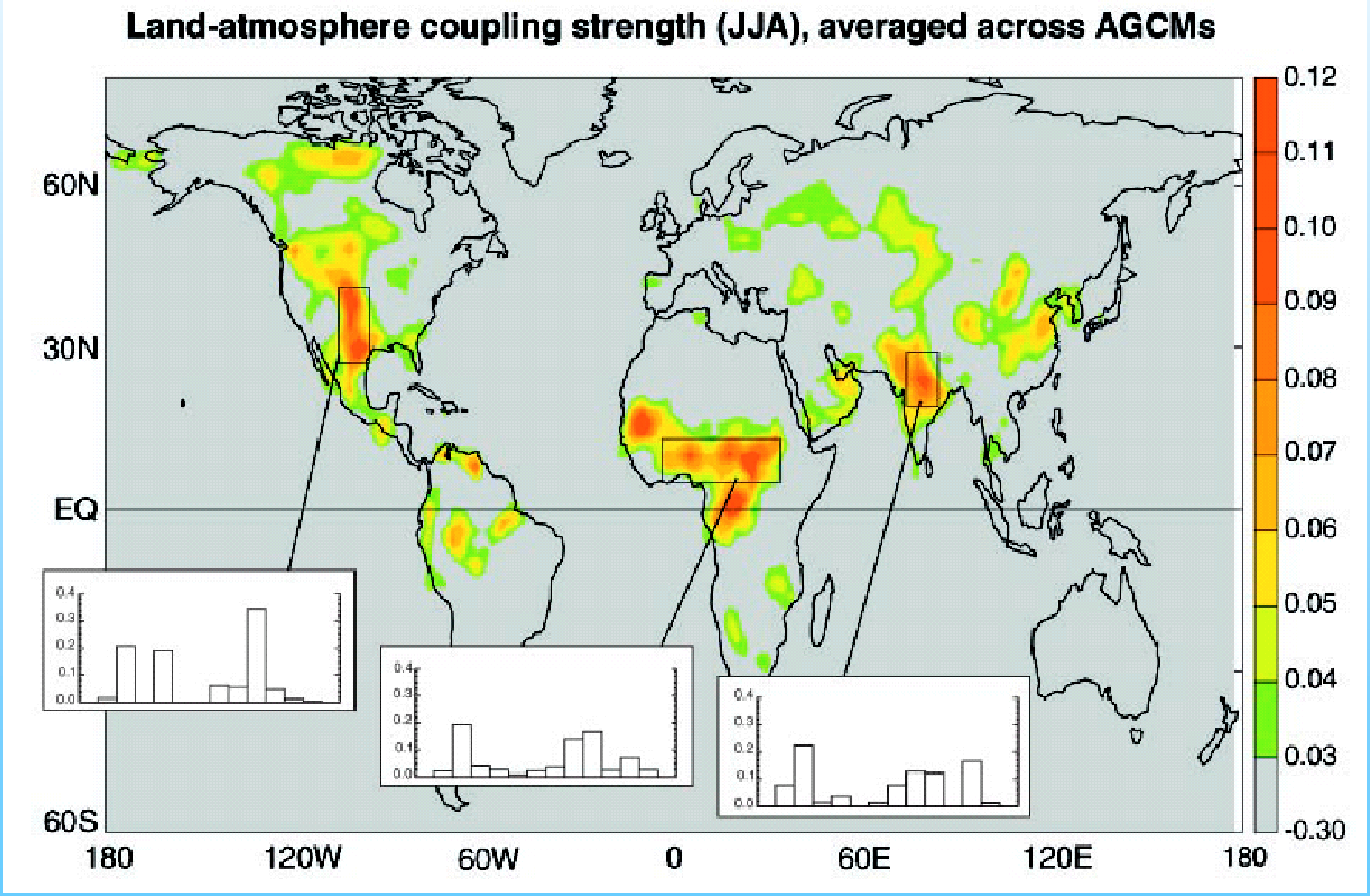
Cosmic-ray hydrometrology:

Measuring moisture at the land surface using cosmic-ray neutrons

Marek Zreda

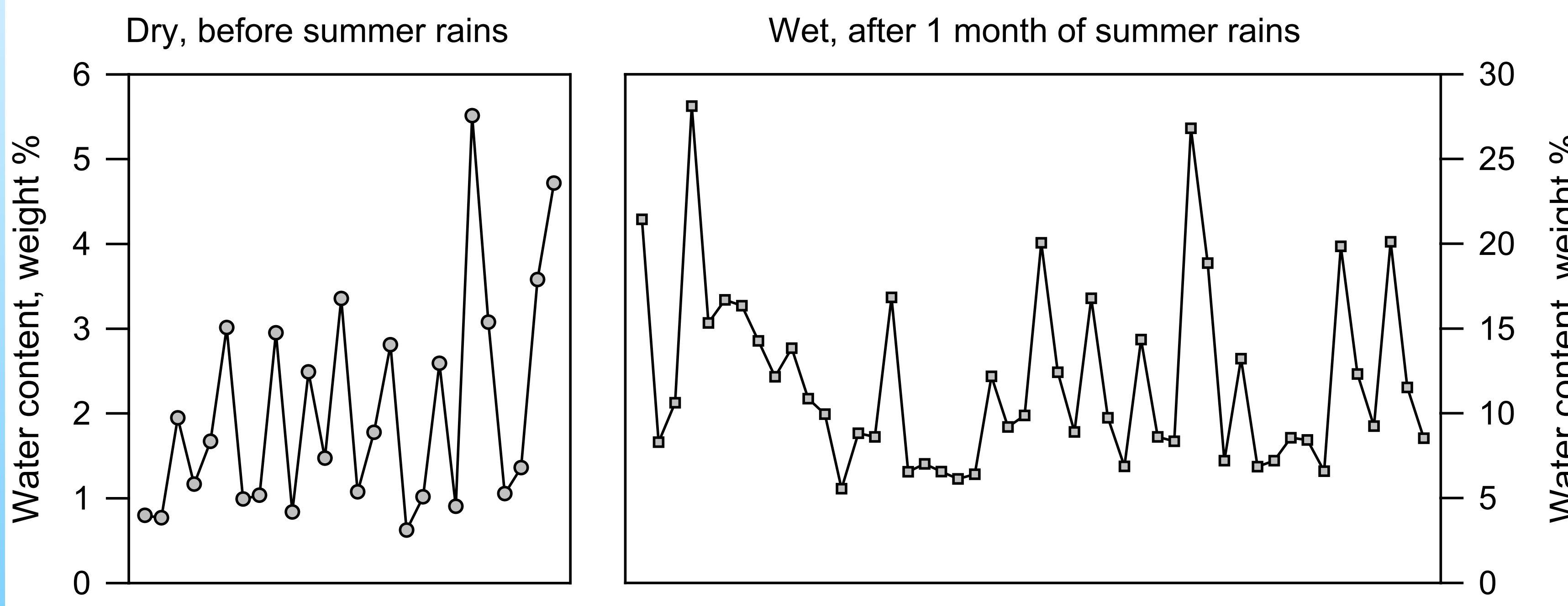
ATM & HWR seminar, 29 January 2009

Impact of soil moisture on precipitation



Spatial variations of soil moisture

(San Pedro River, AZ)



The cosmic-ray soil moisture probe ...

… was developed to measure soil moisture at an intermediate spatial scale with arbitrary temporal resolution

The COSMOS objective

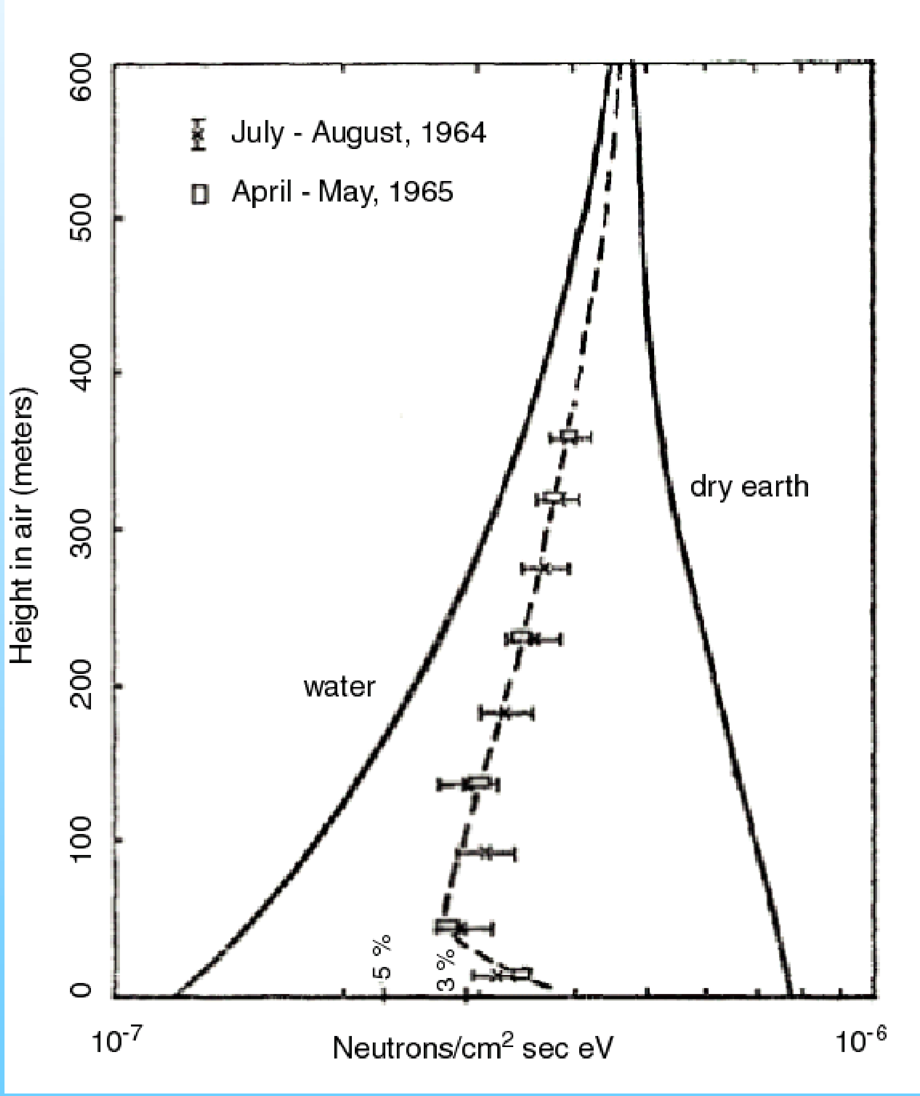
To install a network of cosmic-ray probes distributed throughout the contiguous USA

to provide soil moisture measurements at an intermediate spatial scale with arbitrary temporal resolution

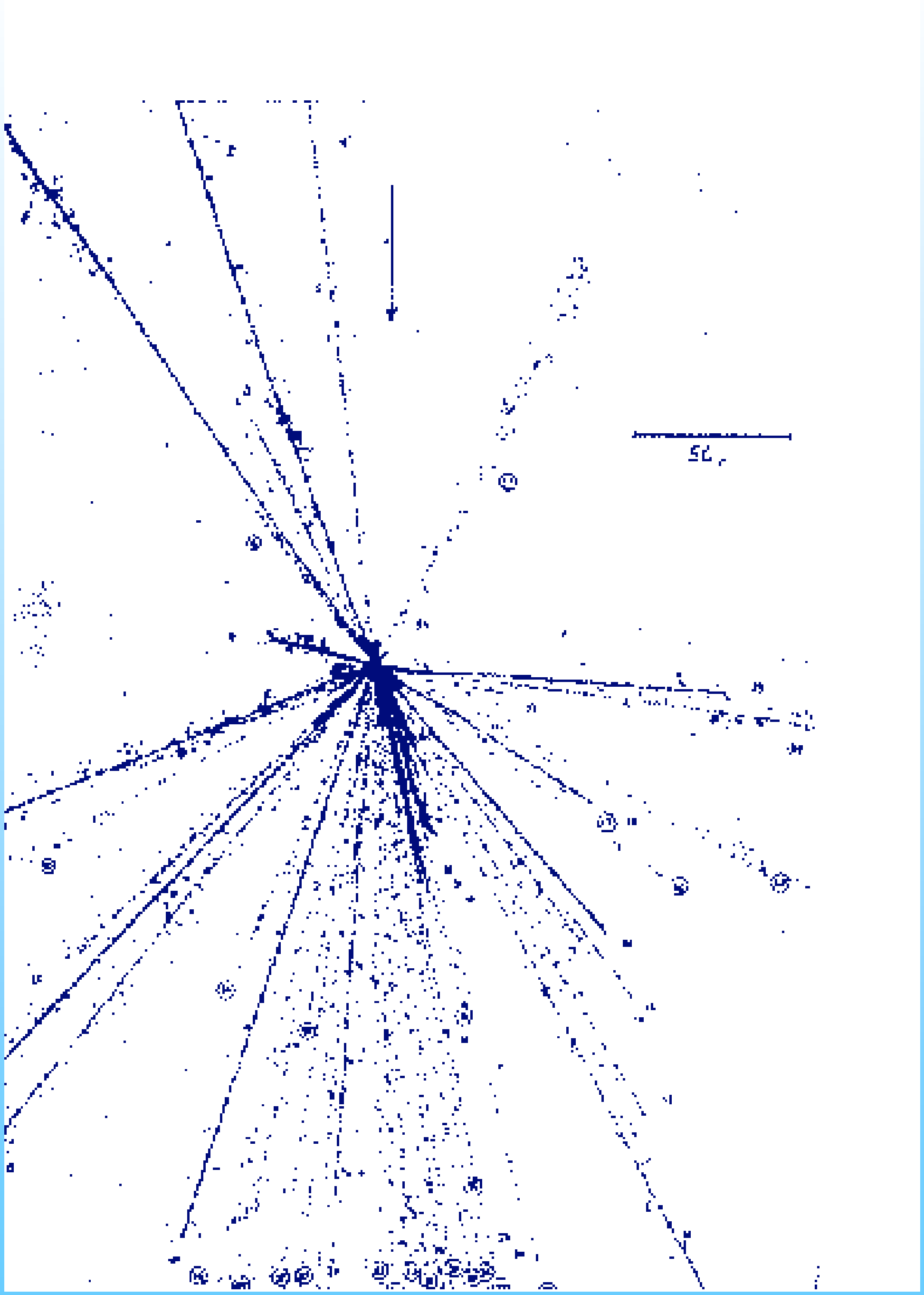
Acknowledgments

People:	**Darin Desilets** **Ty Ferre** Jim Shuttleworth Xubin Zeng Chris Zweck Amy Rice, Russ Scott, Chawn Harlow	COSMOS co-PIs
Funding sources:	**National Science Foundation** **Packard Fellowship in Science and Engineering** Army Research Office AZ Water Sustainability Program	
Other institutions:	Sandia National Laboratories	
Industry:	**Hydroinnova** **Zetetic Institute** Quaesta Instruments General Electric PDT	Hydroinnova Consortium

Cosmic-ray neutrons above the surface



Hendrick L.D. and R.D. Edge, 1966. Cosmic-ray neutrons near the Earth, Physical Review Series II, 145, 1023-1025.



Collision of cosmic-ray proton with atom

(producing many secondary particles)

Discovery of cosmic rays - first clues

In 1910, Father Thomas Wulf took his electroscope 300 metres up the Eiffel Tower and observed a 64% reduction in the leakage rate. He had expected that radiation from the ground would have been absorbed by the atmosphere and he concluded that there must be a contribution from radiation coming down through the atmosphere.

electroscope

not Wulf

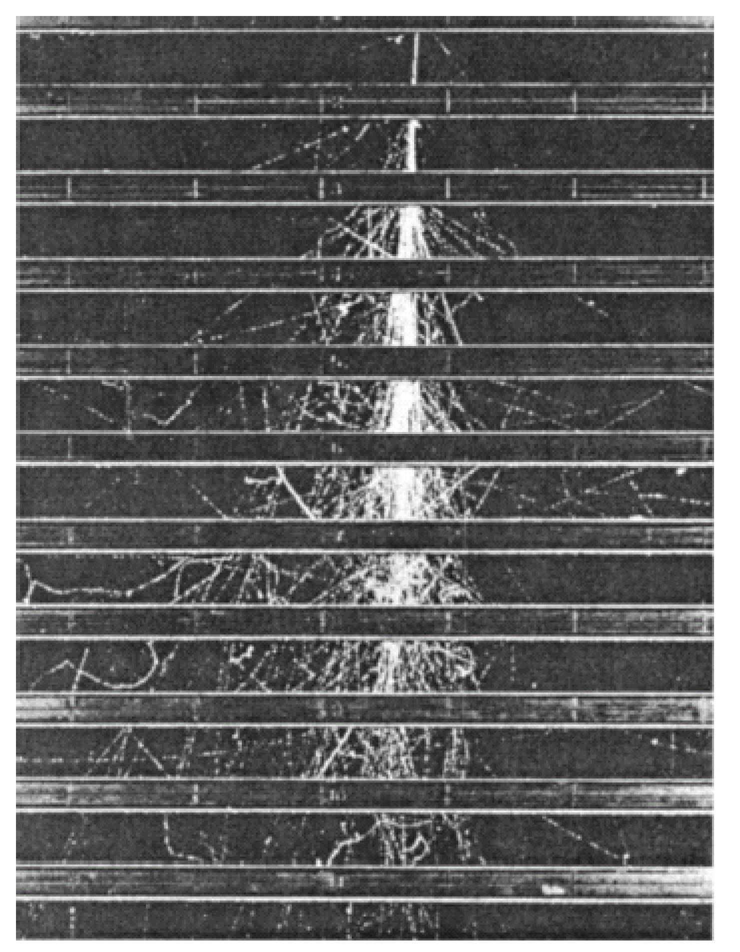
Discovery of cosmic rays by Victor Hess

"... in 1912, I was able to demonstrate by means of ... balloon ascents, that the ionization ... noticeably increased from 1,000 m ..., and at 5 km ... reached several times the ... value at earth level. I concluded that this ionization might be attributed to the penetration of the earth's atmosphere from outer space by ... unknown radiation of exceptionally high penetrating capacity, which was still able to ionize the air at the earth's surface noticeably."

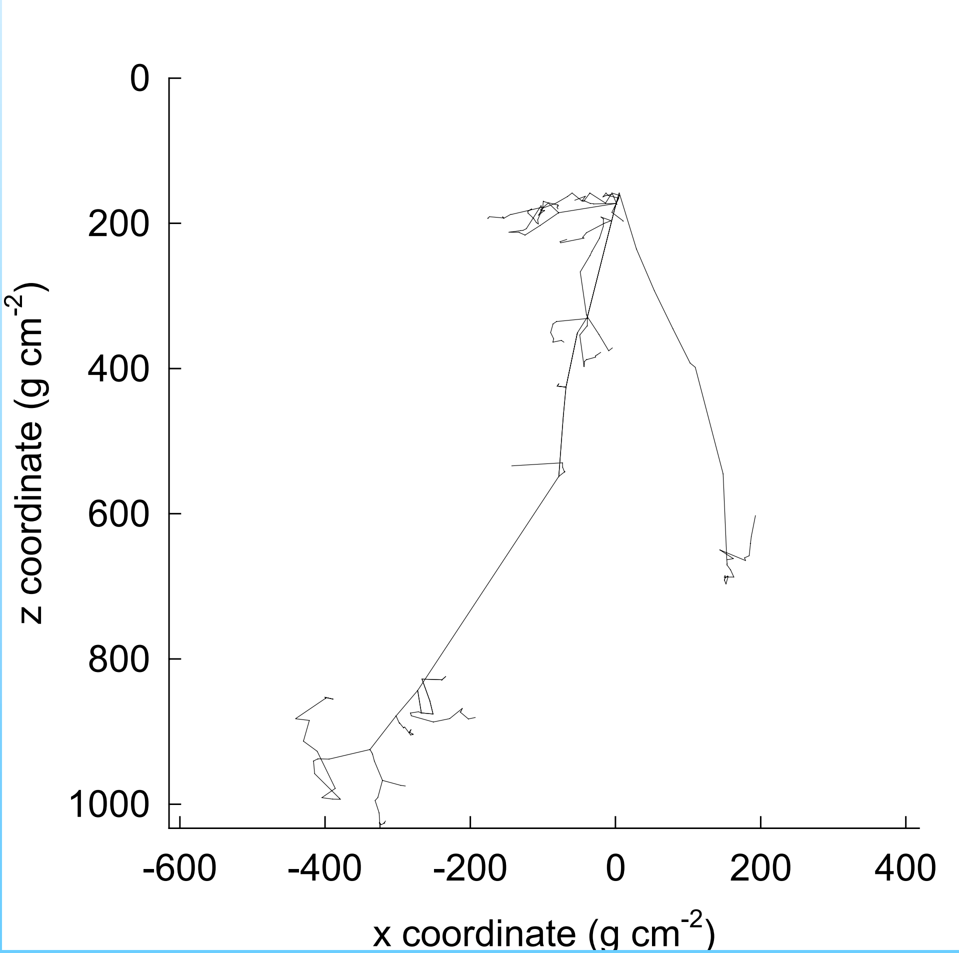
"... to clarify the origin of this radiation, ... I undertook a balloon ascent at the time of a nearly complete solar eclipse on the 12th April 1912, and took measurements at heights of two to three kilometres. As I was able to observe no reduction in ionization during the eclipse I decided that, essentially, the sun could not be the source of cosmic rays ..."

Production of secondary cosmic-ray particles

Secondary cosmic-ray particles produced in copper plates in a large cloud chamber. [D. Skobeltzyn, 1927.]



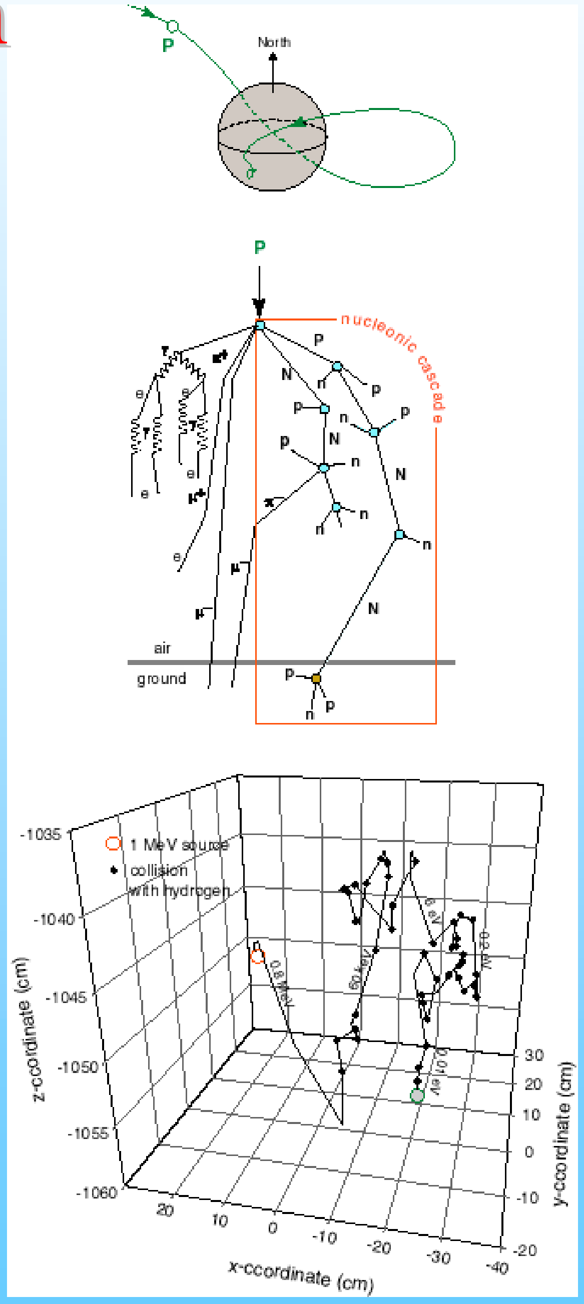
Cascade initiated by a 10 GeV primary. All trajectories above 1 MeV are shown. [MCNPX simulation, courtesy of D. Desilets, Sandia National Laboratories.]



Cosmic rays on Earth

- Primary - mostly protons and alphas
- Interact with magnetic field
  - intensity depends on geomagnetic latitude
- Interact with atmospheric nuclei
- Produce secondary particles - cascade
  - intensity depends on barometric pressure
- Produce fast neutrons
  - slowing down by elastic collisions
  - leads to thermalization
  - and then absorption

The last three processes depend on the chemical composition of the medium, in particular on its hydrogen content.



Space:

incoming high-energy cosmic-ray proton

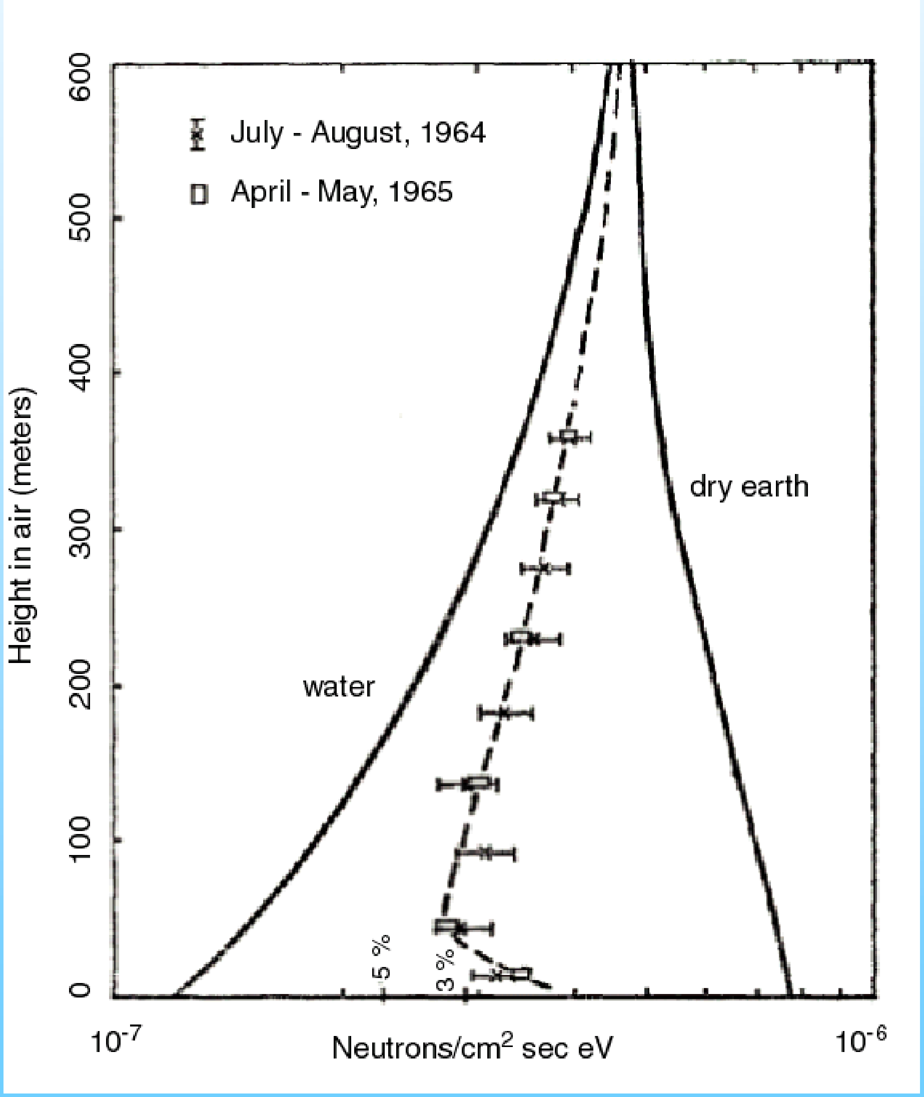
Atmosphere:

generation of secondary cosmic rays

Ground:

scattering absorption

Cosmic-ray neutrons above the surface



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Moderating and absorption properties

Top ten elements (red) contributing to macroscopic absorption and moderating (slowing) power in an "average rock."

Element	A	σ_{th}
H	1.0079	**0.3326**
B	10.811	**767**
C	12.011	0.0035
O	15.9994	0.00019
Na	22.9898	**0.53**
Mg	24.305	0.063
Al	26.9815	**0.231**
Si	28.0855	**0.171**
Cl	35.4527	33.5
K	39.0983	**2.1**
Ca	40.078	**0.43**
Ti	47.88	**6.43**
Mn	54.9381	13.3
Fe	55.847	**2.56**
Cd	112.411	2520
Sm	150.36	5922
Gd	157.25	**49700**

A - atomic mass (g/mole); σ_{sc} - elastic scattering cross-section (barns; 1 barn = 10^{-24} cm^2); σ_{th} - thermal neutron capture (absorption) cross-section; NC - number of collisions to thermalize a 1-2 MeV neutron; ξ - average log decrement of energy per neutron collision; SP - stopping power (roughly equal to $\xi\sigma_{sc}$).

Moderating and absorption properties

Top ten elements (blue) contributing to macroscopic absorption and moderating (slowing) power in an "average rock."

Element	A	σ_{sc}	NC	ξ	SP
H	1.0079	22.02	18	1.000	**22.016**
B	10.811	5.24	103	0.174	0.912
C	12.011	5.551	113	0.158	**0.875**
O	15.9994	4.232	149	0.120	**0.508**
Na	22.9898	3.28	211	0.085	**0.277**
Mg	24.305	3.71	223	0.080	**0.297**
Al	26.9815	1.503	247	0.072	**0.109**
Si	28.0855	2.167	257	0.070	**0.151**
Cl	35.4527	16.8	323	0.055	0.930
K	39.0983	1.96	355	0.050	**0.099**
Ca	40.078	2.83	364	0.049	**0.139**
Ti	47.88	4.06	434	0.041	0.167
Mn	54.9381	2.17	497	0.036	0.078
Fe	55.847	11.62	505	0.035	**0.411**
Cd	112.411	6.5	1009	0.018	0.115
Sm	150.36	39	1348	0.013	0.516
Gd	157.25	180	1409	0.013	2.280

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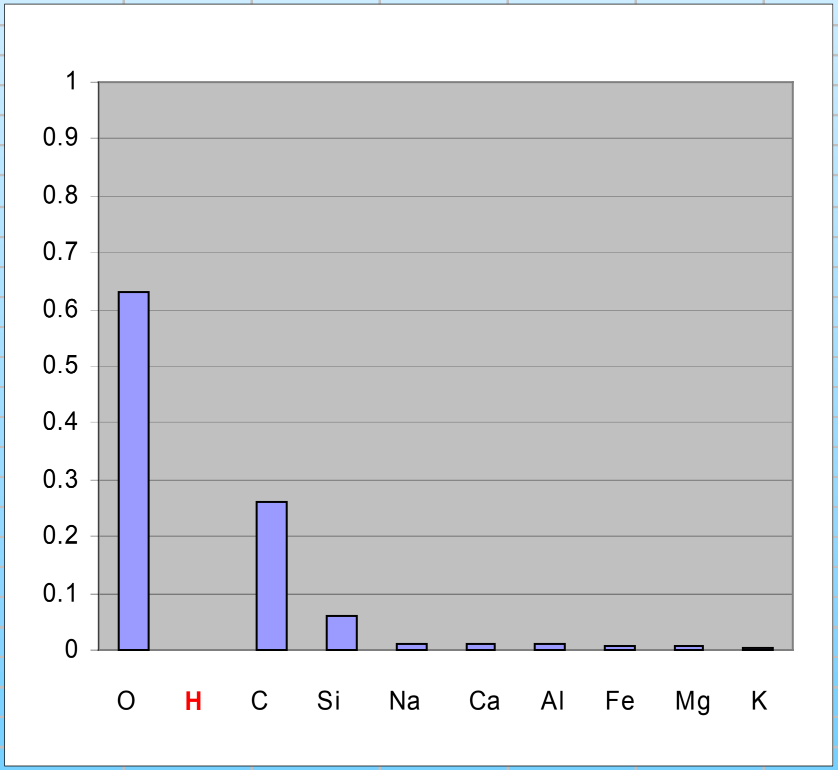
Moderating power in rocks

Input: soil water wt. %: **0**

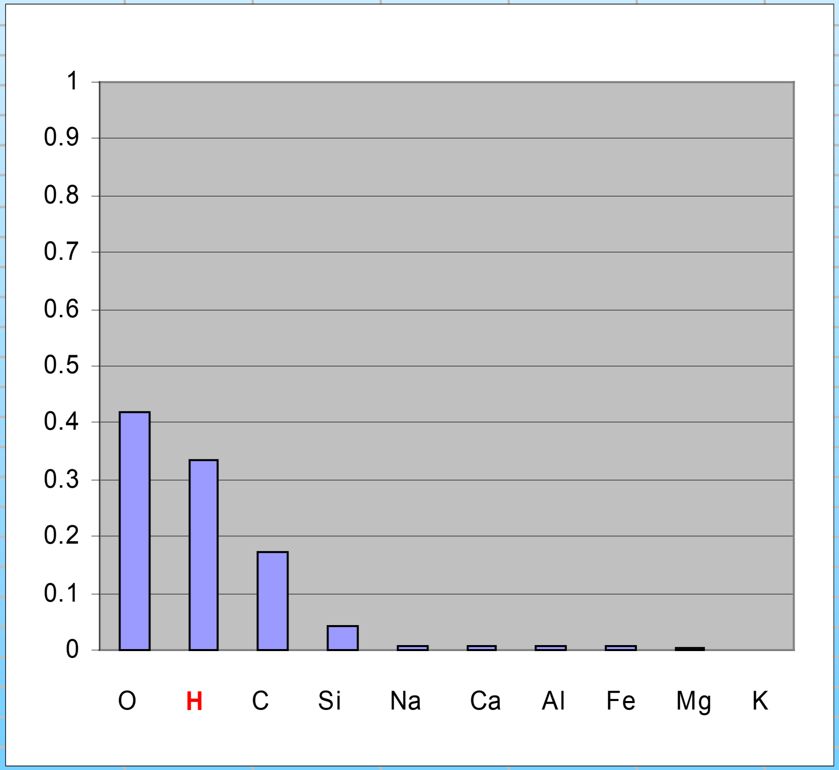
Ouput: contribution of H to total slowing down power of the soil



Moderating power in rocks

Input: soil water wt. %: 0.5

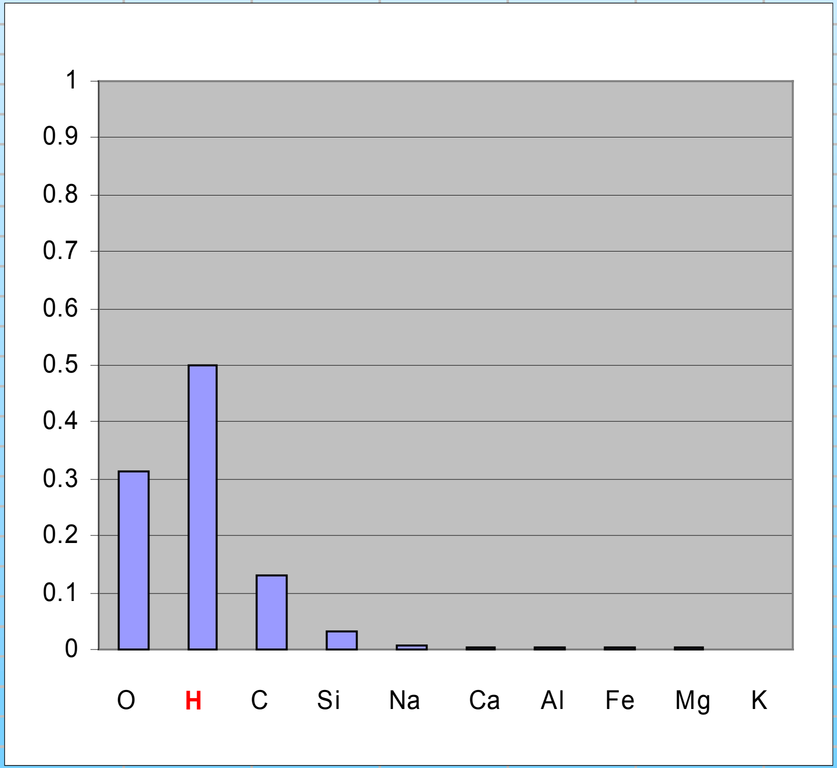
Ouput: contribution of H to total slowing down power of the soil



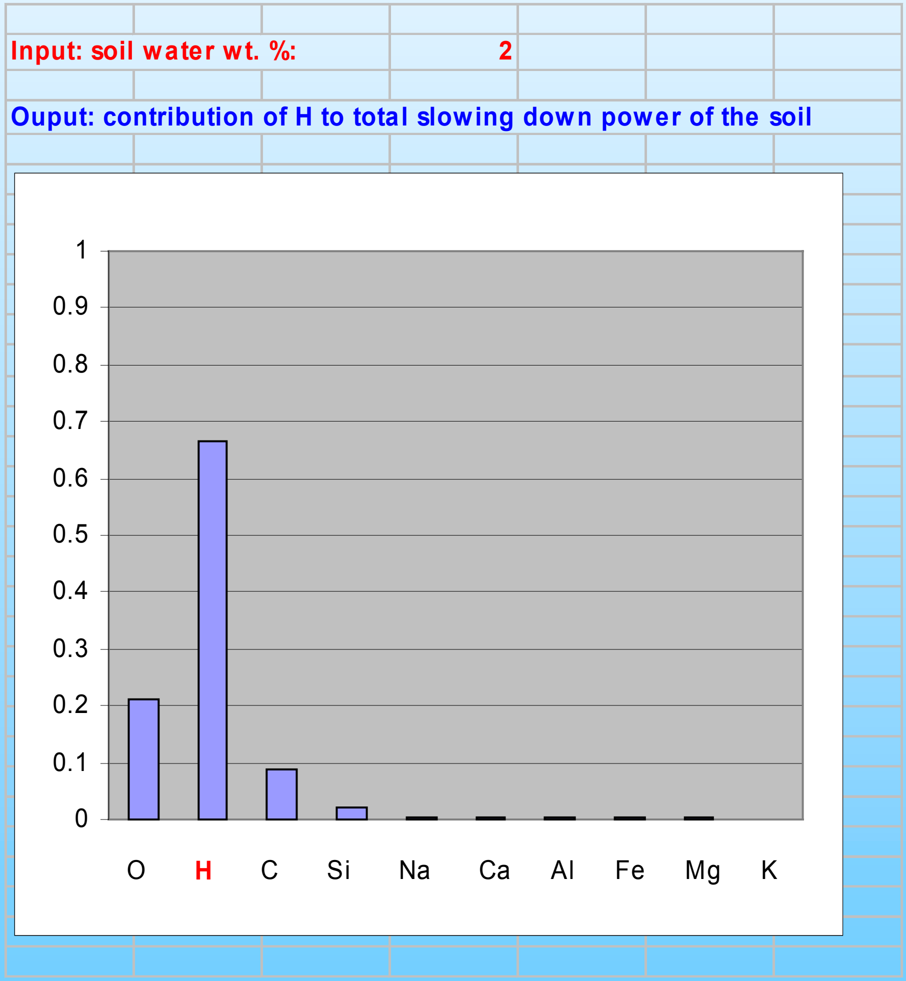
Moderating power in rocks

Input: soil water wt. %: 1

Ouput: contribution of H to total slowing down power of the soil

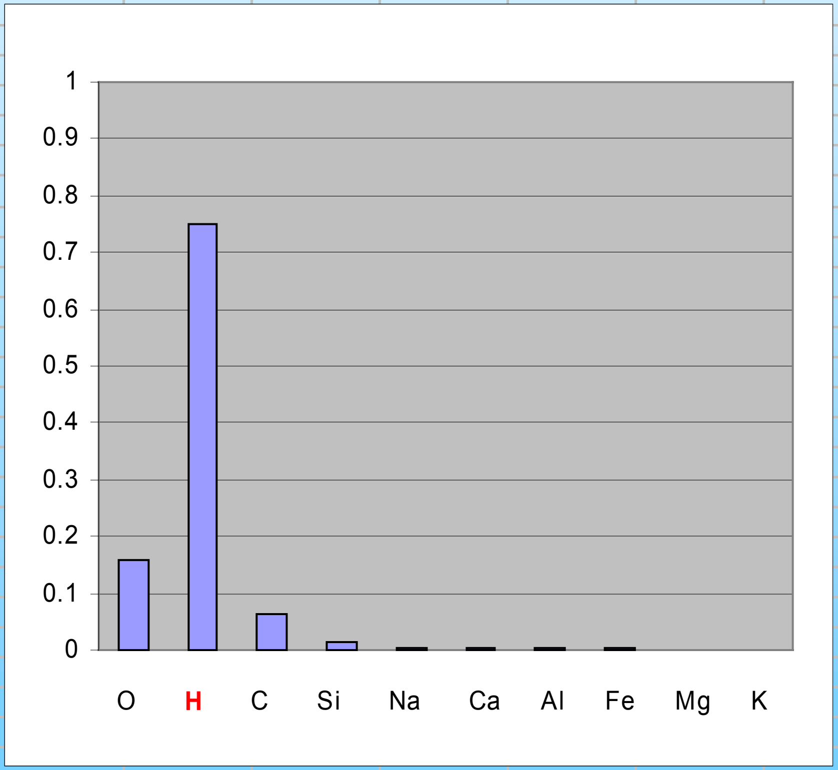


Moderating power in rocks



Moderating power in rocks

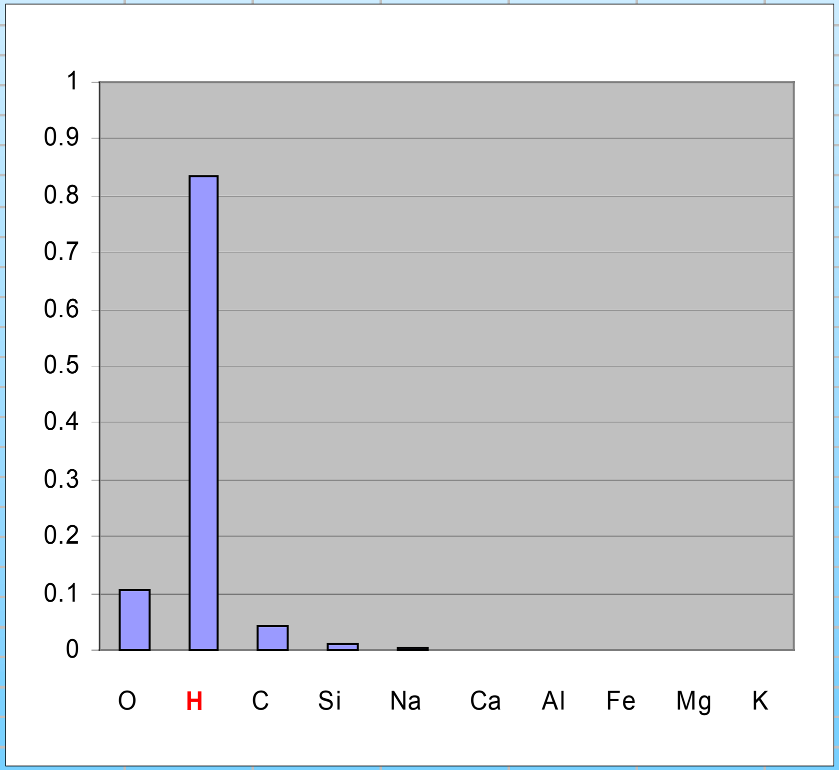
Input: soil water wt. %:			3			
Ouput: contribution of H to total slowing down power of the soil						



Moderating power in rocks

Input: soil water wt. %: 5

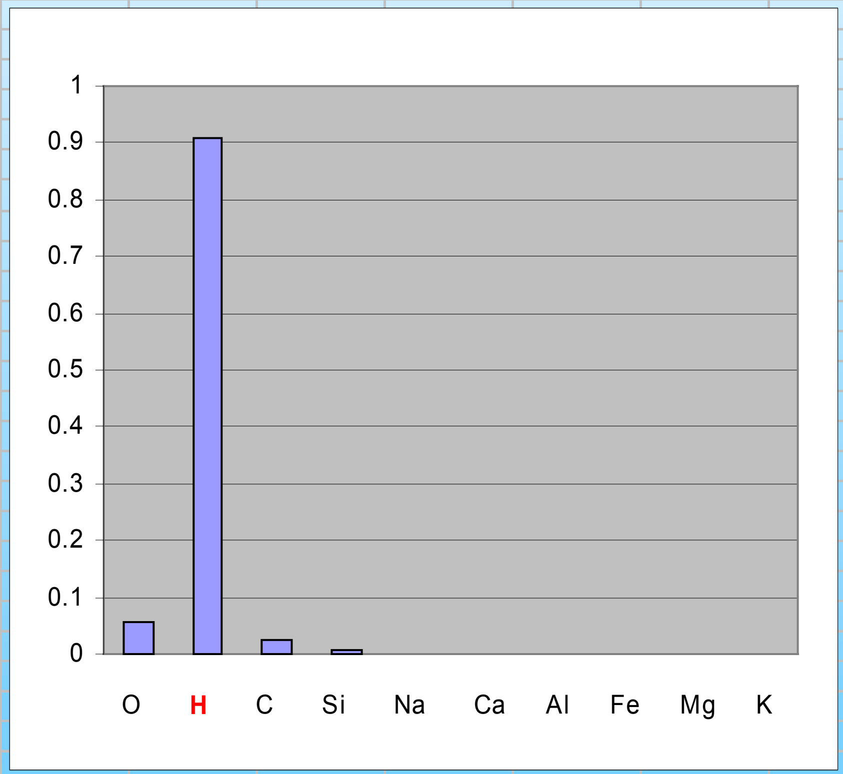
Ouput: contribution of H to total slowing down power of the soil



Moderating power in rocks

Input: soil water wt. %: 10

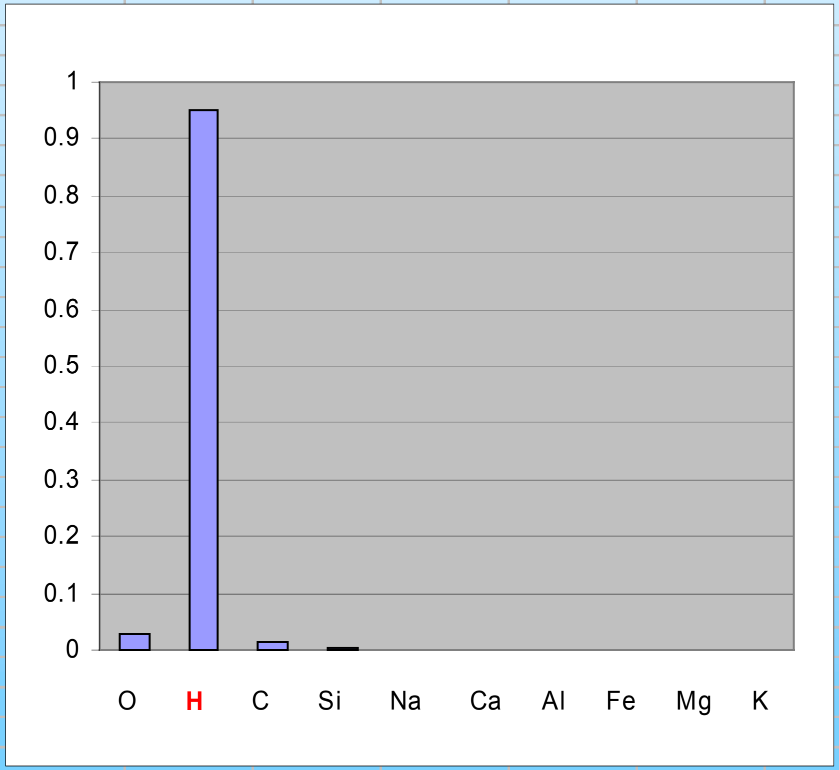
Ouput: contribution of H to total slowing down power of the soil



Moderating power in rocks

Input: soil water wt. %:	20

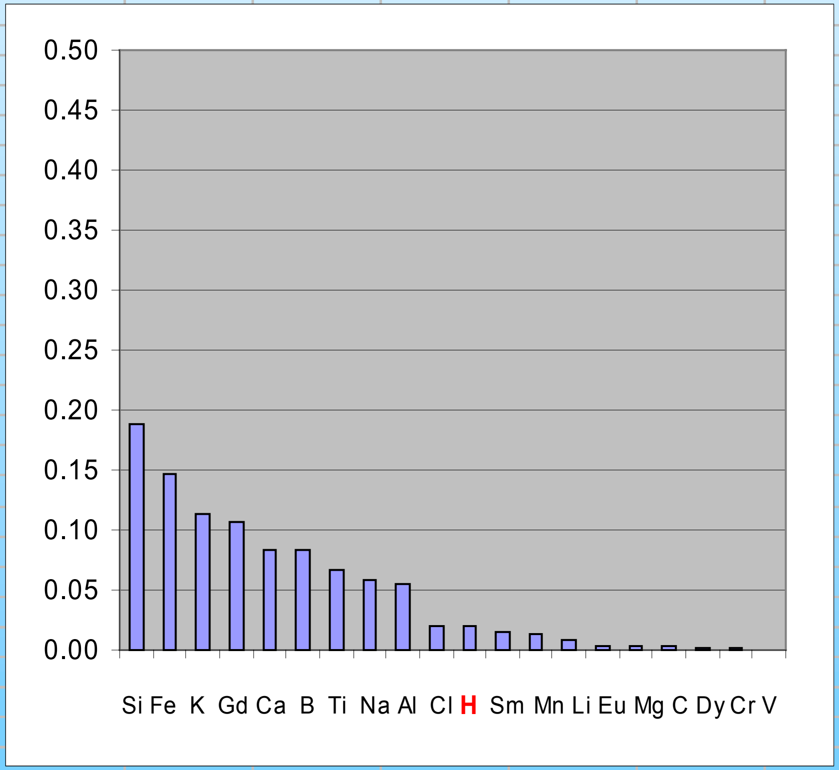
Ouput: contribution of H to total slowing down power of the soil



Absorption power in rocks

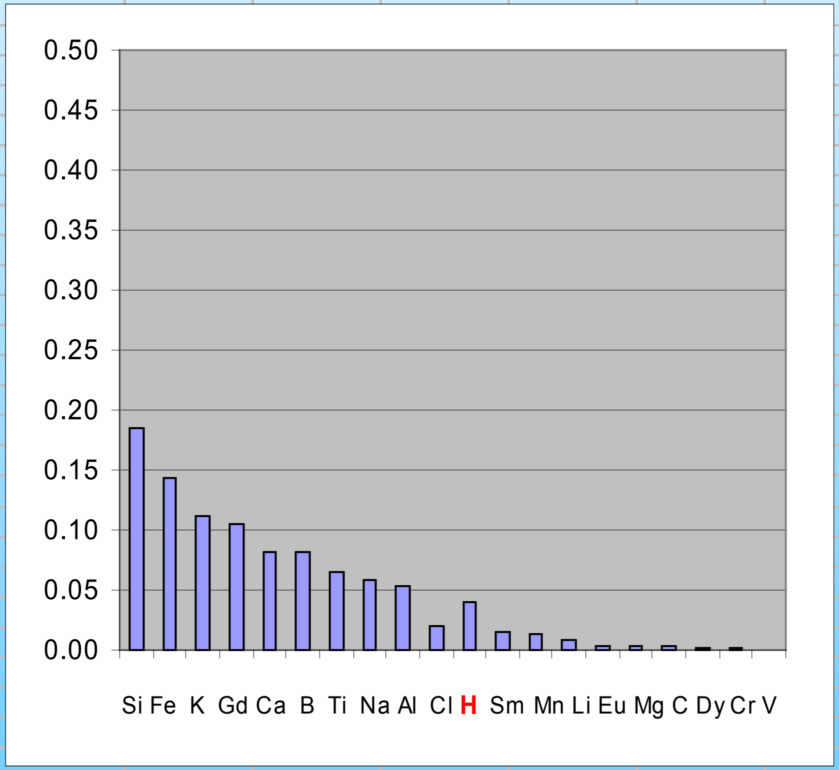
Input: soil water wt. %: 0.5

Ouput: contribution of H to total absorption cross section of the soil

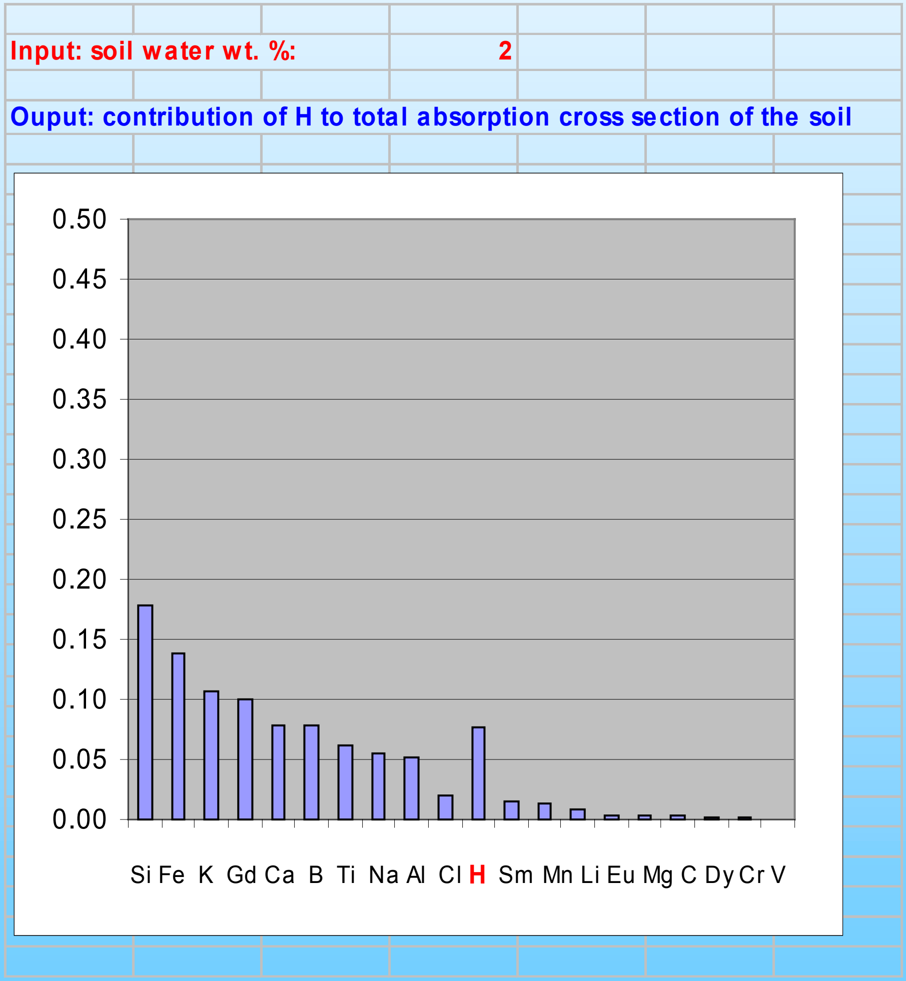


Absorption power in rocks

Input: soil water wt. %:			1			
Ouput: contribution of H to total absorption cross section of the soil						



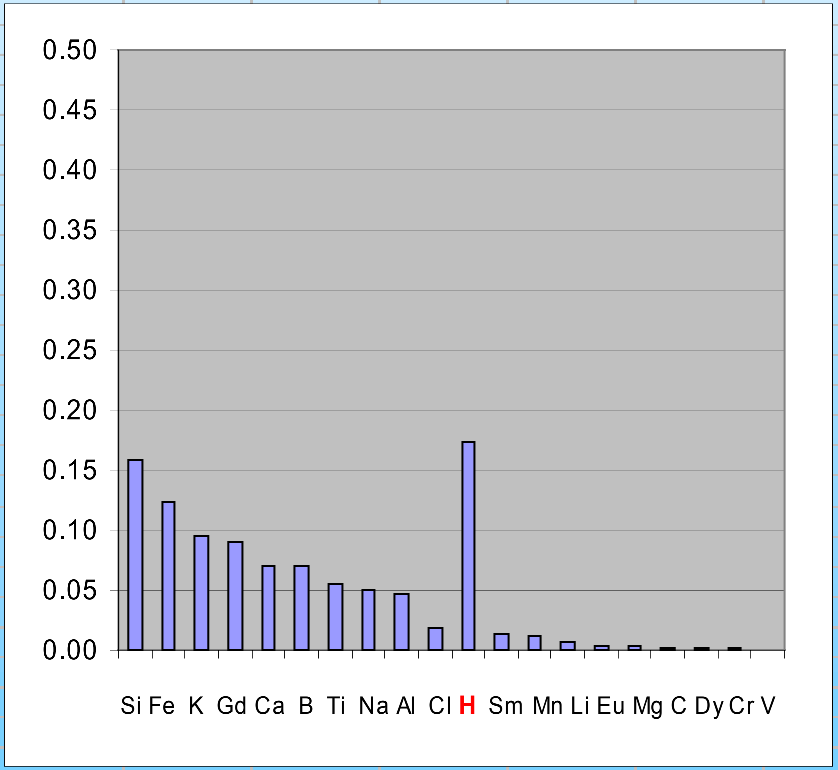
Absorption power in rocks



Absorption power in rocks

Input: soil water wt. %: 5

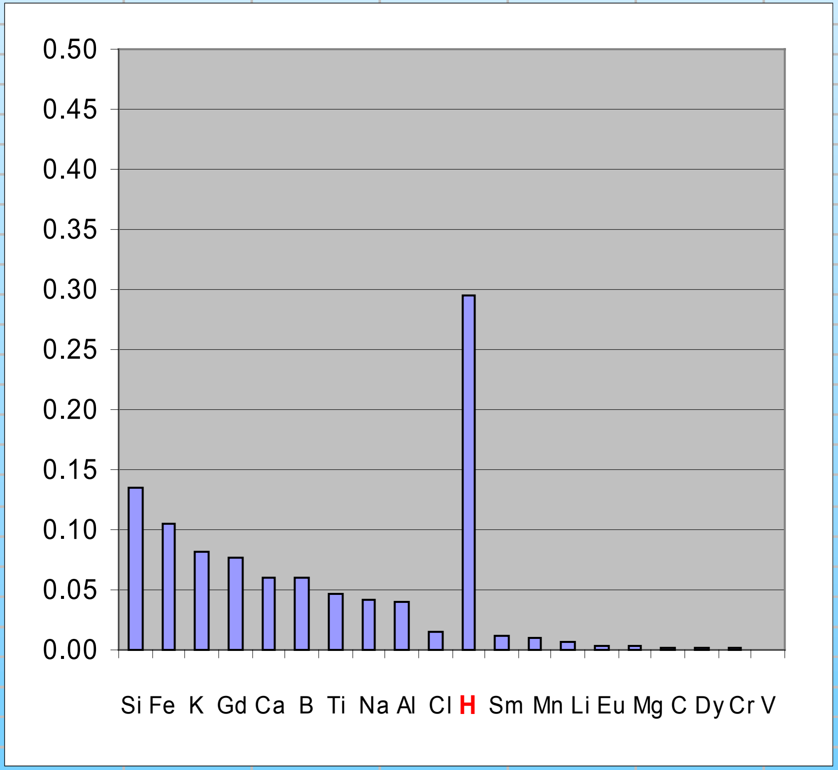
Ouput: contribution of H to total absorption cross section of the soil



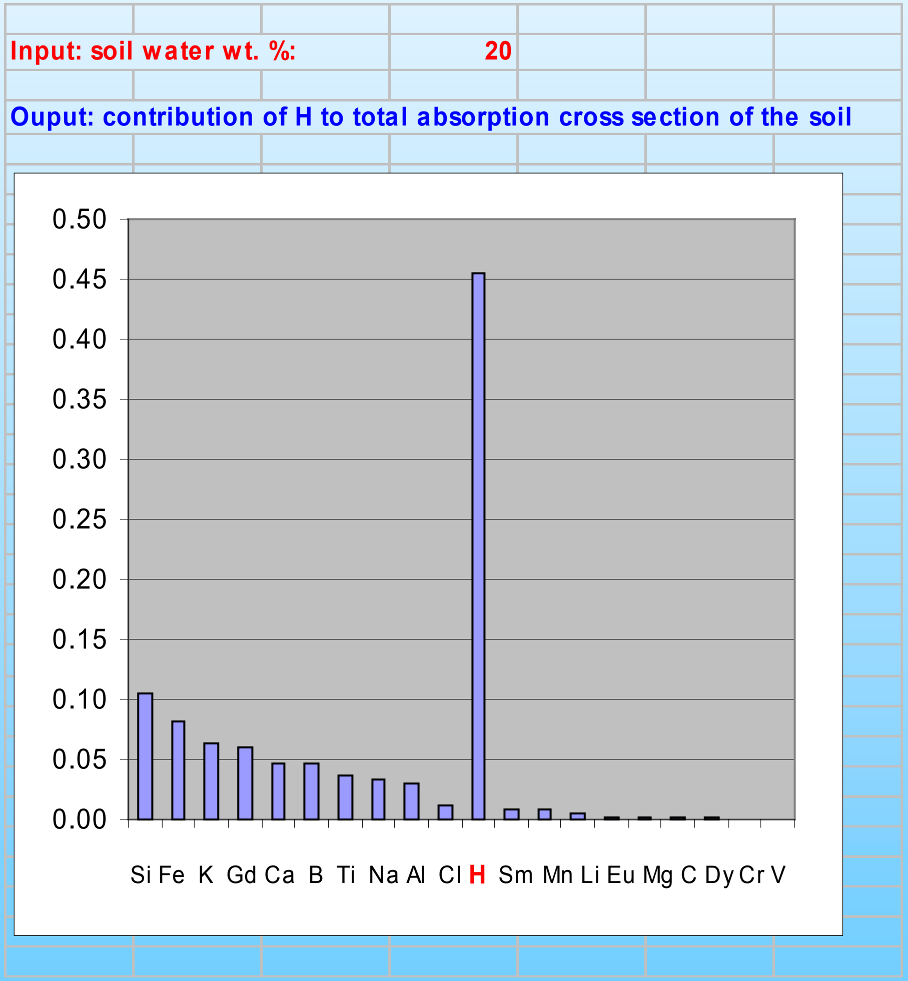
Absorption power in rocks

Input: soil water wt. %:	10

Ouput: contribution of H to total absorption cross section of the soil



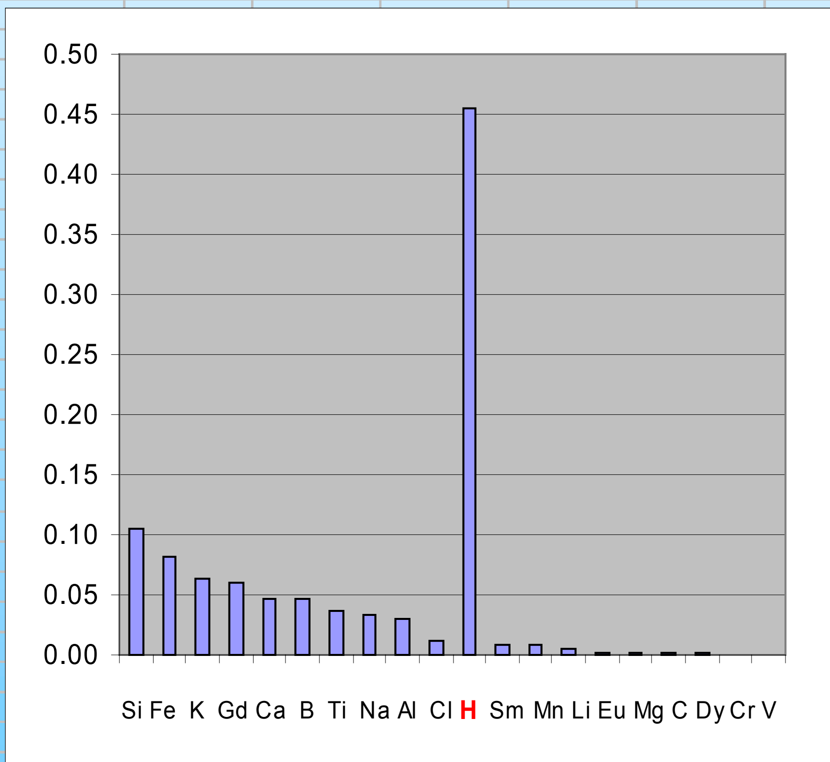
Absorption power in rocks



Absorption and moderating power

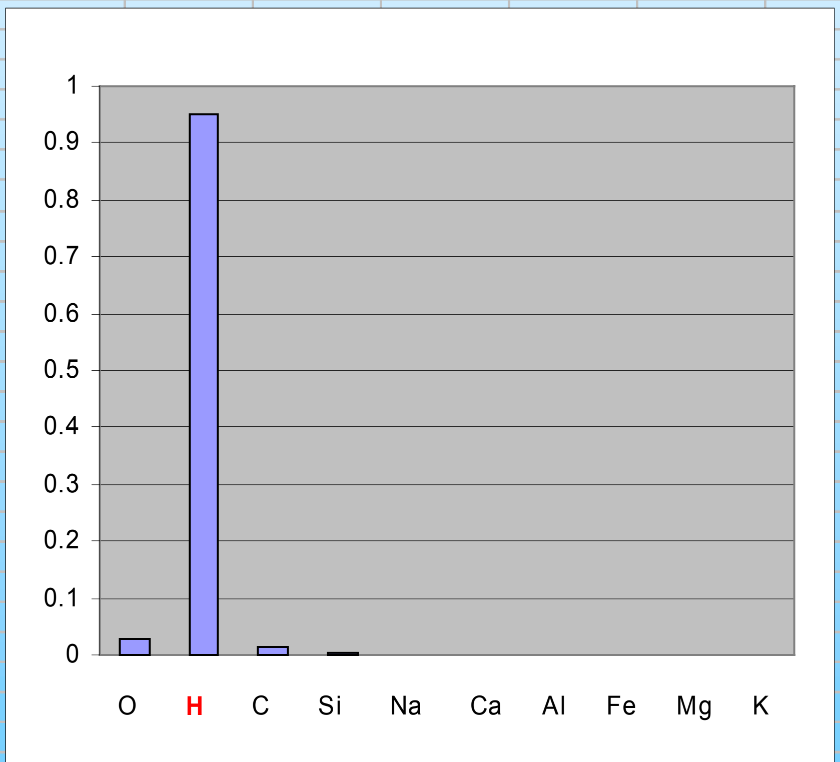
Input: soil water wt. %: 20

Ouput: contribution of H to total absorption cross section of the soil



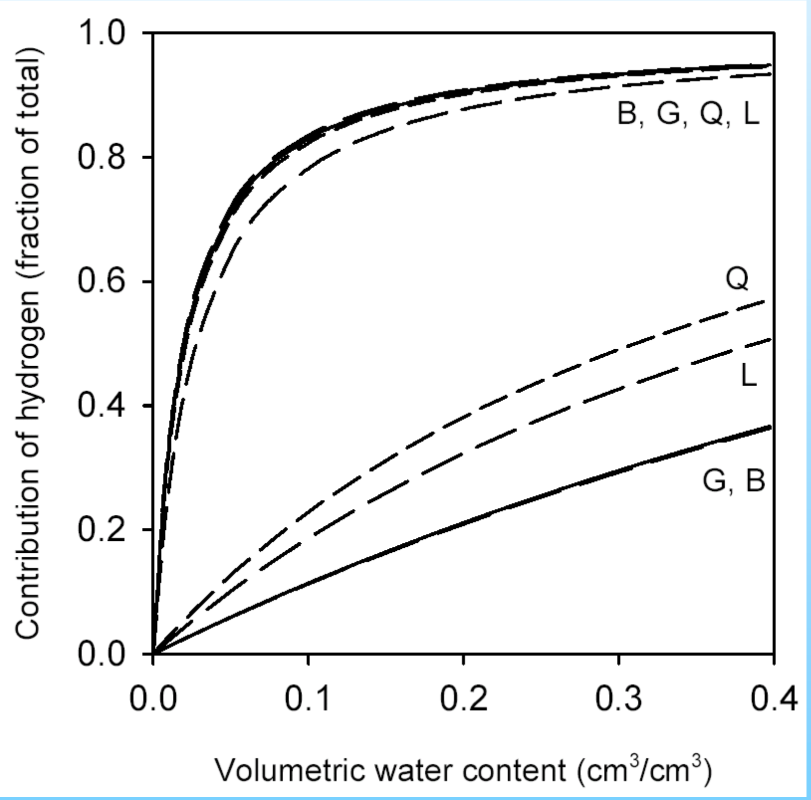
Input: soil water wt. %: 20

Ouput: contribution of H to total slowing down power of the soil



Moderating (slowing) and absorption power

$$\phi\ (\mathrm{E}) = \frac{\mathrm{Q}}{\mathrm{E}\ \Sigma(N \cdot \sigma_{sc} \cdot \xi\ )}$$



ϕ (E) - flux of neutrons of energy E

Q - strength of source function

N - number of atoms of an element

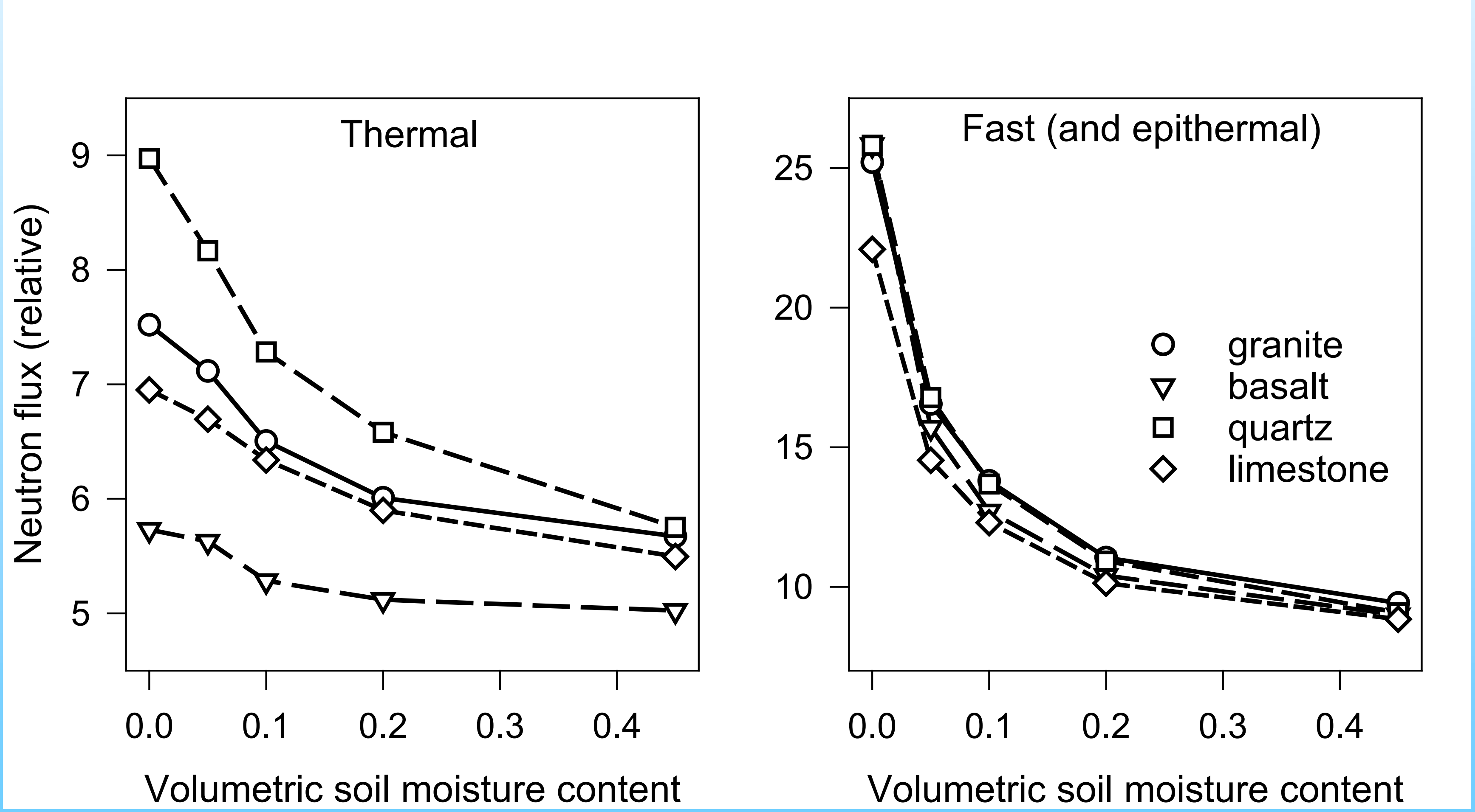
σ_{sc} - scattering cross section for an element

ξ - log decrement of energy per collision

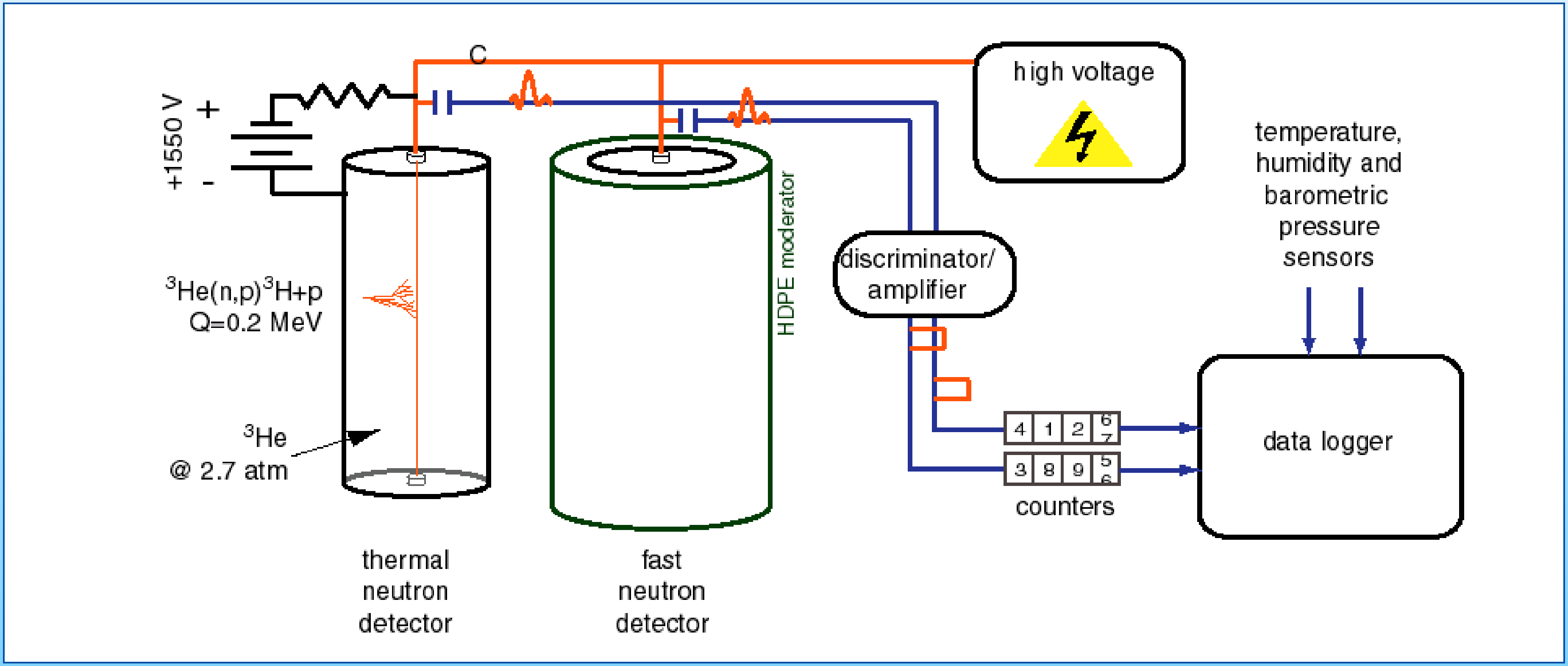
$\sigma_{sc} \cdot \xi$ - slowing down power for an element

$\Sigma(\mathrm{N} \cdot \sigma_{sc} \cdot \xi)$ - slowing-down power of the medium

Neutron response to soil moisture



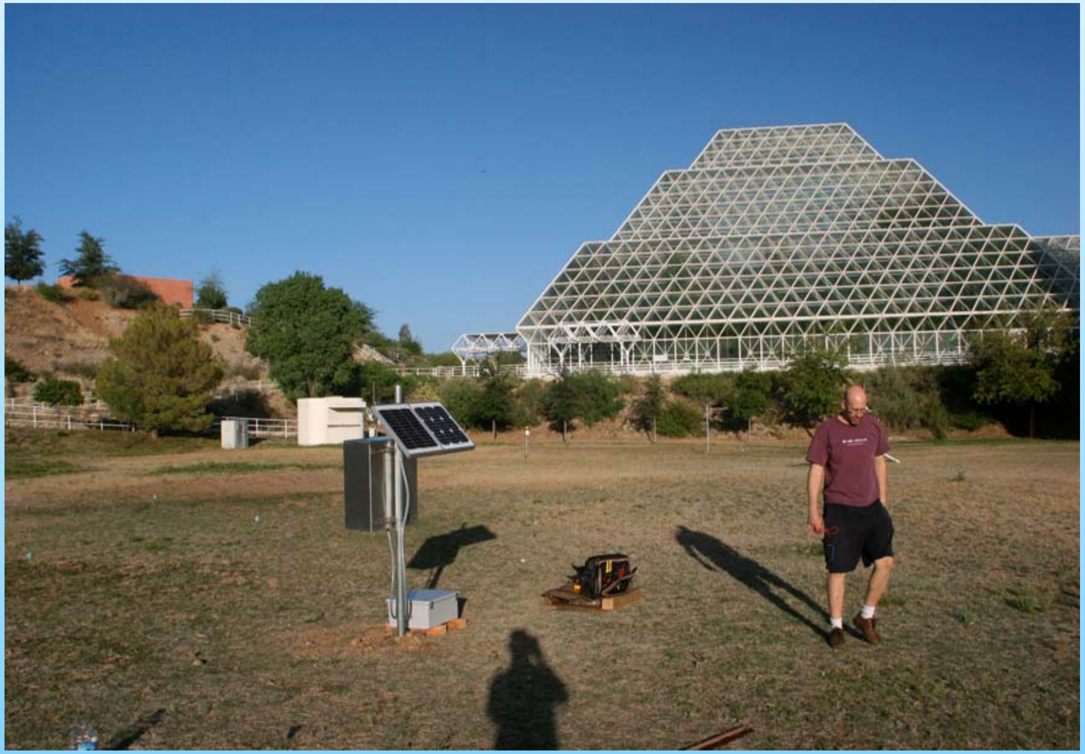
Measurement device: cosmic-ray probe



Cosmic-ray probe, 2007

Generation 2007; used in the San Pedro River valley, near Sierra Vista, Arizona

Cosmic-ray probe, 2008-1

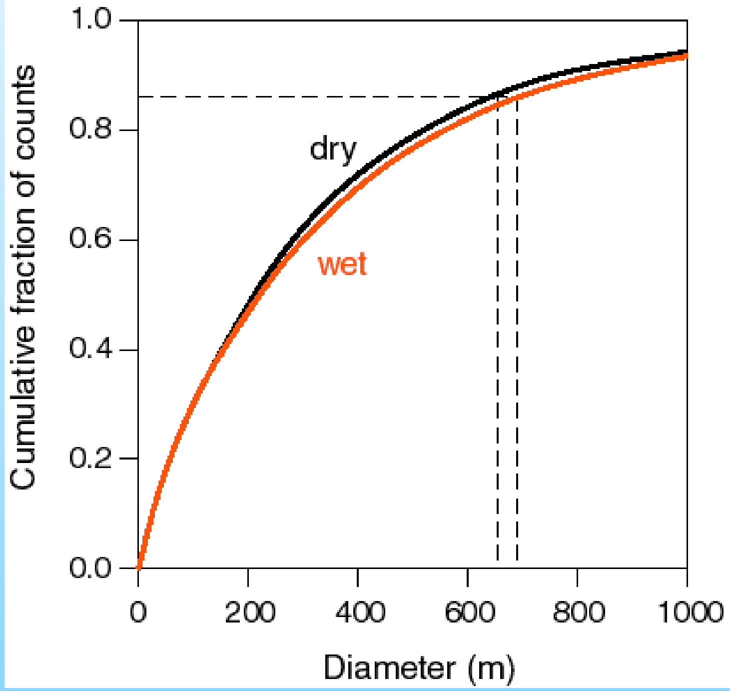


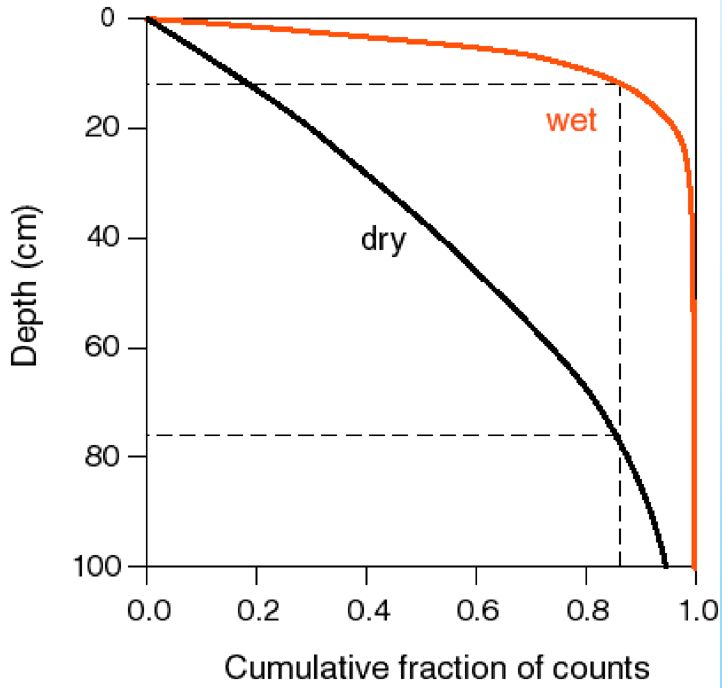
Generation 2008-1 (the COSMOS demo probe); used in the Biosphere 2.

Cosmic-ray probe, 2008-2

Generation 2008-2 (the COSMOS probe); used in the Avra Valley

Measurement volume (modeled)





• 86% of neutrons within radius of 350 m

•Radius increases with decreasing pressure

• 86% of neutrons within depth of 60 cm

• Depth decreases to 12 cm in wet soils

Field confirmation of footprint - setup

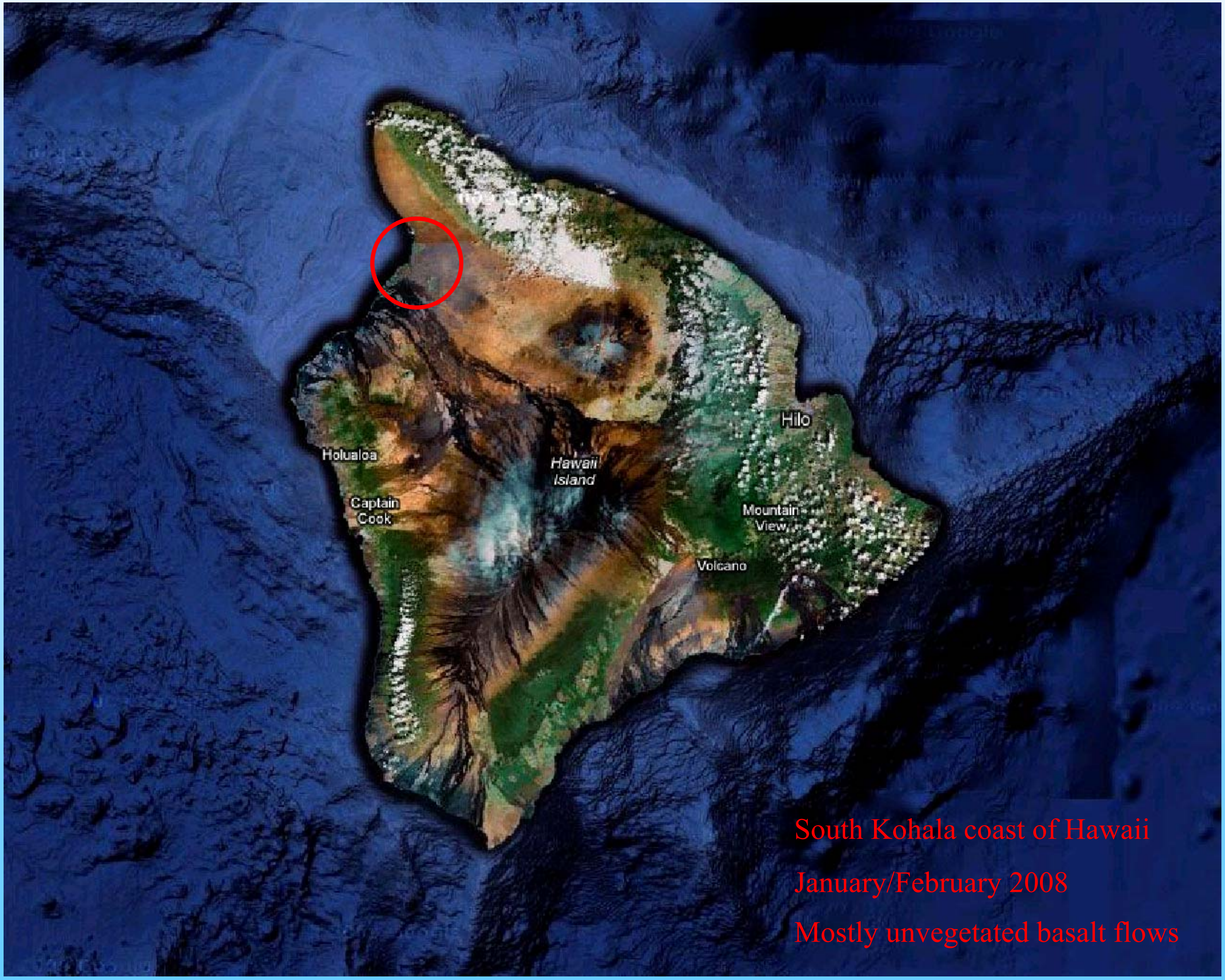
Coastal transect of neutron intensity:

(1) Measurements on South Kohala coast of Hawaii in January 2008

(2) Unmoderated and moderated (2.5 cm HDPE; picture) ^{3}He tubes (i.e., thermal and epithermal neutrons)

(3) Measurements primarily on unvegetated basalt flows

Field confirmation of footprint - Hawaii



Field confirmation of footprint - sites

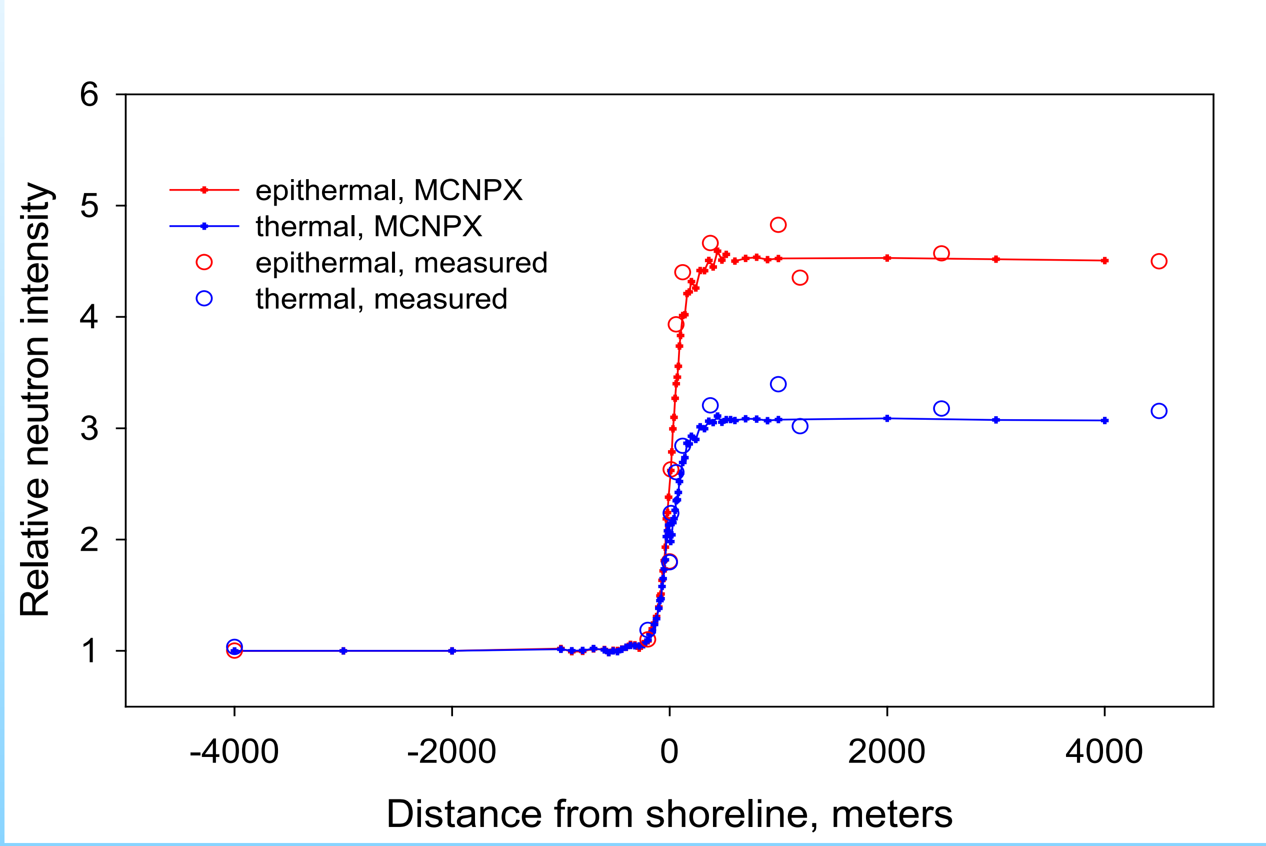
Field confirmation of footprint - sites

Field confirmation of footprint - sites

Field confirmation of footprint - sites

Field confirmation of footprint - sites

Field confirmation of footprint - results

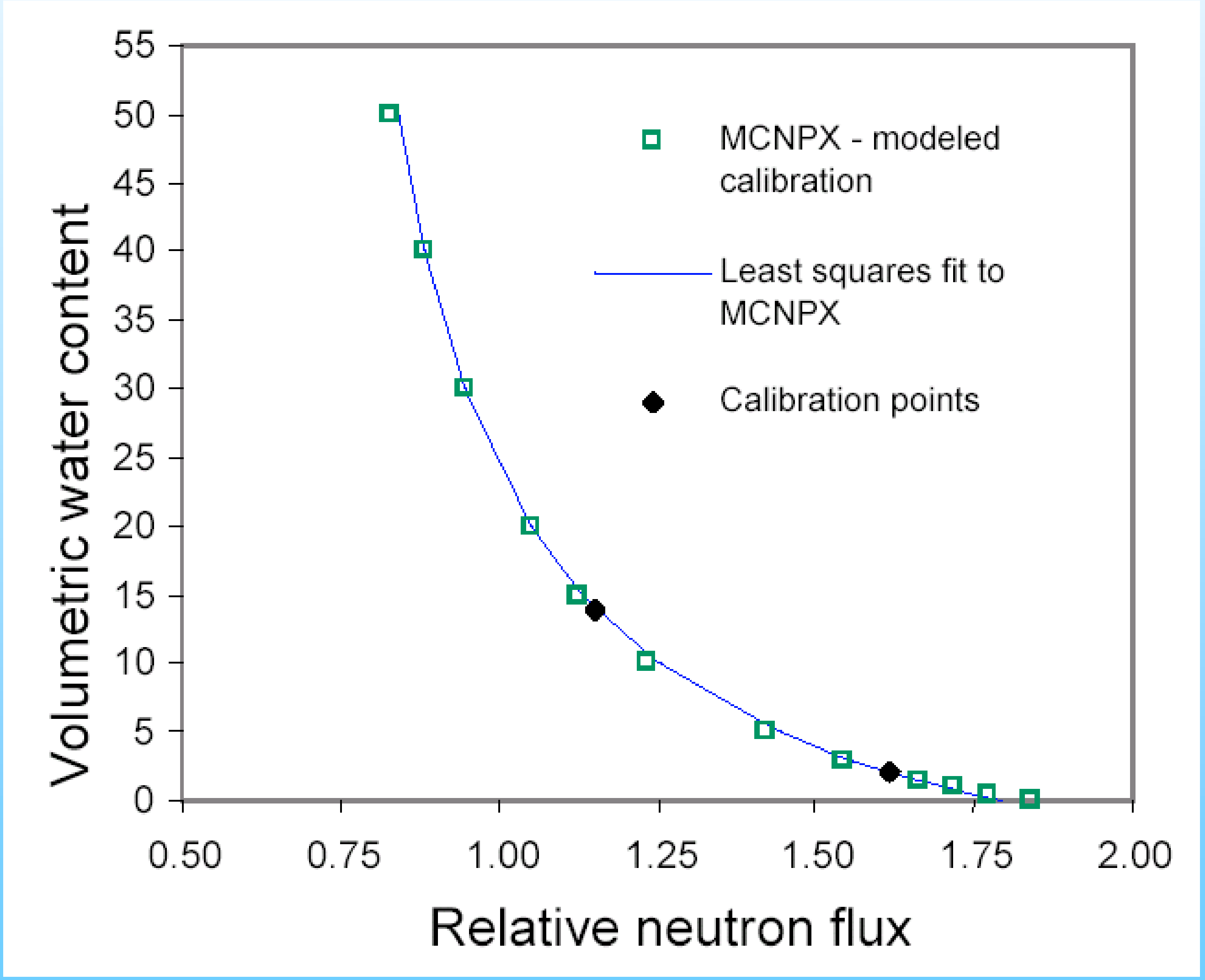


Conclusions from transect

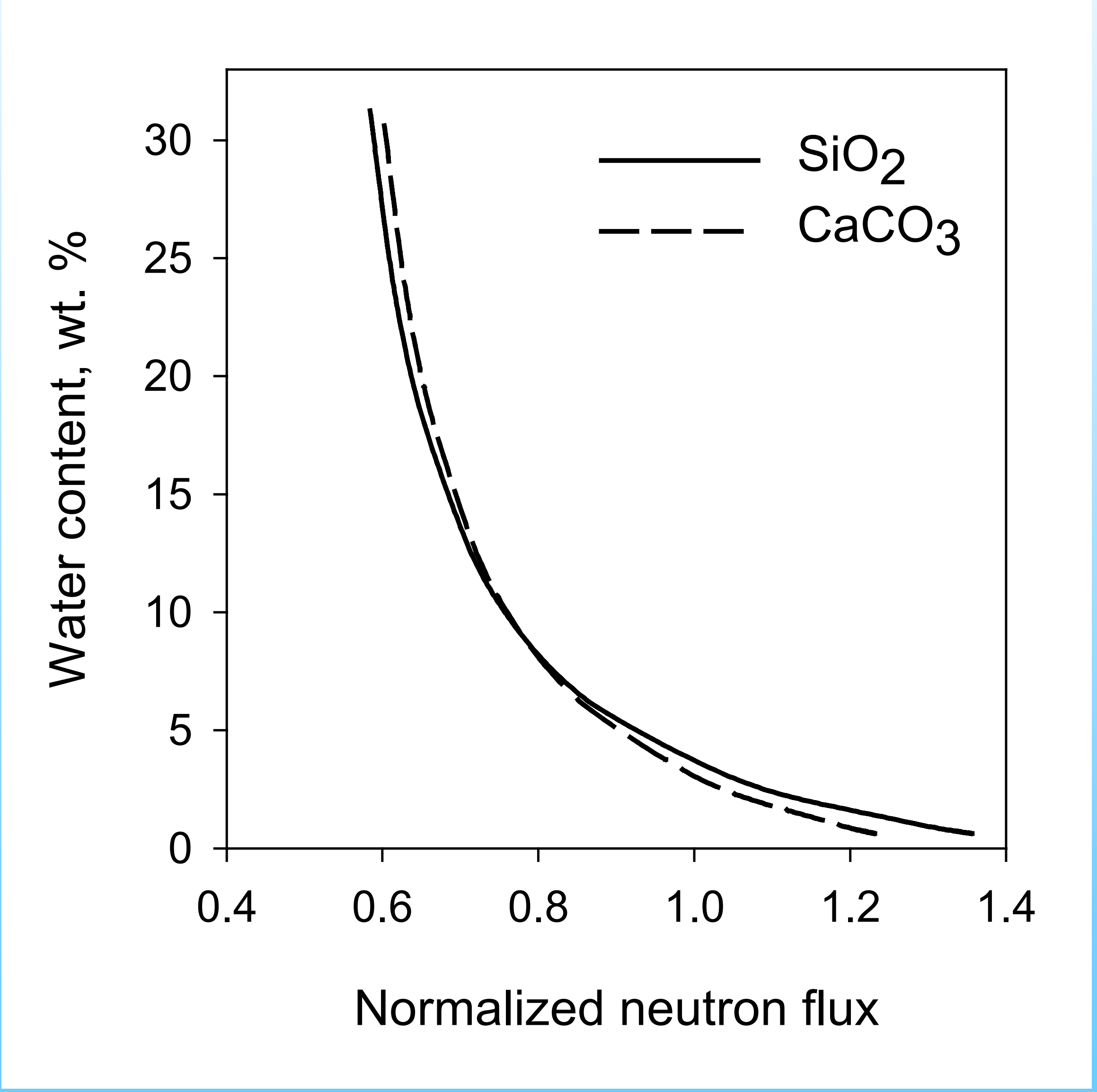
(1) MCNPX can accurately model neutron fluxes near bodies of water

(2) "radius of influence" for low-energy neutrons is approximately 350 m

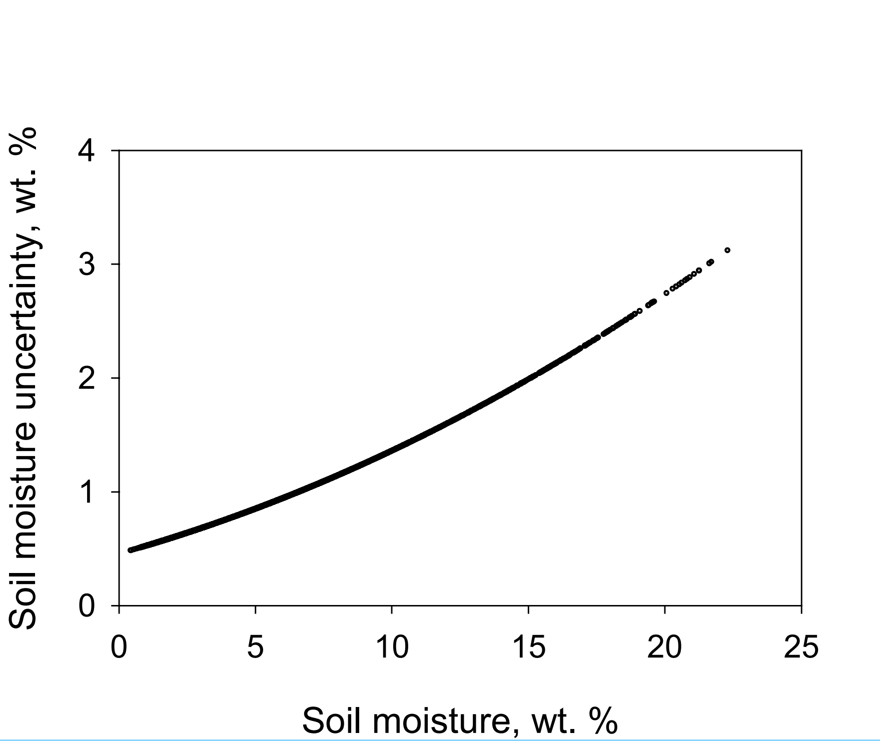
Calibration function

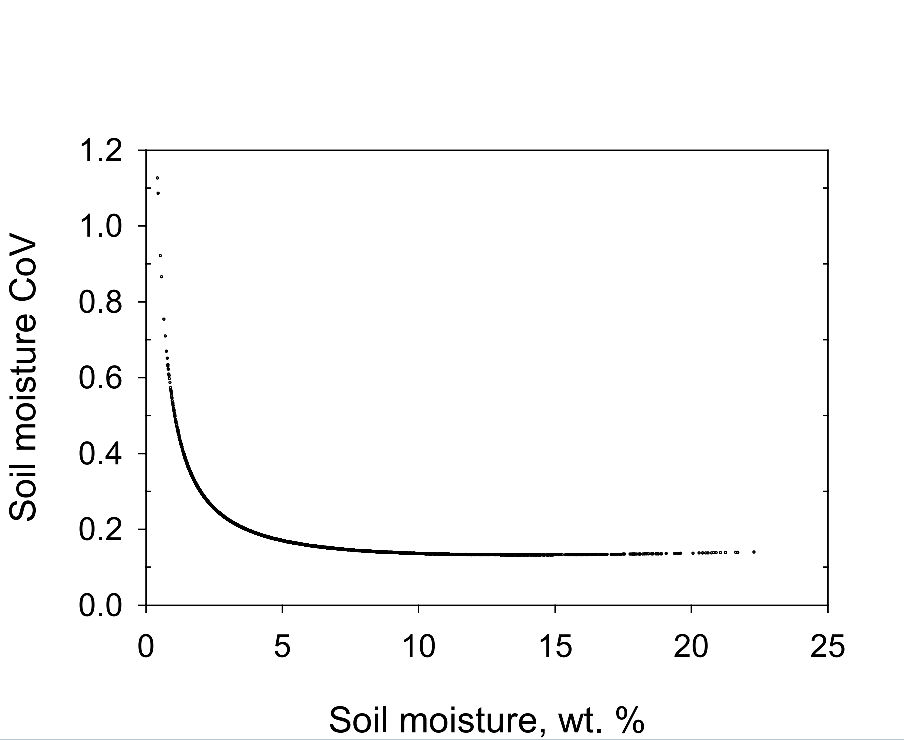


Universal calibration function?



Precision of COSMOS probe





Based on the measurements in the San Pedro River valley, Arizona, 2007-2008

Checking calibration

Table 1. Results of preliminary calibration and validation experiments for the cosmic-ray probe installed in the San Pedro River valley, SE of Tucson, Arizona. Soil moisture contents are in weight percent. Figures in square brackets show the difference between cosmic-ray moisture and average gravimetric moisture.

Gravimetric water content (wt. %)	**14.0±0.8** [a,b]	**7.8±0.5** [a,c]	**2.0±0.3** [a,d]
Experiment 1	Calibration sample	6.2±1.2 [e] [-1.6] [f]	2.2±0.9 [+0.2]
Experiment 2	17.0±2.1 **[+3.0]**	Calibration sample	3.1±1.0 [+1.1]
Experiment 3	13.1±1.5 [-0.9]	6.0±1.0 **[-1.8]**	Calibration point
Experiment 4	Calibration point	6.0±1.0 **[-1.8]**	Calibration point
Experiment 5	Calibration point	Calibration point	2.8±1.0 [+0.8]
Experiment 6	14.7±2.0 [+0.7]	Calibration point	Calibration point

Table notes:
(a) Uncertainty is one standard error of the mean based on between 48 and 63 gravimetric samples.
(b) Samples collected on 7 August 2007, after one month of summer rains.
(c) Samples collected on 6 December 2008, ten days after a day-long rain.
(d) Samples collected on 5 July 2007, just before the first summer rain, and following months without rain.
(e) Uncertainty based on counting statistics of hourly counts. Longer counts would reduce this uncertainty.
(f) Bold letters indicate those experiments in which the difference is significant at one sigma level.

Variations of the cosmic-ray intensity

In space:

with latitude and longitude (geomagnetic cutoff rigidity)

with altitude (pressure)

with depth (mass) - not important for this application

In time:

due to pole position changes

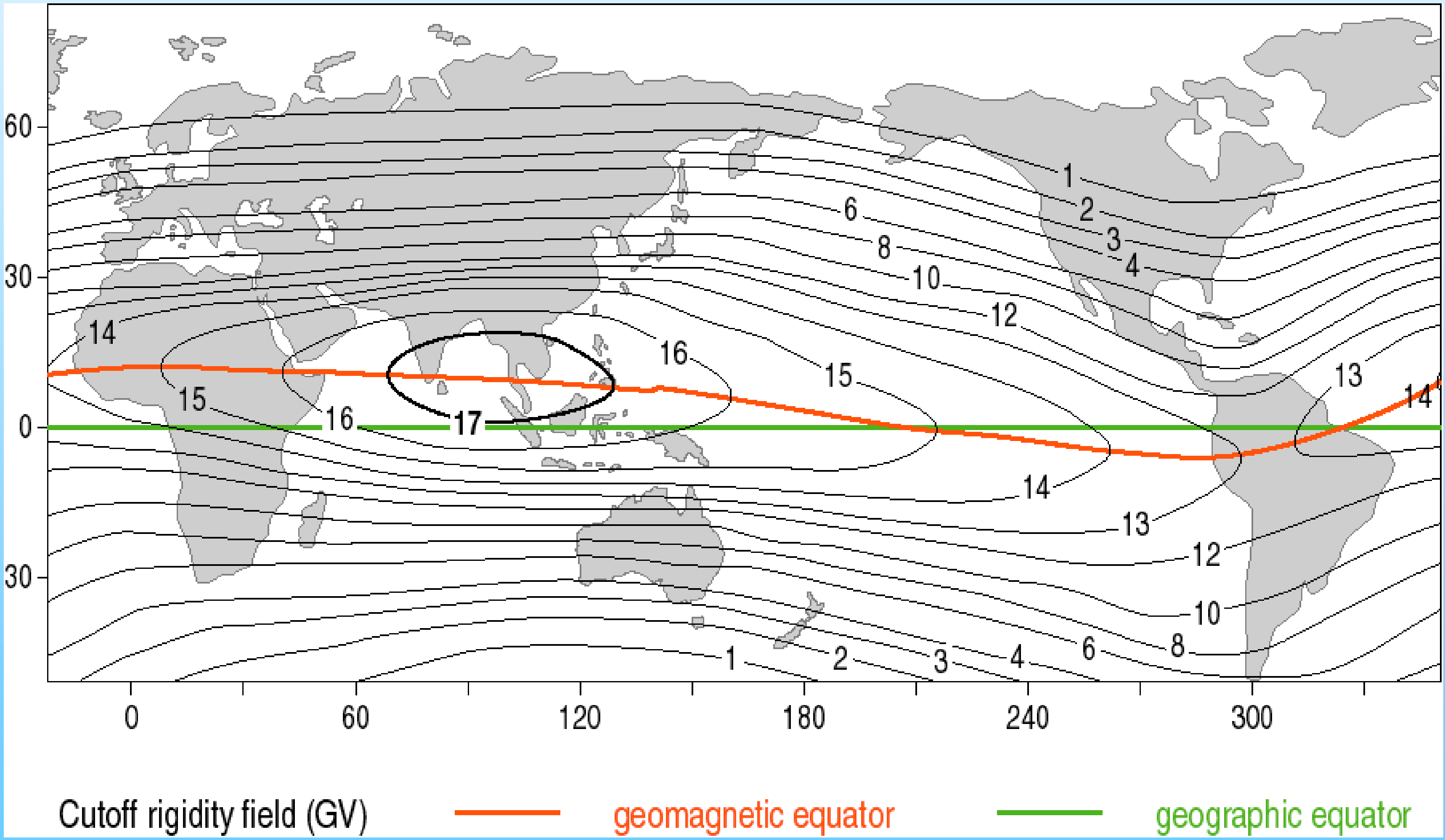
due to solar activity

due to barometric pressure changes

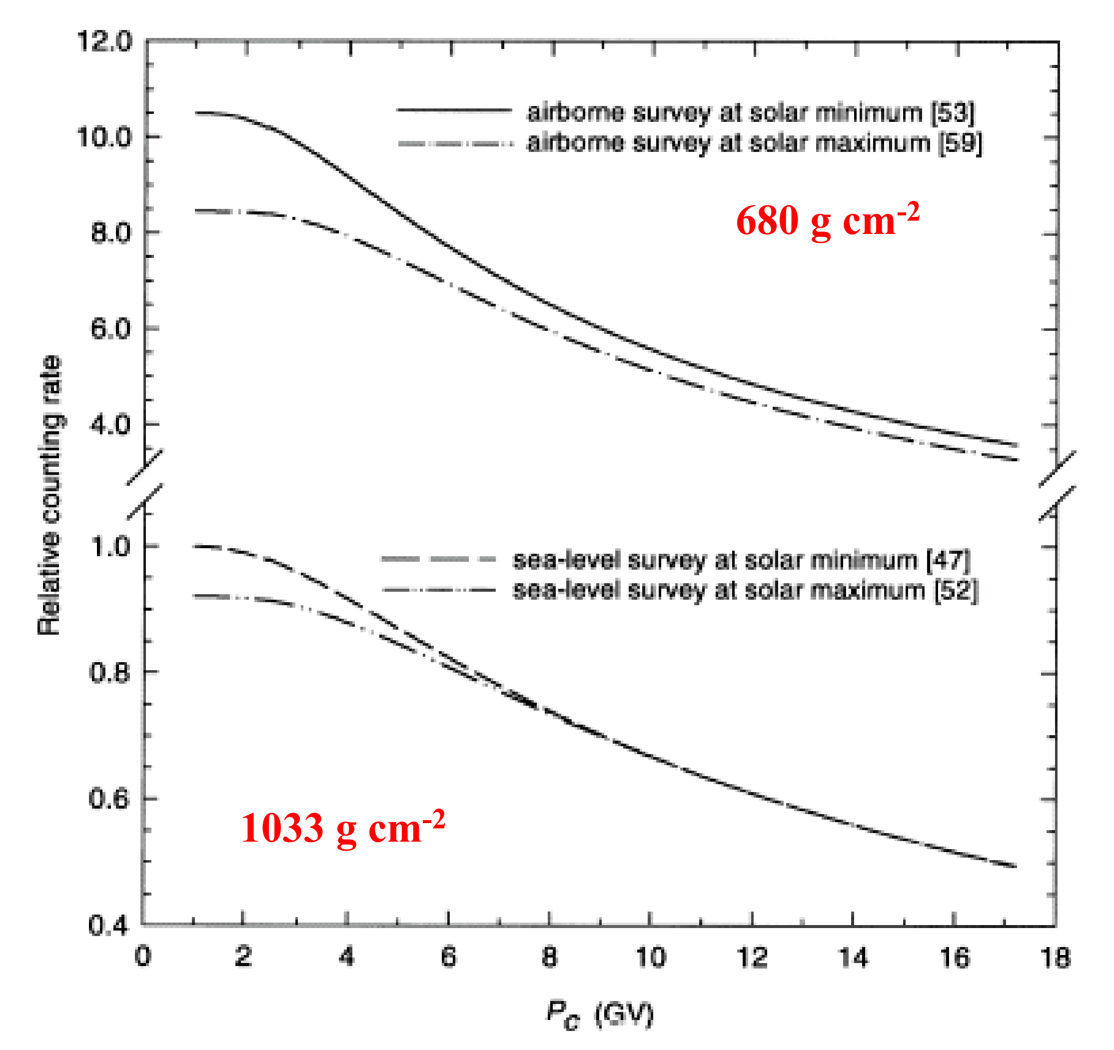
due to paleomagnetic intensity changes - not important

due to long-term galactic cosmic-ray flux changes - not important

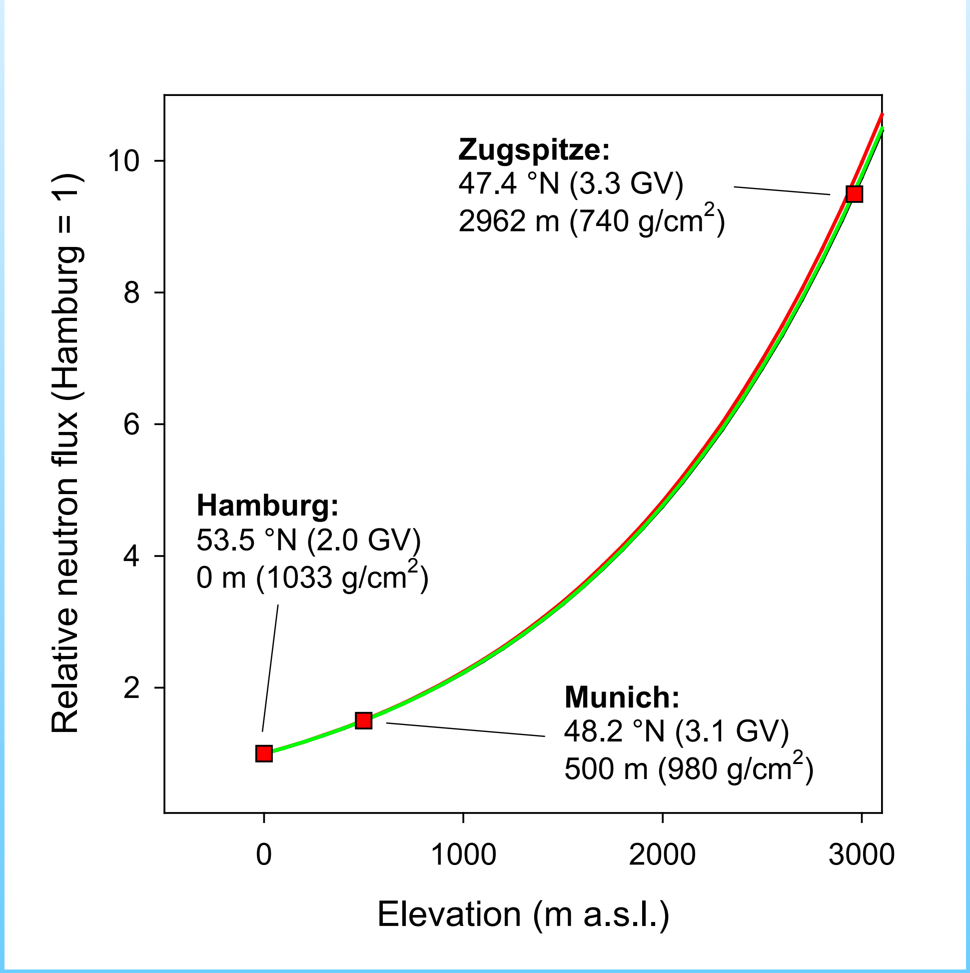
Vertical cutoff rigidity for Epoch 1980



Variations with latitude (cutoff rigidity)



Variations with altitude (pressure)



Temporal variations of cosmic-ray intensity

Due to **changes in the location of the magnetic poles**:

very important at some locations, on temporal scales of years and decades

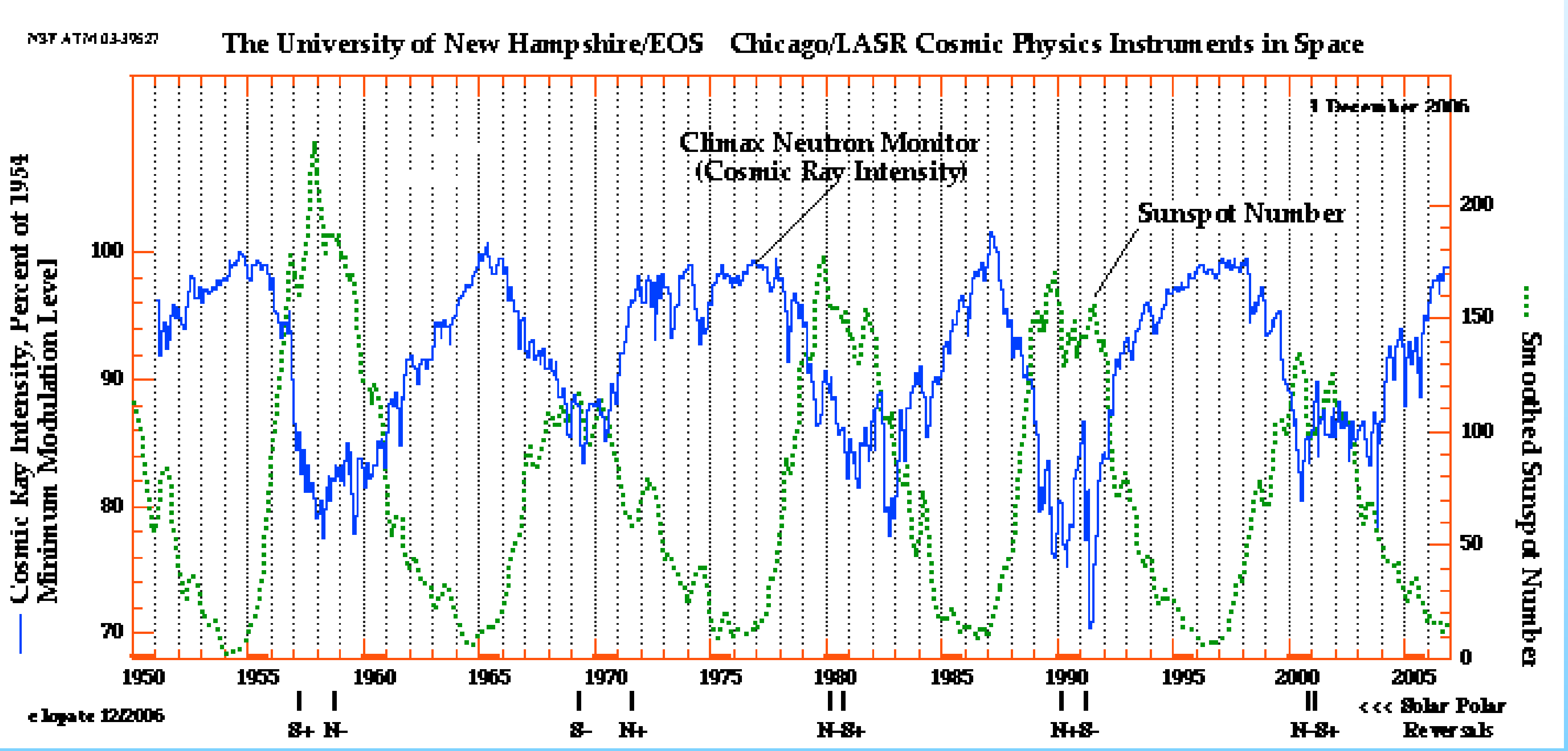
Due to **solar activity**:

important at different temporal scales, e.g., 11-year cycle and diurnal

Due to **barometric pressure changes**:

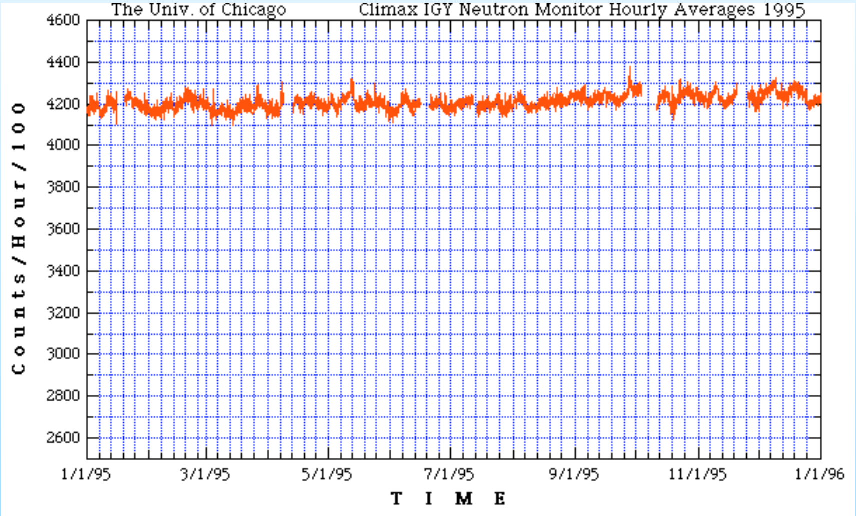
important where changes are more than a few millibars

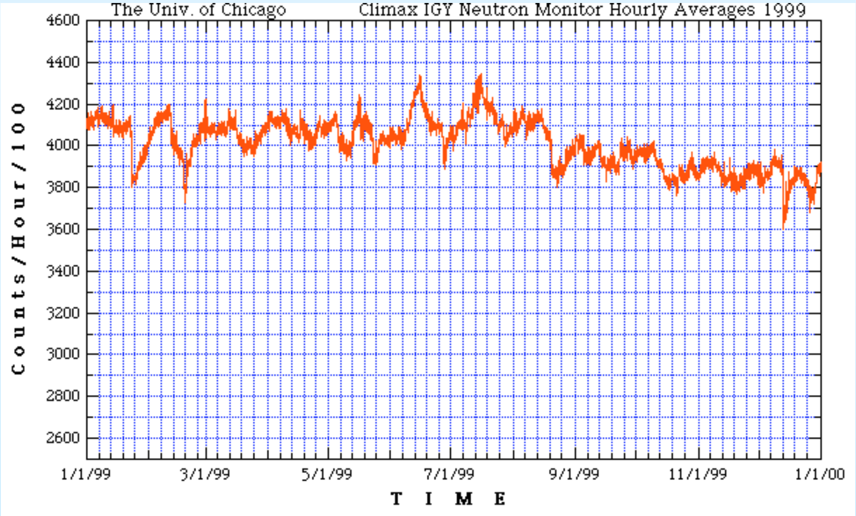
Temporal variations of neutron intensity

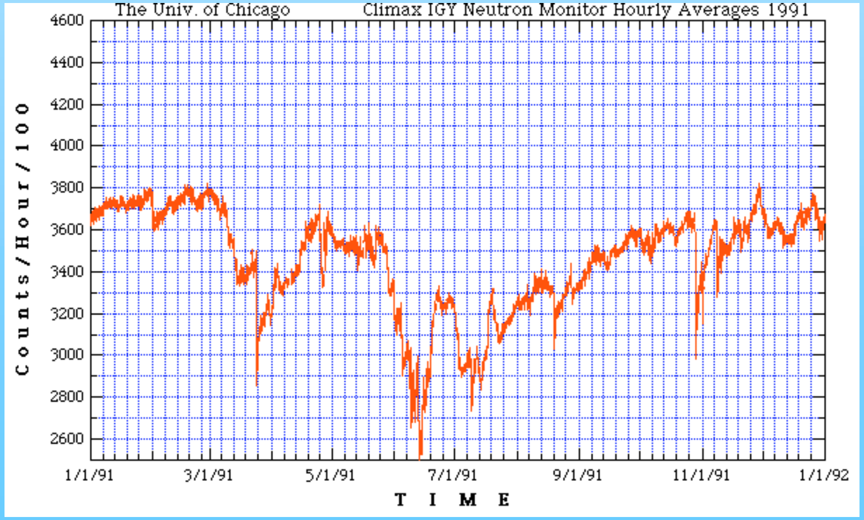


Long-term variations (55 years, five 11-year solar cycles): ca. 30%

Temporal variations of neutron intensity

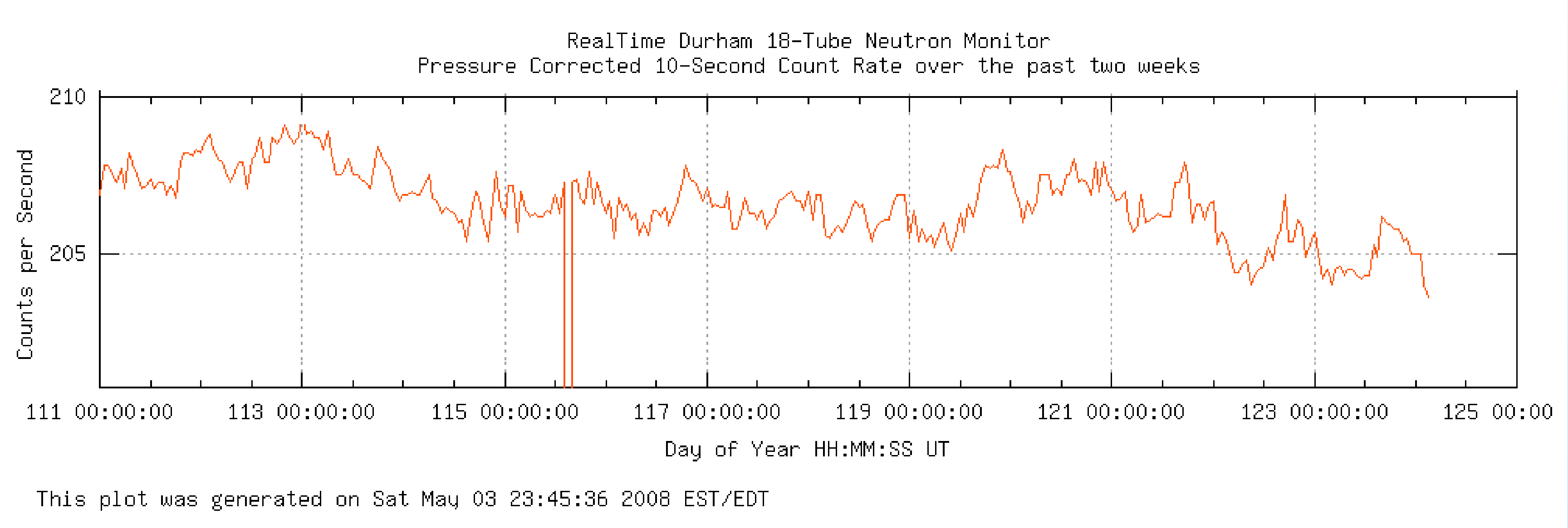






Short-term variations (1 year):
- quiet year: 10%
- active year: 20%
- crazy year: 30%

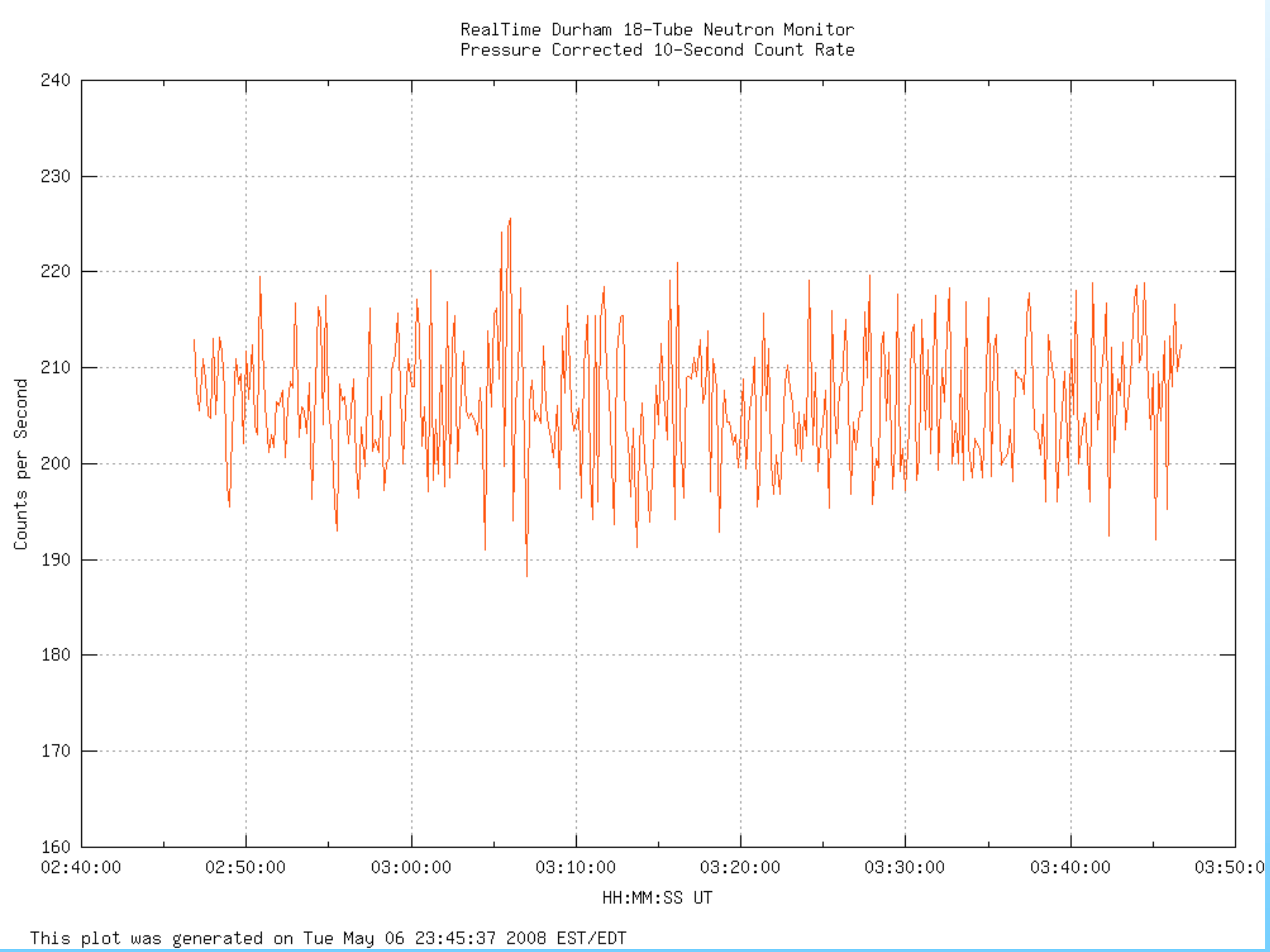
Temporal variations of neutron intensity



Very-short-term variations (2 weeks): 3%
[Including diurnal fluctuations: less than 1%]

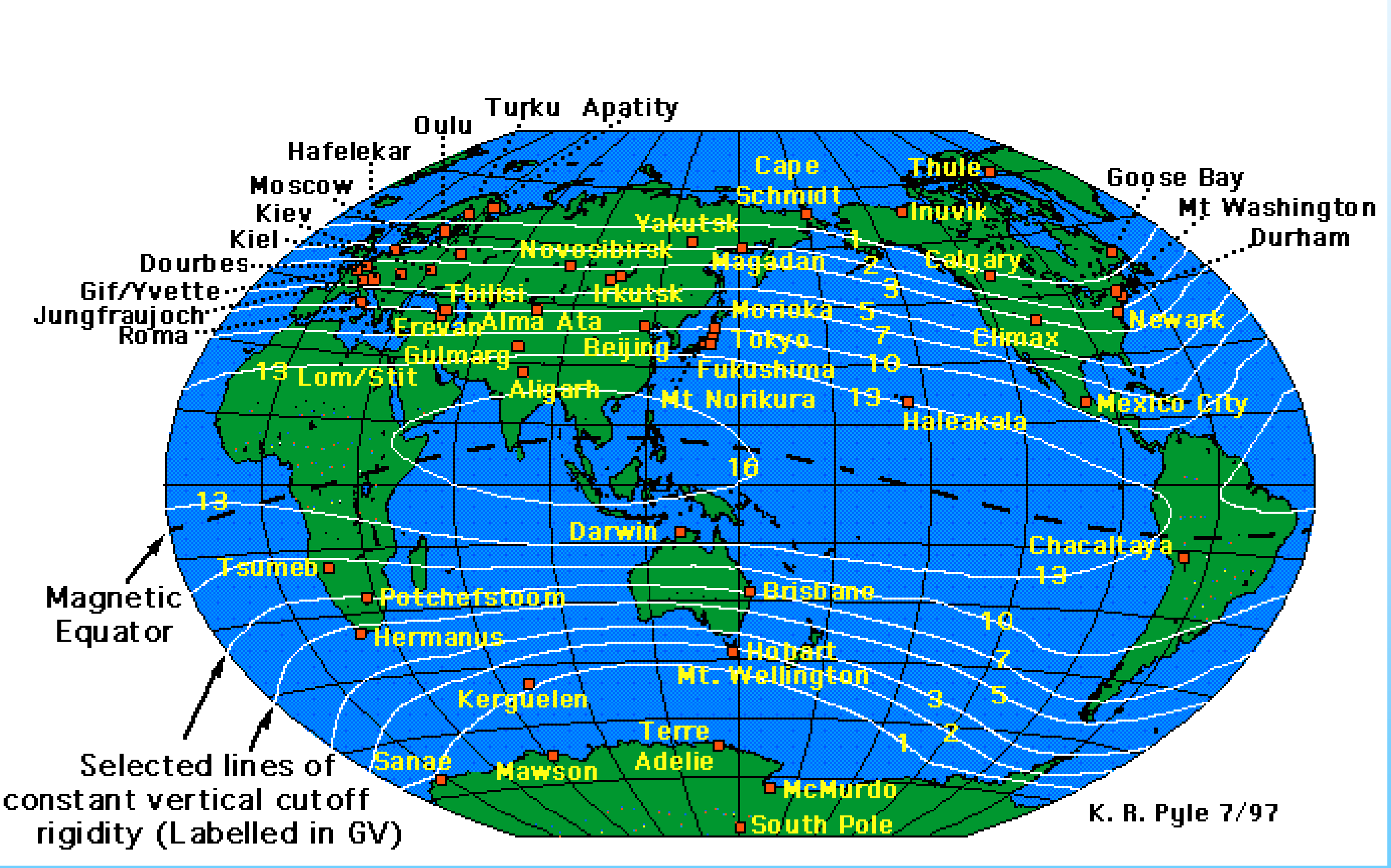
(Note count rate drop after day 115 - possibly power failure)

Temporal variations of neutron intensity



Instantaneous: counting statistics, depends on detector size

Cosmic-ray neutron monitors (2007)

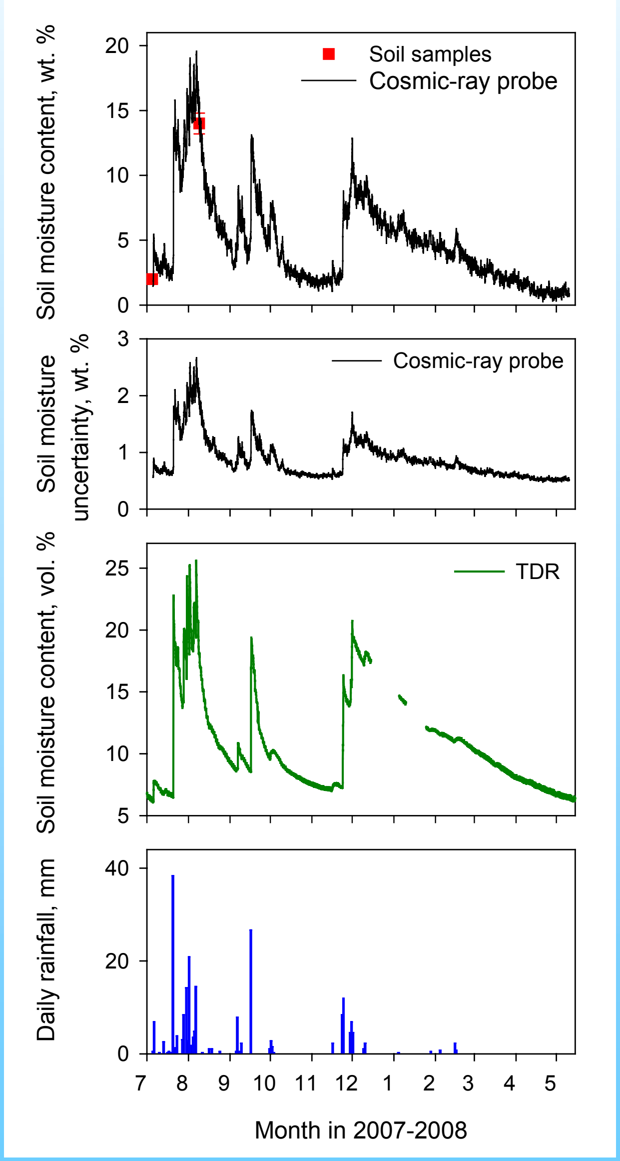


ulysses.sr.unh.edu/NeutronMonitor

Field application - San Pedro River, AZ

- Derived soil moisture from cosmic-ray neutron data
- Compared with gravimetric samples
- With TDR results
- And with precipitation amounts

Cosmic-ray probe, San Pedro River valley, AZ



Other examples

<u>Soil moisture:</u>

Mount Lemmon

Biosphere 2

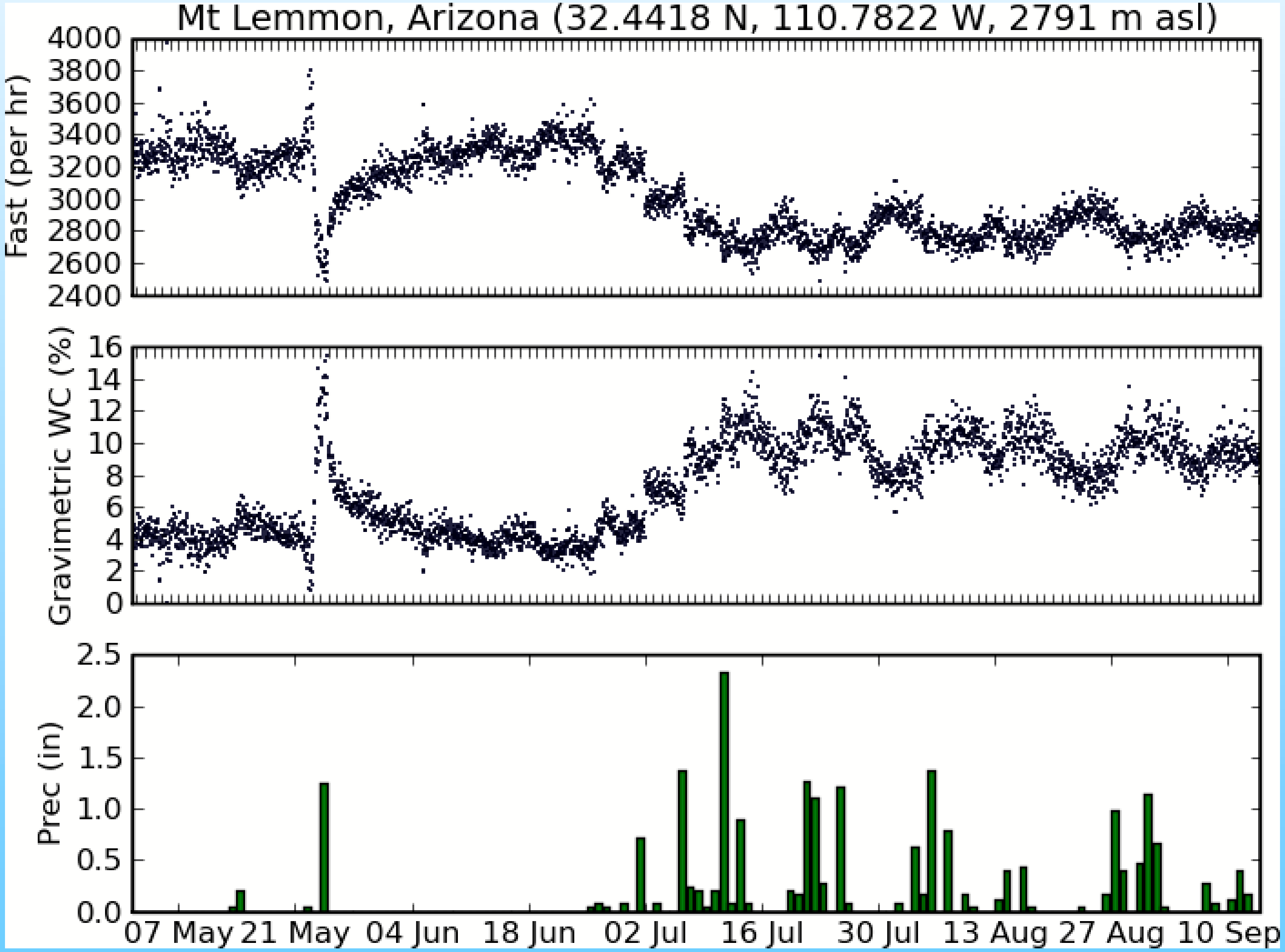
San Pedro

<u>Snow-pack water equivalent:</u>

Mount Lemmon

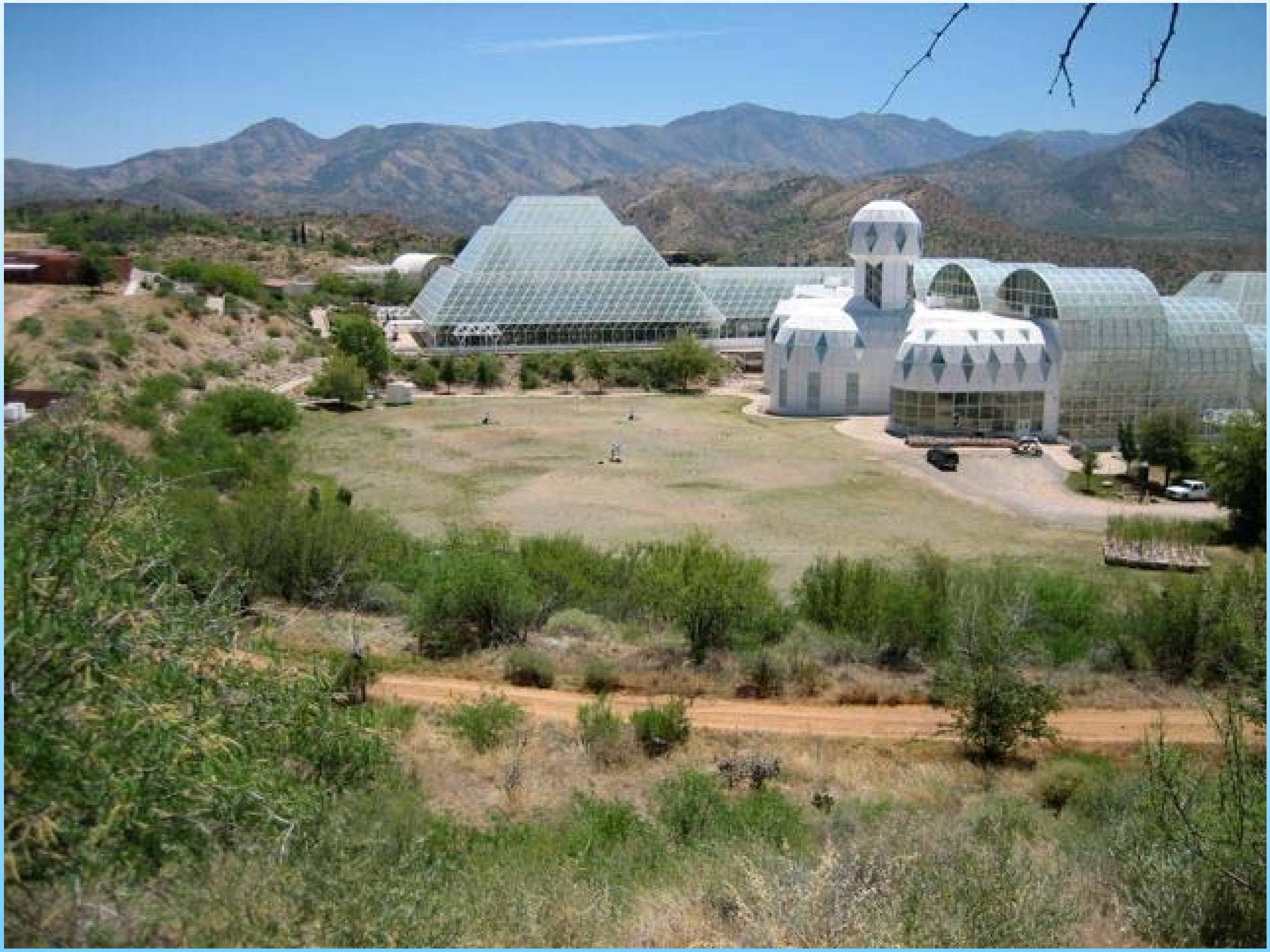
Vallez Caldera

Real-time data - Mt. Lemmon, Arizona

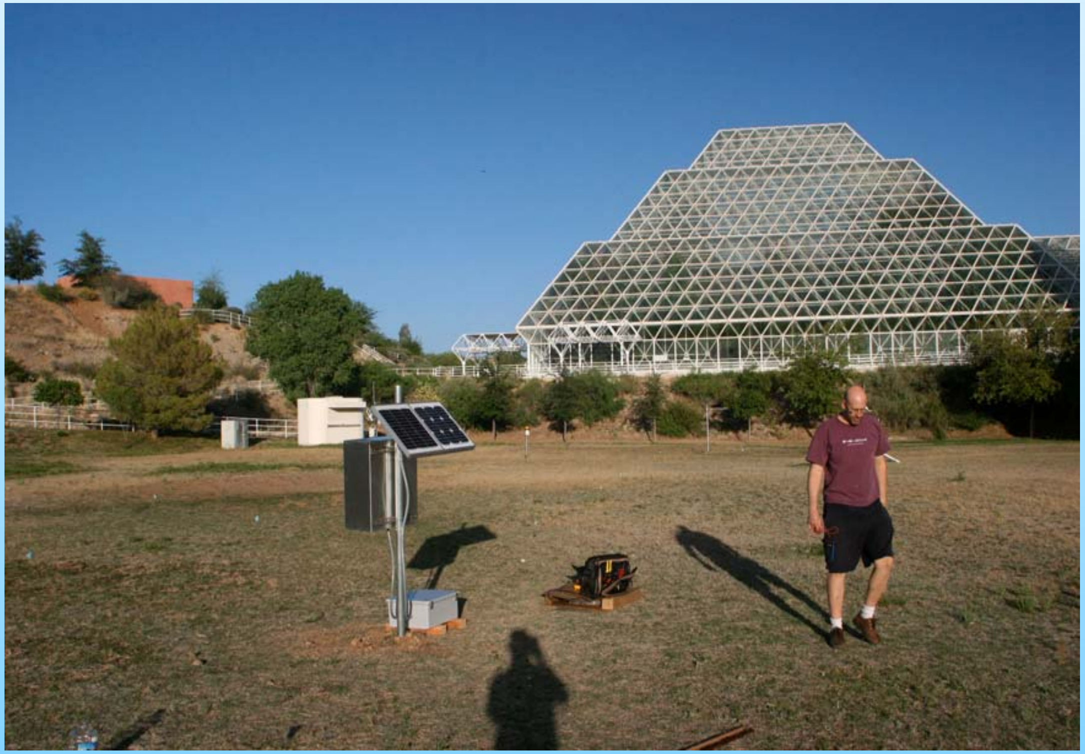


Real-time data - Biosphere 2, Arizona

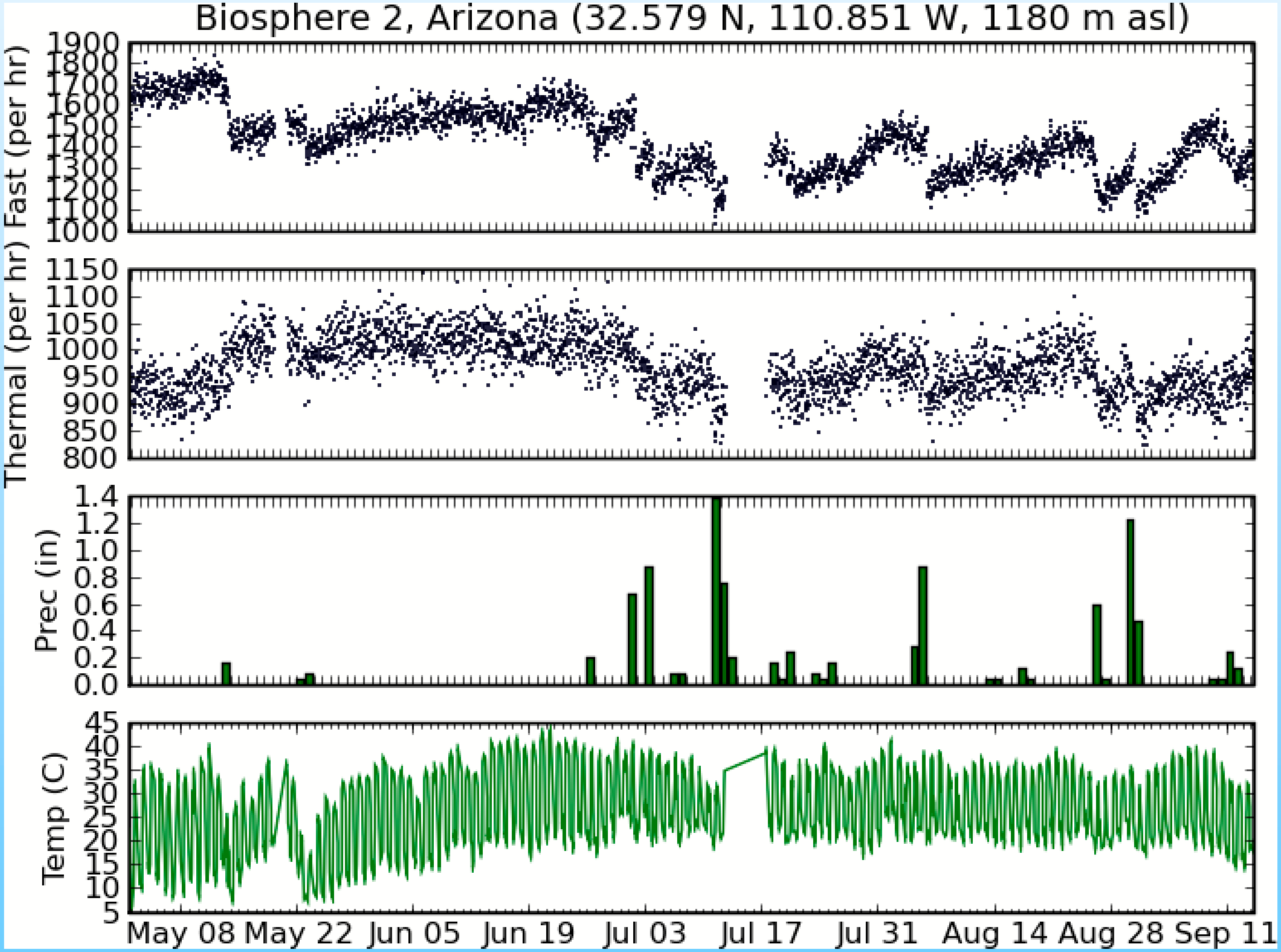
Real-time data - Biosphere 2, Arizona



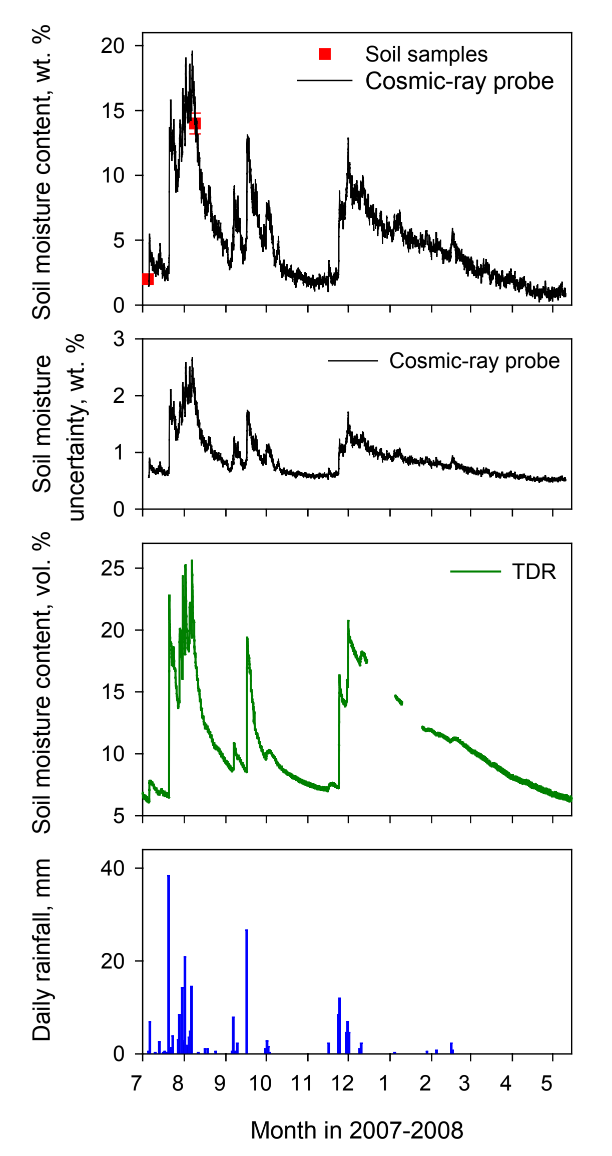
Real-time data - Biosphere 2, Arizona

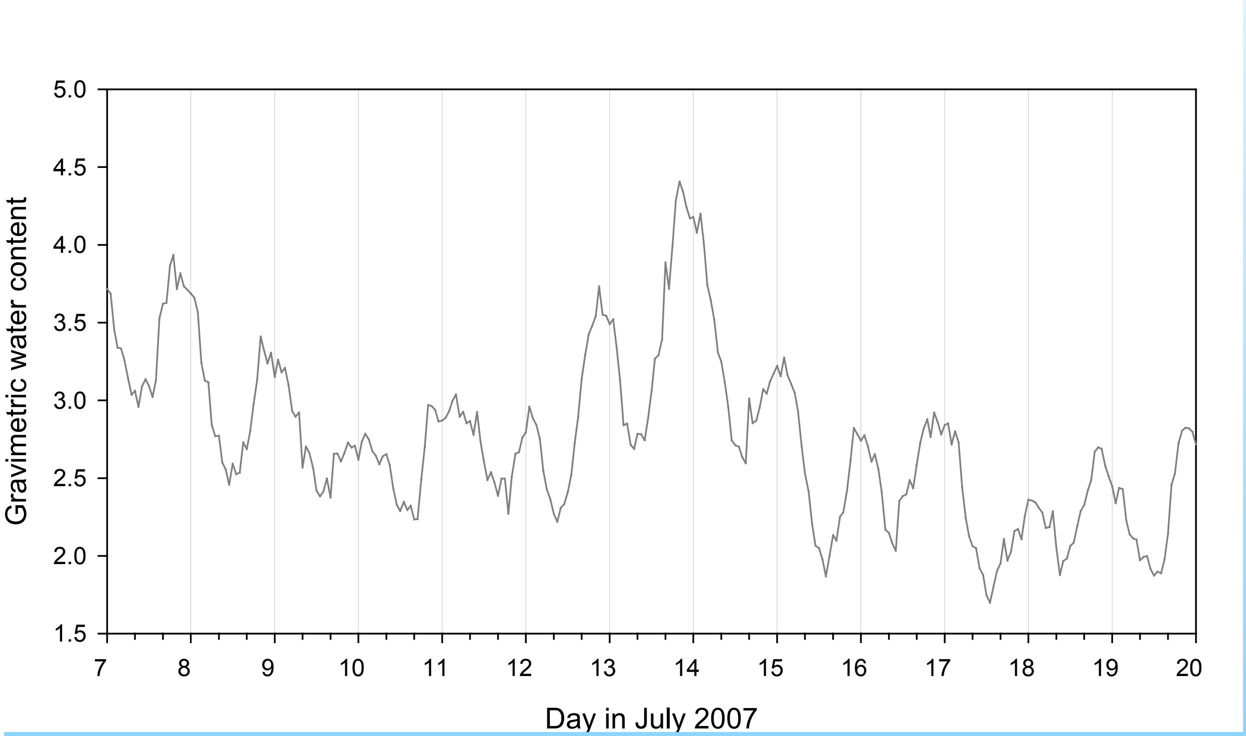


Biosphere 2 - screen capture



San Pedro River valley - diurnal fluctuations

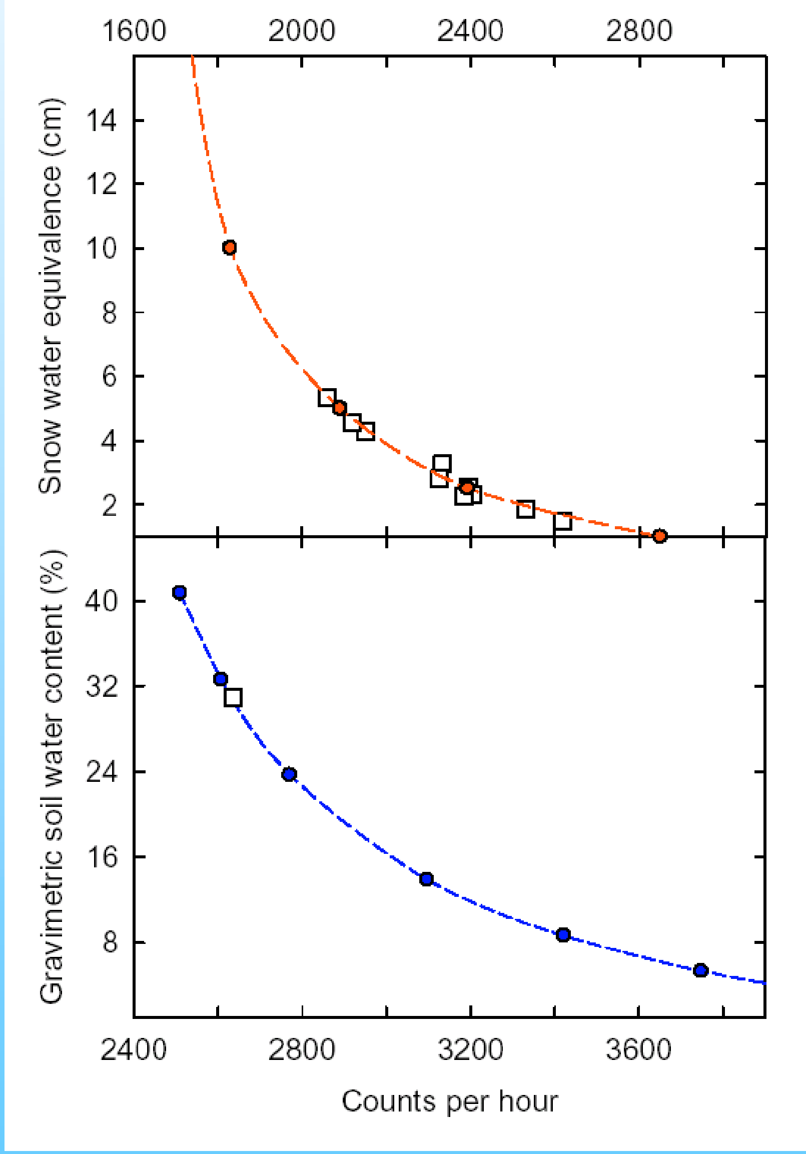




Possible explanation: hydraulic lift?

But could be also related to diurnal variations in the incoming cosmic-ray flux, or moisture changes within plants.

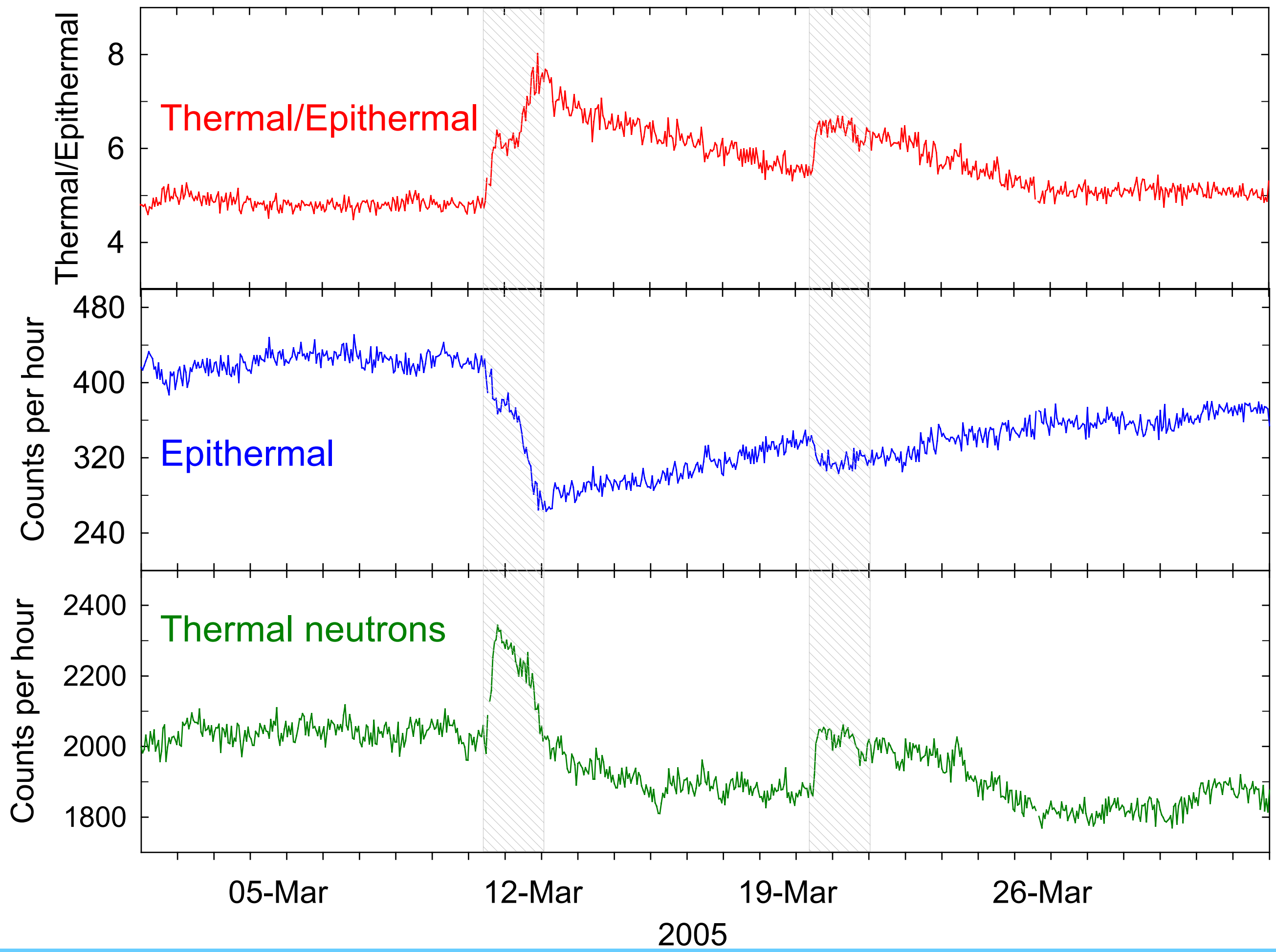
Calibration for snow and for soil moisture



Snow

Soil moisture

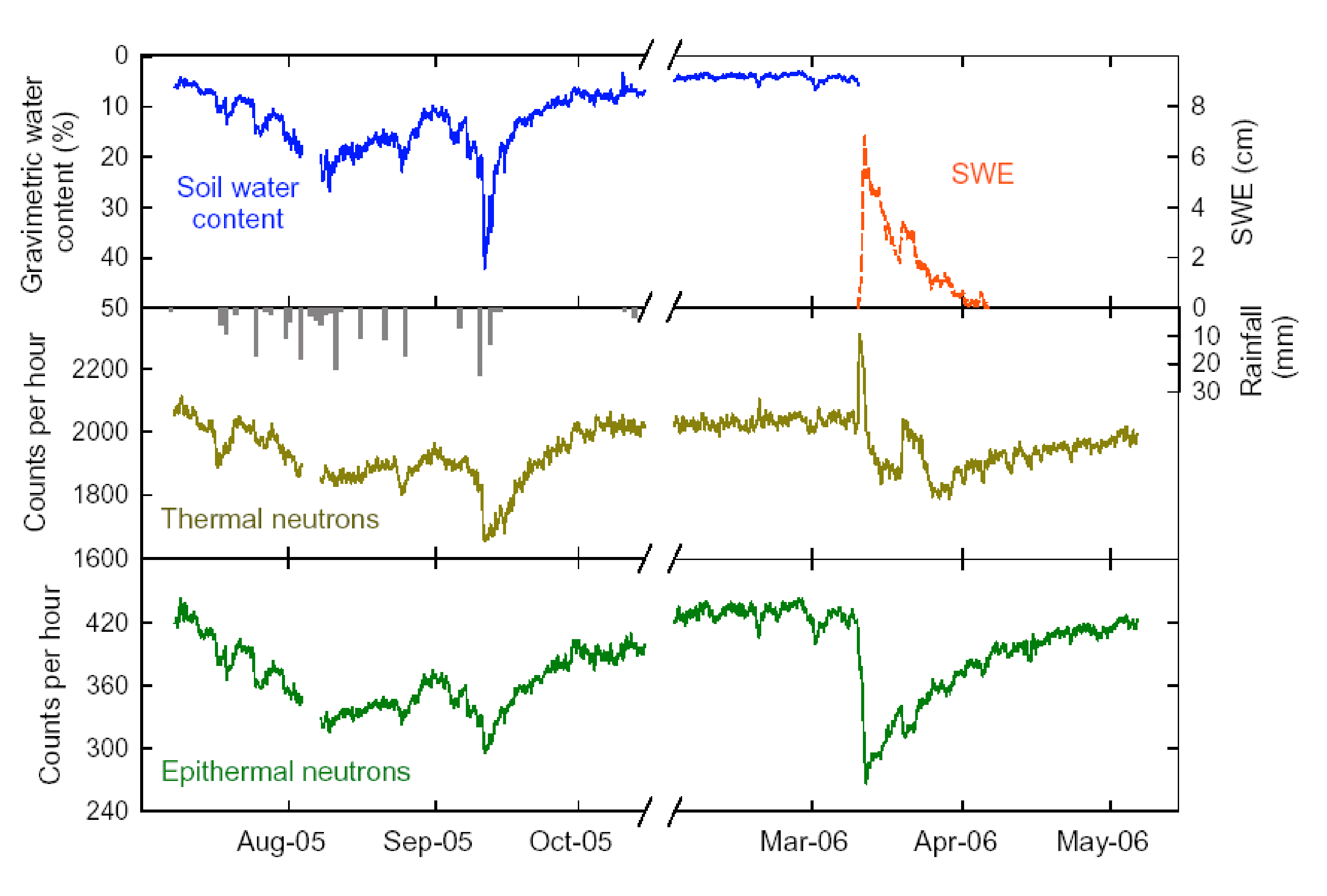
Distinguishing water above ground using thermal and epithermal/fast neutrons



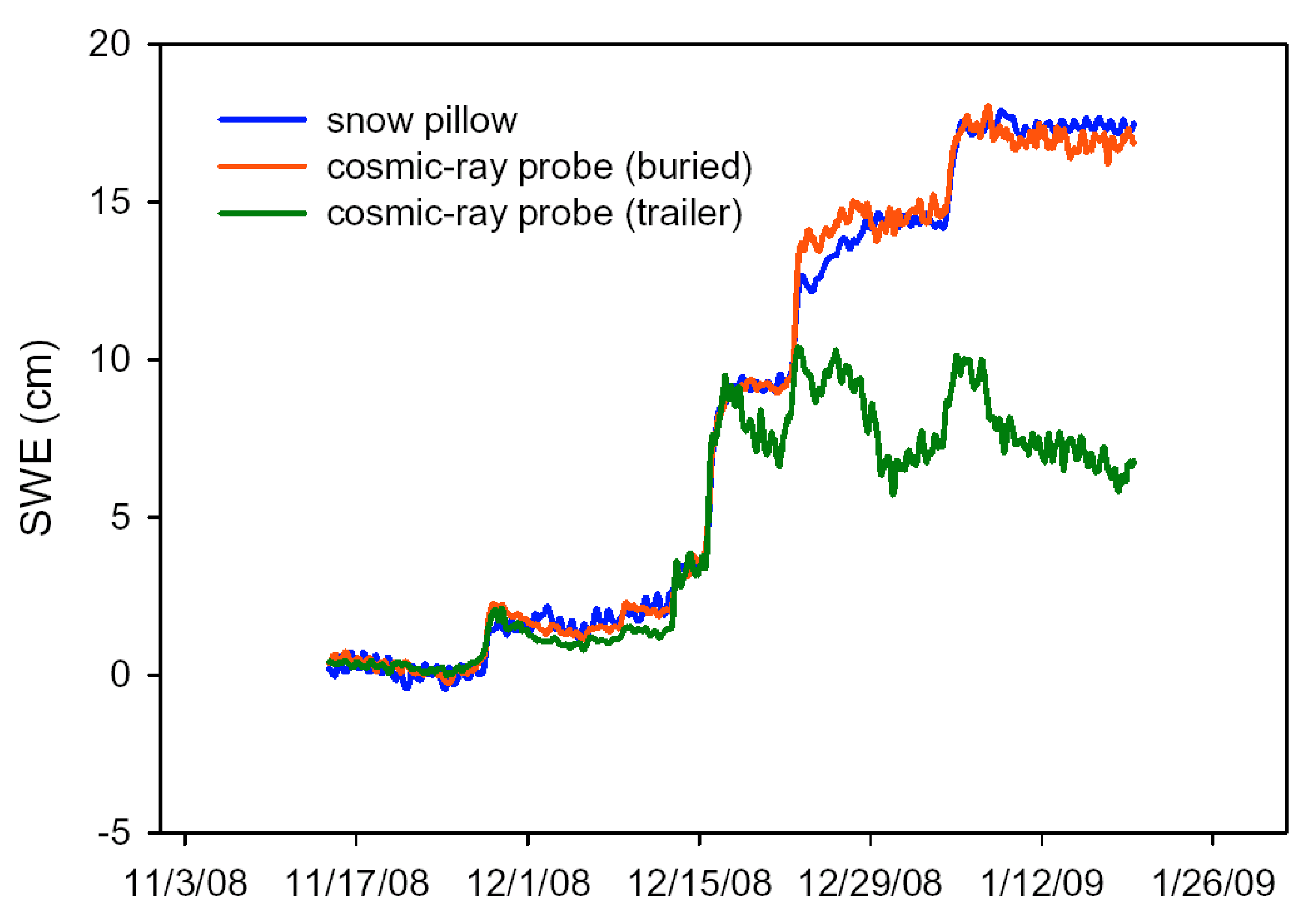
Also possible:

- vegetation water
- intercepted water
- biomass
- permafrost
- irrigation
- roof collapse

Distinguishing water above ground using thermal and epithermal/fast neutrons



Two-detector system



Courtesy of D. Desilets, Sandia National Laboratories

Cosmic-ray probe summary

Sensitive to soil moisture content

Insensitive to soil chemistry

Non-invasive, no contact measurement

Probe above the ground measures neutrons emitted from soil

No artificial source of radiation

Fully automatic measurement and data transfer

Remote configuration and diagnostics

Integrated soil moisture over a footprint of ~700 m

Integrated soil moisture over a depth of 12-70 cm

Possibility of separating water above the surface from soil moisture: possible applications to measuring snow-pack water equivalent, biomass, intercepted water, etc.

The COSMOS network

(1) 500 stations distributed across the contiguous USA:

(a) 450 permanent, half colocated with other climate statiuons;

(b) 50 portable, to be loaned to users.

(2) Each station has a cosmic-ray probe that provides near real-time soil moisture data averaged over a footprint of ~700 m and depth 12-70 cm.

(3) data can be integrated and reported with arbitrary temporal resolution.

(4) Each station has temperature, pressure and relative humidity sensors.

(5) Intended uses:

(a) soil moisture initialization in weather and short-term climate forecasting;

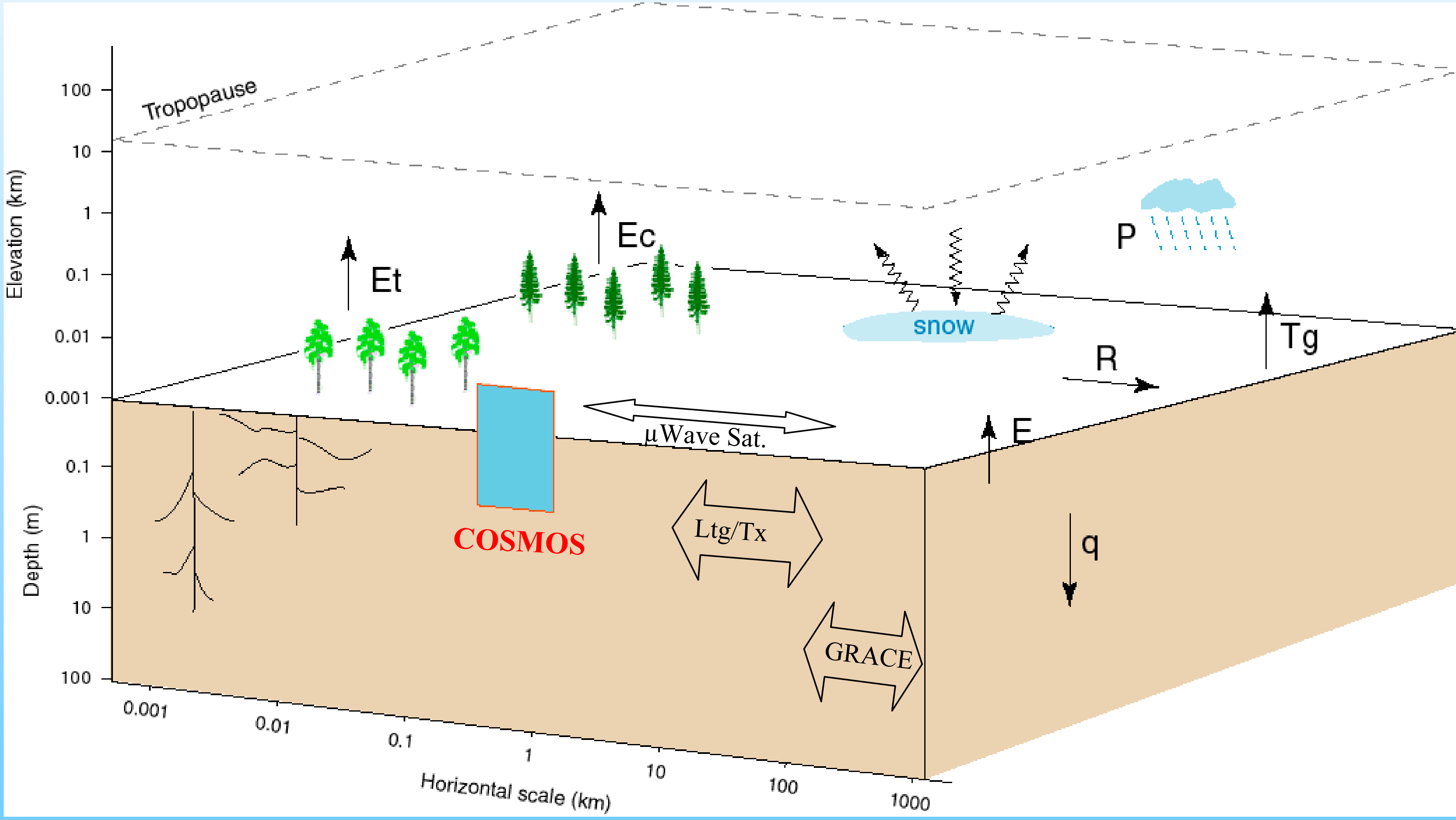
(b) land-atmosphere energy and mass exchange;

(c) drought monitoring;

(d) ecohydrology;

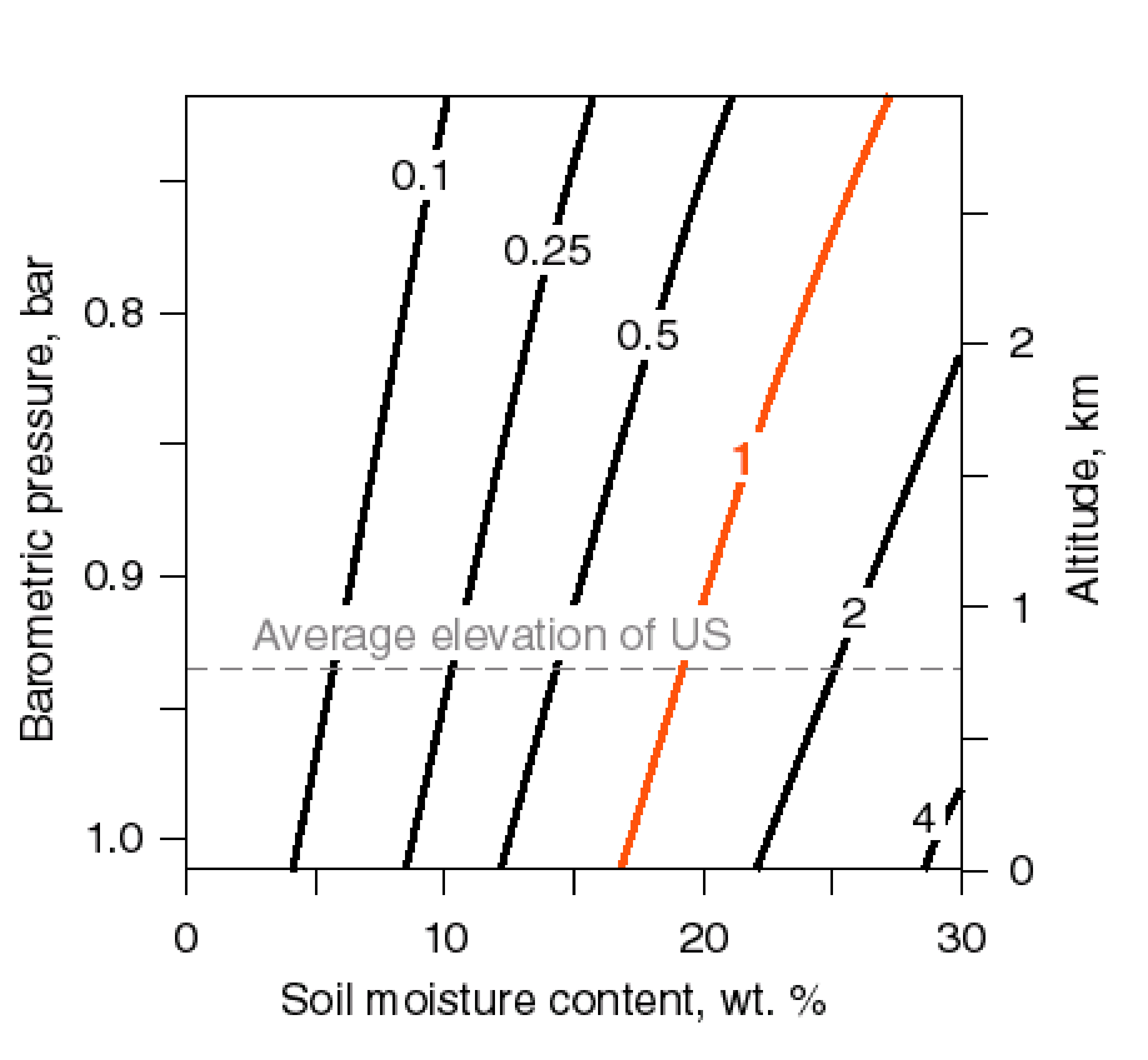
(e) ground validation of satellite remote sensing methods.

COSMOS in context



COSMOS Project: Marek Zreda, Jim Shuttleworth, Xubin Zeng and Chris Zweck

Hours necessary for 2% measurement

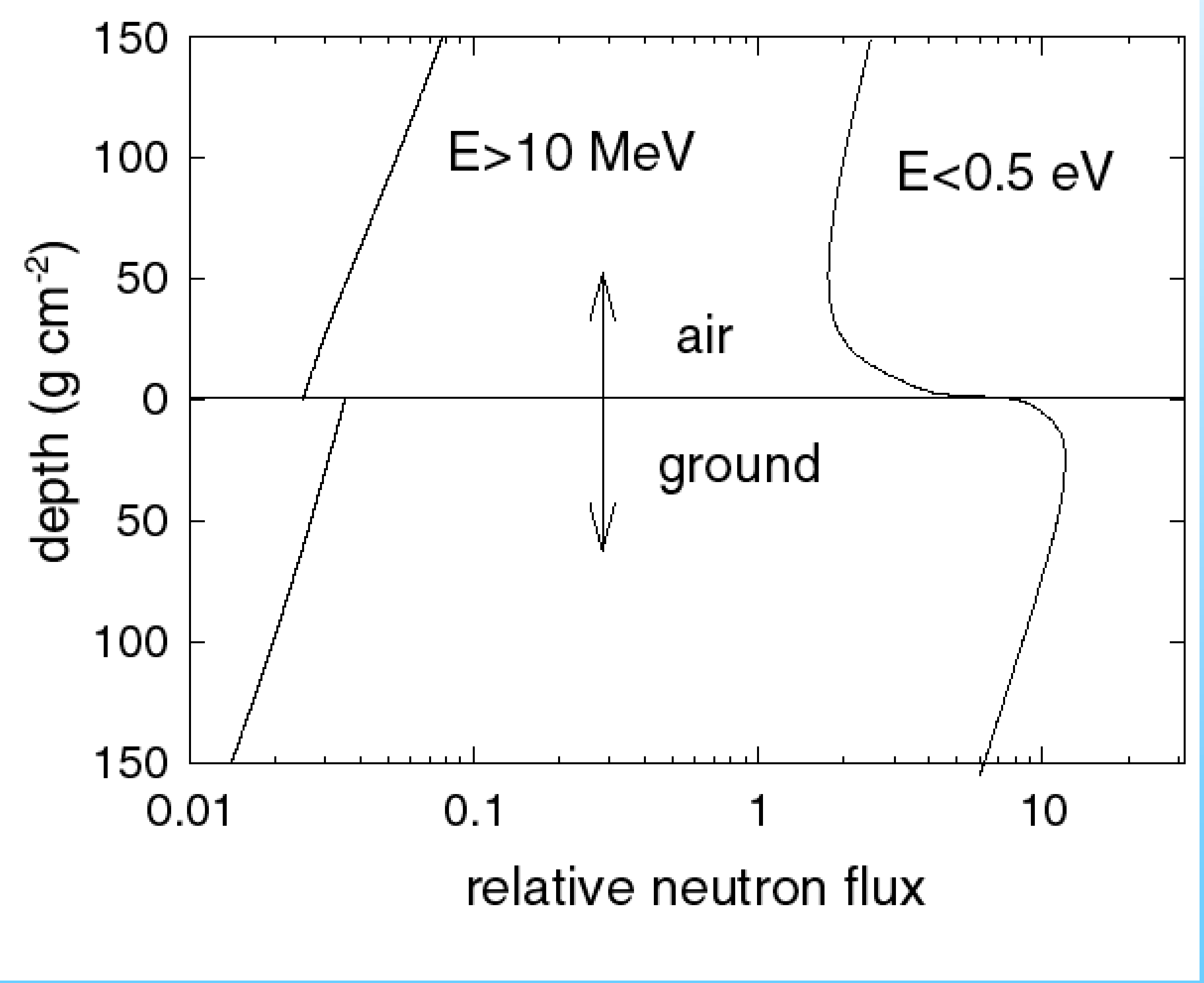


Detector:

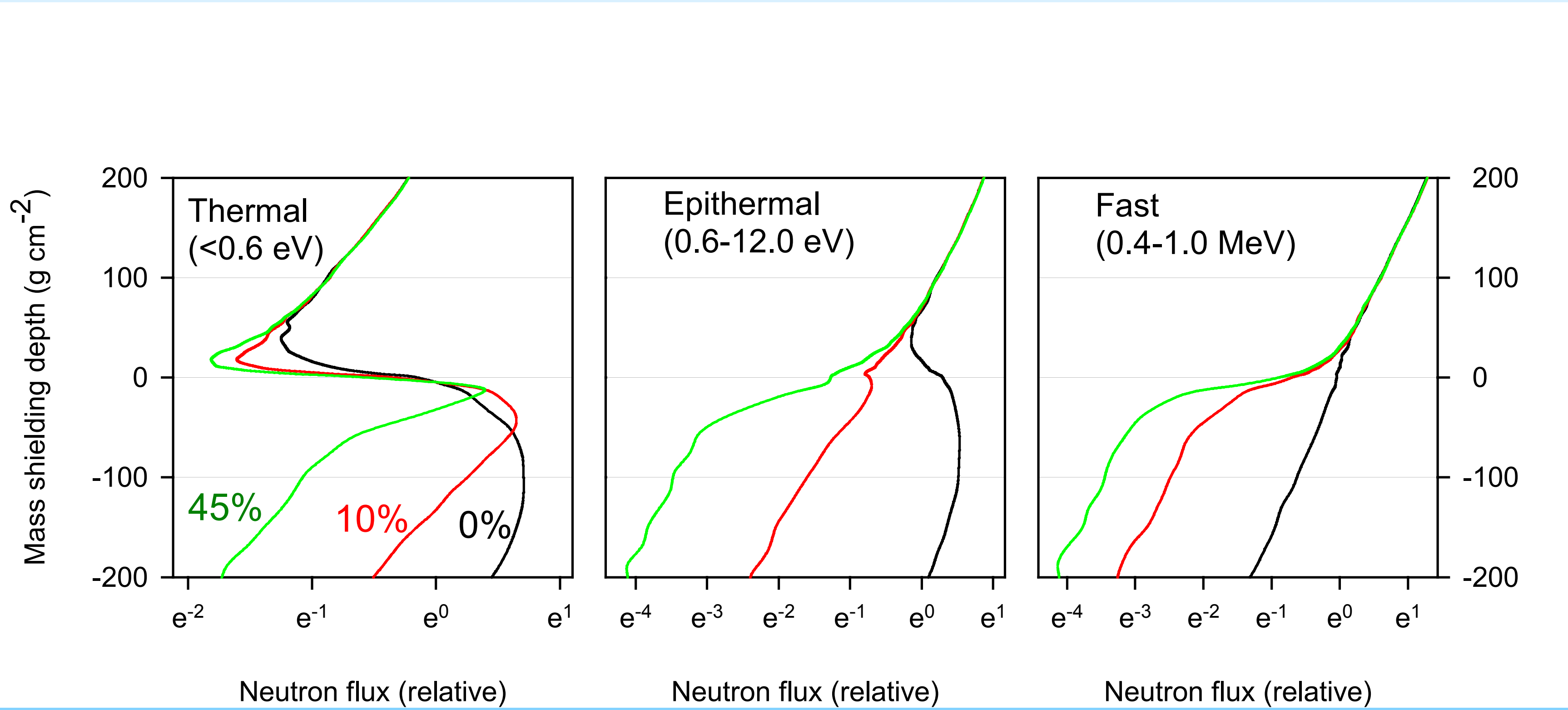
Gas: ^3He
Pressure: 10 atm
Diameter: 2.5 cm
Length: 30 cm

Other detectors will have different times, depending on size and pressure.

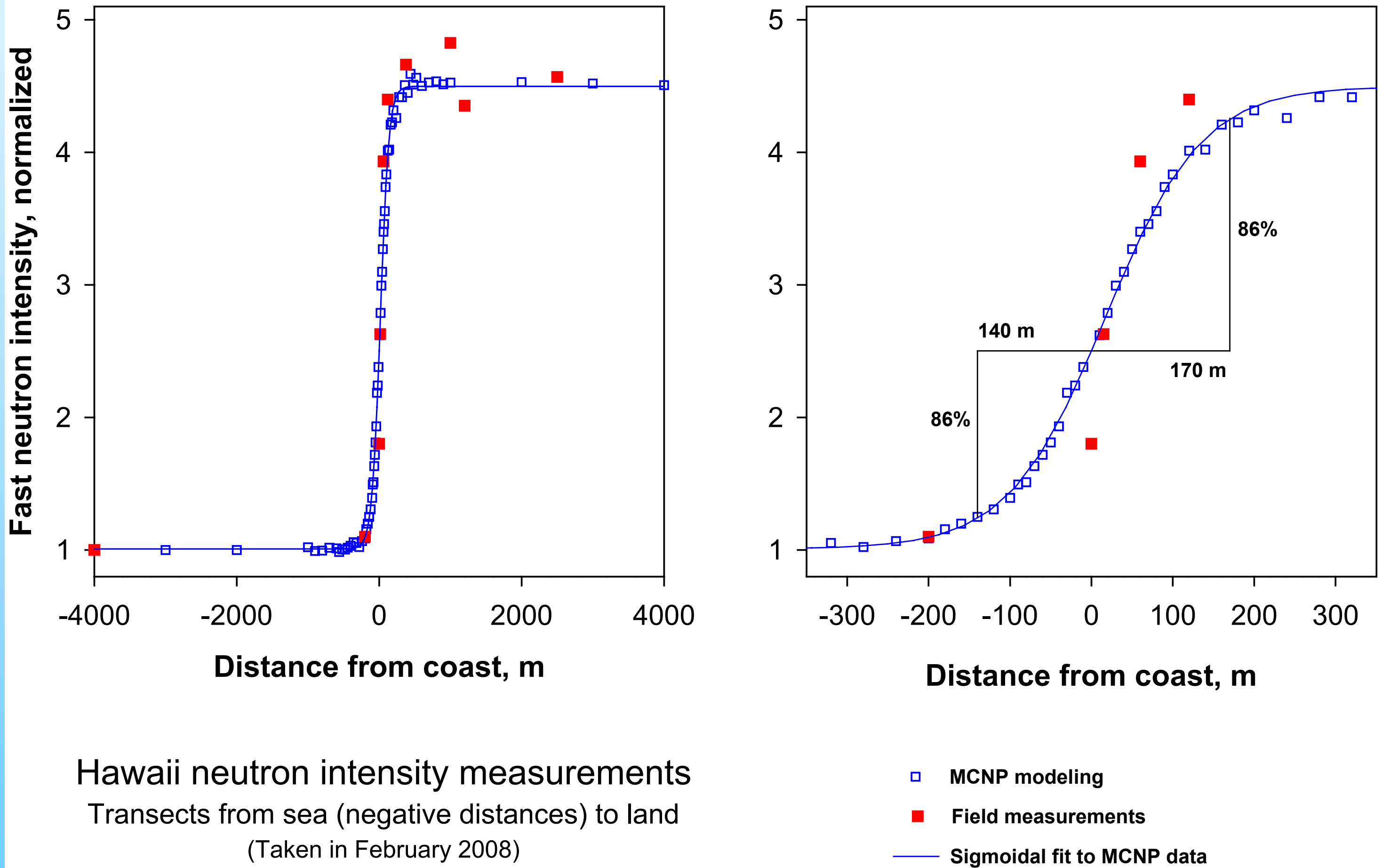
Neutrons near air-ground interface



Neutrons near air-ground interface



Field confirmation of footprint



Hawaii neutron intensity measurements

Transects from sea (negative distances) to land

(Taken in February 2008)