University of Ferrara
PhD in Physics – XXXII cycle

Exploring lower atmosphere and topsoil with gamma-ray spectroscopy

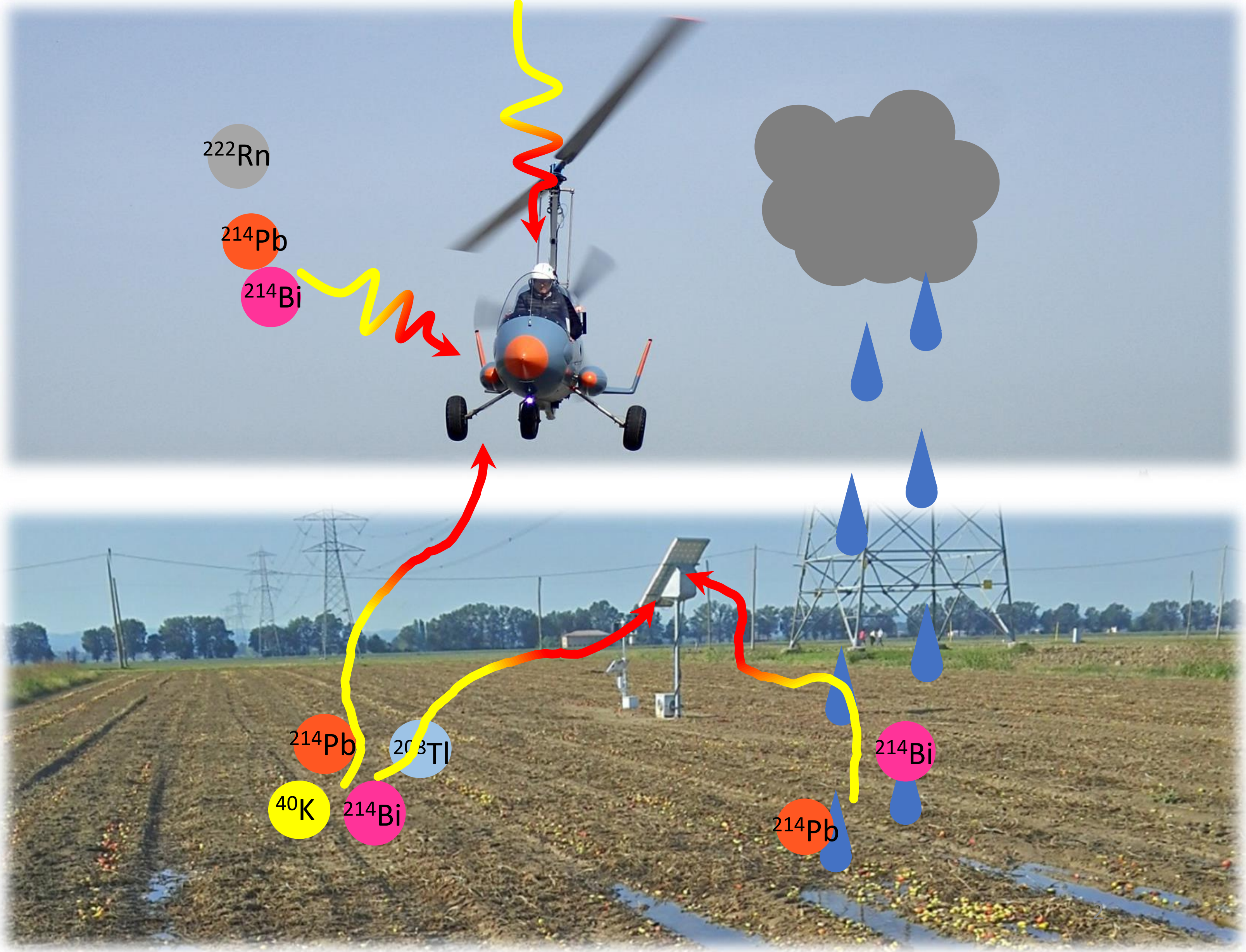
Carlo Bottardi

Ferrara, 16 March 2020

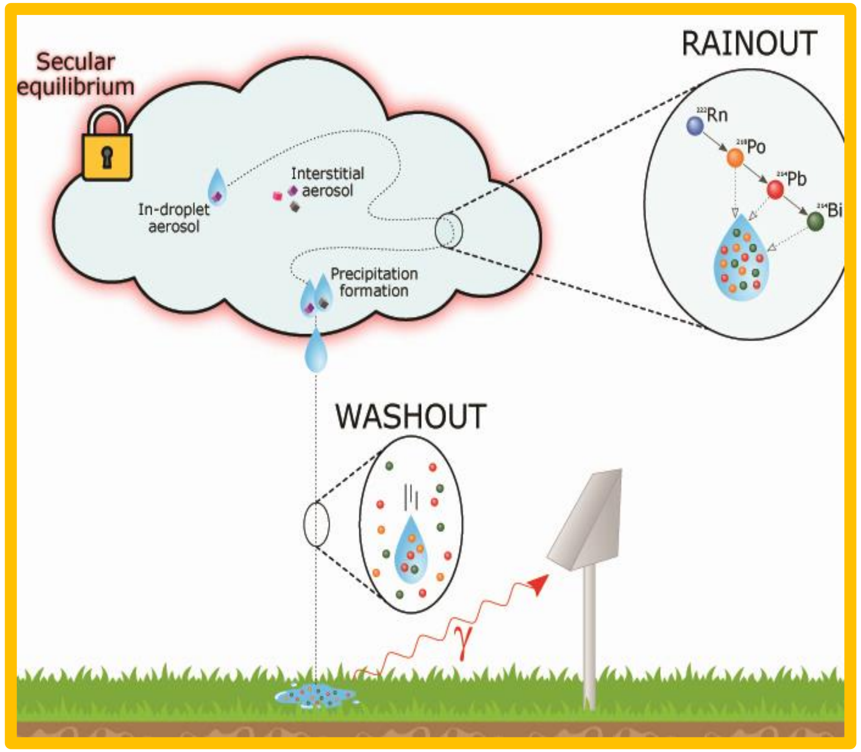
Supervisor: Prof. Fabio Mantovani

Outline

- Studying radon in lower atmosphere with airborne gamma-ray spectroscopy
- From the atmosphere to the soil: ^{214}Pb rain-induced gamma activity
- Gamma-ray spectroscopy in the framework of precision agriculture and soil water content
- Main goals reached in my PhD



Scientific motivations of my PhD: gamma spectroscopy for studying…



1) Radon in lower atmosphere because:

- ^{222}Rn is a proxy for air pollution;
- ^{222}Rn is a tracer for the study of the diurnal mixed layer;
- it's possible to measure concentrations ~ 1 Bq/m^3 in real time.

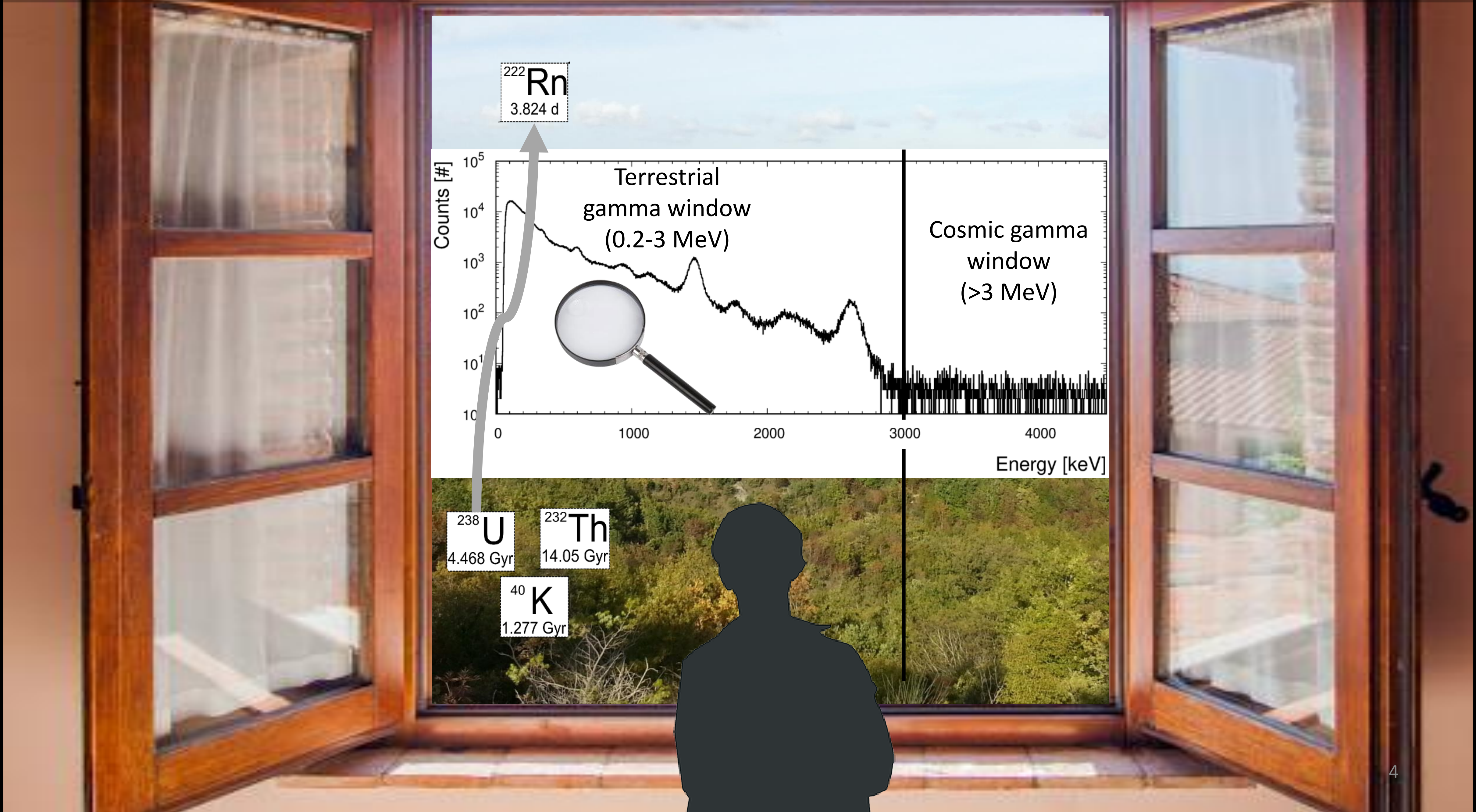
2) Rain-induced gamma activity because:

- represents a background for in-situ non-stop monitoring detector;
- has a radiological impact to human population;
- it's a tracer to study aerosol wet scavenging processes.

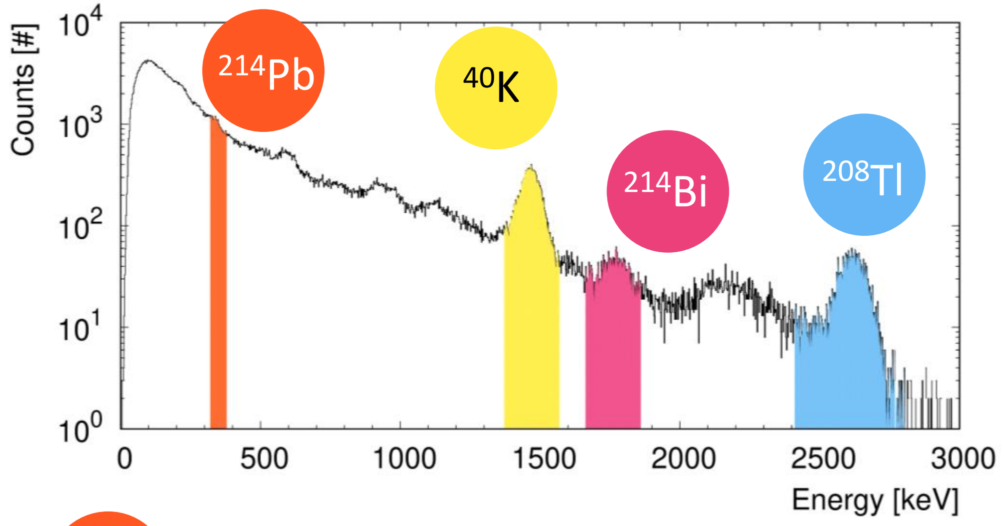
3) Soil water content for precision agriculture because:

- its measurement extends in an area comparable to satellites' resolution;
- gives real-time, non disruptive and automatics measurements;
- can improve the irrigation planning.

Observing the natural radioactivity with gamma-ray spectroscopy



Notable gamma emitters of terrestrial radioisotopes (^{238}U, ^{232}Th, ^{40}K)

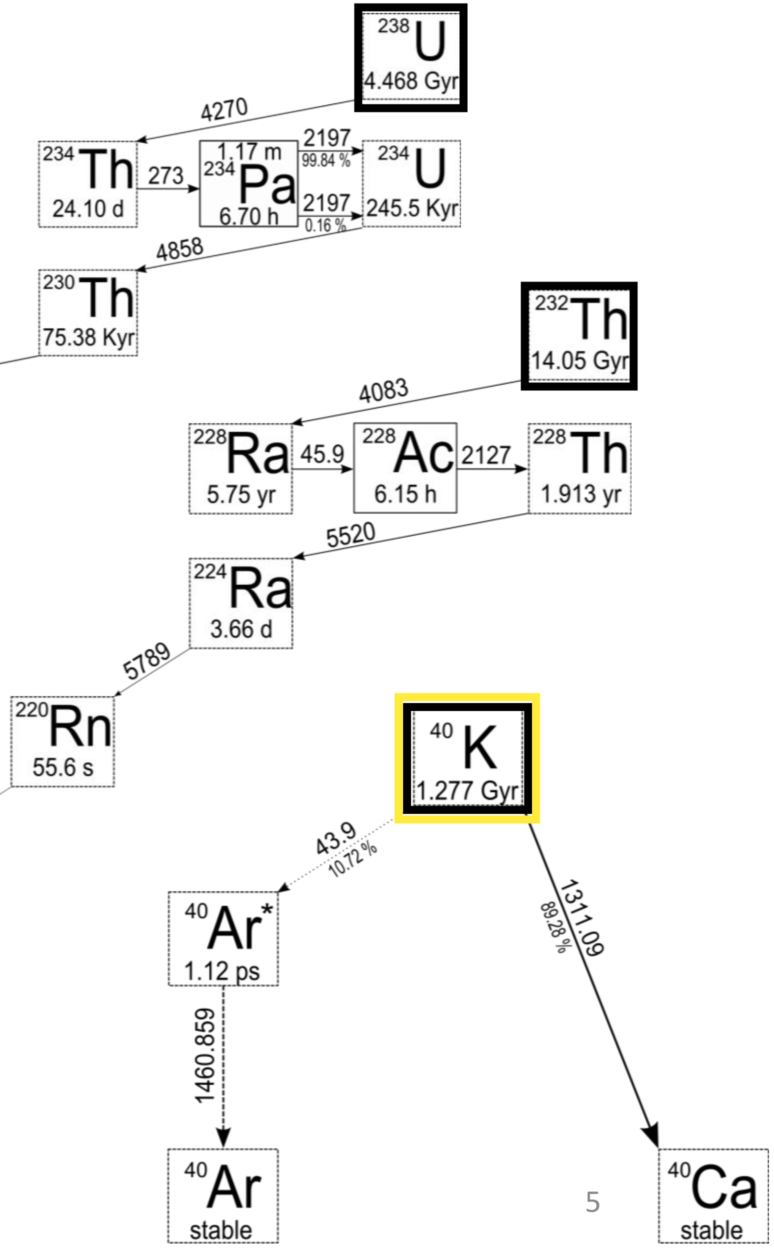
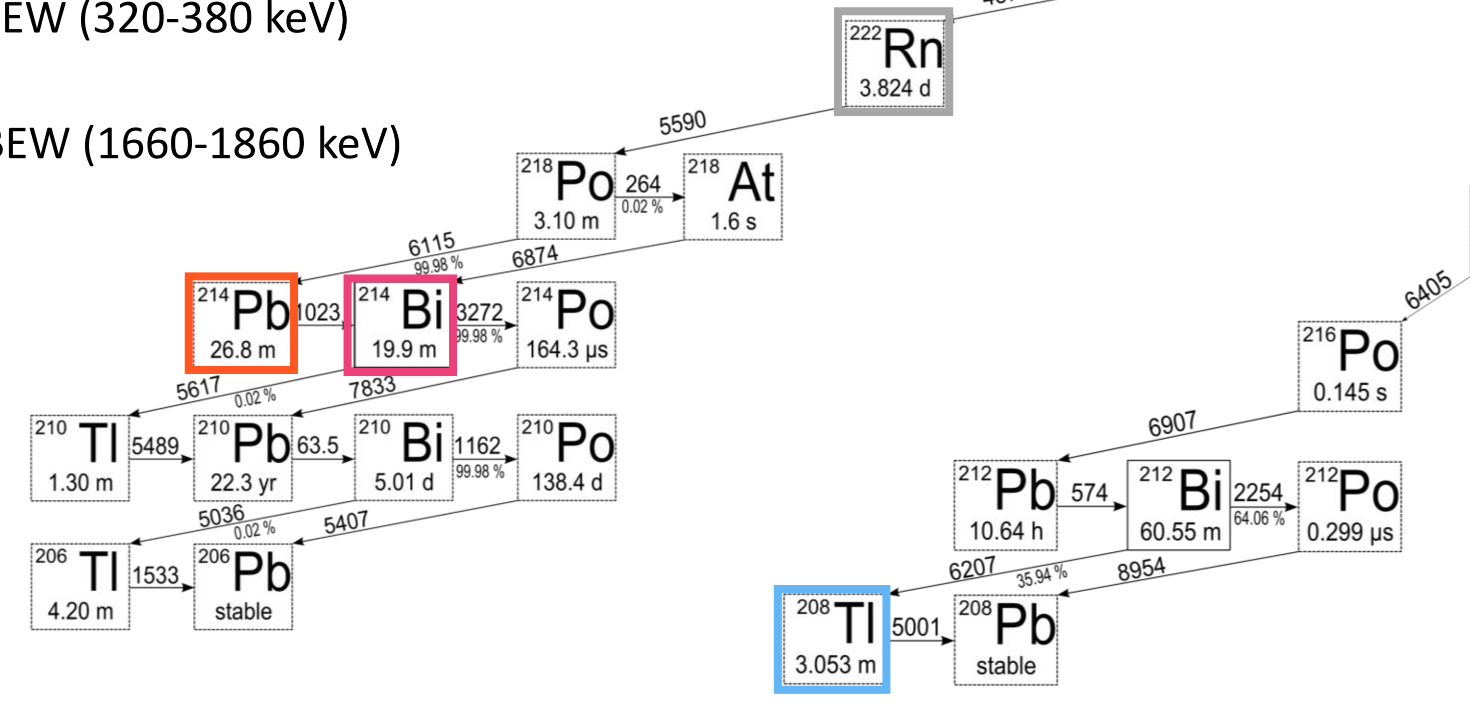


^{208}Tl → 2410-2810 keV

^{40}K → 1370-1570 keV

^{214}Pb → PEW (320-380 keV)

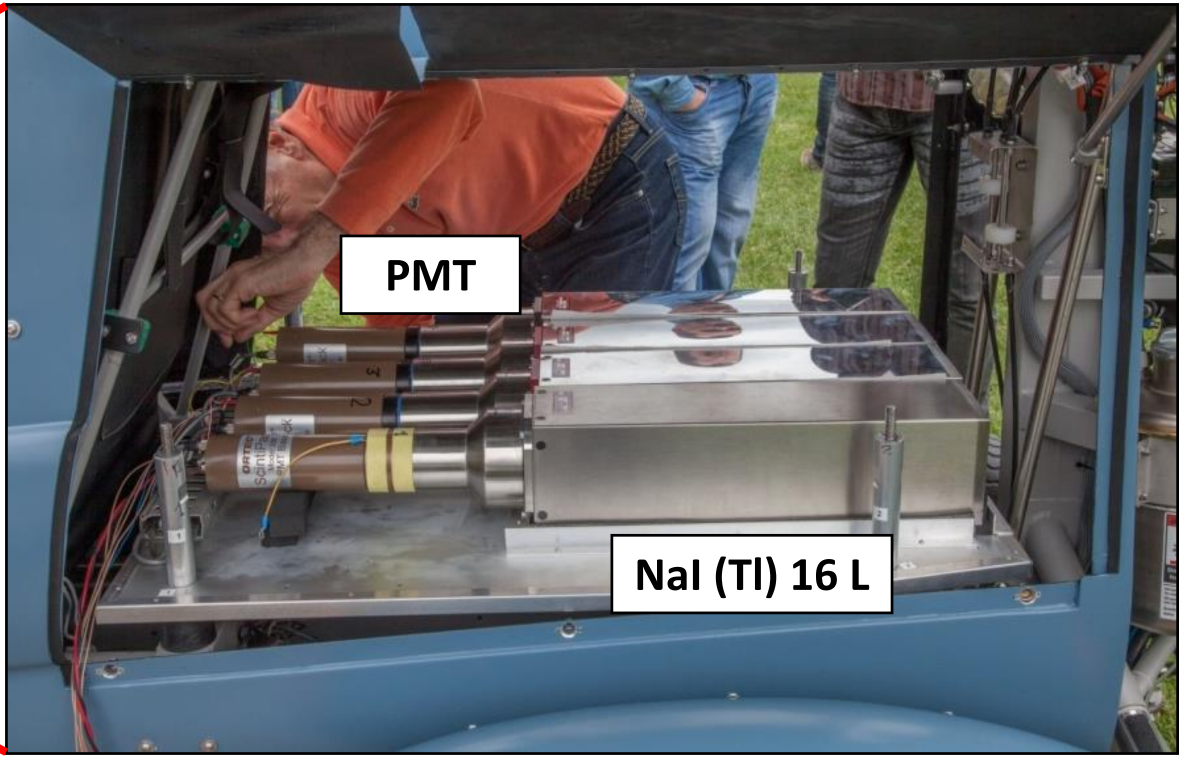
^{214}Bi → BEW (1660-1860 keV)

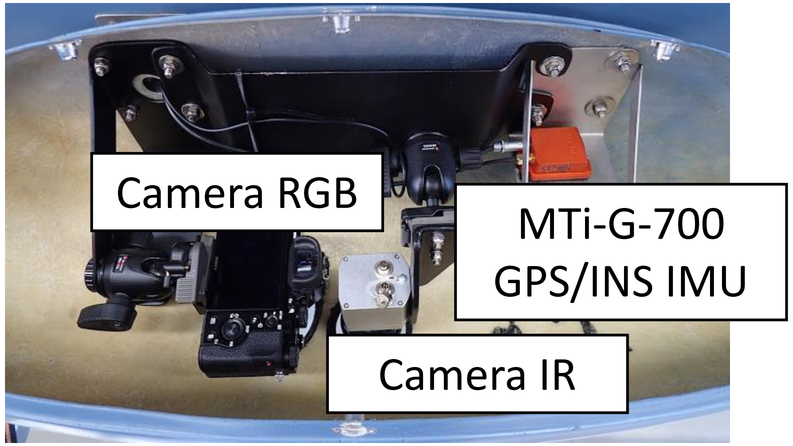



Gamma ray spectroscopy is like a window on the world
…for observing radon in the air!

Instrumentation for Airborne Gamma-Ray Spectroscopy (AGRS)

Radgyro: the experimental autogyro devoted to airborne multiparametric measurements



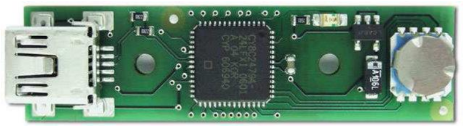


Other equipment:

3 GNSS single freq. EVK-6 u-blox + GPS ANN-MS act. antenna

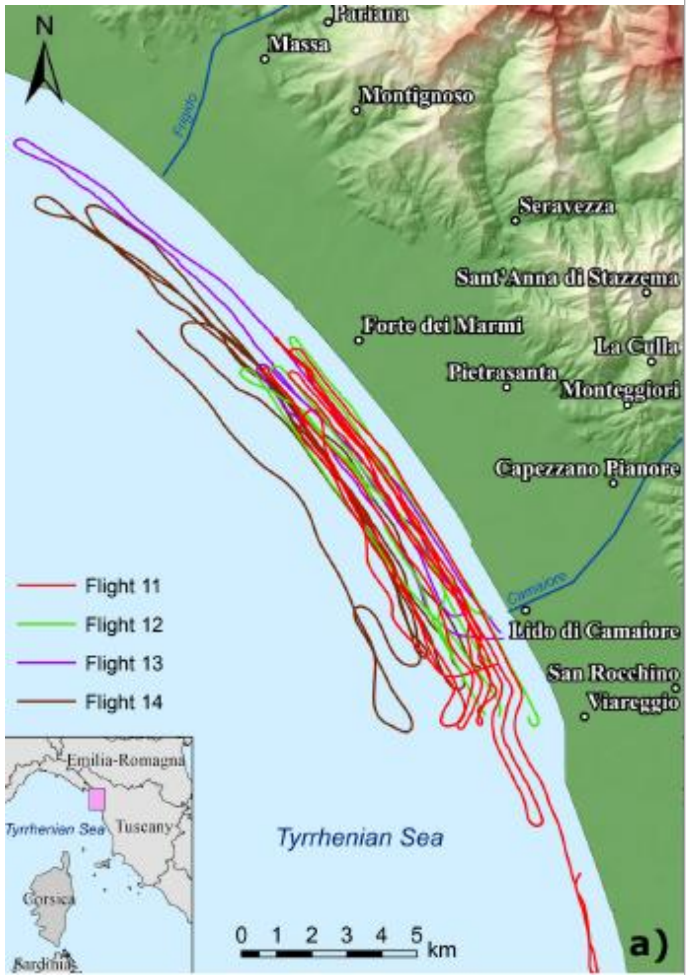
Micro Radar Altimeter

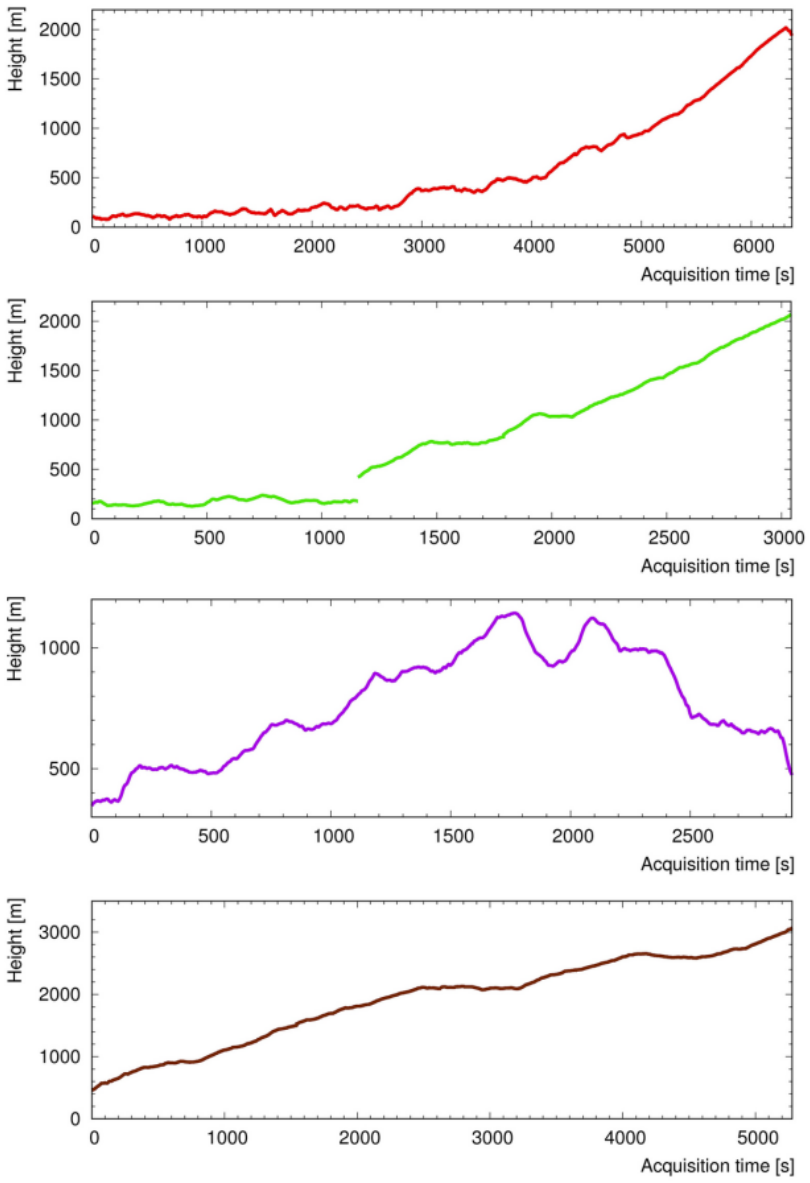
USB Sensor Atmospheric Pressure



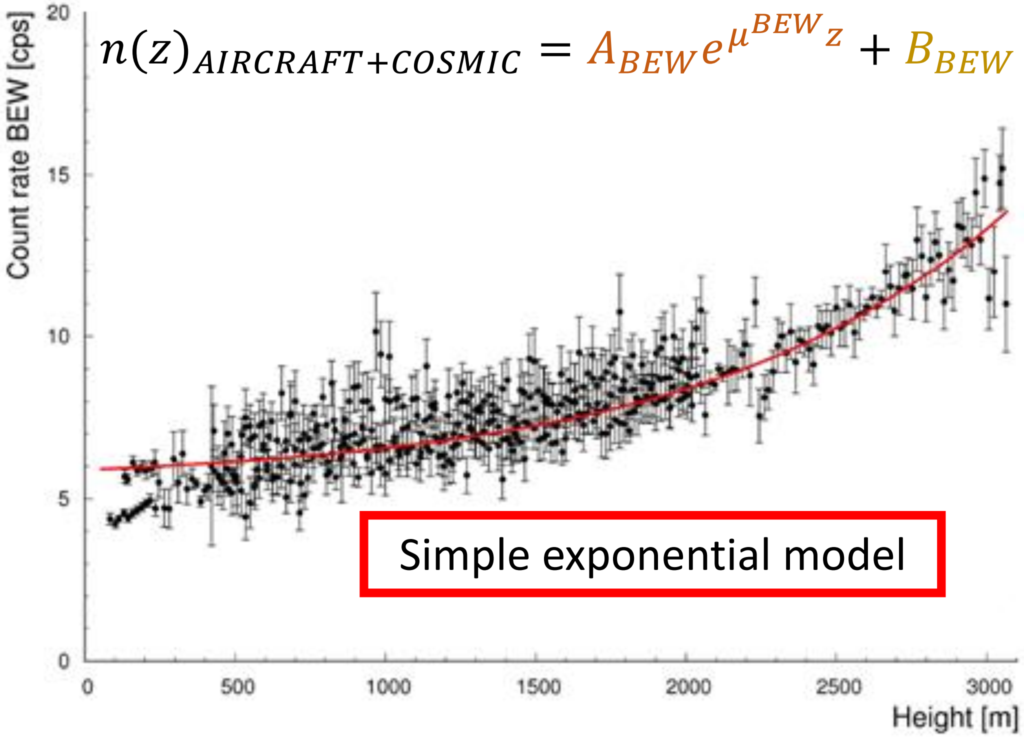
Radioactivity during specific surveys over the sea

~ 5 hours of total data acquisition within altitude range of **77 - 3066 m**





$$n(z)_{AIRCRAFT+COSMIC} = A_{BEW}e^{\mu^{BEW}z} + B_{BEW}$$



I expect the radioactivity in the region BEW is represented by the cosmic rays $A_{BEW}e^{\mu^{BEW}z}$ (exponentially increasing with height) and the intrinsic radioactivity of the aircraft B_{BEW} (constant).

BUT I need to take into account the atmospheric radon (^{222}Rn). NEW

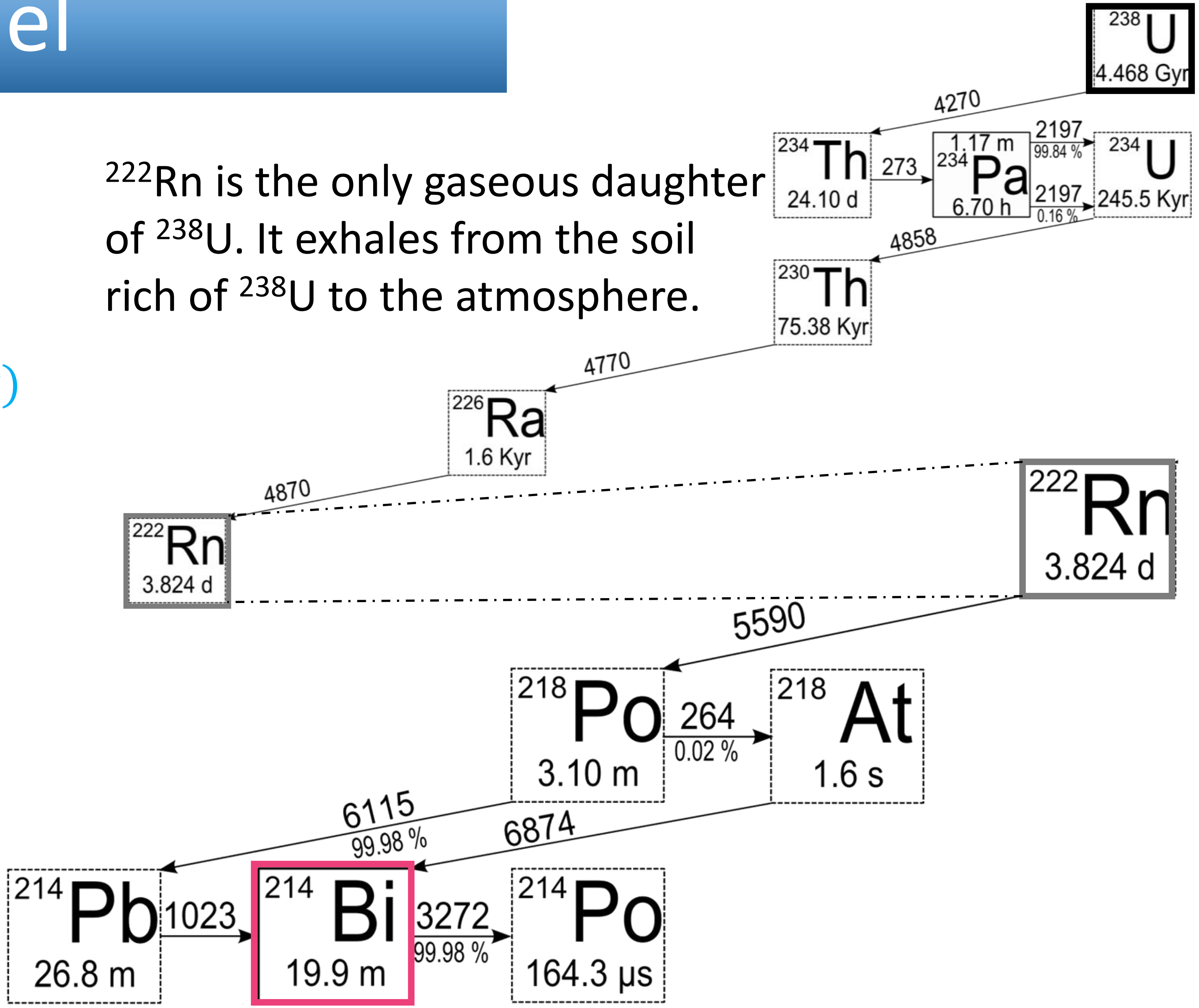
A new model

- In presence of ^{222}Rn and therefore ^{214}Bi the **count rate in ^{214}Bi energy window has a new altitude dependent component:**

$$n_{BEW}(z) = A_{BEW} e^{\mu^{BEW} z} + B_{BEW} + n_{Rn}(z)$$

- Recent studies on ^{222}Rn suggest a sudden reduction in its concentration in air above an height of ~ **1-2 km**.

^{222}Rn is the only gaseous daughter of ^{238}U. It exhales from the soil rich of ^{238}U to the atmosphere.



A new model

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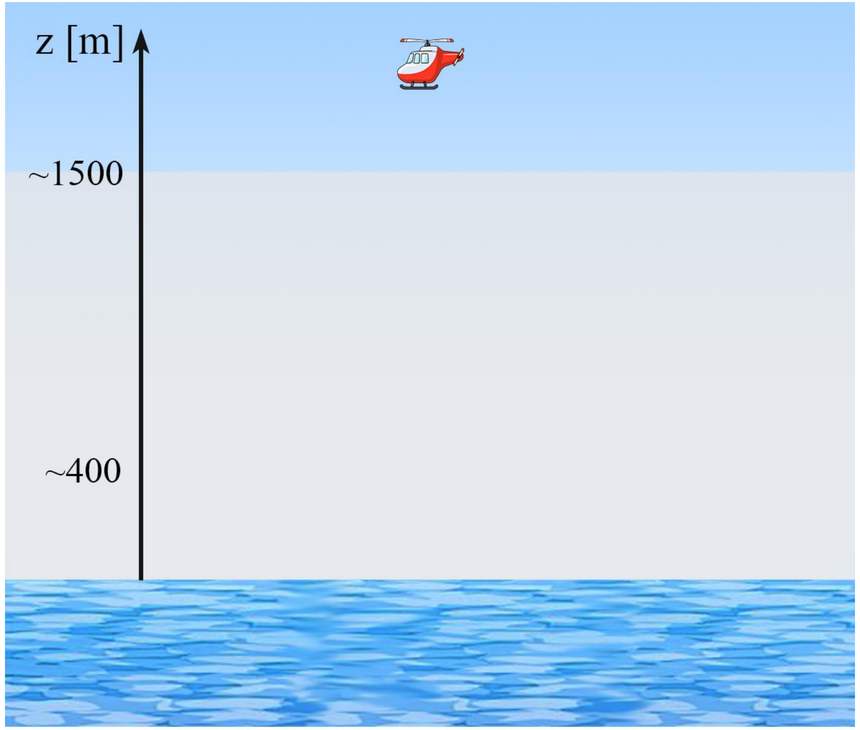
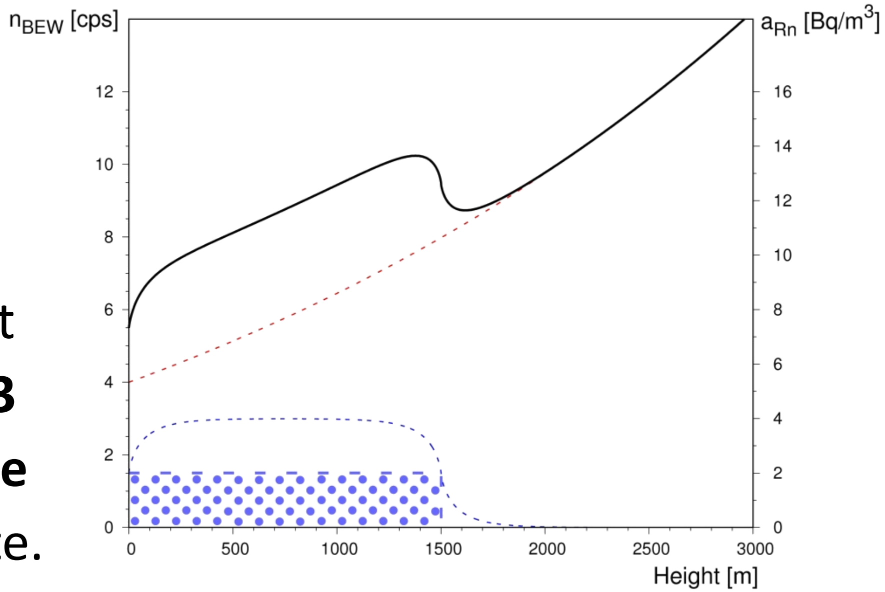
NEW

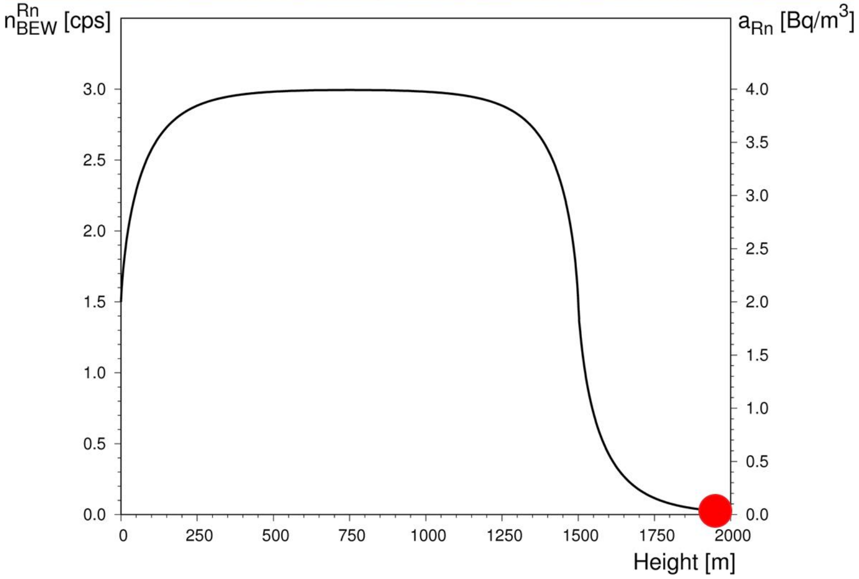
- Recent studies on ^{222}Rn suggest a sudden reduction in its concentration in air above an height of ~ **1-2 km**.

- I aimed to develop a real-time method for recognizing this ^{222}Rn boundary layer with AGRS measurements, taking into account that only a sphere of **r ~ 400 m (2.3 ^{214}Bi** unscattered photon **mean free path**) contributes to ^{214}Bi count rate.

Therefore a $n_{BEW}(z)$ as the following is expected:



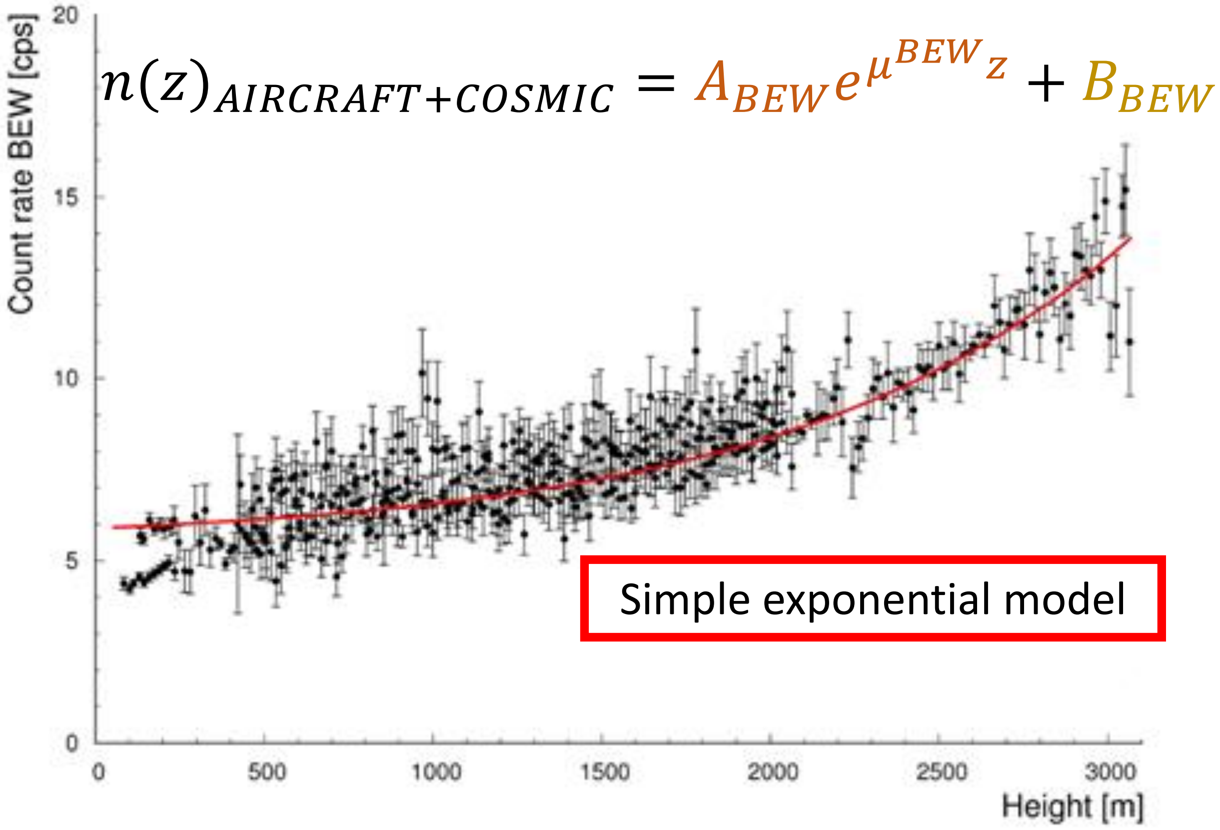




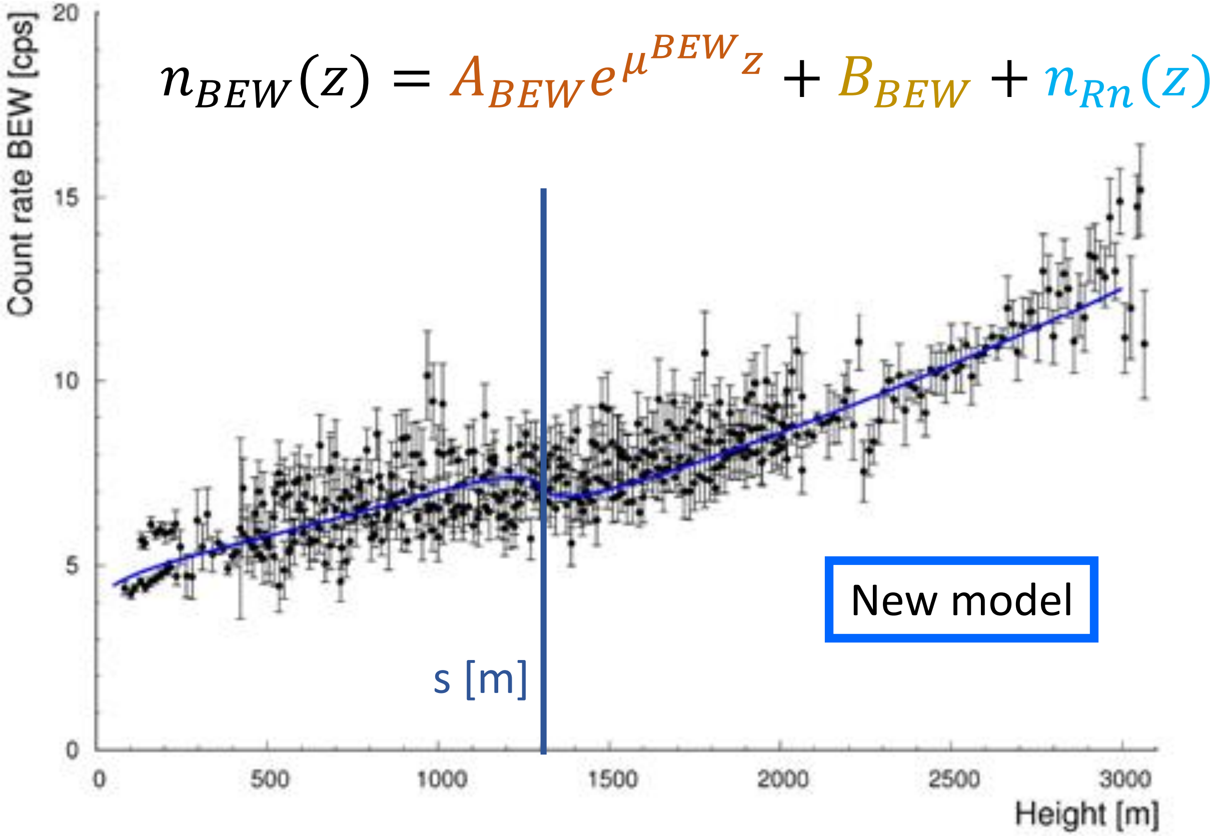
2 fits of AGRS data: a comparation

The theoretical models are applied for fitting the experimental count rate in BEW

$$n(z)_{AIRCRAFT+COSMIC} = A_{BEW} e^{\mu^{BEW} z} + B_{BEW}$$



$$n_{BEW}(z) = A_{BEW} e^{\mu^{BEW} z} + B_{BEW} + n_{Rn}(z)$$



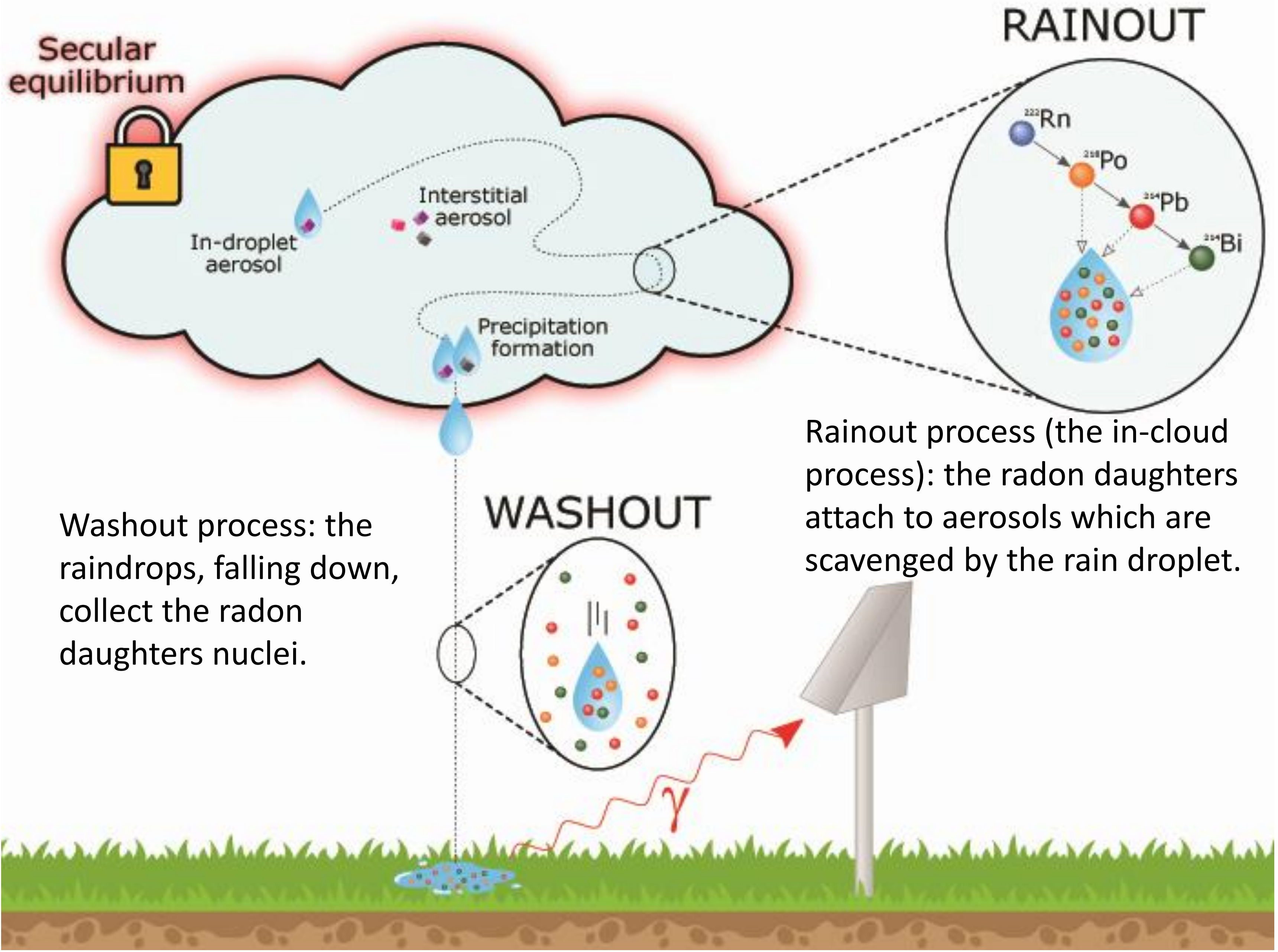
Theoretical model	$A_{BEW} \pm \delta A_{BEW}$ [cps]	$\mu_{BEW} \pm \delta\mu_{BEW}$ [m^{-1}]	$B_{BEW} \pm \delta B_{BEW}$ [cps]	$s \pm \delta s$ [m]	$C \pm \delta C$ [cps]	Reduced χ^2
S. exp. model	0.39 ± 0.07	$(2.01 \pm 0.1)\cdot 10^{-3}$	5.5 ± 0.3	/	/	5.0
New model	8.2 ± 0.2	$(2.54 \pm 0.06)\cdot 10^{-4}$	-4.9 ± 0.2	1318 ± 22	0.68 ± 0.05	2.1

Concentration of Rn=(0.96 ± 0.07) Bq/m³ distribuited up to (1318 ± 22) m

- The **new model** fits the data better than the **simple exponential model.**
- The mean ^{222}Rn concentration and ^{222}Rn boundary layer are in agreement with the literature : **a_{Rn} ~ 1 Bq/m³, s ~ 1500 m.**

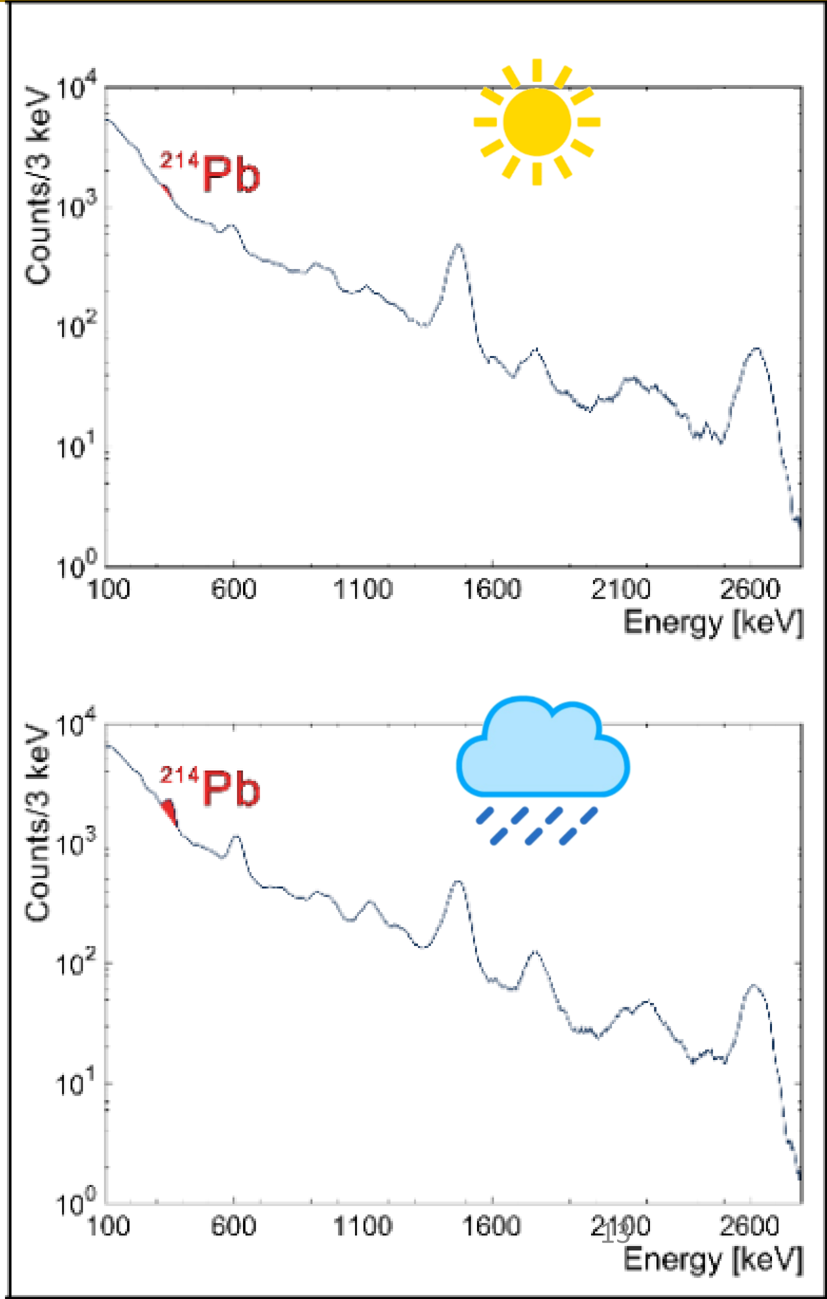
Gamma ray spectroscopy is like a window on the world
…for observing the activity in rain water

Genesis and effect of the rain-induced gamma activity



Rainout process (the in-cloud process): the radon daughters attach to aerosols which are scavenged by the rain droplet.

Washout process: the raindrops, falling down, collect the radon daughters nuclei.



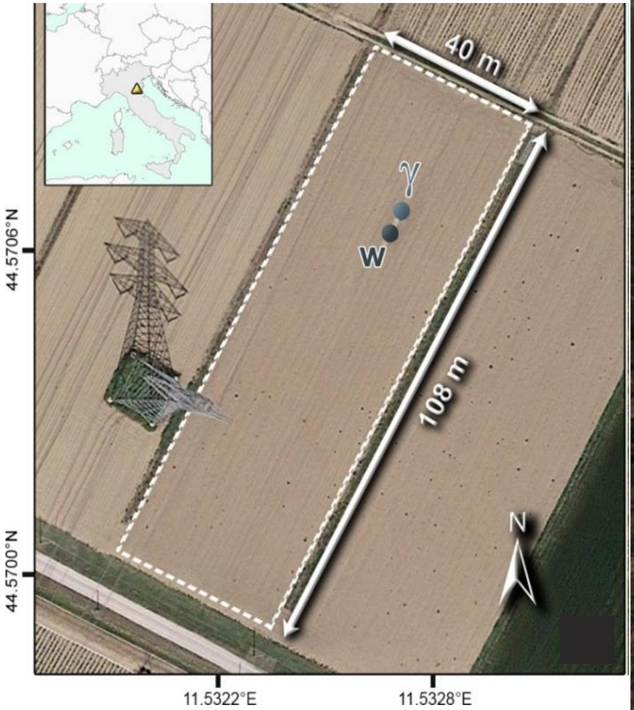
A proximal gamma-ray spectroscopy experiment

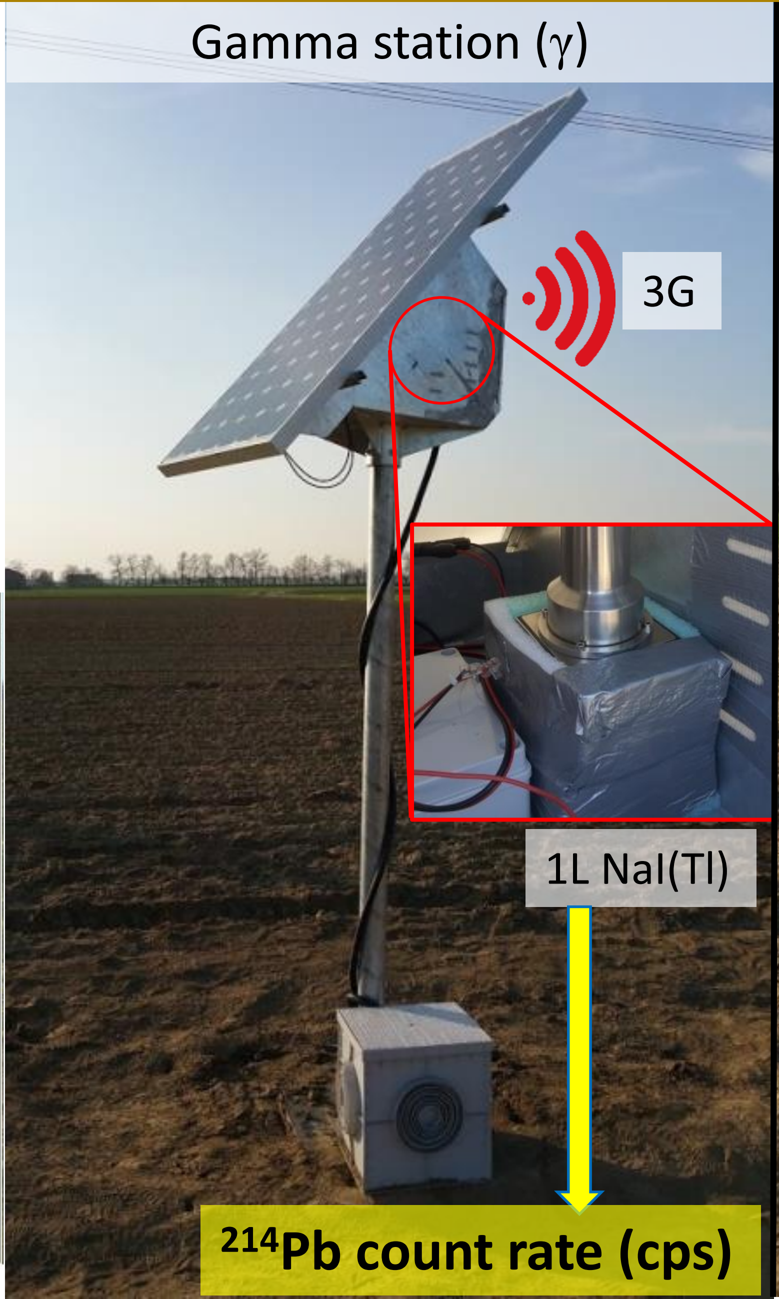
Experimental test field of the Acqua Campus of CER (Emilia-Romagna, Italy).

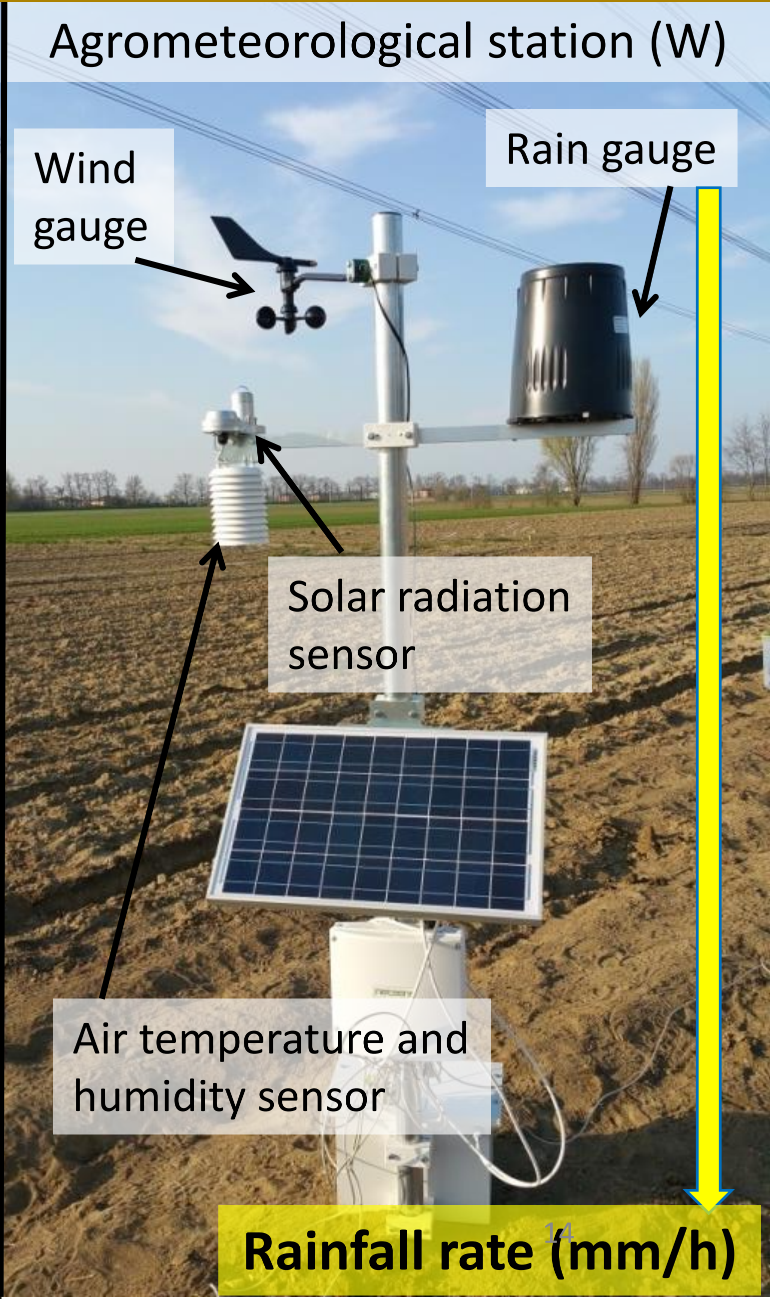
Period of data acquisition : **4th April – 2nd November 2017**.

2 stations: **gamma station** (γ) and **agrometeorological station** (W)

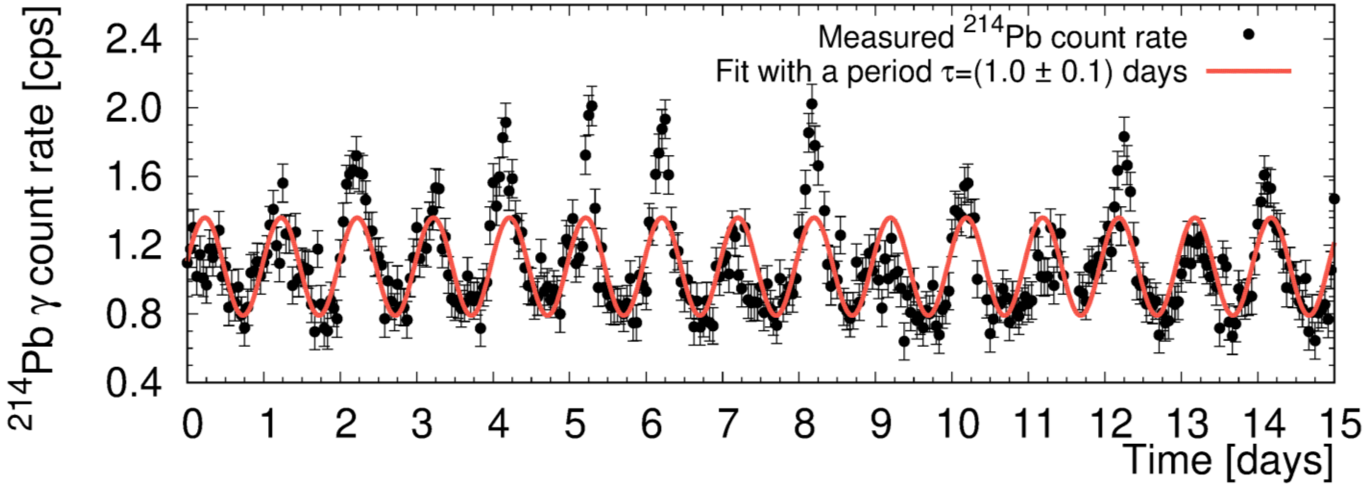
The gamma activity and the meteorological parameters are "quantized" in 15 min = **0.25 h of temporal resolution.**



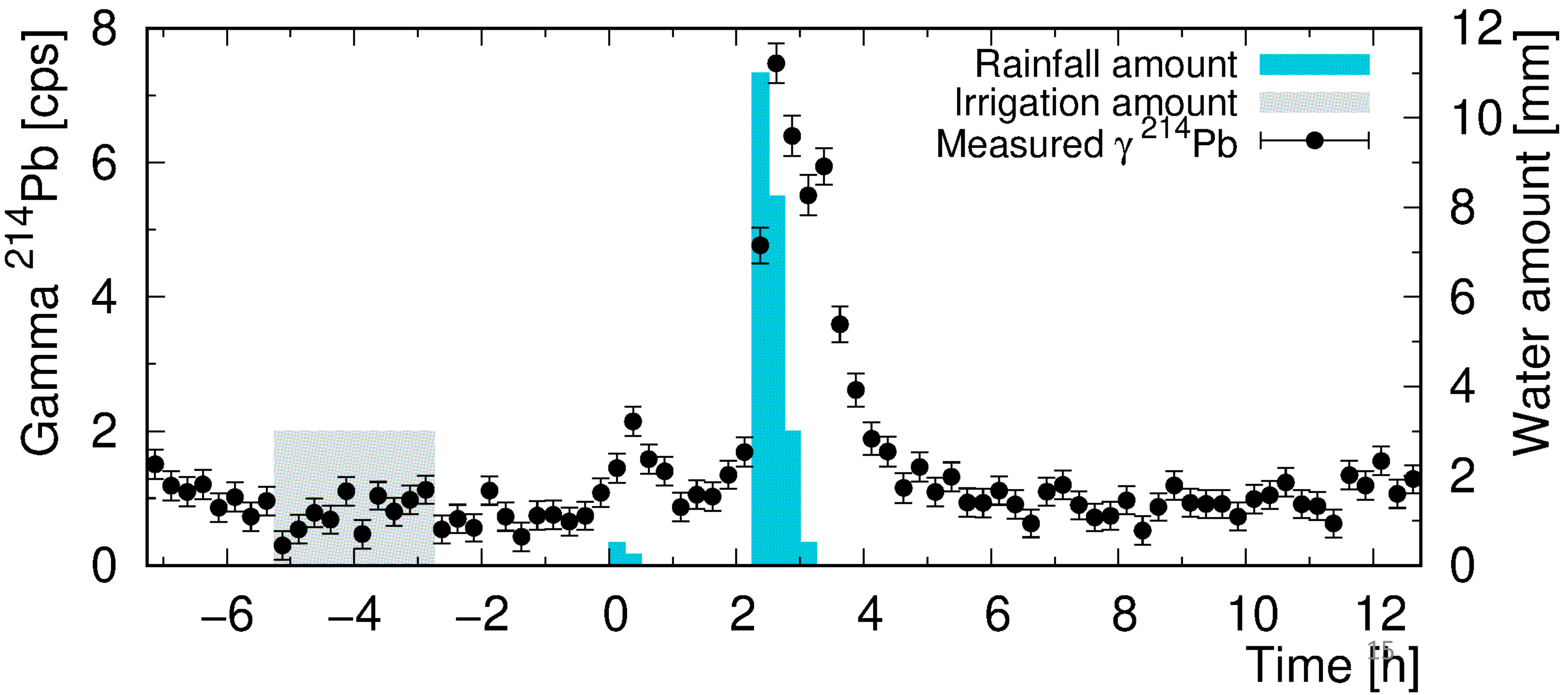




What happens during a sunny day and a rainy day



The count rate shows a daily fluctuation with amplitude ~ 0.26 cps with mean ~ 1.00 cps: very small compared to the rain gamma activity increase.



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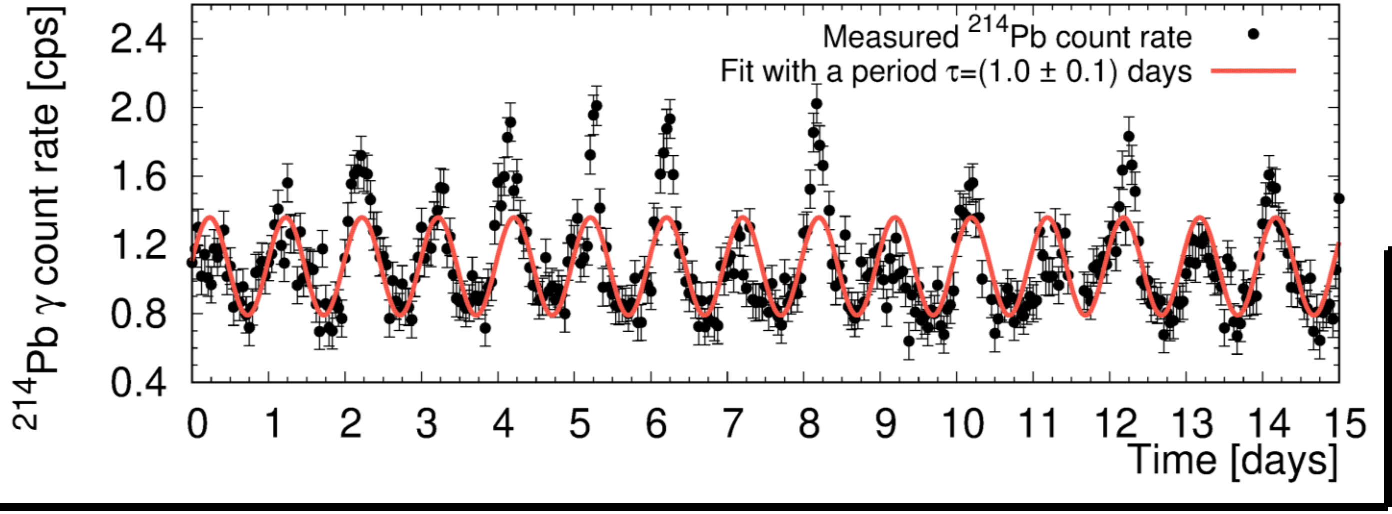
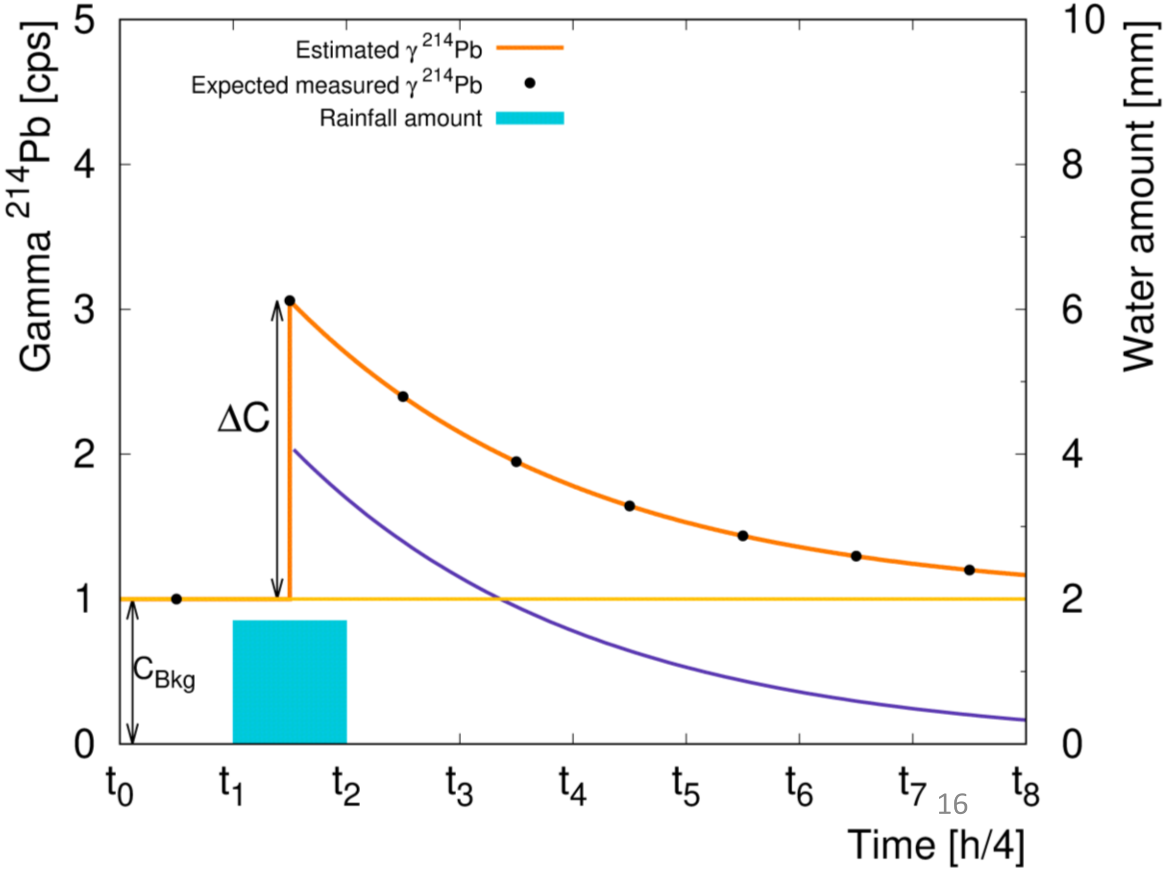


The count rate shows a daily fluctuation with amplitude ~ 0.26 cps with mean ~ 1.00 cps: very small compared to the rain gamma activity increase.

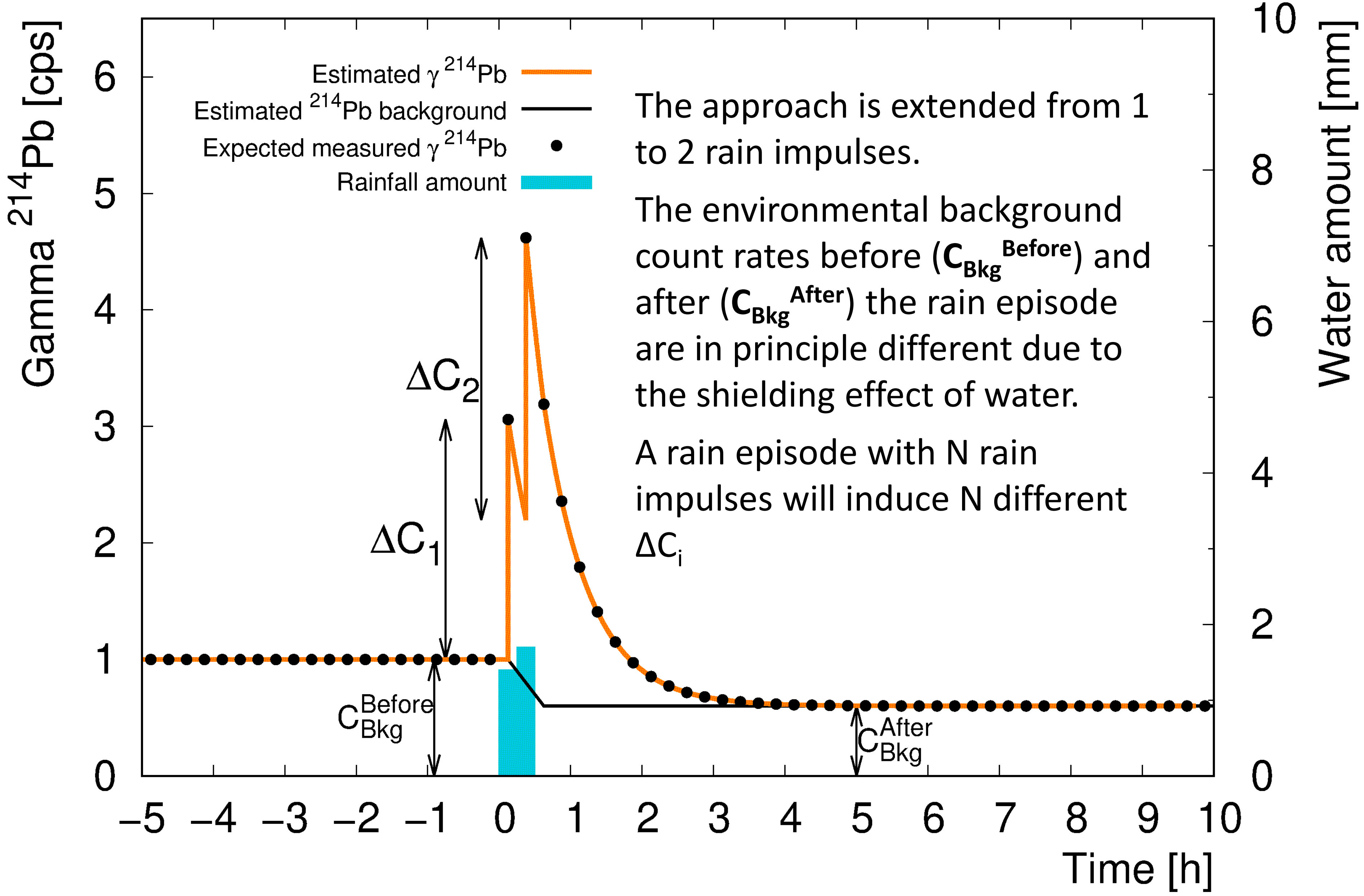
$$C_{Pb}(t) = \Delta C e^{-\lambda_{Pb}(t-t_1-450s)} + C_{Bkg}$$



Let's take a rain episode with duration = the detector resolution: 900 seconds.

- $C_{Pb}(t)$ is the PEW count rate predicted by the model.
- C_{Bkg} is the environmental background count rate: the number of net PEW cps not due to the rain, assumed to be constant in time.
- The count rate $C_{Pb}(t)$ is assumed to be = C_{Bkg} before the rain and to suddenly increase by **ΔC** in the middle of the temporal bin, when the rain activity "**hits**" the detector, then it decreases exponentially due to ^{214}Pb radioactive decay.

Generalizing to a longer rain episode



The approach is extended from 1 to 2 rain impulses.

The environmental background count rates before (**C_{Bkg}^{Before}**) and after (**C_{Bkg}^{After}**) the rain episode are in principle different due to the shielding effect of water.

A rain episode with N rain impulses will induce N different ΔC_i

How can ΔC_i be parametrized?

NEW

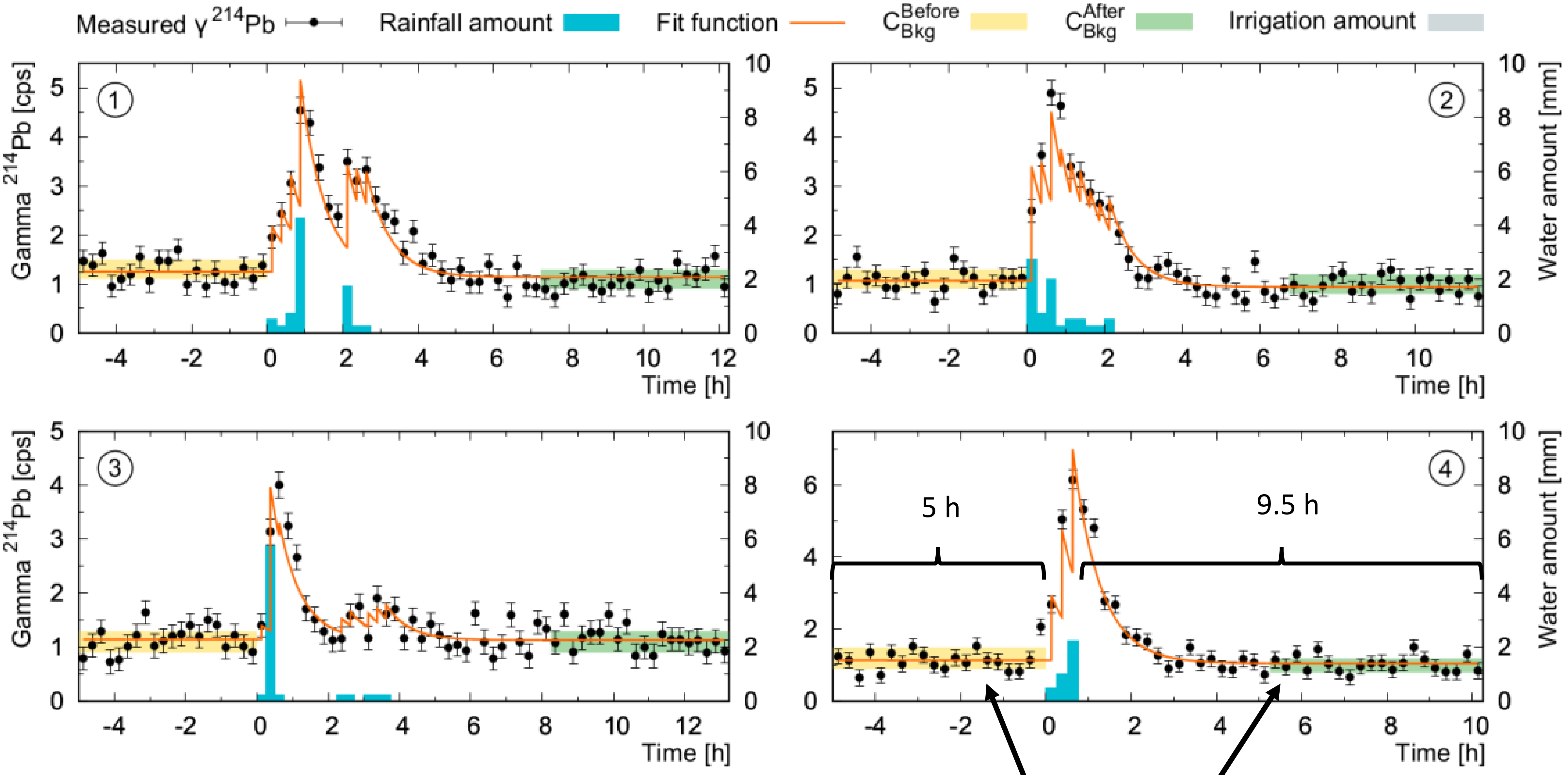
$$\Delta C_i = \Delta T \cdot A \cdot R_i^{\,d}$$

ΔT = 0.25 h is the detector resolution.

R_i [mm/h] is the rain rate in the i-th interval of time.

A and **d** are free parameters. They are **constant** over the single episode but can in principle change for different episodes.

Experimental data and model fit



12 rain episodes analyzed. 4 fit parameters: **A**, **d**, C_{Bkg}^{Before}, C_{Bkg}^{After}

Results of the analysis

N. episode	Date [DD/MM/YYYY]	Duration [hh:mm]	Precipitation [mm]	Rate [mm/h]	$A \pm \delta A$ [cps mm^{-d} h^{d-1}]	$d \pm \delta d$ [adim]	$C_{Bkg}^{Before} \pm \delta C_{Bkg}^{Before}$ [cps]	$C_{Bkg}^{After} \pm \delta C_{Bkg}^{After}$ [cps]
1	17/04/17	2:45	8.0	2.9	2.6 ± 1.0	0.48 ± 0.06	1.25 ± 0.05	1.14 ± 0.04
2	27/04/17	2:15	7.8	3.4	1.5 ± 0.6	0.77 ± 0.06	1.07 ± 0.05	0.94 ± 0.04
3	04/05/17	0:45	6.3	8.3	1.0 ± 0.4	0.75 ± 0.07	1.15 ± 0.05	1.13 ± 0.04
4	25/06/17	0:45	3.8	5.0	5.4 ± 3.2	0.42 ± 0.09	1.14 ± 0.05	1.05 ± 0.04
5	28/06/17	1:30	15.3	10.2	3.4 ± 0.7	0.34 ± 0.03	1.14 ± 0.04	1.00 ± 0.03
6	11/07/17	3:15	23.5	7.2	2.5 ± 0.5	0.48 ± 0.04	0.77 ± 0.05	0.99 ± 0.04
7	06/08/17	1:45	18.3	10.4	1.4 ± 0.3	0.71 ± 0.05	1.36 ± 0.05	0.94 ± 0.05
8	10/08/17	1:30	13.0	8.7	3.4 ± 0.2	0.16 ± 0.09	1.15 ± 0.05	0.83 ± 0.06
9	02/09/17	0:45	3.8	5.0	2.6 ± 1.0	0.48 ± 0.05	1.35 ± 0.05	1.02 ± 0.04
10	07/09/17	1:45	5.5	3.1	4.6 ± 3.7	0.23 ± 0.11	0.94 ± 0.05	0.86 ± 0.04
11	24/09/17	1:15	9.0	7.2	0.7 ± 0.6	0.99 ± 0.15	1.50 ± 0.05	1.06 ± 0.04
12	06/10/17	3:45	19.0	5.1	4.0 ± 0.8	0.39 ± 0.03	1.34 ± 0.05	1.05 ± 0.04

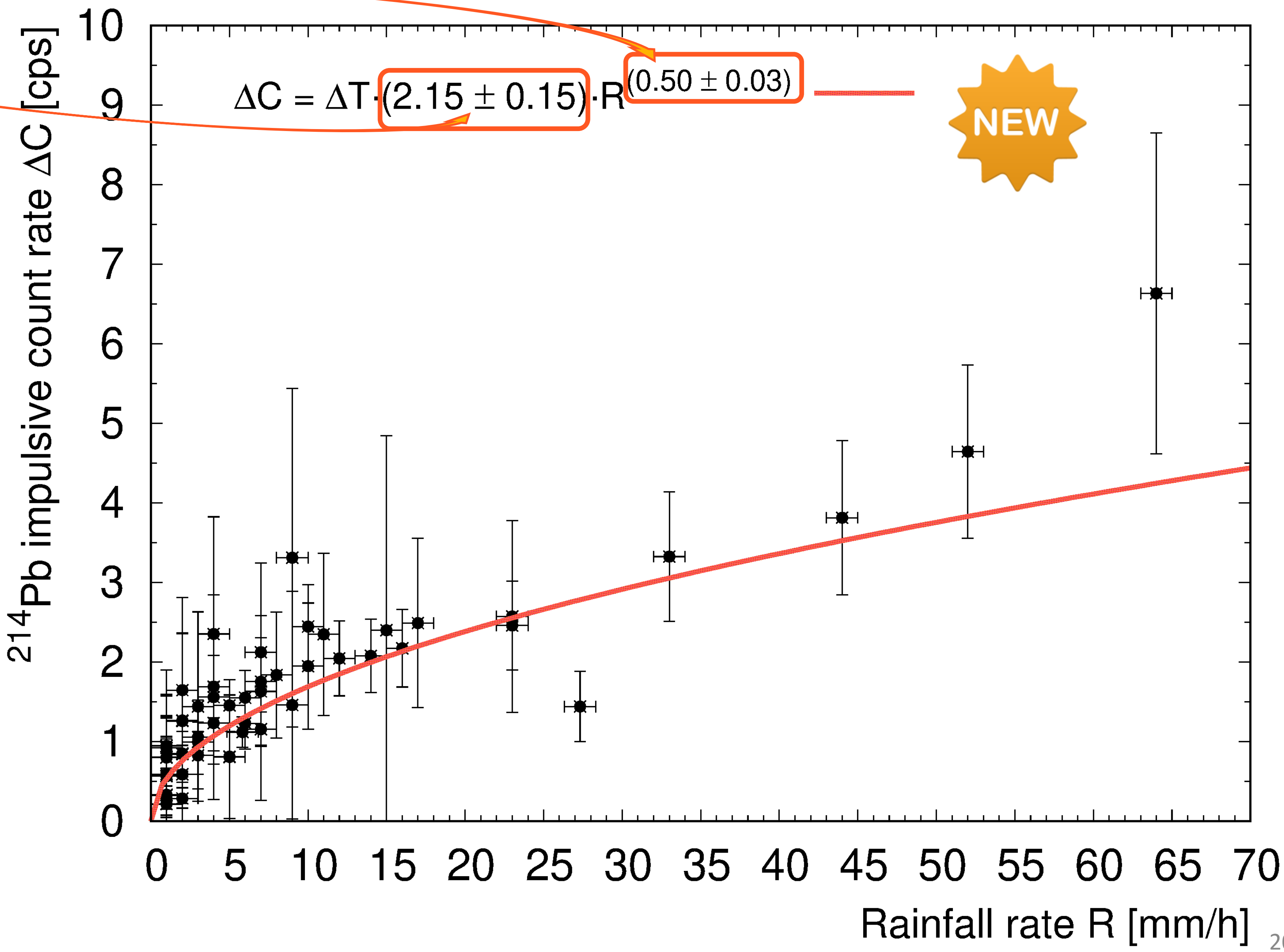
- The *A* and *d* parameters are characterized by some variability among the different rain episodes.
- C_{Bkg}^{Before} is, as expected, generally larger than C_{Bkg}^{After} due to the shielding power of rain water penetrated into the soil or deposited on its surface.

The typical rain episode

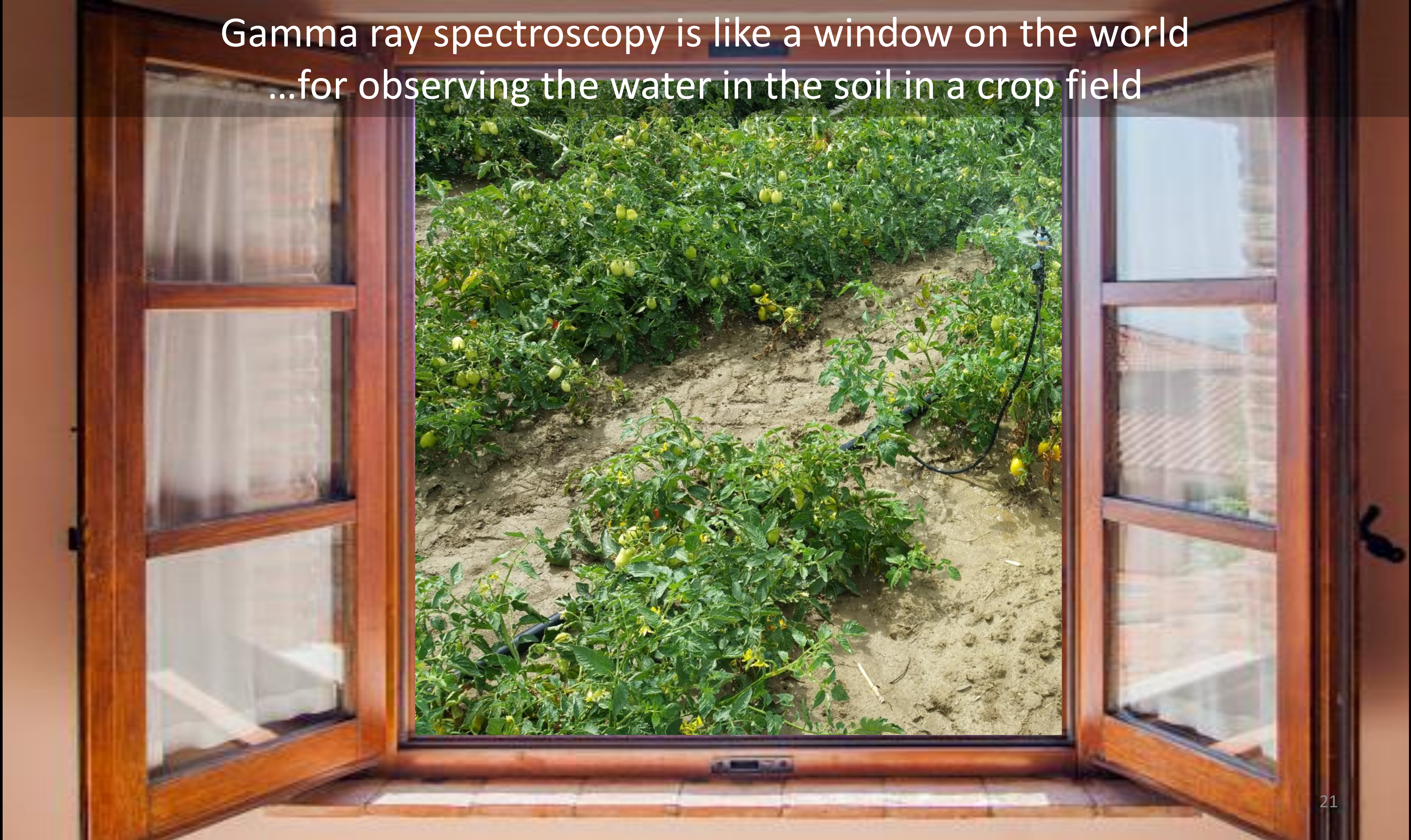
$$\Delta C = \Delta T \cdot A \cdot R^{d}$$

- **ΔC [cps]** = impulsive count rate parameter.
- **ΔT [h]** = detector time resolution = 0.25 h.
- **R [mm h^{-1}]** = rain rate.
- **A [cps mm^{-d} h^{d-1}]** = proportional constant.
- **d [adim]** = power of R.

- The 82 0.25 h impulses of rain of the selected episodes were reported in figure.
- This allows to determine the A and d parameters that describe the **ΔC** dependence on the rain rate R for the mean rain episode.
- The d value is in agreement with the literature.



Gamma ray spectroscopy is like a window on the world
…for observing the water in the soil in a crop field



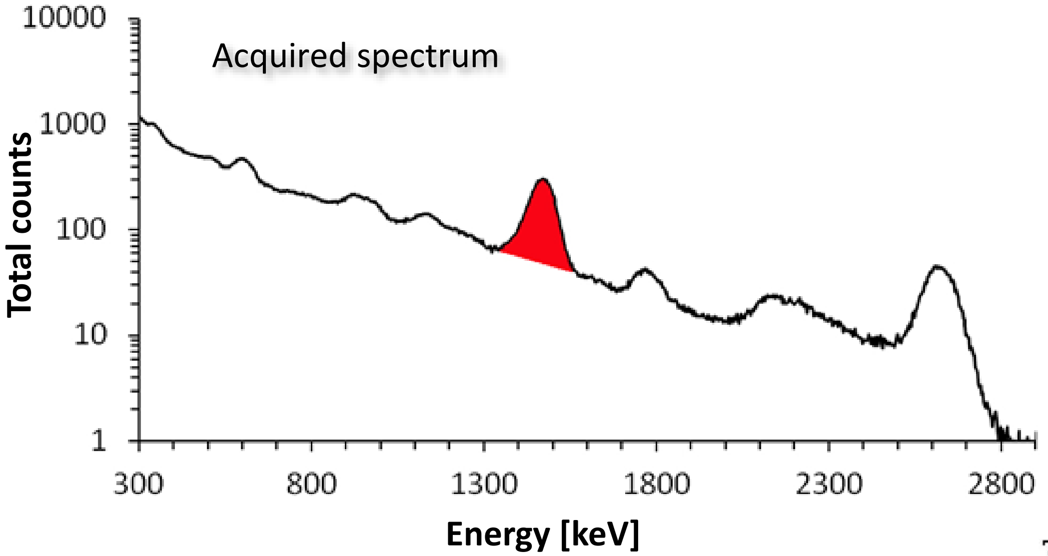
^{40}K signal for soil water content measurements

Since the water shields terrestrial gamma ray, why don’t use proximal gamma spectrometry for measuring the soil water content in precision agriculture?

$$\theta = \frac{33.6}{S(K)} - 1.20$$

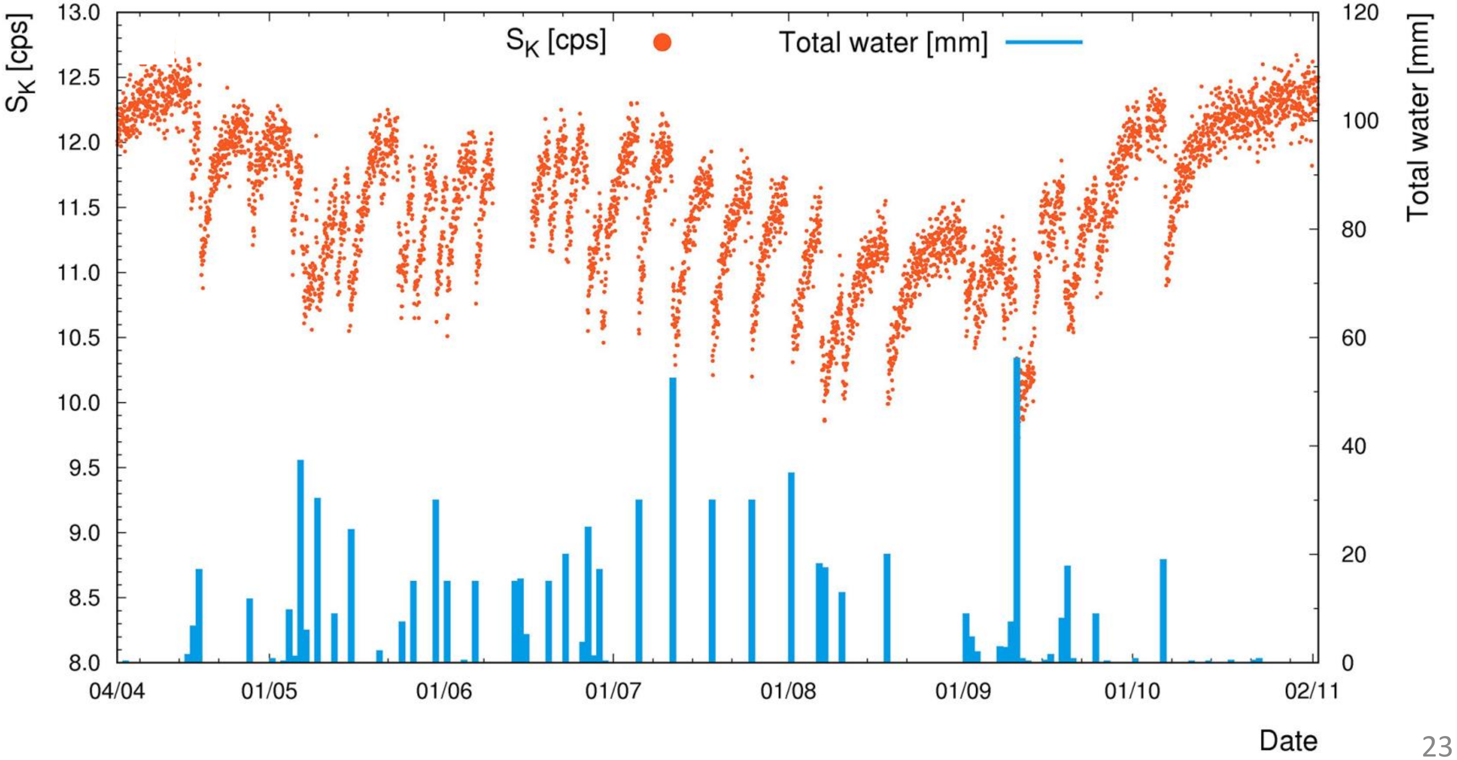
The soil water content θ is inversely proportional to the signal S (K) produced by the ^{40}K decay measured by the gamma spectrometer

7 months of data taking

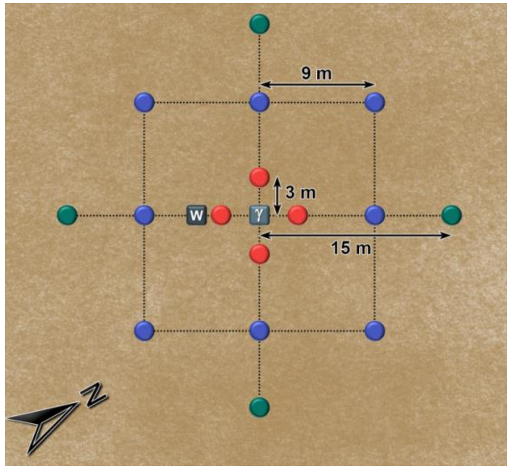


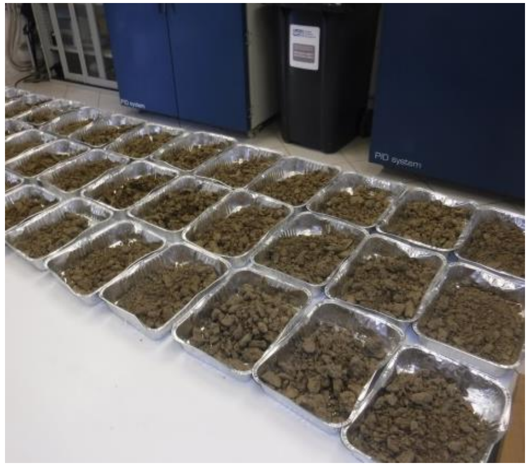
- 15 minutes acquired spectrum
- Total counts ~ 180 10^3
- Net counts in ^{40}K window ~ 6 10^3
- Statistical noise of ~ 0.5 % for 1h acquisition
- I acquired 20502 spectra (~260 GB)

In a typical soil ~ 95% of the gamma radiation is emitted from the top **25 cm** of the soil.
Cumulative contribution of ground radioactivity in percentage as function of the source radius detected at height of 2.3 m reaches ~ 95% at ~ **25 m** of radius.



A calibration for the gamma measurements





On 18 Sept. 2017, 16 samples were collected at different distance: the gravimetric water content $\mathbf{w_{CAL}}$ was measured

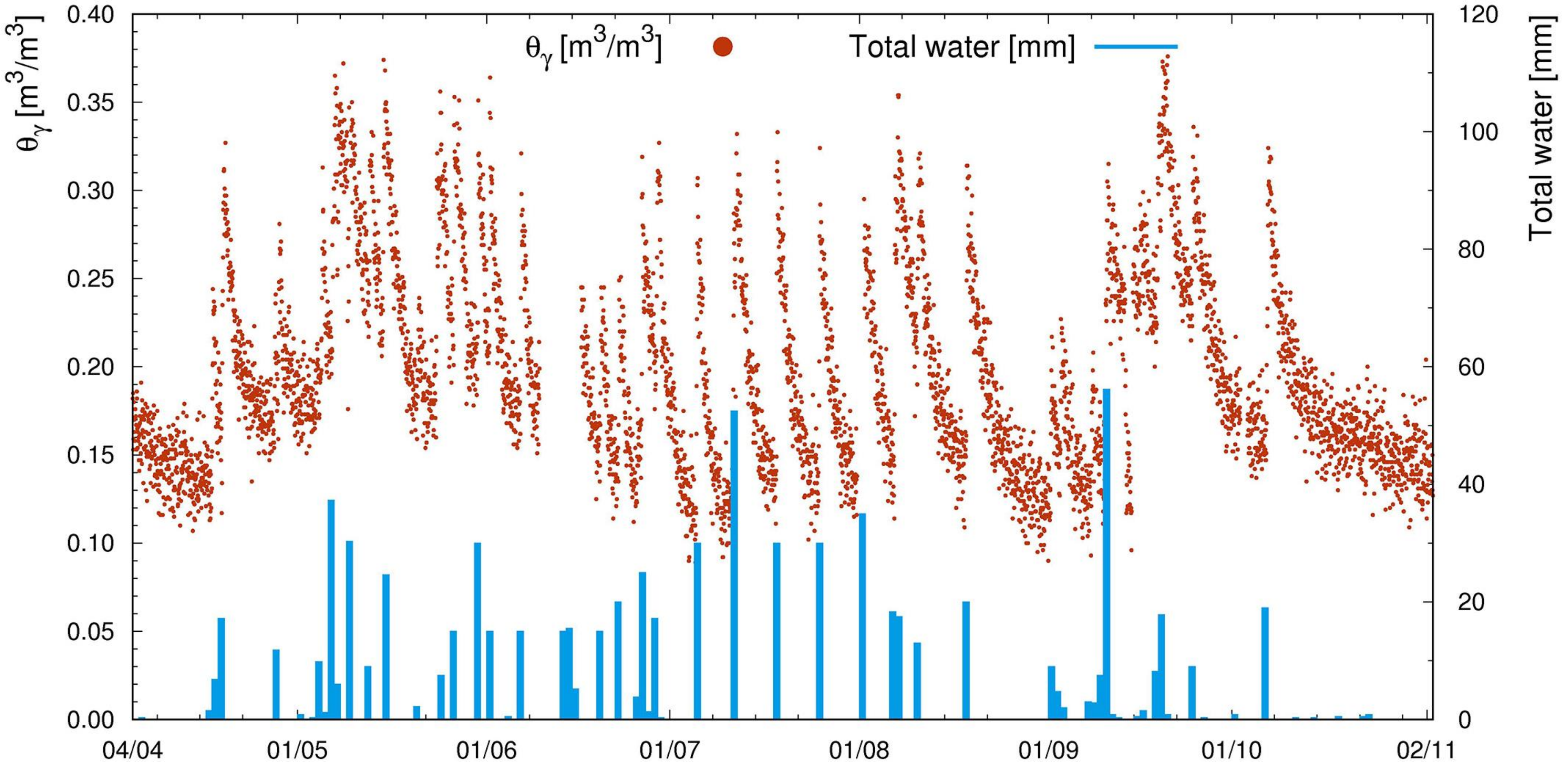
$$w_t \left[\frac{kg}{kg}\right] = \frac{CR_{CAL}[cps]}{CR_i[cps]}(0.899 + w_{CAL}) - 0.899$$

$$\theta \left[\frac{m^3}{m^3}\right] = \frac{V_{water}}{V_{dry\ soil}} = w_t \times \frac{\rho_{dry\ soil}}{\rho_{water}}$$

NEW

The gravimetric water content w at time t inferred by K counts rates is obtained after setting the calibration data: gravimetric water content ($\mathbf{w_{CAL}}$) and count rate in ^{40}K window ($\mathbf{CR_{CAL}}$)

Soil water content measurements



Bare soil			
Date	θ_G [m³/m³]	θ_γ [m³/m³]	$\Delta\theta$
21/09/17	23.7 ± 1.5	24.5 ± 1.1	3.4 %

With plants			
Date	θ_G [m³/m³]	θ_γ [m³/m³]	$\Delta\theta$
24/07/17	16.7 ± 2.8	17.0 ± 1.9	1.8 %
26/07/17	26.5 ± 2.8	24.3 ± 1.3	-8.3 %
28/07/17	18.9 ± 1.5	17.9 ± 1.5	-5.7 %

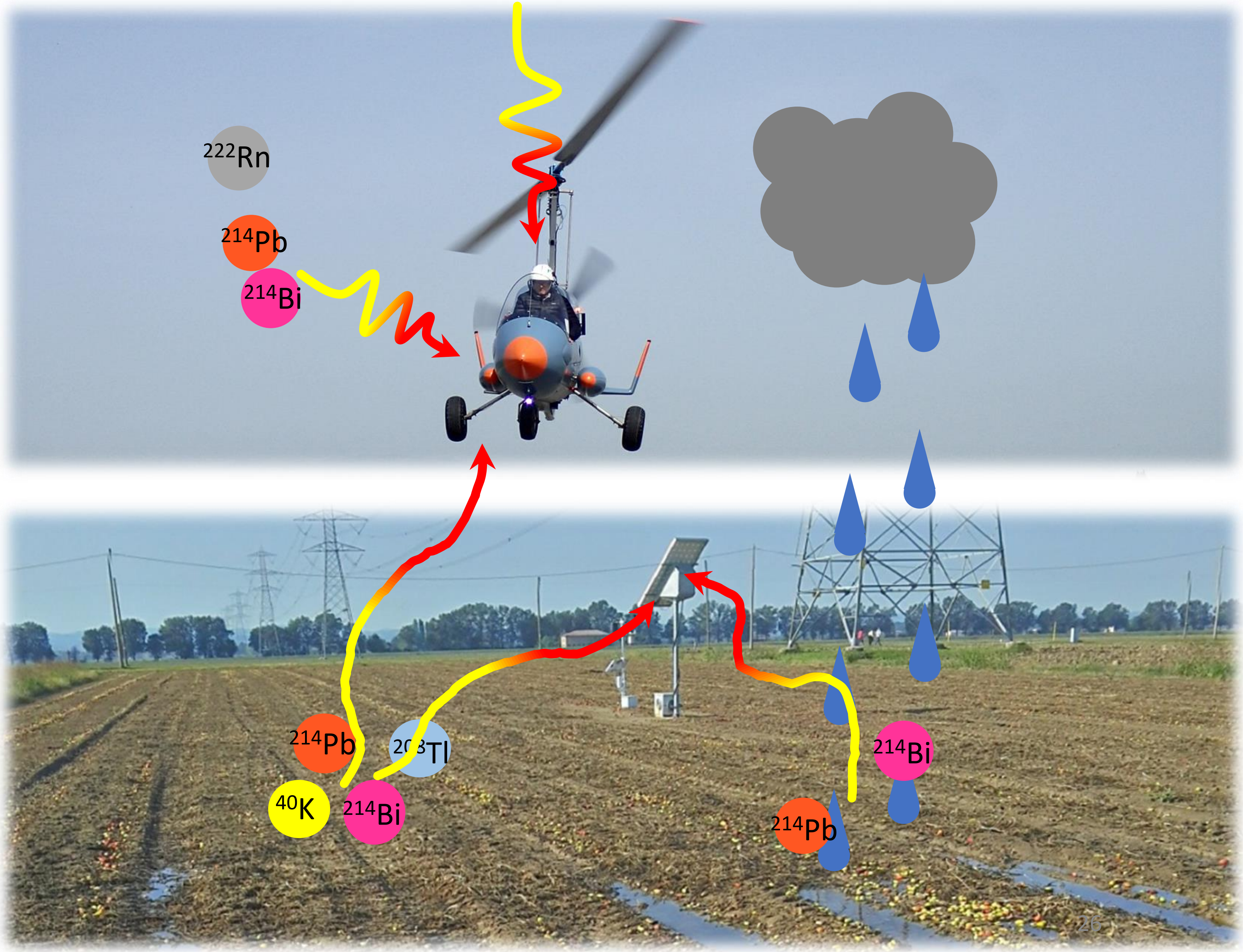
The soil water contents θ_γ are 1σ compatible with gravimetric field measurements θ_G with a maximum difference between the central values of **8.3%**

Main goals reached in my Phd

A new theoretical model of radiometric data vertical profile lead to estimate the abundance of ^{222}Rn in atmosphere and the height of the ^{222}Rn layer.

A new model to modelize the ^{214}Pb rain-induced gamma activity in function of the rain intensity: every impulse of rain instantaneously increases the count rate proportionally to the square root of the rain rate.

Soil water contents from gamma and gravimetric measurements are in excellent agreement, compatible at 1σ level.




Thank you

List of publications

C. Bottardi, M. Albéri, M. Baldoncini, E. Chiarelli, M. Montuschi, K. Raptis, A. Serafini, V. Strati and F. Mantovani. *Rain rate and radon daughters' activity.* Submitted

Albéri, M., M. Baldoncini, **C. Bottardi**, E. Chiarelli, S. Landsberger, K. Raptis, A. Serafini, V. Strati and F. Mantovani. *Training future engineers to be ghostbusters: hunting for the spectral environmental radioactivity*. Education Sciences, 9, 15 (2019). DOI 10.3390/educsci9010015

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