UMONS Université de Mons

WRMISS: Workshops on Radiation Monitoring for the International Space Station

6-8 Sep 2022 Mons (Belgium)

Agenzia Spaziale Italiana

AstroParticle Experiments 4 Space Radiobiology

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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.

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 sinergies
- Case Study :
  - Dose Effects Relationship (DER)
  - Target Effects vs Non Target Effects

INTRODUCTION

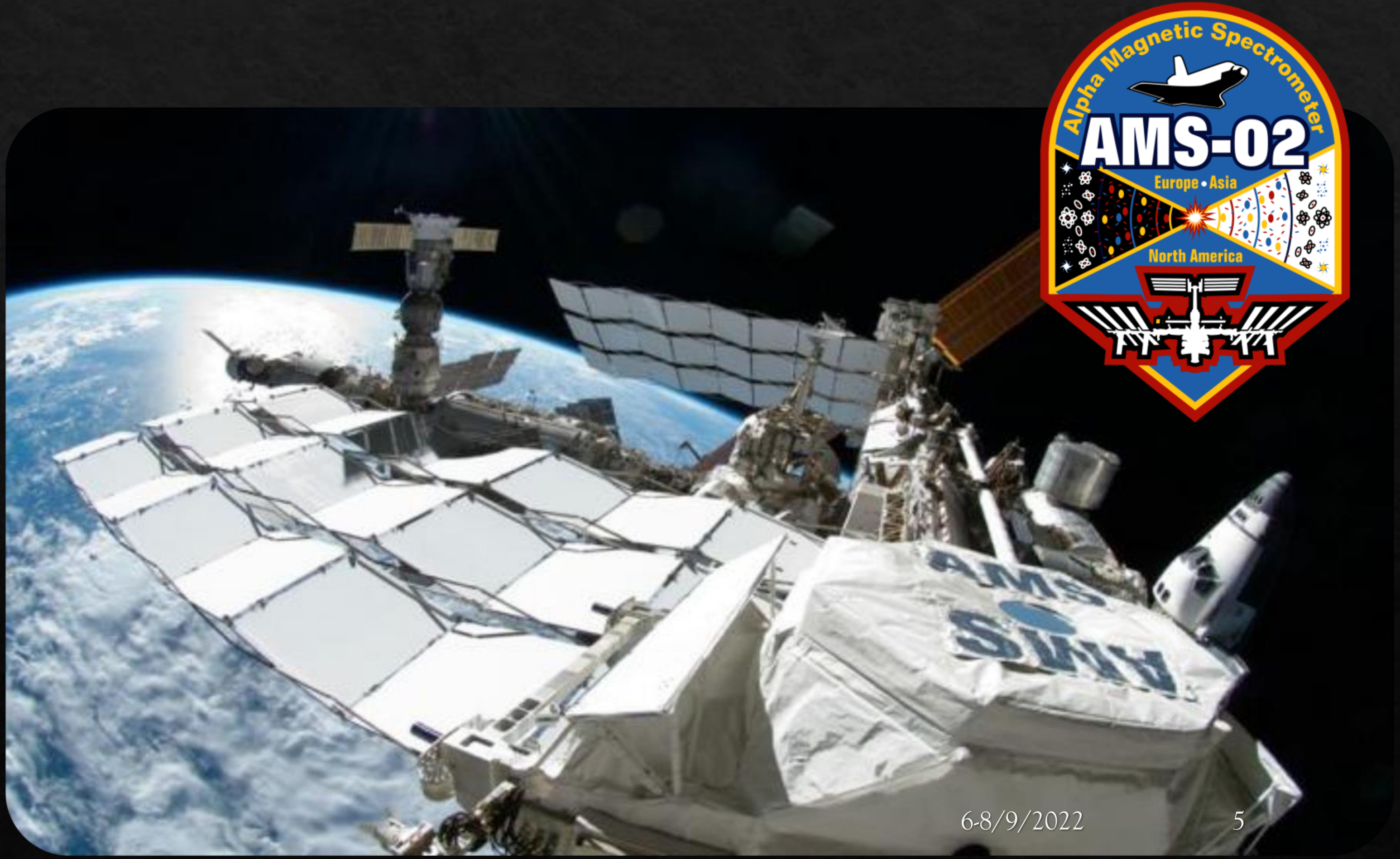
Alpha Magnetic Spectrometer (AMS)

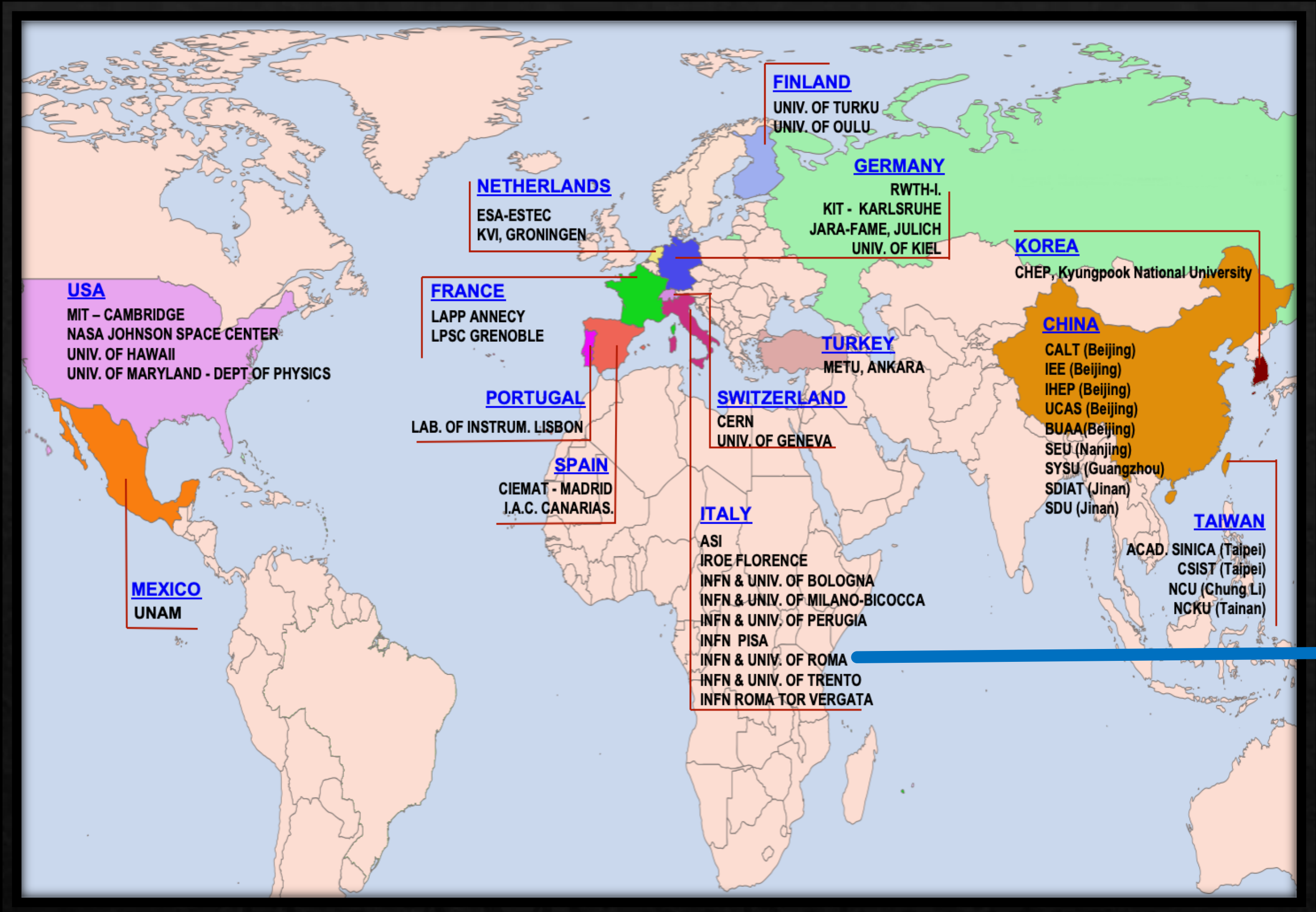
INFN ROMA SAPIENZA RESEARCH GROUP

The AMS SPRB collaboration was created in 2017 by the synergy of the AMS INFN Roma Sapienza (Italy) group leaded by Alessandro Bartoloni with the medical physics research group leaded 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





The AMS collaboration

(http://ams02.space)

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

The AMS02 detector has collected so far more than <u>200 billion</u> Cosmic Rays events.

More Info in the AMS-02 webpage:

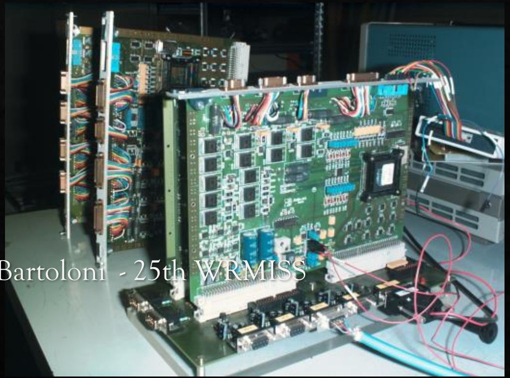
https://ams02.space

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 – Test – Integrate – Fly

2001-2003
- Engineering Modules to test system functionalities

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

2006-2008
- Flight & Spare Modules Production and qualification of electronics now installed on the ISS

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

Available Thesis

Strategies for preventing radiobiological effects in space
Galactic Cosmic Rays induced Target and Non Target Effects in space
AMS02 Charged Particle characterization for Space Radiobiology investigations

INFN Roma AMS-02 wiki:
https://wiki.infn.it/strutture/roma1/experiments/ams2/home

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.**

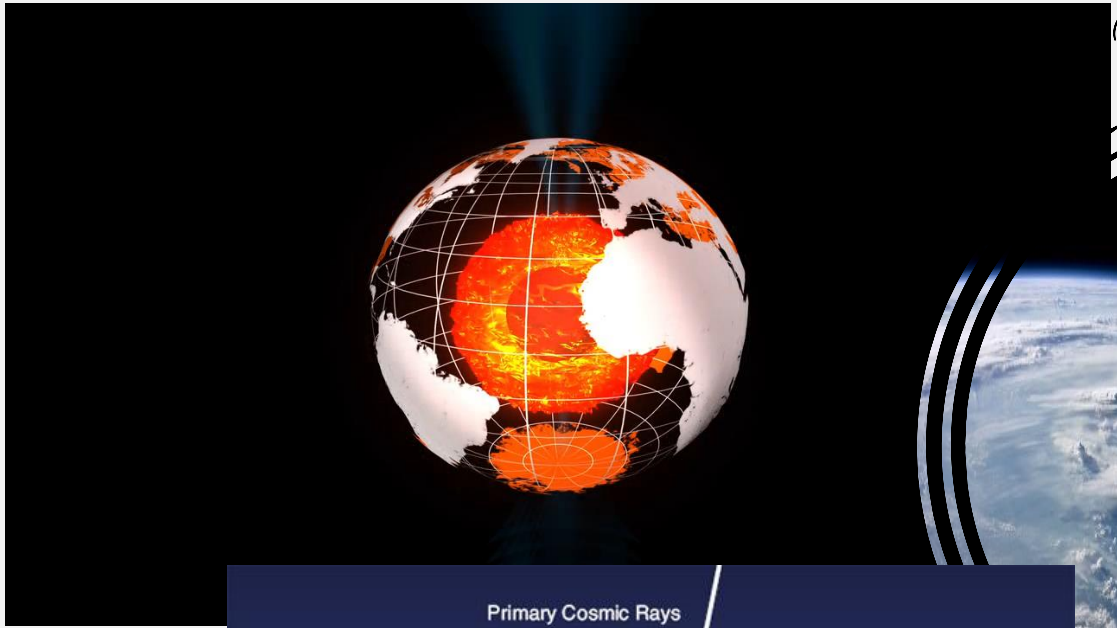
Dr. Lidia Strigari

Medical Physics Department

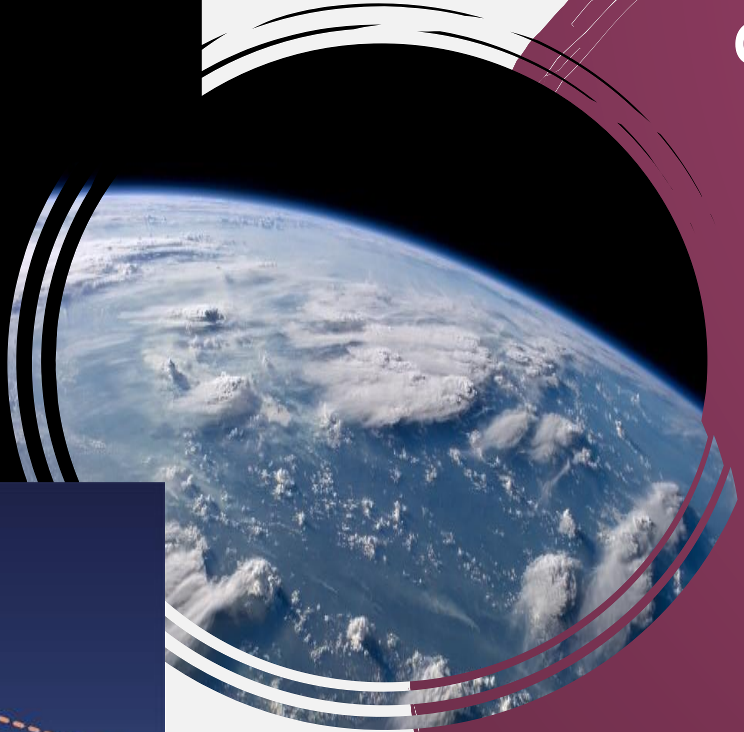
IRCCS Azienda Ospedaliero-Universitaria di Bologna, Italy

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)

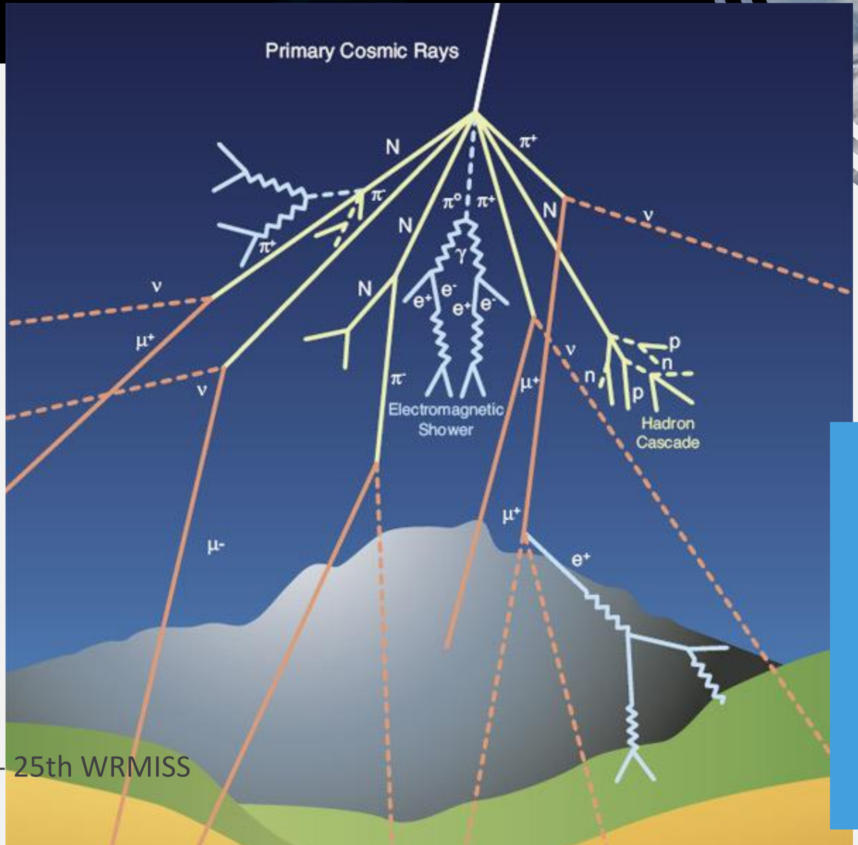


Cosmic Rays Interactions with the geo-magnetosphere

Earth is a cocoon !!!

Magnetosphere stops/deflects 99.9% of charged particles

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



(credit : CERN)

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

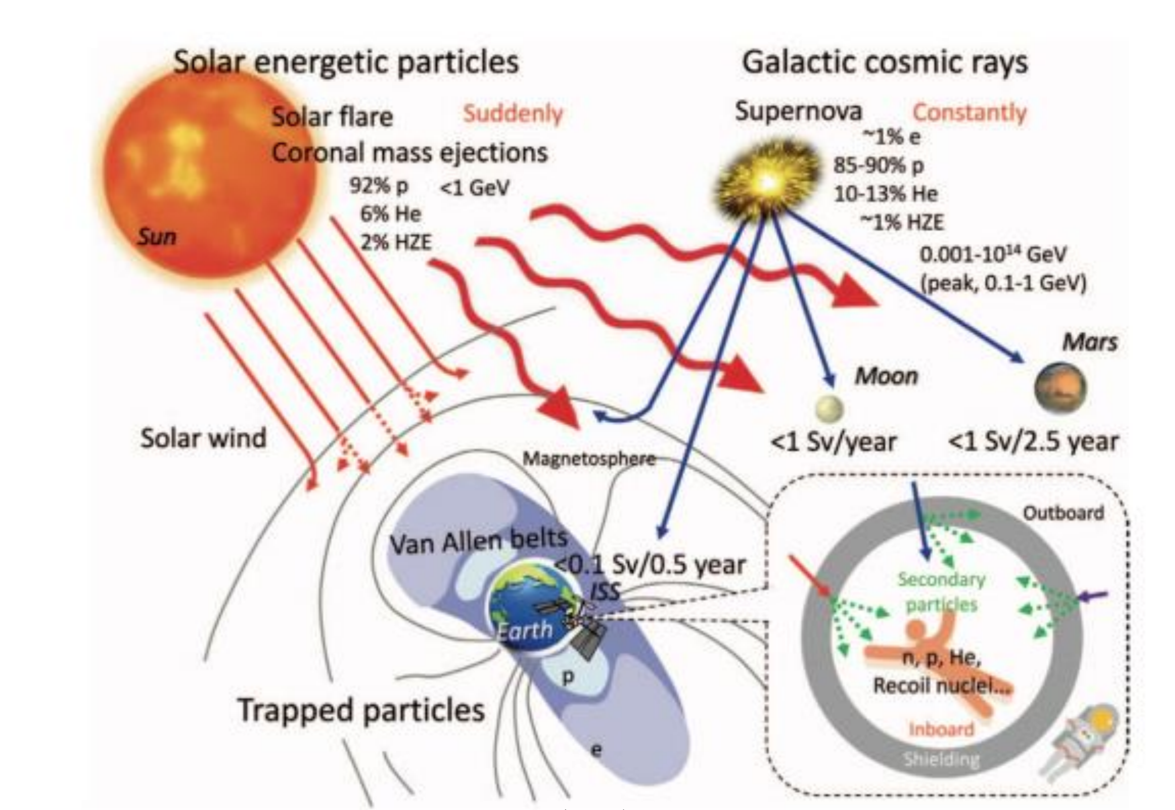
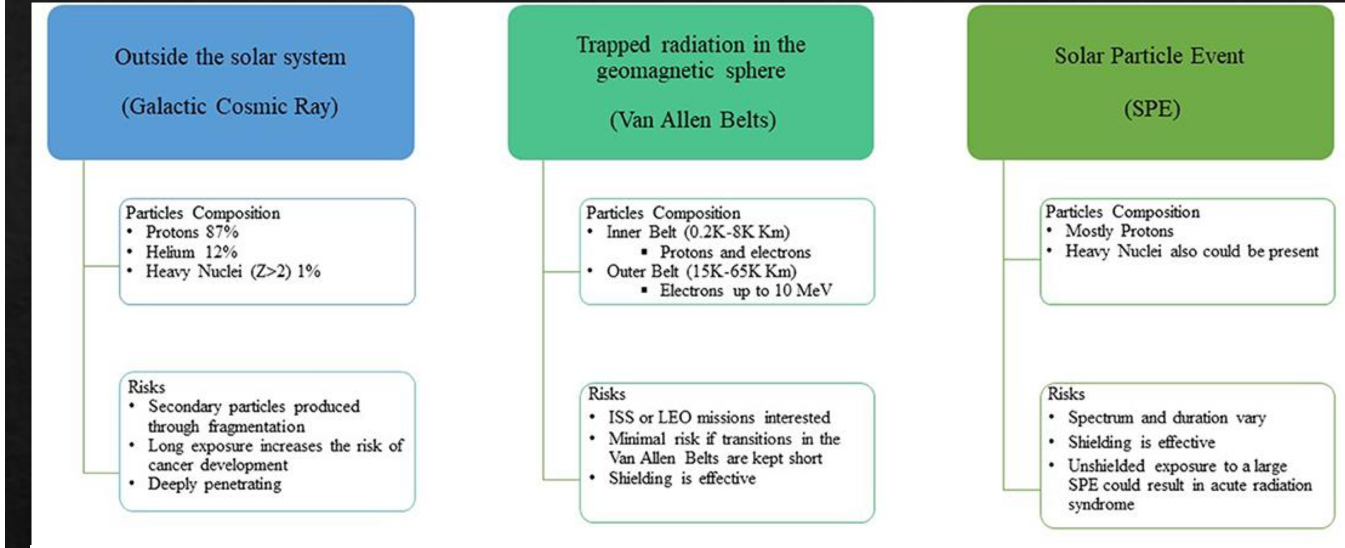


Image courtesy of European Space Agency (ESA)



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)**

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

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

Limits and concerns

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

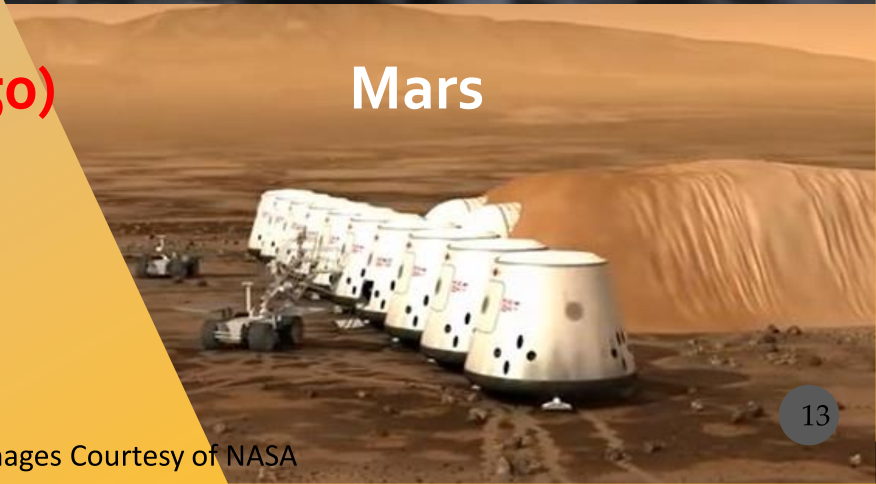
The limit in carrying out the missions are due to health effects

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

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

x150-200

x300-400



x250 (x750)

Images Courtesy of NASA

A new era in human space exploration is coming …

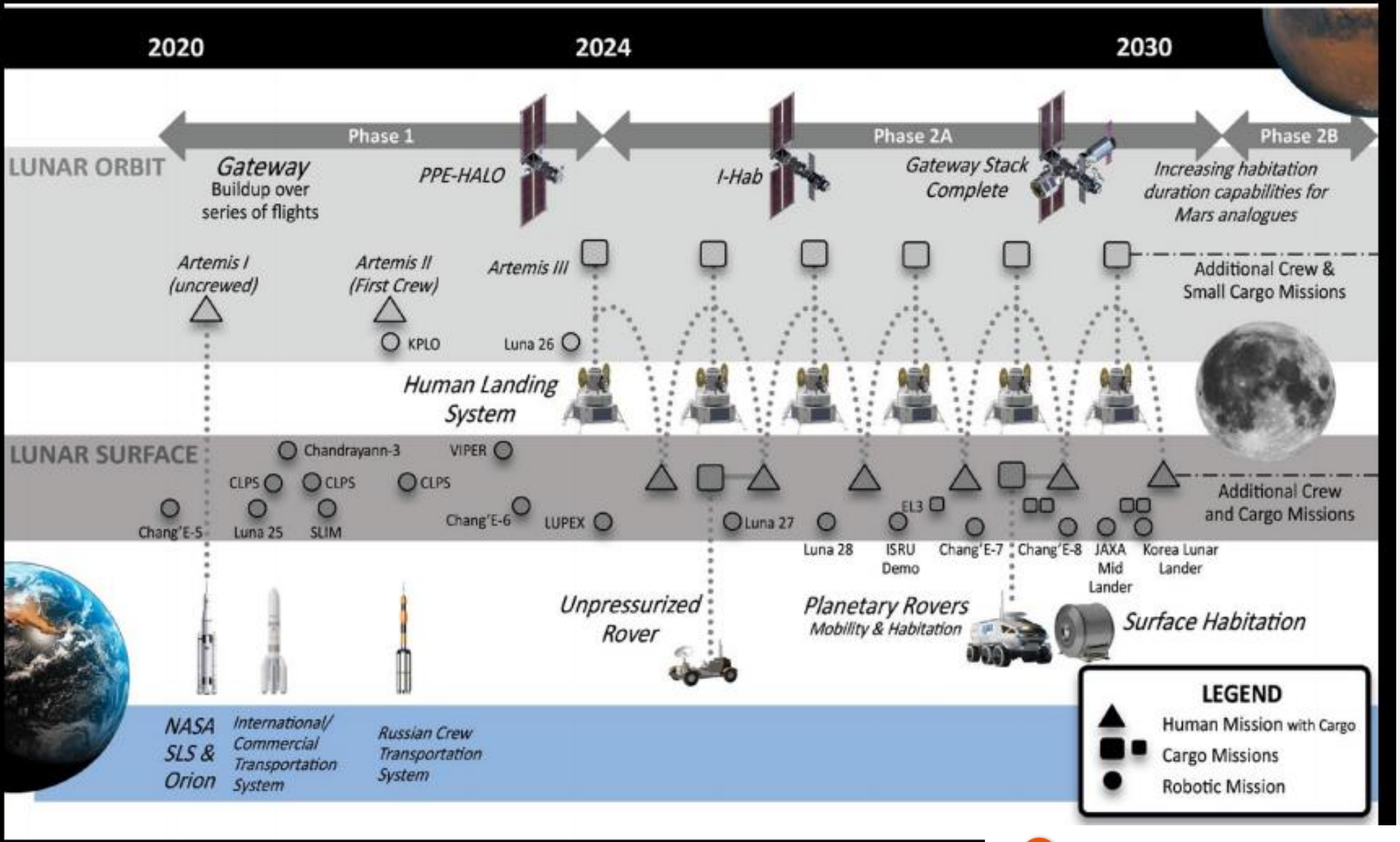


Figure 1. Updated ISECG Lunar Surface Exploration Scenario.

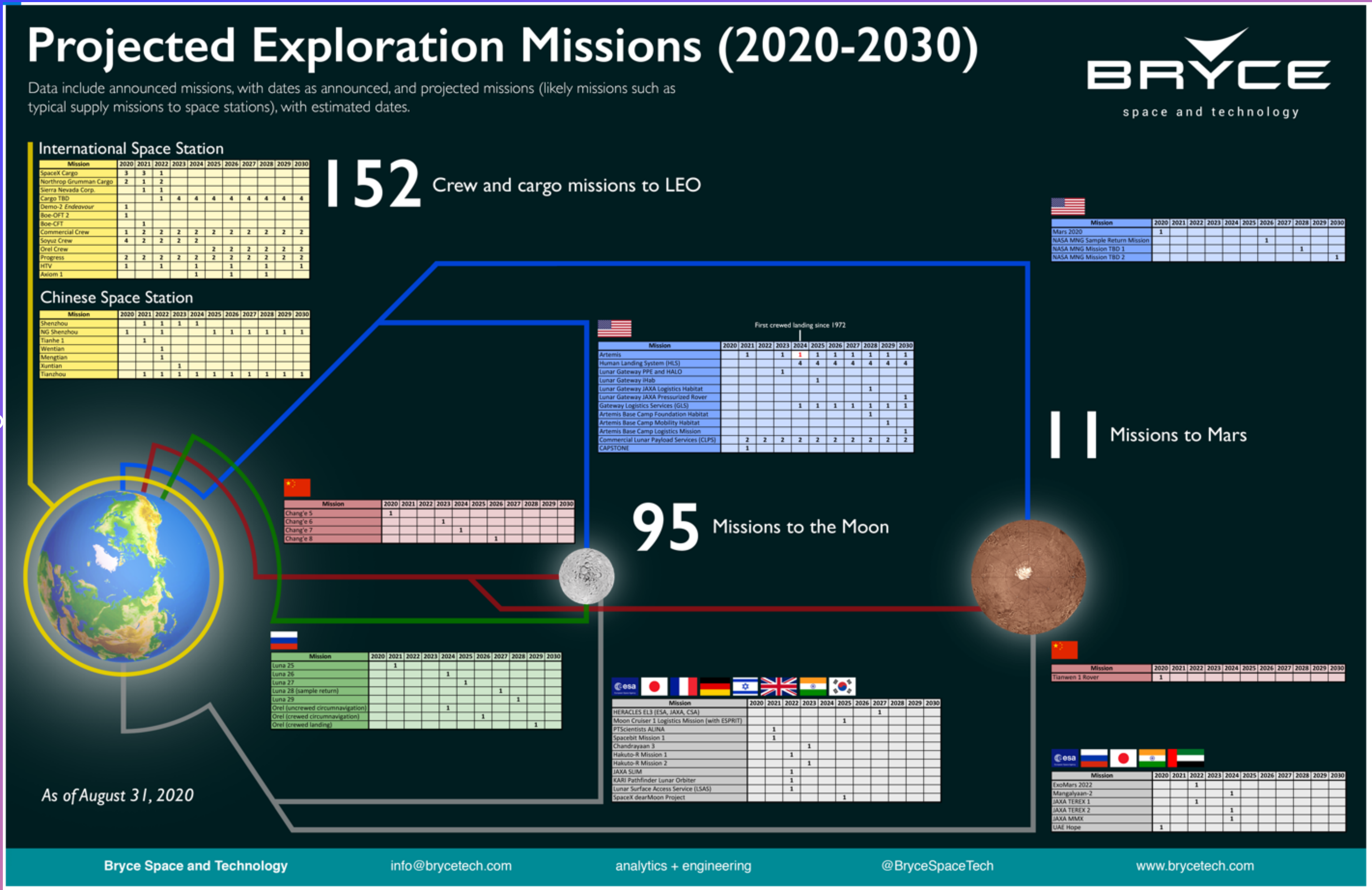
«Global Exploration Roadmap
Lunar Surface Exploration Scenario
update August 2020»

International Space Exploration Coordination Group
(ISECG)

ISECG

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 explor

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



Cosmic Ray Detectors in Space

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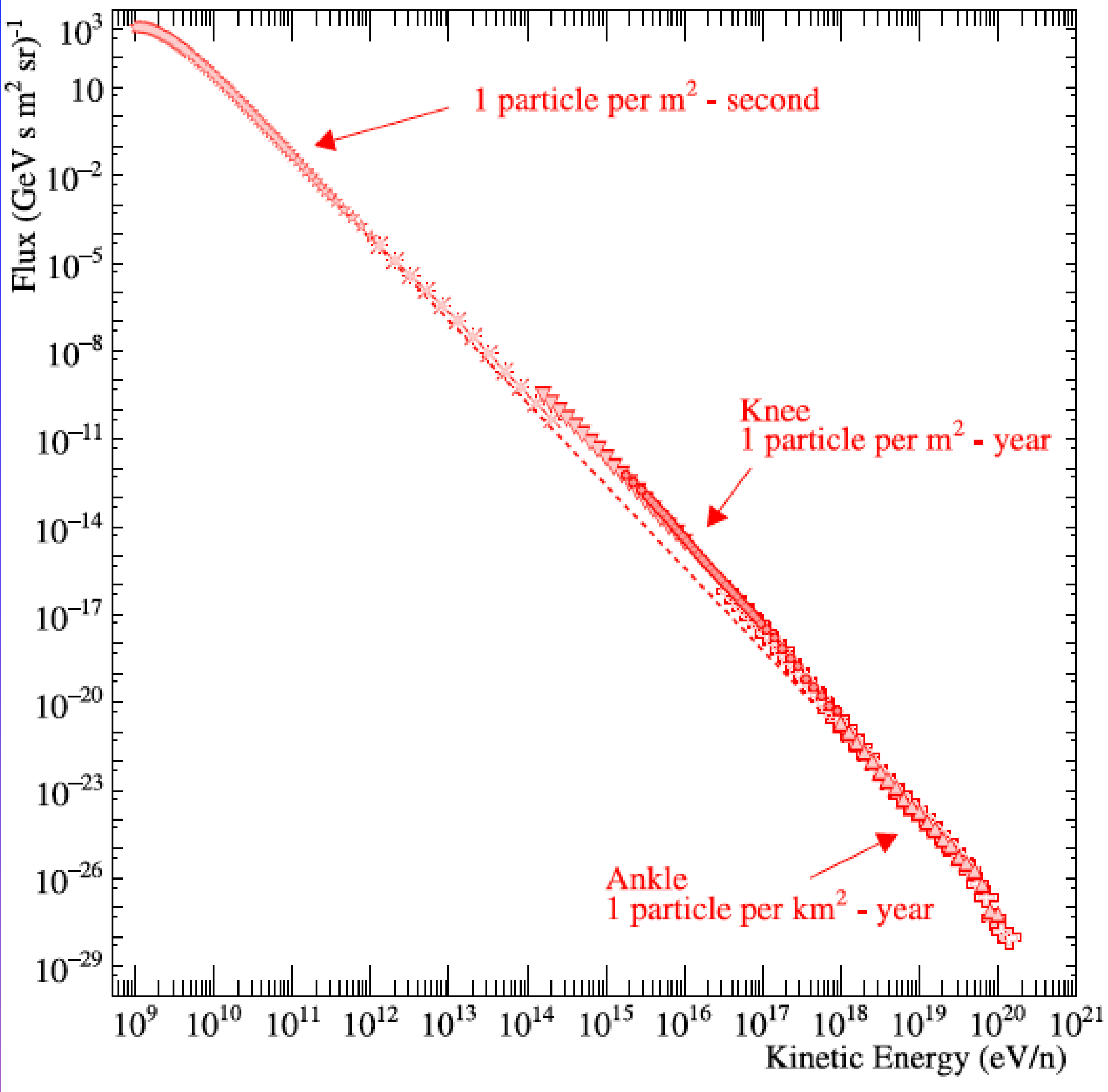


Credit C.Sparvoli

Energetic particles and completely ionized nuclei from outer space

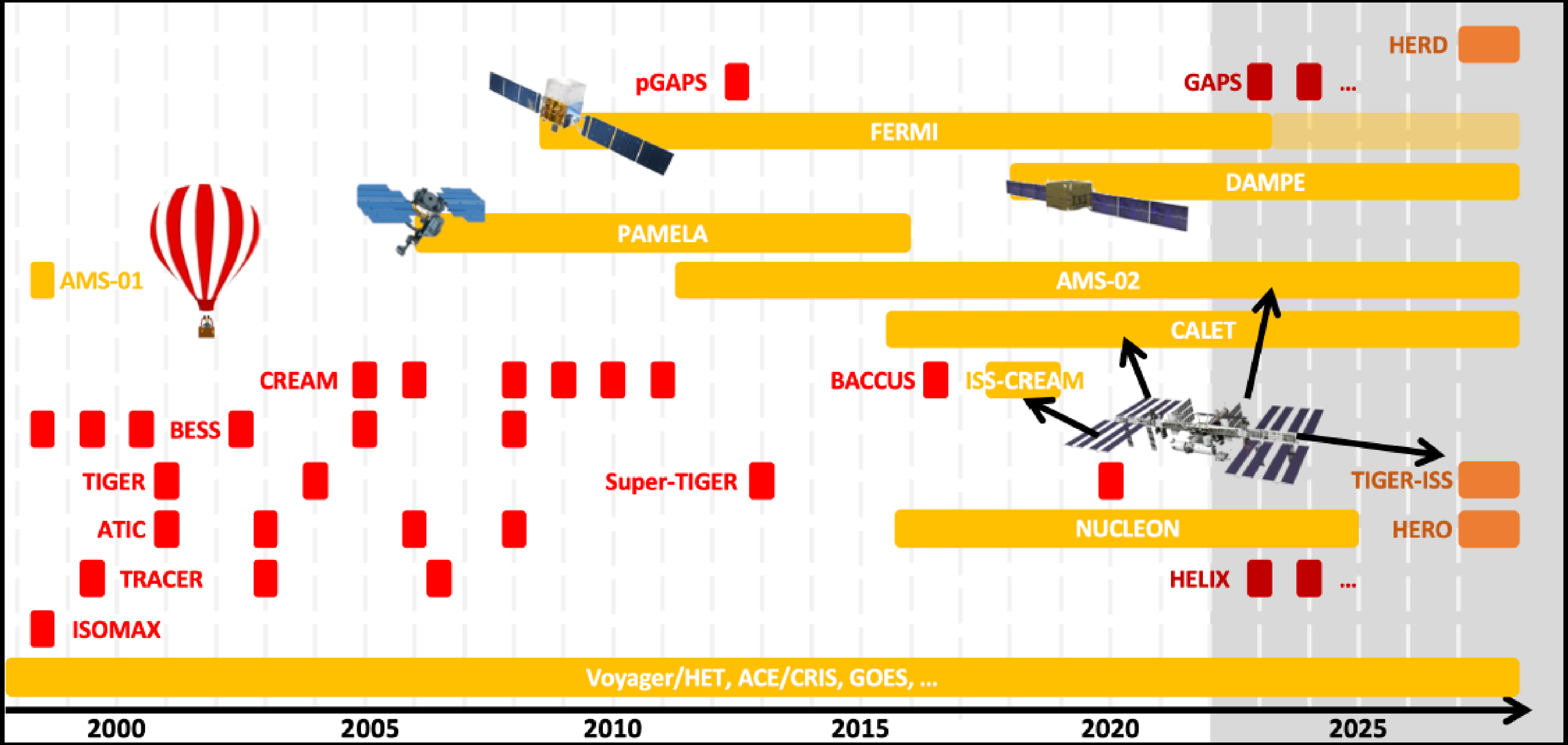
Many orders of magnitude in energy and flux

E < 100 TeV: direct detection
E > 100 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, …)*
γ = 2,7 for energy <100 TeV
γ = 3,3 for energy >100 TeV

Timeline of Direct Measurement of CRs from 2000

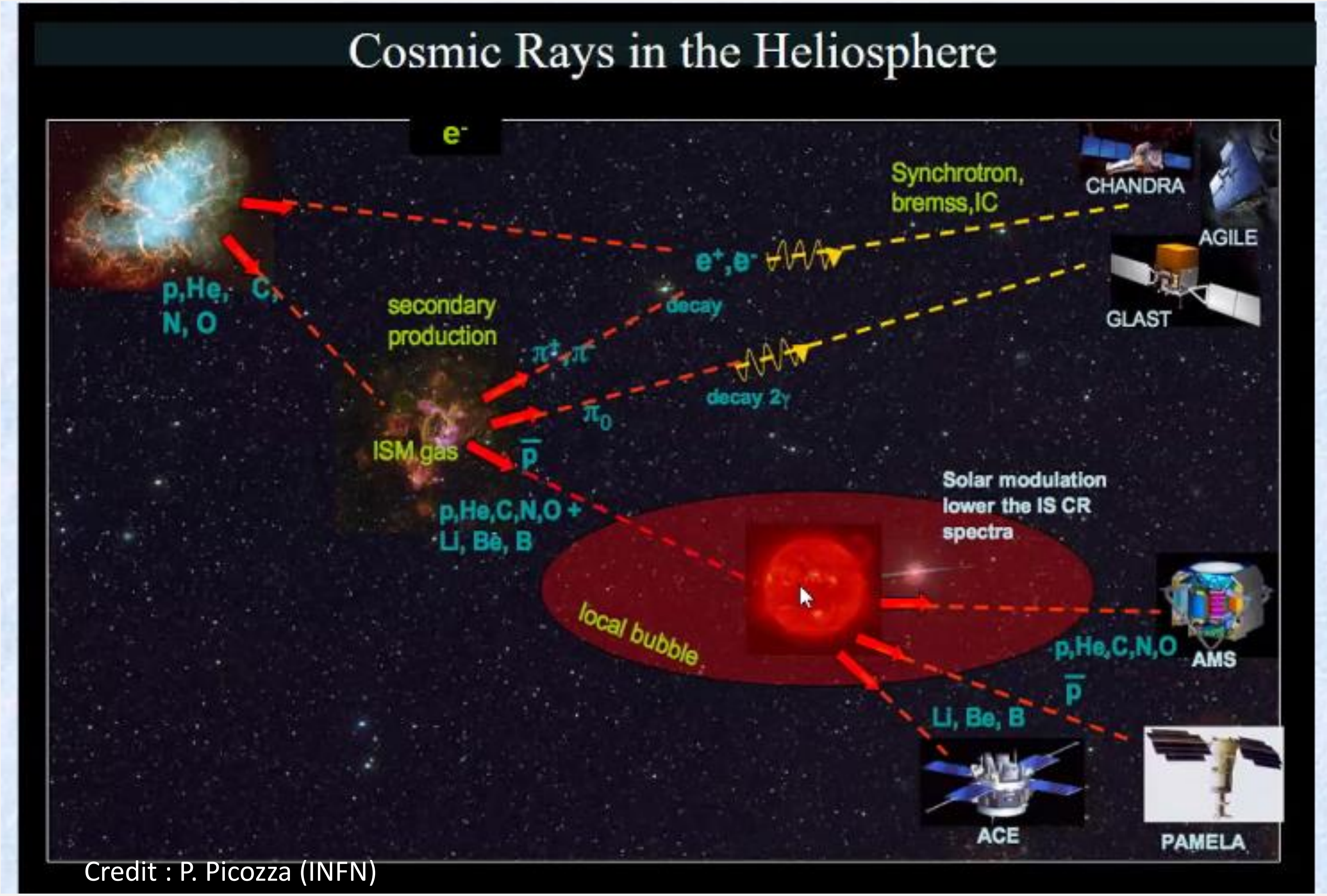


3 possible platform for instruments and detectors
baloons , Satellites , International Space Station

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.

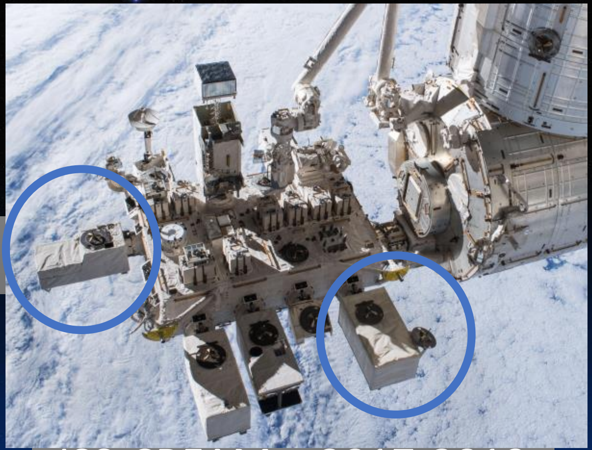


Principal Operating Cosmic Ray Space Detectors

International Space Station based

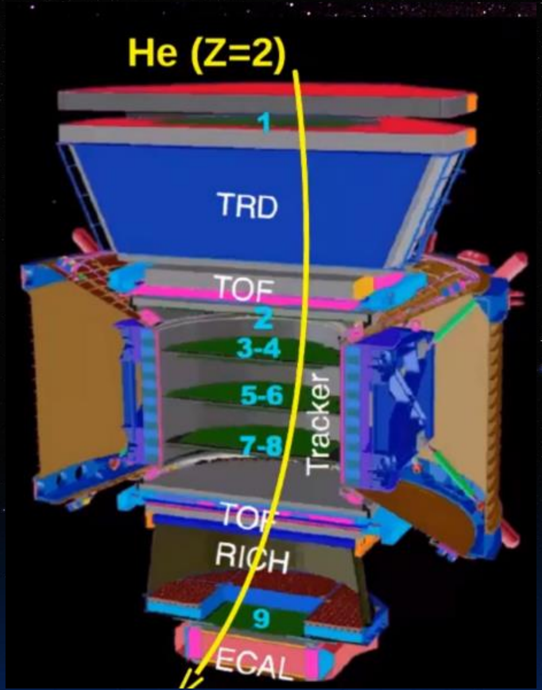
AMS02 – 2011

CALET - 2015



ISS-CREAM – 2017-2019

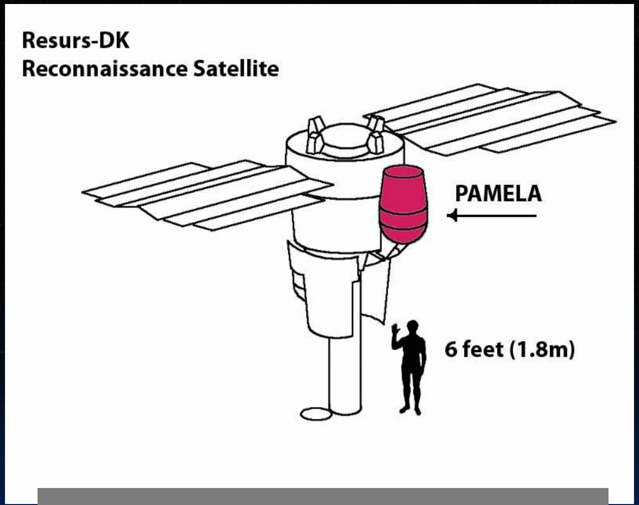
an ensemble of instruments each one designed to capture and measure the cosmic ray particles



Satellite Based

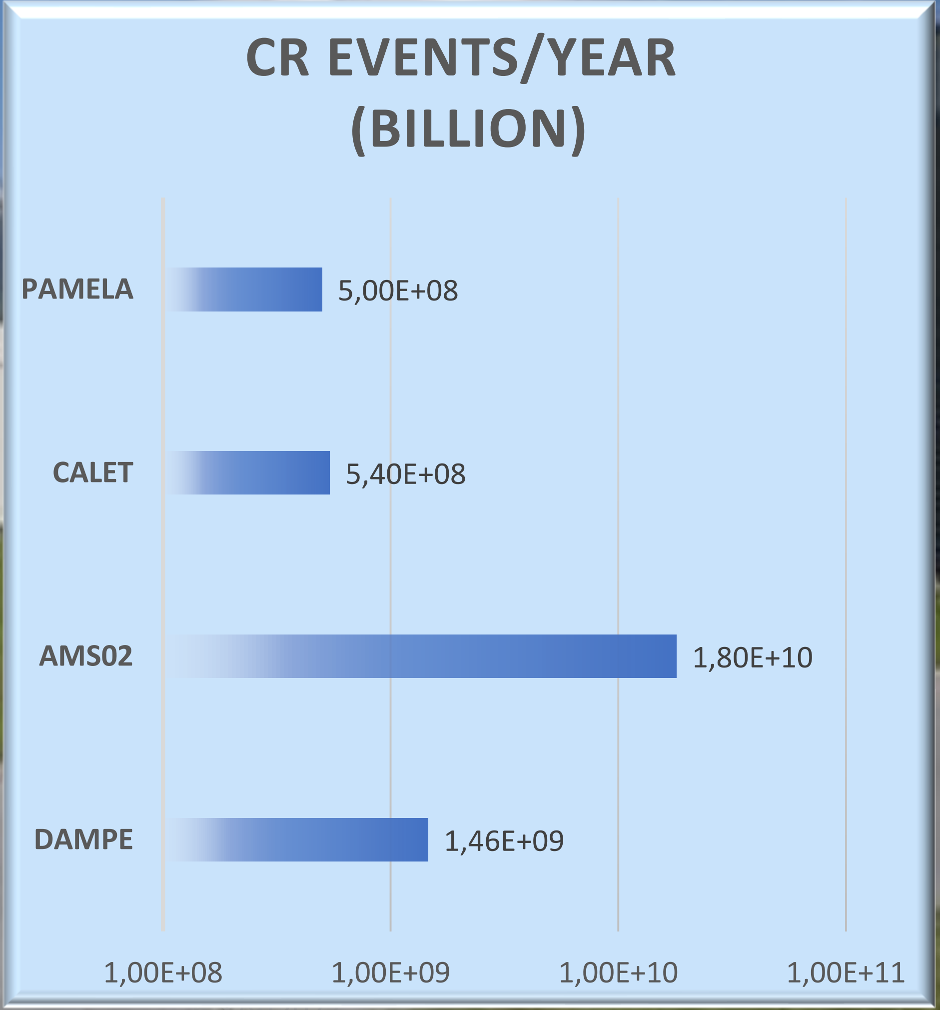
ACE - 1997

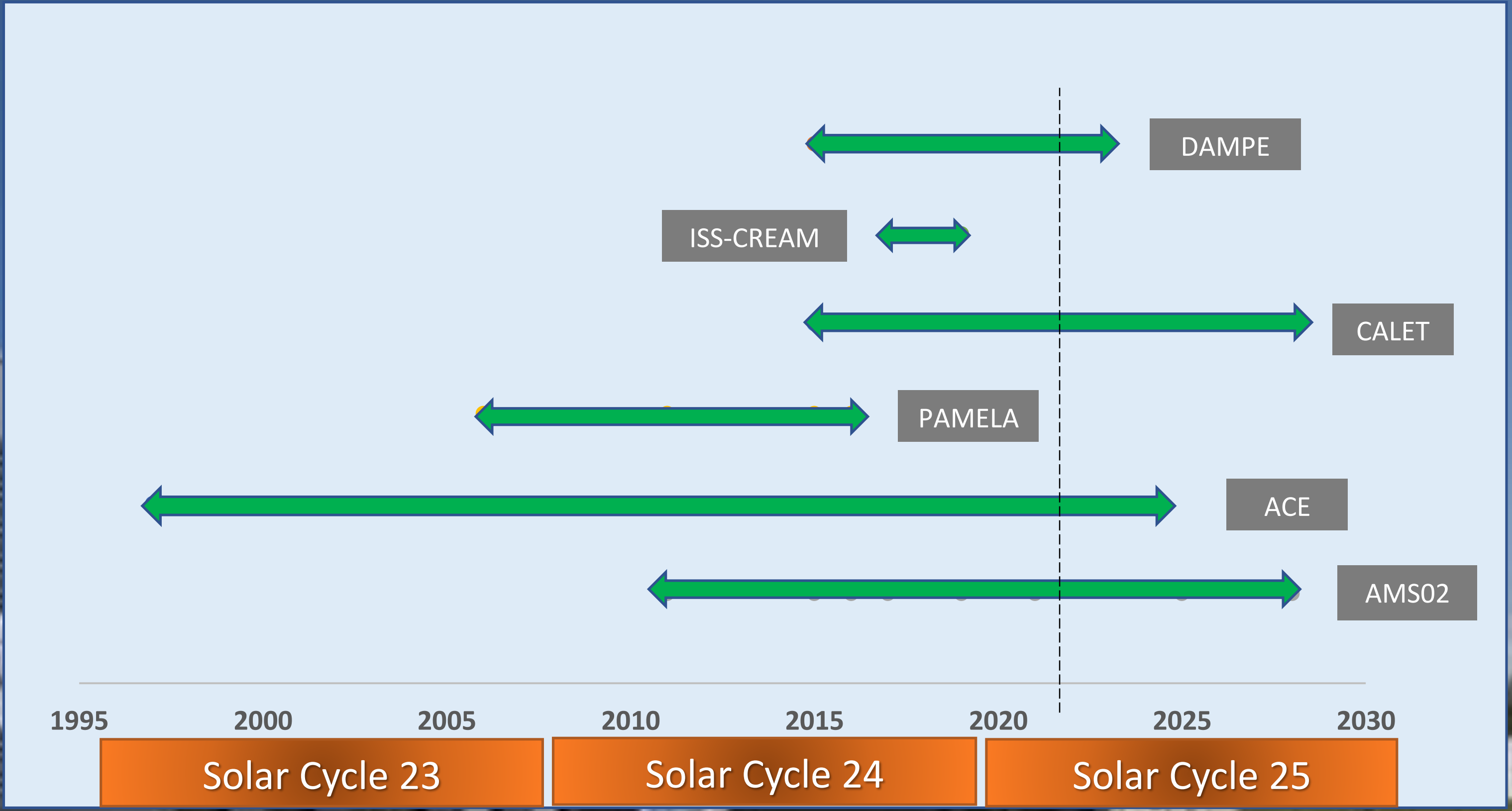
DAMPE - 2017



PAMELA – 2006-2016

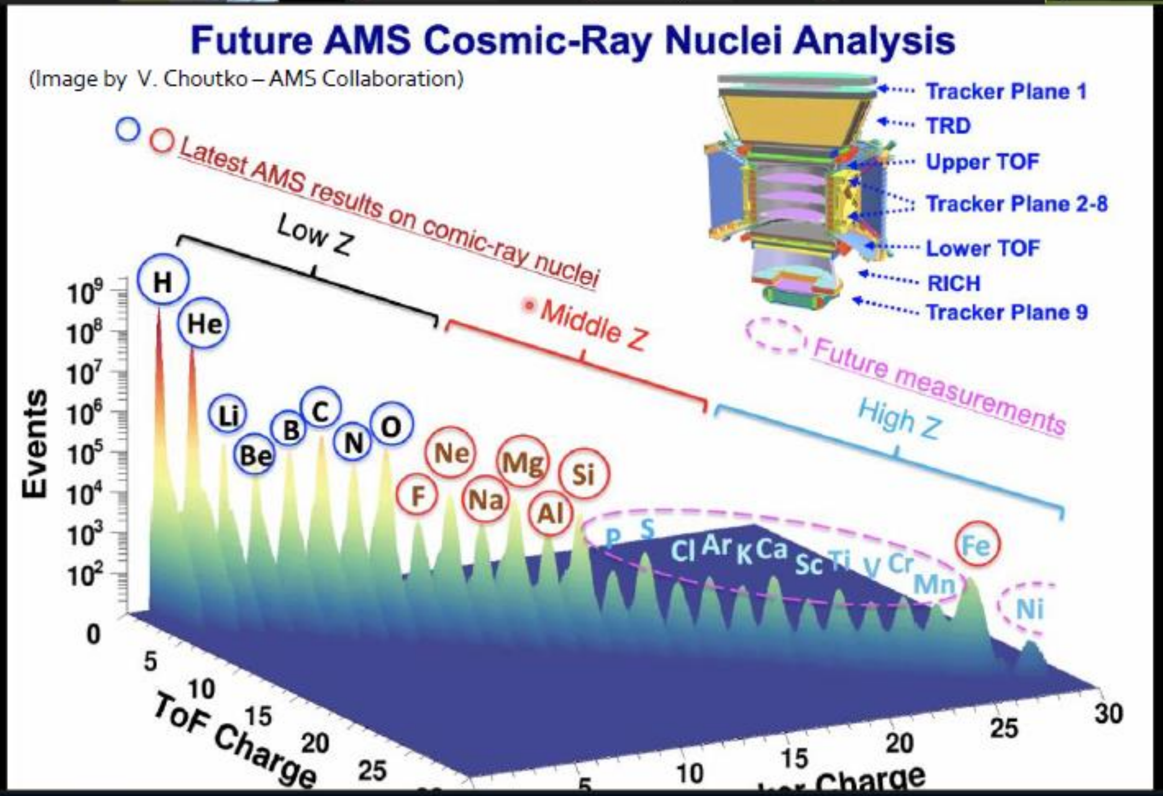
Missions Operations





Cosmic Ray Components Identification

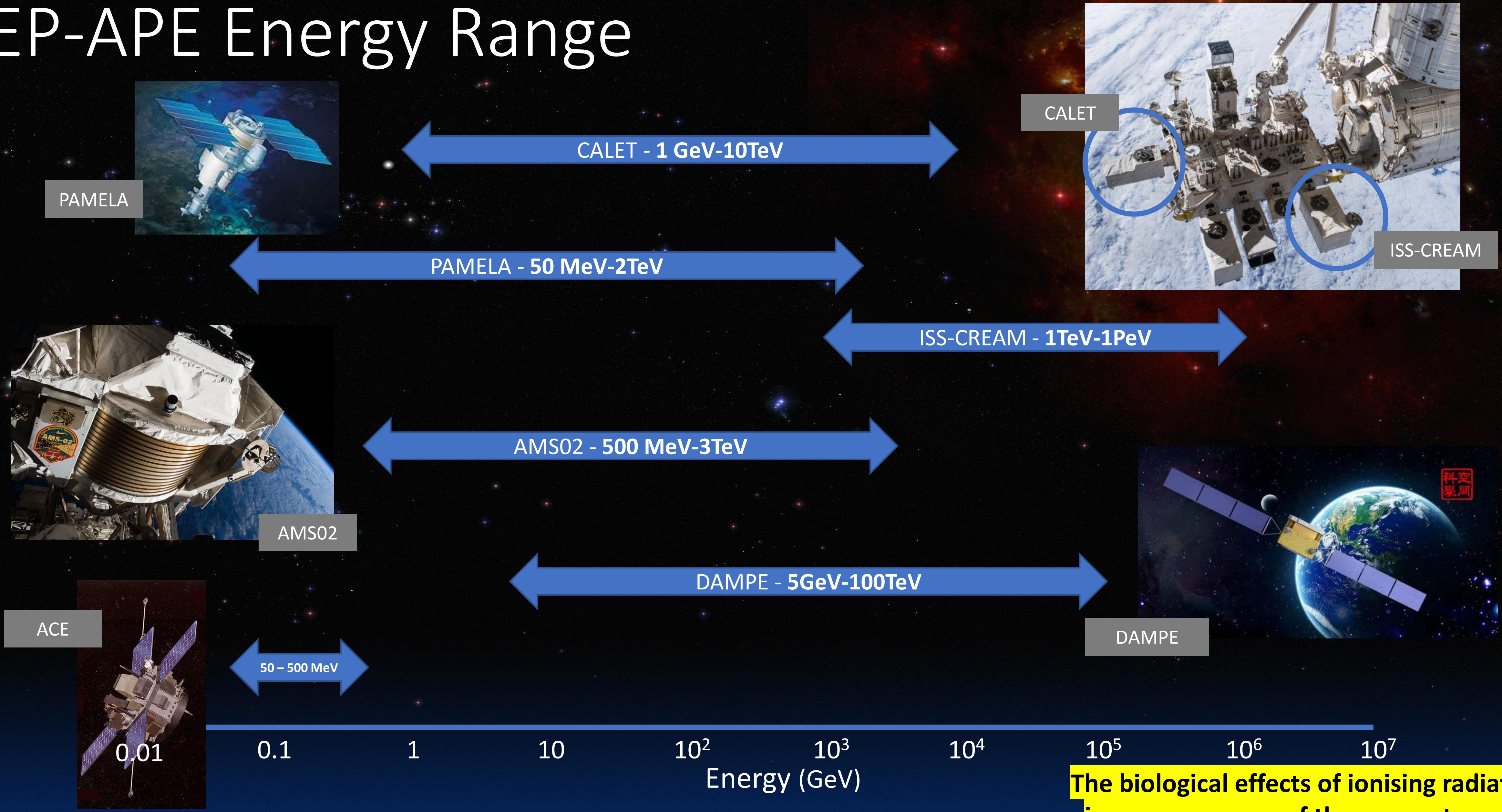
e+,e-	ALL
p+,p-	ALL
D,He	ALL
Low-Z (<=8)	ALL (PAMELA up to Z=6)
Middle-Z	AMS02, CALET, ISS-CREAM, ACE, DAMPE
High-Z (>14)	AMS02, CALET, ISS-CREAM, ACE, DAMPE



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

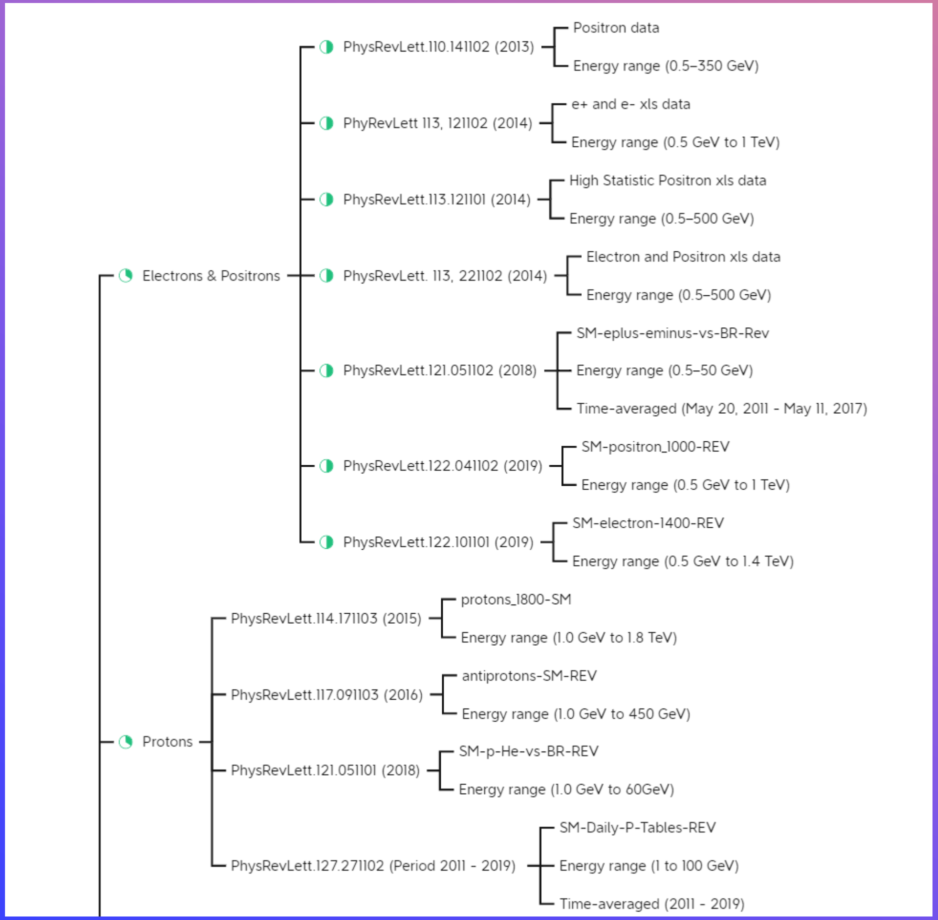
Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer
AMS Collaboration • M. Aguilar (Madrid, CIEMAT) et al. (Feb 25, 2021)
Published in: *Phys.Rev.Lett.* 126 (2021) 8, 081102

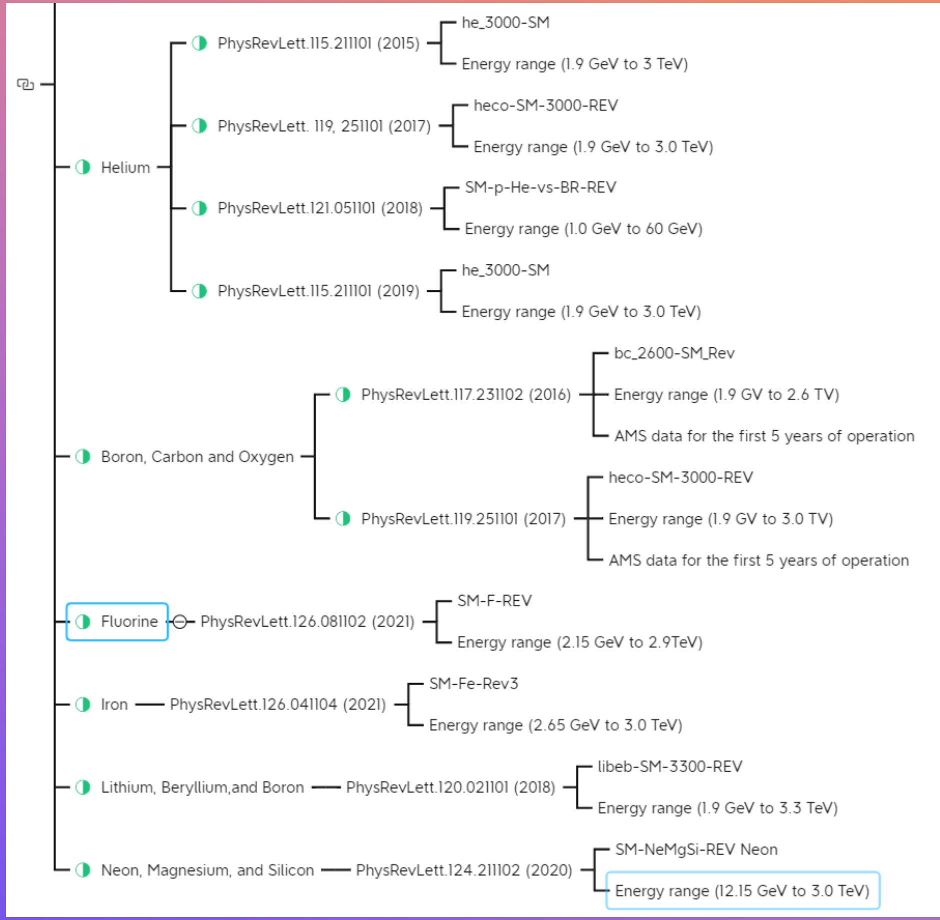
HEP-APE Energy Range

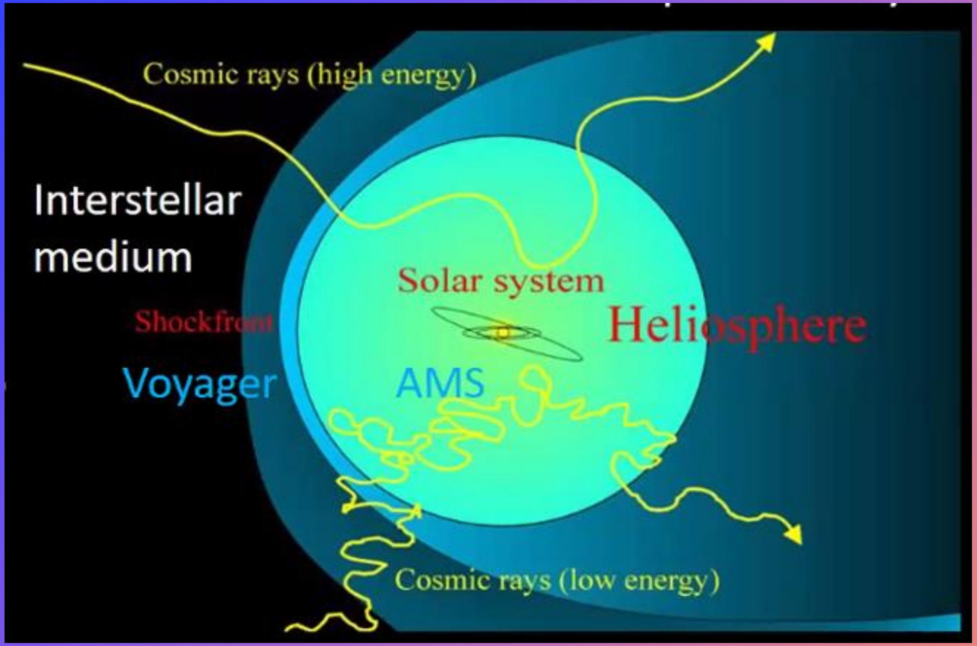


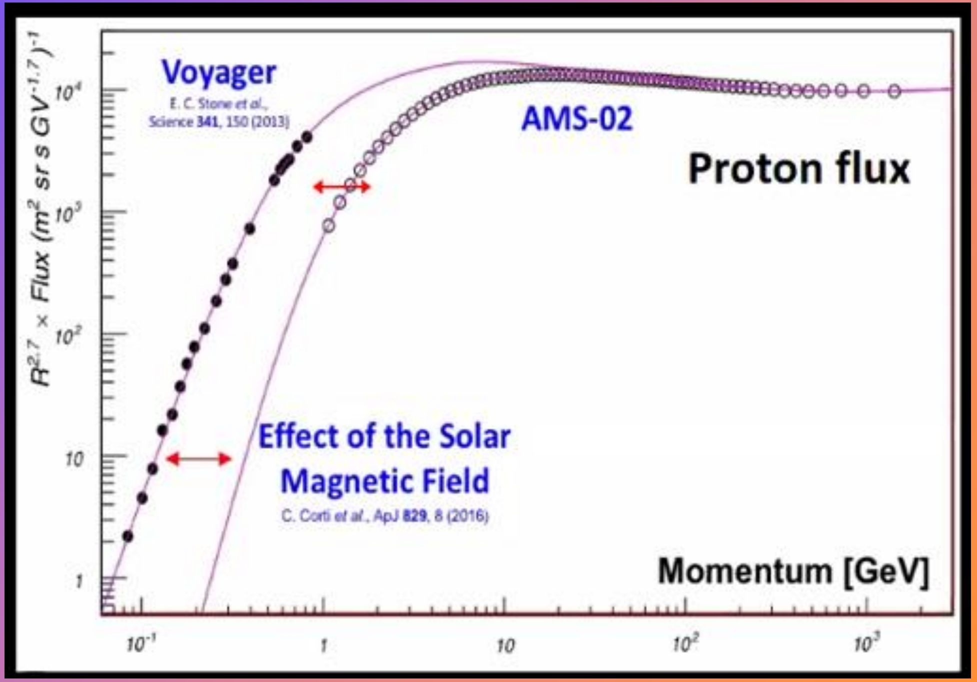
The biological effects of ionising radiation is a consequence of the energy transfer by ionization and excitation to body cells

AMS02 PUBLISHED CRS









Credit S.Ting & AMS Collaboration

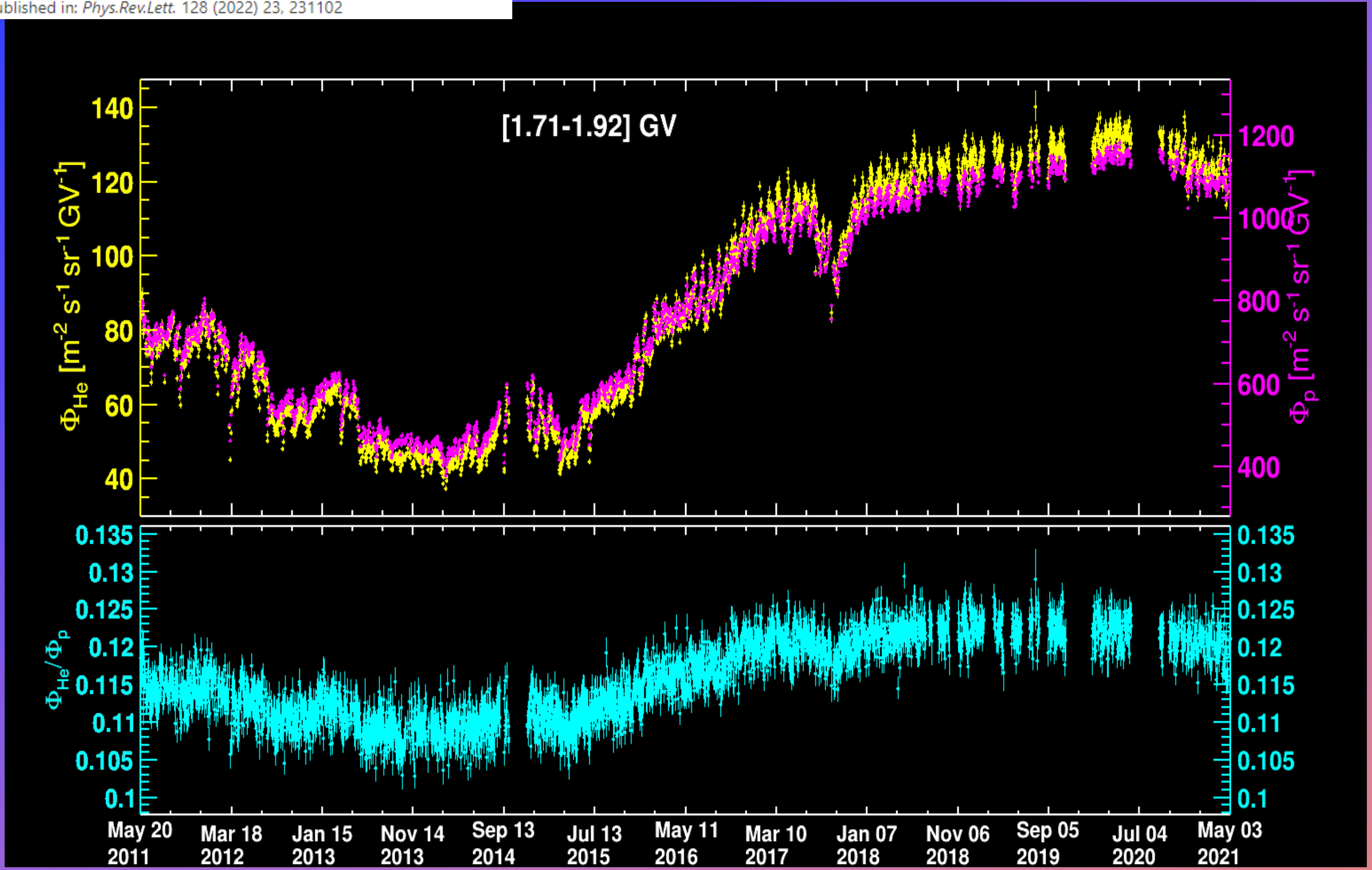
Cosmic Rays Solar Modulation

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

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)

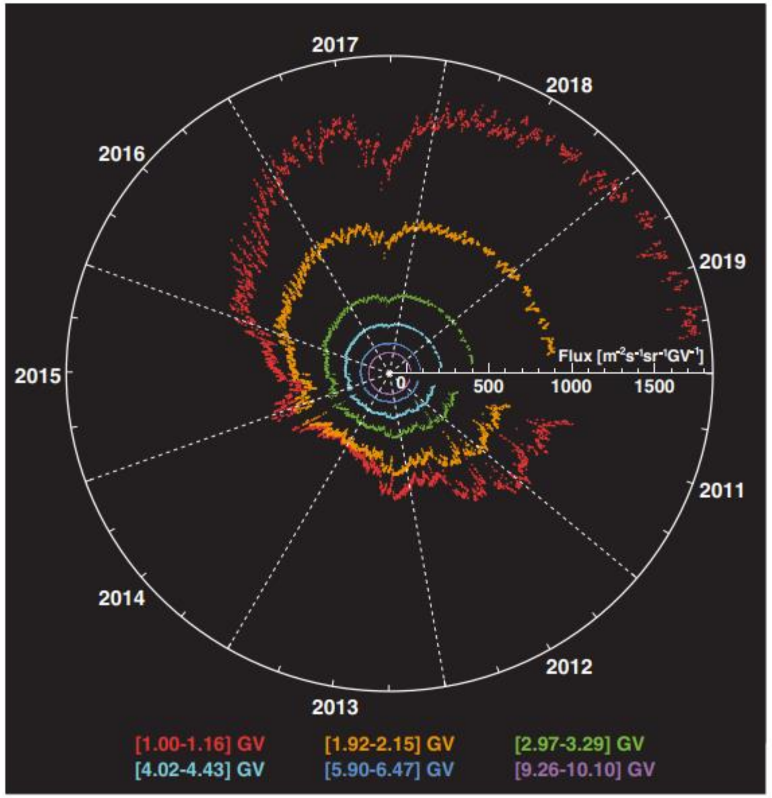


FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data

Short term Solar Modulation of GCR

Daily Proton and Helium Fluxes and Helium to Proton flux ratio

Properties of Daily Helium Fluxes

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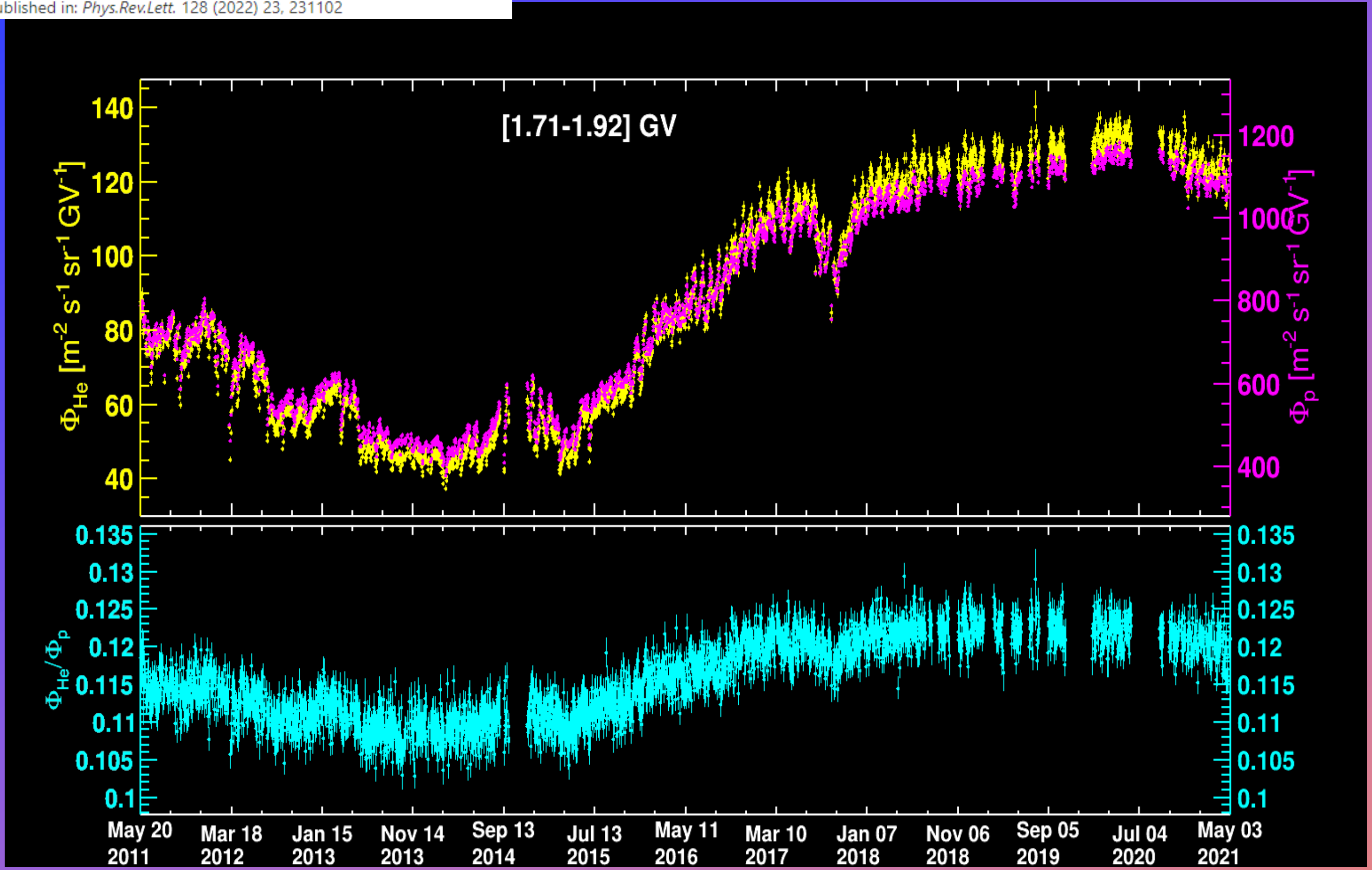

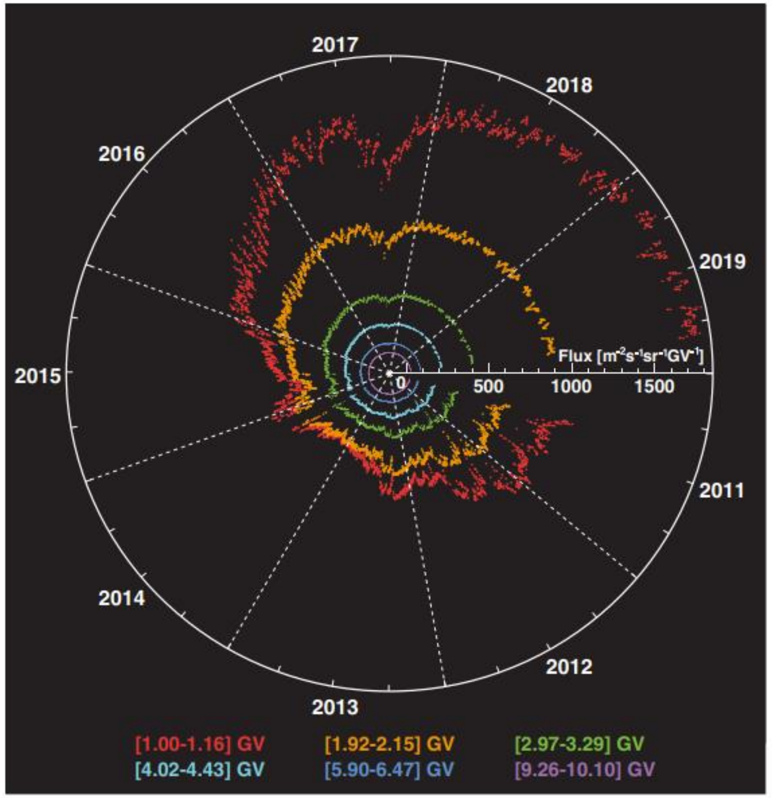

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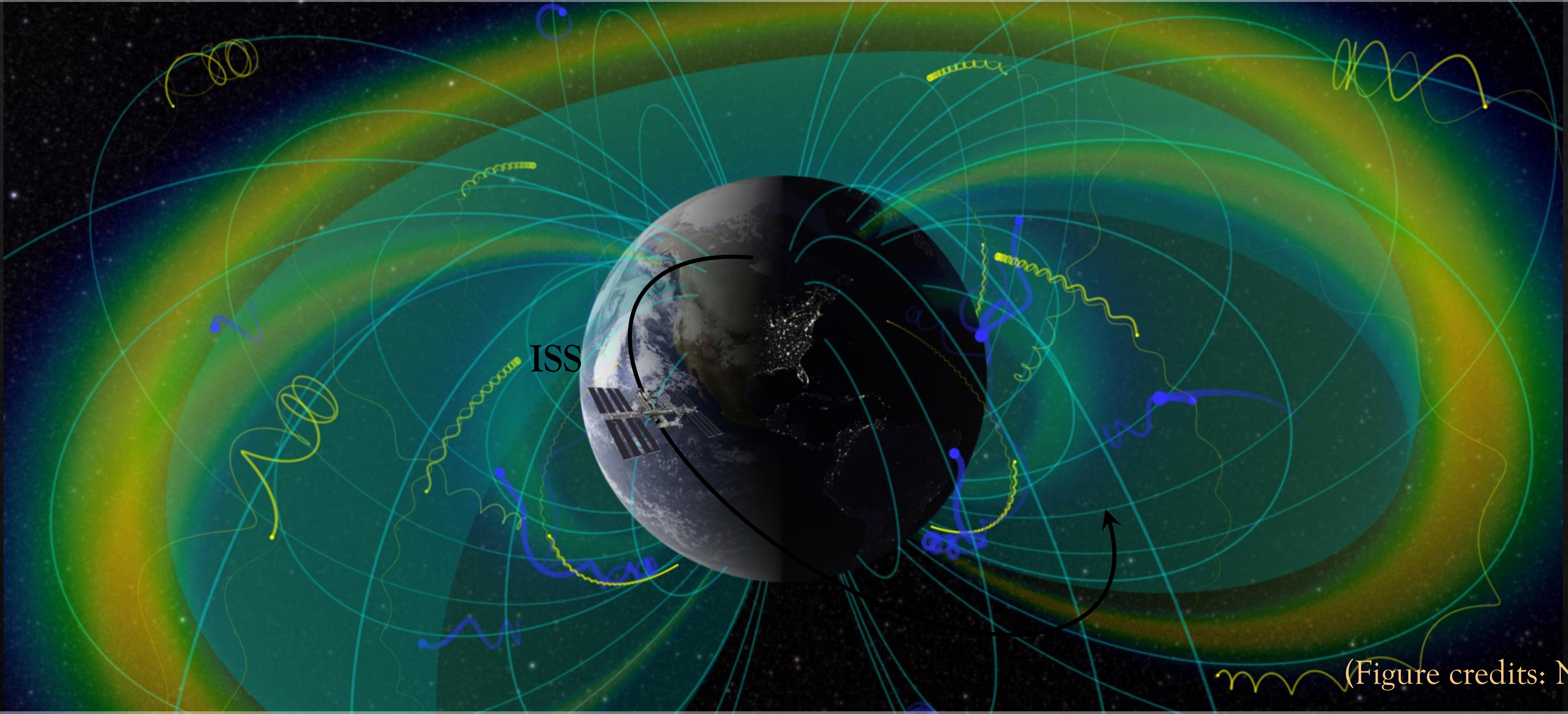
Short term Solar Modulation of GCR

Daily Proton and Helium Fluxes and Helium to Proton flux ratio

Cosmic Rays in the Magnetosphere

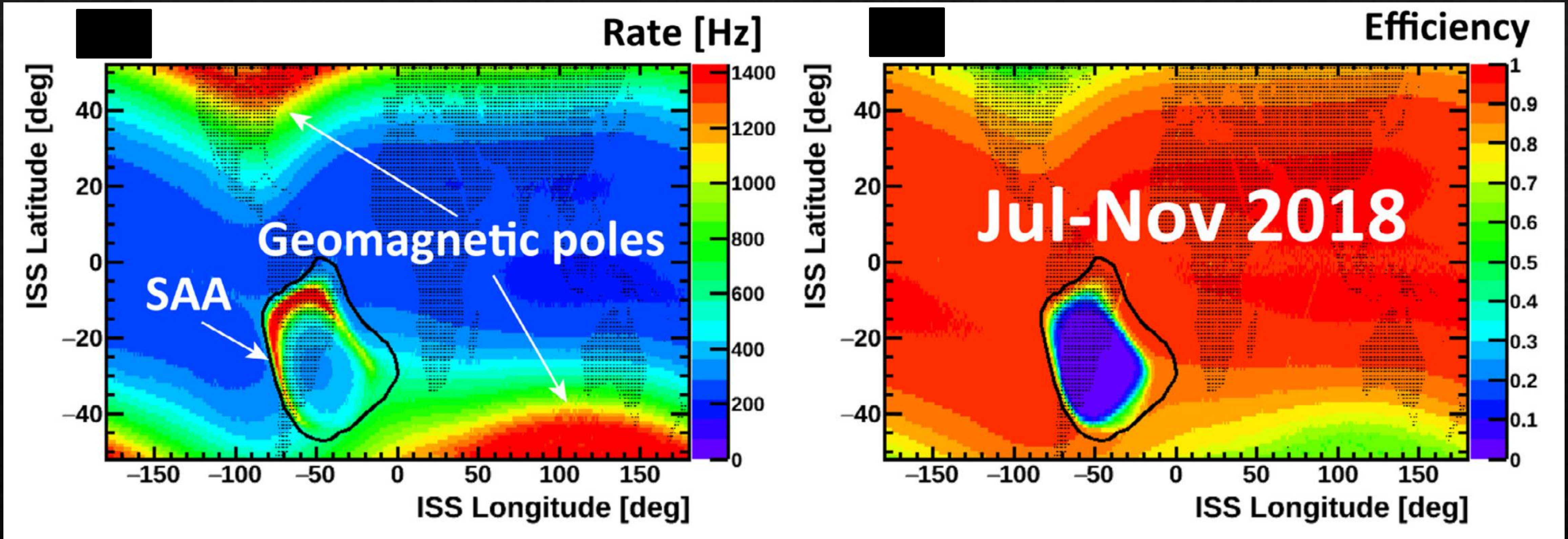


(Figure credits: NASA)

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 Anomaly 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.



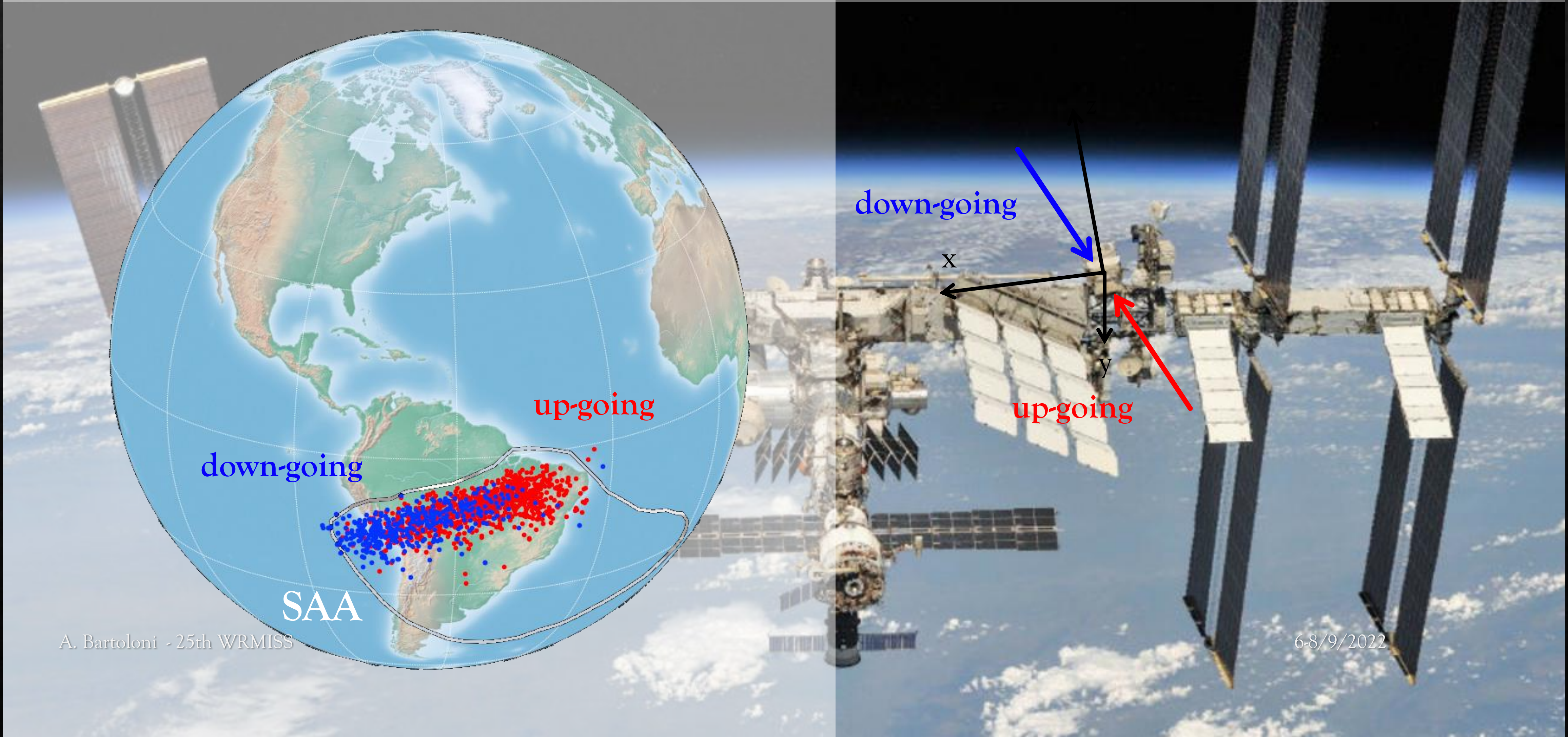
M. Aguilar et al., Phys. Rep. **894** (2021) 1–116.

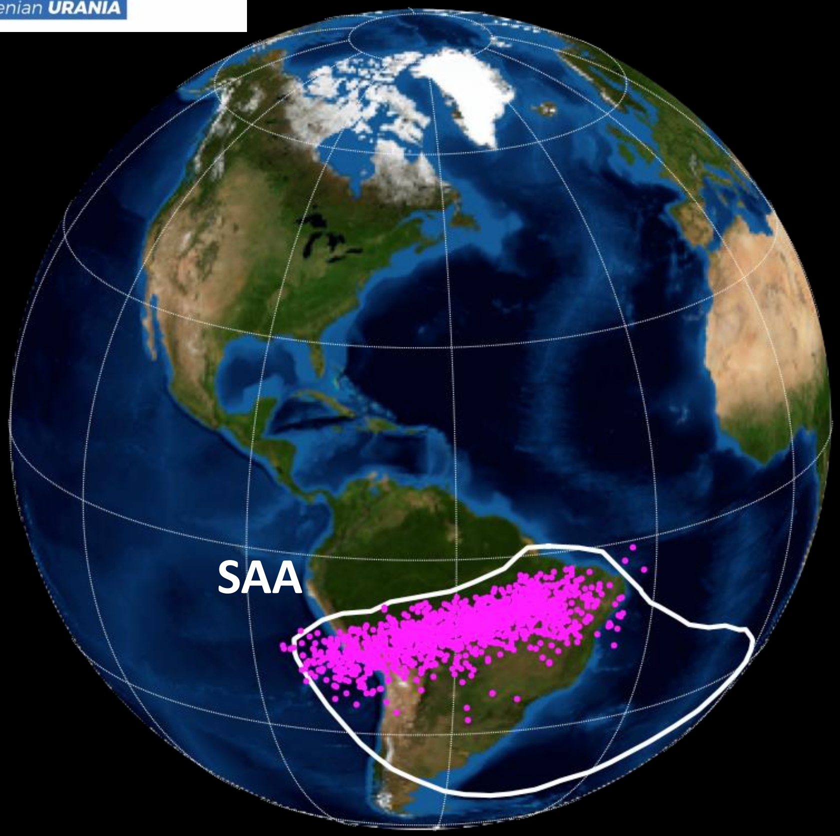
Energetic particle with charge up to 2 are known to exist in this region.
While there is no previous observation of energetic (R>1GV) Z>2 particles inside SAA.

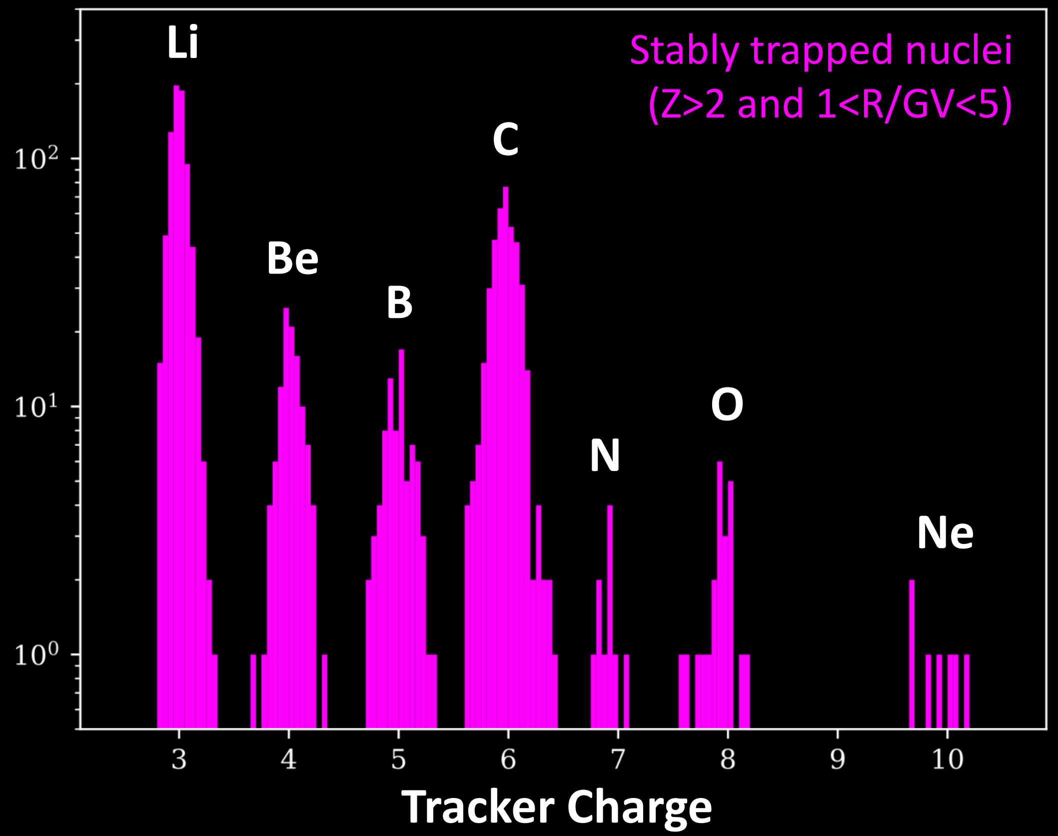
Credit A.Oliva
& AMS Collaboration

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.







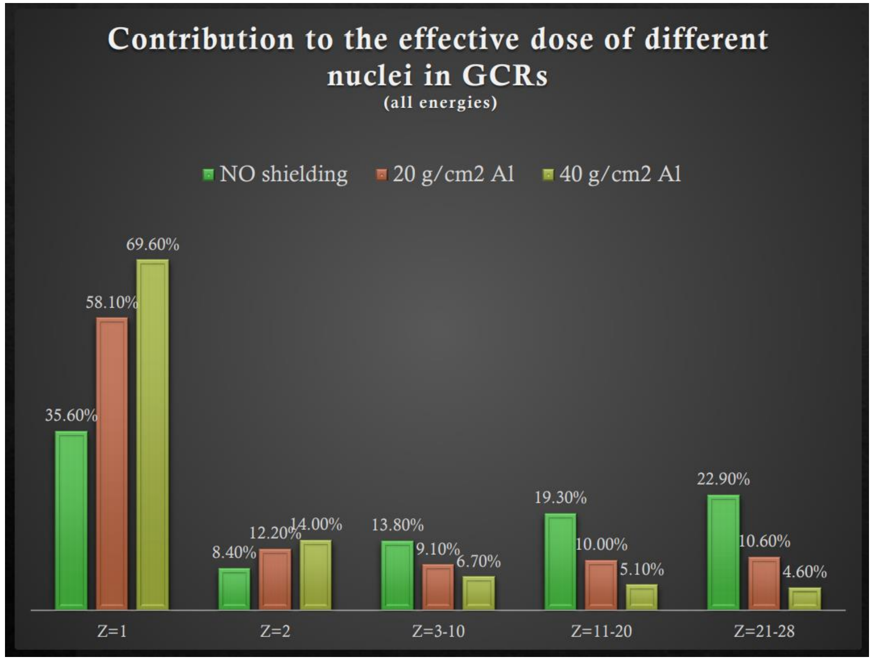
- 10 years of AMS-02 data have been used to look for ions with Z>2 below geomagnetic cutoff;
- A **stably trapped** population has been clearly identified below 5 GV in the SAA region;
- This population has properties (rigidity, charge, arrival direction) distinctly different from GCRs;
- This is a high-Z,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

Credit A.Oliva
& AMS Collaboration

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

- Environmental GCR model : BON2010 [4]
- ICRP 60 Radiation Quality Factors
- ICRP 103 for Tissue Weights
- "FAX": Female Adult voXel phantom[5]
- Transport Code : HZETRN-π/EM[6]



A. Bartoloni [a*], L. Strigari[b]
SIF 2019

1) Environmental Model Characterization:

- Use the enormous data at energies > 1GeV
- 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.

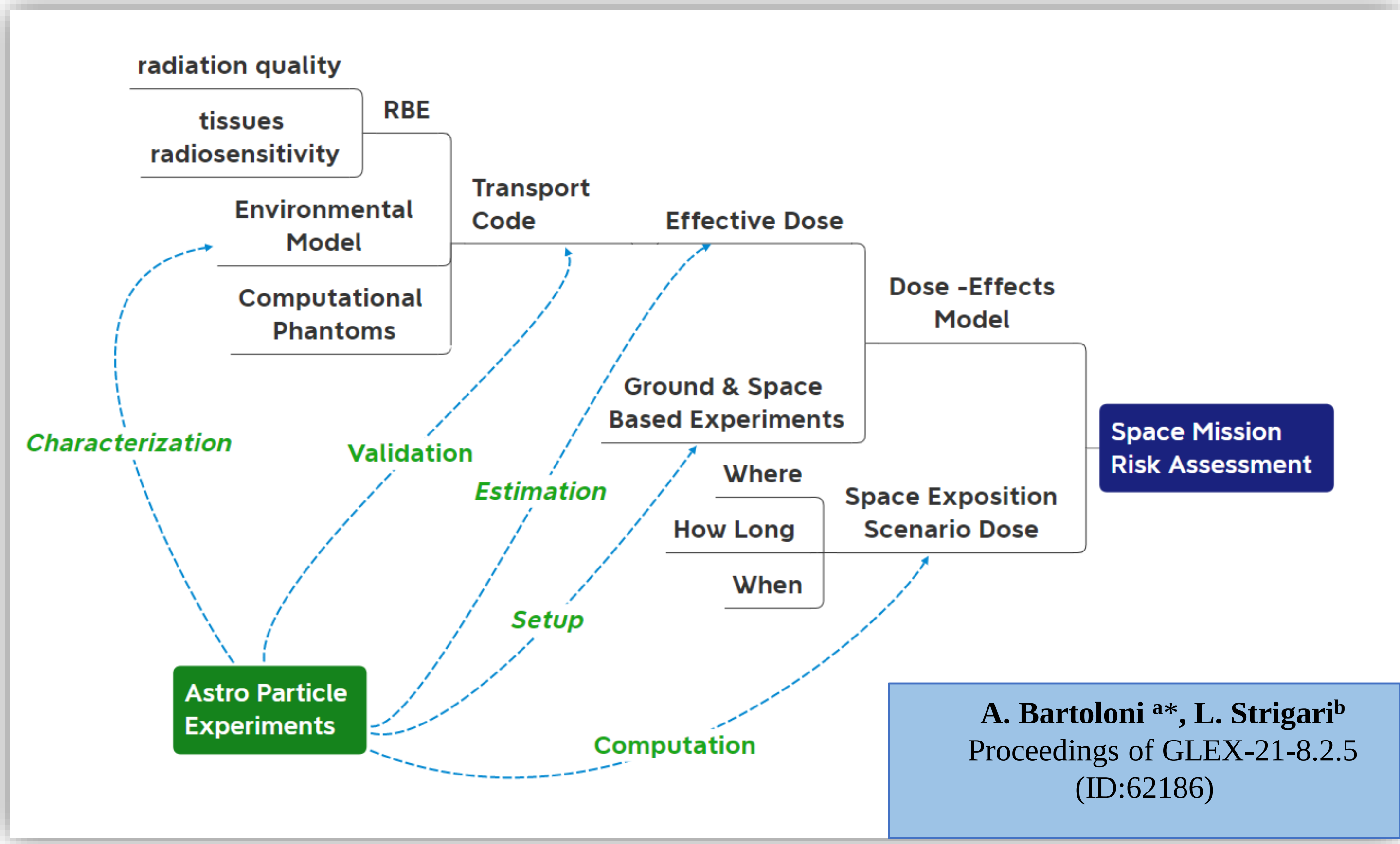
3) Transport Code Validation :

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

A synergy with Astroparticle researches

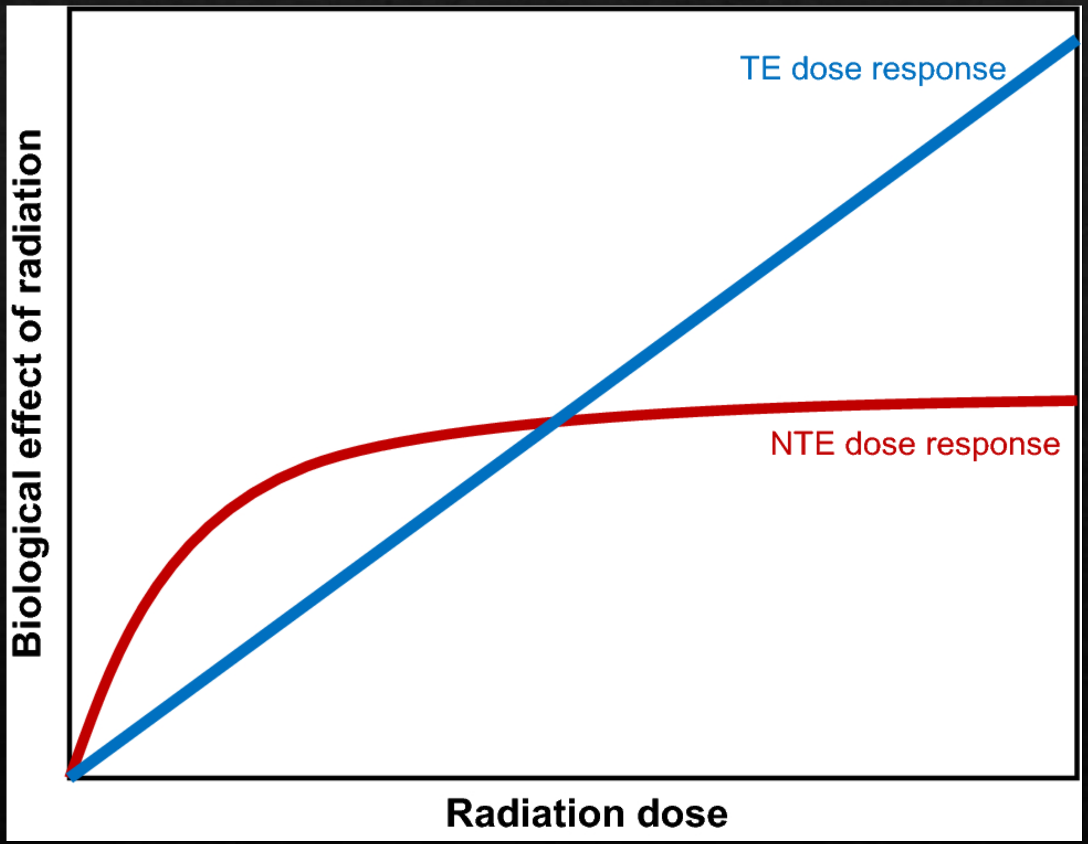
A Case Study :

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

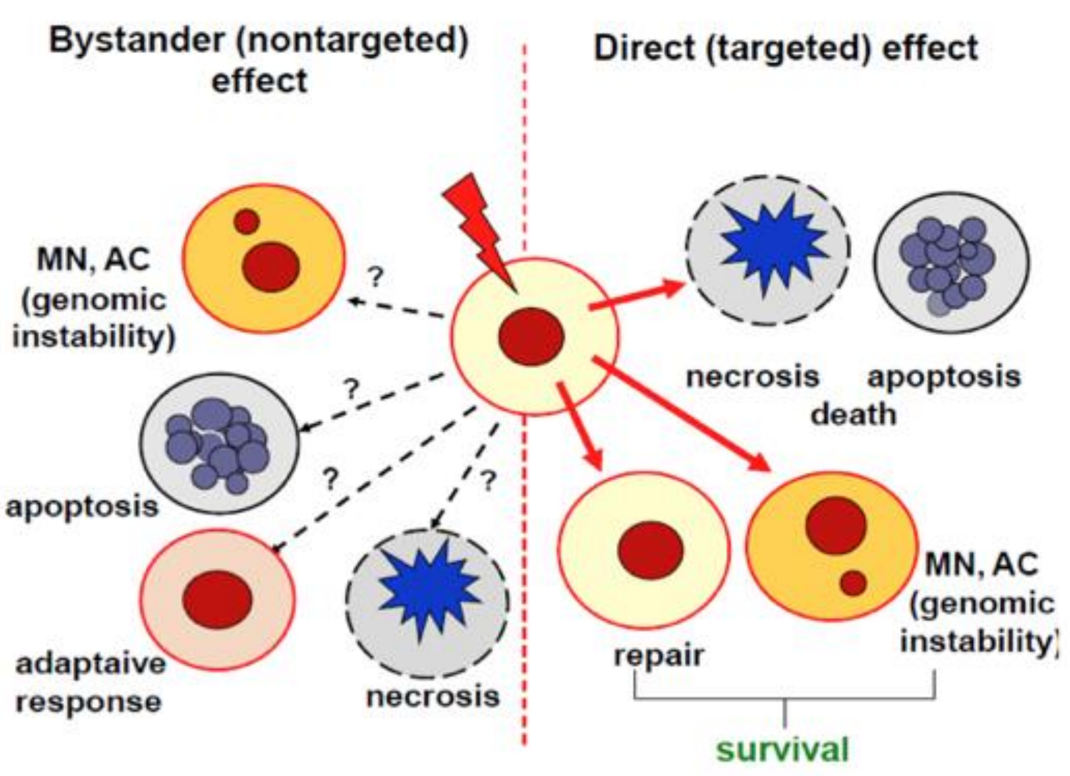


Target Effects (TE) vs Non Target Effects (NTE)

- 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, Eliedonna 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).

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

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

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

Where:

- **H0** 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. $S(D) = 1 - (1-B)^n, B = e^{\frac{-D}{D_0}}[1 + \sum_2^N \frac{\left(D/D_0\right)^{N-1}}{(N-1)!}]$

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

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

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

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

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

7. $S(D) = e^{-\frac{n_0 - C_0}{1 - \frac{C_0}{n_0}e^{kT(C_0 - n_0)}}}$

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 cm^2.
- Background Prevalence is H0 = 0.026

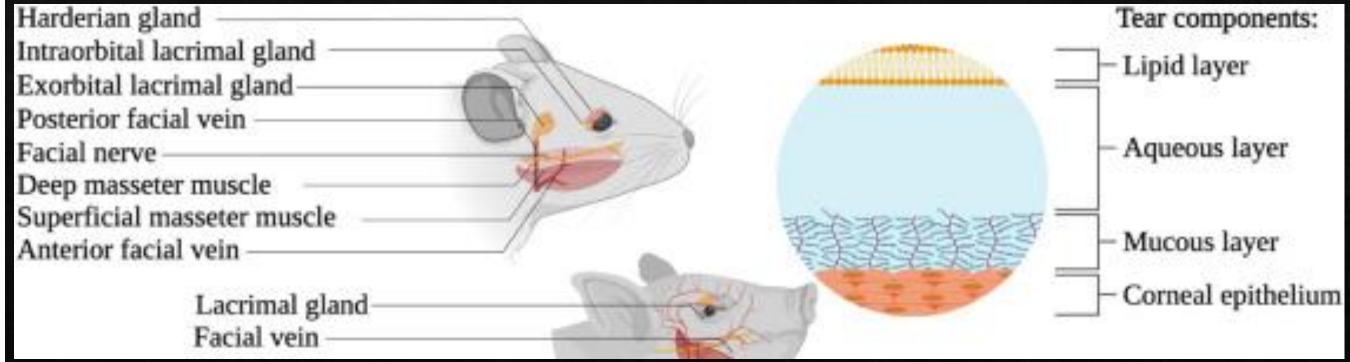
TABLE II
Prevalence of Harderian Gland Tumors after ^{60}Co Gamma Irradiation

Dose (Gy)	Mice: Number	At risk	With tumors	Prevalence[a] (%)
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.

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

Ion and energy	Dose (Gy)	Mice: Number	With tumors	At risk	Prevalence[a] (%)
Controls	0	198	155	4	2.6 ± 2.5
Protons (250*A* 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



Hazard Function
Targe 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
- $N_{Bys} = Fluence * A_{Bys}$
- A_{Bys} is the number of bystander cells surrounding a cell traversed directly from a HZE particle that receive an oncogenic signal.

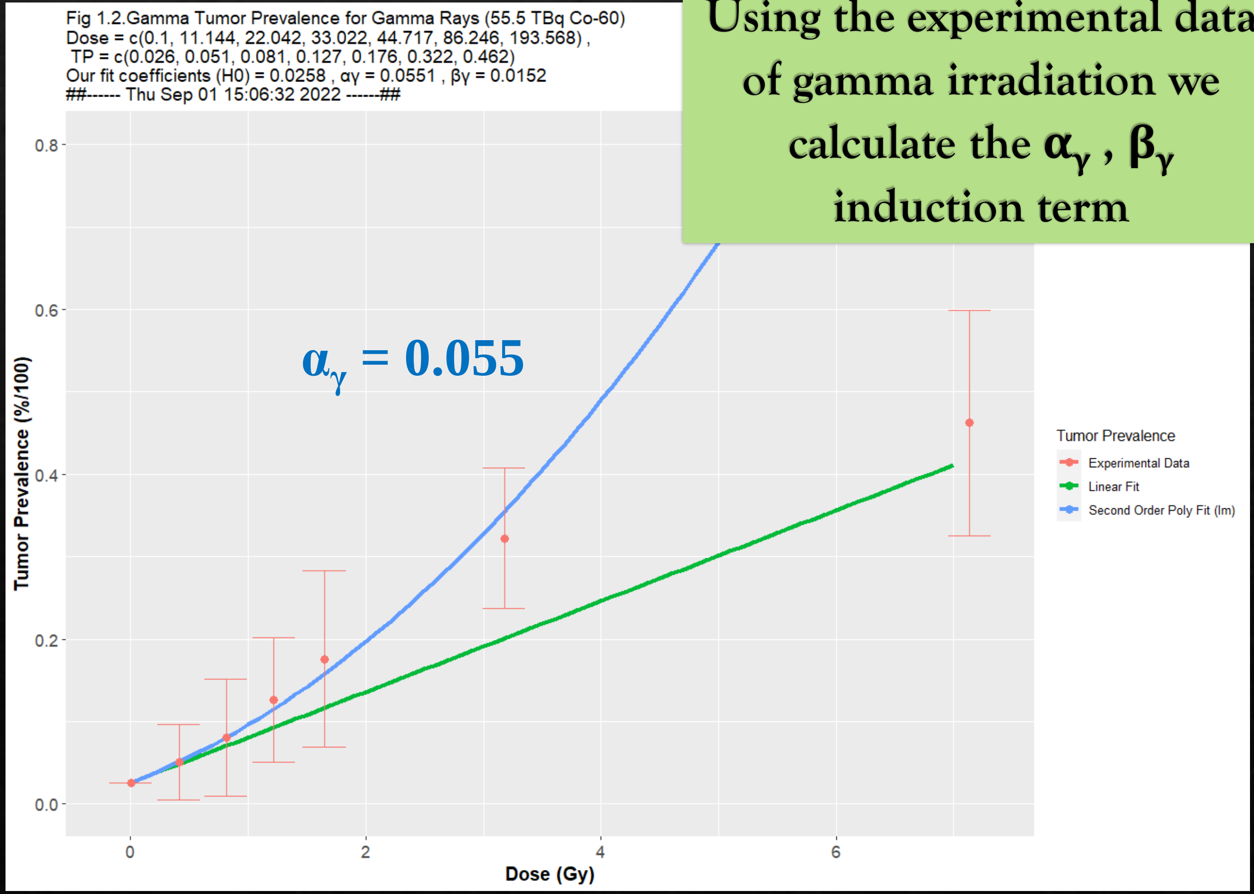
Results: Effective Pseudo-Biological Action Cross Section

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

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

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,
- Vc 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

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

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

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

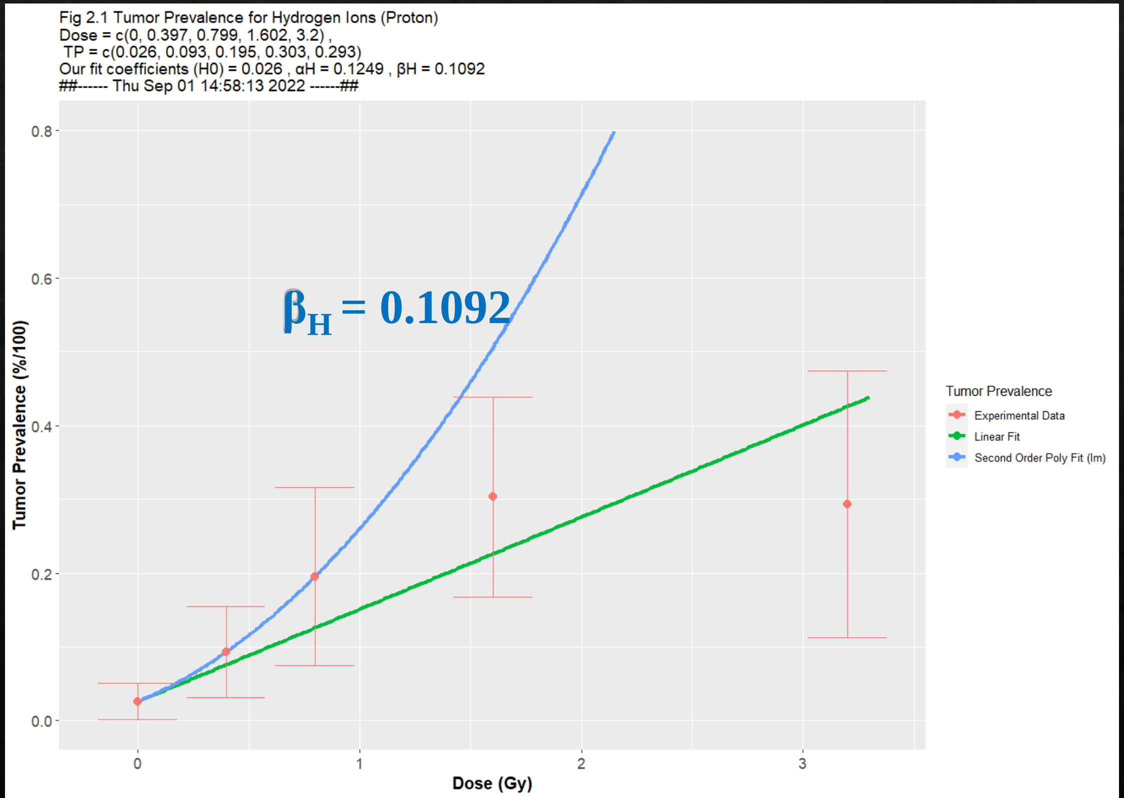
$$\eta_H = 0.00048 * 0.4e^{-0.00281*0.4}\,[1 - e^{-216*F}]$$

Where:

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

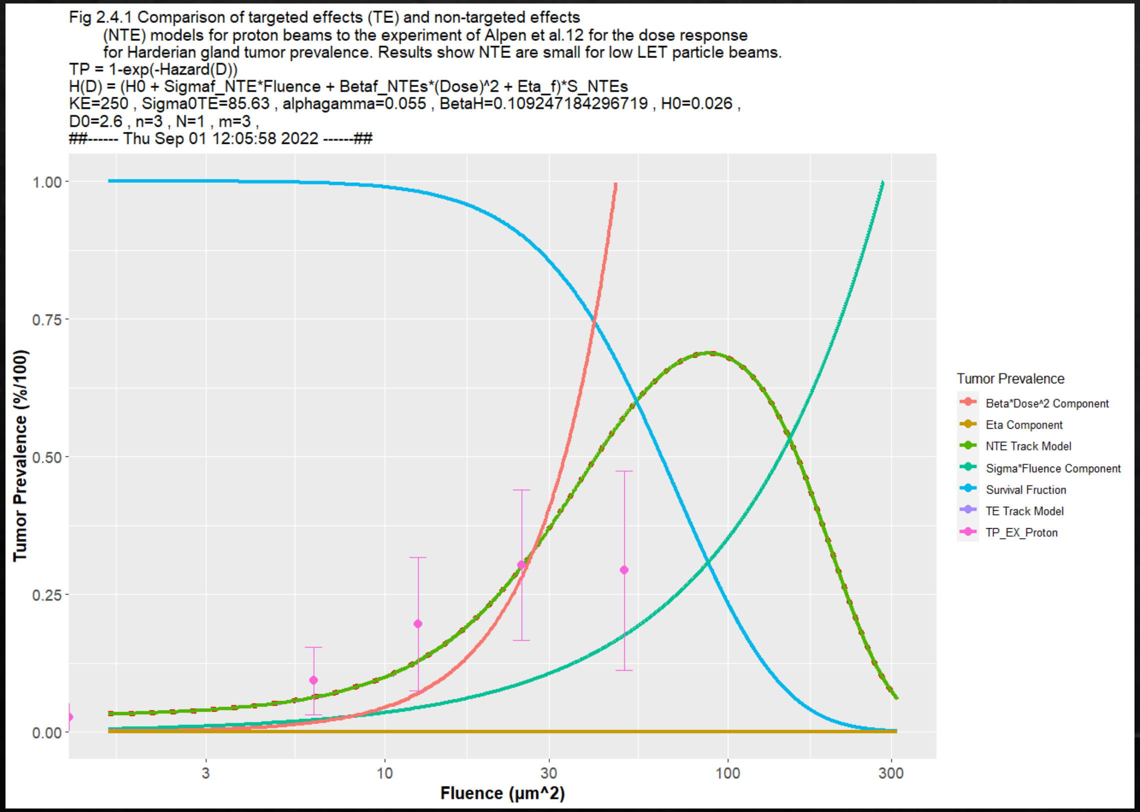
For the cell survival probability is used the target theory n-target N-hit model (nTNH) with n =3 , N = 1

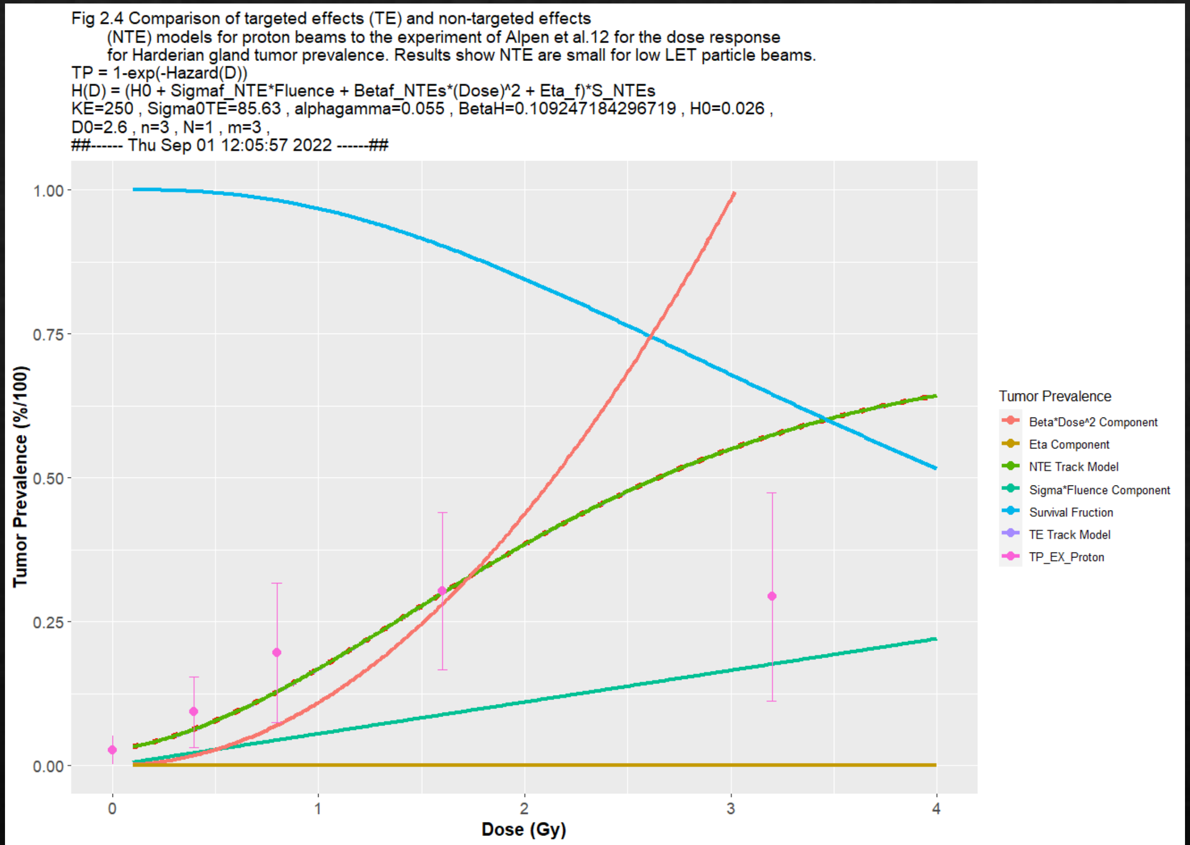
Using the experimental data of 250A MeV Hydrogen irradiation we calculate the α_H , β_H induction term



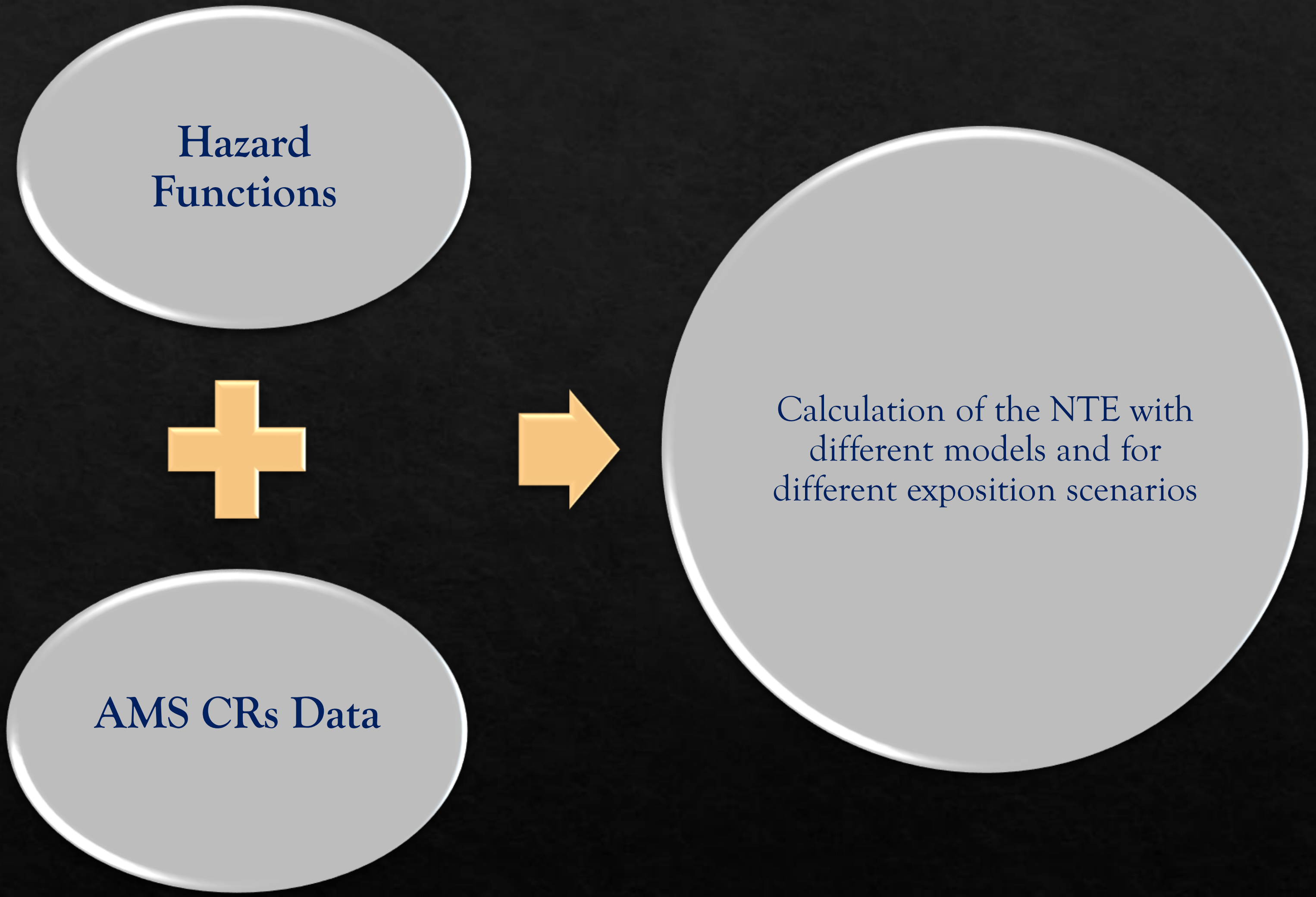
Results: TE vs NTE for Protons

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.





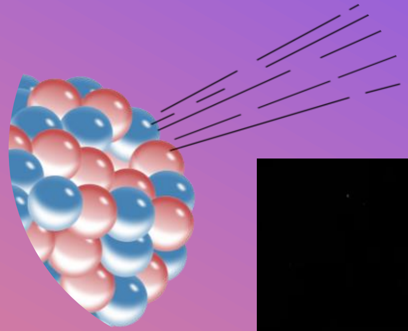
Results: Tool for NTE components evaluation

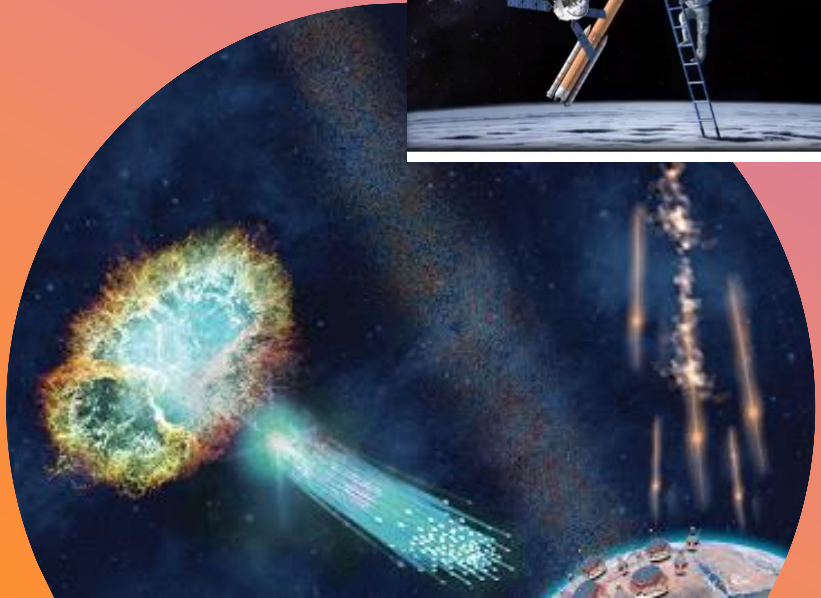


Summary

- 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 !

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

BACKUP SLIDE

Dose-Effects Relationship

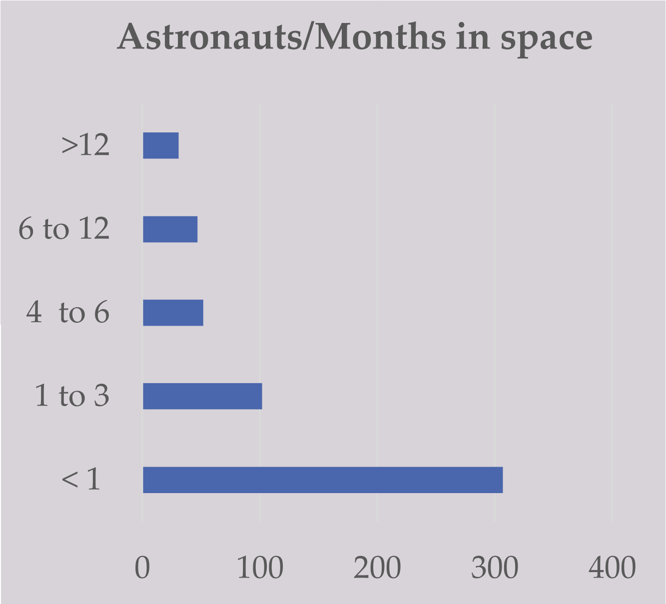
The known dose-effect relationships are based on a limited number of astronauts

(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.

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



Needs of an improvements

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
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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*]

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

Dose-Effects Models for Space Radiobiology:

An Overview on Dose-Effect Relationships

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

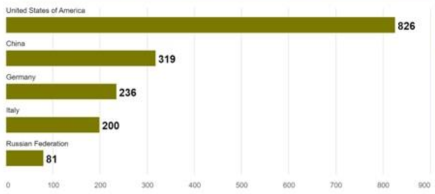
Based on a *PubMed* search including 53 papers reporting the collected **dose-effect relationships after space missions or in ground simulations**, 7 significant dose-effect relationships (e.g., eye flashes, cataract, central nervous systems, cardiovascular disease, cancer, chromosomal aberrations, and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



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

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

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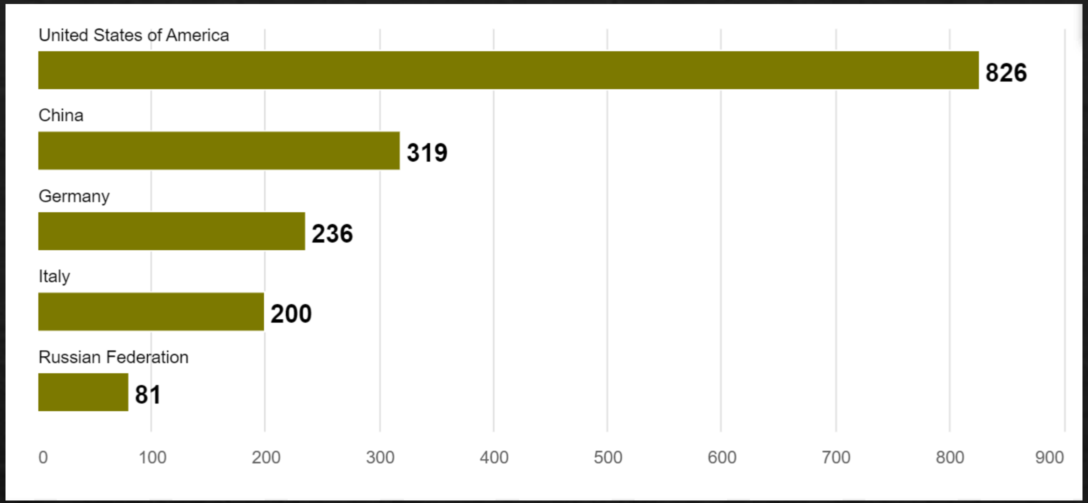

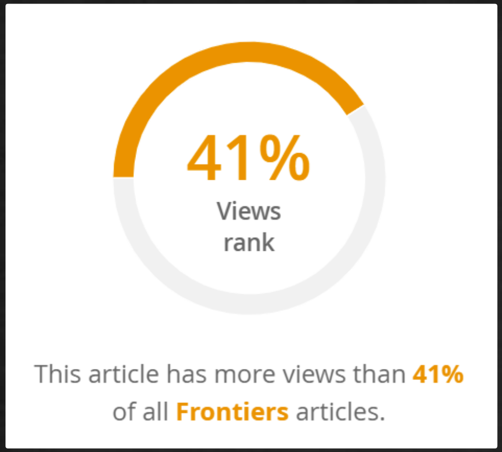

Article Statistics (June 2022)

THE RESEARCH TOPIC INITIATIVE

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Research Topic

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

frontiers in Astronomy and Space Sciences

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

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Participating Journals

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

Frontiers in Astronomy and Space Sciences
Astrobiology

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

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

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**".

-

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Mālamalama
1907
Ua mau ke ea o ka 'āina i ka pono

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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

The Badhwar-O'Neill 2020 GCR Model

T. C. Slaba[1] and K. Whitman[2]

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

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

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

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 ±15% of a large fraction of the available measurements (26,269 of 27,646 → 95%).