Cosmic Rays in the eaRth's atmosphere

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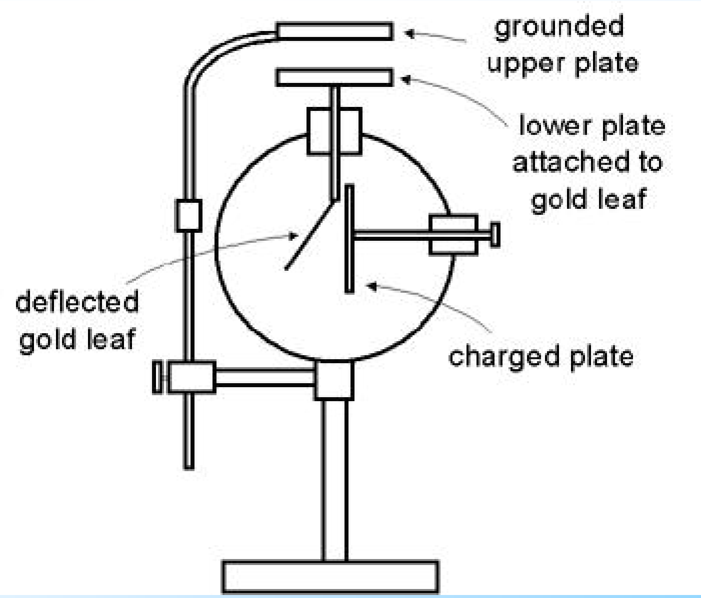
Outline

- What are cosmic rays?
- What are solar cosmic rays?
- What can we learn with cosmic rays?
- How can we catch them?
- What happens to them in the atmosphere?
- What happens to the atmosphere?

What are cosmic rays?

The study of cosmic rays has a long story.

1900 : By measuring the accumulated static charge, ***C.T.R. Wilson*** discovered the permanent ionization in the air. It was then (erroneously) believed to be only due to the natural radioactivity of the Earth.

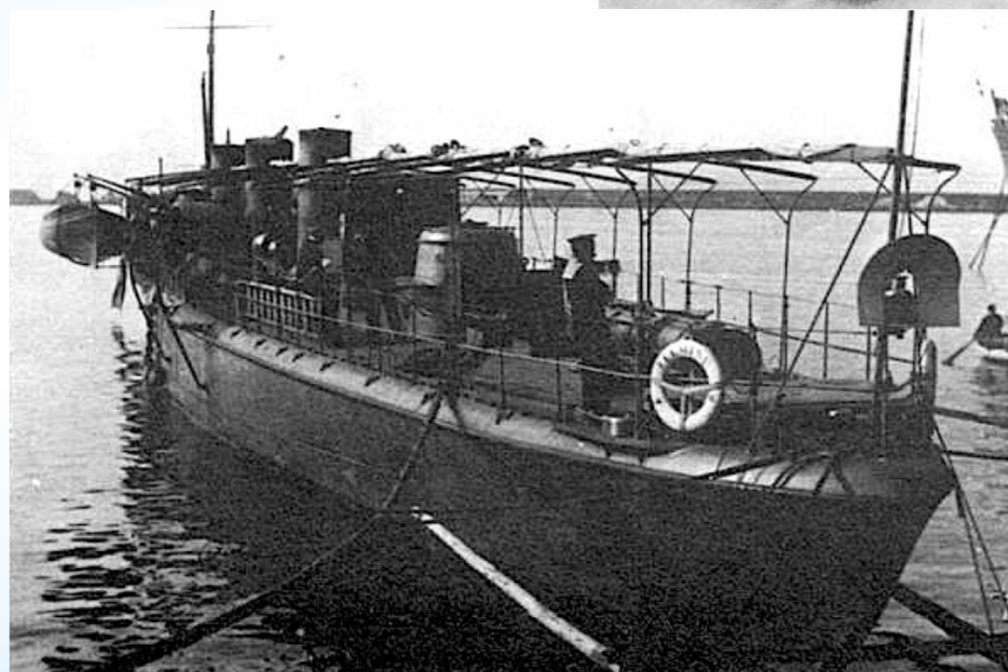


Milestones of CR research

1911-1912:

Domenico Pacini used an electrometer aboard a ship.

The ionization rate didn’t change à not from the soil.

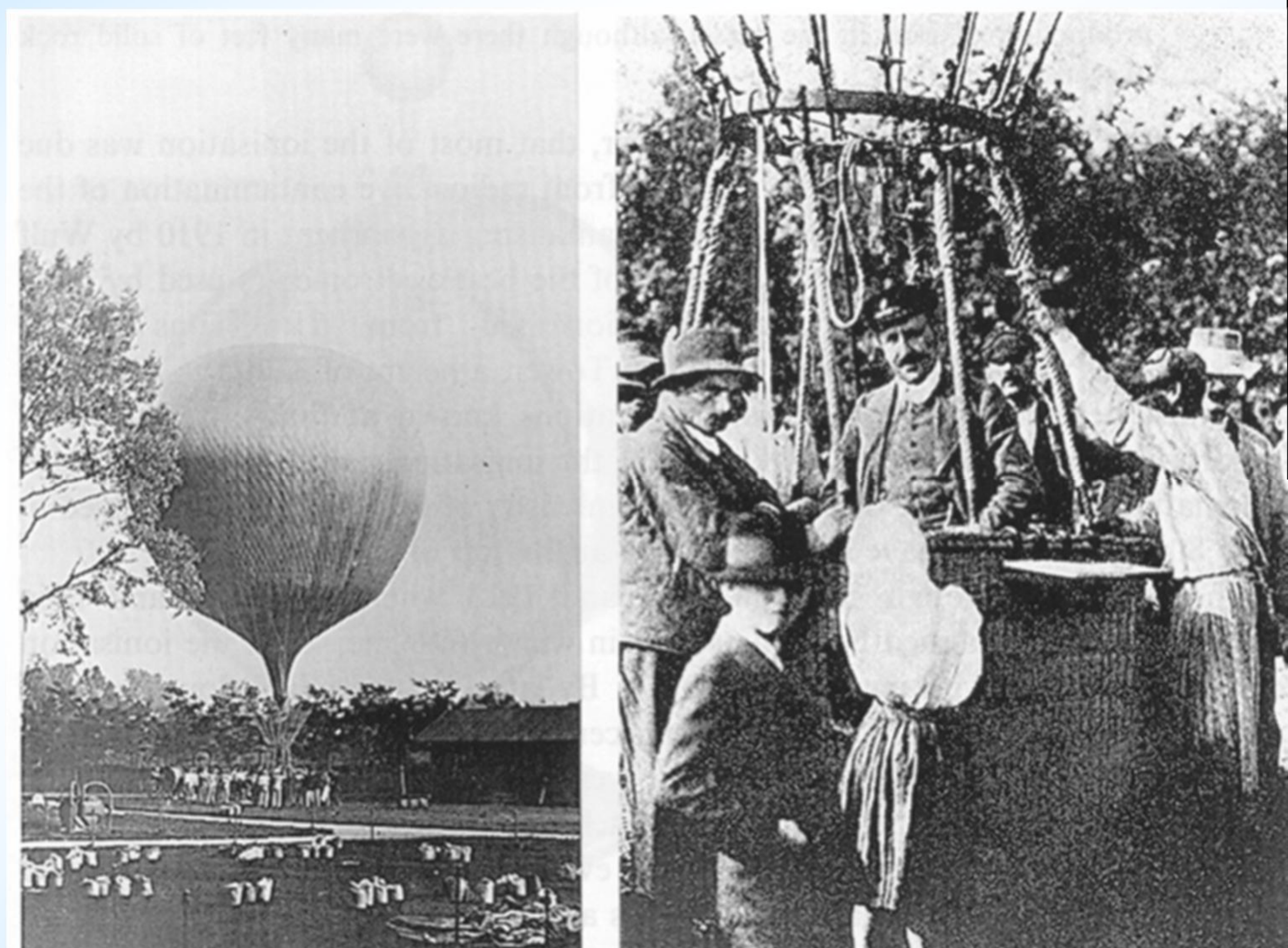


We found however from our observations, that there is no relationship between the state of the sea and the value of the penetrating radiation, so *we do not have any evidence to attribute oscillations of this magnitude to the decay products of radioactive emissions released into the sea by the effect of waves.*

Milestones of CR research

1912:

Victor Hess (Nobel Prize 1936)
launched an electrometer aboard
a balloon to the altitude of 5 km.
The ionization rate first decreased
till 700 m but then increased with
altitude à space origin for ionization.
It was easy to show that the ionizing
radiation was not of solar origin.



Cosmic rays: General facts

- CR is not a ray but a particle (stripped atoms ranging from a single proton (H) ~90%, a-particles (^{4}He) ~10%, up to iron nuclei and beyond, also antimatter).

- Extra-terrestrial **origin**: sun, stars, neutron star, black holes, supernova explosions, active galactic nuclei, radio galaxies, etc.

- **Energy**: highly energetic – up to 10^{20} eV (~20 J)

- **Density** near Earth:

number density ~10^{-10} cm^{-3} (1 particle in 10,000 m^3)

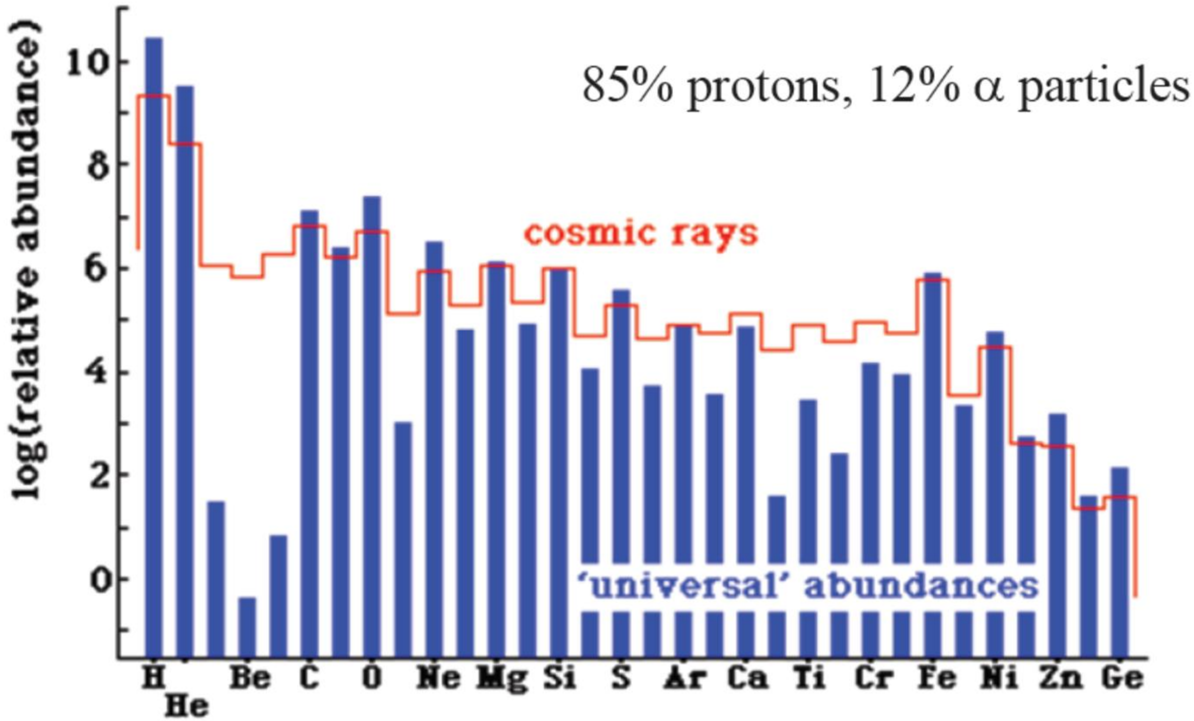
energy density ~ 1 eV cm^{-3}

flux in Space: ***~1 cm^{-2} sec^{-1}***

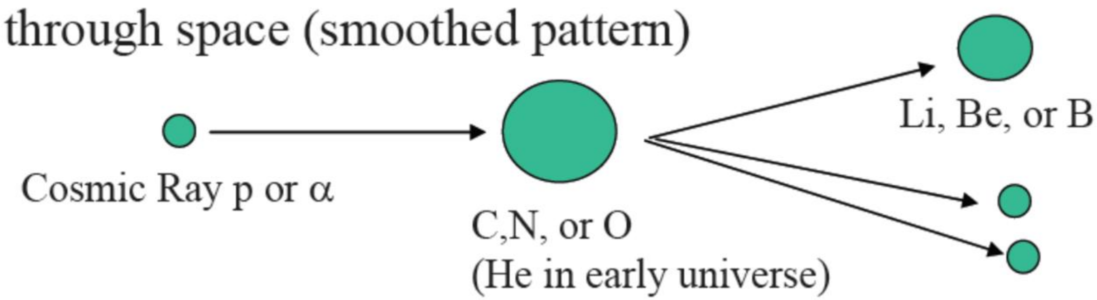
flux at Earth: ***~1 m^{-2} sec^{-1}***

Chemical composition

Primaries: energetic ions of all stable isotopes:

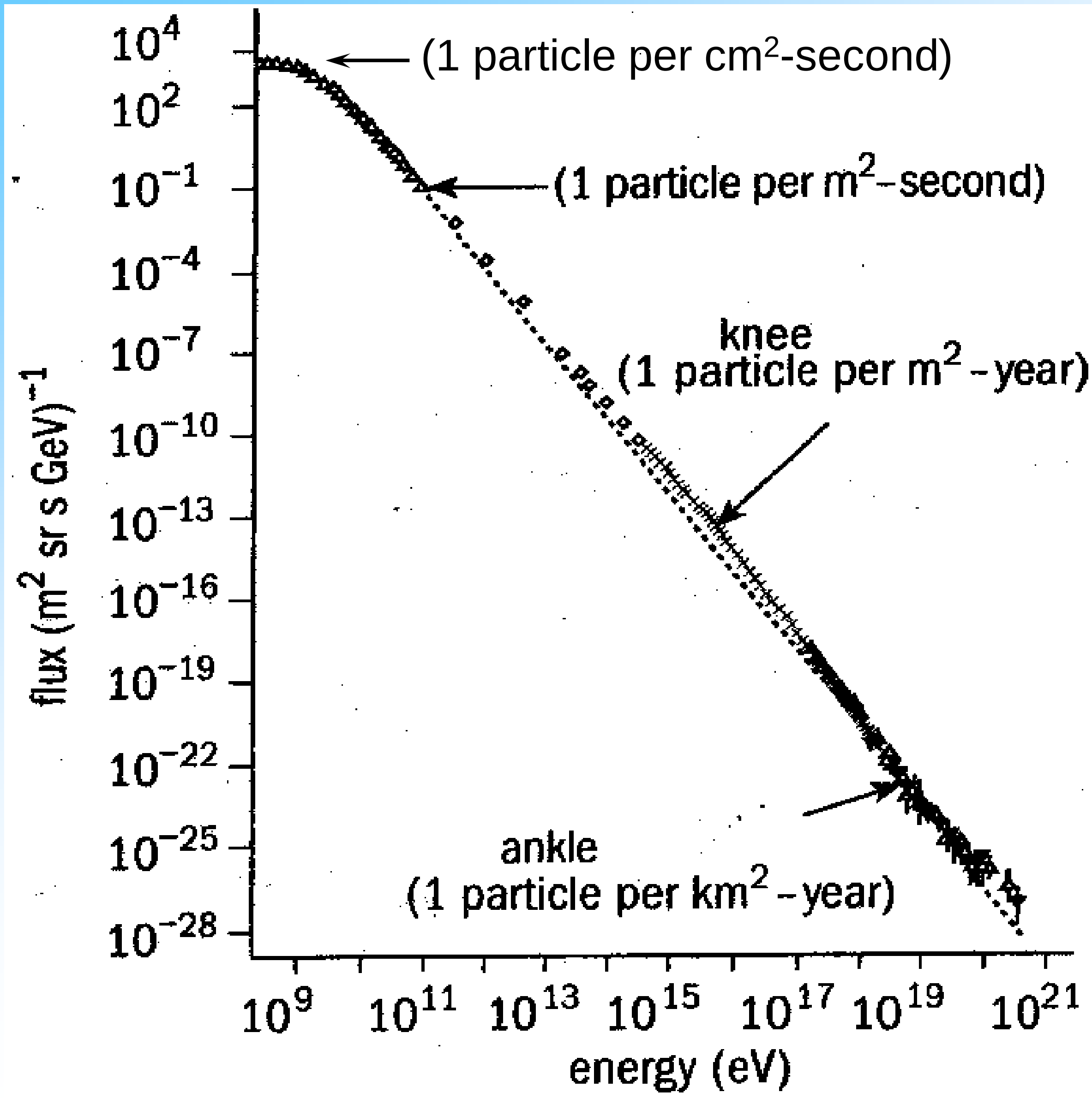


Similar to solar elemental abundance distribution but differences due to spallation during travel through space (smoothed pattern)



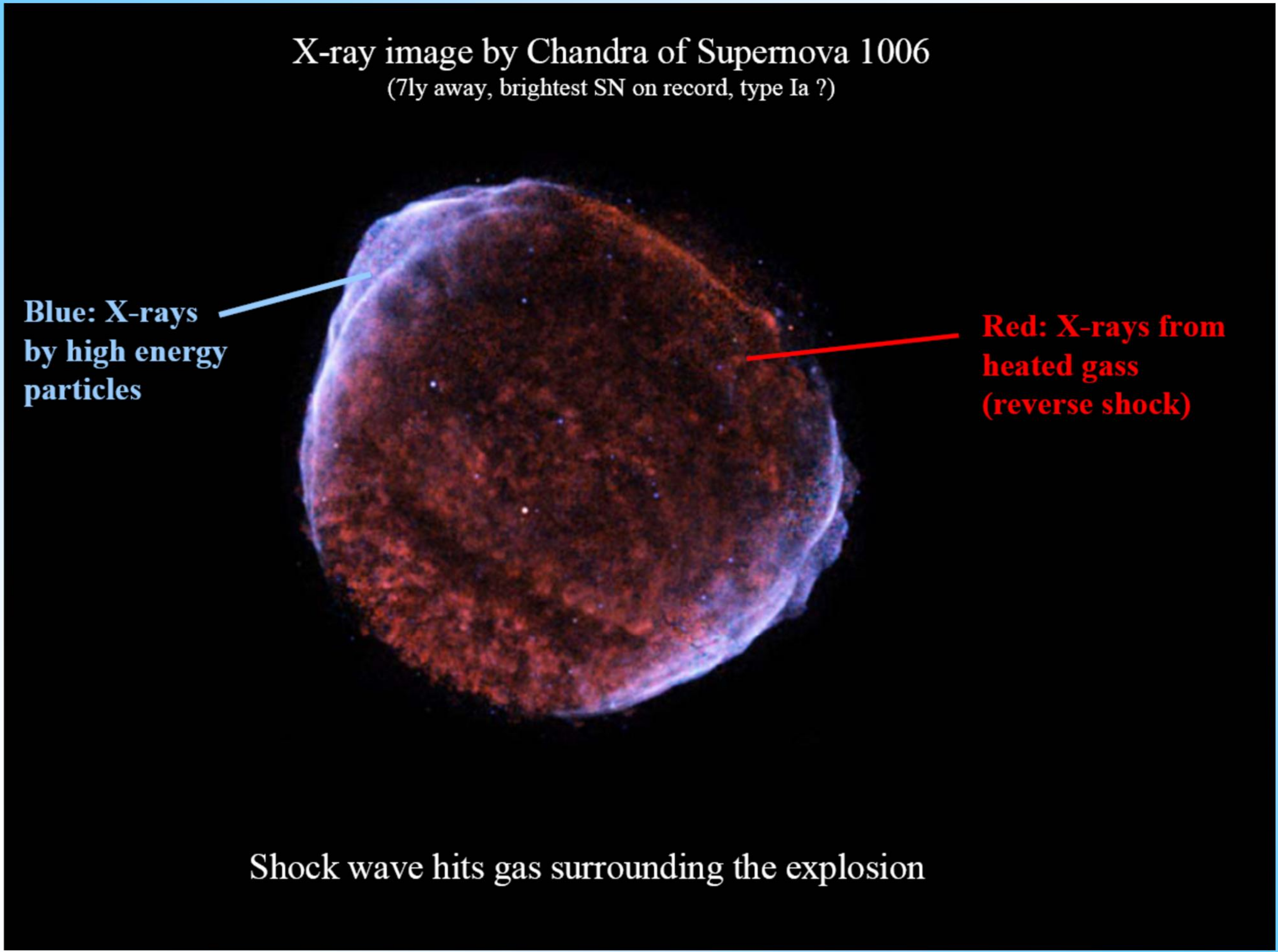
Major source of ^{6}Li, ^{9}Be, ^{10}B in the Universe (some ^{7}Li, ^{11}B)

Galactic cosmic rays: spectrum and composition

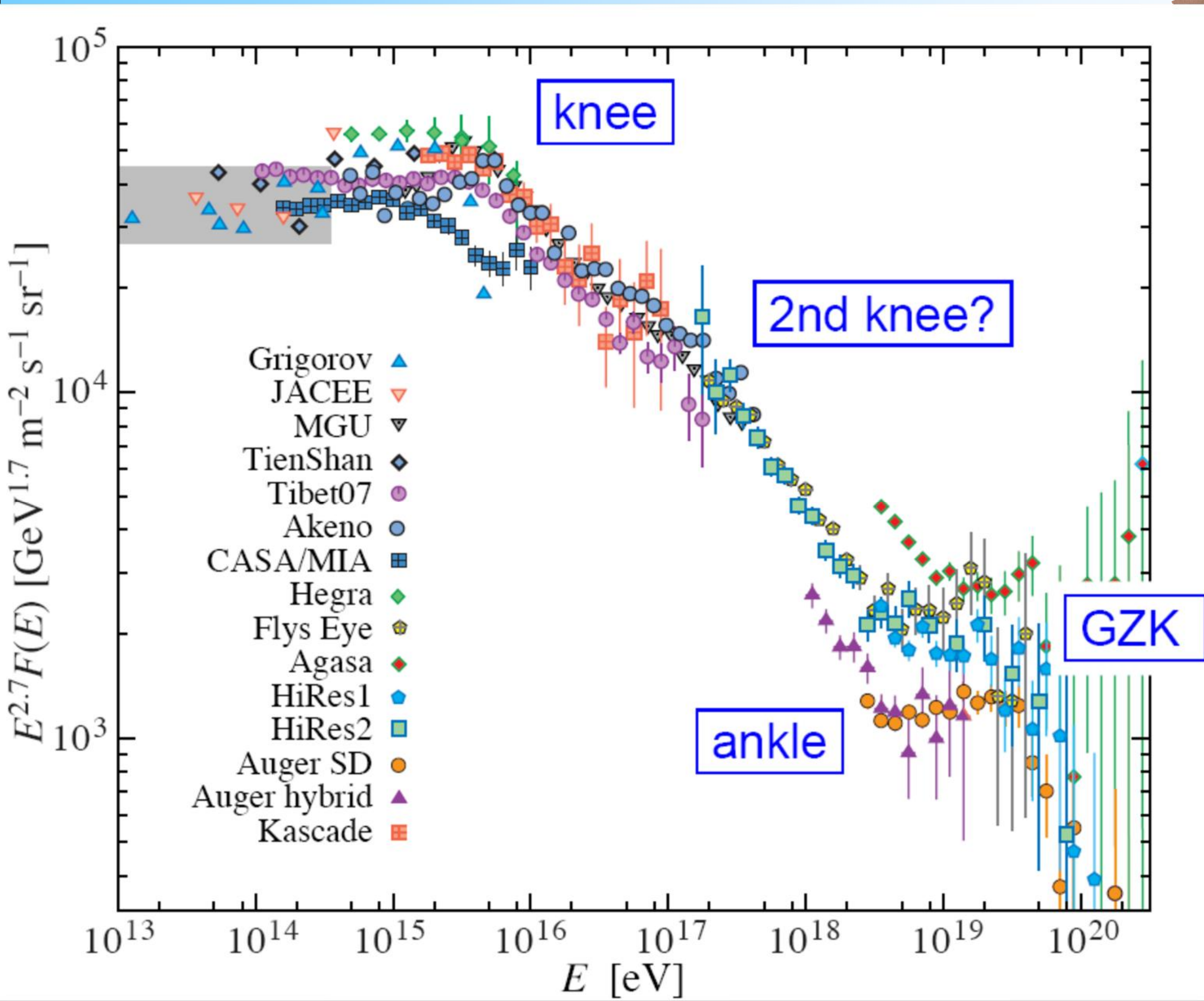


particle	charge	# / proton
protons	1	1
helium	2	10^{-1}
L, M, H	3-20	1.5-5 10^{-4}
VH	20-30	4 10^{-5}
SH	>30	10^{-8}
electrons	-1	10^{-3}
antiprotons	-1	5 10^{-5}

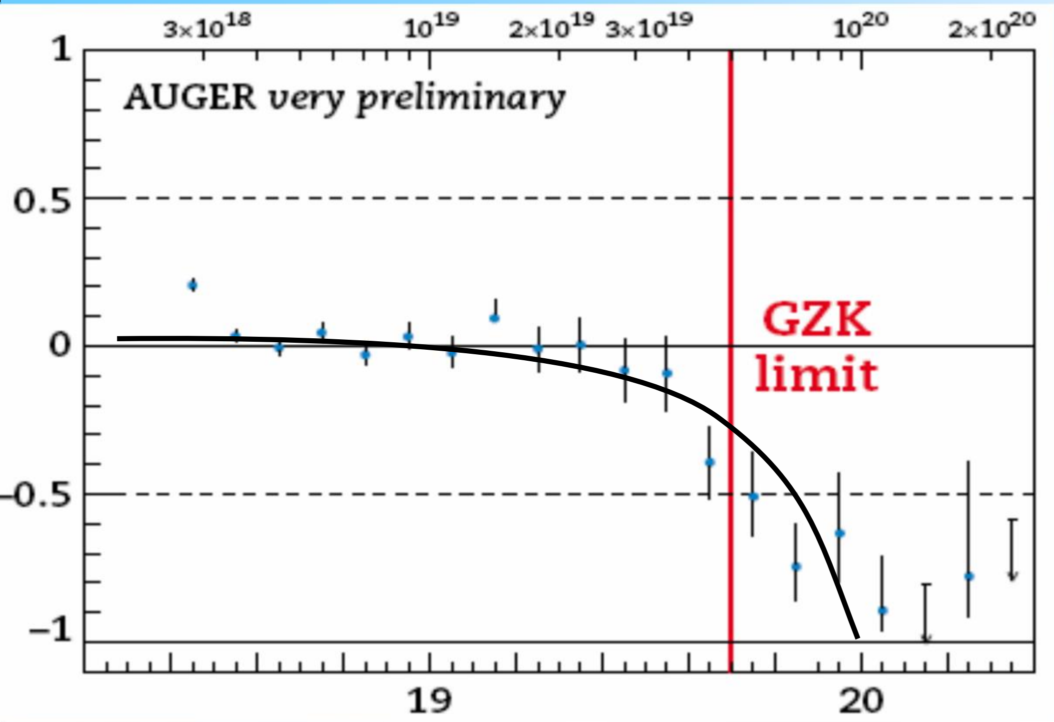
Acceleration: Supernova



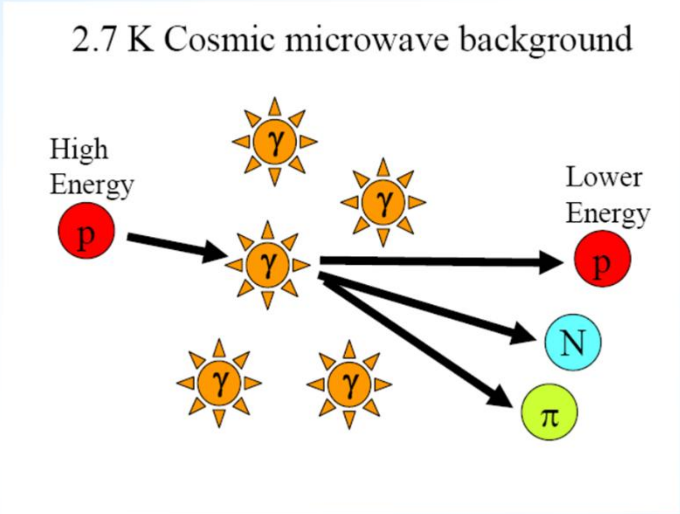
Normalized GCR spectrum



Greisen-Zatsepin-Kuzmin (GZK) cutoff



$^{10}\log(E)$ [eV]



Threshold for photo pion production: 4 10^{19}eV

Higher energy protons would be slowed down by this effect by 1/e over 15 Mpc (Galaxy ~0.03 Mpc).
If cosmic rays come from >> 15 Mpc, energy cutoff at **~10^{20}eV** (GZK cutoff)

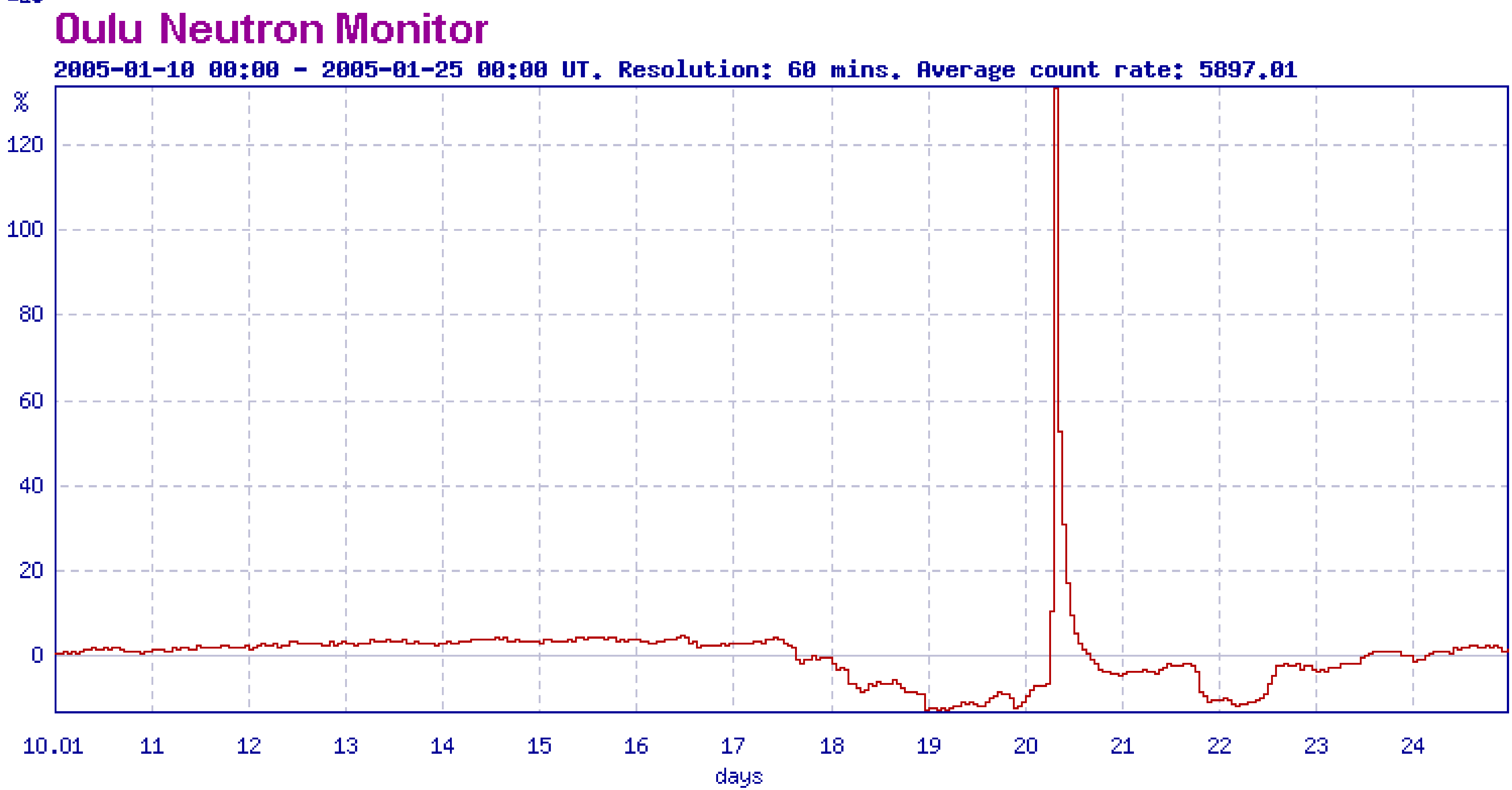
40 events > 4 10^{19} eV
7 events > 10^{20} eV
Record: 15-10-1991
Fly's Eye: 3 10^{20} eV

Summary

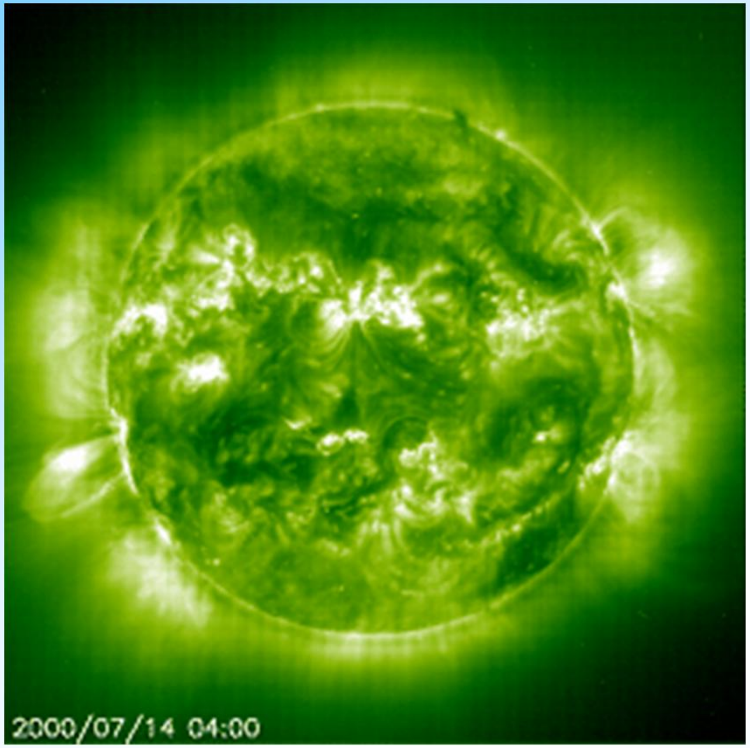
- **CRs are accelerated in SN remnants up to some max energy, then may be re-accelerated in magnetic clouds.**
- **Cosmic rays are trapped in the Galaxy due to its magnetic field, where they diffuse for 10^7 years.**
- **At high energy CRs are mostly of extra-galactic origin.**
- **The knee in the spectrum is either due to a less effective acceleration or to propagation effects.**
- **The ankle is believed to be the transition site from galactic to extragalactic CRs…**
- **GKZ (Greisen, Zatsepin & Kuzmin) cutoff due to interaction with 2.7 K CMB (cosmic microvawe background) >10^{20} eV**

What are solar cosmic rays or solar energetic particles?

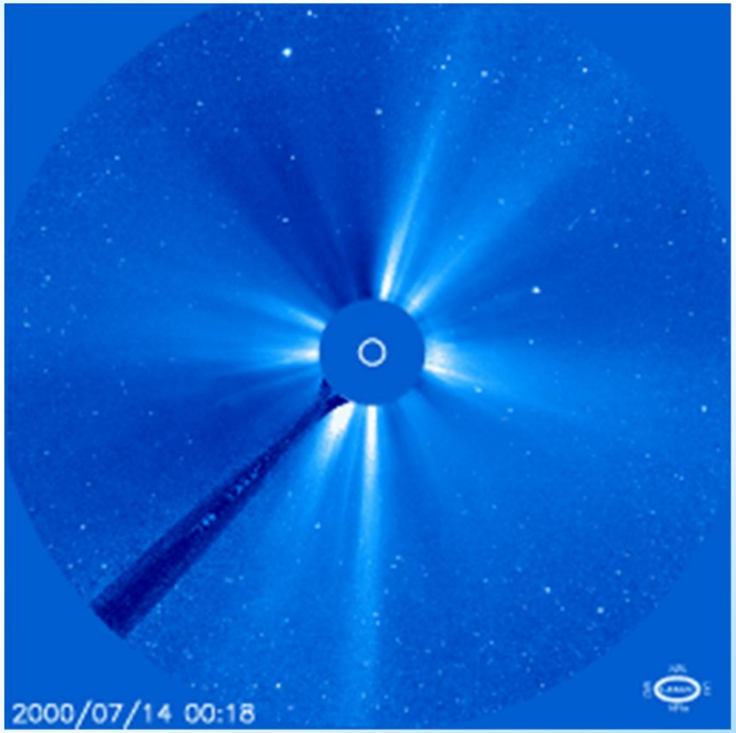
GLE 69, 20-01-2005



Solar flares and energetic particles



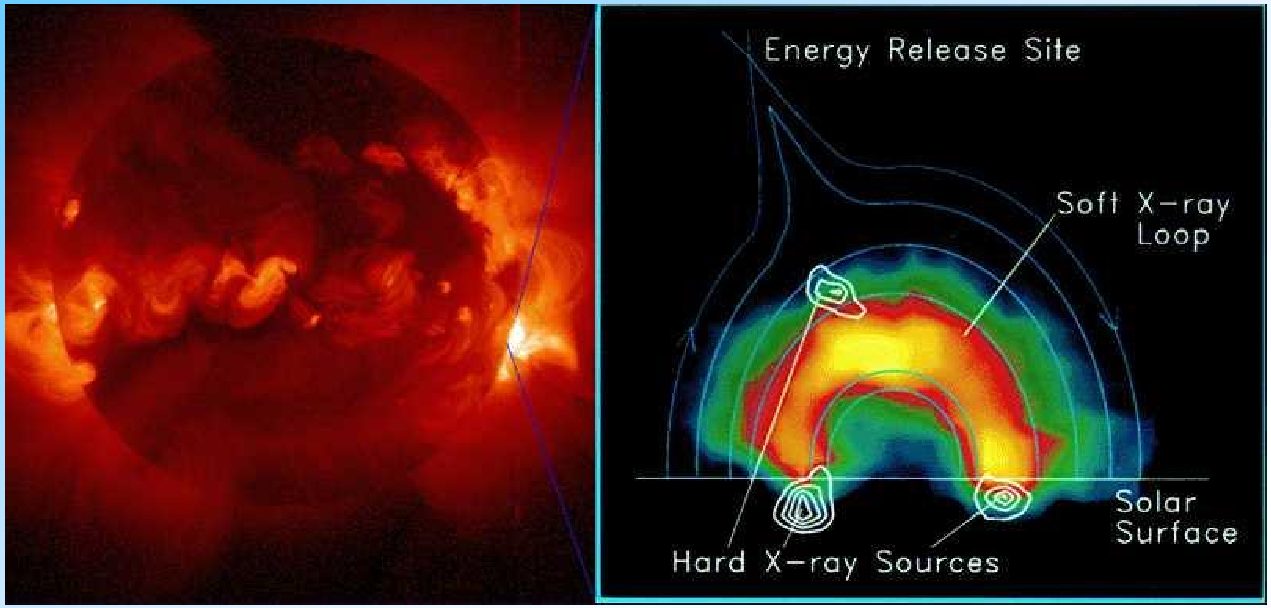
EIT 195 Å

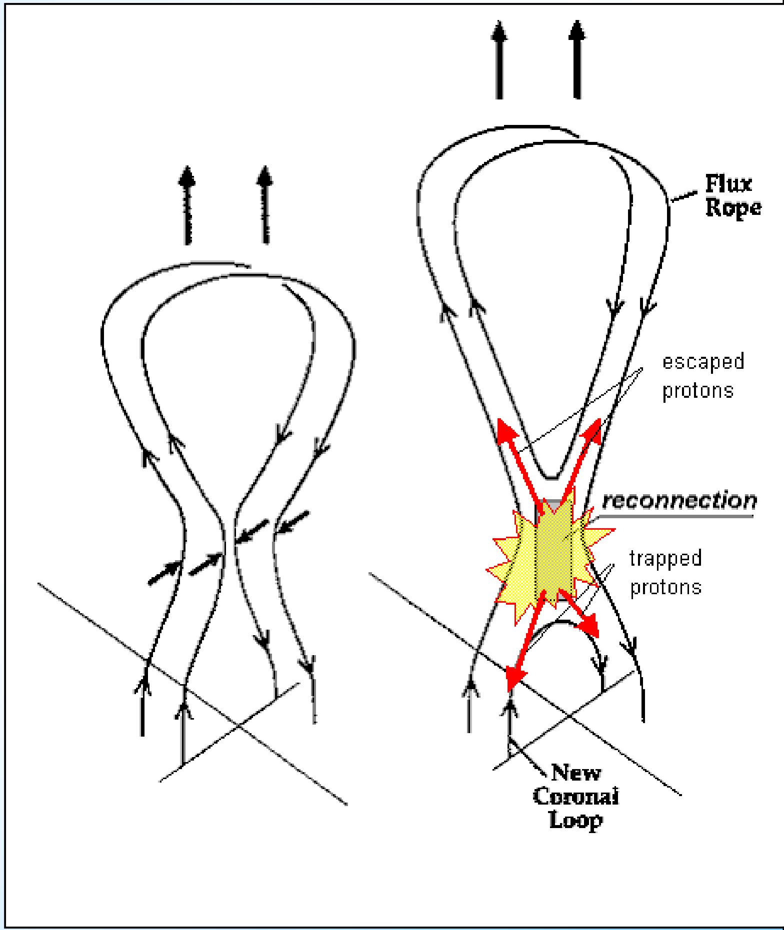


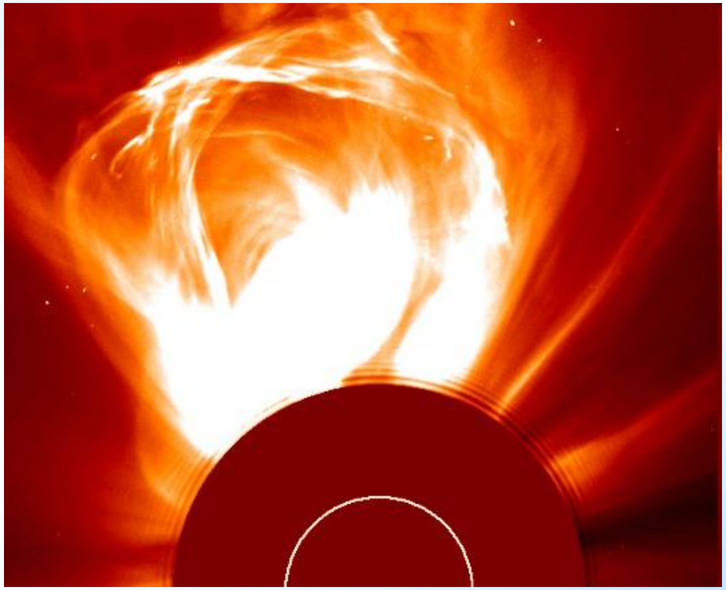
LASCO C3

SOHO (Credit NASA)

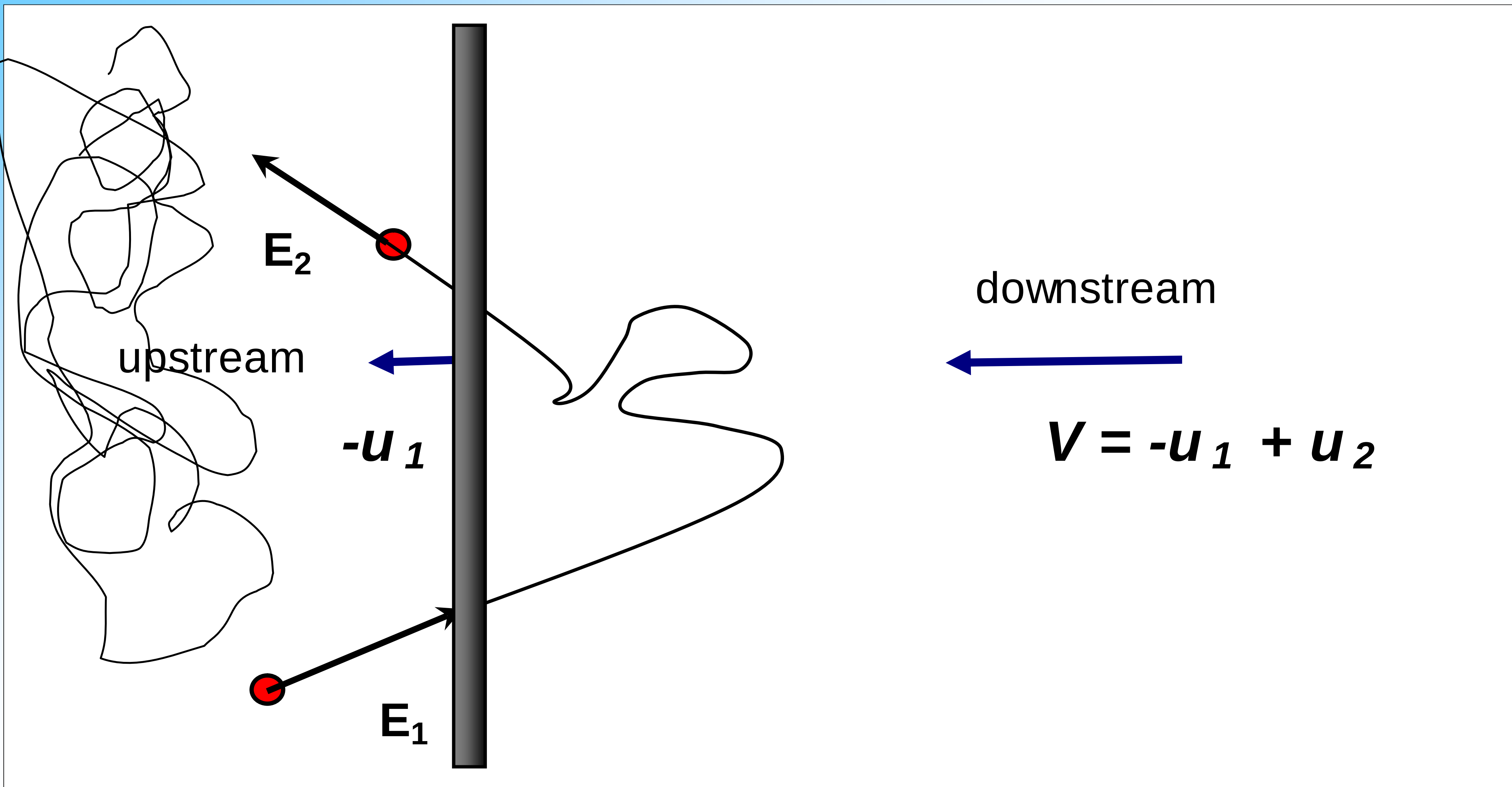
Solar cosmic ray acceleration



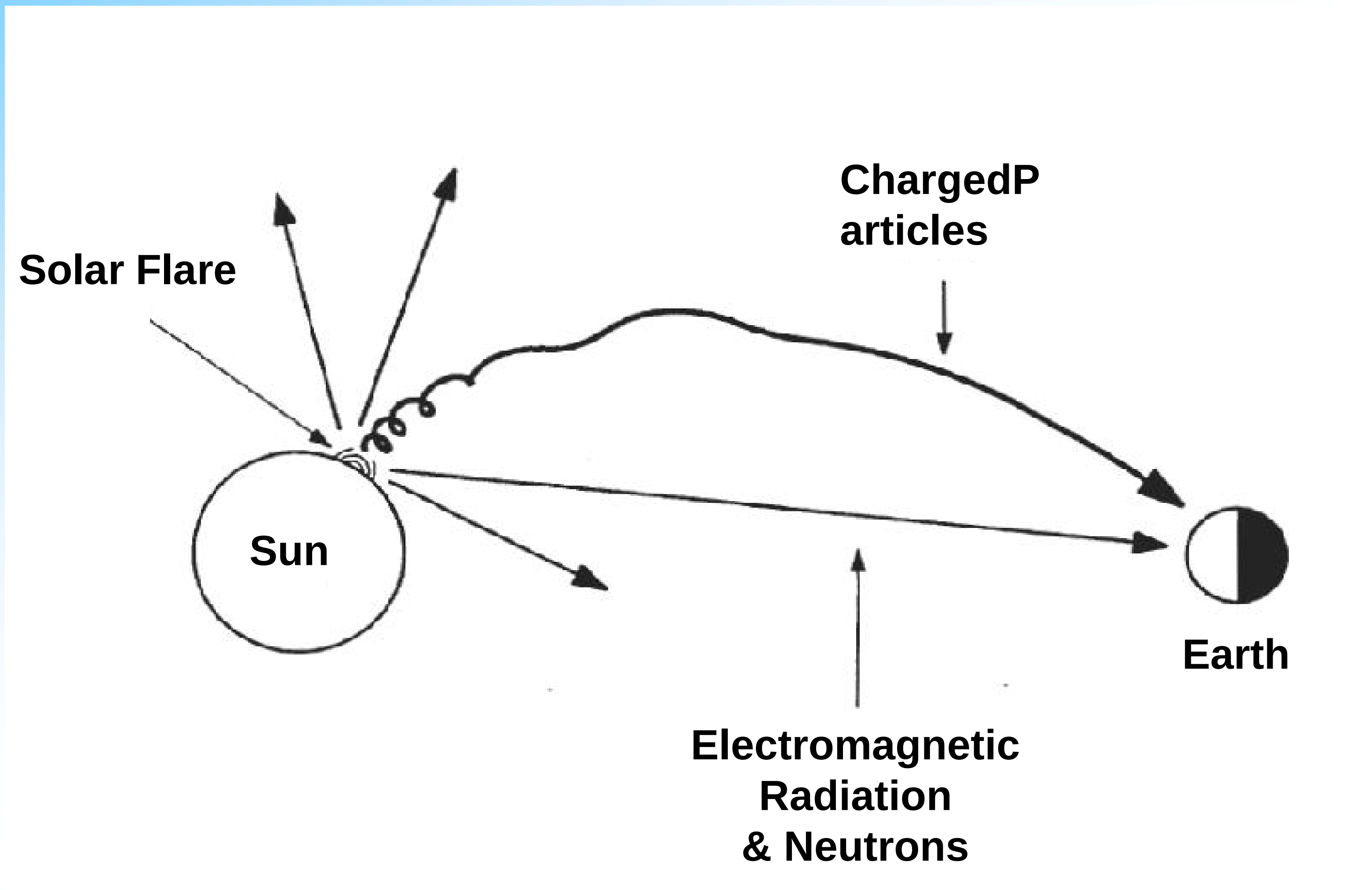




Fermi 1: collision with a shock

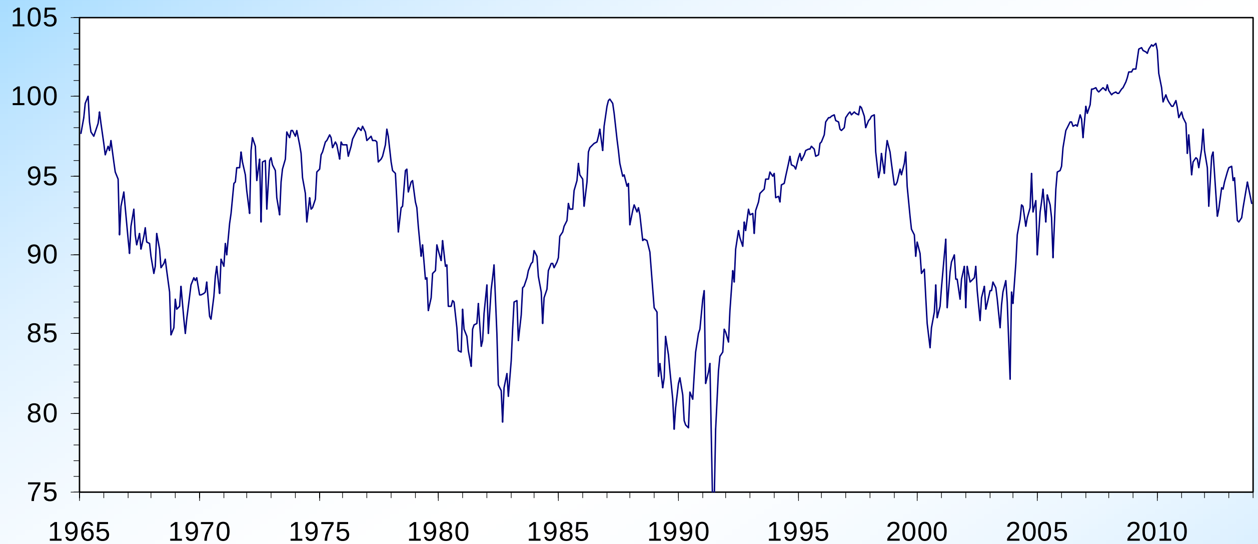


Solar Cosmic Rays

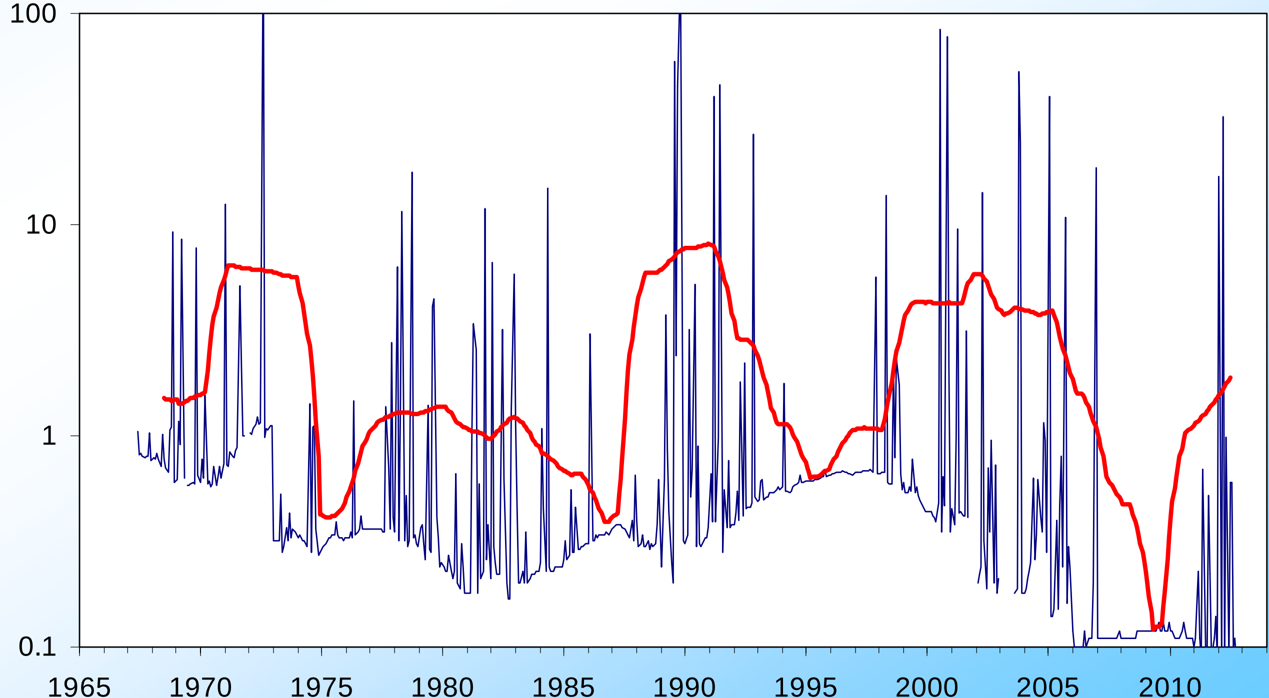


Time variability

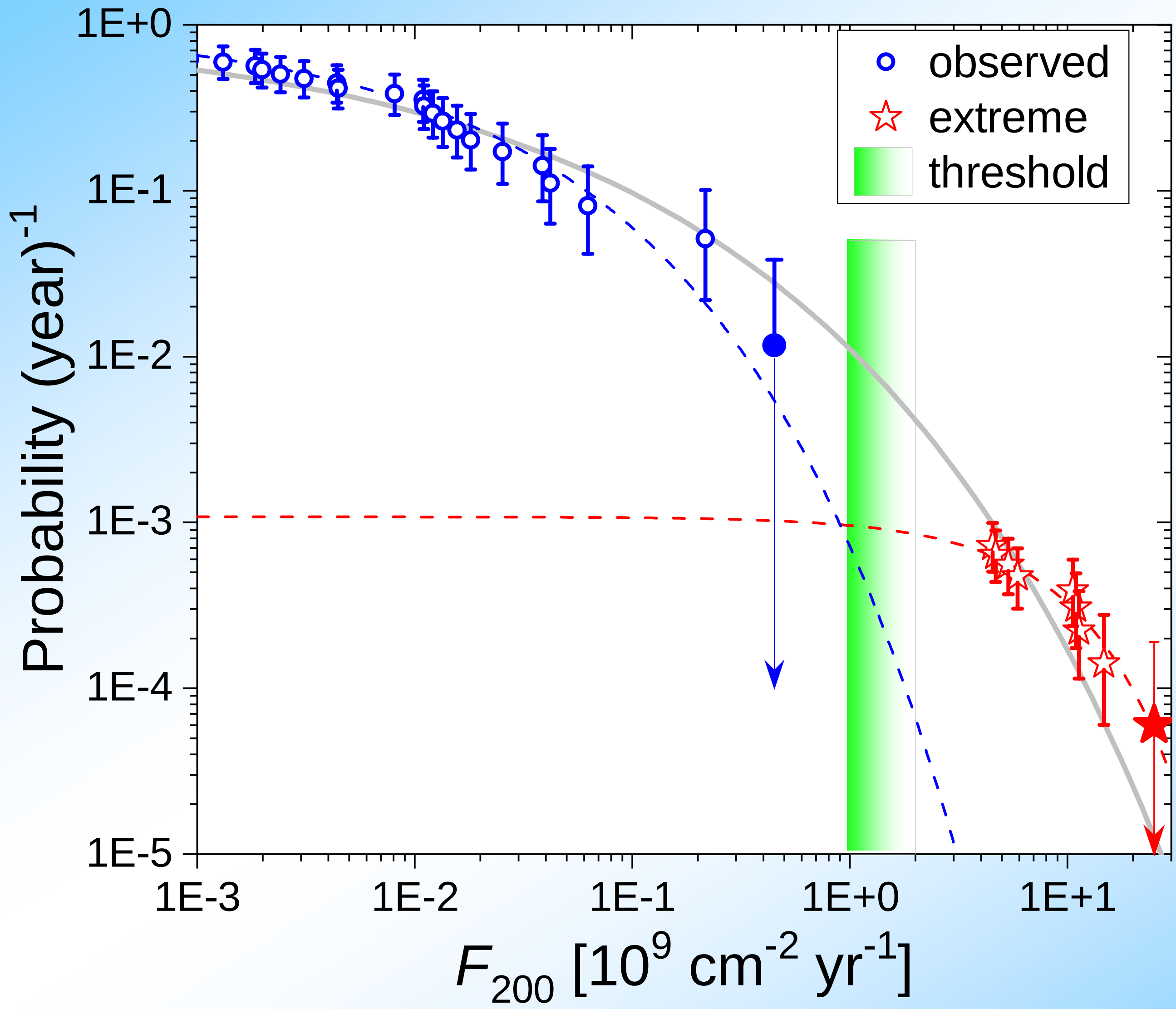
GCR – Oulu NM



F (>30 MeV), $(cm^2\ s\ ster)^{-1}$



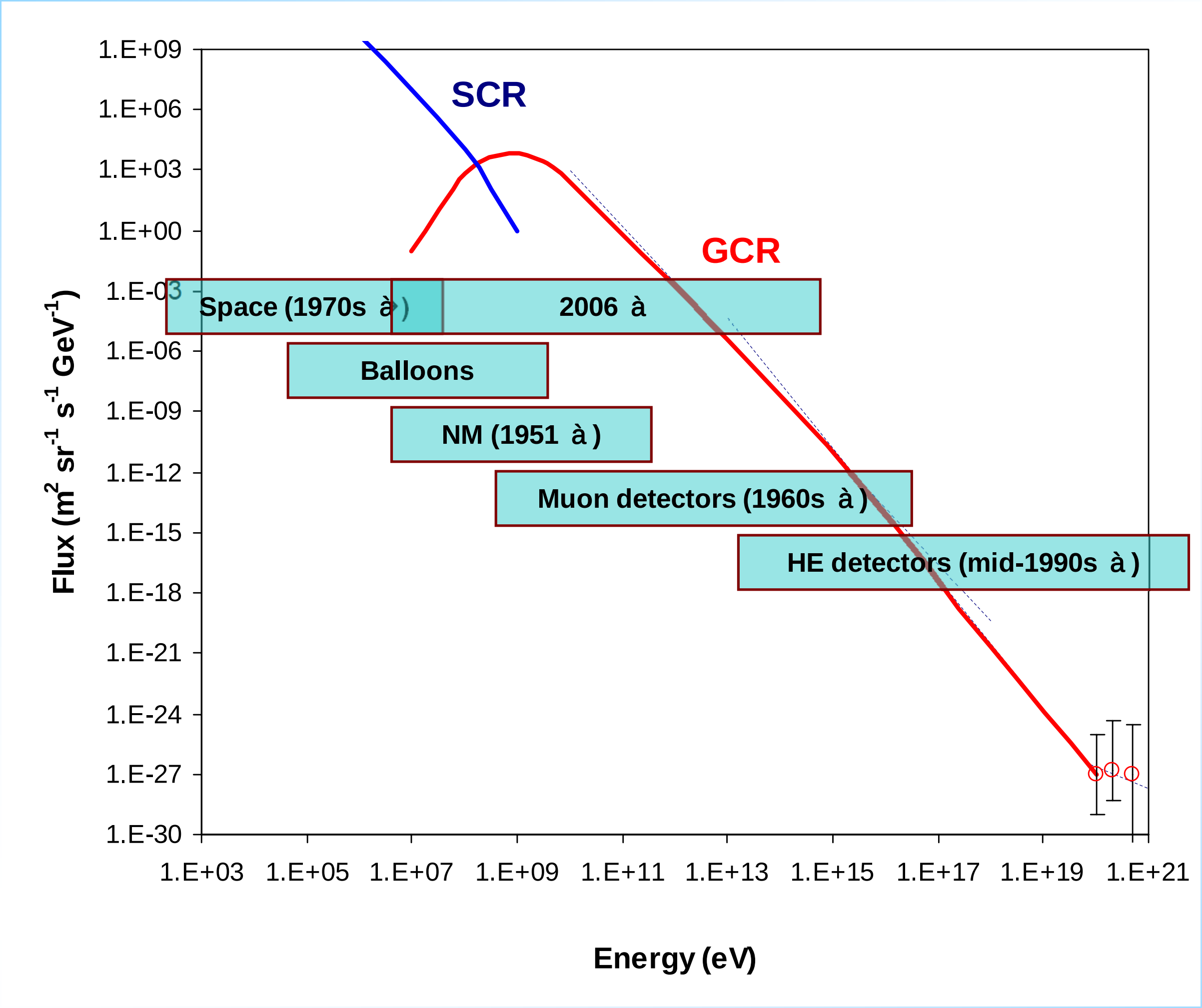
How often do SEP events occur?



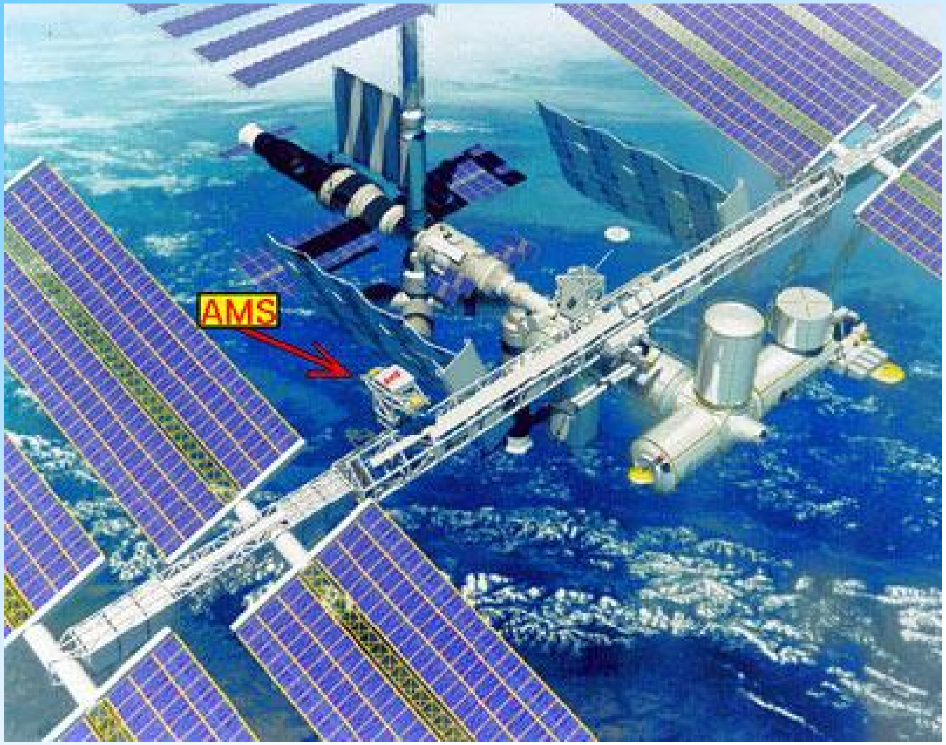
The probability of a SEP event to occur (Usoskin, LRSP, 2023)

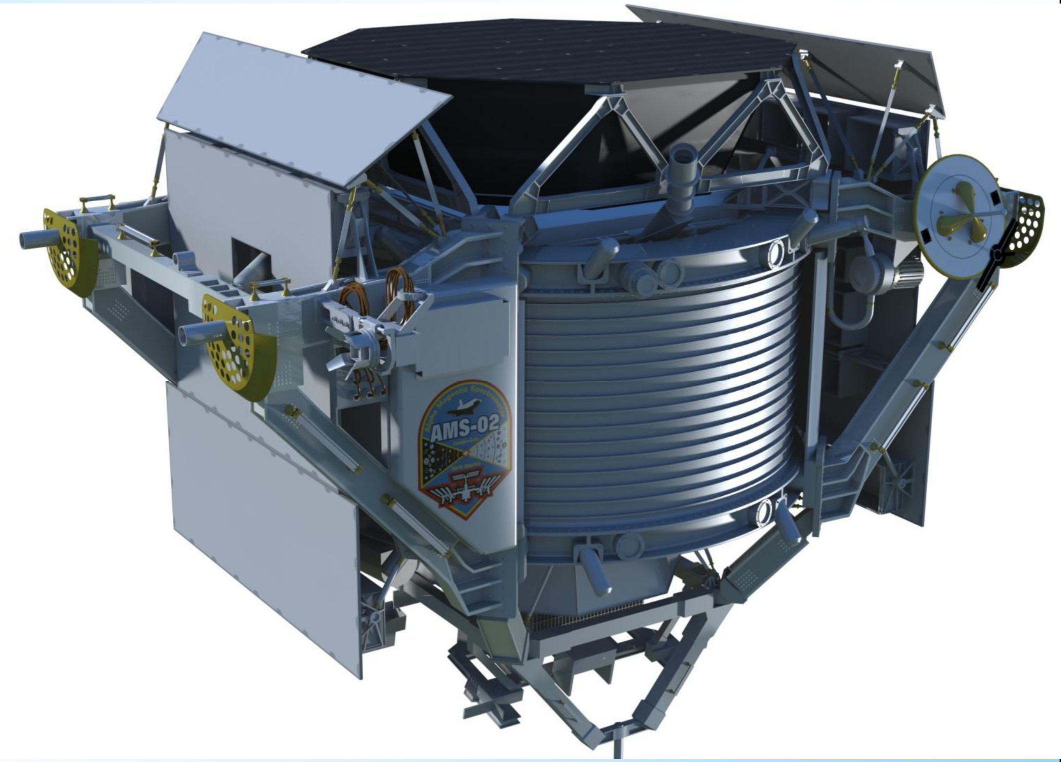
How can we measure cosmic rays?

How can we study them?



Direct measurements - AMS

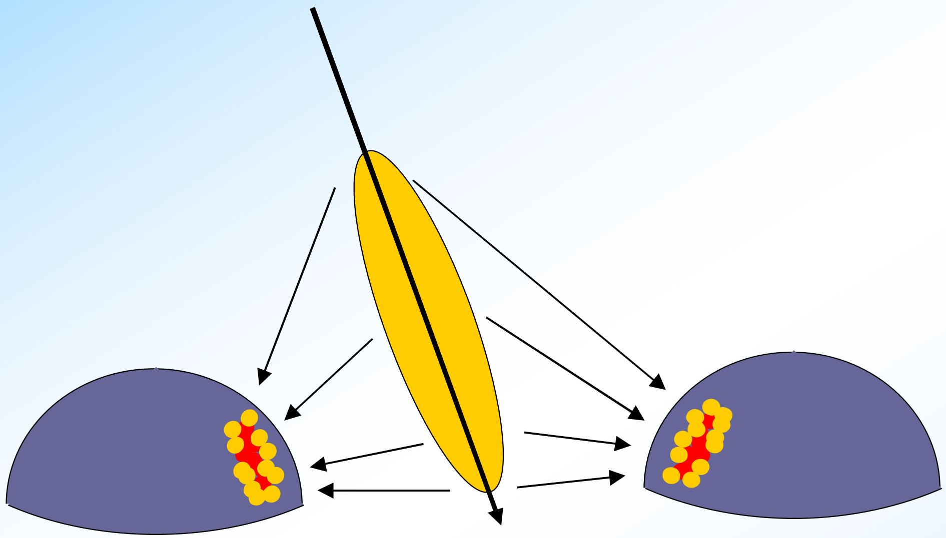




- ***AMS (Alpha Magnetic Spectrometer).***
- AMS-1 (June 1998),
- AMS-2 (launched 16.05.2011)
  - **Weight** 8,500 kg; **Volume** 64 cubic meters; **Power** 2,500 watts; **Data downlink** 9 Mbps (average); **Subsystems** 15 among particle detectors and supporting subsystems
  - **Launch** 16th May 2011, the last Endeavour flight, **Mission duration** through the lifetime of the ISS, until 2020 or longer (it will not return back to Earth), **Construction** 1999-2010, **Cost** $1.5 billion

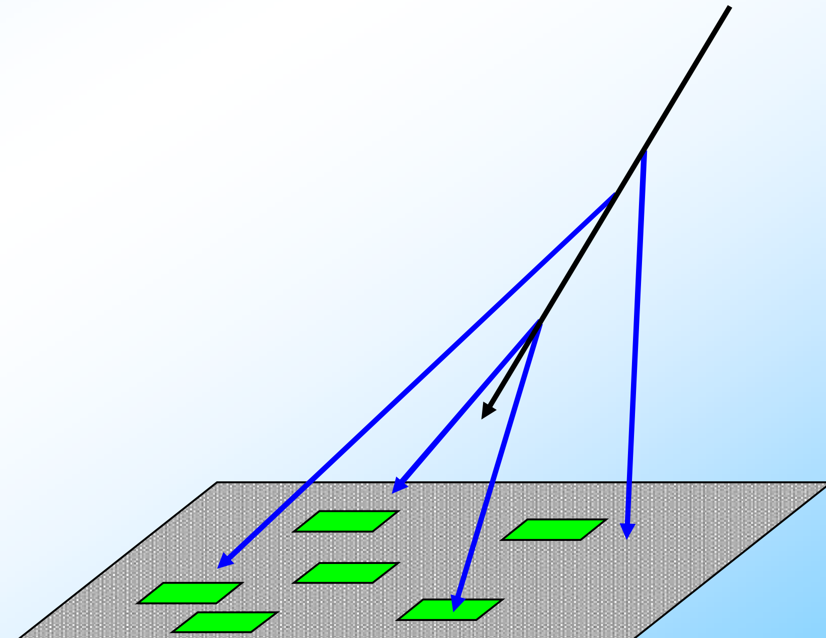
Detection of HE cosmic rays

fluorescence
(ultra-violet → 'visible')



multi-pixel cameras
(stereoscopic view)

ground array



muon detectors
(arrival time → direction)

Neutron monitor

Neutron monitor (NM) measures the nucleonic component of the atmospheric cascade. Sensor tubes are filled with BF_3

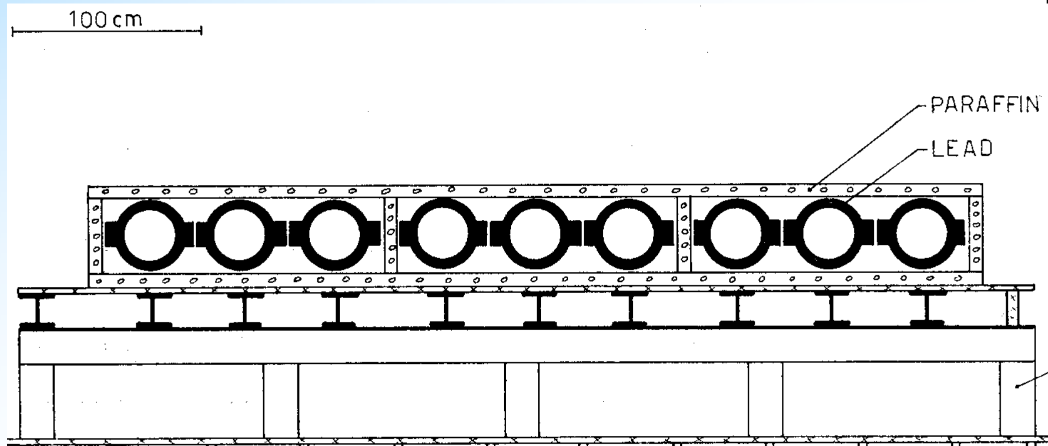
$$^{10}B + n \rightarrow {}^{7}Li + a$$

Fast helium and Li strip electrons from neutral atoms in the tube, leading to a charge avalange in the tube.

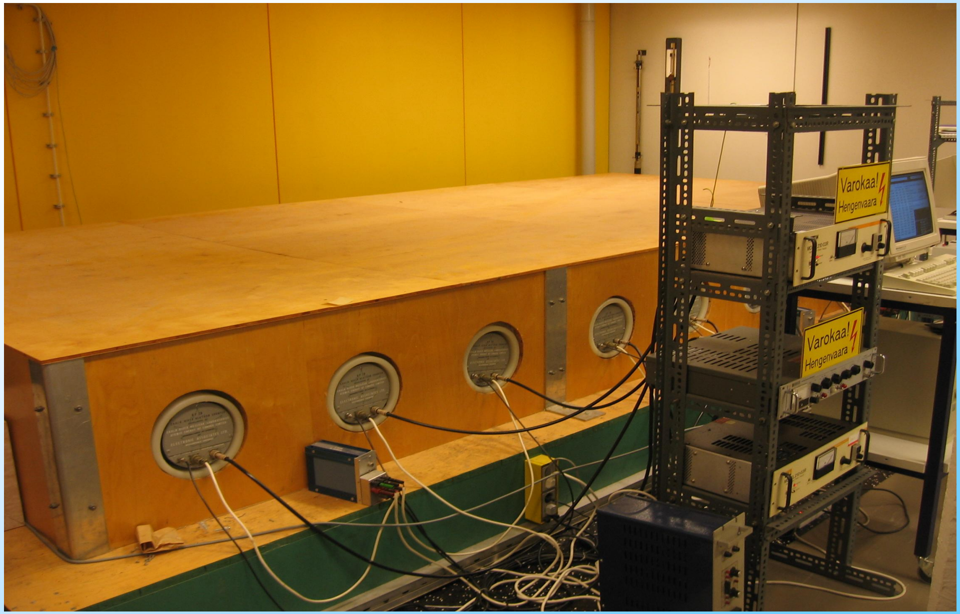
A new type of counting tubes, filled with ^{3}He :

$$^{3}He + n \rightarrow {}^{3}H + p + g(\,7.65\ MeV)$$

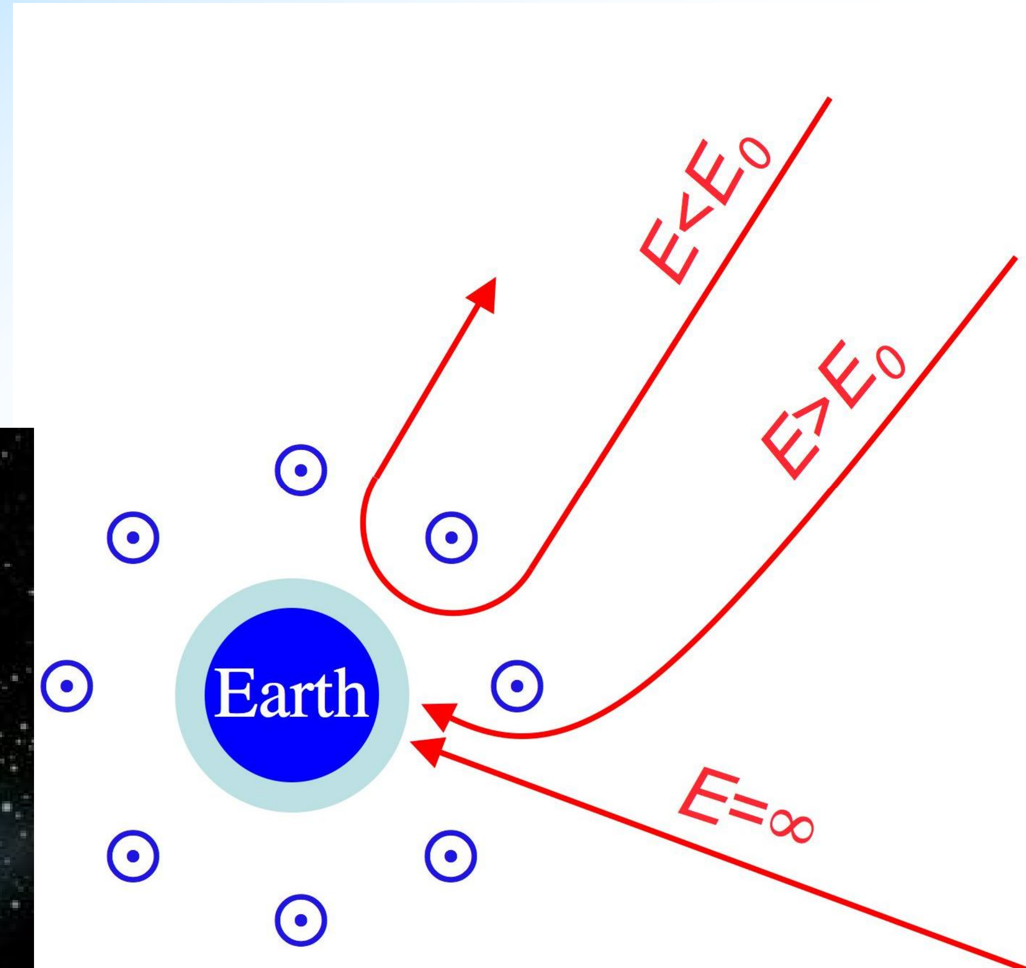
The effective energy range is 0.3 – 50 GeV which is roughly equal to the effective energy range of solar modulation of CR.



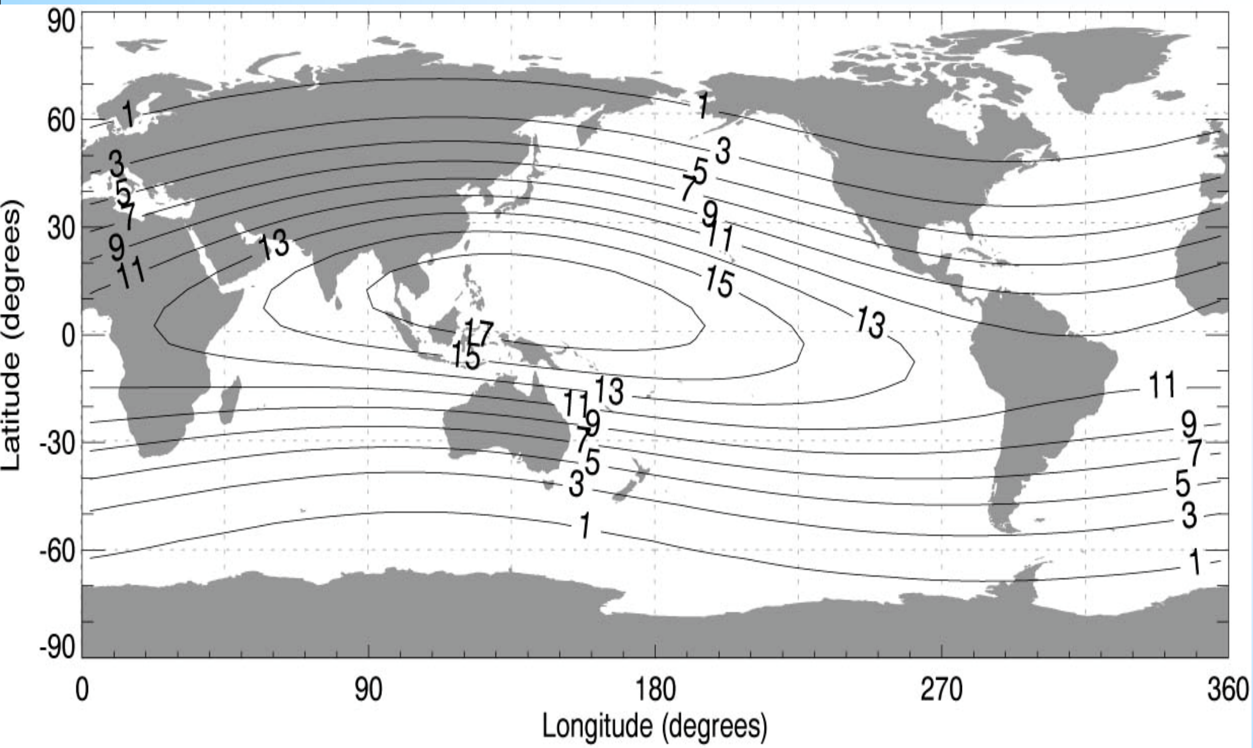
Scheme of a NM. The outer paraffin layer is a pre-moderator. The lead layer is a moderator + neutron multiplicator. The inner plastic layer is the final moderator, making neutrons almost thermal.



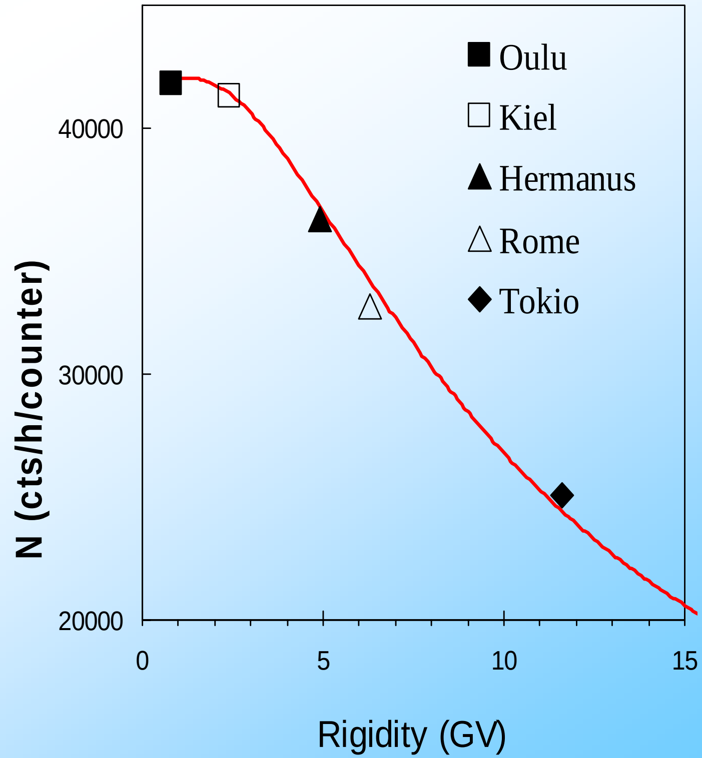
Bending of charged particles in MF



Geomagnetic cutoff

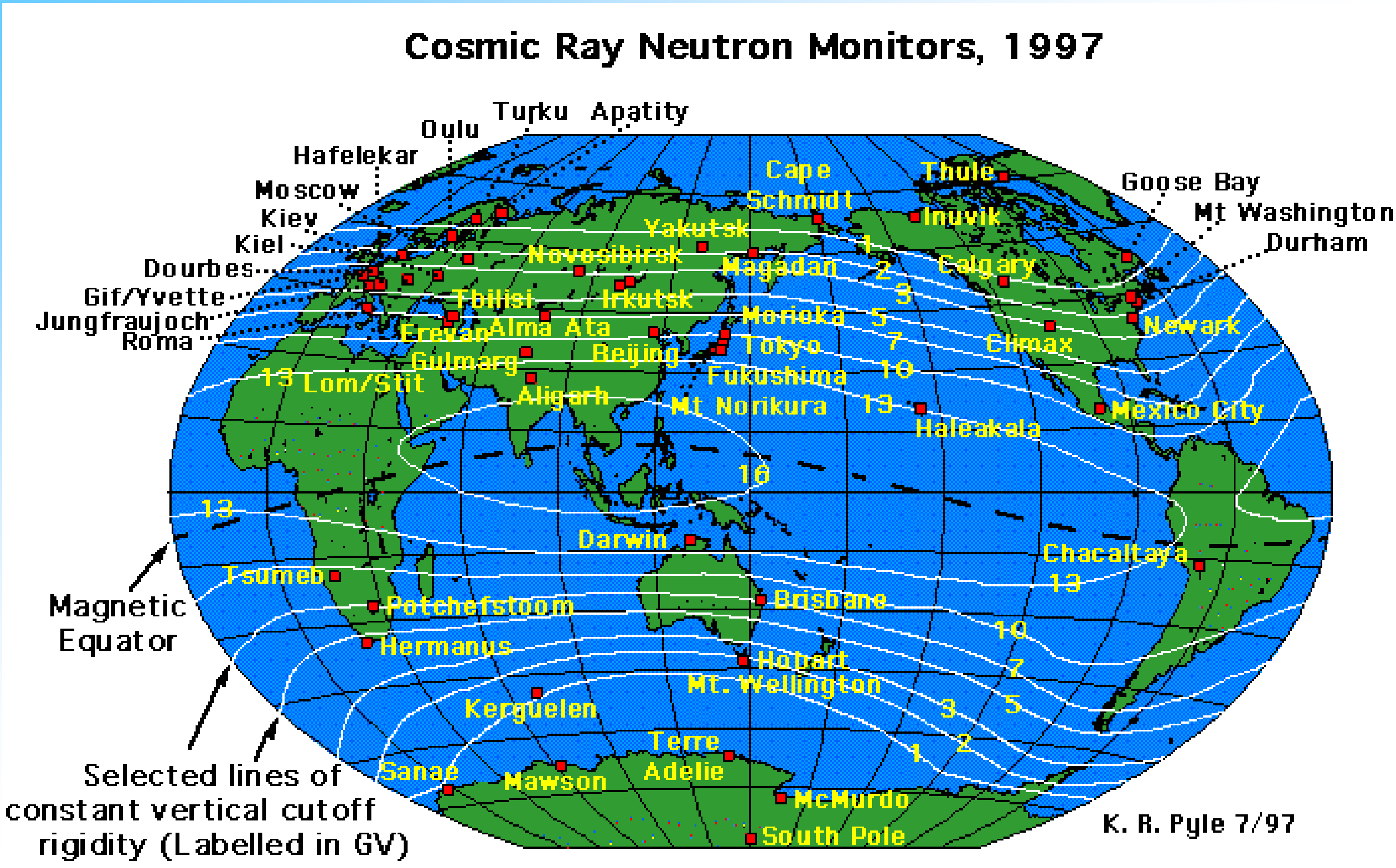


Isolines of vertical geomagnetic cutoff rigidities for 2000.



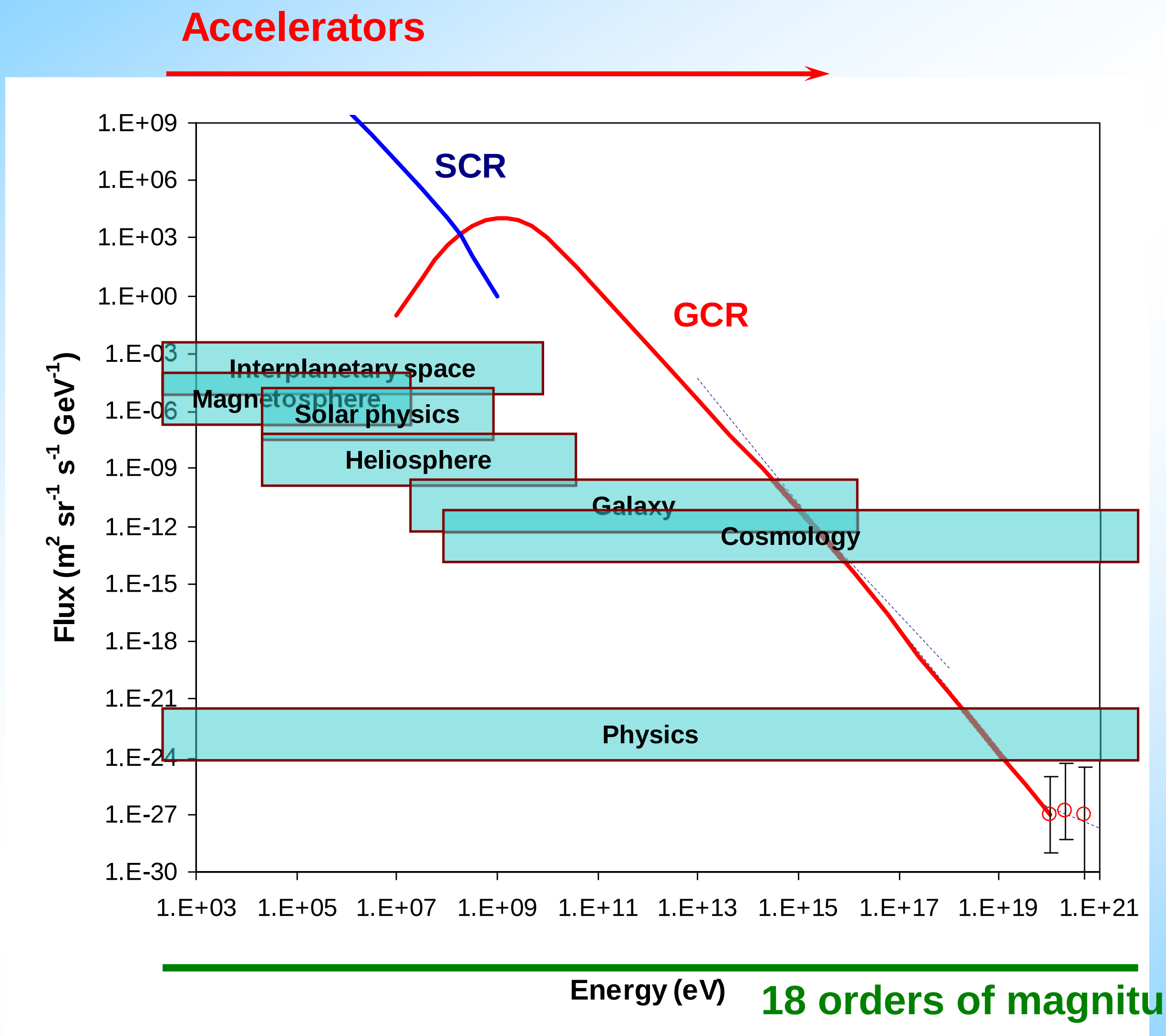
CR vs. geomagnetic cutoff rigidity.

Worldwide network of NMs



What can we learn?

What can we learn from CR ?



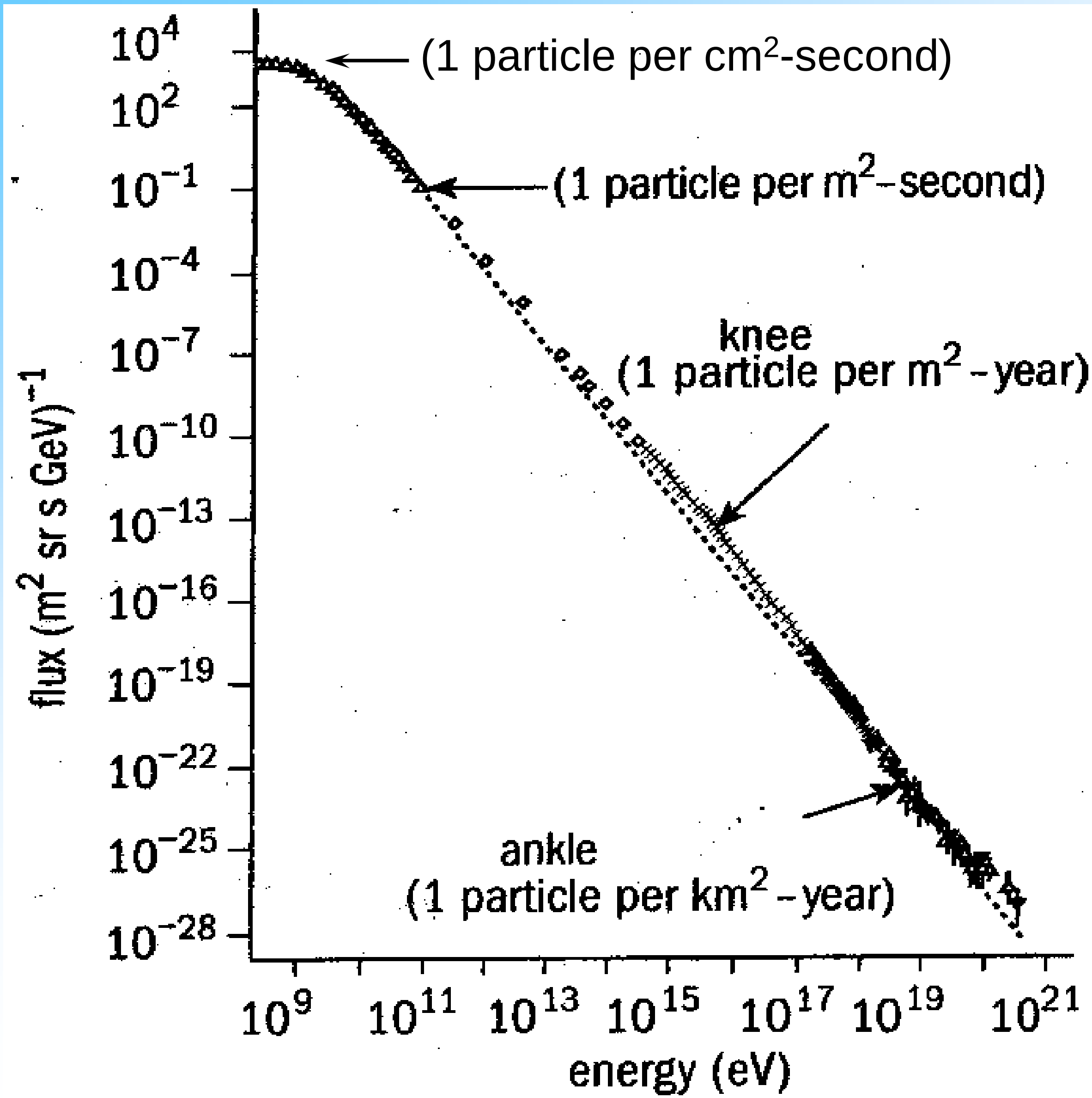
37 orders of magnitude !

18 orders of magnitude

Cosmic ray physics

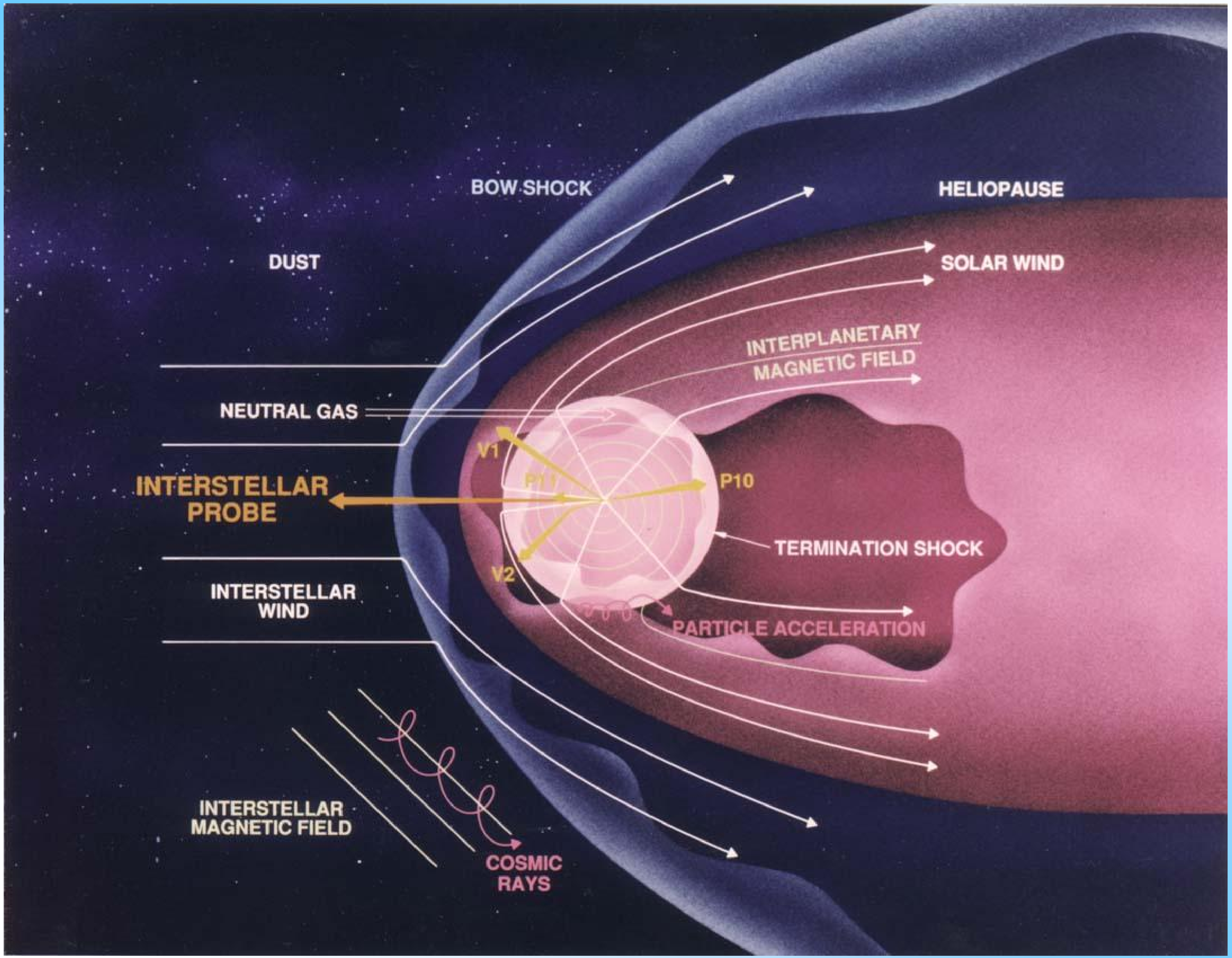
- Nuclear physics (object of research):
  - » Energies unreachable at laboratories;
- Astrophysics+cosmology (tool)
  - » Composition à cosmology, astrophysics;
  - » Origin à probe for energetic phenomena in space;
  - » Transport à probe for parameters of the matter;
- Geophysics, space physics (subject)
  - » CR influence on atmospheric properties

Galactic cosmic rays: mostly low energy



How do they vary?

The heliosphere



Transport equation

Transport equation (guiding center approximation):

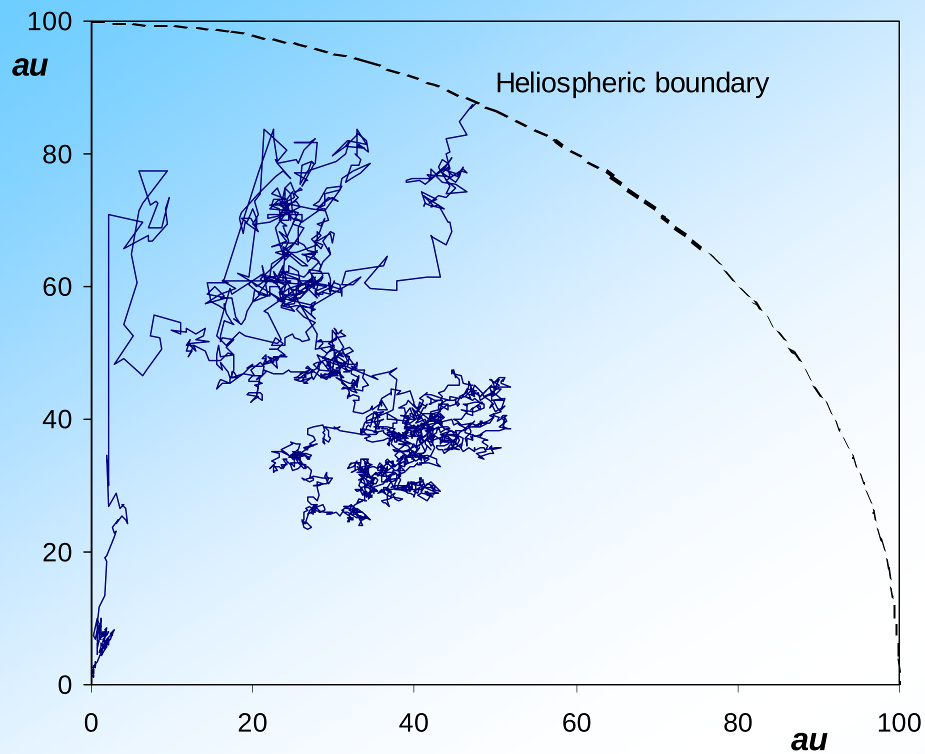
$$\frac{\partial f}{\partial t} = -\left(\mathbf{V} + \langle \mathbf{v}_D \rangle\right)\cdot\nabla f + \nabla\cdot\left(\mathbf{K}^{(S)}\cdot\nabla f\right) + \frac{1}{3}\left(\nabla\cdot\mathbf{V}\right)\frac{\partial f}{\partial \ln P}$$

convection + drift — diffusion — adiabatic cooling

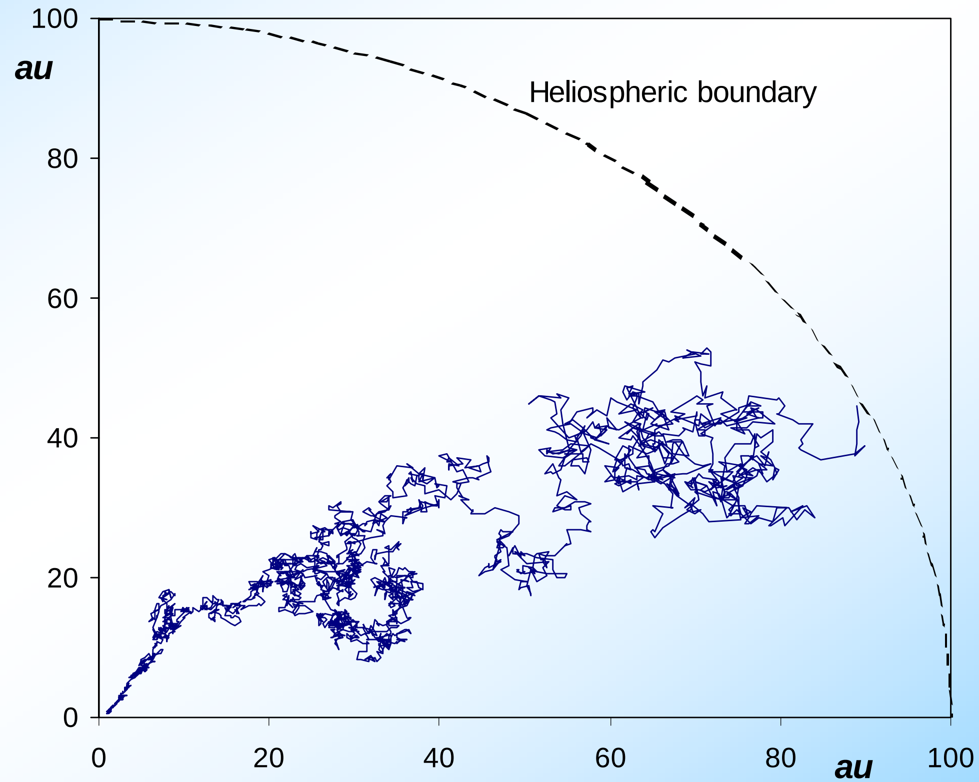
diffusion coefficient $k \propto B^{-n}$, $n = 1\text{-}1.5$

$$\mathbf{K} = \begin{vmatrix} k_\parallel & 0 & 0 \\ 0 & k_\perp & k_T \\ 0 & -k_T & k_\perp \end{vmatrix} = \mathbf{K}^{(S)} + \mathbf{K}^{(A)}$$

Heliospheric transport

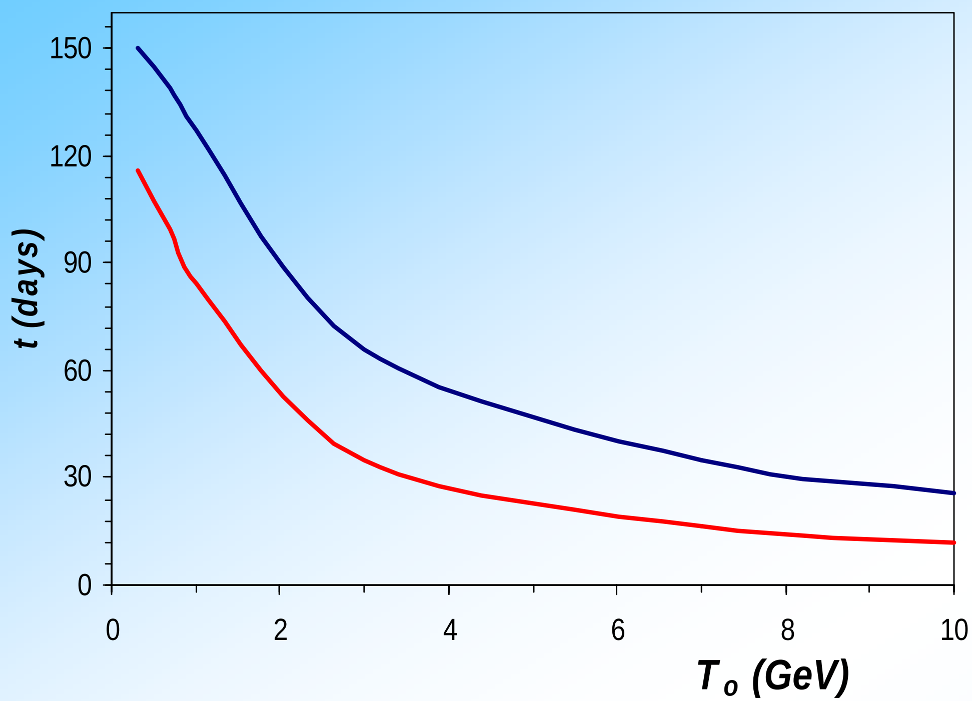


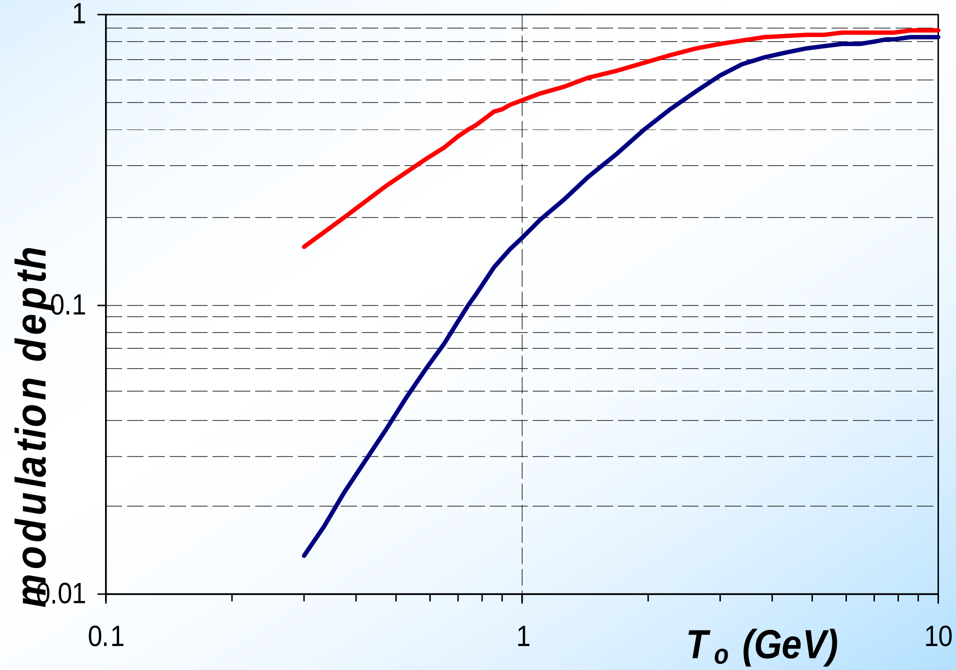
Test particle tracing: 1 GeV.



Test particle tracing: 10 GeV.

Heliospheric modulation

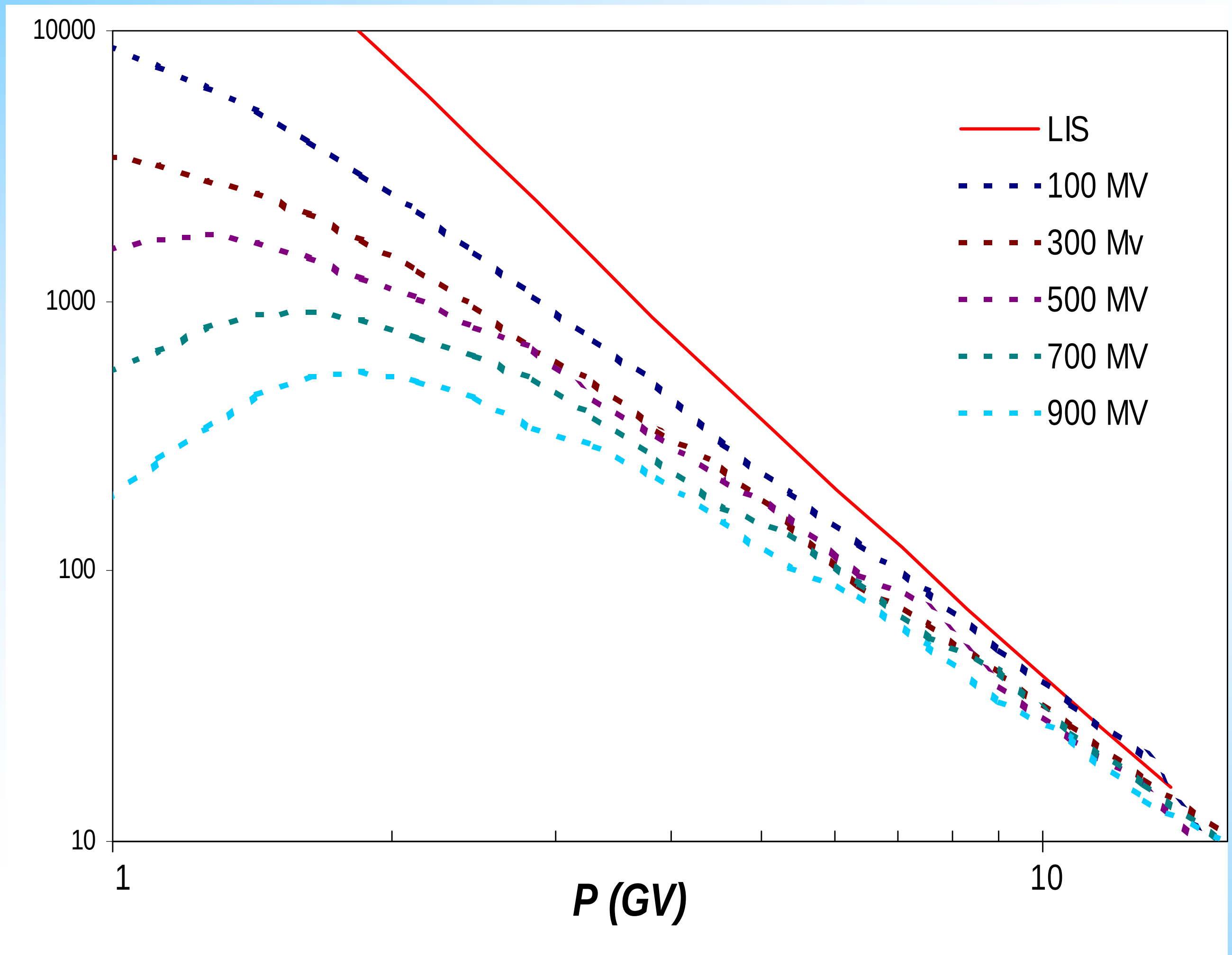




Average time spent by GCR in the heliosphere.

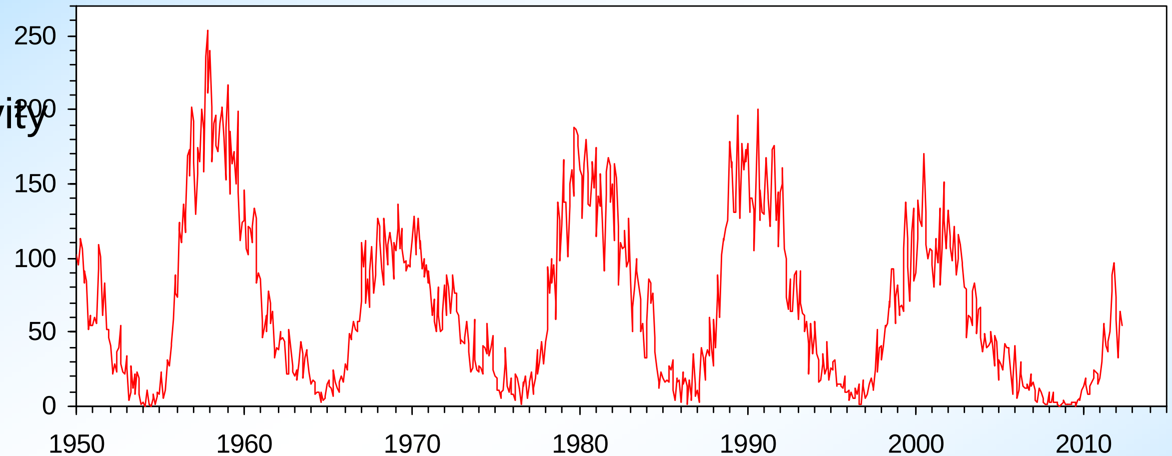
Attenuation

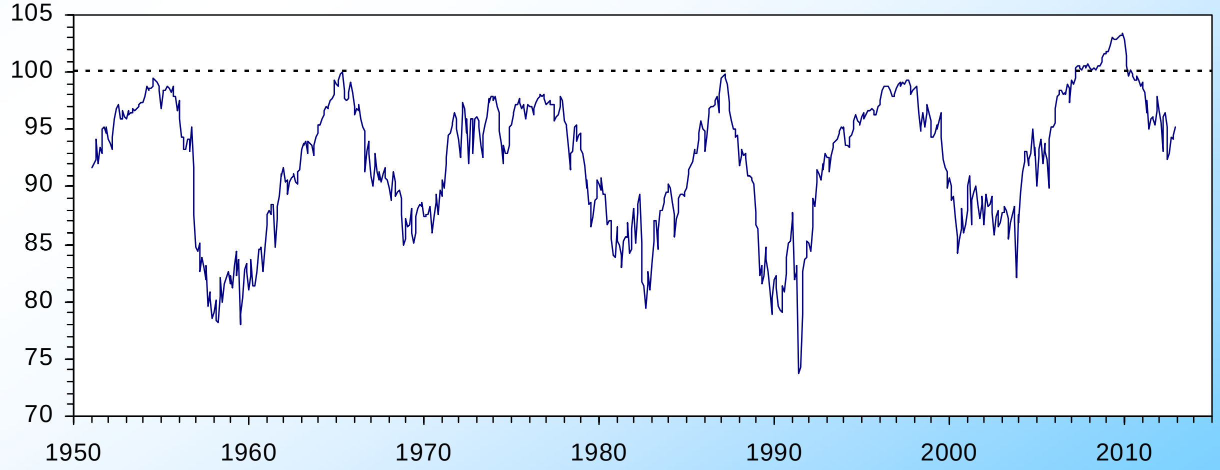
Heliospheric modulation: spectra



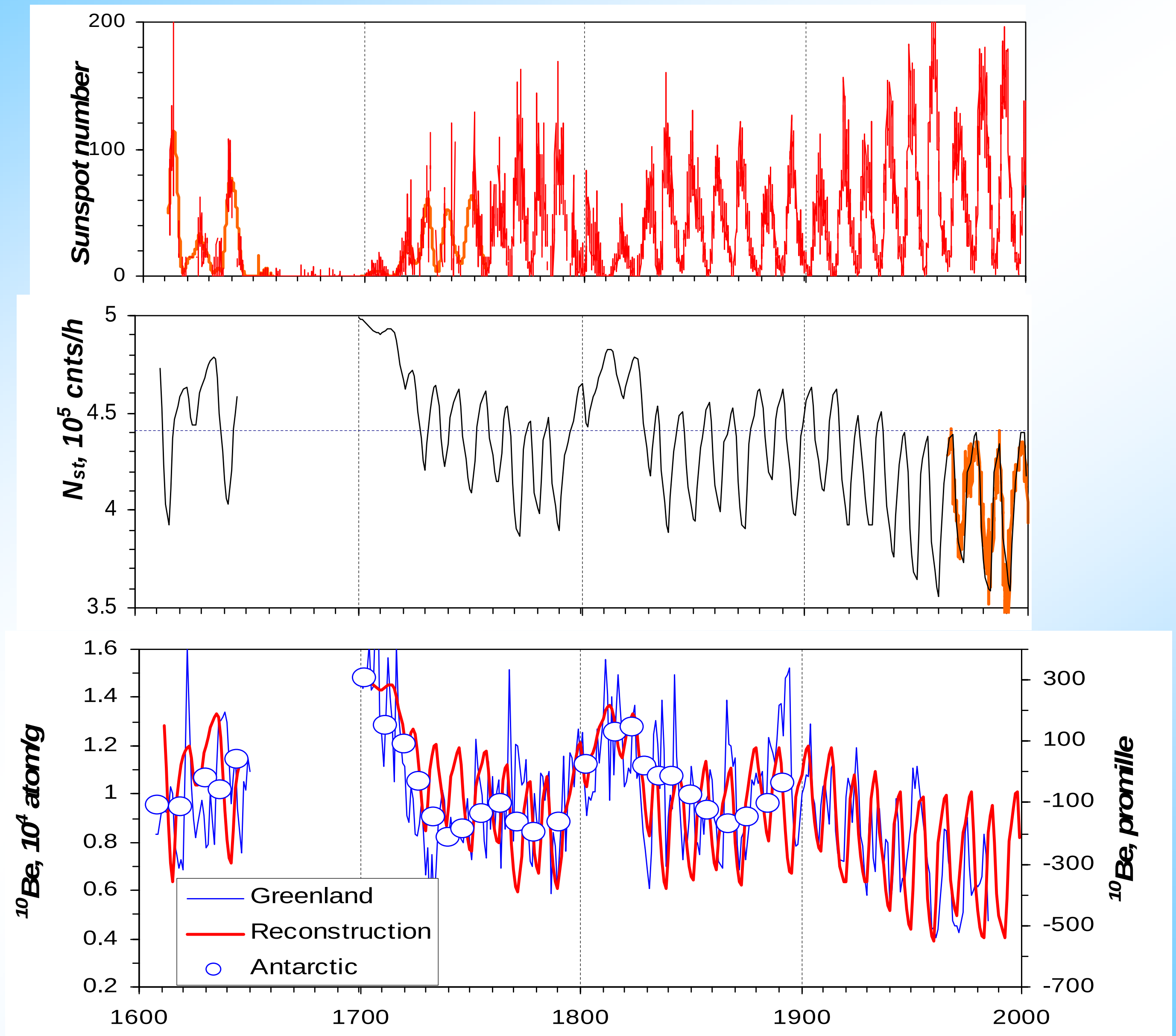
solar cycle variations

- 11-year cycle is modulated by solar activity
- 22-year cycle is determined by charge-dependent drift effects
- Modulation is caused:
  - HMF strength;
  - Trubulence in the SW/HMF;
  - Solar wind velocity and density;
  - Propagation barriers (MIR, CMIR, GMIR)





Long-term CR



200
100
0
Sunspot number
5
4.5
4
3.5
N_{st}, 10^5 cnts/h
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
^{10}Be, 10^4 atom/g
300
100
-100
-300
-500
-700
^{10}Be, promille
Greenland
Reconstruction
Antarctic
1600
1700
1800
1900
2000

CR variations

type		amplitude	nature
Long-term variations			
millenia	+/-	factor of 2	Geomagnetic field variations (depends on location)
millenia	+	few %	Supernova explosions in the vicinity
> 10^6 years	+/-		Local galactic surrounding
Periodic variations			
11-year cycle	-	upto 30%	Solar modulation of GCR in the heliosphere
27-day	+/-	few %	Long-lived asymmetry of solar wind structure
diurnal	+/-	few %	Local anisotropy of CR fluxes due to convection by solar wind and diffusion along IMF lines
Sporadic variations			
GLE	+	1-300 %	Increase of CR intensity due to arrival of solar cosmic rays
Forbush decreases	-	up to 30%	CR decrease due to shielding effect of an interplanetary shock passing the Earth

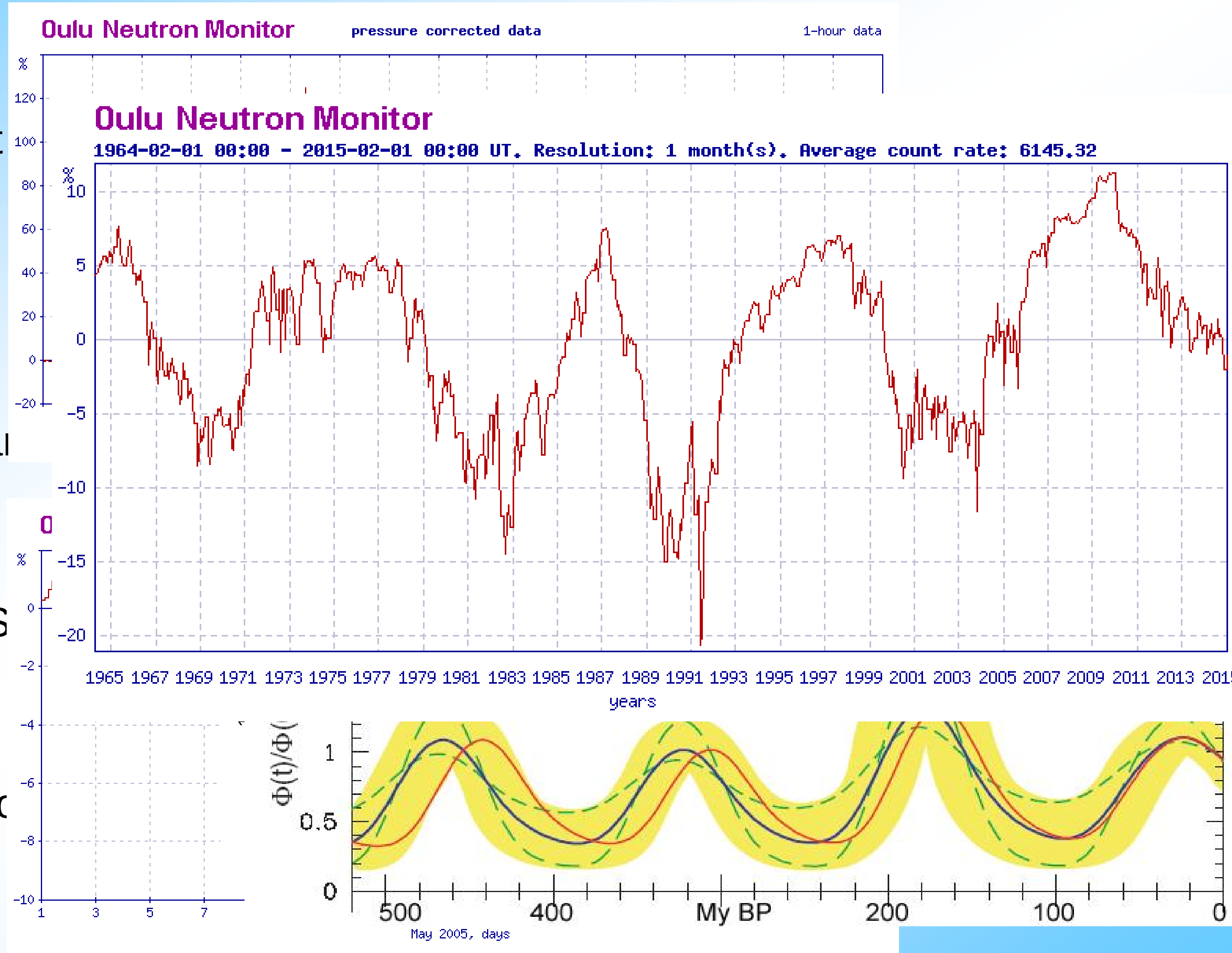
Cosmic ray variations

- Days: transient

- 11-year cycle: solar

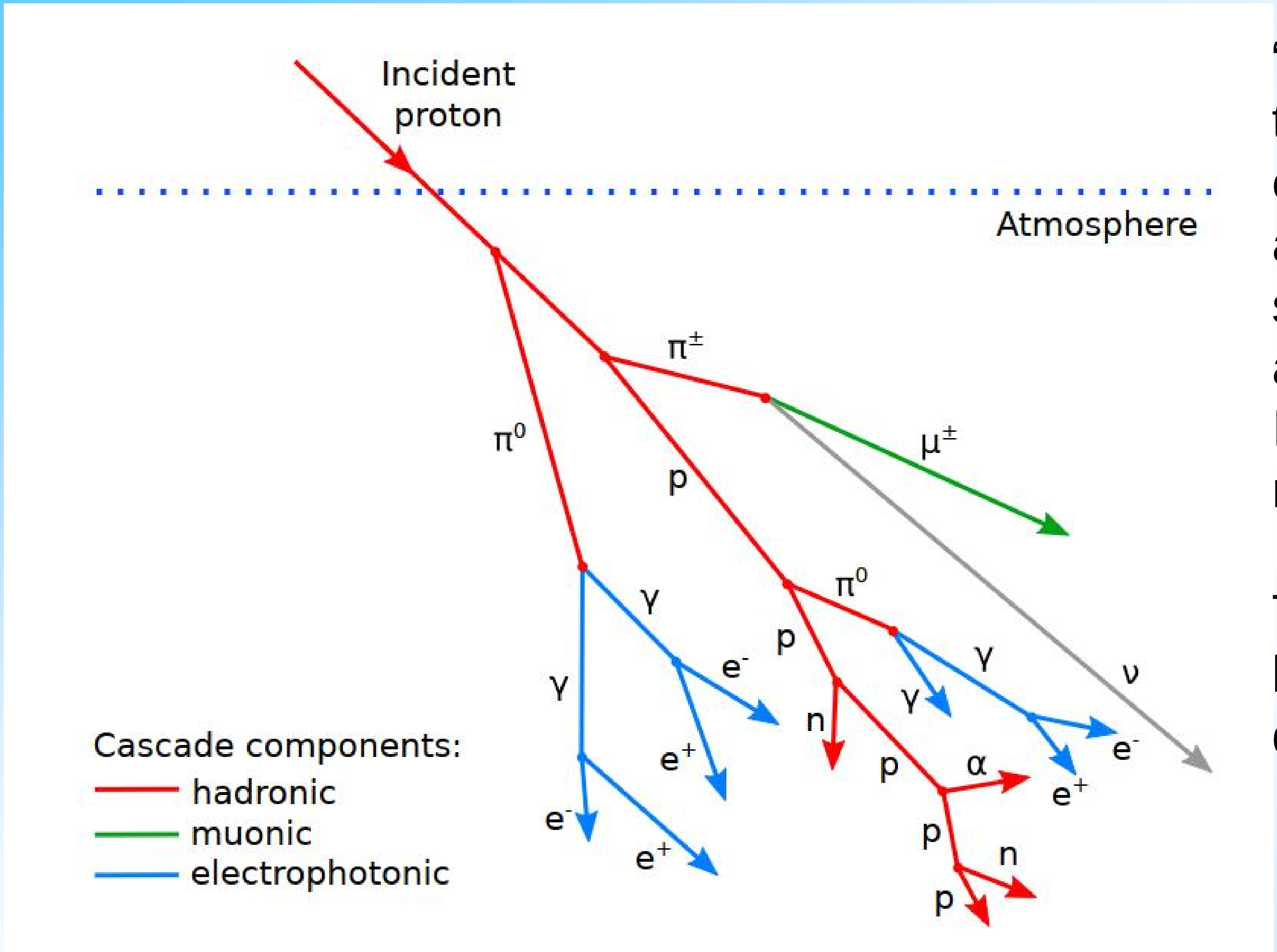
- Long-term scale (S

- Local galactic surro



What happens to cosmic rays in the atmosphere?

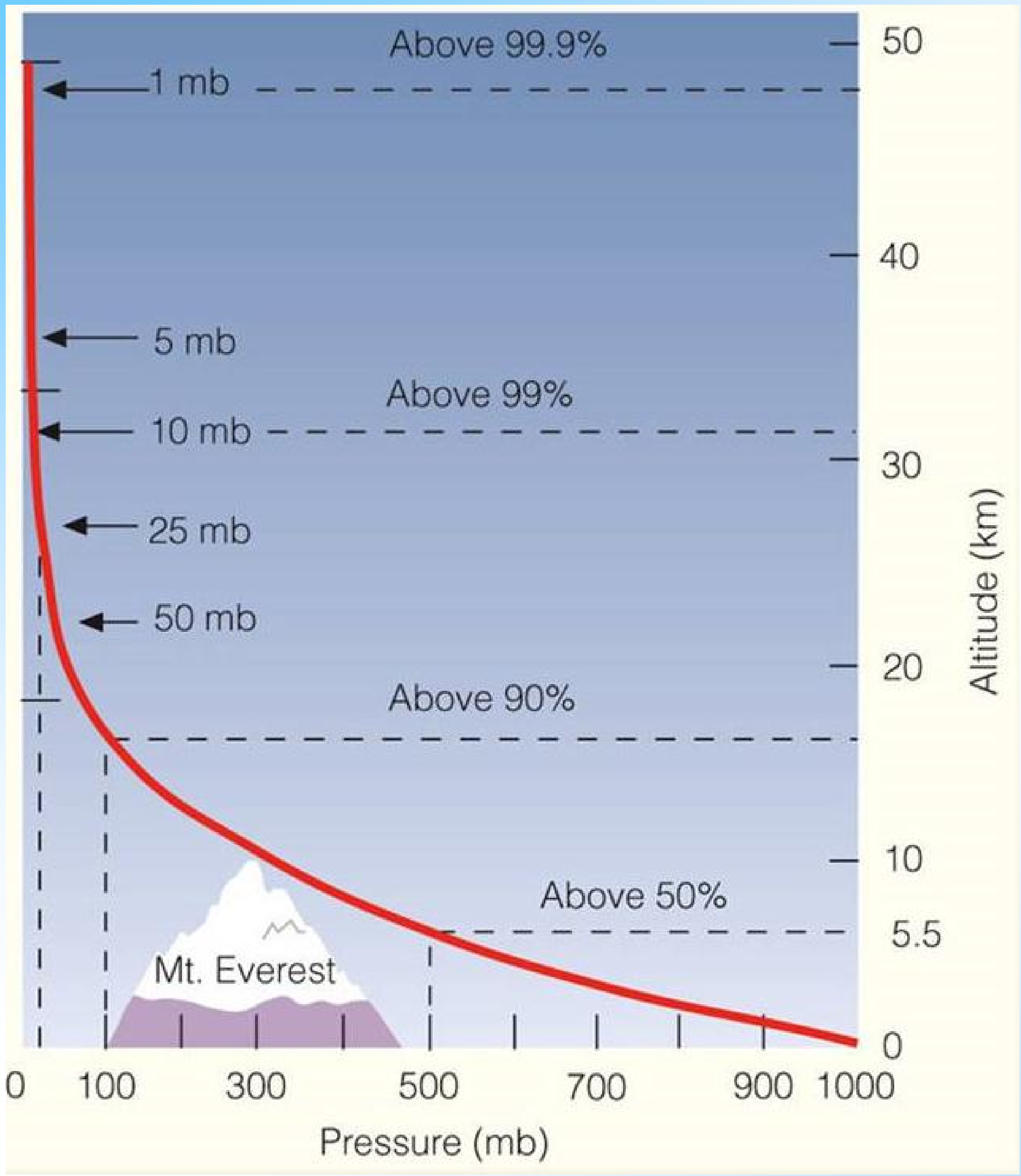
Atmospheric cascade



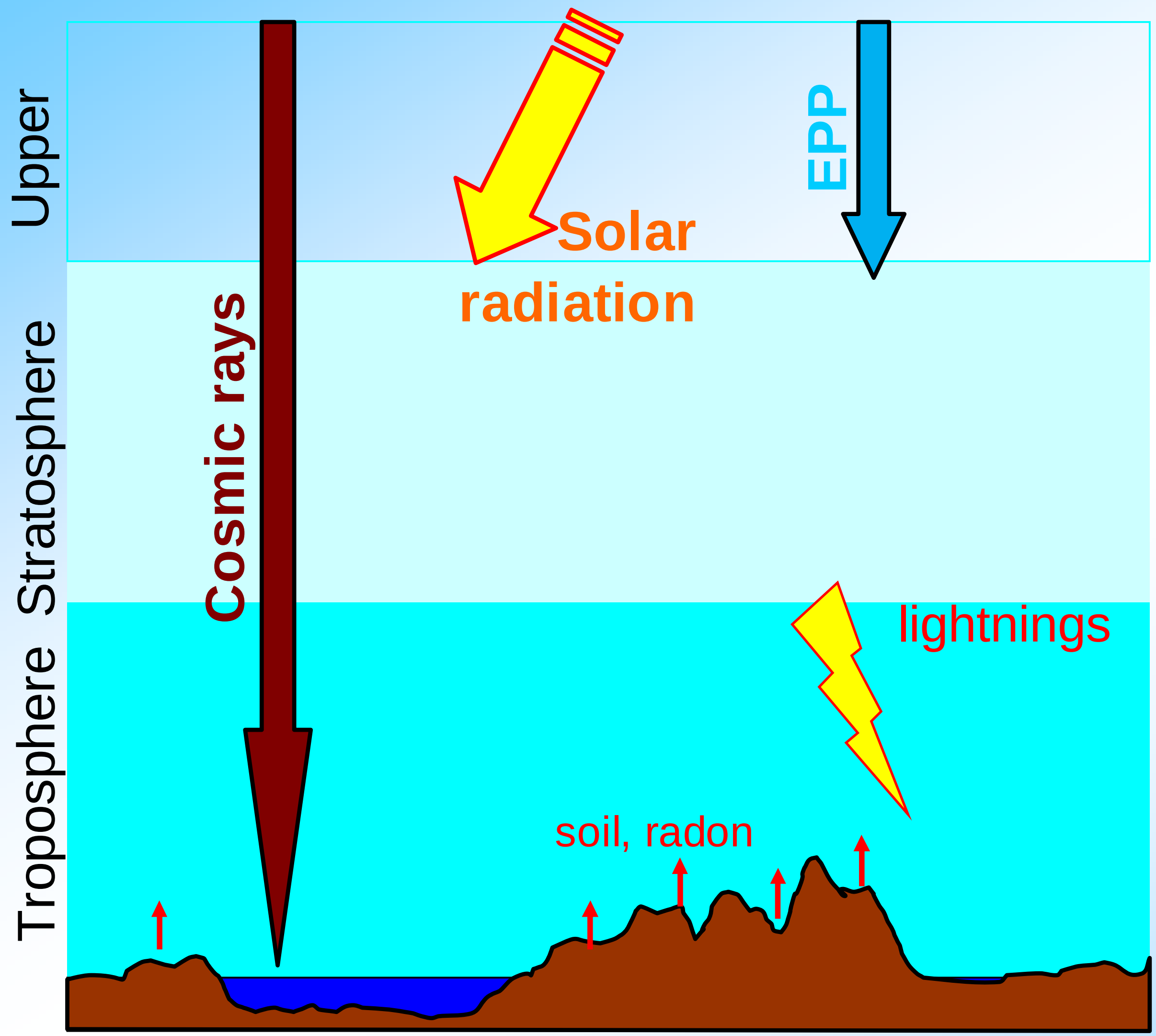
"Showers" are produced by the collision of a primary high-energy particle with nuclei of air molecules. Then secondary particles collide again to produce tertiary, etc. It may take 10 steps before reaching the surface.

The width of the shower can be up to hundred meters, depending on the energy.

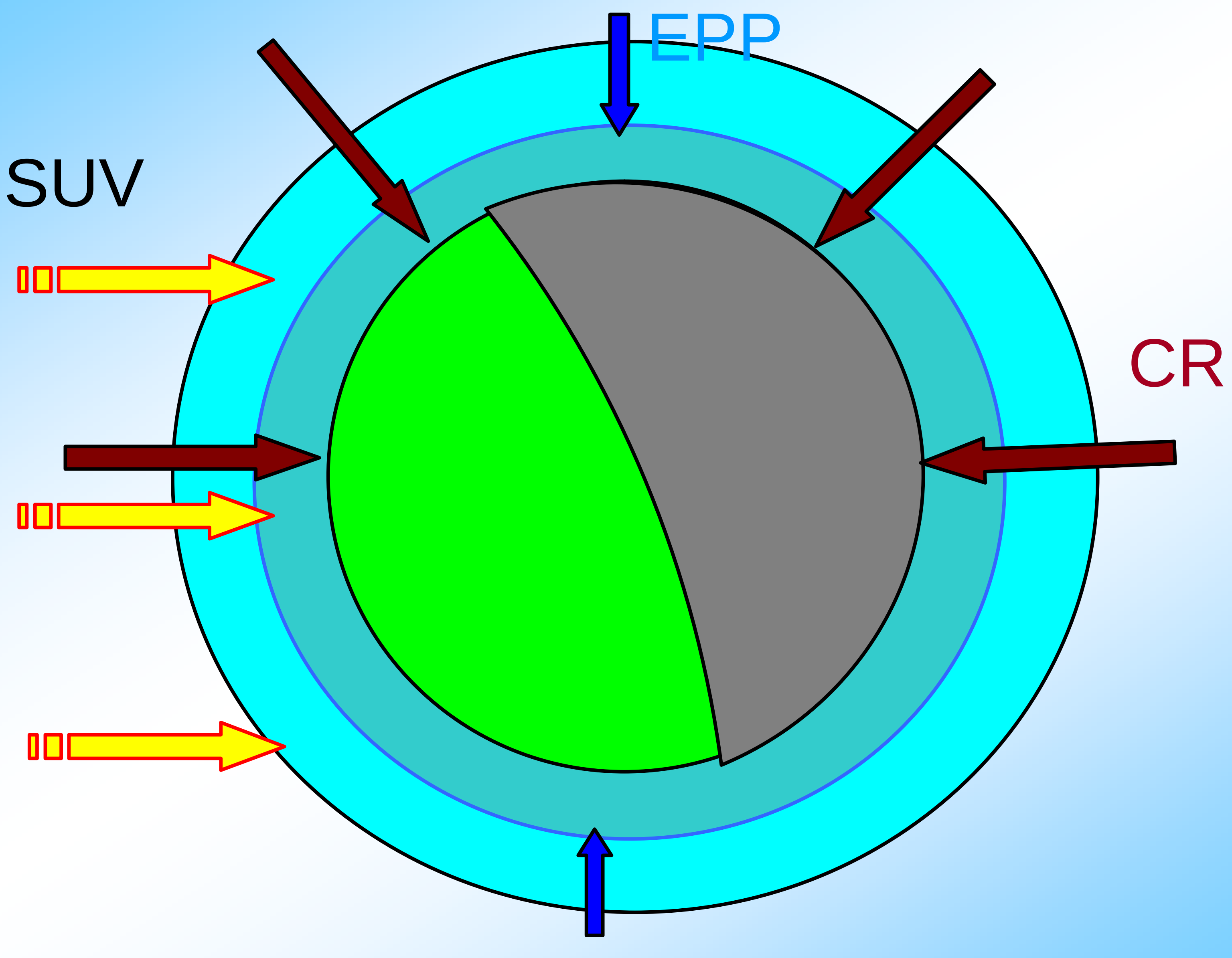
Atmospheric profile



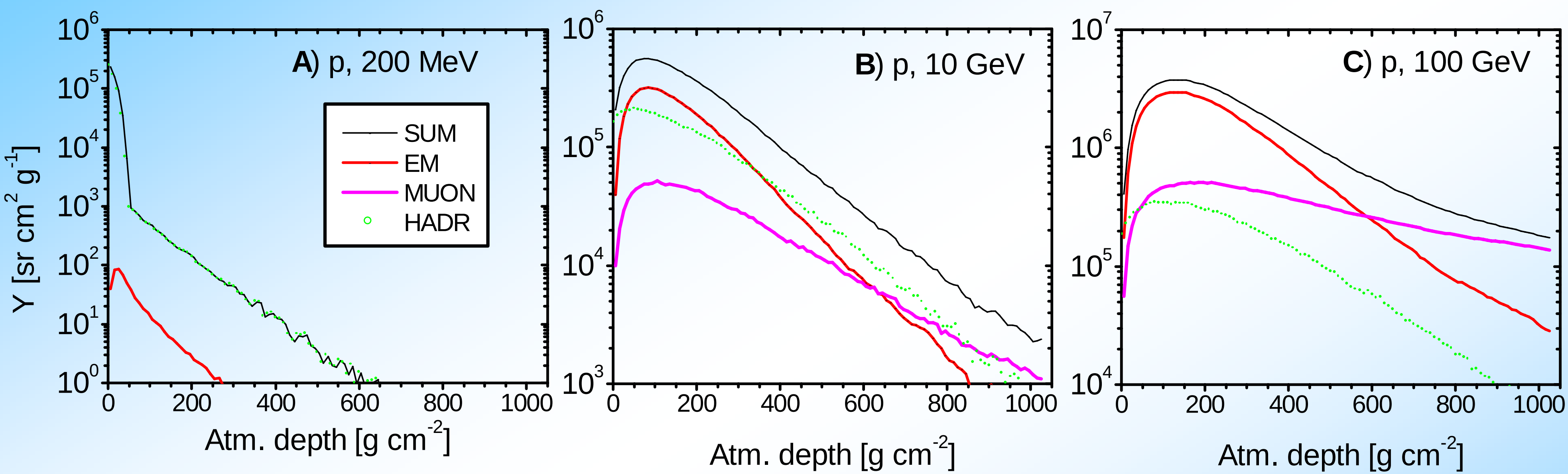
Atmospheric ionization: sources



Atmospheric ionization: sources

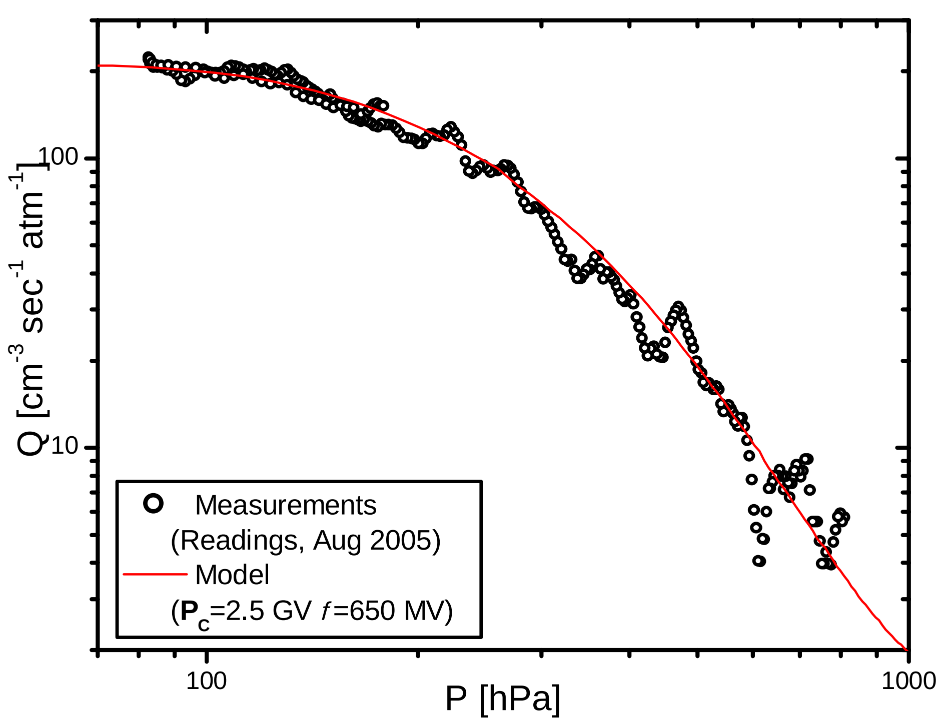


Cosmic rays induced ionization: details

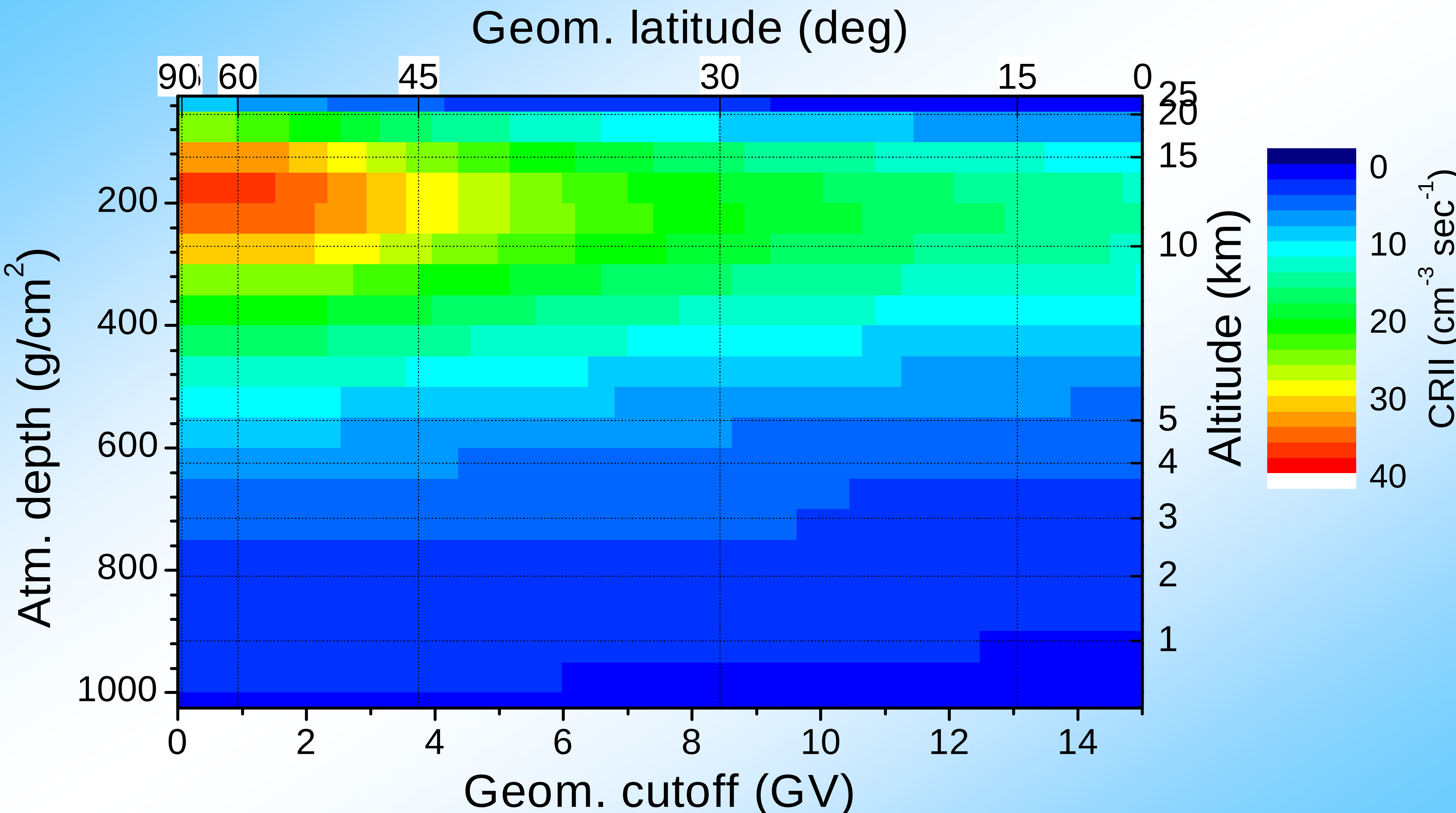


OuluCRAC:CRII model

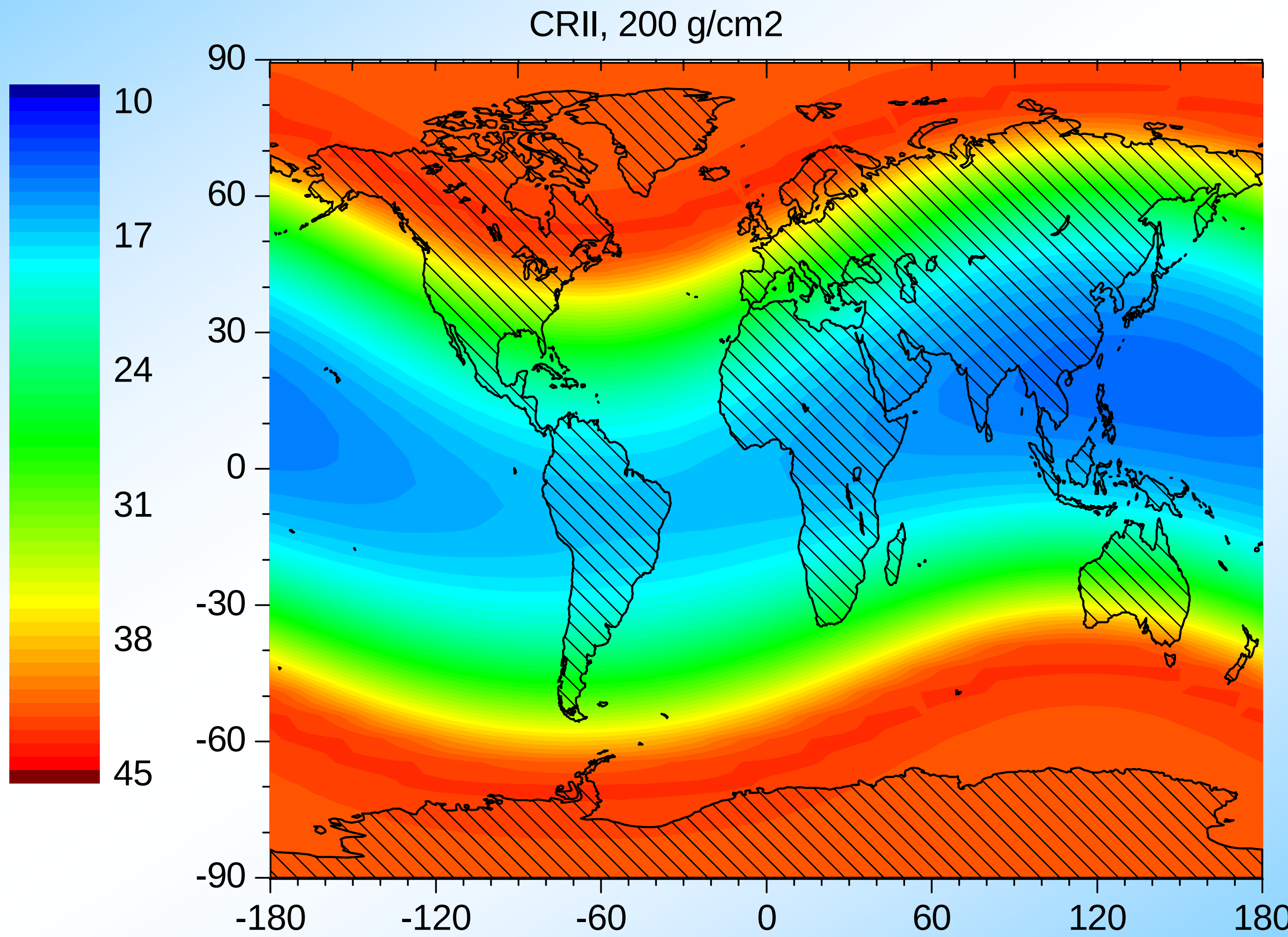
Comparison with measurements



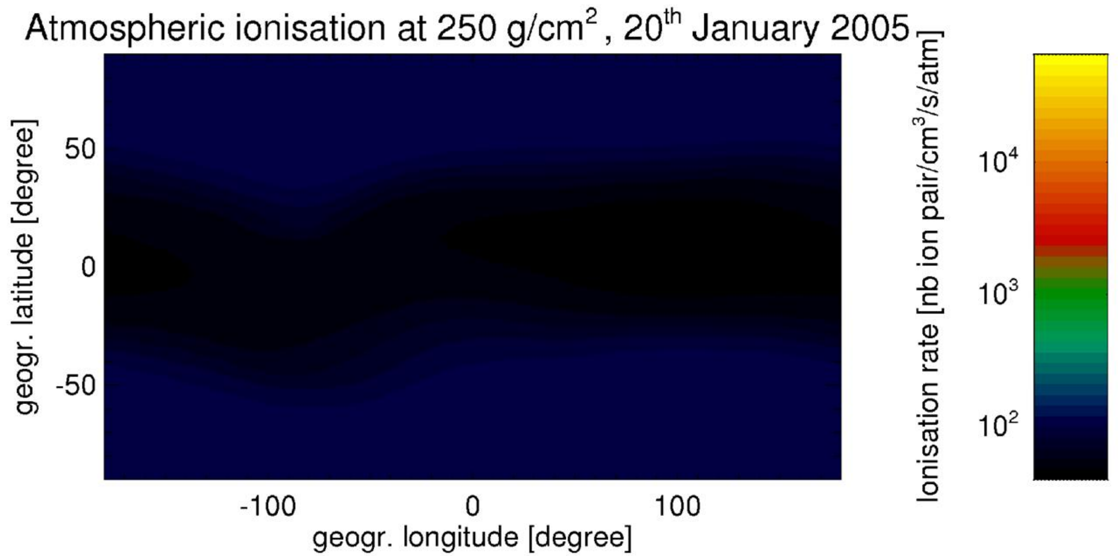
CRII: altitude vs. latitude

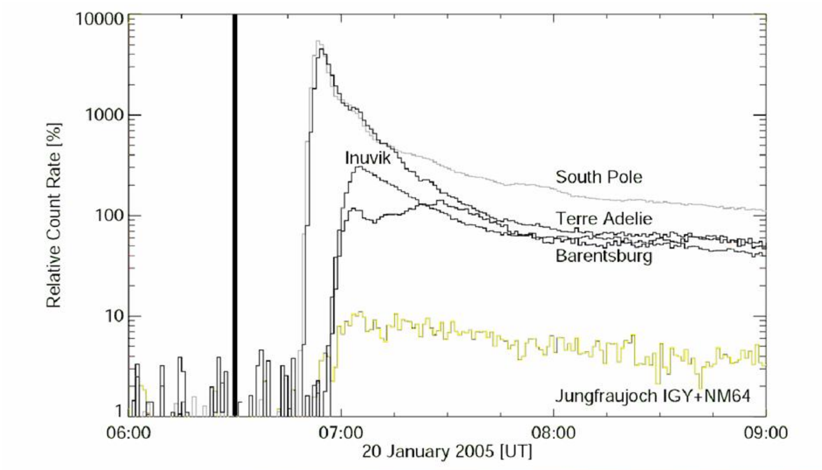


Spatial distribution of CRII (cm^{-3} sec^{-1}) at 12 km



SEP effect (20-01-2005): anisotropy effect





Simulations by the ATMOCOSMIC model (Courtesy L. Desorgher and the U. Bern group)

Atmosphere is not plasma

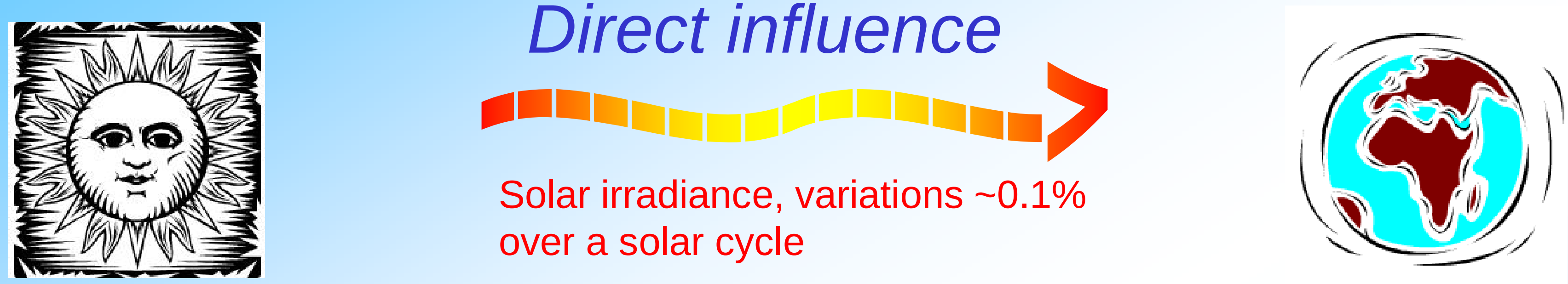
Fractional ionization rate ~10^{-18} sec^{-1}

Degree of ionzation ~10^{-16}

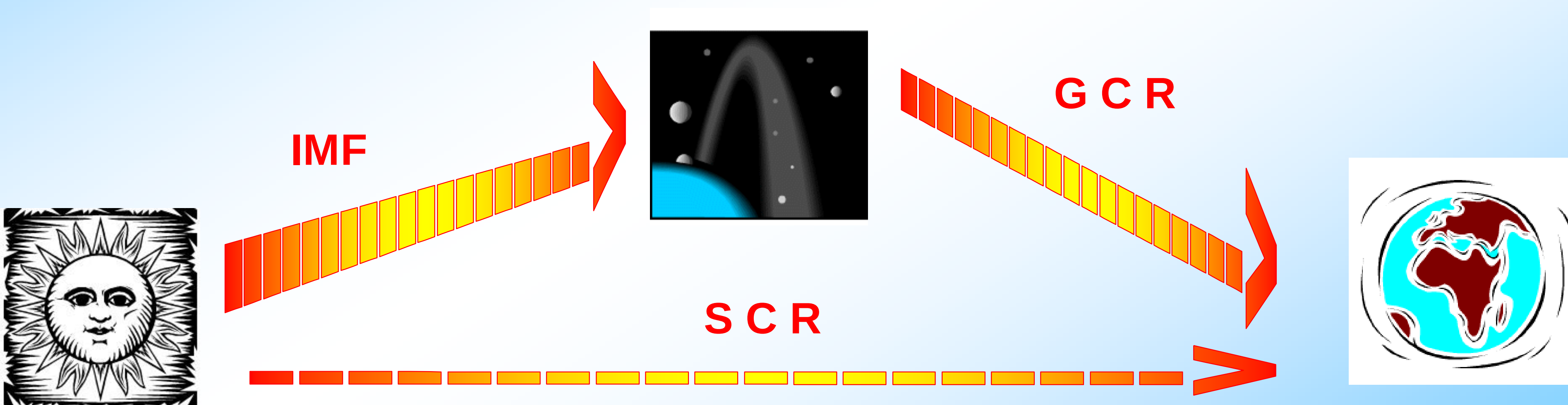
What happens with the atmosphere in the presence of cosmic rays?

Sun à Earth relation

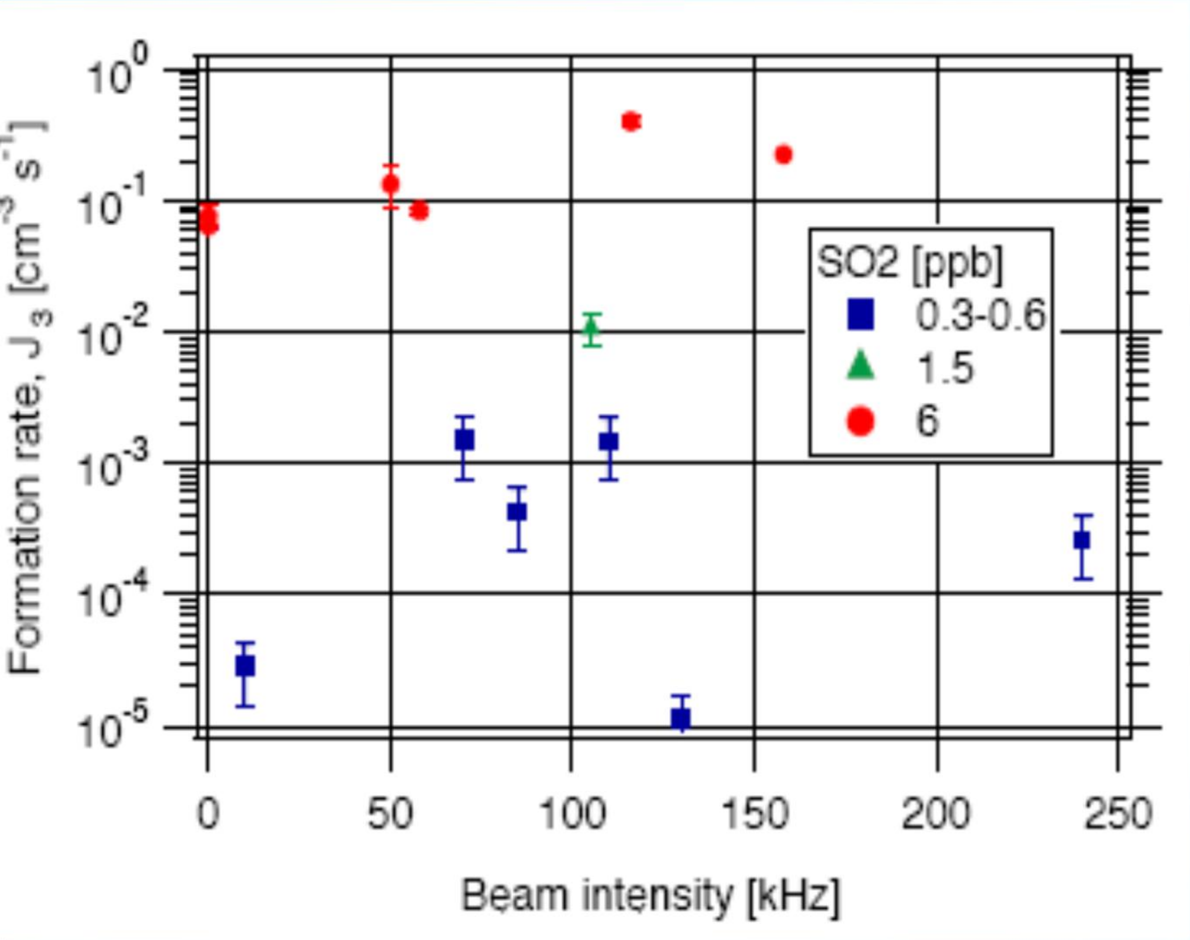
Direct influence

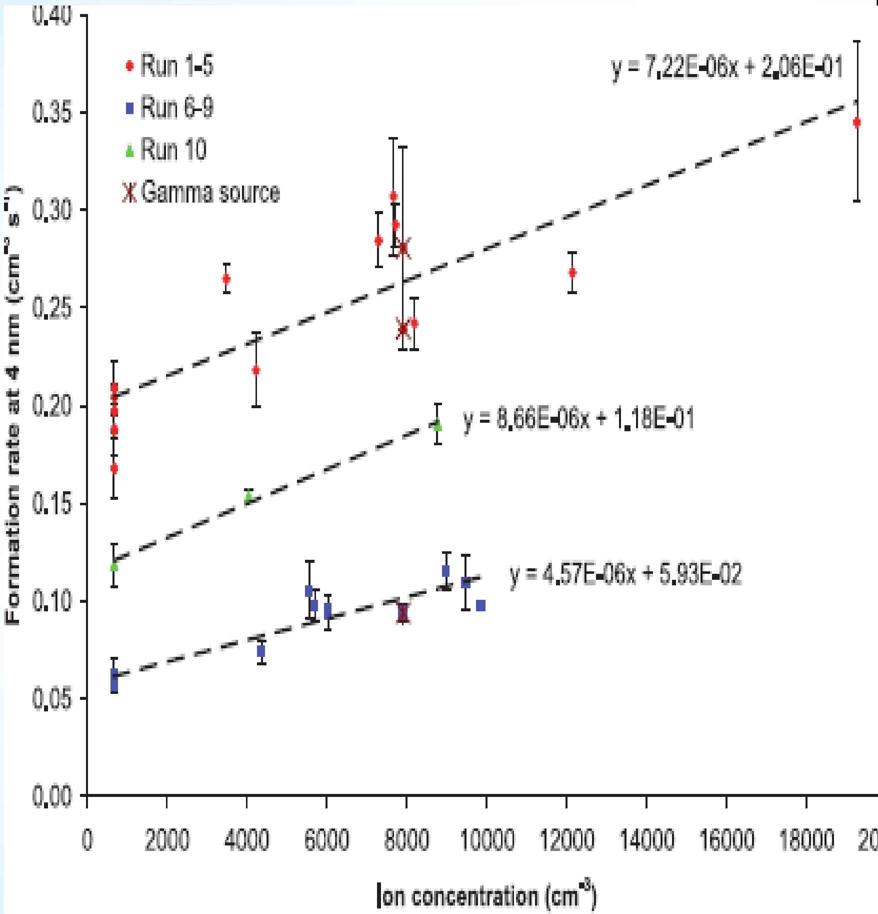


Indirect influence



CLOUD+SKY experiment





Duplissi et al. (2010), Enghoff et al. (2011)

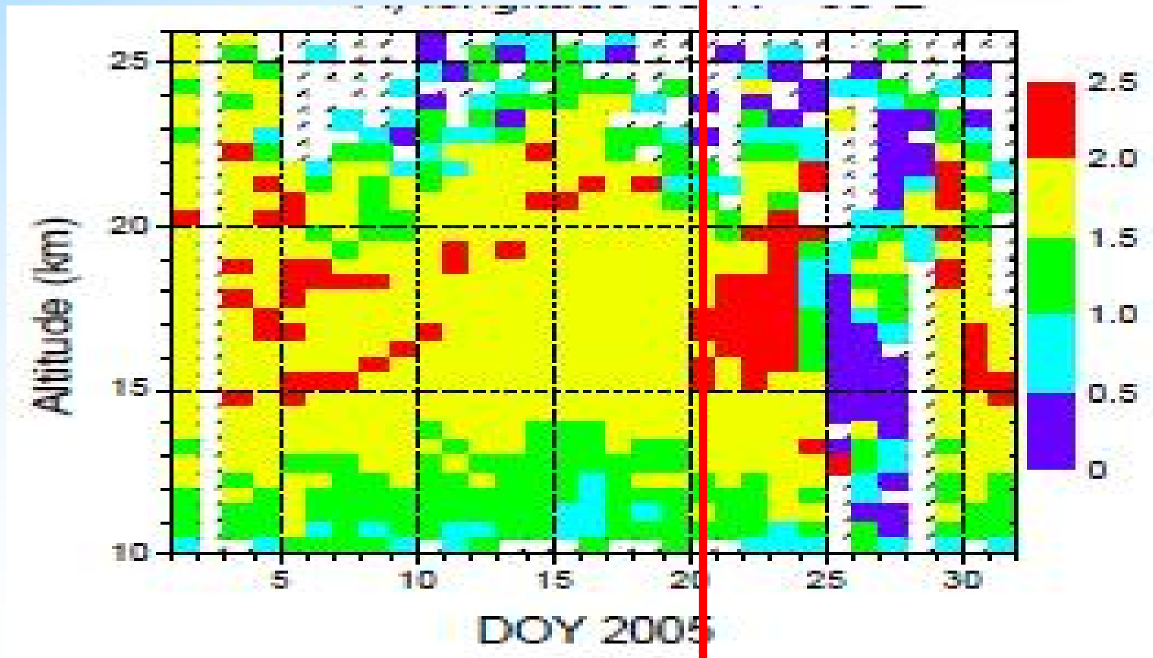
A 10-fold increase of ionization (typical changes 25%) à 2-fold formation rate, BUT…

A 10-fold increase in SO2 (typical) à 1000-fold formation rate change.

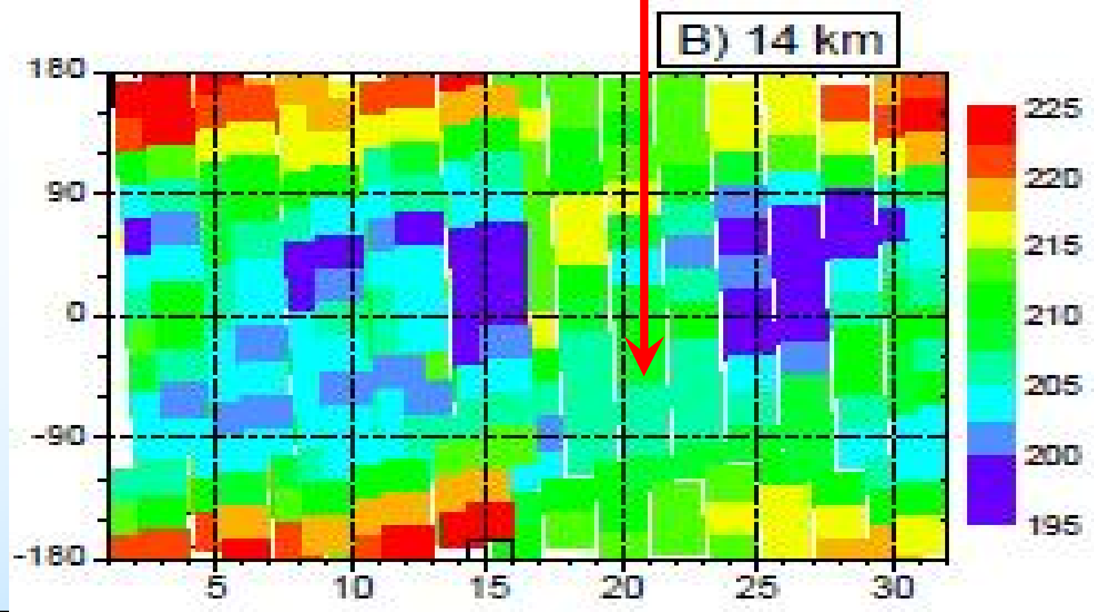
Temperature, humidity also affect…

Jan.2005: stratospheric aerosols

Angstrom exponent calculated from SAGE III aerosol extinction as a function of altitude and time in the Northern Polar region (latitude 66–73).



Temperature in the same region at 14 km heights



Effect of SEP on polar strato. aerosols

SEP event	GLE %	NH effect	NH temp	SH effect	SH temp
2005-Jan-20	5400	**YES** (strong)	**Cold**	**YES (weak)**	Warm
1989-Sep	400	YES (weak)	**Cold**	NO	Warm
2000-Jul-14	60	NO	Warm	--	--
2001-Apr-15	240	NO	Warm	NO	Warm
2003-Oct	50	NO	Warm	NO	**Cold**

The direct effect is weak (Mironova & Usoskin, 2008, 2012, 2013)

Summary

- ü *Cosmic rays include several species (GCR, SCR, ACR) which are different in source, energy spectra and temporal variability.*

- ü *Cosmic rays initiate a complicated cascade (shower) in the atmosphere.*

- ü *Cosmic rays form the main source of atmospheric ionization and related physical-chemical changes in the low-mid atmosphere.*

- ü *The direct effect of CR on the atmosphere is very weak. Indirect is unknown.*

THANK YOU !