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

RIGHT UP THERE FOR 350 YEARS

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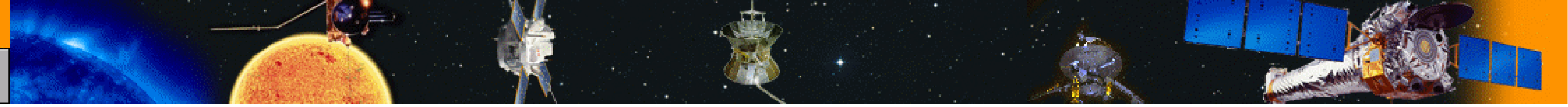
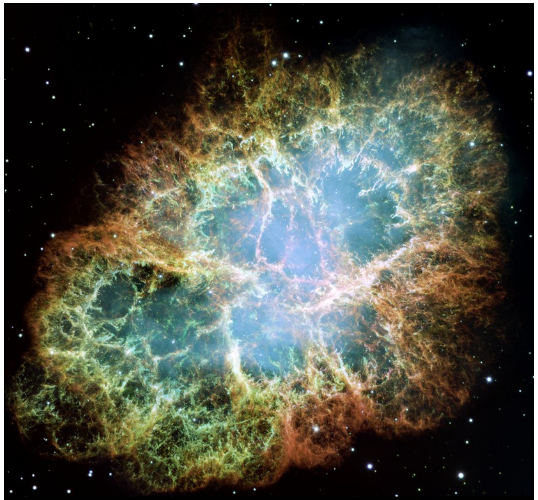
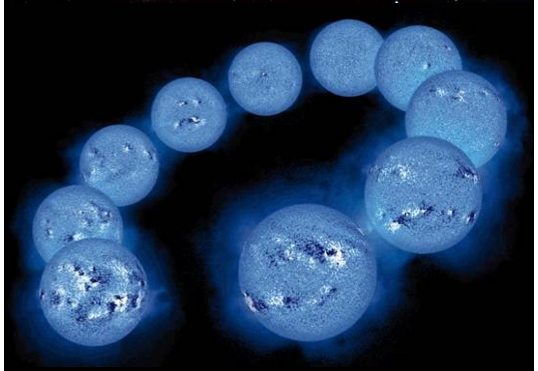
Structure of my Talk

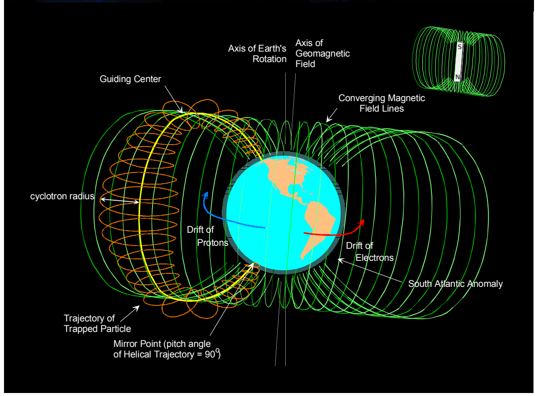
- Origin and transport of radiation in the heliosphere
- Particle radiation at Earth: ISS (and Mir)
- Particle radiation at and on the Moon
- Particle radiation during the cruise to Mars: MSL
- Particle radiation on the surface of Mars: MSL
- Implications for human exploration



Space Radiation Sources Close to Earth







Galactic Cosmic Rays:

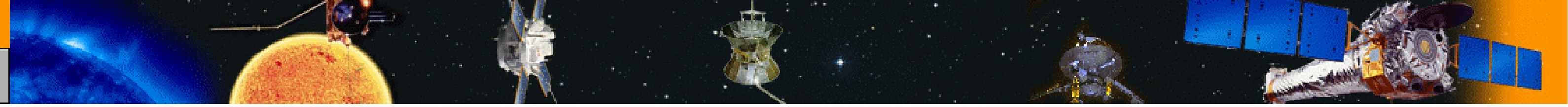
Very high energies, H through U
Solar modulation, predictable
Highly penetrating

Solar Energetic Particles:

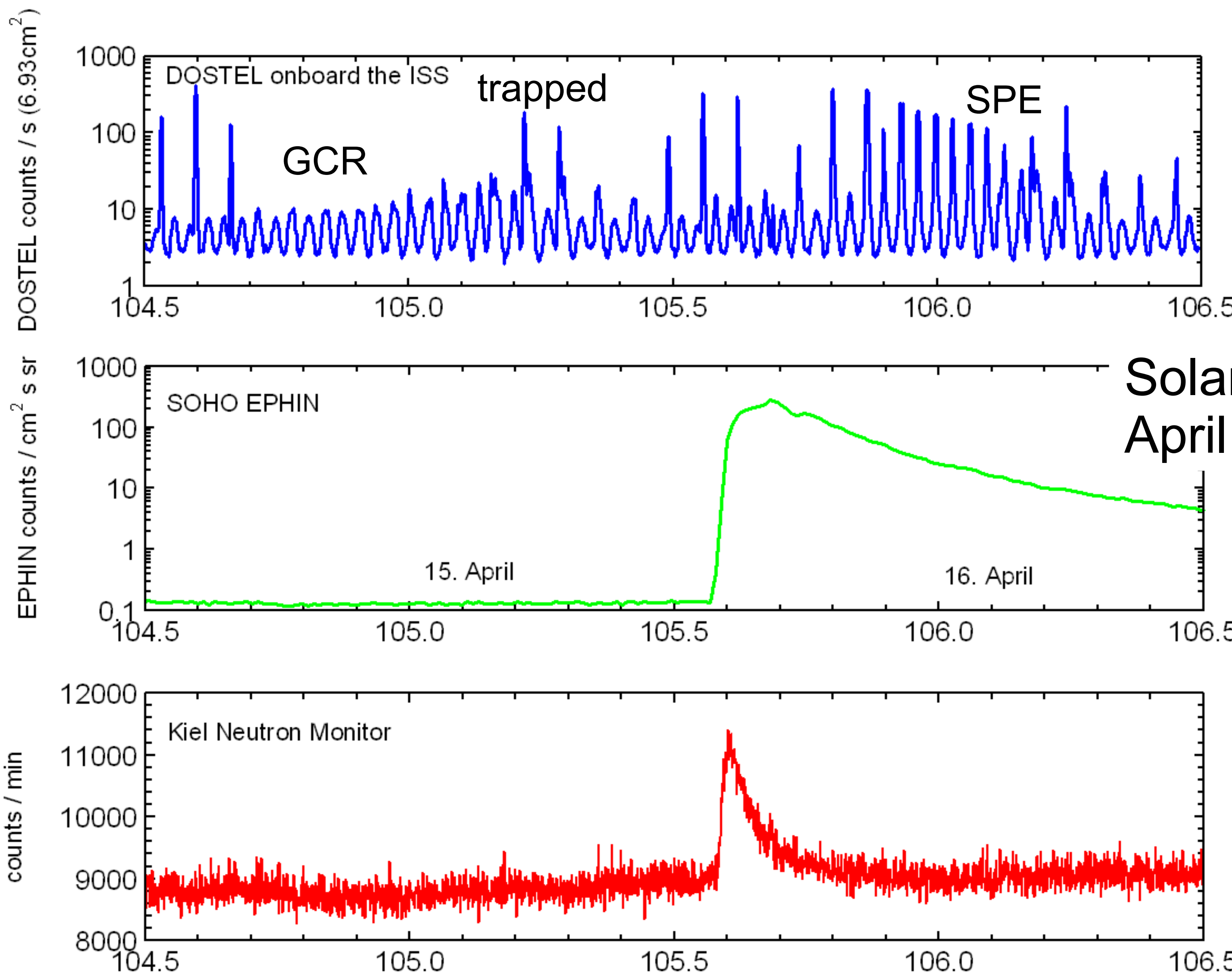
High energies
Solar activity, unpredictble
High dose rate variability (up to ~1000)
Can be shielded

Trapped Radiation (Radiation Belts):

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



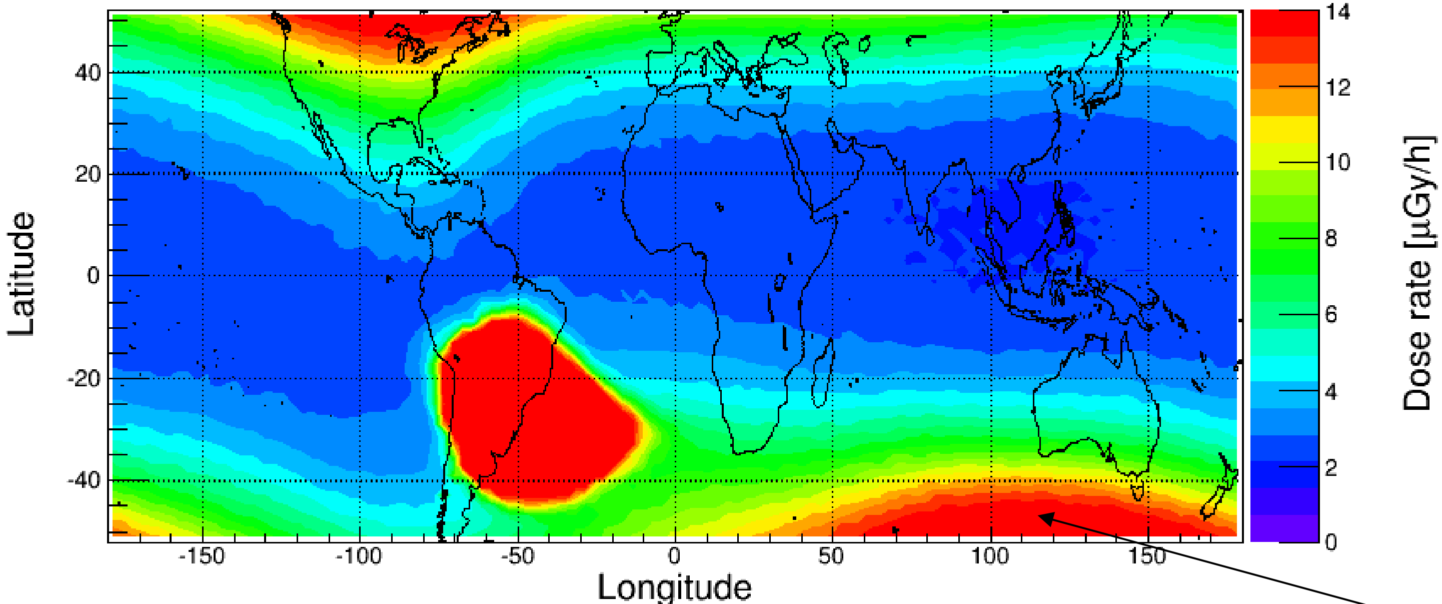
Radiation Sources Close to Earth: Solar



Solar Particle Event:
April 2001

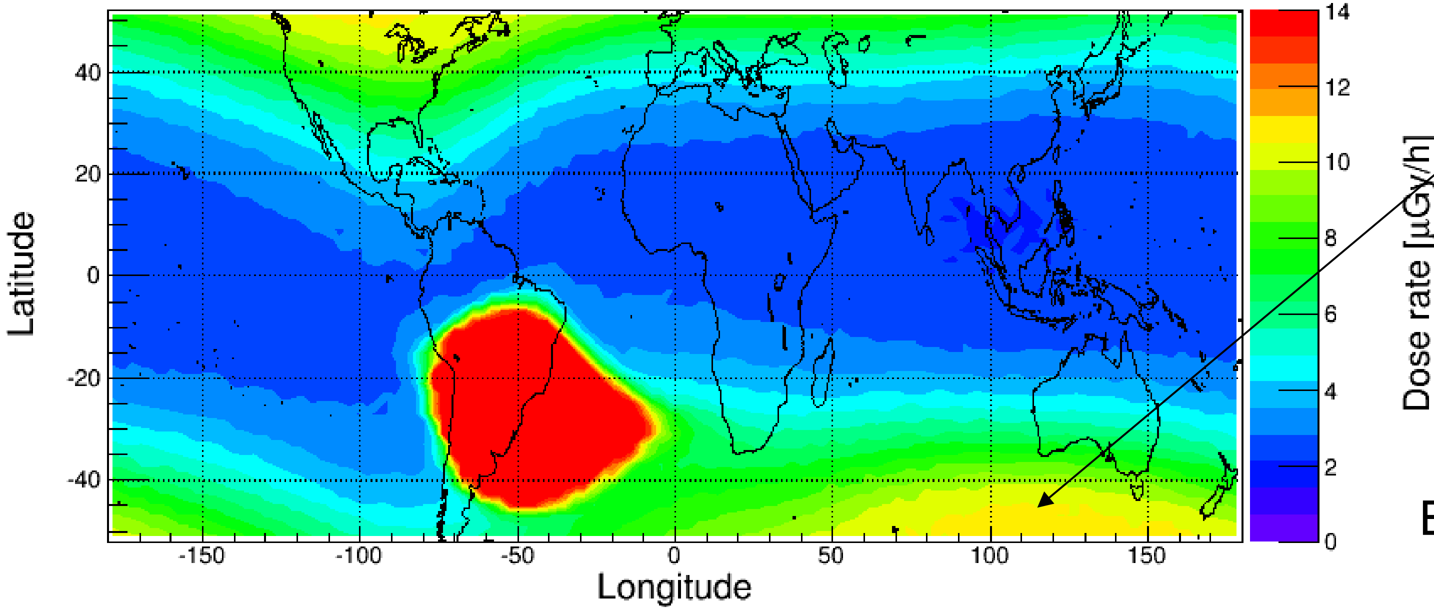
Courtesy: S. Burmeister

Radiation Sources Close to Earth: GCR



2009
closer to
solar min

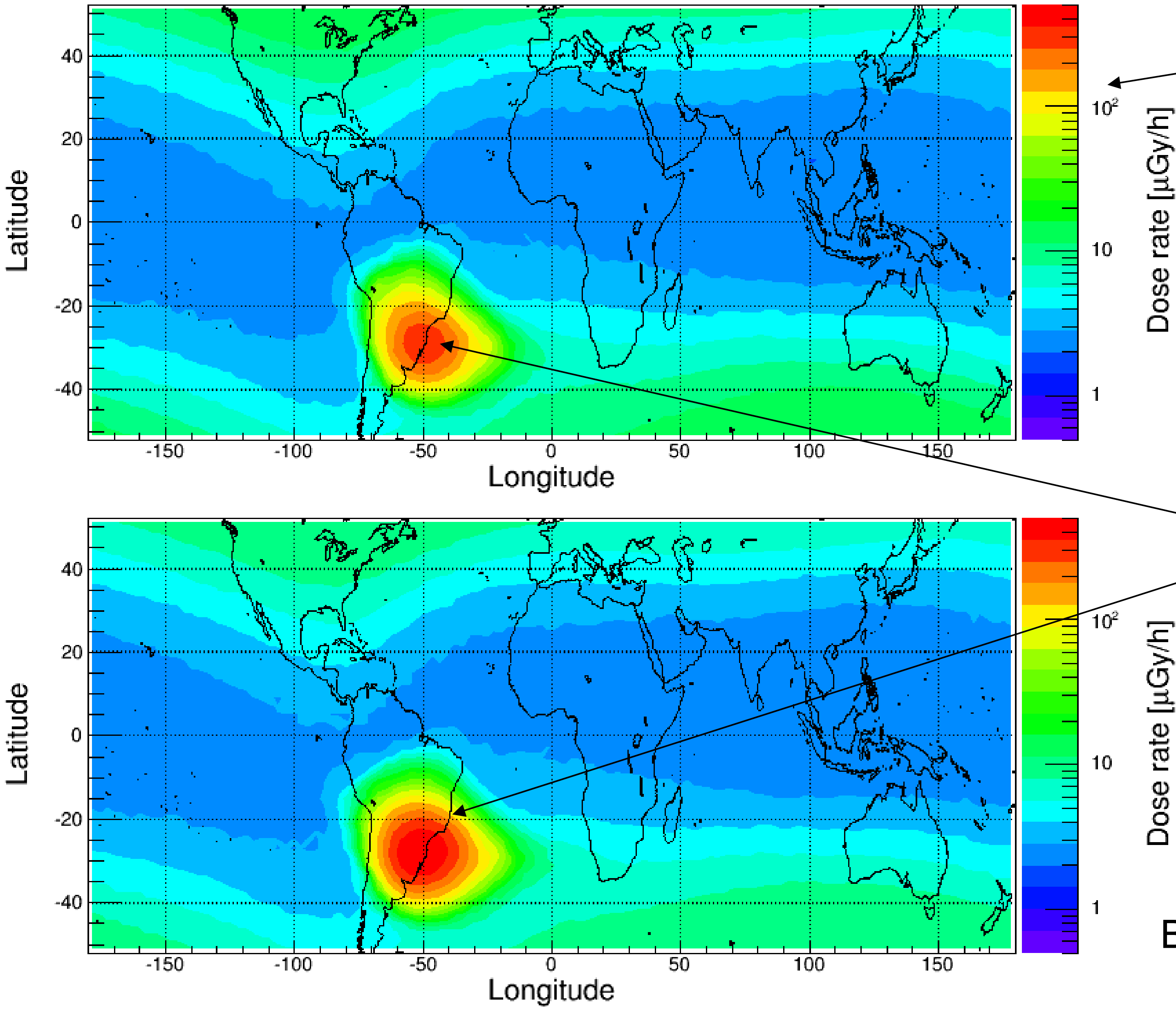
GCR



2013
closer to
solar max

Burmeister et al., 2016

Radiation Sources Close to Earth: Trapped



Log scale!

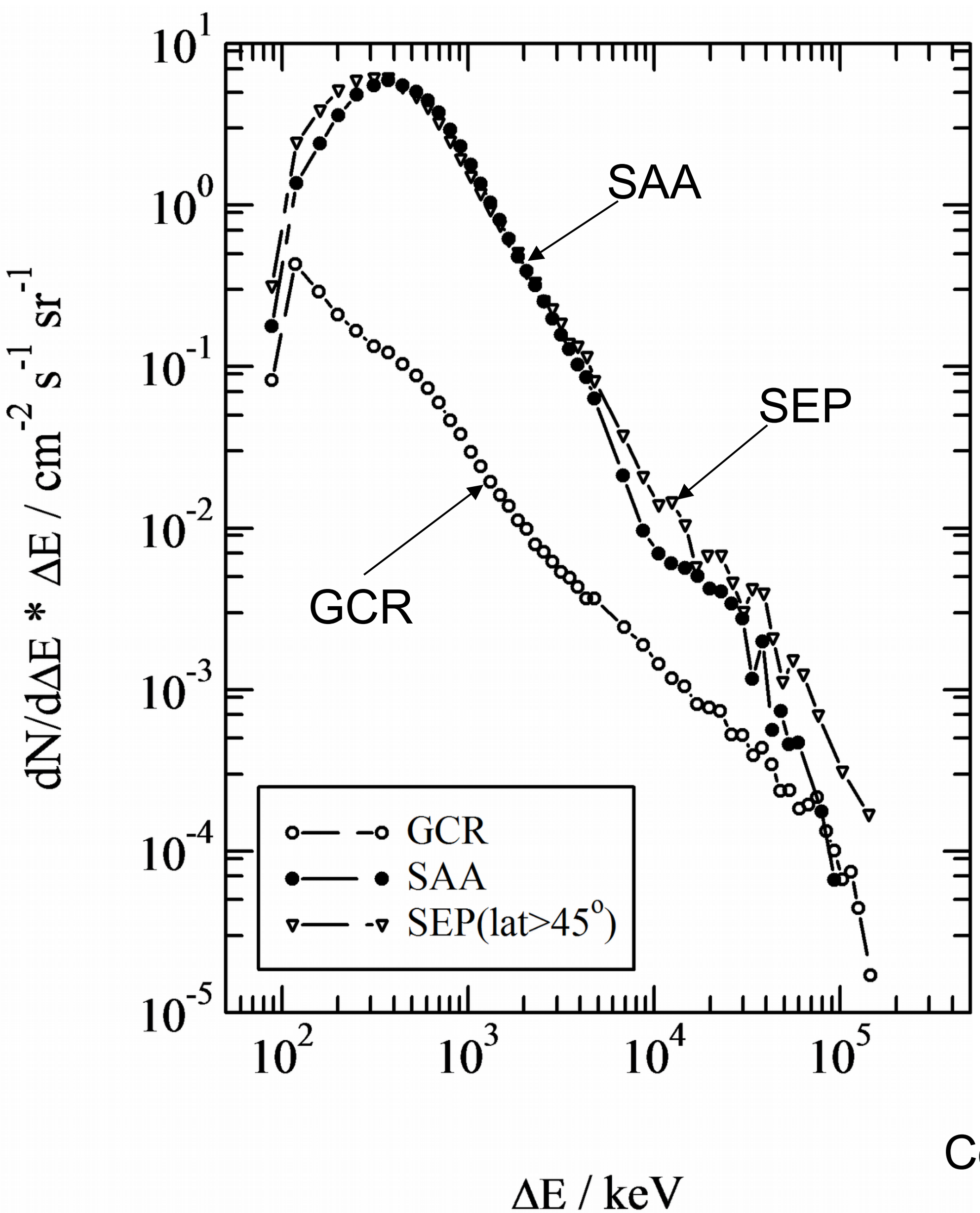
2009
@ 350 km

SAA
(trapped)

2013
@ 420 km

Burmeister et al., 2016

Radiation Sources Close to Earth: Comparison



Nov 1997 SPE:

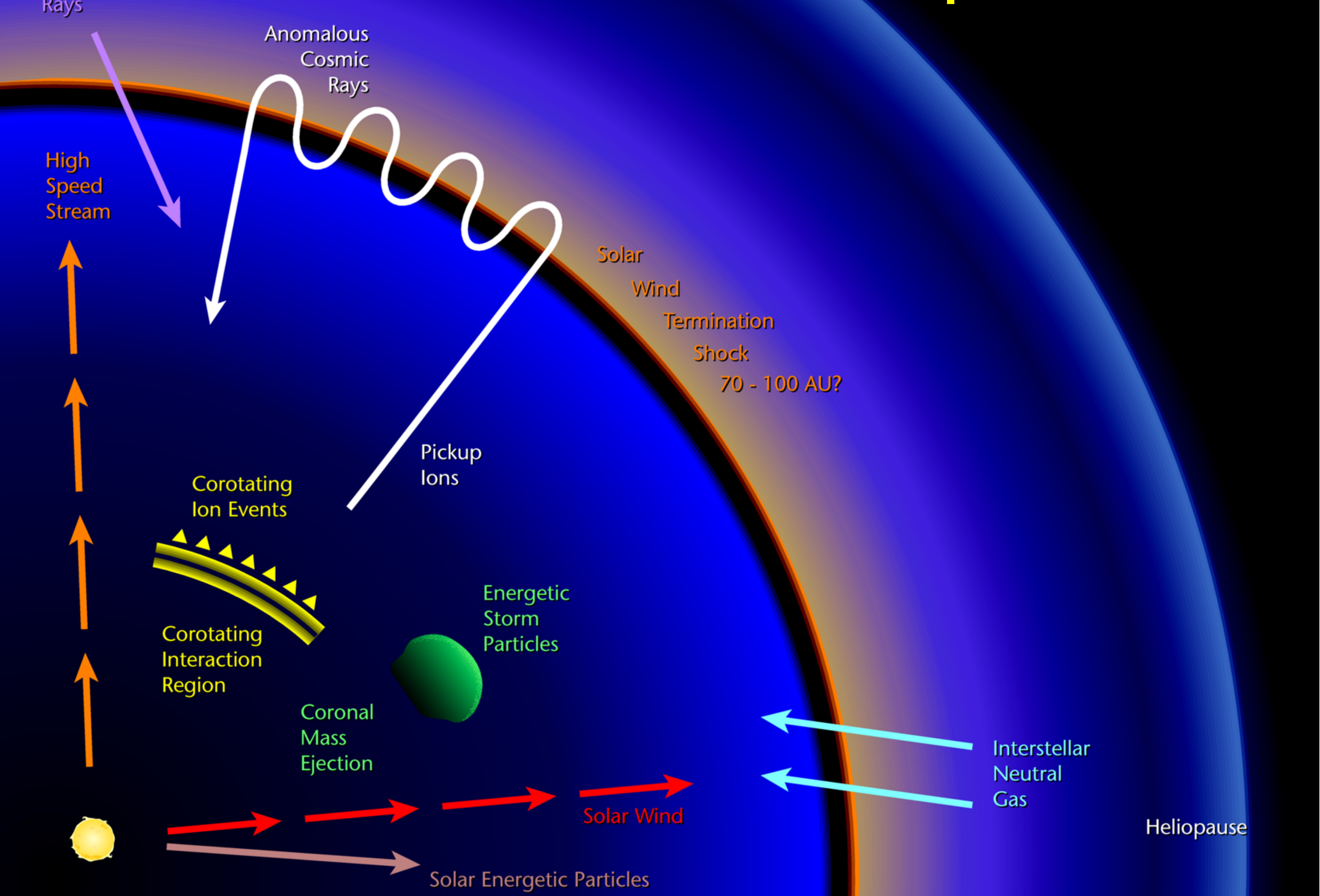
Measurements in Mir

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

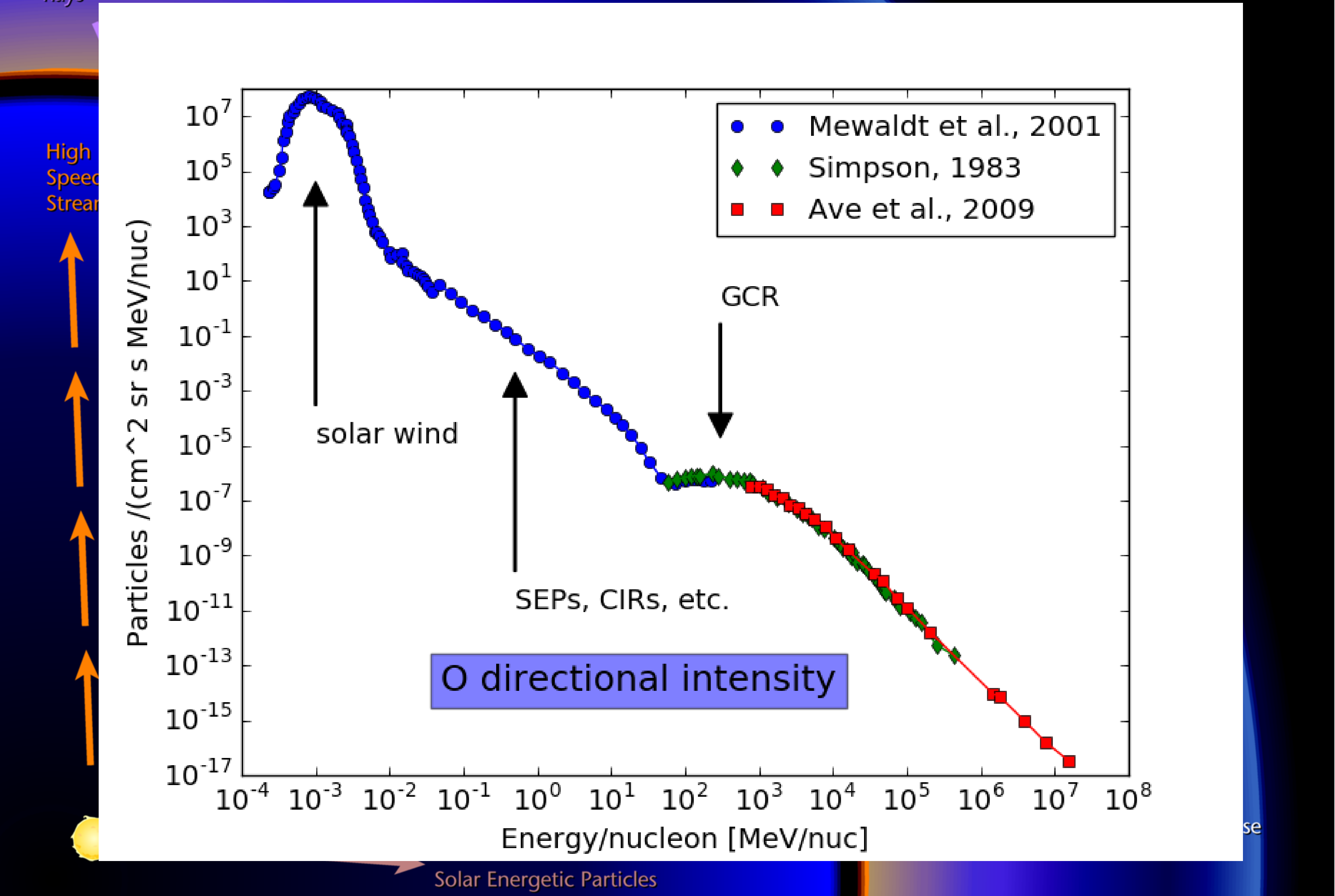
Measured spectrum of energy deposit in a 315 micron Si solid-state detector.

Courtesy: S. Burmeister

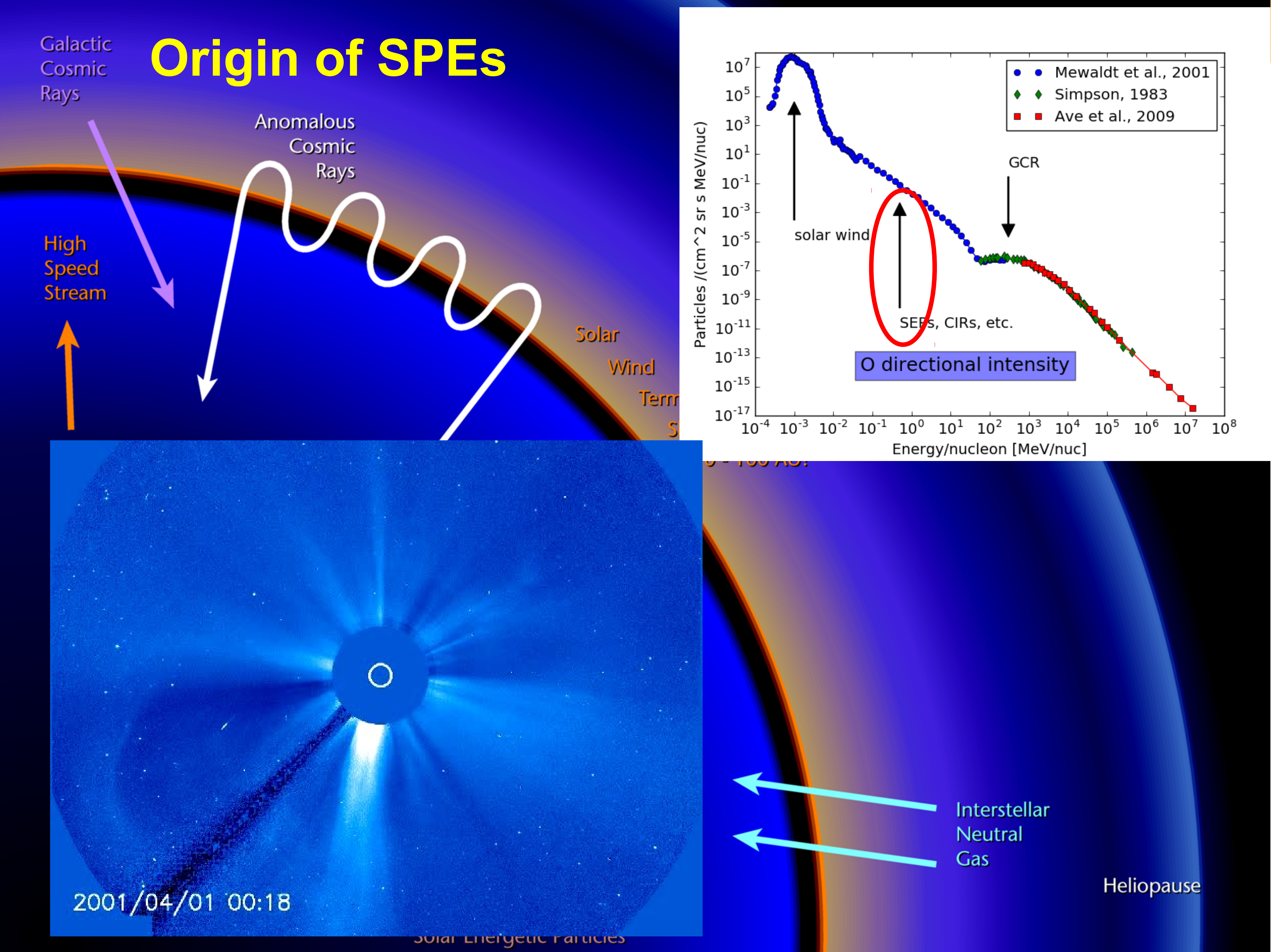
Particle Radiation in the Heliosphere



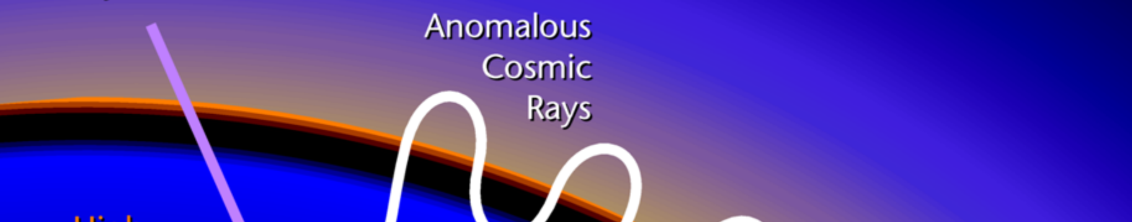
Particle Radiation in the Heliosphere

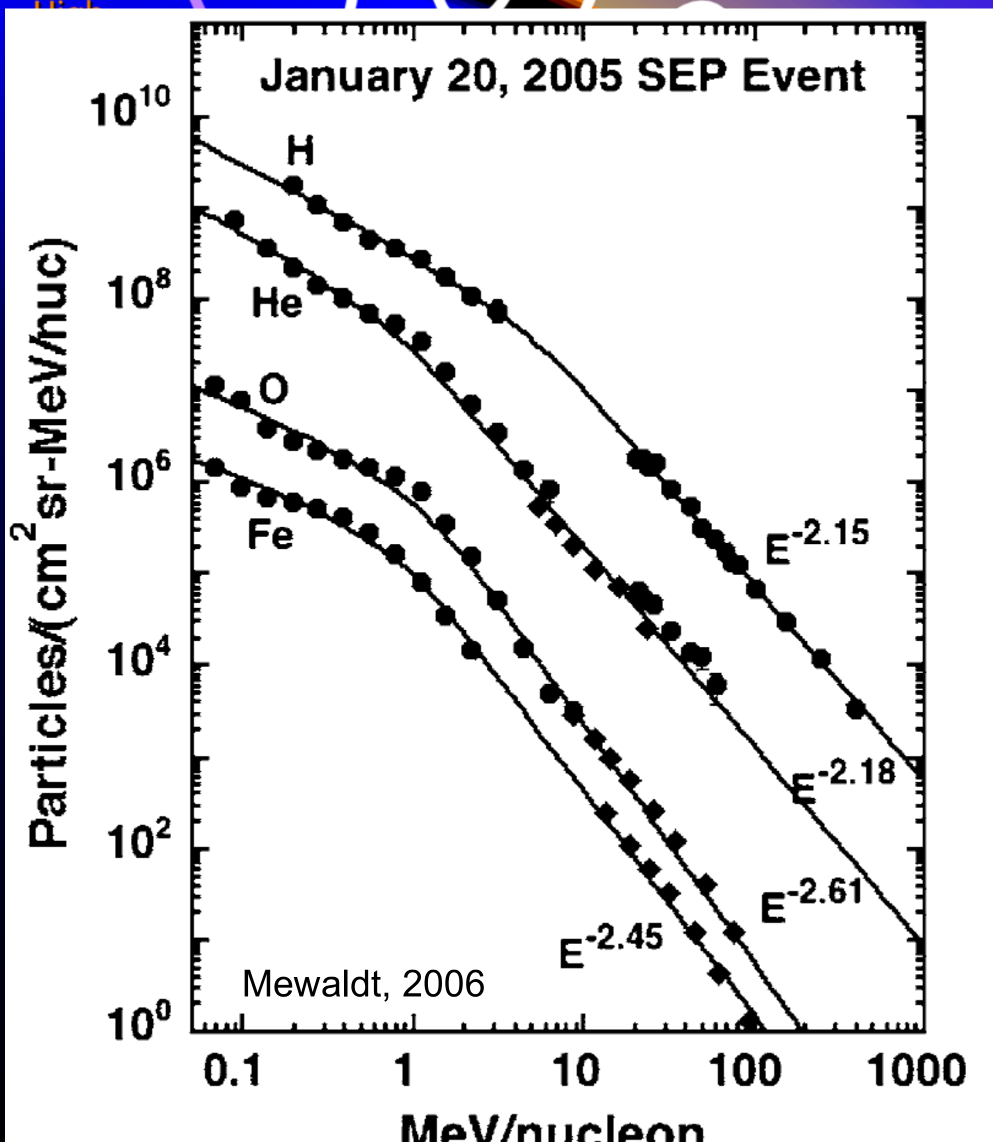


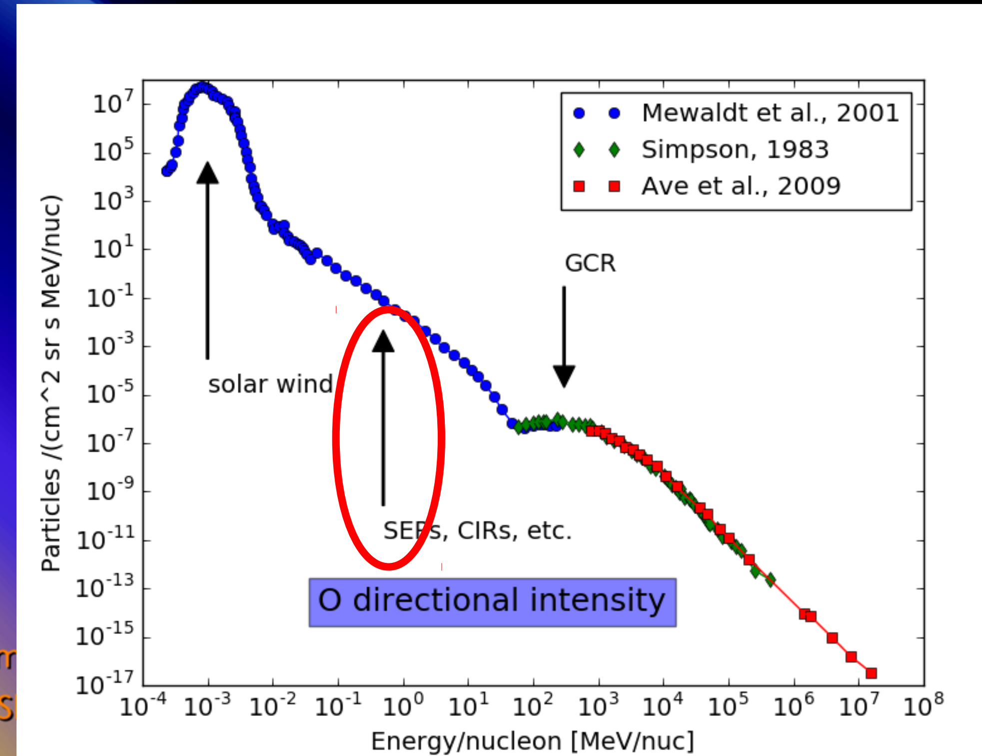
Origin of SPEs

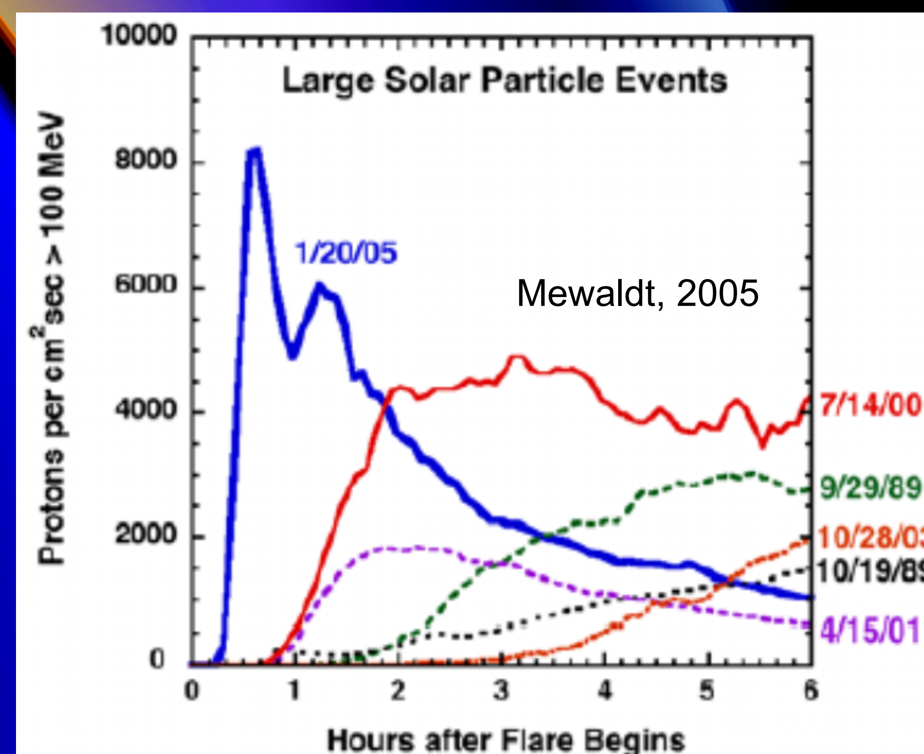


Origin of SPEs





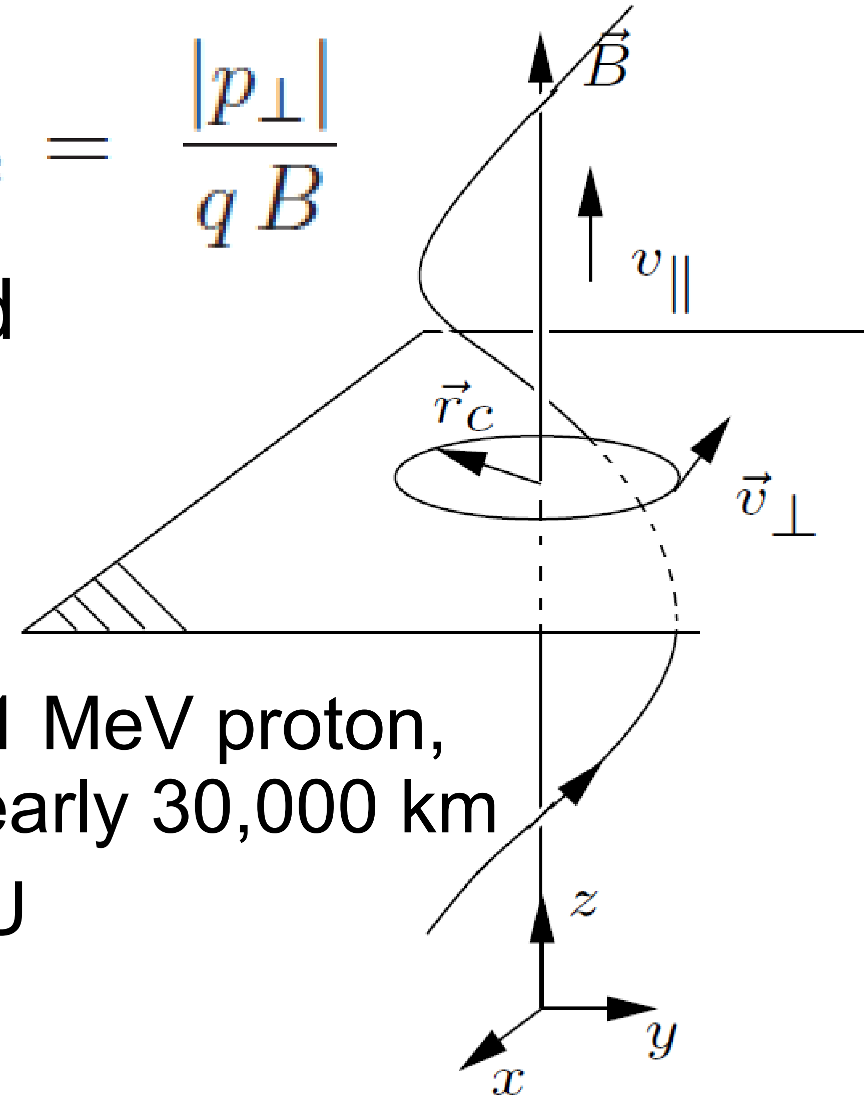




Radiation Transport in the Heliosphere

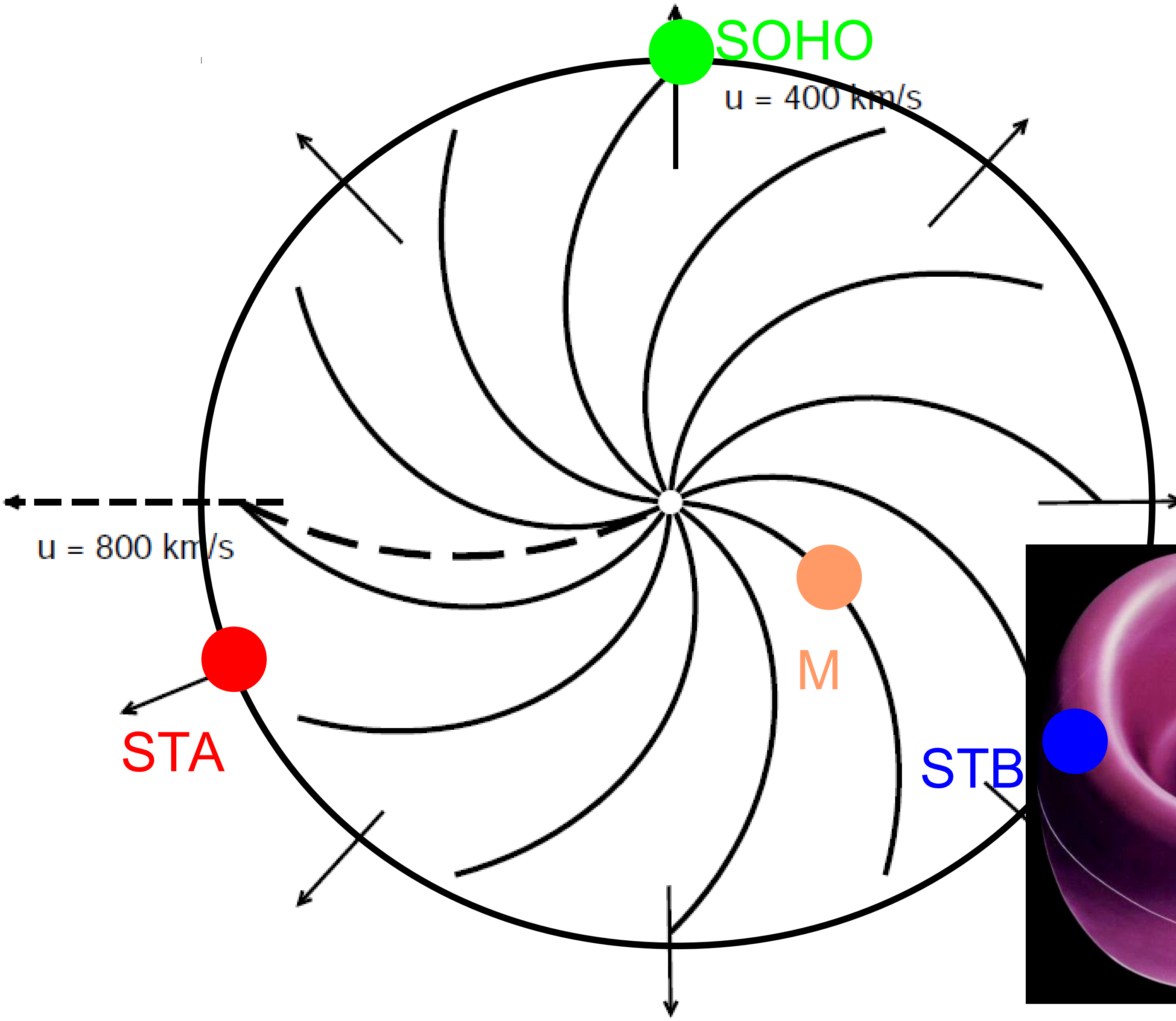
- Electrically charged ions and electrons
- Interplanetary magnetic field controls propagation
- Solar magnetic field matters

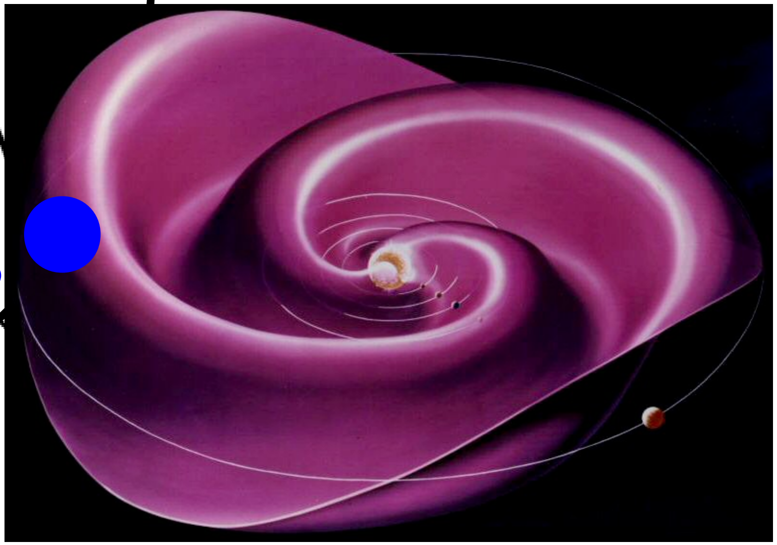
$$r_c = \frac{|p_\perp|}{q\,B}$$



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

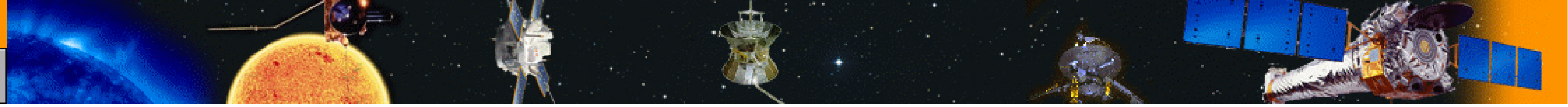
Large-scale interplanetary magnetic field organized along Parker spiral



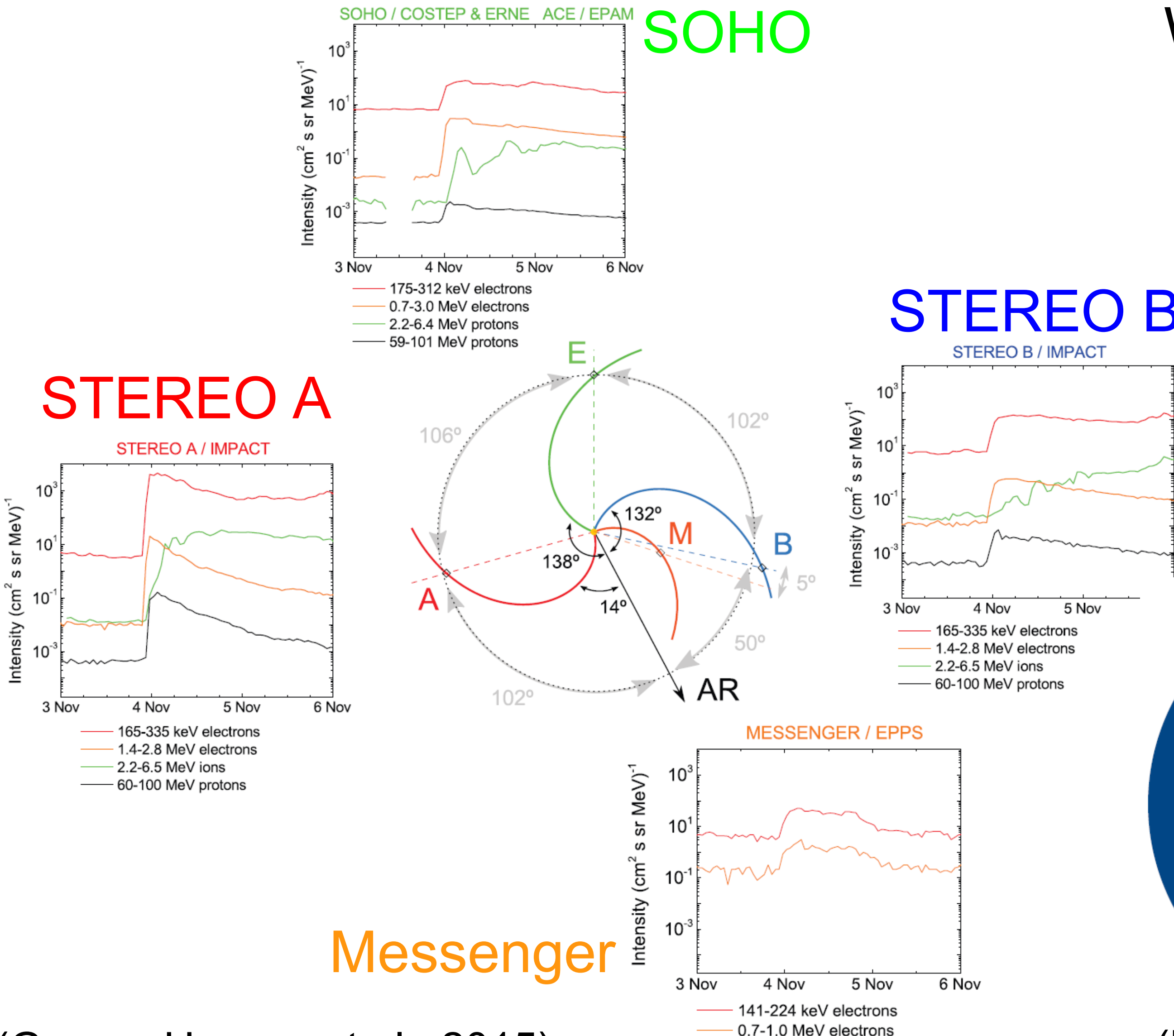


Charged energetic particles are tied to magnetic field...

SOHO, STEREO, Messenger widely separated in Nov‘ 11



How does the Sun connect to the heliosphere?



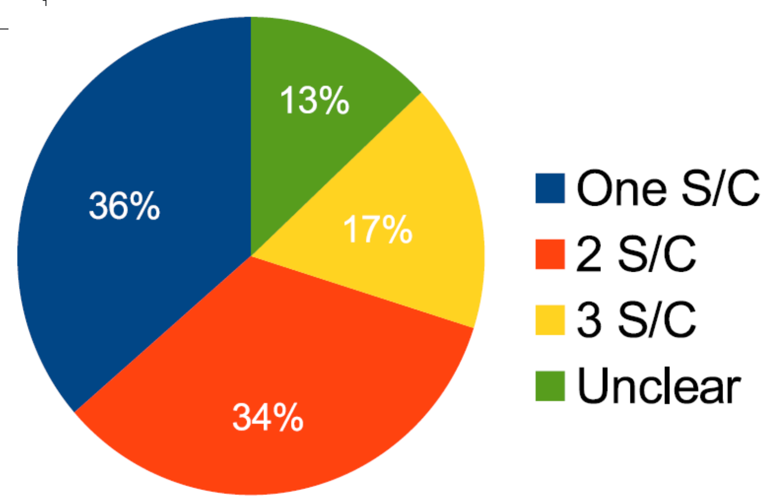
(Gomez-Herrero et al., 2015)

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

This is sobering...

(can we connect S-H?)

… but also at 1 AU!



(Richardson et al., 2014)

We need to better understand the connection!

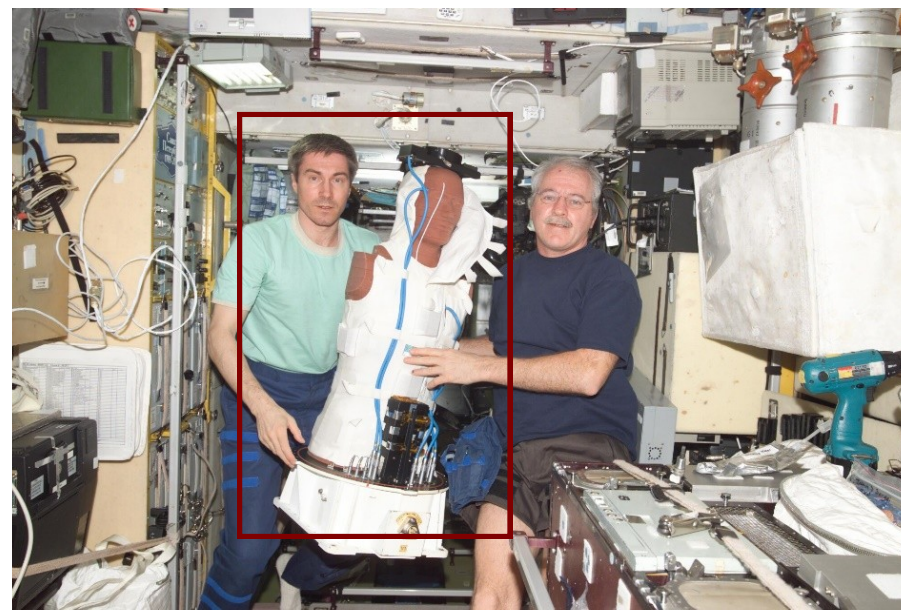
Radiation Protection in Space: ISS

ISS027E011851

Personal Dosimeters

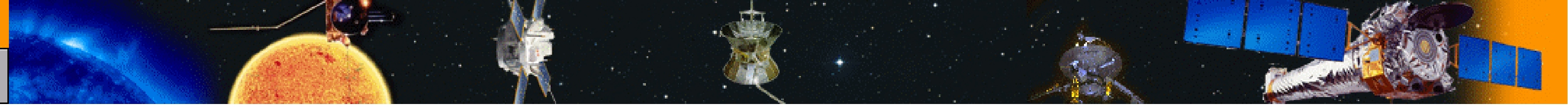
Radiation is *the* long-lasting risk for astronauts. Radiation damage can persist after the end of a long-duration space flight.

Radiation must be measured!

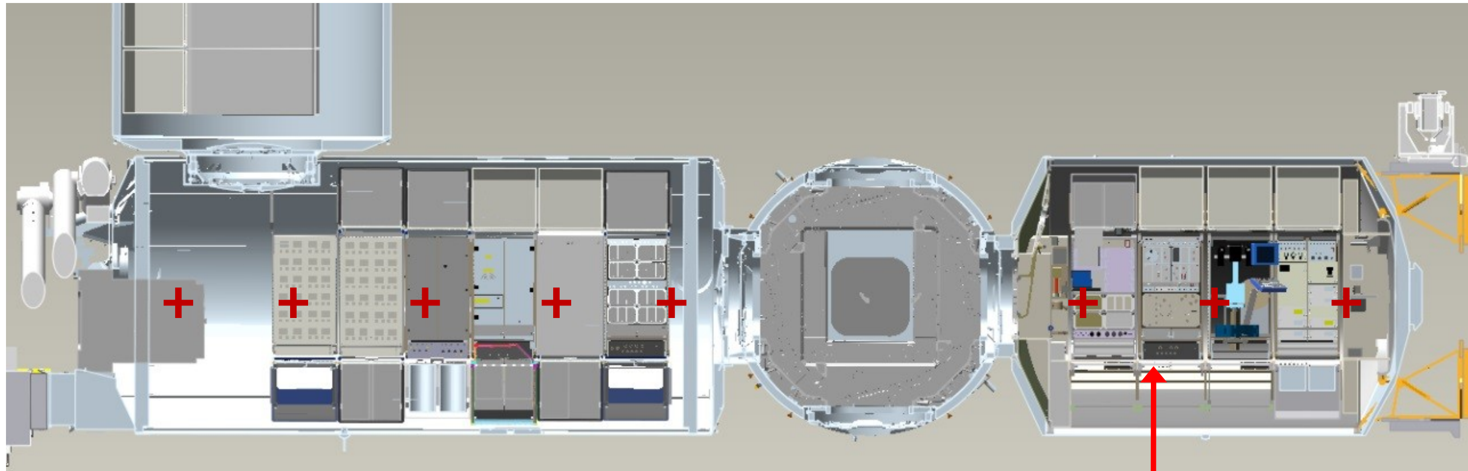


Phantom experiments
MATROSHKA

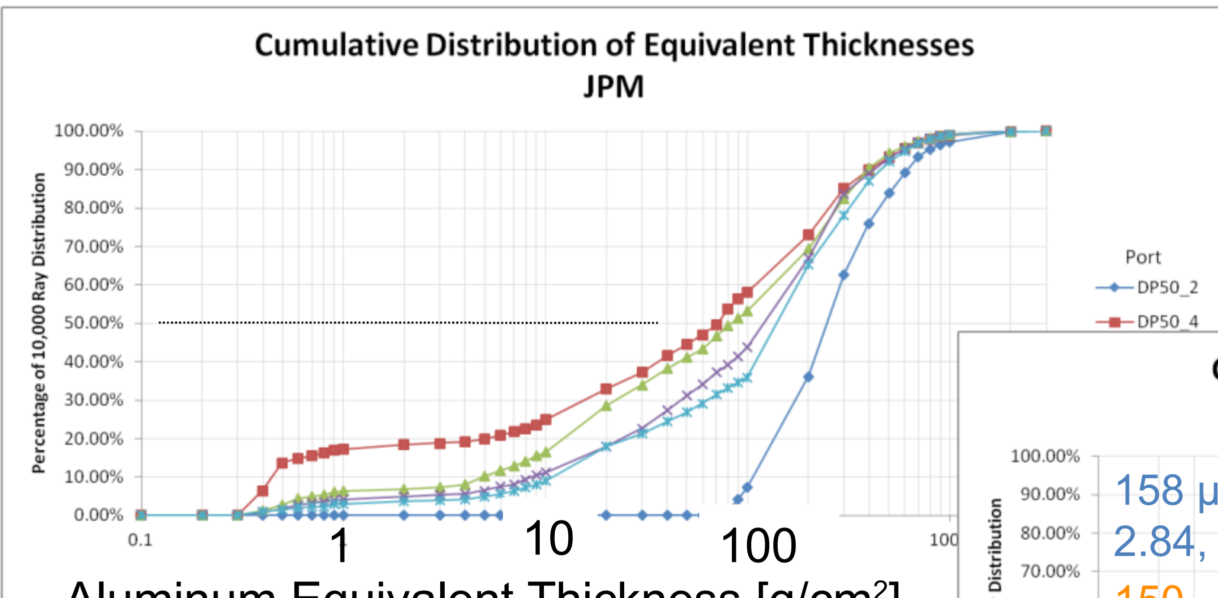
(Photos courtesy G. Reitz)

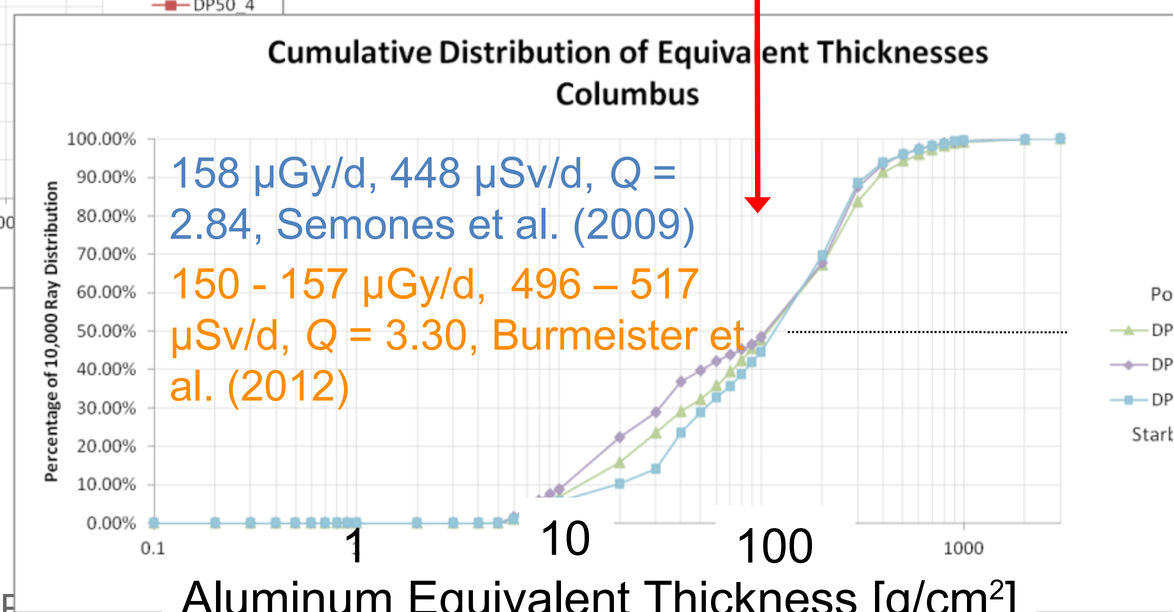


Radiation Protection in Space: ISS



COLUMBUS module
median shielding ≈100 g/cm2



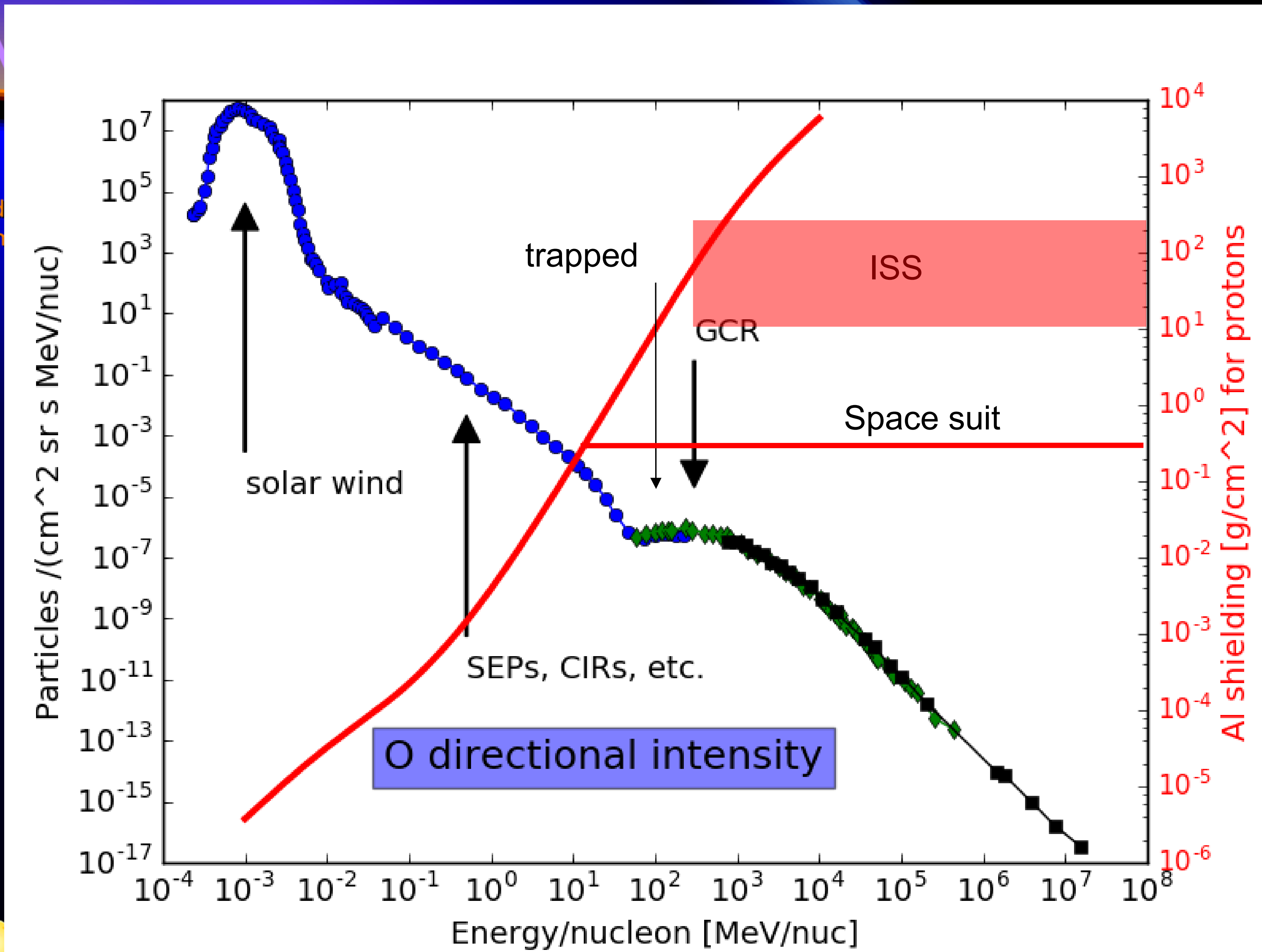


(courtesy Daniel Matthiä)

Radiation in Space

Galactic Cosmic Rays

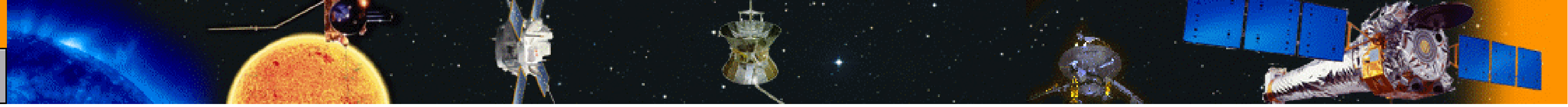
High Speed Stream



Solar Energetic Particles

Origin of Galactic Cosmic Rays: Supernovae

How are nuclei simultaneously created and accelerated?

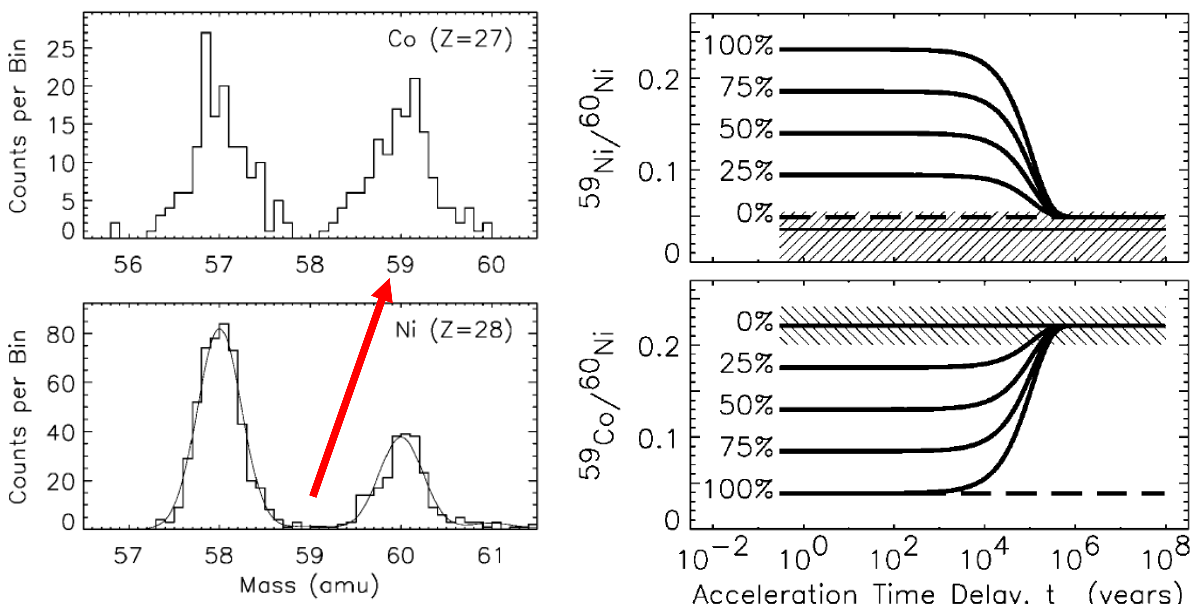


Origin of Galactic Cosmic Rays: OB-Associations

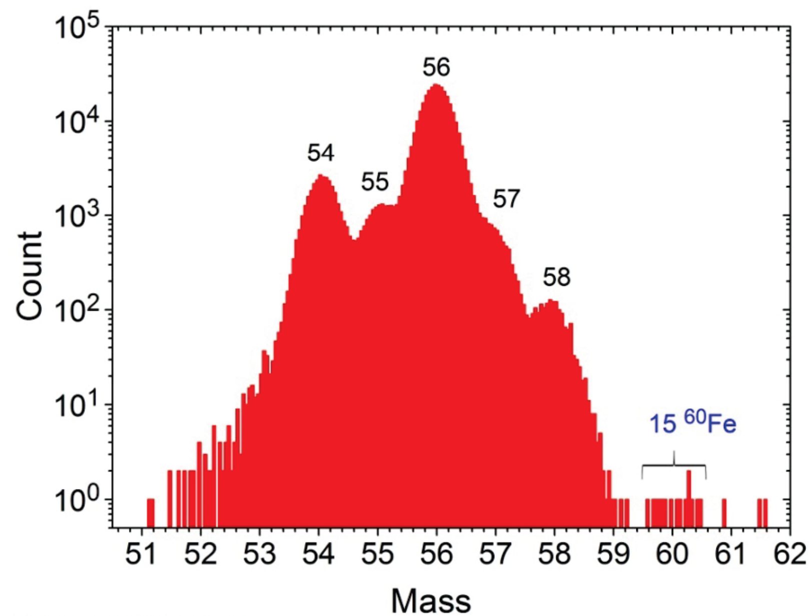
^{59}Ni decays into ^{59}Co via electron capture $T_{1/2}$ = 76,000 years

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

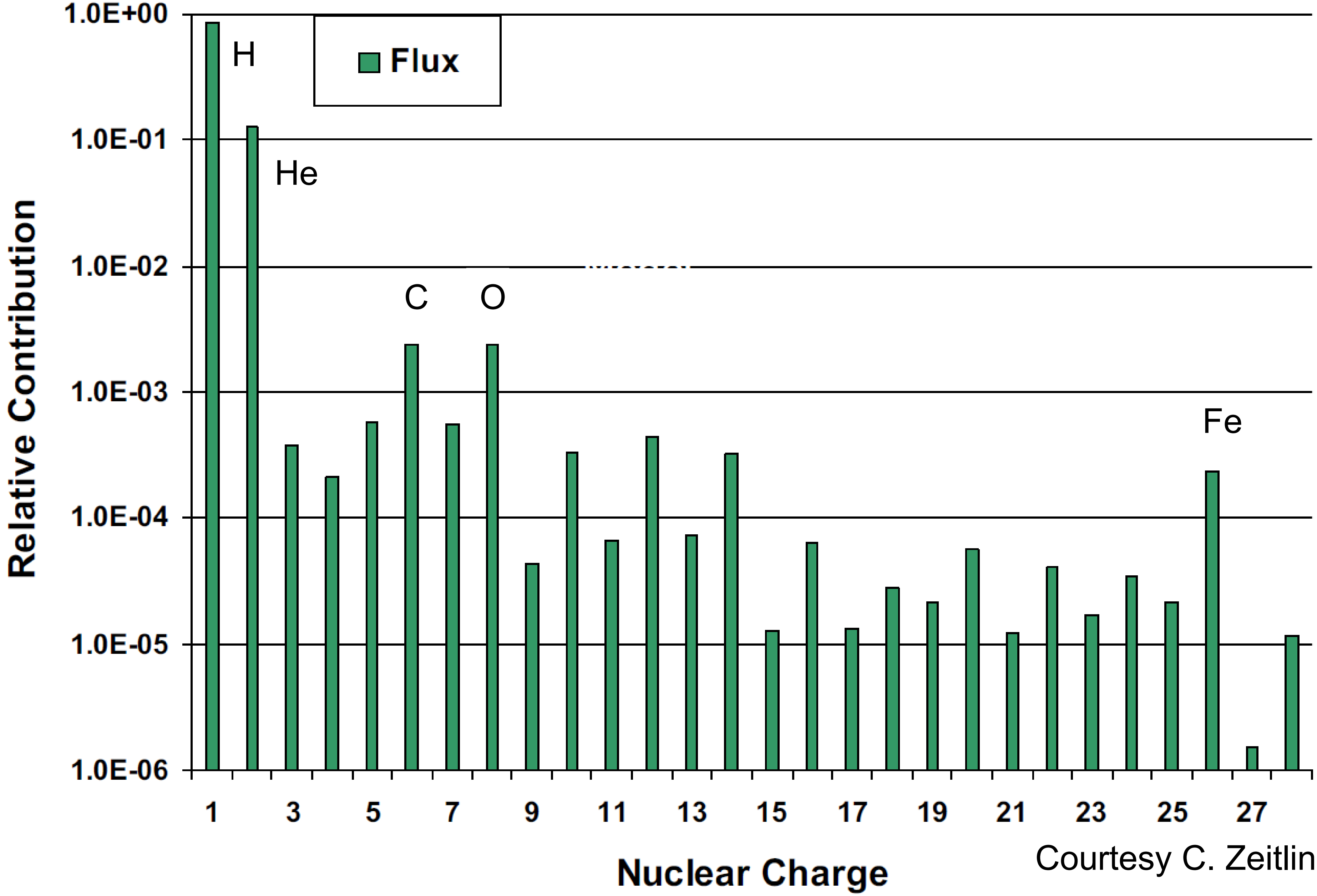


Israel et al., 2015

One supernova creates GCR nuclei, a second one accelerates them

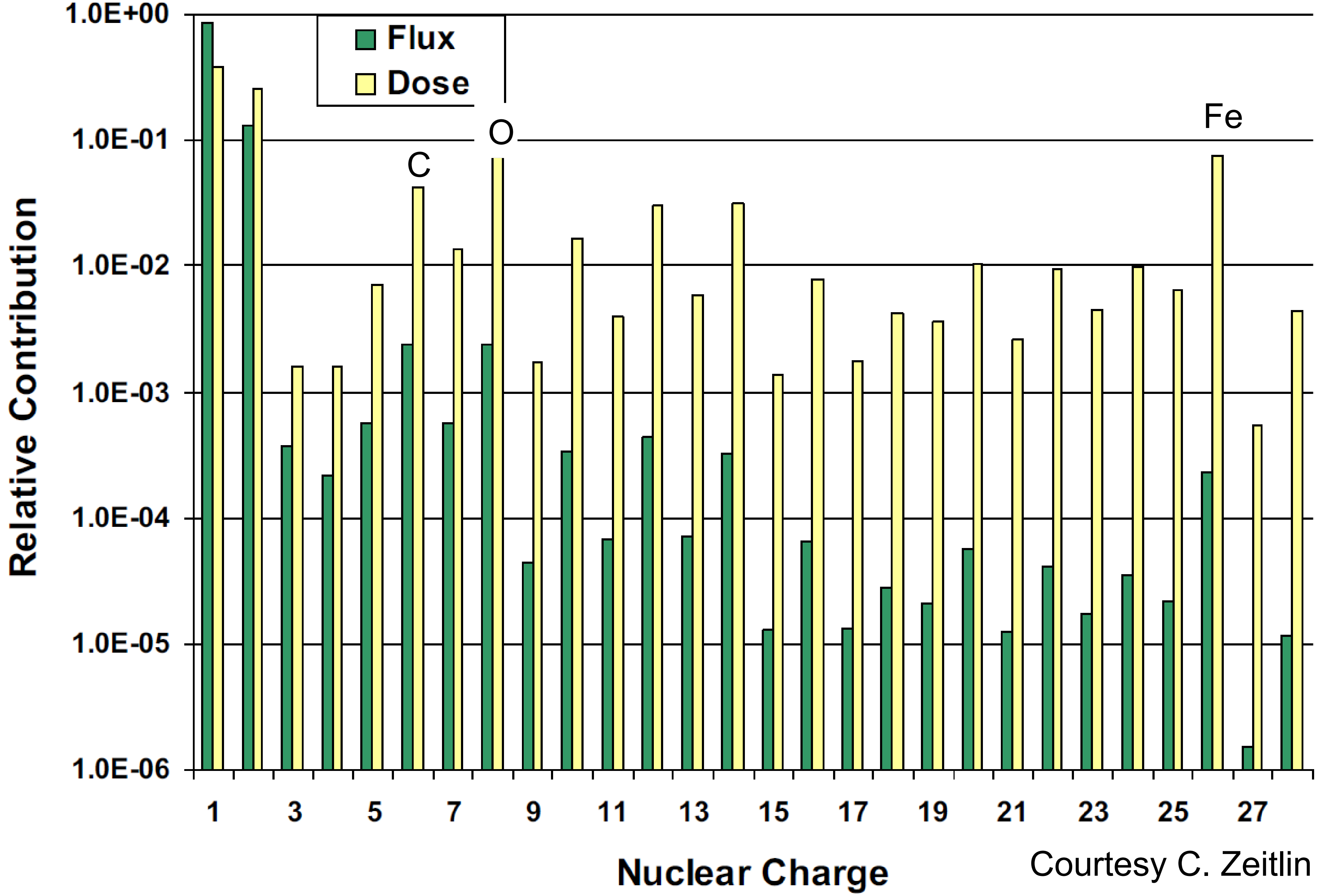
==> OB Associations

Composition of Galactic Cosmic Rays



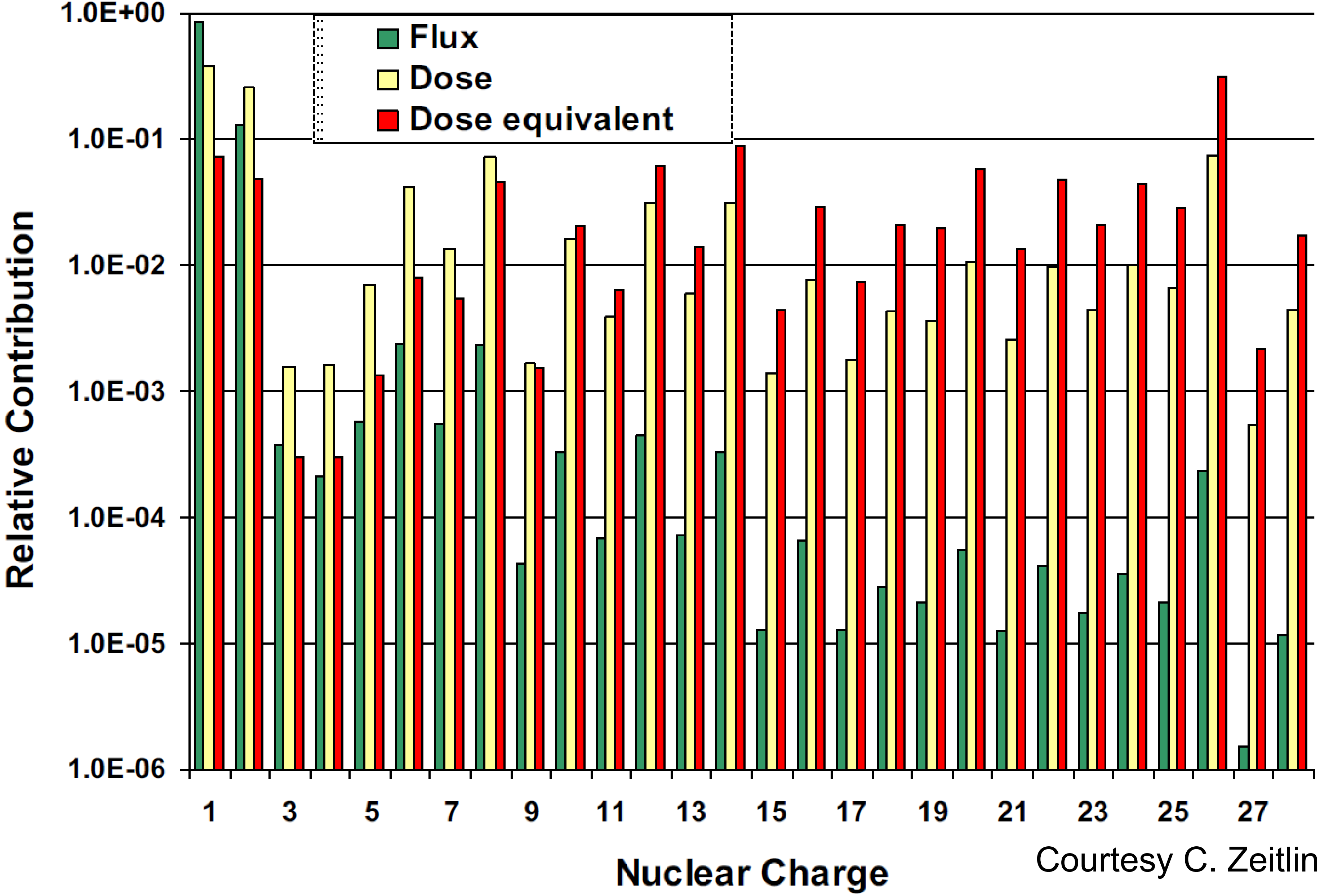
Courtesy C. Zeitlin

Composition of Galactic Cosmic Rays & Dose



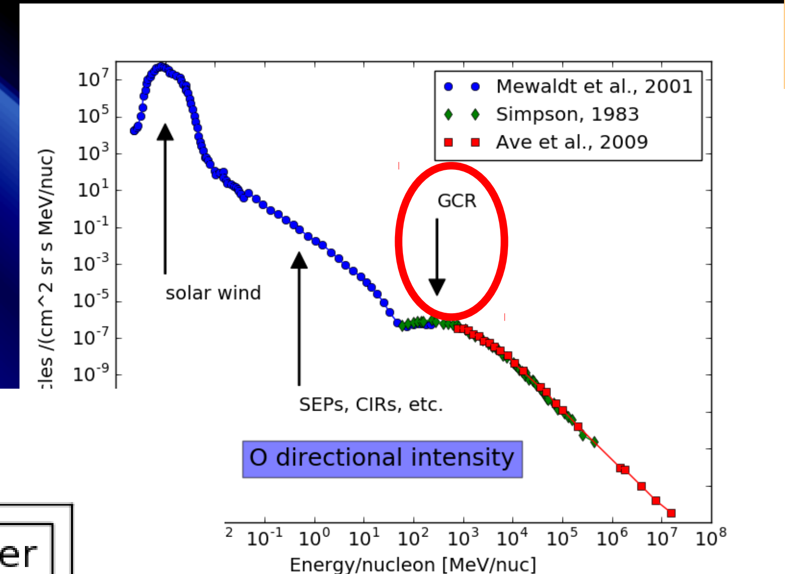
Courtesy C. Zeitlin

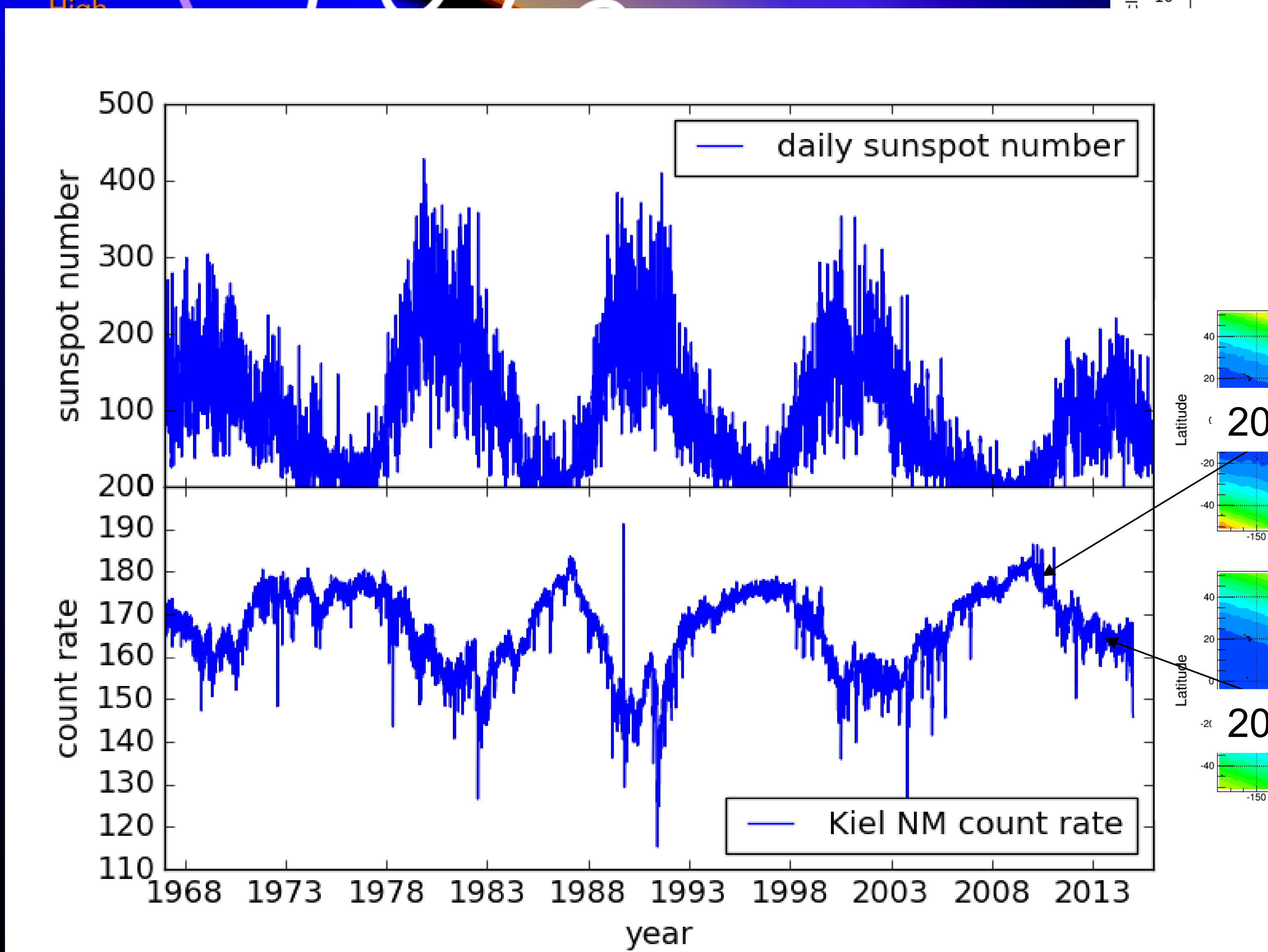
Composition of Galactic Cosmic Rays & Dose

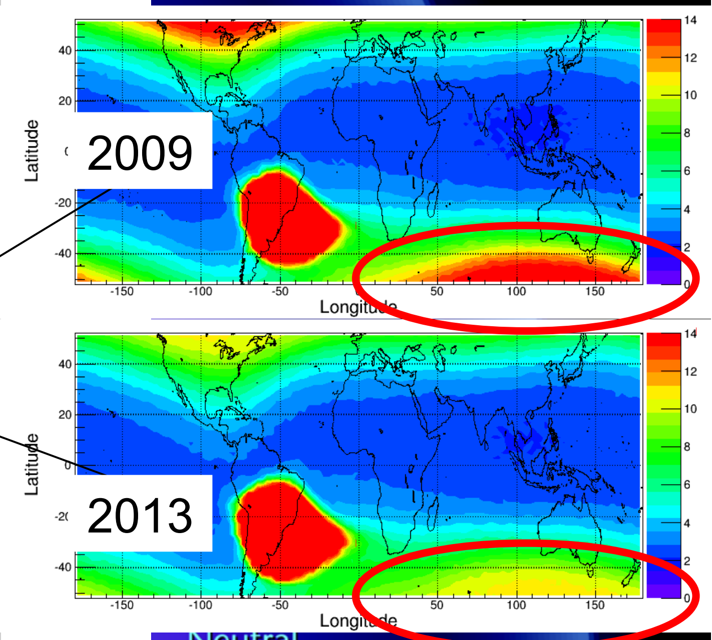


Courtesy C. Zeitlin

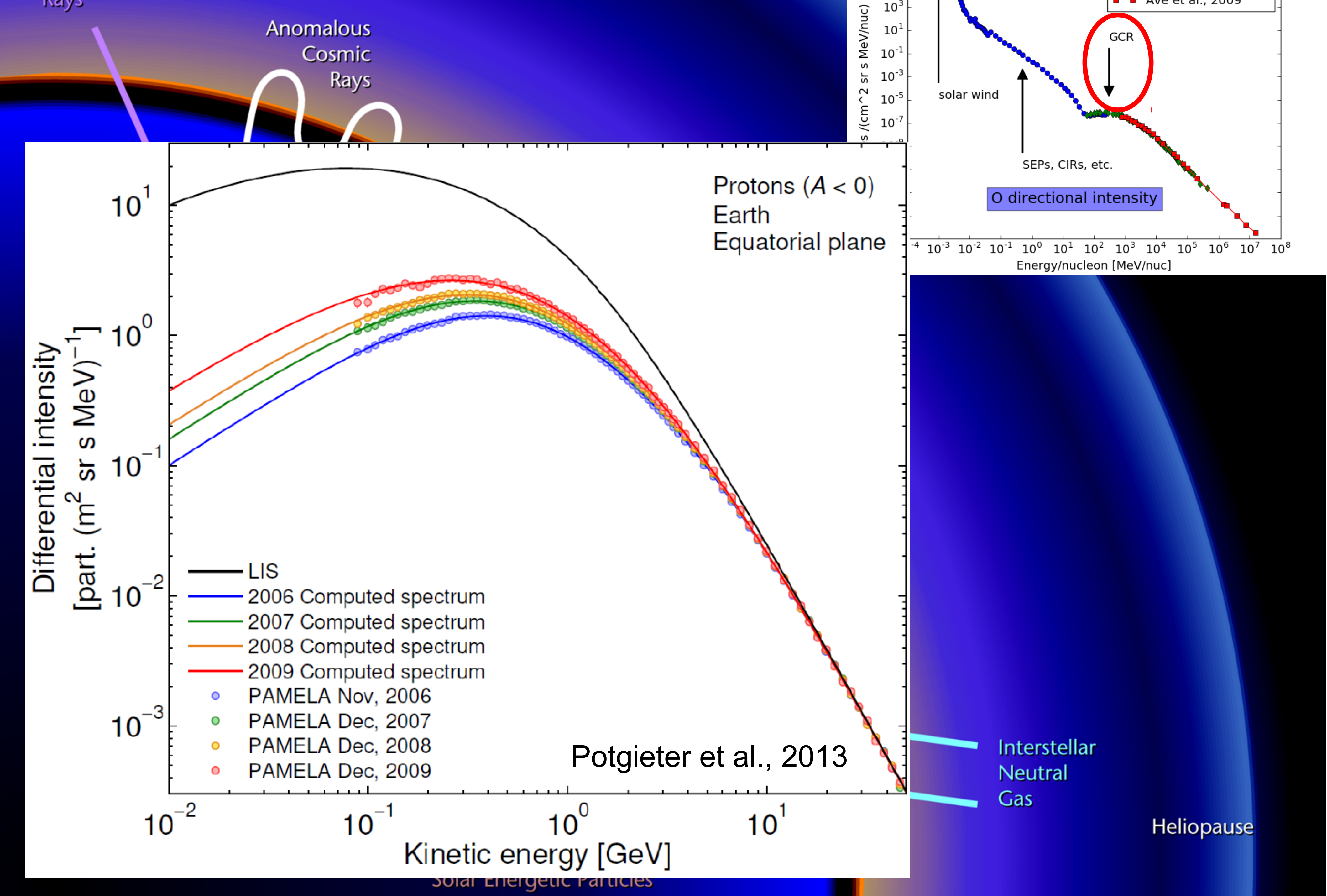
GCR Modulation



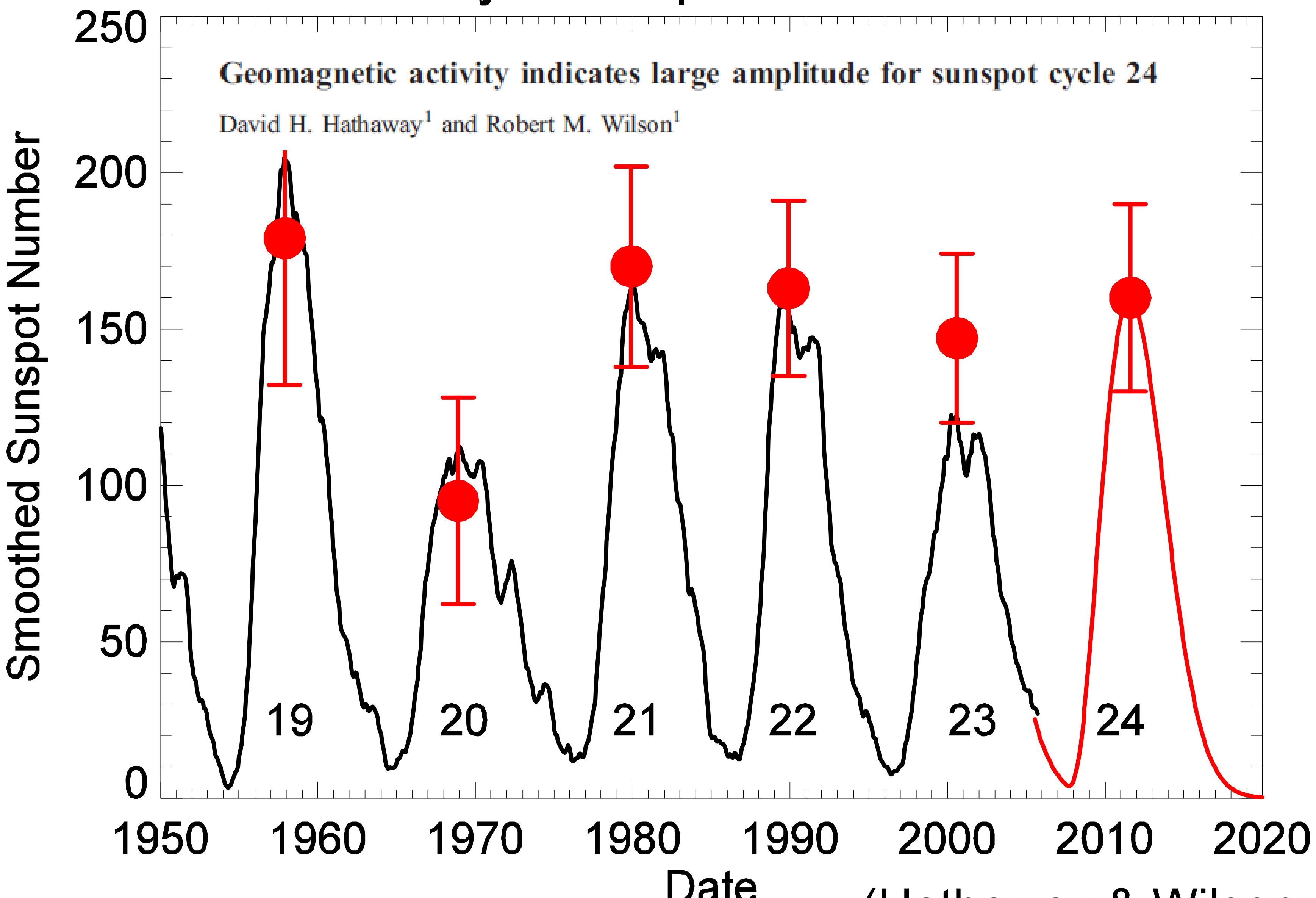




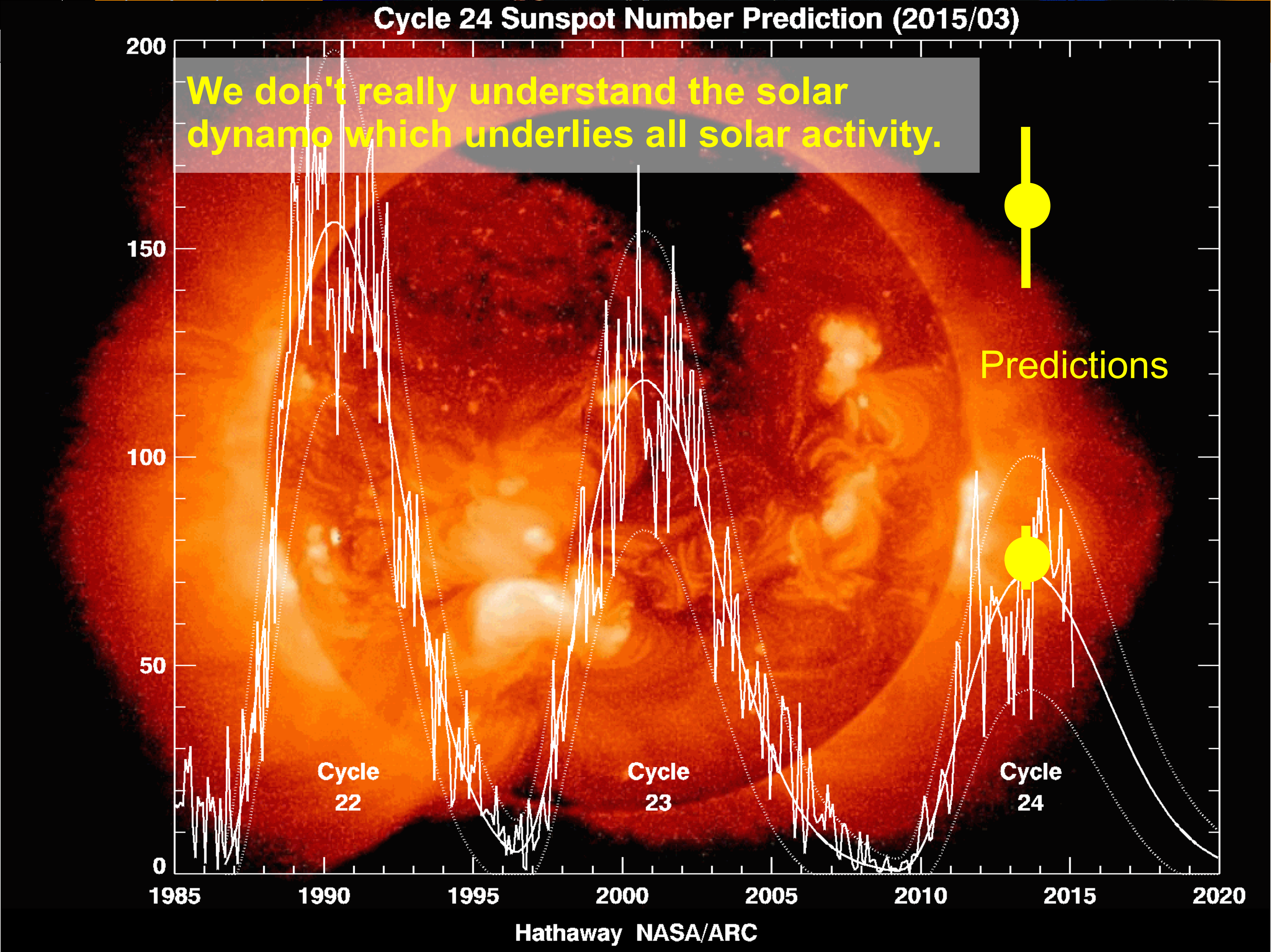
GCR Modulation

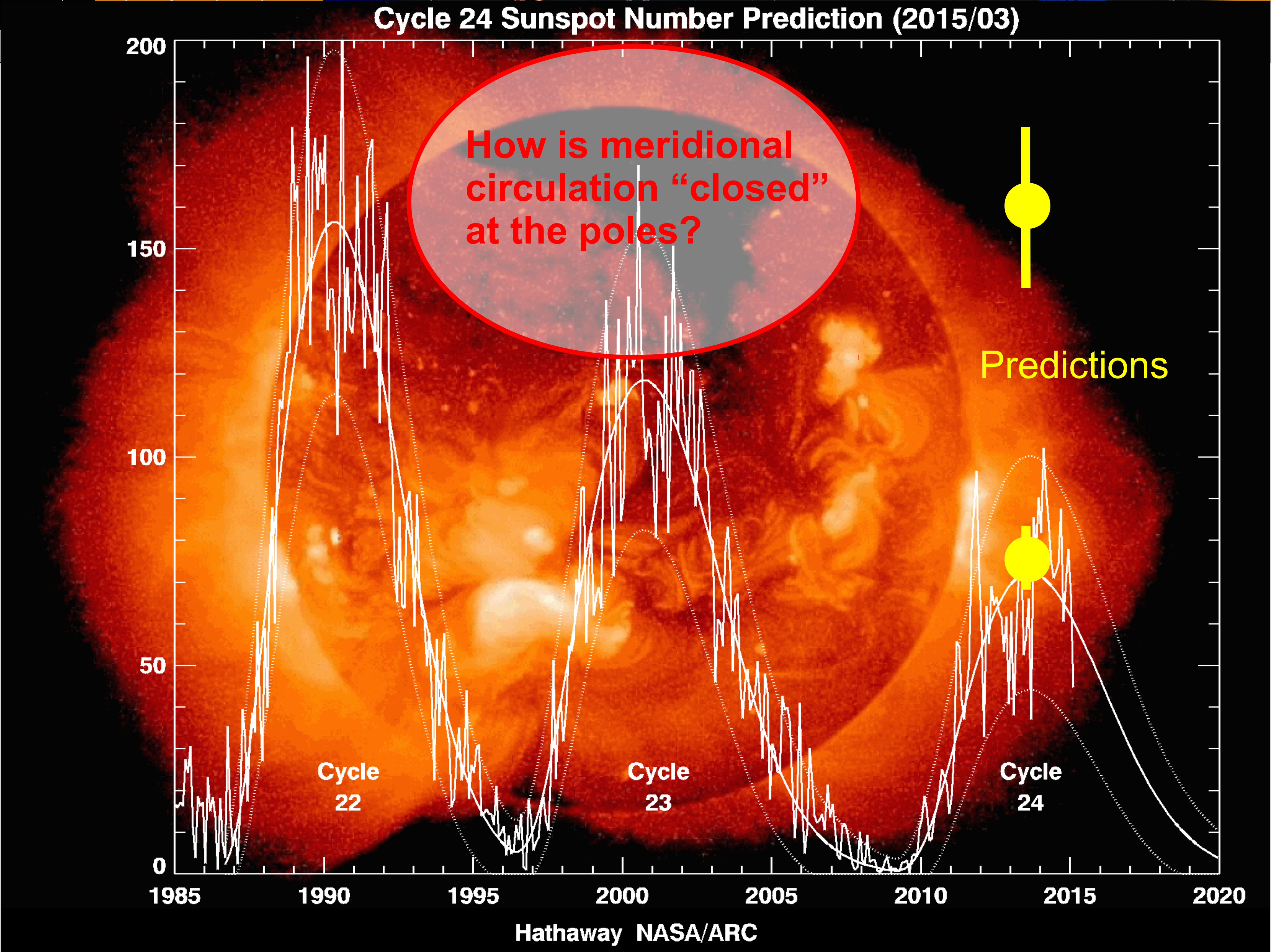


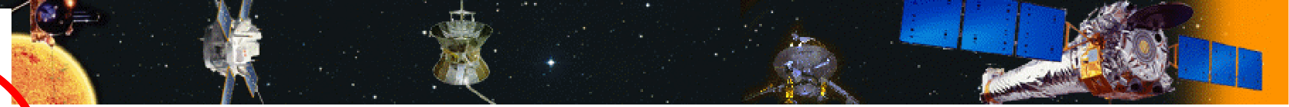
Solar Cycle Amplitude Predictions

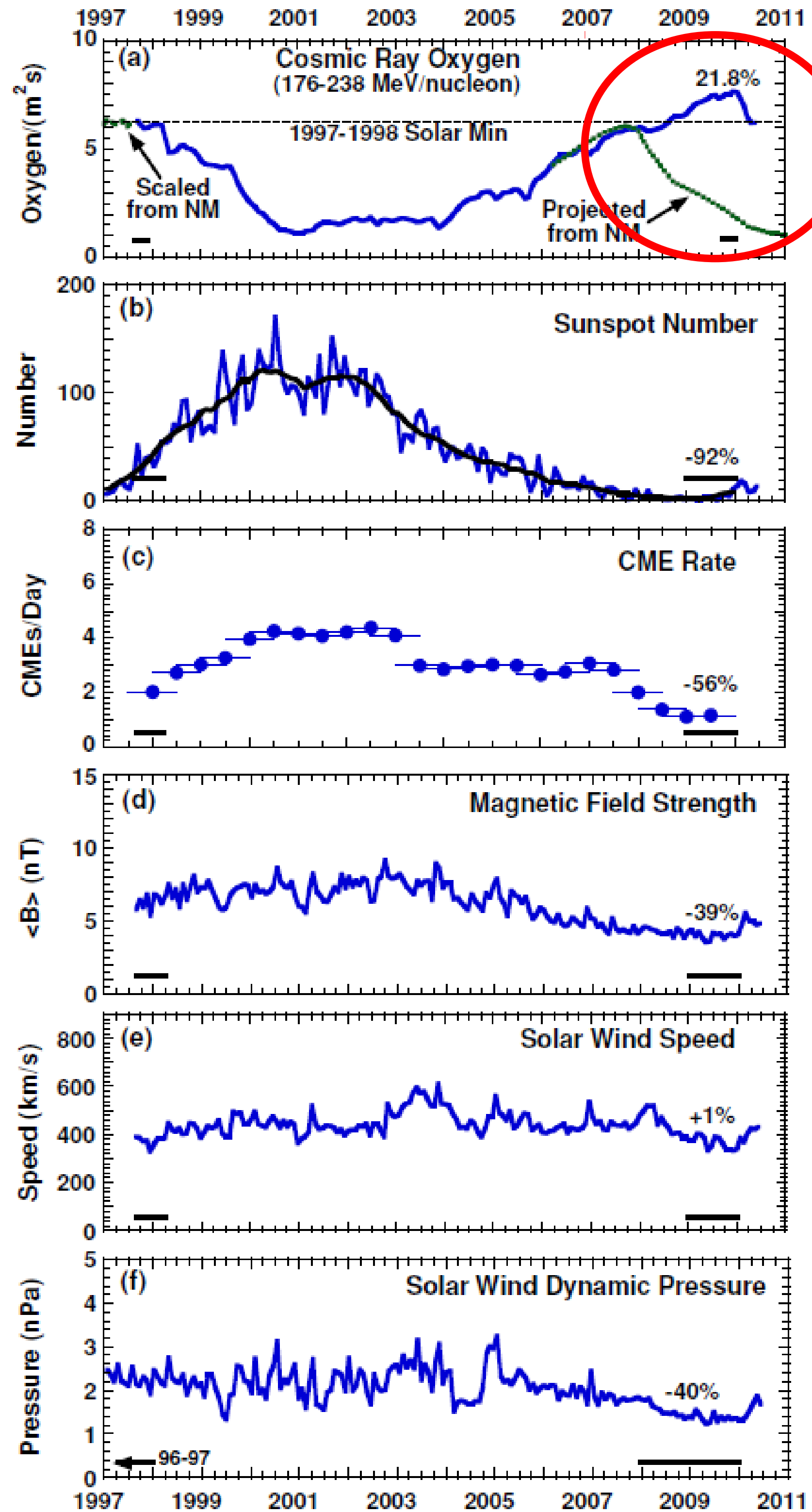


(Hathaway & Wilson, 2006)


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





The Consequence:

RECORD-SETTING COSMIC-RAY INTENSITIES IN 2009 AND 2010

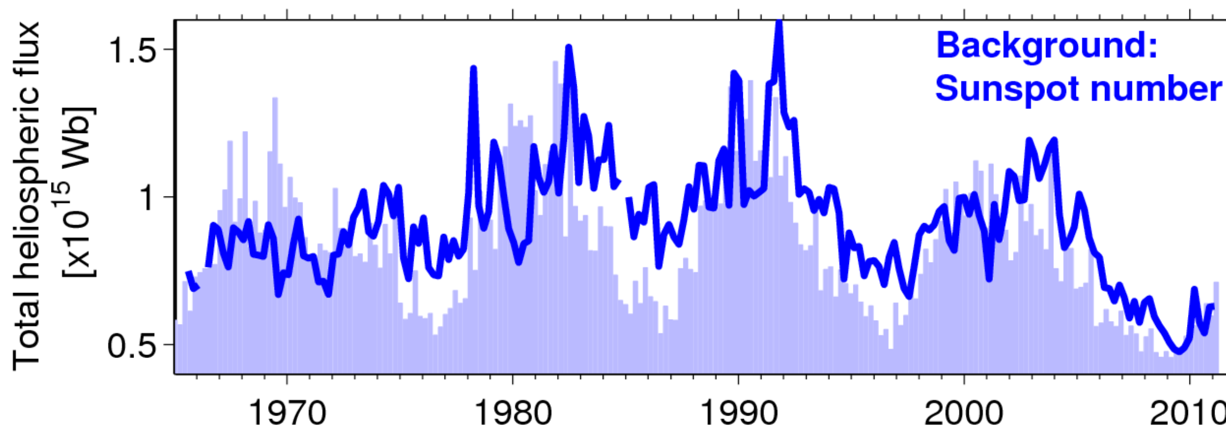
R. A. Mewaldt[1], A. J. Davis[1], K. A. Lave[2], R. A. Leske[1], E. C. Stone[1], M. E. Wiedenbeck[3], W. R. Binns[2], E. R. Christian[4], A. C. Cummings[1], G. A. de Nolfo[4], M. H. Israel[2], A. W. Labrador[1], and T. T. von Rosenvinge[4]

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

… were all not predicted.

solar orbiter

We need to better understand the Sun!



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

Risks Assessments for all DRMs (Jan 2015)

Human Spaceflight Risks 01/12/15	In Mission Risk - Operations						Post Mission Risk – Long Term Health					
	Low Earth Orbit 6 Months	Low Earth Orbit 12 Months	Deep Space Sortie 30 Days	Lunar Visit/Habitation 1 year	Deep Space Journey/Habitation 1 Year	Planetary 3 years	Low Earth Orbit 6 Months	Low Earth Orbit 12 Months	Deep Space Sortie 30 Days	Lunar Visit/Habitation 1 year	Deep Space Journey/ Habitation 1 Year	Planetary 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	[illegible]	RM	RM	RM
Risk of Bone Fracture	A	A	A	A	A	A	A	[illegible]	[illegible]	A	A	RM
Team Performance Decrements#	A	A	A	A	RM	RM	A	[illegible]	[illegible]	A	A	A
Reduced Muscle Mass, Strength	A	A	A	A	A	RM	A	[illegible]	[illegible]	[illegible]	A	A
Reduced Aerobic Capacity	A	A	A	A	A	RM	A	[illegible]	[illegible]	A	A	A
Sensorimotor Alterations	A	A	A	A	A	RM	A	[illegible]	[illegible]	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

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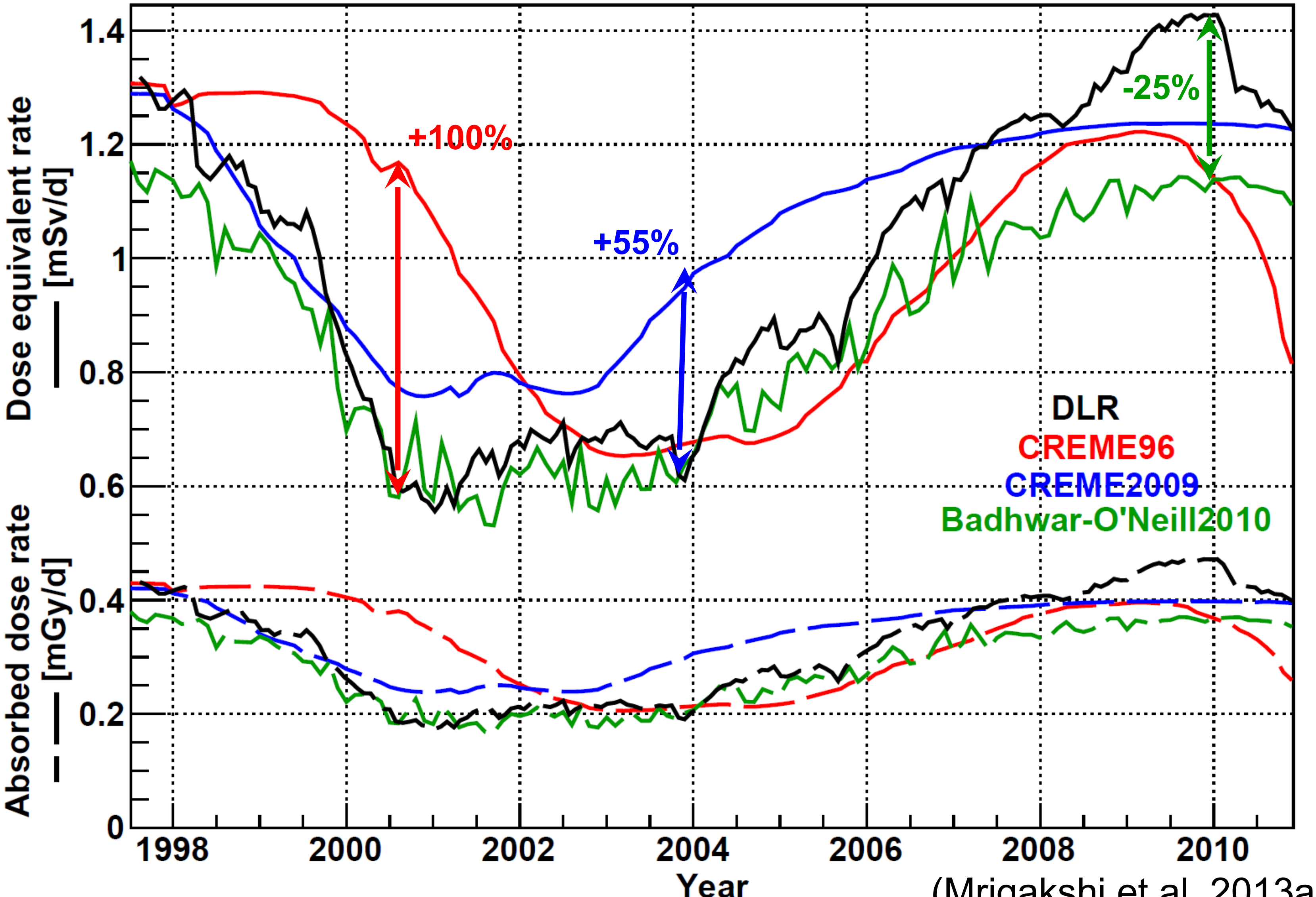
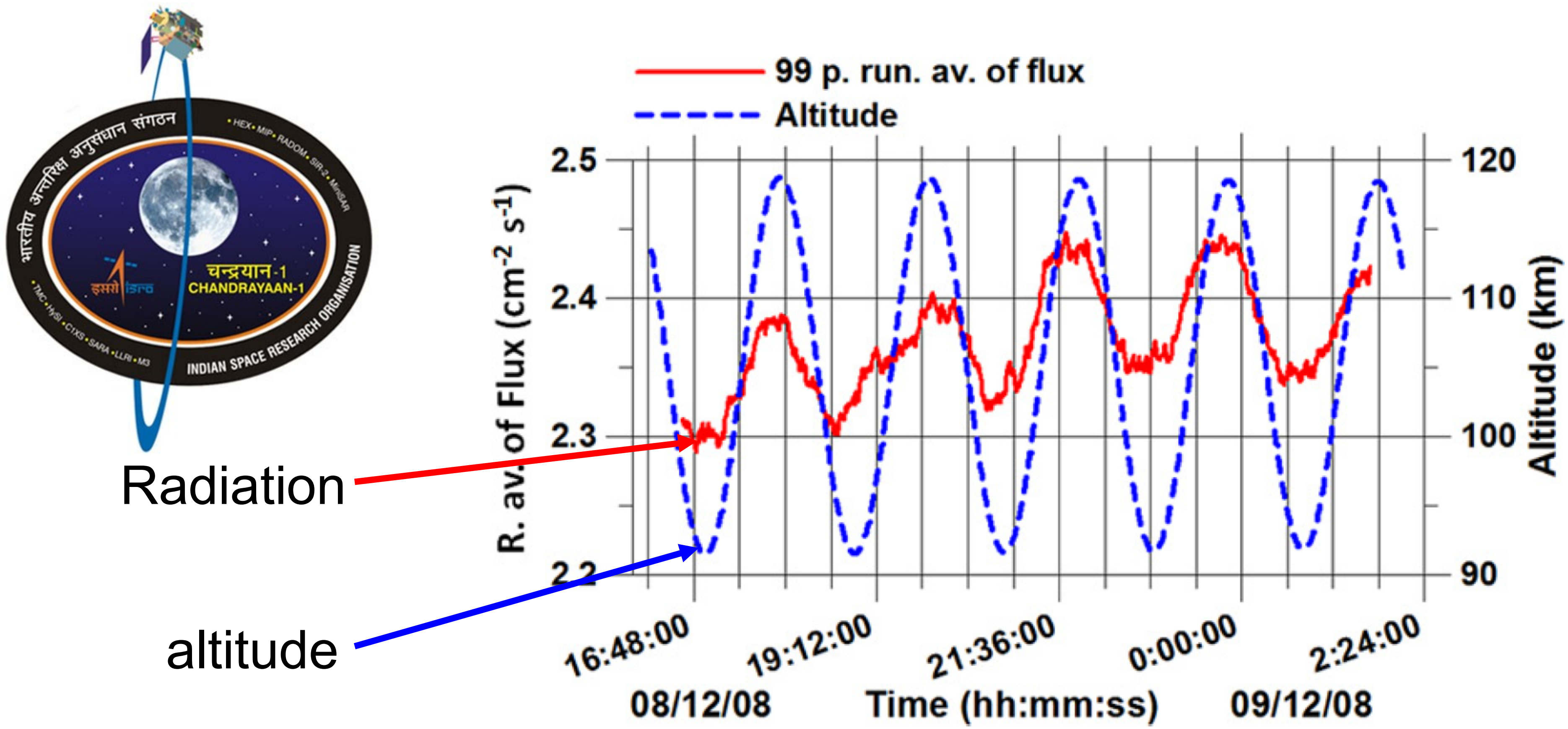
GCR models show substantial differences in their predictions



(Mrigakshi et al. 2013a)

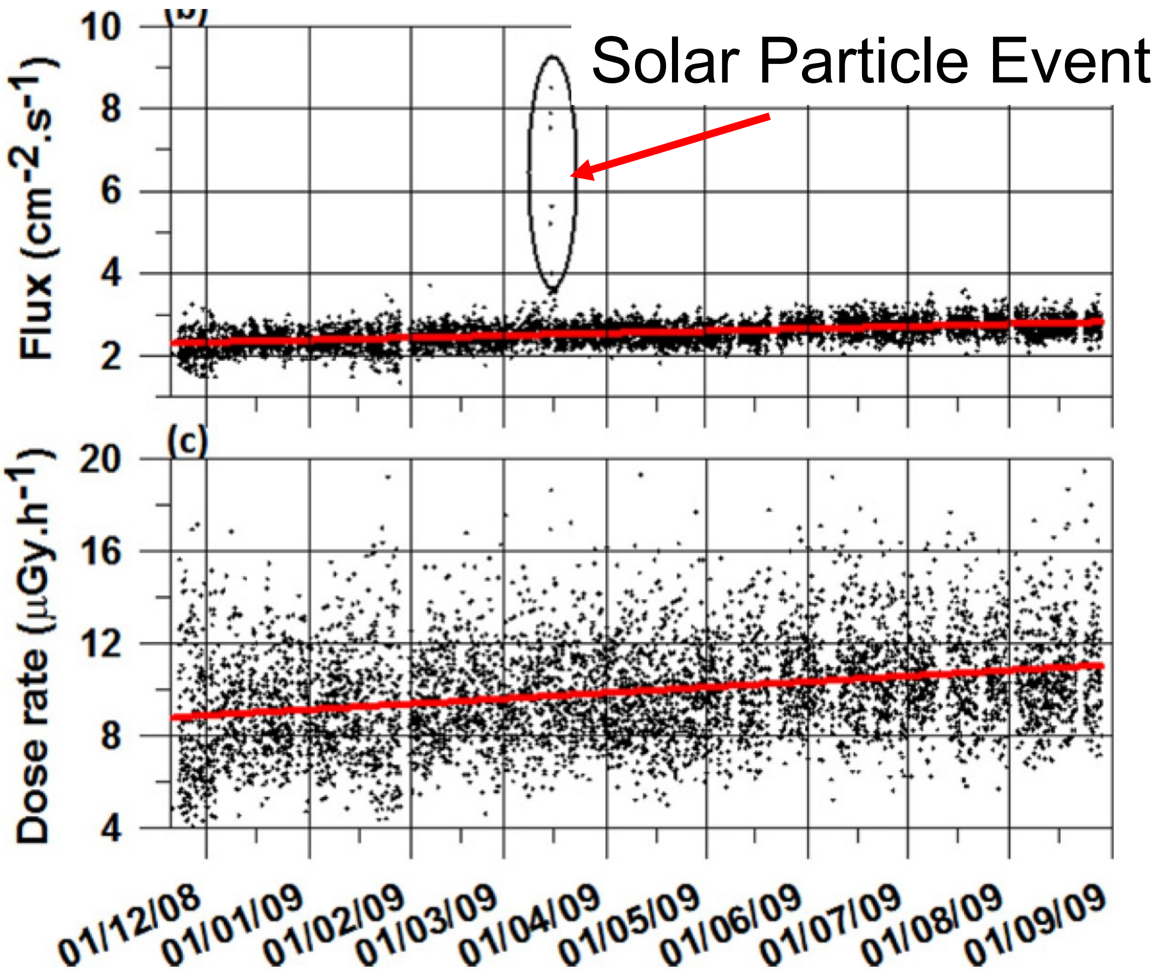
Dose Rate Measurements at the Moon?



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?



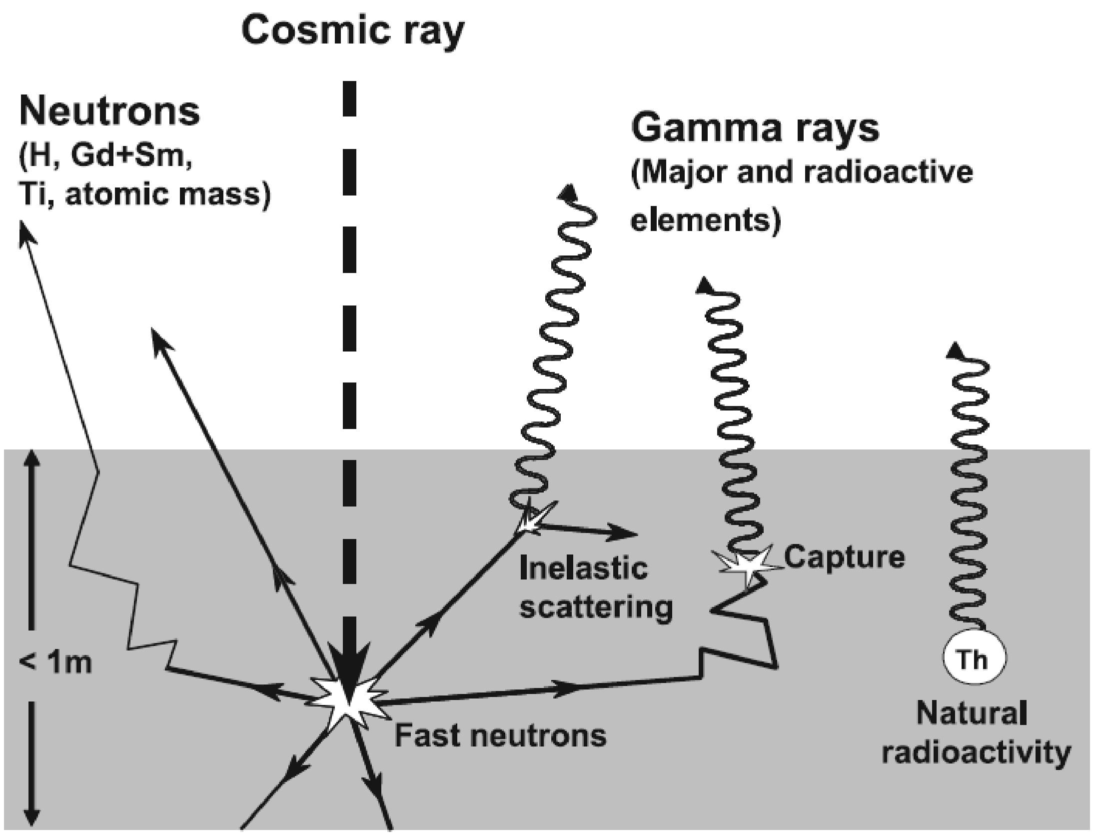
Dose rates :

~ 100 km: 227 µGy/d

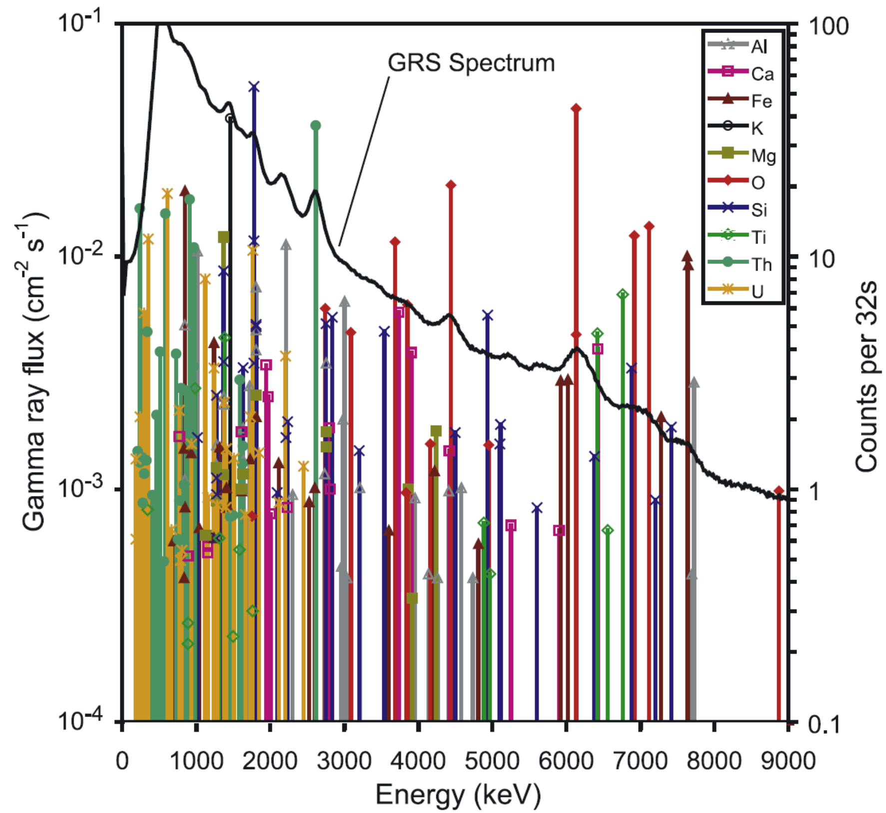
~ 200 km : 257 µGy/d

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

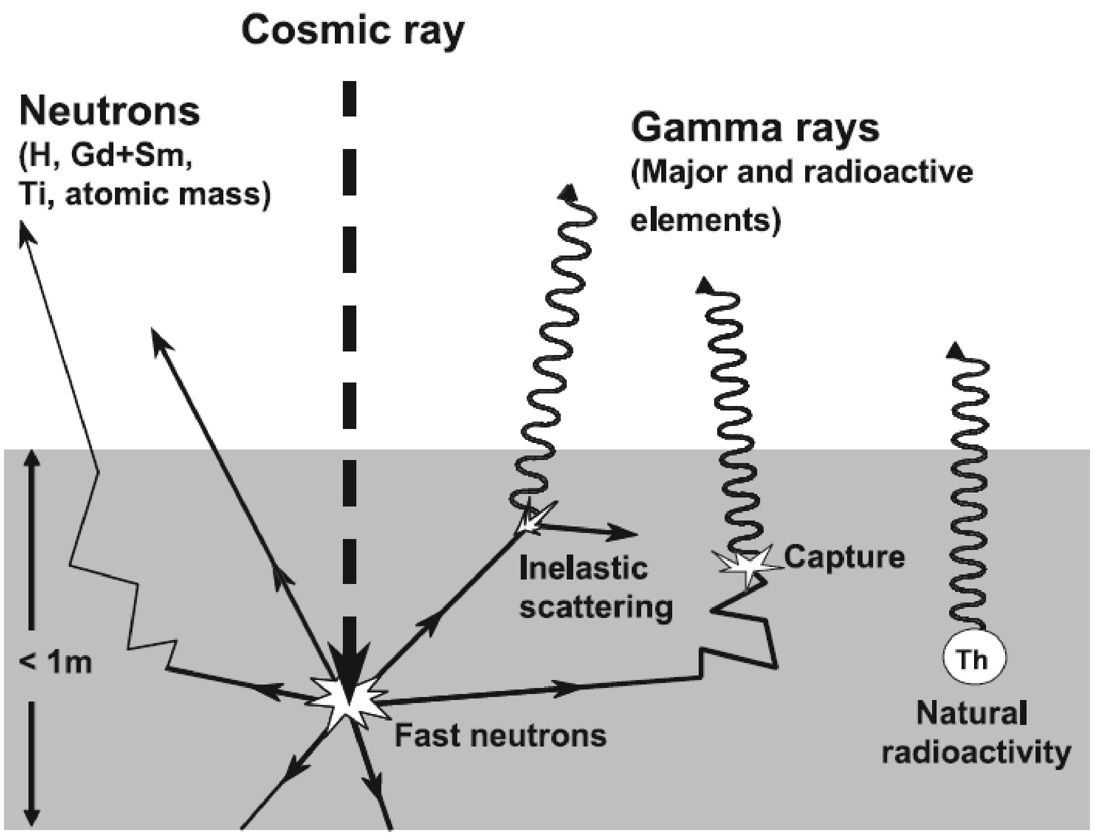


Prettyman et al., 2006

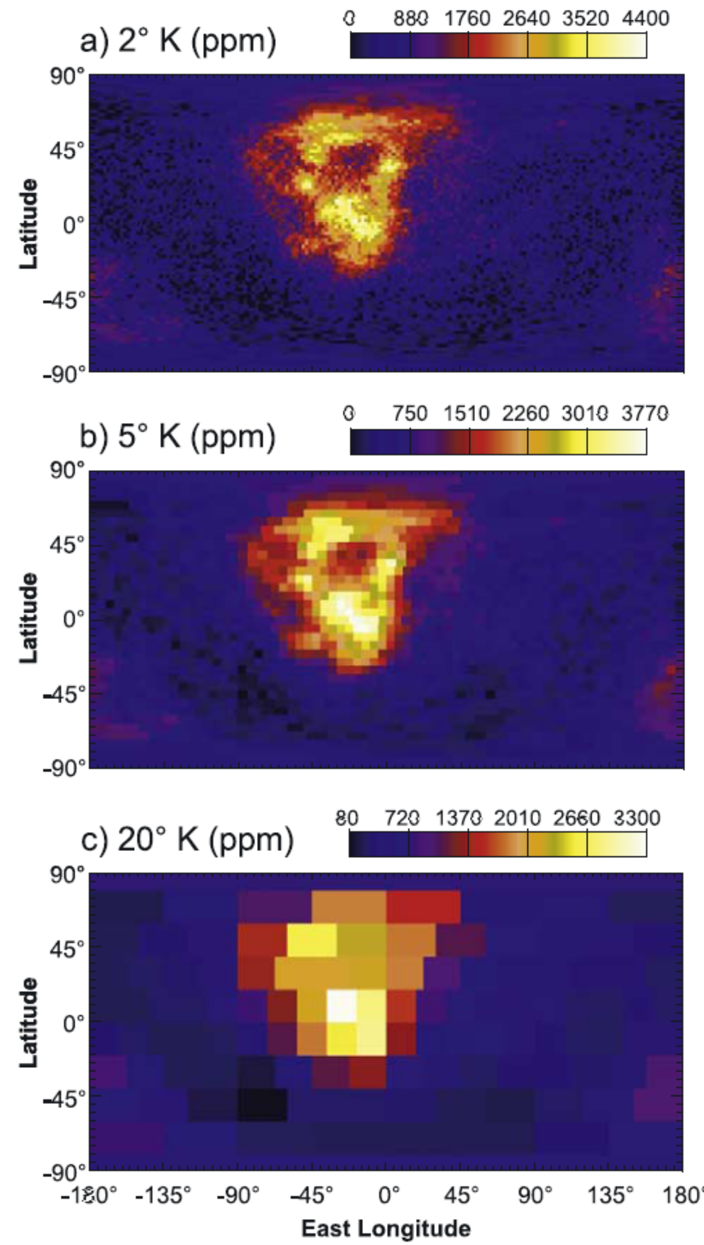


Interaction of GCR with lunar regolith leads to excited nuclei and gamma ray line emission

Particle Radiation Measurements at the Moon

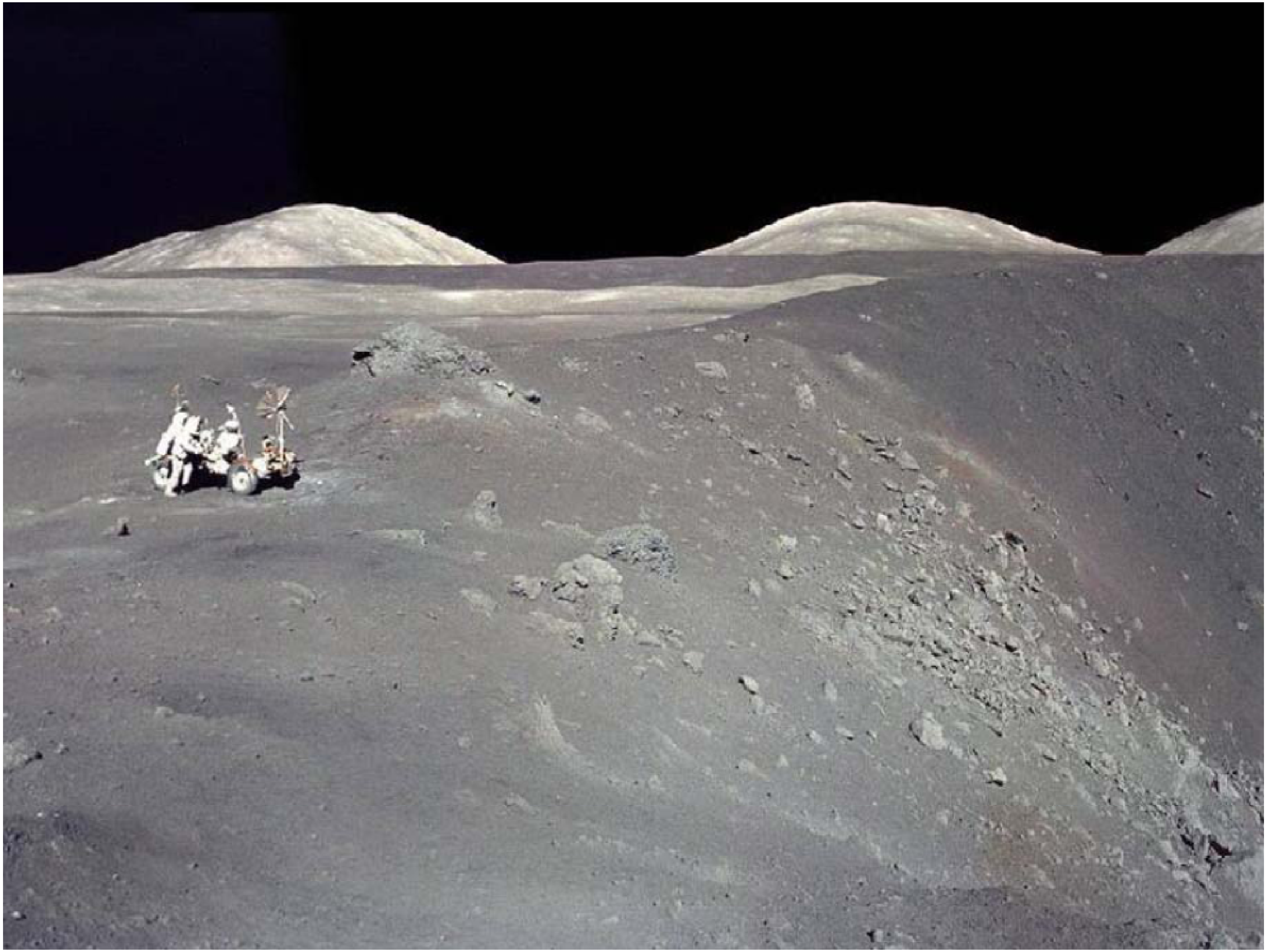


Prettyman et al., 2006



Interaction of GCR with lunar regolith leads to excited nuclei and gamma ray line emission

Dose Rate Measurements on the Moon

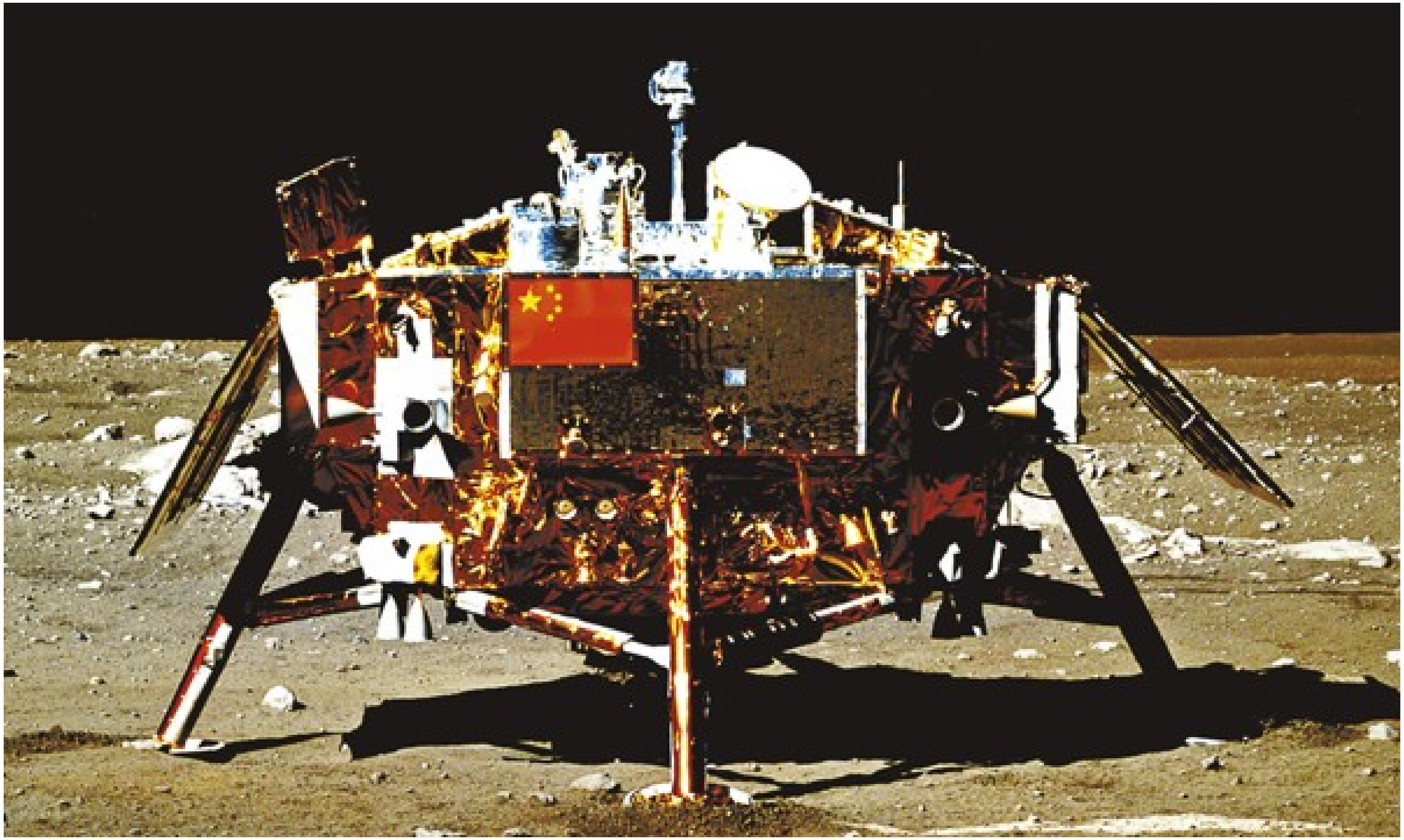


Dose Rate Measurements on the Moon?

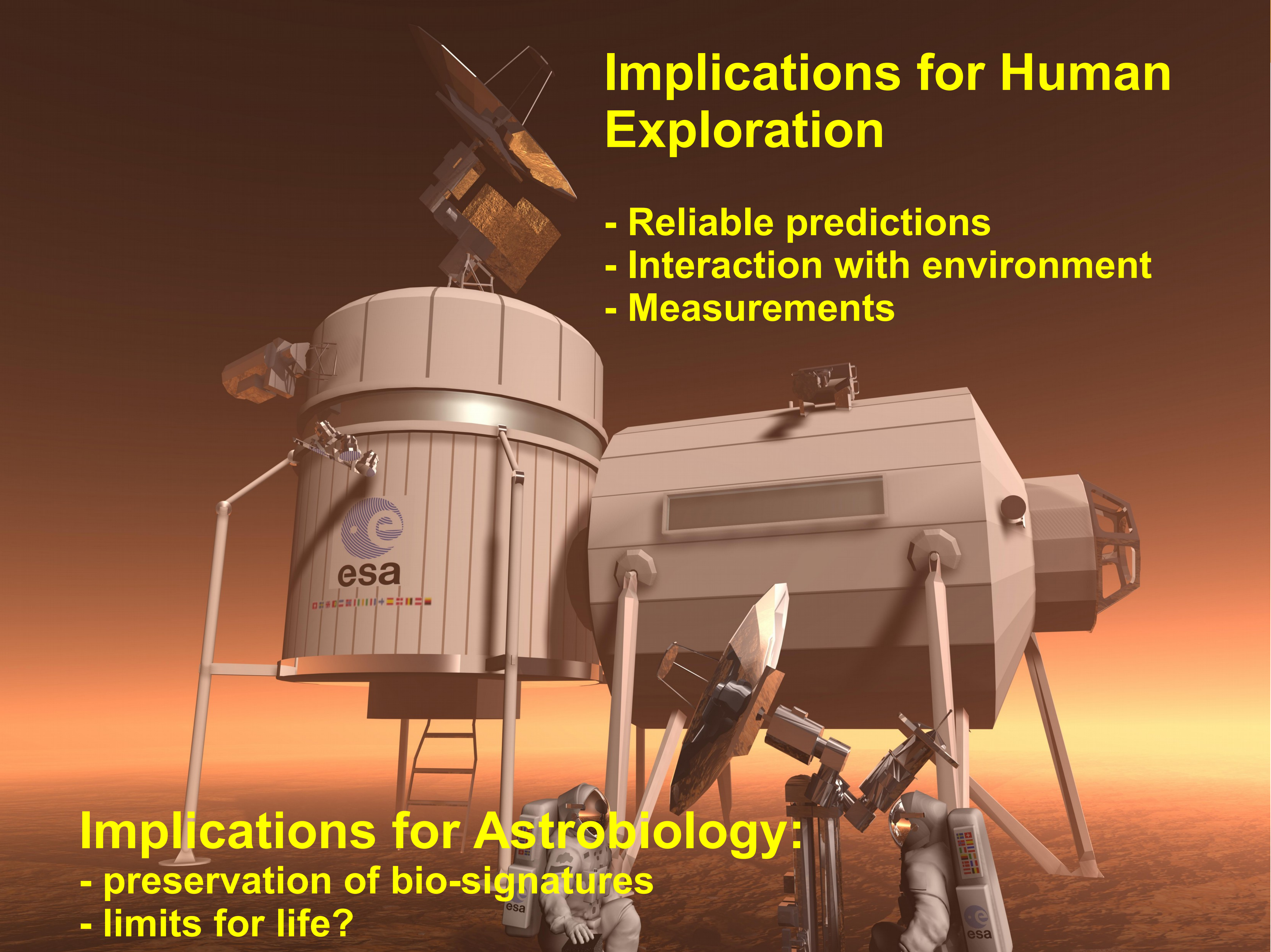
Dose Rate Measurements on the Moon?

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

Implications for Astrobiology:

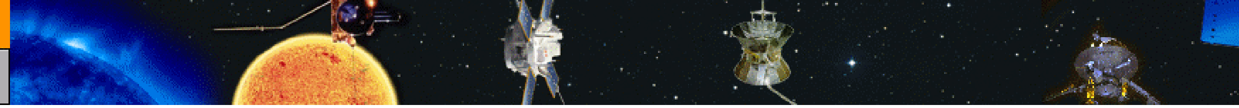
- preservation of bio-signatures
- limits for life?

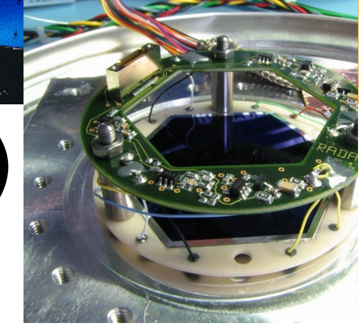
Radiation Measurements on Mars

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

?



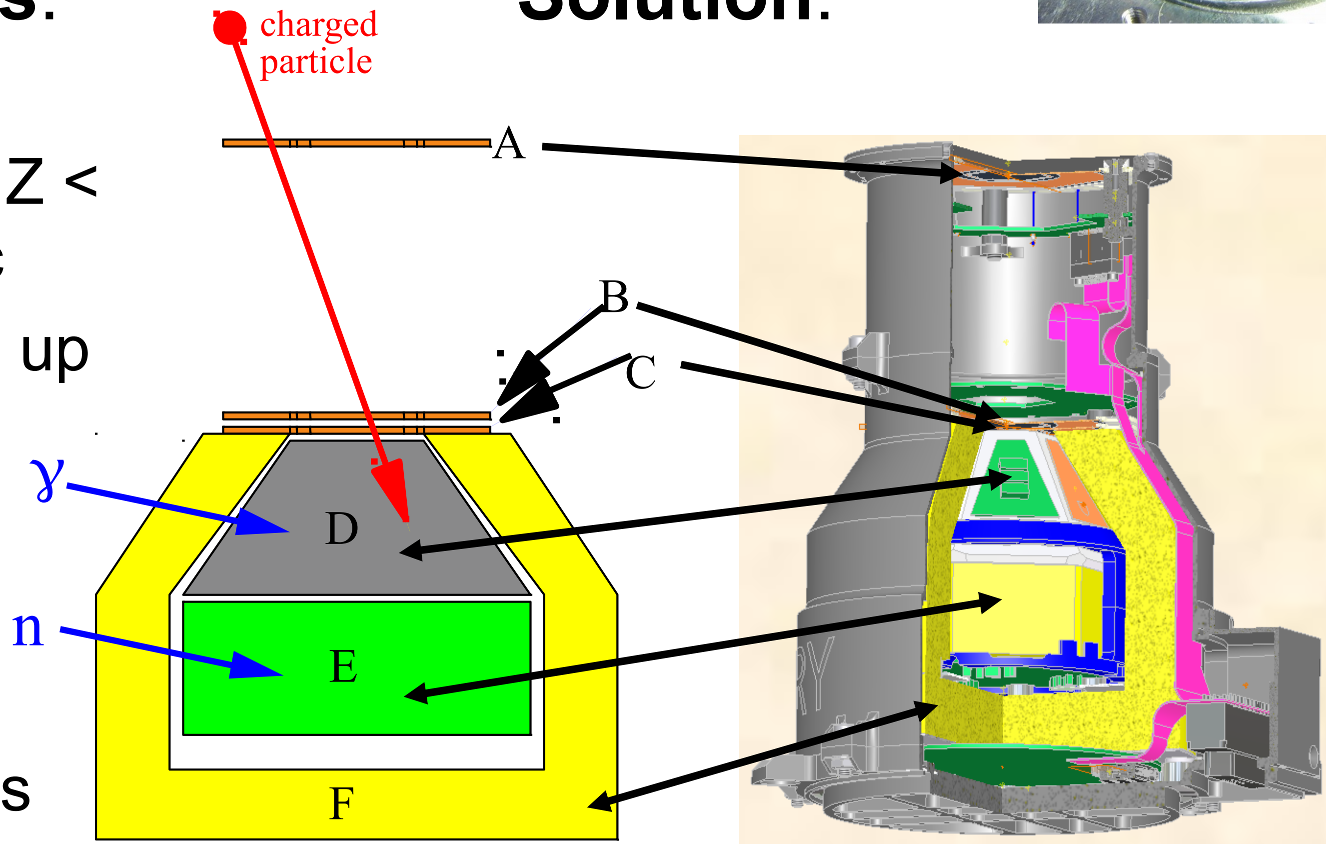


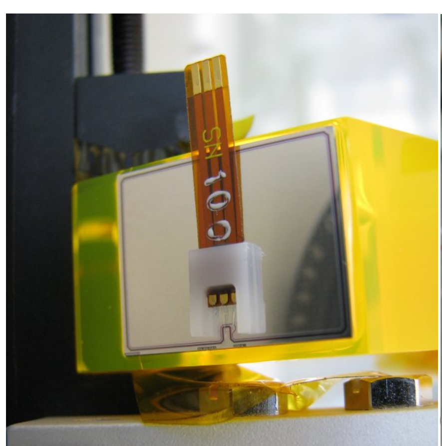
The Radiation Assessment Detector (RAD)

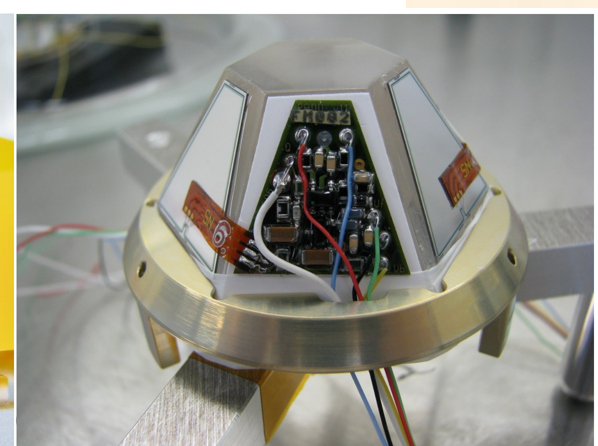
Requirements:

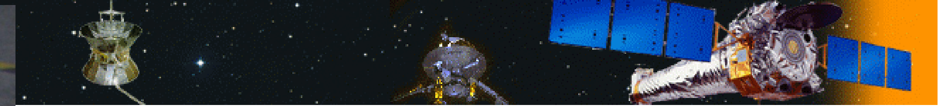
- Charged particles (1 < Z < 27) up to 100 MeV/nuc
- Neutral particles (n, γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations

Solution:









RAD:

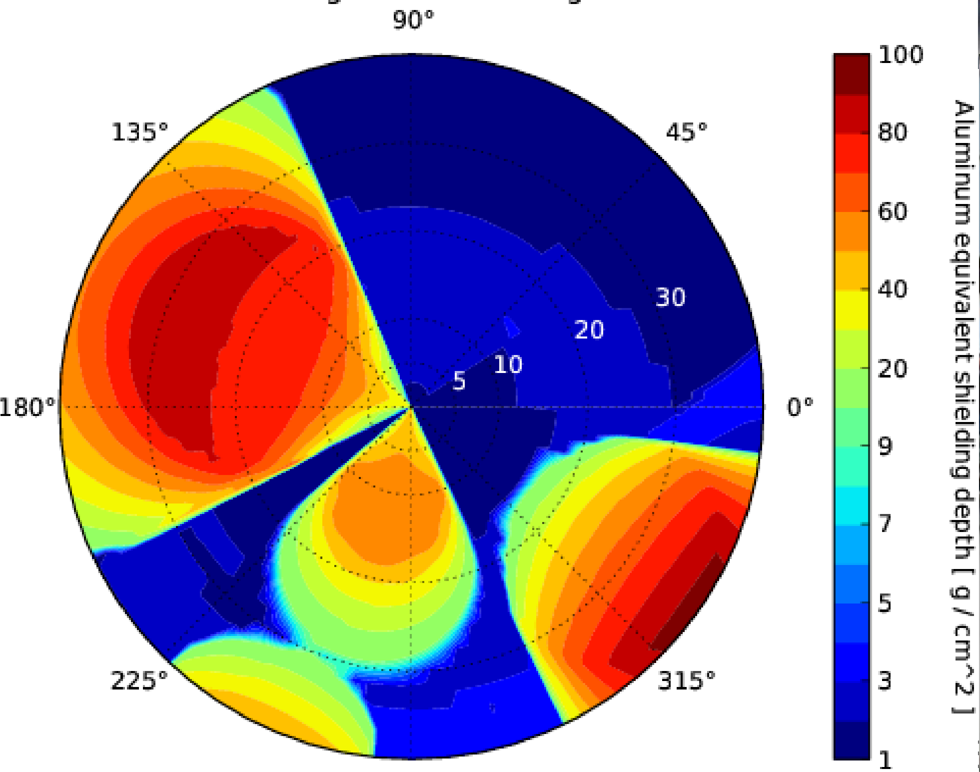
- Mass: 1,56 kg
- Power: 4,2 W
- Data rate: ~130 bps
- RSH: FM & FS

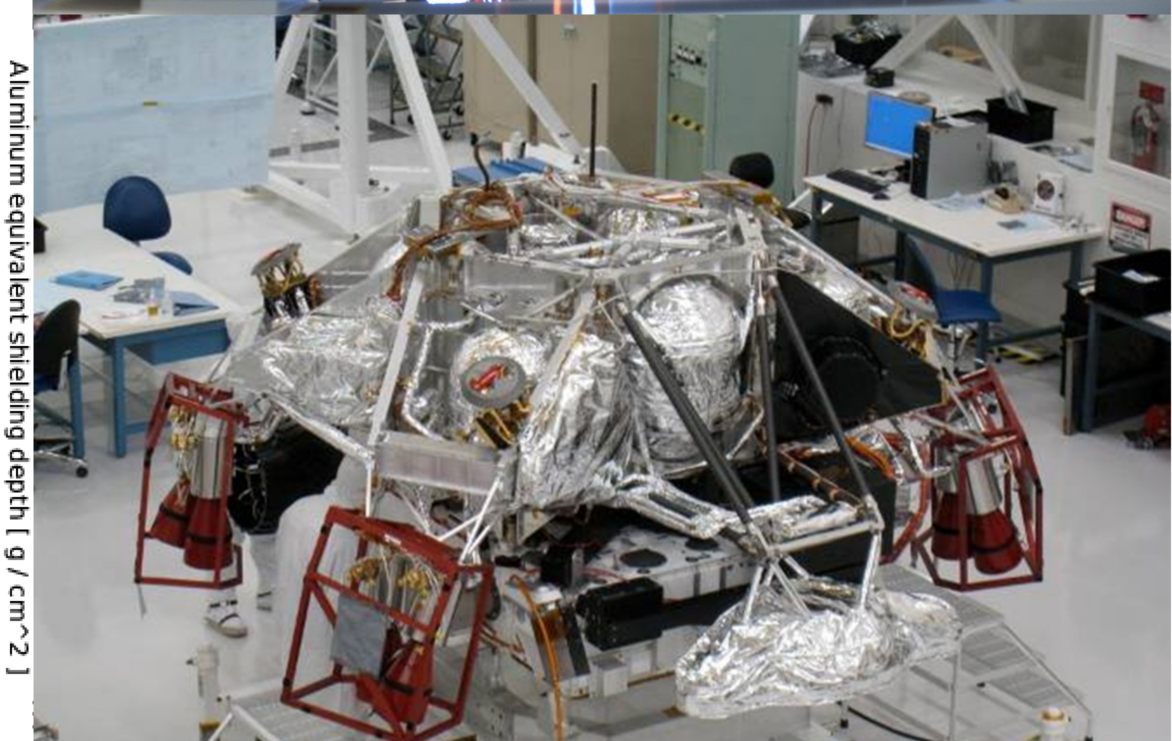
During cruise, RAD was heavily shielded by inhomogeneous and anisotropic structures.

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

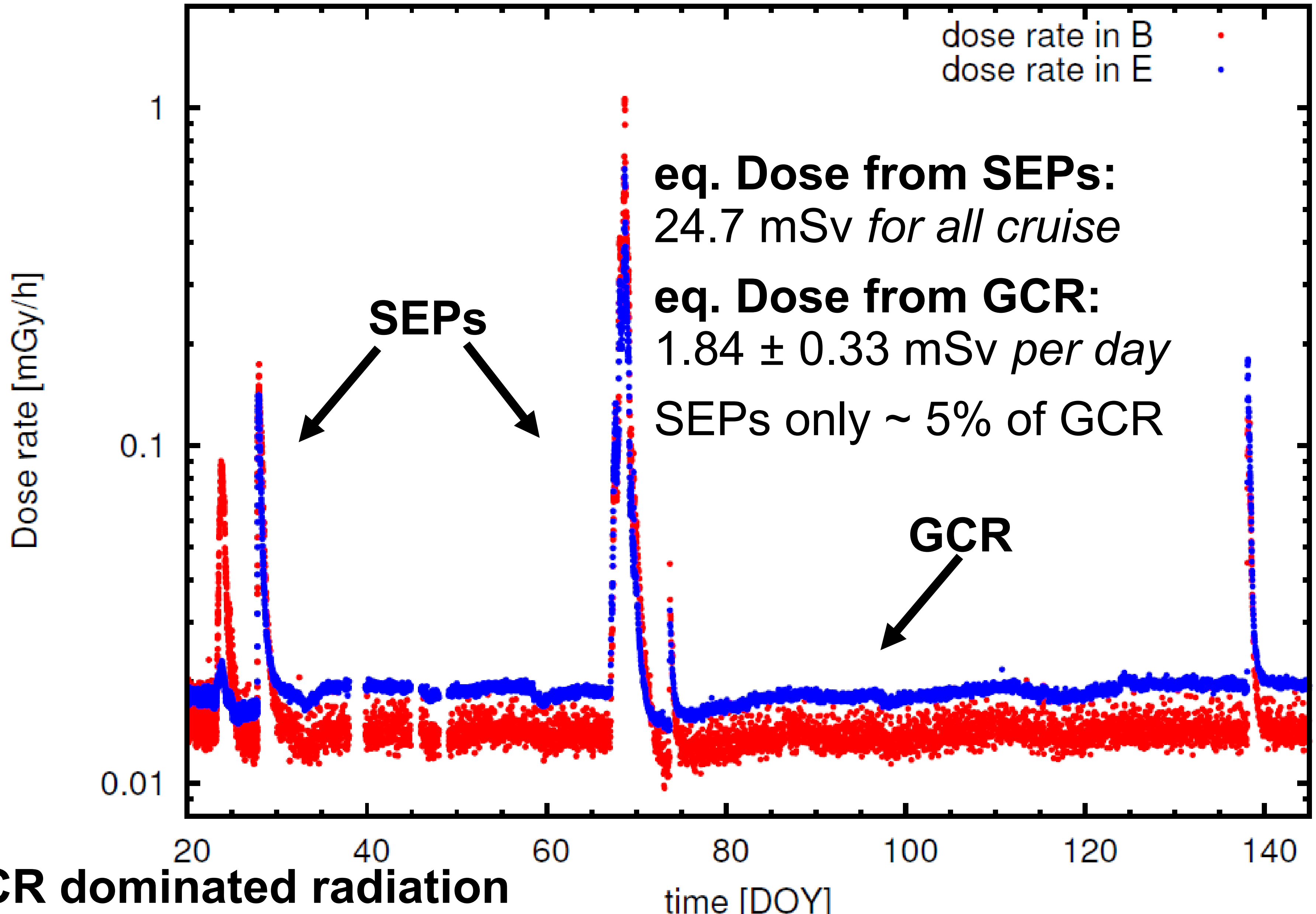
This complicates interpretation of data.

RAD Shielding in Cruise Configuration





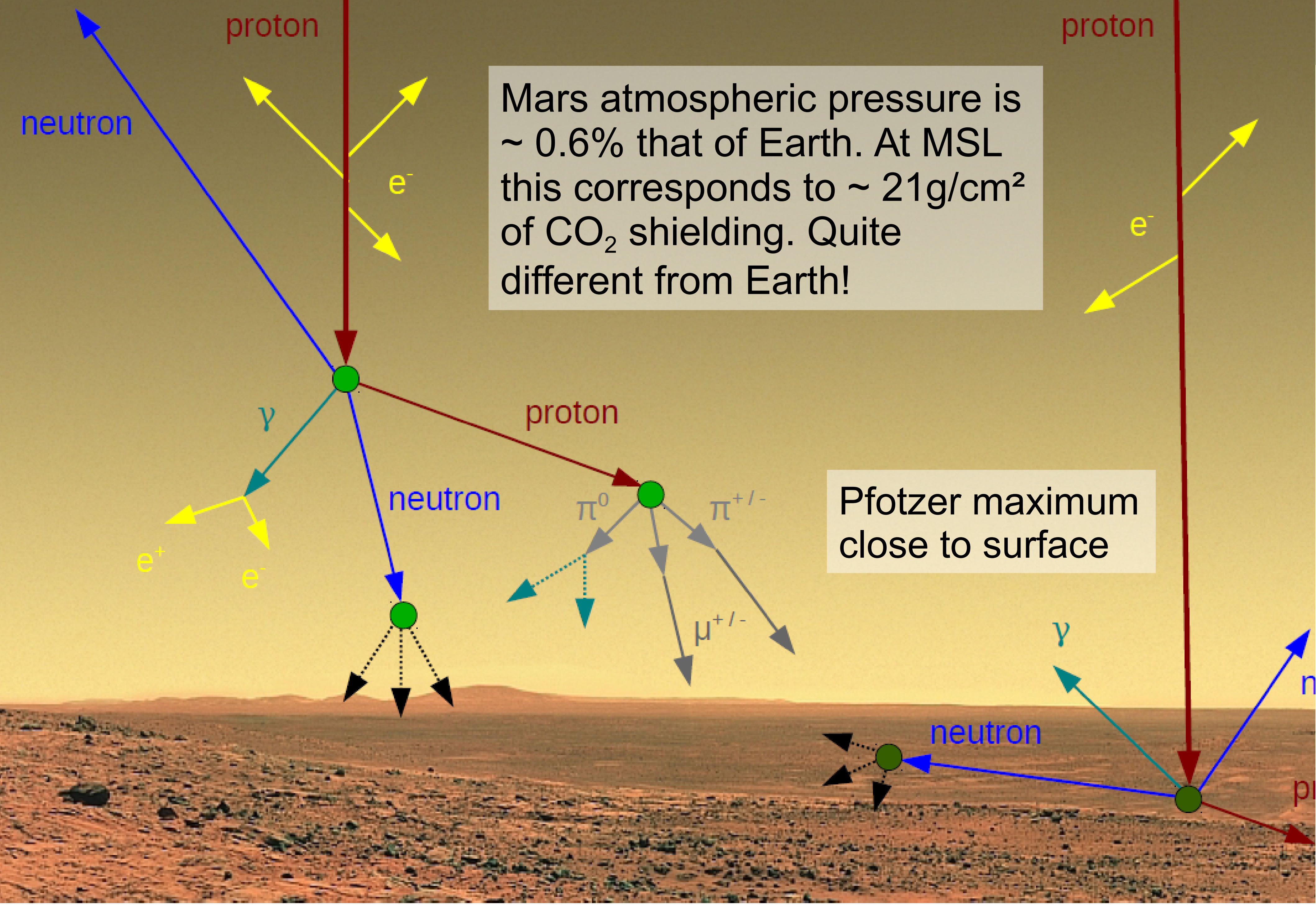
Summary of cruise radiation environment of MSL



GCR dominated radiation exposure during RAD's cruise

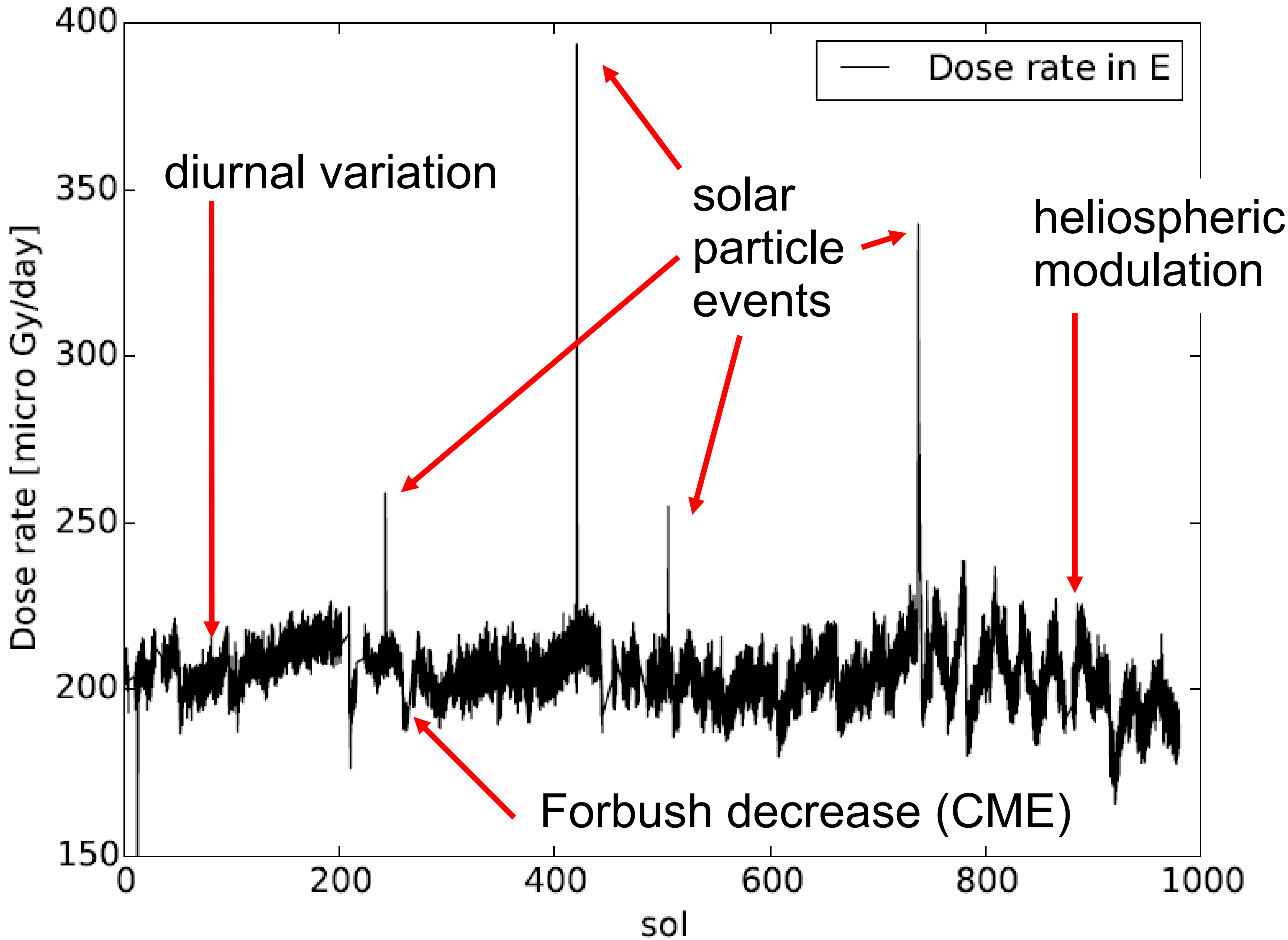
Summary of cruise radiation environment of MSL (This can be measured accurately!)

		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!	

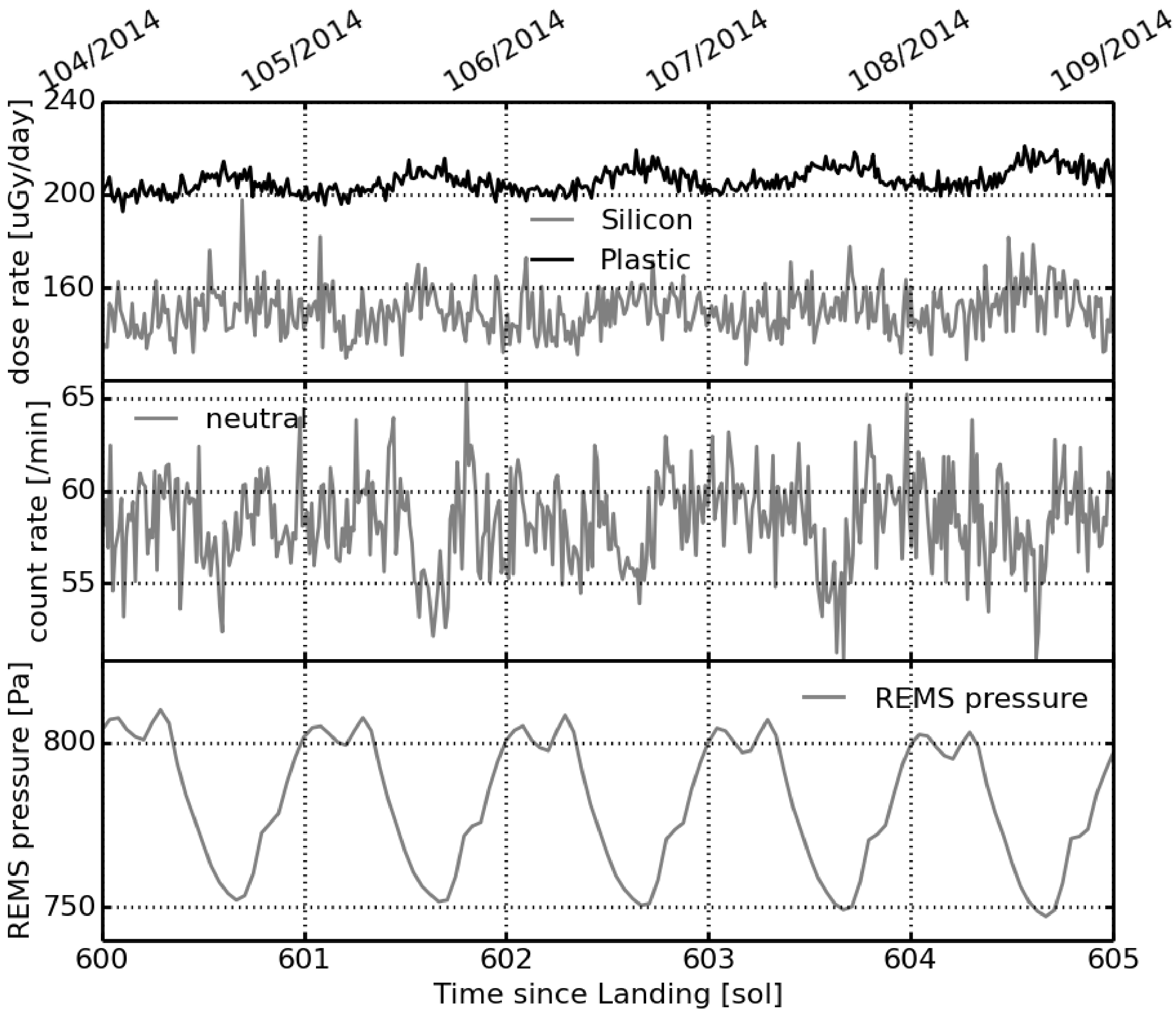


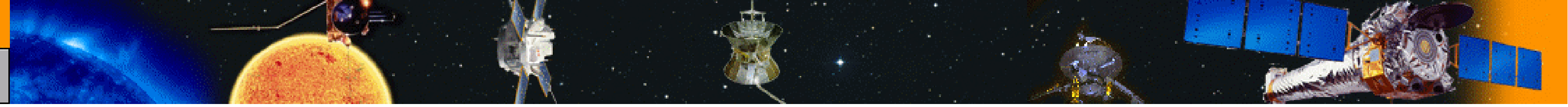
Secondary radiation (neutrals!) plays an important role! (Ehresmann, 2011)

RAD Surface Measurements

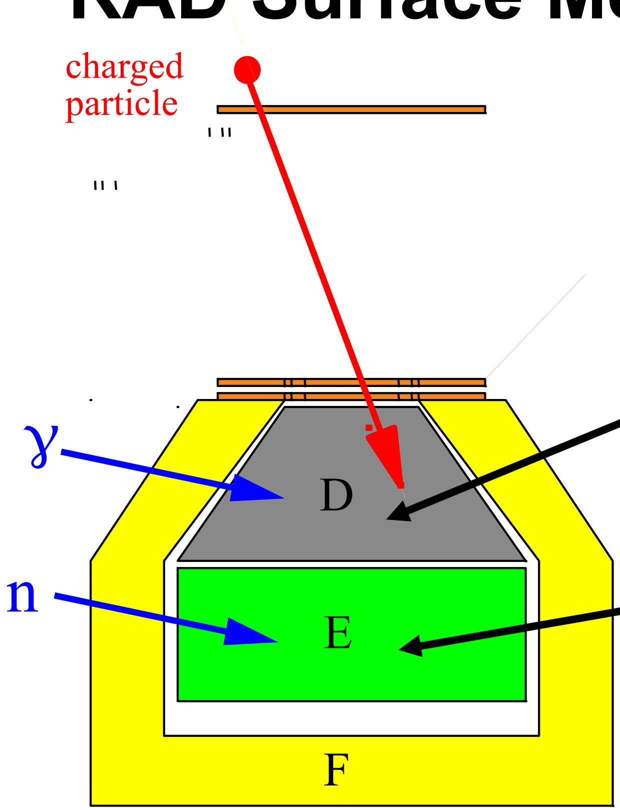


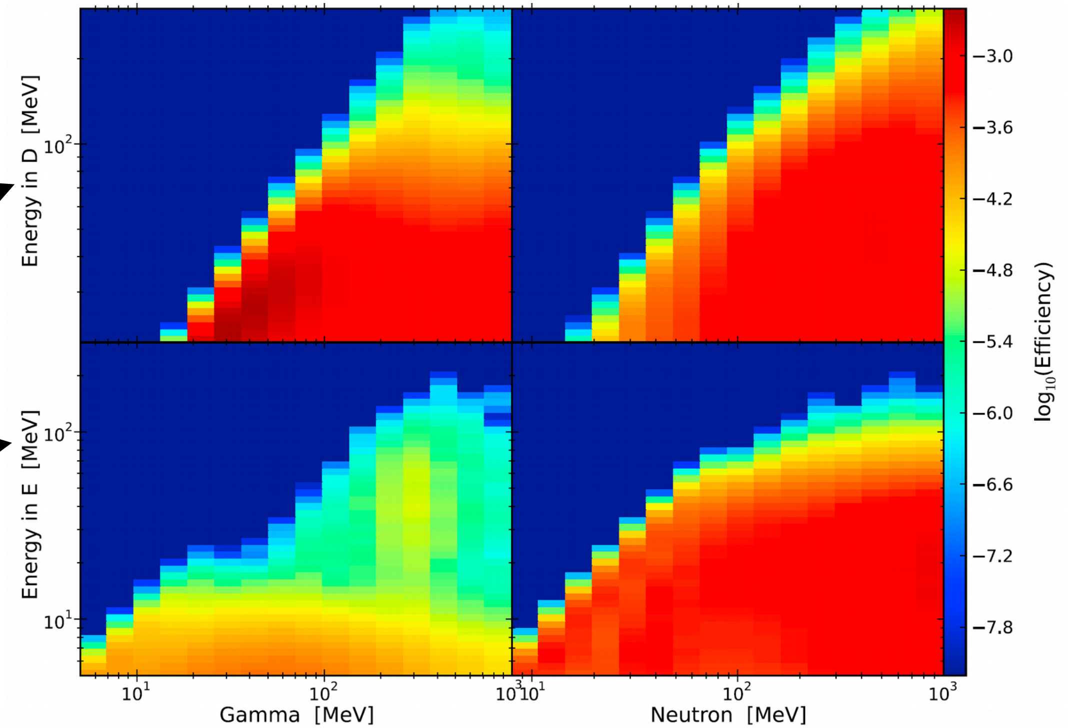
RAD Surface Measurements

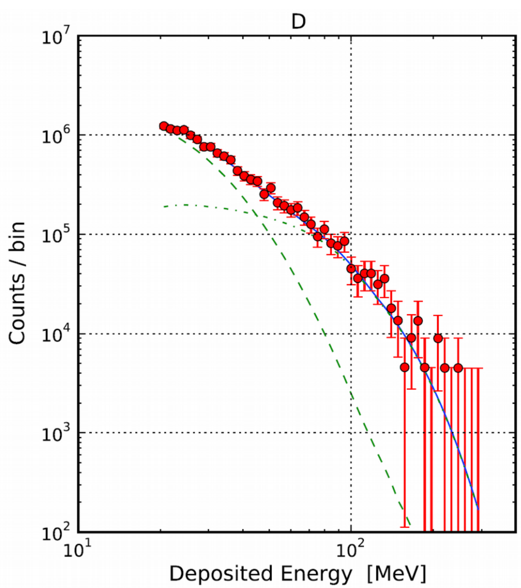


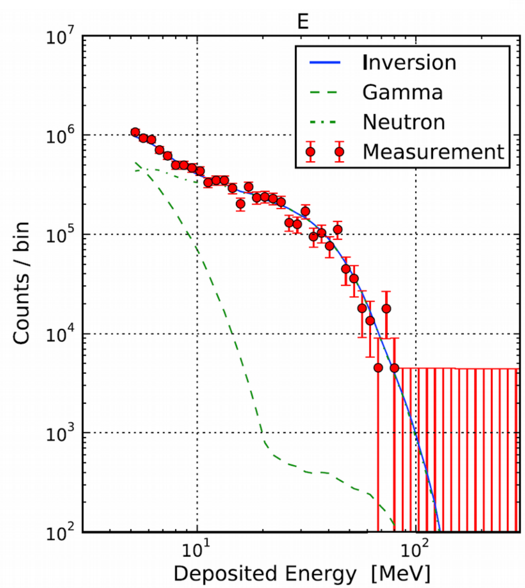


RAD Surface Measurements of n and γ







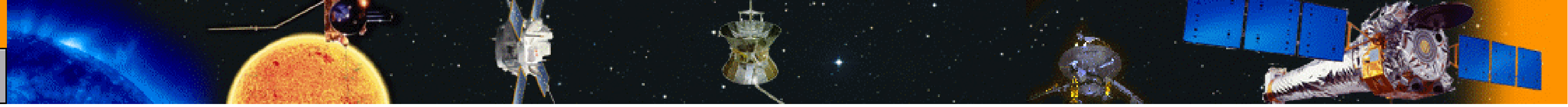


Need to invert

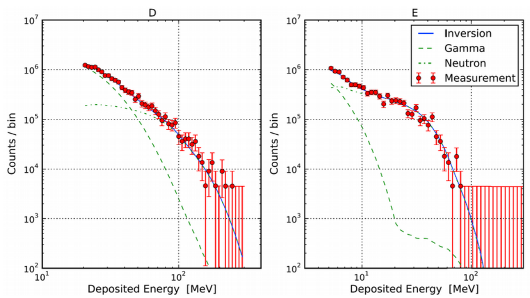
$$\vec{z} = \mathbf{A} f \quad \text{where}$$

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{D\gamma} & \mathbf{A}_{Dn} \\ \mathbf{A}_{E\gamma} & \mathbf{A}_{\mathbf{En}} \end{pmatrix}$$

accounting for Poisson statistics.



RAD Surface Measurements of n and γ



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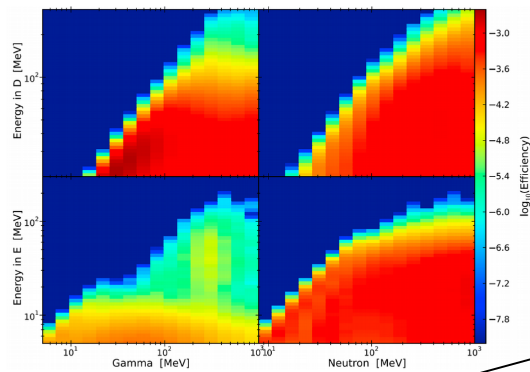

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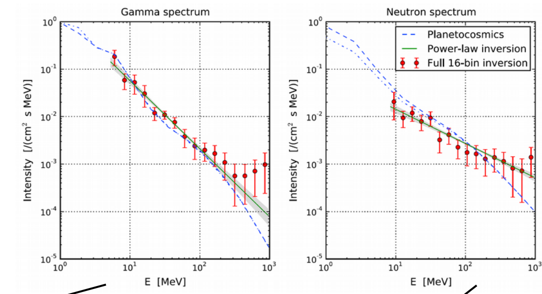
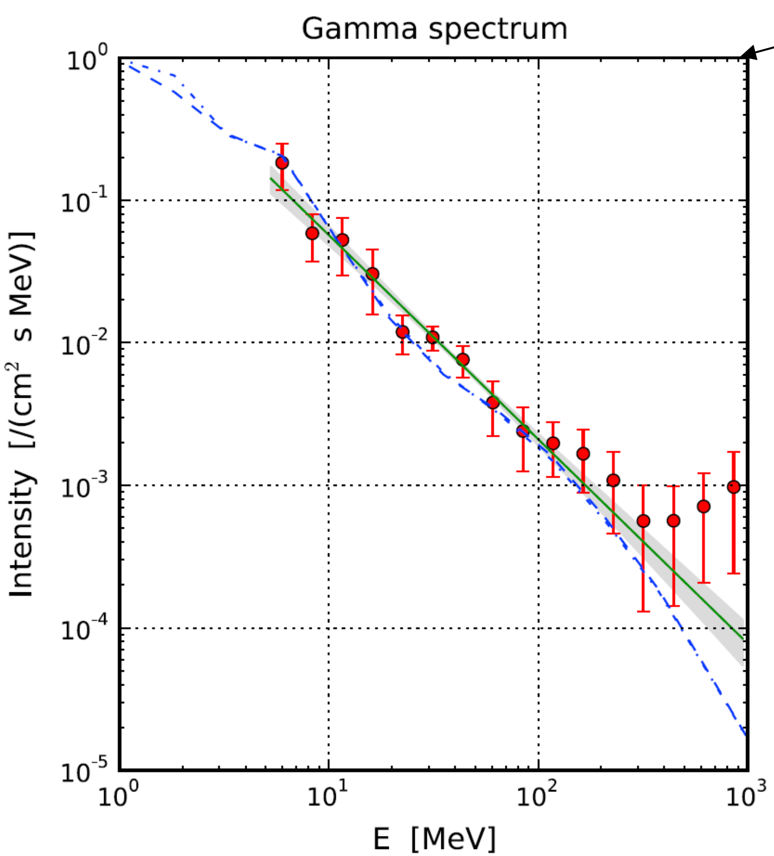
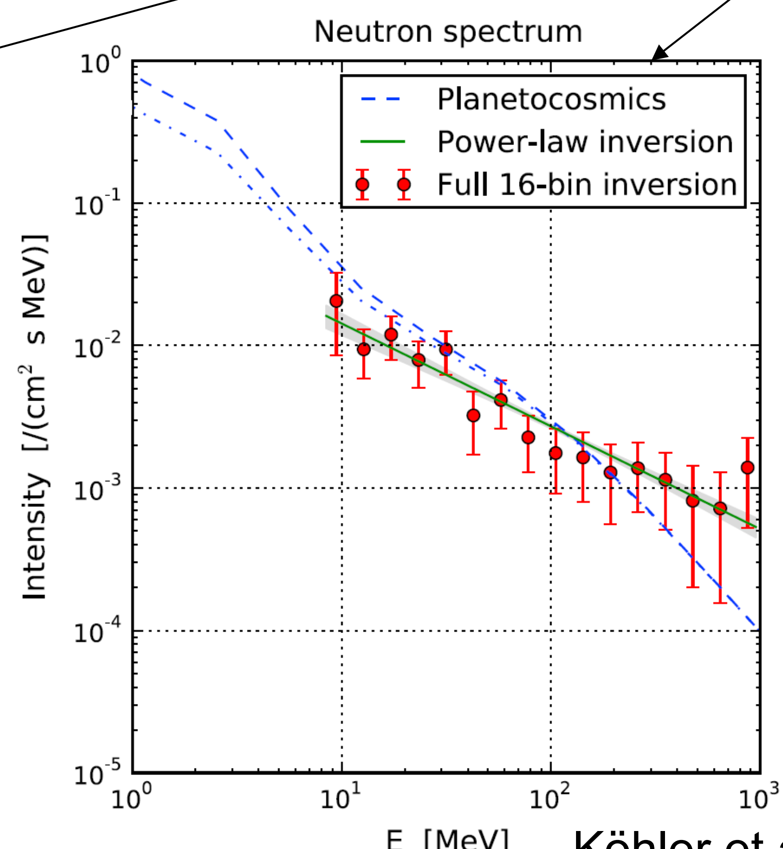






Köhler et al., 2014

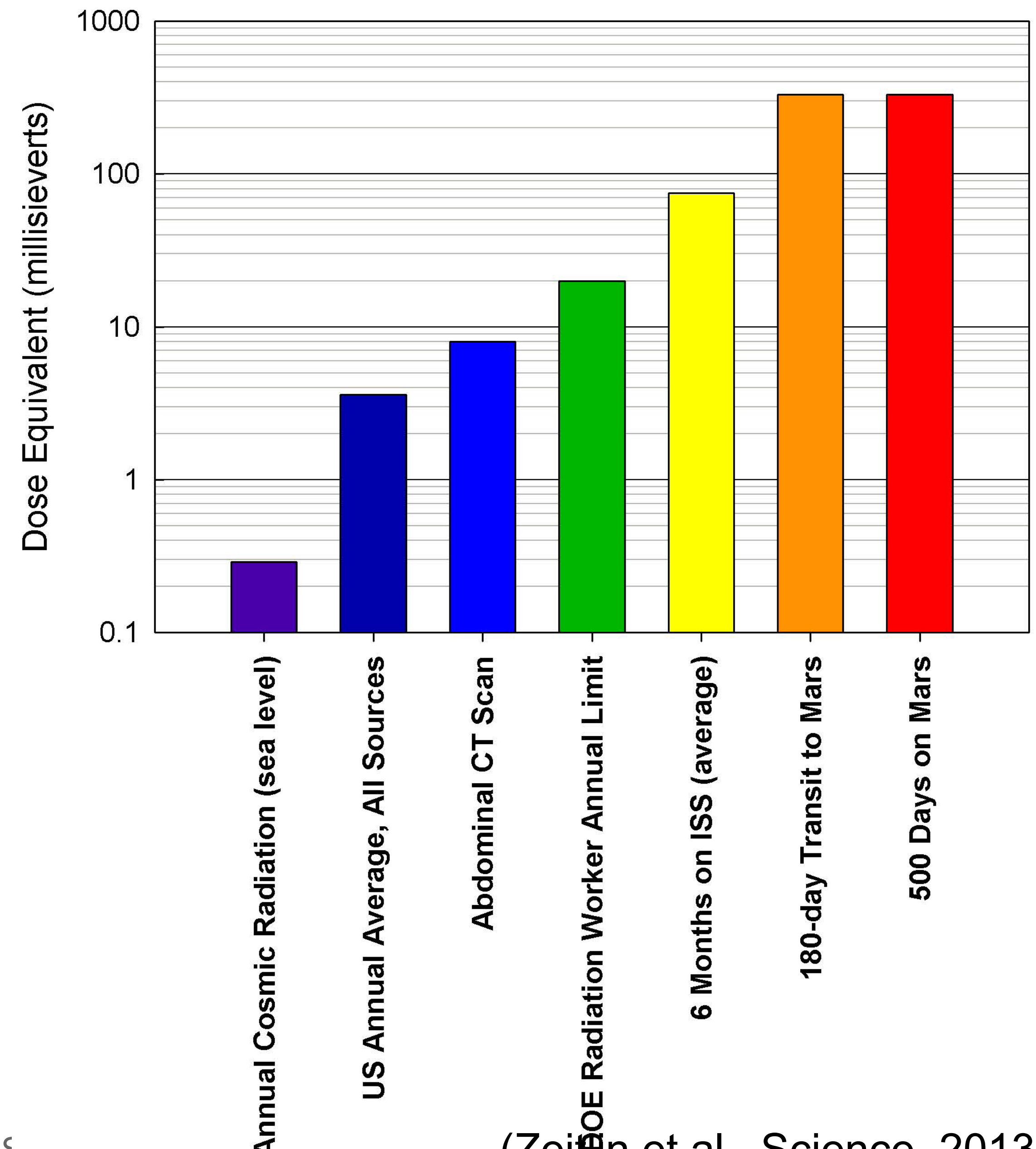
Summary of RAD measurements

Radiation exposure on a mission to Mars:

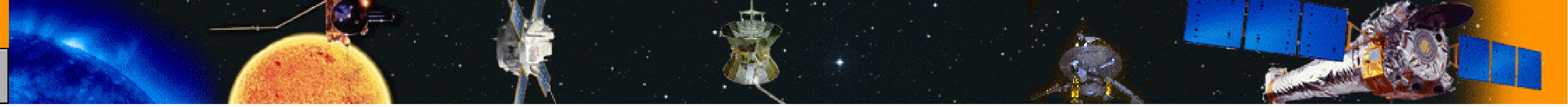
Cruise: 662 +/- 108 mSv
Mars: 320 +/- 50 mSv

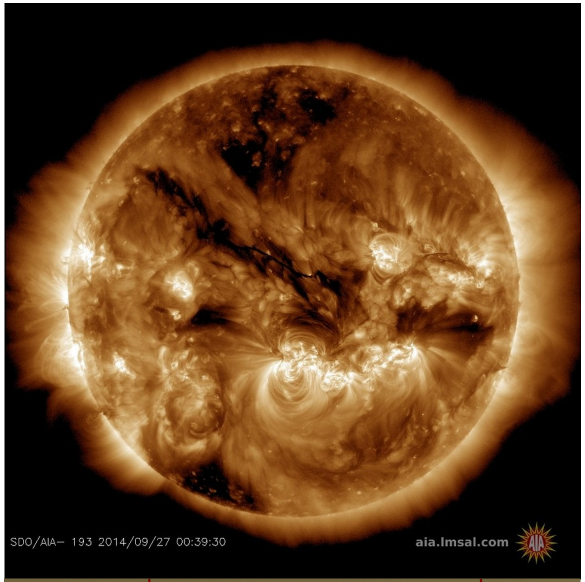
Total ~ 1000 mSv

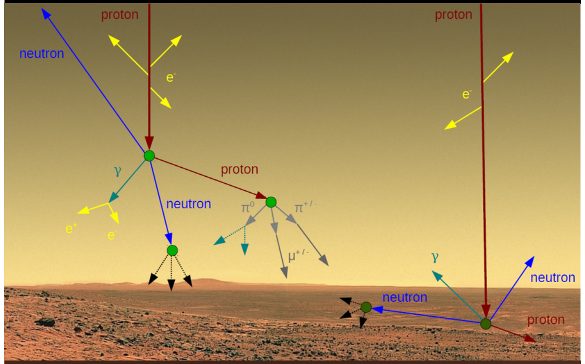
<u>For comparison:</u>
6 months ISS: 75-90 mSv
radiation worker: 20 mSv/y
CT-scan: 8 mSv

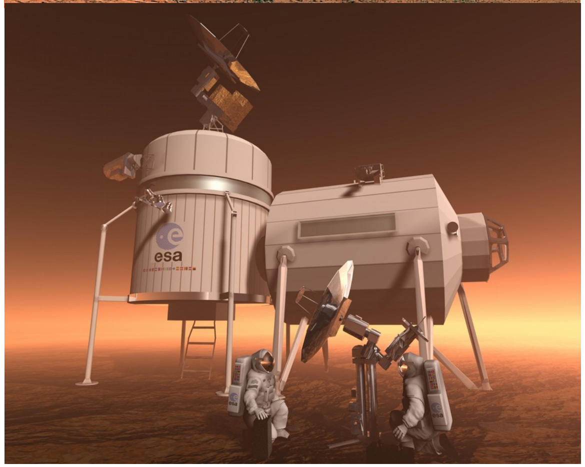


(Zeitlin et al., Science, 2013)









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

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

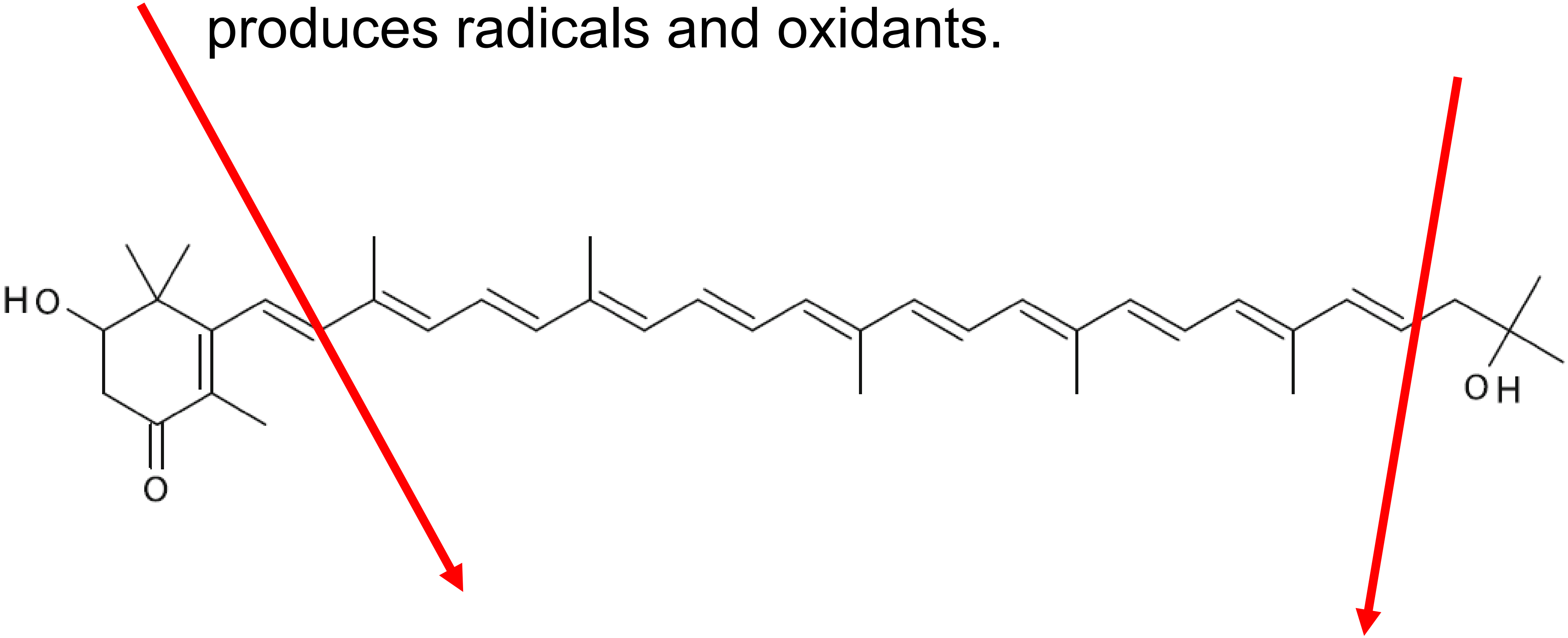
DLR

esa

NASA

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)

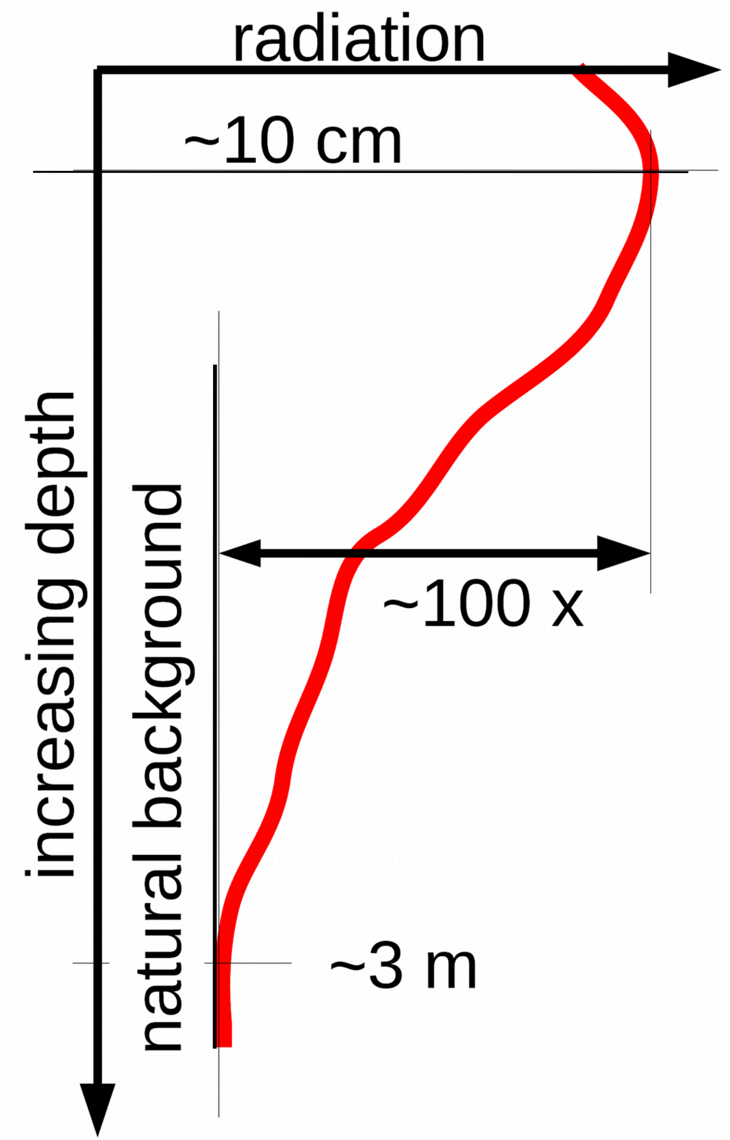
How long could organic molecules survive ionizing radiation environment?

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.

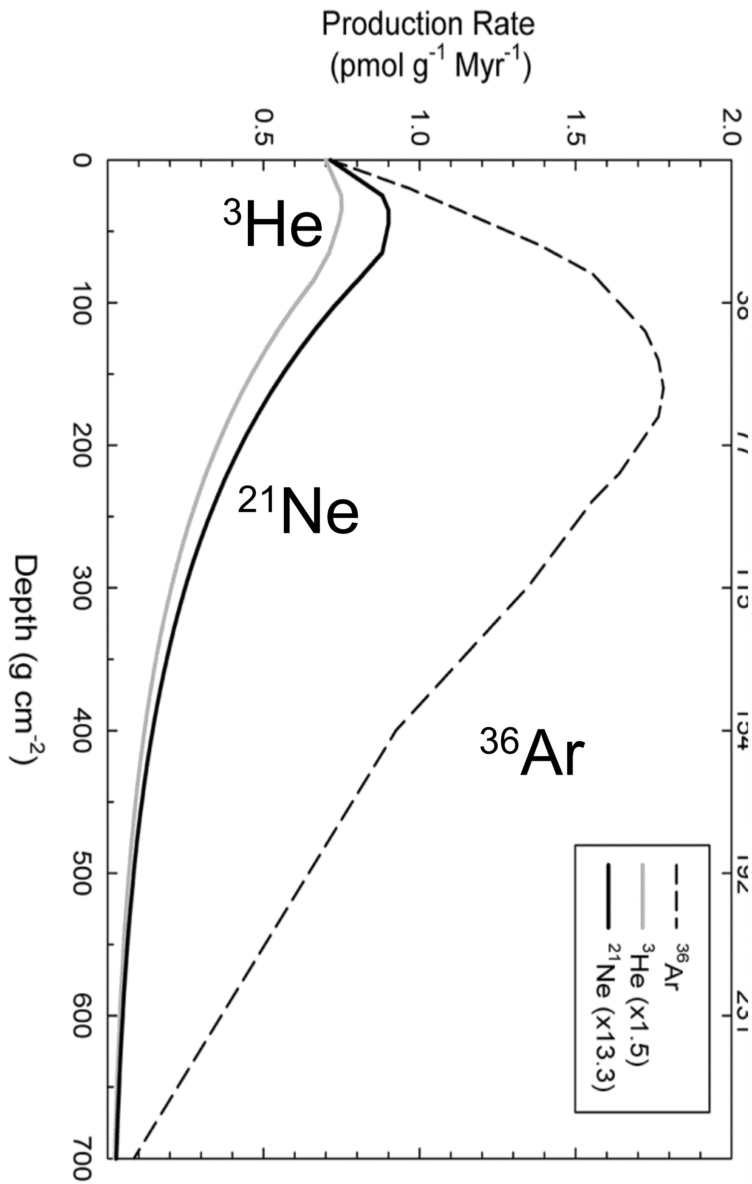
How many after 3.8 Gy?

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

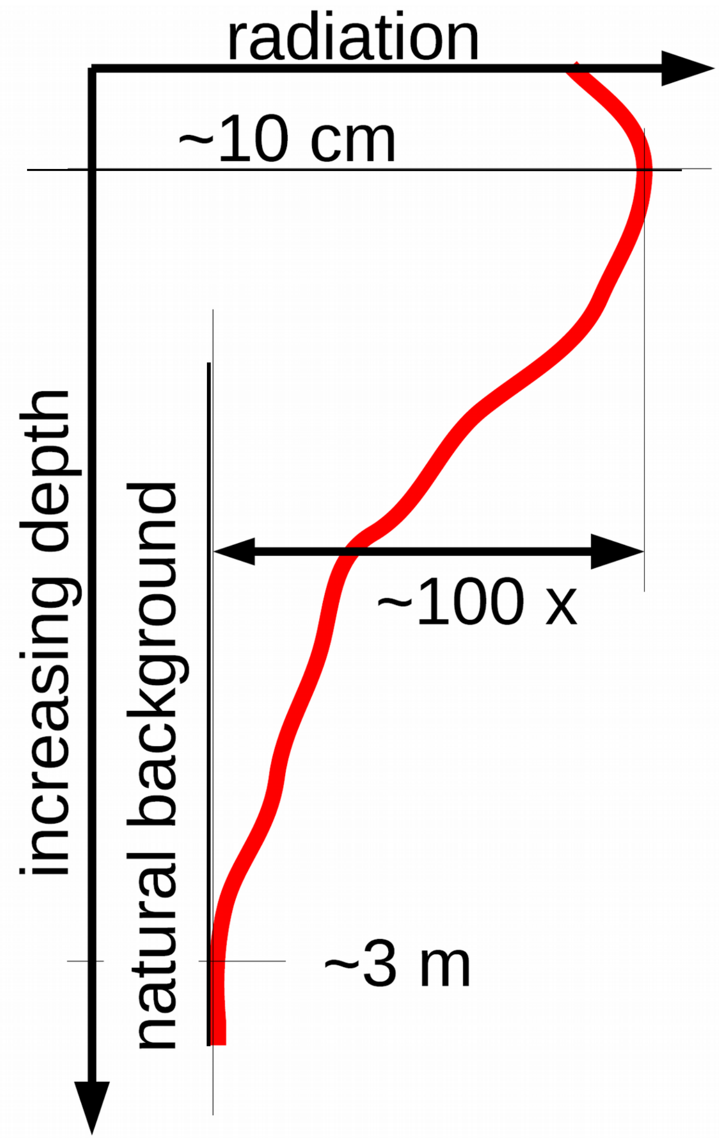


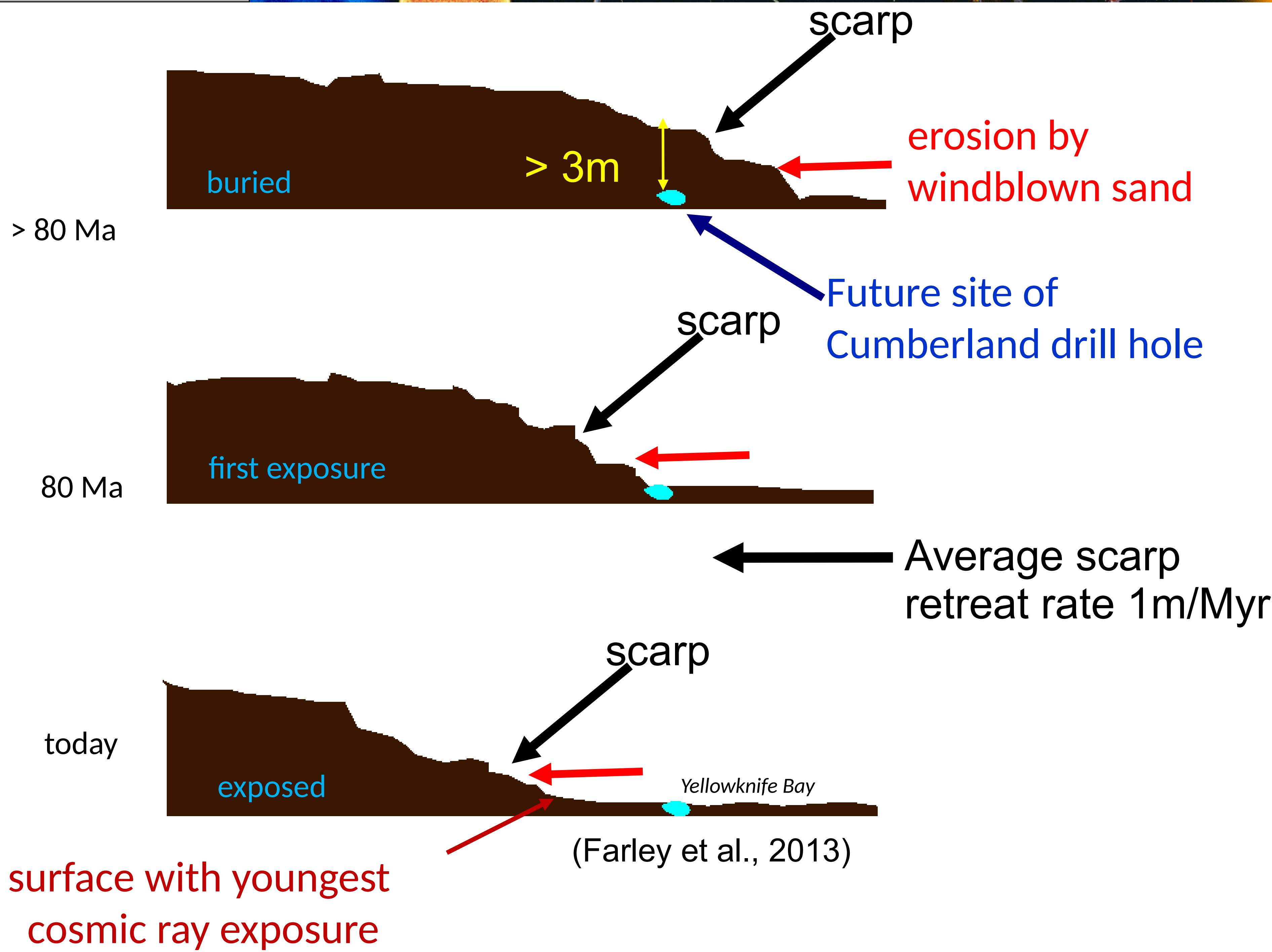
Age determination with cosmogenic isotopes

Sheepbed was exposed for only 80 ± 30 million years!

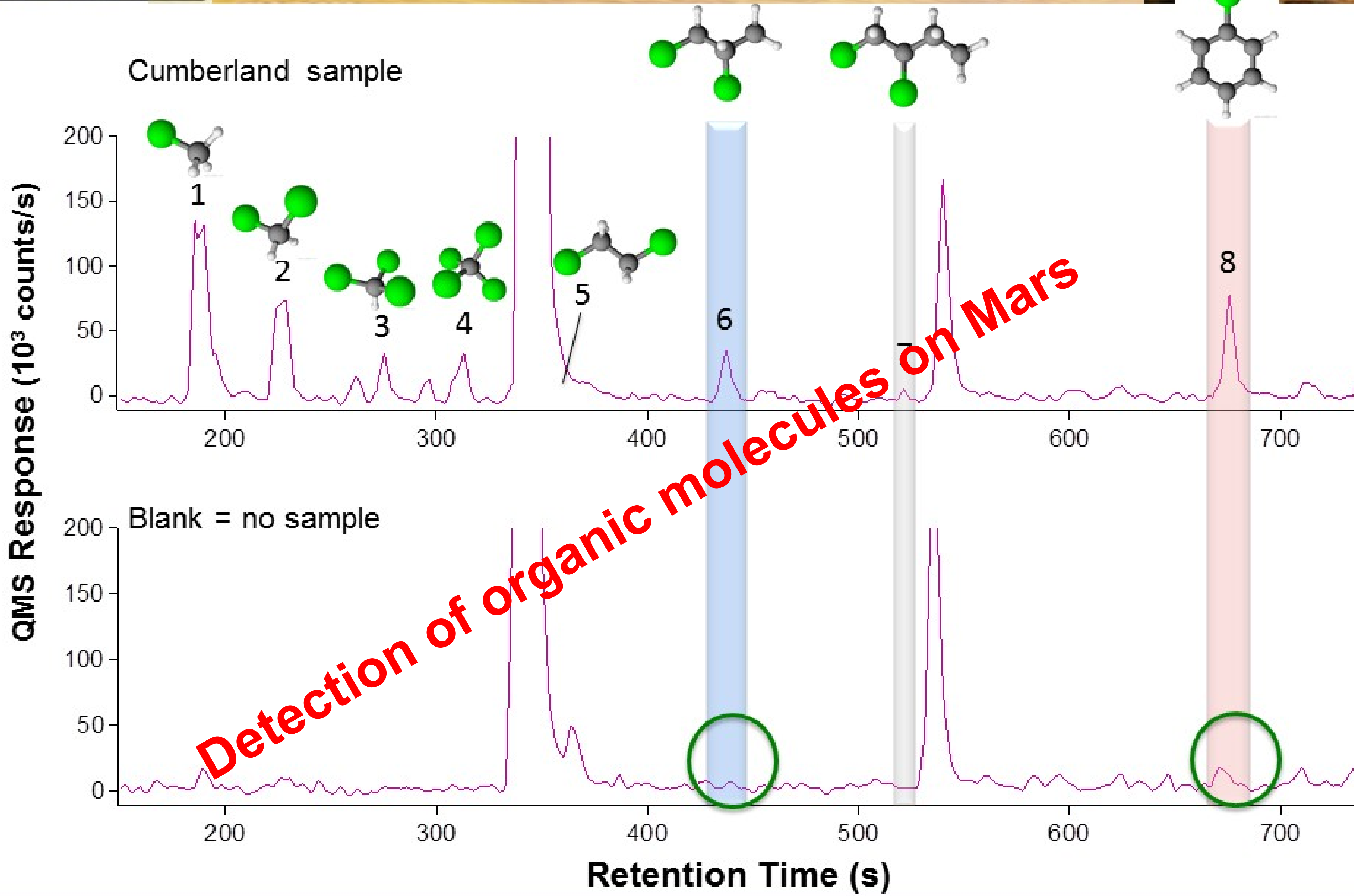


(Farley et al., Science, 2013)




scarp
erosion by windblown sand
> 3m
buried
> 80 Ma
Future site of Cumberland drill hole
scarp
first exposure
80 Ma
Average scarp retreat rate 1m/Myr
scarp
today
exposed
Yellowknife Bay
(Farley et al., 2013)
surface with youngest cosmic ray exposure

Some of the SAM Data



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?

Christian-Albrechts-Universität zu Kiel

Supported by:
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