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Natural radioactivity, its components and effects on measurement

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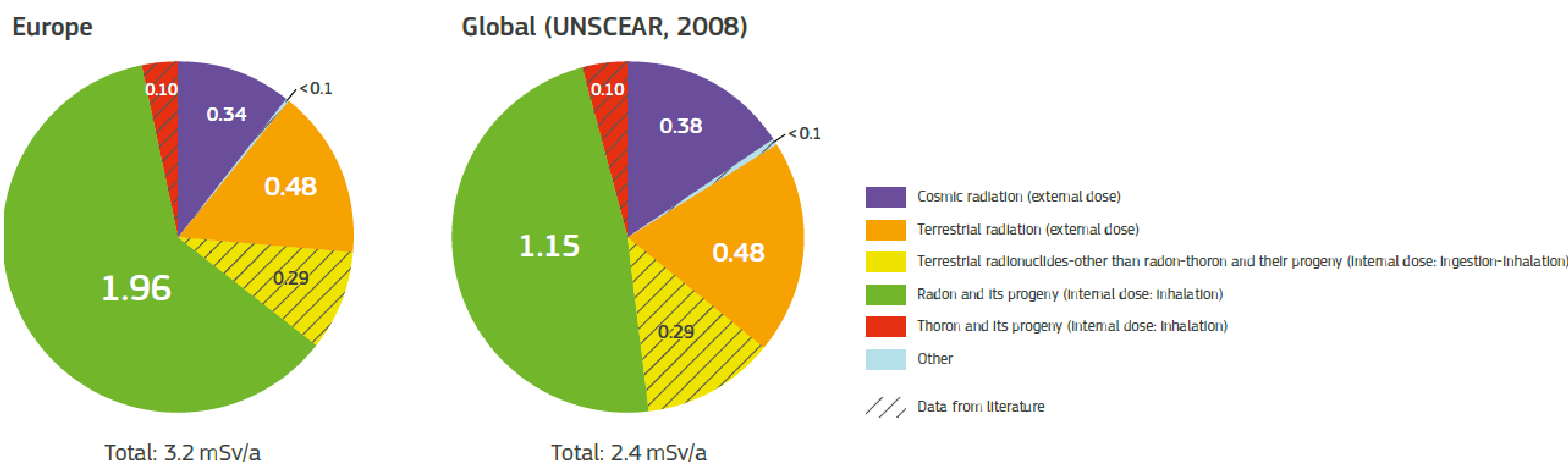
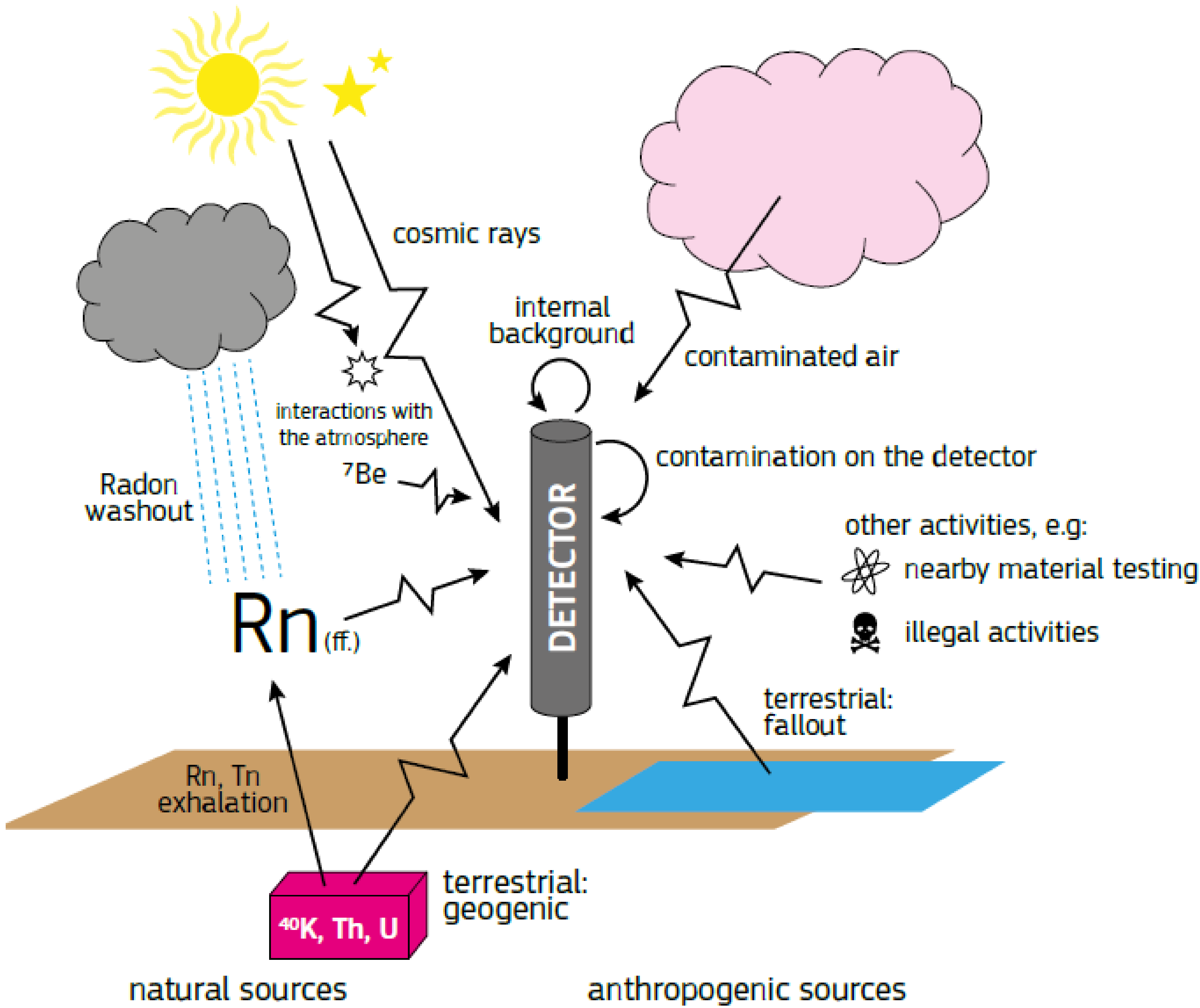
Main sources of natural exposure for the public and population-weighted average annual effective

Exposure sources	Doses		
	Internal		External
	Ingestion	Inhalation	
Terrestrial radionuclides	^{40}K, uranium and thorium series	^{40}K, uranium and thorium series	Terrestrial radiation (^{40}K, uranium and thorium series)
	Radon, thoron and their progenies	Radon and its progeny	Radon, thoron and their progenies
		Thoron and its progeny	
Cosmic radiation	Cosmogenic radionuclides	Cosmogenic radionuclides	Directly ionising, photon and neutron component



Components of the ambient dose rate



Components of the ambient dose rate

1. Terrestrial natural radiation:

a. Gamma rays emitted by primordial natural radionuclides and their progeny in the ground.

b. Gamma-radiating radionuclides generated by induced nuclear reaction of cosmic rays.

2. Cosmic radiation: Composed of penetrating ionizing radiation, both particulate and electromagnetic. Depending on their origin, the cosmic rays vary greatly in their energy and composition.

3. Airborne natural radiation:

a. ^{222}Rn and ^{220}Rn exhalation from the soil with further decay into gamma radiating isotopes of Pb and Bi.

b. Short lived radon progenies are transported to the ground by scavenging and washout by raindrops. Dose rate can be increased a factor or 2-3 for a half hour.

c. Cosmic radiation can induce nuclear processes in and generate so-called cosmogenic gamma radiating radionuclides such as ^{7}Be that can precipitate to the ground.

4. Terrestrial and airborne artificial radiation: gamma rays emitted by artificial radionuclides in and on the ground. These are radionuclides from global fallout (from atmospheric nuclear bomb testing) and from fallout due to nuclear accidents.

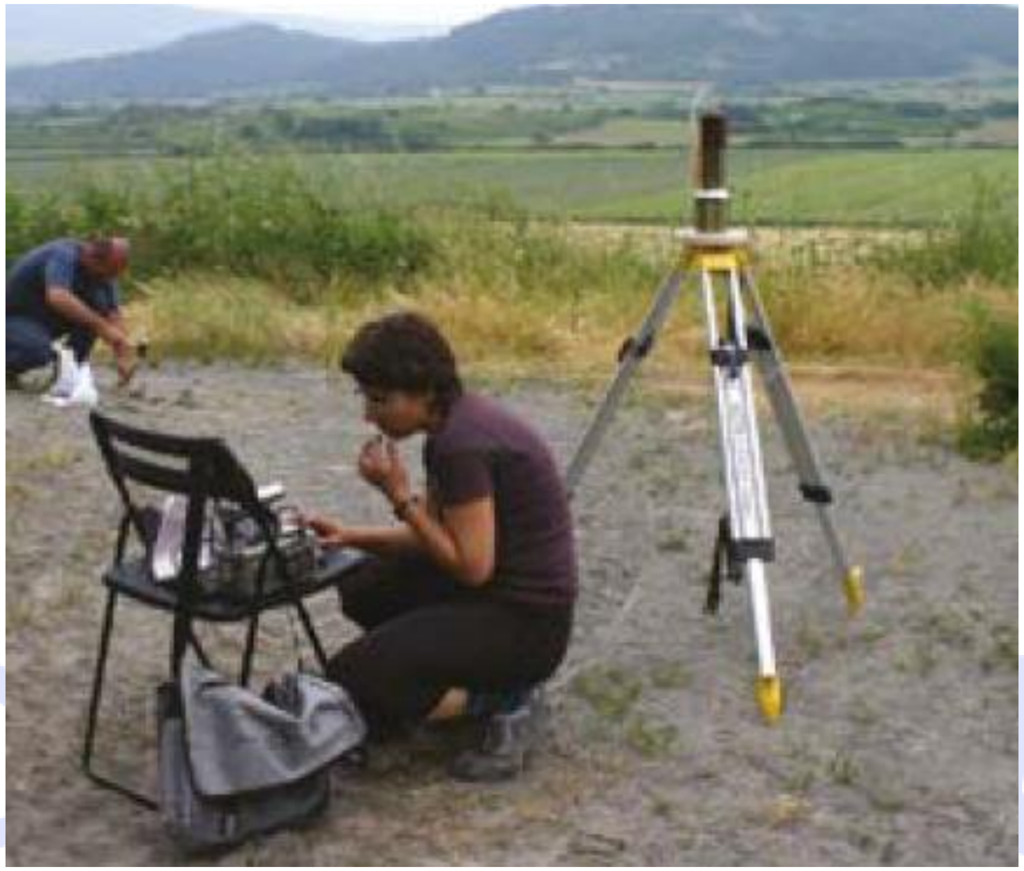
Side effects measuring ambient dose rate

1. **Intrinsic background of the instrument:** Radioactivity of technical components and electronic noise.

2. **Contamination of the monitor:** Airborne natural and artificial radionuclides will be deposited on the housing of the detector and contribute to the signal.

3. **Particular signals:** nearby activities involving nuclear methods or gamma-ray sources or lightning occurrence.

4. **Spurious signals:** Signal loss, system malfunction, highly anomalous readings.



Terrestrial natural radiation

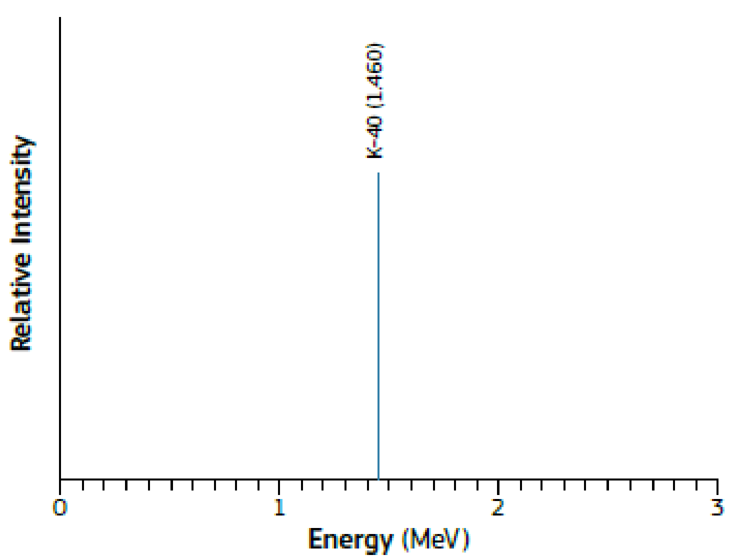
Terrestrial natural radiation can be defined as the **gamma-ray field of a rock-soil medium** is generated by the natural radionuclides in rocks–soils and it is affected by their composition and physical state.

Primordial radionuclides of potassium (^{40}K), thorium (^{232}Th and progeny) and uranium (^{238}U and progeny) are the fundamental sources of radioactivity in rocks. The halflives of prominent natural radionuclides are very long, and they are **permanent sources** of terrestrial radiation.

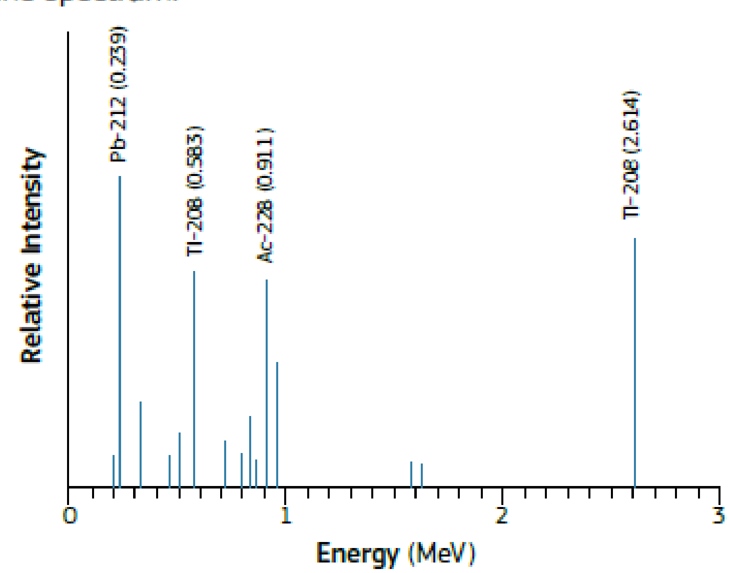
Terrestrial Gamma Dose Rate, TDGR (UNSCEAR 2008):

$$TGDR(nGy/h) = 0.0417 \cdot C_{K\text{-}40}\,(Bq/kg) + 0.604 \cdot C_{Th\text{-}232}\,(Bq/kg) + 0.462 \cdot C_{U\text{-}238}\,(Bq/kg)$$

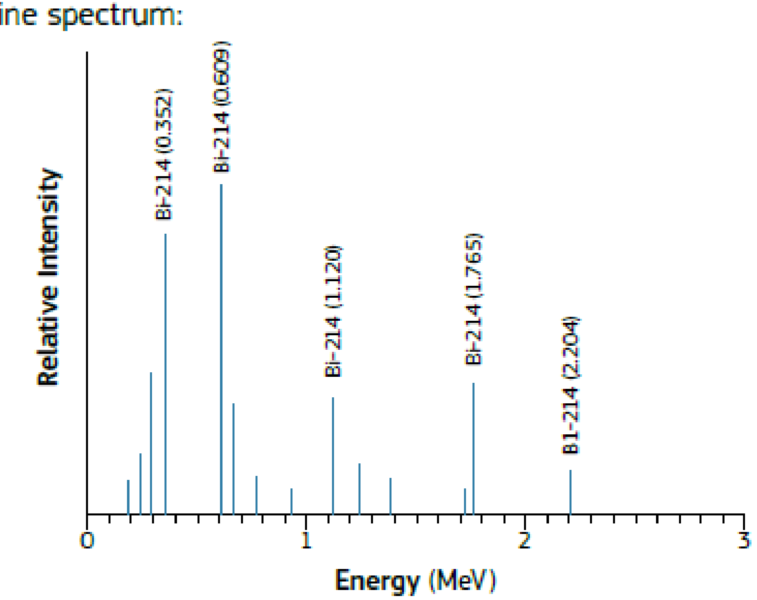
K line spectrum:



Th line spectrum:

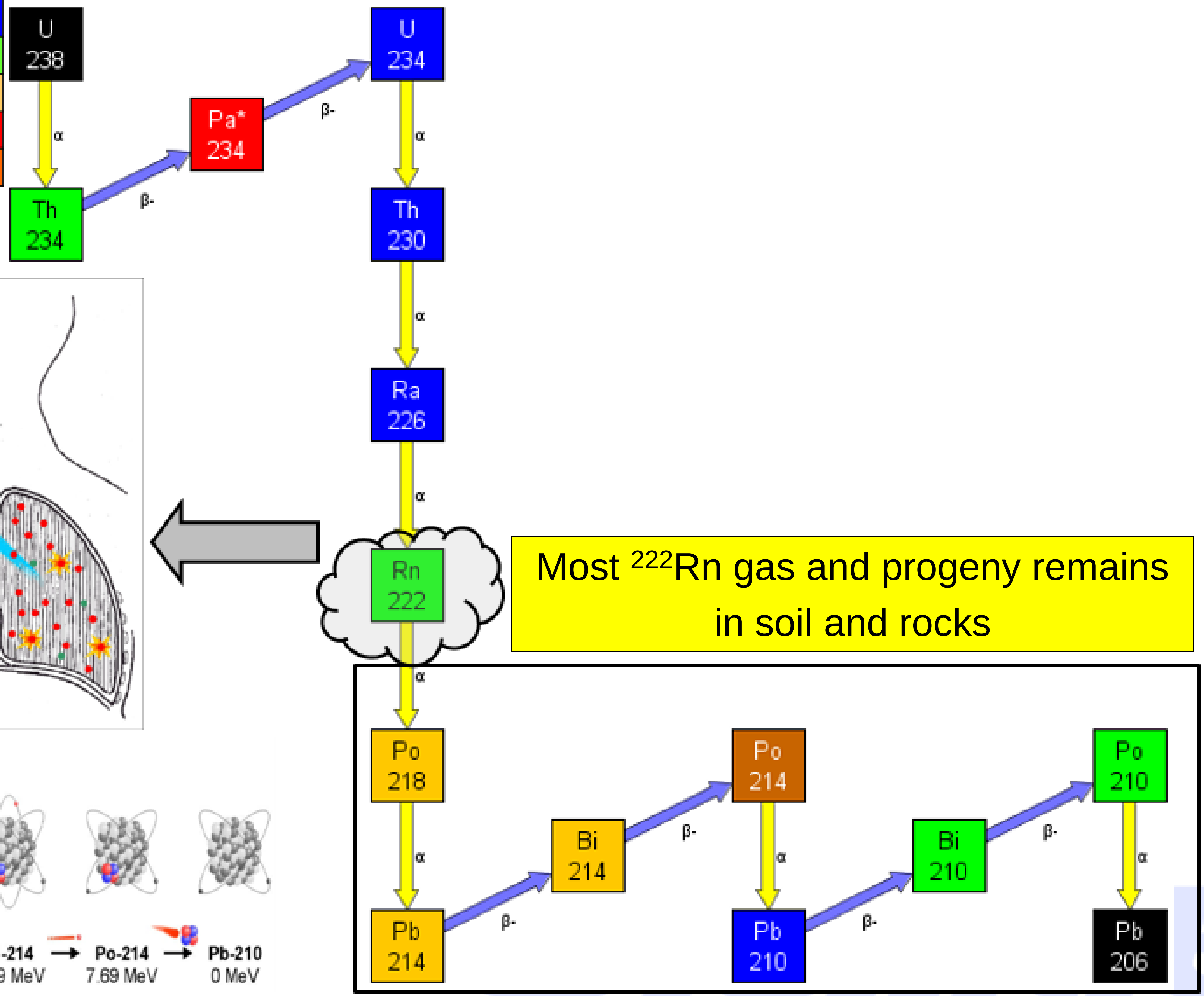


U line spectrum:

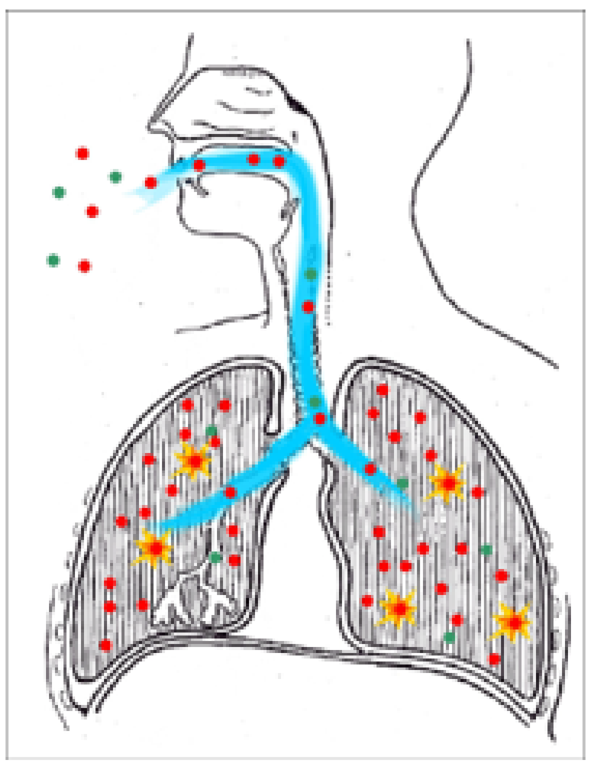


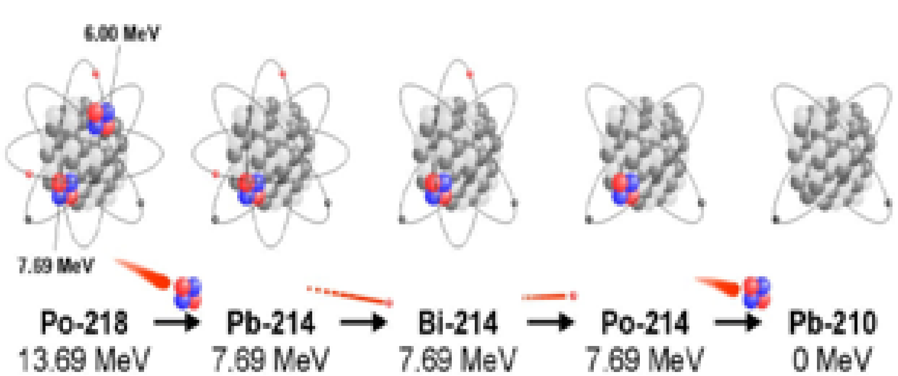
Terrestrial natural radiation

$T_{1/2} > 10^9$ a
20 a < $T_{1/2}$ < 10^9 a
3 d < $T_{1/2}$ < 30 d
3 min < $T_{1/2}$ < 30 min
1 min < $T_{1/2}$ < 2 min
$T_{1/2}$ < 1 s



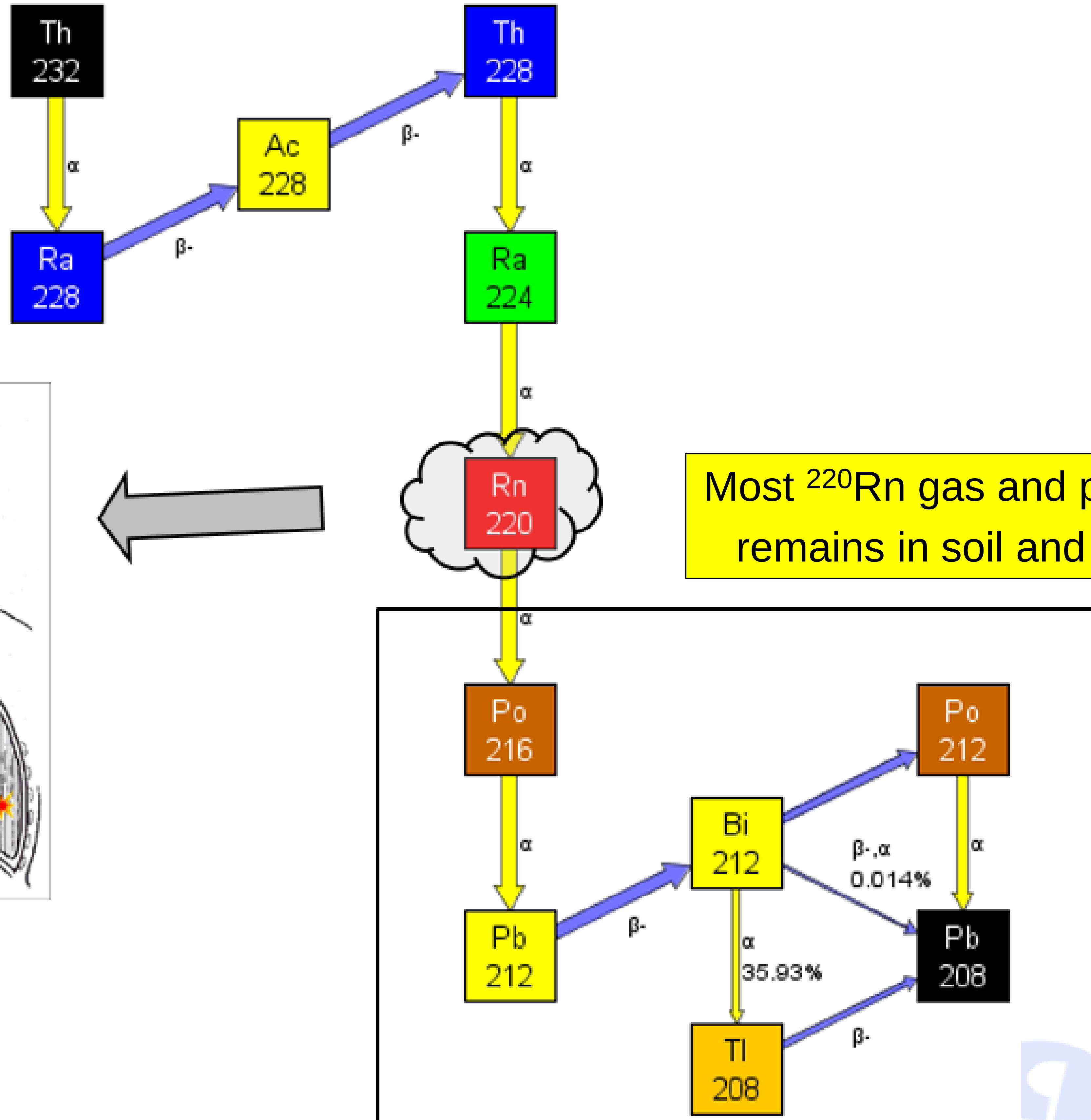
Most ^{222}Rn gas and progeny remains in soil and rocks

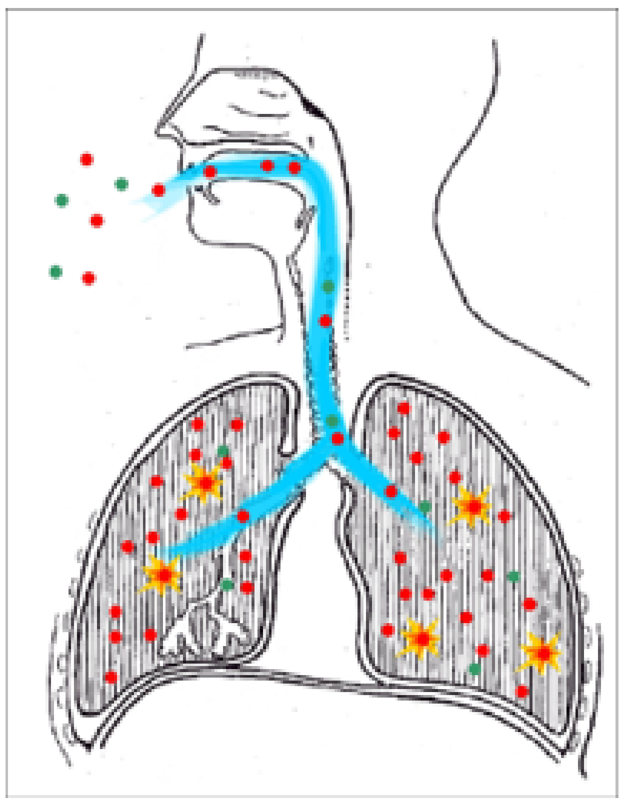




Terrestrial natural radiation

$T_{1/2} > 10^9$ a
2 a < $T_{1/2}$ < 7 a
3 d < $T_{1/2}$ < 4 d
1 h < $T_{1/2}$ < 11h
2 min < $T_{1/2}$ < 3 min
1 s < $T_{1/2}$ < 1 min
$T_{1/2}$ < 1 s

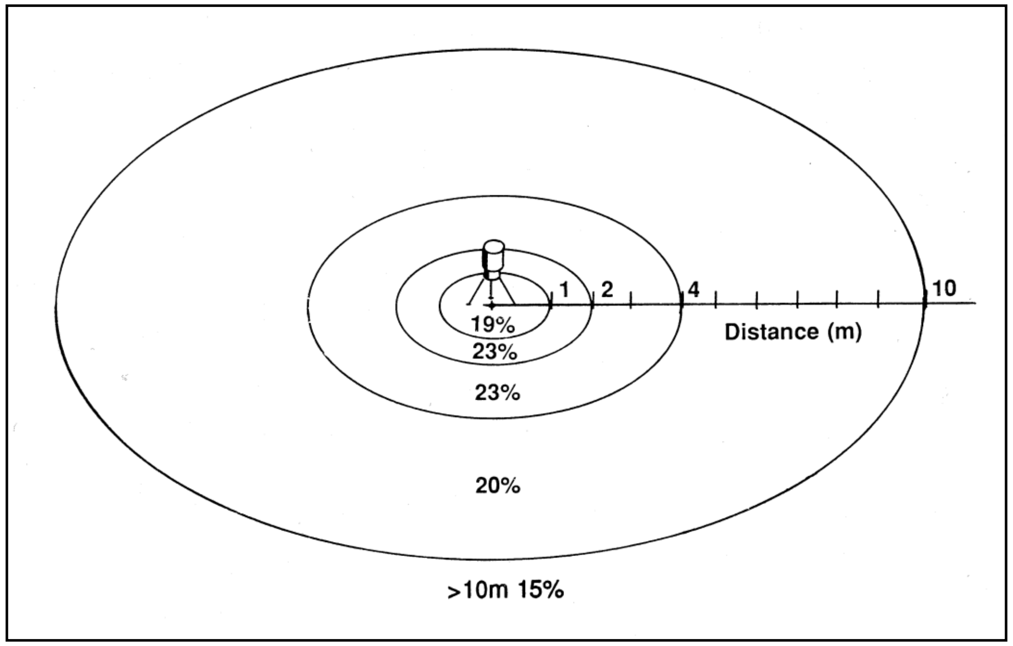


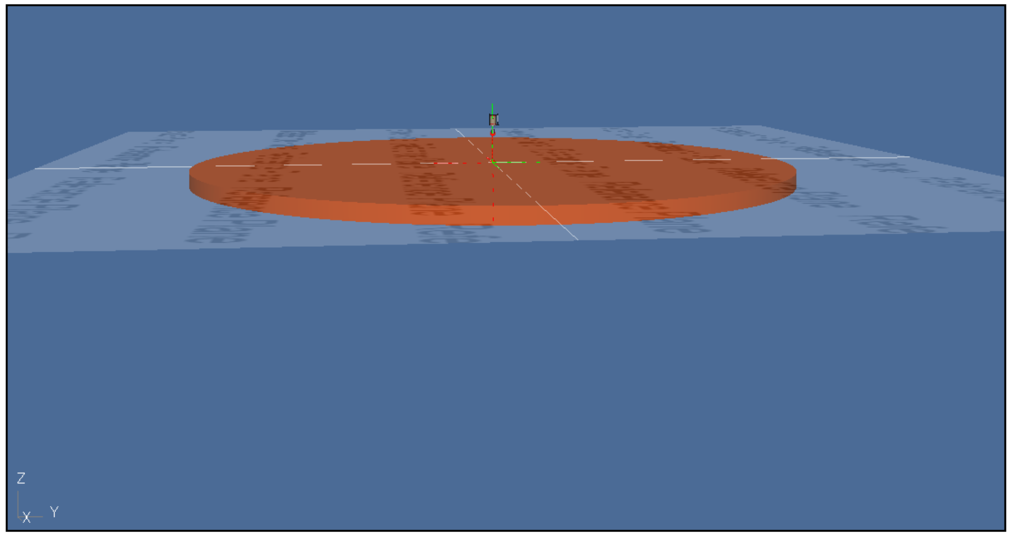


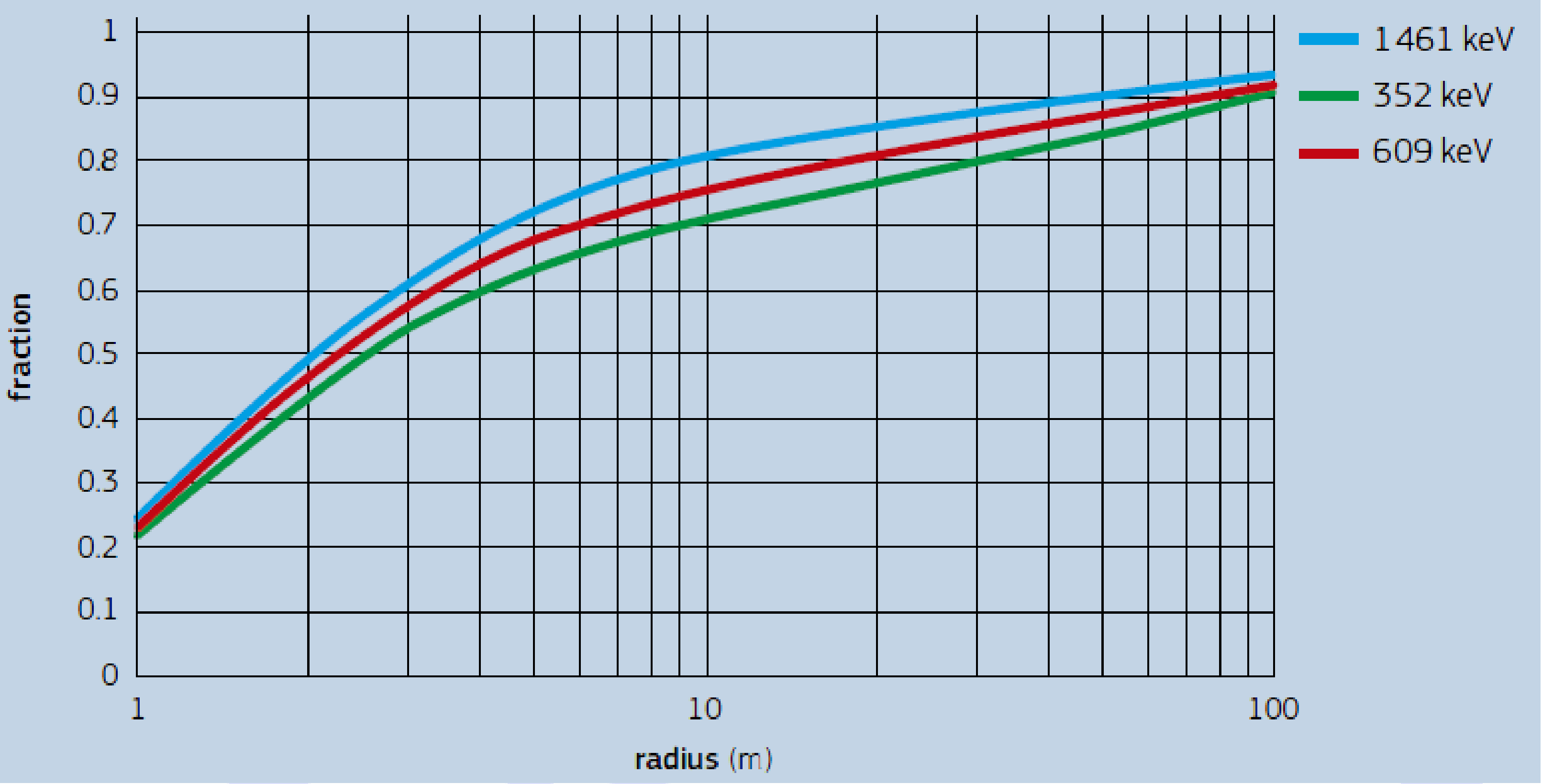
Most ^{220}Rn gas and progeny remains in soil and rocks

Terrestrial natural radiation

- Natural radionuclides are assumed **homogeneously distributed** on the ground.
- About 70 to 80 % of gamma dose rate originates **from the area within 10 m surrounding the monitor.** To capture 90 %, a surrounding of **100 m is necessary**.
- Gamma rays generated by natural radionuclides in rocks are nearly absorbed by any media having the area density 100 g/cm^2. Thus 95 % of the gamma radiation recorded on the Earth's surface originates **from the top 35 cm of the soil**. Therefore, terrestrial radiaton reflects the Earth's surface geological setting.







Spatial variability on the terrestrial natural radiation

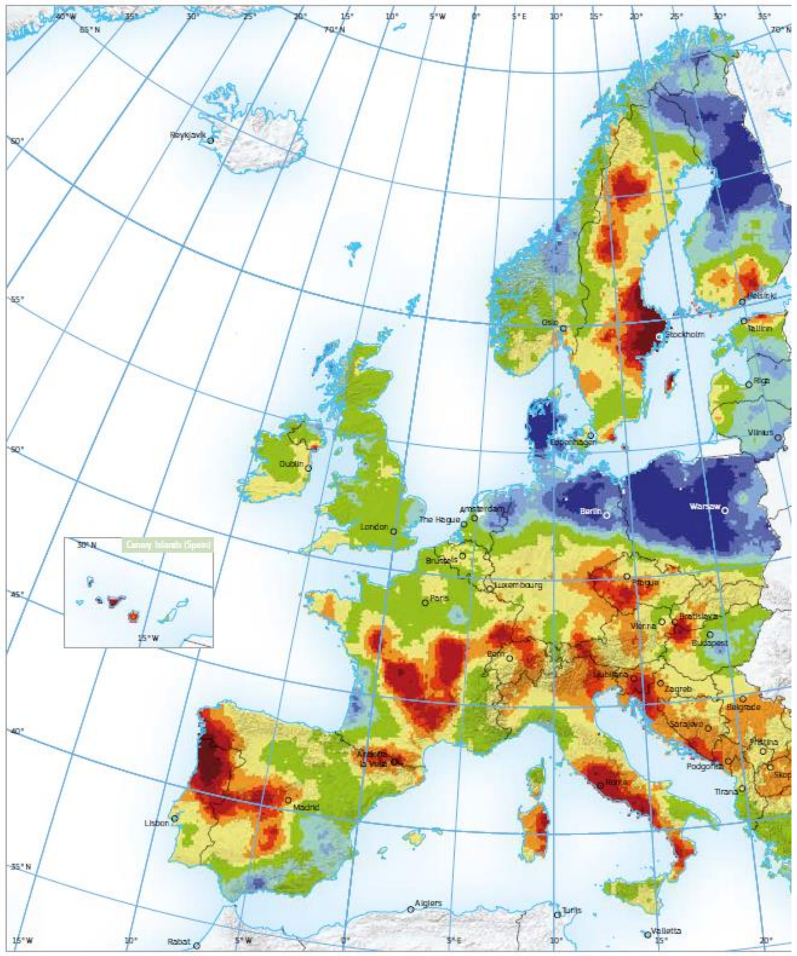
Locality	Rock	K	Th	U	Dose rate
		g/kg	mg/kg	mg/kg	nGy/h
1 Adršpach	sandstone	1	2.1	0.6	9.9
2 Krucemburk	sandstone	9	4.2	1.8	33
3 Příbram	schist, graywacke	10	5.2	2.4	40
4 Dol. Rožínka	paragneiss	17	8.7	3.5	63.9
5 Říp	alkaline basalt	12	13.6	3.4	68.9
6 Příbram	granodiorite	20	13	3.4	78.5
7 Budišov	durbachite	32	24	5.9	135.2
8 Bezděz	phonolite	51	32	8.6	195.3
9 Teplice - Cínovec	rhyolite	47	41	12	231.6

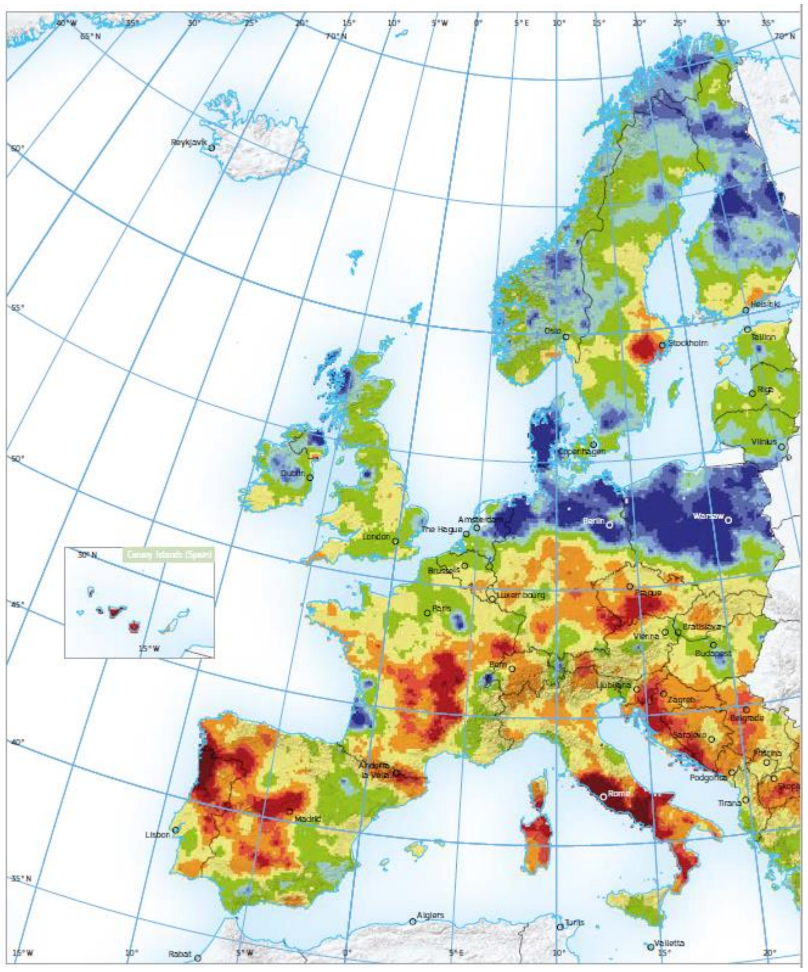
The influence of topsoil geology on Terrestrial natural radiation

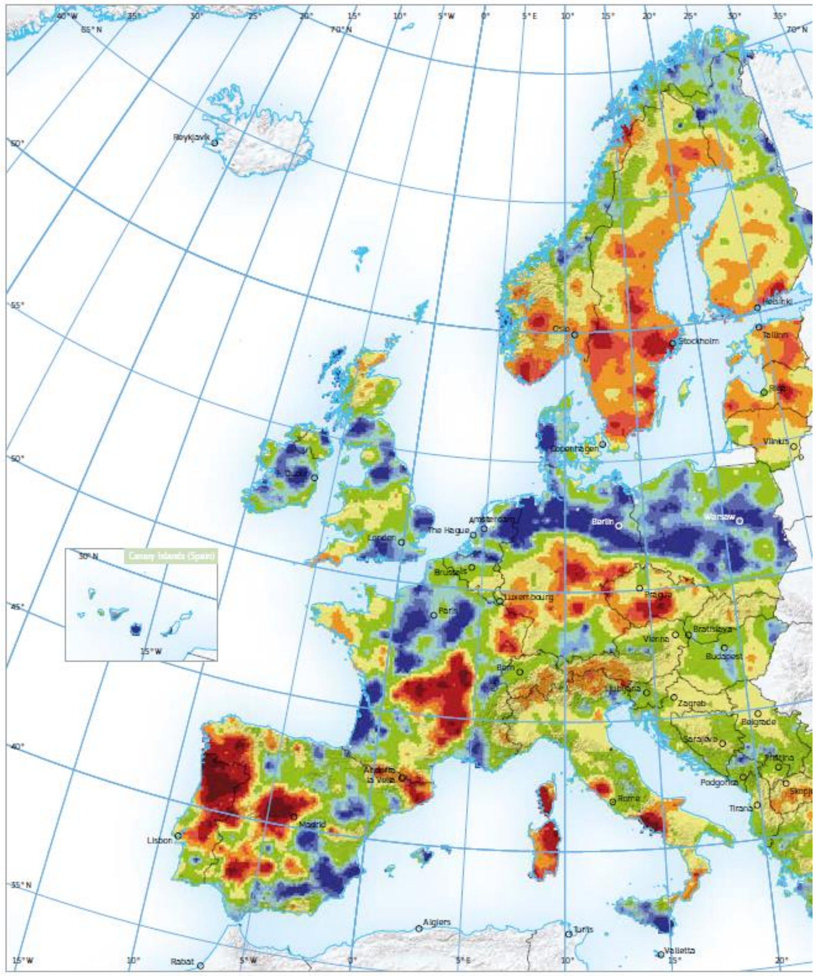
	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
Limestone	15	15	160
Travertine	7	20	3
Marlstone	35	11	273
Granite	79	93	1 076
Syenite	146	106	971
Gabbro	17	20	324
Rhyolite	69	94	1 239
Trachyte	96	126	1 338
Basalt	81	117	892
Schist	36	42	668
Gneiss	123	61	962
Slate	49	66	617
Tuff	147	224	1 506

	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
Tuff	147	224	1 506
Clay	51	49	555
Chalk	15	15	112
Gypsum	18	16	105
Lime	19	11	109
Pozzolana	187	253	1 397
Pumice	269	66	1 073
Shale	174	131	493
Brick	51	49	555
Concrete	59	85	340
Cement	50	35	235
Aggregates	23	23	388

The influence of topsoil geology on Terrestrial natural radiation







Map of estimated total concentration of uranium in topsoil over Europe
(mg/kg)

- 6.27 - 94.00 (99%ile - Max)
- 4.58 - 6.27 (95 - 99%ile)
- 4.15 - 4.58 (90 - 95%ile)
- 3.56 - 4.15 (75 - 90%ile)
- 2.94 - 3.56 (50 - 75%ile)
- 2.10 - 2.94 (25 - 50%ile)
- 1.66 - 2.10 (15 - 25%ile)
- 1.43 - 1.66 (10 - 15%ile)
- 1.13 - 1.43 (5 - 10%ile)
- 0.21 - 1.13 (Min - 5%ile)

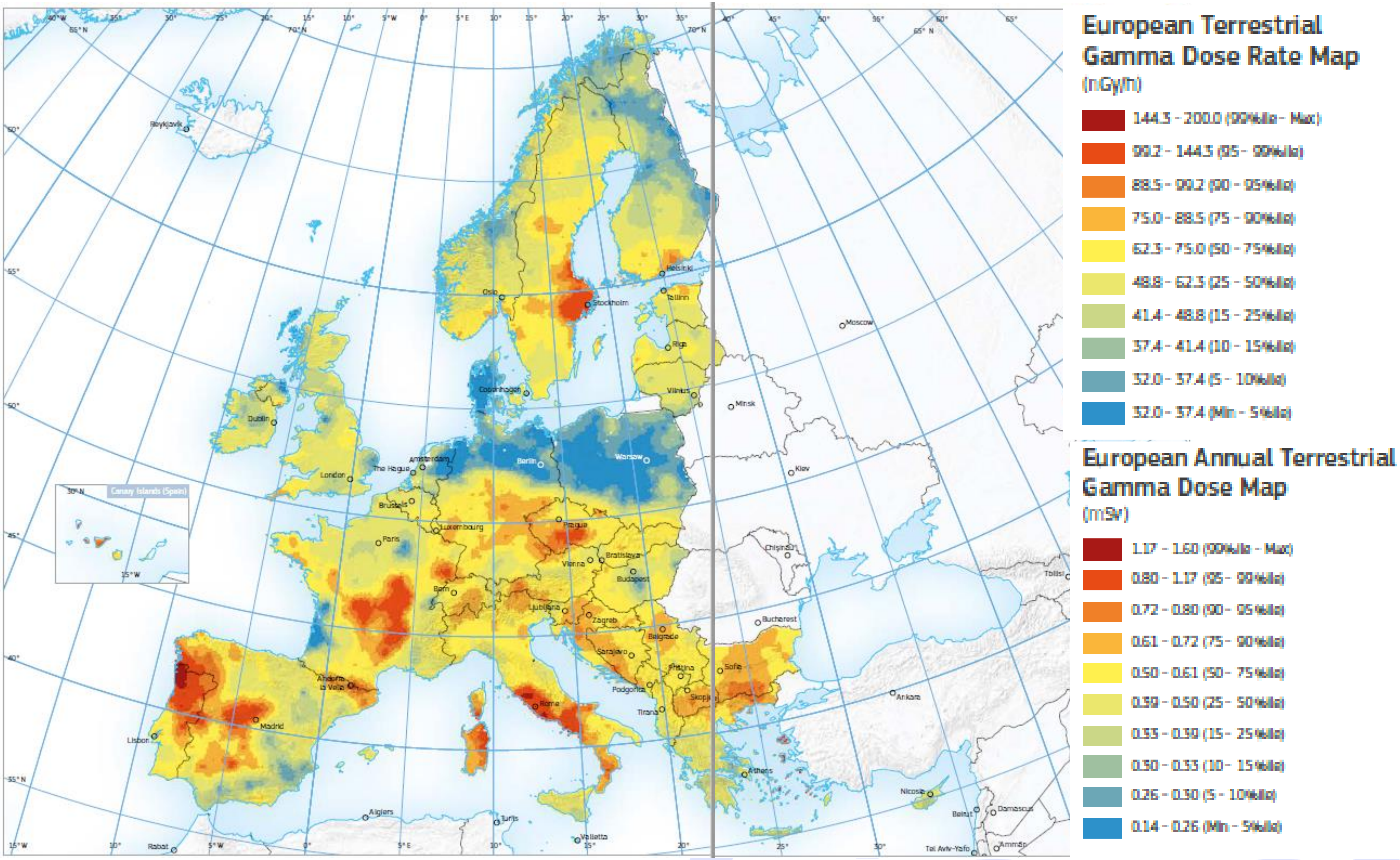
Map of estimated total concentration of thorium in topsoil over Europe
(mg/kg)

- 20.3 - 84 (99%ile - Max)
- 15.8 - 20.3 (95 - 99%ile)
- 14.2 - 15.8 (90 - 95%ile)
- 11.8 - 14.2 (75 - 90%ile)
- 9.3 - 11.8 (50 - 75%ile)
- 7.0 - 9.3 (25 - 50%ile)
- 6.0 - 7.0 (15 - 25%ile)
- 5.5 - 6.0 (10 - 15%ile)
- 4.8 - 5.5 (5 - 10%ile)
- 0.3 - 4.8 (Min - 5%ile)

Map of estimated total concentration of K_2O in topsoil over Europe
(wt%)

- 3.74 - 9.54 (99%ile - Max)
- 3.03 - 3.74 (95 - 99%ile)
- 2.76 - 3.03 (90 - 95%ile)
- 2.36 - 2.76 (75 - 90%ile)
- 1.90 - 2.36 (50 - 75%ile)
- 1.48 - 1.90 (25 - 50%ile)
- 1.30 - 1.48 (15 - 25%ile)
- 1.19 - 1.30 (10 - 15%ile)
- 1.03 - 1.19 (5 - 10%ile)
- 0.03 - 1.03 (Min - 5%ile)

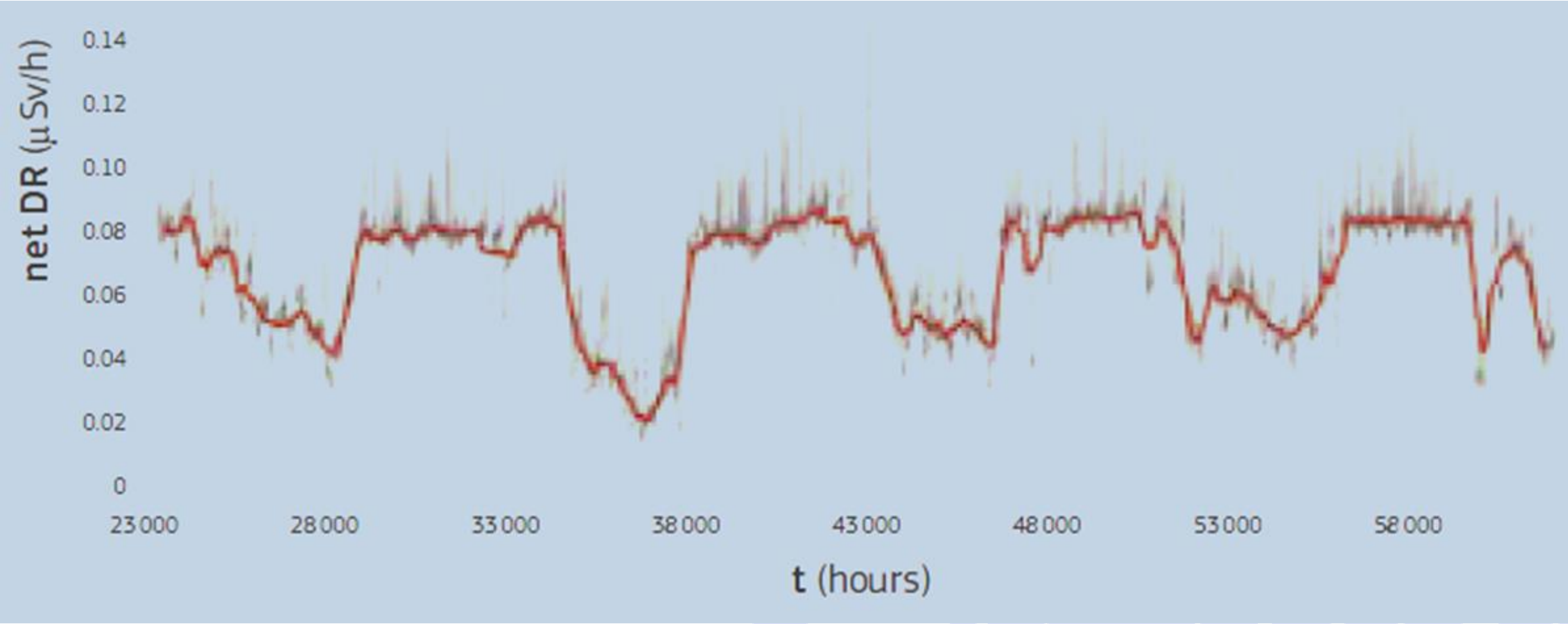
Spatial variability on Terrestrial natural radiation



Temporal variability on Terrestrial natural radiation: precipitations

In general, **precipitations reduces TGDR** due to a greater attenuation in wet soil. The levels gradually increases as the ground dries.

Snow cover is more effective at attenuation than equivalent rainfall because it remains on the surface instead of draining immediately into the soil: About 20 cm depth of snow reduces the TGDR by 26% and 58%, for snow densities of 0.1 and 0.4 g·cm^{-3} respectively.

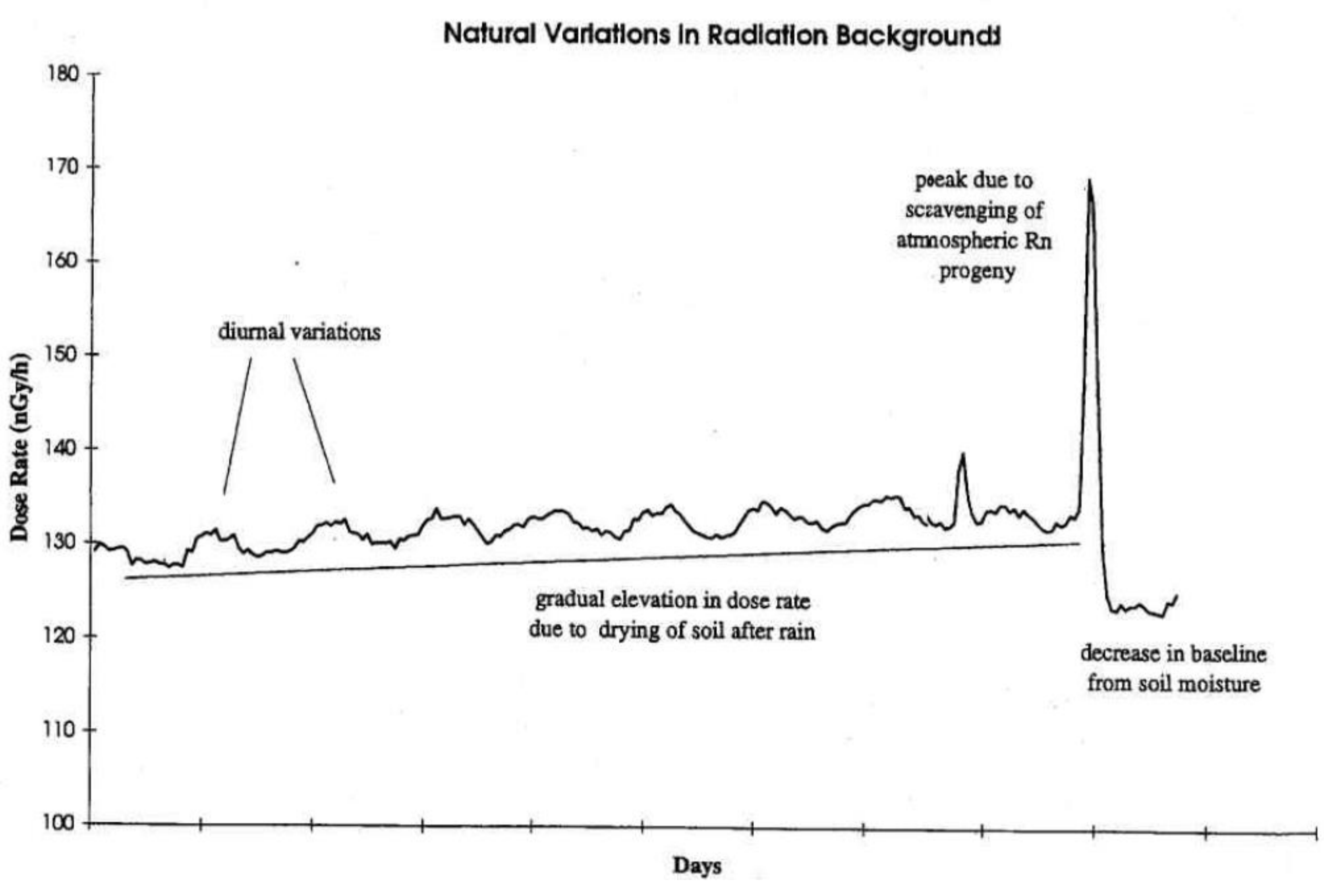


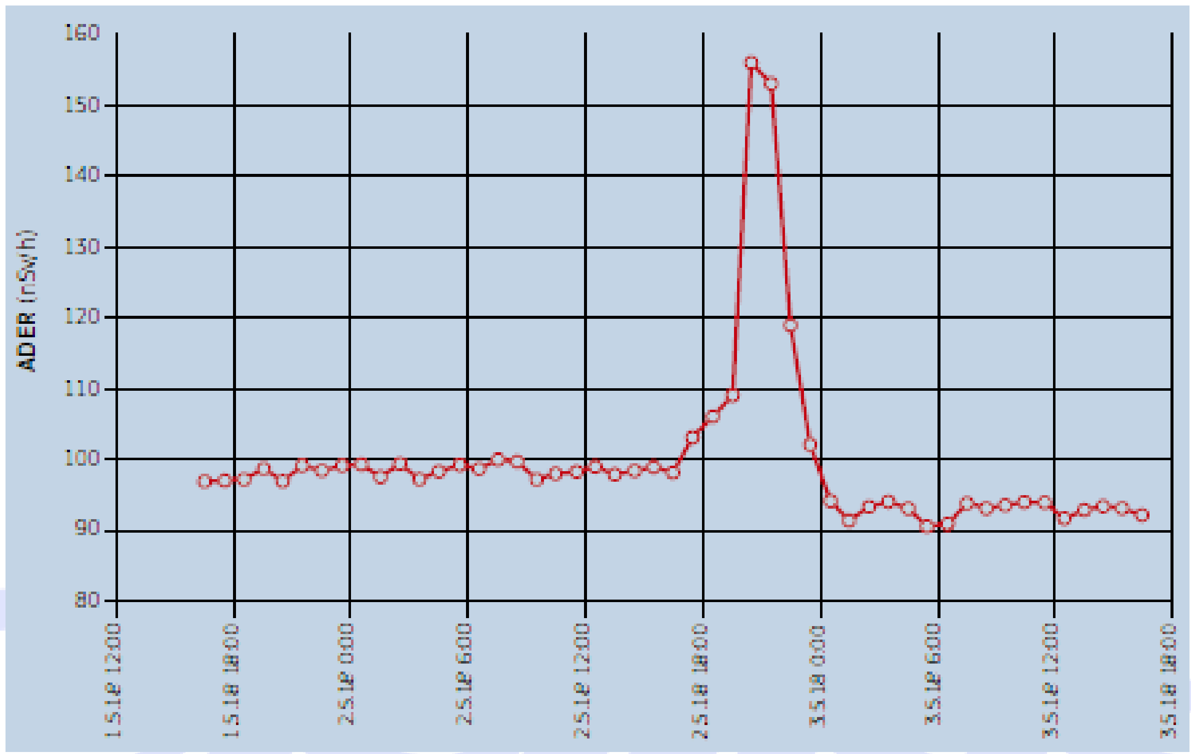
Temporal variability on Terrestrial natural radiation: radon

Diurnal variations are associated with daily temperature changes and the accompanying atmospheric turbulence. Radon exhaled from soil during the night stays near the surface while the air is cold, with the gamma emitting progeny causing an increase in TGDR. As the air warmed during the day, vertical diffusion reduces radon concentration and TGDR reduces.

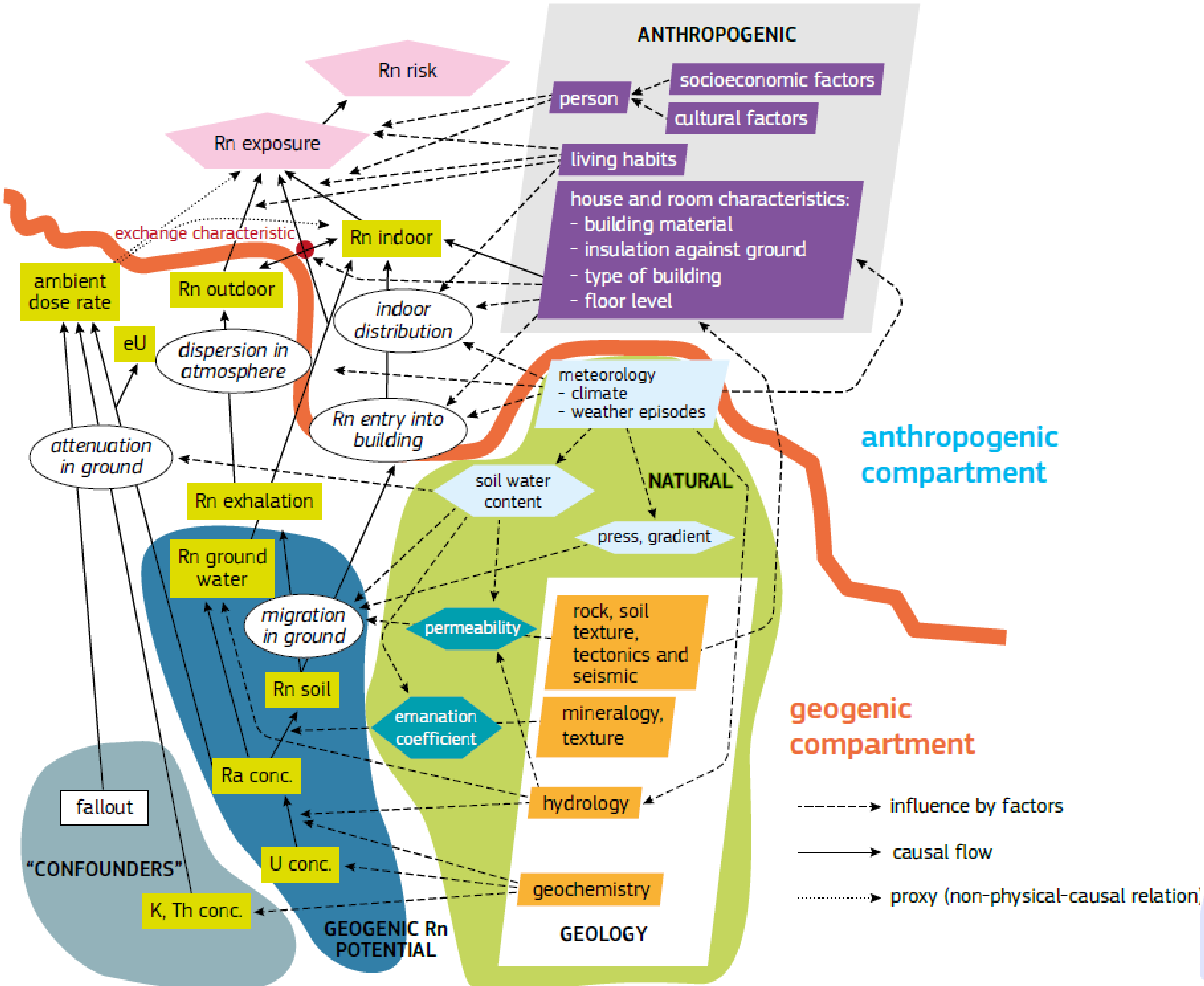
Continuous **drying of soil** facilitates the radon exhalation and produces a slightly increase of TGDR.

After a thunderstorm, the short-lived radon progeny are **wash-out or scavenged** to the ground where they decay within few hours. After that TGDR is slightly lower than before rain, due the now wet soil and the 'clean' atmosphere.

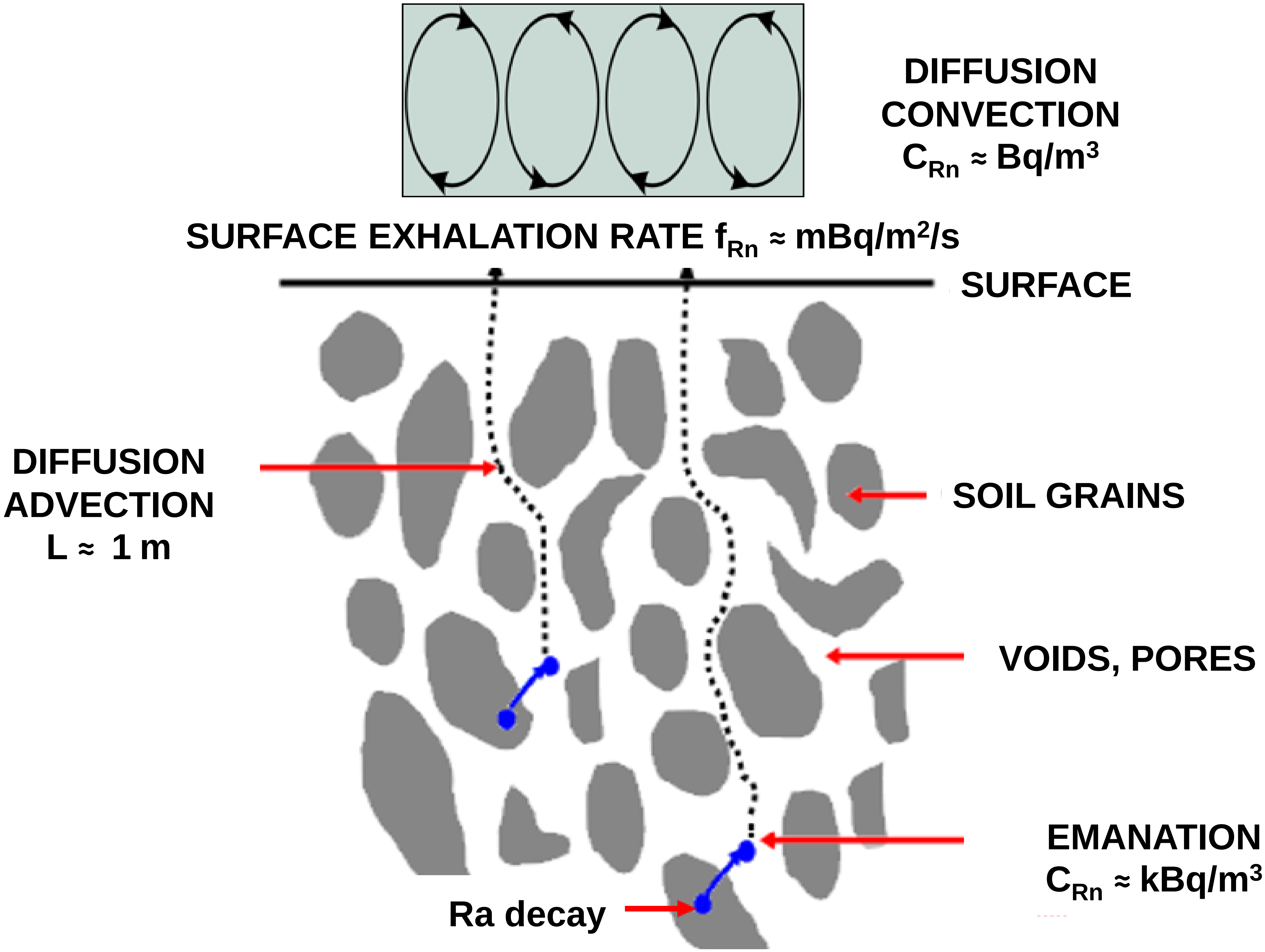




Radon: from rock to risk



Radon transport in soil



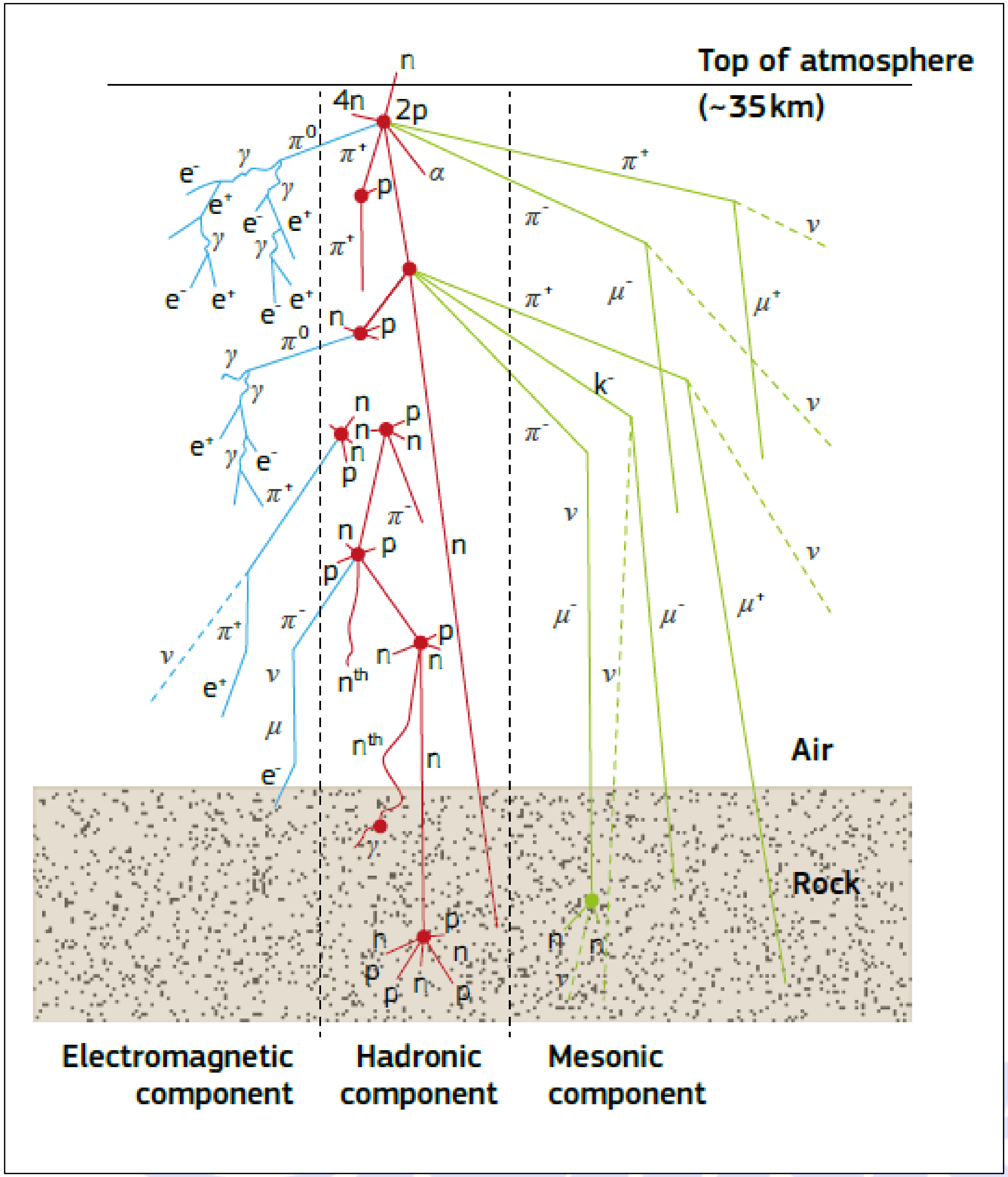
Cosmic radiation

Cosmic rays are atomic nuclei accelerated to high energy levels, thus creating electrons, gamma rays, neutrons and mesons when interacting with atmospheric nuclei:

Galactic cosmic radiation (GCR) are stable, charged particles (protons 87%, 12% alpha particles and 1% heavy nuclei) that have been accelerated to enormous energy levels(0.1 – 10 GeV, near light speed) by astrophysical sources located somewhere in our universe.

Solar wind (SW), is generated at the Sun and consist mostly of protons (98%) and alpha particles (2%) with lower energies (< 100 MeV), but do not have any heavier nuclei or energetic electrons.

Almost **90% of cosmic rays that reach Earth's surface are created by GCR**. Some rare ground level events (GLE) with particles with 1 GeV come from the Sun.



Cosmic radiation: altitude dependence

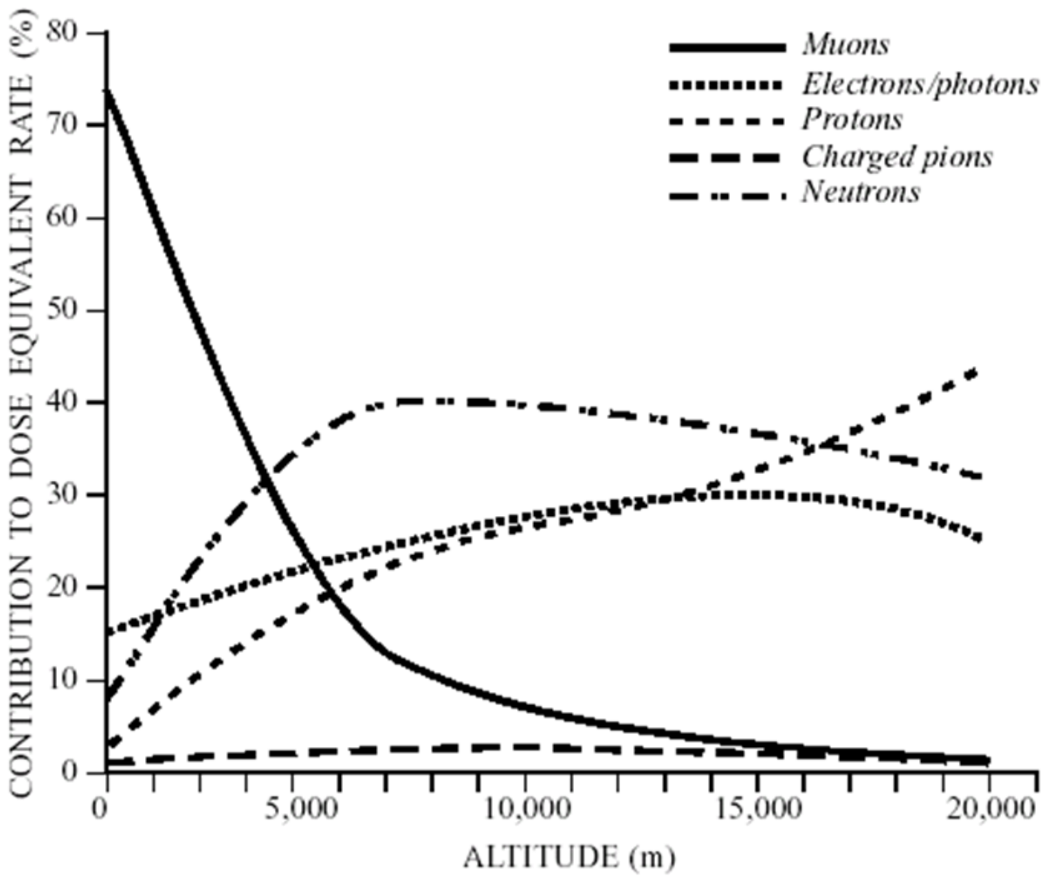
Cosmic Dose Rate at ground level (CDR) is due to:

- 50% to direct ionizing radiations (muons).
- 30% to photons/electrons
- 20% to neutrons

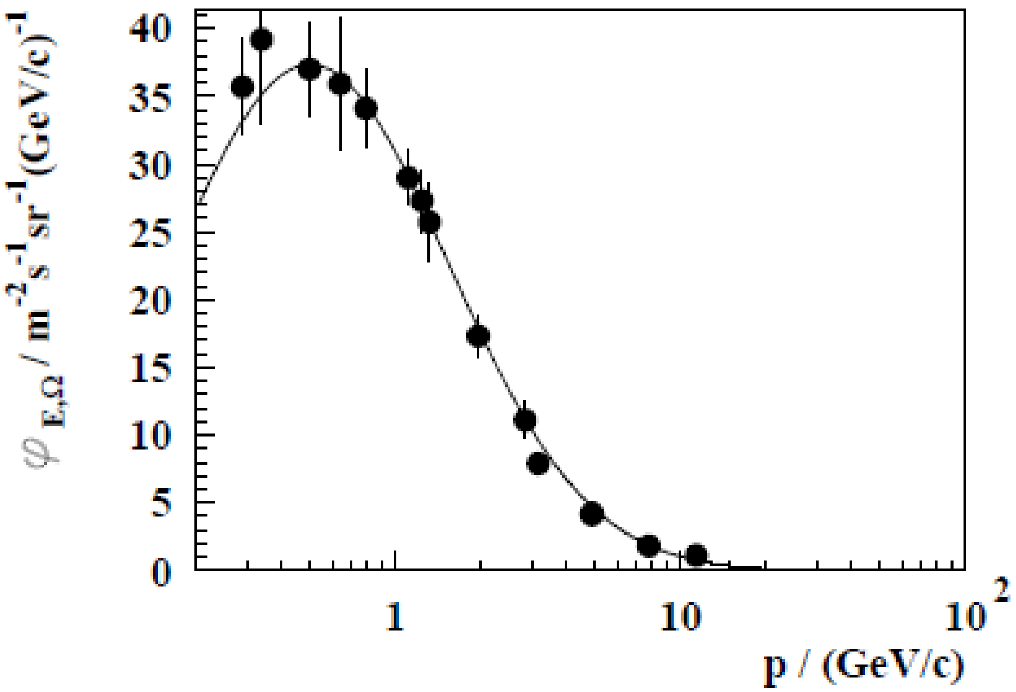
Altitude dependence for muons and photons is described as:

$$\dot{E}_1(z) = \dot{E}_1(0)\,[0.21e^{-1.649z} + 0.79e^{0.4528z}]$$

where $E_1(0)$= 240 µSv/a or 32 nSv/h



Muons

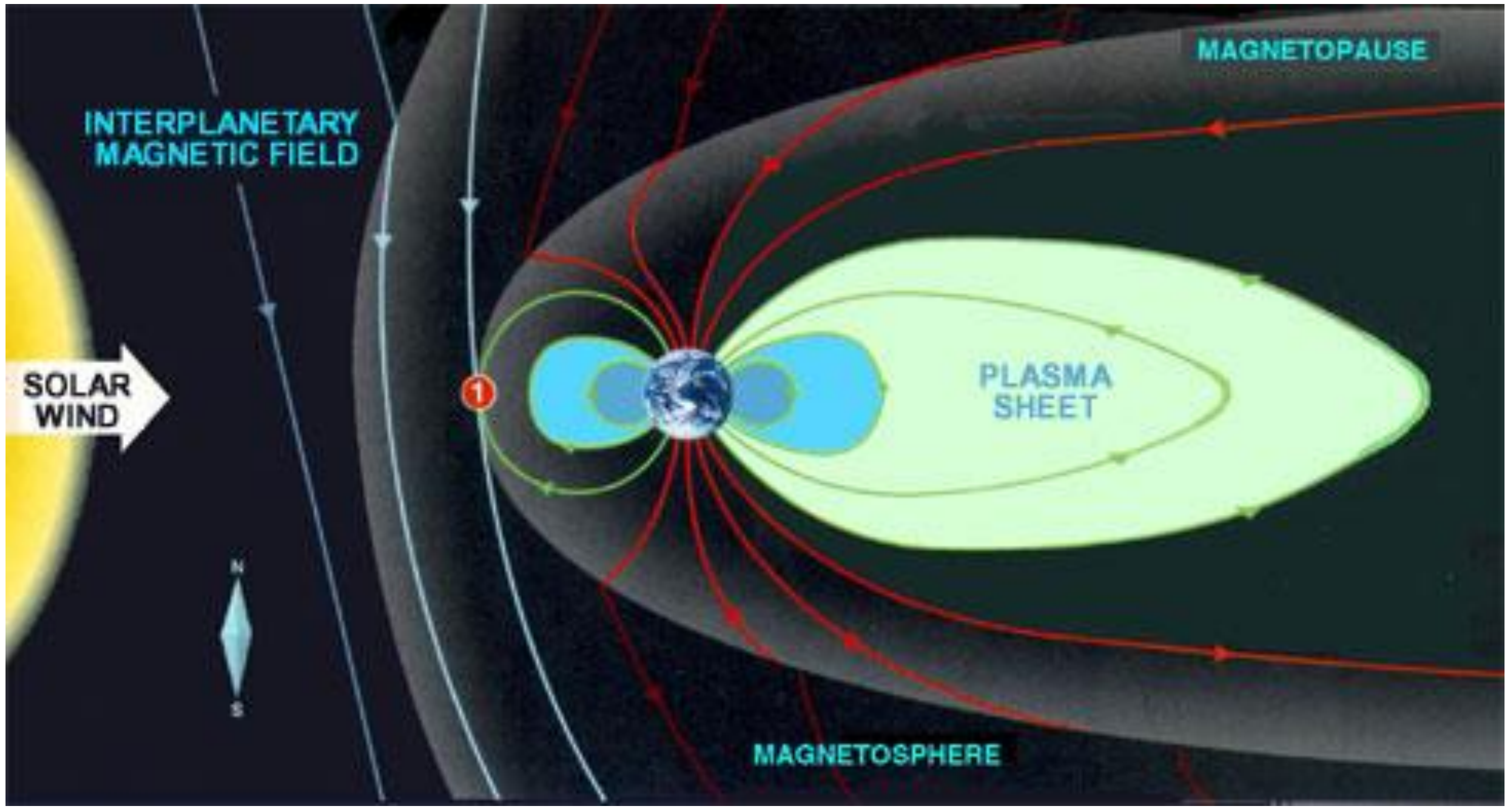


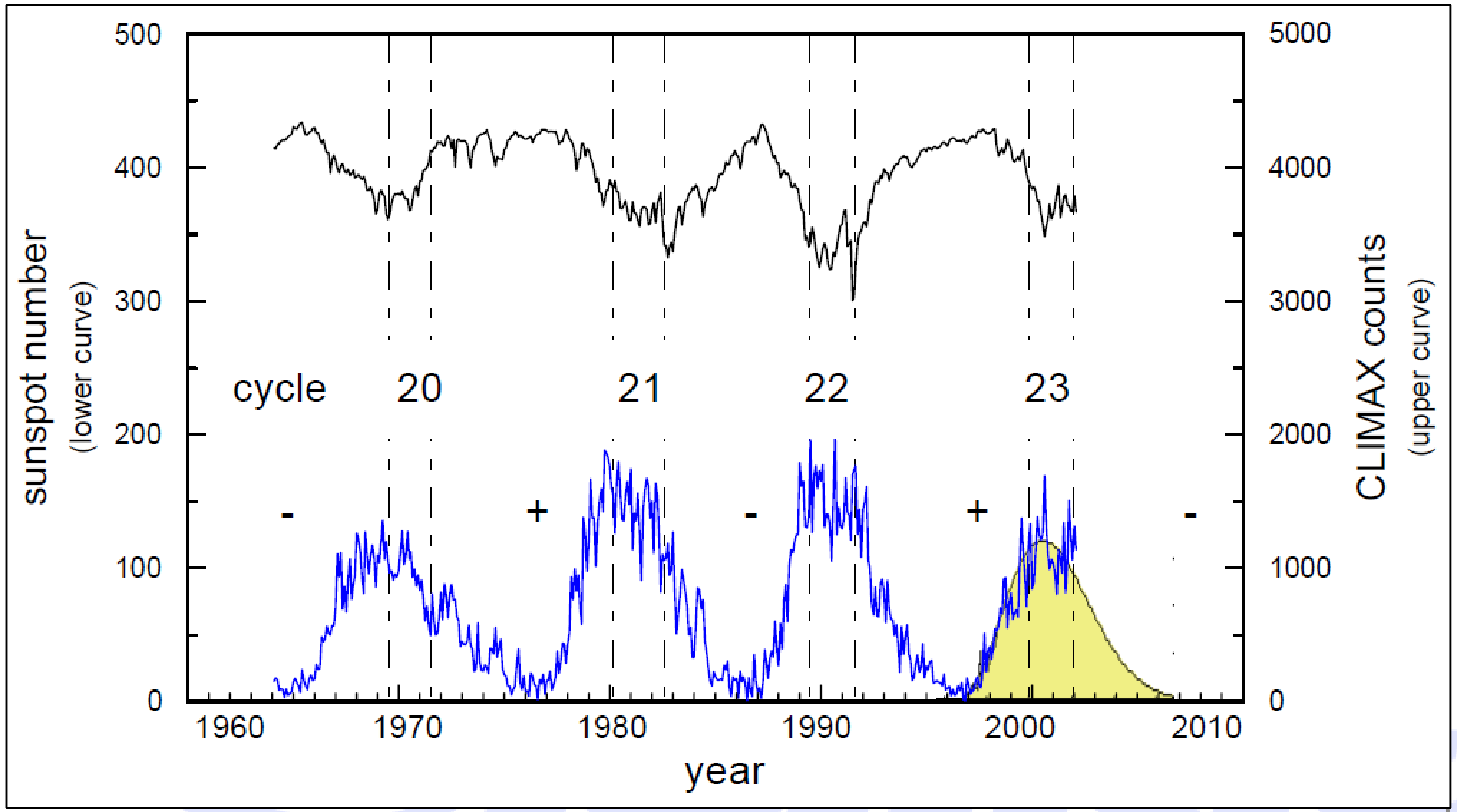
Cosmic radiation: temporal variability

The SW and its associated magnetic field affect the GCR in the vicinity of the Earth and obstruct their entry into the atmosphere; in other words**, an increase in SW results in a decrease in GCR, and therefore a decrease CDR**.

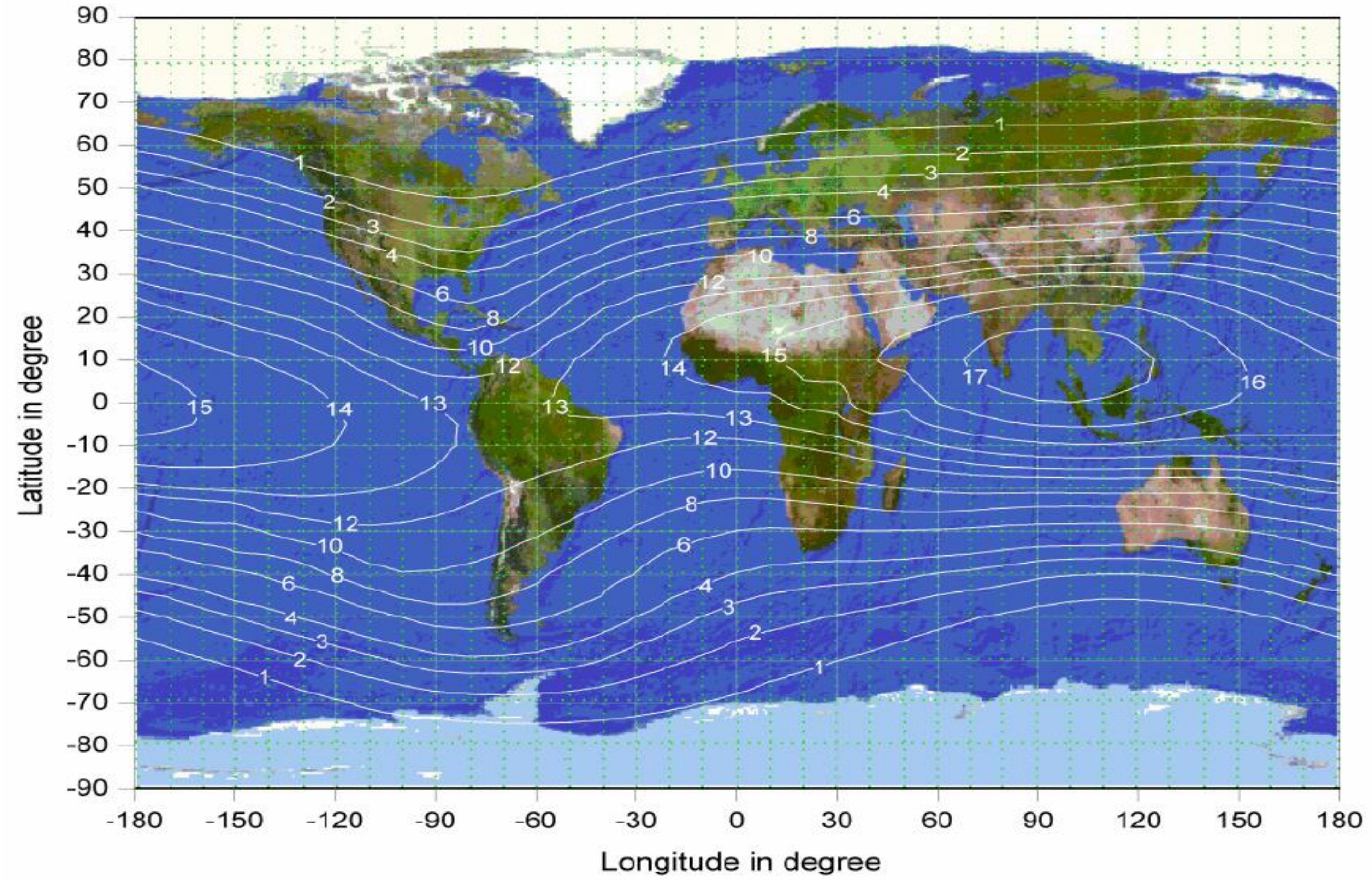
SW is associated with the **number of sunspots**, which can be considered an indicator of disturbances in the Sun's magnetic field, varies from year to year and exhibits a **nearly 11-year cycle.**

The CDR may be considered as averages over the 11-year solar cycle, with **a range of variation of about 10%.**





Cosmic radiation: latitude dependence



Geomagnetic latitude, Bm = arcsen [senλ senλ_p + cosλ cosλ_p cos($\phi - \phi_p$)]

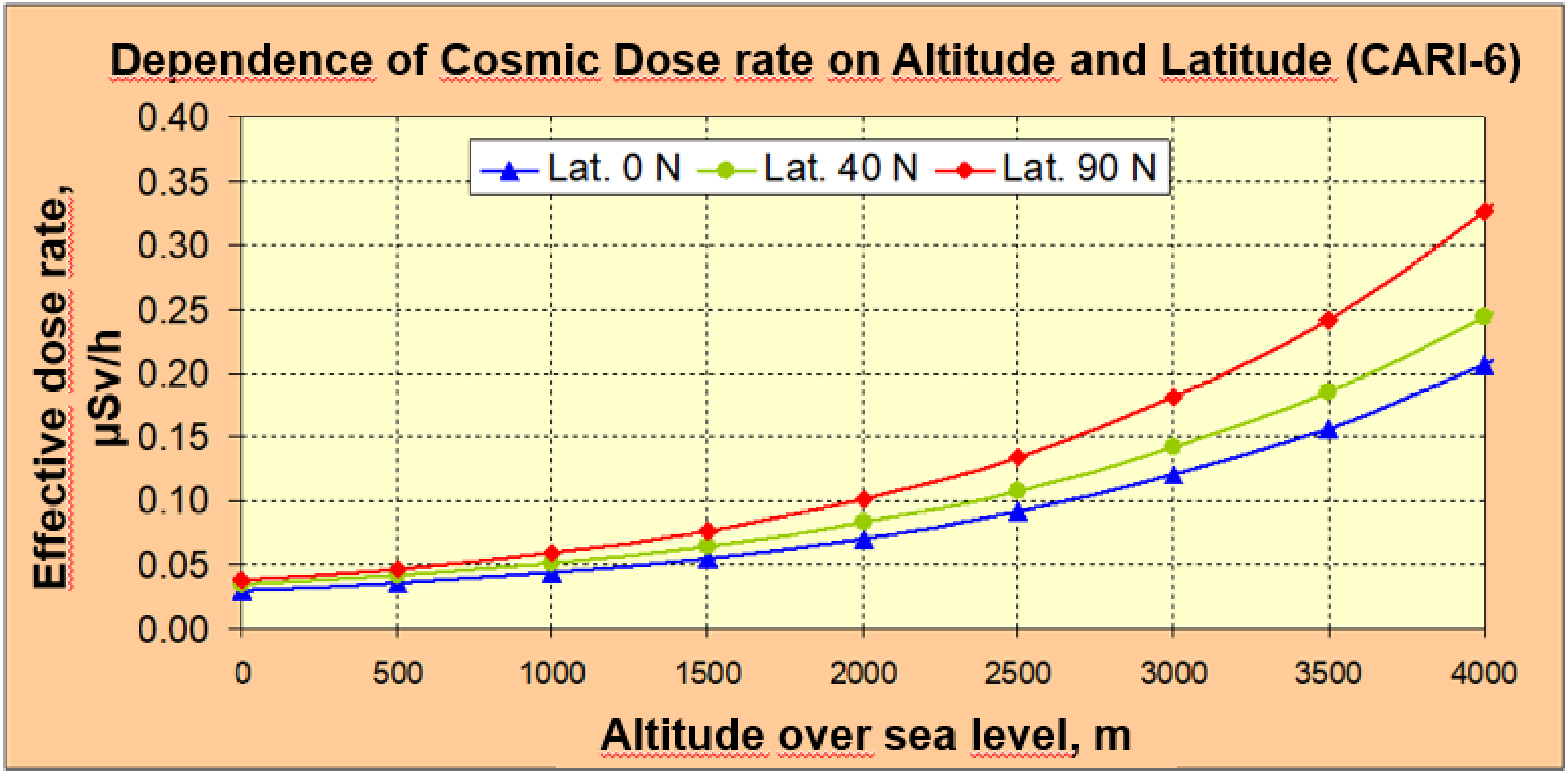
λp = 79.3ºN, ϕ*p* =289.89ºE are the coordinates of the Magnetic Noth Pole

Verical Rigidity, Rc(GV) = 14.9 cos^{4}Bm

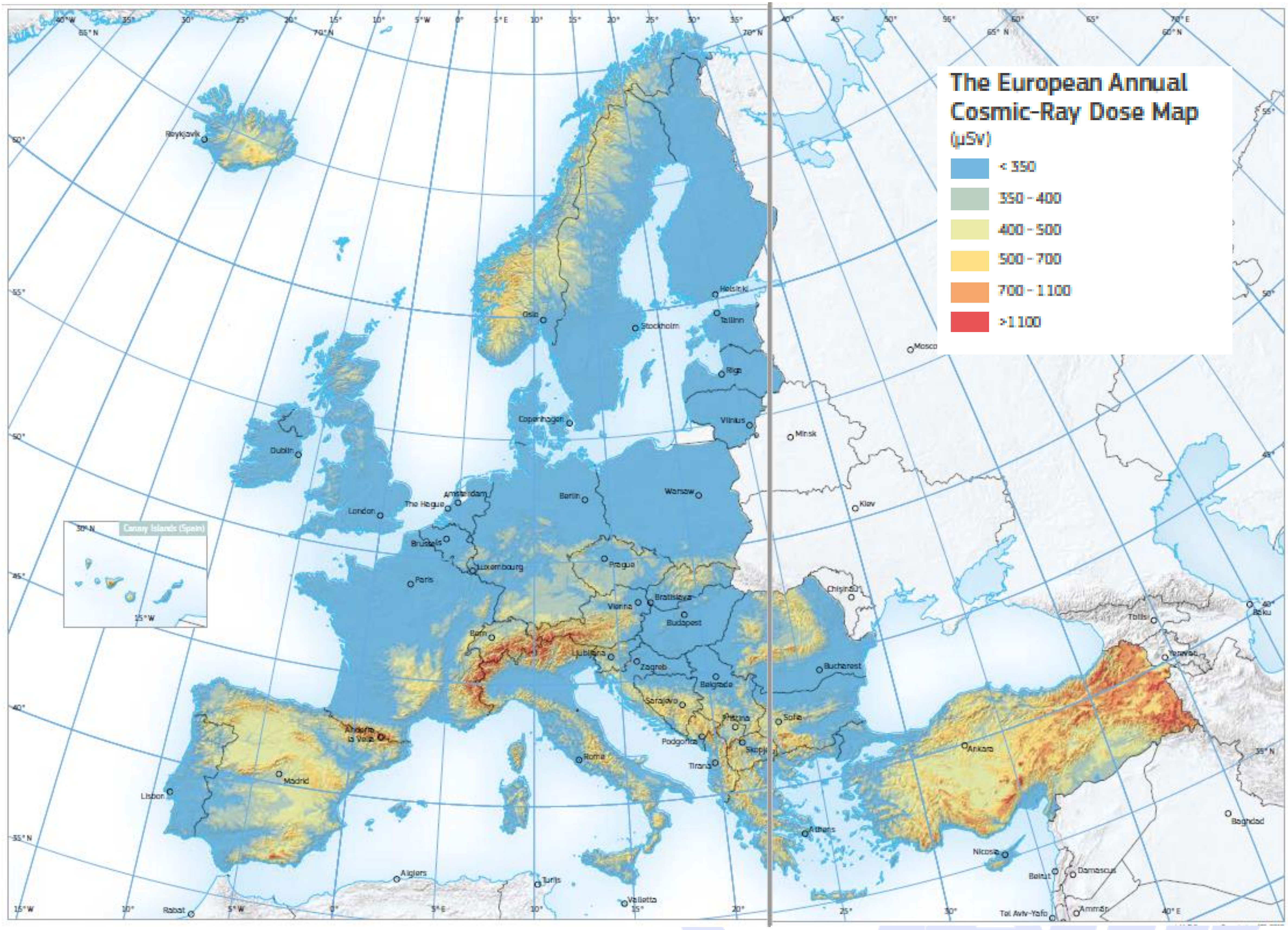
Rc = 0 GV in the Poles ⇒ Minimum deflection by the Earth's magnetosphere

Rc ≈ 15 GV near the equator ⇒ Maximum deflection by the Earth's magnetosphere

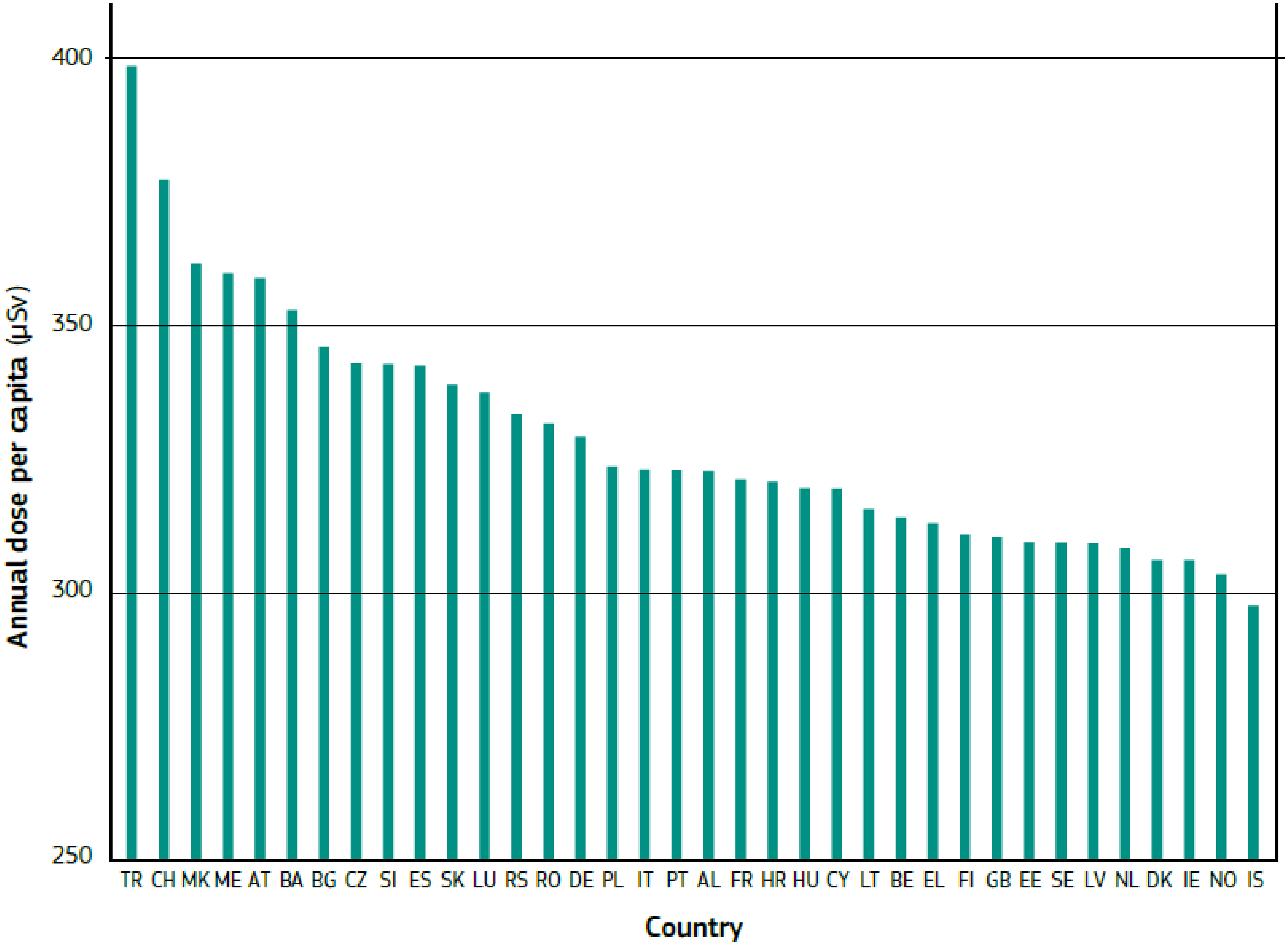
Cosmic radiation:
Altitude and latitude dependence



Cosmic radiation: spatial variability



Cosmic radiation: spatial variability



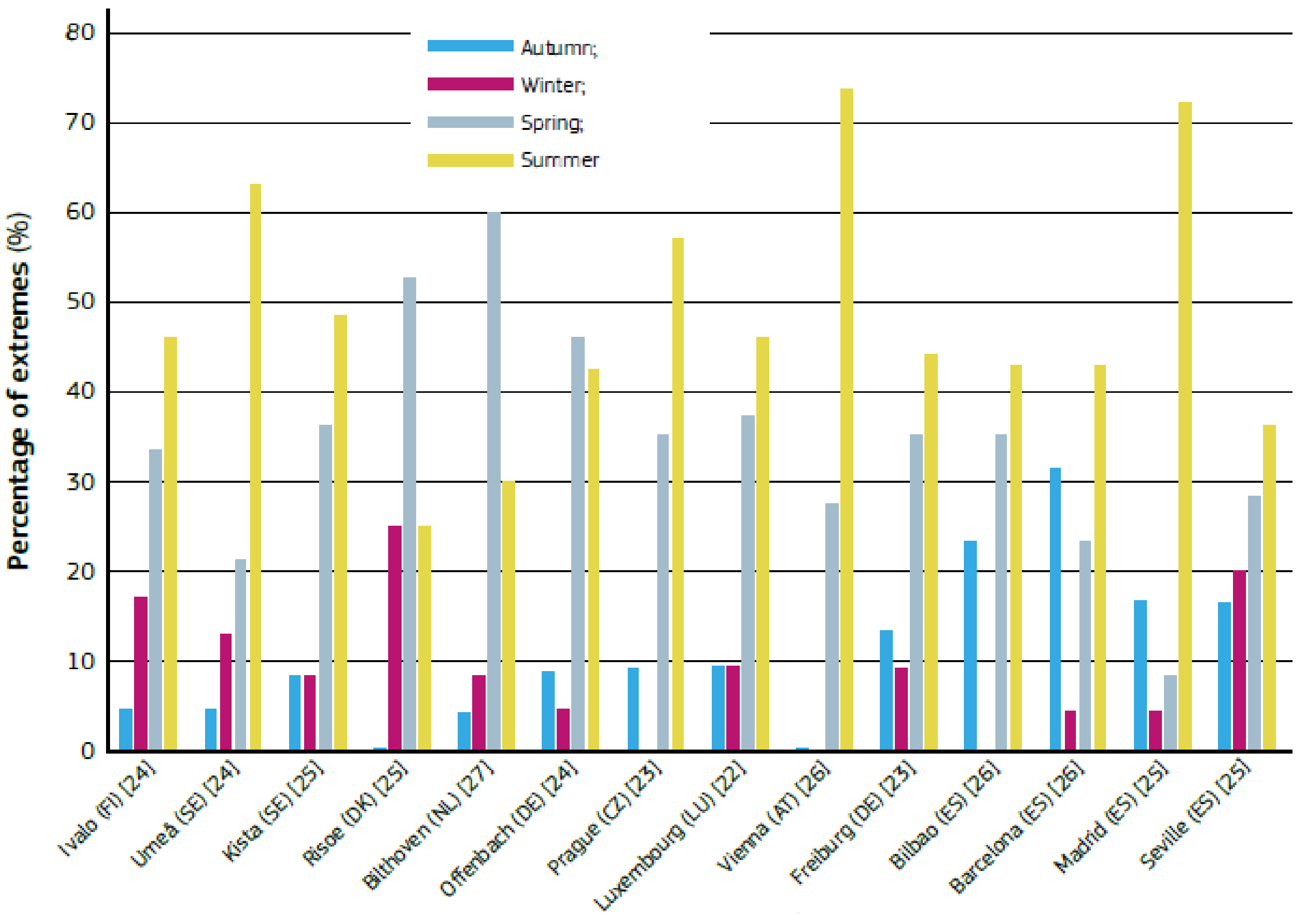
Cosmogenic radionuclides

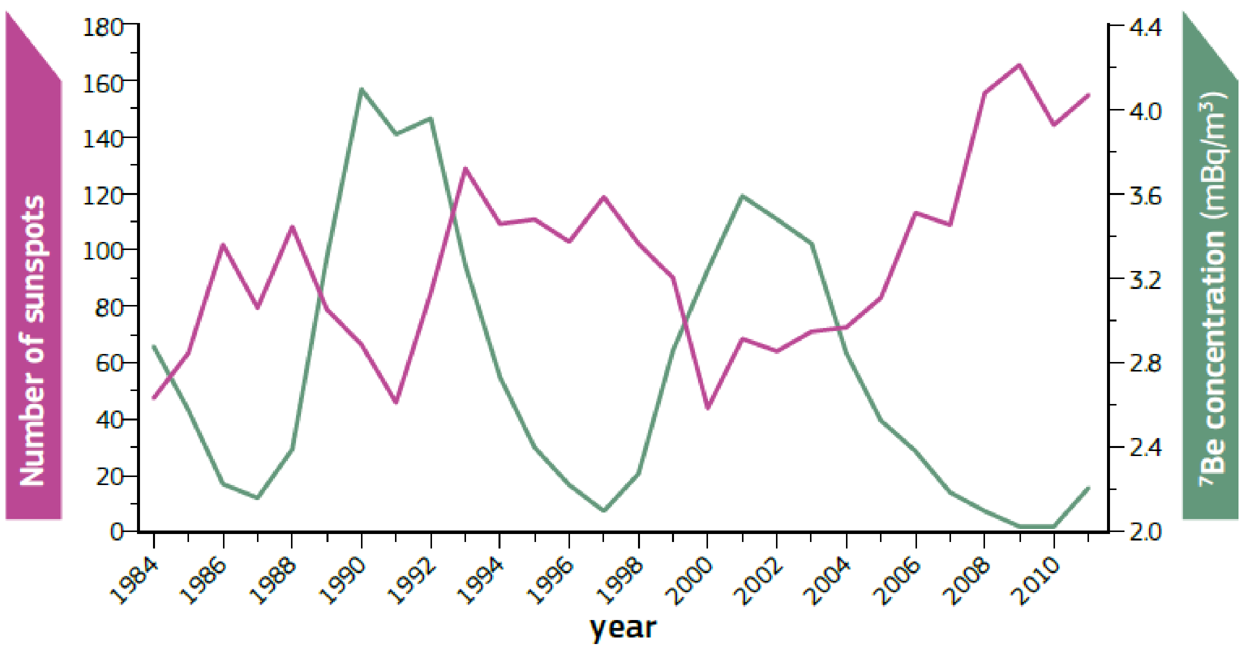
Radionuclide	Half-life	Major radiations	Target nuclides	Typical concentrations (Bq/kg)		
				Air (troposphere)	Rainwater	Ocean water
^{10}Be	$1.6*10^{6}$ a	β	N, O			$2*10^{-8}$
^{26}Al	$7.2*10^{5}$ a	$β^{+}$	Ar			$2*10^{-10}$
^{36}Cl	$3*10^{5}$ a	β	Ar			$1*10^{-5}$
^{81}Kr	$2.3*10^{5}$ a	K X ray	Kr			
^{14}C	$5.7*10^{3}$ a	β	N, O			$5*10^{-3}$
^{32}Si	$1.7*10^{2}$ a	β	Ar			$4*10^{7}$
^{39}Ar	$2.7*10^{2}$ a	β	Ar			$6*10^{-8}$
^{3}H	$1.2*10^{1}$ a	β	N, O	$1.2*10^{-3}$		$7*10^{-4}$
^{22}Na	2.60 a	$β^{+}$	Ar	$1*10^{-6}$	$2.8*10^{-4}$	
^{35}S	87.4 d	β	Ar	$1.3*10^{-4}$	$7.7\text{-}107*10^{-3}$	
^{7}Be	53.3 d	γ	N, O	$1*10^{-2}$	$6.6*10^{-1}$	
^{37}Ar	35.0 d	K X ray	Ar	$3.5*10^{-5}$		
^{33}P	25.3 d	β	Ar	$1.3*10^{-3}$		
^{32}P	14.3 d	β	Ar	$2.3*10^{-4}$		
^{28}Mg	20.9 h	β	Ar			
^{24}Na	15.0 h	β	Ar		$3.0\text{-}5.9*10^{-3}$	
^{38}S	2.83 h	β	Ar		$6.6\text{-}21.8*10^{-2}$	
^{31}Si	2.62 h	β	Ar			
^{18}F	110 min	$β^{+}$	Ar			
^{39}Cl	56.2 min	β	Ar		$1.7\text{-}8.3*10^{-1}$	
^{38}Cl	37.2 min	β	Ar		$1.5\text{-}25*10^{-1}$	
^{34m}Cl	32.0 min	$β^{+}$	Ar			

Cosmogenic radionuclides are negligible from the radiation protection point of view, but they are of high importance in environmental applications such as tracing or dating.

Cosmogenic radionuclides

^{7}Be is a cosmogenic radionuclide generated by cosmic ray spallation reactions with N and O. Once produced, mainly in the stratosphere (67 %) and secondarily in the upper troposphere, ^{7}Be rapidly attaches to ubiquitous submicron aerosol particles in the ambient air. Aerosols are transported by wind and redistributed vertically through gravitational sedimentation and are ultimately removed mainly by wet and secondarily by dry deposition in the lower troposphere. Therefore, in addition to its radioactive decay, ^{7}Be is removed from the atmosphere by the same removal mechanisms as for fine aerosols.



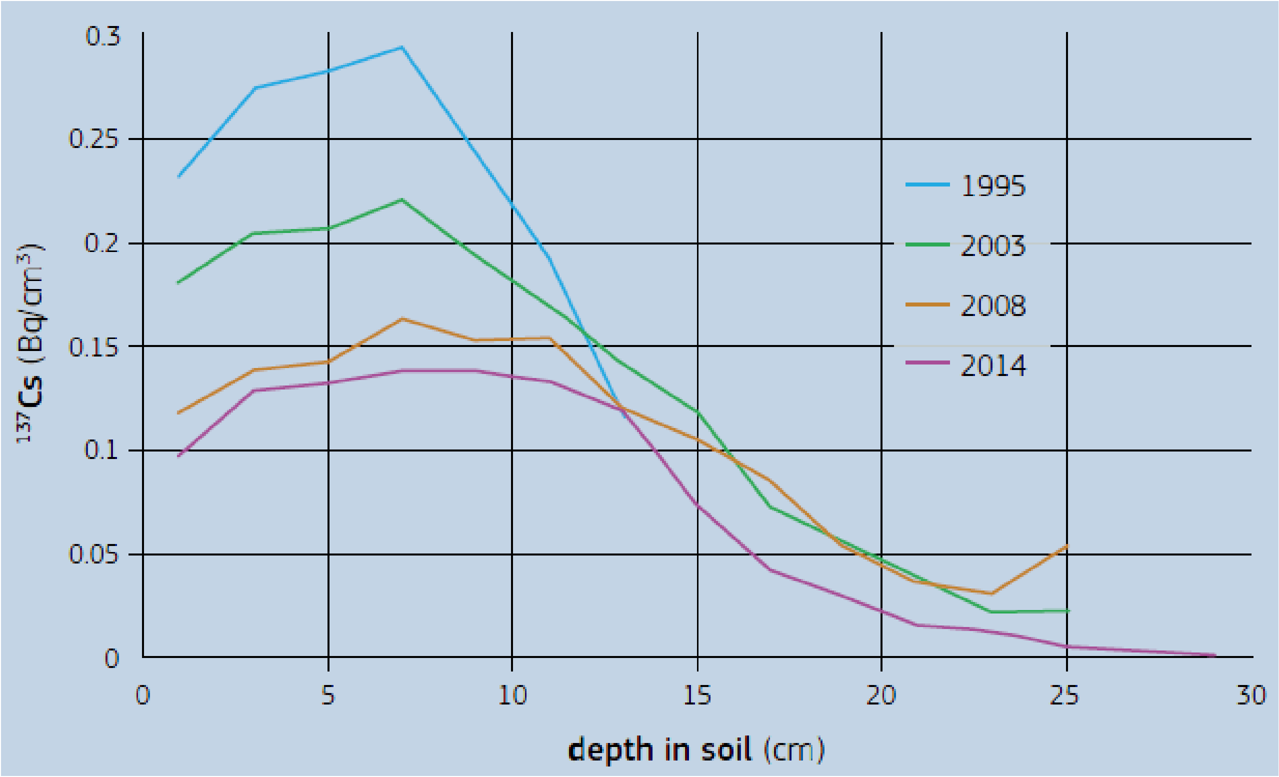


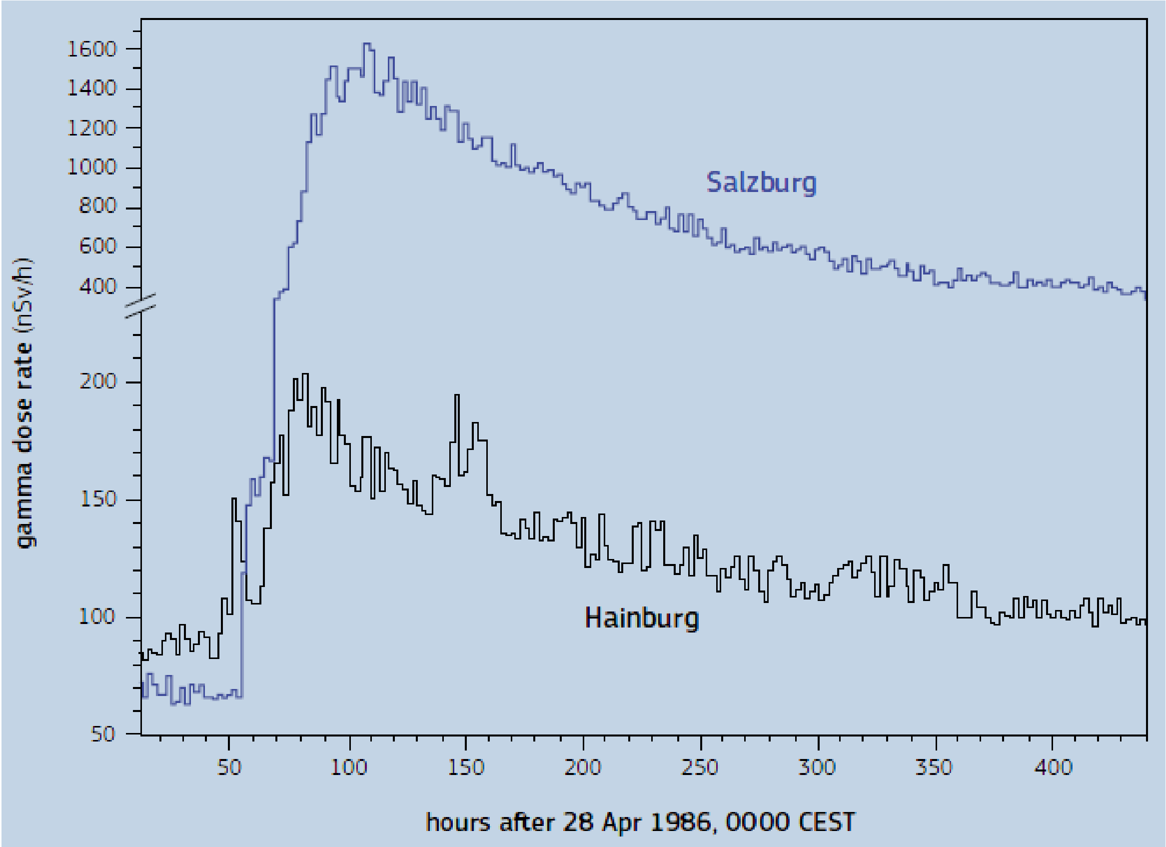
Seasonal variability of ^{7}Be extreme values over 95% percentile

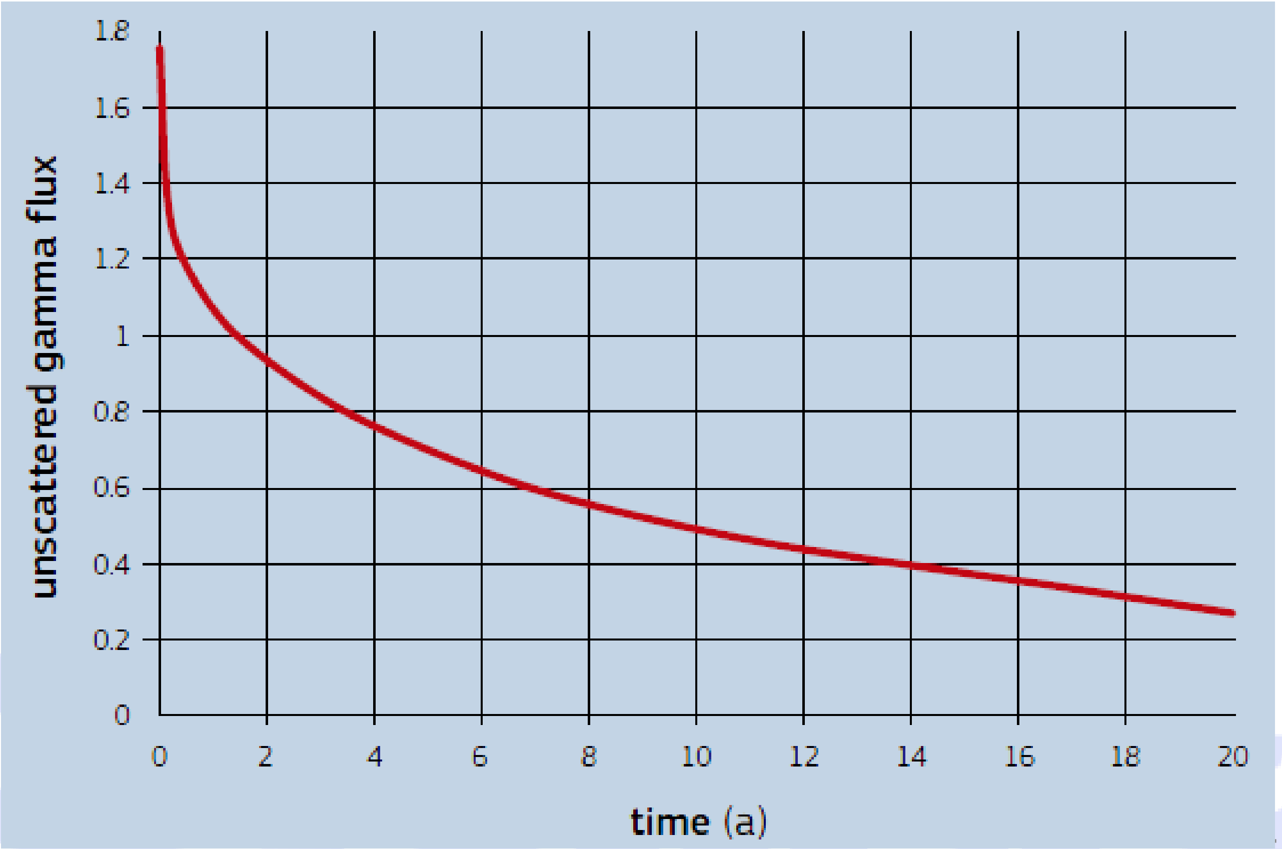
Dependence of ^{7}Be values with Sun's activity

Terrestrial and airborne artificial radiation

During the first days to weeks after the Chernobyl accident, dominant radionuclides, which contributed most to the ambient dose rate, were iodine and tellurium isotopes. Due to their short half-lives their contribution soon disappeared. For months to a few years, radionuclides such as ^{134}Cs, ^{106}Ru, ^{125}Sb and ^{144}Ce contributed to the dose rate. Today (2022), more than 36 years after the accident, only the long-lived ^{137}Cs can be detected. Consequently, the gamma-ray flux above ground also changes with time.







Summary of doses due to natural radiation

Component	Spatial variability	Temporal variabilty
Externa Terrestrial	Annual dose: 0.3 – 1.8 mSv Strong correlation with soil surface geology	Dose rates can highly increase for a few hours due to Rn events (exhalation or progeny scavening). Dose rates can decrease due to attenuation in wet soil or snow cover. These factors have small effect on anual dose
Cosmic radiation	Annual dose: 0.3 - 1.1 mSv Increases noticeably with altitude and less with latitude	Annual dose vary about 10% during the 11-year Sun's cycle

Calibration of ambient dose rate monitors: Free field method

1) The instrument is exposed to a known H_{ref} from a certified radioactive point source:

$$H_{Source} = H_{Primary} + H_{Build\ in\ air} + H_{Ground\ albedo} + H_{Ambient\ dose}$$

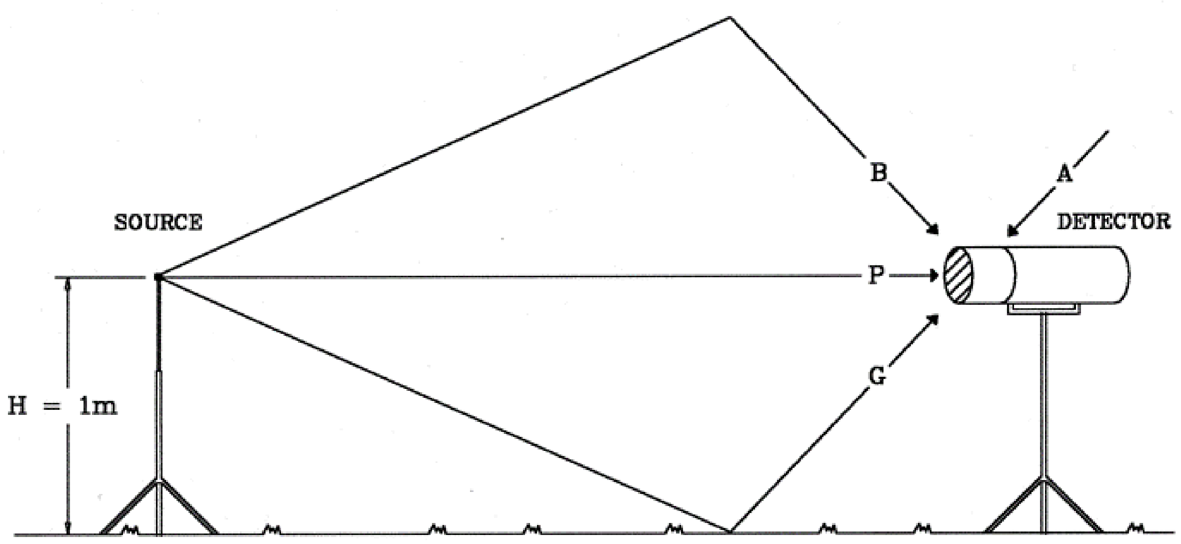
2) The radioactive source is removed and a background measurement is perfomed

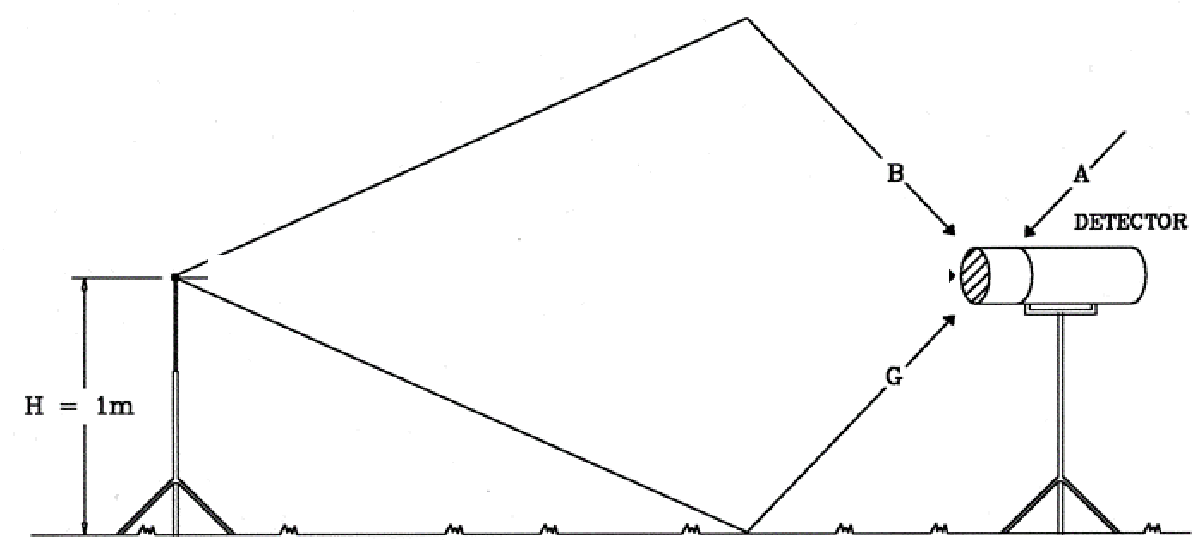
$$H_{BKGND} = H_{Build\ in\ air} + H_{Ground\ albedo} + H_{Ambient\ dose}$$

3) By difference: $H_{Source} - H_{BKGND} = H_{Primary}$

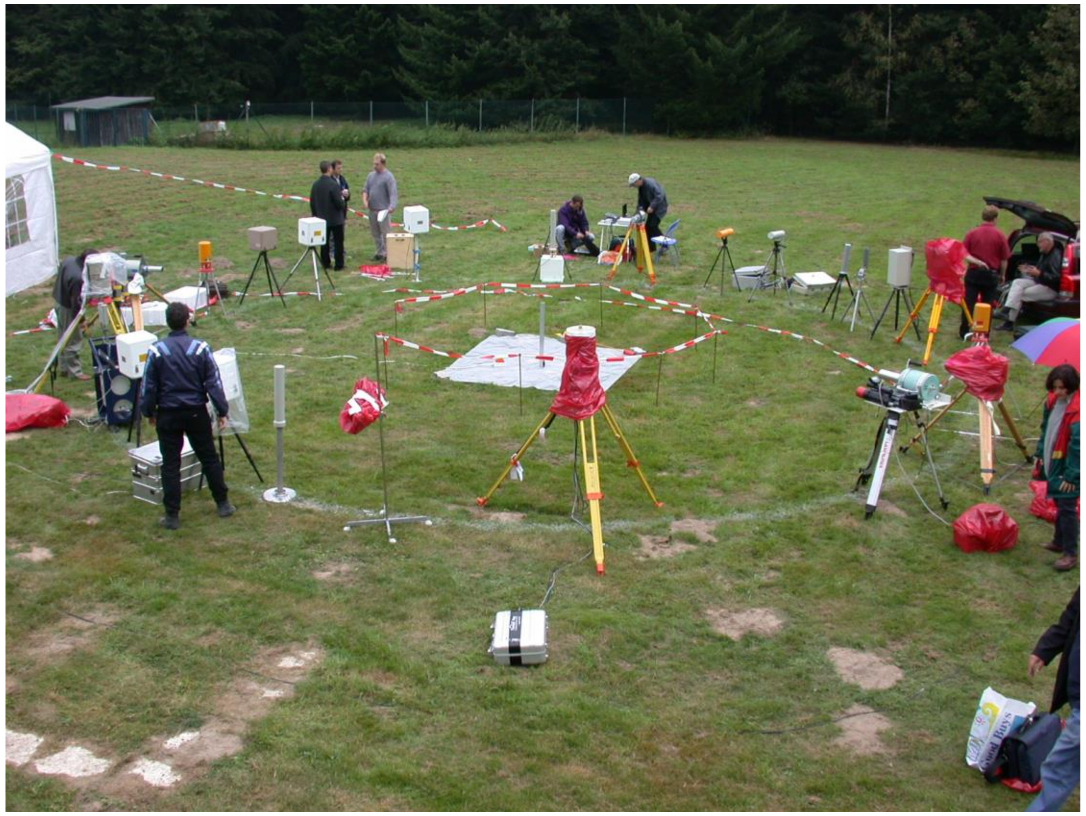
4) The calibration factor is: $N_H = H_{ref} / H_{source}$

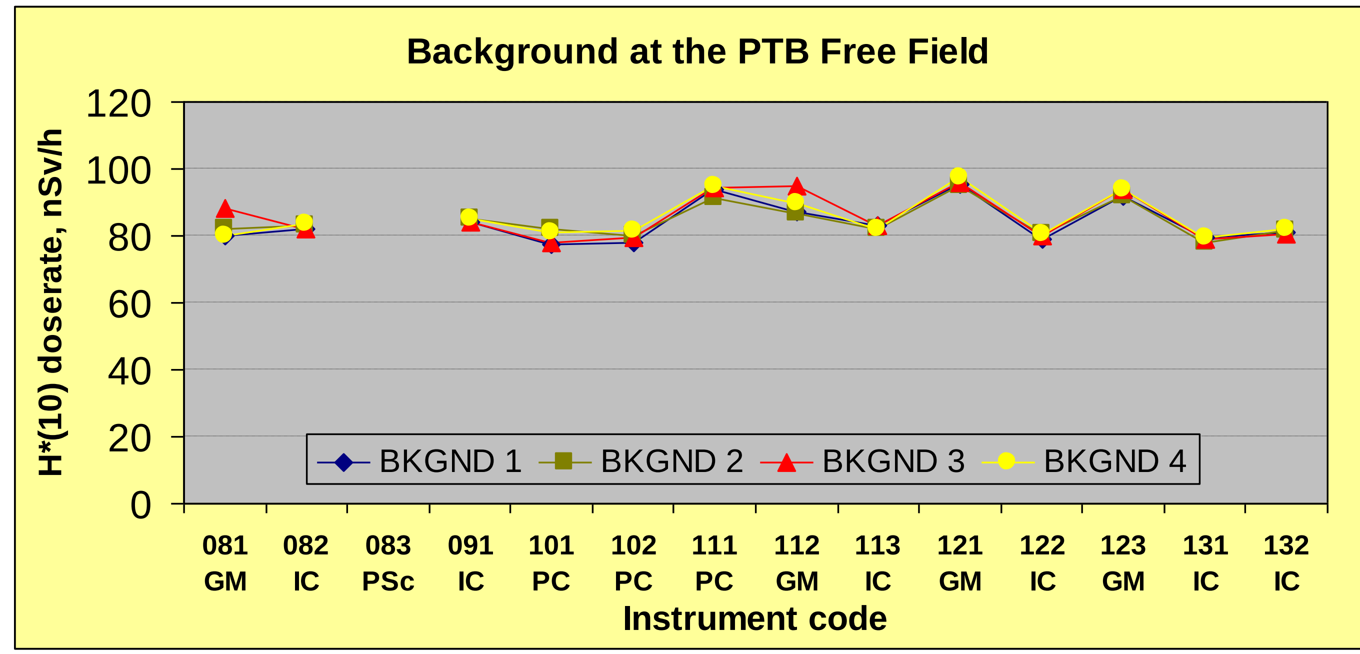
5) The instrument response is $R_H = 1/N_H = H_{source} / H_{ref}$

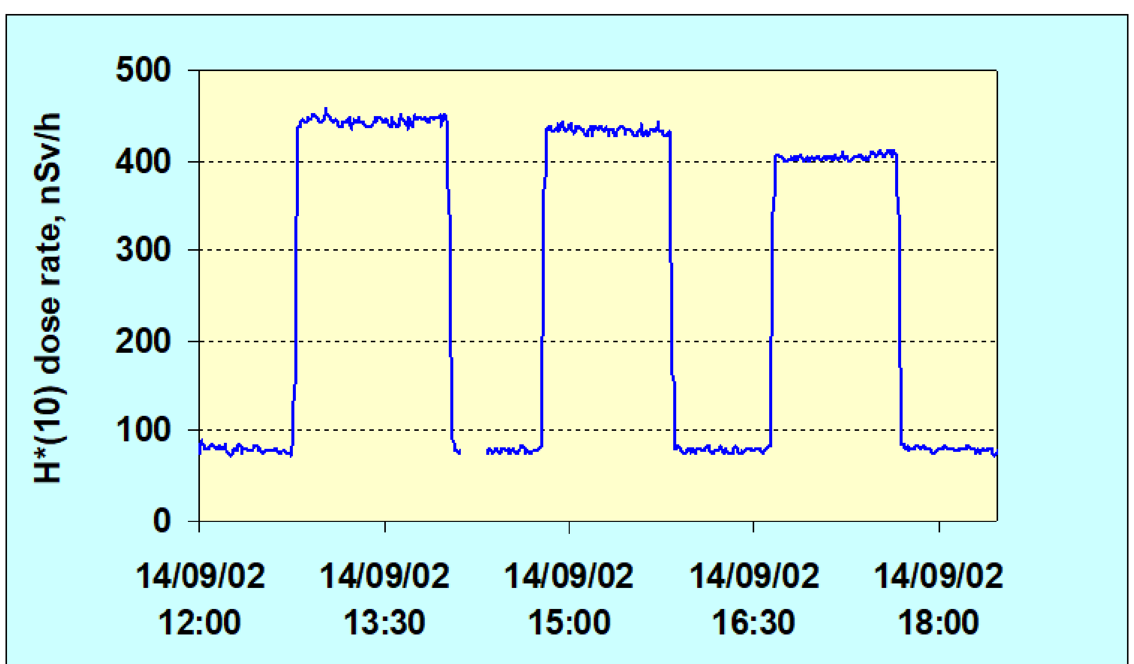


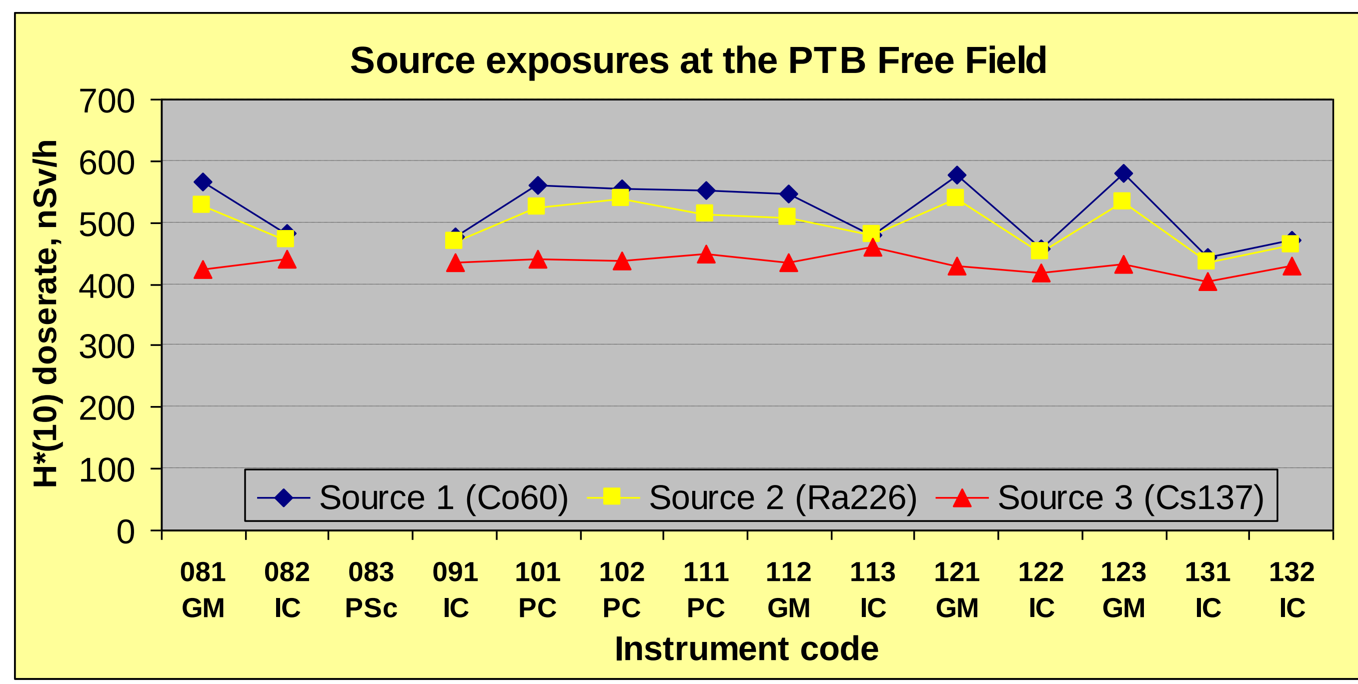


Calibration of ambient dose rate monitors: Free field method









Calibration of ambient dose rate monitors: Shadow-shield method

1) The instrument is exposed to a known H_{ref} from a certified radioactive point source:

$$H_{Source} = H_{Primary} + H_{Build\ in\ air} + H_{Ground\ albedo} + H_{Ambient\ dose}$$

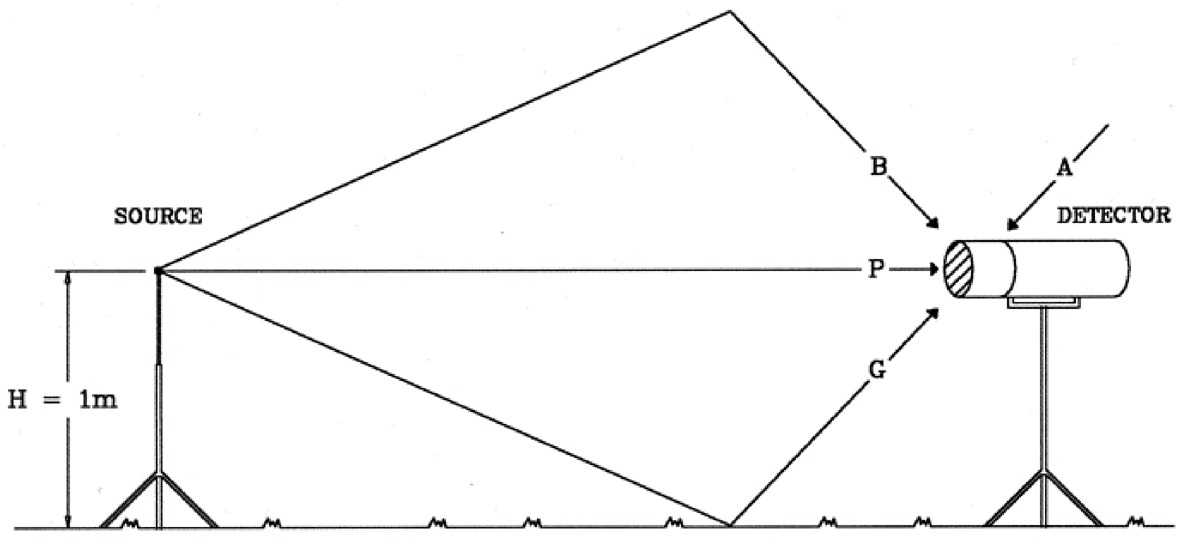
2) An adequate lead shield is interposed between the source and the instrument:

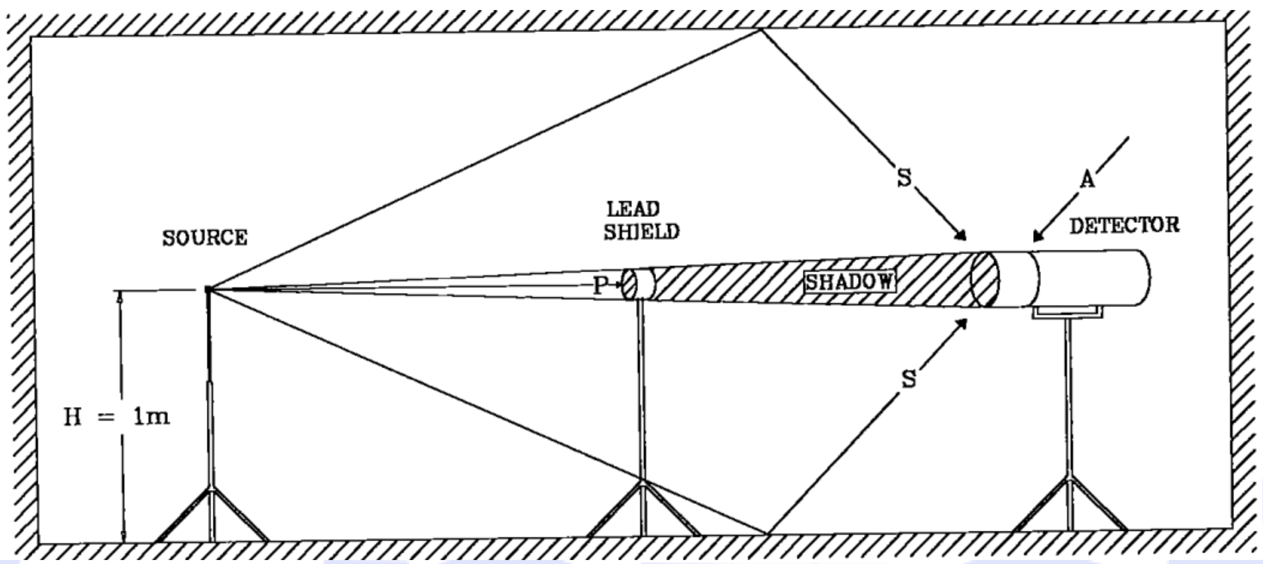
$$H_{Lead} = H_{Build\ in\ air} + H_{Ground\ albedo} + H_{Ambient\ dose}$$

3) By difference: $H_{Source} - H_{Lead} = H_{Primary}$

4) The calibration factor is: $N_H = H_{ref} / H_{source}$

5) The instrument response is $R_H = 1/N_H = H_{source} / H_{ref}$





Estimating the inherent background

1) The readings of a instrument H_{site} at any site can be expressed as:

$$H_{site} = H_{cosmic} + H_{terrestrial} + H_{artificial} + H_{inherent}$$

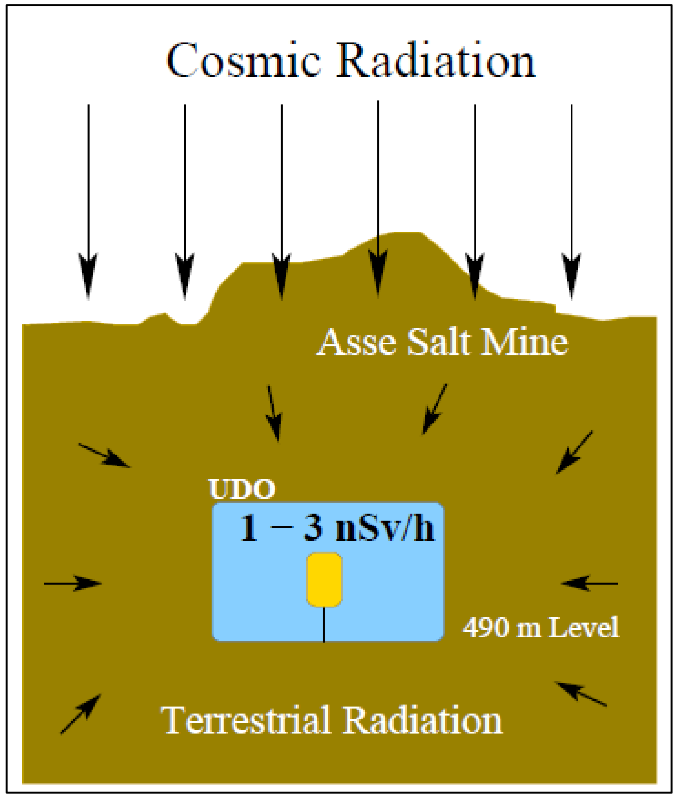
2) UDO laboratory is an underground laboratory about 500 m deep in a salt mine managed by PTB (Germany) where the activity concentration of natural nuclides are in the range of 1 Bq/kg or even lower. As consequence $H_{UDO} < 3$ nSv/h. It can be considered that there are not terrestrial neither cosmic component.

3) If background measurements are performed at UDO with the instrument:

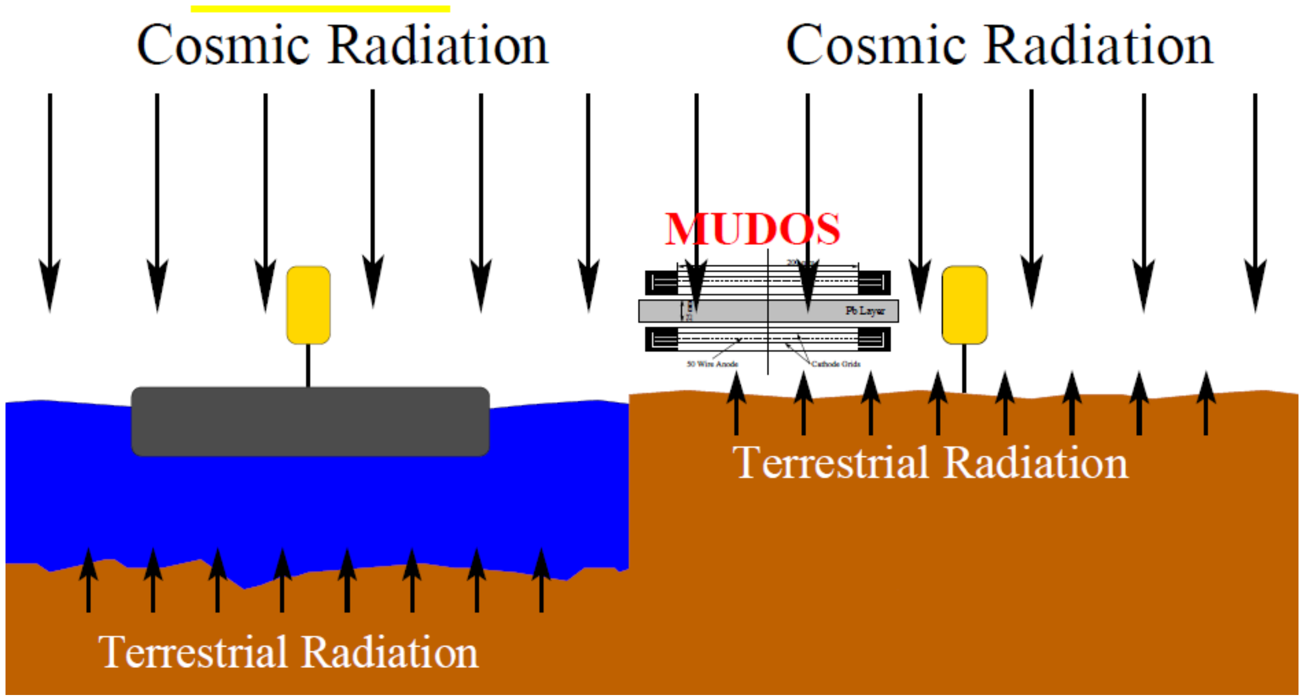
$$H_{Bkgnd} = H_{UDO} + H_{inherent}$$

3) Then $H_{inherent} = H_{Bkgnd} - H_{UDO}$

4) Most instruments have shown $H_{inherent}$<10 nSv/h, with some exceptions up to 60 nSv/h



Estimating the cosmic component



1) The readings of a instrument H_{shore} at a field site at the shore of a water facility (lake, reservoir, swimming pool, harbor, …) can be expressed as:

$$H_{shore} = H_{cosmic} + H_{terrestrial} + H_{artificial} + H_{inherent}$$

2) The instrument is then moved into a floating platform or boat into the water with at least 3-5 m depth. In these conditions $H_{terrestrial} \approx 0$ and $H_{artificial} \approx 0$:

$$H_{boat} = H_{cosmic} + H_{inherent}$$

3) Then $H_{cosmic} = H_{boat} - H_{inherent}$

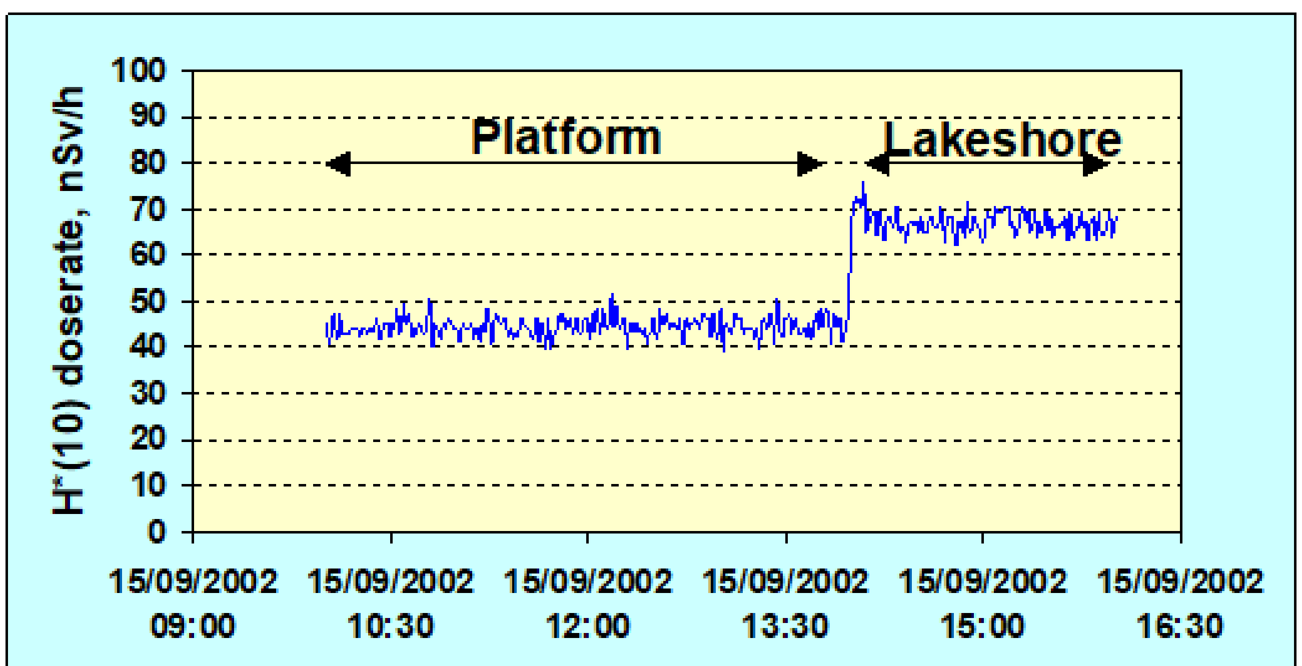
4) Reference values for cosmic component $H_{cosmic\ ref}$ can be measured with muon detectors.

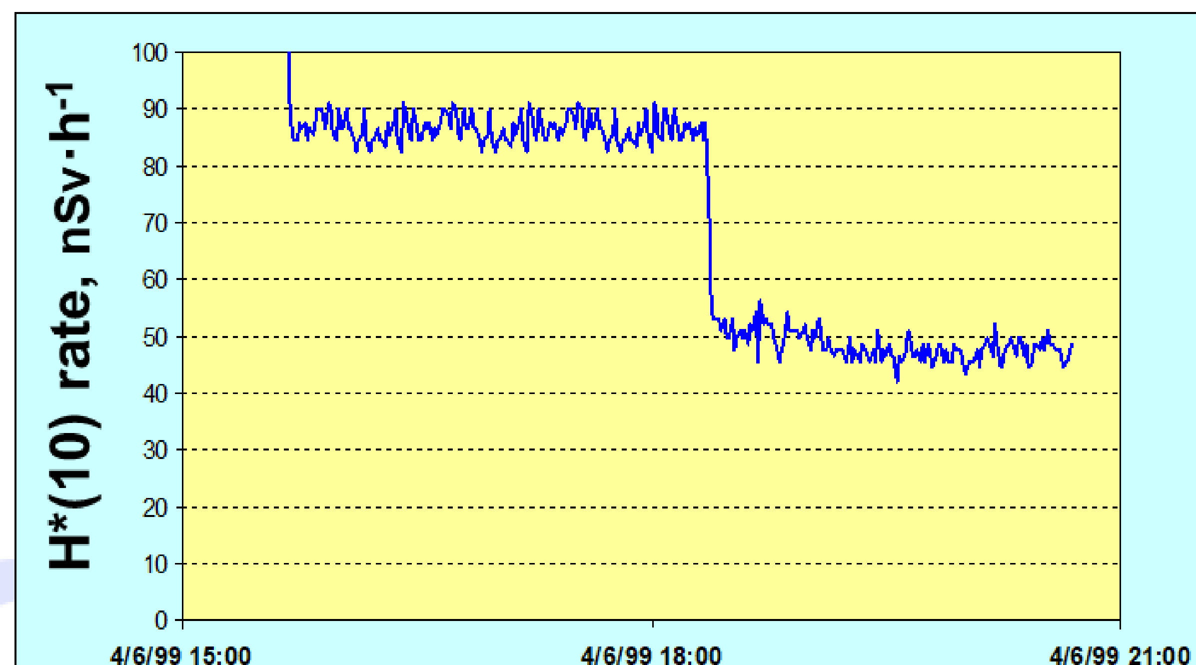
5) The instrument response is $R_{cosmic} = H_{cosmic} / H_{cosmic\ ref}$

Estimating the cosmic component

Near Braunschweig (Germany)

Cruise in Roskilde Fjord (Denmark)





In situ gamma spectrometry and ambient radiation components

Terrestrial

^{40}K: 1460 keV

^{238}U Series:

- ^{234}Th: 93 keV
- $^{234}Pa(m)$: 1001 keV
- ^{226}Ra: 186 keV
- ^{214}Pb: 295-352 keV
- ^{214}Bi: 609-1120-1765 keV

^{232}Th Series:

- ^{228}Ac: 911 keV
- ^{224}Ra: 241 keV
- ^{212}Pb: 239 keV
- ^{212}Bi: 727 keV
- ^{208}Tl: 583 - 2615 keV

^{235}U: 144-186 keV

Cosmic

Cosmogenic:

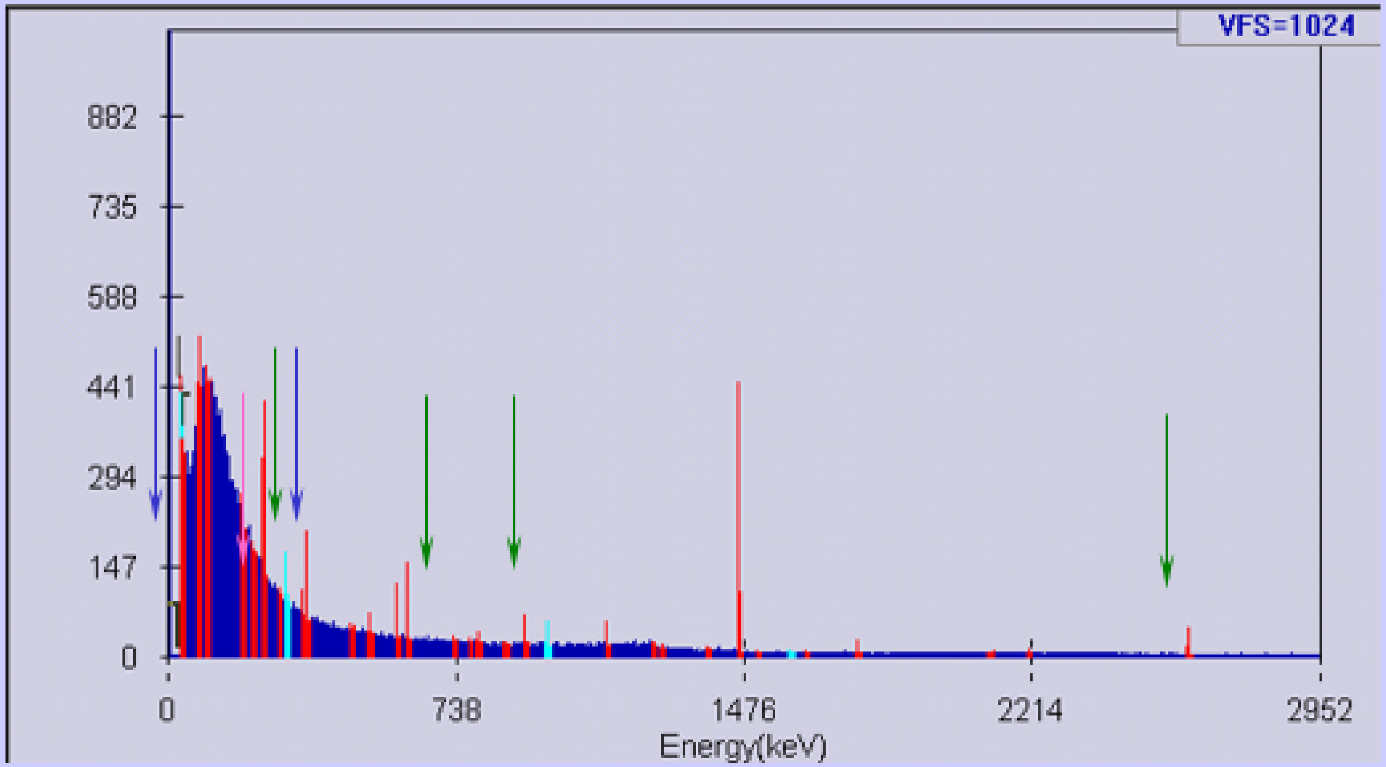
^{7}Be: 478 keV

Continuous BKGND above 2.6 MeV

Man-made

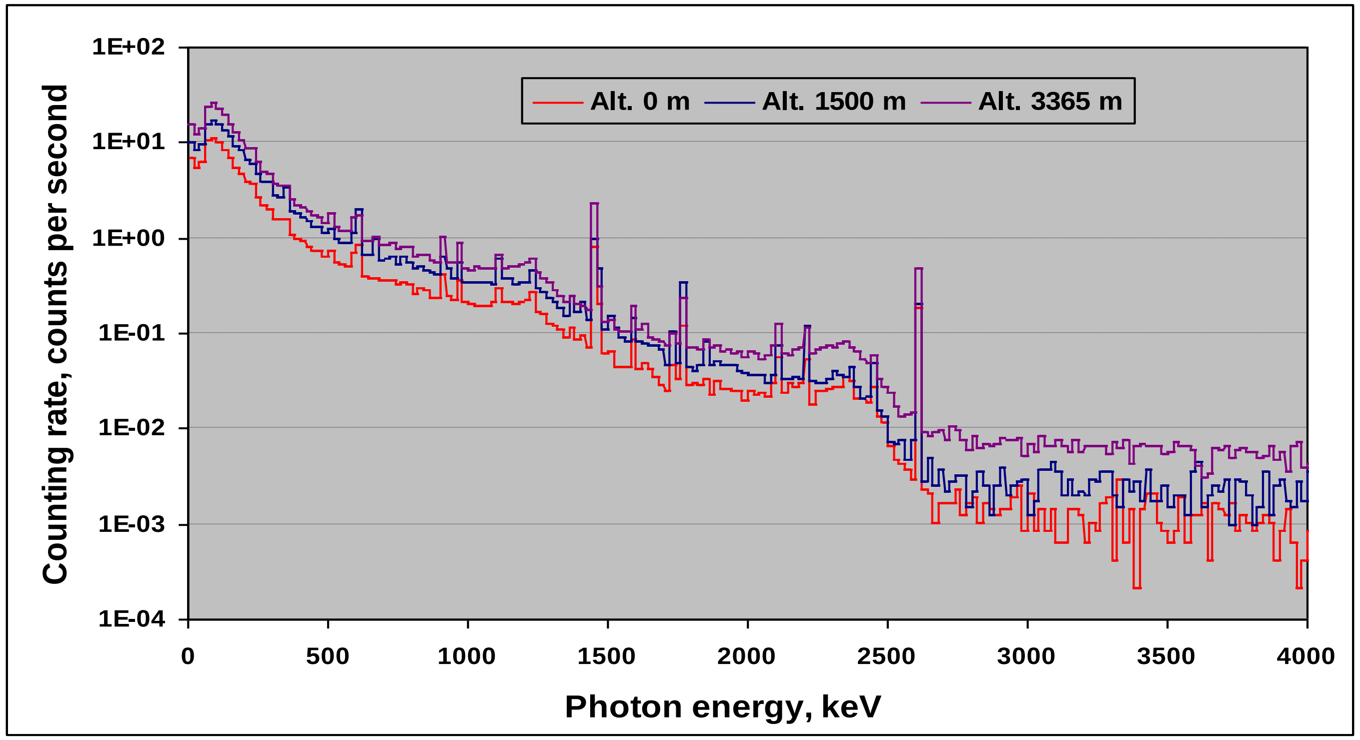
^{137}Cs, ^{134}Cs, ^{125}Sb

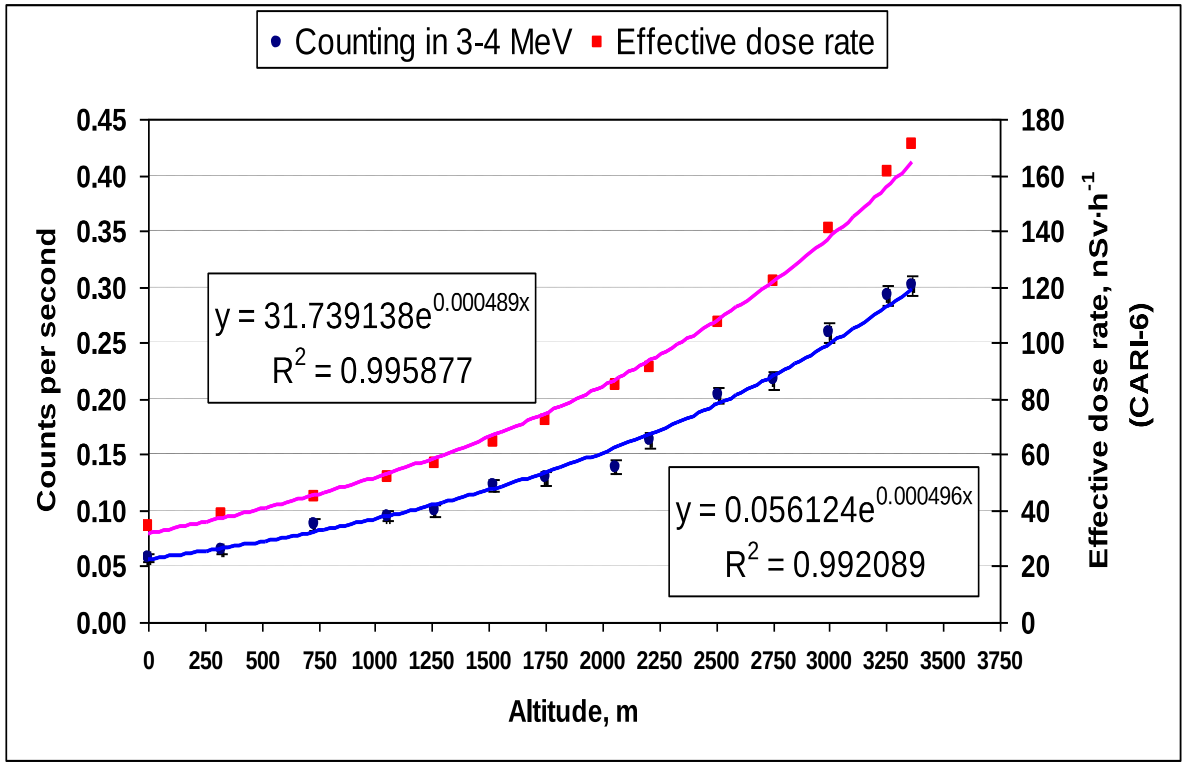
^{60}Co, ^{241}Am, ...

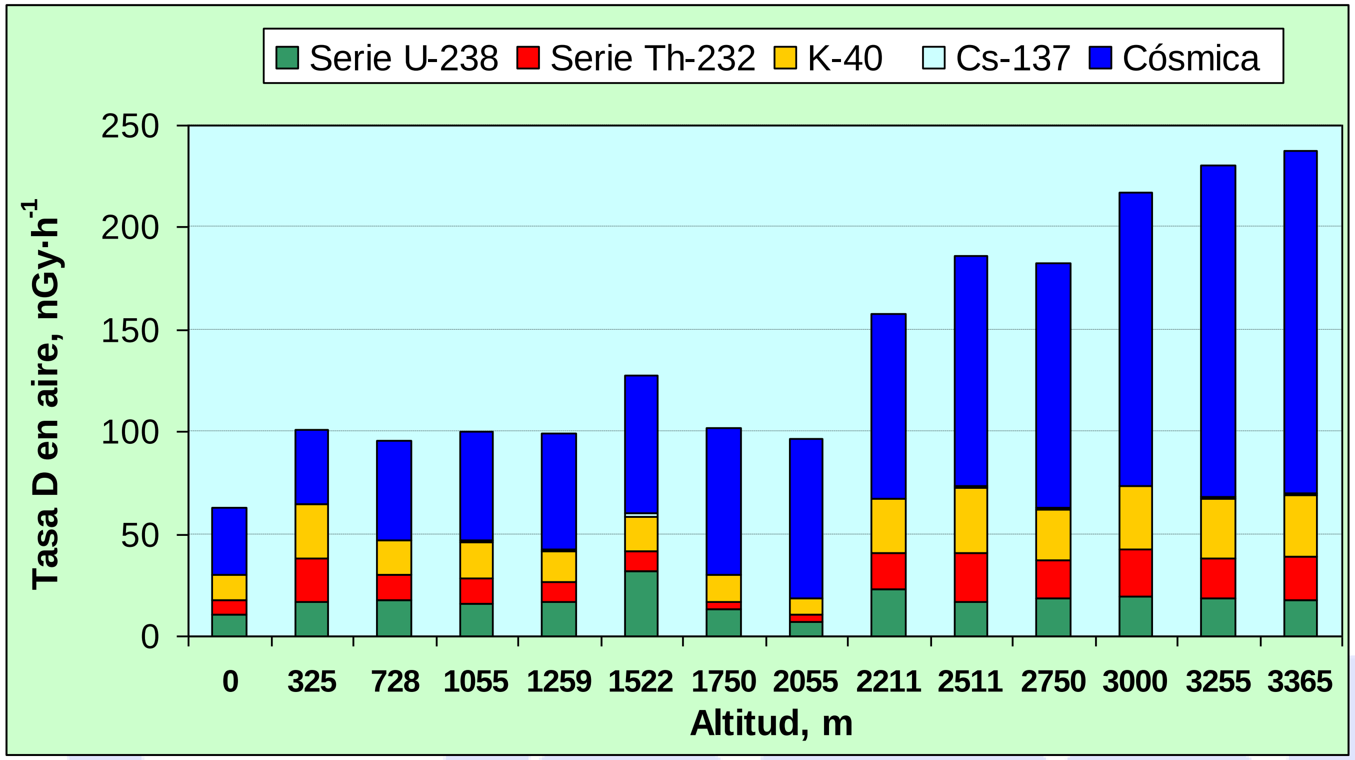


Uncollided flux: scattered radiation

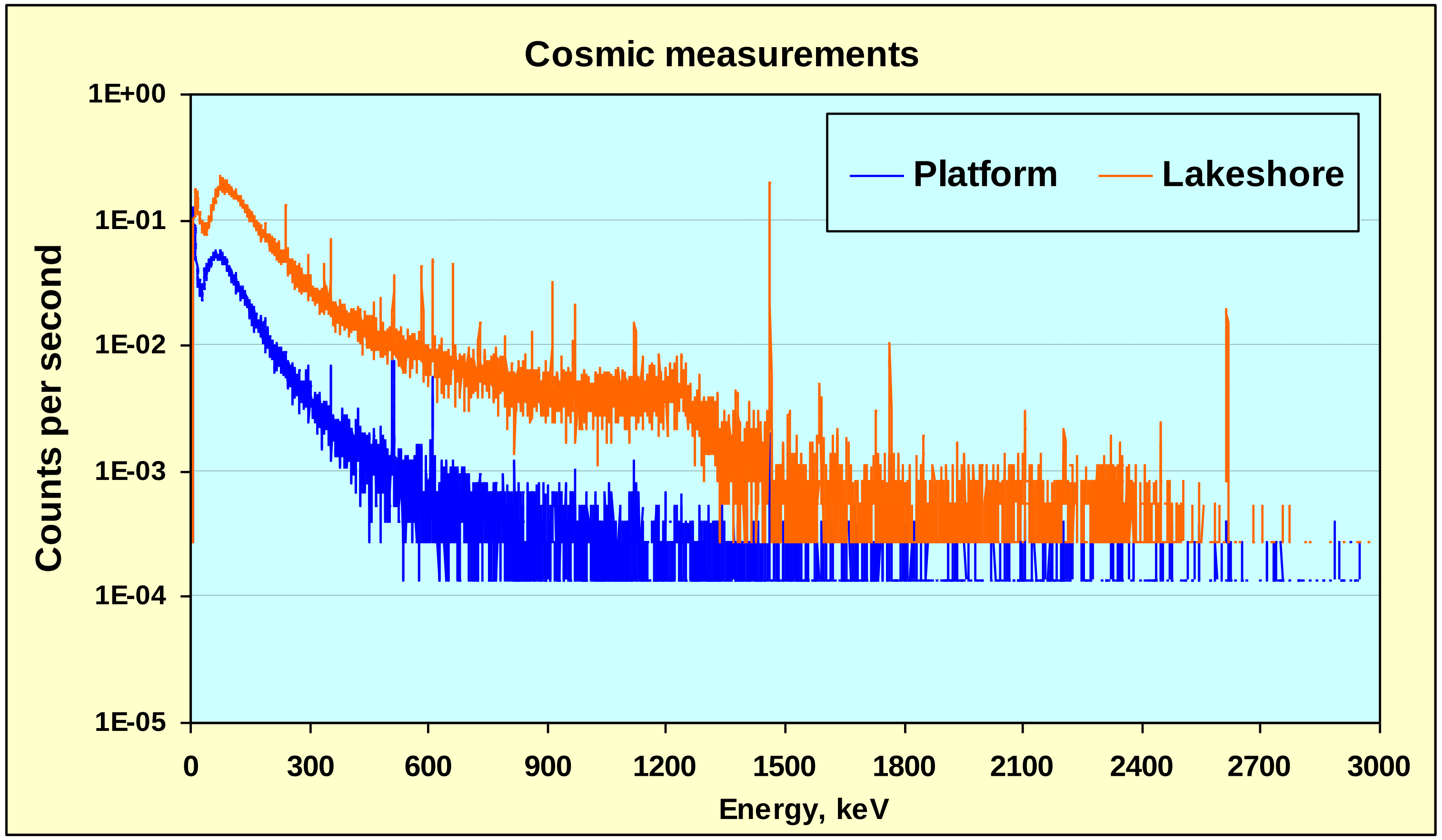
A method to estimate the cosmic component using in situ gamma spectrometry

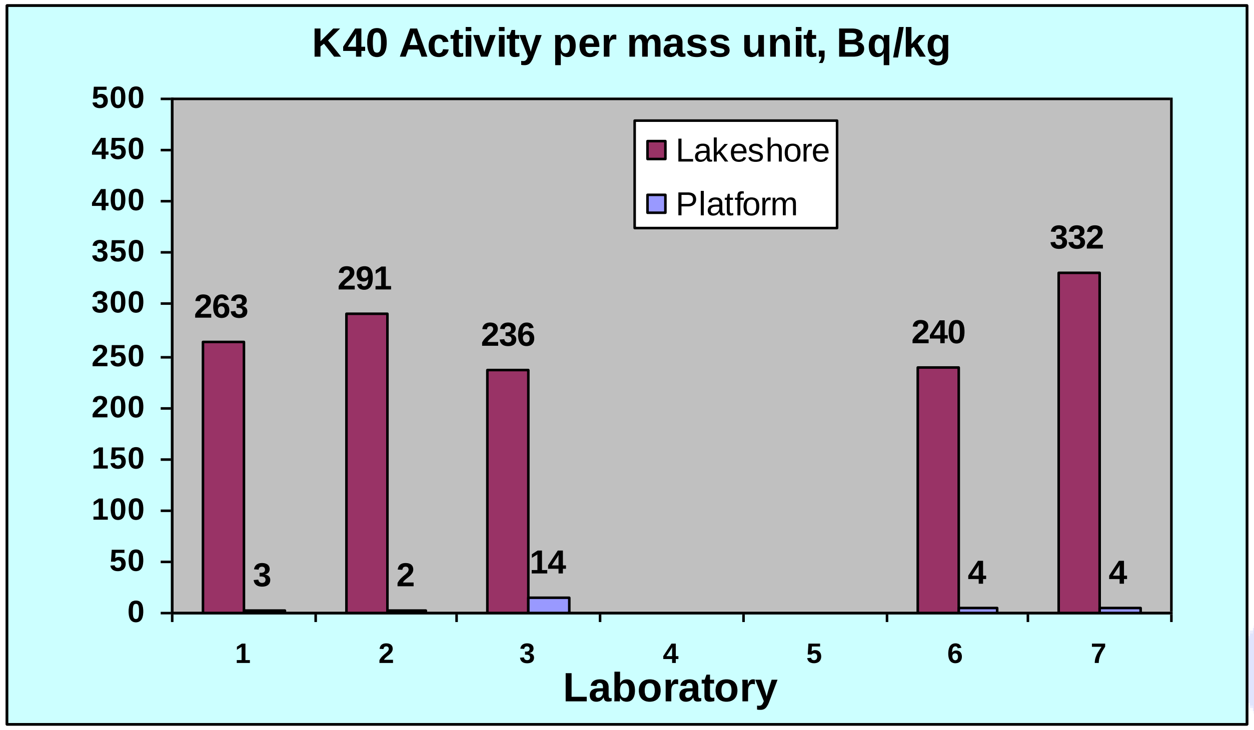


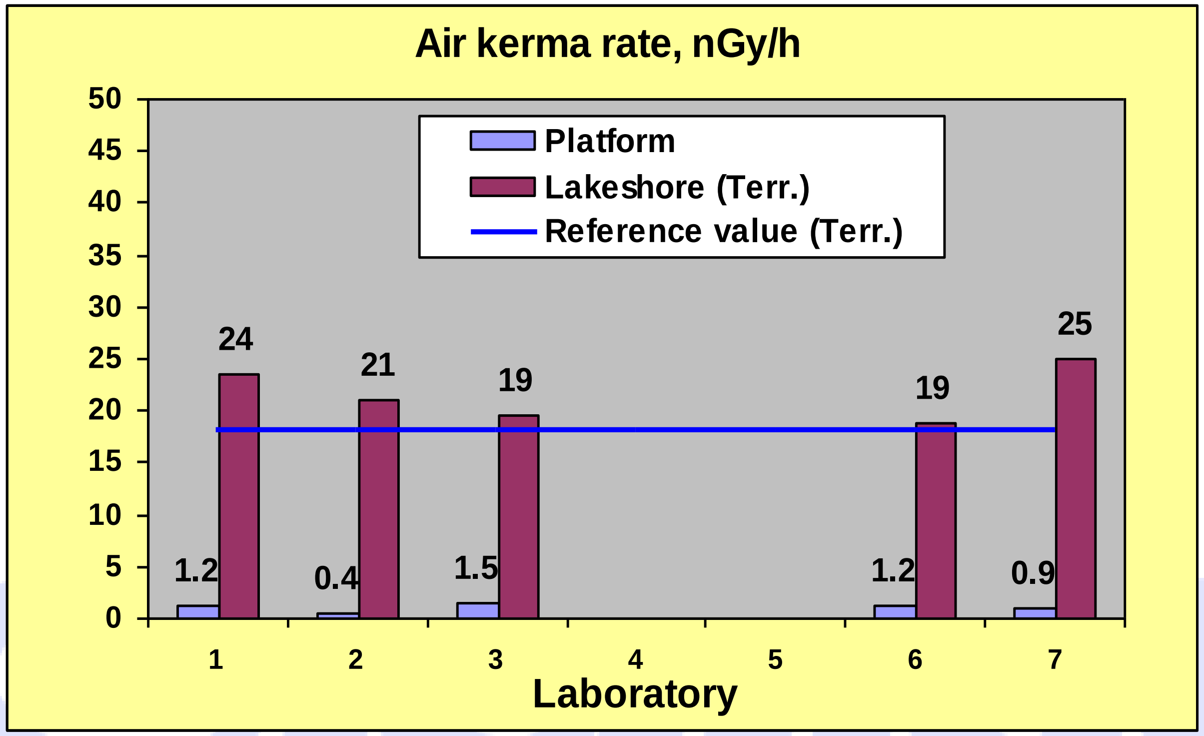




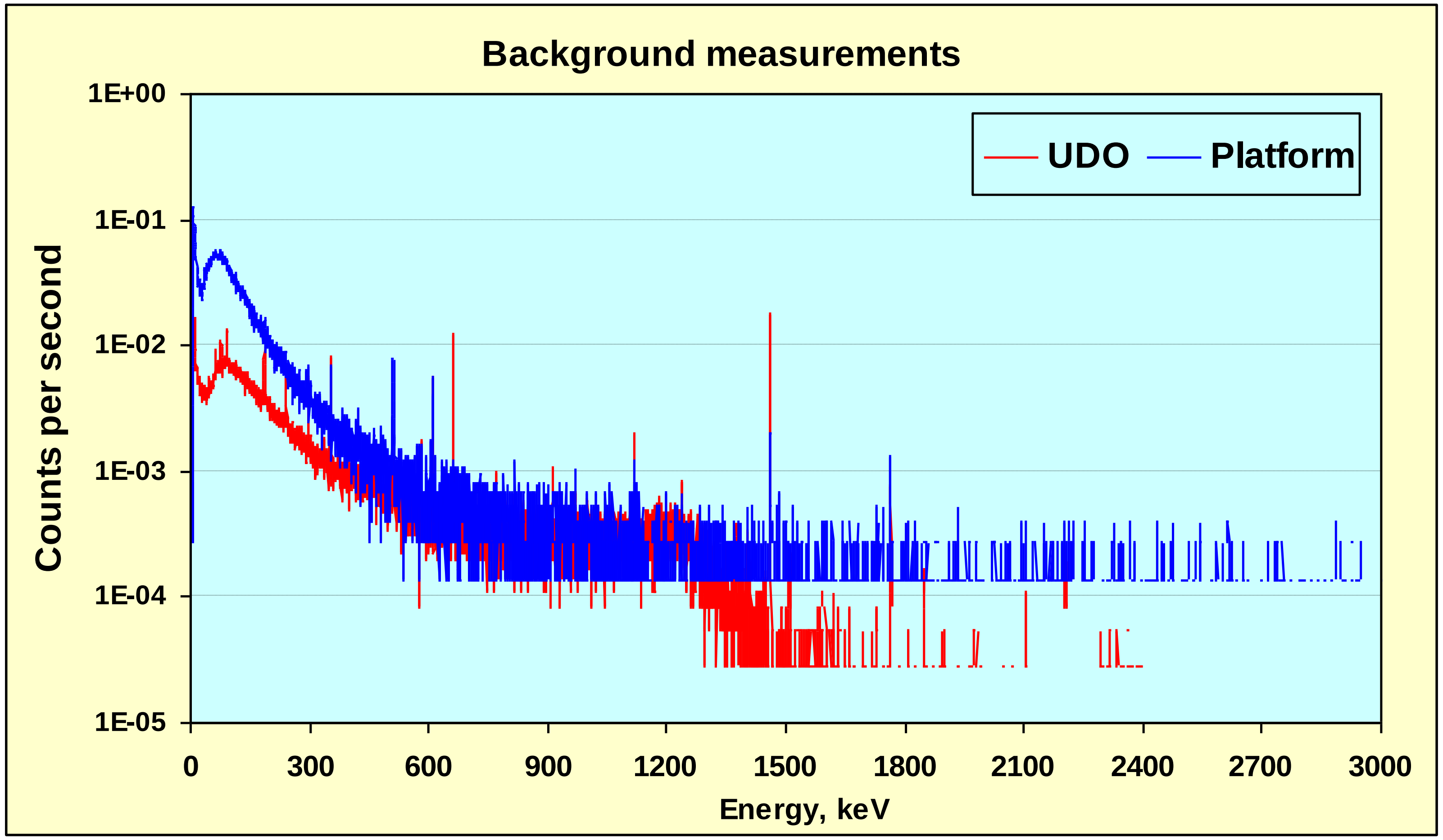
In situ gamma spectrometry in the water platform for cosmic radiation estimate

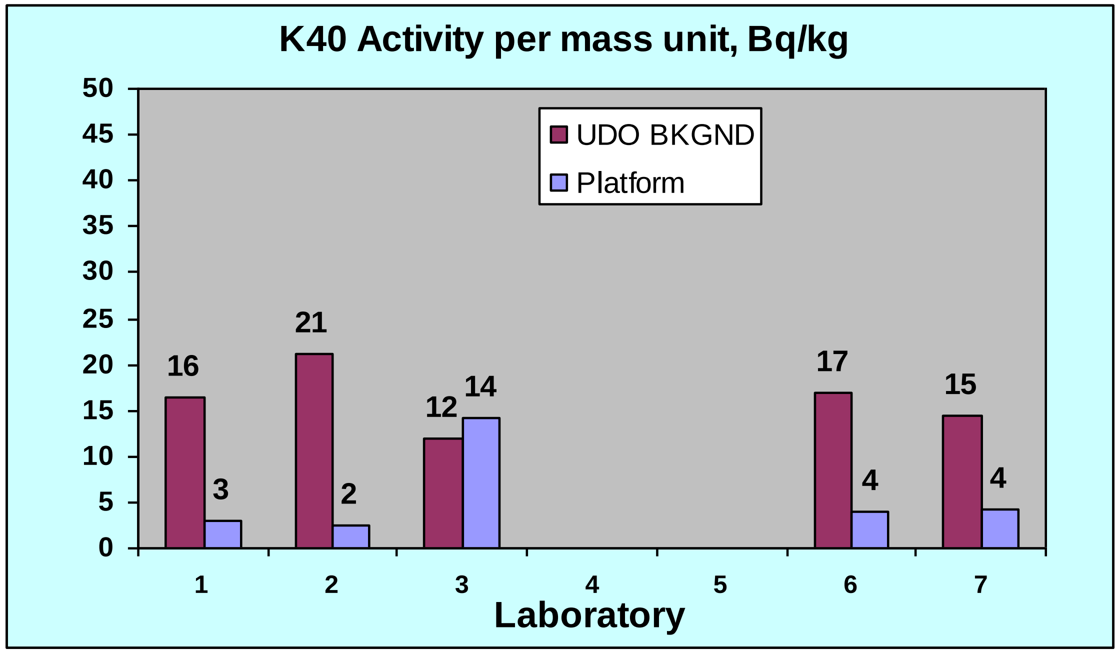


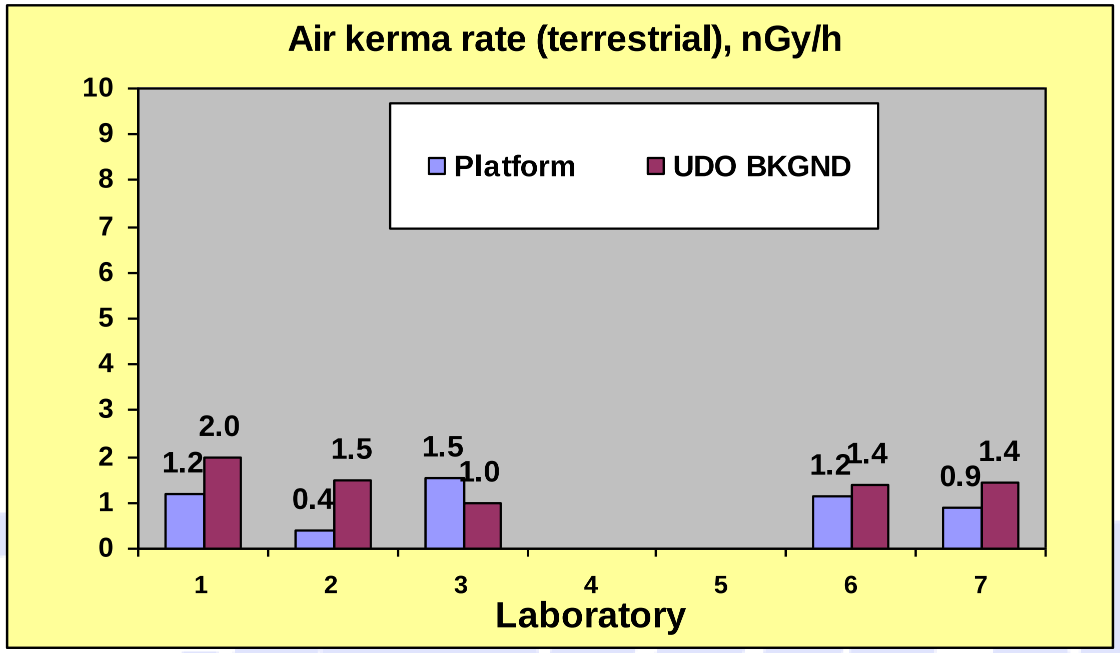




In situ gamma spectrometry comparing the water platform and UDO background







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Thanks for
your attention