



Agenzia Spaziale Italiana

UMONS
Université de Mons

**WRMISS: Workshops on Radiation Monitoring for the
International Space Station**

6-8 Sep 2022 Mons (Belgium)



AstroParticle Experiments 4 Space Radiobiology

A. Bartoloni

Istituto Nazionale di Fisica Nucleare
Rome-Sapienza Division,
Rome, Italy

We gratefully acknowledge the strong support from the AMS collaboration and from the Italian Space Agency (ASI) within the agreement ASI-INFN n. 2019-19-HH.0.

6-8/9/2022

1

In the near future, all the space agencies are working to restart the human exploration of space outside the Low Earth Orbit (LEO). Crewed space missions in this and the next decade will see the presence of humans on the Moon and Mars surface. One of the main showstoppers to be investigated for safe exploration and colonization is the biological effects of ionizing radiation that can compromise the health of astronauts/space workers.

The Astroparticle experiments presently operating in space (e.g., AMS02, ACE-Explorer, ...) could play a principal role in this vital task. Such experiments are actual cosmic ray observatories and a source of information crucial to investigating the fundamental physics open problems (e.g., Dark Matter, Antimatter) and improving the knowledge of radiobiology effects in space.

In this paper, a review of the past, present, and planned Astroparticle experiments operating would be presented and highlighted some of the possible contributions and improvements in the space radiobiology research field.

Also, will be presented some examples of progress in understanding the biological effects of radiation in space using the pieces of information acquired for astronomy and Astroparticle science and where such information has been used to enhance the space radiation field characterization and, consequently, improve crucial radiobiological issues in space (e.g., dose-effect models).

Finally, the use of the vast amounts of data taken from such experiments will open a new era of studies performed in different exposure scenarios that will allow a safe human space exploration outside of the Low Earth Orbit by addressing important radiation protection open questions, such as the dose relationship for cancer and non-cancer risk, the possible existence of dose threshold(s) for different biological systems and endpoints, and the possible role of radiation quality in triggering the biological response.

Outline

- ◇ AMS INFN Roma Sapienza Research Group
- ◇ Space Radiation Environment
- ◇ Cosmic ray Detectors in Space
- ◇ Possible synergies
- ◇ Case Study :
 - ◇ Dose Effects Relationship (DER)
 - ◇ Target Effects vs Non Target Effects

INTRODUCTION

Alpha Magnetic Spectrometer (AMS)

INFN ROMA SAPIENZA RESEARCH GROUP



The AMS SPRB collaboration was created in 2017 by the synergy of the AMS INFN Roma Sapienza (Italy) group led by Alessandro Bartoloni with the medical physics research group led by Lidia Strigari currently at IRCCS university Hospital of Bologna (Italy)

Alpha Magnetic Spectrometer AMS02

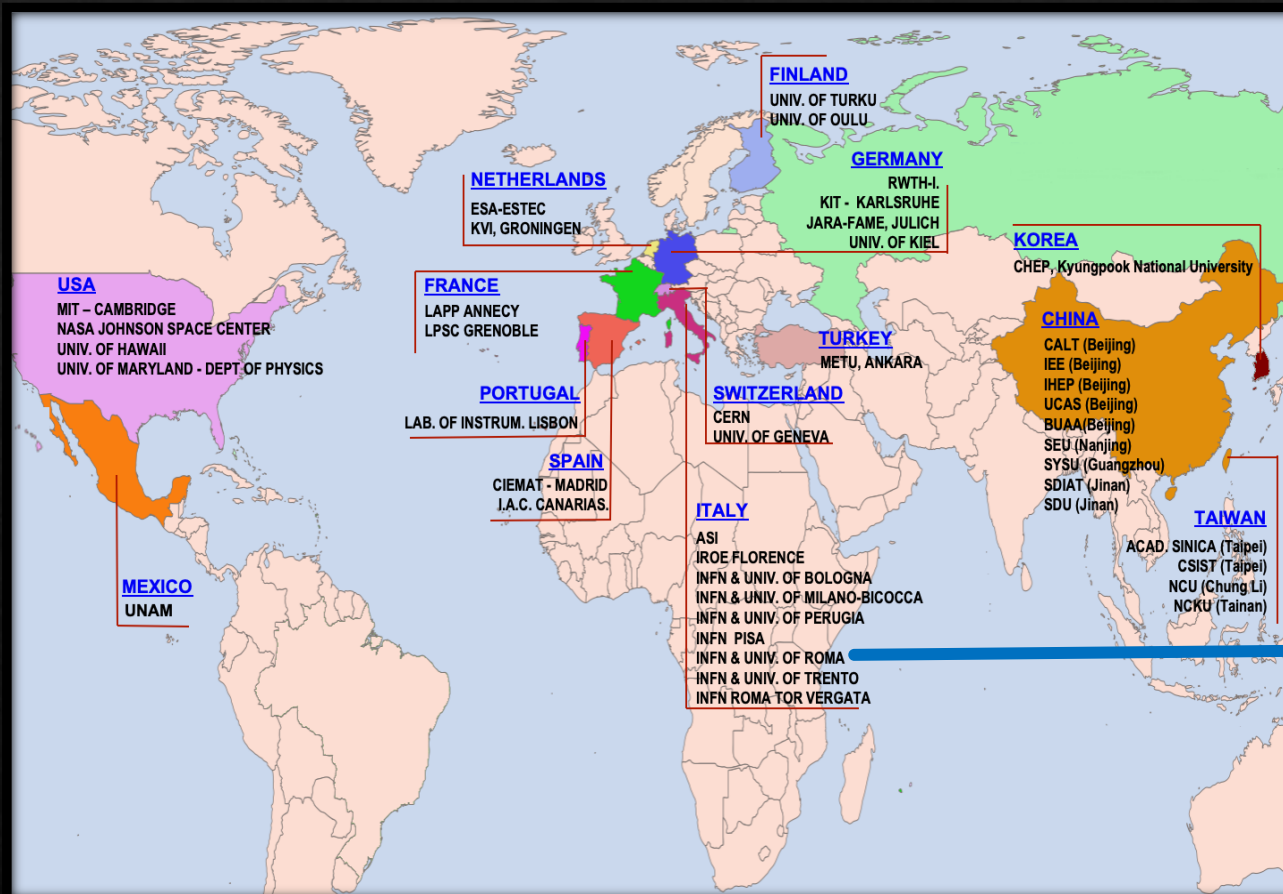
AMS is a particle detector measuring Galactic Cosmic Ray fluxes.
It was installed on the International Space Station (ISS) on May 19, 2011



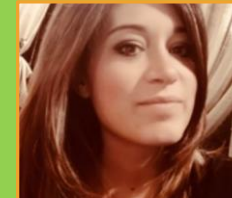
A. Bartoloni - 25th WRMISS



6-8/9/2022



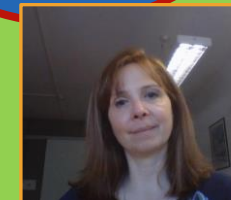
Silvia Strolin



Miriam Santoro



Lidia Strigari



Aboma Negasa Guracho



Alessandro Bartoloni



Giuseppe Della Gala



Giulia Paolani



The AMS collaboration

(<http://ams02.space>)

An international collaboration made of 44 Institutes
from America, Asia and Europe

A. Bartoloni - 25th WRMISS

The AMS02 detector has collected so far more than **200 billion** Cosmic Rays events.

More Info in the AMS-02 webpage:

<https://ams02.space>

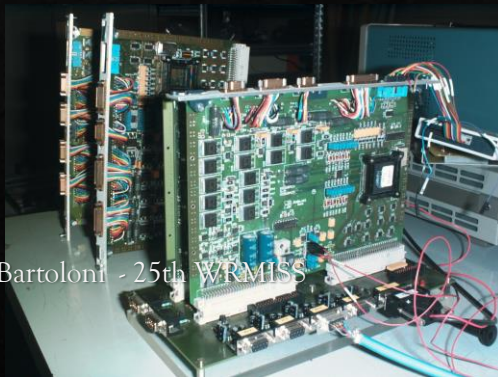
6-8/9/2022



The INFN Roma and the Sapienza university joined the AMS collaboration in 2001.

The group has taken part to the construction of the **Transition Radiation Detector (TRD)**, having as main task the responsibility to develop the slow control electronics of the GAS System of the TRD (UG-Crate).

The UG-CRATE was part of a safety-critical system and the group took care of all the phases of the development (Design-Test-Integrate-Fly) following the NASA requirements.



A. Bartoloni - 25th WRMHSS





At INFN Roma AMS group, led by **Alessandro Bartoloni**, the primary activity is the use of the AMS measurements of cosmic rays to improve the space radiobiology knowledge with a primary emphasis on *the space radiation relevance and risk for human space exploration*.

In this topic, there is a strong collaboration and participation to the Roma group of the Medical Physics department of the IRCCS University Hospital of Bologna, led by **Lidia Strigari**.



Dr. Lidia Strigari

Medical Physics Department

IRCCS Azienda Ospedaliero-Universitaria di Bologna, Italy

A. Bartoloni - 25th WRMISS



SPACE RADIATION & ASTRONAUT SAFETY

«To fully understand the relationship between ionizing radiation and biology, and to solve problems in this field, researchers incorporate fundamentals of **biology, physics, astrophysics, planetary science, and engineering**» *(credit : NASA)*

(credit : ESA)

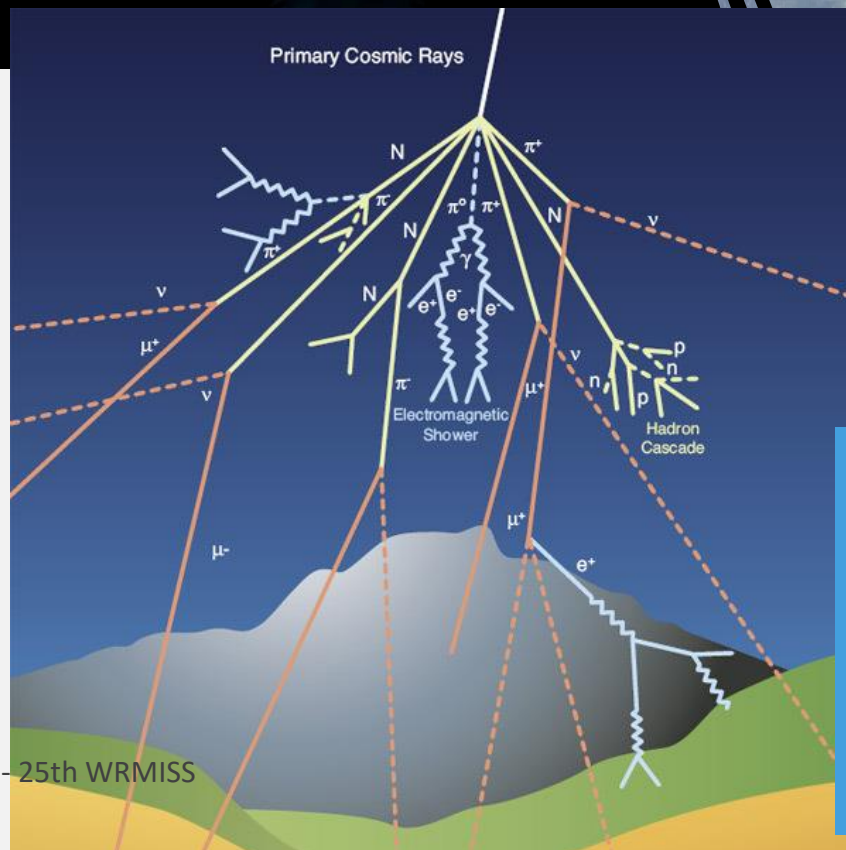


Cosmic Rays Interactions with the geo-magnetosphere

Earth is a cocoon !!!

Magnetosphere stops/deflects 99.9% of charged particles

the Earth Atmosphere is equivalent to a metal shielding 1 meter thick



The annual cosmic ray “dose” at sea level is around **0.27 mSv**

<10% of “background radiation”
(Radon, Soils, Foods, Medical,..)

Origin of Space Radiation and Consequent Risk

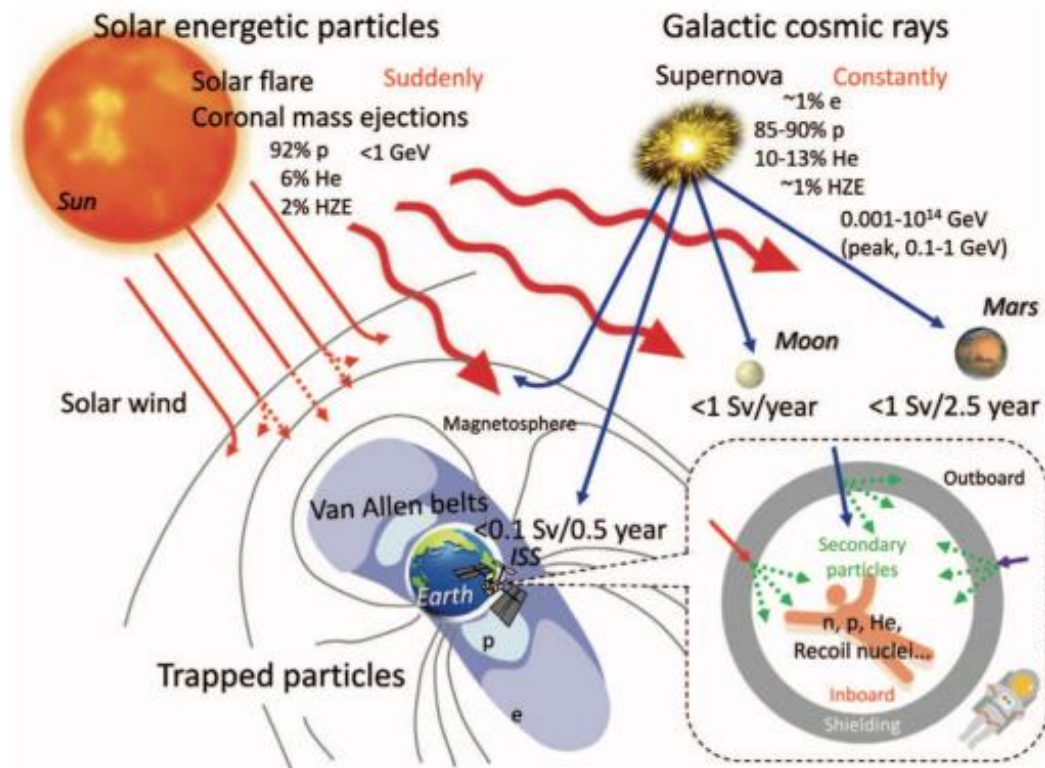
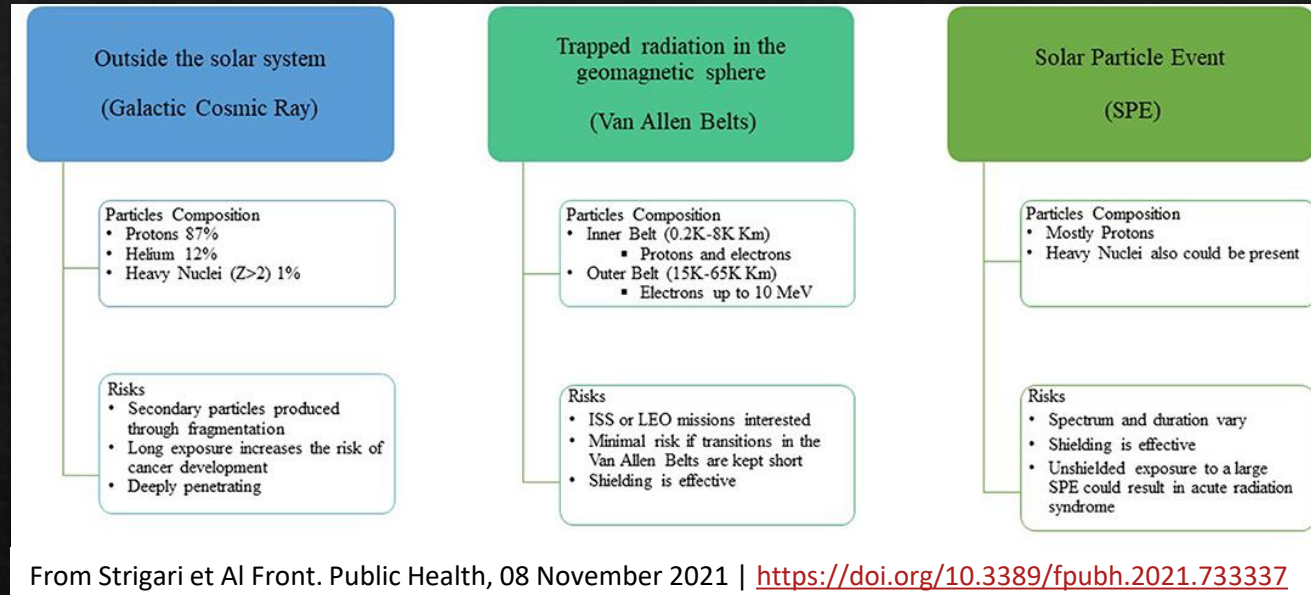


Image courtesy of European Space Agency (ESA)



From Strigari et Al Front. Public Health, 08 November 2021 | <https://doi.org/10.3389/fpubh.2021.733337>

Space Radiation composition

- Galactic Cosmic Rays (GCR)
- Particle emitted by the Sun (SEP) during isolated events
- Particle trapped in Earth's magnetic field (Radiation Belt)

None of the 3 components is constant in time, mainly due to the solar activity

Human Space activities must cope with the high radiation environment of outer space.

Limits and concerns

The manned spaceflight especially the one beyond the LEO could represent a concern for the health of astronauts.

x150-200



LEO-ISS

The limit in carrying out the missions are due to health effects

- short-term (<hours)
- acute effects (<months)
- late effects including severe toxicity

x300-400



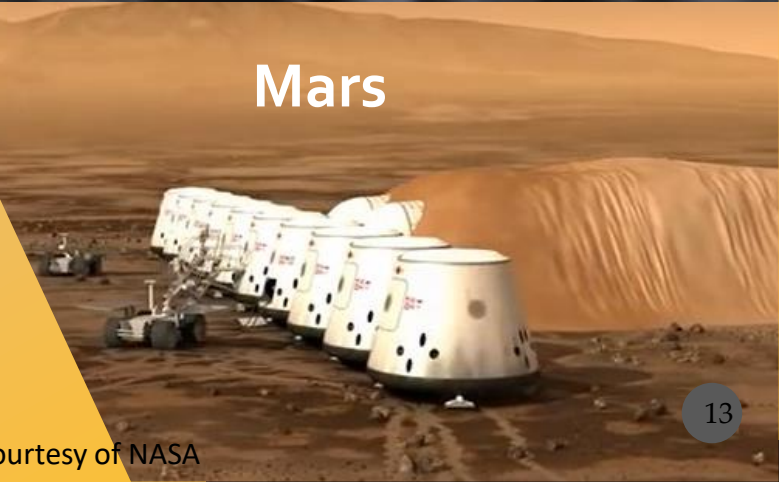
Moon

Radioprotection in space is a difficult jobs due to the presence of different species of particle and nuclei that present different characteristics in penetrating the barrier and shielding

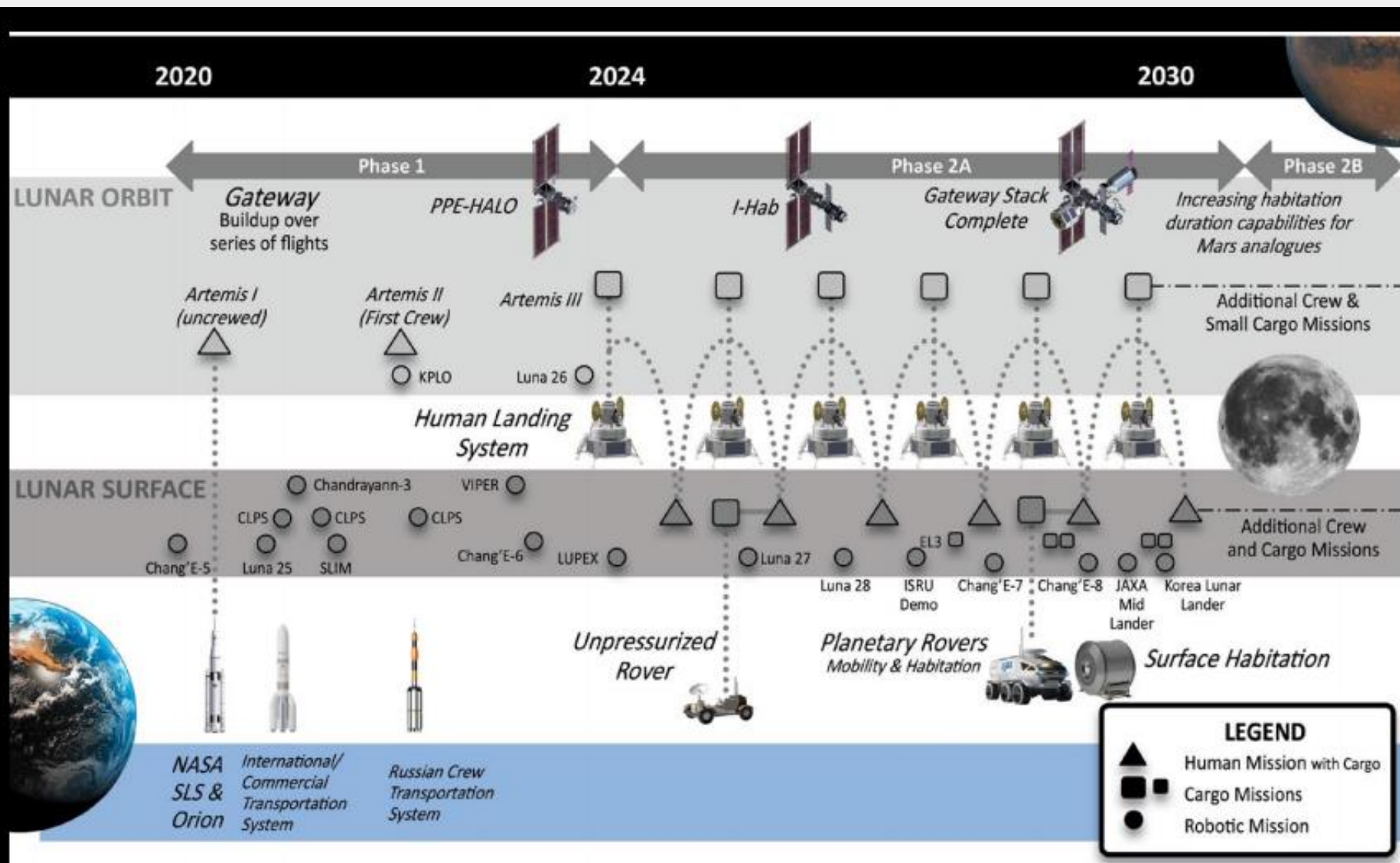
x250 (x750)

we will go to the moon we
SS 300 kilometers from

Mars



A new era in human space exploration is coming ...



«Global Exploration Roadmap Lunar Surface Exploration Scenario update August 2020»

International Space Exploration
Coordination Group
(ISECG)

Figure 1. Updated ISECG Lunar Surface Exploration Scenario.
A. Bartoloni - 25th WRMISS



The International Space Exploration Coordination Group (ISECG) is a forum set up by 14 space agencies to advance the Global Exploration Strategy through coordination of their mutual efforts in space exploration.

BLEO Space Exploration is restarted ! (IAC2021 . 11/2021)

Projected Exploration Missions (2020-2030)

Data include announced missions, with dates as announced, and projected missions (likely missions such as typical supply missions to space stations), with estimated dates.



International Space Station

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
SpaceX Cargo	3	1	1								
Northrop Grumman Cargo	2	1	2								
Siemens Nevada Corp.	1	1									
Cargo TBD				1	4	4	4	4	4	4	4
Demo-2 Endeavour	1										
Boe-OST 2	1										
Boe-CFT	1										
Commercial Crew	1	2	2	2	2	2	2	2	2	2	2
Soyuz Crew	4	2	2	2	2						
Orel Crew						2	2	2	2	2	2
Progress	2	2	2	2	2	2	2	2	2	2	2
HTV	1	1	1	1	1	1	1	1	1	1	1
Axiom 1					1	1	1	1	1	1	1

Chinese Space Station

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Shenzhou	1	1	1	1							
NG Shenzhou	1	1			1	1	1	1	1	1	1
Tianhe 1				1							
Wentian				1							
Mengtian				1							
Kunlun					1						
Tianzhou	1	1	1	1	1	1	1	1	1	1	1

152 Crew and cargo missions to LEO



As of August 31, 2020

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Chang'e 5	1										
Chang'e 6				1							
Chang'e 7					1						
Chang'e 8						1					

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Luna 25		1									
Luna 26				1							
Luna 27					1						
Luna 28 (sample return)						1					
Luna 29							1				
Orel (uncrewed circumnavigation)					1						
Orel (crewed circumnavigation)						1					
Orel (crewed landing)							1				

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Artemis	1			1	1	1	1	1	1	1	1
Human Landing System (HLS)				1	4	4	4	4	4	4	4
Lunar Gateway PPE and HALO				1							
Lunar Gateway Hub					1						
Lunar Gateway JAXA Logistics Habitat						1					
Lunar Gateway JAXA Pressurized Rover							1				
Lunar Gateway Logistics Services (GLS)					1	1	1	1	1	1	1
Artemis Base Camp Foundation Habitat								1			
Artemis Base Camp Mobility Habitat									1		
Artemis Base Camp Logistics Mission										1	
Commercial Lunar Payload Services (CLPS)		2	2	2	2	2	2	2	2	2	2
CAPSTONE		1									

95 Missions to the Moon

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
ORACLES ELB (ESA, JAXA, CSA)							1				
Moon Cruiser 1 Logistics Mission (with ESPRIMO)								1			
PTScentists ALUNA		1									
Spacebit Mission 1		1									
Chandrayaan 3			1								
Rakuto-R Mission 1				1							
Rakuto-R Mission 2					1						
JAXA SLIM					1						
ESA's Pathfinder Lunar Orbiter						1					
Lunar Surface Access Service (LSAS)							1				
SpaceX dearMoon Project								1			

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Mars 2020	1										
NASA MNG Sample Return Mission							1				
NASA MNG Mission TBD 1								1			
NASA MNG Mission TBD 2									1		

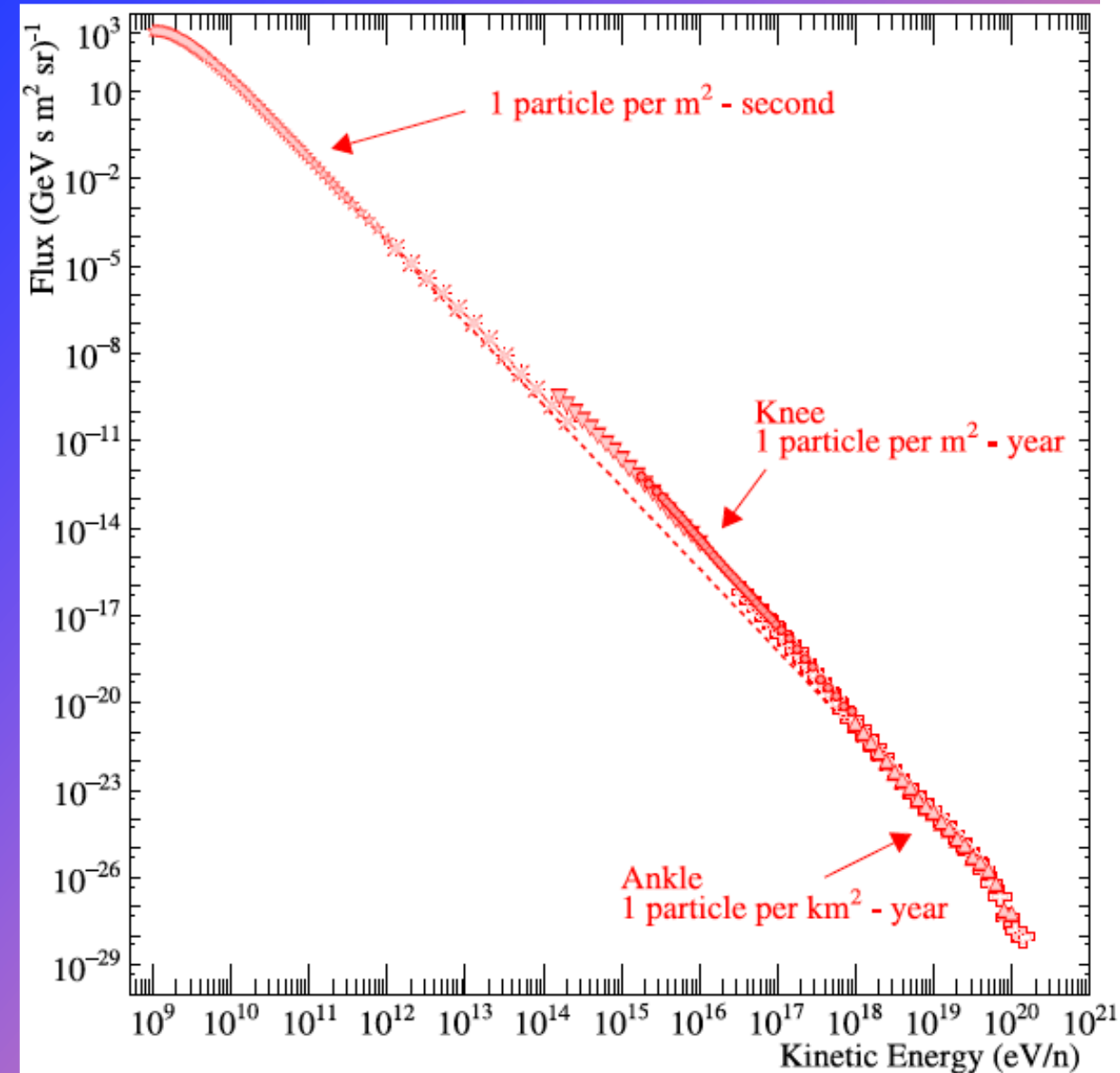
11 Missions to Mars

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Tianwen 1 Rover	1										

Mission	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
ExoMars 2022			1								
Mangalyaan-2					1						
JAXA TEREK 1				1							
JAXA TEREK 2						1					
JAXA MMX							1				
UAE Hope	1										

Cosmic Ray Detectors in Space

«



Credit C.Sparvoli

Energetic particles and completely ionized nuclei from outer space

Many orders of magnitude in energy and flux

$E < 100 \text{ TeV}$: direct detection

$E > 100 \text{ TeV}$: detection of extensive-air-shower

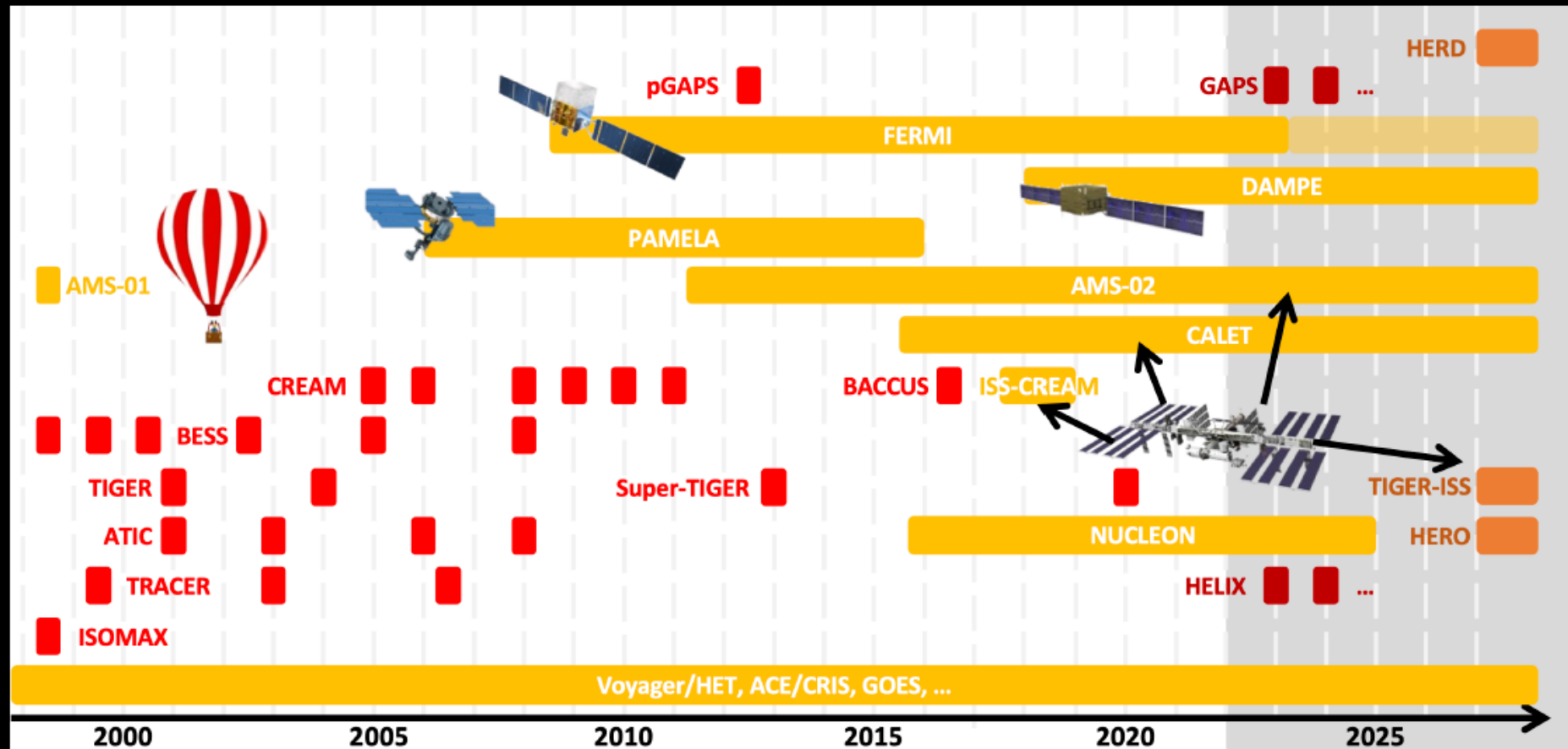
The all-particle spectrum is a “power law” in many orders of magnitude of energy and intensity

with several features (*knee, ankle, ...*)

$\gamma = 2,7$ for energy $< 100 \text{ TeV}$

$\gamma = 3,3$ for energy $> 100 \text{ TeV}$

Timeline of Direct Measurement of CRs from 2000

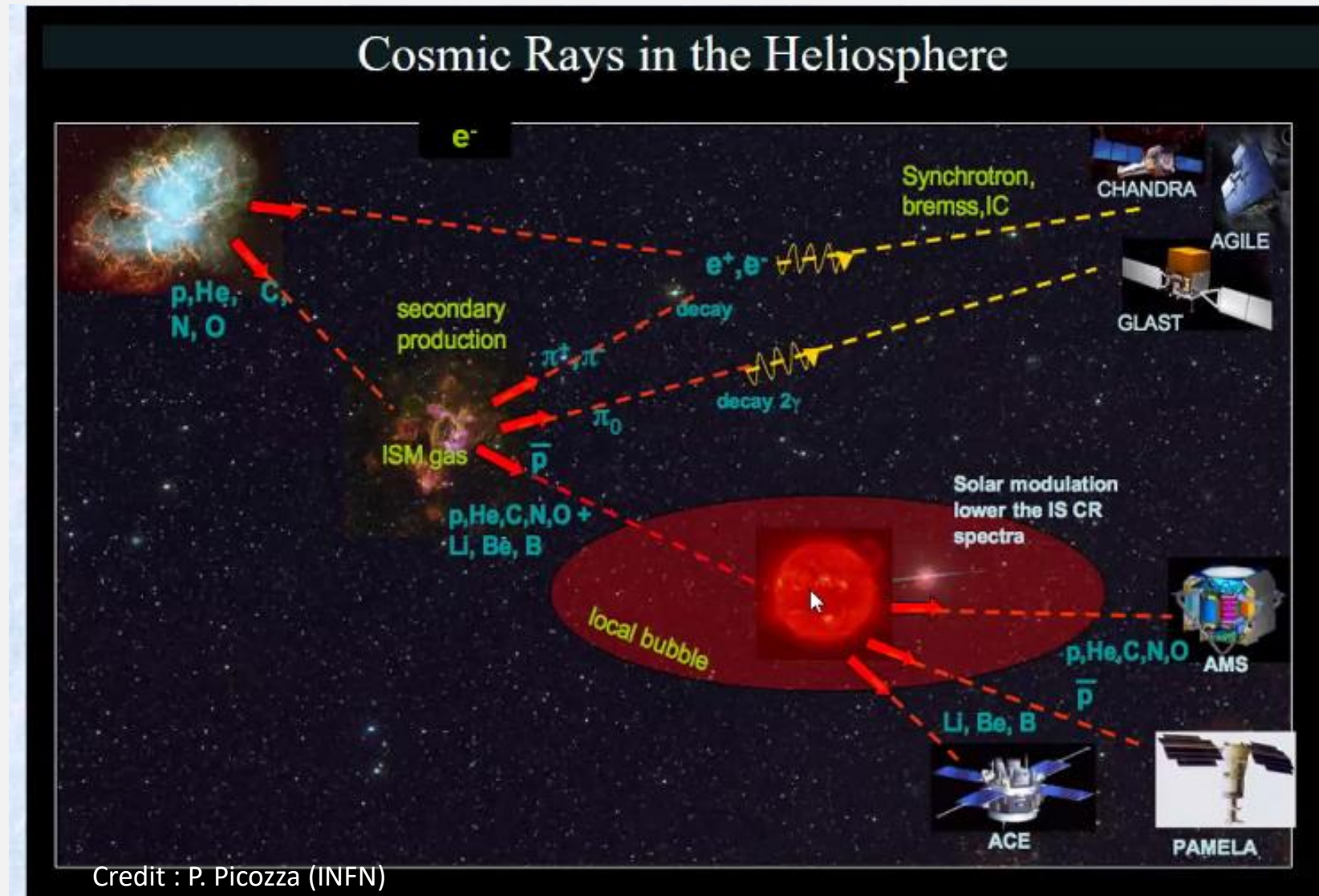


3 possible platform for instruments and detectors
balloons , Satellites , International Space Station

Cosmic Ray Observatory

“A **cosmic-ray** observatory is a scientific installation built to detect high-energy-particles coming from space called **cosmic rays**.

This typically includes photons (high-energy light), electrons, protons, and some heavier nuclei, as well as antimatter particles.



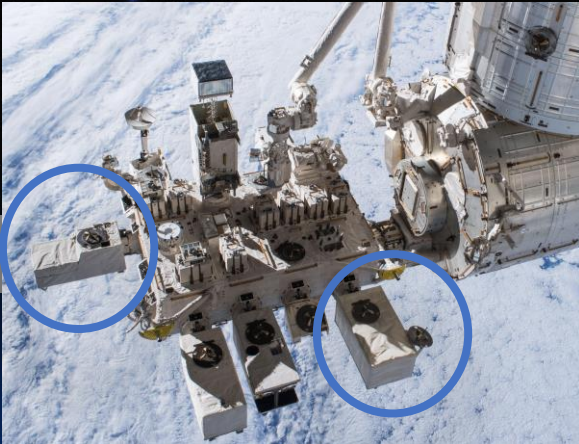
Principal Operating Cosmic Ray Space Detectors

International Space Station based



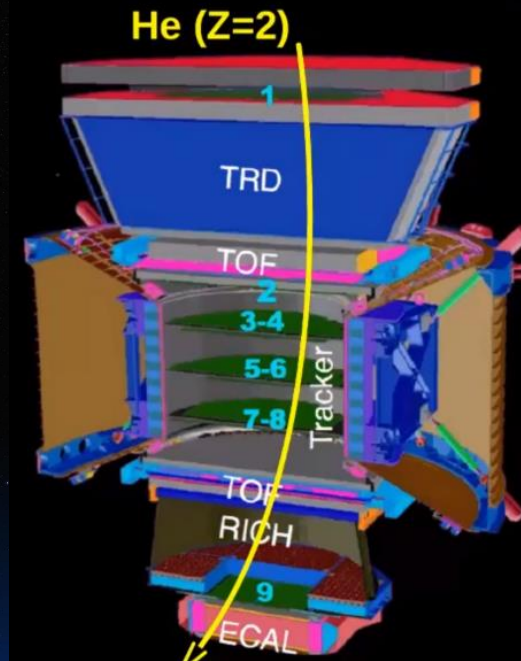
AMS02 – 2011

CALET - 2015



ISS-CREAM – 2017-2019

an ensemble of instruments
each one designed to
capture and measure the
cosmic ray particles



Satellite Based

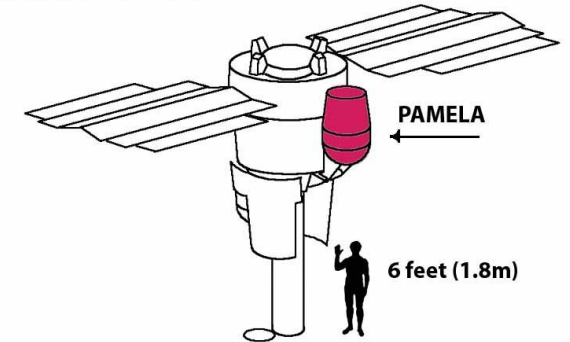


ACE - 1997



DAMPE - 2017

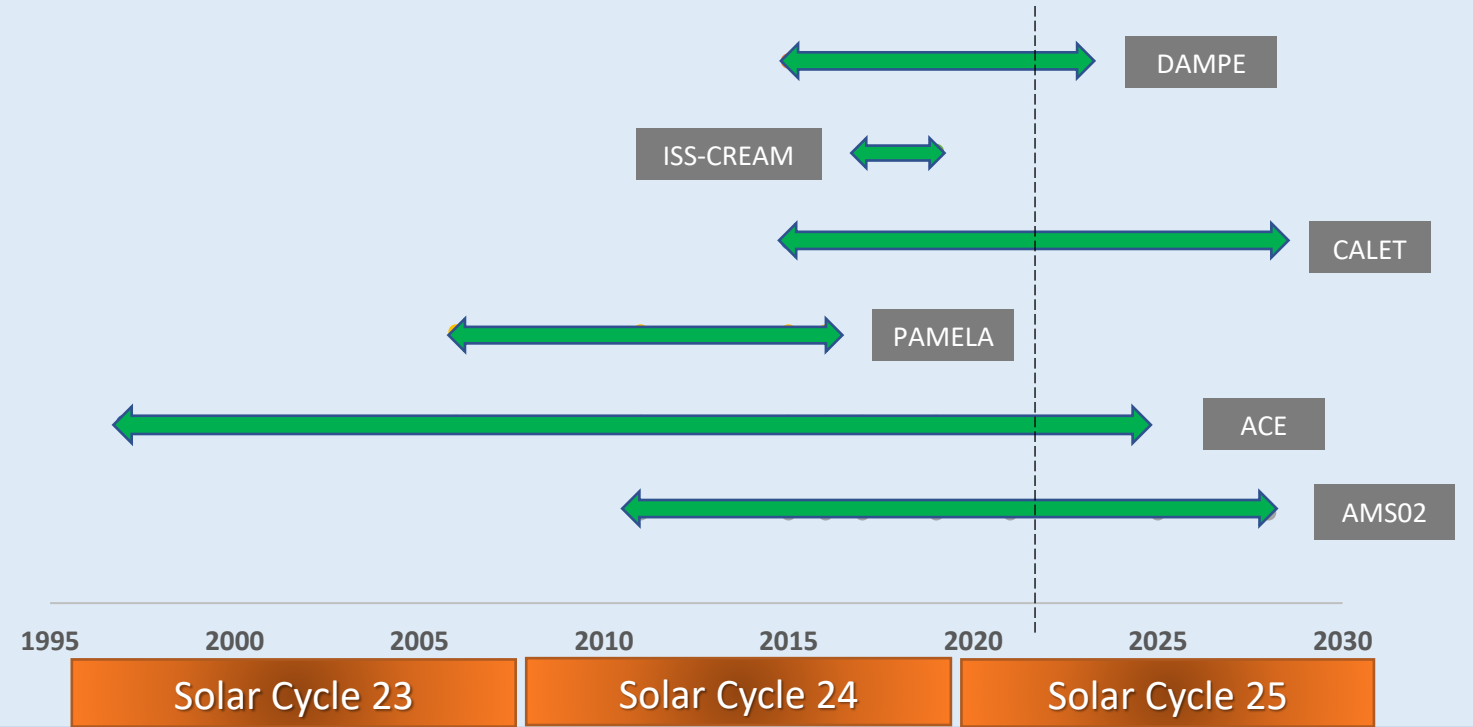
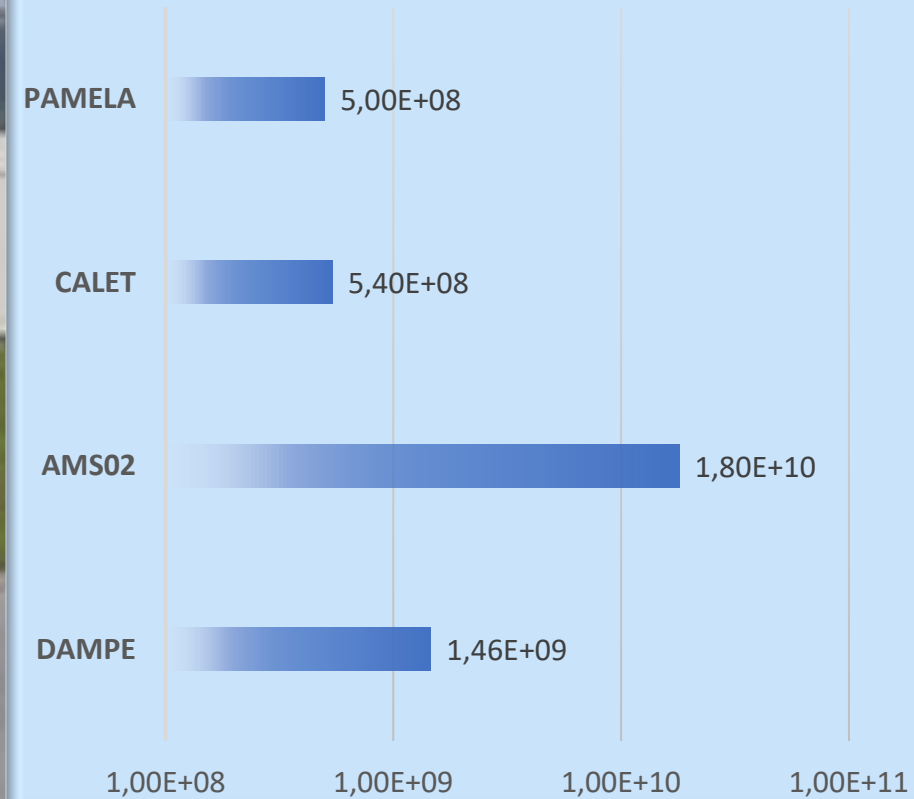
Resurs-DK
Reconnaissance Satellite



PAMELA – 2006-2016

Missions Operations

CR EVENTS/YEAR (BILLION)



Cosmic Ray Components Identification

e^+, e^- ✓ ALL

p^+, p^- ✓ ALL

D, He ✓ ALL

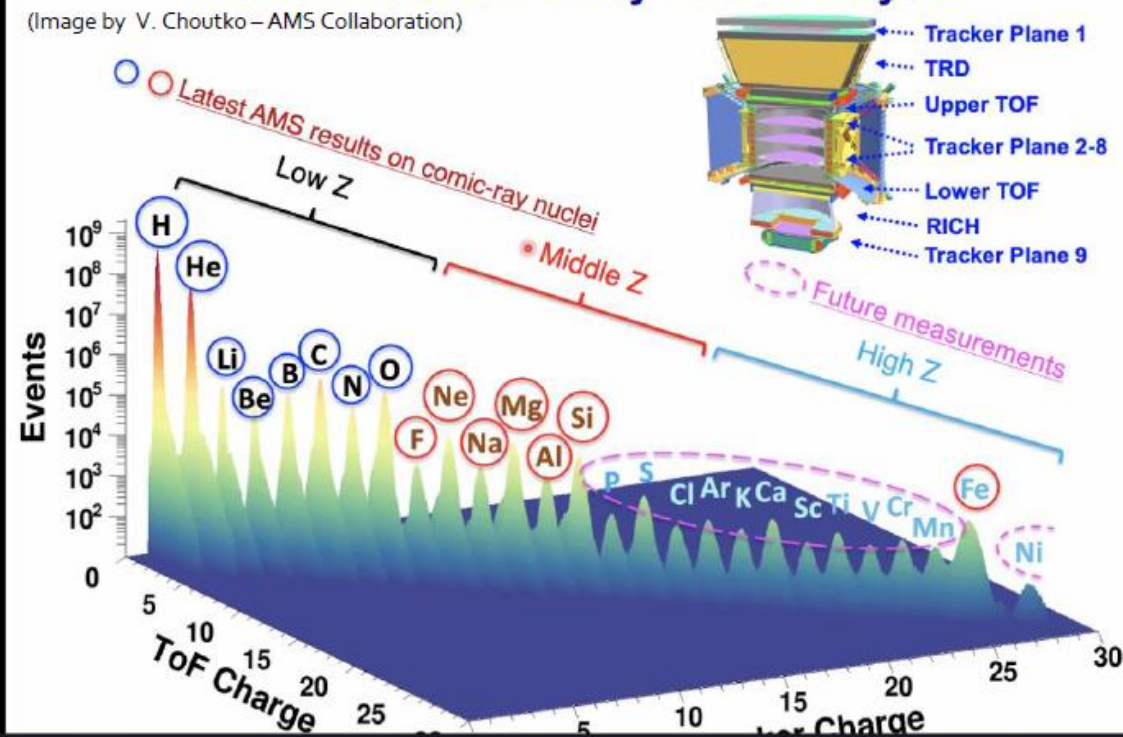
Low-Z (≤ 8) ✓ ALL (PAMELA up to $Z=6$)

Middle-Z ✓ AMS02, CALET, ISS-CREAM, ACE, DAMPE

High-Z (>14) ✓ AMS02, CALET, ISS-CREAM, ACE, DAMPE

Future AMS Cosmic-Ray Nuclei Analysis

(Image by V. Choutko – AMS Collaboration)



Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer

AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Jan 29, 2021)

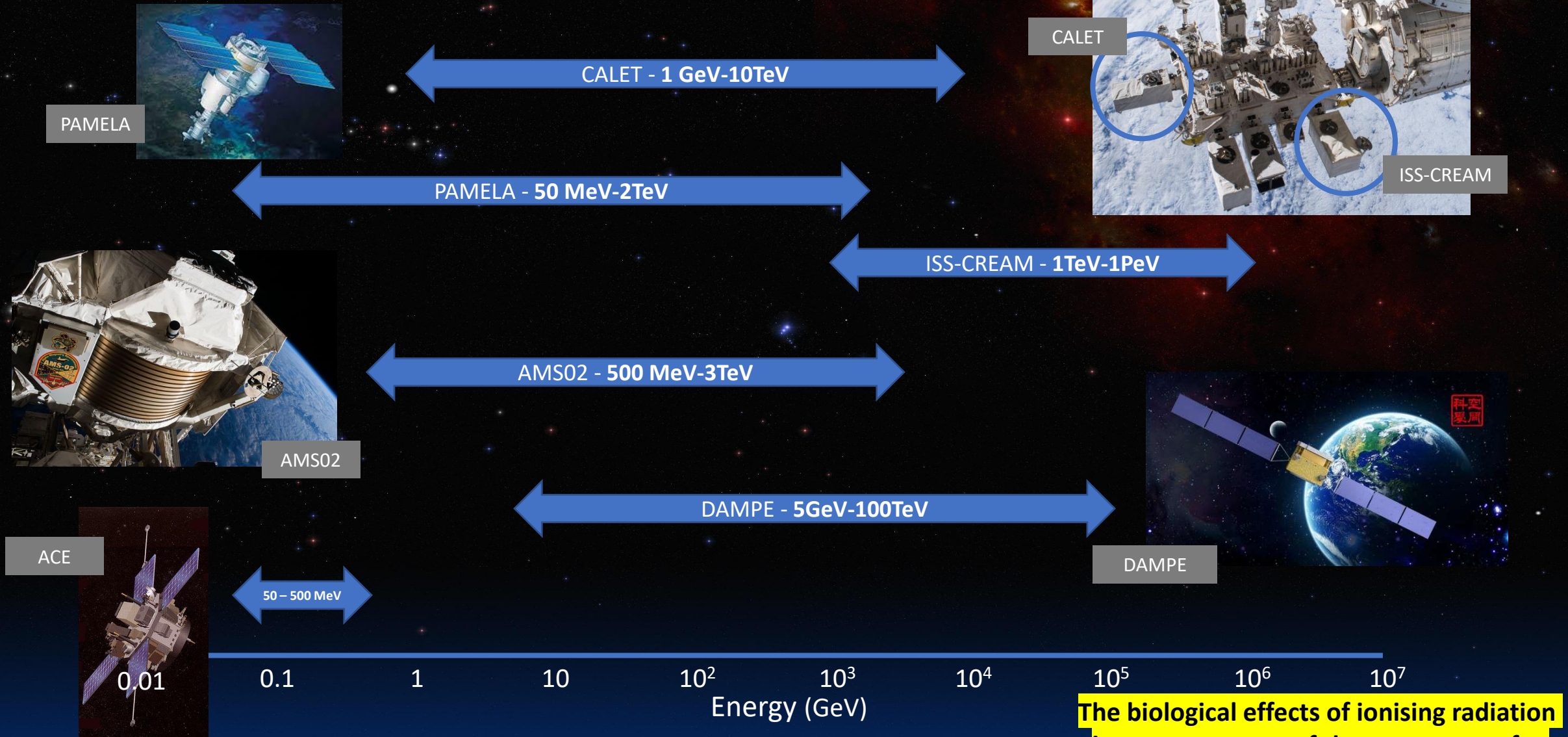
Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041104

Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer

AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Feb 25, 2021)

Published in: *Phys.Rev.Lett.* 126 (2021) 8, 081102

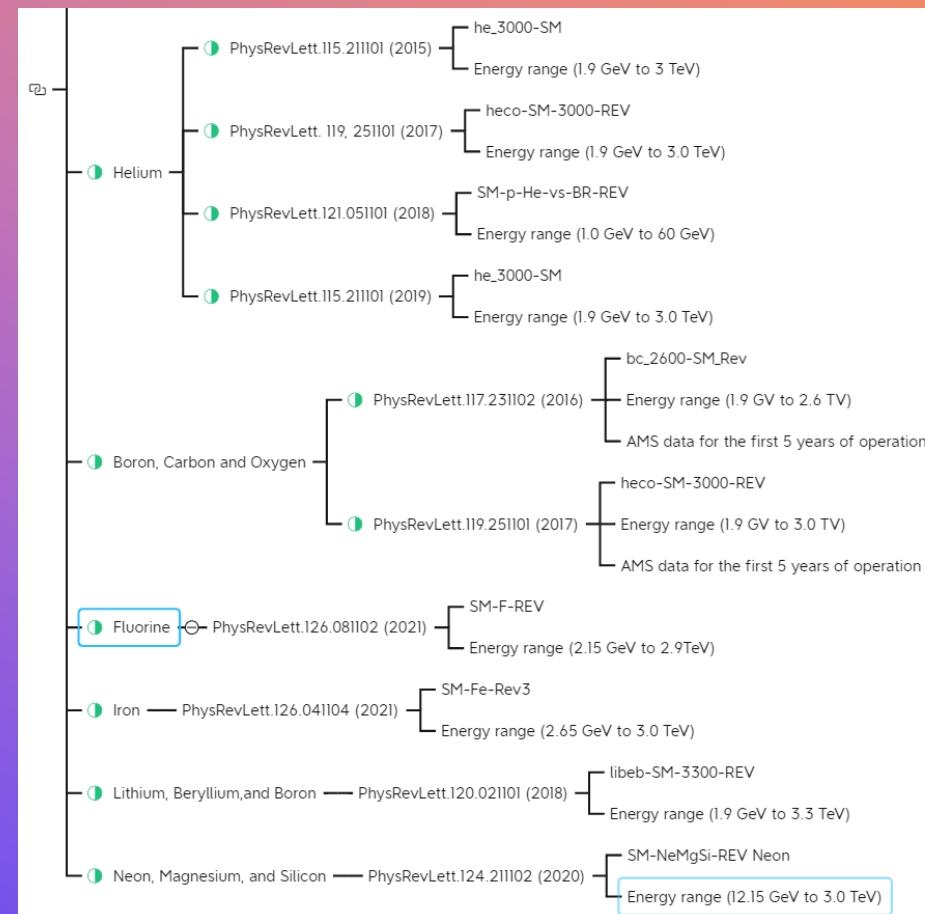
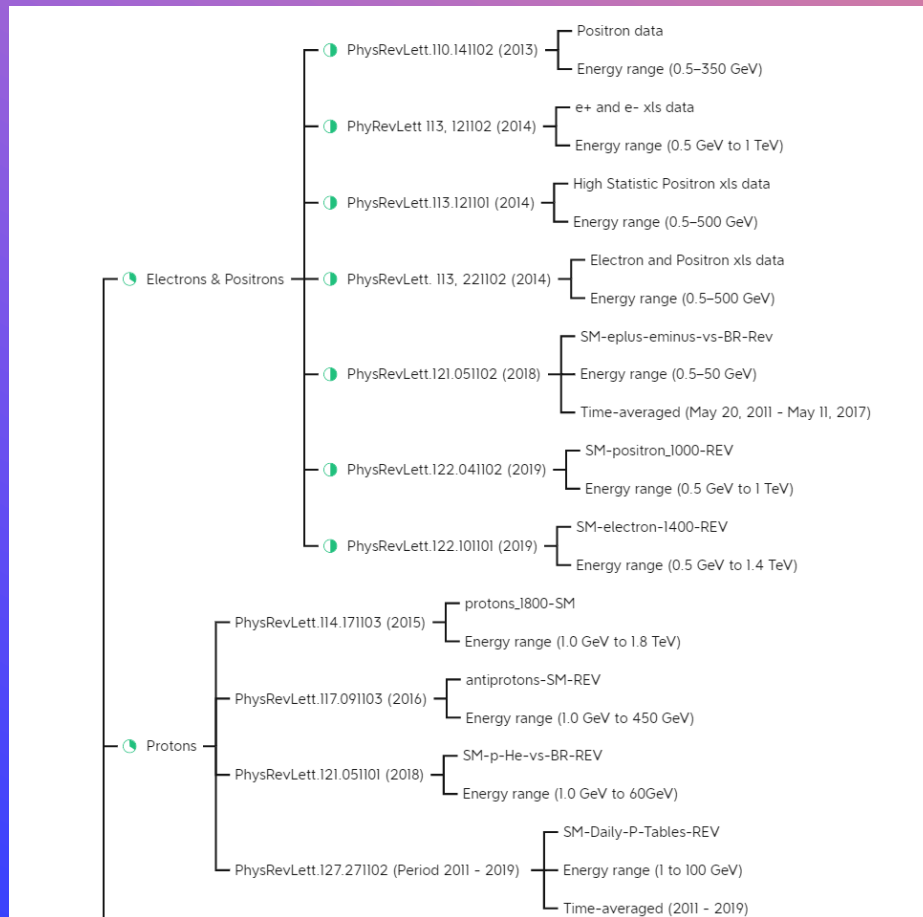
HEP-APE Energy Range

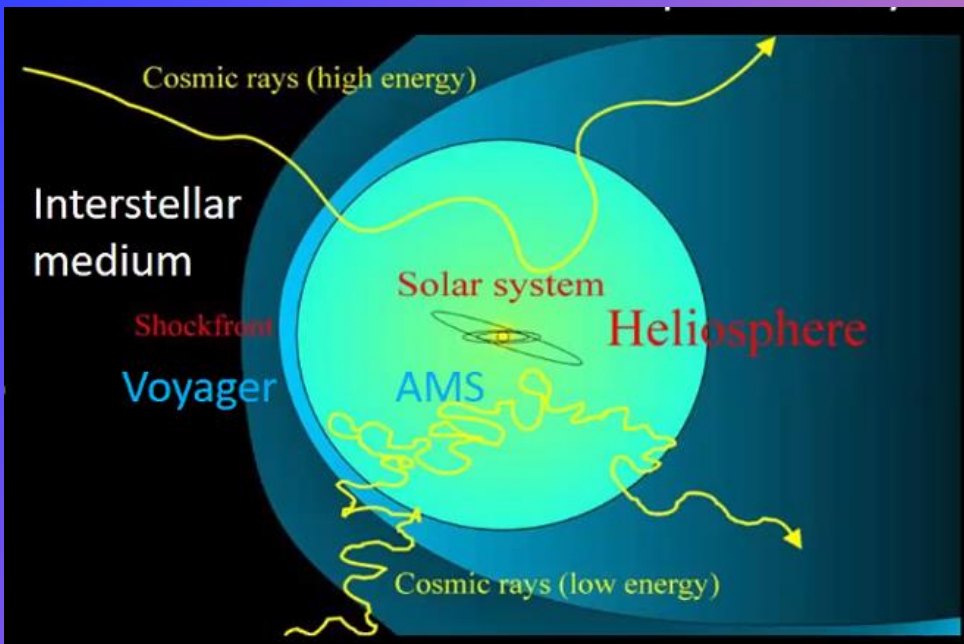


The biological effects of ionising radiation is a consequence of the energy transfer by ionization and excitation to body cells

AMS02 PUBLISHED CRS

A. BARTOLONI - 25TH WRMISS



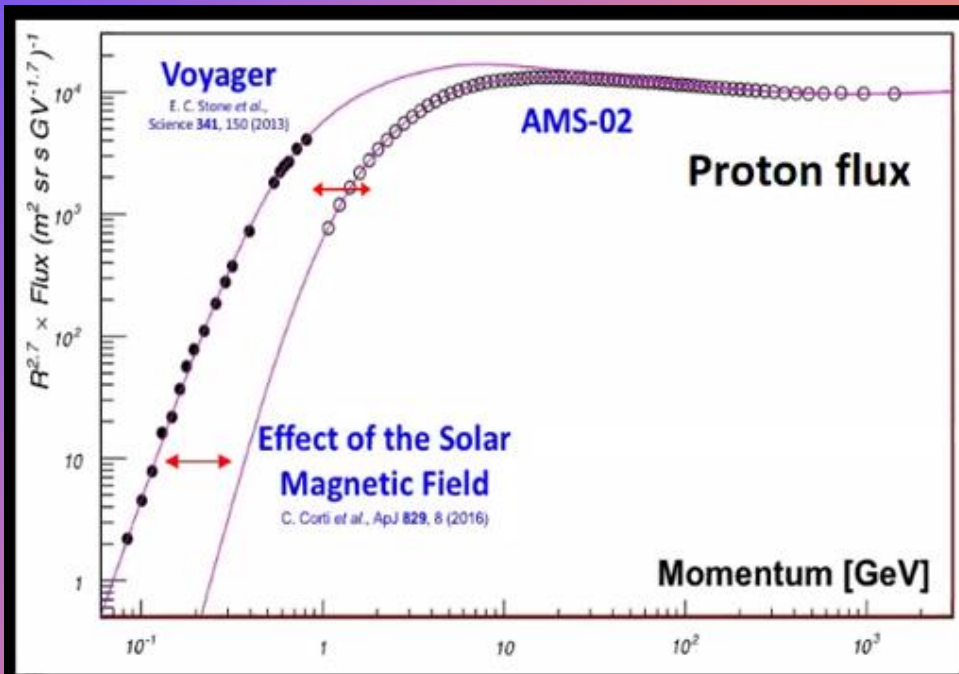


Cosmic Rays Solar Modulation

Cosmic rays from interstellar medium are «screened» by the Heliosphere.

This effect is particularly visible at low energies

Measurements of time evolution of cosmic ray fluxes of different particles over an extended period of time is very valuable



Credit S.Ting & AMS Collaboration

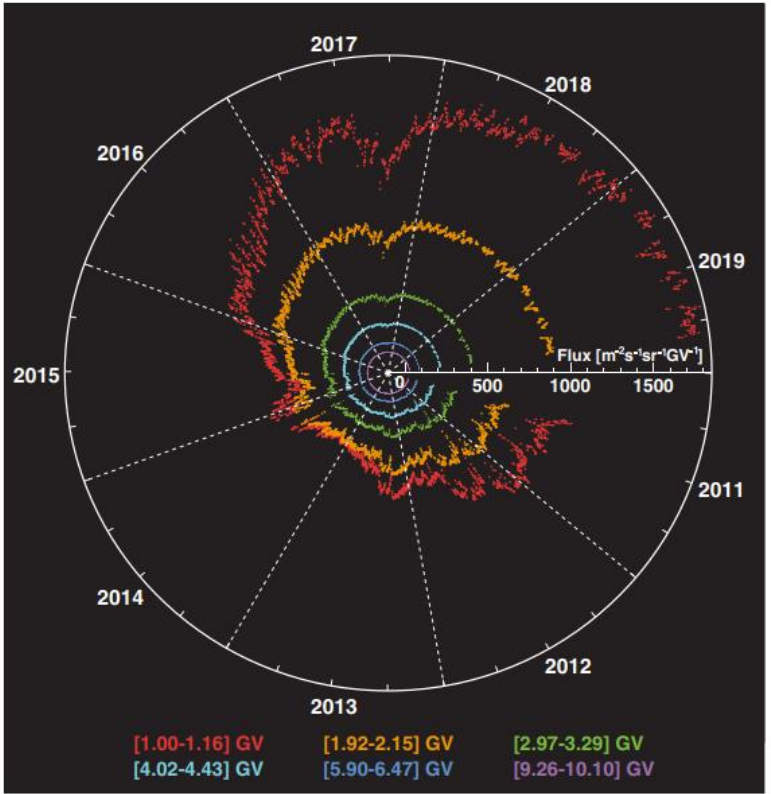
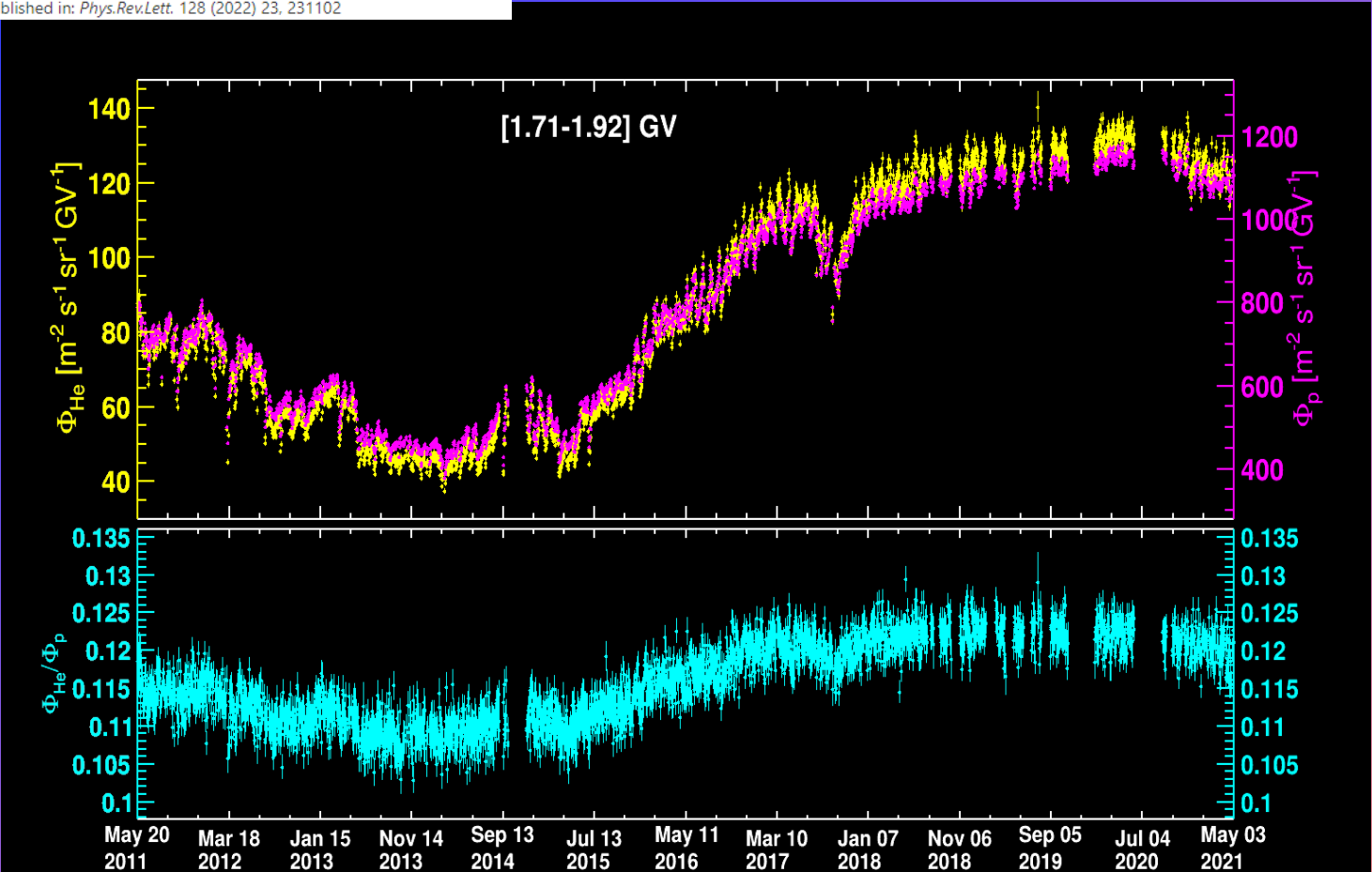


FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data

Short term Solar Modulation of GCR

Daily Proton and Helium Fluxes and Helium to Proton flux ratio

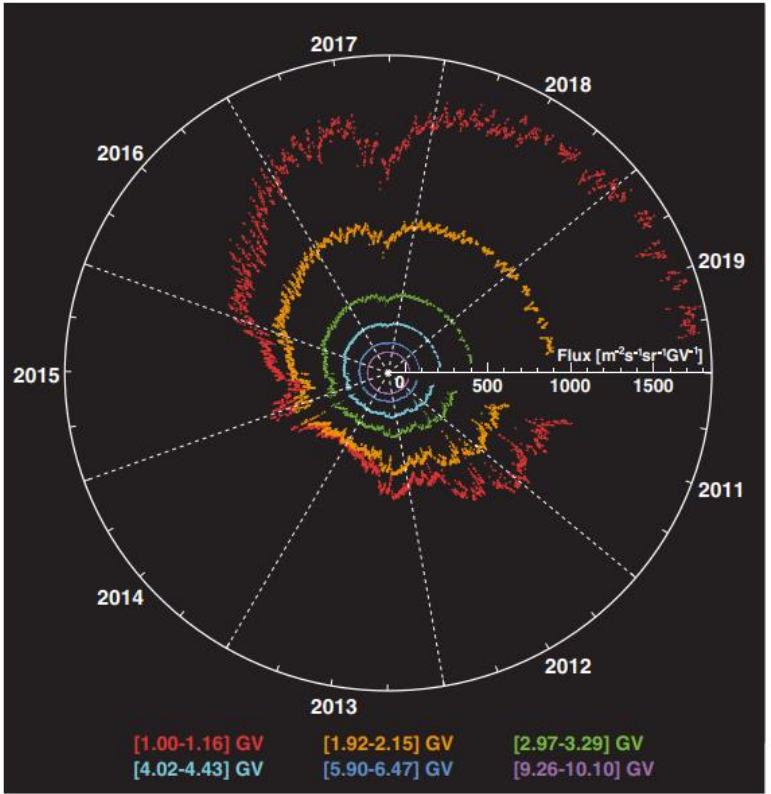
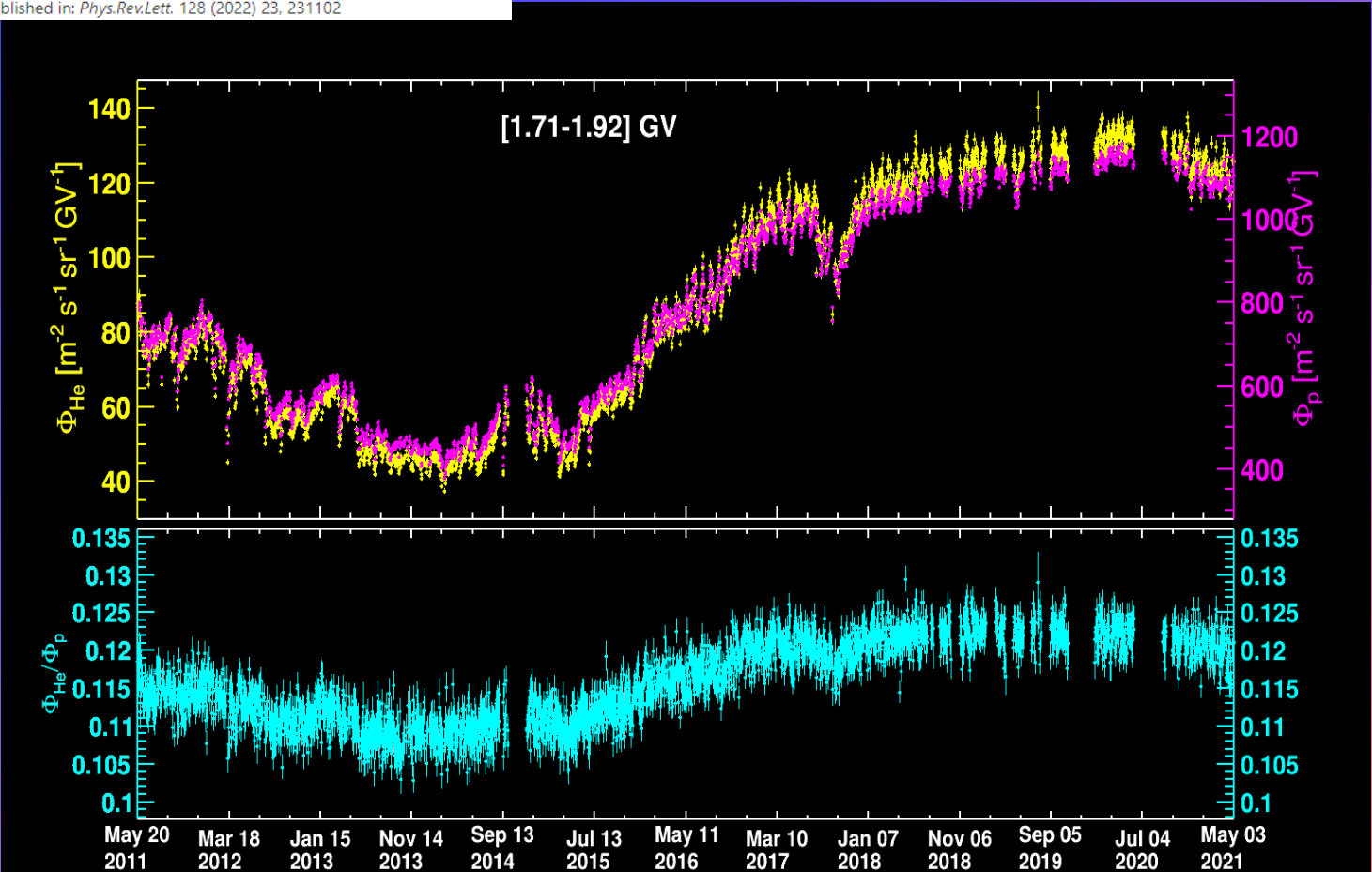
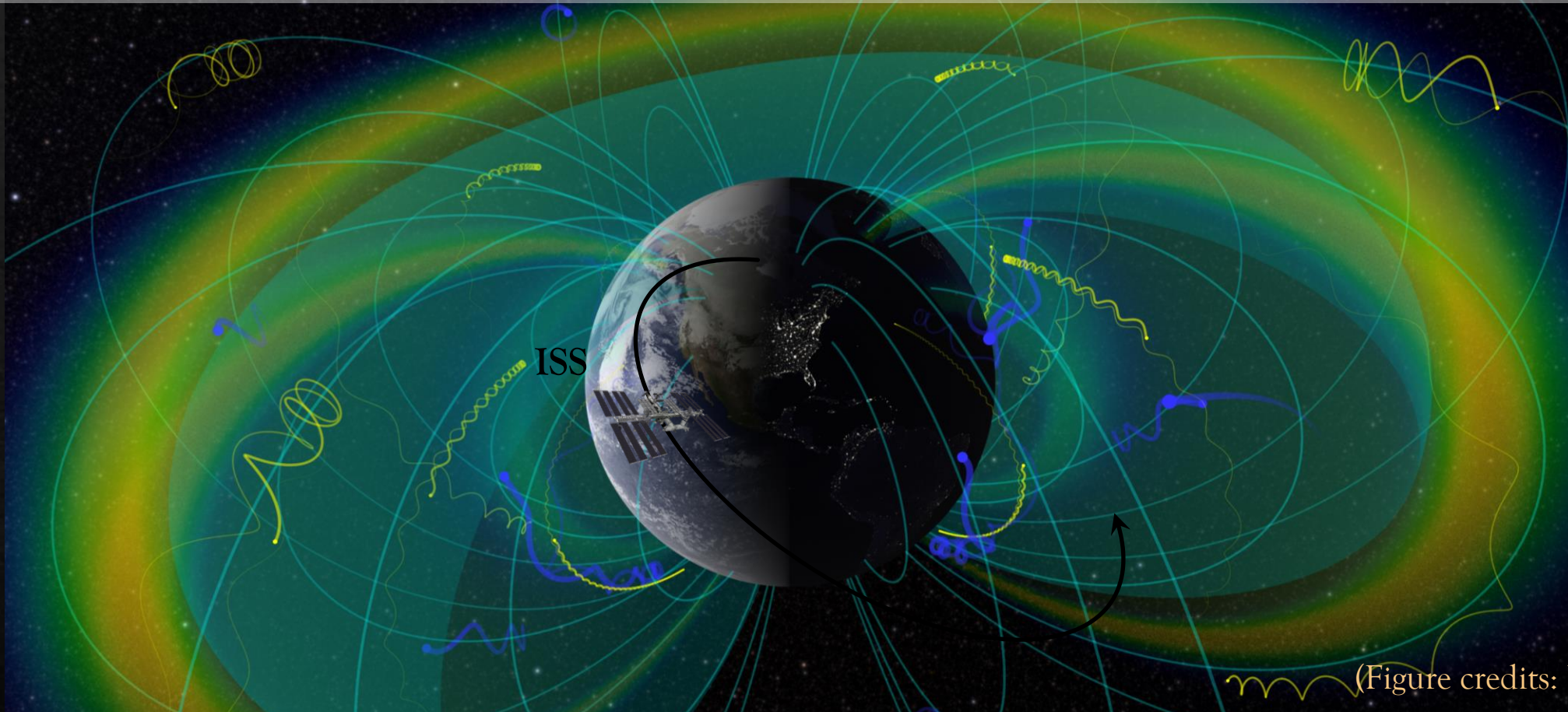


FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data

Short term Solar Modulation of GCR

Daily Proton and Helium Fluxes and Helium to Proton flux ratio

Cosmic Rays in the Magnetosphere



(Figure credits: NASA)

Particles **trapped** in the Earth magnetic field create regions of **high radiation** called **Van Allen belts**.
The ISS crosses one of the belts over South America, causing a sudden increase of the observed radiation known as the **South Atlantic Anomaly**.

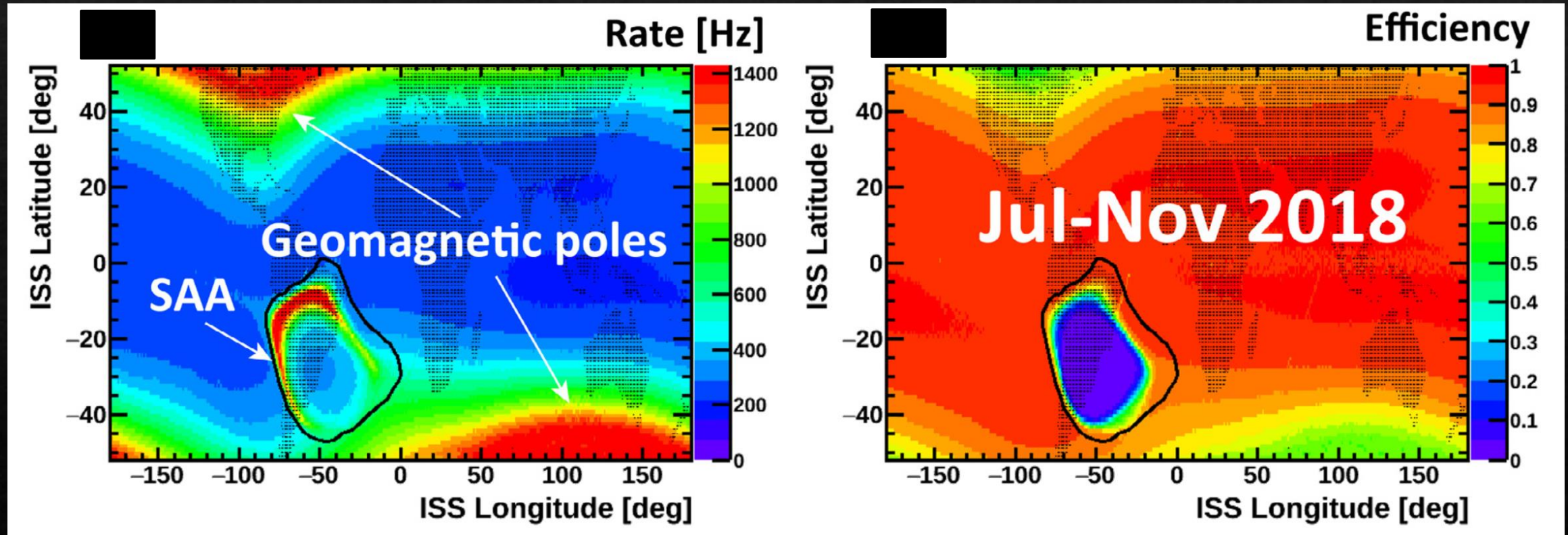


The South Atlantic Anomaly²⁹ as Seen by AMS

Incoming particle rate at the poles and in the SAA is high.

This causes low collection efficiency, mostly in the inner part of the SAA.

However, the efficiency is high on the external sides of the SAA.



M. Aguilar et al., Phys. Rep. **894** (2021) 1–116.

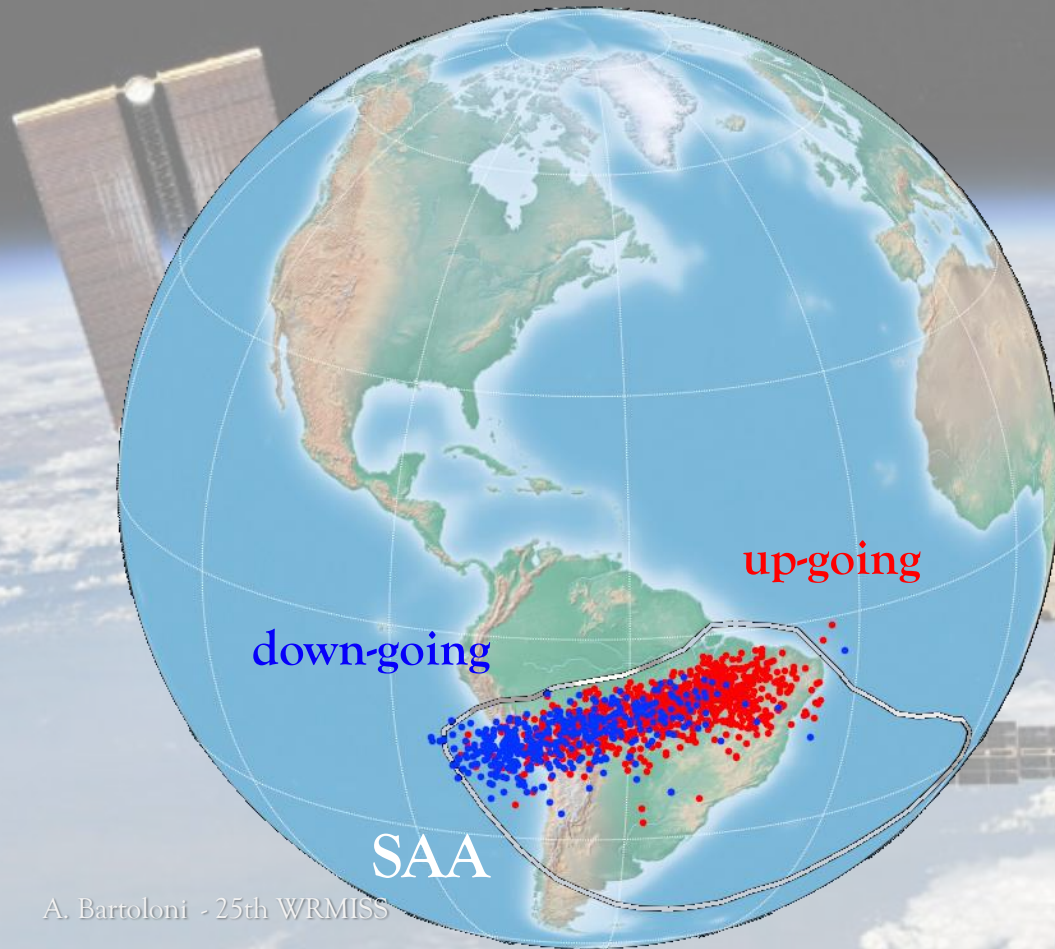
Energetic particle with charge up to 2 are known to exist in this region.

While there is no previous observation of energetic ($R > 1\text{GV}$) $Z > 2$ particles inside SAA.

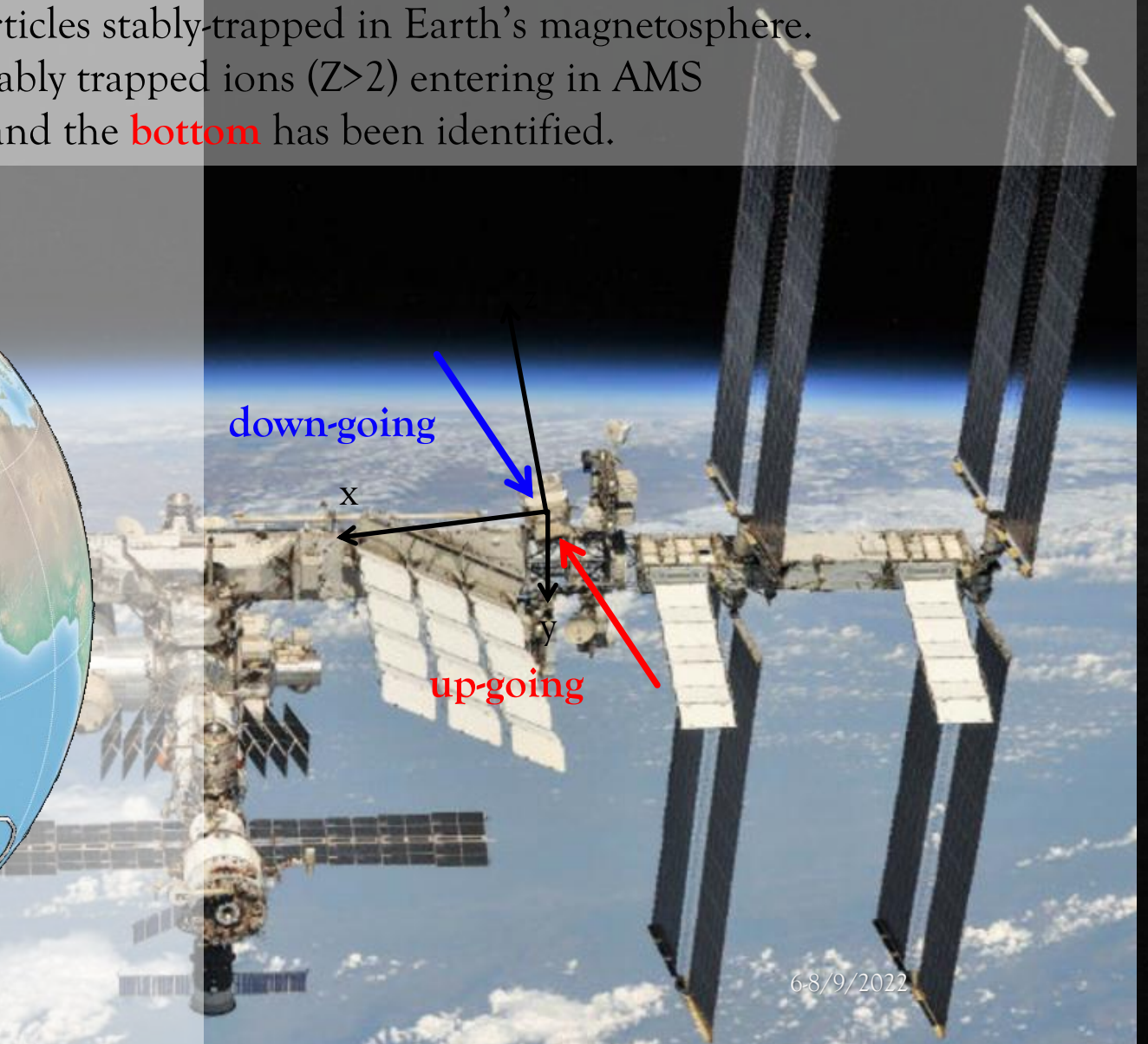
Stably Trapped Nuclei in the SAA

Backtracing allows to select particles stably-trapped in Earth's magnetosphere.

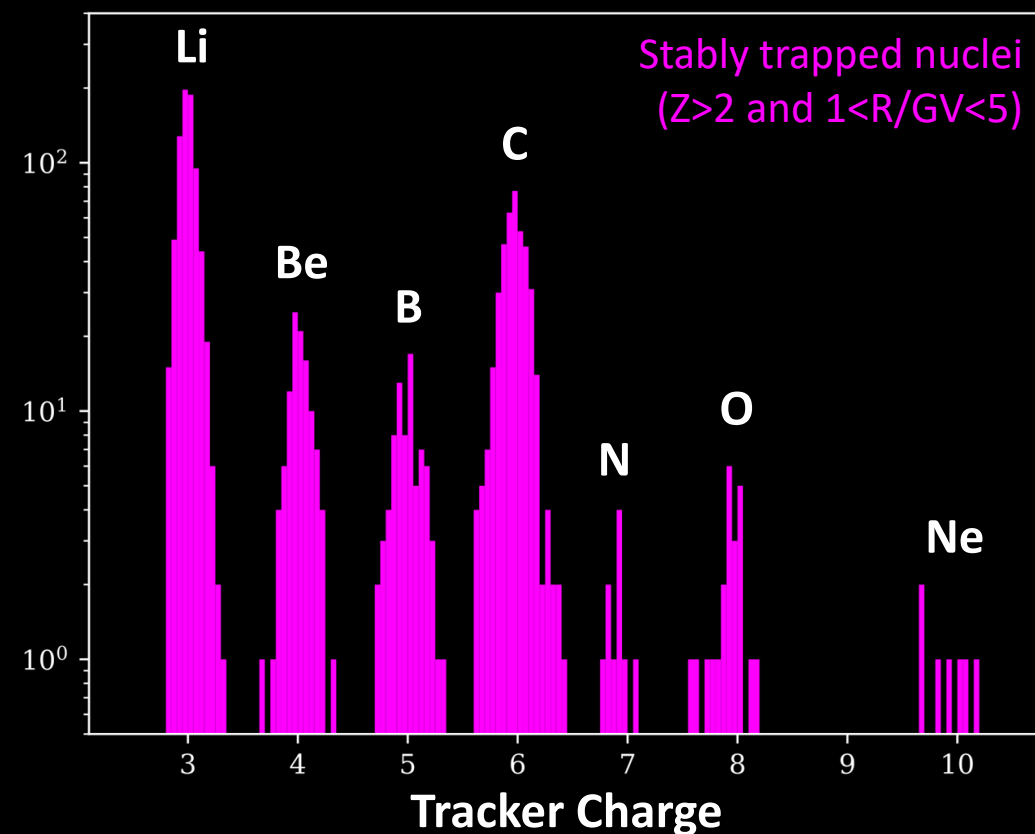
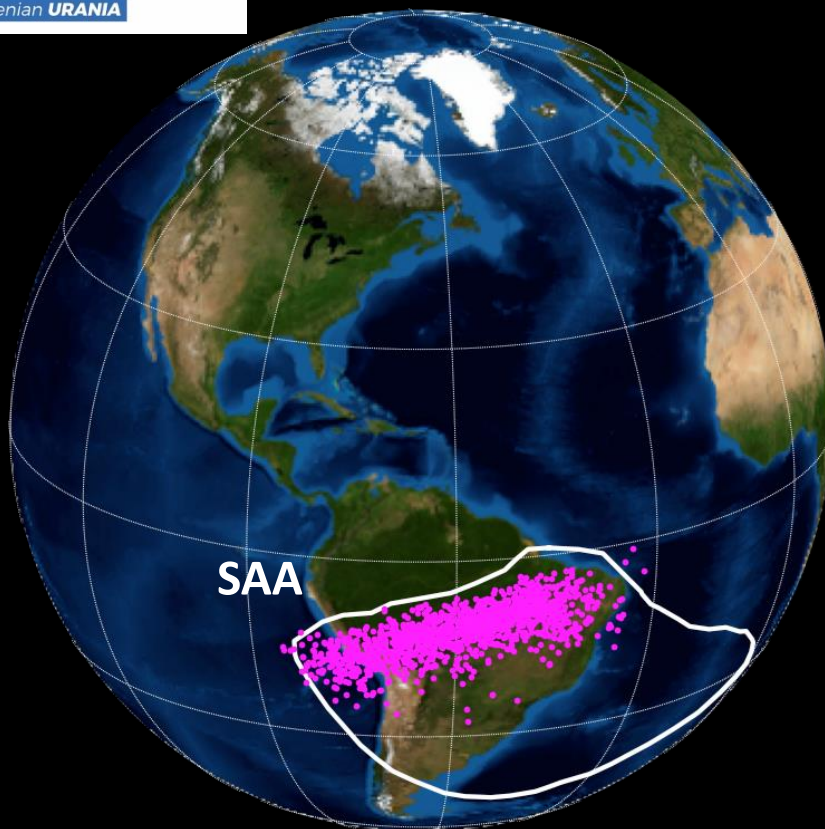
A clear population of stably trapped ions ($Z > 2$) entering in AMS both from the **top** and the **bottom** has been identified.



A. Bartoloni - 25th WRMIS



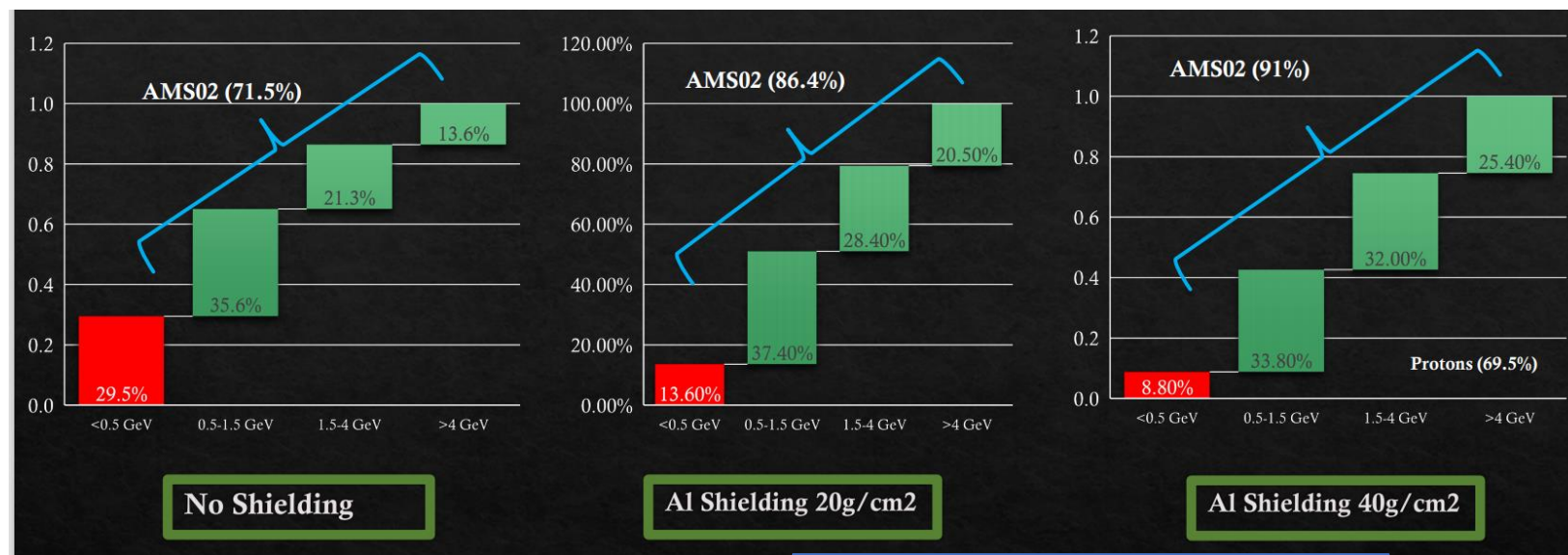
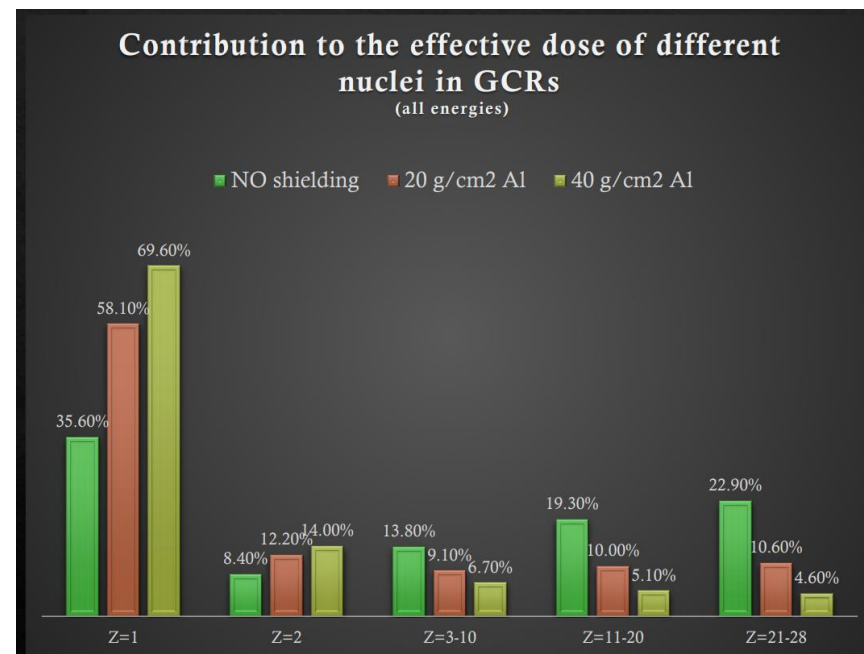
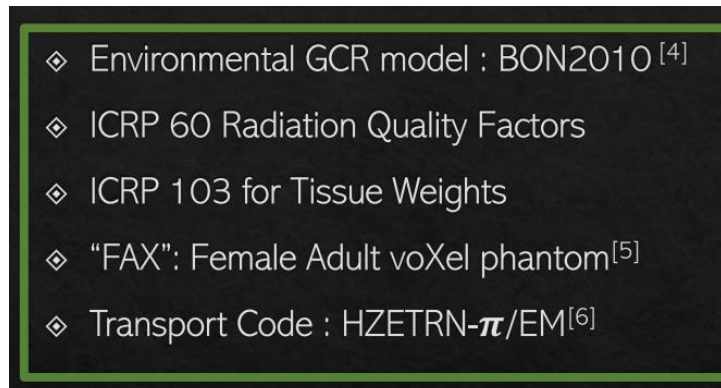
6-8/9/2022



- 10 years of AMS-02 data have been used to look for ions with $Z > 2$ below geomagnetic cutoff;
- A **stably trapped** population has been clearly identified below 5 GV in the SAA region;
- This population has properties (rigidity, charge, arrival direction) distinctly different from GCRs;
- This is a high-Z, high-energy population (up to 5 GV) never observed before.

GCR sensitivity analysis

- Identifications of CR components of the CR that are of interest for the computation of possible risks associated with the manned exploratory space missions in LEO and BLEO scenarios.
- Use of space radiation sensitivity studies we also recognised that they correspond with the data taken by the astroparticle experiments



1) *Environmental Model Characterization:*

- Use the enormous data at energies $> 1\text{GeV}$
- Improve affects the accuracy and precision of the risk assessment potentially underestimating the actual damage.

2) *Dose Equivalent Estimation:*

- Measurements only of absorbed doses, by passive dosimeters, are insufficient for investigating biological effects or assessing radiation risk for astronauts.
- LET distributions, their QFs (up to 30), and RBE of high-LET particles constituting the space radiation environment.

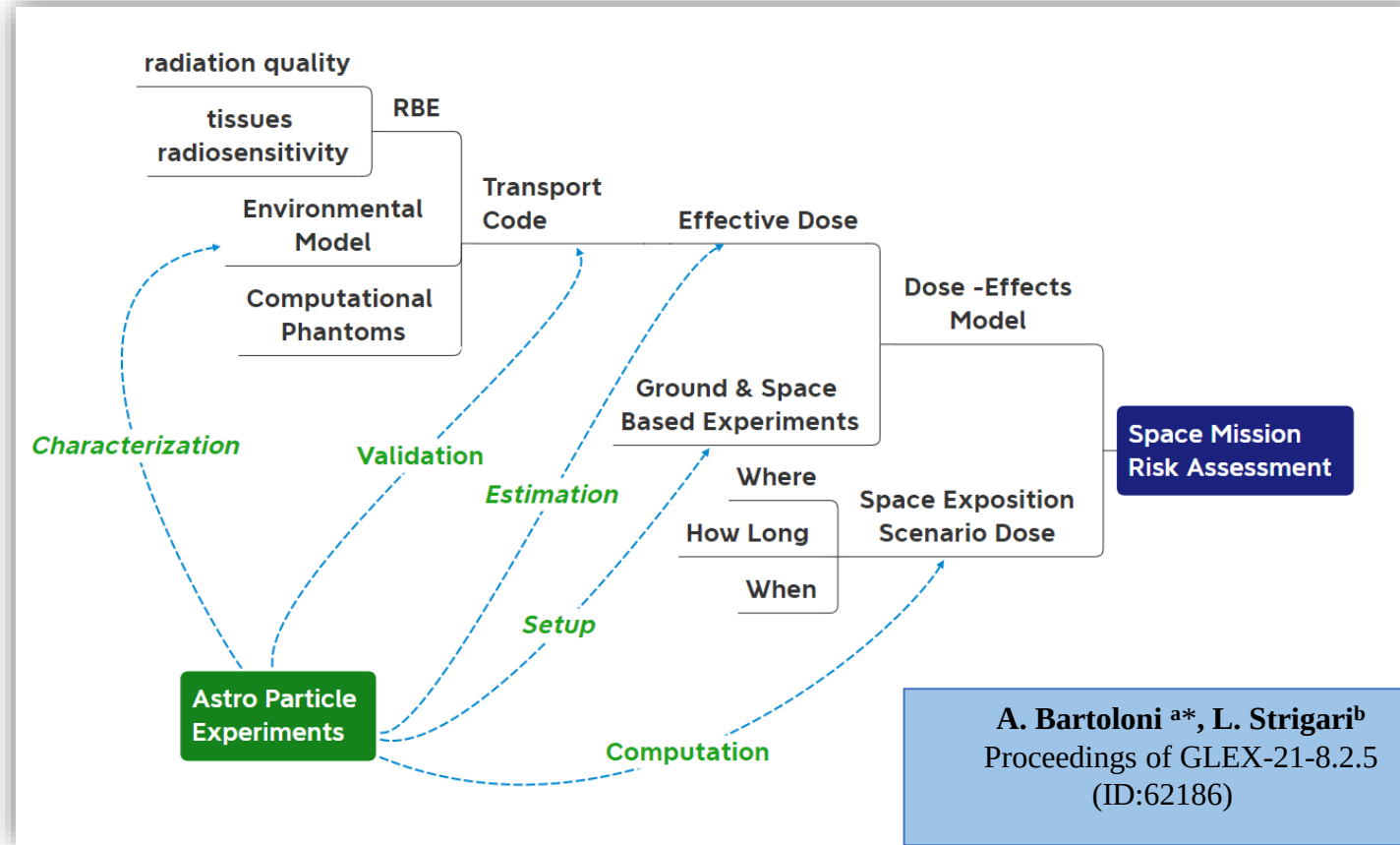
3) *Transport Code Validation :*

- Monte Carlo (MC) simulation code can be further implemented to better describe the interaction with the matter of GCR environments thanks to the improvement of accuracy of cross sections at high energy of elementary particles (electrons, protons), light and heavy nuclei (Helium to Iron and beyond).
- The implementation of transport code at these energies allows predicting the particle interactions with the known geometries of installed detectors. The determination of ray / particle tracing, energy spectrum and deposited energies collected in several materials can serve for a subsequent MC transport code validation (e.g. through a possible Bayesian approach).
- The calculations of dose equivalents allow generating an accurate and precise database for subsequent MC simulation codes validation applied to human tissues. Moreover, MC codes can be used for designing ad hoc shielding of spacecrafts and space landers.

4) *Space Exposition Scenario Dose Computation:*

- Implementation of Montecarlo codes to calculate the dose and so predict/describe the effects of GCR particles interacting with cells, tissues/organs and astronauts, which can be modeled as geometries with increasing details and complexities.

5) *Ground or Space based Experiment setup definition:*



A synergy with Astroparticle researches

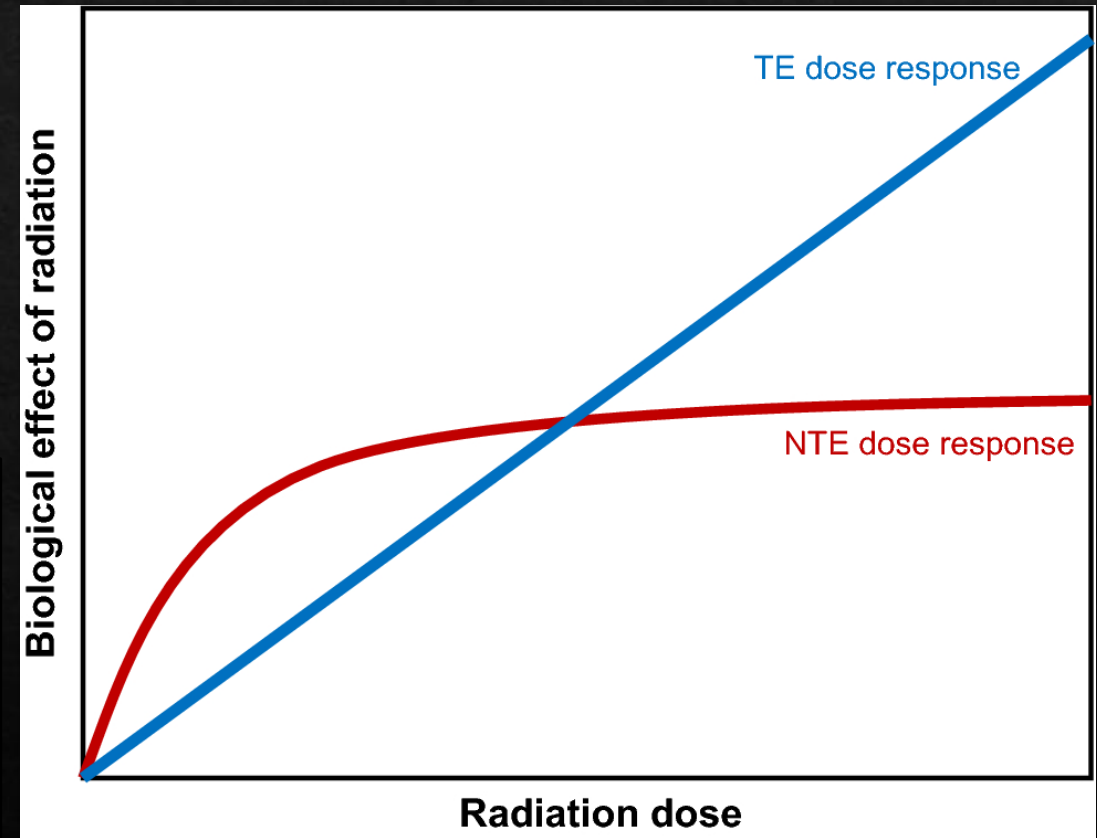
A Case Study :

Dose Effects Relationship - Target Effects vs Non Target Effects

Dose-Effect Relationship

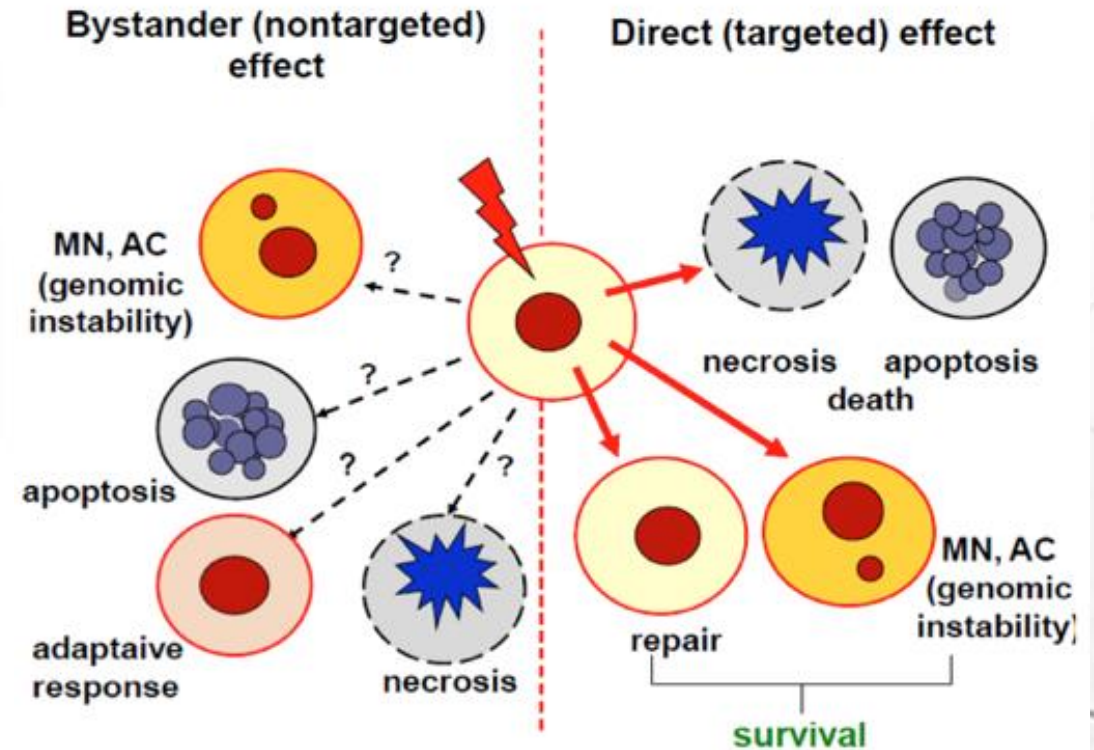
Crucial point is to predict the toxicity of the space radiation expected for the astronauts/space workers and the creation of reliable *mathematical models* that describe the correlation between the exposition to IR and the possible damages to the organs at risk

Aim: to implement a platform including the more reliable dose-effect models for space radiation, we developed an ad hoc software in R-script language



Target Effects (TE) vs Non Target Effects (NTE)

- Non-targeted effects (NTEs) include bystander effects where cells traversed by heavy ions transmit oncogenic signals to nearby cells, and genomic instability in the cells progeny.
- Studies on the Harderian gland, chromosomal aberrations at low dose and many mechanistic studies support the NTE model, with evidence of a **supra-linear effect at low doses** of NTE compared to a linear effects for TE
- This NTE are expected also at the **dose-rates that occur in space.**



Non-Targeted Effects Models Predict Significantly Higher Mars Mission Cancer Risk than Targeted Effects Models

F. Cucinotta, Elidedonna E. Cacao • Published 12 May 2017 • Biology, Physics • Scientific Reports

Materials & Methods: Hazard Function for Tumor Prevalence (TP)

Prevalence is the number of people/cell with a specific disease or condition in a given population at a specific time. This measure includes both newly diagnosed and pre-existing cases of the disease.

Tumor prevalence (TP) is described by a Hazard function, H , which is dependent on radiation type for γ -rays while for charged particles is dependent on the charge number (Z), kinetic energy (E) and fluence (F).

$$TP = 1 - e^{-H(Z,E,F)}$$

$$H_{\gamma} = H_0 + [\alpha_{\gamma}D + \beta_{\gamma}D^2] * S(D)$$

$$H_{CP}(Z, E, F) = H_0 + [\Sigma F + \beta D^2] * S(D)$$

Where:

- H_0 represents the background prevalence
- α_{γ} and β_{γ} are the linear and quadratic coefficient with dose Induction terms
- Σ is pseudo-biological action cross section taking in account the particle track structure models
- $S(D)$ is the **Cell Survival Probability**.

Results: R-script Library includes the most used Cells Survival Probability models

1. Theory n-target N-hit model (nTNH)
Two special case of nTNH including:
 - Theory single Target single hit model (sTSH)
 - Theory single Target N-hit model (sTNH)
2. Theory Linear Quadratic Model (LQ)
3. Linear Quadratic Model modified by hyper-radiosensitivity(HRS) effect.
4. Theory Linear Quadratic Cubic Model (LQC) for high dose.
5. Sublesion Theory Repair – misRepair Model (S-RMR)
6. Sublesion Theory Lethal – potentially lethal Model (S-LPL)
7. Sublesion Theory Saturable Repair Model (S-SR)

$$1. \quad S(D) = 1 - (1 - B)^n, B = e^{\frac{-D}{D_0}} \left[1 + \sum_2^N \frac{\left(\frac{D}{D_0}\right)^{N-1}}{(N-1)!} \right]$$

$$2. \quad S(D) = e^{-\alpha D - \beta D^2}$$

$$3. \quad S(D) = \exp\left\{-\alpha \left(1 + \left(\frac{\alpha_s}{\alpha} - 1\right) e^{\frac{-D}{D_0}}\right) D - \beta D^2\right\}$$

$$4. \quad S(D) = e^{-\alpha D - \beta D^2 - \gamma D^3}$$

$$5. \quad S(D) = e^{-aD} \left[1 + \left(\frac{aD(1 - e^{(-\lambda T)})}{\varepsilon} \right) \right]^{\varepsilon \phi}$$

$$6. \quad S(D) = e^{-(n_L - n_{PL})D} \left[1 + \frac{n_{PL}D}{\epsilon} (1 - e^{-\epsilon_{PL} t_r}) \right]^{\epsilon}$$

$$7. \quad S(D) = e^{-\frac{n_0 - c_0}{1 - \frac{c_0}{n_0} e^{kT(c_0 - n_0)}}$$

Materials and Methods: Experimental Data Set (Alpen et. al. 1997)

Prevalence of Harderian Gland Tumors

- Gammas 55.5TBq Co60
- Hydrogen with energy 250A, LET 0.4 KeV/μm
- Exposition time in between 60 sec. to 120 sec.
- Irradiation field is 3 x 5 cm².
- Background Prevalence is H0 = 0.026

TABLE VII

Prevalence of Harderian Gland Tumors after Irradiation with Protons, Neon Ions, and Niobium Ions

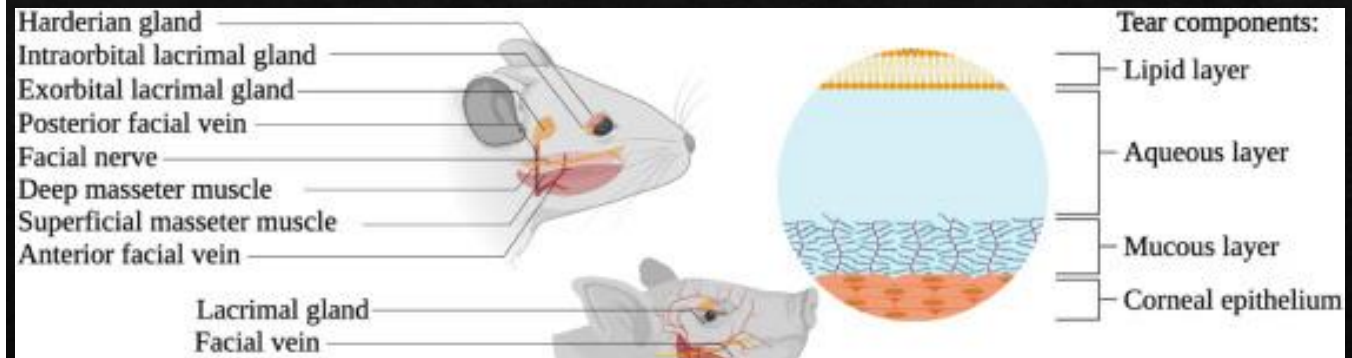
Ion and energy	Dose (Gy)	Mice			Prevalence ^a (%)
		Number	With tumors	At risk	
Controls	0	198	155	4	2.6 ± 2.5
Protons (250A MeV)	0.40	47	43	44	9.3 ± 6.1
	0.80	42	41	8	19.5 ± 12.1
	1.60	48	43	13	30.2 ± 13.7
	3.20	28	7	24	29.2 ± 18.2

TABLE II

Prevalence of Harderian Gland Tumors after ⁶⁰Co Gamma Irradiation

Dose (Gy)	Mice			Prevalence ^a (%)
	Number	At risk	With tumors	
0	198	155	4	2.6 ± 2.5
0.4	292	229	11	4.8 ± 2.7
0.8	278	161	15	9.3 ± 4.5
1.6	244	117	16	13.7 ± 6.2
3.2	181	115	37	32.2 ± 8.5
7.0	90	52	24	46.2 ± 13.6

^a ±95% CI.



Hazard Function

Target Effect (TE) vs Non-Target Effects (NTE)

The NTE model assumes a non-linear type response in addition to the linear dose term at low doses.

The η function represents the NTE contribution, which is parameterized as a function of the particle Linear Energy Transfer (L).

We tuned the radiobiological parameters to reproduce available experimental data

$$H_{TE}(Z, E, F) = H_0 + [\Sigma F + \beta D^2] * S$$

$$H_{NTE}(Z, E, F) = [H_0 + \Sigma F + \beta D^2 + \eta] * S$$

$$\eta = \eta_0 L e^{-\eta_1 L} [1 - e^{-N_{Bys}}]$$

Where:

- L is the Linear Energy Transfer of the particle
- $N_{Bys} = \text{Fluence} * A_{Bys}$
- A_{Bys} is the number of bystander cells surrounding a cell traversed directly from a HZE particle that receive an oncogenic signal.

Results: Effective Pseudo-Biological Action Cross Section

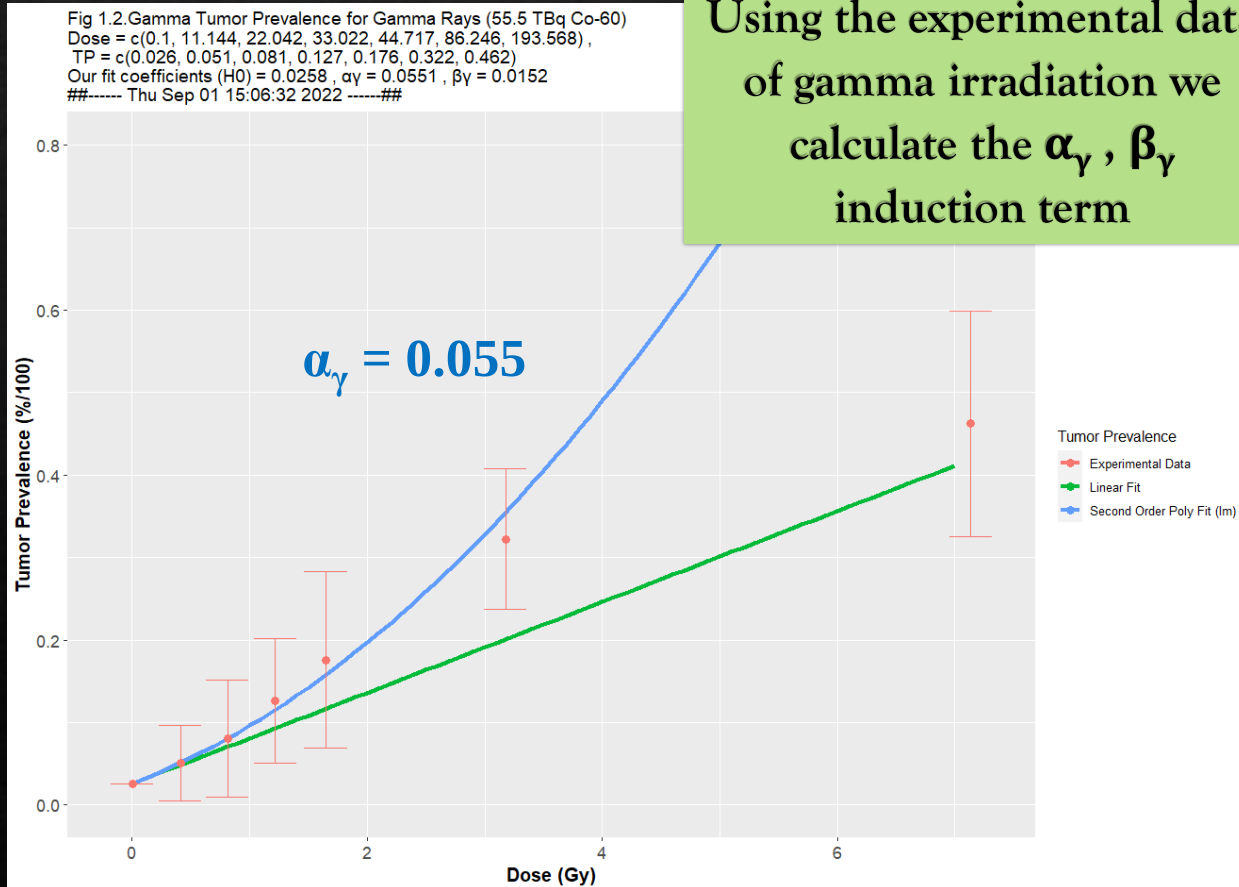
$$\Sigma(Z, E) = \Sigma_0 P(Z, E) + \frac{\alpha_\gamma L}{6.24} [1 - P(Z, E)], \quad P(Z, E) = \left[1 - e^{\left(-\frac{Z^{*2}}{kv_c^2}\right)}\right]^m$$

$$\Sigma(1, 250) = \Sigma_0 P(Z, E) + \frac{0.55 \cdot 0.4}{6.24} [1 - P(1, 250)], \quad P(1, 250) = \left[1 - e^{\left(-\frac{Z^{*2}}{kv_c^2}\right)}\right]^3$$

Where:

- * Σ_0 and k are parameters of his cellular track structure model
- * α_γ is the linear regression coefficient for acute doses of γ -rays for the same endpoint
- * Z^* is the effective charge number of the particle,
- * V_c is the particle velocity relative to the velocity of light
- * m is the number of target in a single cell

Using the experimental data of gamma irradiation we calculate the α_γ , β_γ induction term



Results: α_H and β_H Calculation

$$TP_H = 1 - e^{-H_H(1,250,F)}$$

$$H_{TE}(1,250,F) = 0.026 + [\Sigma(1,250) * F + 0.1092 * D^2] * S$$

$$H_{NTE}(1,250,F) = 0.026 + [\Sigma(1,250) * F + 0.1092 * D^2 + \eta_H] * S$$

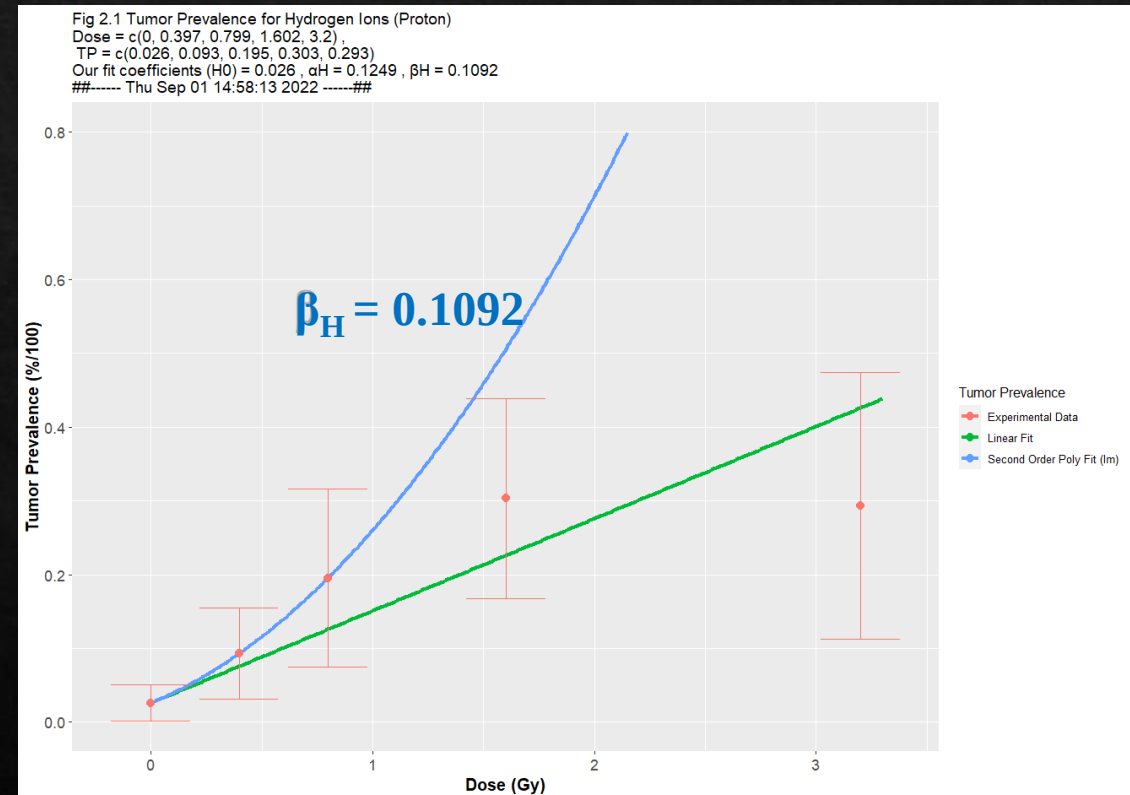
$$\eta_H = 0.00048 * 0.4e^{-0.00281*0.4} [1 - e^{-216*F}]$$

Where:

* β_H is the quadratic coefficient with dose Induction terms, irradiation for hydrogen

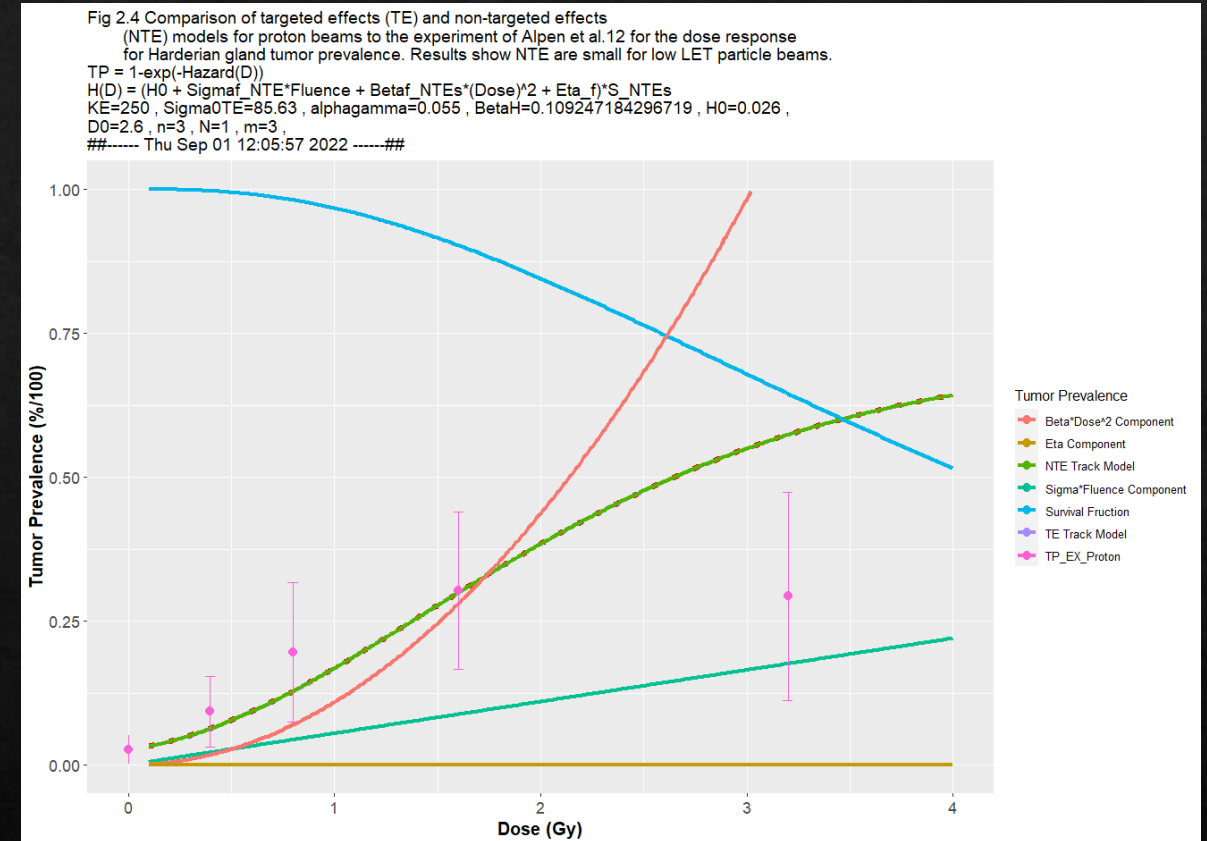
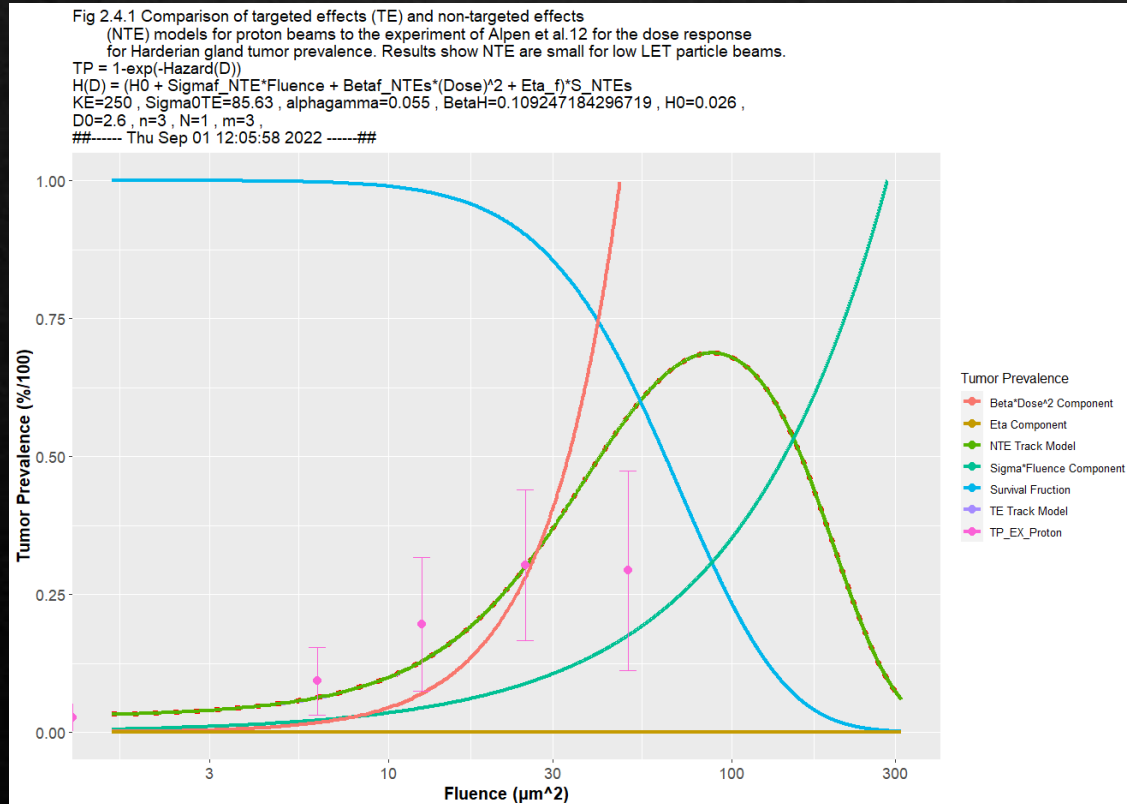
For the cell survival probability is used the target theory n-target N-hit model (nTNH) with $n=3$, $N=1$

Using the experimental data of 250A MeV Hydrogen irradiation we calculate the α_H , β_H induction term

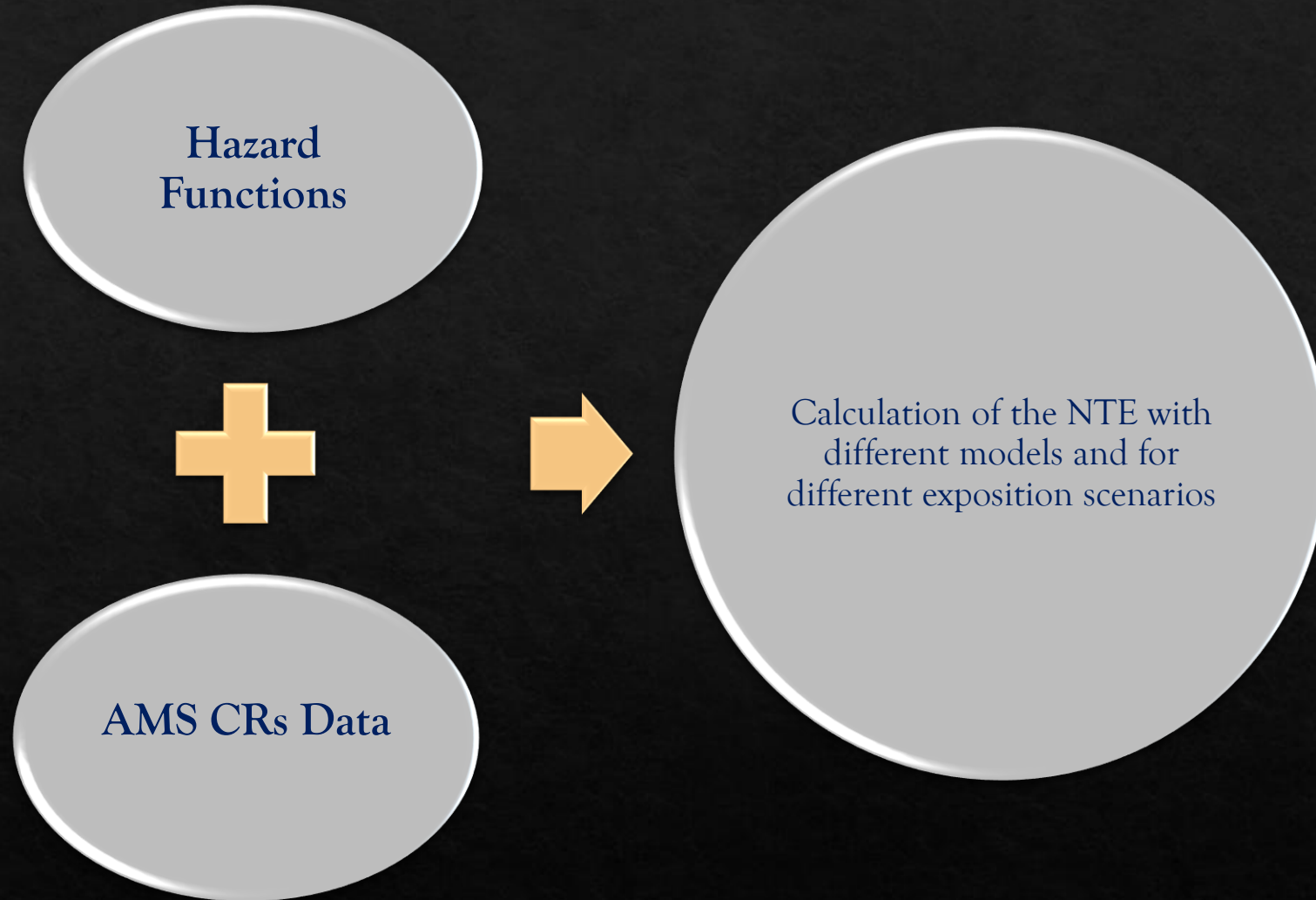


Results: TE vs NTE for Protons

Calculation of the TE and NTE TP models showing for Proton 250A Mev there is no relevant differences in the tumor Prevalence versus dose as expected.



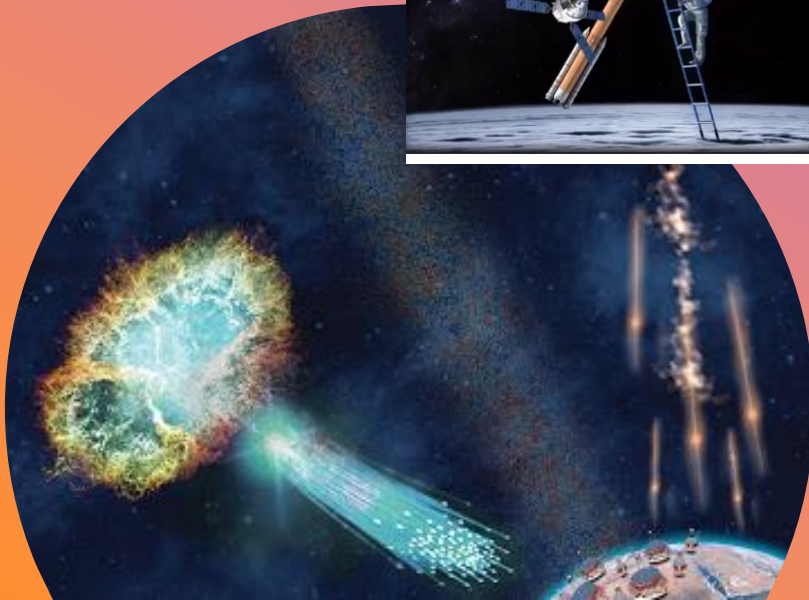
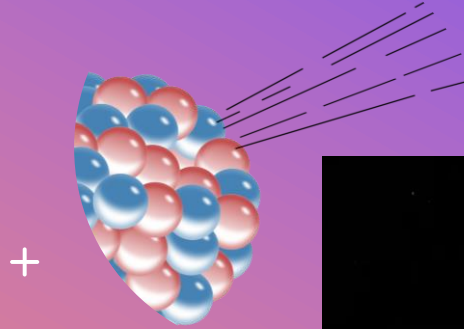
Results: Tool for NTE components evaluation



Summary

- In the coming years there will be a great interest for space human mission non only to explore but also for a permanent presence of humans in LEO and outside the geo-magnetosphere
- Space Radiation is a main concern and the first one showstopper in many human exploration scenarios.
- Astroparticle Experiments are a principal source of information to perform this investigations complementary to what is usually done in the research field.
- Dose-Effects models knowledge could benefit from the use of such information, a synergy with the experience from the clinical field is crucial to perform this task
- At INFN ROMA AMS Group we are developing a platform including the more reliable dose-effect models for space radiation and the AMS data

«To fully understand the relationship between ionizing radiation and biology, and to solve problems in this field, researchers incorporate fundamentals of **biology, physics, astrophysics, planetary science, and engineering.**» *(credit : NASA)*



THANKS FOR THE ATTENTION !

Alessandro Bartoloni

Alessandro.Bartoloni@cern.ch

[Alessandro Bartoloni](#)

[AMS02 INFN ROMA and Sapienza University Web Site](#)

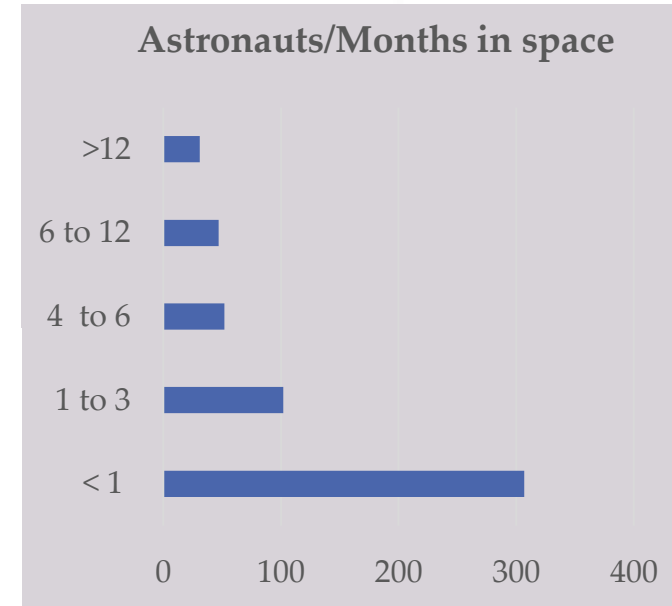
BACKUP SLIDE

Dose-Effects Relationship

The known dose-effect relationships are
based on a limited number of
astronauts
(hundreds)

Total Space Radiation Dose (mGy)	<0.2	0.2–1.99	2–3.99	4–10.99	≥11	Total
# Astronauts	14	19	11	15	14	73
# Cancer Deaths	2	2	1	0	2	7
# Cardiovascular Disease Deaths	1	4	1	1	0	7
# Accident Deaths	6	5	0	0	1	12
# Other Deaths	1	0	1	0	1	3
# Unknown Deaths	1	0	0	3	1	5
Mean Medical Dose (SD)	2.4 (6.4)	27.7 (13.6)	34.4 (20.8)	29.1 (15.6)	32.5 (21.7)	25.1 (19.4)
Mean Year at Birth (SD)	1932.6 (4.1)	1931.7 (5.2)	1931.6 (2.5)	1932.2 (4.4)	1931.5 (3.3)	1931.9 (4.1)
Mean Age at Entry into Astronaut Corps (SD)	31.6 (2.7)	32.2 (3.4)	33.0 (2.5)	31.8 (2.8)	32.5 (2.2)	32.2 (2.8)
Mean Follow up Time (SD)	29.3 (23.6)	40.3 (15.0)	46.4 (12.9)	50.7 (7.8)	48.1 (7.5)	42.8 (16.1)
Total Group Person Years	409.9	766.5	510.1	760.8	673.4	3120.8
Mean Age at Death (SD)	57.7 (23.8)	65.7 (15.9)	64.5 (14.9)	78.2 (19.9)	74.9 (10.2)	65.2 (19.1)
Mean Current Age of Living Astronauts (SD)	79.9 (2.9)	82.1 (3.9)	84.9 (3.1)	83.6 (3.6)	83.8 (2.3)	83.4 (3.4)

Table 1. Early astronaut cohort demographics binned by total space radiation dose category. SD = standard deviation.



Needs of an improvements

Radiation Exposure and Mortality from Cardiovascular Disease and Cancer in
Early NASA Astronauts S.Robin et Al - 2018

REVIEW article

Front. Public Health, 08
November 2021
Sec.Radiation and Health
<https://doi.org/10.3389/fpubh.2021.733337>

This article is part of the Research Topic
Medical Application and Radiobiology Research of
Particle Radiation
[View all 16 Articles >](#)

Dose-Effects Models for Space Radiobiology: An Overview on Dose-Effect Relationships

 Lidia Strigari¹,  Silvia Strolin¹,  Alessio Giuseppe Morganti² and
 Alessandro Bartoloni^{3*}

We did and publish in 2021
an extensive review of the
existent literature





COSPAR 2022
44th SCIENTIFIC ASSEMBLY
16-24 July 2022, Athens, Greece
Hosted by the Hellenic Republic



Dose-Effects Models for Space Radiobiology: An Overview on Dose-Effect Relationships

Lidia Strigari^{1,2}, Silvia Strolin^{1,2}, Alessio Giuseppe Morganti³ and Alessandro Bartoloni²

¹Department of Medical Physics, IRCCS Azienda Ospedaliero-Universitaria di Bologna, Bologna, Italy
²Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Roma 1, Roma, Italy
³Radiation Oncology Center, School of Medicine, Department of Experimental, Diagnostic and Specialty Medicine - DIMES, University of Bologna, Bologna, Italy

41%
Views rank

This article has more views than 41% of all Frontiers articles.

45%
Downloads rank

This article has more downloads than 45% of all Frontiers articles.



Space radiobiology is an interdisciplinary science that examines the biological effects of ionizing radiation on humans involved in aerospace missions. The dose-effect models are one of the relevant topics of space radiobiology. Their knowledge is crucial for optimizing radioprotection strategies, the risk assessment of the health hazard related to human space exploration, and reducing damages induced to astronauts from galactic cosmic radiation. Dose-effect relationships describe the observed damages to normal tissues or cancer induction during and after space flights. They are developed for the various dose ranges and radiation qualities characterizing the actual and the forecast space missions.

Based on a PubMed search including 53 papers reporting the collected dose-effect relationships after space missions or in ground simulations, 7 significant dose-effect relationships (e.g., eye flashes, cataract, central nervous systems, cardiovascular disease, cancer, chromosomal aberrations, and biomarkers) have been identified.

For each considered effect, the absorbed dose thresholds and the uncertainties/limitations of the developed relationships are summarized and discussed. The current knowledge on this topic can benefit from further *in vitro* and *in vivo* radiobiological studies, an accurate characterization of the quality of space radiation, and the numerous experimental dose-effects data derived from the experience in the clinical use of ionizing radiation for diagnostic or treatments with doses like those foreseen for the future space missions.

The growing number of pooled studies could improve the prediction ability of dose-effect relationships for space exposure and reduce their uncertainty level. Novel research in the field is of paramount importance to reduce damages to astronauts from cosmic radiation before Beyond Low Earth Orbit exploration in the next future. The study aims at providing an overview of the published dose-effect relationships and illustrates novel perspectives to inspire future research.

Model	Study Type	Dose Range/Threshold or LET	#Papers	Reliability	Priority
Eye Flashes	Spaceflight	LET>5-10 KeV/μm	4	****	*
Cataract	Spaceflight	8 mSv	5	***	***
CNS	Ground/Simulations	100-200 mGy	11	**	*****
CVD	Spaceflight	1000 mGy	4	*	***
Cancer	Ground/Simulations	0.1-4,500 mSv	8	***	*****
	Spaceflight	< 100 mGy	2		
Biomarkers or Chromosomal Aberrations	Ground/Simulations	< 100 mGy	9	***	*****
	Spaceflight	<5-150 mGy	11		
	Ground/Simulations	< 10,000 mGy	4		
Other Risks	Ground/Simulations	2,000 mGy	2	*	***

*= Very Low, **=Low, ***=Medium, ****= High, ***** = Very High.

United States of America

826

China

319

Germany

236

Italy

200

Russian Federation

81



<https://doi.org/10.3389/fpubh.2021.733337>

We made and publish in 2021
an extensive review of the
existent literature to use as
starting point for improvements
this research areas

<https://doi.org/10.3389/fpubh.2021.733337>

REVIEW article

Front. Public Health, 08
November 2021
Sec. Radiation and Health
<https://doi.org/10.3389/fpubh.2021.733337>

This article is part of the Research Topic
Medical Application and Radiobiology Research of
Particle Radiation
[View all 16 Articles >](#)

Dose-Effects Models for Space Radiobiology: An Overview on Dose- Effect Relationships



Lidia Strigari¹,



Silvia Strolin¹,



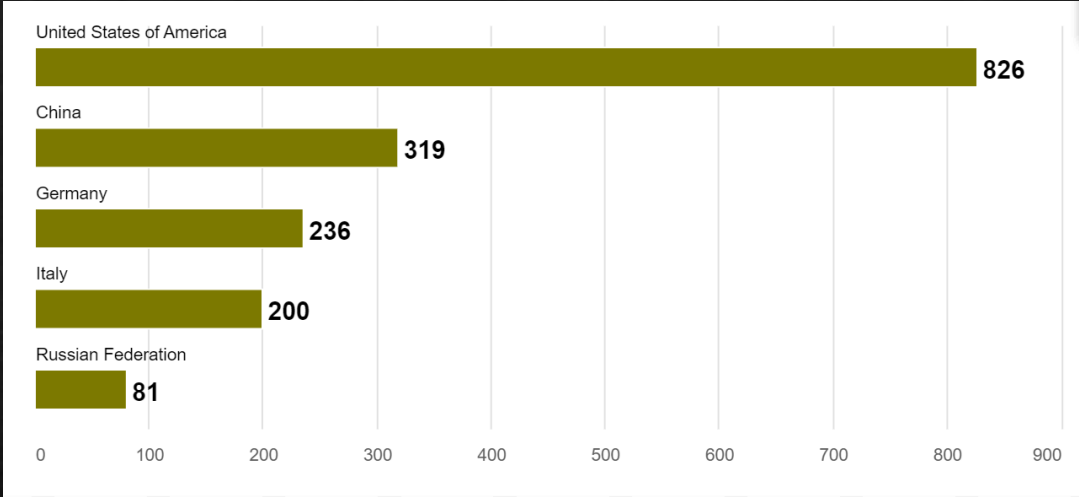
Alessio Giuseppe Morganti² and



Alessandro Bartoloni^{3*}

Model	Study Type	Dose Range/Threshold or LET	#Papers	Reliability	Priority
Eye Flashes	Spaceflight	LET>5-10 KeV/μm	4	****	*
Cataract	Spaceflight	8 mSv	5	***	***
CNS	Ground/Simulations	100-200 mGy	11	**	*****
CVD	Spaceflight	1000 mGy	4	*	***
	Ground/Simulations	0.1-4,500 mSv	8		
Cancer	Spaceflight	< 100 mGy	2	***	*****
	Ground/Simulations	< 100 mGy	9		
Biomarkers or Chromosomal Aberrations	Spaceflight	<5-150 mGy	11	***	*****
	Ground /Simulations	< 10,000 mGy	4		
Other Risks	Ground/Simulations	2,000 mGy	2	*	***

*= Very Low, **=Low, ***=Medium, **** = High, ***** = Very High.

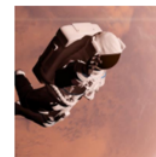


Article Statistics (June 2022)



THE RESEARCH TOPIC INITIATIVE

*Research Topics are Open Access
themed article collections (similar in
nature to classical special issues) with:
a dedicated landing page, Continuous
publication, Advanced impact metrics,
Cross-disciplinarity, Multiple article
types, e-book production*



Research Topic

Astroparticle Experiments to Improve the Biological Risk Assessment of Exposure to Ionizing Radiation in the Exploratory Space Missions

The actual and next decade will be characterized by an exponential increase in the exploration of the Beyond Low Earth Orbit space (BLEO). Moreover, the firsts tentative to create structures that will enable a permanent human presence in the BLEO are forecast. In this context, a detailed space radiation field characterization will be crucial to optimize radioprotection strategies (e.g., spaceship and lunar space stations shielding, Moon / Mars village design, ...), to assess the risk of the health hazard related to human space exploration and to reduce the damages potentially induced to astronauts from galactic cosmic radiation. On the other side, since the beginning of the century, many astroparticle experiments aimed at investigating the unknown universe components (i.e., dark matter, antimatter, dark energy, ...) have been collecting enormous amounts of data regarding the cosmic rays (CR) components of the radiation in space.

Such experiments essentially are actual cosmic ray observatories, and the collected data (cosmic ray events) cover a significant period and permit to have integrated not only information of CR fluxes but also their variations on time daily. Further, the energy range is exciting since the detectors operate using instruments that allow measuring CR in a very high energy range, usually starting from the MeV scale up to the TeV, not usually covered by other space radiometric instruments. Last is the possibility of acquiring knowledge in the full range of the CR components and their radiation quality. The collected data contains valuable information that can enhance the space radiation field characterization and, consequently, improve the radiobiology issues concerning one of the most relevant topics of space radiobiology represented by the dose-effect models.

This articles collection accepts original research papers and review papers relating (but not limited to) the following topics:

- The analysis and proposal on how to use these astroparticle experiments data to enhance the space radiation field characterization and, consequently, improve the radiobiology issues in space concerning one of the most relevant topics of space radiobiology represented by the dose-effect models and relationship.
- The proposal of new methods or instruments to use the astroparticle experiments to improve the space radiobiology knowledge (i.e., real-time dosimetry, monitoring of solar activities, ...)

Keywords: Cosmic Ray, Space Radiation, Space Radiobiology, Astro-Particle Experiments, Human Space Exploration

Participating Journals

Manuscripts can be submitted to this Research Topic via the following journals:

Frontiers in
Astronomy and Space Sciences
Astrobiolgy

Frontiers in
Physics
Radiation Detectors and Imaging

Frontiers in
Public Health
Radiation and Health



A new scientific language is needed to support the exploratory space missions because of the return of humans outside the Low Earth Orbit. The keywords are *Peacefully, Safely, Transparently*.

In that context, a priority is to keep the space exploration community secure and safe, and a crucial part is a detailed and accurate ionizing radiation health effects characterization.

Participate in creating part of this new language joining this interdisciplinary Frontiers Research Topic!

*Research Topics are Open Access themed article collections (similar in nature to classical special issues) with:
a dedicated landing page, Continuous publication, Advanced impact metrics, Cross-disciplinarity, Multiple article types, e-book production*



Topic Editors



Alessandro Bartoloni
National Institute of
Nuclear Physics of Rome
Rome, Italy



Nan Ding
Institute of Modern
Physics, Chinese
Academy of Sciences
(CAS)
Lanzhou, China



Gianluca Cavoto
Sapienza University of
Rome
Rome, Italy



Cristina Consolandi
University of Hawaii at
Manoa
Honolulu, United States



Lidia Strigari
Dipartimento di Fisica
Medica, IRCCS Azienda
Universitaria di Bologna
Bologna, Italy

Improve the Radiation Health Risk Assessment for Humans in Space Missions

Since 2018, the INFN Roma Sapienza AMS group has collaborate with researchers and scientists to investigate the possibilities of using the CRD to improve the radiation health risk assessment for humans in space missions.

Collaborations were mainly focused on creating synergy within different scientific communities (radiobiology, medical physics, radiotherapy, and nuclear medicine) and institutions (Research, Universities, Space Agencies and Industry).

In 2019 we organize at INFN Roma Sapienza a thematic meeting with participants from ESA and Thales Alenia Space

**SPACE RADIOBIOLOGY
AND
PRECISION GALACTIC COSMIC RAY MEASUREMENTS**

ON HOW THE AMS02 EXPERIMENT ON THE INTERNATIONAL SPACE STATION CAN HELP THE
RADIATION HEALTH HAZARD ASSESSMENT IN EXPLORATORY SPACE MISSIONS

LUNEDÌ 4 NOVEMBRE 2019
DIPARTIMENTO DI FISICA – AULA CONVERSI



14:30-14:45
Introduzione
A. Bartoloni – INFN Roma



14:45-15:35
High precision measurements of charged cosmic rays in space with the Alpha Magnetic Spectrometer.
M. Paniccia, Università di Ginevra



15:35-16:20
ESA Human Spaceflight Radiation Research Programme activities.
L. Surdo, European Space Agency



16:20-17:05
Shielding design for long duration human exploratory space missions : issues and future perspective.
M. Giraudo, Thales Alenia Space





<https://agenda.infn.it/event/20462/>

The Research Topic Initiative

- While progressing in the research activity raised the awareness that to make progress in such a field it was required a new scientific language able to connect and create **synergy** between different scientific communities.
- Firstly, cause to **understand the relationship between ionizing radiation and biology** and to solve problems in this field, researchers incorporate fundamentals of biology, physics, astrophysics, planetary science, and engineering.
- Further **space exploration and colonization** collects the worldwide hopes of a new era characterized by transparency and peacefully development. In that sense, these expectations coincide with the primary scientific interest, and science could play a breakthrough role in such direction.
- Among the many possibilities thus, we decided, supported and asked by the [Frontiers Editorial team](#), to launch this research topic named "**Astroparticle Experiments to Improve the Biological Risk Assessment of Exposure to Ionizing Radiation in the Exploratory Space Missions**".

-

TOPIC EDITORS

+
A. BARTOLONI - 25TH WRMISS^O



Alessandro
Bartoloni



Cristina
Consolandi



Lidia
Strigari



Nan
Ding



Gianluca
Cavoto



We created a research topic **editorial board** that was representative of **different scientific cultures** and **geographic areas** and invited many researchers and scientists from many different research areas due to the strong interdisciplinarity of the topic.

Space Weather



RESEARCH ARTICLE

10.1029/2020SW002456

Key Points:

- The Badhwar-O'Neill 2020 GCR model is presented
- The updated model is calibrated using new AMS-02 and PAMELA data
- Solar activity is described using ACE/CRIS daily integral flux measurements

Correspondence to:

T. C. Slaba,
tony.c.slaba@nasa.gov

Citation:

Slaba, T. C., & Whitman, K. (2020). The Badhwar-O'Neill 2020 GCR model. *Space Weather*, 18, e2020SW002456. <https://10.3847/10.1029/2020SW002456>

The Badhwar-O'Neill 2020 GCR Model

T. C. Slaba¹ and K. Whitman²

¹NASA Langley Research Center, Hampton, VA, USA, ²University of Houston, Houston, TX, USA

Abstract The Badhwar-O'Neill (BON) model has been used for some time to describe the galactic cosmic ray (GCR) environment encountered in deep space by astronauts and sensitive electronics. The most recent version of the model, BON2014, was calibrated to available measurements to reduce model errors for particles and energies of significance to astronaut exposure. Although subsequent studies showed the model to be reasonably accurate for such applications, modifications to the sunspot number (SSN) classification system and a large number of new high-precision measurements suggested the need to develop an improved and more capable model. In this work, the BON2020 model is described. The new model relies on daily integral flux from the Advanced Composition Explorer Cosmic Ray Isotope Spectrometer (ACE/CRIS) to describe solar activity. For time periods not covered by ACE/CRIS, the updated international SSN database is used. Parameters in the new model are calibrated to available data, which include the new Alpha Magnetic Spectrometer (AMS-02) and Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) high-precision measurements. It is found that the BON2020 model is a significant improvement over BON2014. Systematic bias associated with BON2014 has been removed. The average relative error of the BON2020 model compared to all available measurements is found to be <1%, and BON2020 is found to be within $\pm 15\%$ of a large fraction of the available measurements (26,269 of 27,646 $\rightarrow$ 95%).