Space Radiation Characterization for Safe Human Space Exploration and Settlements

Alessandro Bartoloni
On behalf of the AMS Roma Sapienza group
Italian Institute for Nuclear Physics (INFN)

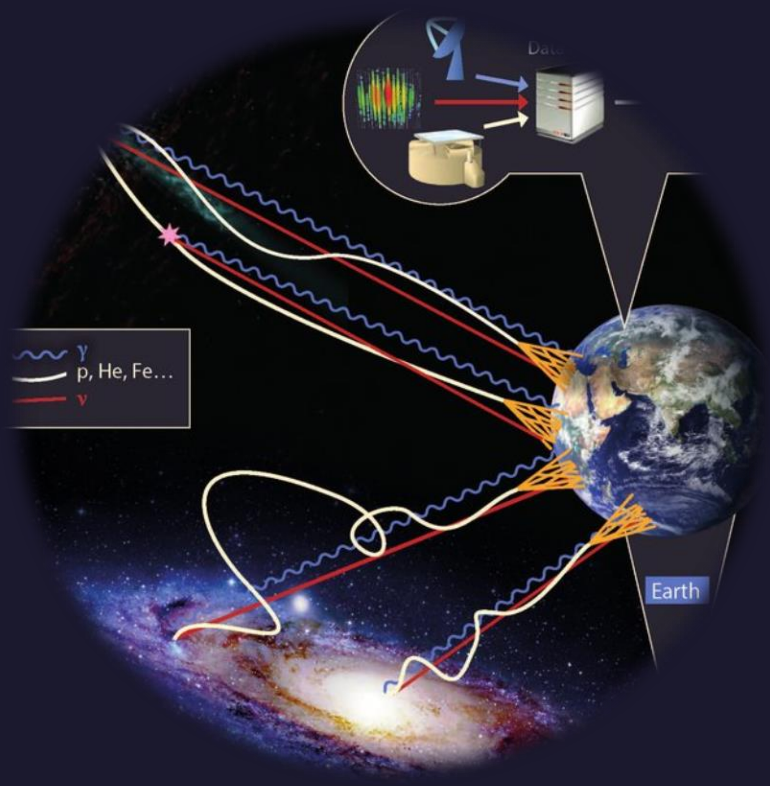
I gratefully acknowledge the strong support from the AMS collaboration, from the INFN Scientific Committee CNS2 and from the Italian Space Agency (ASI) within the agreement ASI-INFN n. 2019-19-HH.0

SPACEOPS 2023
THE 17th INTERNATIONAL CONFERENCE ON SPACE OPERATIONS
6-10 March 2023
Dubai, United Arab Emirates

Outline & Keywords

- The AMS Roma Sapienza Group
- Space Radiation Characterization
- AstroParticle Experiments
- Enabling Research @ AMS Roma Group

AMS02
(Space Cosmic Ray Detectors)



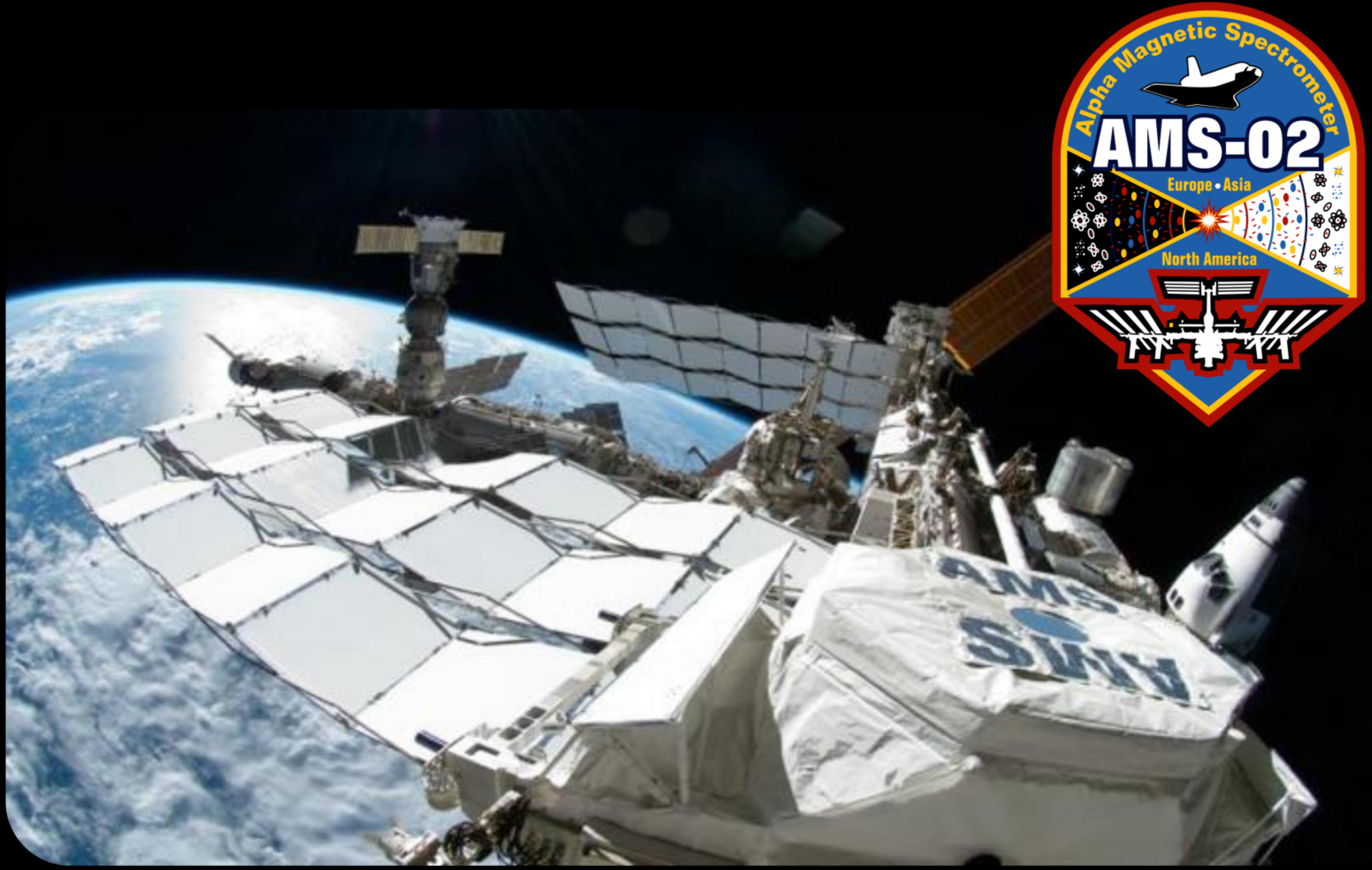
Space Radiation & Radiobiology

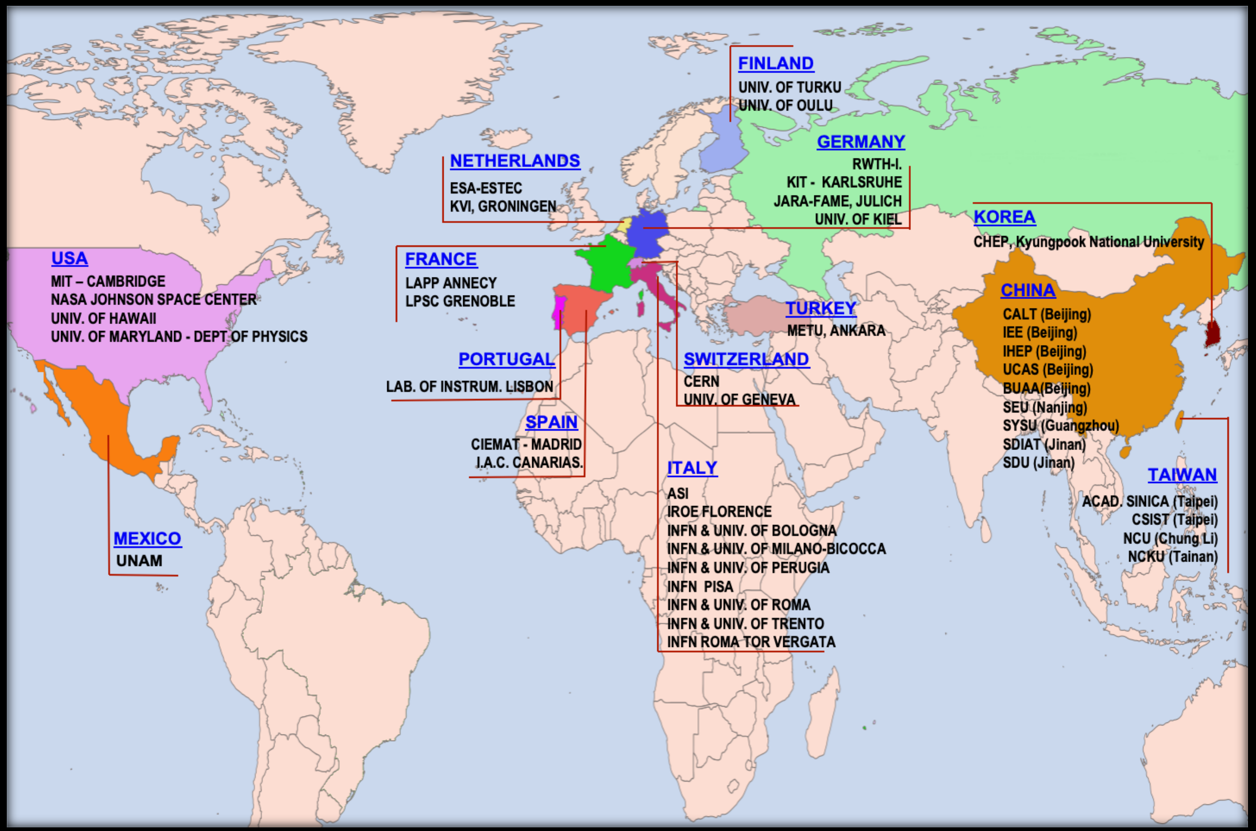
Human Space Exploration

The AMS Roma Sapienza Research Group

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





The AMS collaboration

(http://ams02.space)

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

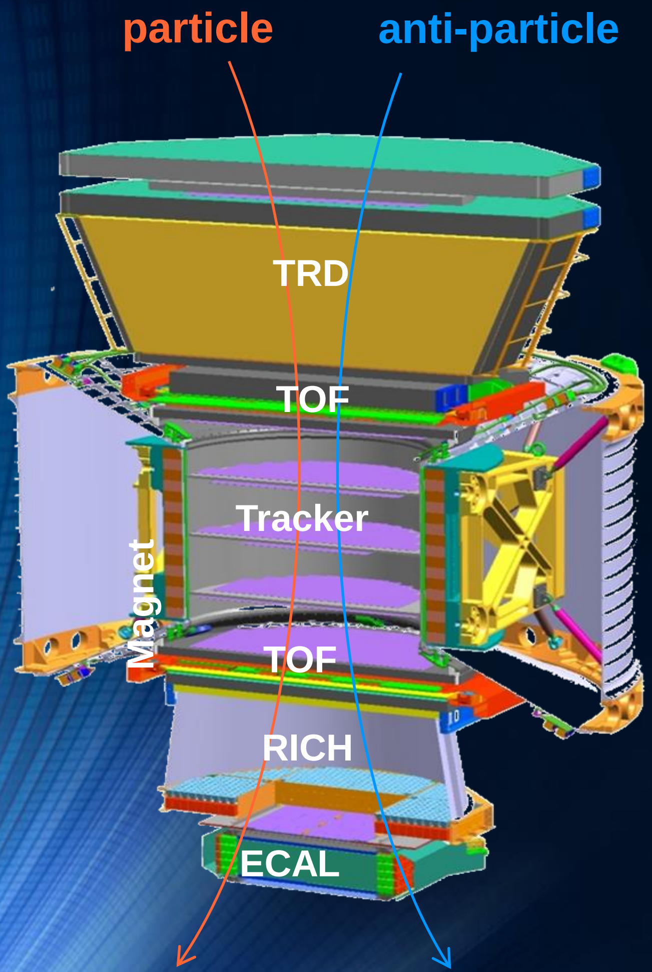
It uses the unique environment of space to study the universe and its origin by searching for antimatter, dark matter while performing precision measurements of cosmic rays' composition and flux.

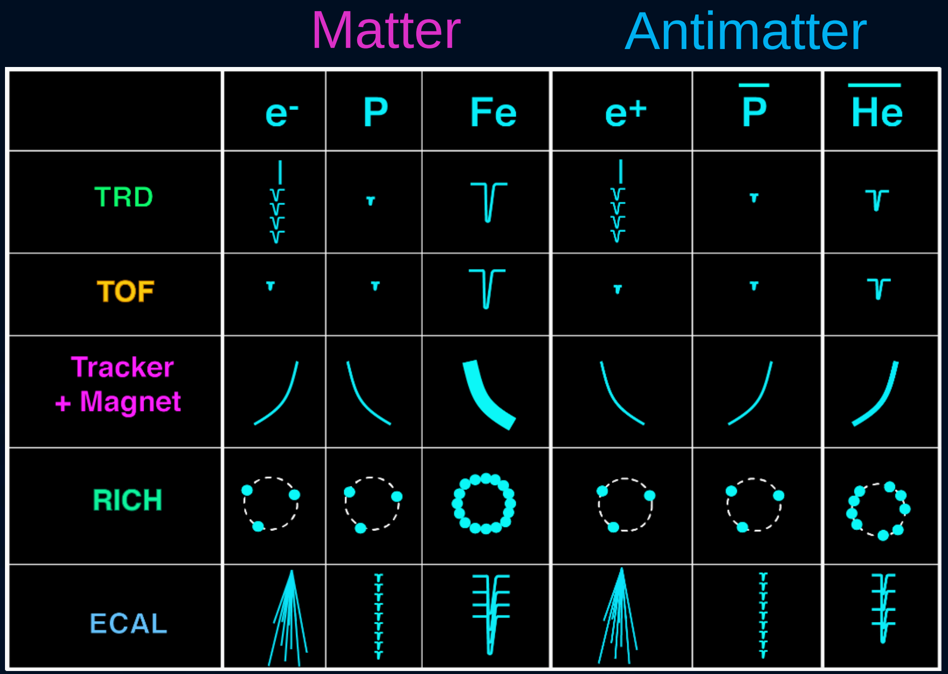
The AMS Payload Operation Control Center at CERN operates 365 days year h24

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

More Info in the AMS-02 webpage:
https://ams02.space

AMS is a space version of a precision detector used at accelerators

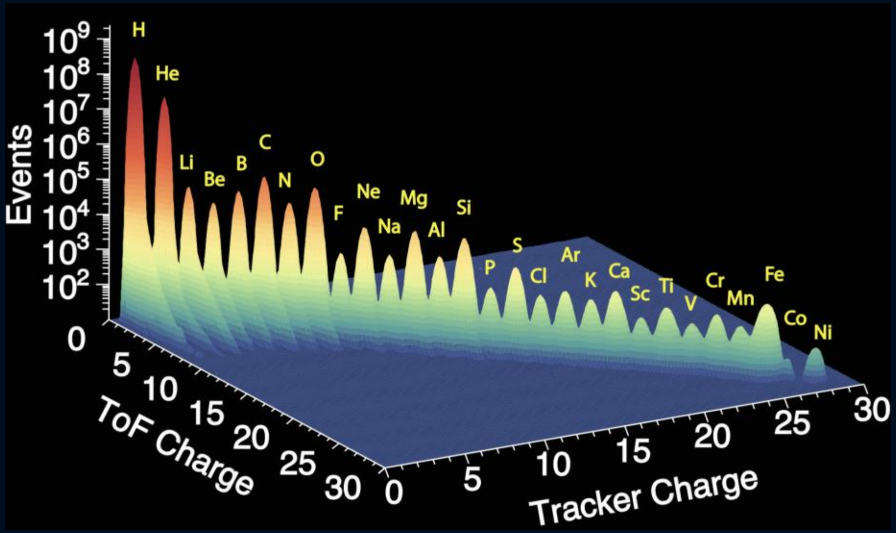




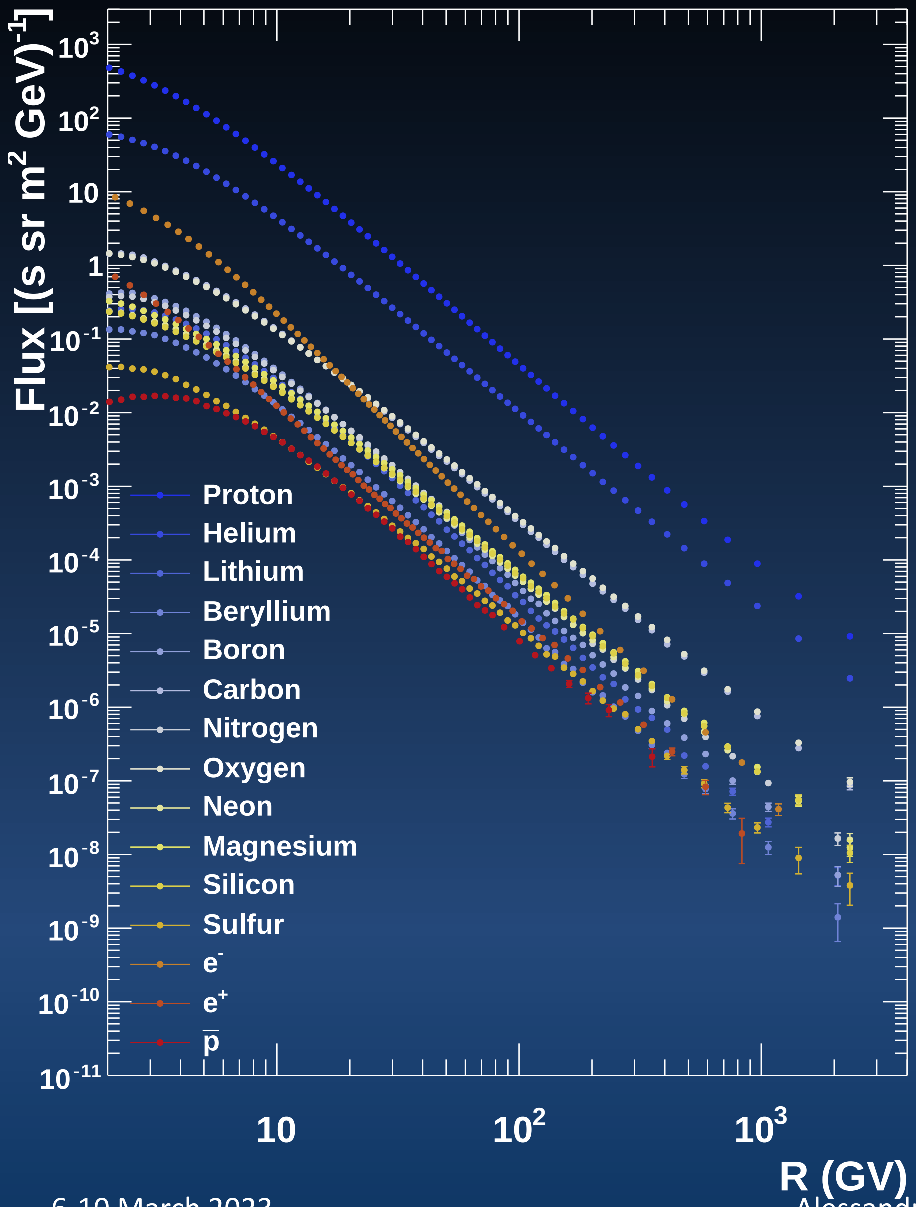
Cosmic-ray properties

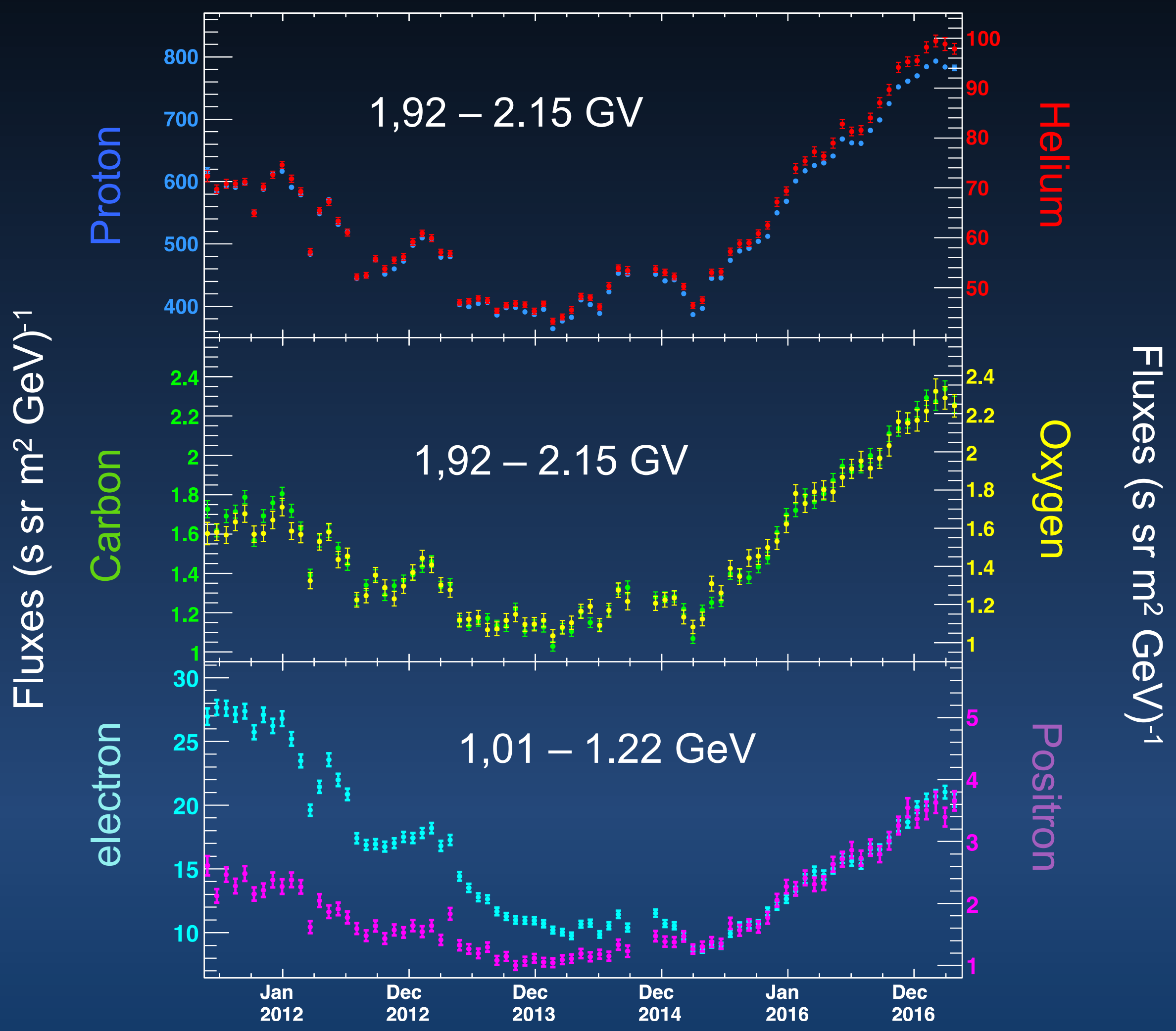
Dark Matter searches

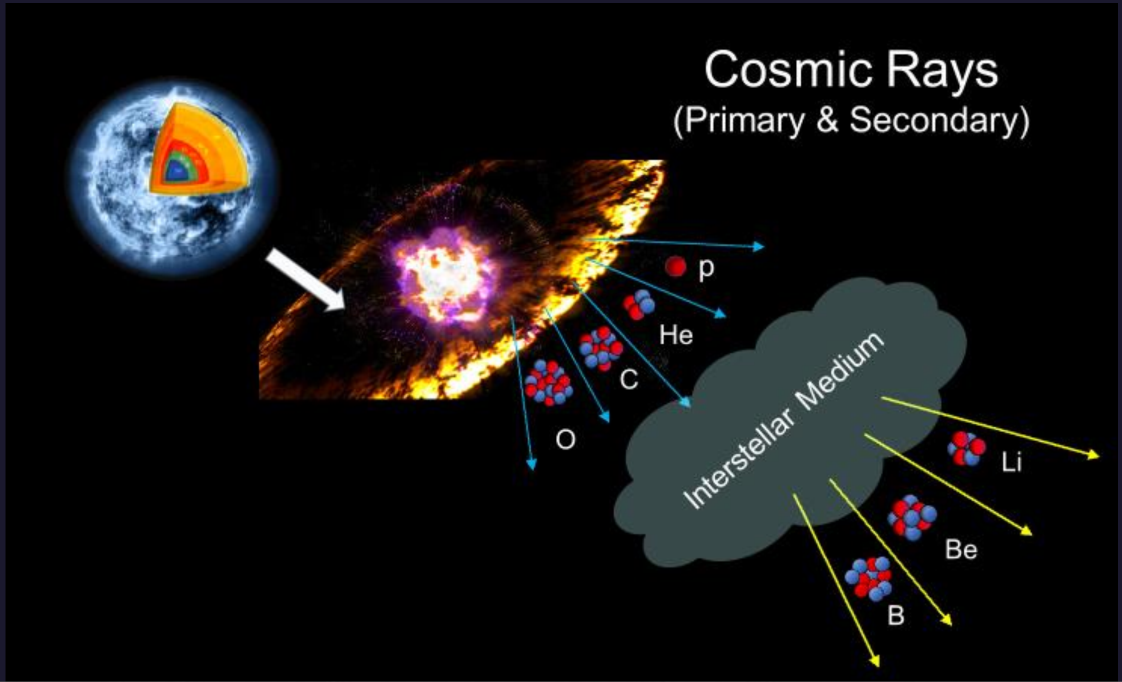
Primordial antimatter searches

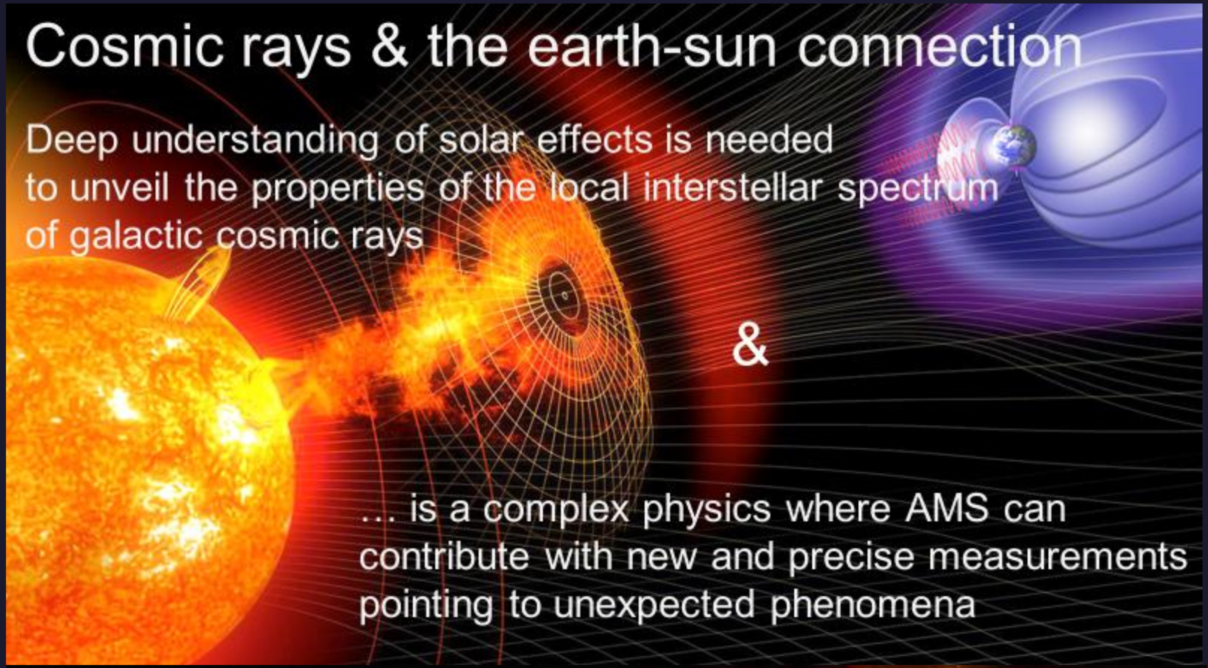


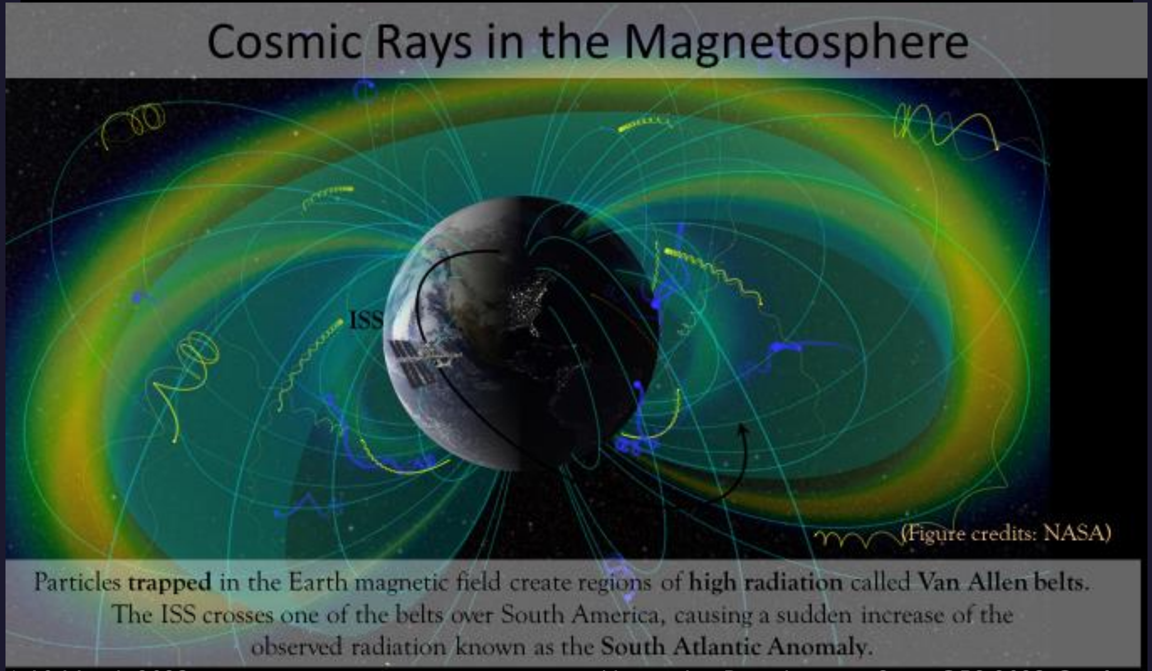
AMS – Measurements

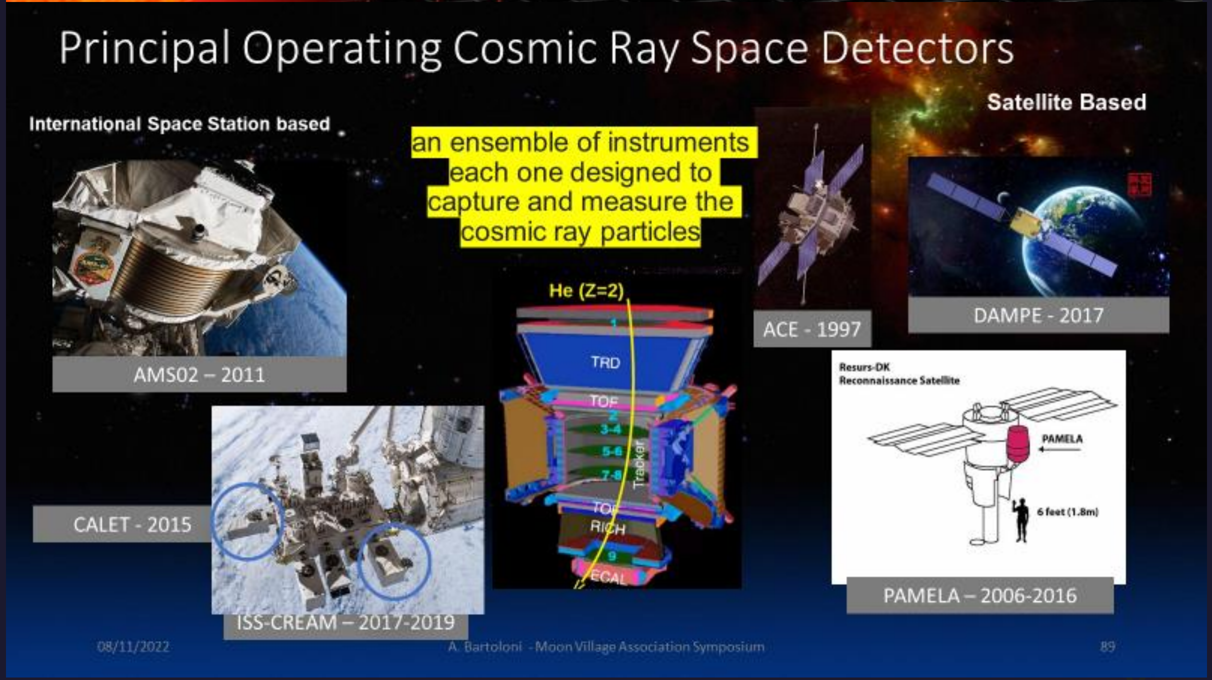





Cosmic Rays
(Primary & Secondary)
p
He
C
O
Interstellar Medium
Li
Be
B


Cosmic rays & the earth-sun connection
Deep understanding of solar effects is needed to unveil the properties of the local interstellar spectrum of galactic cosmic rays
&
... is a complex physics where AMS can contribute with new and precise measurements pointing to unexpected phenomena

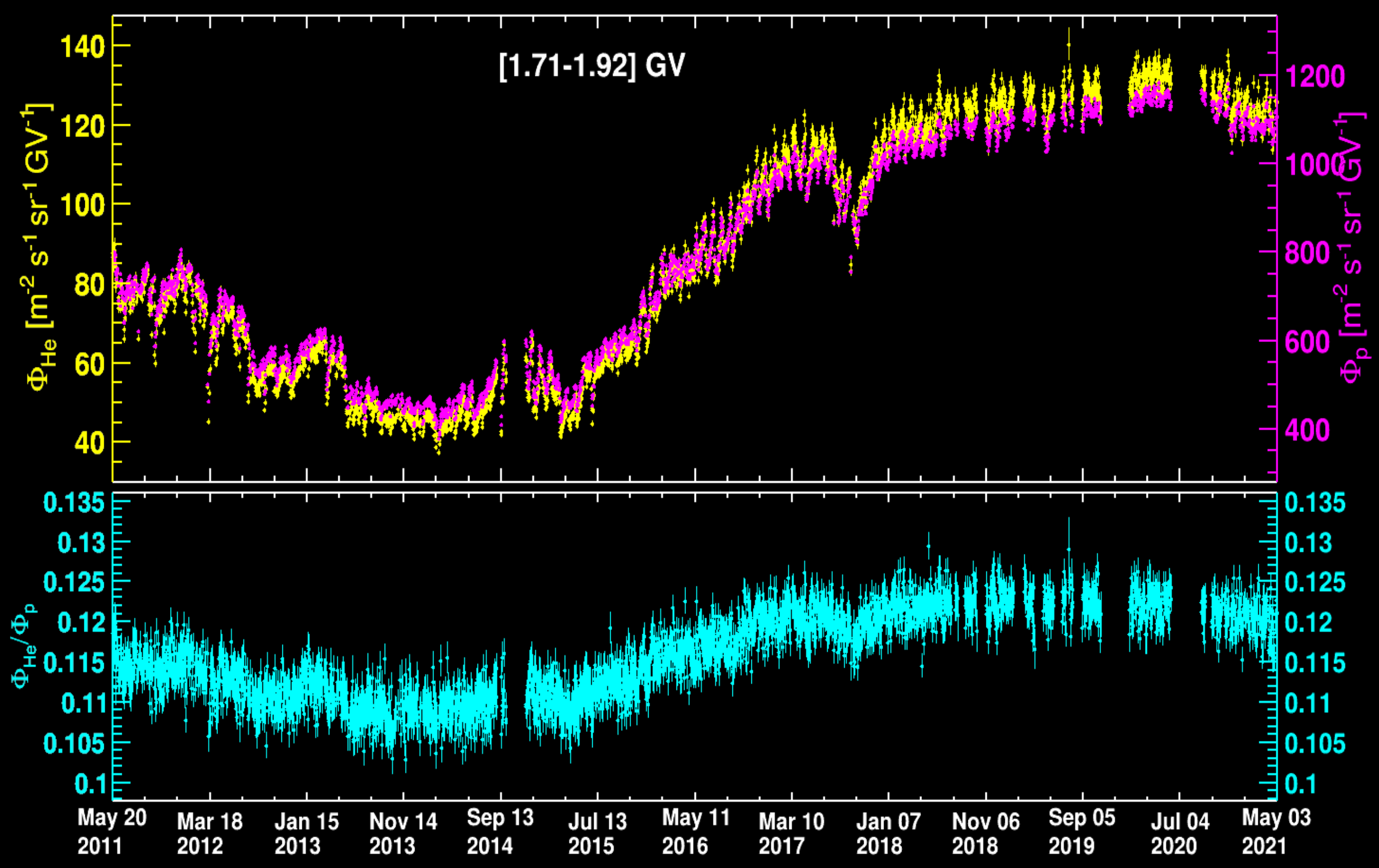

Cosmic Rays in the Magnetosphere
ISS
(Figure credits: NASA)
Particles trapped in the Earth magnetic field create regions of high radiation called Van Allen belts. The ISS crosses one of the belts over South America, causing a sudden increase of the observed radiation known as the South Atlantic Anomaly.


Principal Operating Cosmic Ray Space Detectors
International Space Station based
an ensemble of instruments each one designed to capture and measure the cosmic ray particles
Satellite Based
AMS02 – 2011
He (Z=2)
TRD
TOF
Tracker
RICH
ECAL
ACE - 1997
DAMPE - 2017
Resurs-DK Reconnaissance Satellite
PAMELA
6 feet (1.8m)
CALET - 2015
ISS-CREAM – 2017-2019
PAMELA – 2006-2016
08/11/2022
A. Bartoloni - Moon Village Association Symposium
89

Properties of Daily Helium Fluxes

AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Jun 10, 2022)

Published in: *Phys.Rev.Lett.* 128 (2022) 23, 231102



Periodicities in the Daily Proton Fluxes from 2011 to 2019 Measured by the Alpha Magnetic Spectrometer on the International Space Station from 1 to 100 GV

AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Dec 27, 2021)

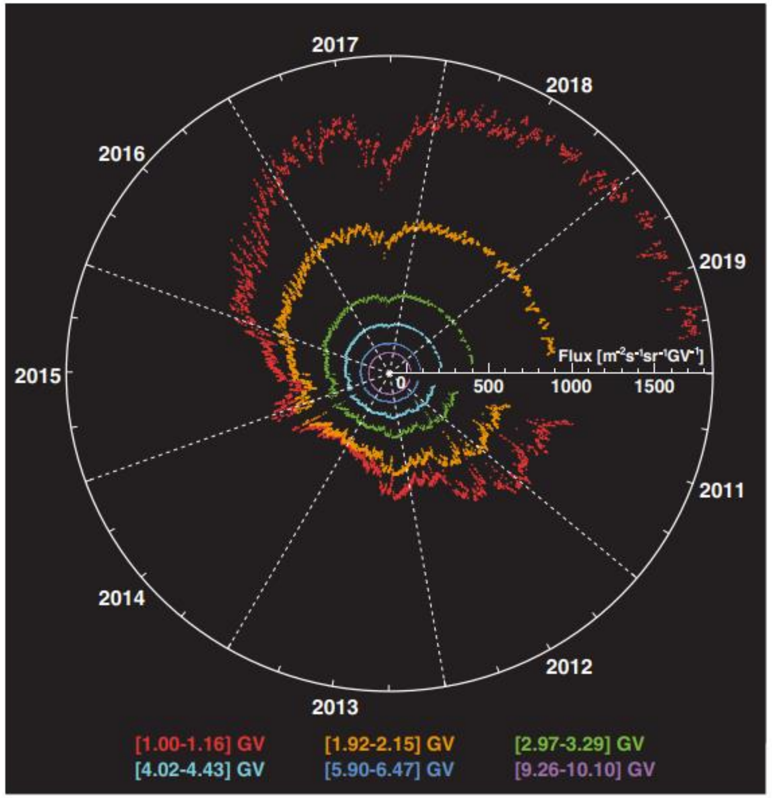


FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data

Short term Solar Modulation of GCR

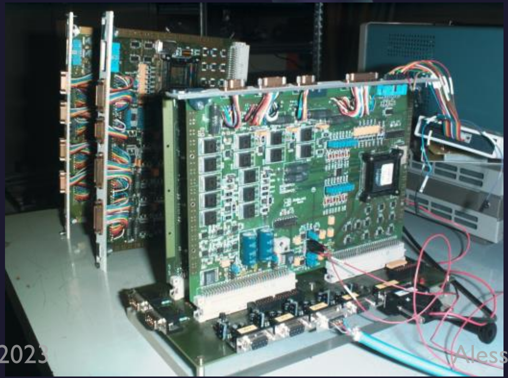
Daily Proton and Helium Fluxes and Helium to Proton flux ratio

Part of the AMS02 experiment was built at Rome (INFN & Sapienza)

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.



Design

2001-2003
- Engineering Modules

Test

2004-2005
- Qualification Modules (EMC-Thermo/Vacuum-Vibration Test)

Integrate

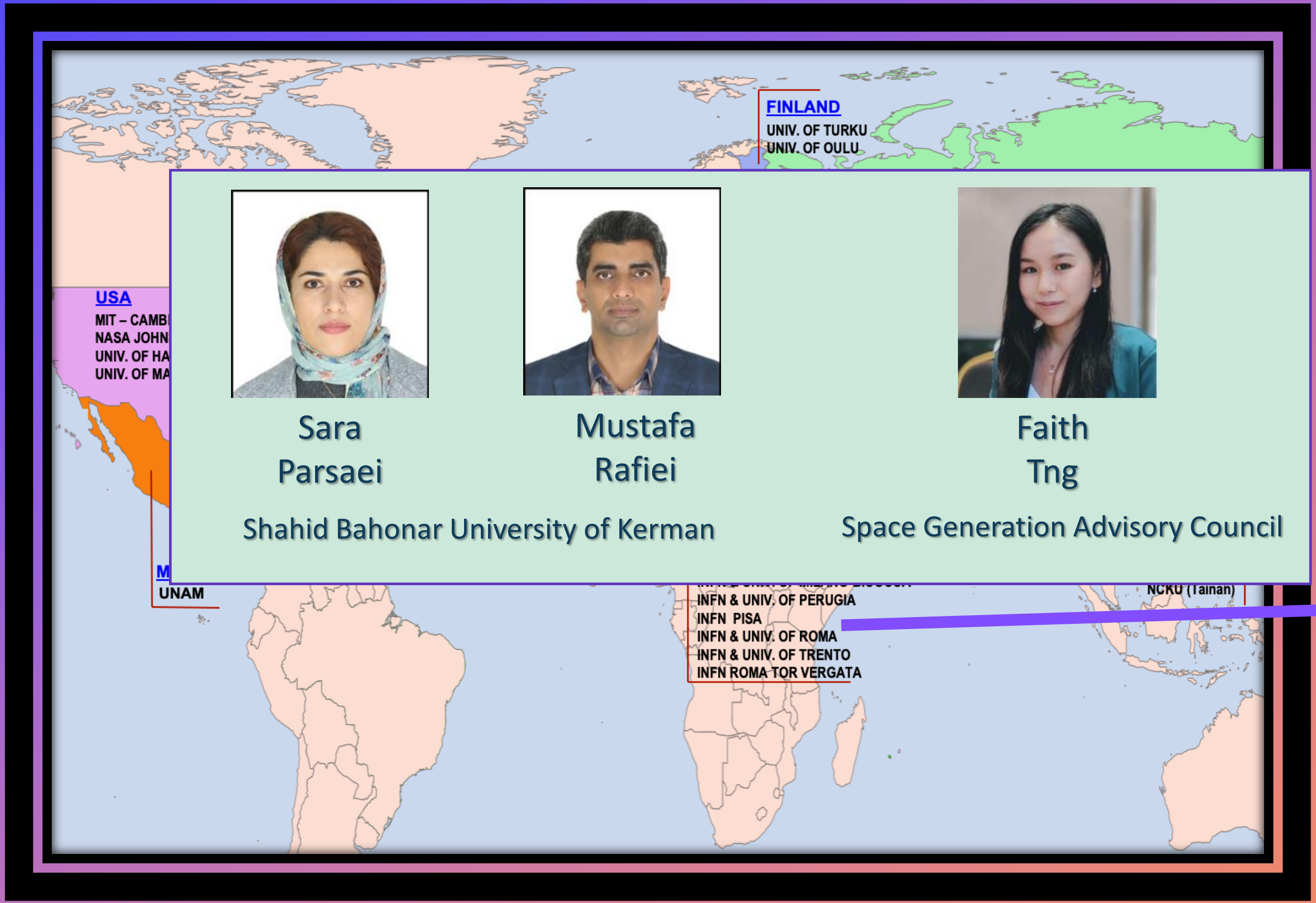
2006-2008
- Flight & Spare Modules production (now on ISS)

Fly

2009-2011
- UGPD-Crate Assembly in AMS02 and Space Qualification at ESA-ESTEC
- Launch ops at NASA-MSFC

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

AMS INFN
ROMA SAPIENZA GROUP



Sara
Parsaei

Mustafa
Rafiei

Shahid Bahonar University of Kerman

Faith
Tng

Space Generation Advisory Council

Aboma Negasa
Guracho

Alessandro
Bartoloni

- Giuseppe
Della Gala

Silvia
Strolin

Giulia
Paolani

Miriam
Santoro

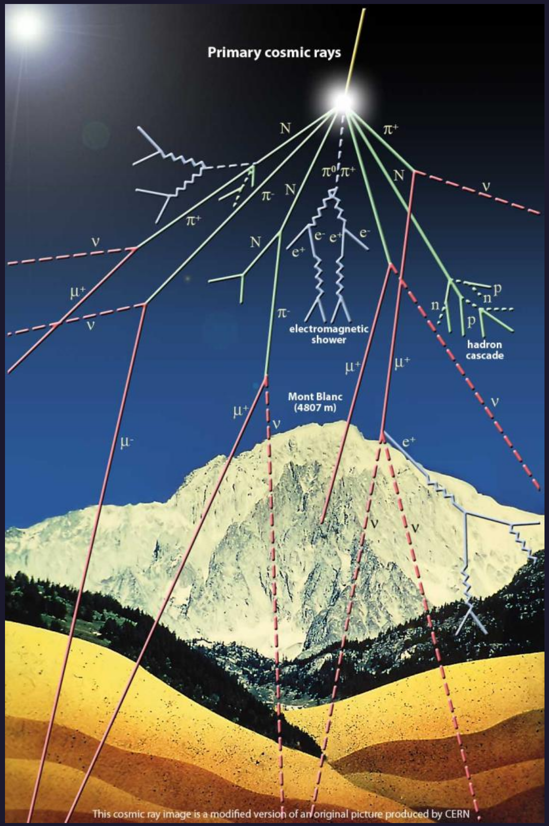
Lidia
Strigari

Cosmic rays (CR) approaching our planet interact with the Earth's magnetic field and atmosphere, and such interaction protects humans living on the Earth's surface.

The Magnetosphere rejects most particles (99%) while the rest loose most energy going through the atmosphere before reaching the Earth's surface.

Completely different is the situation in space where the CR interacting with the human body release some energy and can be dangerous for the human health.

In this regard, this is one of the main concerns for safe space exploration as planned for the coming years by all the national space Agencies.



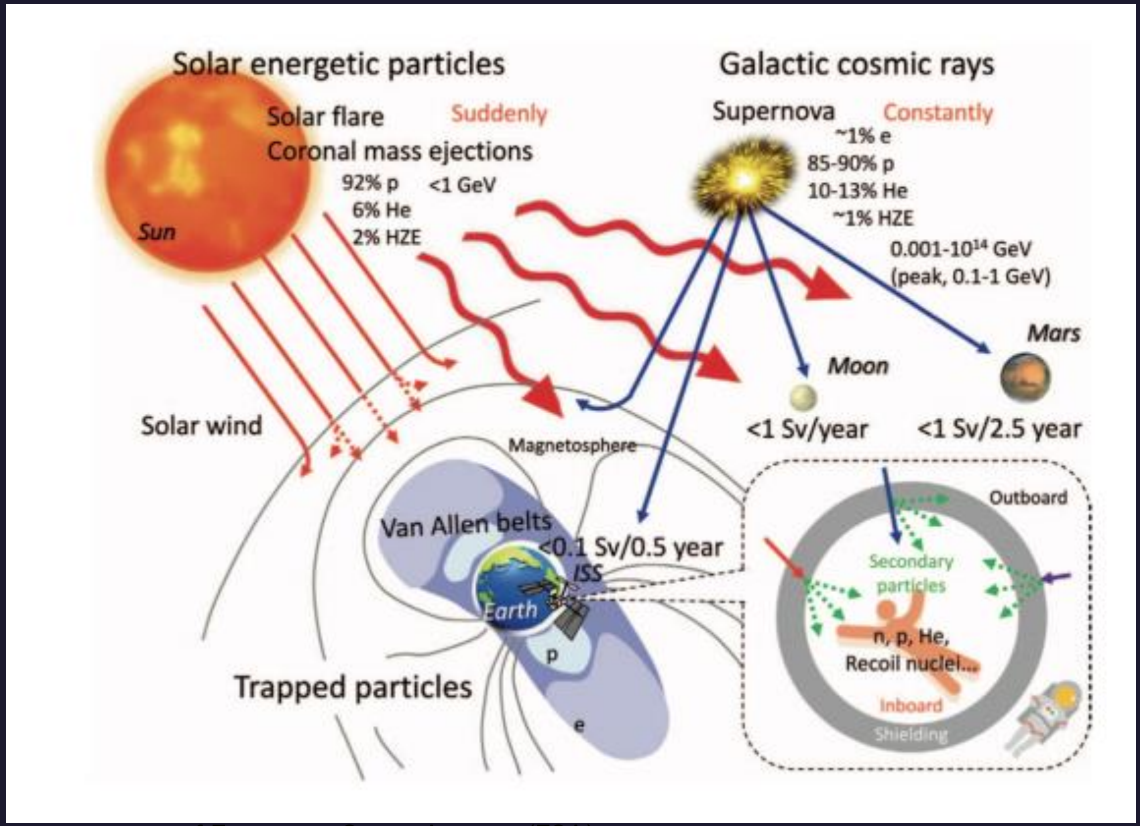


Image courtesy of European Space Agency (ESA)

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.

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

Collaborations were mainly focused on creating synergy within different scientific communities

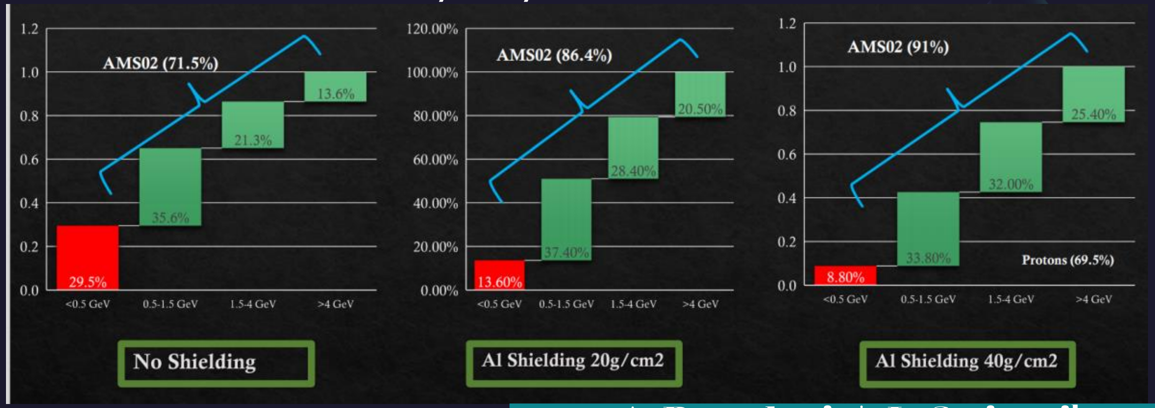
(radiobiology, medical physics, radiotherapy, and nuclear medicine)

and Institutions playing a crucial role in the human space exploration

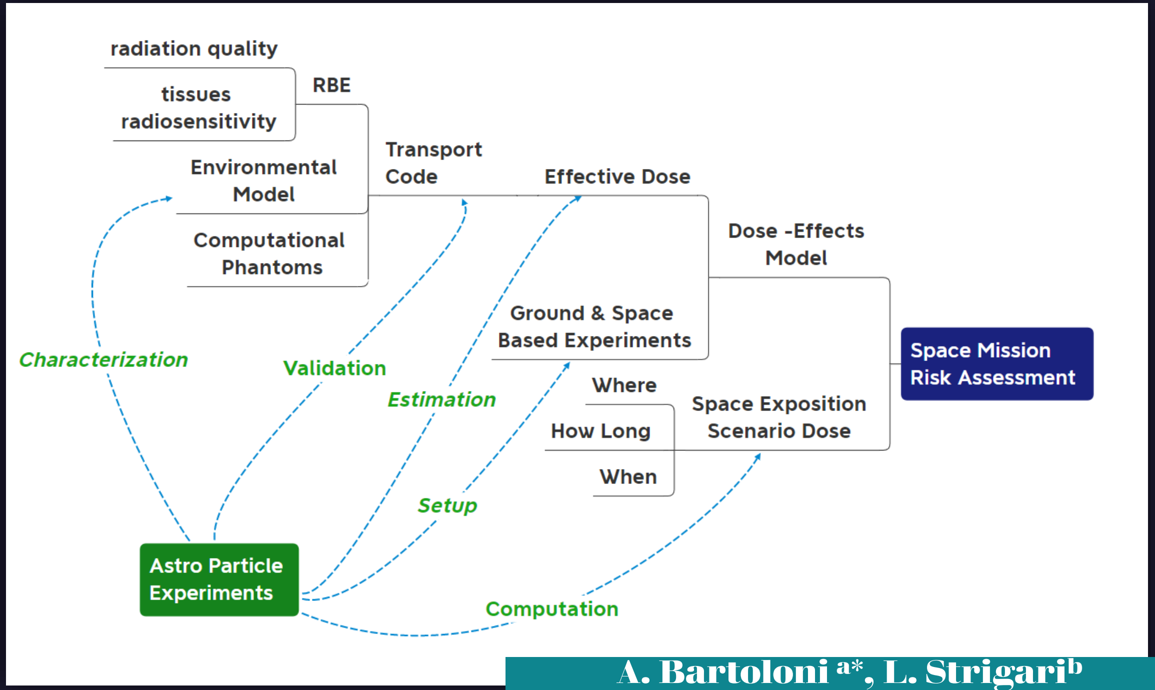
(Research, Universities, and National Space Agencies).

We have many studies on the capabilities and possibilities in that direction, especially regarding the AMS02 and also we identify many opportunities for improvement.

AMS02 GCR sensitivity analysis



A. Bartoloni [a*], L. Strigari [b]
SIF2019



A. Bartoloni [a*], L. Strigari [b]
GLEX-21-8.2.5 (ID:62186)

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)*

The manned spaceflight especially Beyond the Low Earth Orbit (BLEO) could represent a concern for the health of astronauts.

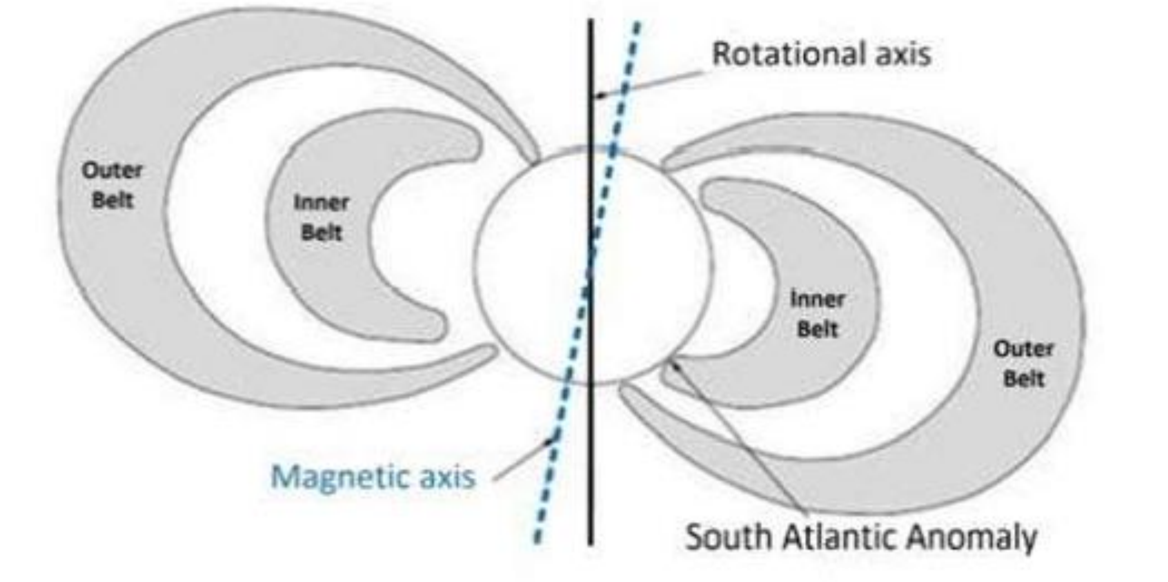
Images Courtesy of NASA

Travelling to the Moon to Stay

Apollo 11 data reports from dosimetry 1.8 mGy that the are optimistically equal to 1.8 mSv (Sievert indicates the biological effects).

Less that the annual dose expected on the Earth (2.-4.5 mSv)

Flight Path



Radiation Quality

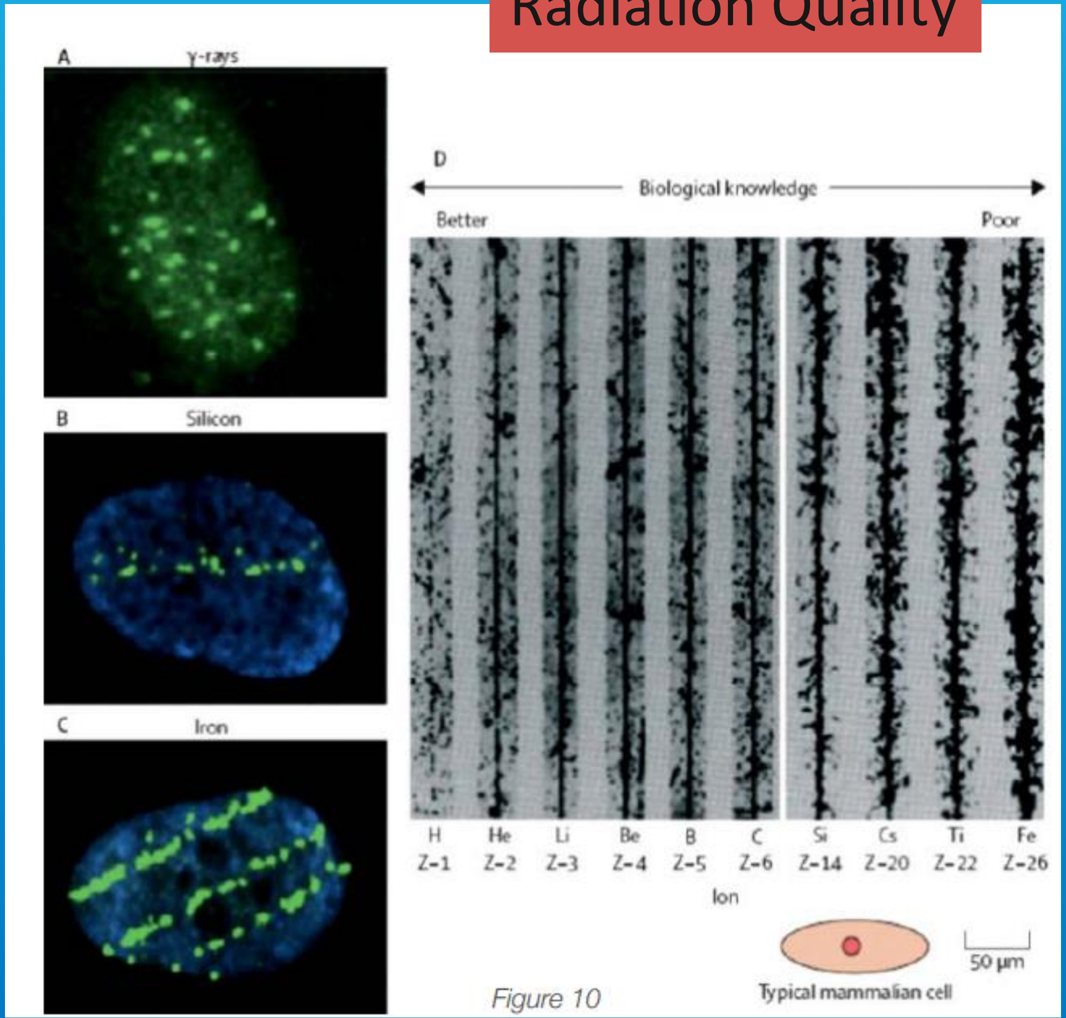


Figure 10

Travelling through the VAB (Worst Case Flight Path)

Radiation Analysis for Moon and Mars Missions

Andreas Märki

Märki Analytics for Space, Erlenbach ZH, Switzerland

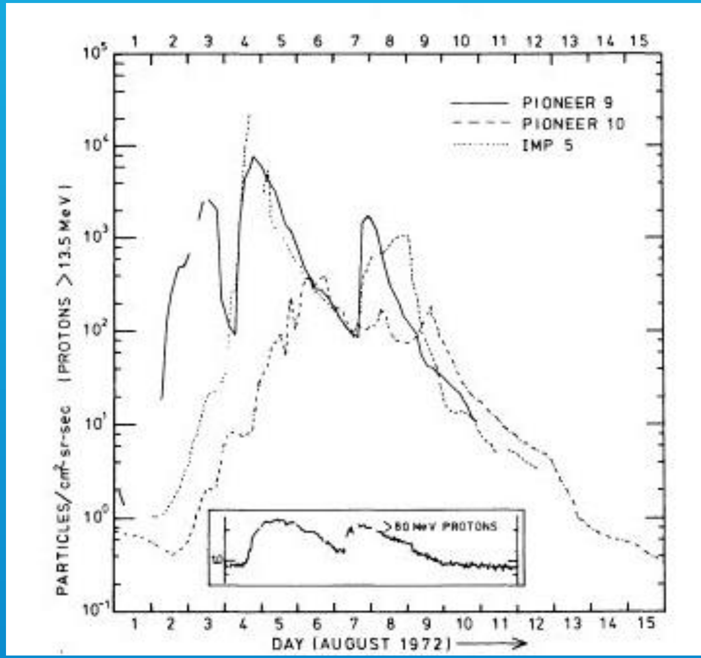
Table 2. *Determination of the Radiation Dose for 4mm Al Shielding through the VAB.*

	Zone	Time in Zone	Dose Calculation	Dose
Path to the Moon	1E3 … 1E4 p^+	400s ≈ 7min	400s * (1/300)*465mSv/h	>0.2 mSv
	1E4 … 1E5 e^-	≈0s	≈0 mSv	≈0 mSv
	1E5 … 1E6 e^-	800s ≈ 13min	800s * (1/30)*355mSv/h	>2.6 mSv
	>(≈) 1E6 e^-	700s ≈ 12min	700s * (1/3)*355mSv/h	>(≈) 23.0 mSv
	1E6 … 1E5 e^-	2700s=45min	2700s * (1/30)*355mSv/h	>8.9 mSv
	1E5 … 1E4 e^-	1383s ≈ 23min	1383s * (1/300)*355mSv/h	>0.5 mSv
Total Outward				>35.2 mSv
Return Path	1E4 … 1E5 e^-	1500s=25min	1500s * (1/300)*355mSv/h	>0.5 mSv
	1E5 … 1E6 e^-	1200s=20min	1200s * (1/30)*355mSv/h	>3.9 mSv
	1E5 … 1E4 e^-	≈0s	≈0 mSv	≈0 mSv
Total Return				>4.4 mSv
Total Resulting Dose				>39.6 mSv
				>39.6 mGy
Apollo 11 Mission Dose				1.8 mGy

This analysis reports more than 70 mSv from VAB Protons and Electrons using a 4mm Aluminum shields

The 4 August 1972 Solar Flare

April 1972

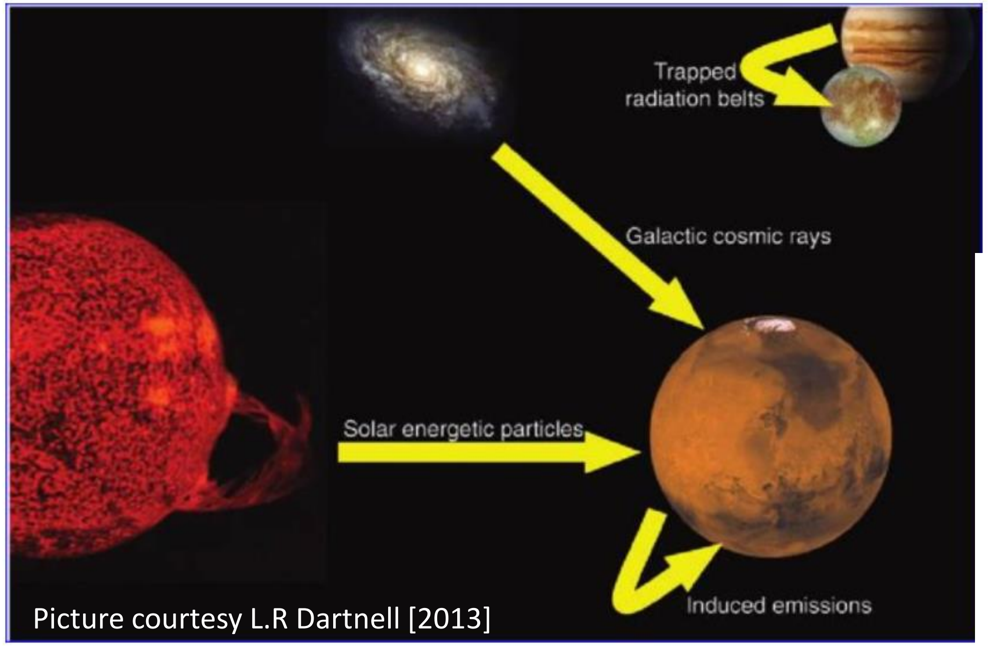


August 1972

December 1972

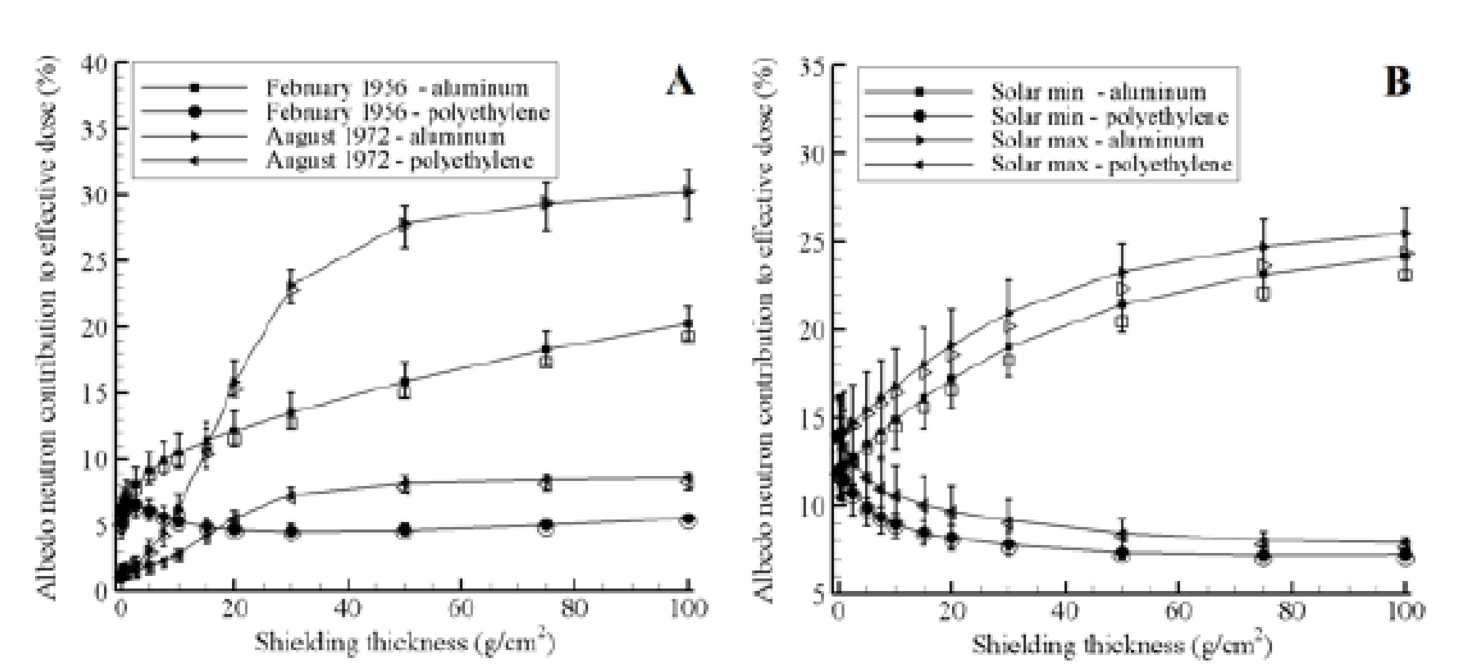
Sun Activities

GCR and SEP interaction with the lunar surface



Picture courtesy L.R Dartnell [2013]

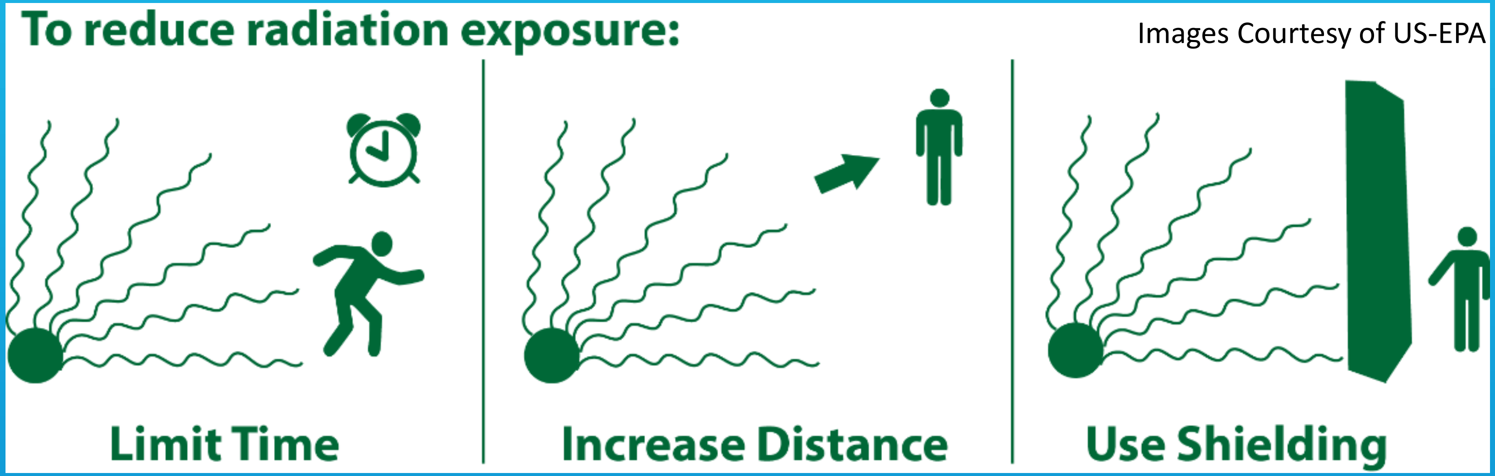
Albedo Ionizing Radiation



Percent Contribution to Effective Dose from Albedo Neutrons on Lunar Surface behind different types of shield From Slaba et Al [2011]

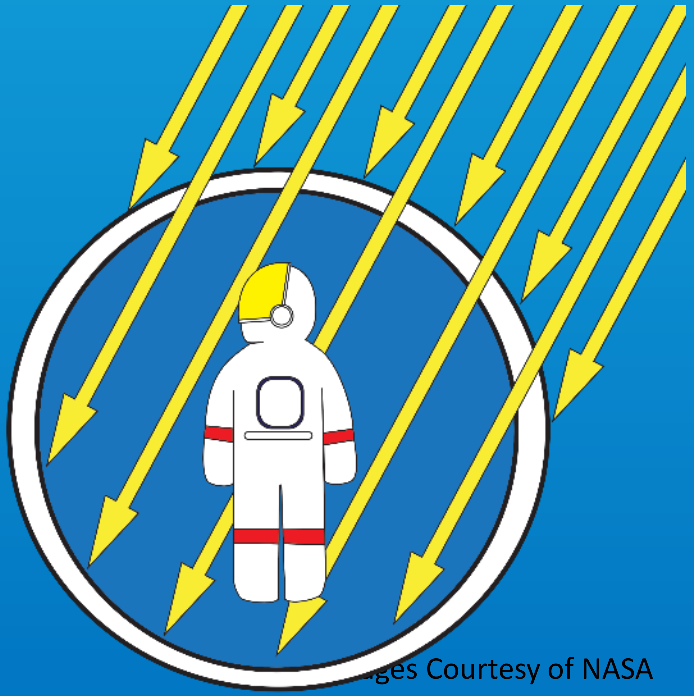
On the surface of the Moon the free space GCR or SPE environments interact with the planetary surface, yielding a back-scattered radiation field.

Radioprotection criteria used on Earth….



Images Courtesy of US-EPA

…do not work in space !



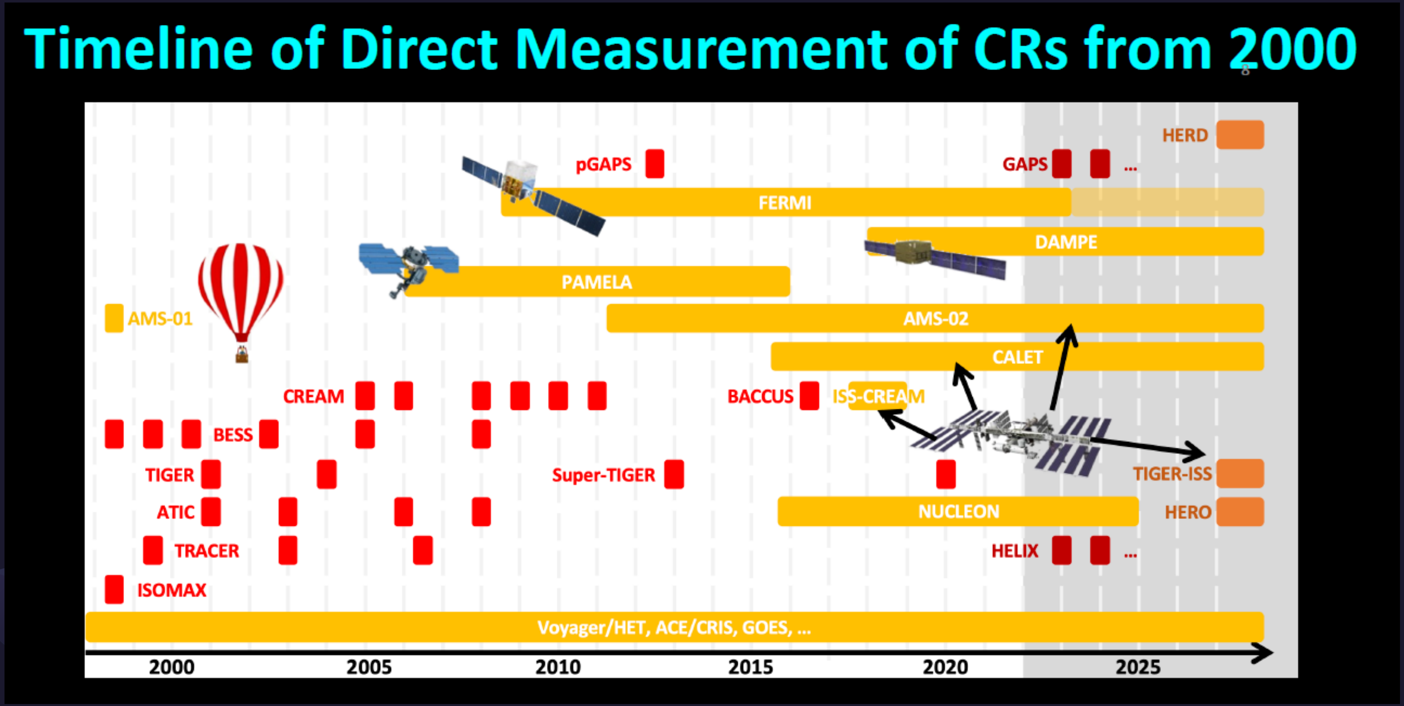
…ges Courtesy of NASA

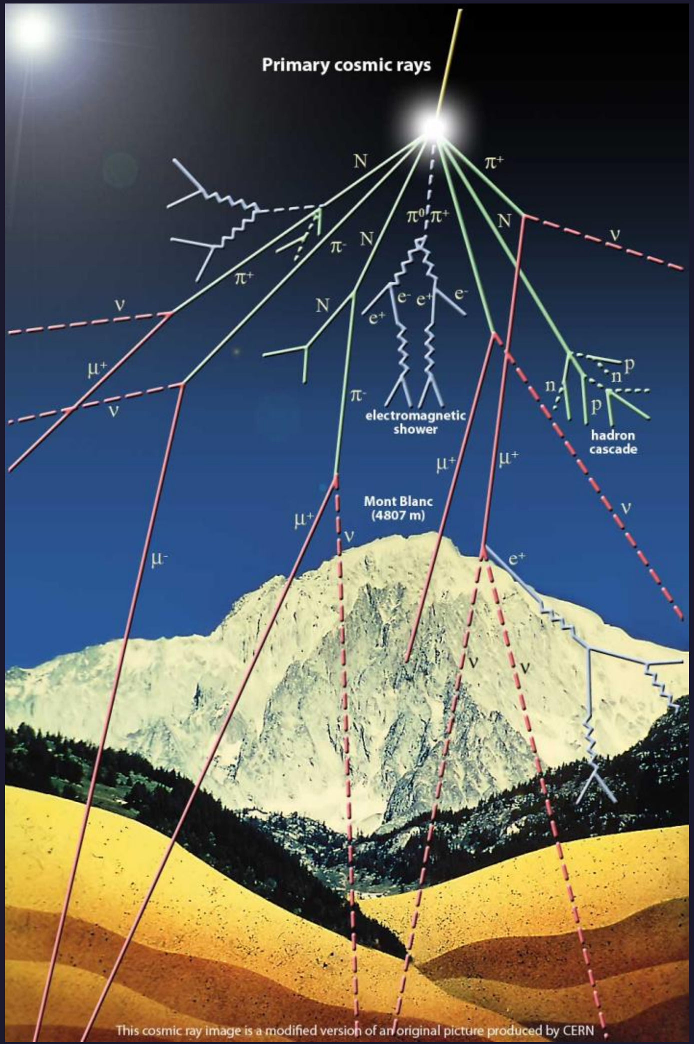
Cosmic Ray Detectors in Space

Astroparticle Experiments in Space

In the last two decades, many astroparticle experiments have been built and deployed in space to investigate many open questions in fundamental physics and cosmology, for example, the dark matter and dark energy existence and composition or the existence of primordial antimatter.

A particular class of experiments, the CR Detectors (CRD), are designed to produce a complete inventory of charged particles and nuclei in CR since the knowledge of this information is crucial to solving the above physics open problems.



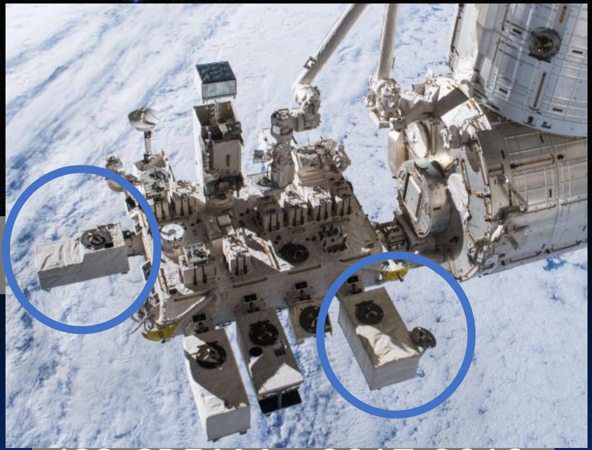


Principal Operating Cosmic Ray Space Detectors

International Space Station based

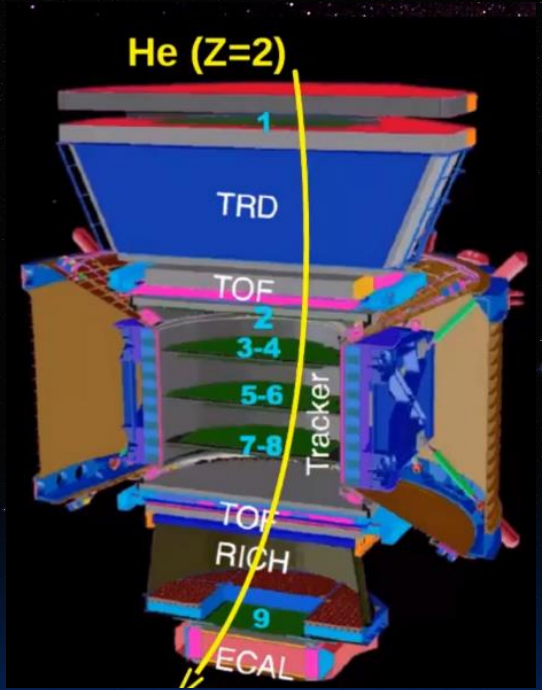
AMS02 – 2011

CALET - 2015



ISS-CREAM – 2017-2019

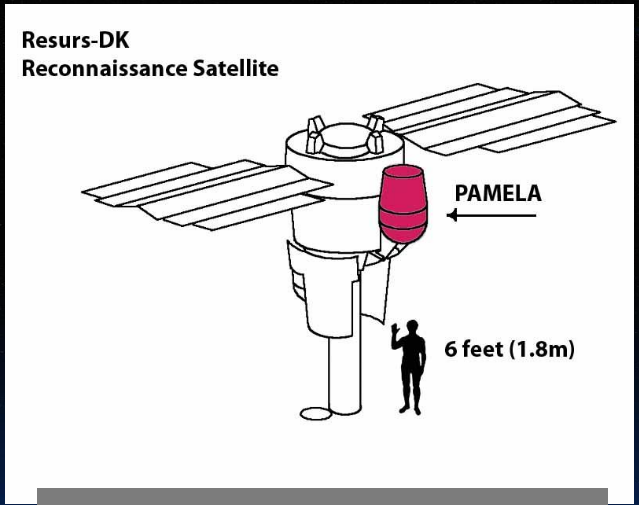
an ensemble of instruments each one designed to capture and measure the cosmic ray particles



Satellite Based

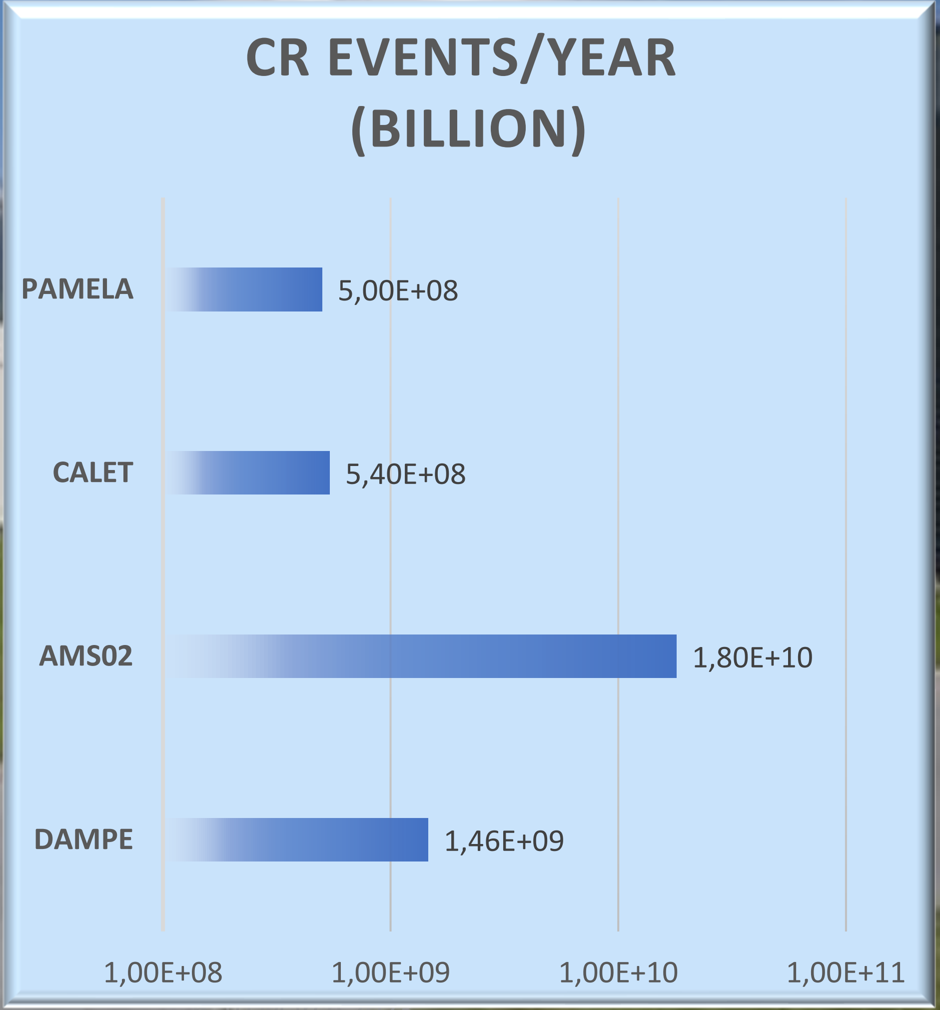
ACE - 1997

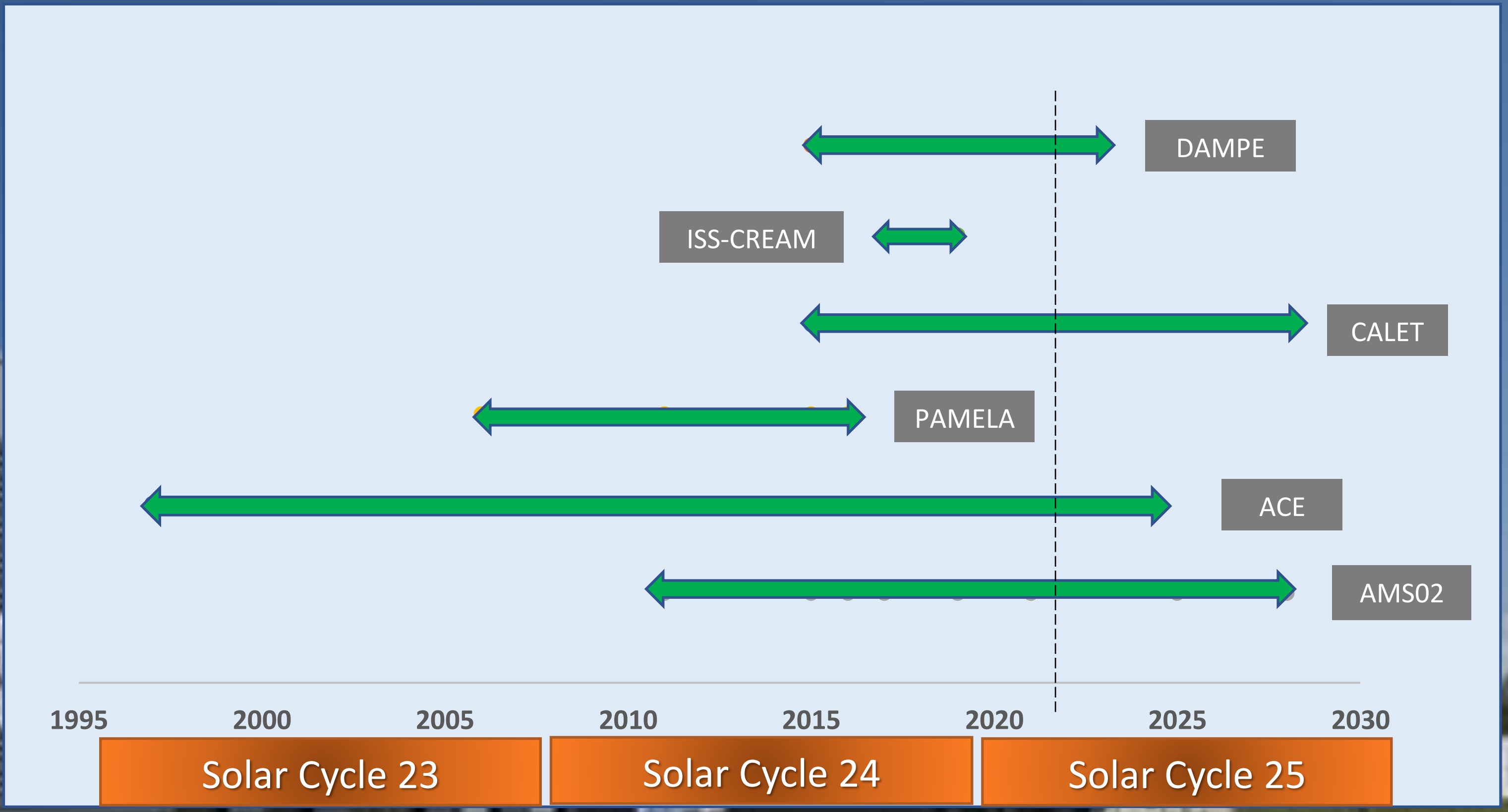
DAMPE - 2017



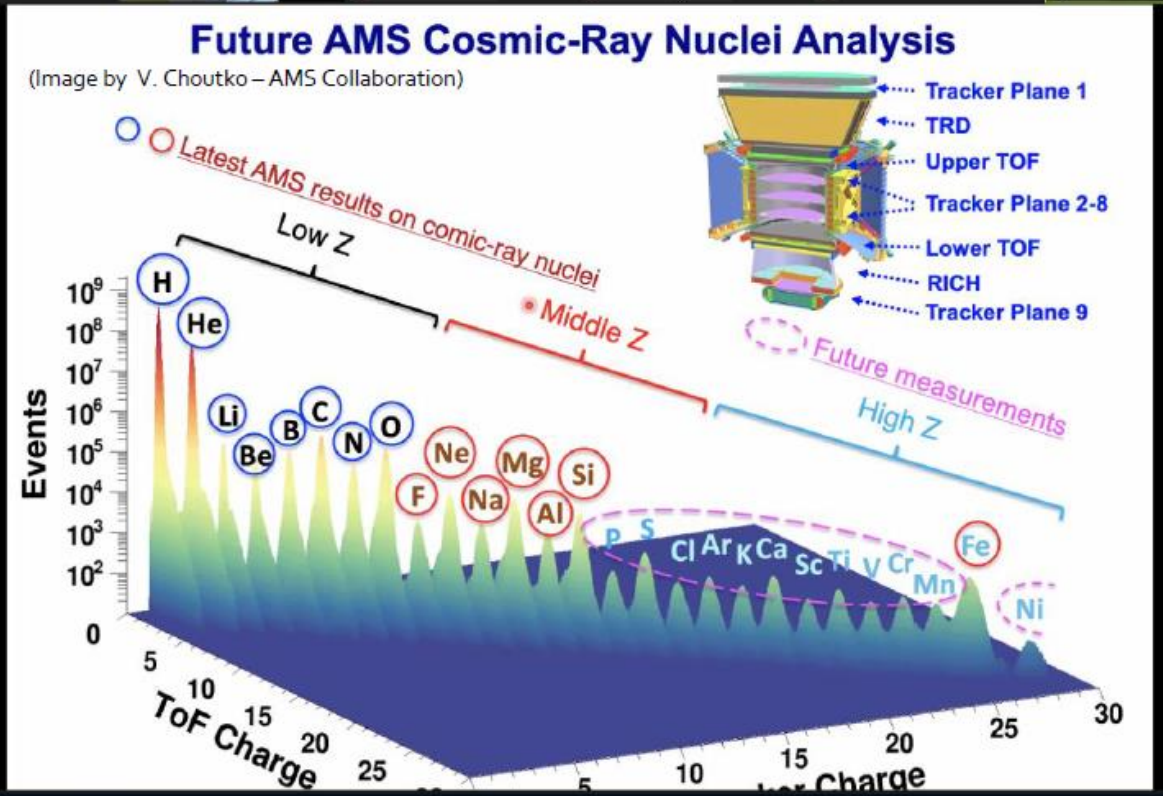
PAMELA – 2006-2016

Missions Operations





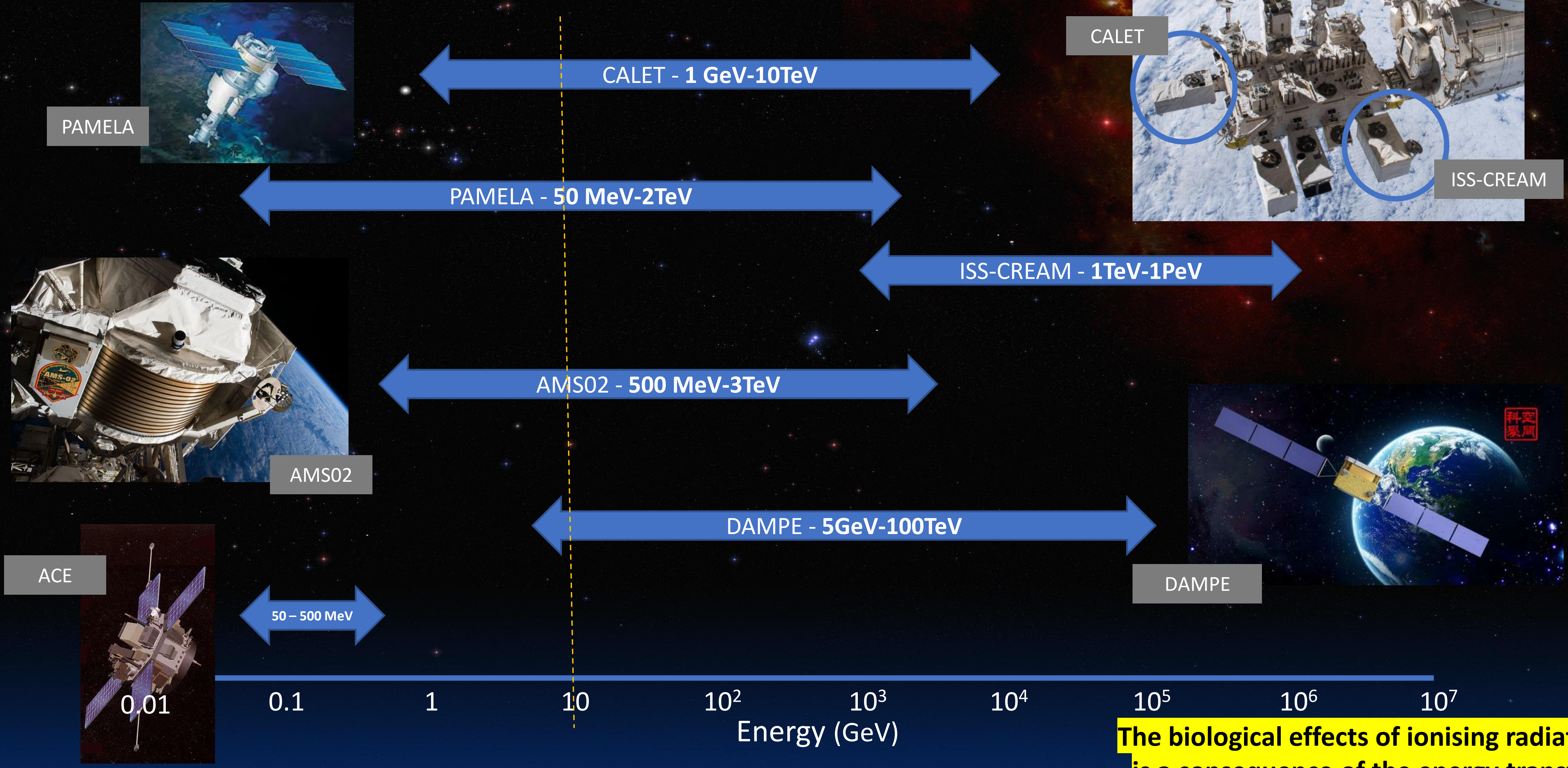
Cosmic Ray Components Identification	
e+,e-	ALL
p+,p-	ALL
D,He	ALL
Low-Z (<=8)	ALL (PAMELA up to Z=6)
Middle-Z	AMS02, CALET, ISS-CREAM, ACE, DAMPE
High-Z (>14)	AMS02, CALET, ISS-CREAM, ACE, DAMPE



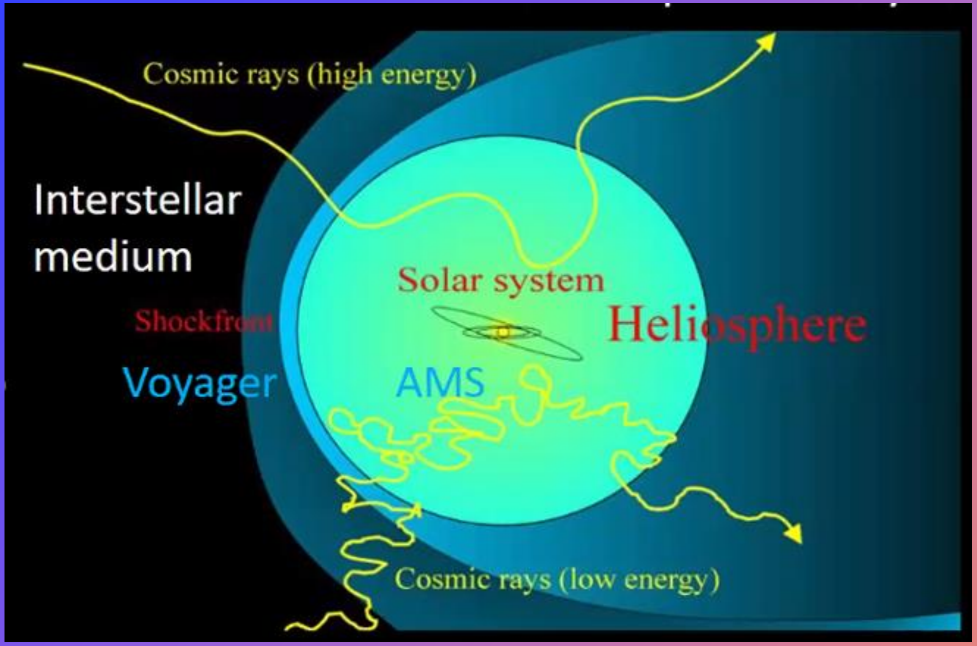
Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer
AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Jan 29, 2021)
Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041104

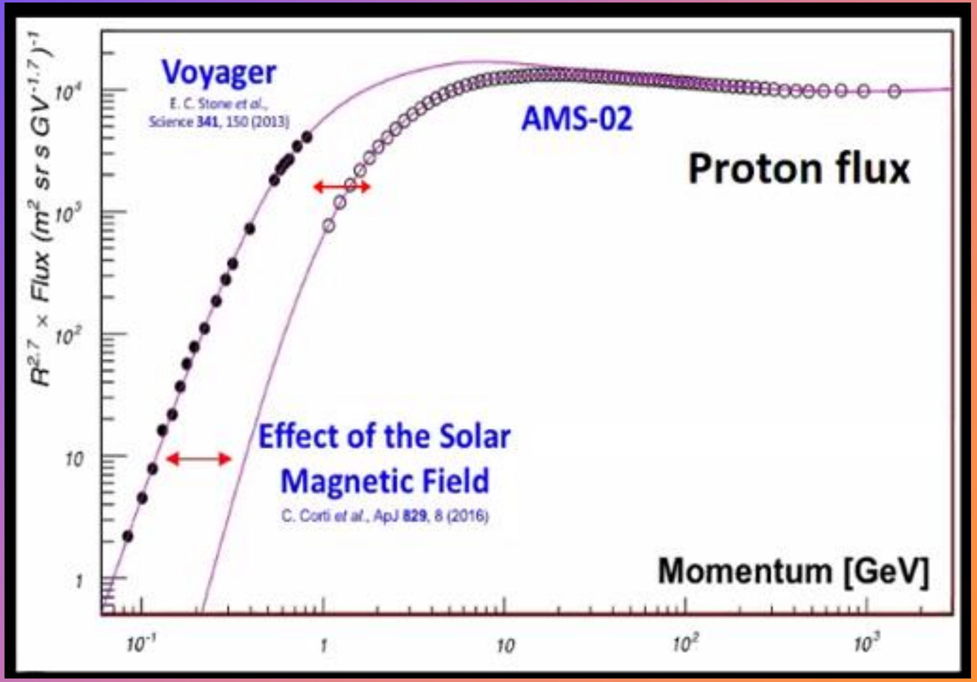
Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer
AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Feb 25, 2021)
Published in: *Phys.Rev.Lett.* 126 (2021) 8, 081102

CRDs Energy Range



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





Credit S.Ting & AMS Collaboration

Cosmic Rays Solar modulation

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

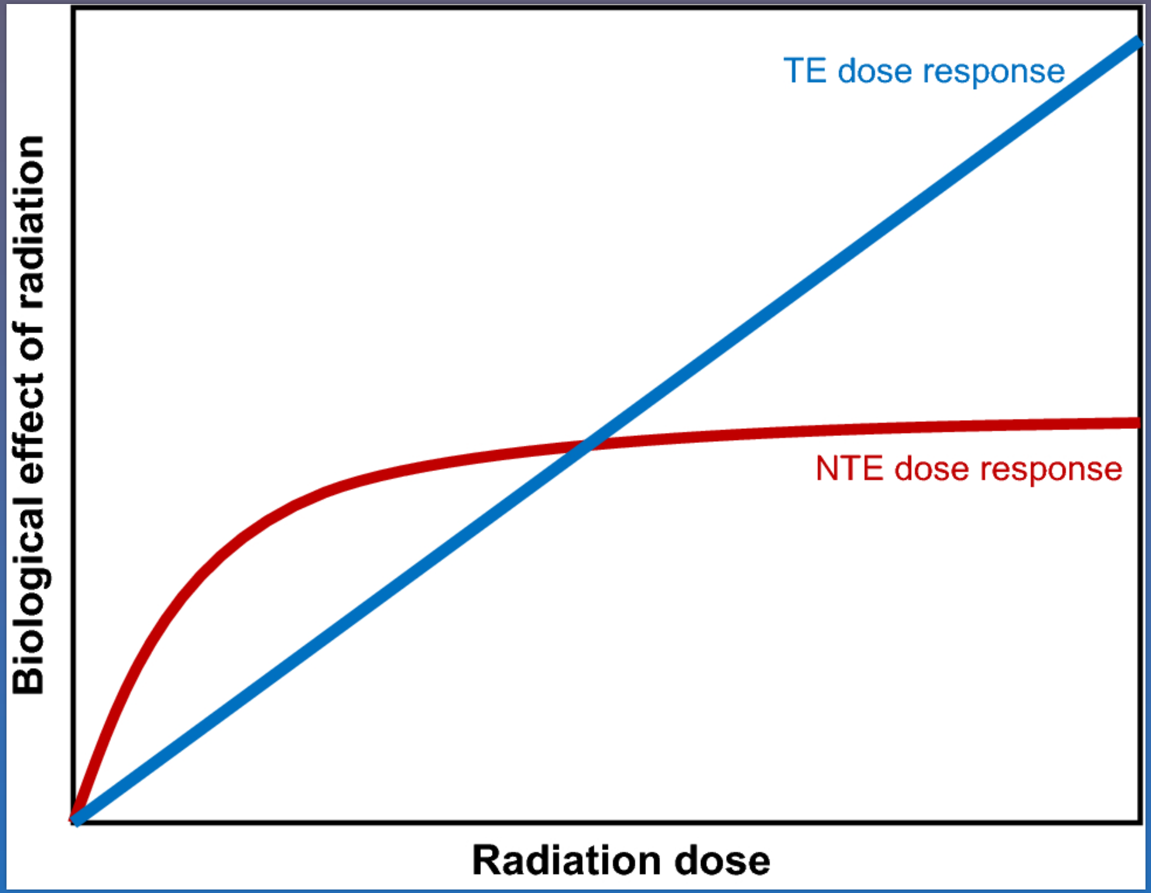
This effect is particulary visibile at low energies

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

Enabling Research @ AMS Roma Group

Dose-Effect Relationship (DER)

A crucial point to predict the toxicity of the space radiation expected for the astronauts/space workers is the creation of reliable mathematical models that describe the correlation between the exposition to IR and the possible damage to the organ at risk.

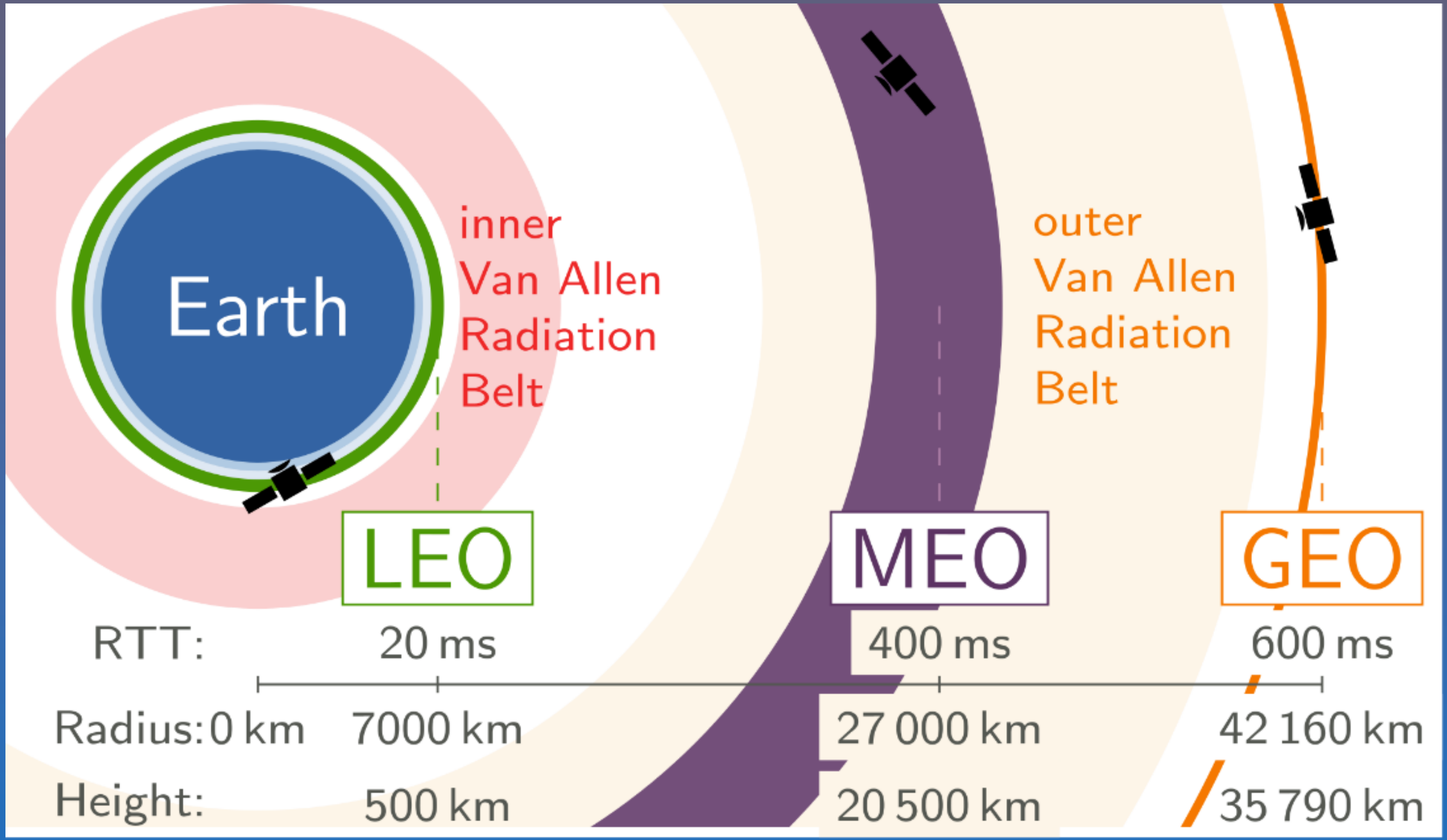


The known dose-effect relationships are based on a limited number of astronauts

3 only reached a sub-orbital flight, 567 people reached the LEO

24 traveled in BLEO + 12 walked on the Moon

574 people have gone into space according to the FAI criterion (as 20 July 2021)



Space travelers have spent a cumulative total of over 77 years

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

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

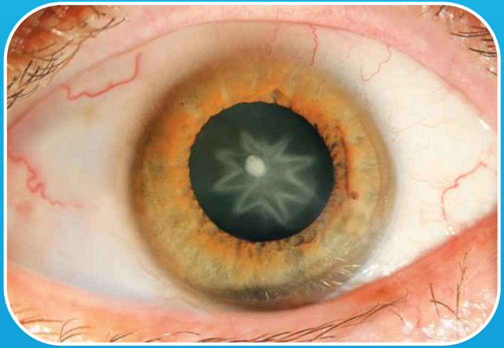
Lidia Strigari[1], Silvia Strolin[1], Alessio Giuseppe Morganti[2] and Alessandro Bartoloni[3*]

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

Articles dose-effect models exploration and identification

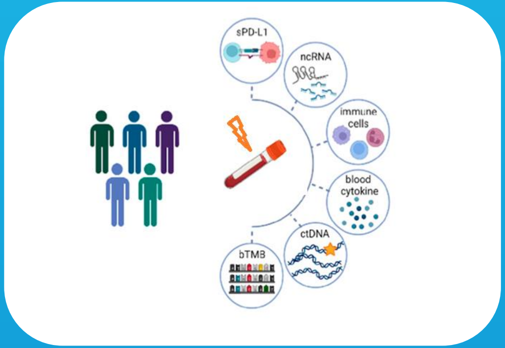
- **Identification of**
  - Types of irradiation
  - Data
  - Models
- **Experimental Type**
  - In Vitro
  - Pre-clinical
  - Clinical
- **Study Type**
  - Ground
  - Simulation
  - Spaceflight

«Eye-Flashes»

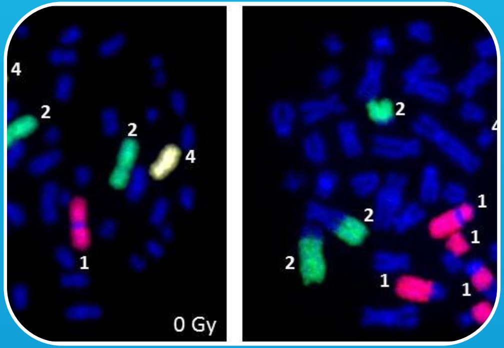


Cataract or

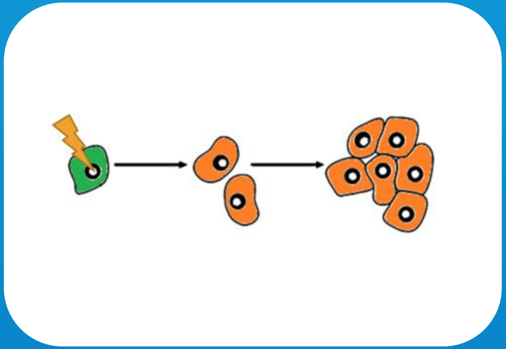
Visual impairments



Biomarkers

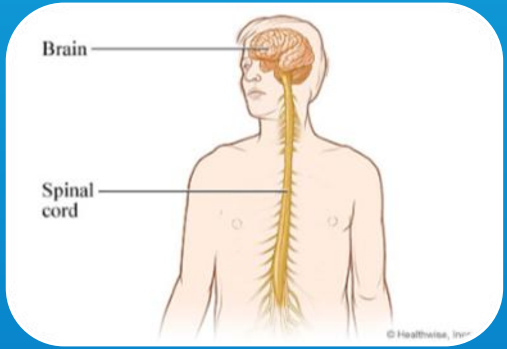


Chromosomal Aberrations

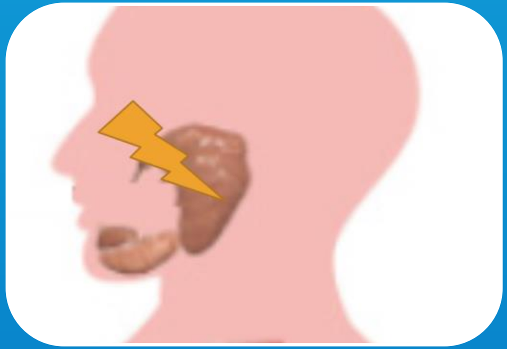


Carcinogenesis

Cardiovascular Disease (CVD)



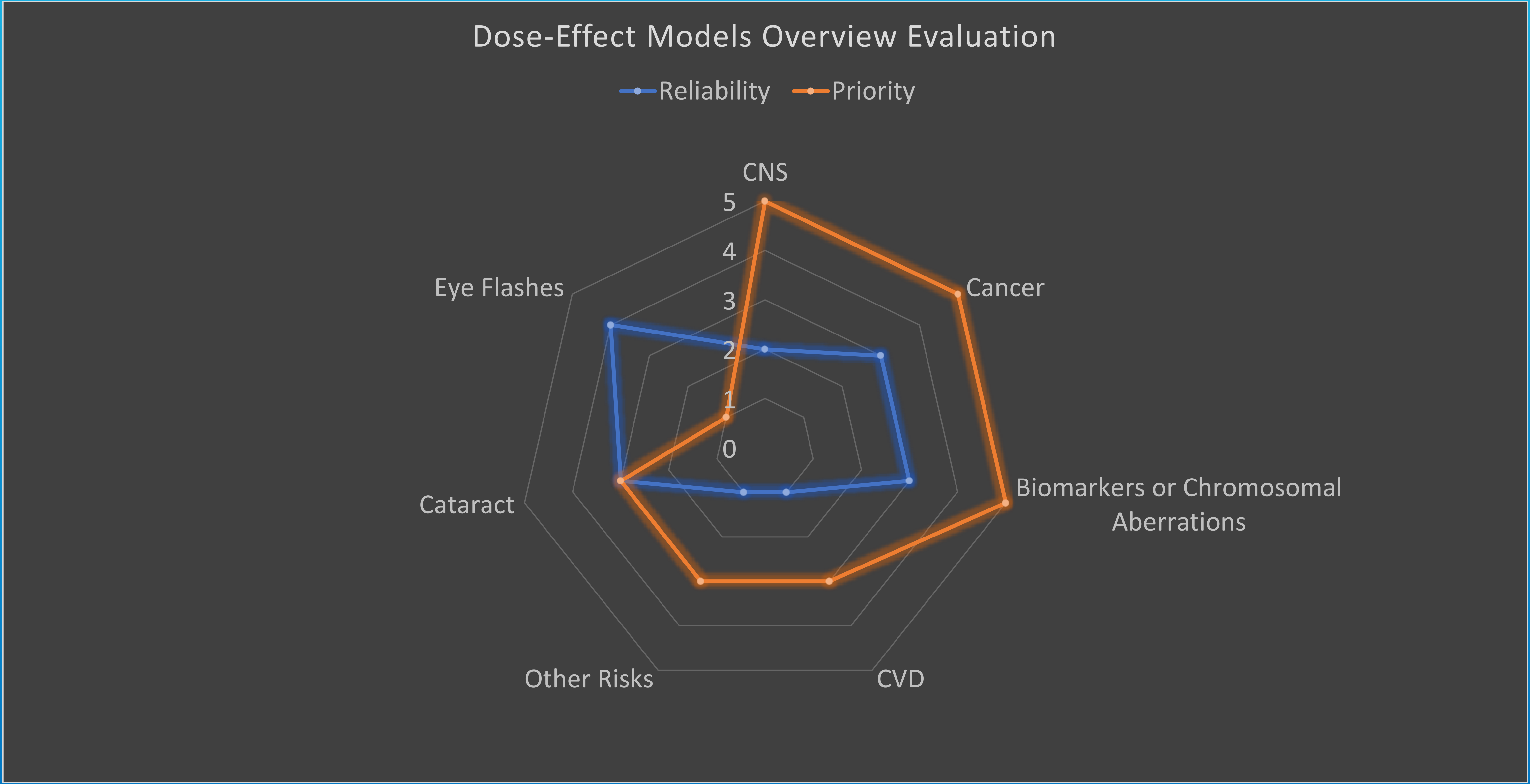
Central Nervous System (CNS)



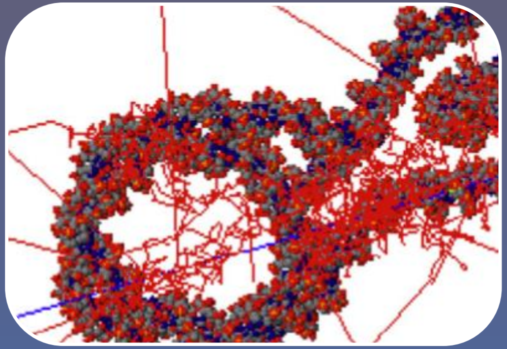
Other Risks

Analysed IR related health hazard

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.*					


Dose-Effect Models Overview Evaluation
Reliability
Priority
CNS
Cancer
Biomarkers or Chromosomal Aberrations
CVD
Other Risks
Cataract
Eye Flashes
5
4
3
2
1
0

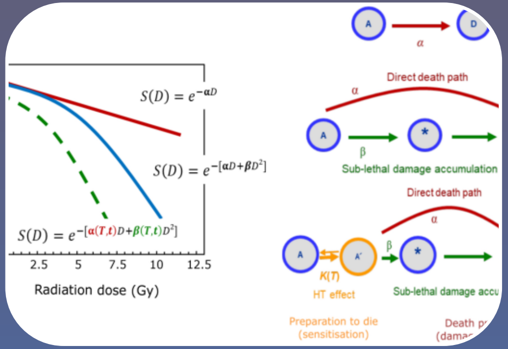
Further investigation are required to produce dose-effects models that will allows to predict the risk due to radiation during the space exploration



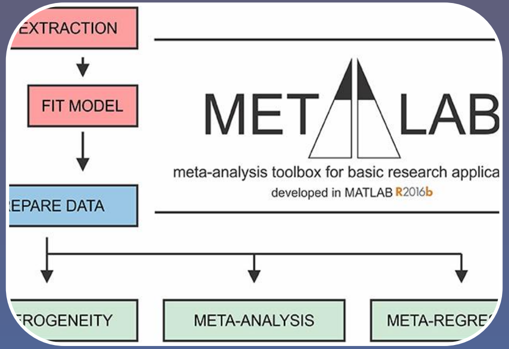
Computer Simulation of interactions of IR with biological matter

»

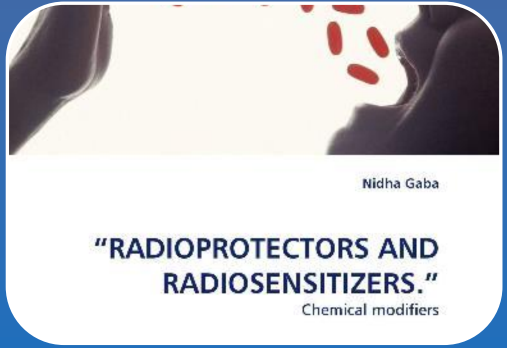
Synergy with the Clinical Field



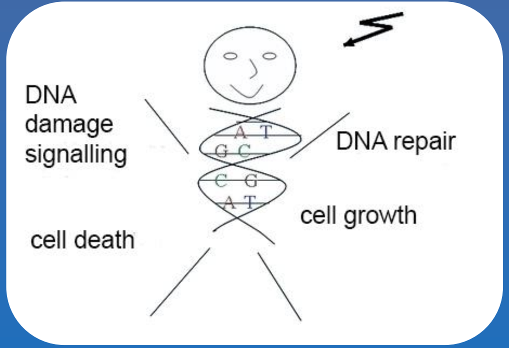
Mathematical Modelling



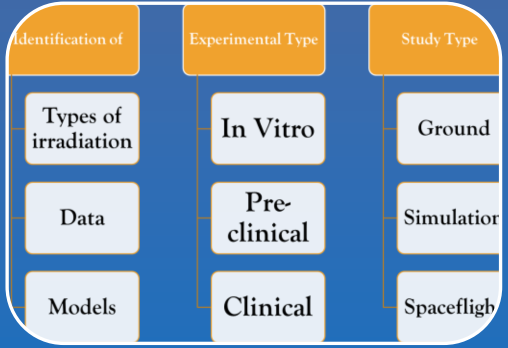
Quantitative Meta Analysis



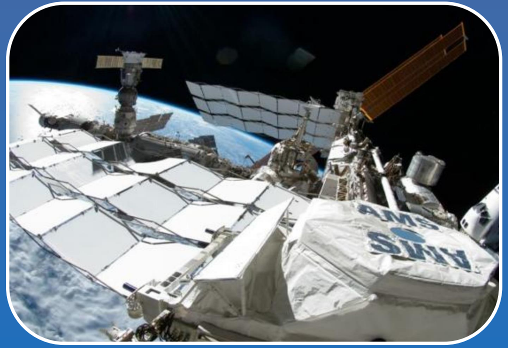
Radioprotectors inclusion in DER



Individual Radio Susceptibility



Dose-Effects Model Integration Platform



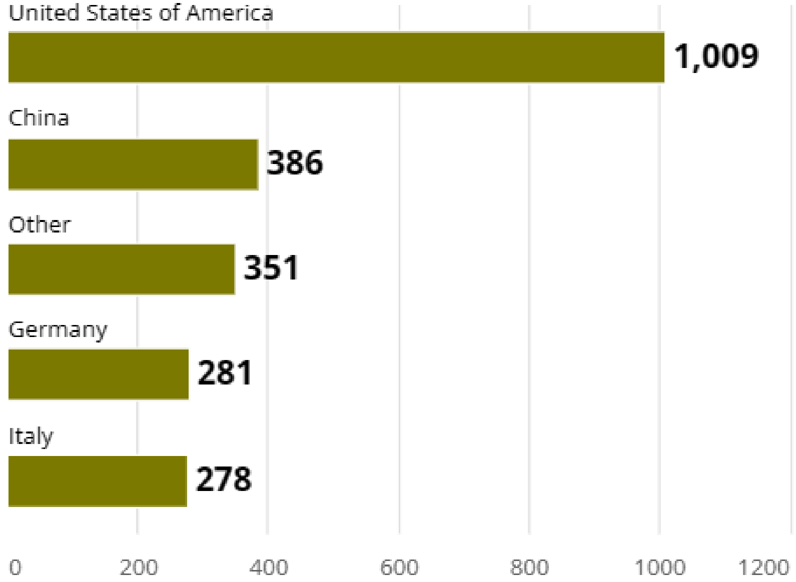
Synergy with Astroparticle Experiments

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

Publication Impact (March 2023)

Loop | Publication Impact | Dose-Effects Models for Space Radiobiology: An Overview on Dose-Effect Relationships (frontiersin.org)

Frontiers in Public Health
Published on 08 Nov 2021



3,781
TOTAL VIEWS

This article has more views than **81%** of all **Frontiers** articles.

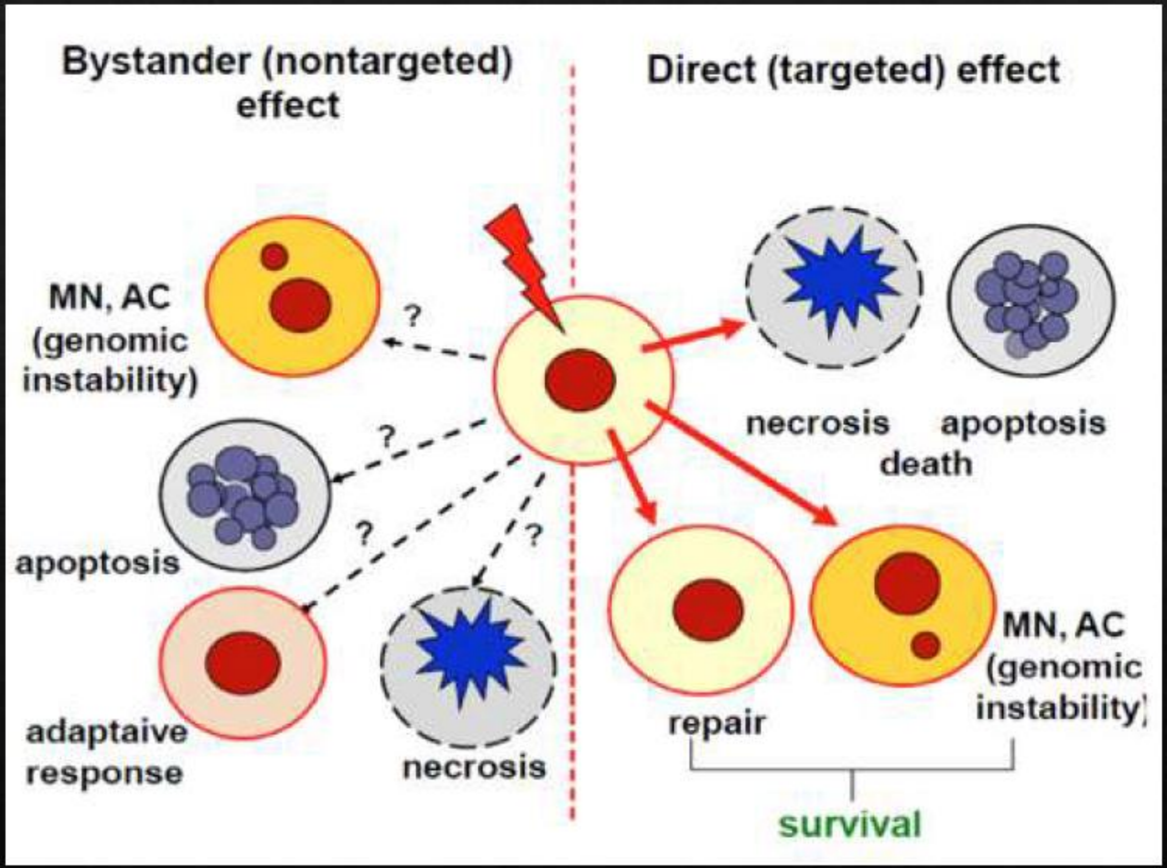
This article has more downloads than **93%** of all **Frontiers** articles.

Target Effects vs Non Target Effects

- Non-targeted effects (NTEs) include bystander effects where cells traversed by heavy ions transmit oncogenic signals to nearby cells, and genomic instability in the cell's 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 .

- These NTEs are expected also at the fluences and for radiation species that occur in space.



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

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

Work in progress at Roma Sapienza AMS group

An example on Research activities on DEM in progress at AMS INFN Roma-Sapienza Group

A Tool for NTE components evaluation

Cell Survival Probability Models

Pre-clinical data (HGT)

AMS CRs Data

Calculation of NTE with different models and for different exposition scenarios

I implemented a platform including the more reliable dose-effect models for space radiation, I developed an ad hoc software in R-script language (> 10,000 code lines).

Journal of Mechanics in Medicine and Biology
"SPACE RADIATION INDUCED BYSTANDER EFFECT IN ESTIMATING THE CARCINOGENIC RISK DUE TO GALACTIC COSMIC RAYS" A. Guracho et al (published in Jan 2023)

Tumor Prevalence Dose Effects Model

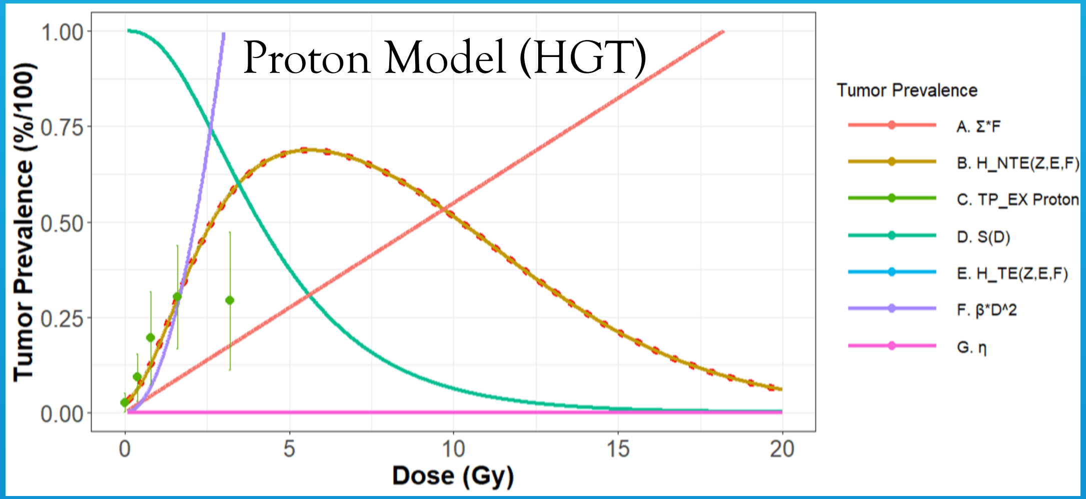
$$TP = 1 - e^{(-H(Z,E,F))}$$

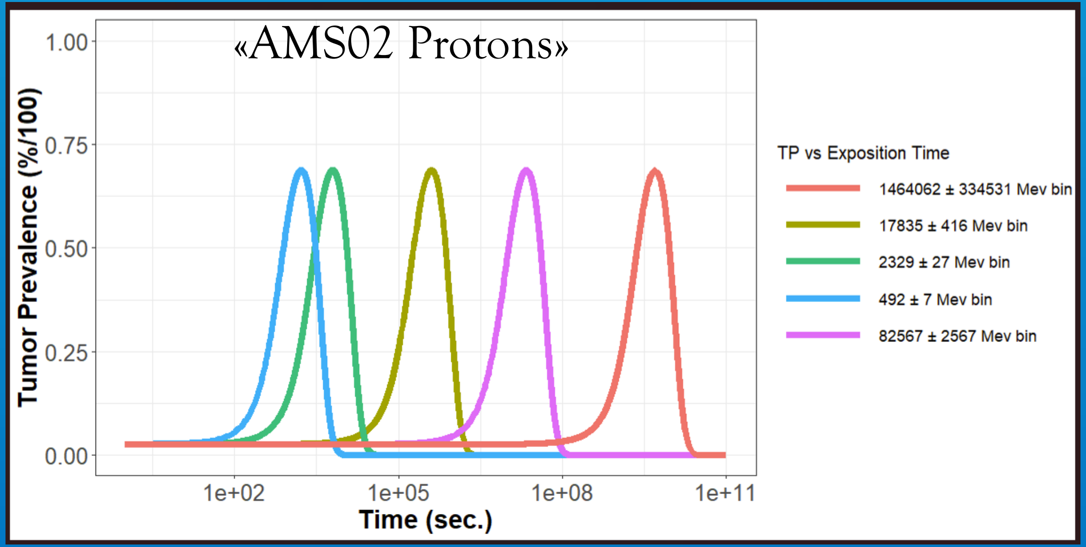
Hazard Function for Target effects

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

Hazard Function for Target + Non Target Effects

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





Conclusions

Technological advancements might realize the dream of human space exploration, and crewed spaceflights to explore the Moon and Mars are on the agenda of space agencies.

In the latest years, significant improvements have been made in the absorbed dose-effect estimation for predicting risks for human health on space exploration.

Unfortunately, the number of events helpful in modeling the radiobiological effects is still limited. On Earth experiments may reinforce knowledge on cancer and non-cancer space-radiation induced effects.

The AMS Roma Sapienza group is part of the scientific community investigating this crucial research topic for safe human exploration of space.

Actual research on DEM are on the evaluation in Non-Target Effects in Carcinogenesis Risk

Thanks for yours attention !

Alessandro Bartoloni

alessandro.bartoloni@cern.ch

AMS02 INFN ROMA and Sapienza University Web Site

References

A. Simpson, Elemental and isotopic composition of the galactic cosmic rays, Annual Review of Nuclear and Particle Science 33 (1) (1983) 323–382. arXiv:https://doi.org/10.1146/annurev.ns.33.175 120183.001543, doi:10.1146/annurev.ns.33.120183.001543. URL https://doi.org/10.1146/annurev.ns.33.120183. 001543

B. E. Benton, E. Benton, Space radiation dosimetry in low-earth orbit and beyond, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 184 (1) (2001) 255–294, advanced Topics in Solid State Dosimetry. doi:https://doi.org/10. 1016/S0168-583X(01)00748-0.URL https://www.sciencedirect.com/science/article/pii/S0168583X01007480

C. J. C. Chancellor, G. B. I. Scott, J. P. Sutton, Space radiation: The number one risk to astronaut health beyond low earth orbit, Life 4 (3) (2014) 491–510. doi:10.3390/life4030491. URL https://www.mdpi.com/2075-1729/4/3/491

D. J. Guo, C. Zeitlin, R. F. Wimmer-Schweingruber, D. M. Hassler, B. Ehresmann, S. Rafkin, J. L. Freiherr von Forstner, S. Khaksarighiri, W. Liu, Y. Wang, Radiation environment for future human exploration on the surface of mars: the current understanding based on msl/rad dose measurements, Astron. Astrophys. Rev. 29 (1) (2021) 8. doi:10.1007/s00159-021-00136-5.

E. M. Aguilar, et al., The alpha magnetic spectrometer (ams) on the international space station: Part ii results from the first seven years, Phys. Rept. 894 (2021) 1–116. doi:10.1016/j.physrep.2020.09.003.

F. O. Adriani, et al., Ten years of pamela in space, Riv. Nuovo Cim. 40 (10) (2017) 473–522. arXiv:1801.10310, doi:10.1393/ncr/i2017-10140-x.

G. F. Alemmanno, Latest results from the dampe space mission, arXiv:2209.06014v1 [astro-ph.HE] 13 Sep 2022 (2022).

H. S. Torii, P. S. Marrocchesi, The calorimetric electron telescope (calet) on the international space station, Adv. Space Res. 64 (12) (2019) 2531–2537. doi:10.1016/j.asr.2019.04.013.

I. A. Bartoloni, G. Paolani, M. Santoro, L. Strigari, S. Strolin, A. N. Guracho, G. Della Gala, High energy physics astroparticle experiments to improve the radiation health risk assessment in space missions, PoS EPSHEP2021(2022) 106. doi:10.22323/1.398.0106.

J. A. Bartoloni, G. Della Gala, A. Guracho, G. Paolani, M. Santoro, L. Strigari, S. Strolin, Astroparticle experiments to improve the radiation health risk assessment for humans in space missions, Proceedings of the International Astronautical Congress, IAC2022 (2022).

K. A. Bartoloni, G. Della Gala, A. Guracho, G. Morganti, A.G. Paolani, M. Santoro, L. Strigari, S. Strolin, Dose-effects models for space radiobiology: an overview on dose-effect relationship, Proceedings of the International Astronautical Congress, IAC2022 (2022).

L. A. Bartoloni, L. Strigari, Can high energy particle detectors be used for improving risk models in space radiobiology ?, Proceedings of the Global Exploration Forum, GLEX2021 A1 (2021).

M. A. Bartoloni, G. Della Gala, A. Guracho, G. Paolani, M. Santoro, L. Strigari, S. Strolin, Space radiation field characterization using the astroparticle operating detectors, Proceedings of the International Astronautical Congress, IAC2021 A1 (2021).

N. L. Strigari, S. Strolin, A. G. Morganti, A. Bartoloni, Dose-effects models for space radiobiology: An overview on dose-effect relationships., Front. Public Health 9:733337 (2021). doi:10.3389/fpubh.2021.733337.

O. A. Bartoloni, N. Ding, G. Cavoto, C. Consolandi, L. Strigari, Astroparticle Experiments to improve the biological risk assessment of exposure to ionizing radiation in the exploratory space missions. (2021). URL https://www.frontiersin.org/research-topics/28918