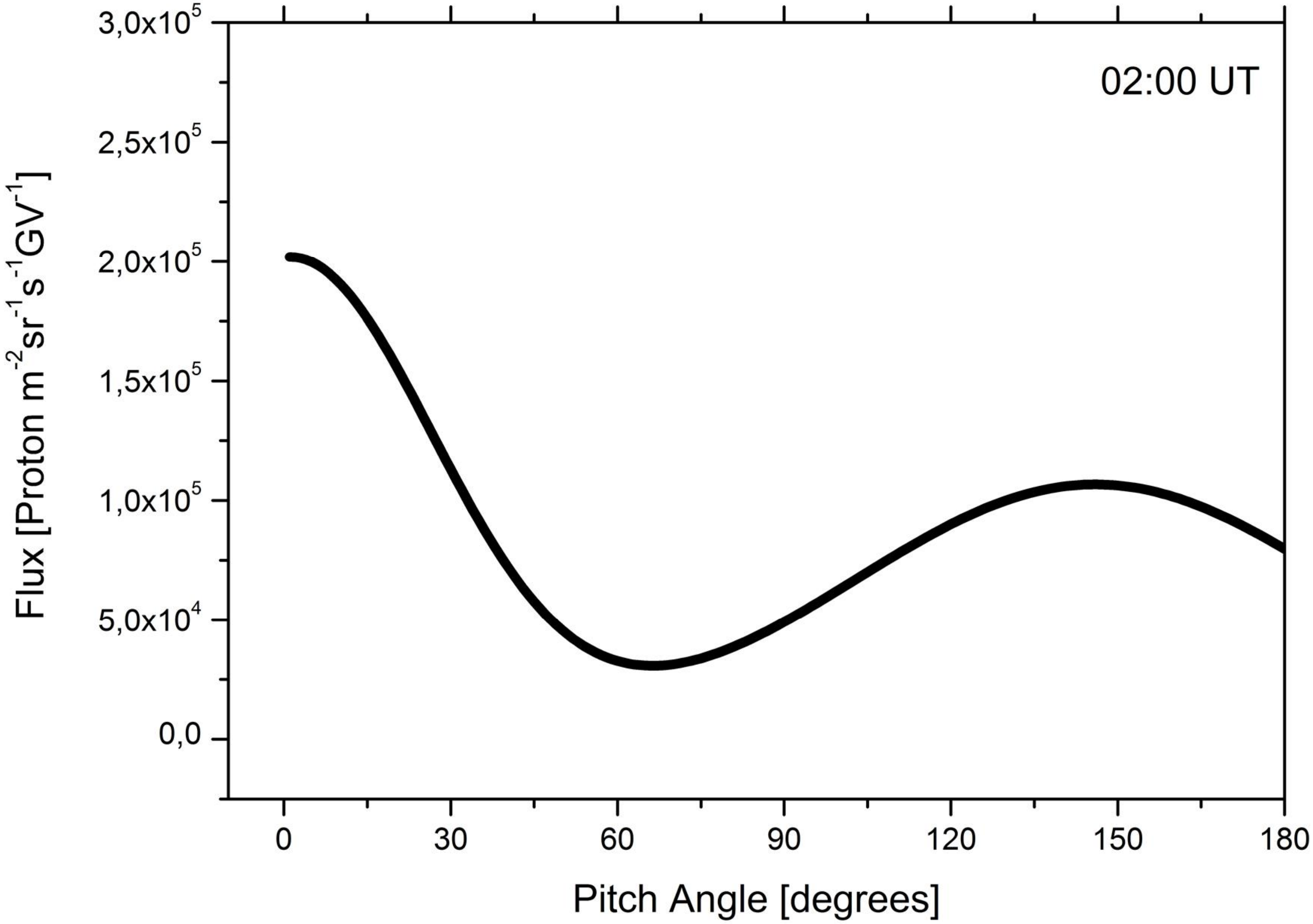
Energy spectrum of GLE 69



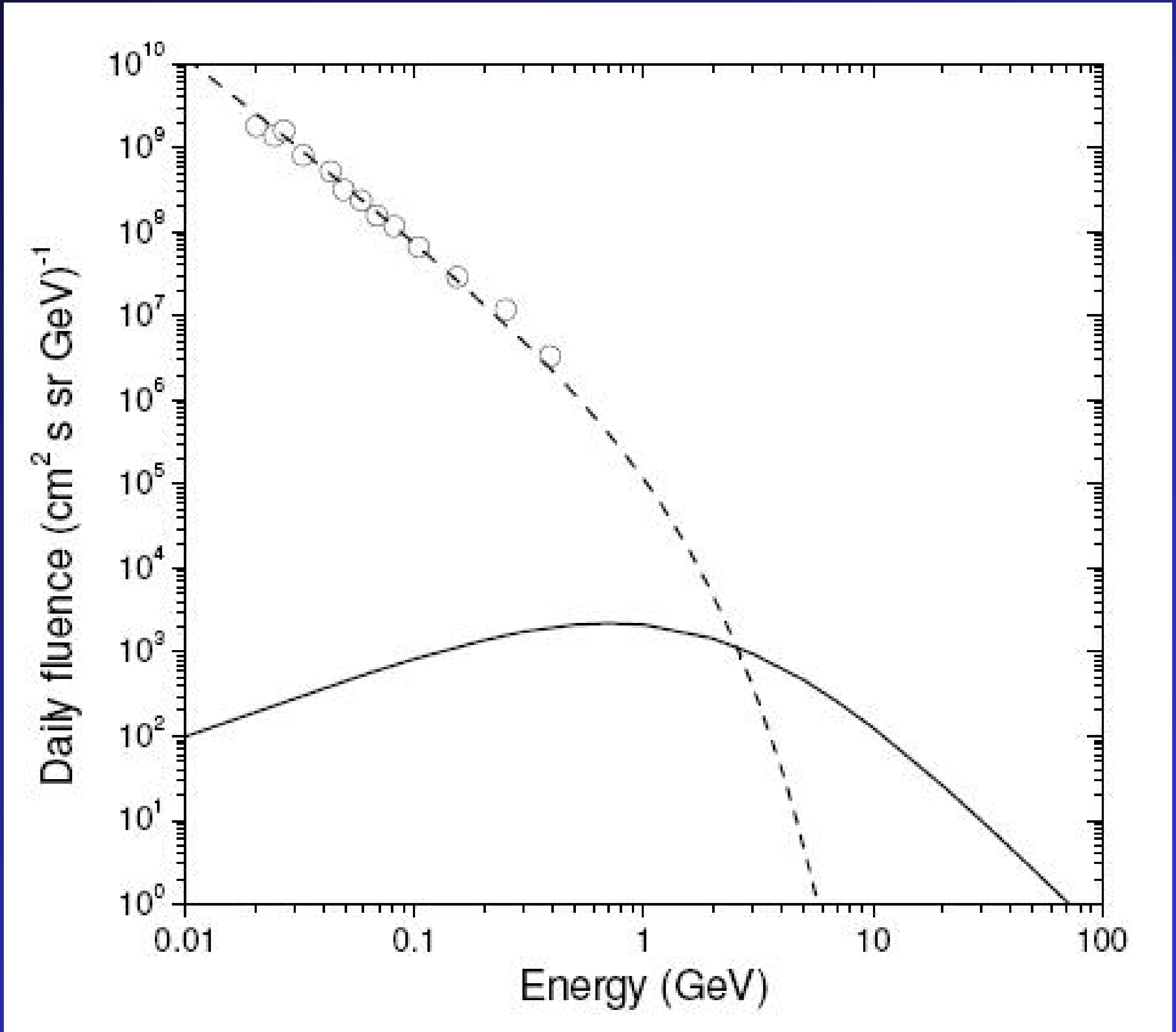
GLE 69: Spectrum



GLE69: anisotropy



GCR-vs-SCR


Daily fluence (cm^2 s sr GeV)$^{-1}$
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
0.01
0.1
1
10
100
Energy (GeV)

Spectrum parameterization

- Band-type spectrum (5 parameters) (Mewaldt et al., 2012)

$$J(>R) = J_0 \cdot R^{-\gamma_1} \exp(-R/R_0), \qquad \text{for } R \le (\gamma_2 - \gamma_1) R_0,$$

$$J(>R) = J_0 \cdot A \cdot R^{-\gamma_2}, \qquad \text{for } R > (\gamma_2 - \gamma_1) R_0,$$

- Bessel function (2 parameters)

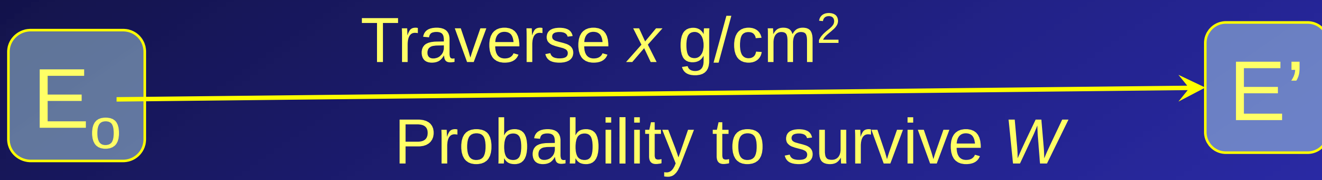
$$dJ/dE = ApK_2\left[(12/mc)(p/\alpha T)\right]^{1/2}.$$

- Power law with exponential roll-over (Ellison-Ramaty, 3 parameters)

$$dJ/dE = KE^{\gamma}\exp(-E/E_0)$$

- Exponent over rigidity (2 parameters)

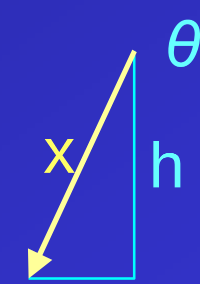
Analytical model: thick target



$$W(E_o, E', A) = \exp\left(- \int_{E'}^{E_o} \frac{dE}{\frac{dE}{dx}(E, A) \cdot \lambda_{\text{in}}(E, A)} \right),$$

$$x = R(E_o) - R(E'),$$

$$\frac{dq}{dx}(x, E_o, A) = \frac{1}{35\ \text{eV}} \cdot \frac{dE}{dx}(E', A) \cdot W(E_o, E', A),$$



$$Y_{\text{A}}(E_o, h) = \int \frac{dq}{dh} \cdot \frac{dF}{d\Omega}\, d\Omega = 2\pi \int_0^1 \frac{dq}{dx}(x, E_o, A)\, d\cos\theta,$$

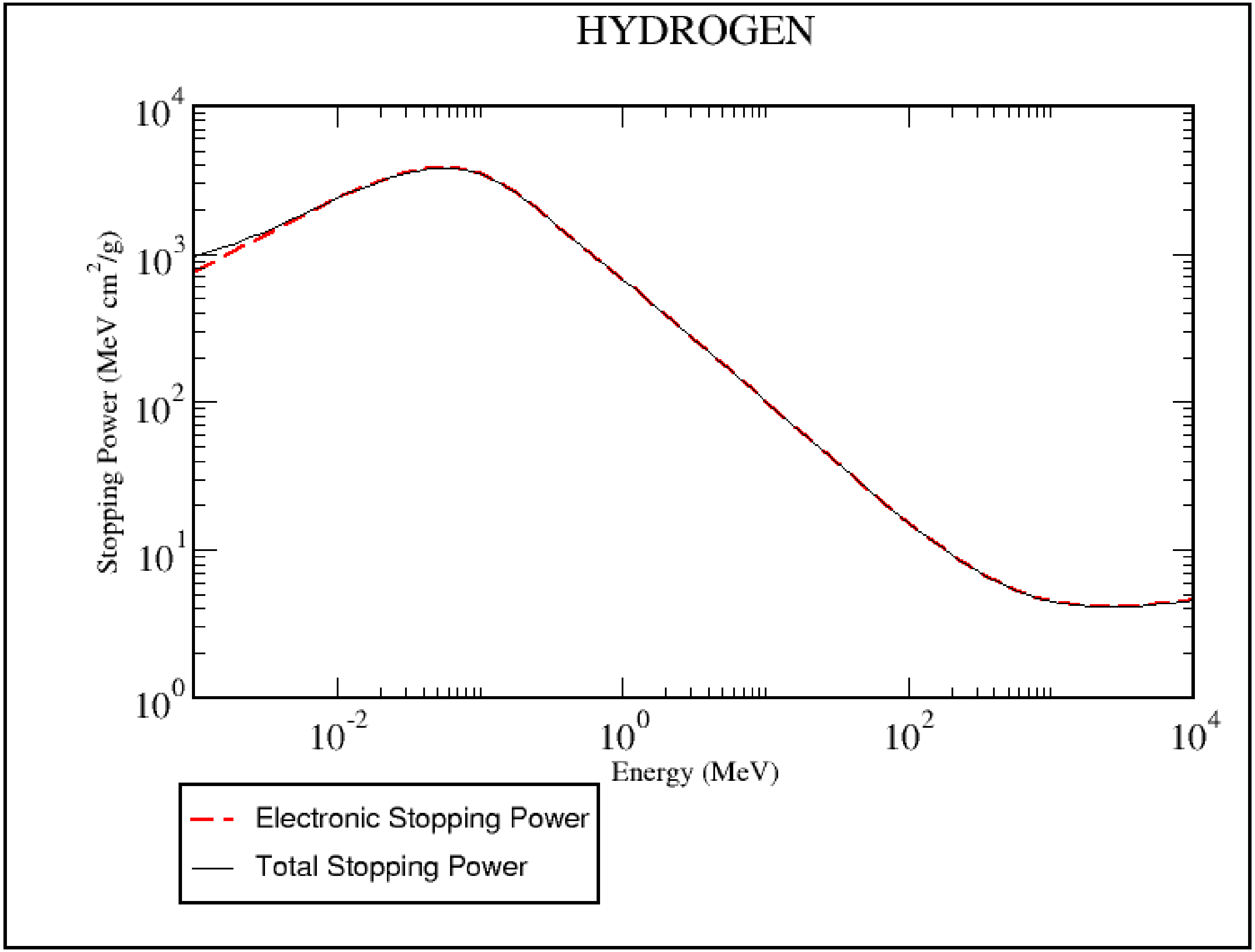
thin target à

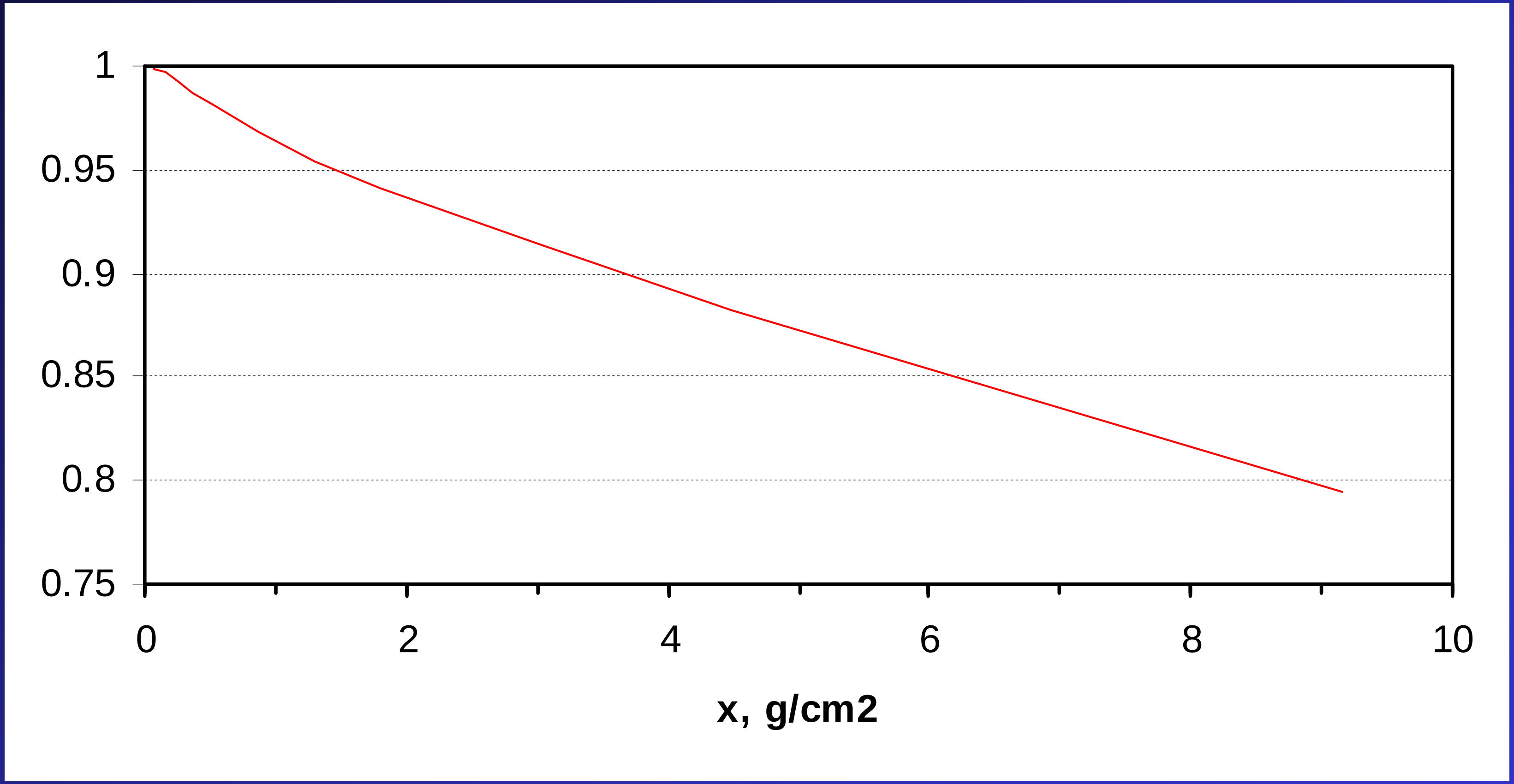
$$Y_{\text{A}}(E_o, h = 0) = \frac{2\pi}{35\ \text{eV}} \cdot \frac{dE}{dx}(E_o, A)$$

Analytical approach

- No nuclear collisions;
- No elastic scattering (particles travel straight);
- Direct ionization energy loss (dE/dx);
- Probability of losing a particle due to an inelastic nuclear process (often neglected);

Stopping power for proton in air dE/dx

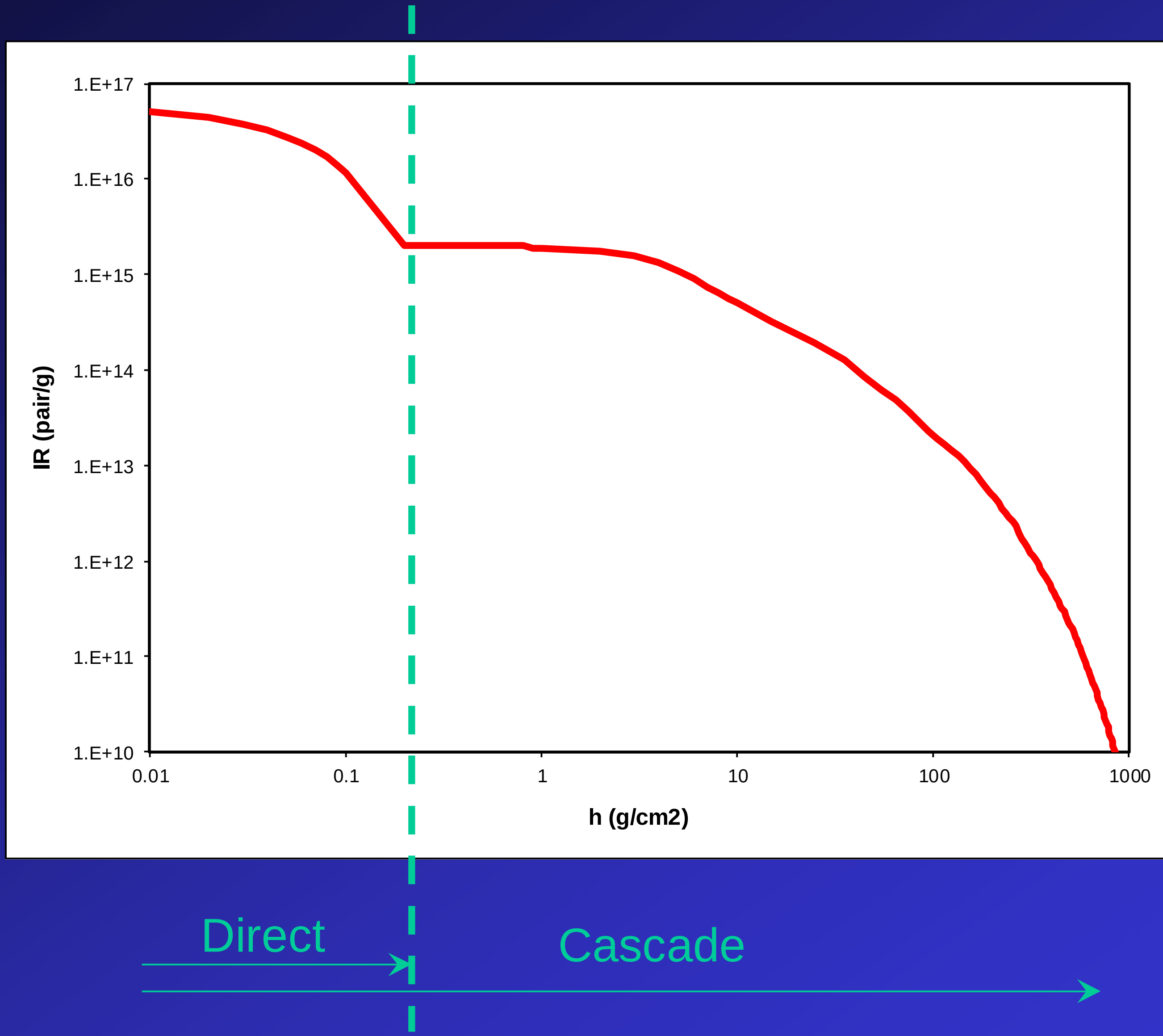




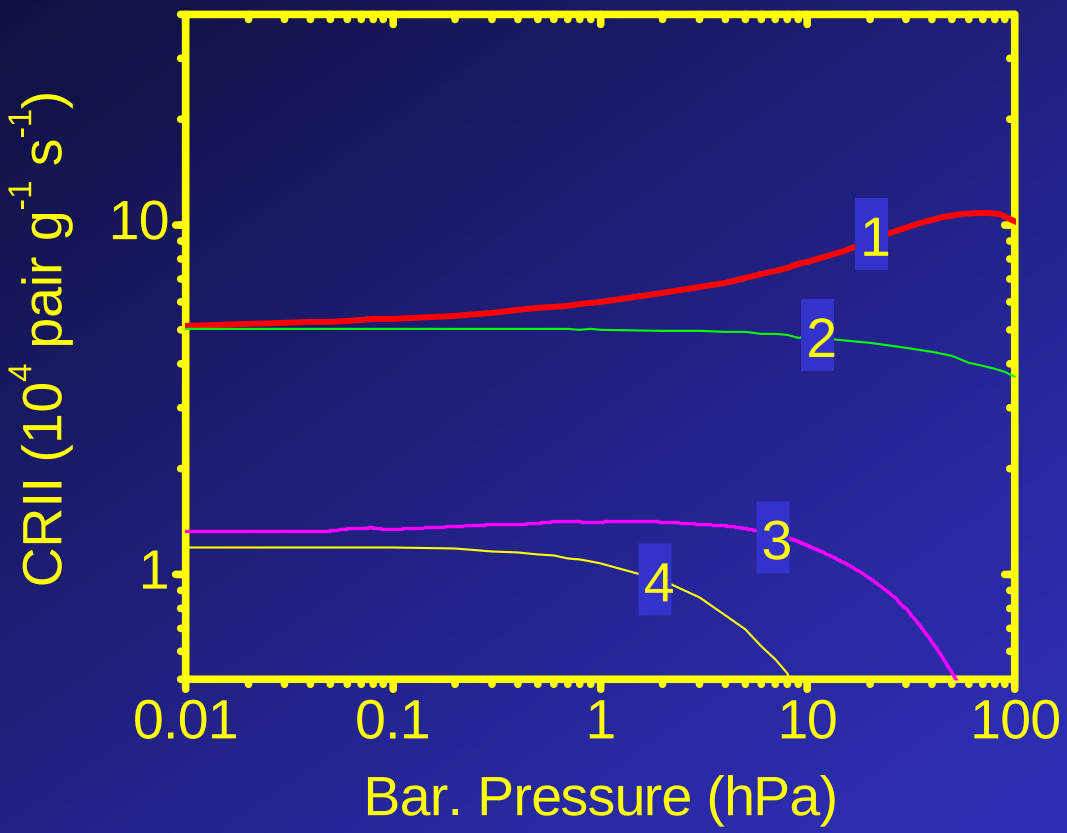
probability of surviving (against nuclear losses) for a 200 MeV proton (isotropic flux) as function of the atmospheric depth

UNIVERSITY of OULU

Hard-spectrum SPE 775 AD



MC-vs- analytical models



CRII (GCR) computed for the upper atmosphere:

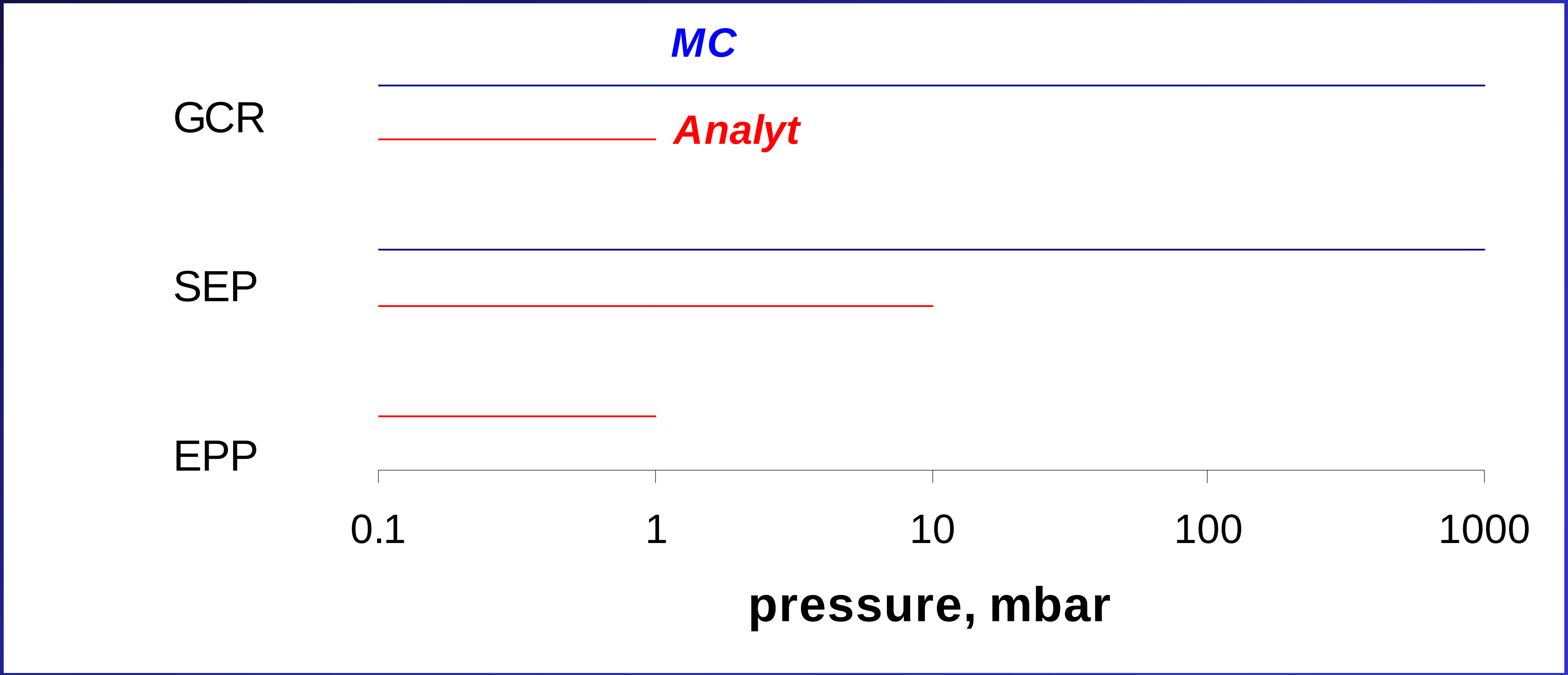
1 – Full Monte-Carlo (CRAC);

2 – Thick target model with full energy range of CR;

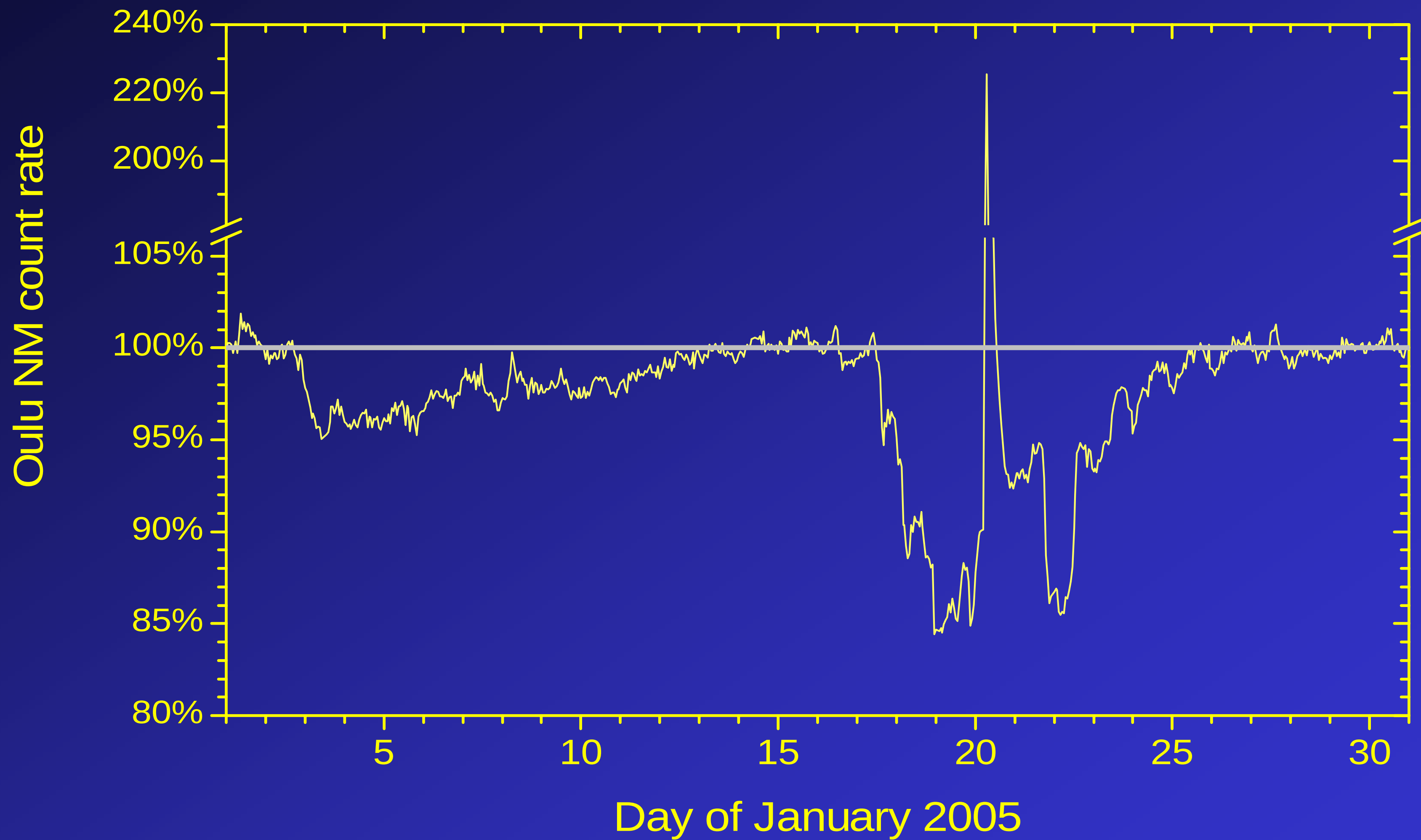
3 – Monte-Carlo with E<500 MeV (e.g., AIMOS);

4 – Thick target model with E<500 MeV (Vitt & Jackman, 1996)

Summary

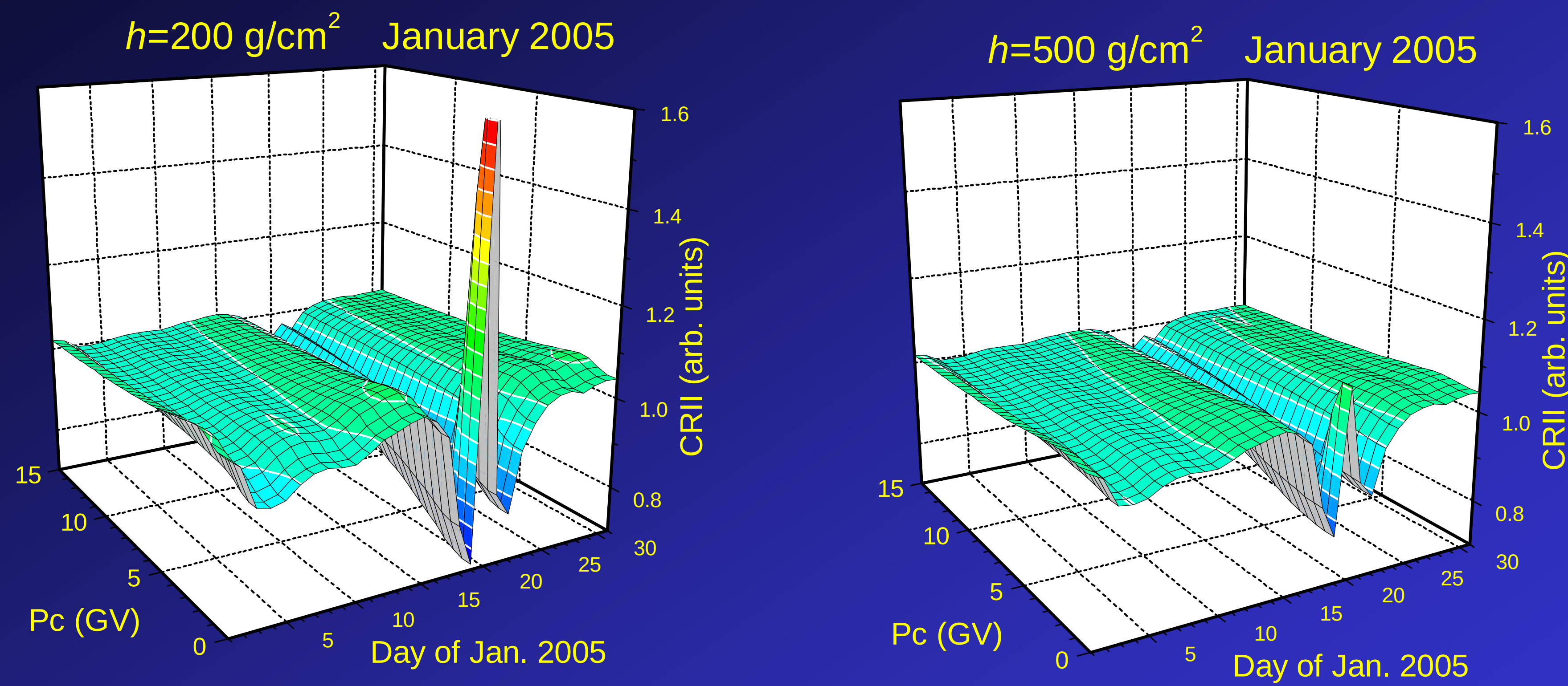


CR time profile for January 2005



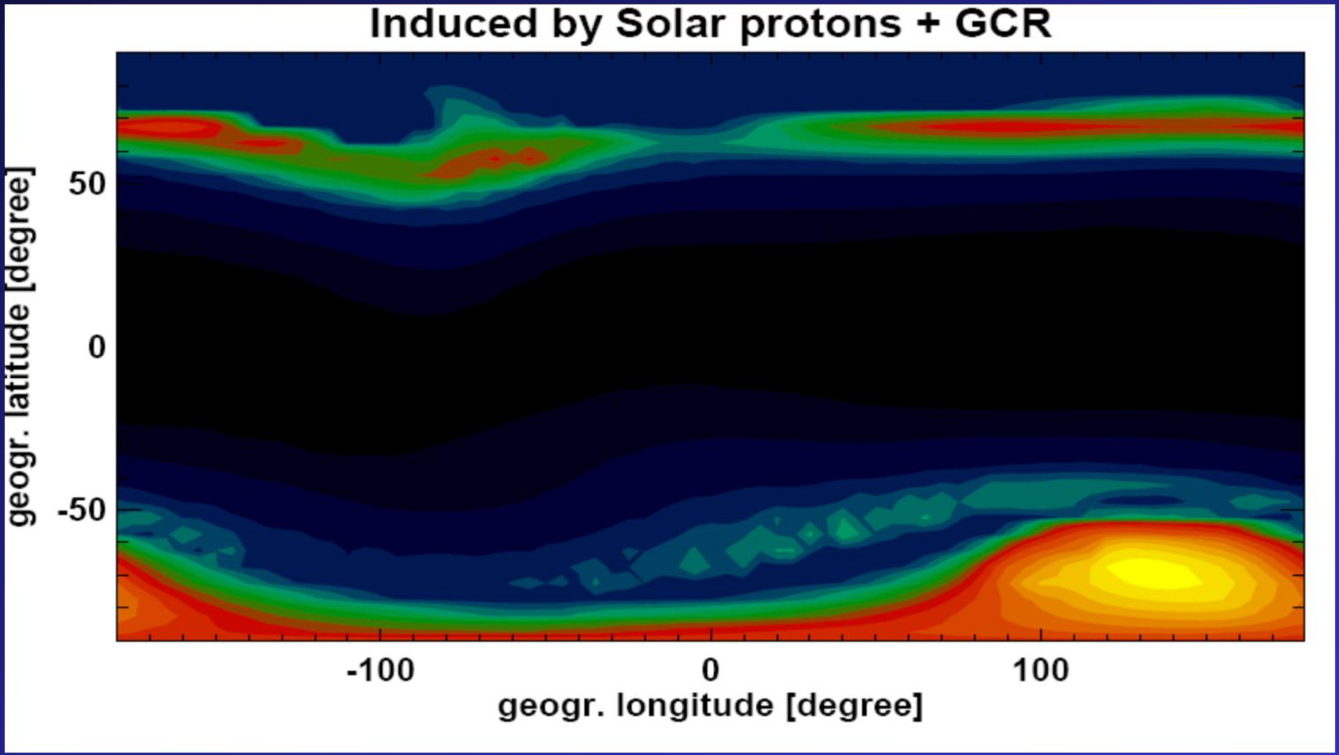
Time profile of Oulu NM hourly count rate for January 2005 (http://cosmicrays.oulu.fi).

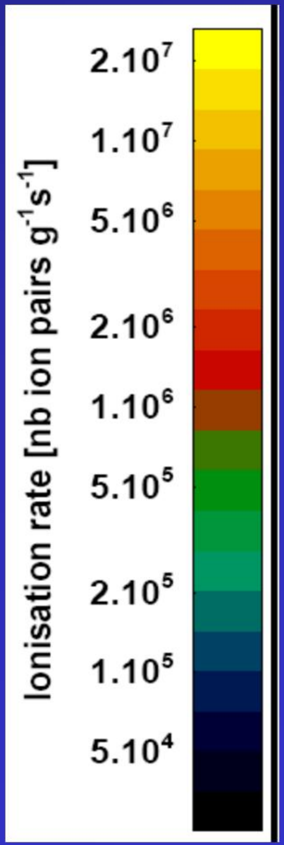
Relative ionization effect of GLE 20-01-2005



The relative ionization (normalized to the average of Jan. 2005) as function of time and *Pc* for two atmospheric depths (200 g/cm^2 – left panel, and 500 g/cm^2 – right panel).

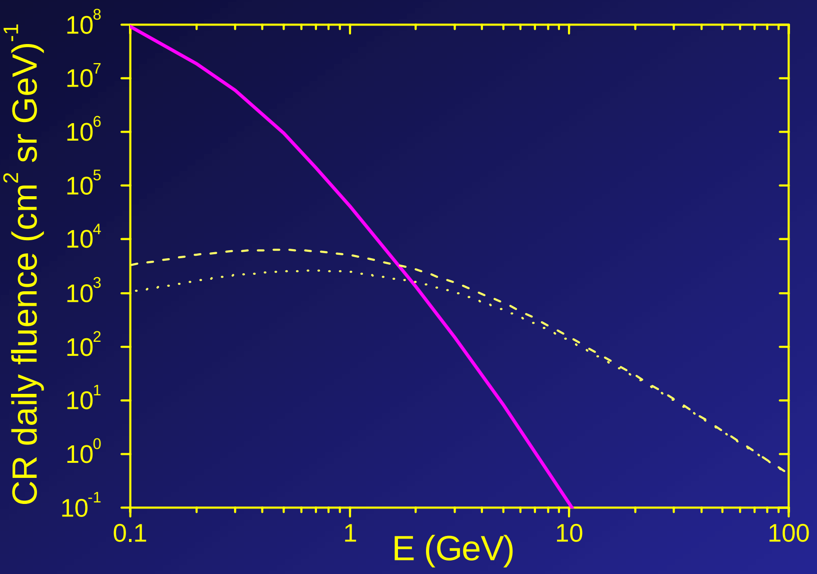
GLE 20-01-2005: peak effect

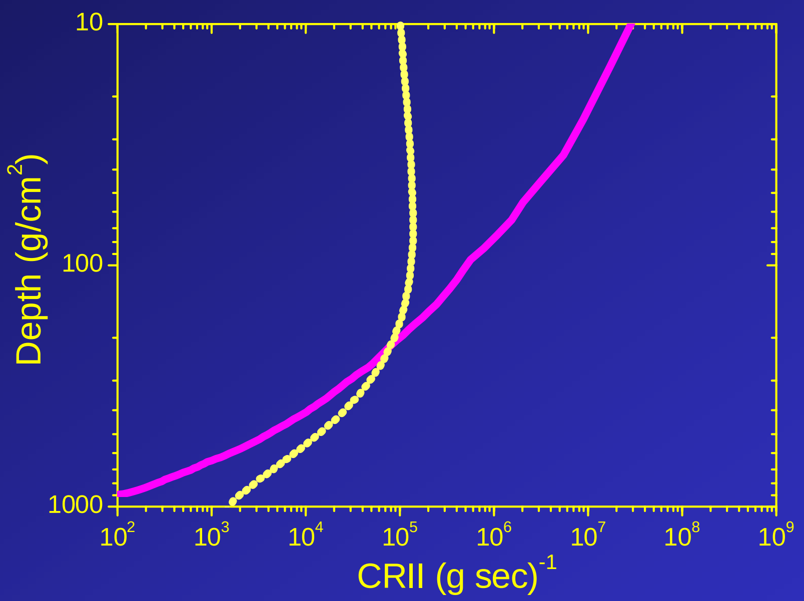




CRII in the upper troposphere (300 g/cm^2) at 06:55 UT of 20-Jan-2005 (ATMOCOSMIC results)

Ionization effect of GLE 20-01-2005

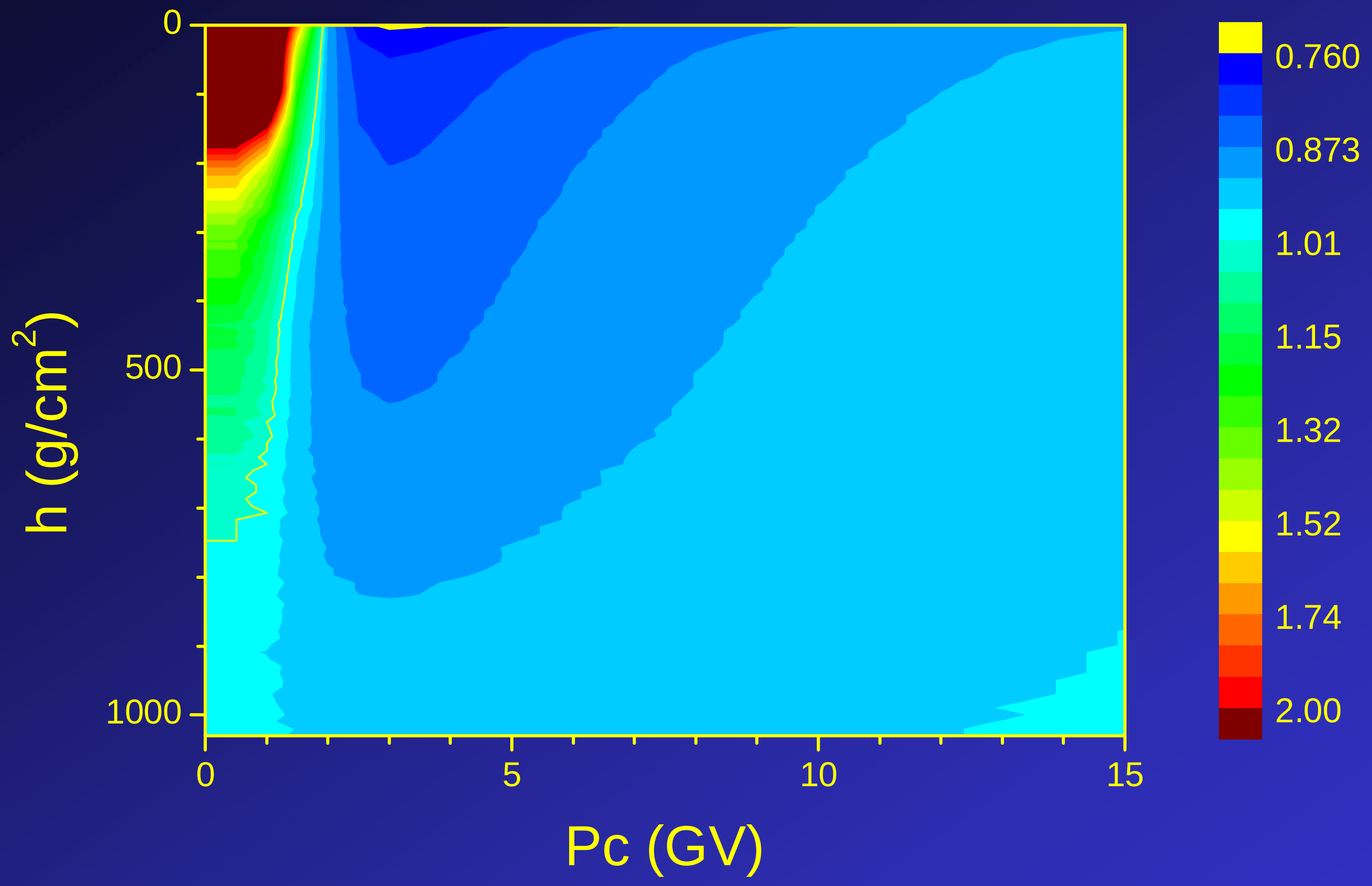




(A) Differential fluence of solar protons from the 20-01-2005 event and the daily fluence of GCR protons for the day of 20-01-2005, including the effect of the Forbush decrease (dotted line). The dashed curve depicts the average GCR proton fluence for January 2005.

(B) The vertical profile of the daily averaged CRII in the polar region from GCR (dotted curve) and SEP (solid curve) separately, for the day of 20 January 2005.

Ionization effect of GLE



$$C(h, Pc) = \frac{I_{SEP} + I_{GCR}}{\langle I \rangle}$$

The relative ionization effect of GLE 20-Jan-2005 as function of the geomagnetic cutoff rigidity *Pc* and atmospheric depth *h.*

Conclusions

- Ü *Modelling task is solved at the level of physical modelling.*

- Ü *Data input is a major problem for EPP, somewhat uncertain for SEP, full clear for GCR.*

- Ü *Truncated models (analytical or with limited energy range) can be used ONLY for the upper polar atmosphere and lower energy particles (SEPs, magnetospheric particles).*

- Ü *All results are for ionization rate à ion concentration is a separate task.*

THANK YOU !