ICRS-13 & RPSD-2016

13th *International Conference on Radiation Shielding*
&
19th Topical Meeting of the *Radiation Protection & Shielding Division*
of the *American Nuclear Society* -2016

4th Plenary invited talk:

"From Earth to Moon, Mars and Beyond – Space Radiation and Implications for Human Exploration"

Prof. Dr. Robert F. Wimmer-Schweingruber

University of Kiel, Germany

High-energy radiation fills space and poses a short-term as well as long-term danger to humans in space, but is also of concern for electronics in spacecraft. The radiation environment on planetary bodies is quite different from that on Earth. On the airless Moon, space radiation is shielded by the massive Moon, but the interaction of radiation with it also generates new, secondary radiation. On Mars, the tenuous atmosphere provides some shielding, but also radiation interaction with it also creates secondary radiation, in addition to what is created in the soil. It is discussed measurements of the space radiation environment at Earth, Moon, en route to Mars and on Mars itself.

Robert Wimmer-Schweingruber („Bob Wimmer") received his PhD in experimental physics from the University of Bern, Switzerland, in 1994. He was asked to return to Bern after a PostDoc in the US, to lead two space projects. He obtained his venia docendi („Habilitation") in 2001 and is now a professor at the University of Kiel, Germany, since 2002, where he heads the Division of Extraterrestrial Physics. He is the Principal Investigator (PI) of three space instruments, and Co-PI and Co-I of many other space experiments.

From Earth to Moon, Mars, and Beyond – Space Radiation and Implications Human Exploration

Robert F. Wimmer-Schweingruber
Extraterrestrial Physics,
IEAP, University of Kiel, Germany
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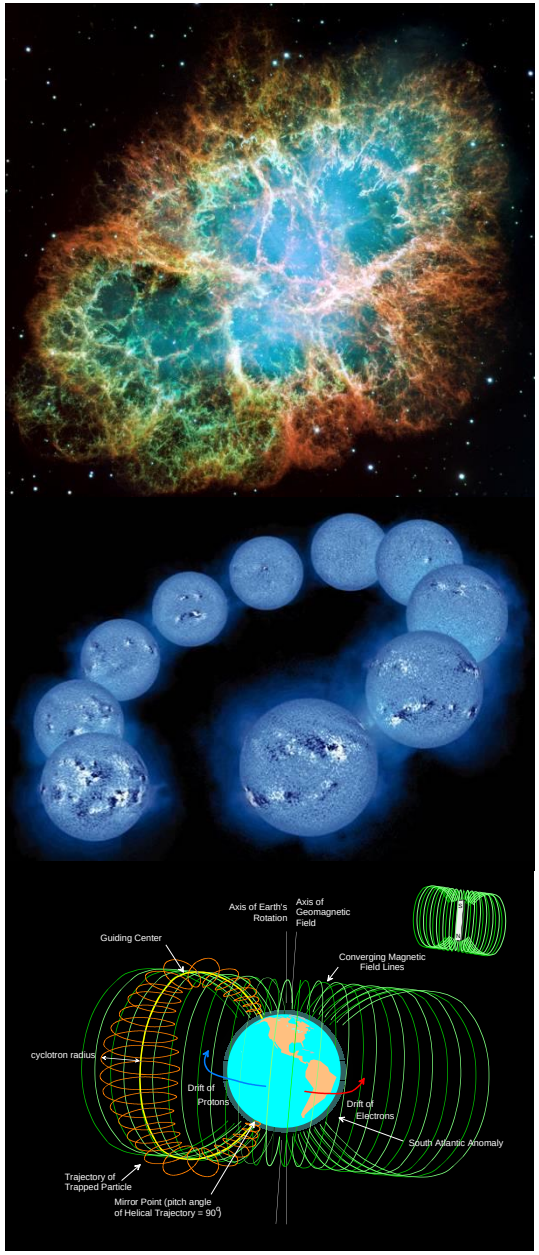
Structure of my talk

- Radiation: Origin & transport in heliosphere
- Implications for human exploration

- Particle radiation at and on the Moon
- Particle radiation during the cruise to Mars
- Mars surface radiation environment
- Implications for human exploration

- ~~Why Mars, why Gale?~~
- ~~Was Mars habitable?~~

Radiation Sources Close to Earth



Galactic Cosmic Rays:

Very high energies, H through U
Solar modulation, predictable
Highly penetrating

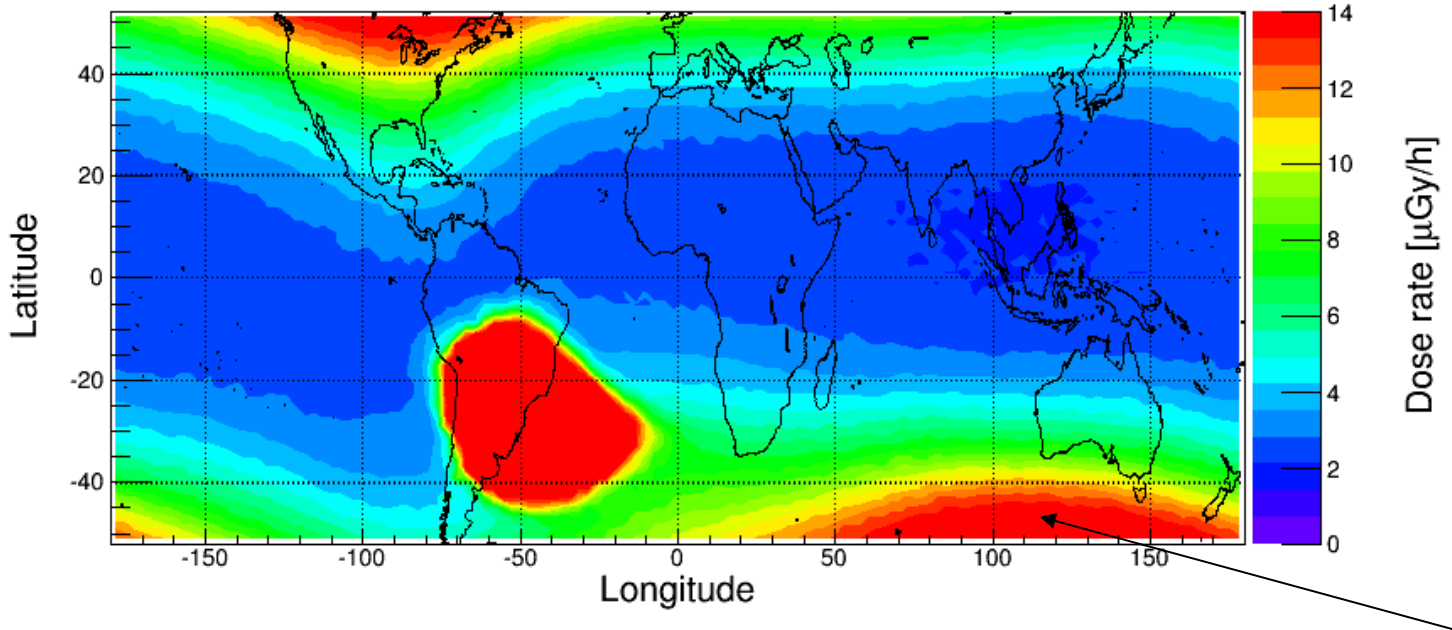
Solar Energetic Particles:

High energies
Solar activity, unpredictble
High dose rate variability (up to ~1000)
Can be shielded

Trapped Radiation (Radiation Belts):

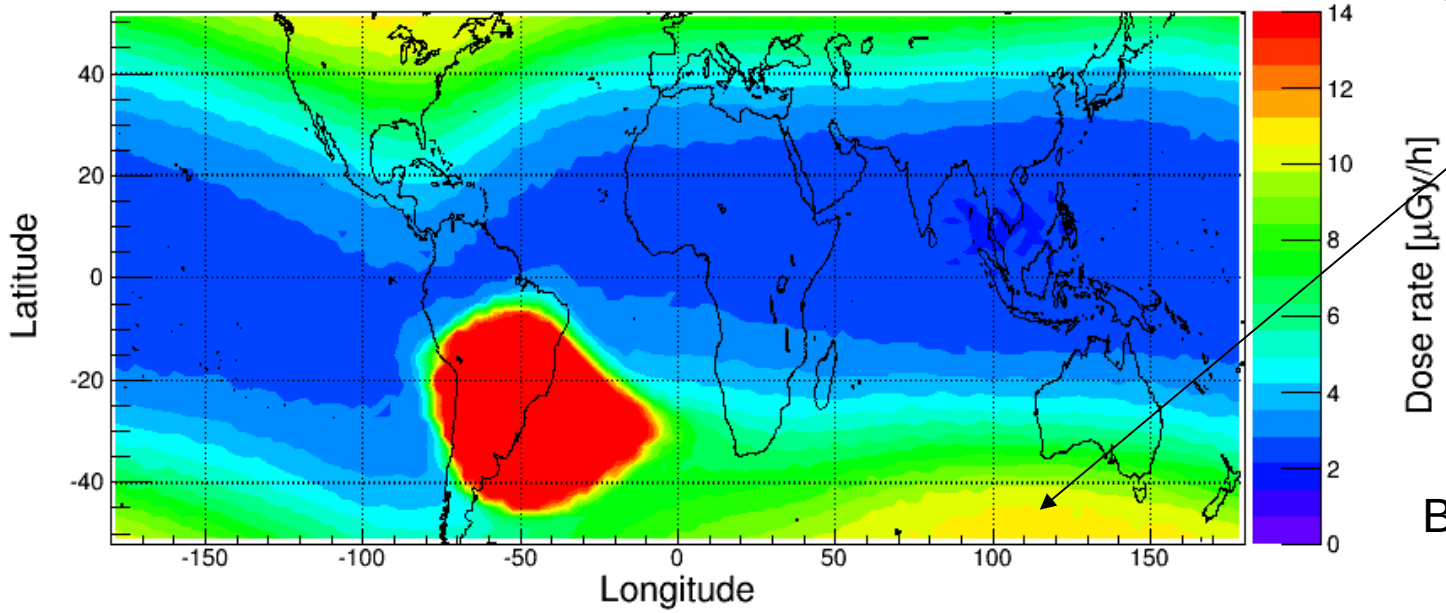
Very high energies, protons, electrons
Very high dose rate
Highly penetrating

Radiation Sources Close to Earth: GCR



2009
closer to
solar min

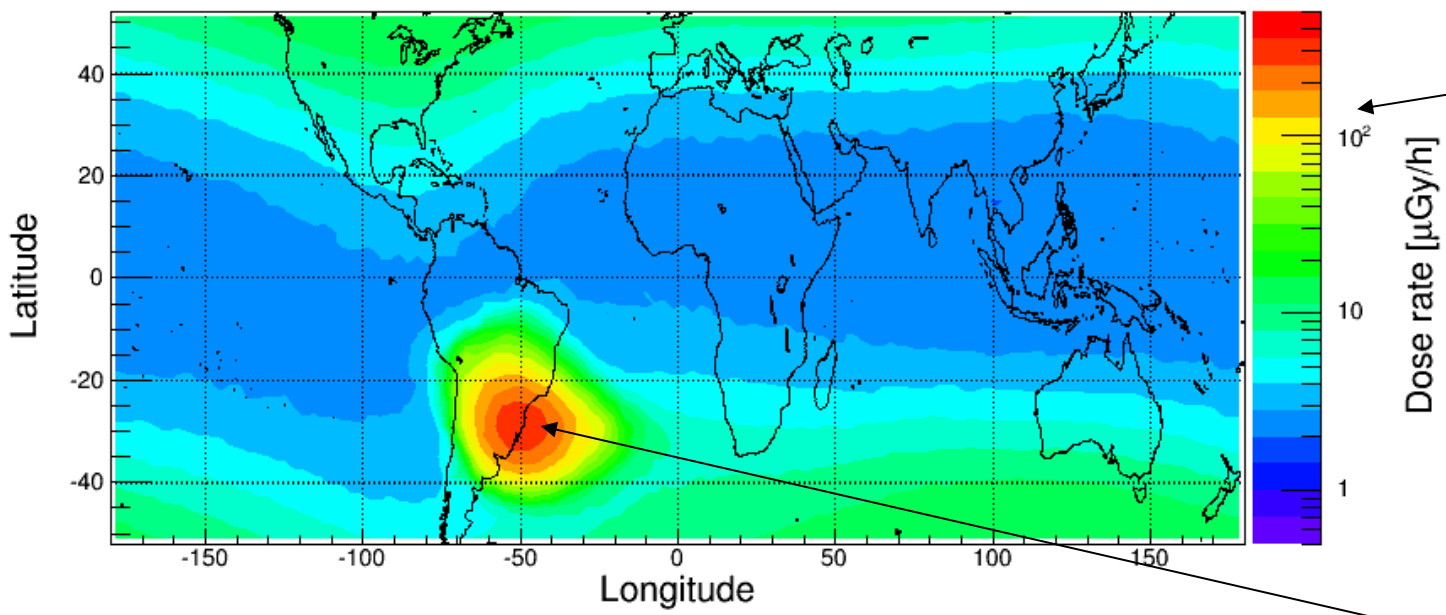
GCR



2013
closer to
solar max

Burmeister et al., 2016

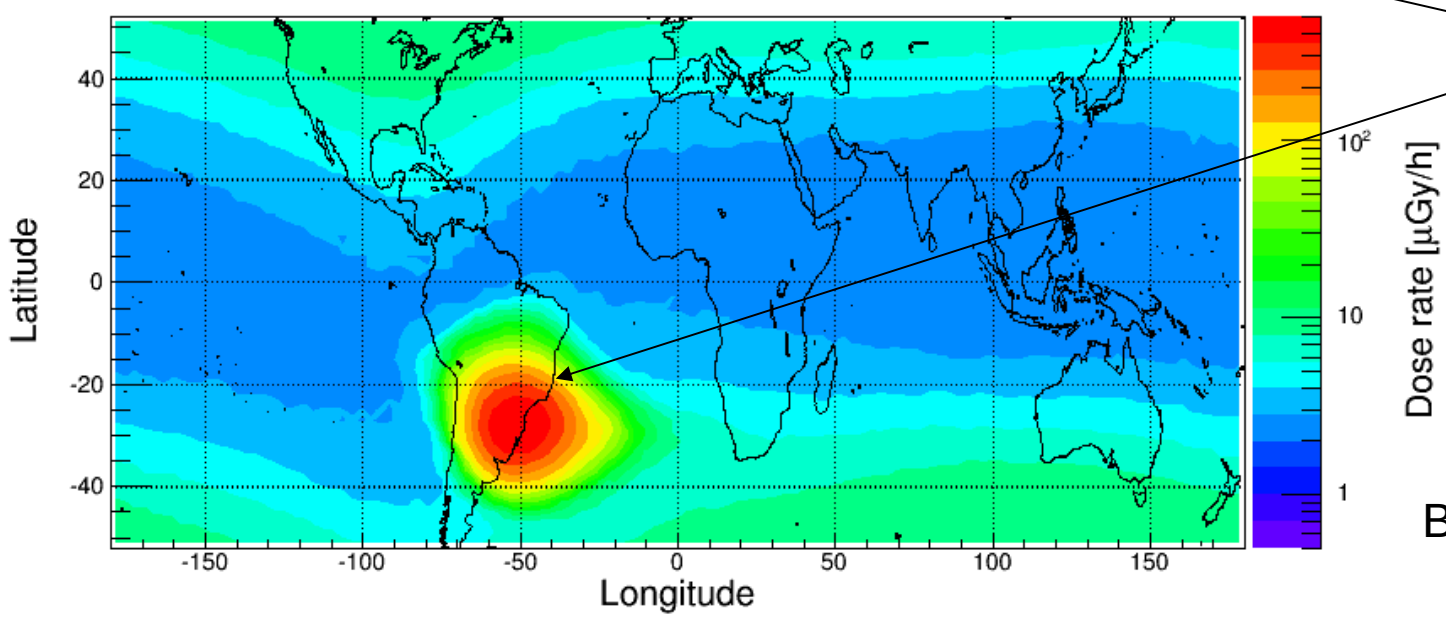
Radiation Sources Close to Earth: Trapped



Log scale!

2009
@ 350 km

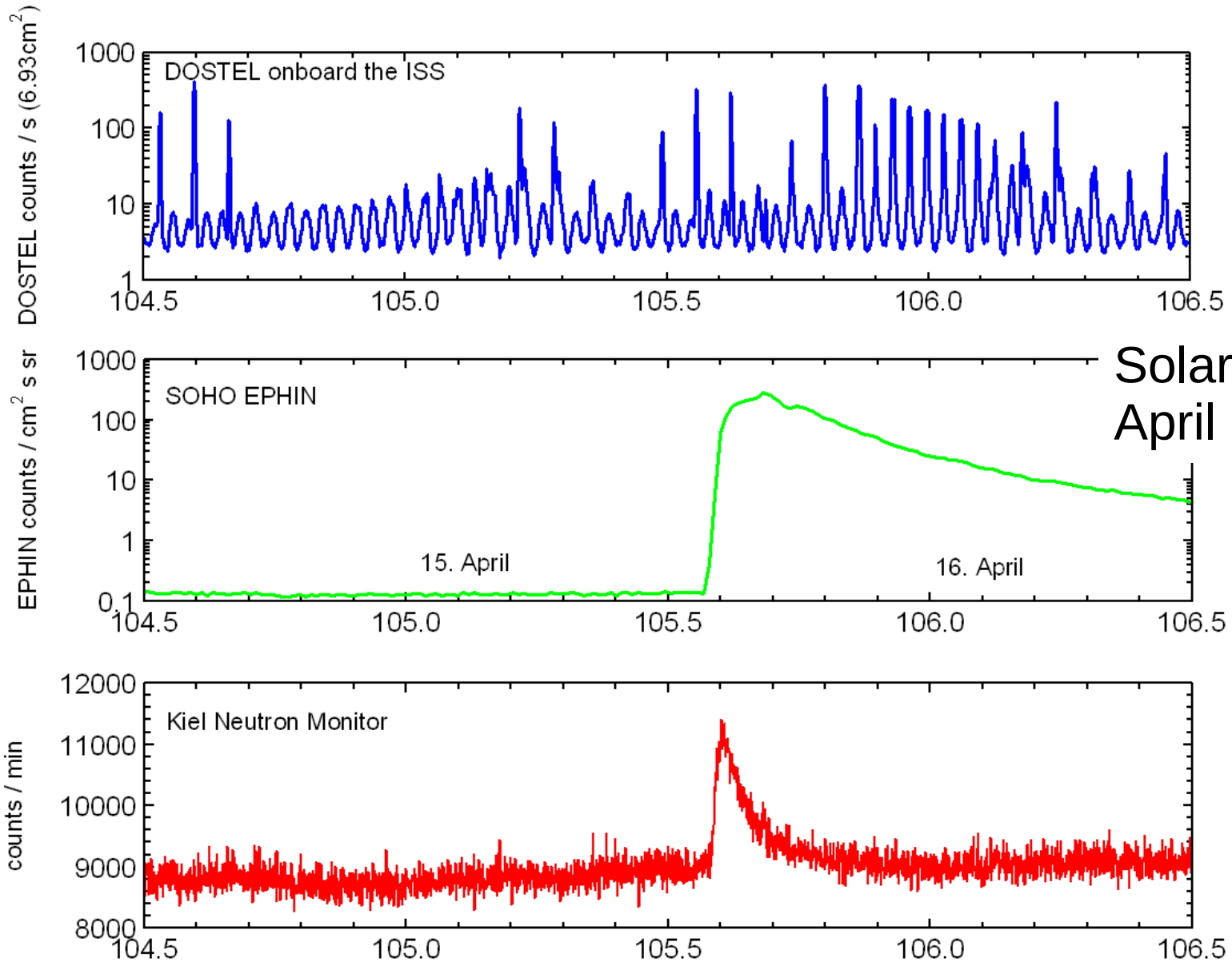
SAA
(trapped)



2013
@ 420 km

Burmeister et al., 2016

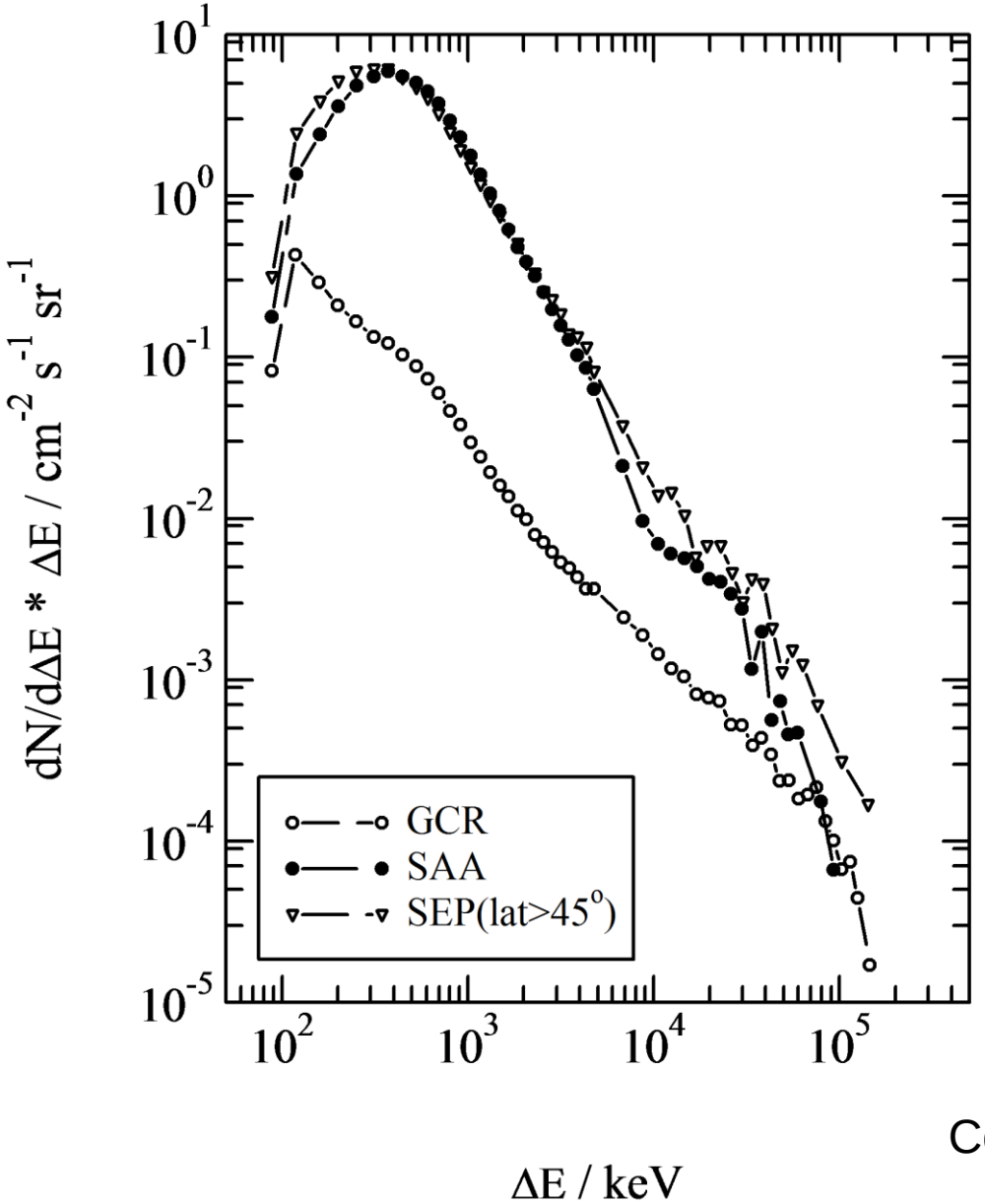
Radiation Sources Close to Earth: Solar



Solar Particle Event: April 2001

Data:
Burmeister
Heber
NMDB

Radiation Sources Close to Earth: Comparison



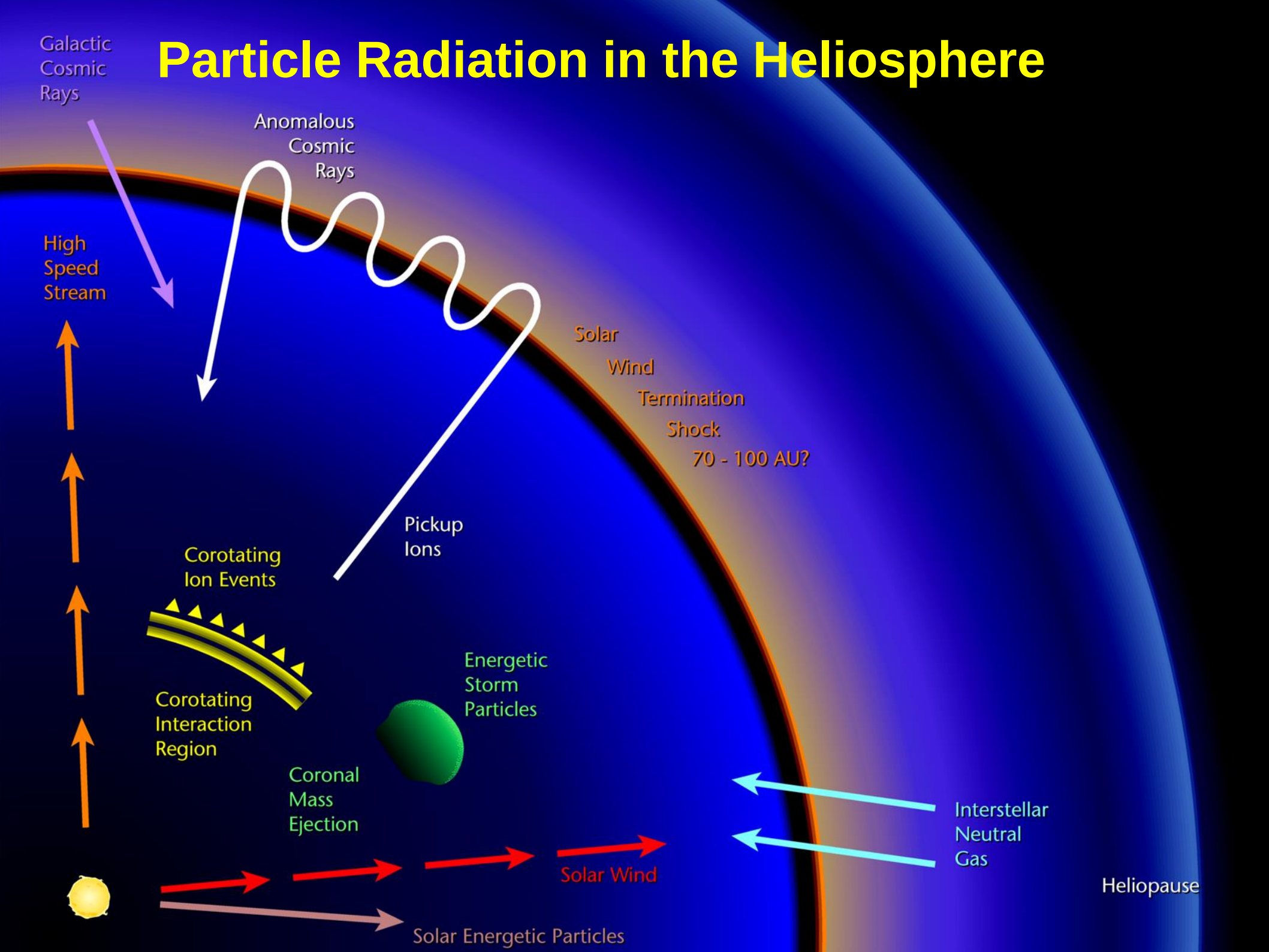
Nov 1997 SPE:

Comparison of the effect of the GCR, SPE, and trapped components

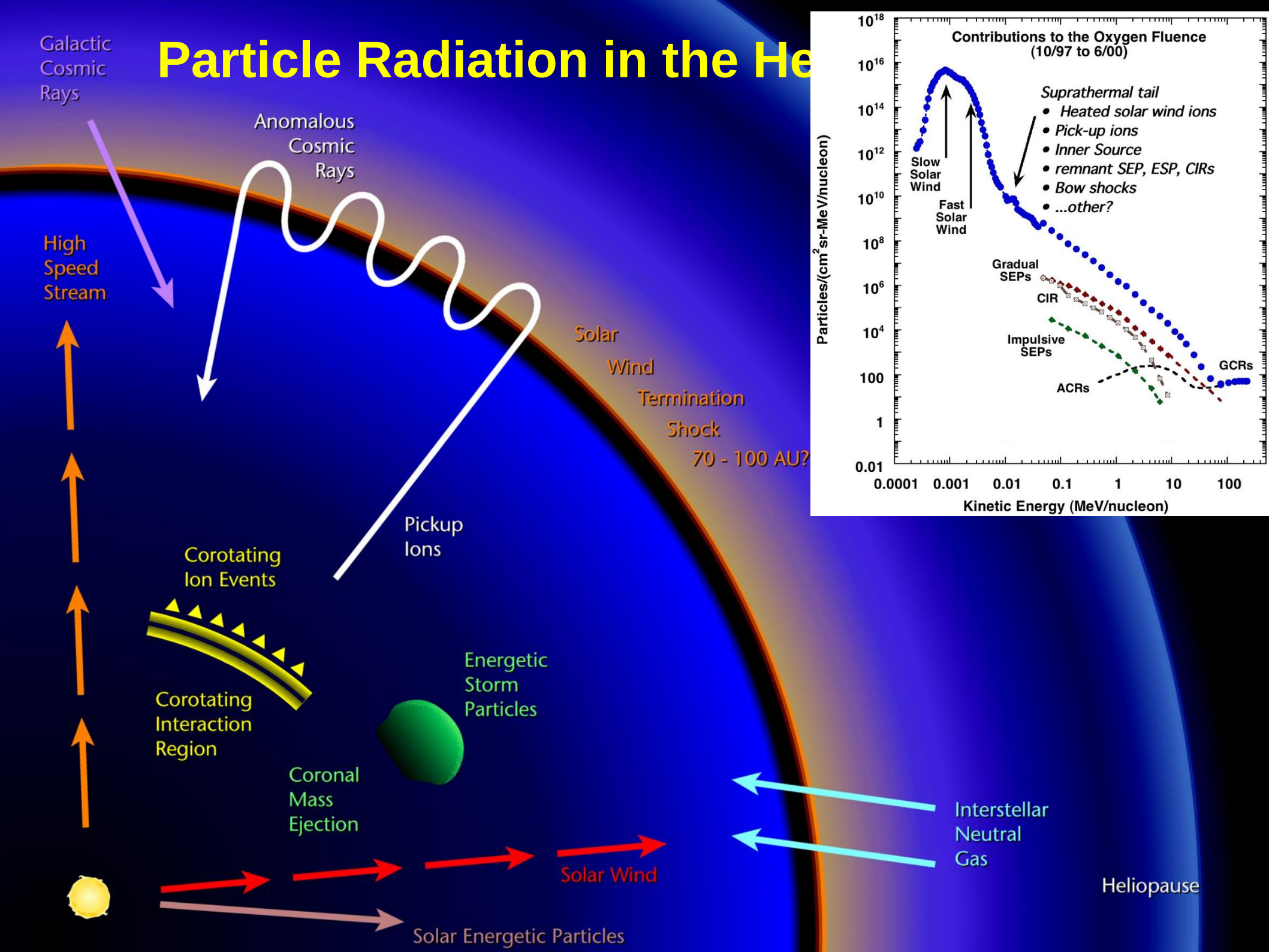
Measured spectrum of energy deposit in a 315 micron Si solid-state detector.

Courtesy S. Burmeister

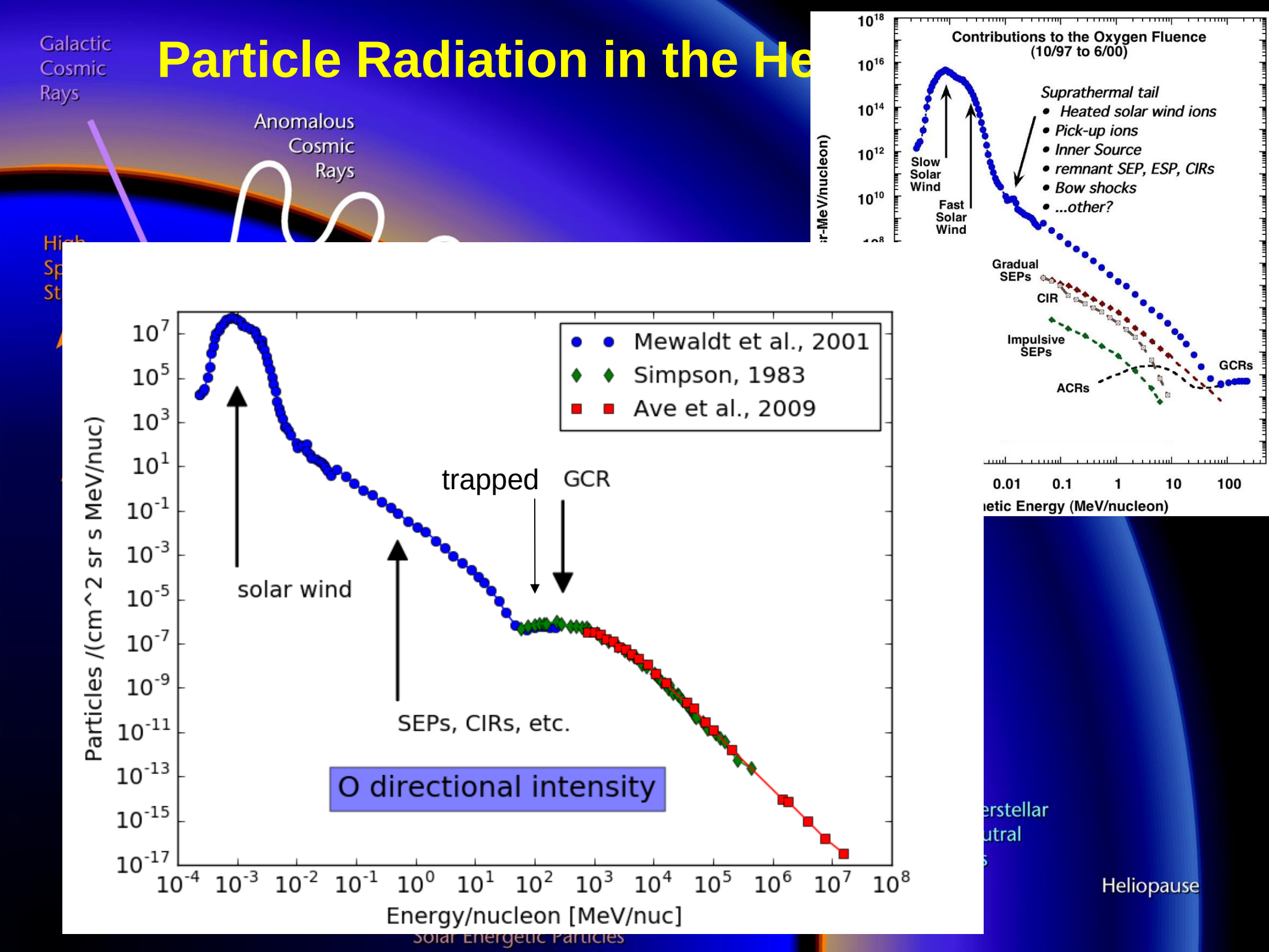
Particle Radiation in the Heliosphere



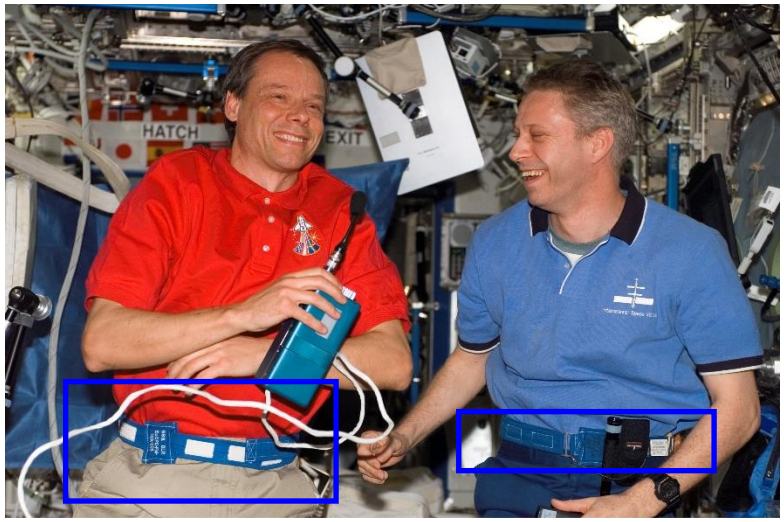
Particle Radiation in the He



Particle Radiation in the He



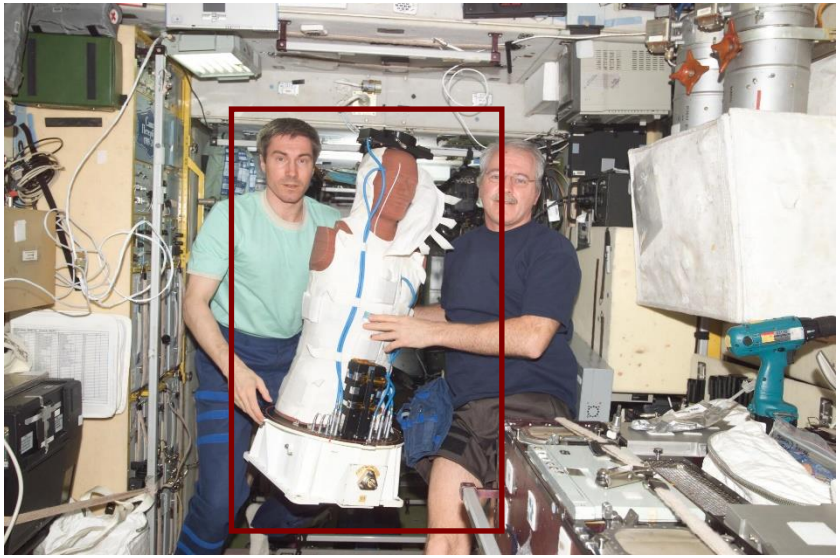
Radiation Protection in Space



Personal Dosimeters

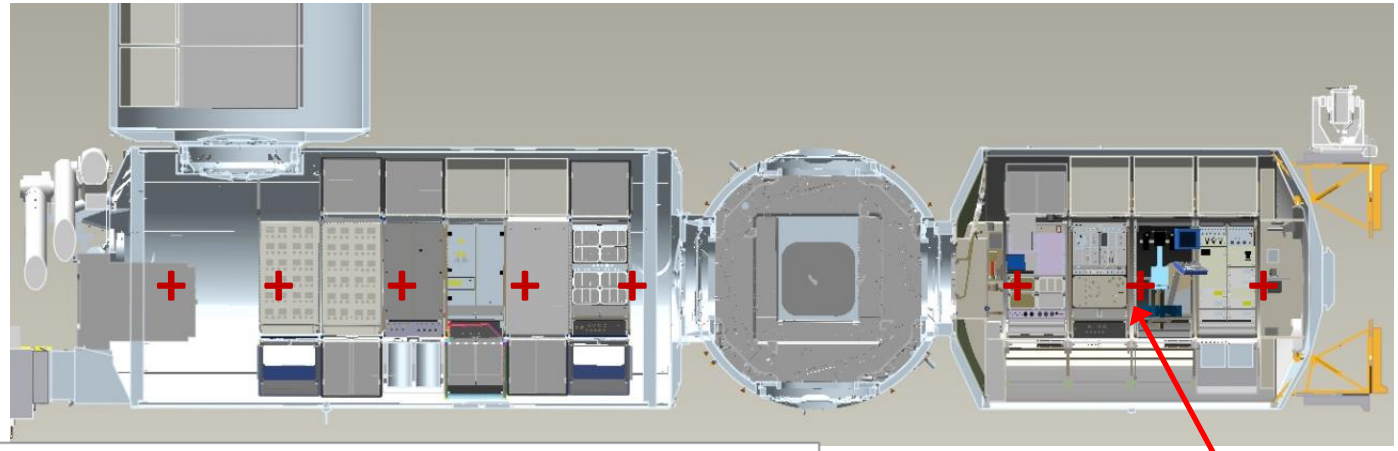
Radiation is *the* long-lasting risk for astronauts. Radiation damage can persist after the end of a long-duration space flight.

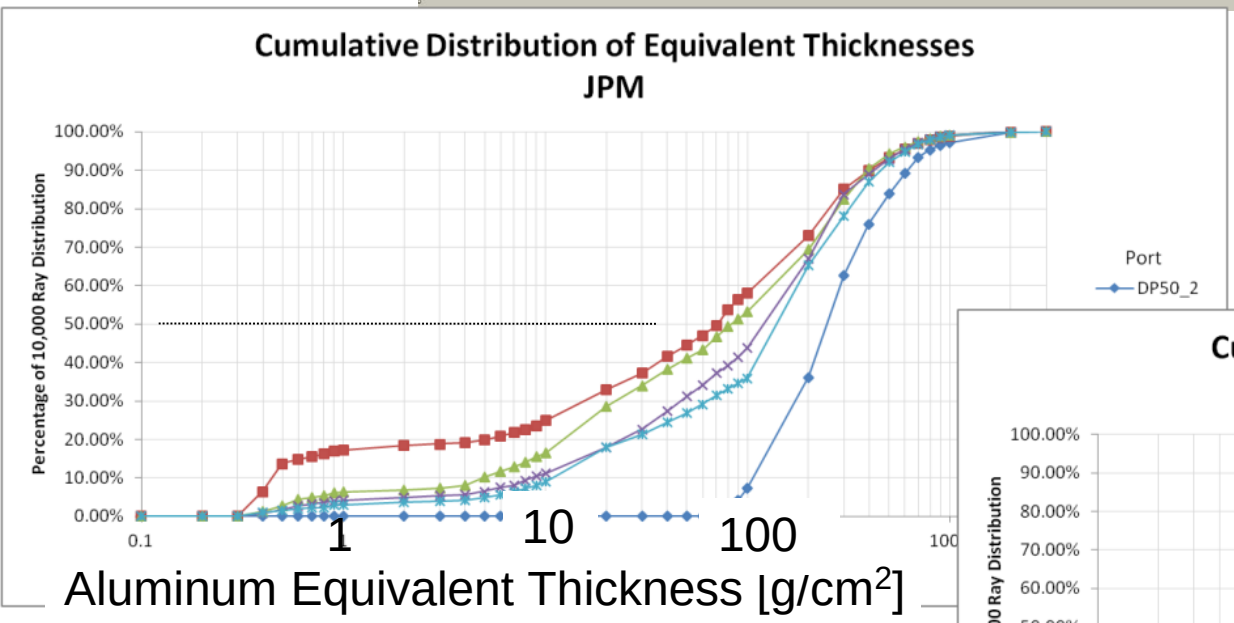
Radiation must be measured!



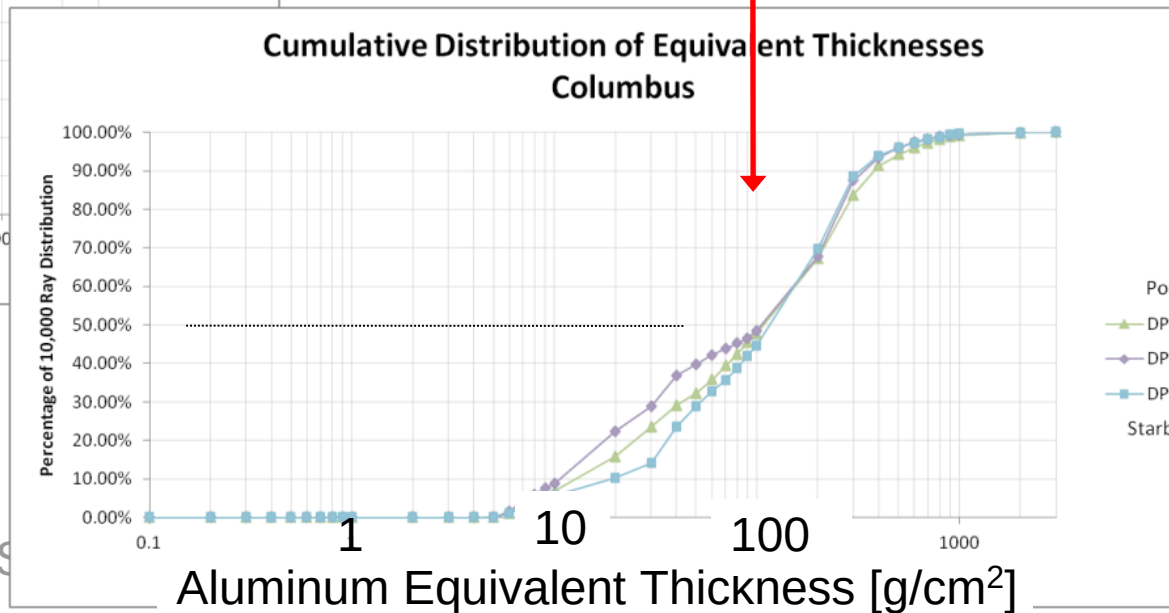
Phantom experiments
MATROSHKA
(Photos courtesy G. Reitz)

Radiation Protection in Space





COLUMBUS
median shielding ≈100 g/cm2

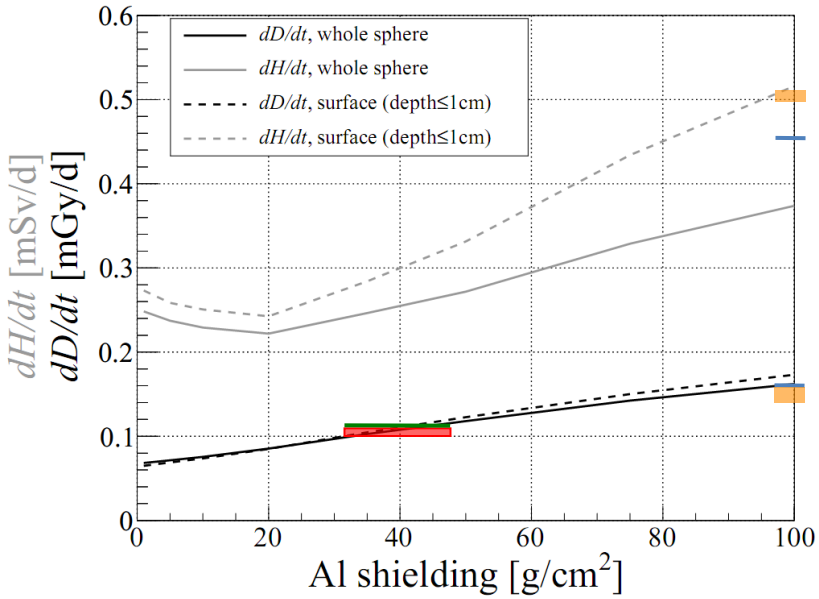


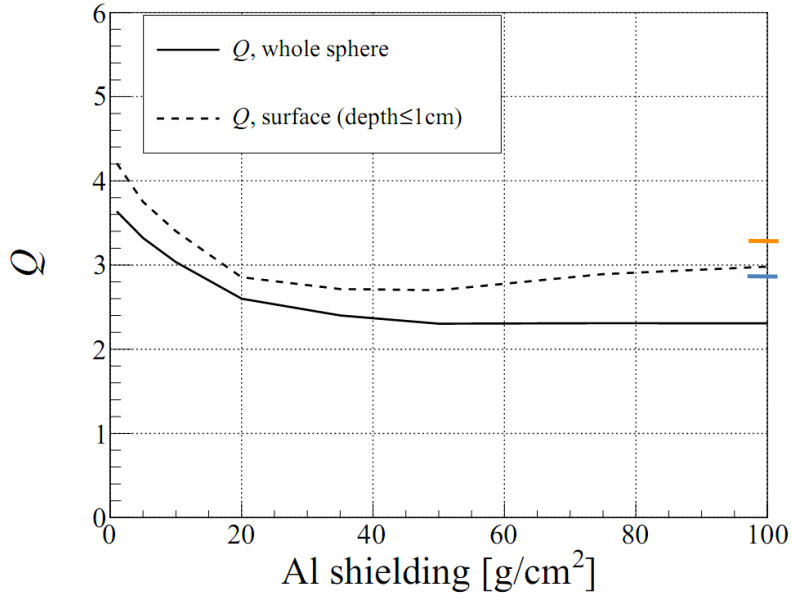
(courtesy Daniel Matthiä)

Radiation Protection in Space

GCR radiation eposure on ISS Dec. 2009 (max. GCR intensity)

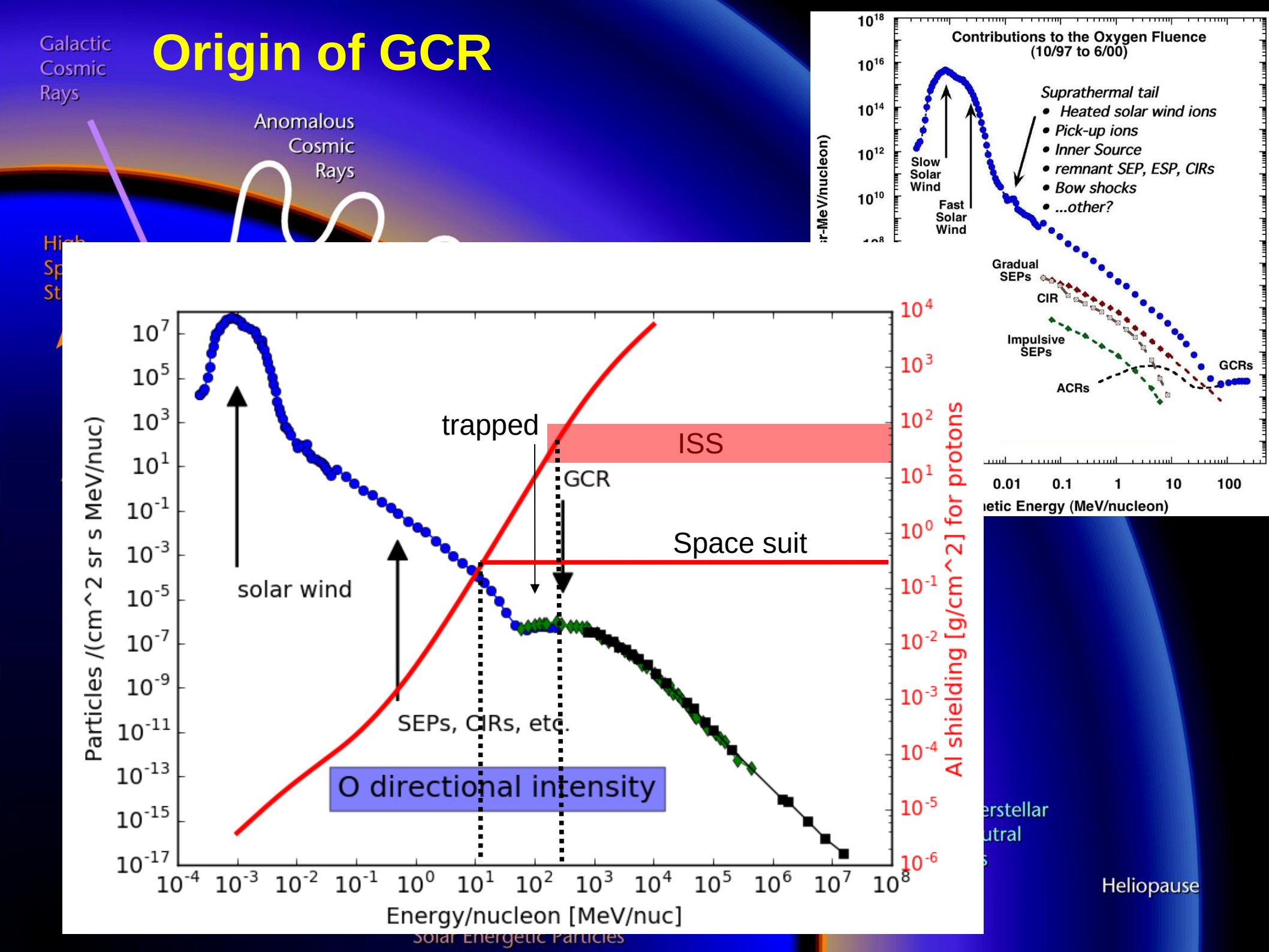
- Dose rates in a water sphere with radius 20 cm
  - surface (depth < 1cm)
  - whole sphere
- Spherical aluminium shielding
- Columbus Module:
  - ≈ 100 g/cm^2, Stoffle et al. (2012)
  - 158 µGy/d, 448 µSv/d, Q = 2.84, Semones et al. (2009)
  - 150 - 157 µGy/d, 496 – 517 µSv/d, Q = 3.30, Burmeister et al. (2012)
- Zvezda Service Module:
  - 32 – 47 g/cm^2, Jardrnickova et al. (2009)
  - 100 – 110 µGy/d, Lishnevskii et al. (2012)
  - 125 µGy/d, Semones et al. (2009)



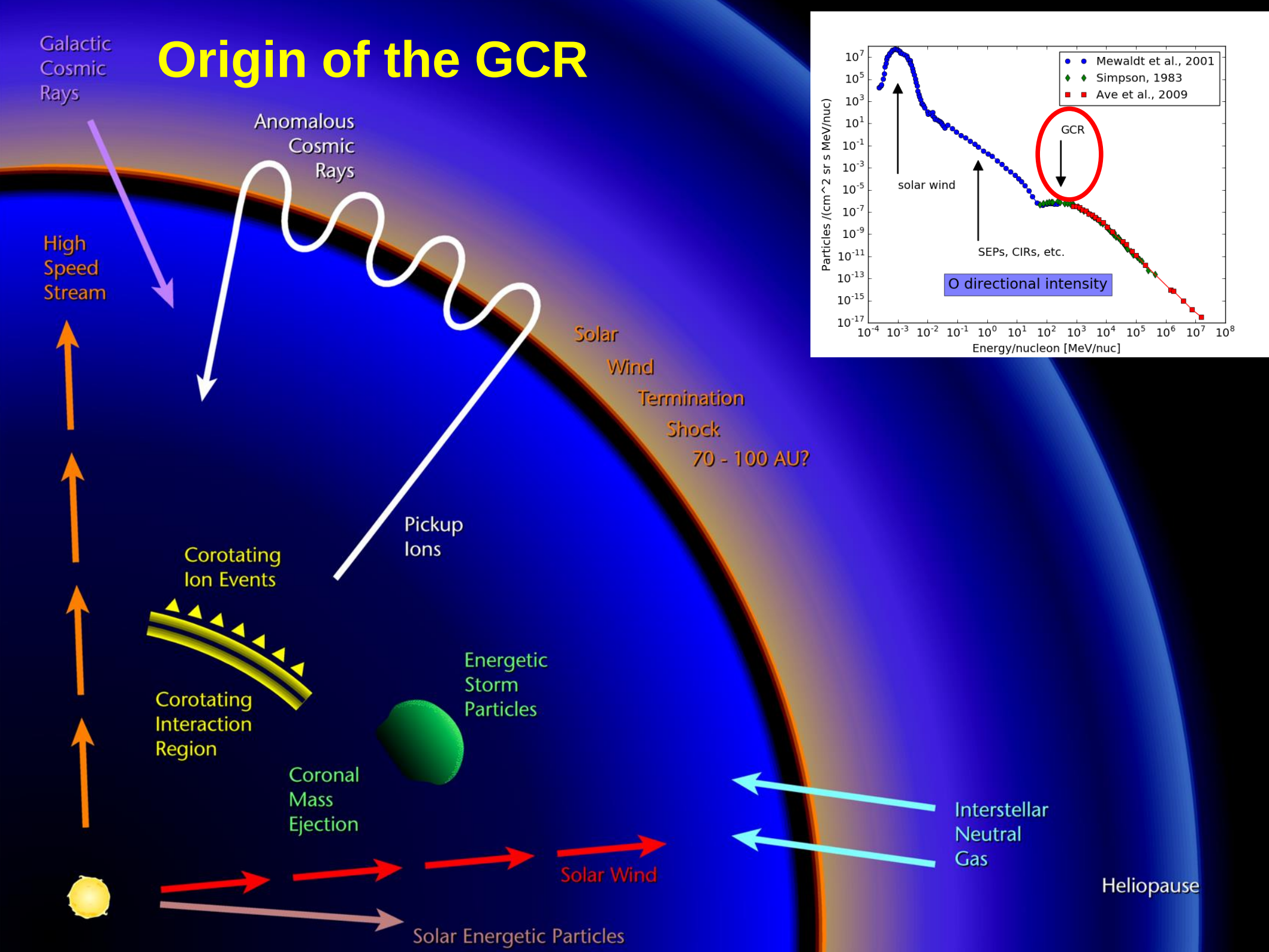


(courtesy Daniel Matthiä)

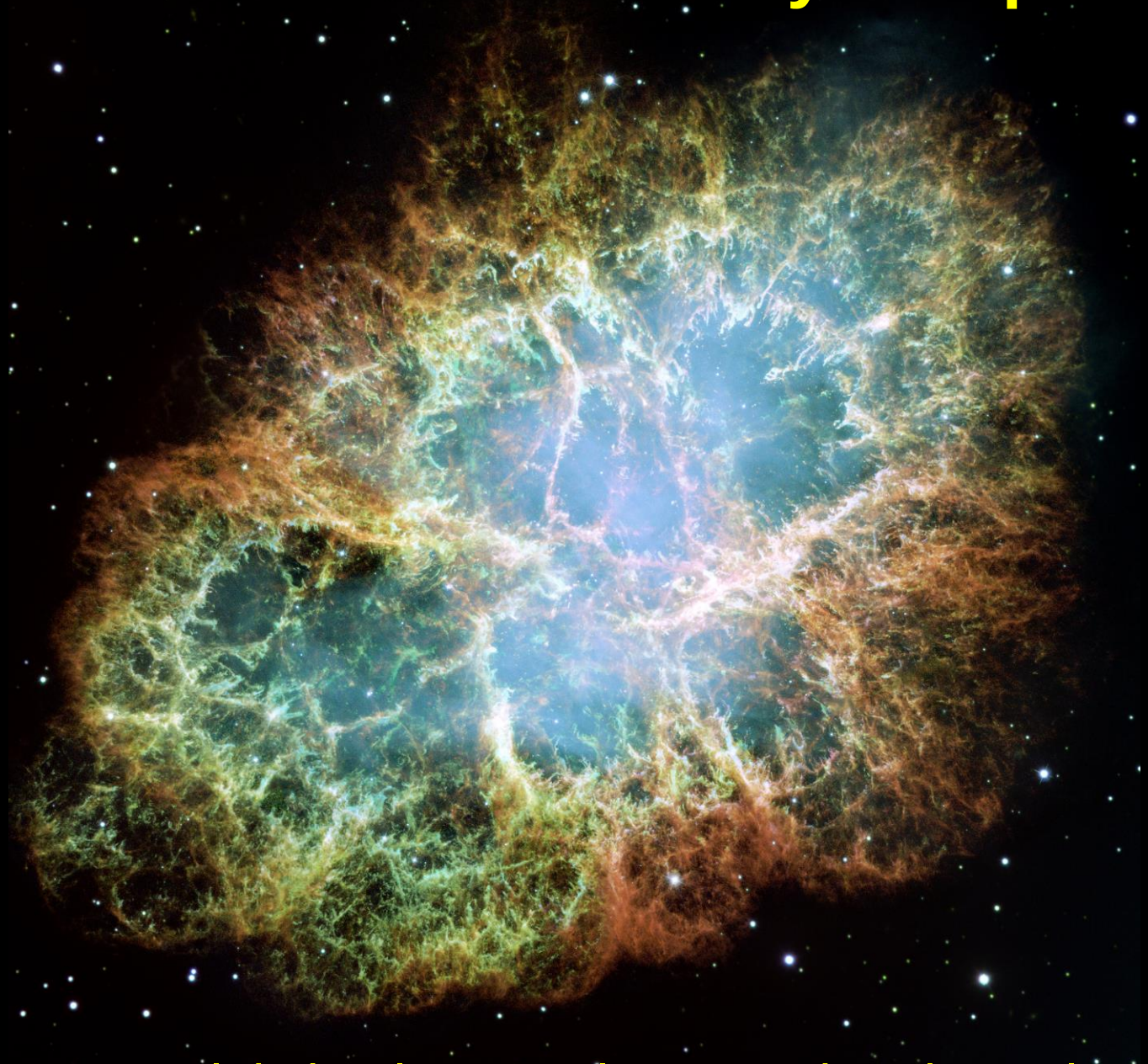
Origin of GCR



Origin of the GCR



Origin of Galactic Cosmic Rays: Supernovae



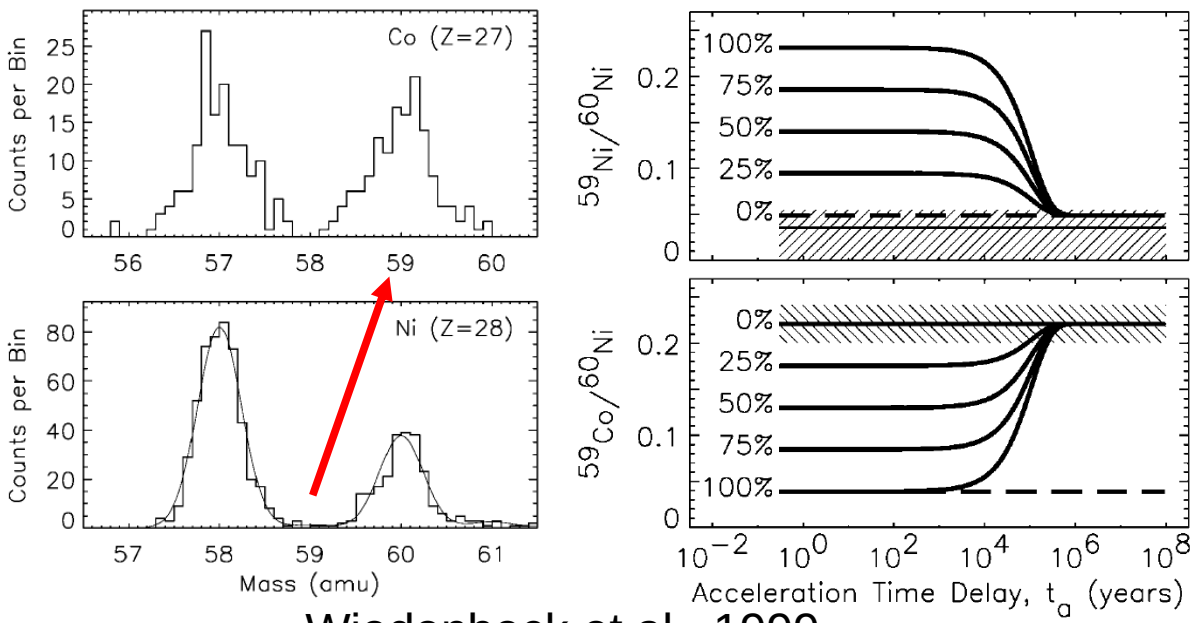
How are nuclei simultaneously created and accelerated?

Origin of Galactic Cosmic Rays: OB-Associations

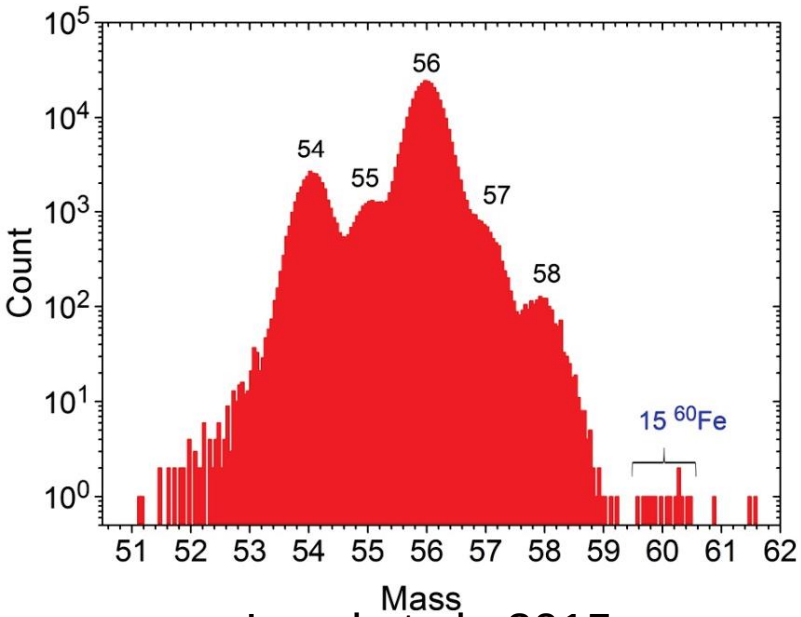
^{59}Ni decays into ^{59}Co via electron capture $T_{1/2}$ = 76,000 years

Measured ^{59}Ni/^{59}Co < 0.055 implies acceleration > 100,000 years after creation of ^{59}Ni

^{60}Fe β-decays into ^{60}Co with $T_{1/2}$ = 2.62 Myrs. Its measurement implies acceleration within few Myrs of nuclei creation



Wiedenbeck et al., 1999



Israel et al., 2015

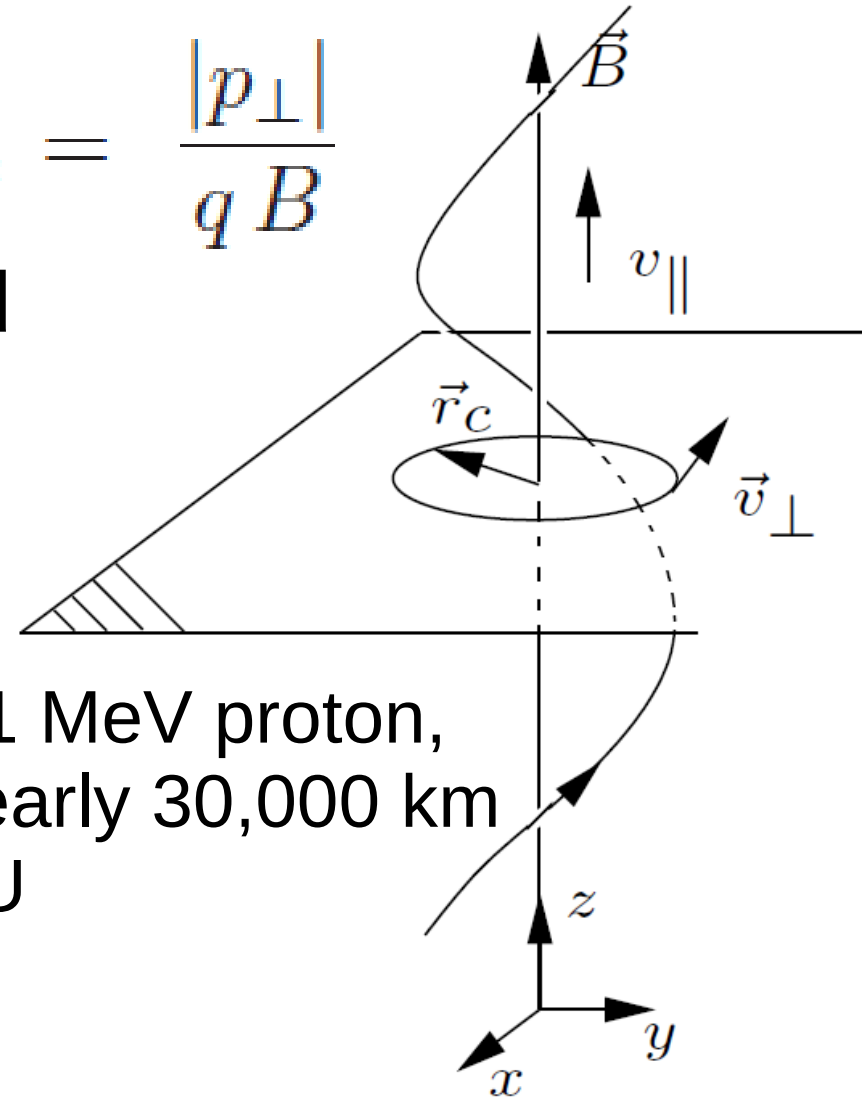
One supernova creates GCR nuclei, a second one accelerates them

==> OB Associations

Radiation Transport in the Heliosphere

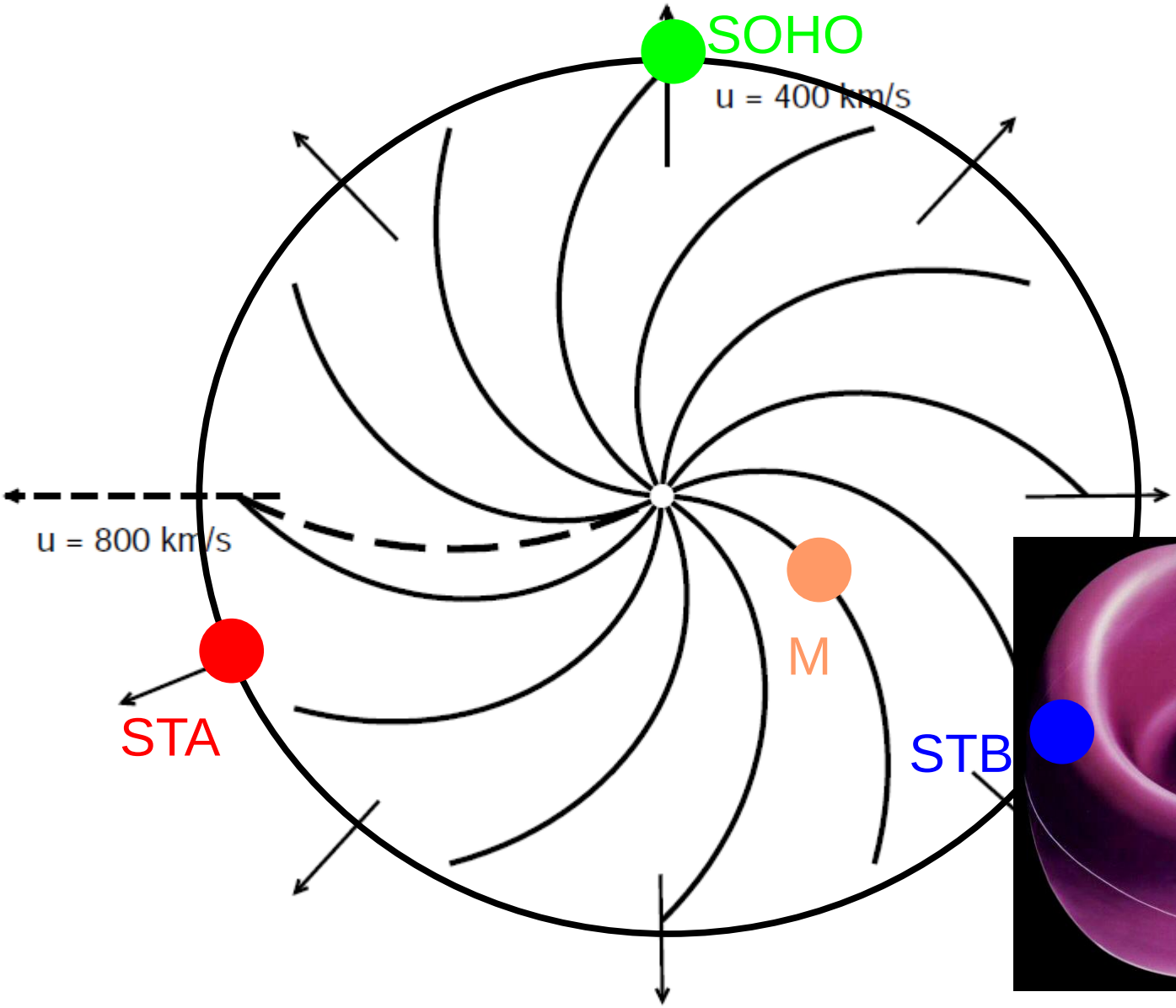
- Electrically charged ions and electrons
- Interplanetary magnetic field controls propagation

$$r_c = \frac{|p_\perp|}{q\,B}$$



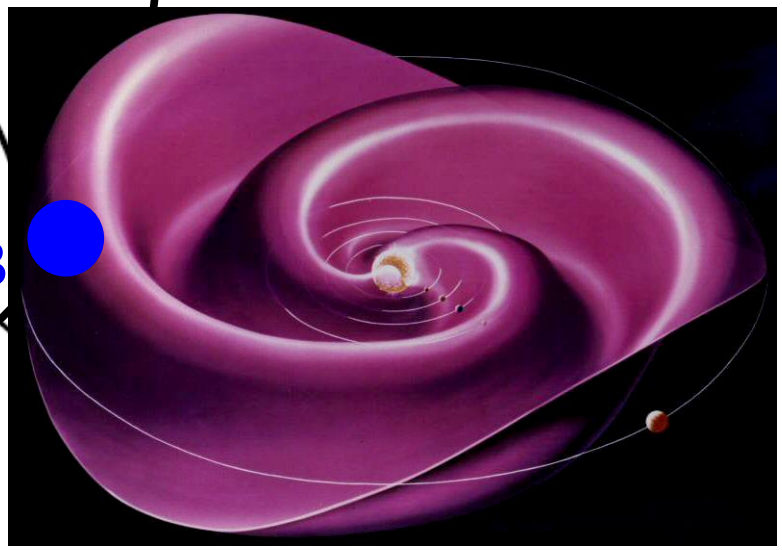
For a 1 MeV proton, r_c is nearly 30,000 km at 1 AU

Large-scale interplanetary magnetic field organized along Parker spiral

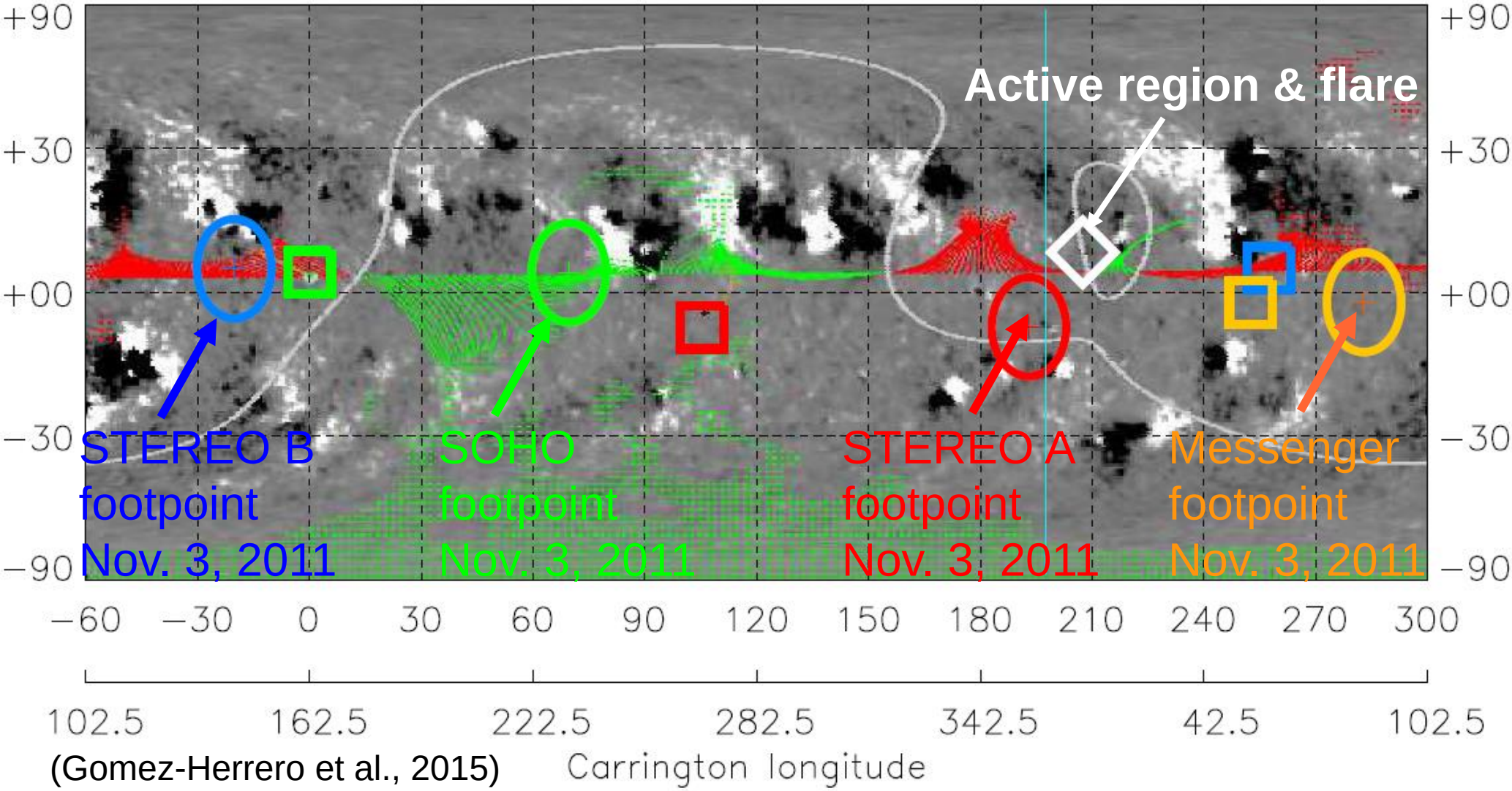


Charged energetic particles are tied to magnetic field...

SOHO, STEREO, Messenger widely separated in Nov‘ 11



Connection Sun-Heliosphere for November 2011

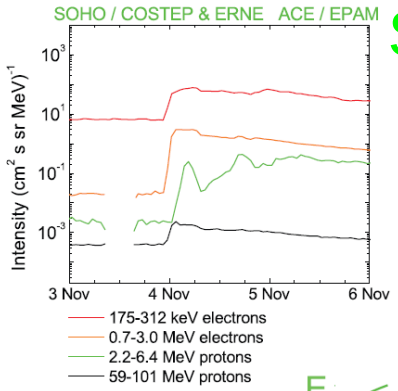


(Gomez-Herrero et al., 2015)

You don't really expect all spacecraft to see the event, do you?

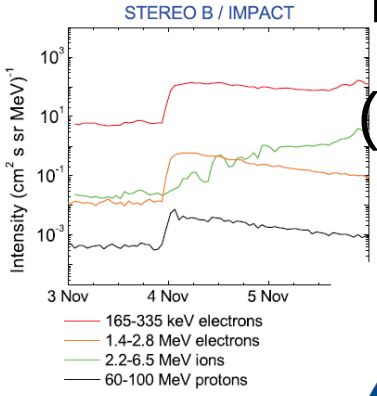
How does the Sun connect to the heliosphere?

SOHO



Wide spread events seen in
- ions,
- electrons,
- and ^{3}He

STEREO B

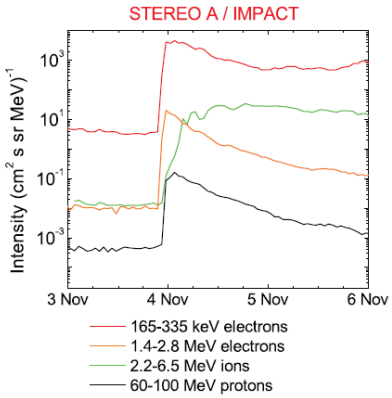


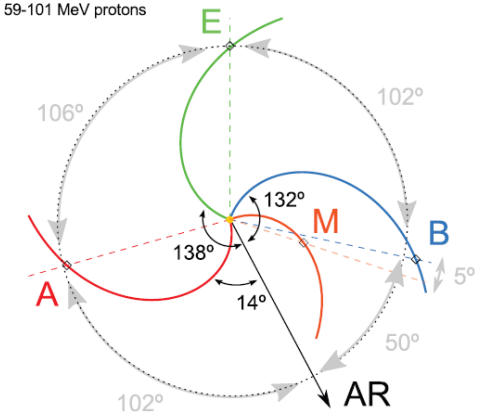
This is sobering...

(can we connect S-H?)

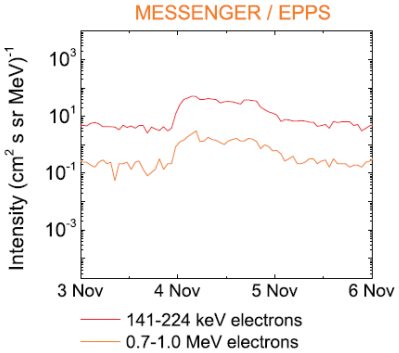
… but also at 1 AU!

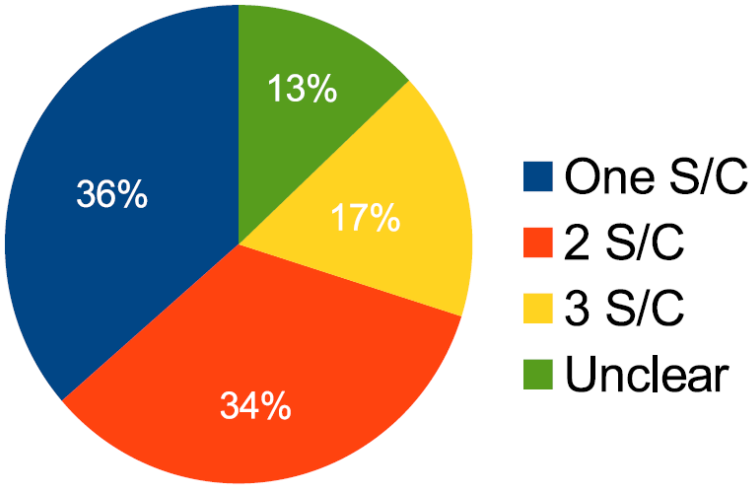
STEREO A





Messenger





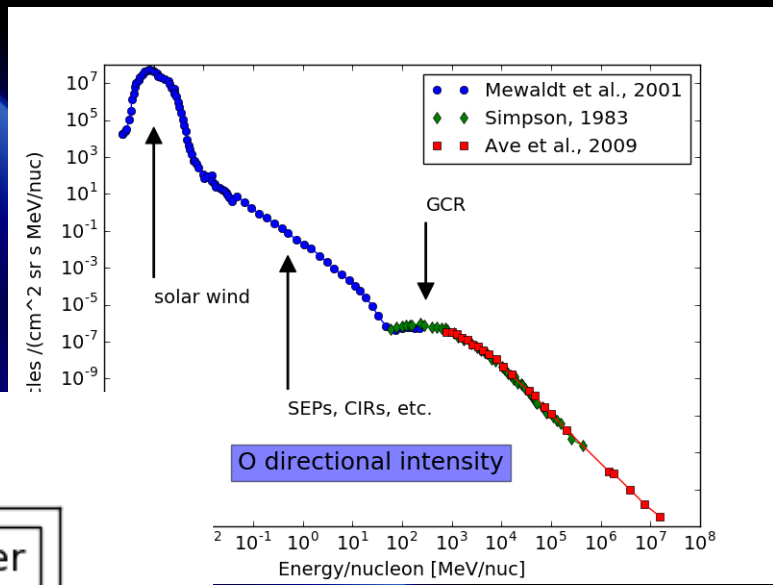
(Gomez-Herrero et al., 2015)

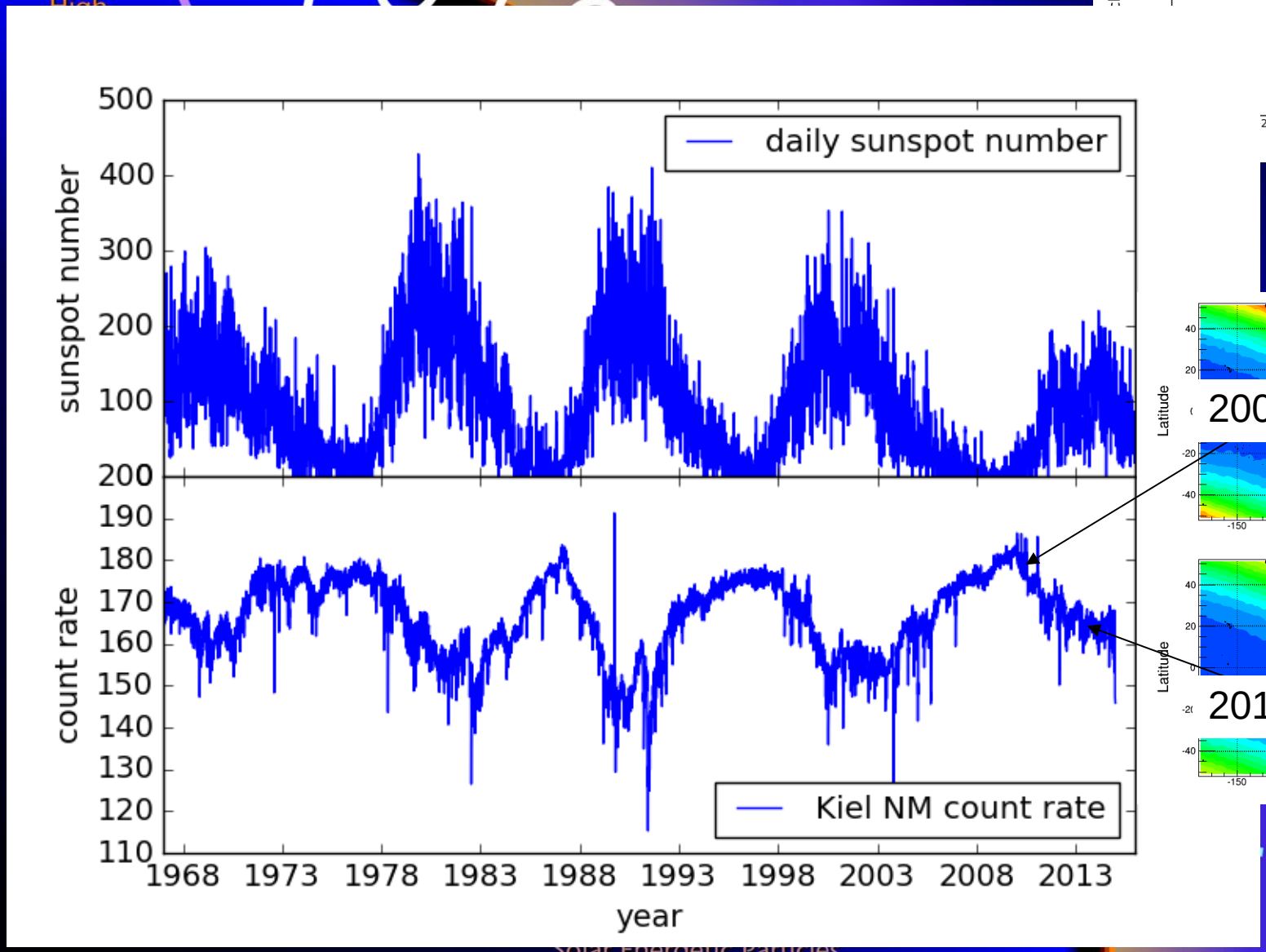
(Richardson et al., 2014)

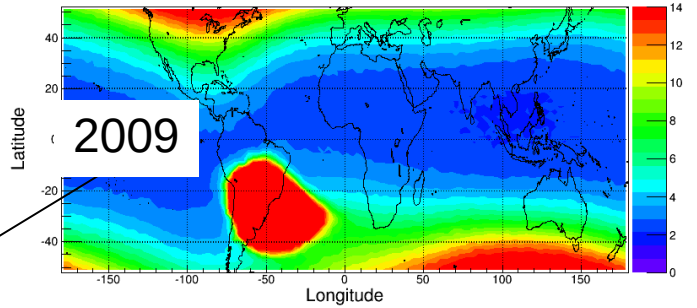
We need to better understand the connection!

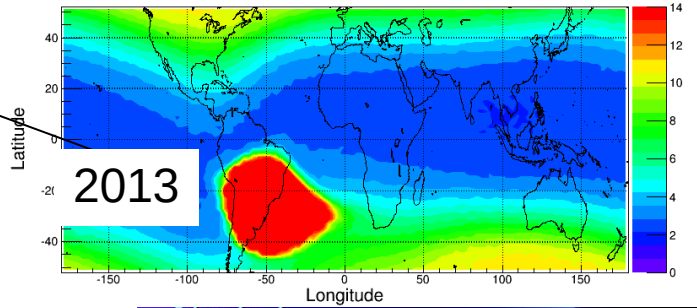
solar orbiter

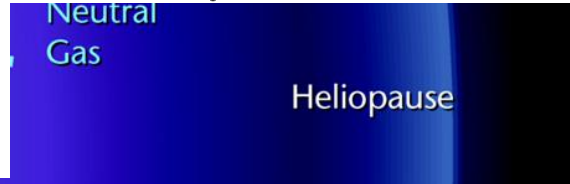
GCR Modulation



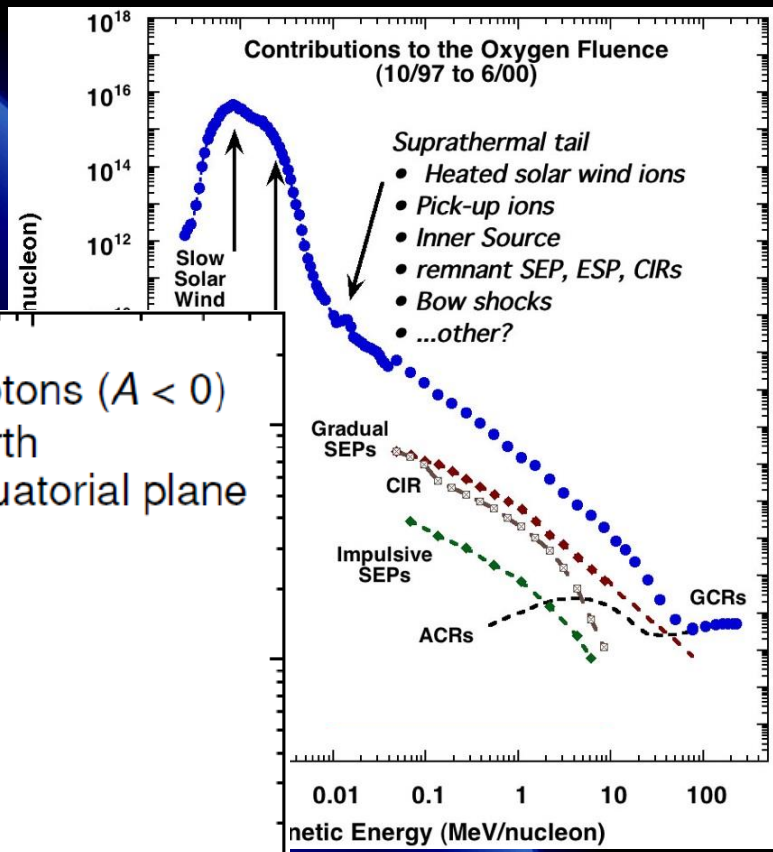


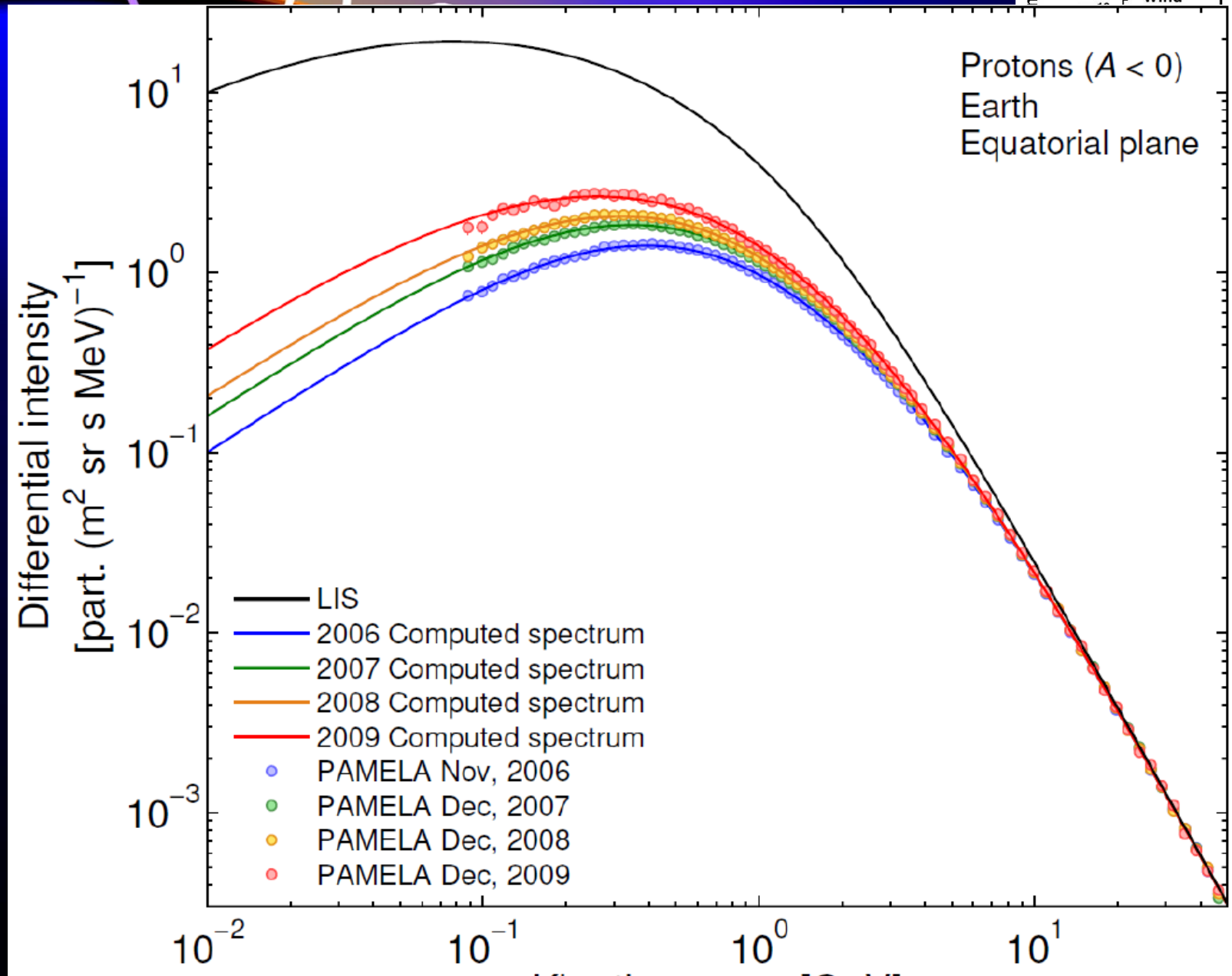


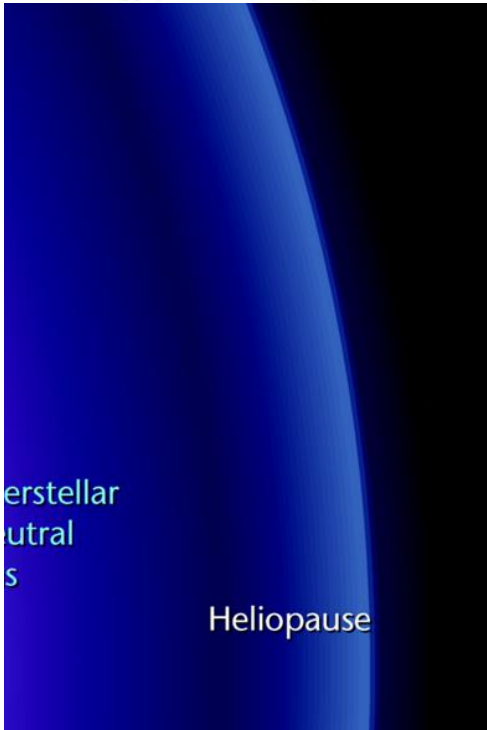




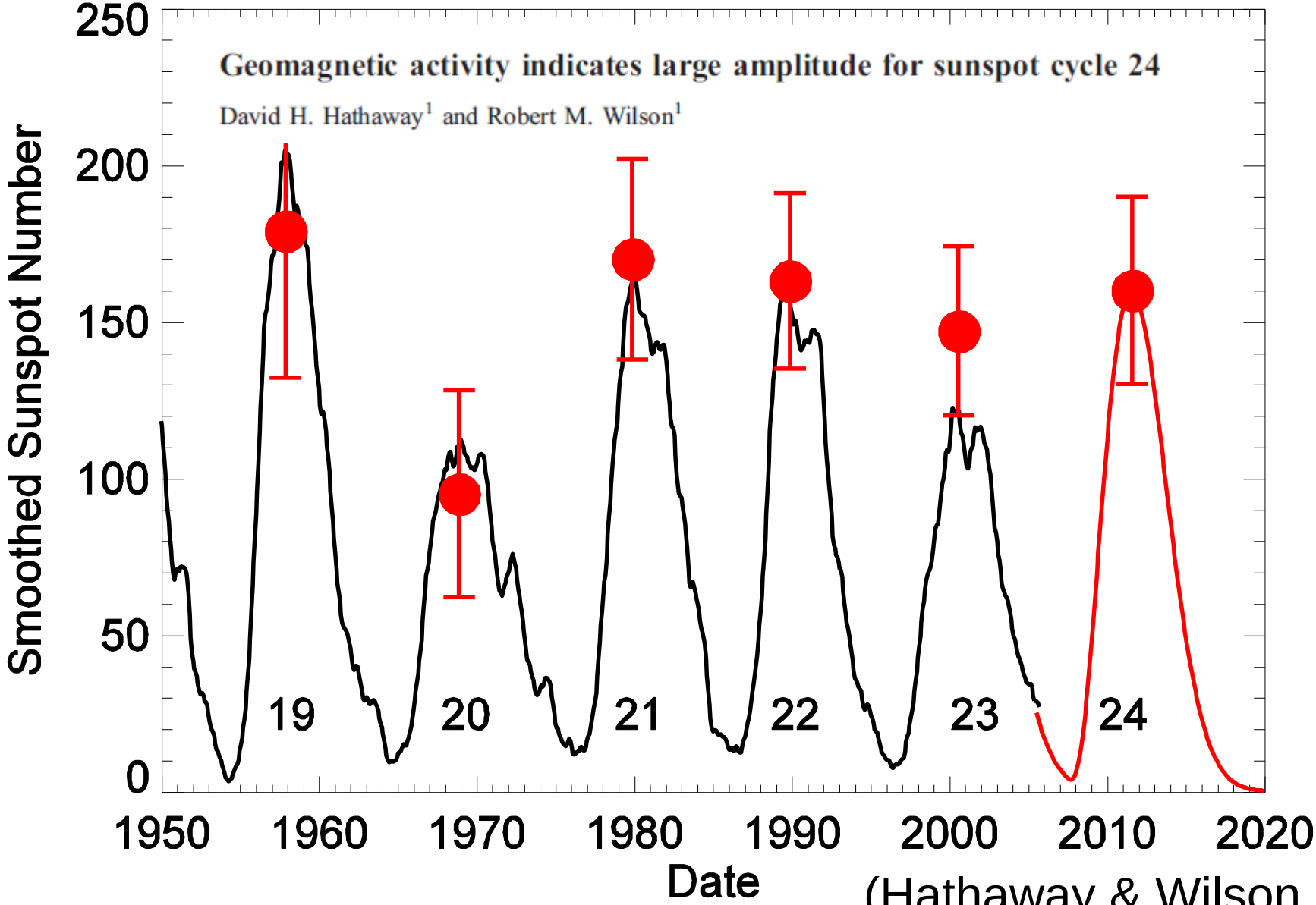
GCR Modulation



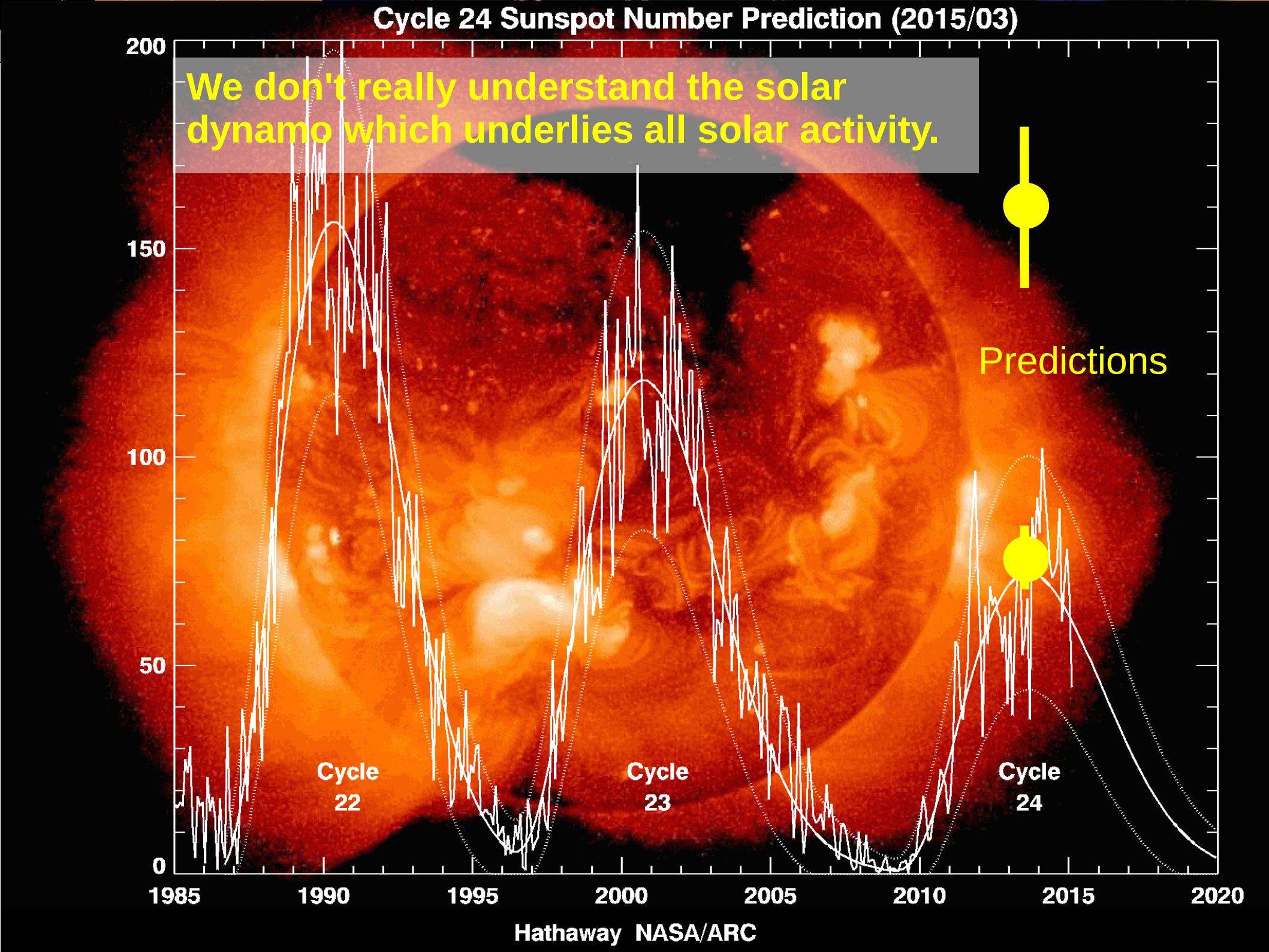


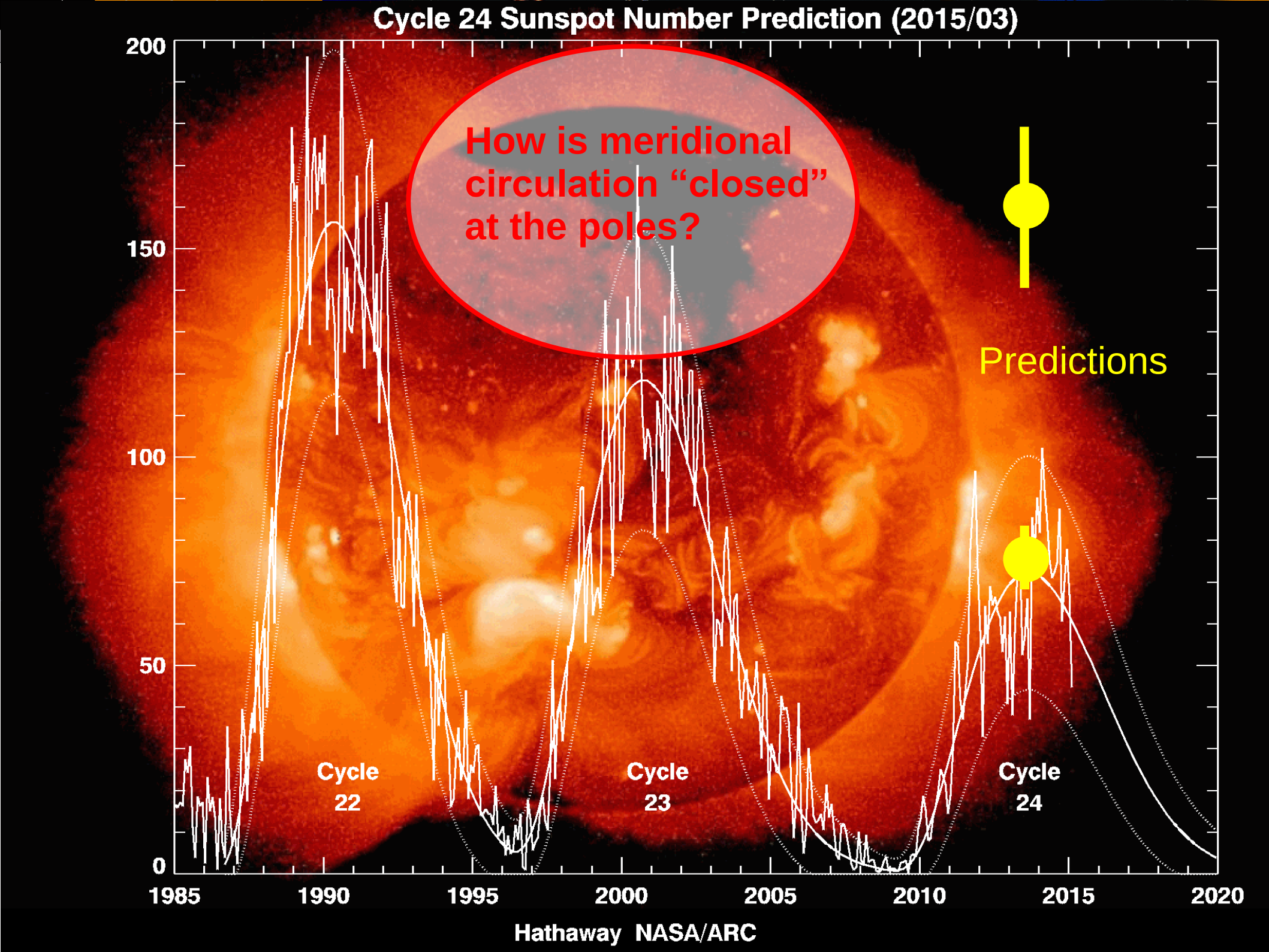


Solar Cycle Amplitude Predictions



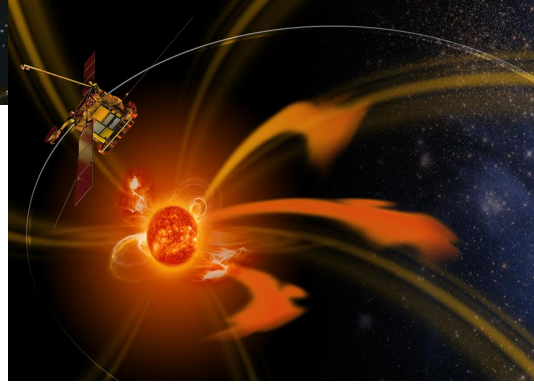
(Hathaway & Wilson, 2006)

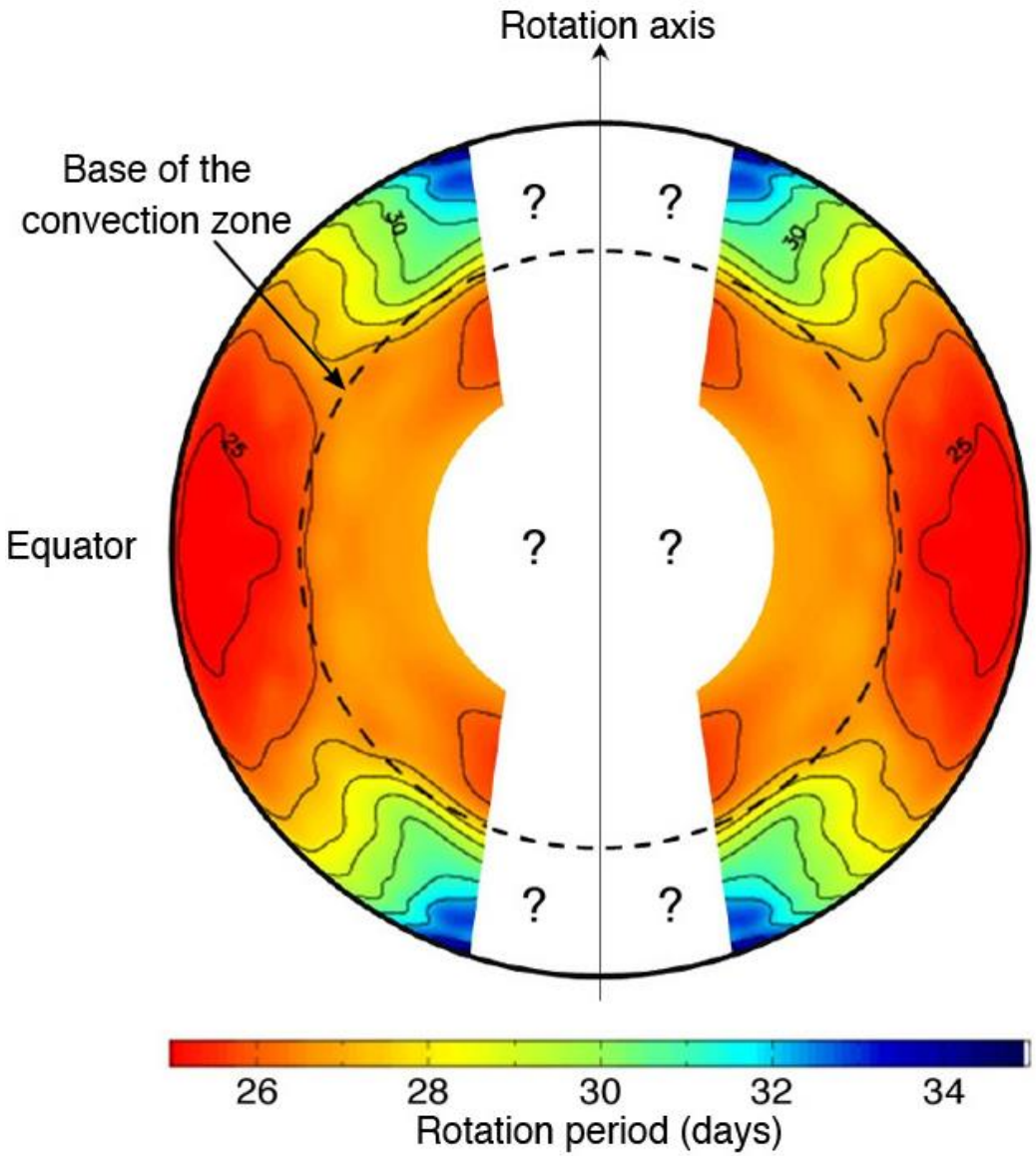

Cycle 24 Sunspot Number Prediction (2015/03)
We don't really understand the solar dynamo which underlies all solar activity.
Predictions
Cycle 22
Cycle 23
Cycle 24
200
150
100
50
0
1985
1990
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC

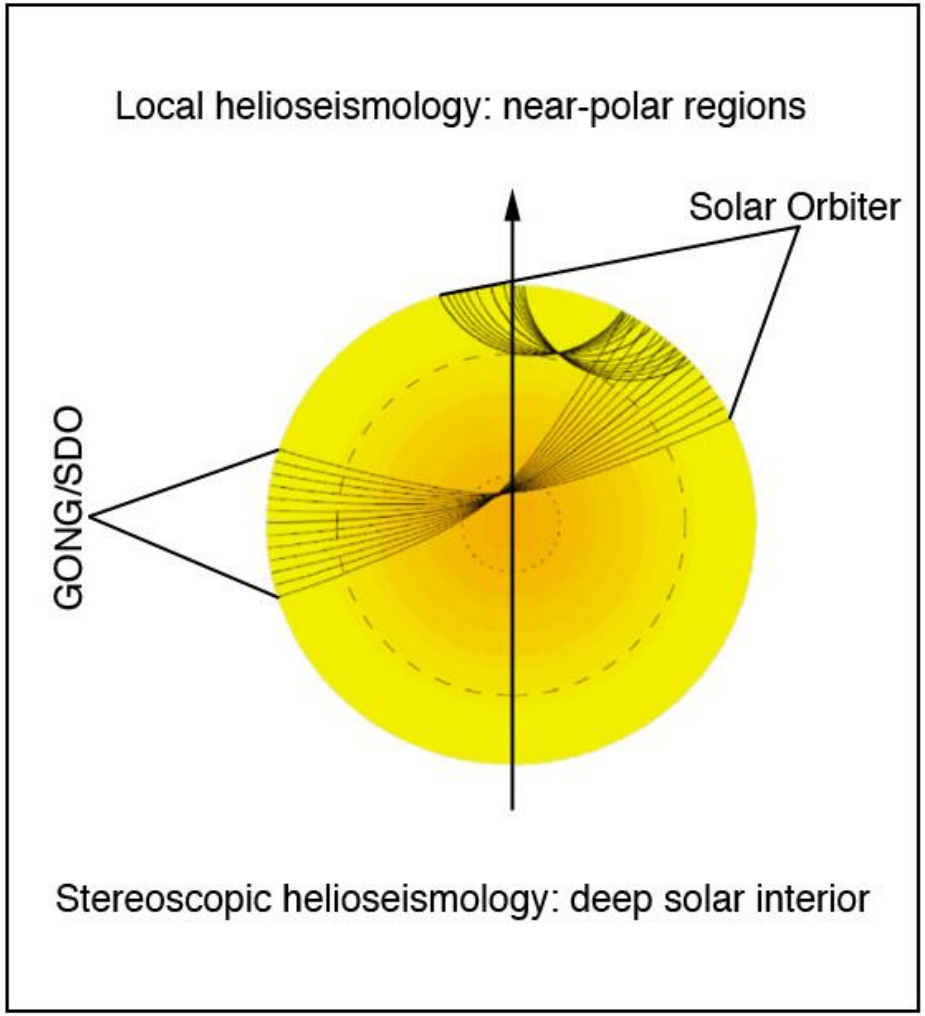

Cycle 24 Sunspot Number Prediction (2015/03)
How is meridional circulation "closed" at the poles?
Predictions
Cycle 22
Cycle 23
Cycle 24
200
150
100
50
0
1985
1990
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC

We don't even know how many polar convective cells there are!

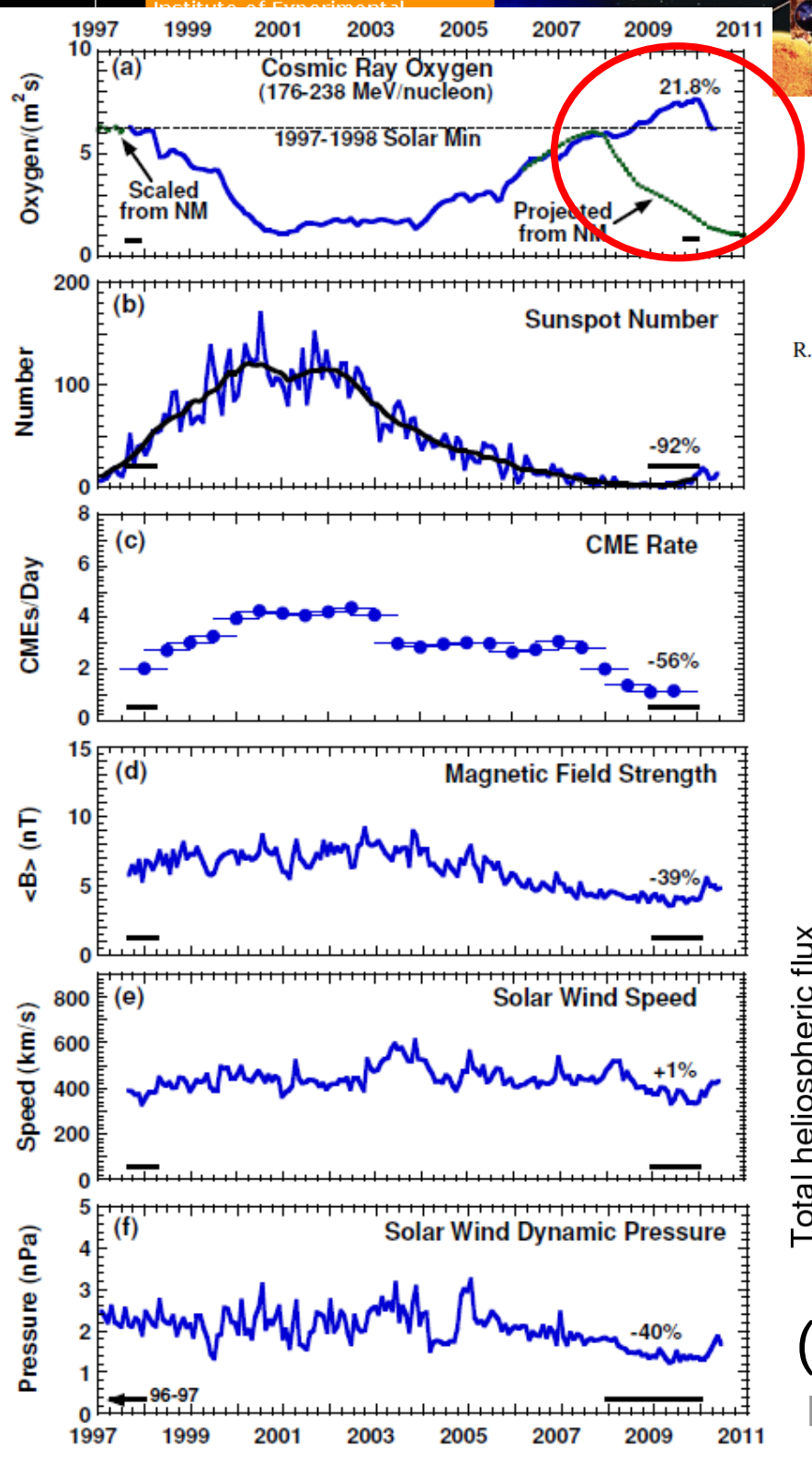
solar orbiter







(Roth, 2007)



The Consequence:

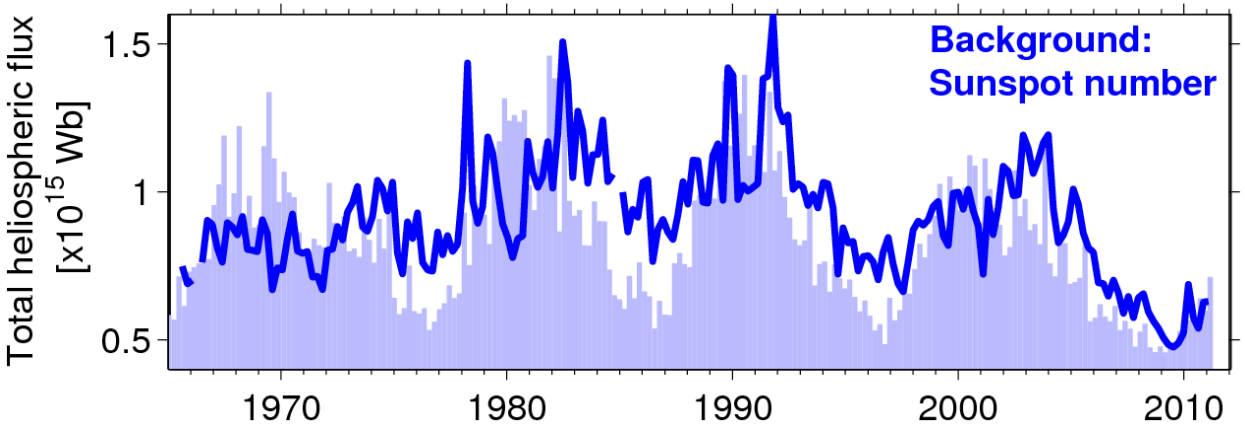
RECORD-SETTING COSMIC-RAY INTENSITIES IN 2009 AND 2010

R. A. Mewaldt[1], A. J. Davis[1], K. A. Lave[2], R. A. Leske[1], E. C. Stone[1], M. E. Wiedenbeck[3], W. R. Binns[2], E. R. Christian[4], A. C. Cummings[1], G. A. de Nolfo[4], M. H. Israel[2], A. W. Labrador[1], and T. T. von Rosenvinge[4]

- Lowest solar wind dynamic pressure
- Smallest total heliospheric flux
- Smallest CME rate

… were all not predicted.

We need to better understand the Sun!



(Mewaldt et al., 2010) (Owens, 2008)

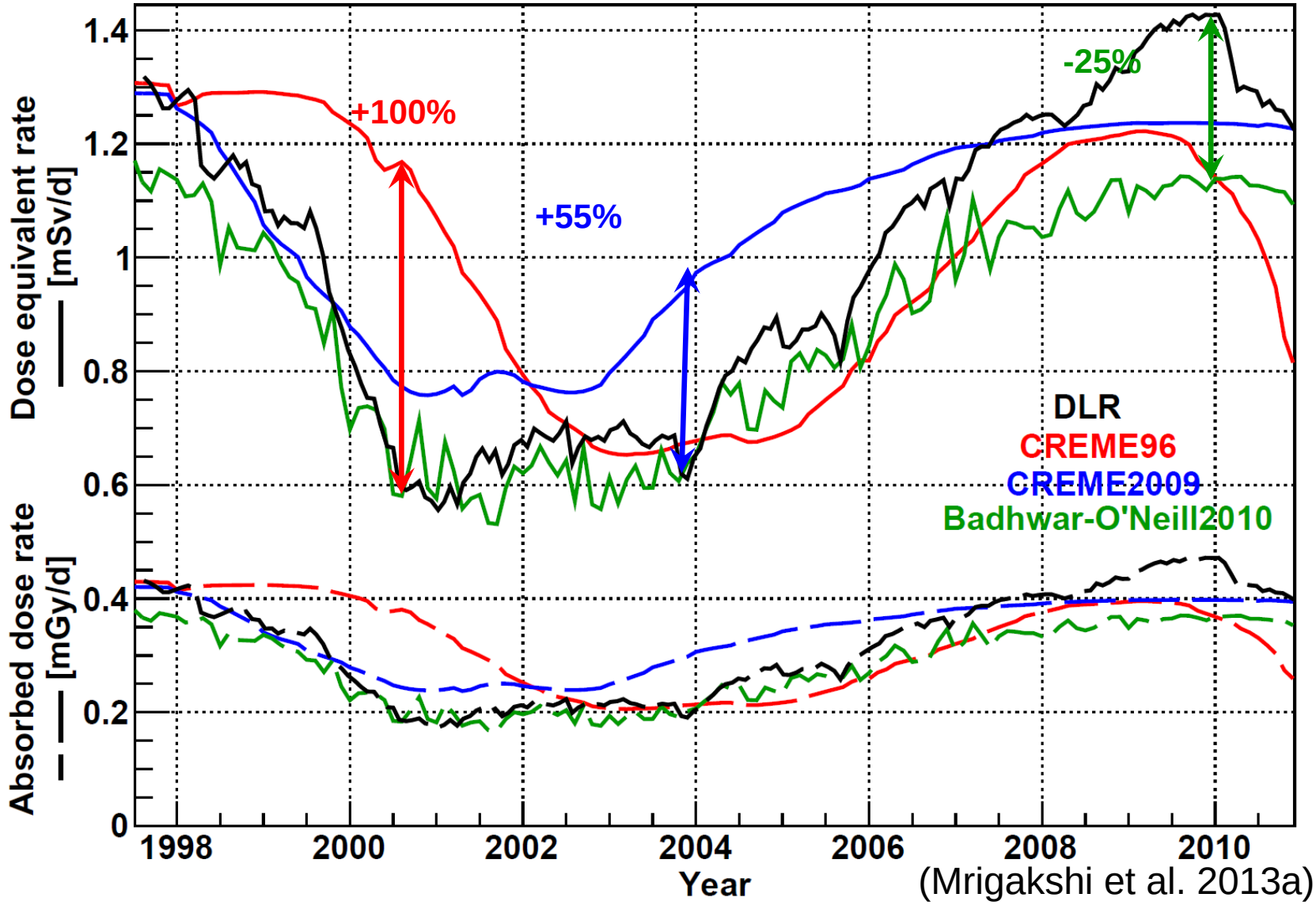
Risks Assessments for all DRMs (Jan 2015)

Human Spaceflight Risks	In Mission Risk - Operations						Post Mission Risk – Long Term Health					
Human Spaceflight Risks 01/12/15	Low Earth Orbit	Low Earth Orbit	Deep Space Sortie	Lunar Visit/Habitation	Deep Space Journey/Habitation	Planetary	Low Earth Orbit	Low Earth Orbit	Deep Space Sortie	Lunar Visit/Habitation	Deep Space Journey/ Habitation	Planetary
	6 Months	12 Months	30 Days	1 year	1 Year	3 years	6 Months	12 Months	30 Days	1 year	1 Year	3 years
VIIP	A	A	A	A	RM	RM	A	A	A	A	RM	RM
Renal Stone Formation	A	A	A	A	RM	RM	RM	RM	RM	RM	RM	RM
Inadequate food and nutrition	A	A	A	A	RM	RM	A	A	A	A	A	RM
Risk of Space Radiation Exposure	A	A	A	A	A	A	A	A	A	RM	RM	RM
Medications Long Term Storage	A	A	A	A	A	RM	A	A	A	A	A	RM
Acute and Chronic Carbon Dioxide	A	A	A	A	RM	RM	A	A	A	A	A	A
inflight Medical Conditions	A	A	A	RM	RM	RM	A	A	A	A	RM	RM
Cognitive or Behavioral Conditions	A	A	A	A	RM	RM	A	A		RM	RM	RM
Risk of Bone Fracture	A	A	A	A	A	A	A			A	A	RM
Team Performance Decrements#	A	A	A	A	RM	RM	A			A	A	A
Reduced Muscle Mass, Strength	A	A	A	A	A	RM	A				A	A
Reduced Aerobic Capacity	A	A	A	A	A	RM	A			A	A	A
Sensorimotor Alterations	A	A	A	A	A	RM	A			A	A	RM
Human-System Interaction Design#	A	A	A	RM	RM	RM	A	A	A	A	A	A
Injury from Dynamic Loads	A	A	RM	RM	RM	RM	A	A	RM	RM	RM	RM
Sleep Loss	A	A	A	A	RM	RM	A	A	A	A	RM	RM
Altered Immune Response	A	A	A	A	RM	RM	A	A	A	A	A	RM
Celestial Dust Exposure	N/A	N/A	A	TBD	TBD	TBD	N/A	N/A	A	TBD	TBD	TBD
Host-Microorganism Interactions	A	A	A	A	RM	RM	A	A	A	A	A	RM
Injury due to EVA Operations	A	A	A	RM	A	RM	A	A	A	RM	RM	RM
Decompression Sickness	A	A	A	A	RM	A	A	A	A	RM	A	RM
Toxic Exposure	A	A	A	A	A	A	A	A	A	A	A	A
Hypobaric Hypoxia	A	A	A	A	A	A	A	A	A	A	A	A
Space Adaptation Back Pain	A	A	A	A	A	A	N/A	N/A	N/A	N/A	N/A	N/A
Urinary Retention	A	A	A	A	A	A	A	A	A	A	A	A
Hearing Loss Related to Spaceflight	A	A	A	A	A	A	A	A	A	A	A	A
Orthostatic Intolerance	A	A	A	A	A	A	A	A	A	A	A	A
Injury from Sunlight Exposure - retired	A	A	A	A	A	A	A	A	A	A	A	A
Risk of electrical shock - Retired	A	A	A	A	A	A	A	A	A	A	A	A

Radiation!

A – Accepted RM- Requires Mitigation Green – controlled **Yellow** – partially controlled Red -- uncontrolled

GCR models show substantial differences in their predictions



(Mrigakshi et al. 2013a)

Dose Rate Measurements at the Moon?

-Only results from two missions in Lunar orbit avaible (CRATER and RADOM) with dose values of a

T.P. Dachev et al. *An overview of RADOM results for earth and moon radiation environment on Chandrayaan-1 satellite, Advances in Spa*
Spence H. E. (CRaTER Science Team)*, An Overview of Results from the Lunar Reconnaissance Orbiter (LRO) Cosmic Ray Telescope f*
J.E. Mazur et al. *New Measurements ot total ionizing dose in the lunar environment, Space Weather, 9, S07002, doi:10.1029/2010SW00*

-Calculations show an Effective Dose of 600 µSv/day taking into account Solar Minimum condition

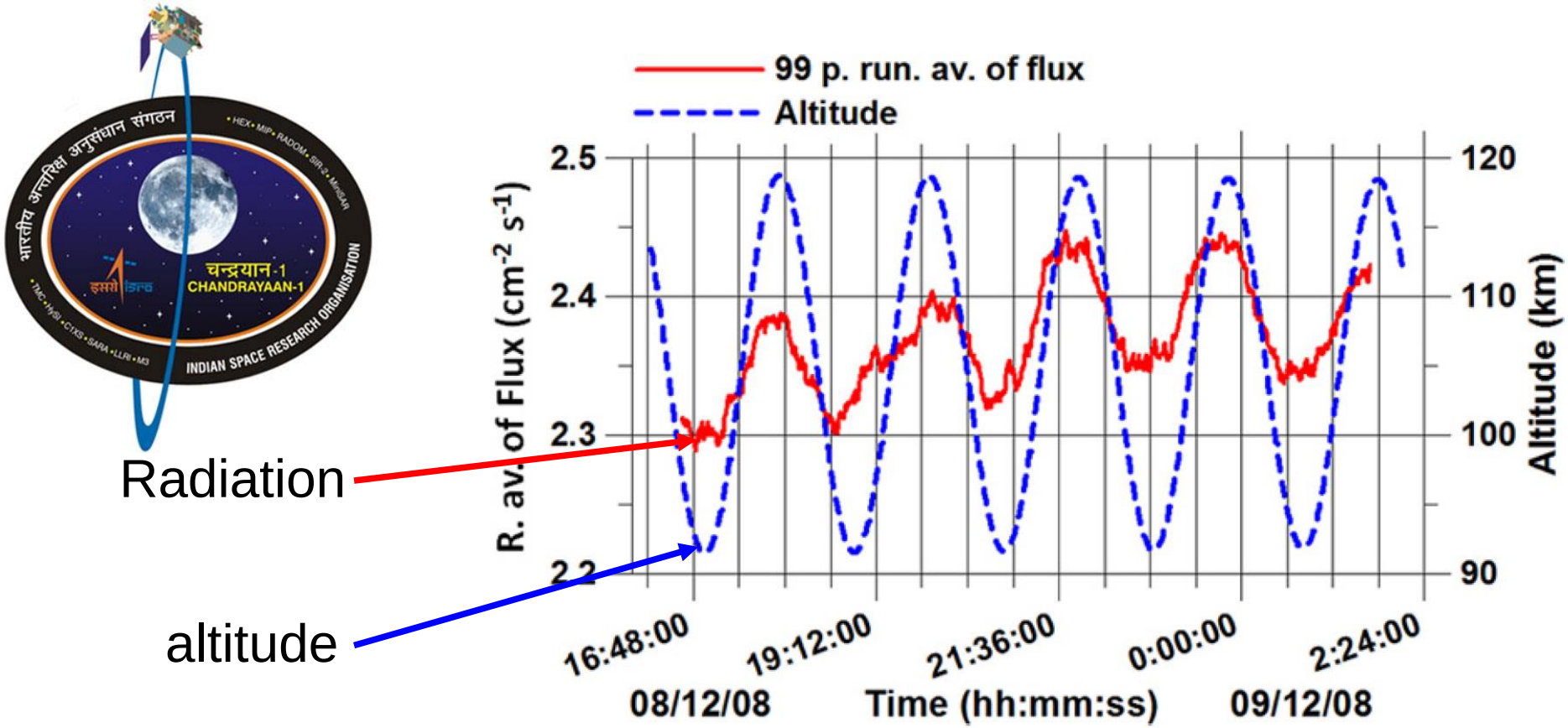
NASA-TP-2003-212158, "Analysis of a Radiation Model of the Shuttle Space Suit"
D. Matthiae*, T. Berger, G. Reitz: DLR – Updated GCR Model / Moon calculations, 2012*

-„Safe haven" to prevent exposures due to SPE needs approx. 80 cm of lunar regolith

D. Matthiae*, T. Berger, G. Reitz: DLR – Updated GCR Model / Moon calculations, 2012*

NO MEASUREMENTS on the LUNAR surface available --> needed as input
a) benchmarking of radiation transport codes
b) prerequisite for future human presence on the Moon

Dose Rate Measurements at the Moon?



Radiation is modulated by changing shielding by the Moon

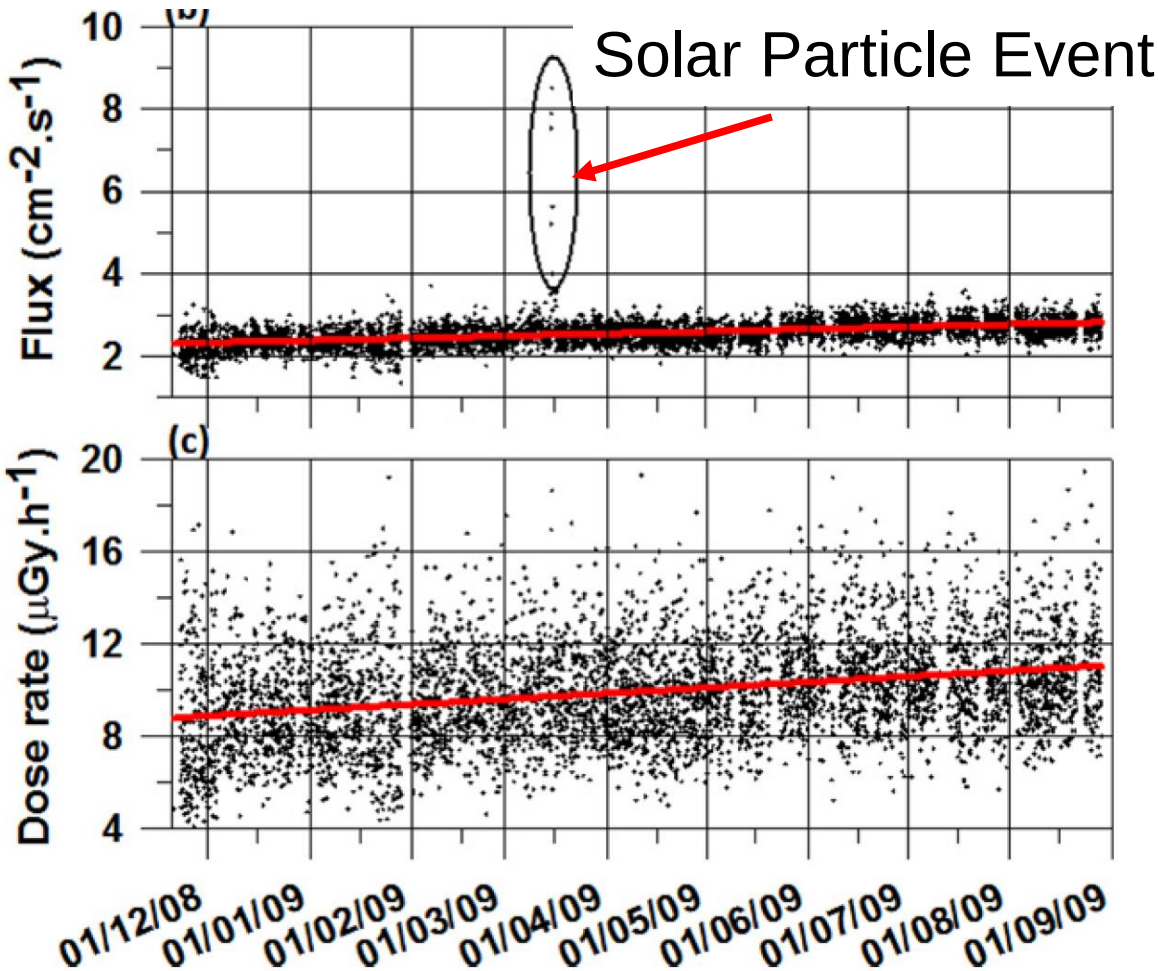
T.P. Dachev et al. An overview of RADOM results for earth and moon radiation environment on Chandrayaan-1 satellite, Advances in Space Research 48 (2011) 779-791

Dose Rate Measurements at the Moon?

Dose rates :

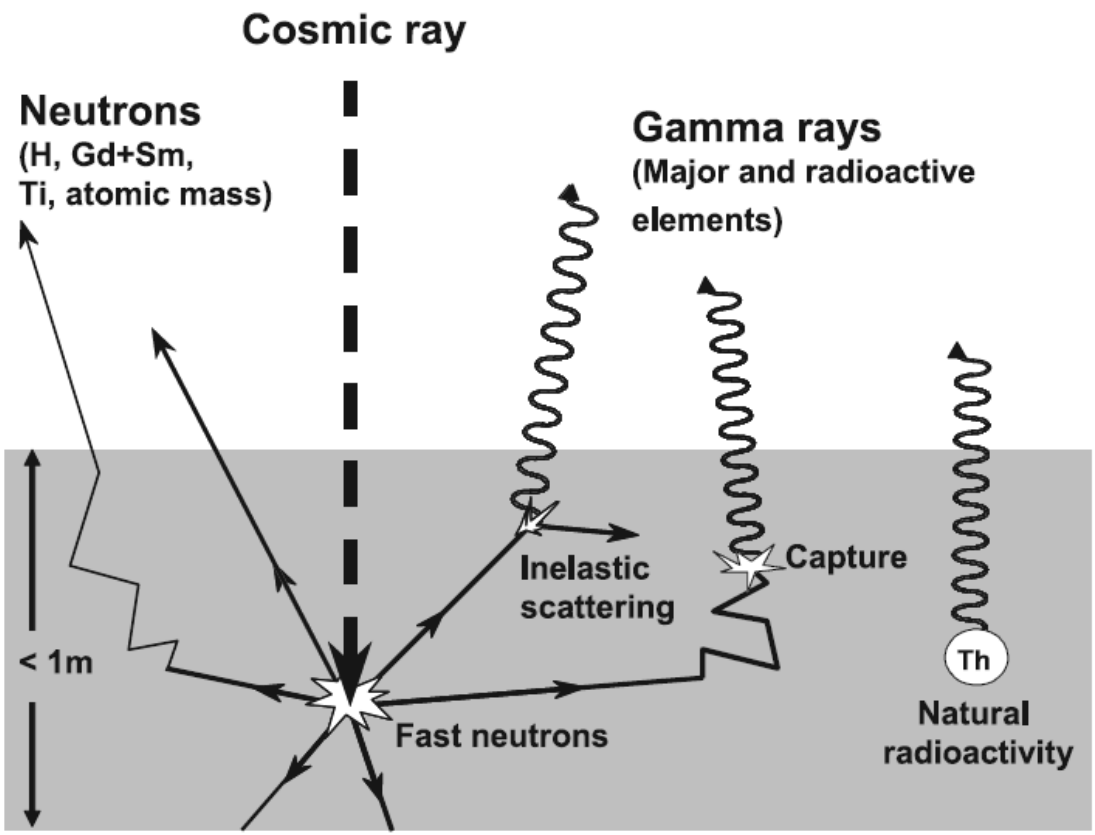
~ 100 km: 227 µGy/d

~ 200 km : 257 µGy/d

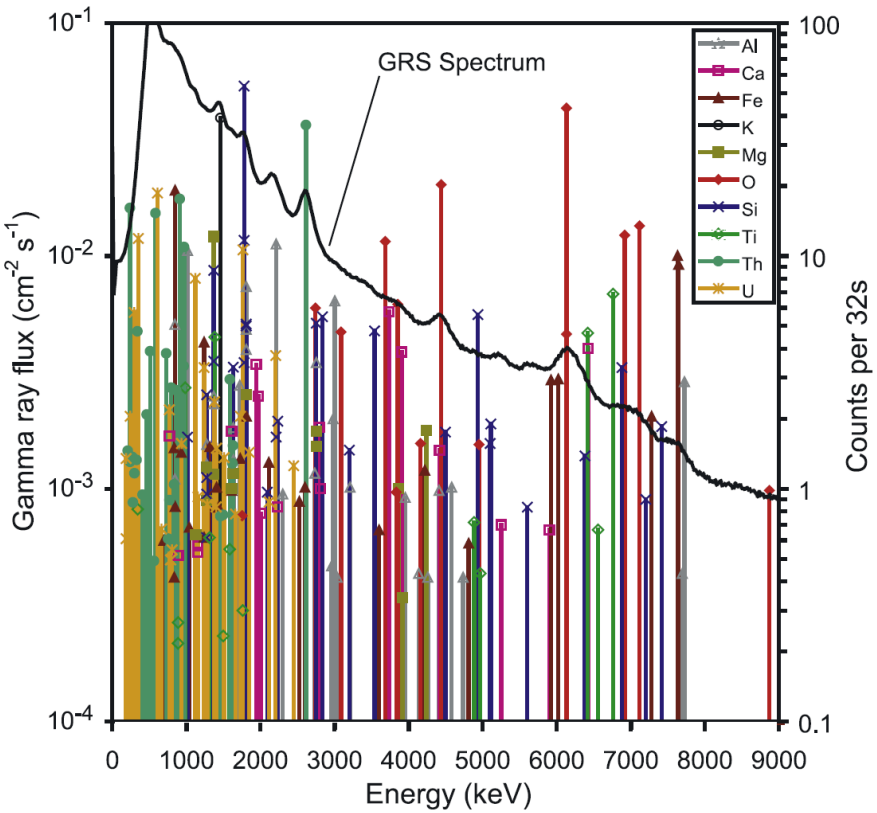


T.P. Dachev et al. An overview of RADOM results for earth and moon radiation environment on Chandrayaan-1 satellite, Advances in Space Research 48 (2011) 779-791

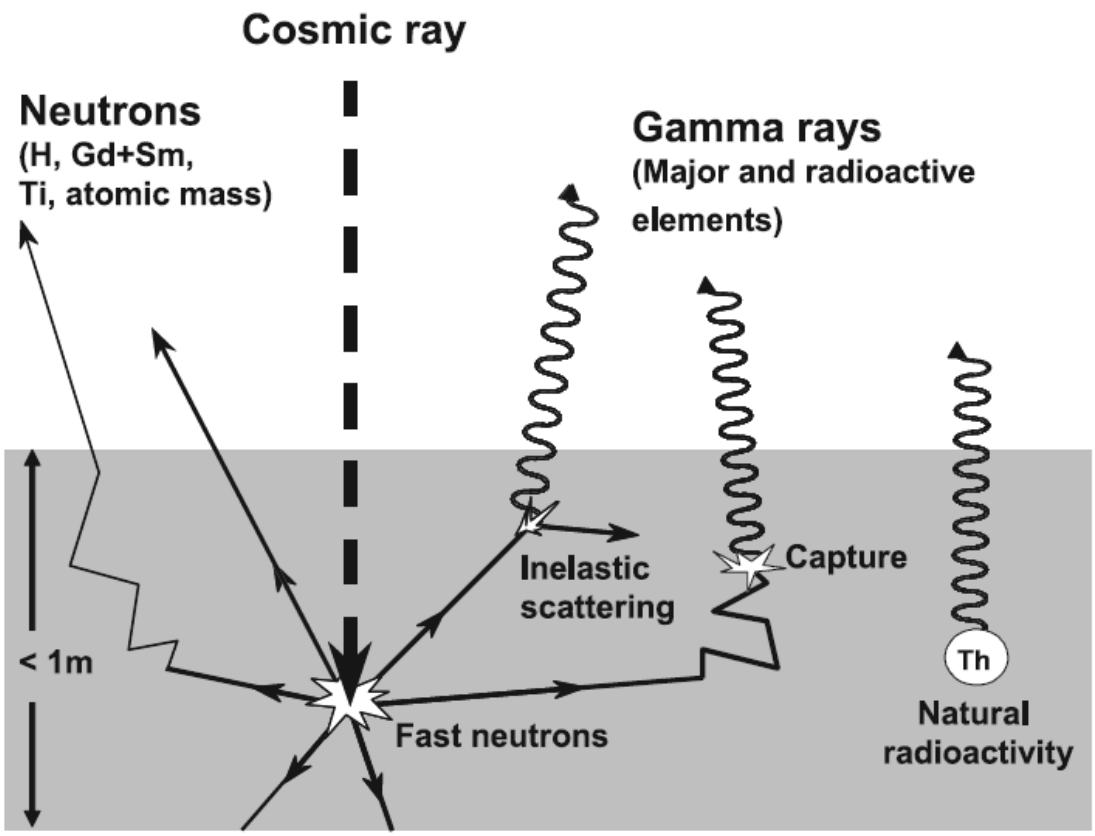
Particle Radiation Measurements at the Moon



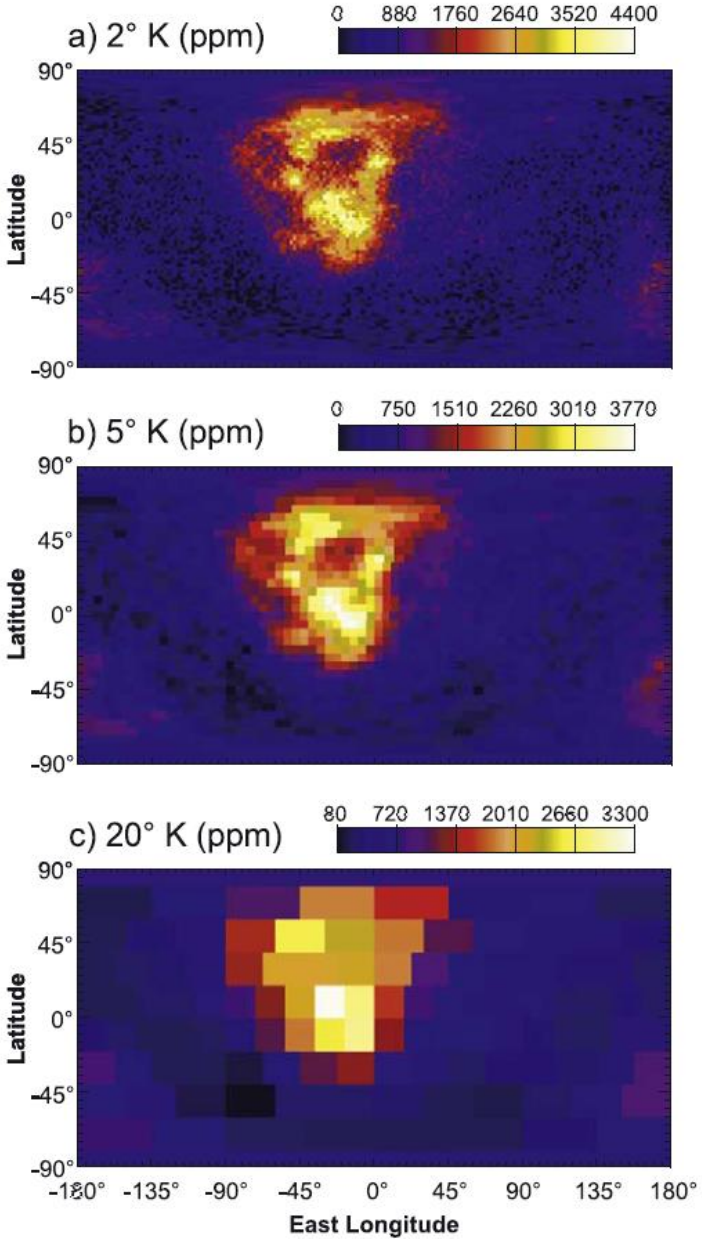
Prettyman et al., 2006



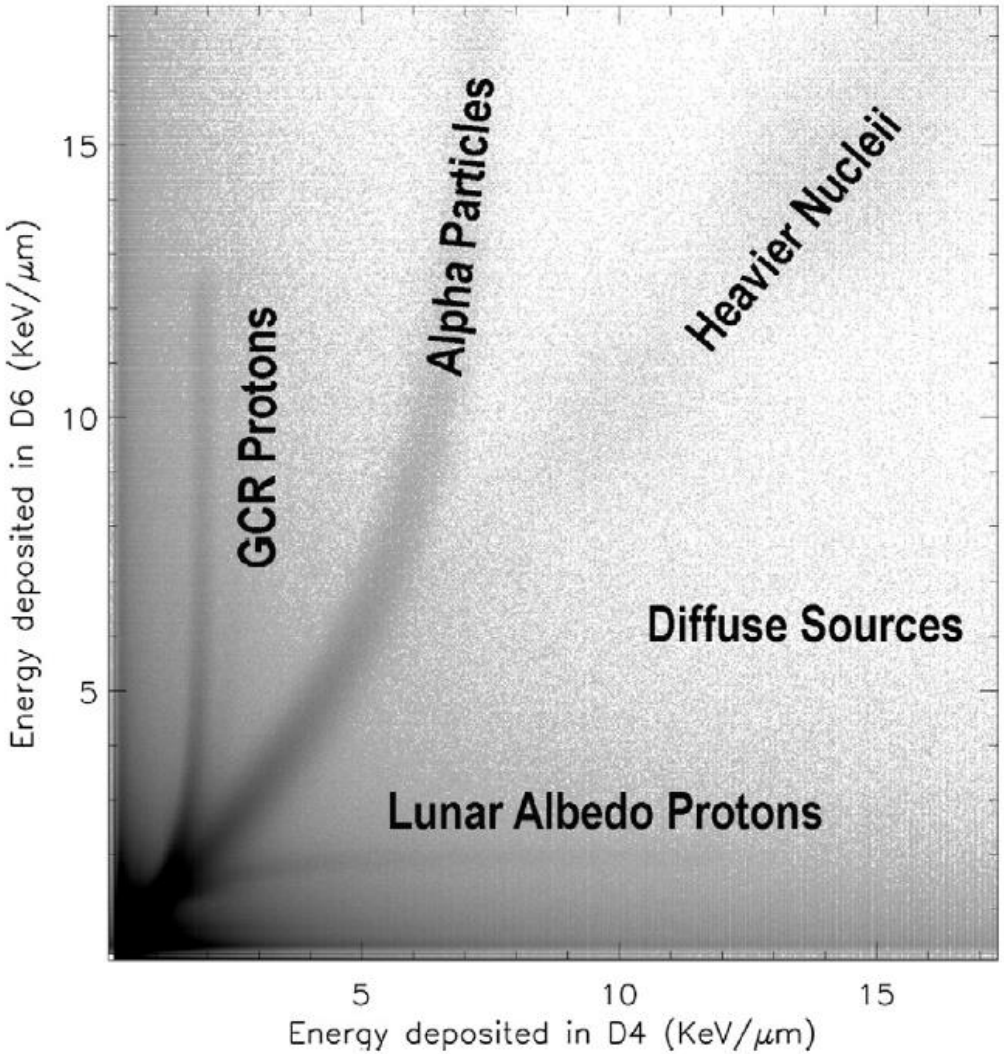
Particle Radiation Measurements at the Moon



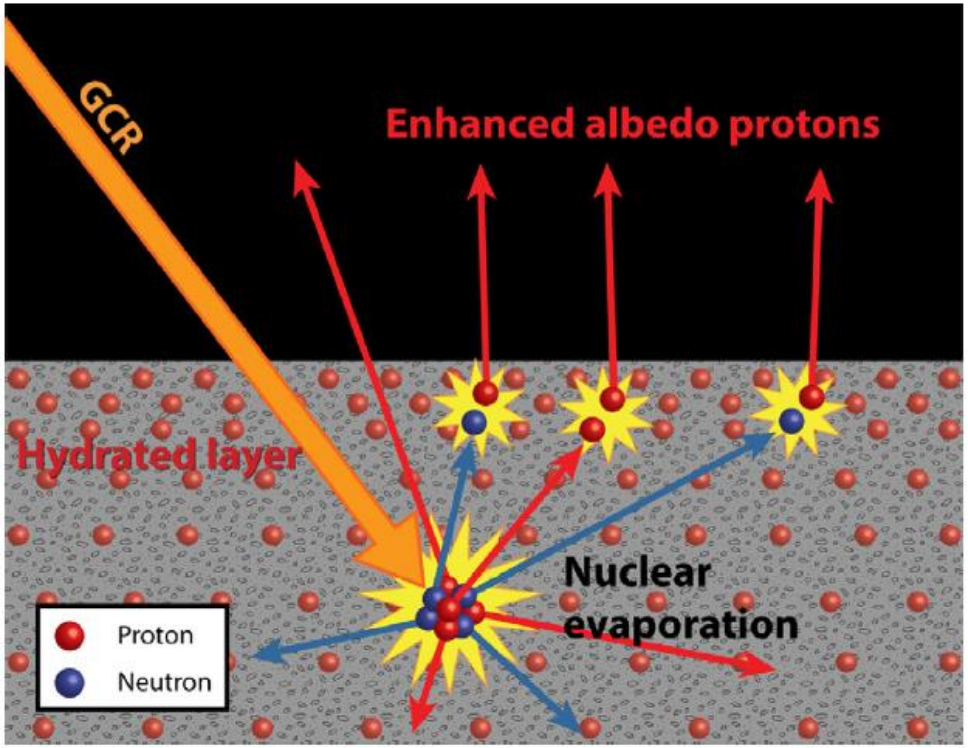
Prettyman et al., 2006



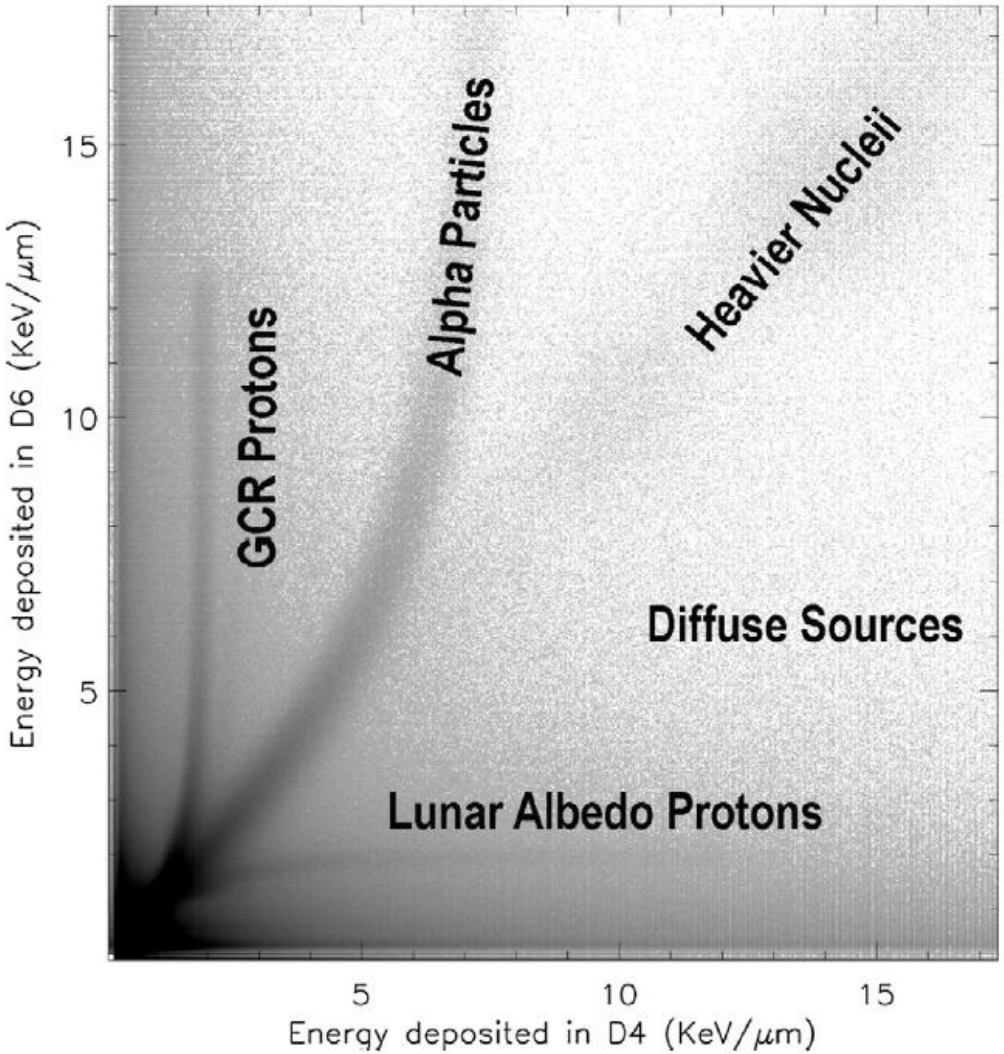
Particle Radiation Measurements at the Moon

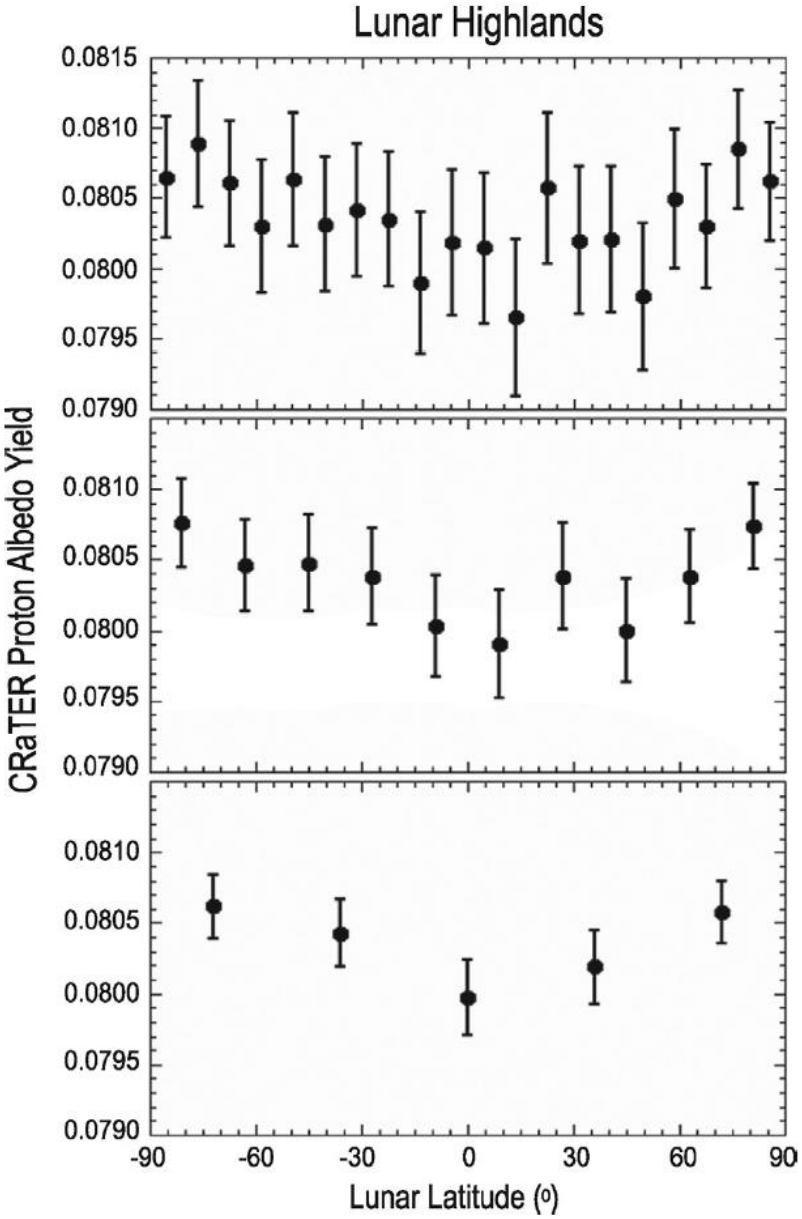


Schwadron et al., 2016



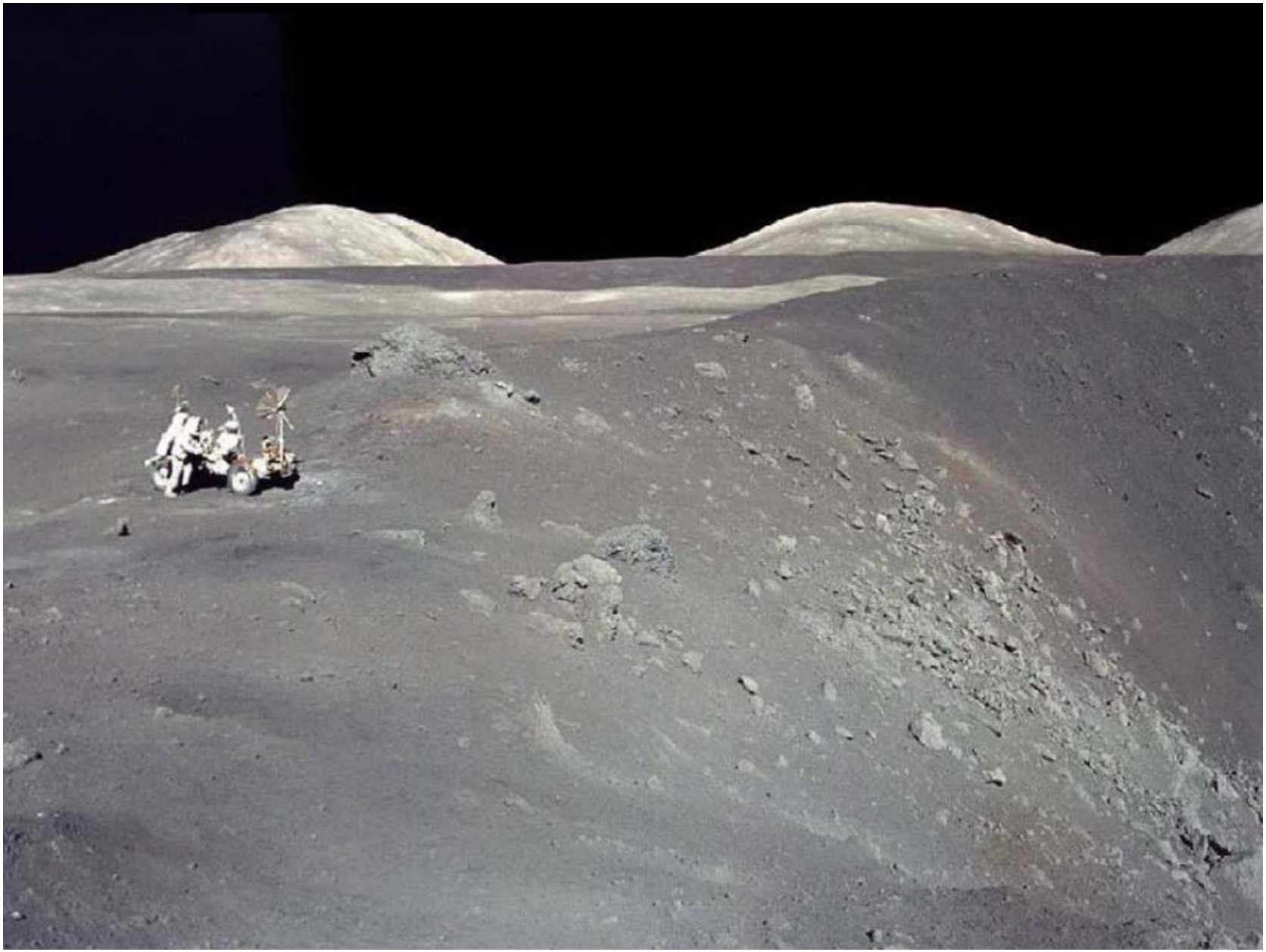
Particle Radiation Measurements at the Moon



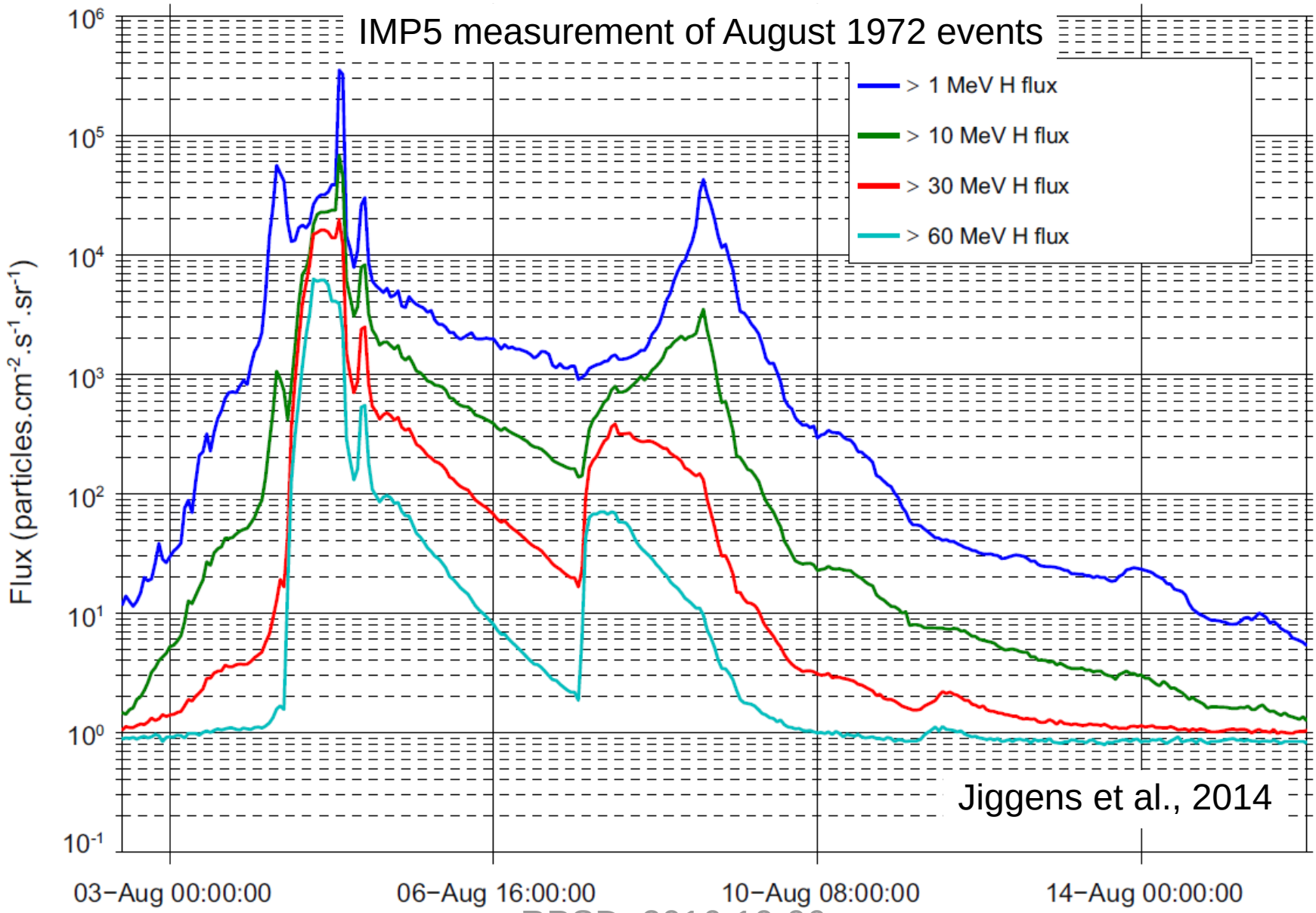


Schwadron et al., 2016

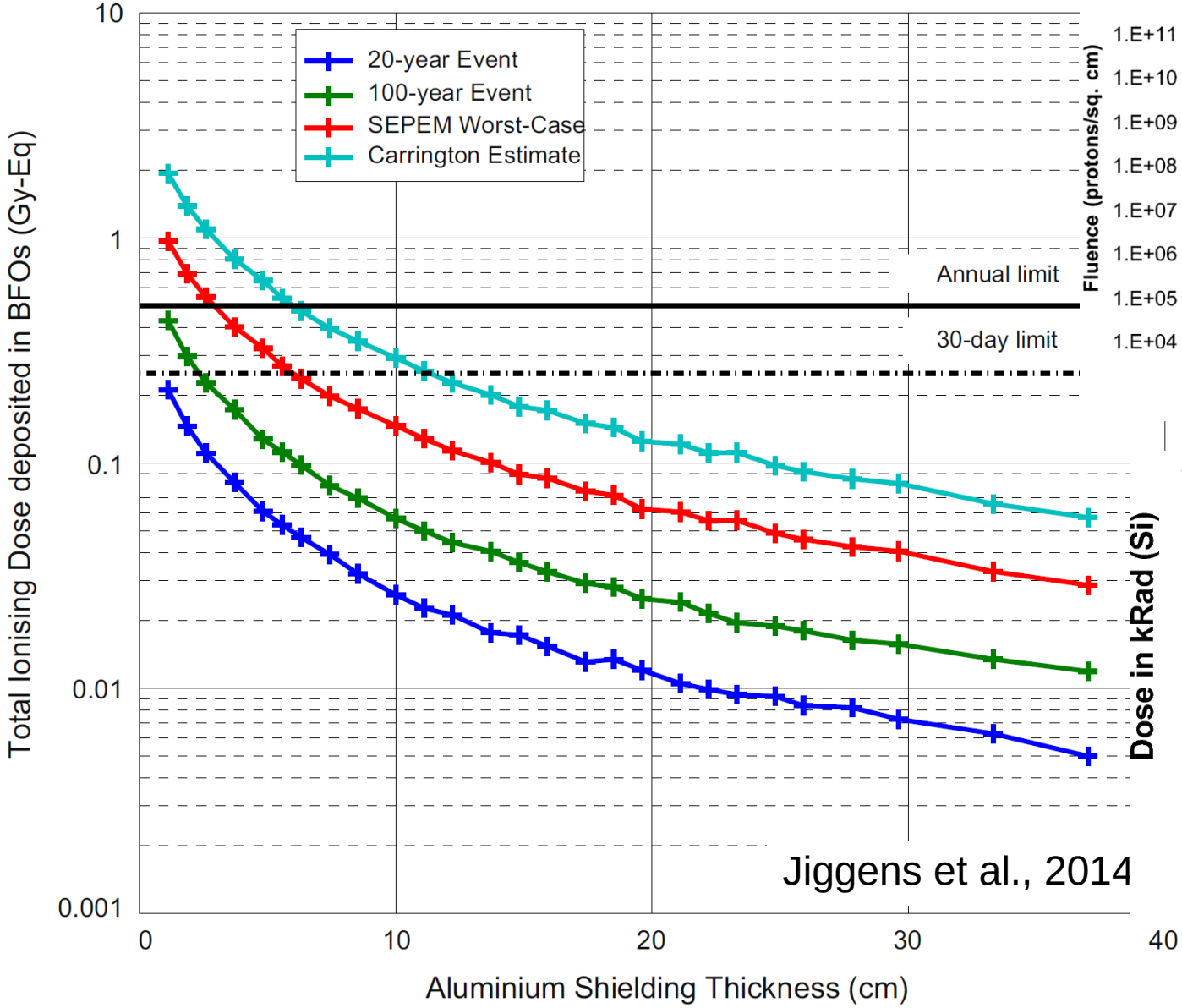
Dose Rate Measurements on the Moon?

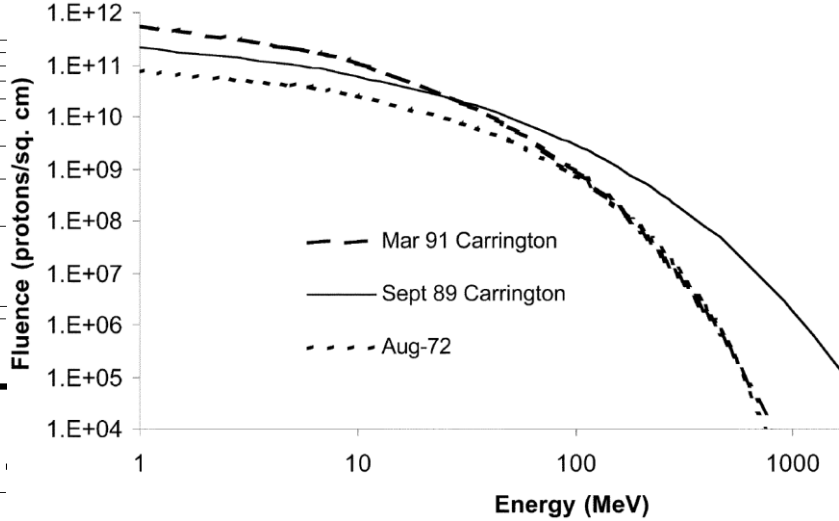


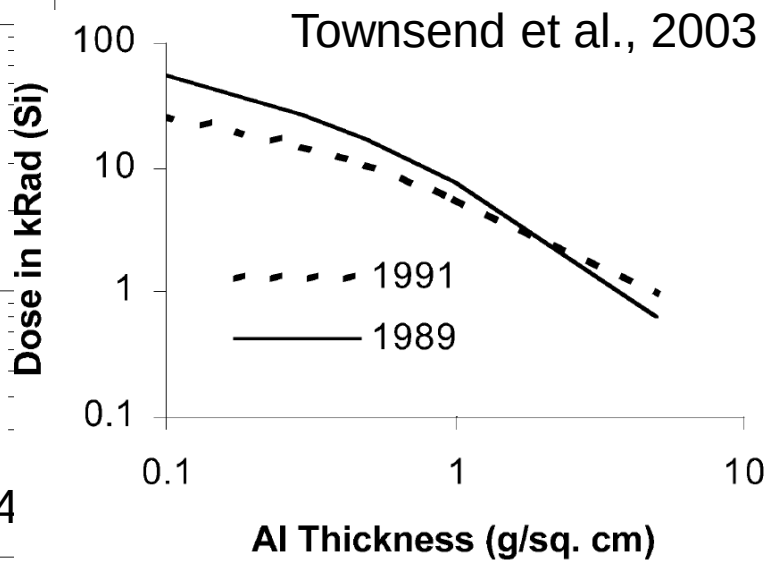
Large solar particle event took place between Apollo 16 and Apollo 17



Efffects of solar particle events





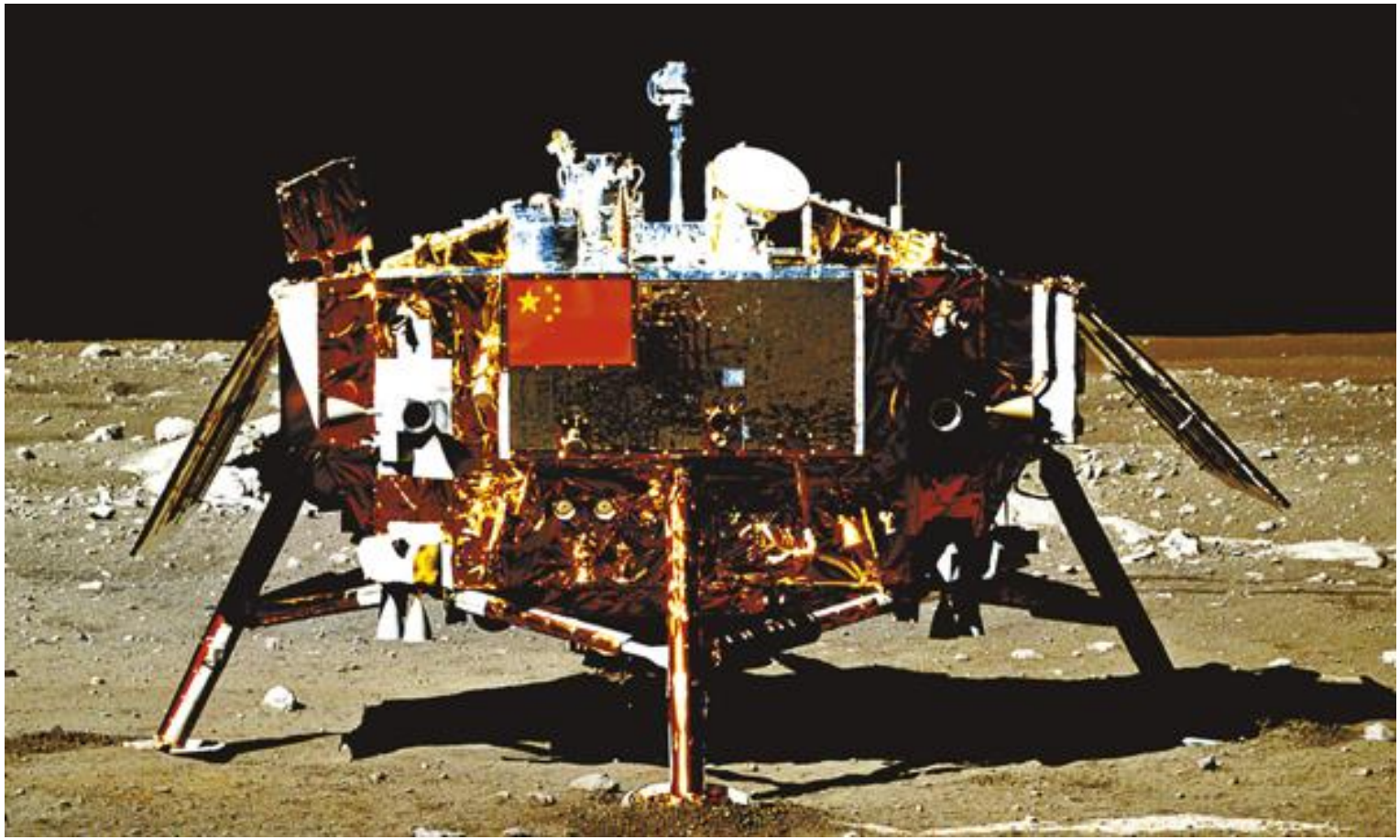


Dose Rate Measurements on the Moon?

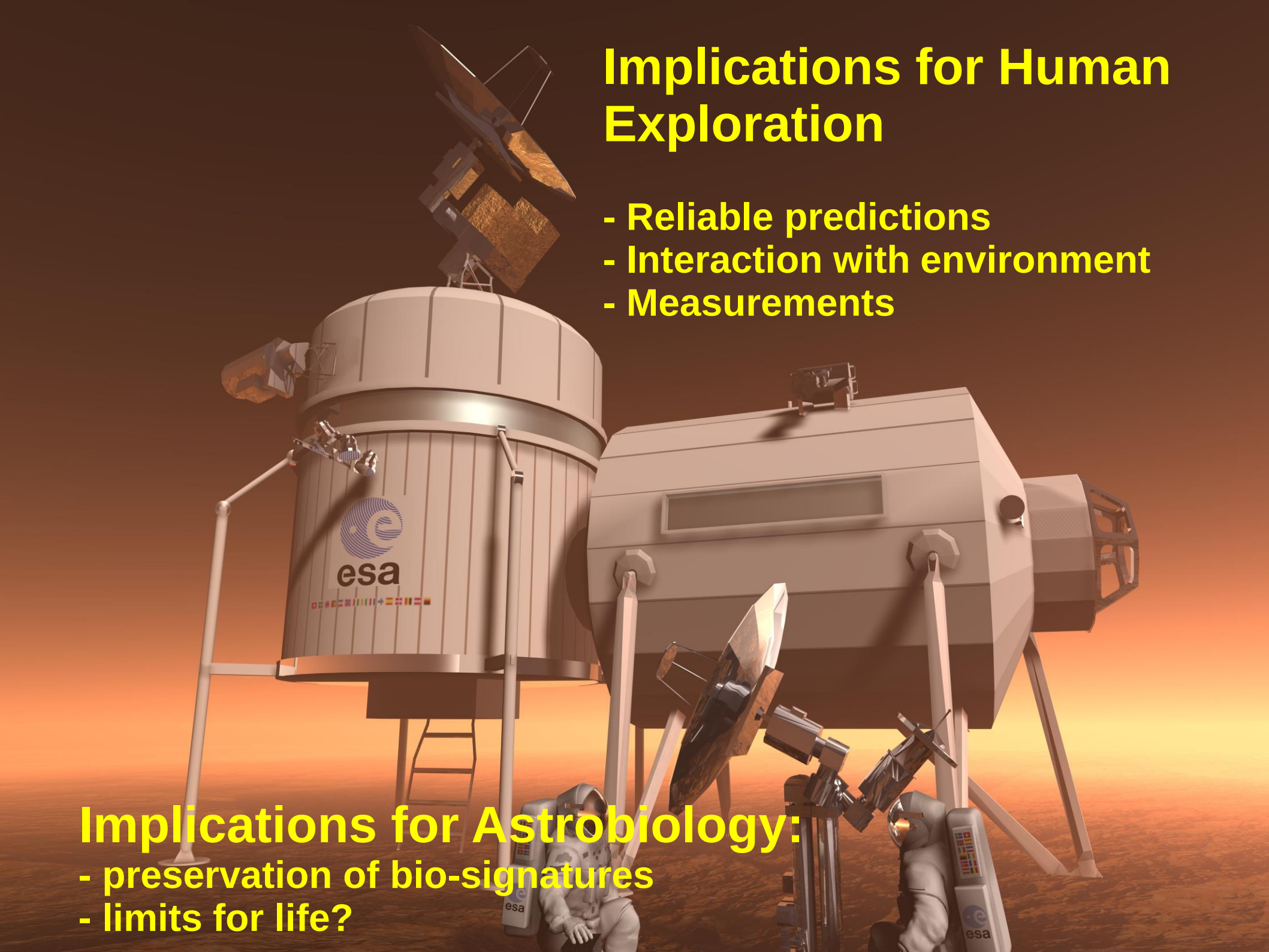
Dose Rate Measurements on the Moon?

None!

Dose Rate Measurements on the Moon?



Lunar Neutron and Dosimetry (LND) Experiment on Chang‘E-4 will provide such measurements (launch 2018)


Implications for Human Exploration
- Reliable predictions
- Interaction with environment
- Measurements
esa
Implications for Astrobiology:
- preservation of bio-signatures
- limits for life?


Maximum production of secondaries lies approximately at the surface of Mars
esa
esa
esa

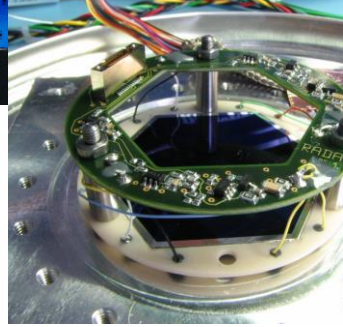
Radiation Measurements on Mars

Requirements

:

- Charged particles (1 < Z < 27) up to 100 MeV/nuc
- Neutral particles (n, γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations

?

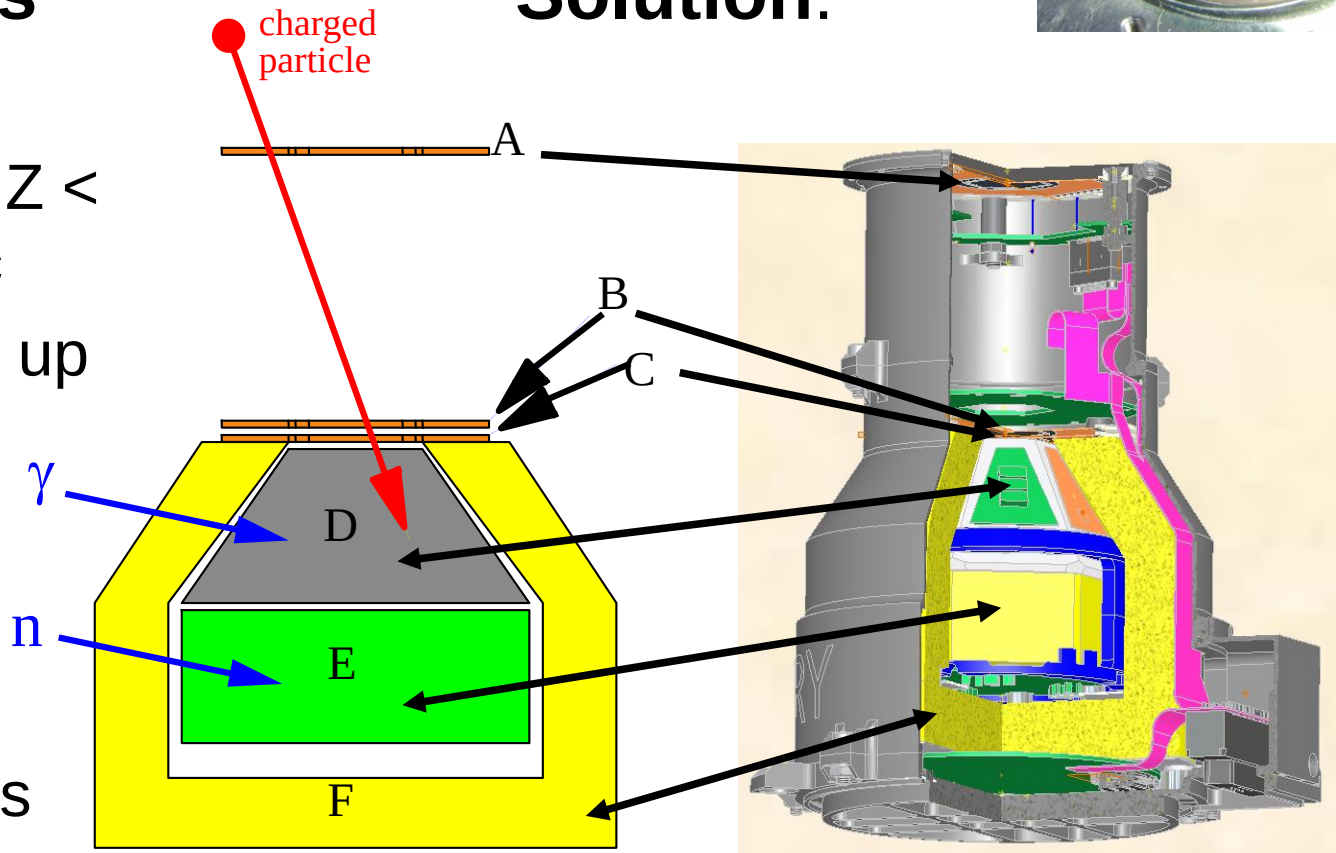


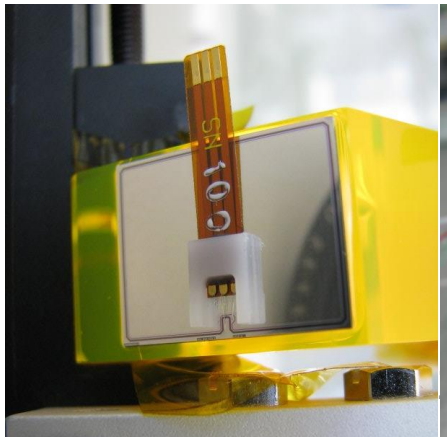
The Radiation Assessment Detector (RAD)

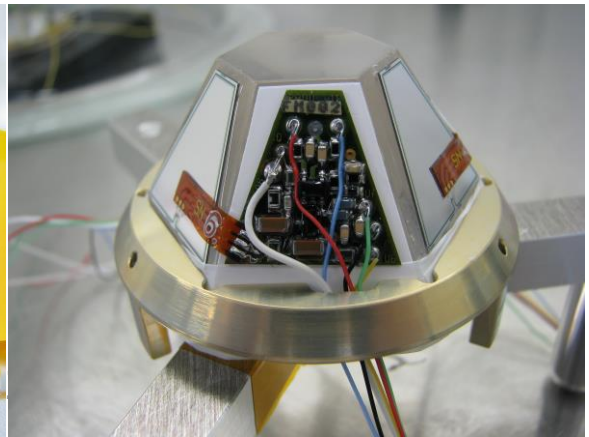
Requirements:

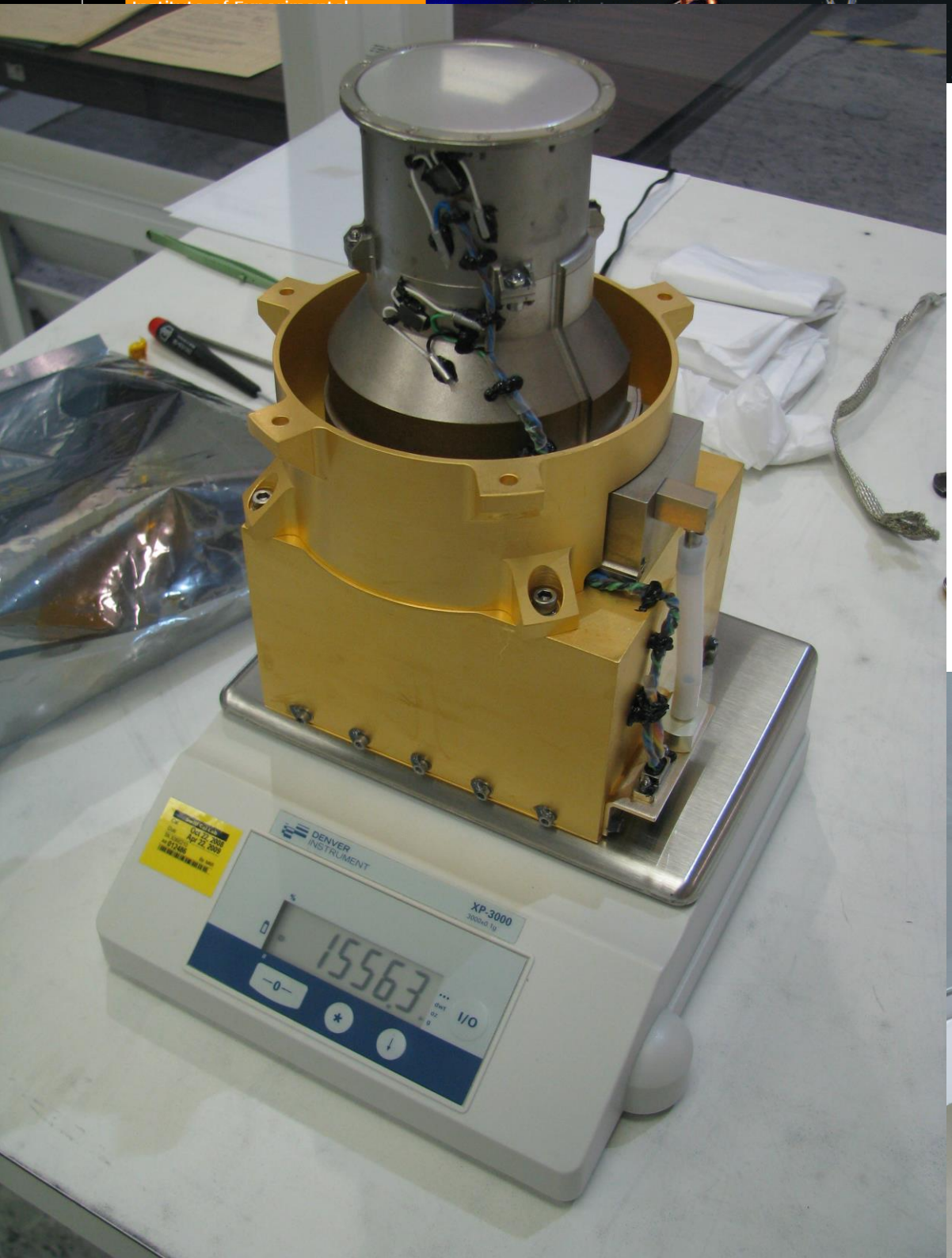
- Charged particles (1 < Z < 27) up to 100 MeV/nuc
- Neutral particles (n, γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations

Solution:





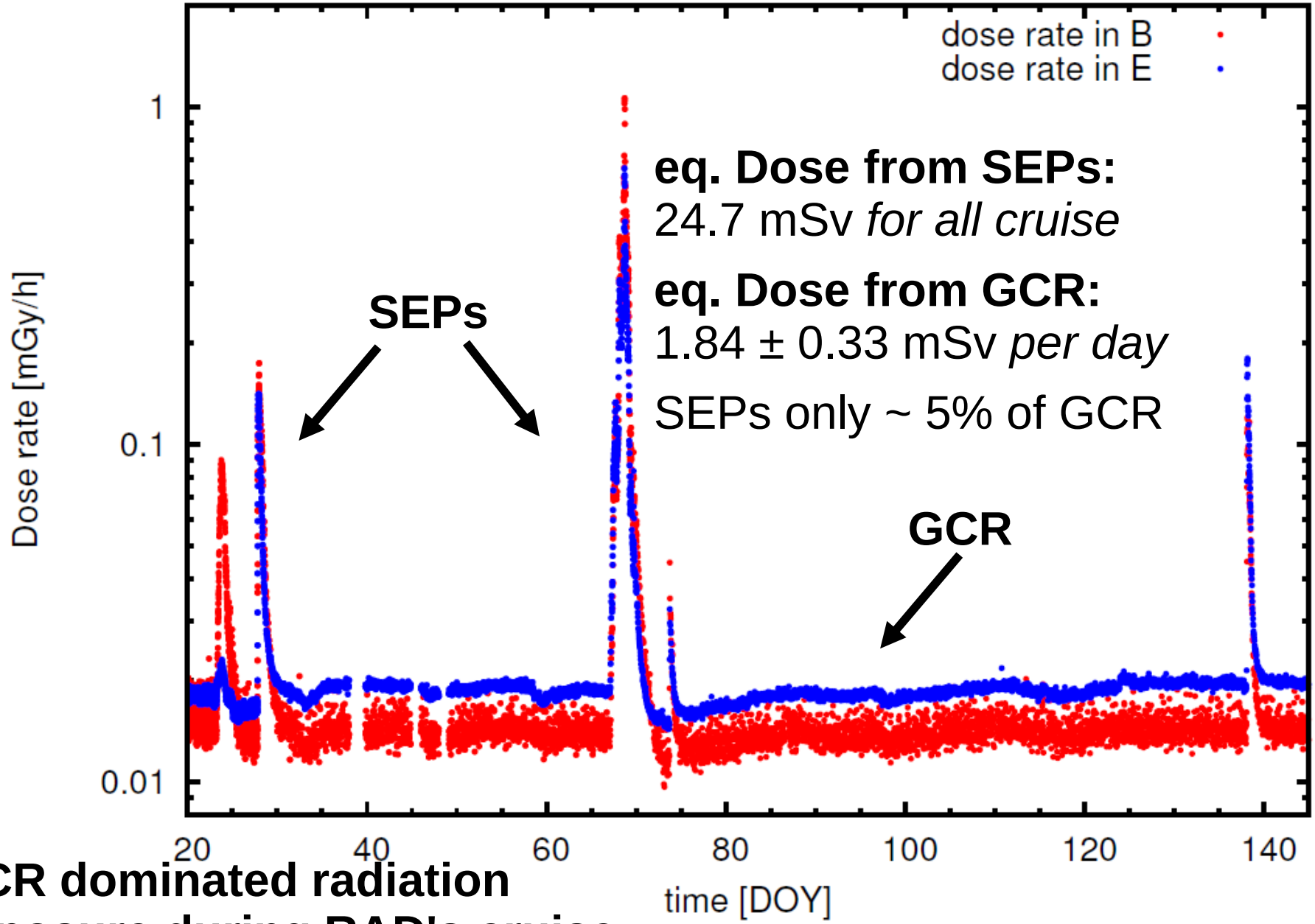




RAD:

- Mass: 1,56 kg
- Power: 4,2 W
- Data rate: ~130 bps
- RSH: FM & FS

Summary of solar particle events seen by MSL



eq. Dose from SEPs:
24.7 mSv *for all cruise*

eq. Dose from GCR:
1.84 ± 0.33 mSv *per day*

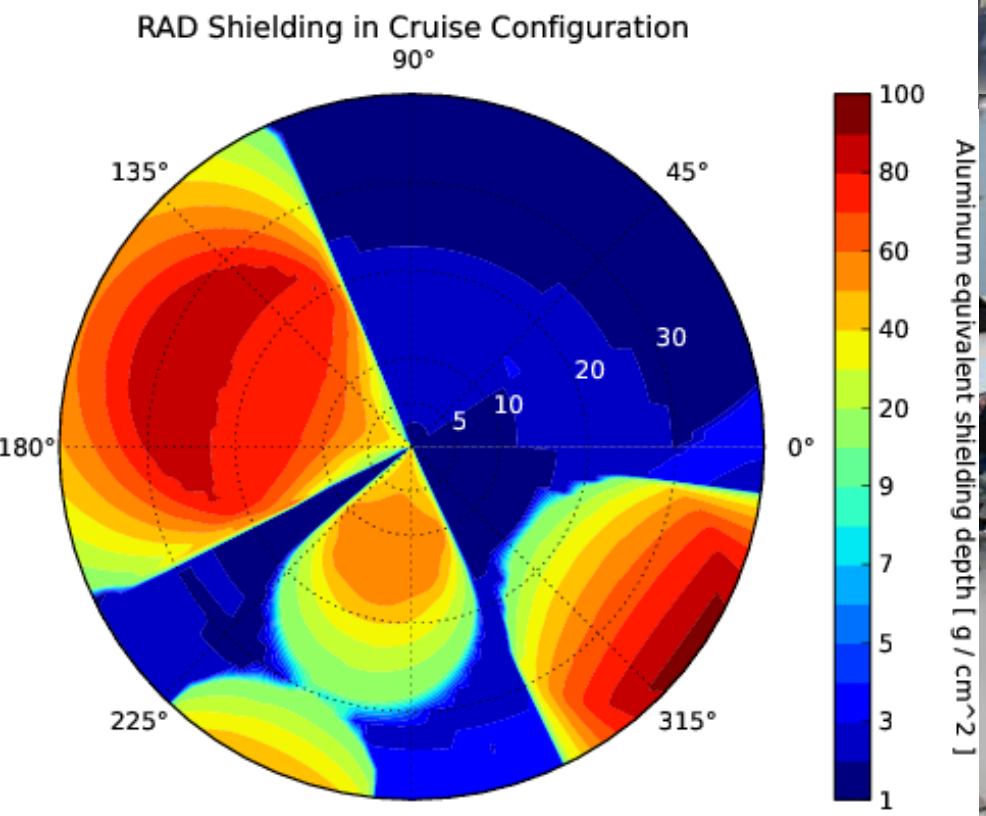
SEPs only ~ 5% of GCR

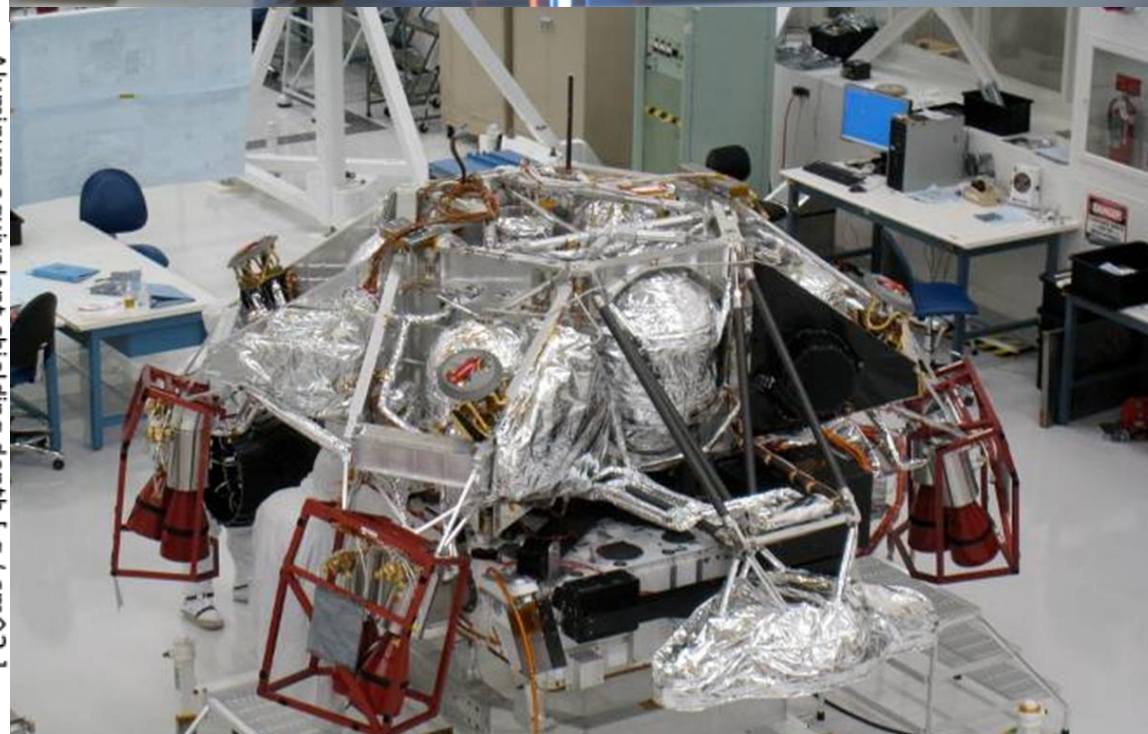
GCR dominated radiation exposure during RAD's cruise

During cruise, RAD was heavily shielded by inhomogeneous and anisotropic structures.

1 g/cm^2 < shielding < 80 g/cm^2

This complicates interpretation of data.





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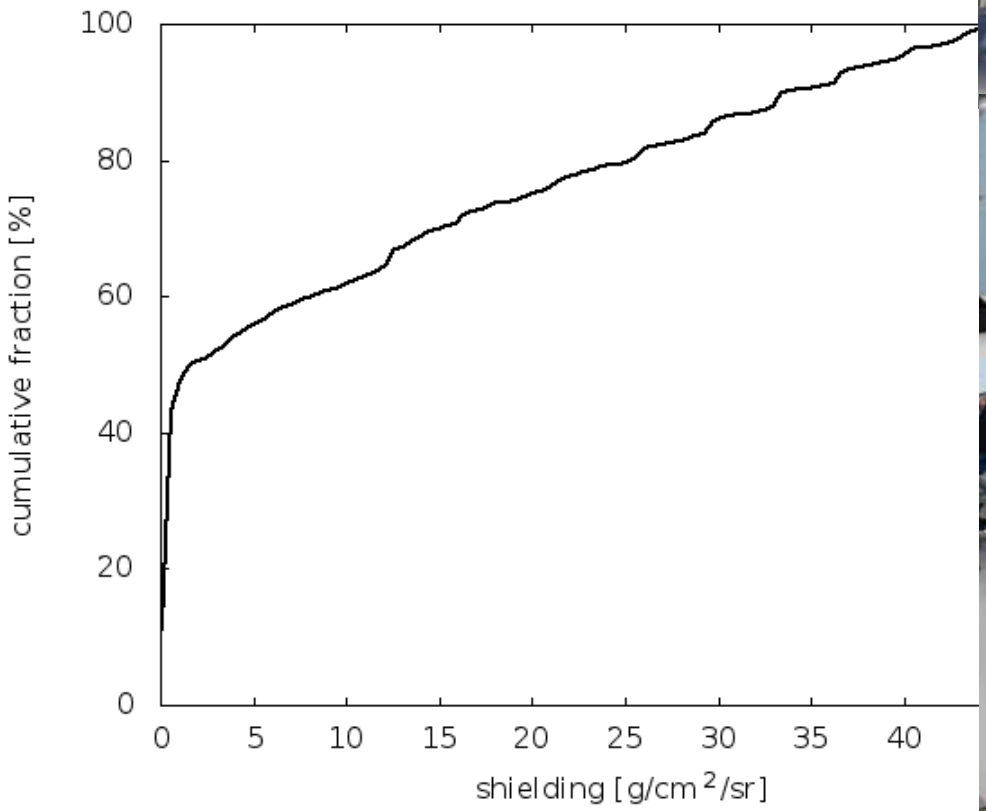
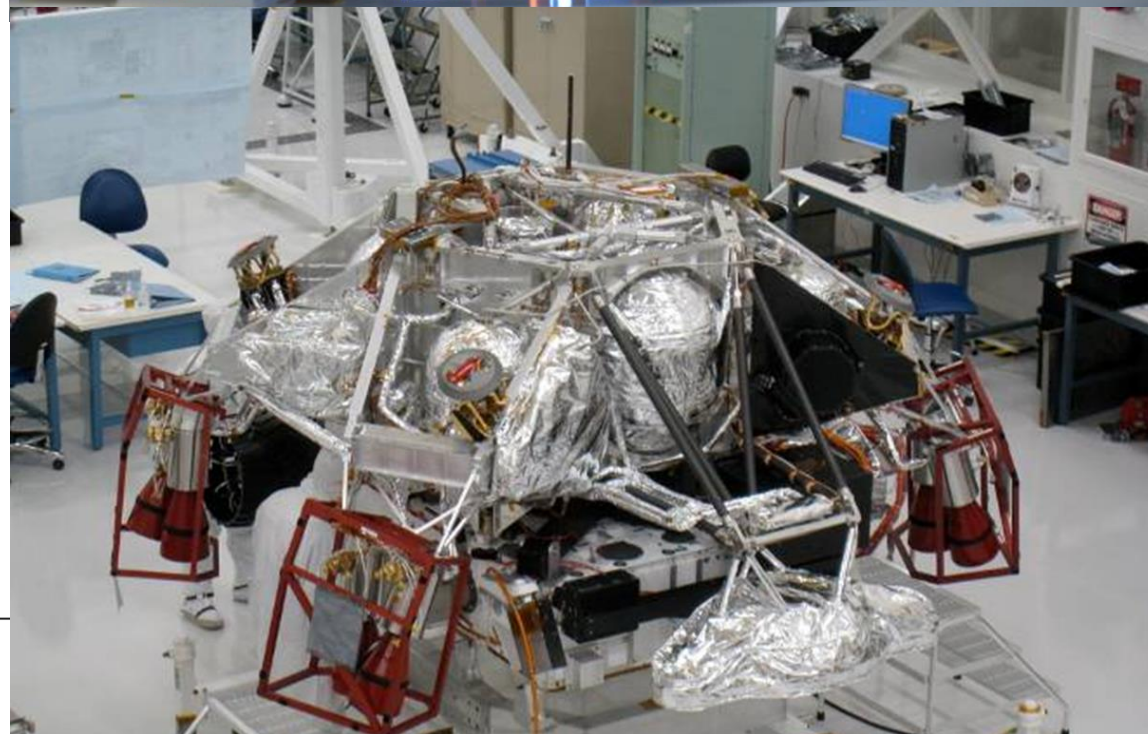
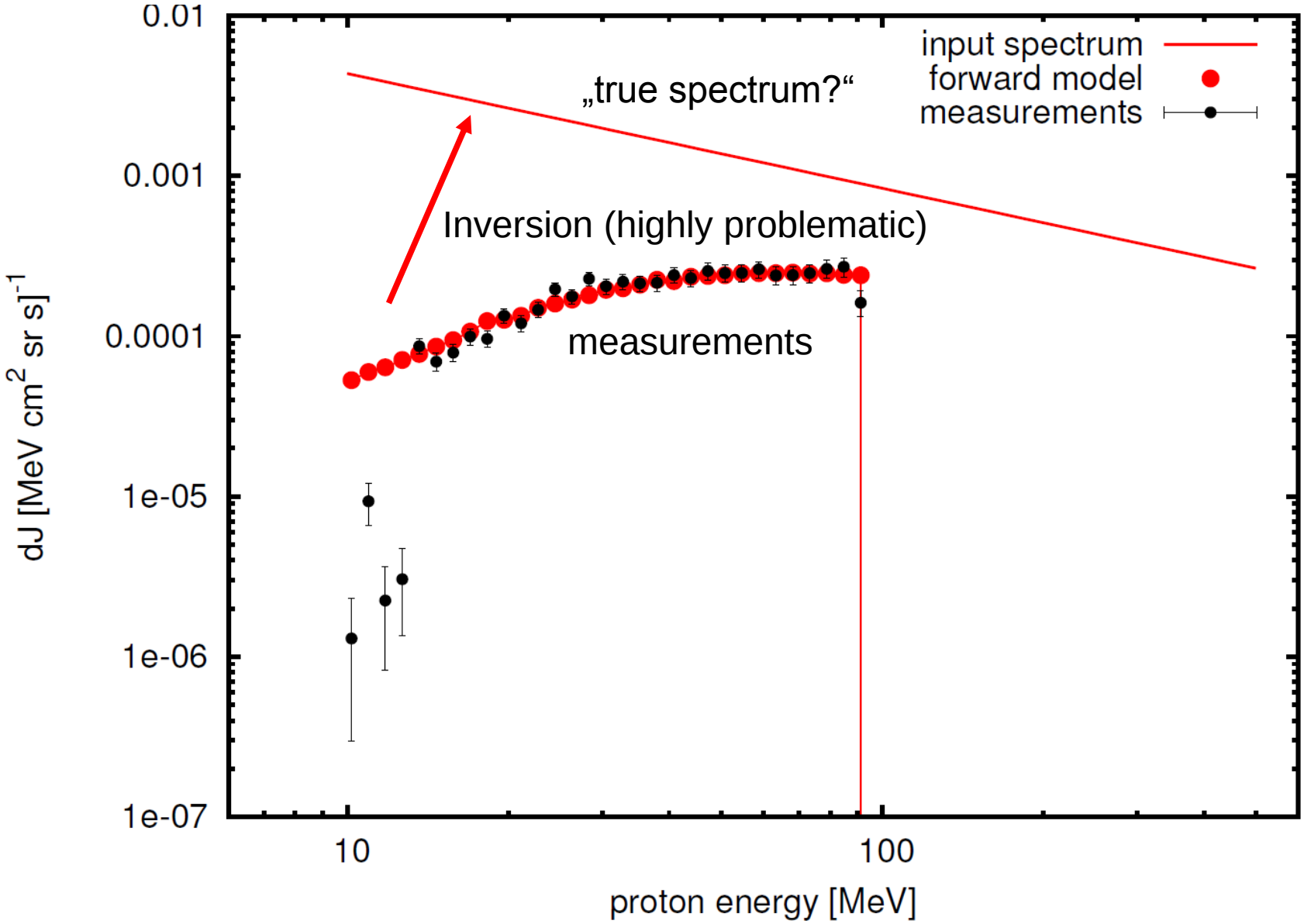




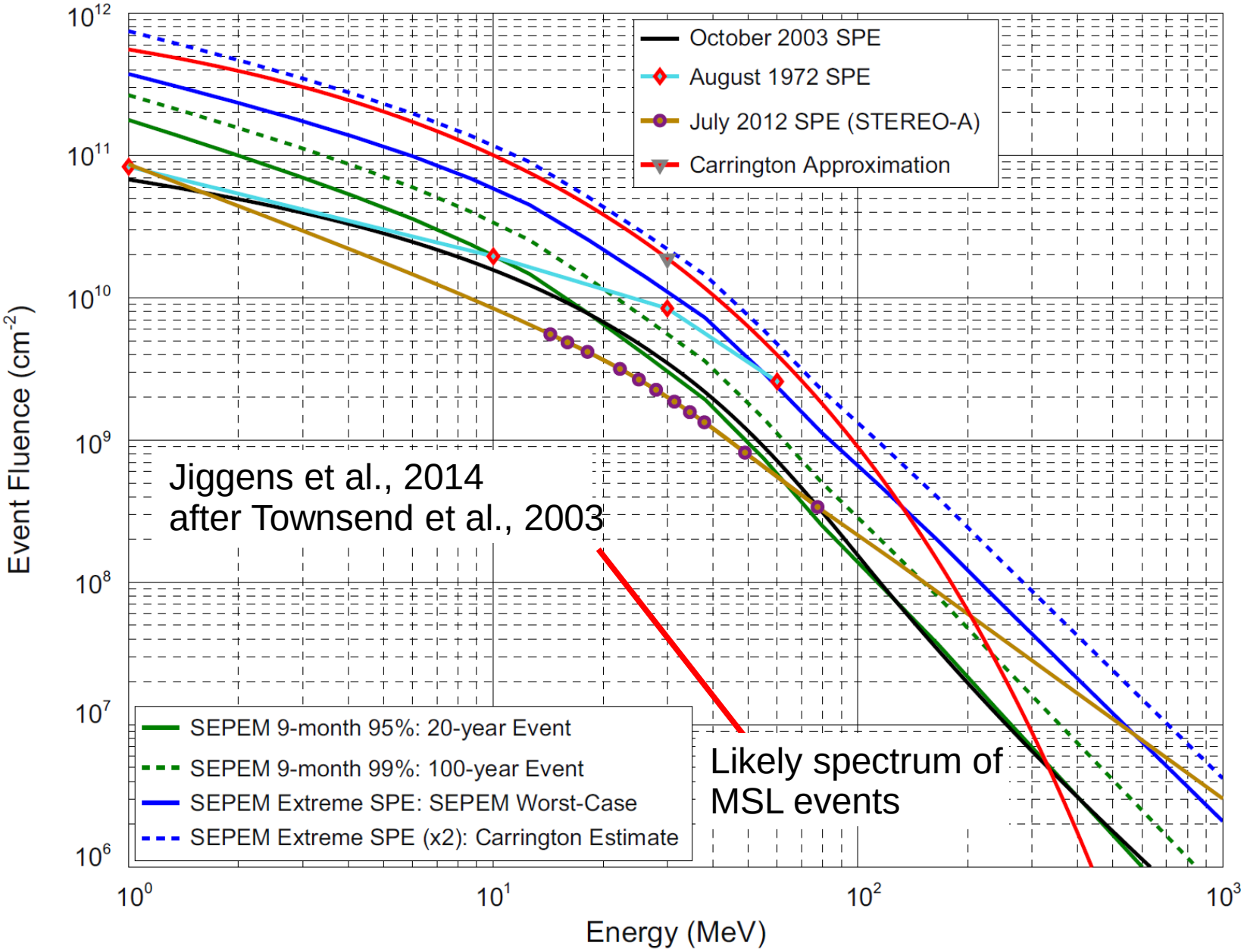
Inversion towards MSL long-term average spectru

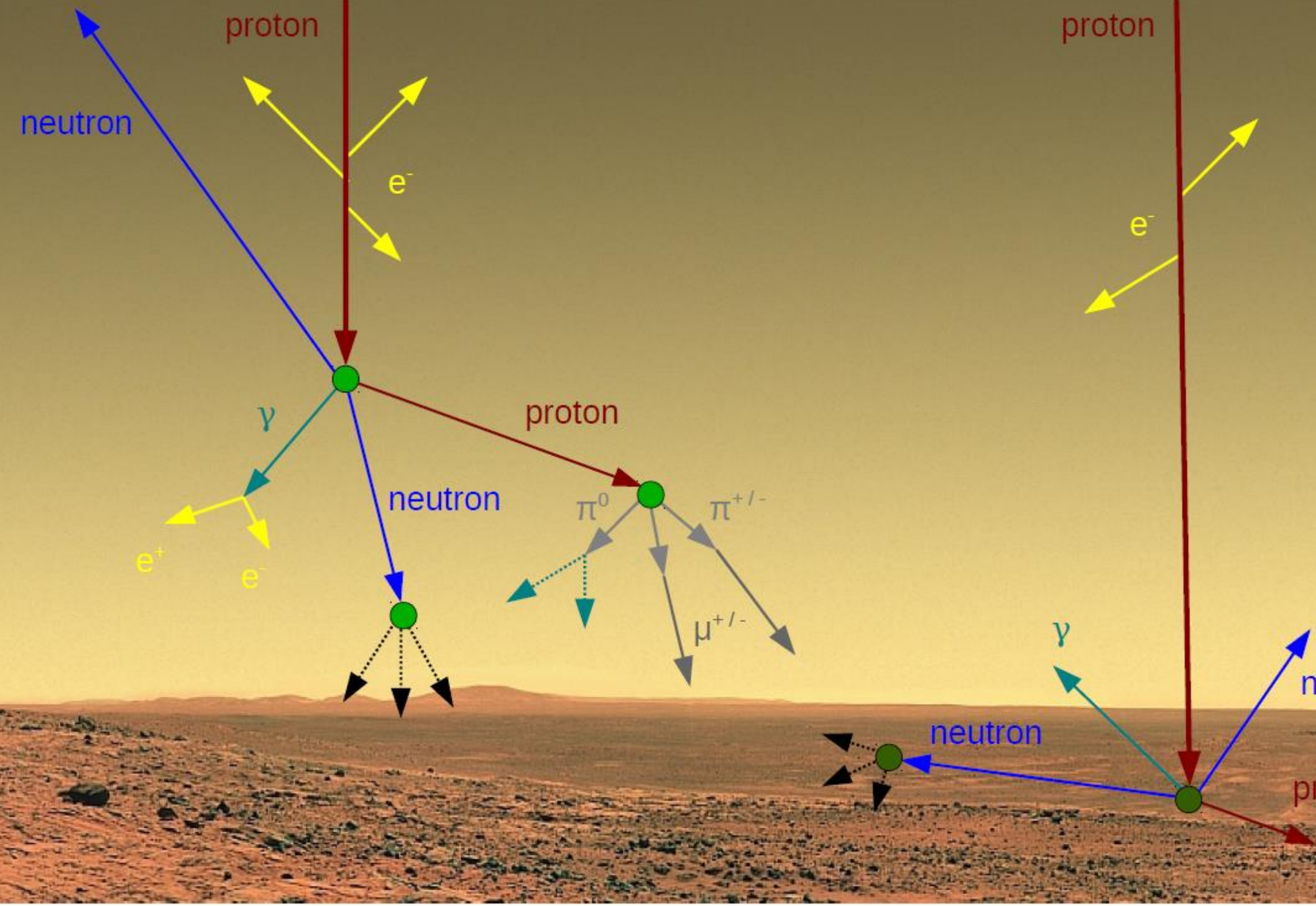


Summary of cruise radiation environment of MSL (This can be measured accurately!)

		Estimated variability	Two 180-day legs return trip
RAD cruise measurement SEPs	**24.7 mSv (5% of all)**	**Orders of magnitude**	**?**
RAD cruise measurement GCR	**1.84 mSv/d**	**0.33 mSv/d ± 20%**	**662 ± 108 mSv ± 20%**
6-month stay of astronaut on ISS	75-90 mSv/(a/2)	20,00%	150-180 mSv
Radiation worker limit (ICRP)	20 mSv/a	n/a	
Average exposure of normal population	4 mSv/a	Wide range, radon!	
Allowable additional exposure norm. pop.	1 mSv/a	n/a	

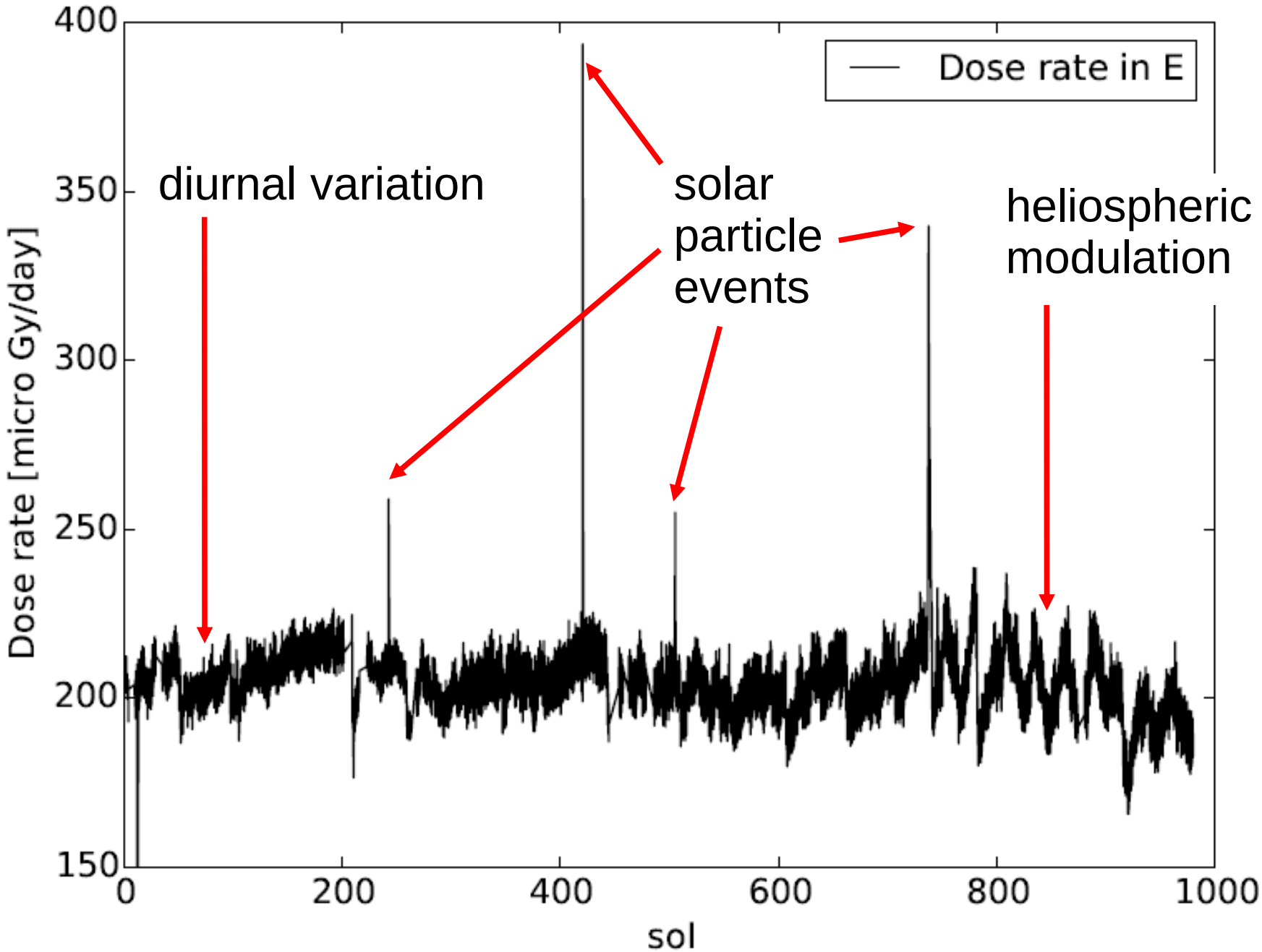
How variable are solar particle events?



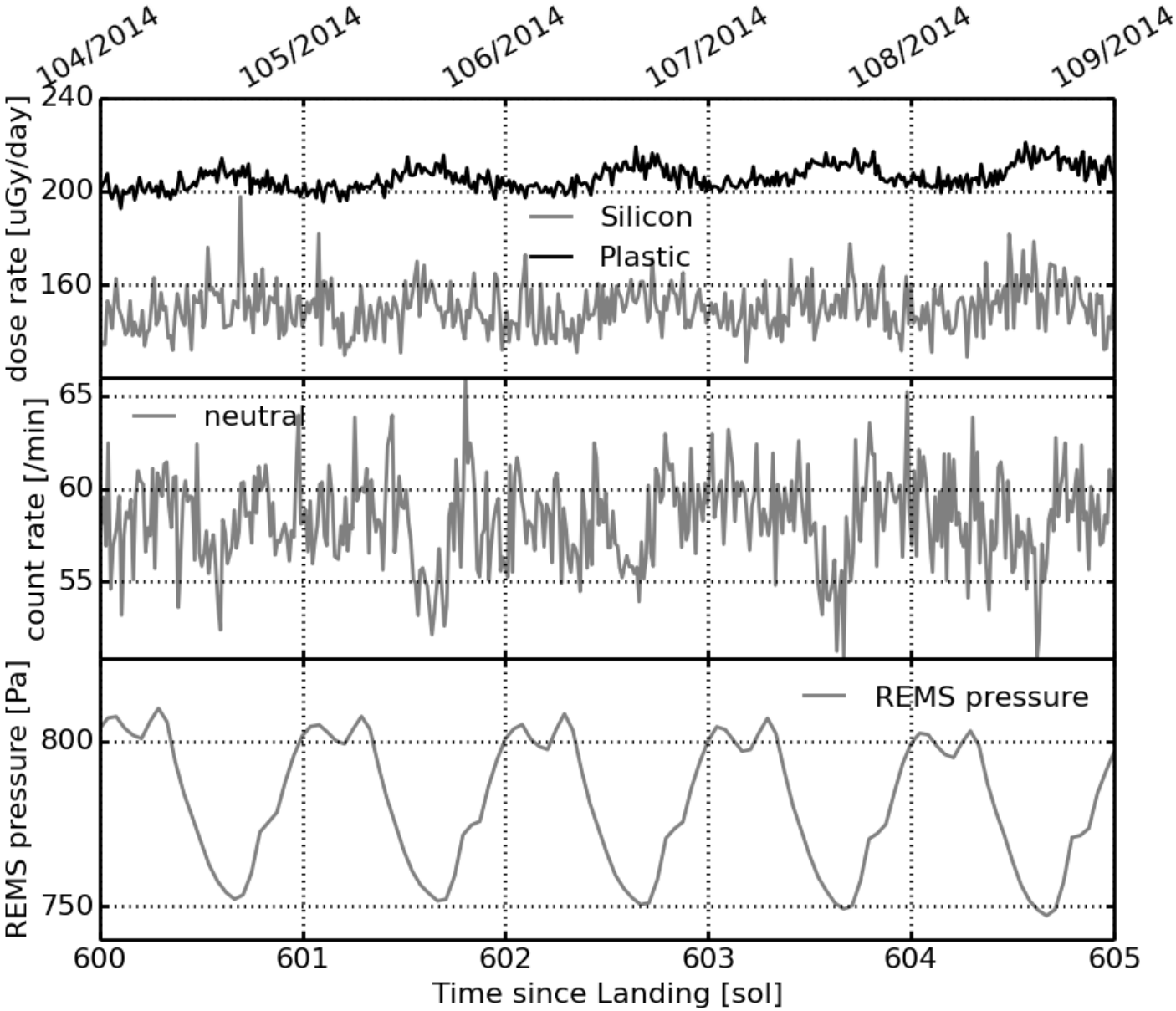


Secondary radiation (neutrals!) plays an important role! (Ehresmann, 2011)

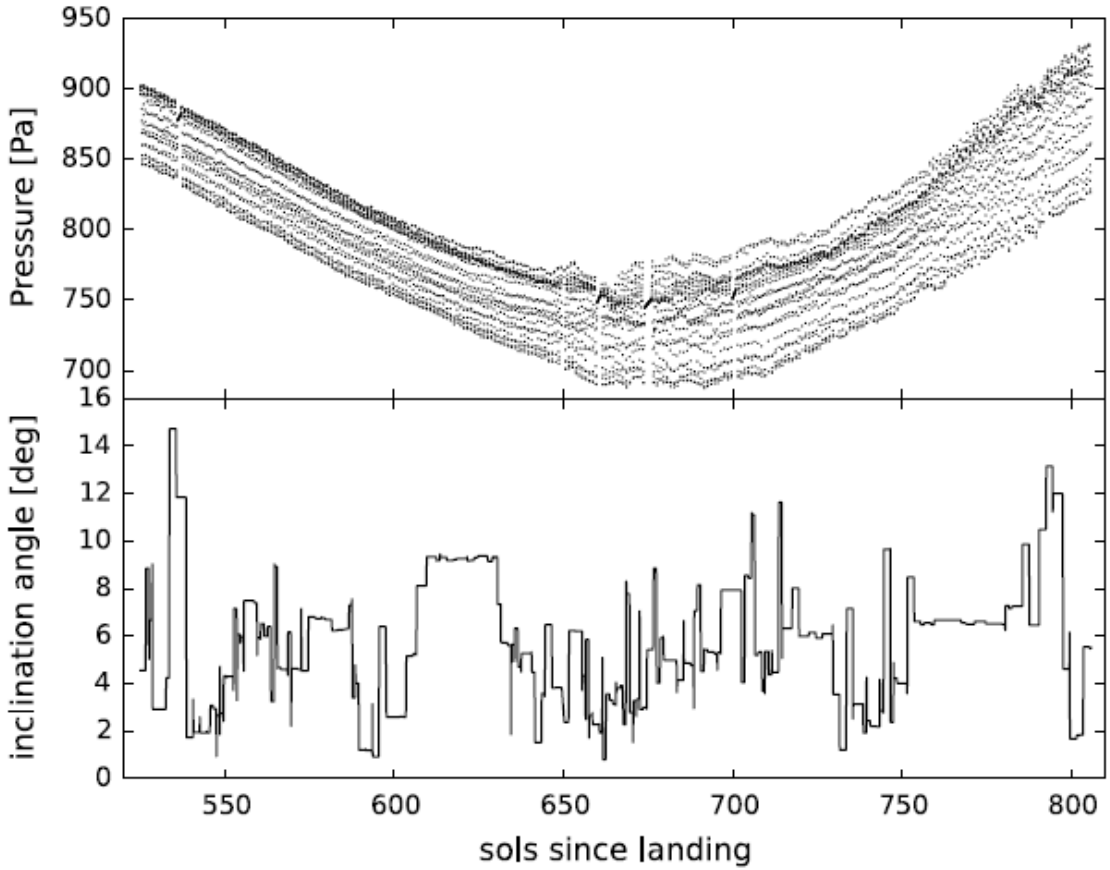
RAD Surface Measurements



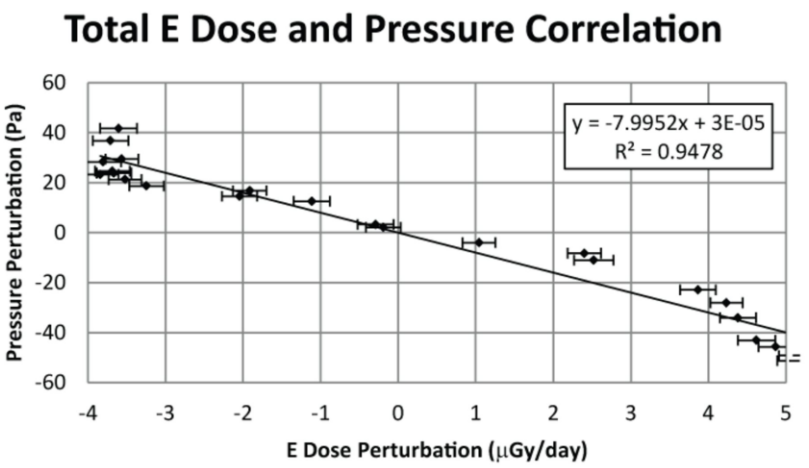
RAD Surface Measurements

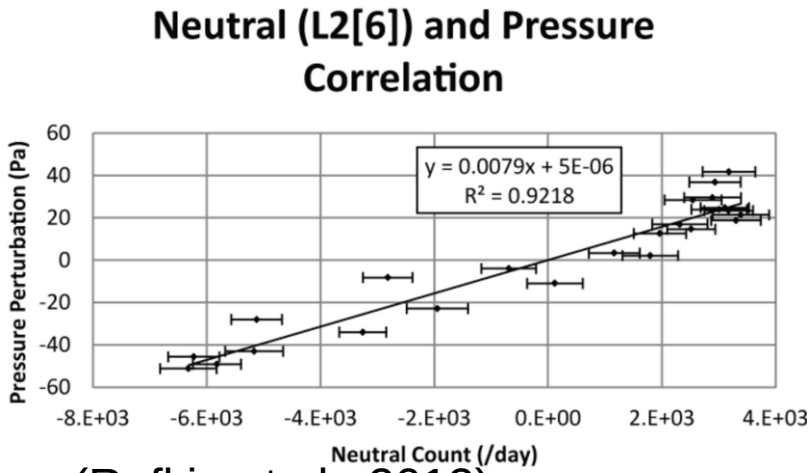


RAD Surface Measurements



(Wimmer-Schweingruber et al., 2015)

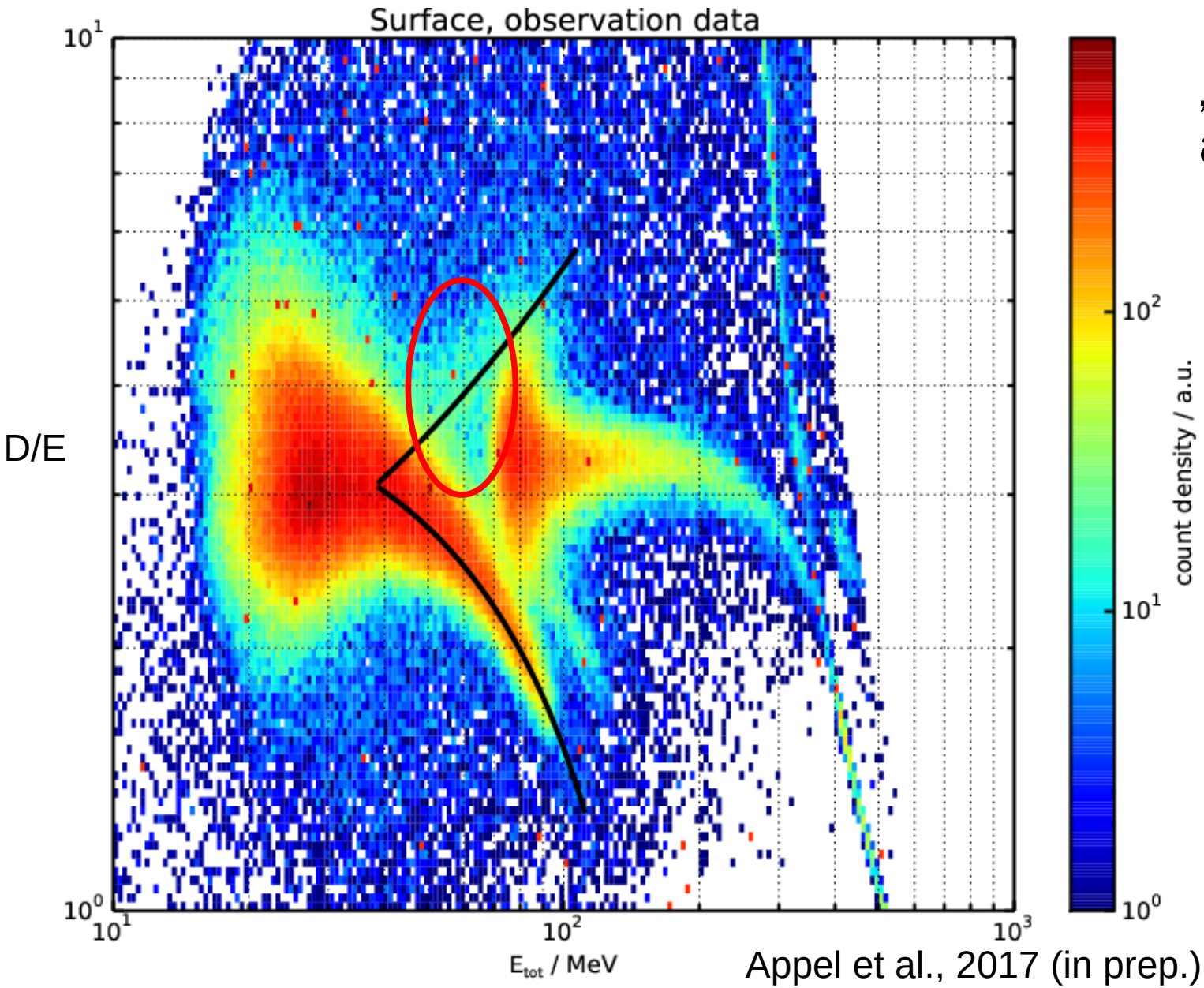




(Rafkin et al., 2013)

- RAD measurements consistent with isotropic Martian surface radiation
- Very thin Martian atmosphere provides only a small amount of shielding
- Shielding effect partially compensated by generation of secondary particles

RAD Surface Measurements



„Albedo“-protons also on Mars

Appel et al., 2017 (in prep.)

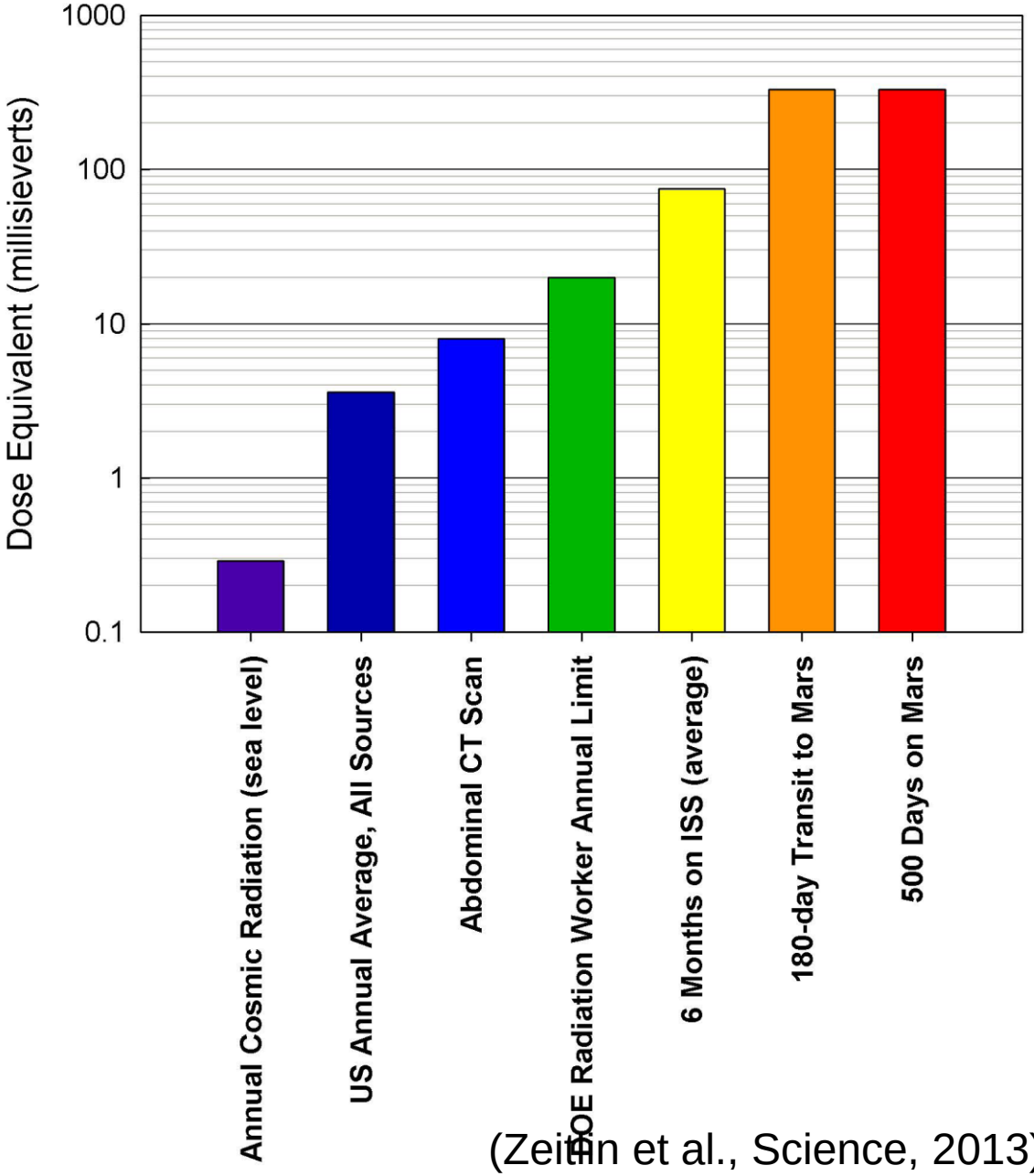
Summary of RAD measurements

Radiation exposure on a mission to Mars:

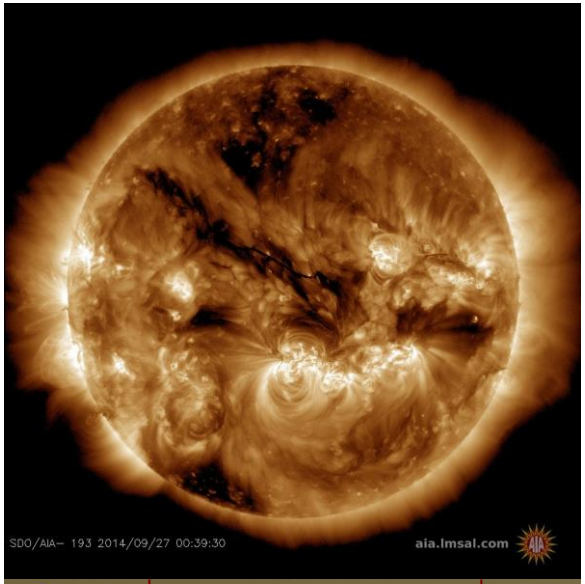
Cruise: 662 +/- 108 mSv
Mars: 320 +/- 50 mSv

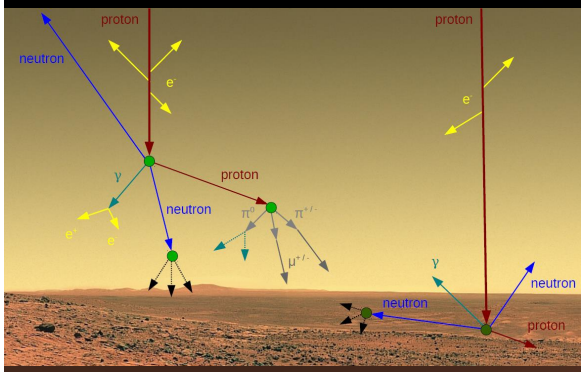
Total ~ 1000 mSv

<u>For comparison:</u>
6 months ISS: 75-90 mSv
radiation worker: 20 mSv/y
CT-scan: 8 mSv



(Zeitlin et al., Science, 2013)





Implications for human exploration

- Space particle radiation is complex!
- “Shielding“ primarily “magnetic“
- Space weather predictions are still very difficult
- Large variability (solar, heliospheric, seasonal, diurnal)
- Secondary radiation important (n/γ)
- Where should we live on Mars?

Implications for non-terrestrial life?
Exo-, astrobiology?

Preservation of bio-signatures?

Summary, Conclusions, and Thanks

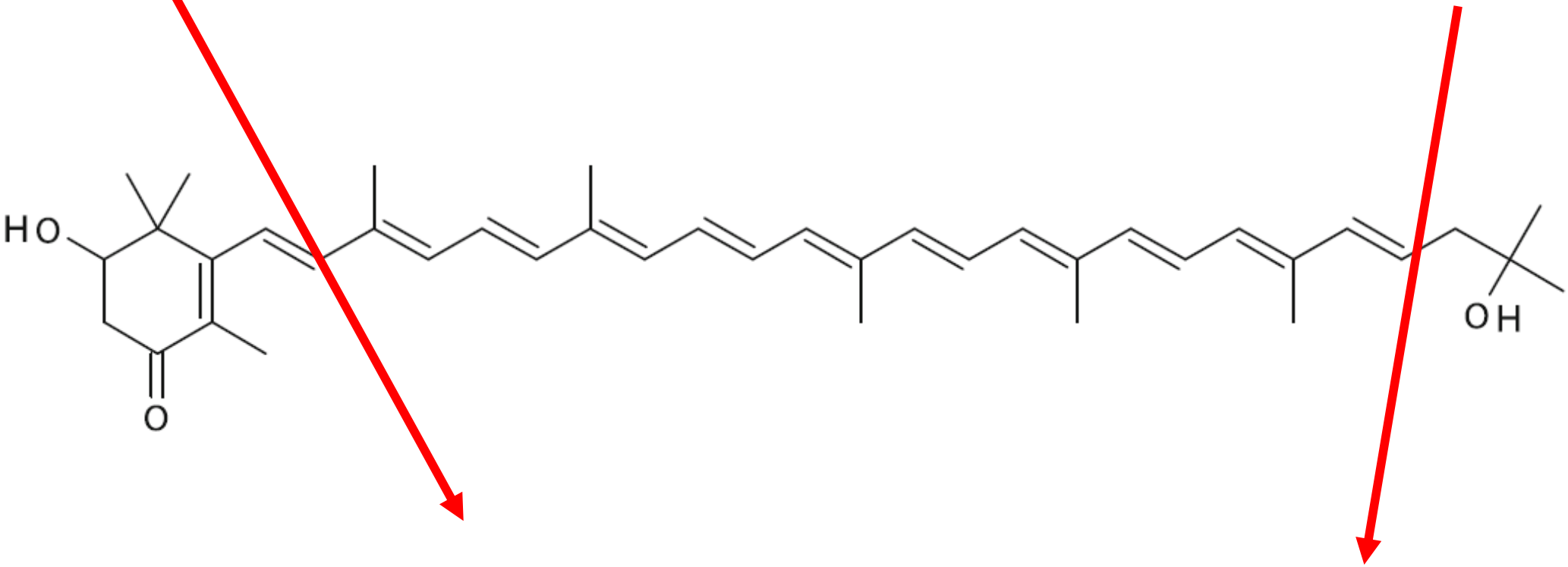
- Radiation in heliosphere very variable
- Models are even more variable...
- First radiation measurements on another planet
- Radiation environment on Mars quite different than on Earth and important for future human exploration
- Modulation is an important „shielding“ factor

Christian-Albrechts-Universität zu Kiel

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag

Destruction of Organic Compounds by Radiation

Ionizing radiation breaks chemical bonds and produces radicals and oxidants.



Result: Destruction of large organic molecules (if there is no repair mechanism)

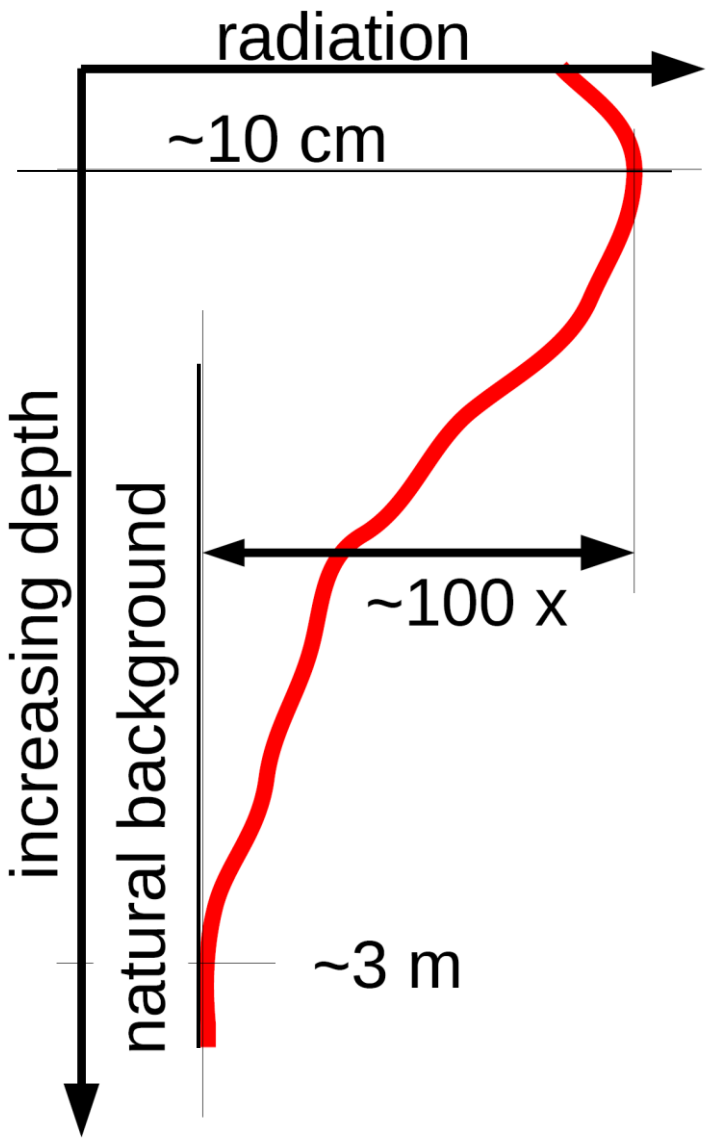
How long could organic molecules survive ionizing radiation environment?

Previous models: 50 – 150 mGy/y
RAD measurements: 76 mGy/y

Organic molecules are efficiently destroyed at a depth of 4-5 cm. In 650 million years only 1/1000 survives.

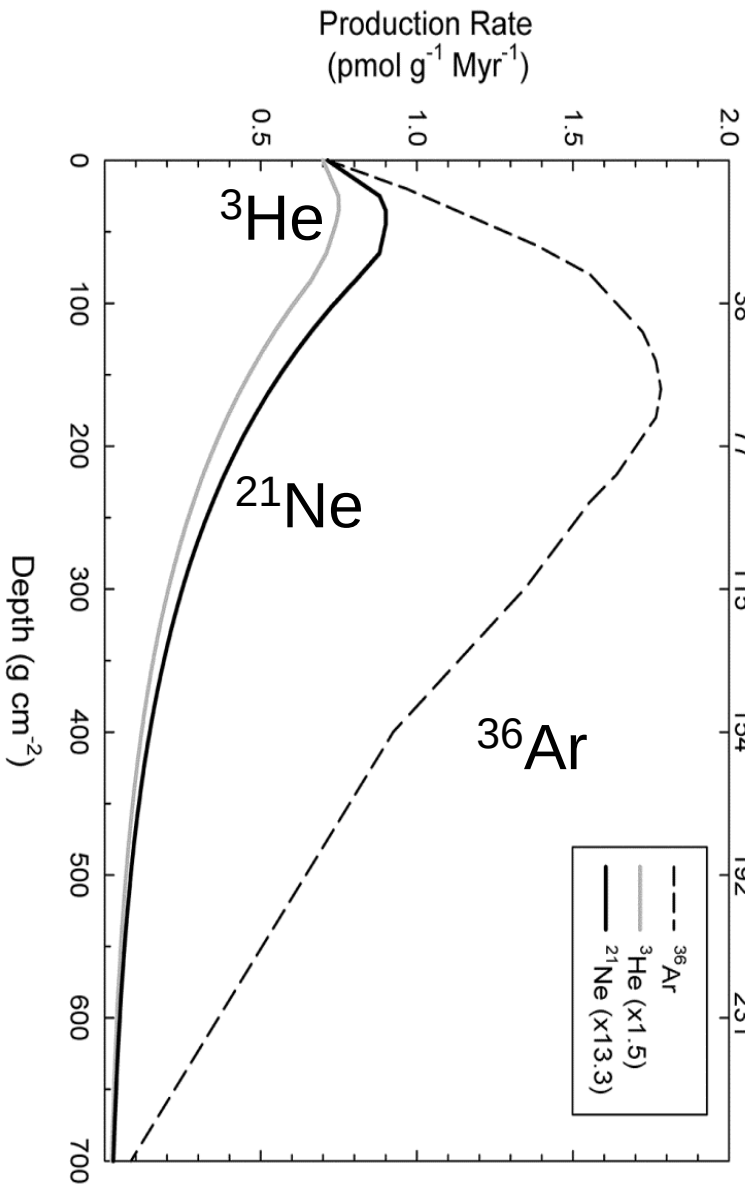
How many after 3.8 Gy?

==> Half of the organics should still be around if the soil were only exposed for 65 million years.

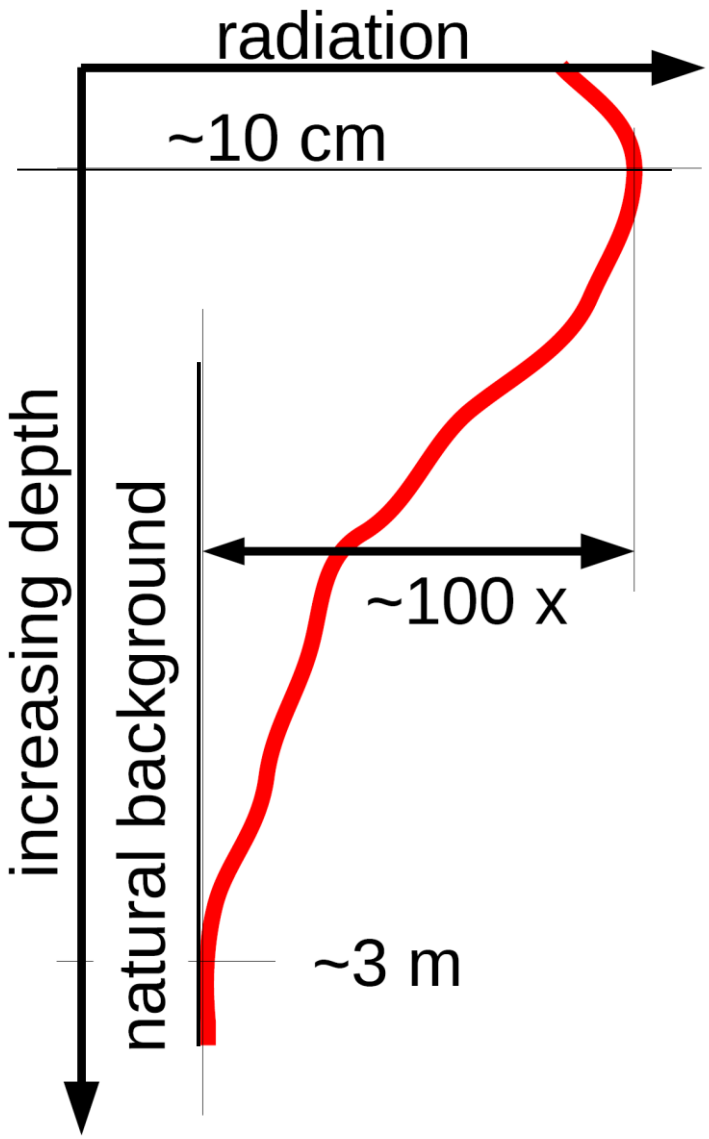


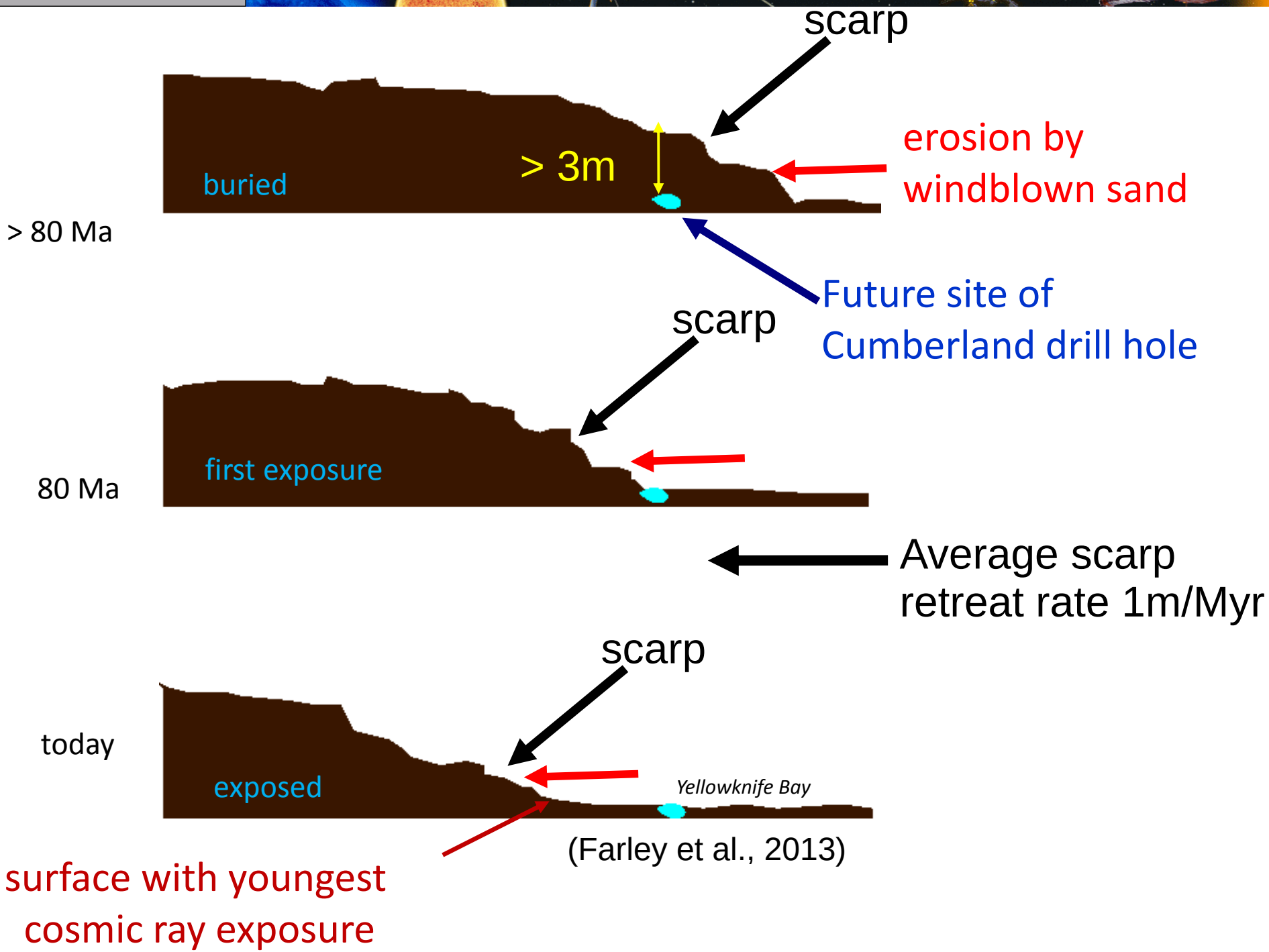
Age determination with cosmogenic isotopes

Sheepbed was exposed for only 80 ± 30 million years!



(Farley et al., Science, 2013)




scarp
erosion by windblown sand
> 3m
buried
> 80 Ma
Future site of Cumberland drill hole
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exposed
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surface with youngest cosmic ray exposure

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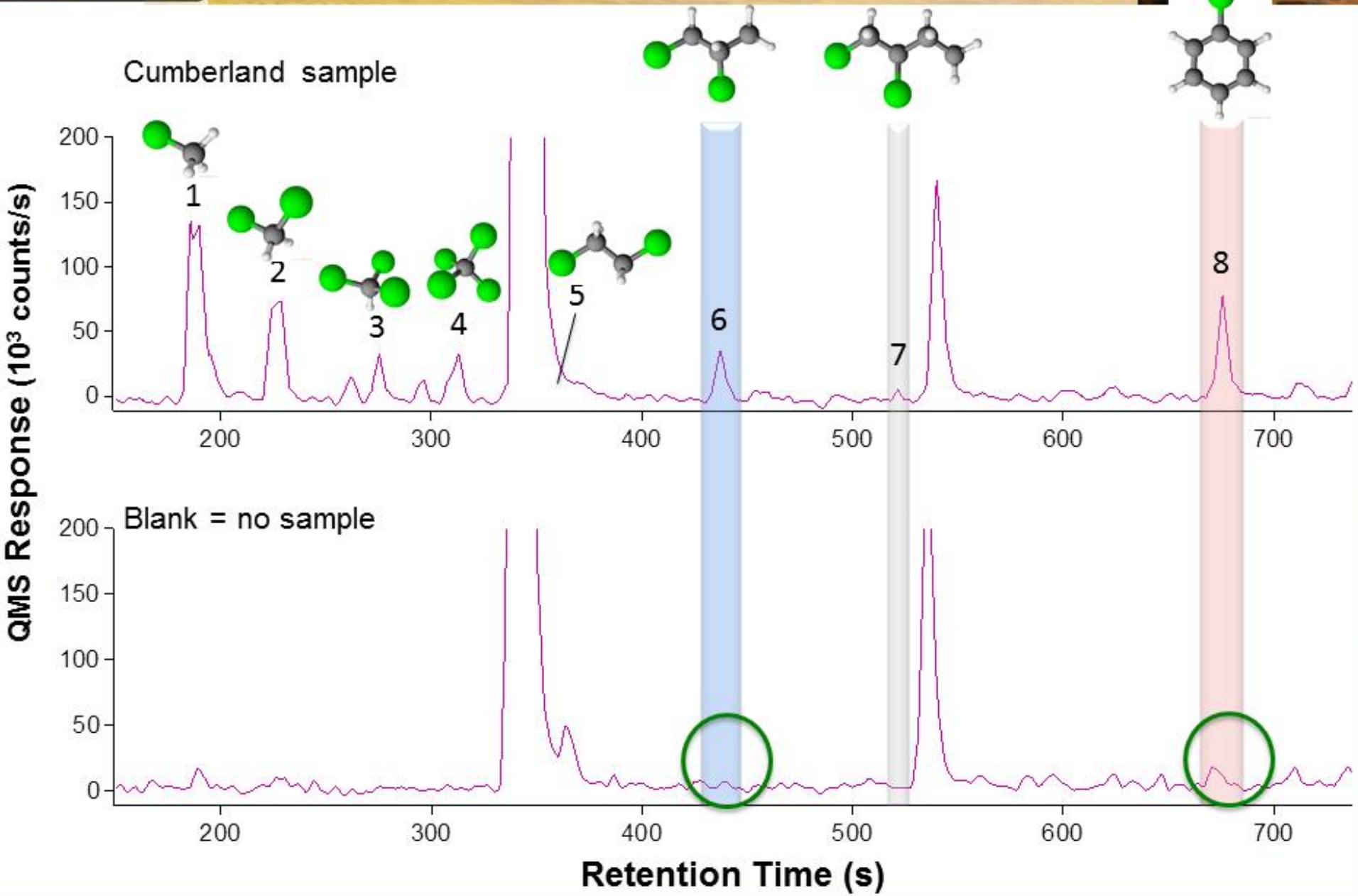

Summary, Conclusions, and Thanks

- Radiation in heliosphere very variable
- Models are even more variable...
- First radiation measurements on another planet
- Radiation environment on Mars quite different than on Earth and important for future human exploration
- Organics can be and have been detected on Mars
- Mars was habitable – but is it still so?

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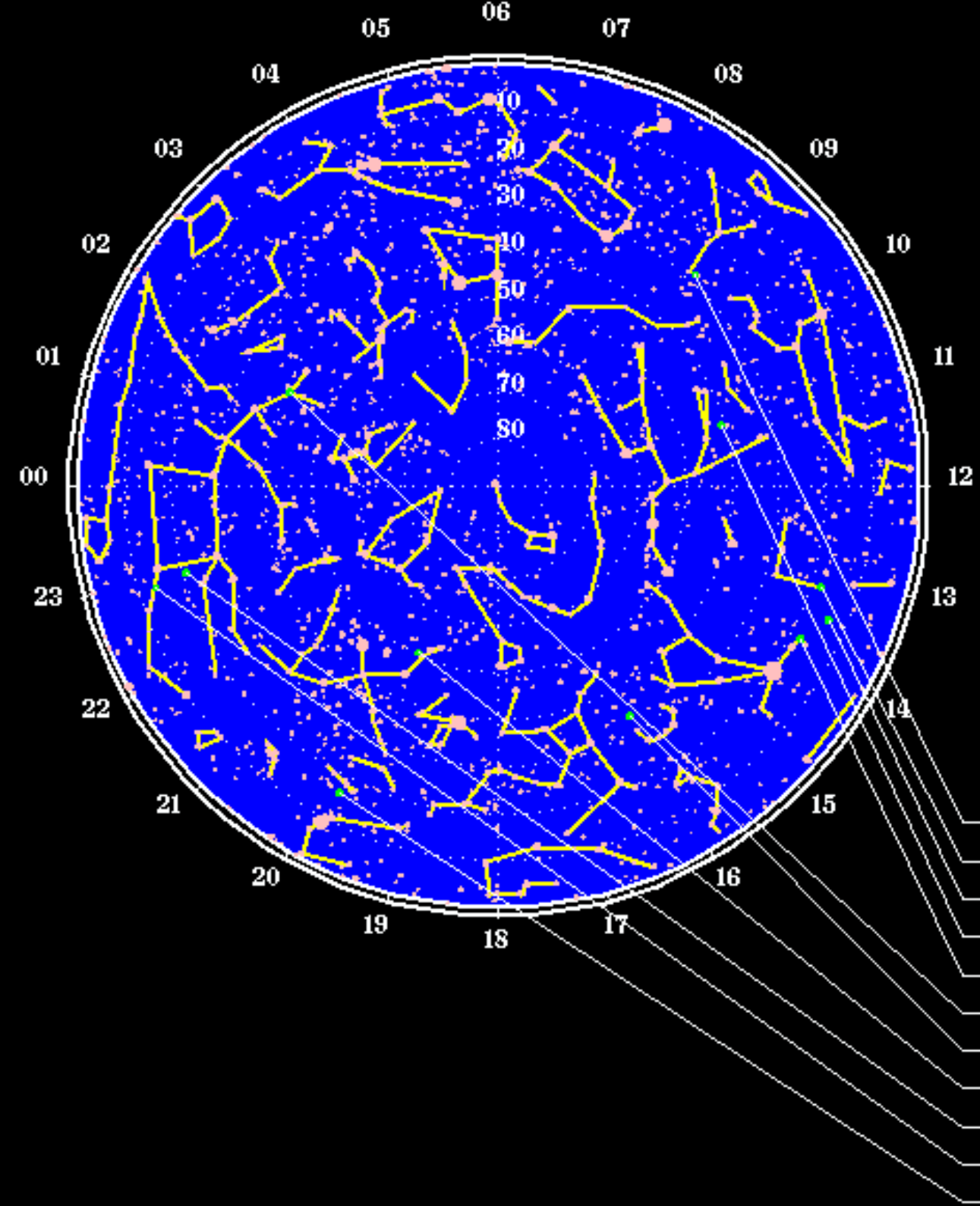
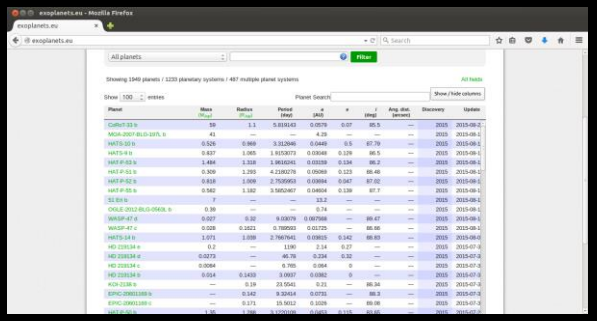
Additional Slides



Yes, there are planets everywhere!



exoplanet.eu/catalog

Catalog

Download VOTable | CSV | DAT

All planets | Filter

Showing 2107 planets / 1349 planetary systems / 511 multiple planet systems

All fields

Show 100 entries

Planet Search

Show / hide columns

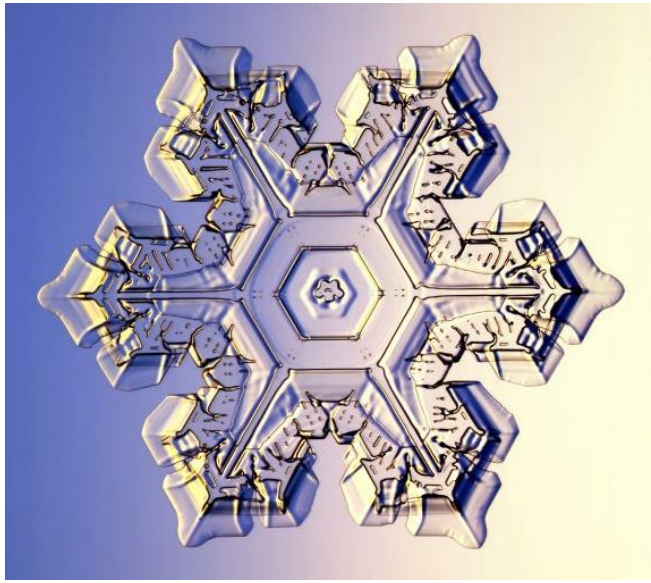
Planet	Mass (M_{Jup})	Radius (R_{Jup})	Period (day)	a (AU)	e	i (deg)	Ang. dist. (arcsec)	Discovery
WASP-121 b	1.184	1.865	1.2749255	0.02544	0	87.6	—	2015
K2-19 b	0.187	0.691	7.9194	0.077	0.119	88.83	—	2015
K2-19 c	0.031	0.434	11.90715	0.1032	0.095	89.91	—	2015
EPIC 201505350 d	—	0.102	2.50856	—	—	—	—	2015
HD 9174 b	1.11	—	1179	2.2	0.12	—	—	2016
HD 68402 b	3.07	—	1103	2.18	0.03	—	—	2016
HD 72892 b	5.45	—	39.475	0.228	0.423	—	—	2016
HD 128356 b	0.89	—	298.2	0.87	0.57	—	—	2016
HD 224538 b	5.97	—	1189.1	2.28	0.464	—	—	2016
HD 165155 b	2.89	—	434.5	1.13	0.2	—	—	2016
HD 147873 b	5.14	—	116.596	0.522	0.207	—	—	2016
HD 147873 c	2.3	—	491.54	1.36	0.23	—	—	2016
Pr 0211 b	1.88	—	2.14609	0.03184	0.017	—	—	2012
Pr 0201 b	0.54	—	4.4264	—	—	—	—	2012
Pr 0211 c	7.95	—	5300	5.8	0.7	—	—	2016
TYC-3667-1280-1 b	5.4	—	26.468	0.21	0.036	—	—	2016

What is life?

Life multiplies

Life is self-organizing

Life adapts to its environment



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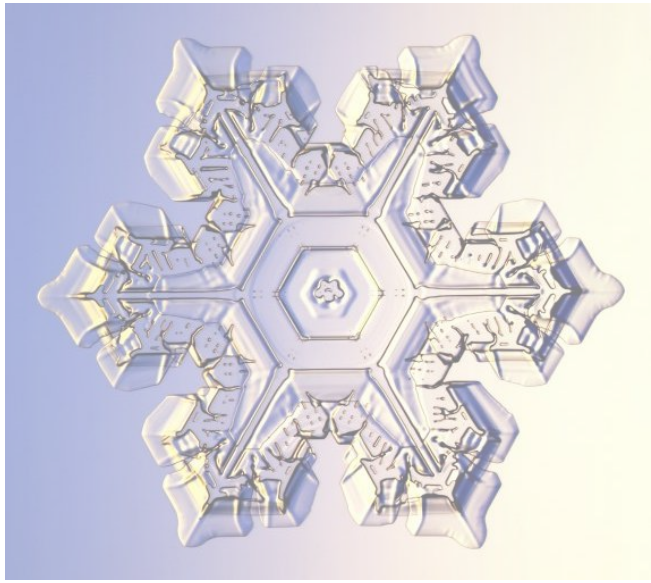


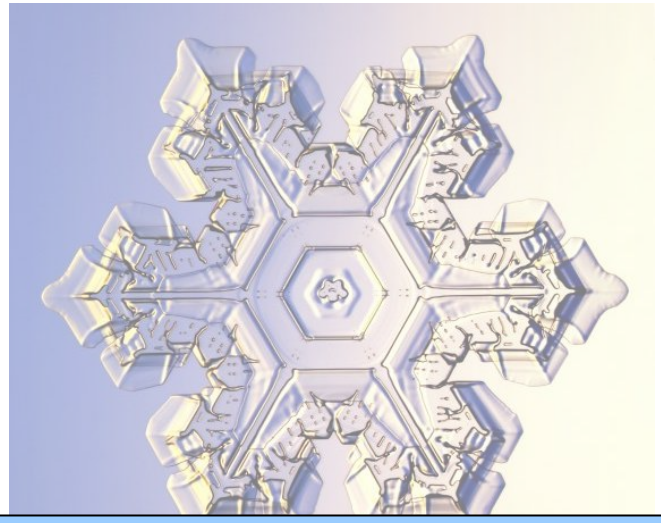
Life must be described differently:
What does life need?

What is life?

~~Life multiplies~~

~~Life is self-organizing~~

~~Life adapts to its environment~~



Life – as we know it – requires:

Liquid Water

stable environment

trace elements

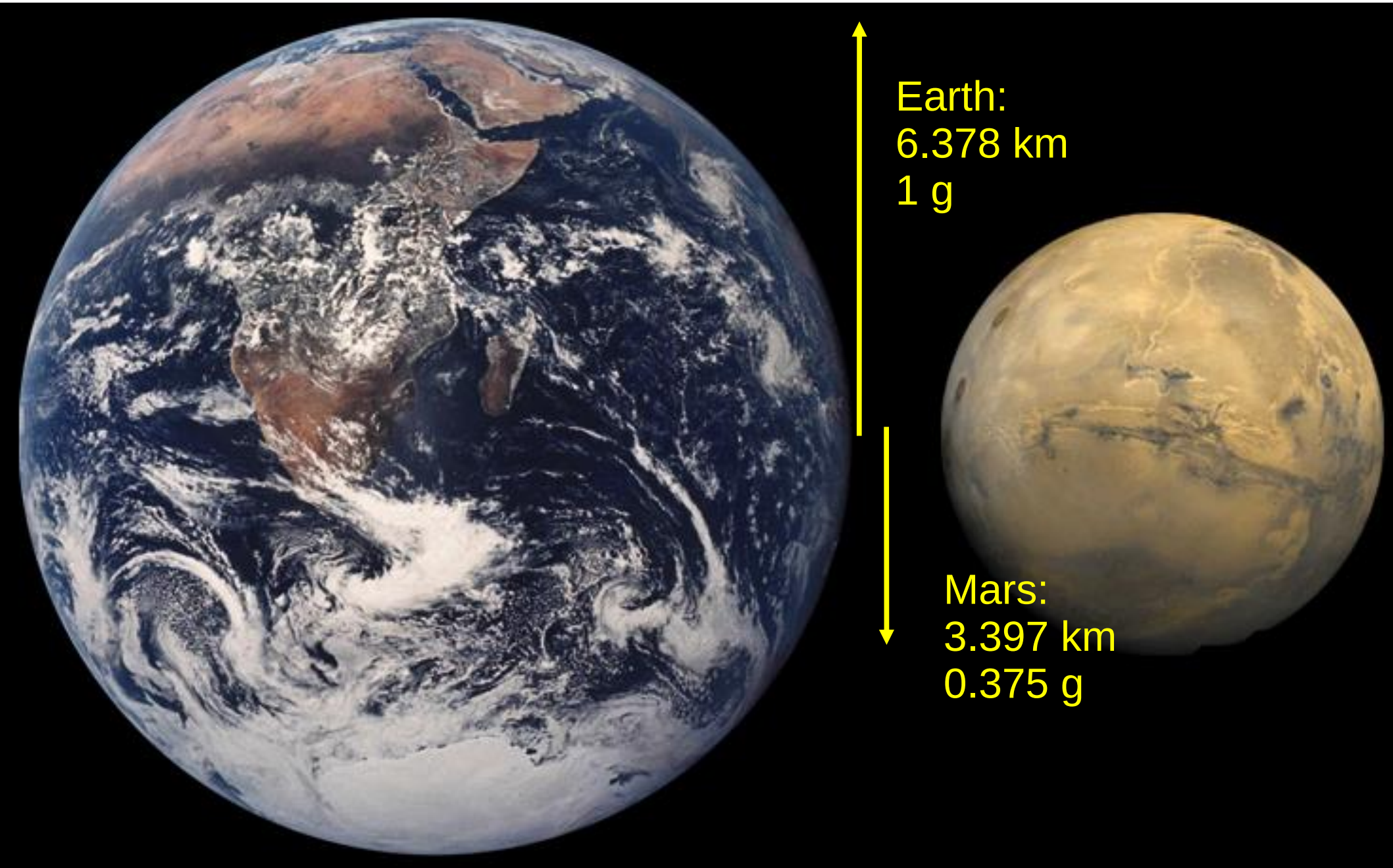
energy

Habitability in the solar system

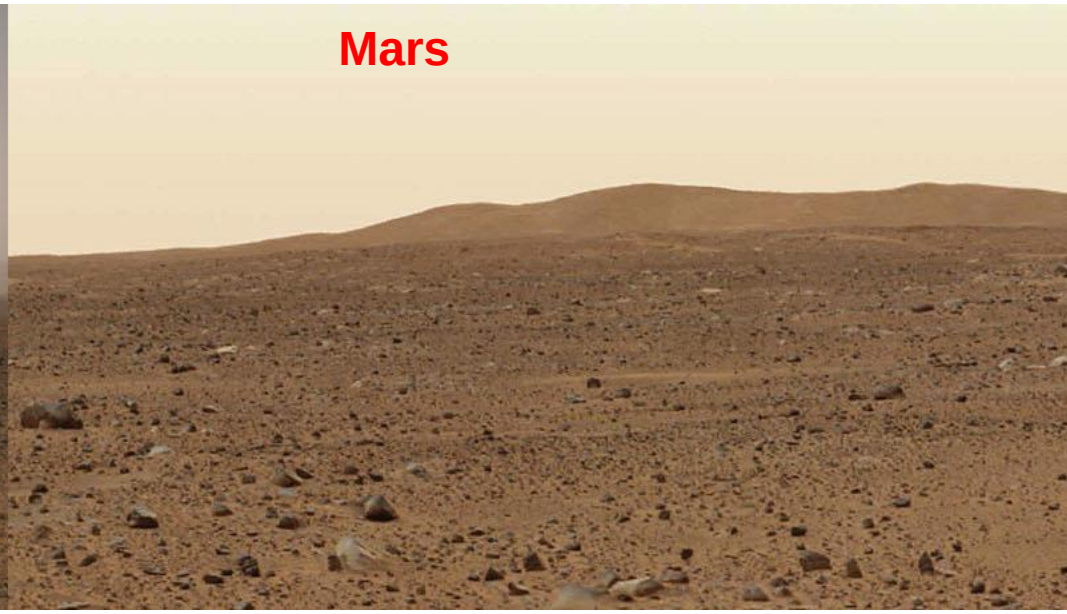
	SURFACE HABITATS		DEEP HABITATS				
	Shallow water		Trapped oceans			Top oceans	
	The Earth	Mars	Ganymede	Callisto	Titan	Europa	Enceladus
Liquid Water	🟢	🟡	🟢	🟢	🟢	🟢	🟢
Stable Environ-ment	🟢	🔴	🟢	🟢	🟢	🟢	🔴
Essential elements	🟢	🟢	🟢	🟡	🟢	🟢	🟢
Chemical Energy	🟢	🟢	🟡	🟡	🟡	🟢	🟢

Earth

Mars



Mars – our neighbor planet



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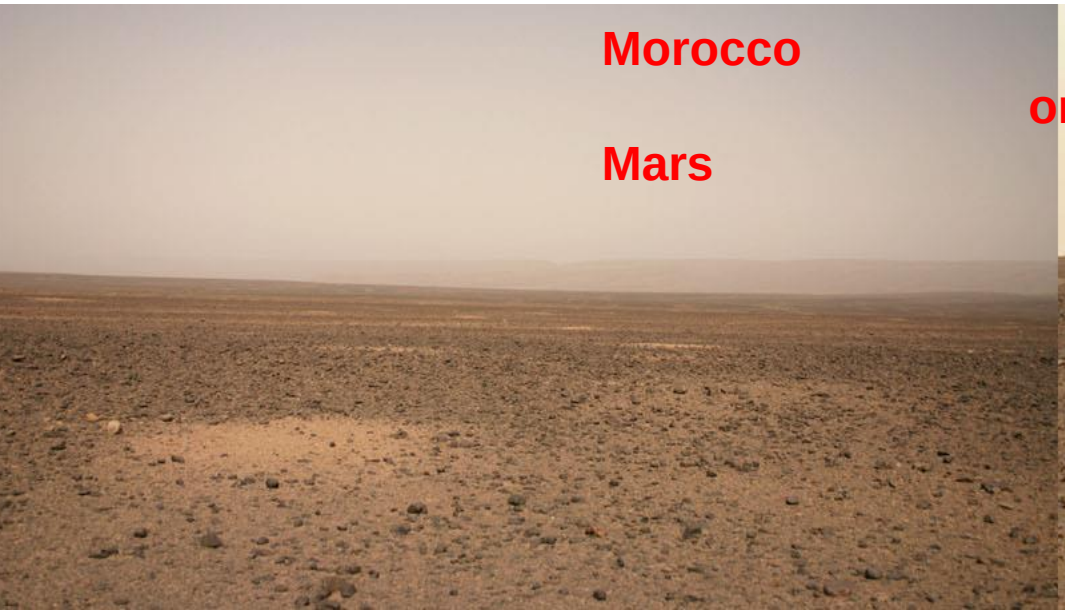

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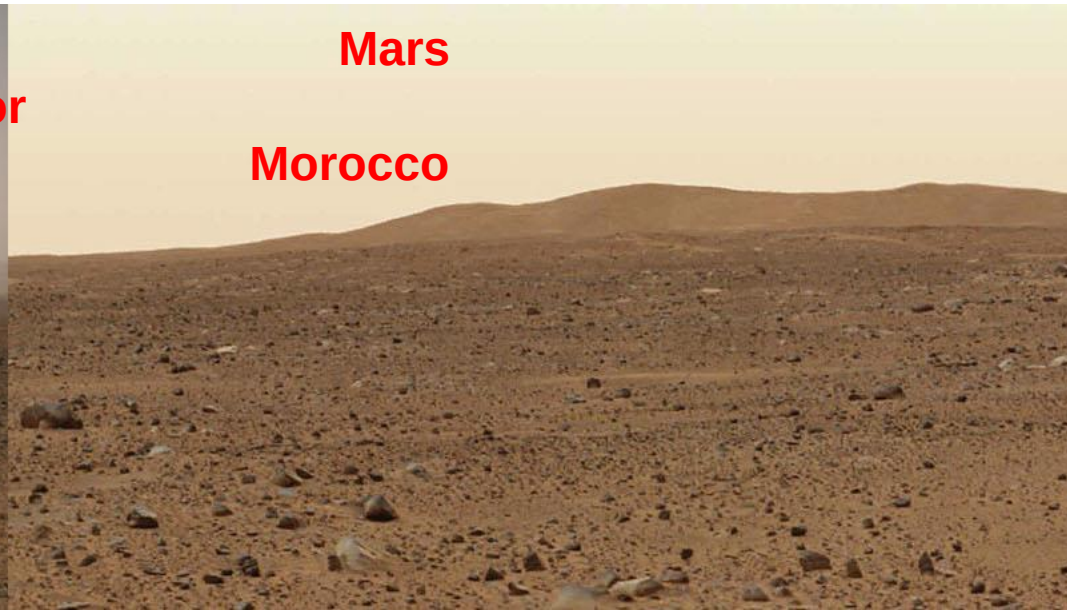

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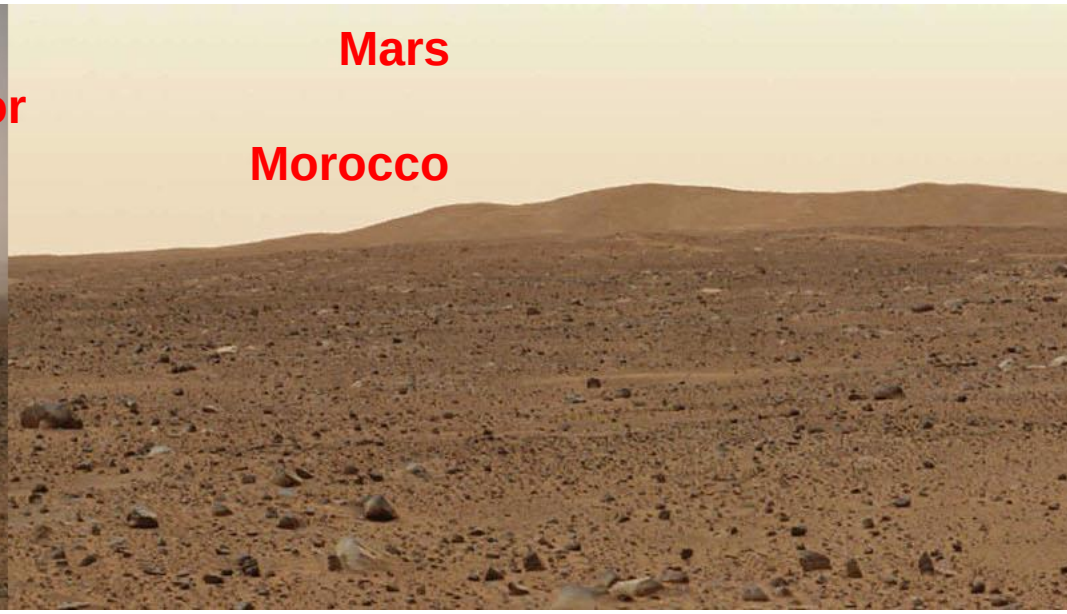

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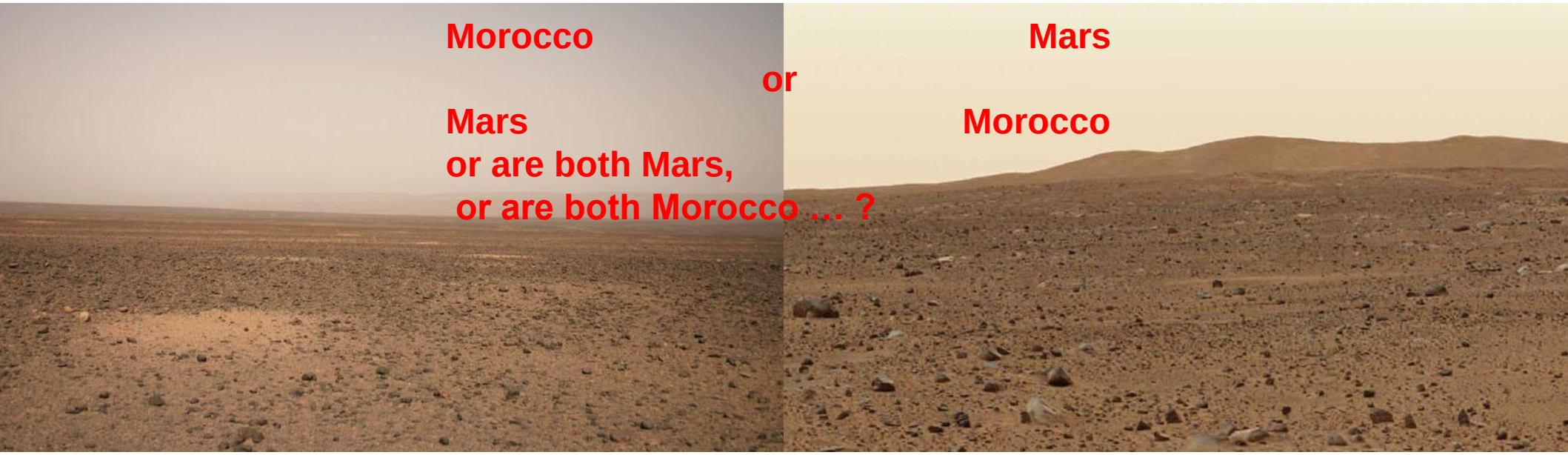

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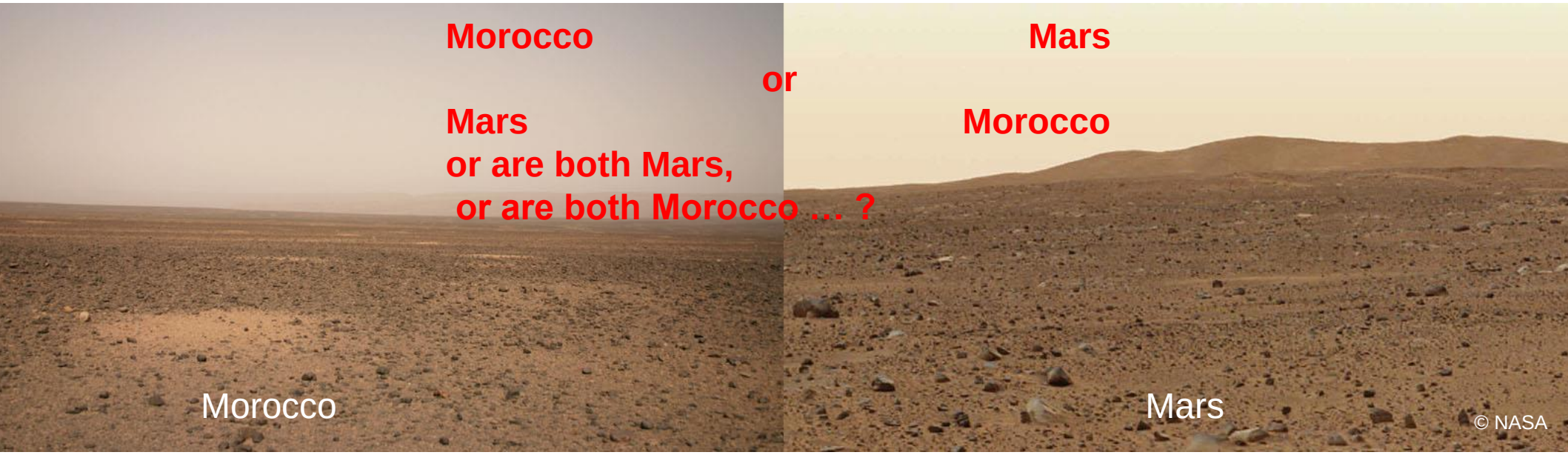
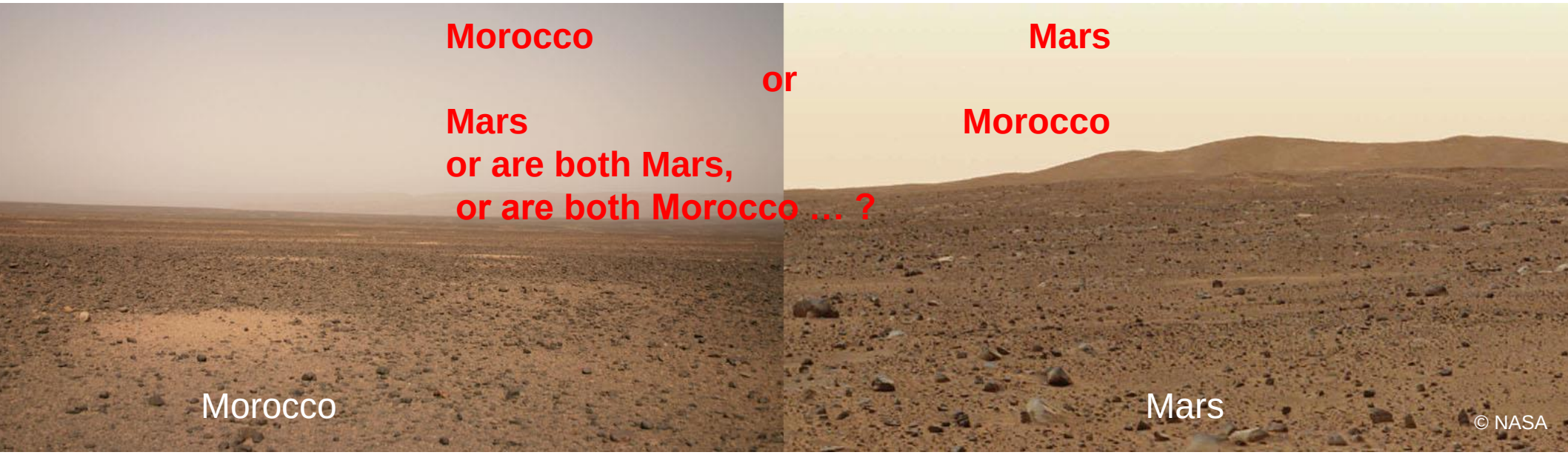
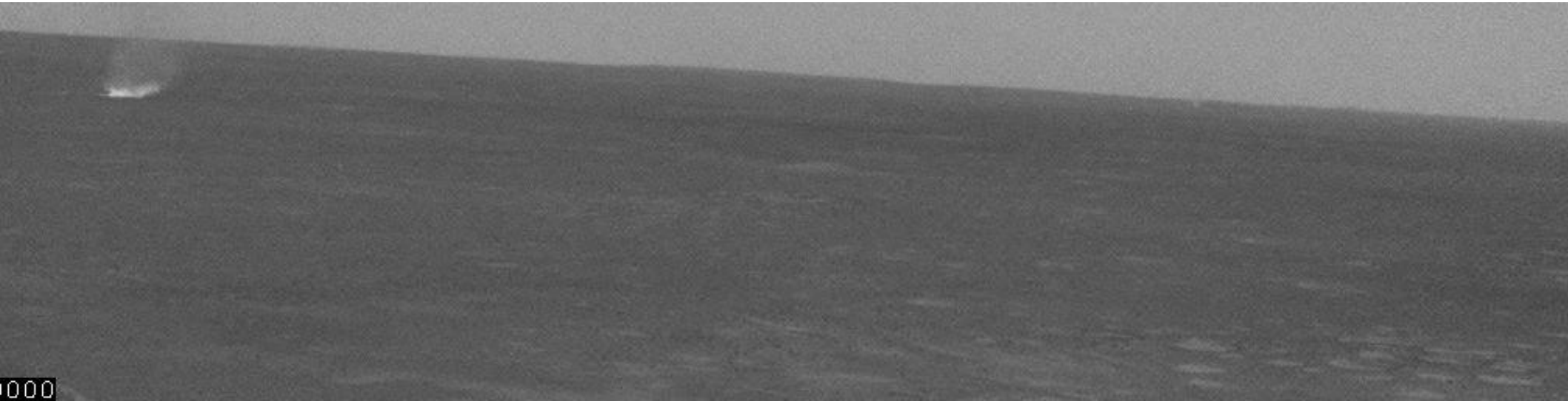


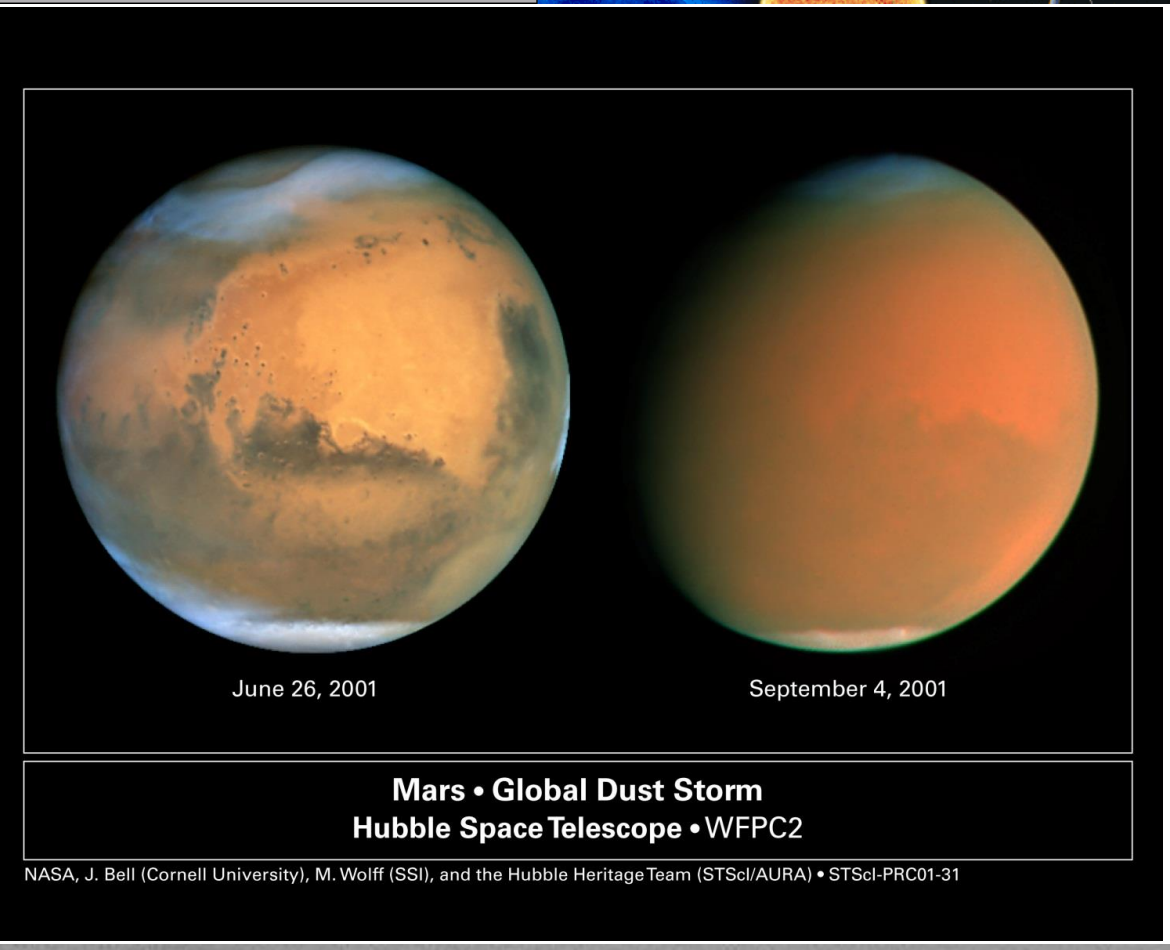
Mars atmosphere:

Surface pressure:	approx. 0,6% Earth value
Temperature at surface:	approx. -130 to + 30°C
Composition:	95% carbon dioxide; 2,7% nitrogen
Earth (for comparison):	78% nitrogen; 21% oxygen

Mars – our neighbor planet

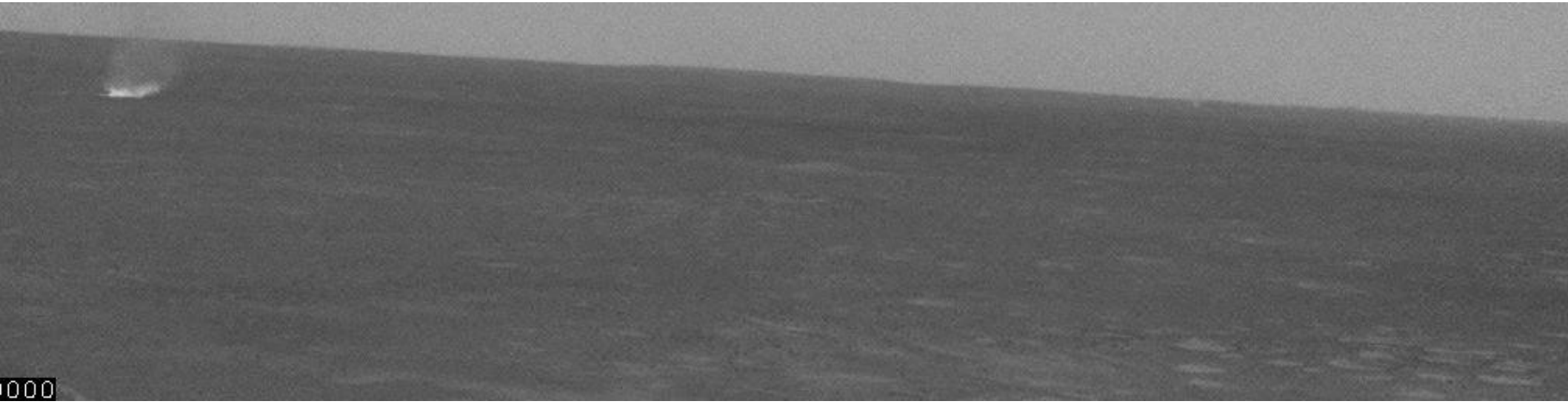


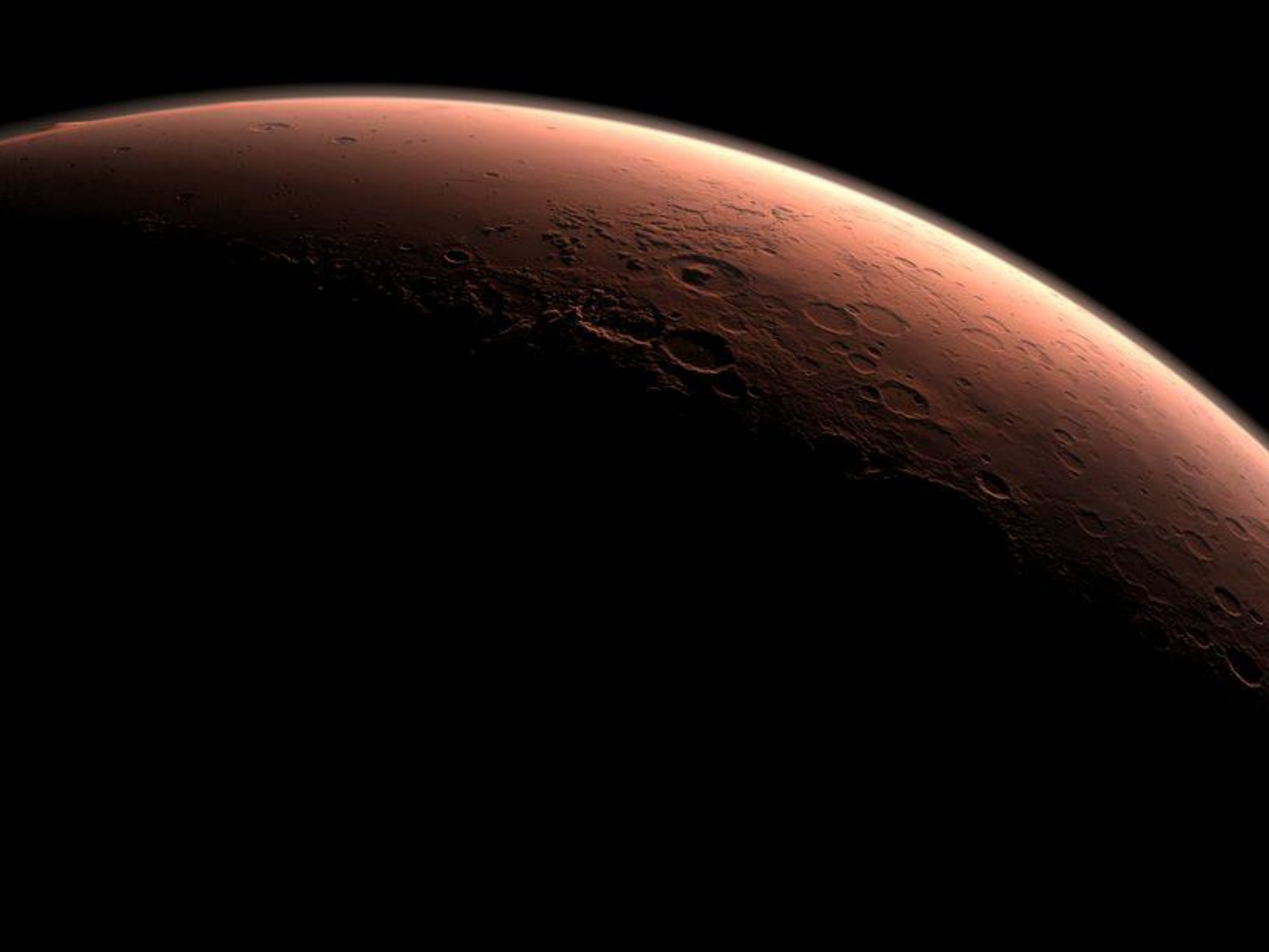




Despite Mars' very thin atmosphere, dust storms can cover Mars nearly completely.

'Everything is dusty'





Google Mars - Mozilla Firefox

Google Mars

www.google.com/mars/

Google

Regions Mountains Plains
Spacecraft Canyons Ridges
Stories Dunes Craters

gale crater

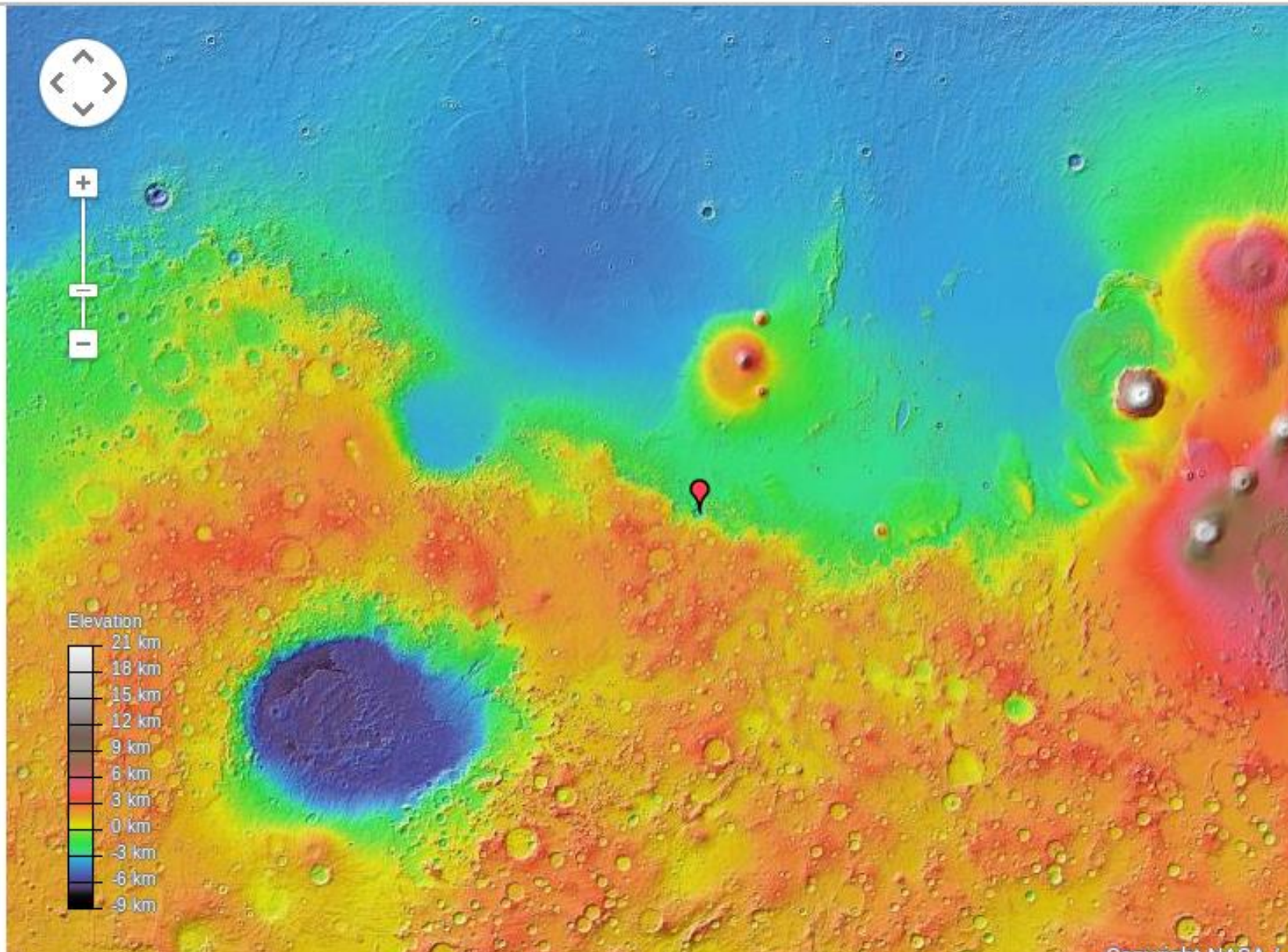
Search

ch results for **gale crater**

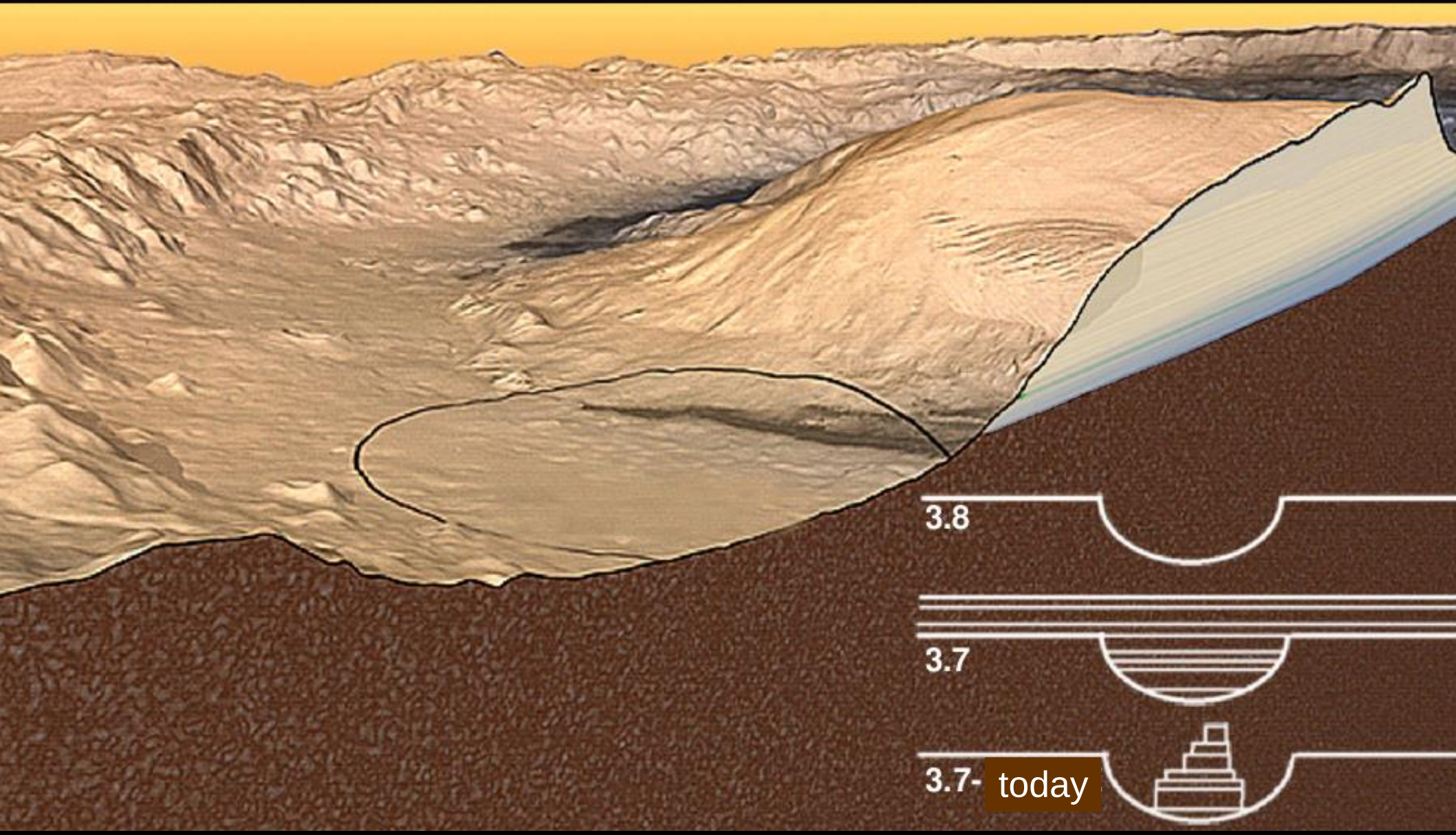
matches
ults to current region

glossary

Gale Crater
Named for: Australian astronomer
Walter F. Gale (1865-1945)

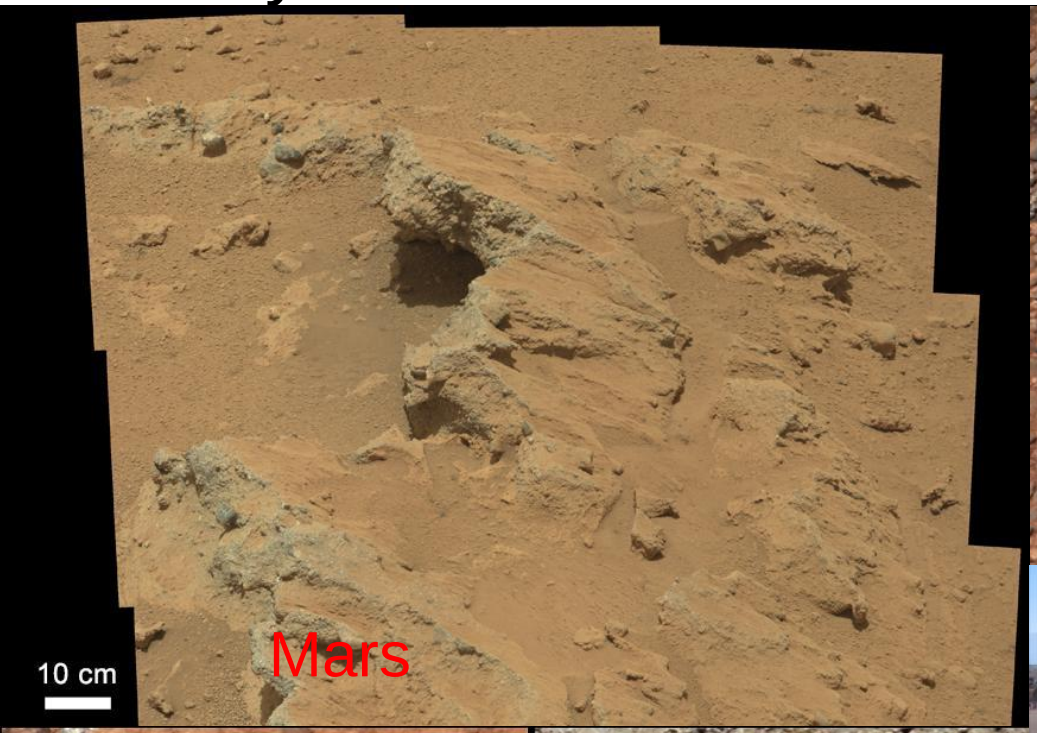


Why Gale crater?

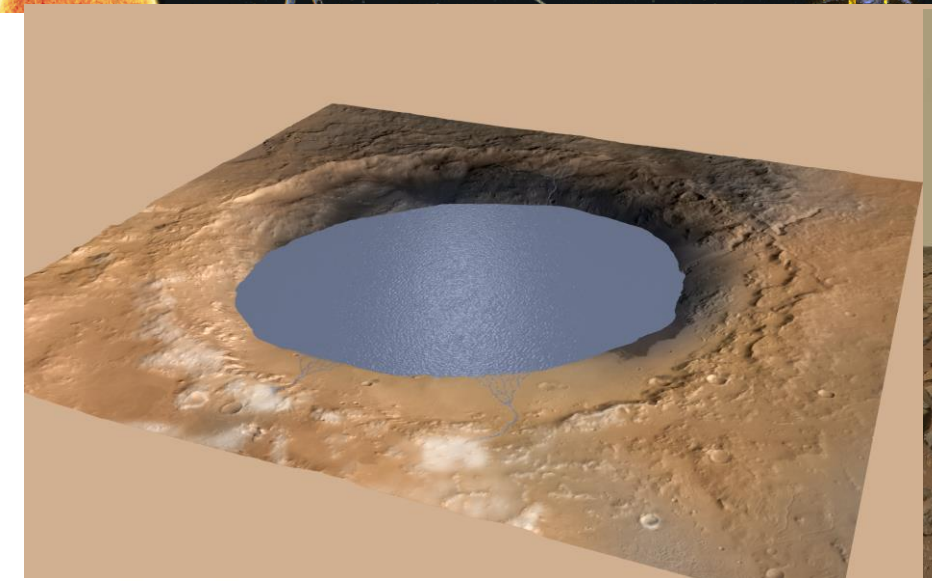


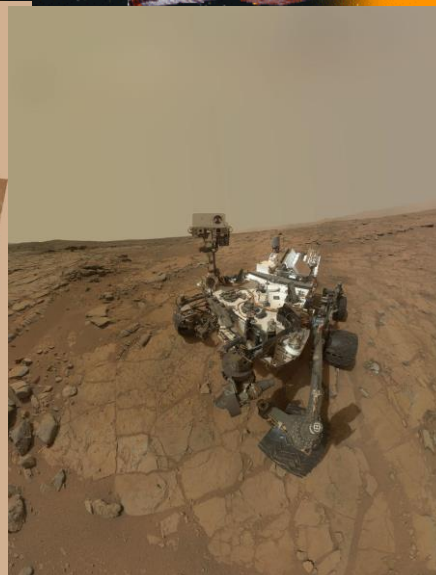
Sediments were deposited some 3.7 billion years ago. Most of them have been eroded away by wind and sand.

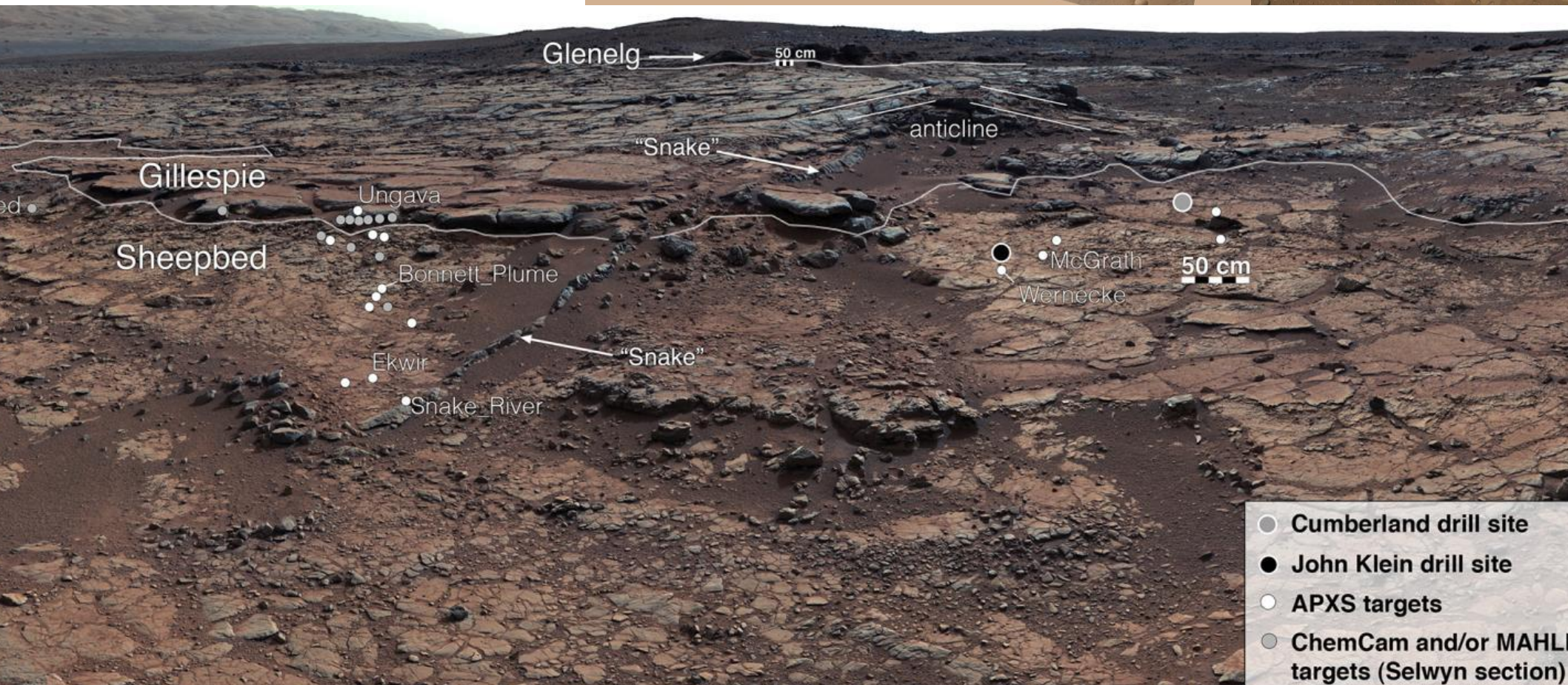
Curiosity landed in the remnants of a river environment...



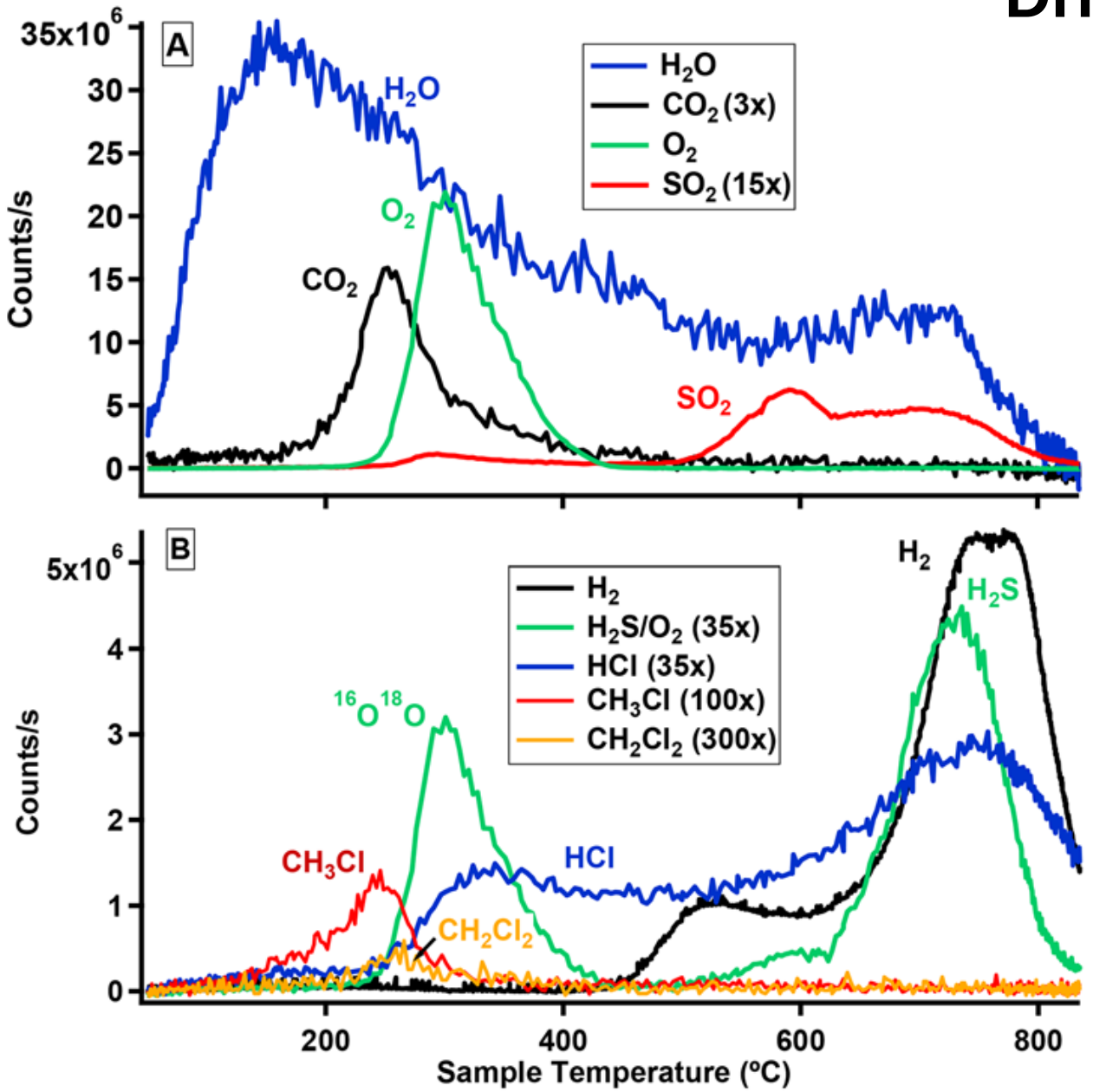
… and drove on into the remnants of an early lake!





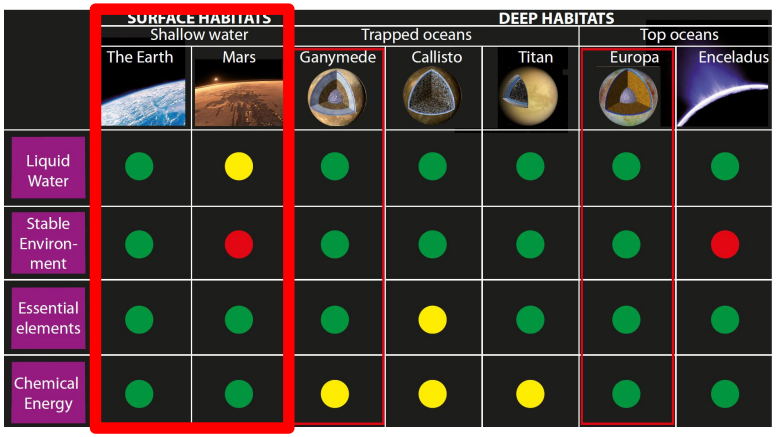


Drill results from SAM



(Ming et al., Science, 2013)

Measurements show that the drilled mudstone contained carbon, nitrogen, oxygen, and sulfur. These elements are needed for life to form.



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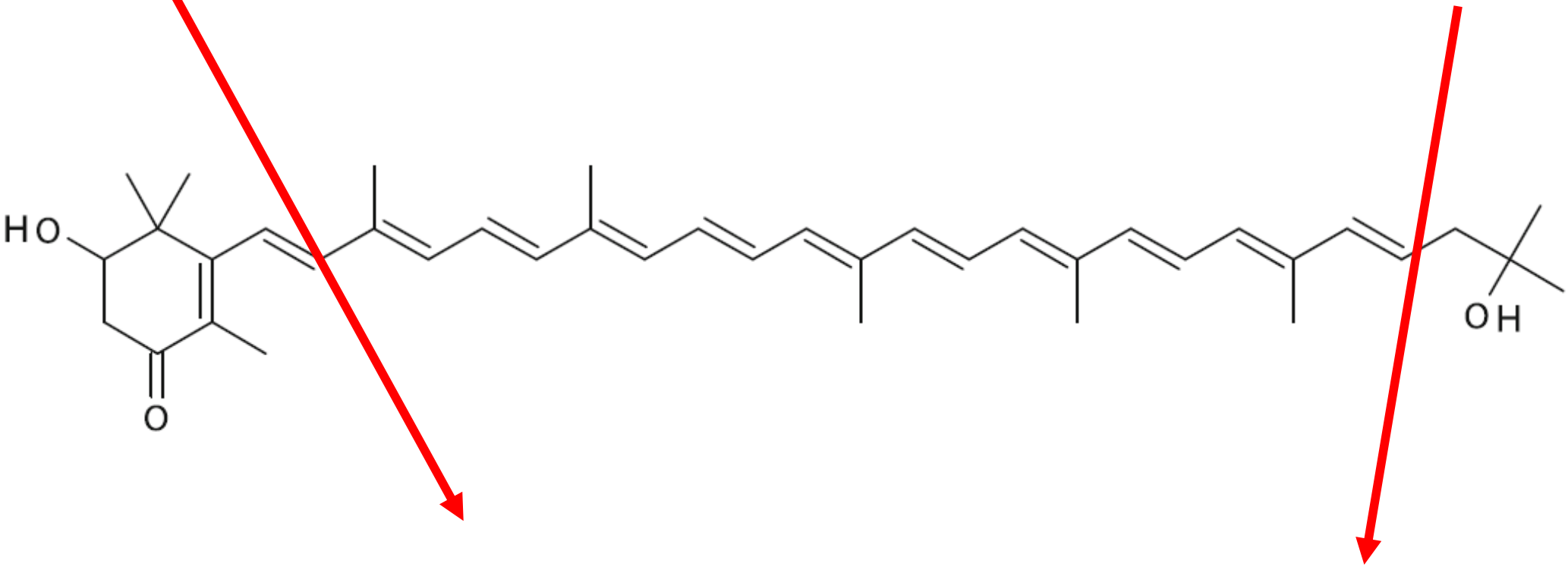

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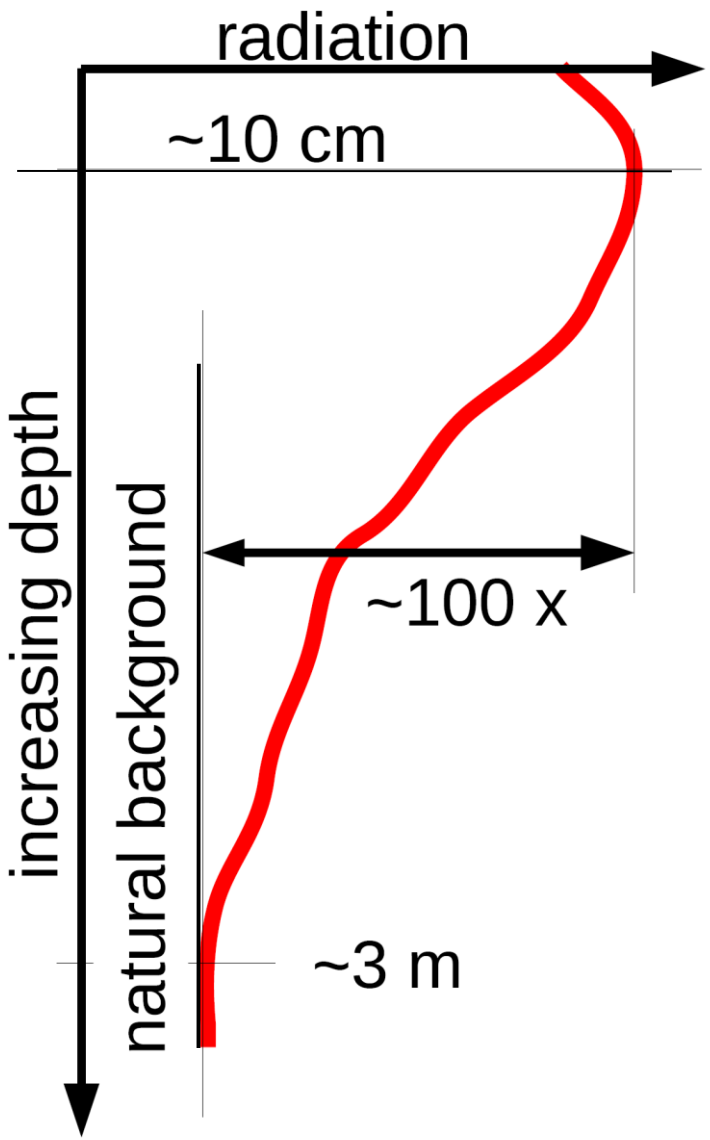

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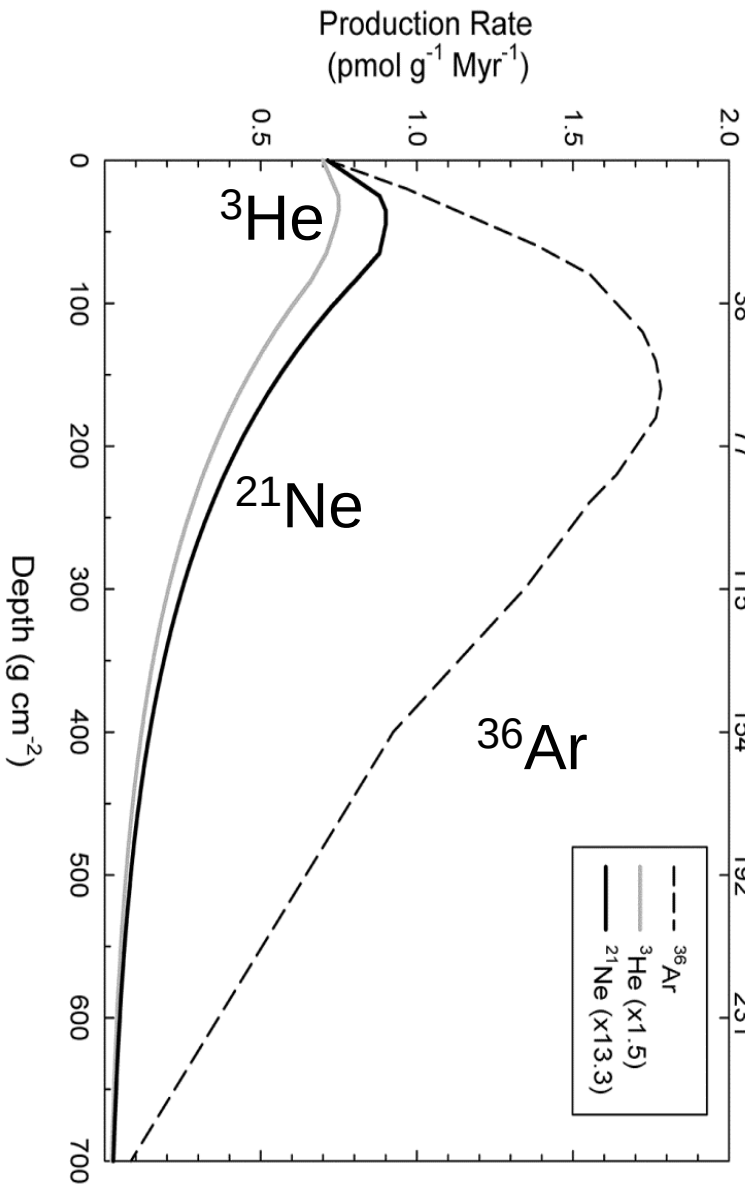

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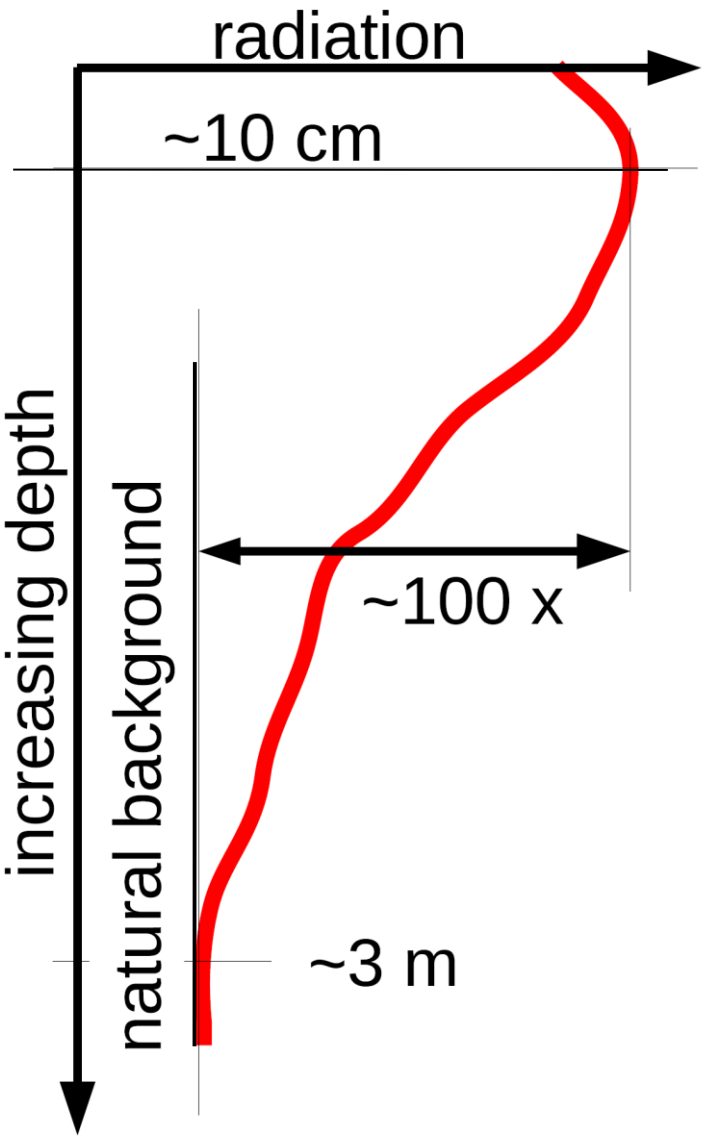

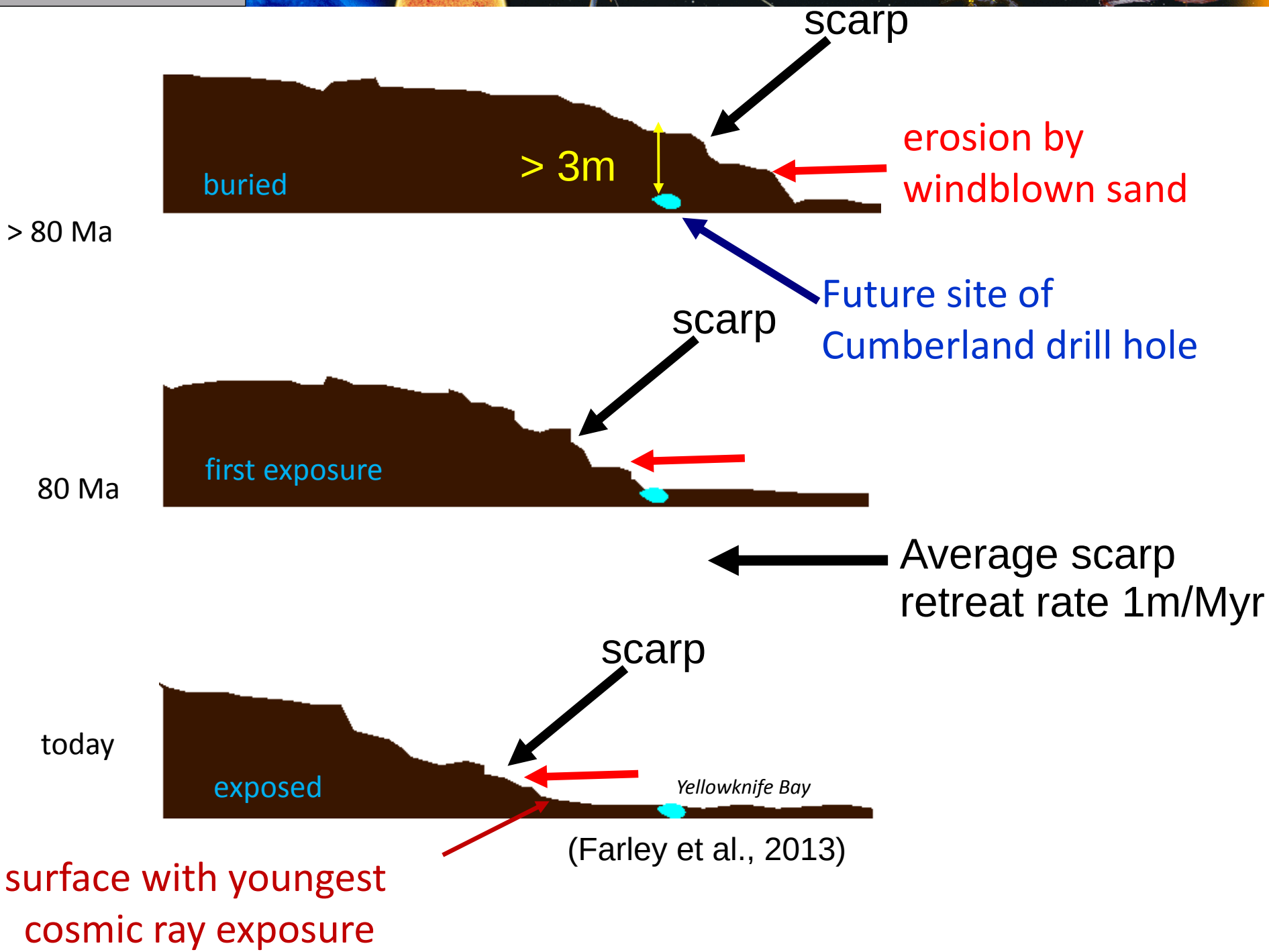
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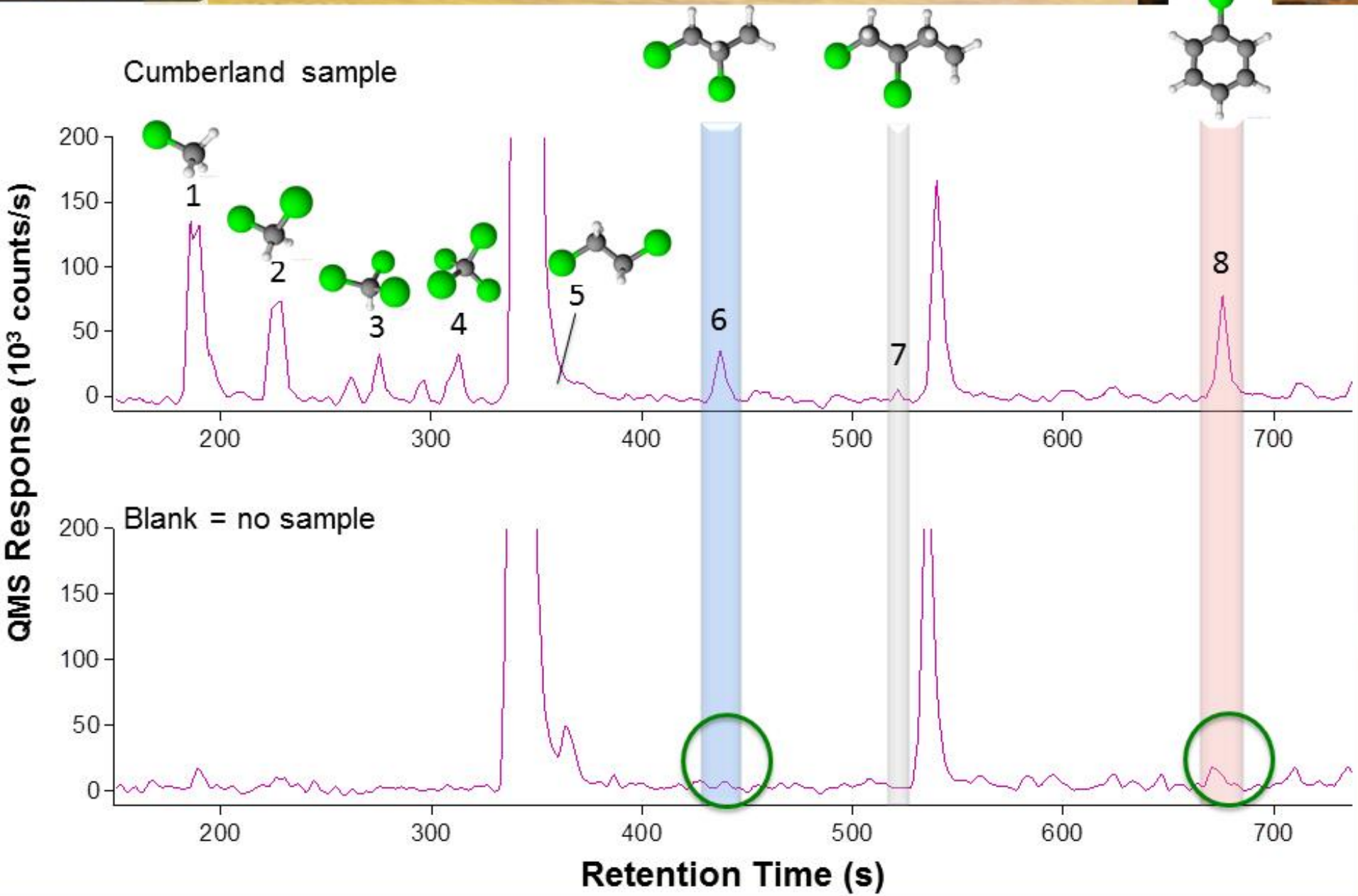

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Backup Slides

Why do we go to the trouble of predicting radiation?

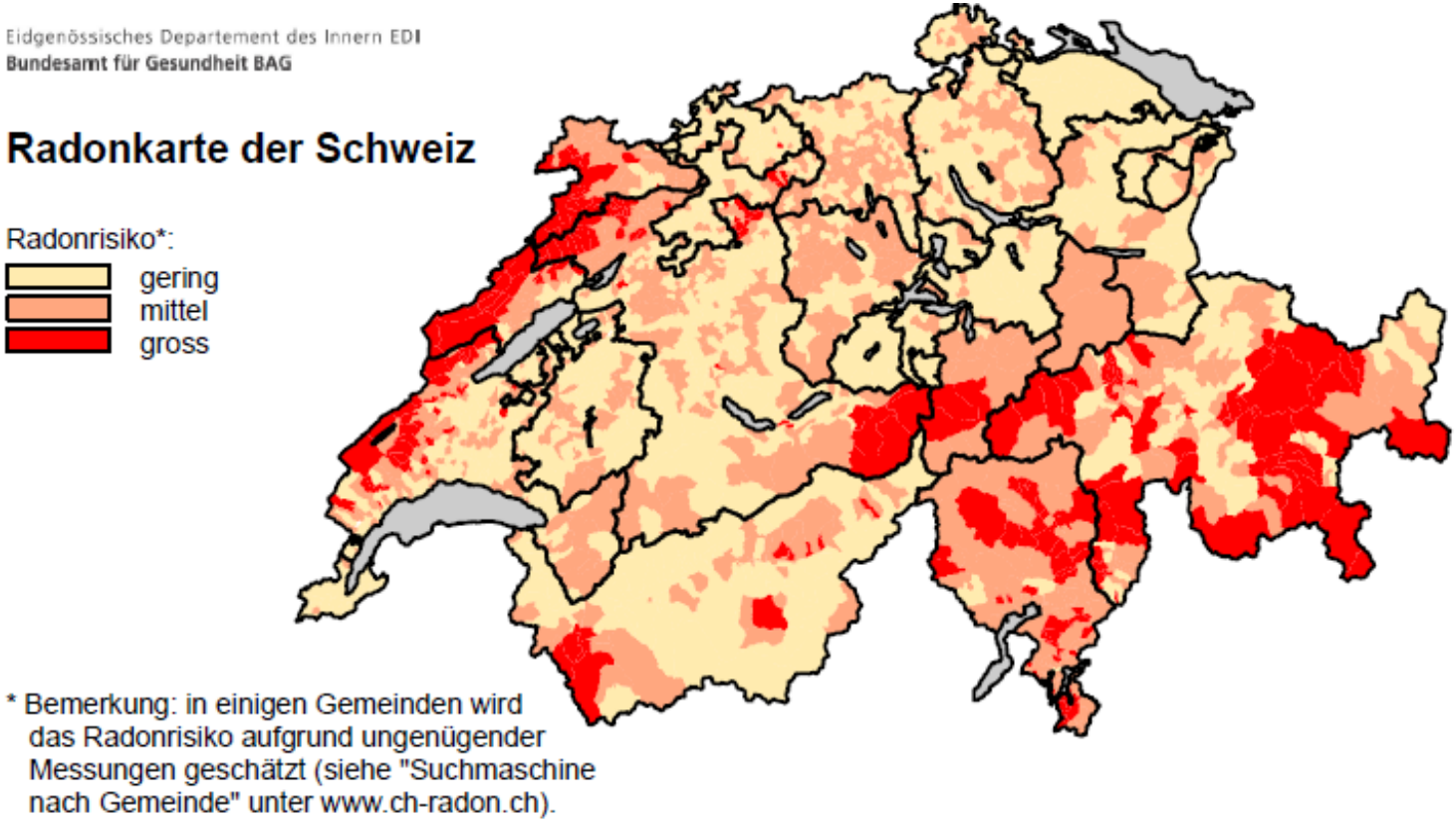
Radiation health primer:

Guarapari, Brasil

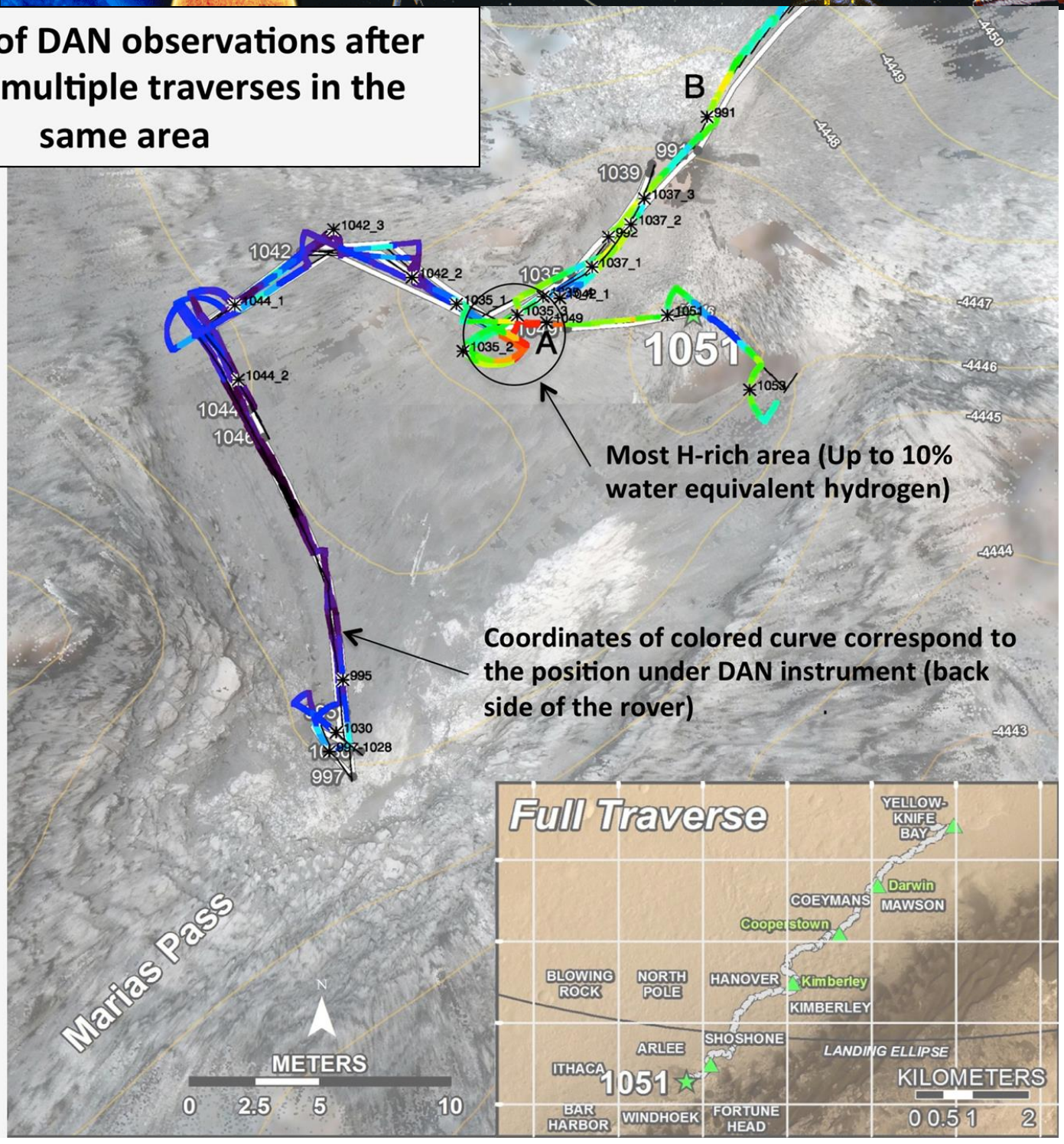
Average exposure:	**few mSv/year**
Allowed additional exposure:	**1 mSv/year**
Variability of exposures:	**from ~1mSv/year to 440 (!) mSv/year**

Variability mainly due to radon. CH: factor 240!

NASA: Cancer risk shall not increase by more than 3%.



Summary of DAN observations after Curiosity multiple traverses in the same area



119.0
101.5
84.0
66.5
49.0

DAN PASSIVE COUNT RATE (cps)

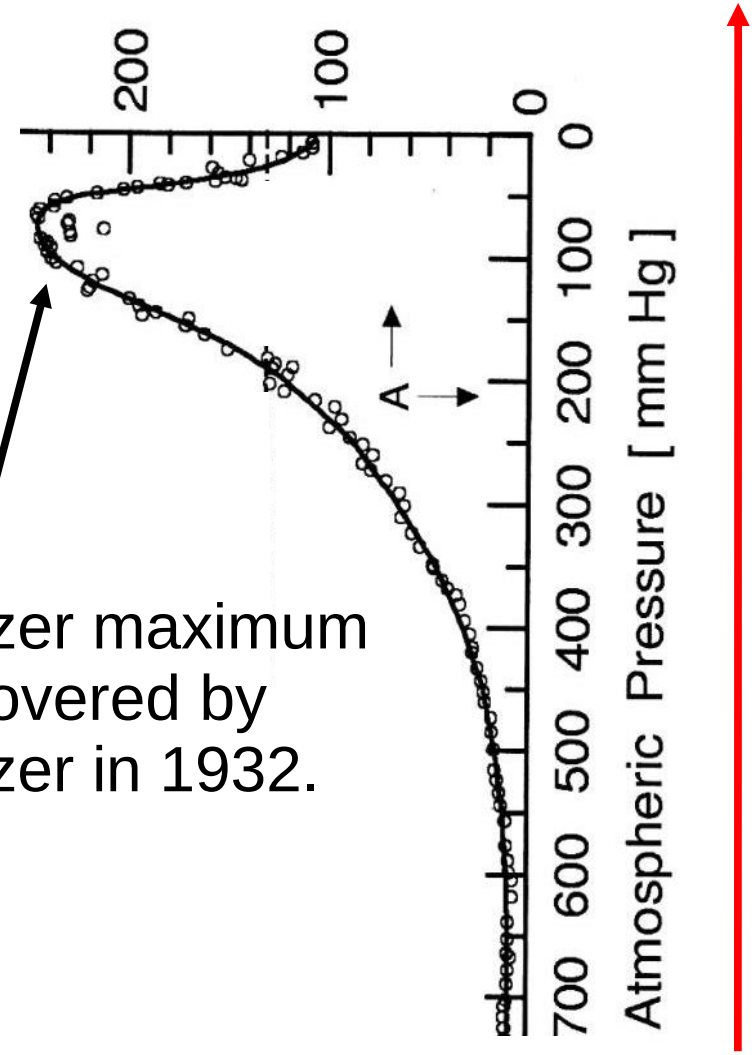
Why does ionization increase with height?

Measurements show count rate increases with height.

Air pressure decreases with height.

If Earth's radiation were ionizing, count rate should decrease with height because there is less air to ionize.

Can only be explained by ionizing agent coming in from outside the Earth ---> extraterrestrial origin! (Millikan)

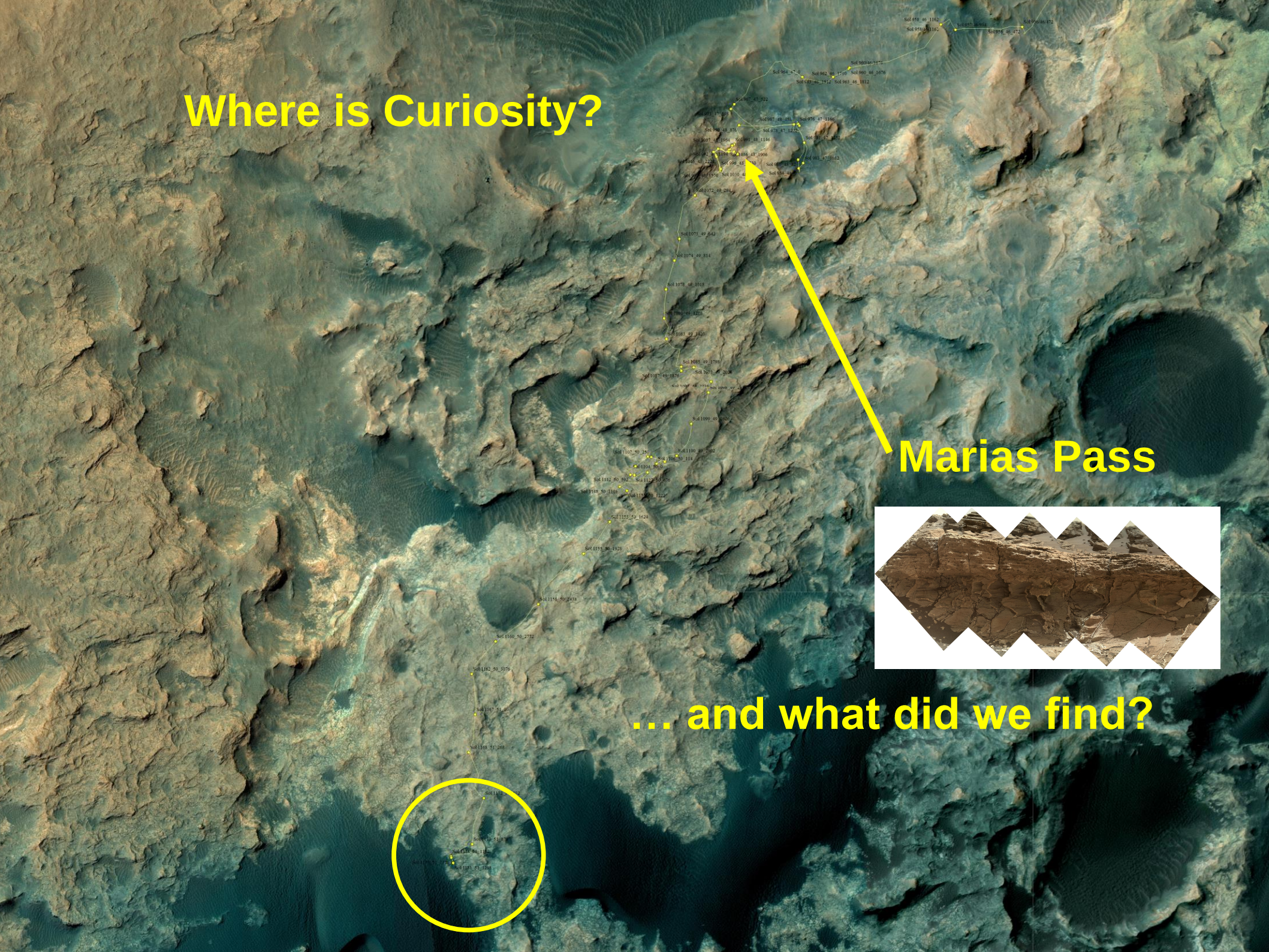


Pfotzer maximum discovered by Pfotzer in 1932.

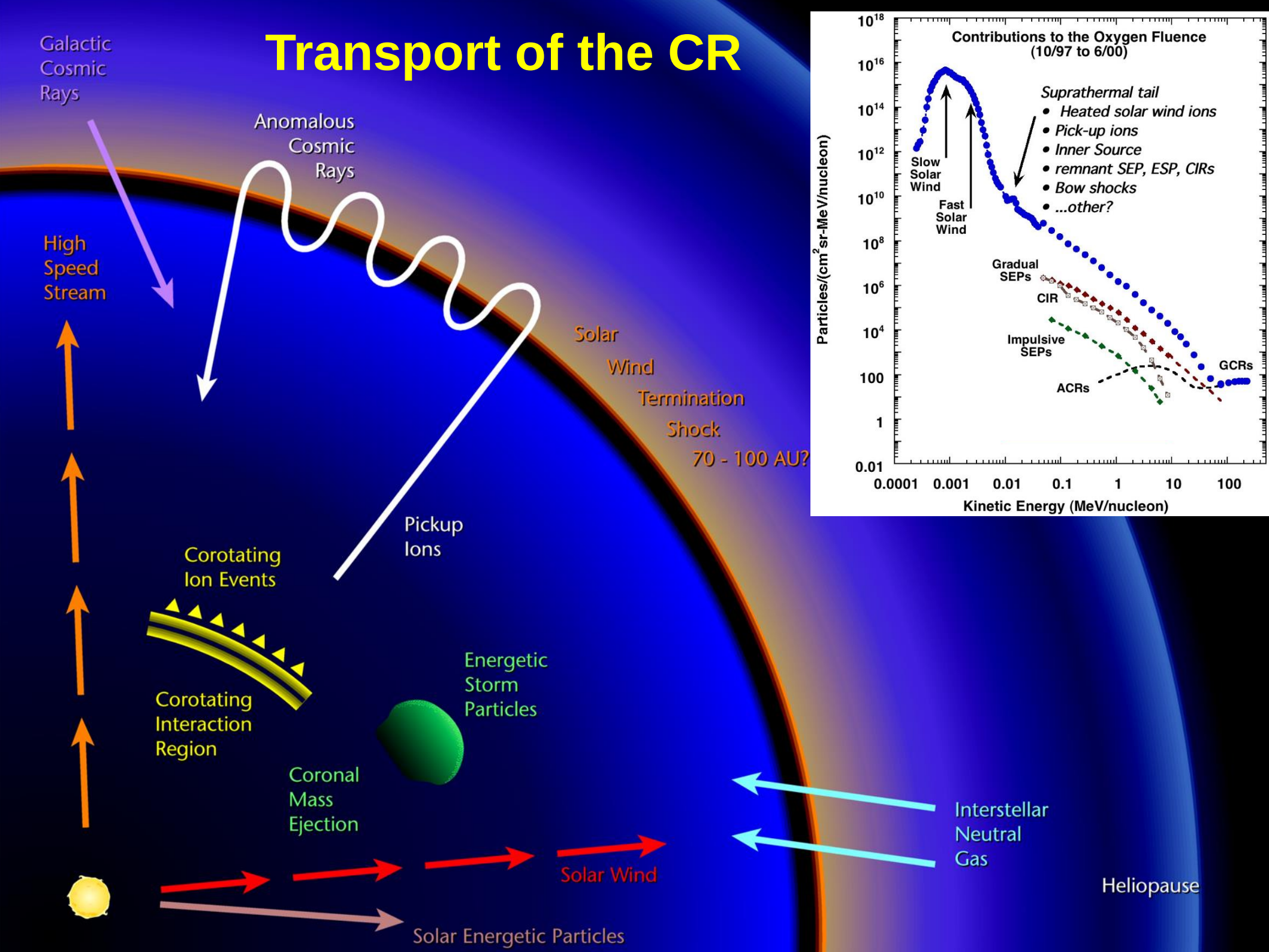
(Grieder, 2002)

Where is Curiosity?

Where is Curiosity?


Where is Curiosity?
Marias Pass
… and what did we find?

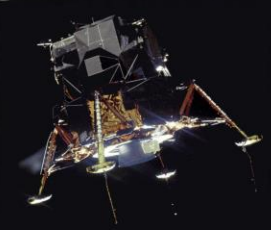
Transport of the CR



From Kiel to Space

Space missions with contributions from CAU Kiel

Apollo 16 and 17 (1972)
The last two moon landings
Cosmic Ray Detector Experiment



International Sun-Earth Explorer (ISEE-2, 1977-1987)
Studied the interaction between solar wind and Earth magnetic field
Charged particle spectrometer

Helios 1 and 2 (1974-1986)
Inner heliosphere missions, which approached the sun closer than any other spacecraft so far
E6 Cosmic Ray Experiment

Azur (1969-1970)
The first German satellite studied the magnetosphere and the Van-Allen radiation belts

Galileo (1989-2003)
NASA mission, which explored Jupiter and its moons. Also carried a probe which descended into Jupiter's atmosphere
Energetic Particles Investigation (EPI) on board of the probe

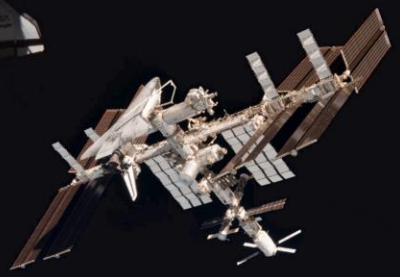
Long Duration Exposure Facility (1984-1990)
Various materials and some biological cells were exposed to open space and cosmic radiation
Free-Flyer Biostack Experiment

Mir (1986-2001)
Russian space station, which enabled the first long-term stays of hummans in space
Dosimetry experiments

Ulysses (1990-2009)
Solar mission, which went outside of the ecliptic to observe the polar regions of the sun and explore the 3D structure of the heliosphere
Kiel Electron Telescope

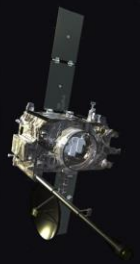
SOlar and Heliospheric Observatory (SOHO, 1995-today)
Allows a wide range of optical and in-situ measurements of the sun
Electron Proton Helium Instrument (EPHIN), CELIAS

Space Shuttle (1981-2011)
American spacecraft, which was used for a wide variety of experiments and other tasks
Several dosimetry experiments starting in 1982



International Space Station (1998-today)
Permanently occupied space station used for a wide variety of scientific experiments
Dosimetry experiments including Matroshka and DOSTEL

Advanced Composition Explorer (ACE, 1997-today)
Specialises in detailed in-situ measurements of the solar wind



STEREO A and B (2006-today)
Two spacecraft observing the sun from different angles, allowing a stereoscopic view of the sun, with optical and in-situ instruments
Solar Electron and Proton Telescope (SEPT), Plasma and Suprathermal Ion Composition (PLASTIC)

Chandra X-Ray Observatory (1999-today)
Observes supernovas, black holes and other high-energy cosmic events
Includes EPHIN as a radiation monitor

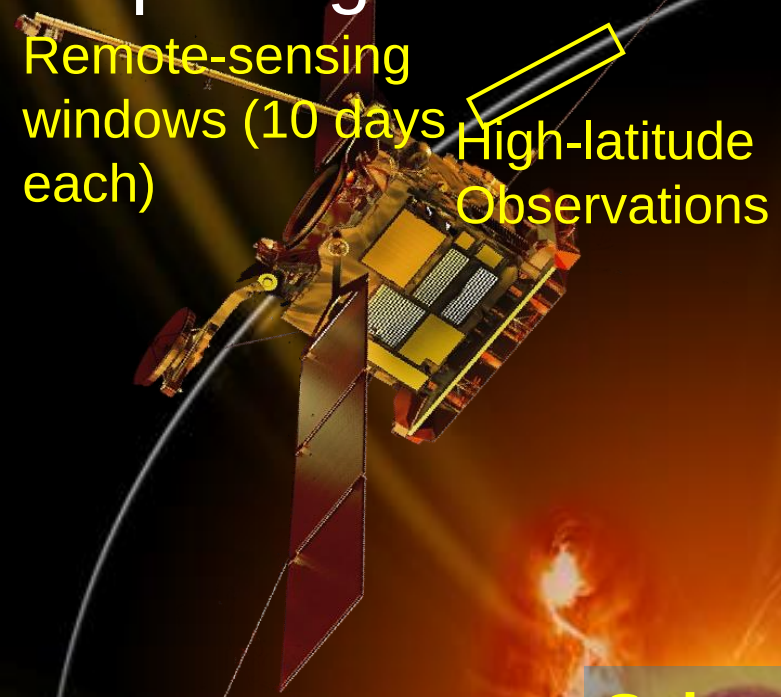
MSL/Curiosity (2011-today)
Mars mission to determine the suitability of Mars for the development of life in the past
Radiation Assessment Detector (RAD)

Solar Orbiter (2018-?)
Inner heliosphere mission, successor to Helios, which will observe the sun with in-situ and optical instruments from a distance of only 0.28 AU
Electron Proton Telescope (EPT), High Energy Telescope (HET) and SupraThermal Electrons and Protons (STEP)

Balloon Flights (ongoing)
Participation in the BEXUS balloon program aimed at students with several instruments
FRED, ADAM

Solar Orbiter

Exploring the Sun-Heliosphere Connection



Mission Summary

Launch: October 2018
Cruise Phase: 2.5 years
Nominal/Extended Mission: 3.5/2.5 years
Orbit: 0.28–0.91 AU (P=150-180 days)
Out-of-Ecliptic View:
Multiple gravity assists with Venus to increase out-of-ecliptic inclination to >33°

Science Focus

How does the Sun create and control the Heliosphere – and why does solar activity change with time ?

1) What drives the solar wind and where does the coronal magnetic field originate?

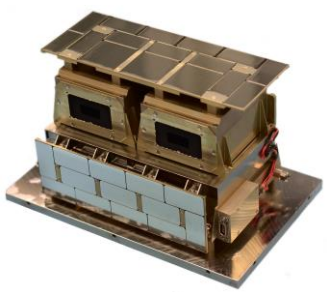
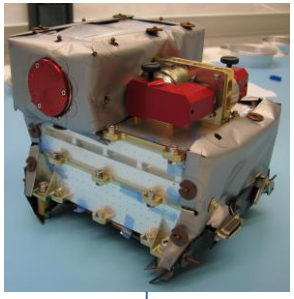
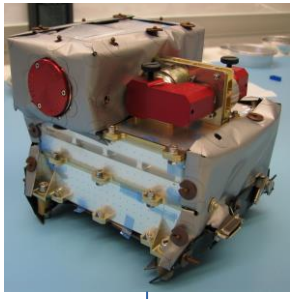
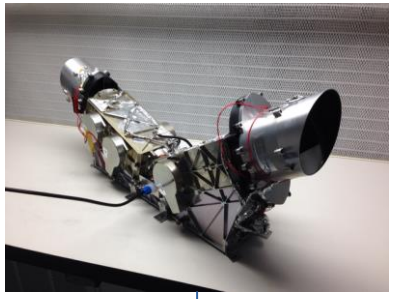
2) How do solar transients drive heliospheric variability?

3) **How do solar eruptions produce energetic particle radiation that fills the heliosphere?**

4) How does the solar dynamo work and drive connections between the Sun and the

EPD - The Team

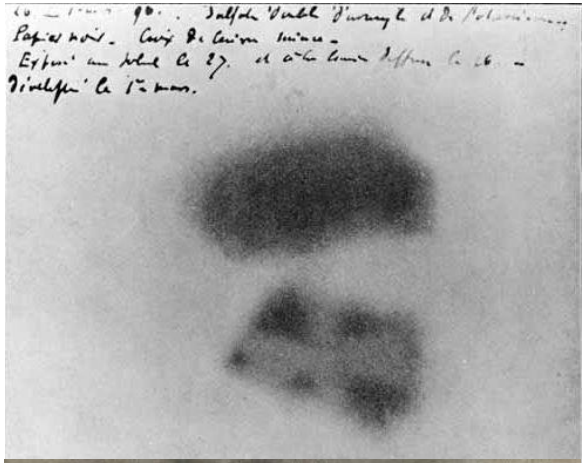
Led by University of Alcala, Spain,
PI: Javier Rodriguez-Pacheco (Alcala)
Co-PI: Robert Wimmer-Schweingruber (Kiel)
Hardware contributions from:

System Engineering:

Main funding agencies:
Spain: Mineco
Germany: DLR
ESA funds SIS as a facility instrument

Background: Radiation on Earth



In 1896 Henri Bequerel and others discovers non-chemical process capable of penetrating black paper and darkening photo plates. It also excites fluorescence.

Marie Curie discovers that uranium salt also ionizes air, strictly proportional to the amount of material.

Pitchblend is four times more effective, therefore, it must contain a new element. Discovery of polonium and radium.

Invention of the word 'radioactivity'.

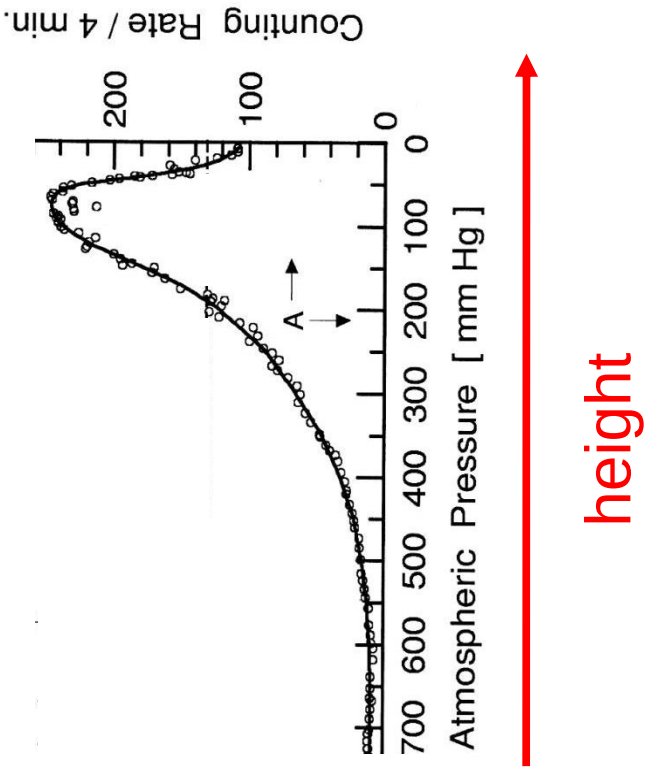
Something can ionize air and penetrate paper.

Ionization is a good measure of radioactivity.

Other early discoveries

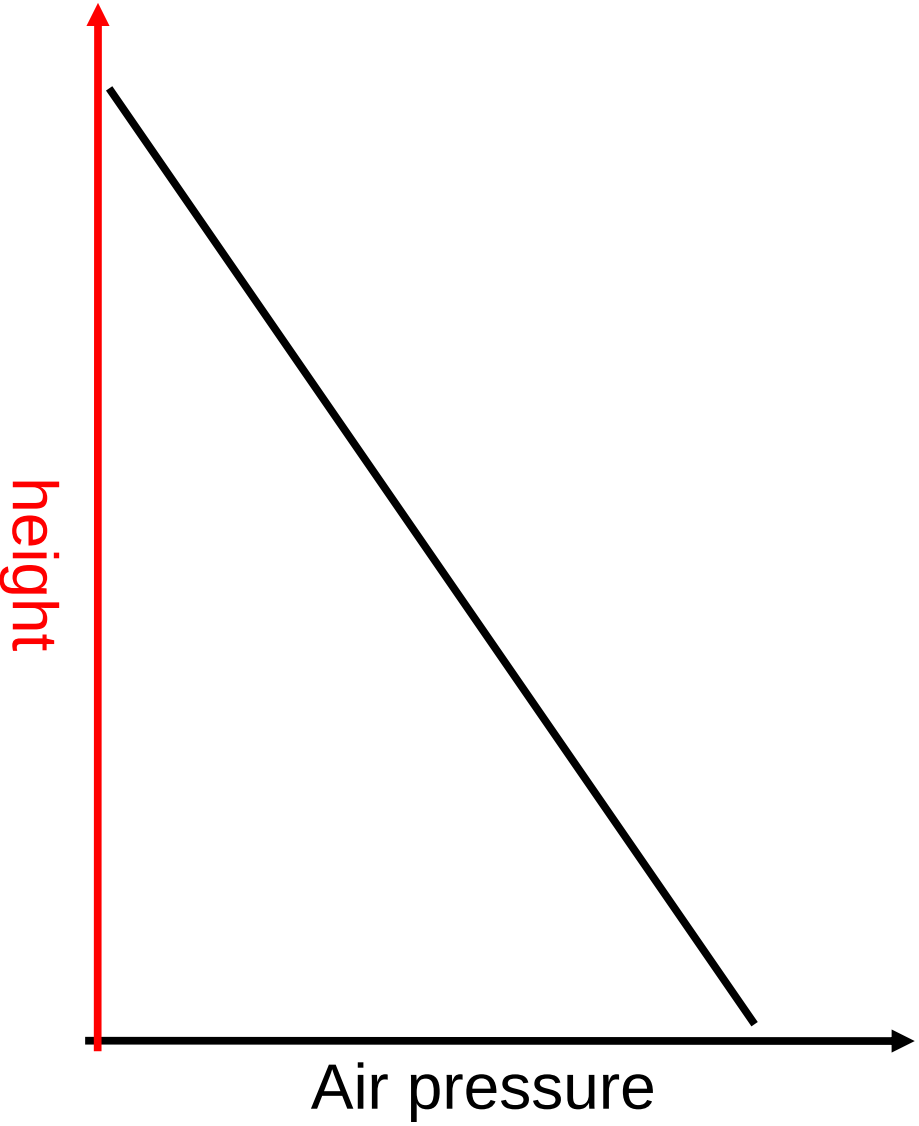
In 1912 Victor Hess discovers 'Höhenstrahlung' at large heights.
Degree of ionization increases with height.

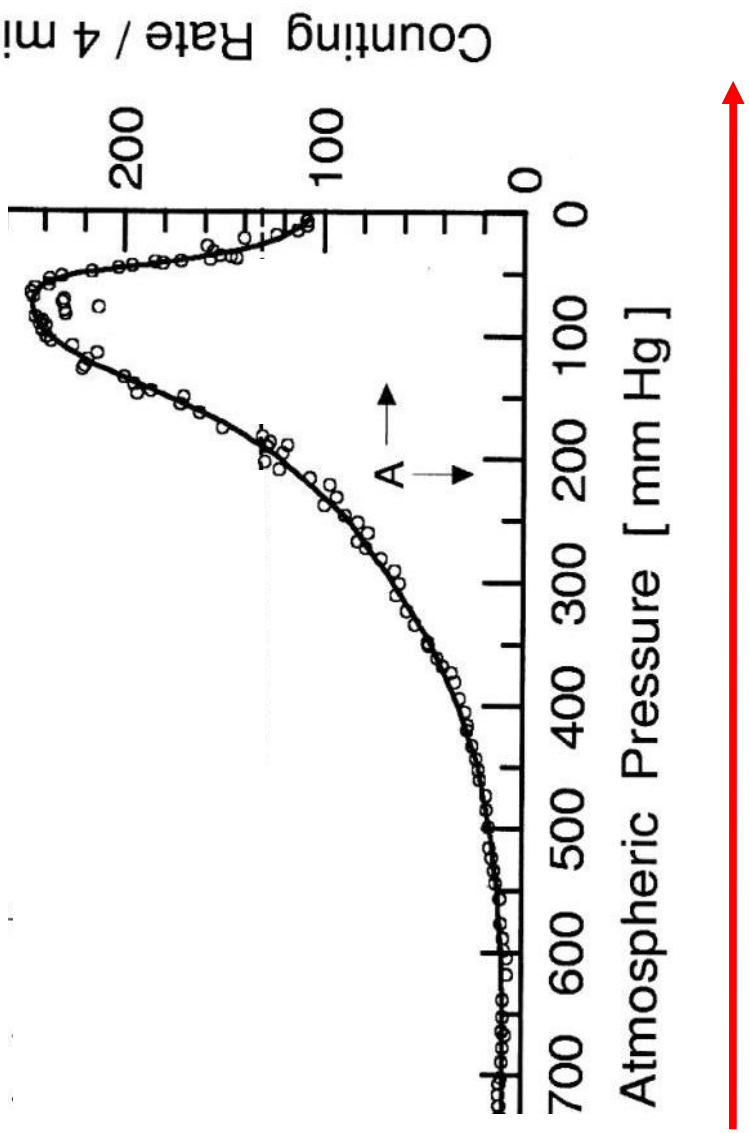
Image credit: NY Times



(Grieder, 2002)

Why does ionization increase with height?





(Grieder, 2002)

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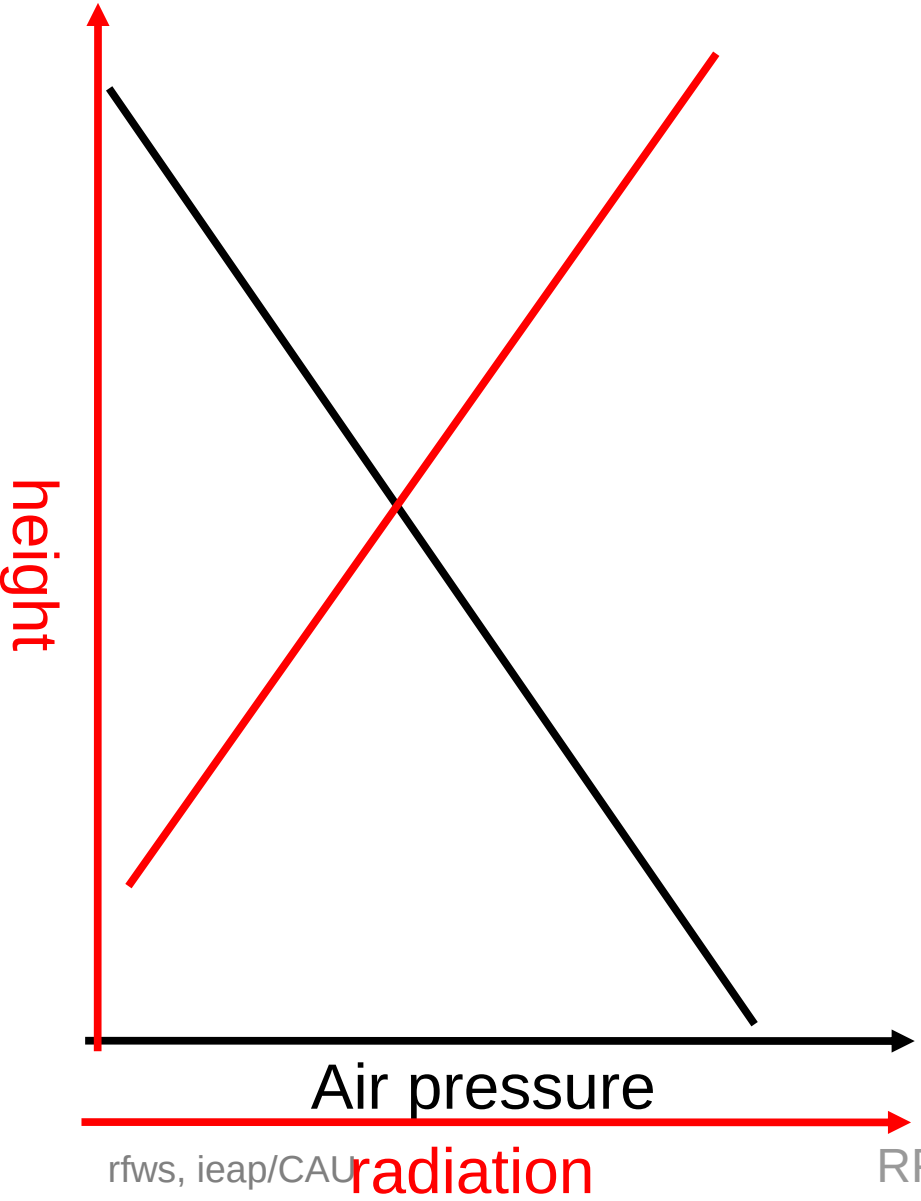
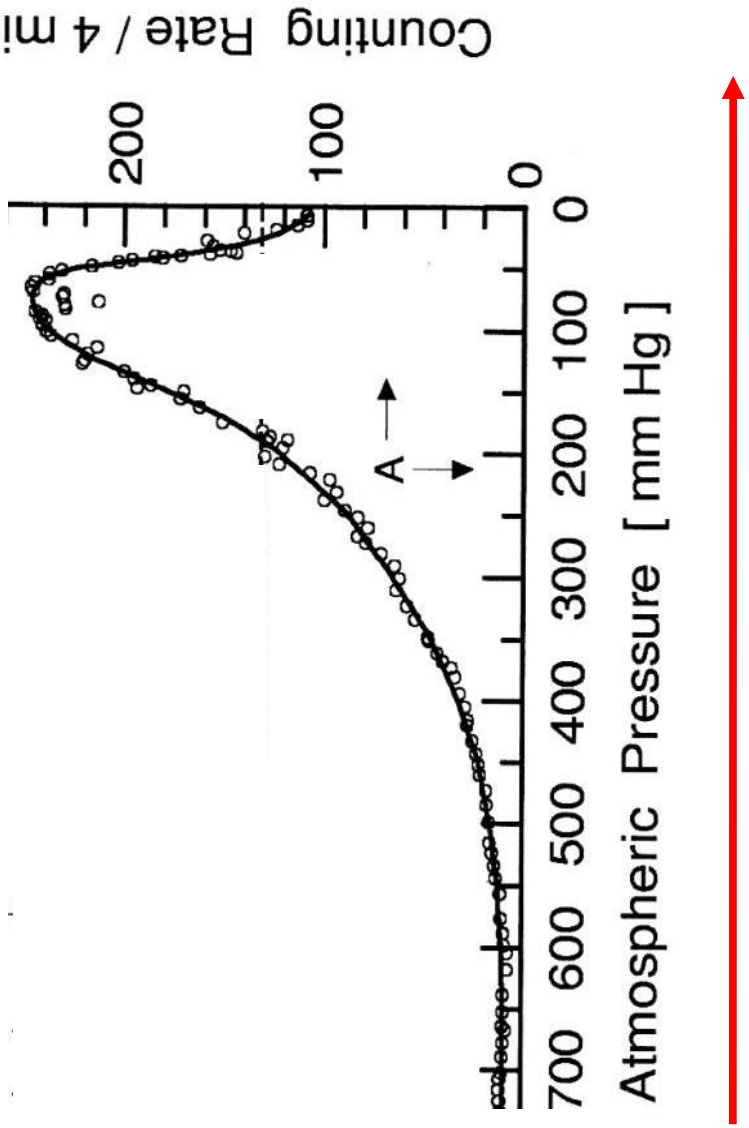
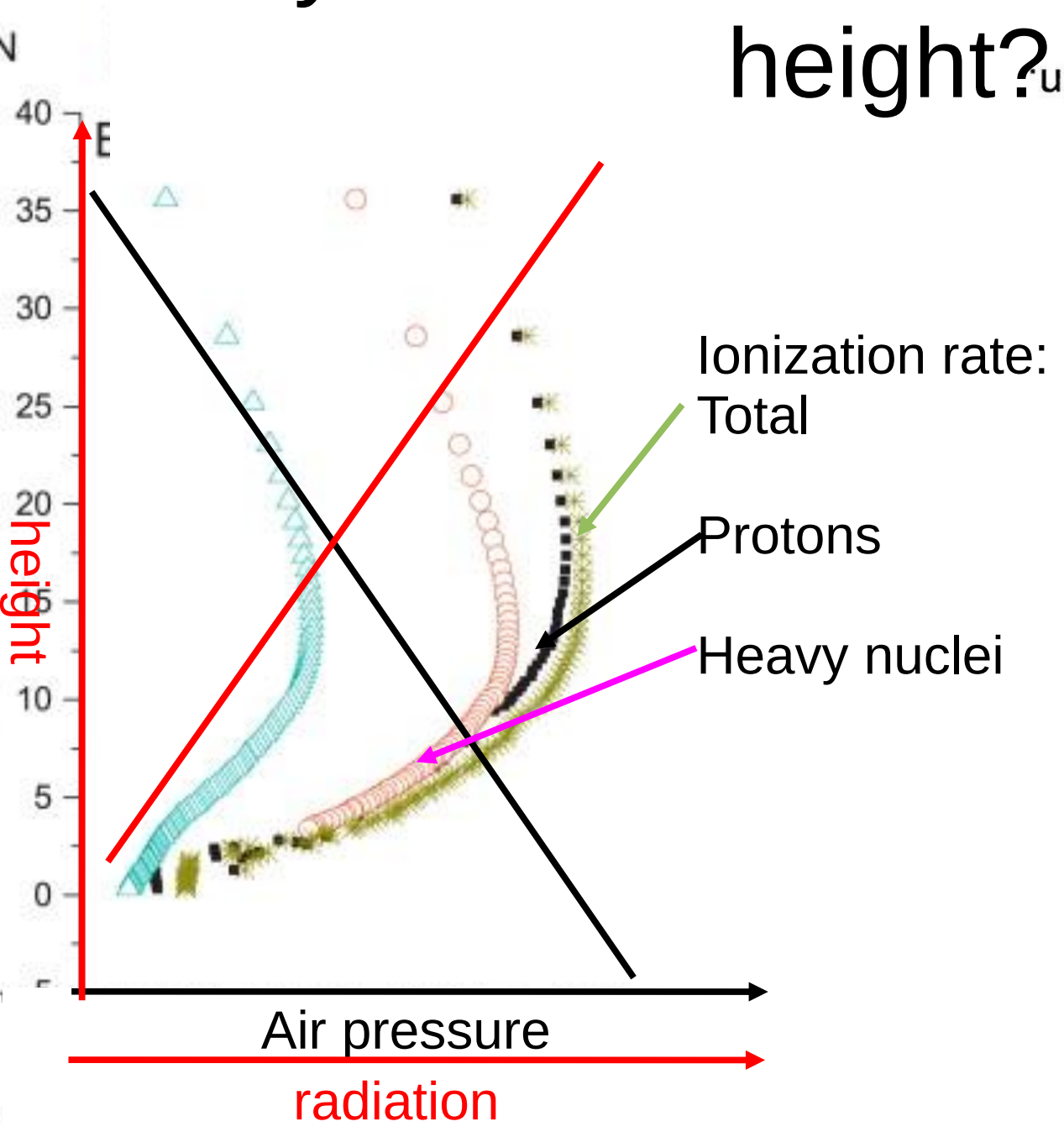
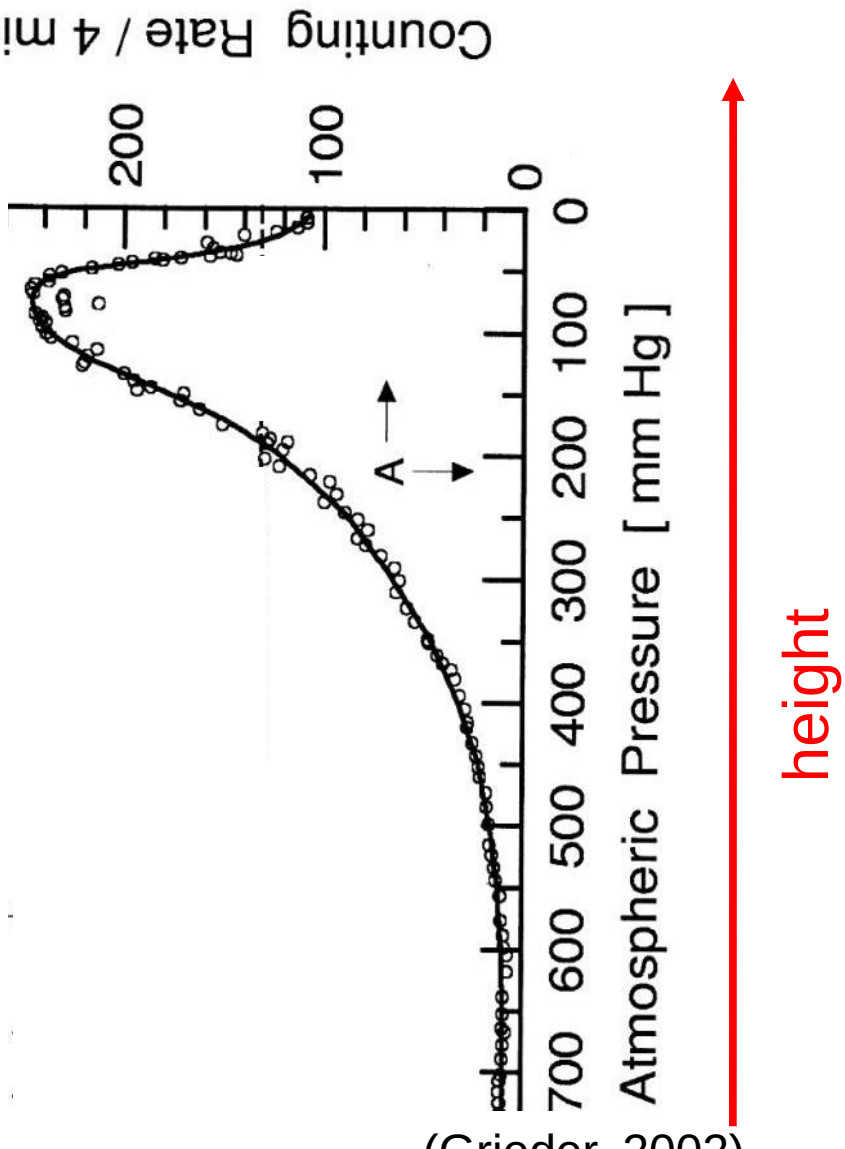




(Grieder, 2002)

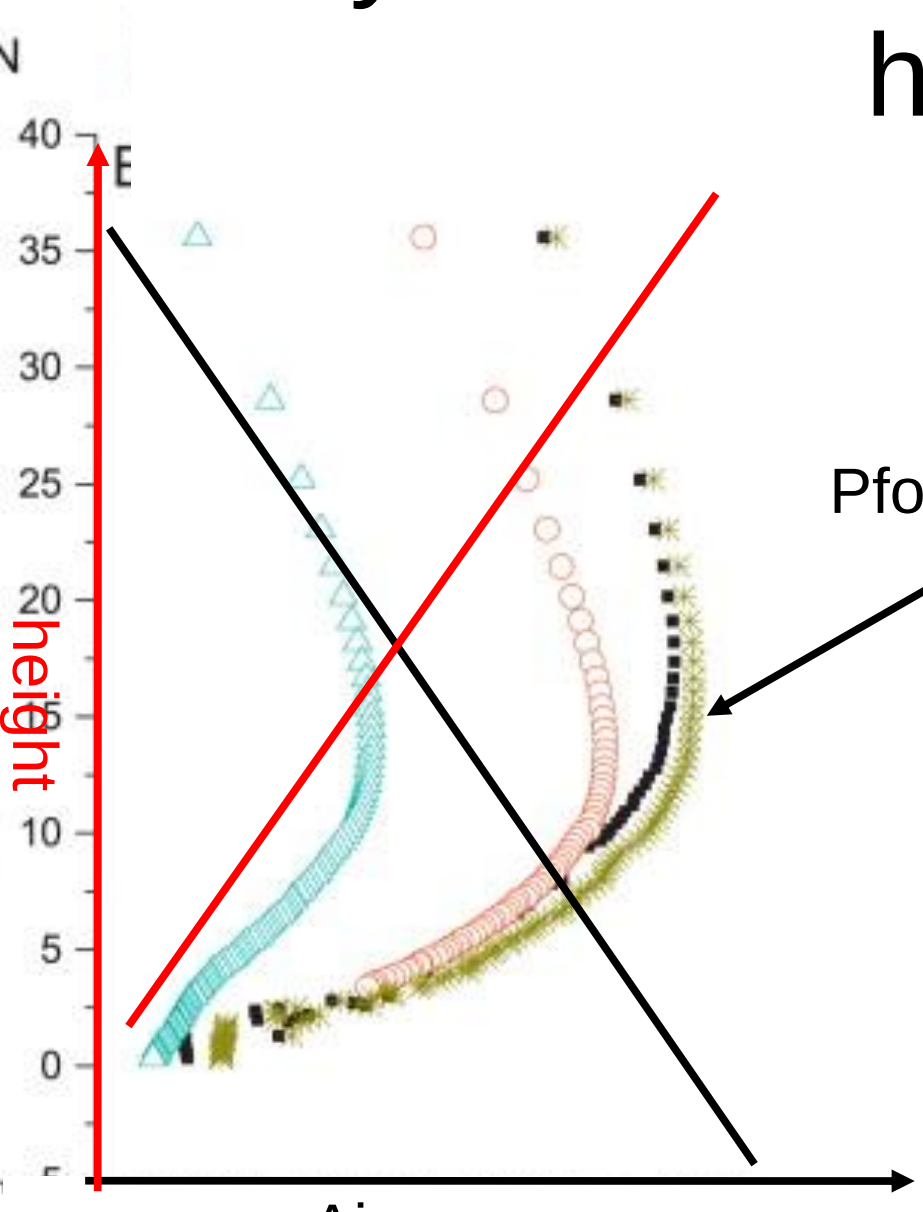
Why does ionization increase with height?





(Grieder, 2002)

Why does ionization increase with height?



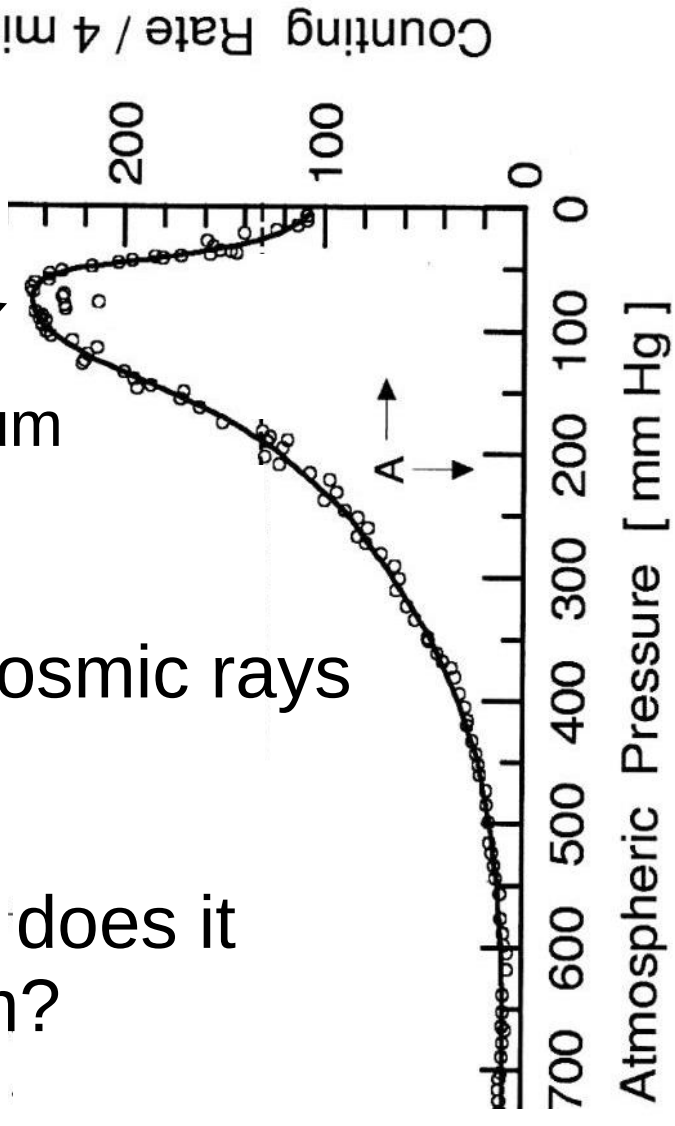
Air pressure

radiation

Pfotzer maximum

Millikan: cosmic rays

OK, …,
but where does it
come from?

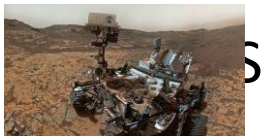


height

(Grieder, 2002)

Radiation exposure and altitude

224 Gm



SL/RAD 26 µSv/h × **260**

SL/RAD 77 µSv/h × **770**

420 km

DOSIS 3D 30 µSv/h × **300**

10 km

~ 4 µSv/h × **40**

3 km

~ 0.2 µSv/h × **2**

50 m

~ 0.1 µSv/h × **1**

[D. Hassler et al. 2014, Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover, Science], [Thomas Berger]