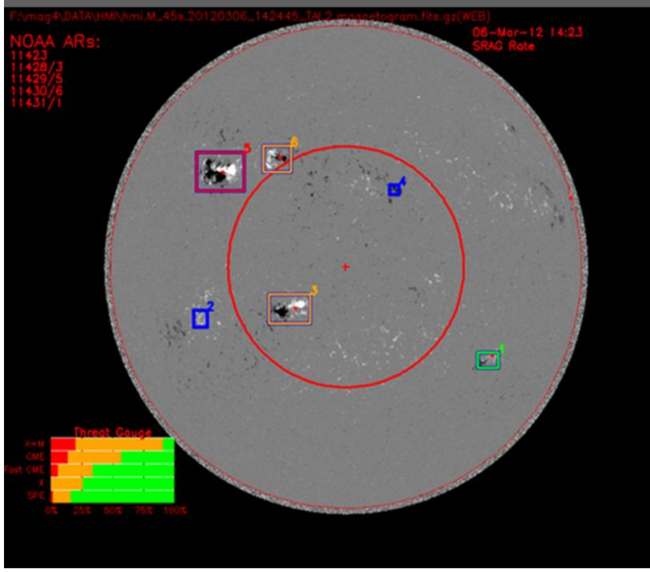
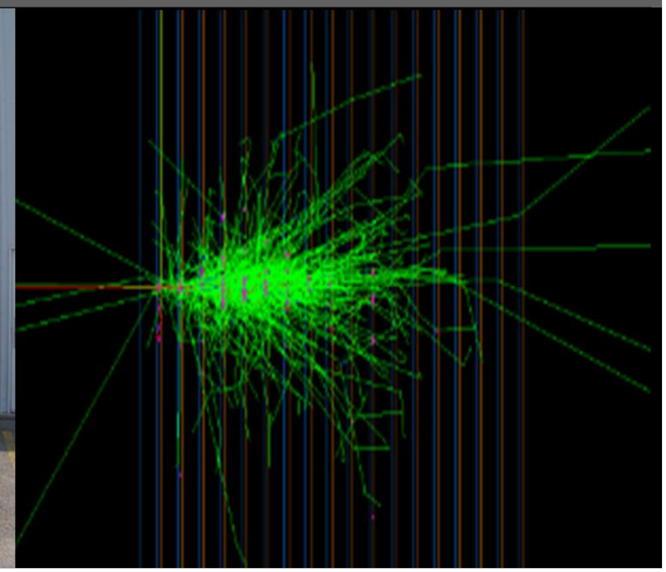
National Aeronautics and Space Administration

## SCIENCE & TECHNOLOGY OFFICE



# Towards Radiation-Smart Structures and Designs

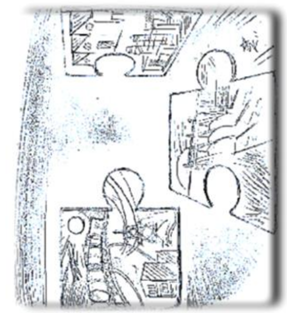
*Nasser Barghouty*

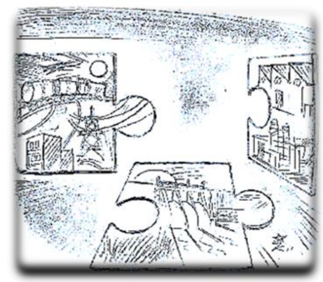
Astrophysics Office, NASA-MSFC

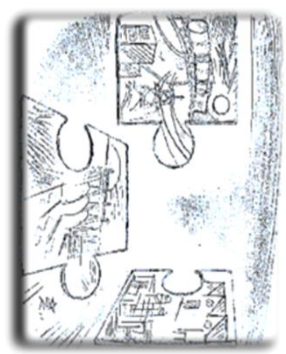
**WSU, March 30, 2016, Wichita, KS**

# Way Points

- ✓ **Space Radiation**
  *understanding the problem*
- ✓ **Few things about cosmic rays**
  *from the problem solver perspective*
- ✓ **Few things about cosmic rays**
  *from the astrophysicist perspective*
- ✓ **Space Radiation**
  *engineering the solution*



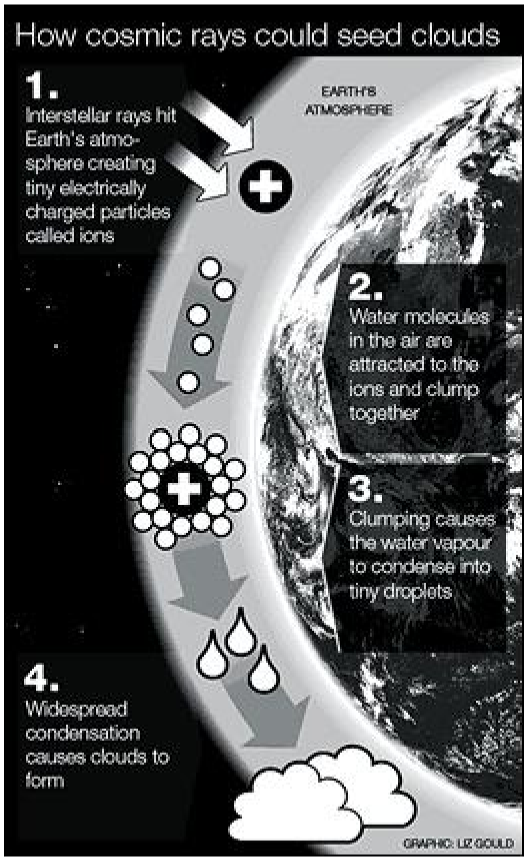




*…if you have a question, please do interrupt me and ask…*

# *"Cosmic rays blamed for global warming"*

**By Richard Gray, Science Correspondent, Sunday Telegraph**
(UK)
11/02/2007




Dr. Svensmark (Danish National Space Center) and co-workers believe cosmic rays affect and impact our climate significantly and they should be considered more carefully in large-scale climate models.
[Space Science Reviews **93**, 175 (2000);
Physical Review Letters **85**, 5004 (2000).]

Cosmic rays-and-clouds connection has been made before as were cosmic rays and other geophysical phenomena, e.g., C-14

However, this recent conjecture goes farther!

# **Space Radiation:** *What is it and why a problem*?

## The Problem

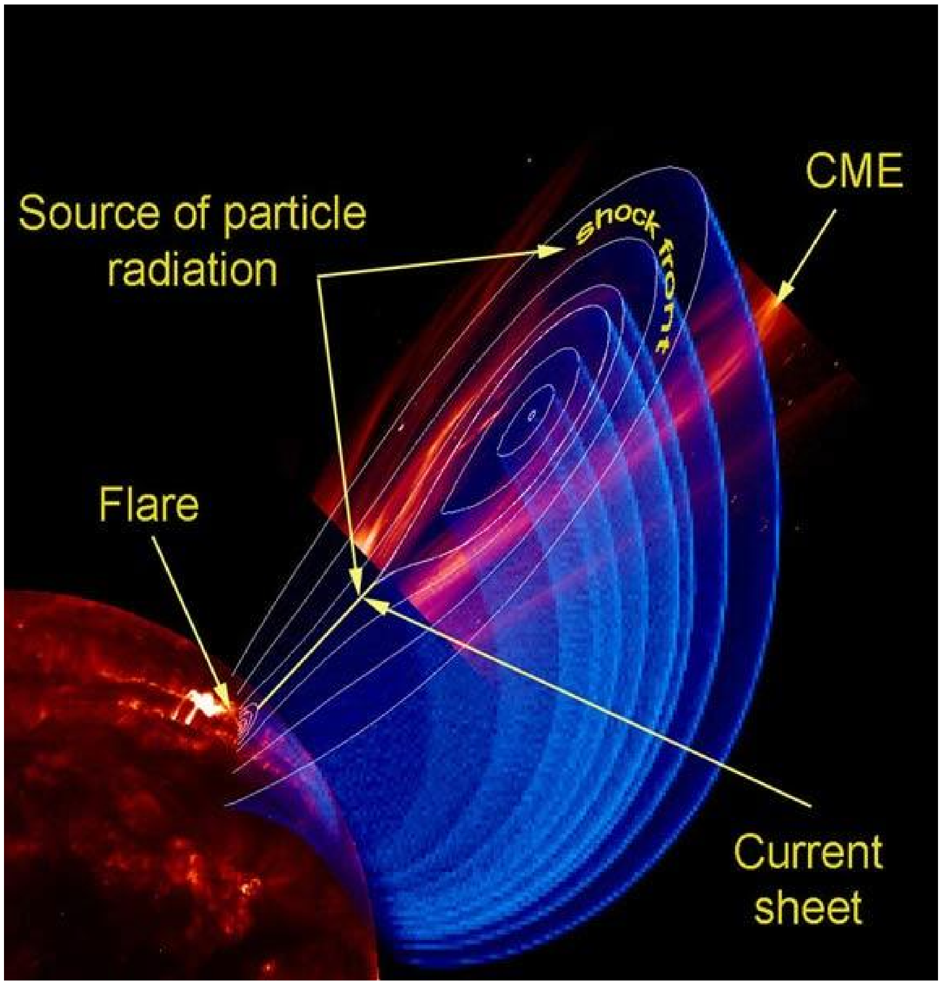
- In **deep space** outside the protection of the Earthʼs atmosphere and magnetic field, radiation levels are known to be a major hazard to our astronauts and our missions
- From space physics and from 50 years plus of space-based observations, we now know that Galactic Cosmic Rays (or **GCR**) and Solar Energetic Particles (**SEP**) are the two main sources of this high-level of so-called **ionizing radiation**… but there are challenges!

## The Challenges

- Effective shielding against the combined effects of GCRs and SEPs can be mass prohibitive
- Shielding effectiveness of new, potential shielding materials (or combinations) is not that well characterized
- Little data to guide dose and risk assessment models
- Known, **large uncertainties and variabilities** in radiobiological effects
- Other uncertainties and variabilities? (e.g., in generalization and scale-up of shielding or protection solutions)

# **Space Radiation:** Natural Sources

## Two main sources of ionizing radiation:

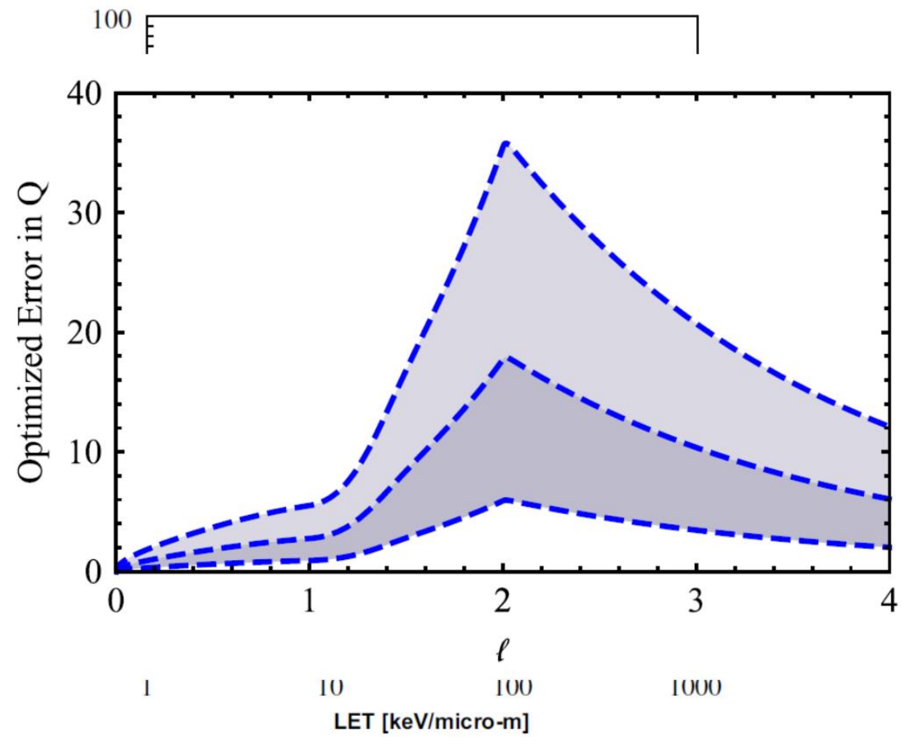



# Uncertainties in radiobiological effects

Å The radiation quality factor (or óQô factor) is *introduced* to differentiate the radio-biological effects due to different radiation sources **at the same energy**

Å Large uncertainties -and variabilities- in the radiation quality factor is seen as a main hindrance toward reliable dose and risk estimates

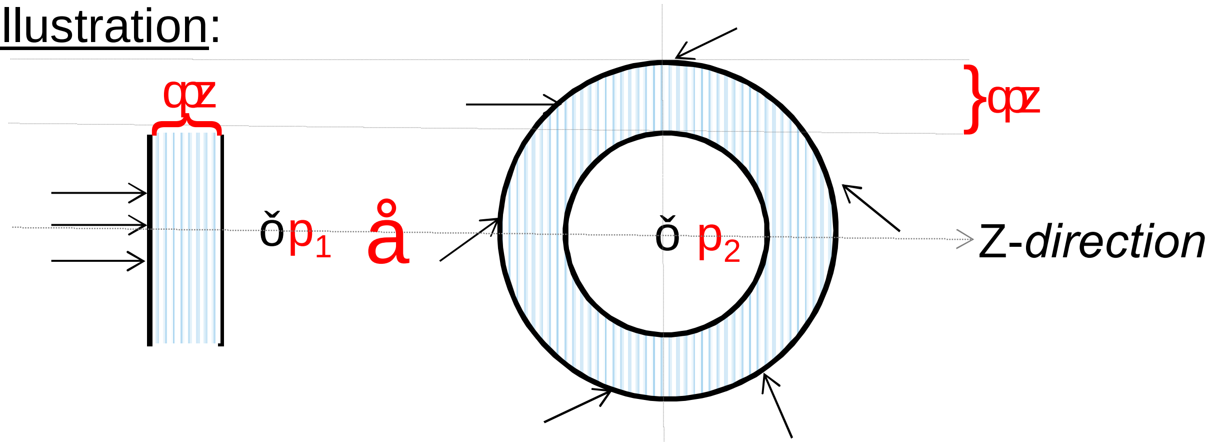
Å These variabilities can be simulated (i.e., óMonte Carloôed) or captured analytically using stochastic analysis tools

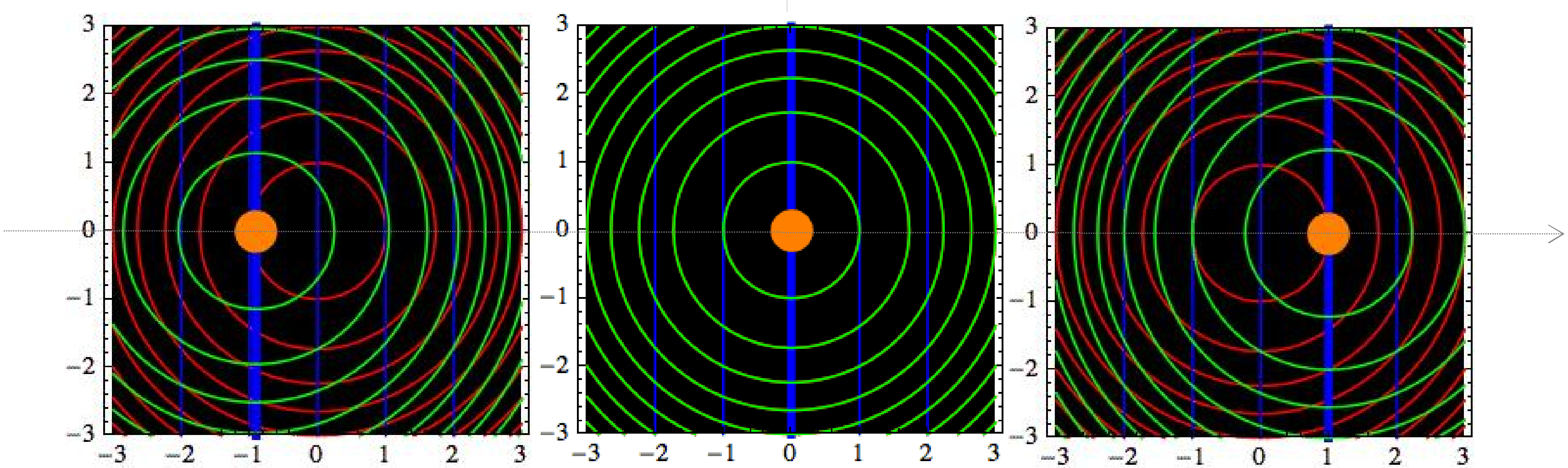


# Others

Complex geometry and material composition -in the presence of known physical uncertainties- are expected to produce sizable errors in any radiation protection solution.

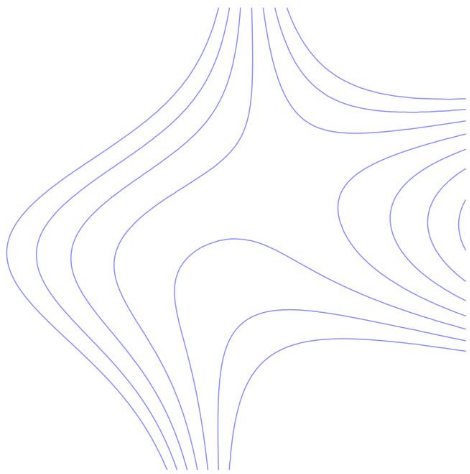
<u>A 2-D illustration</u>:

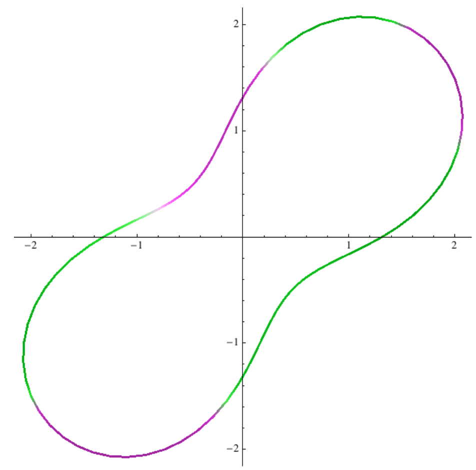


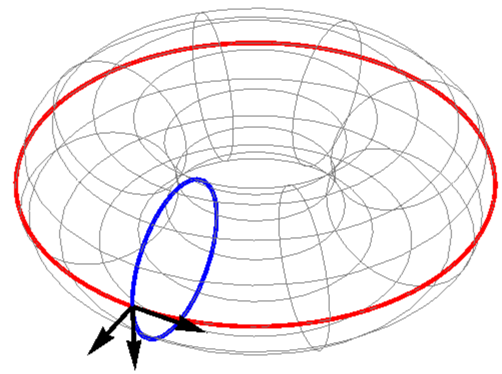



# Others

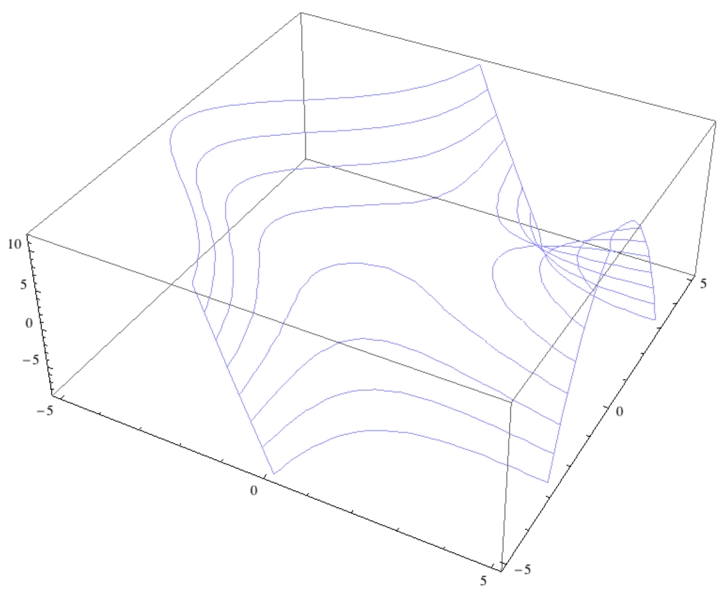
A 3-D illustration:

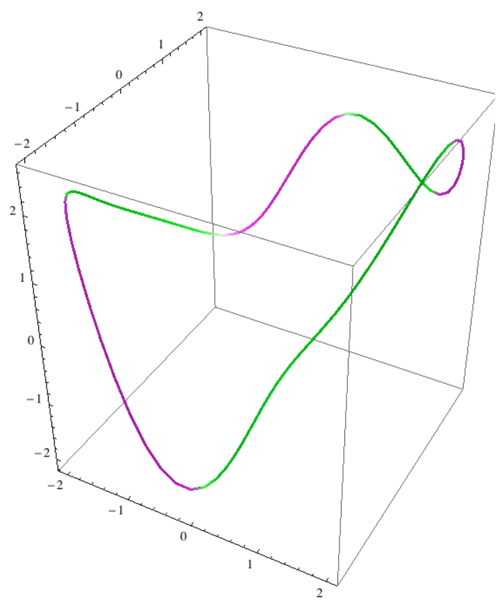


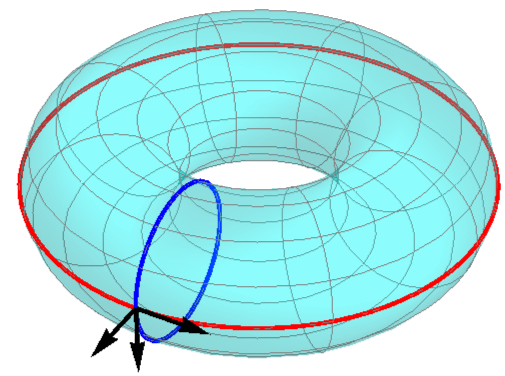




Unlikely?



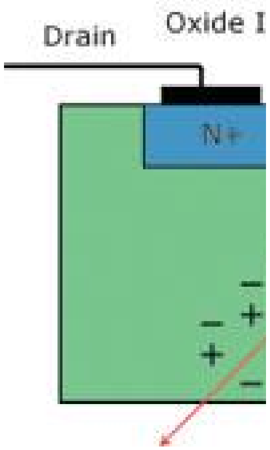


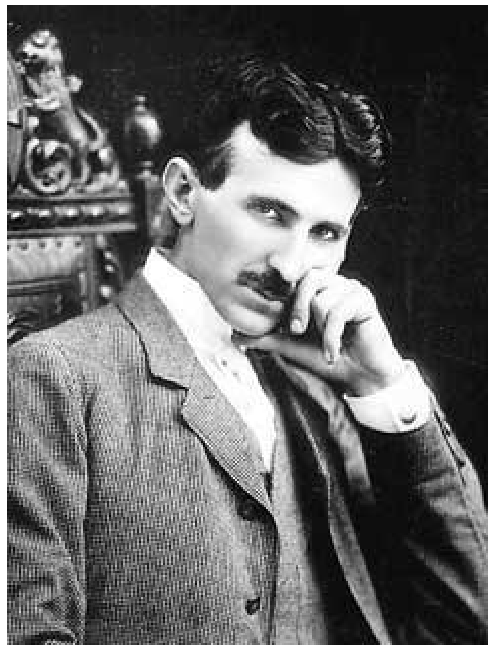


# Appetizers…

## *"Toyota recall might be caused by cosmic rays"*

ñI have harnessed the cosmic rays and caused them to operate a motive device.ò



Nikola Tesla
1856-1943

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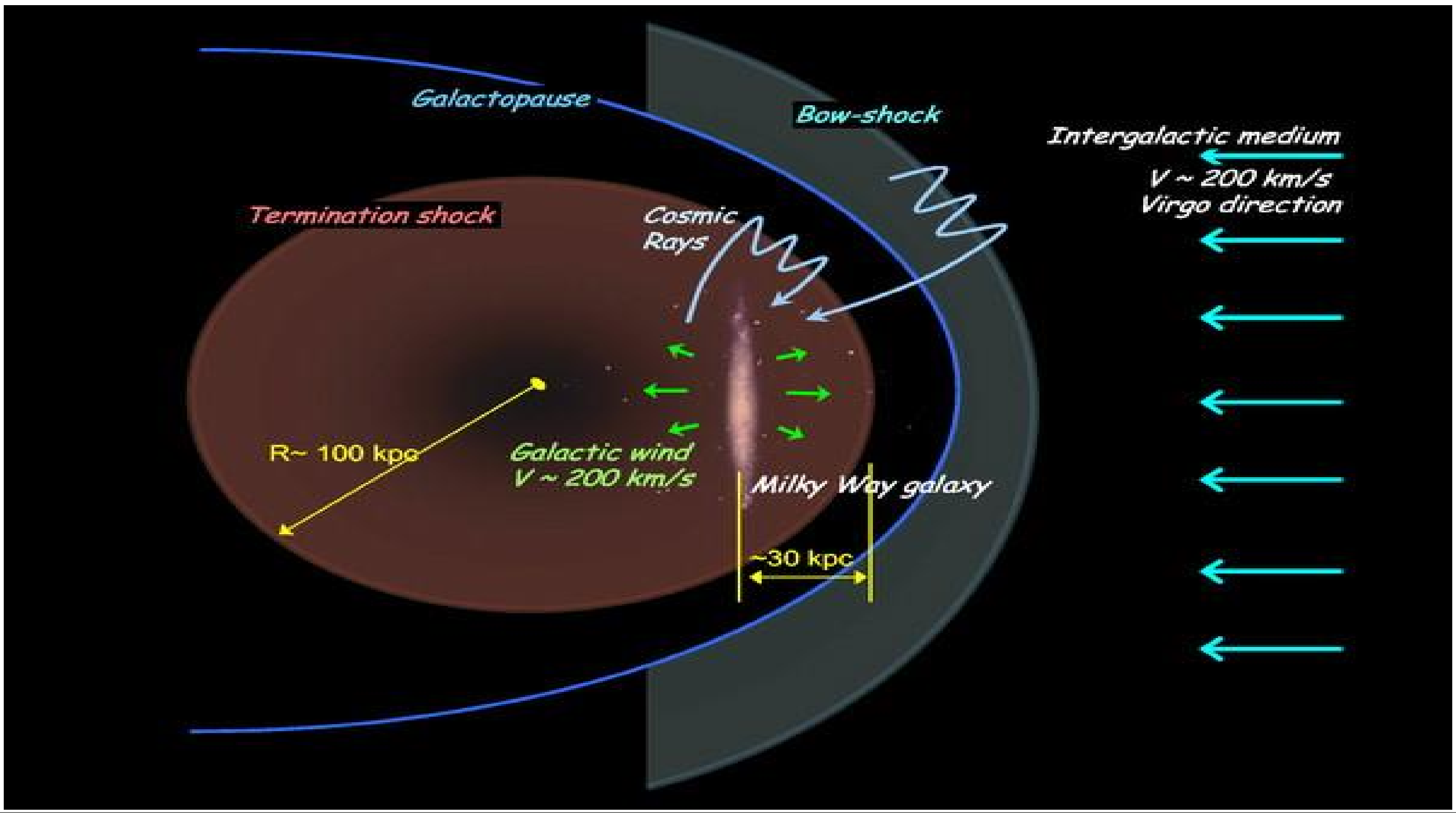
# Appetizers…

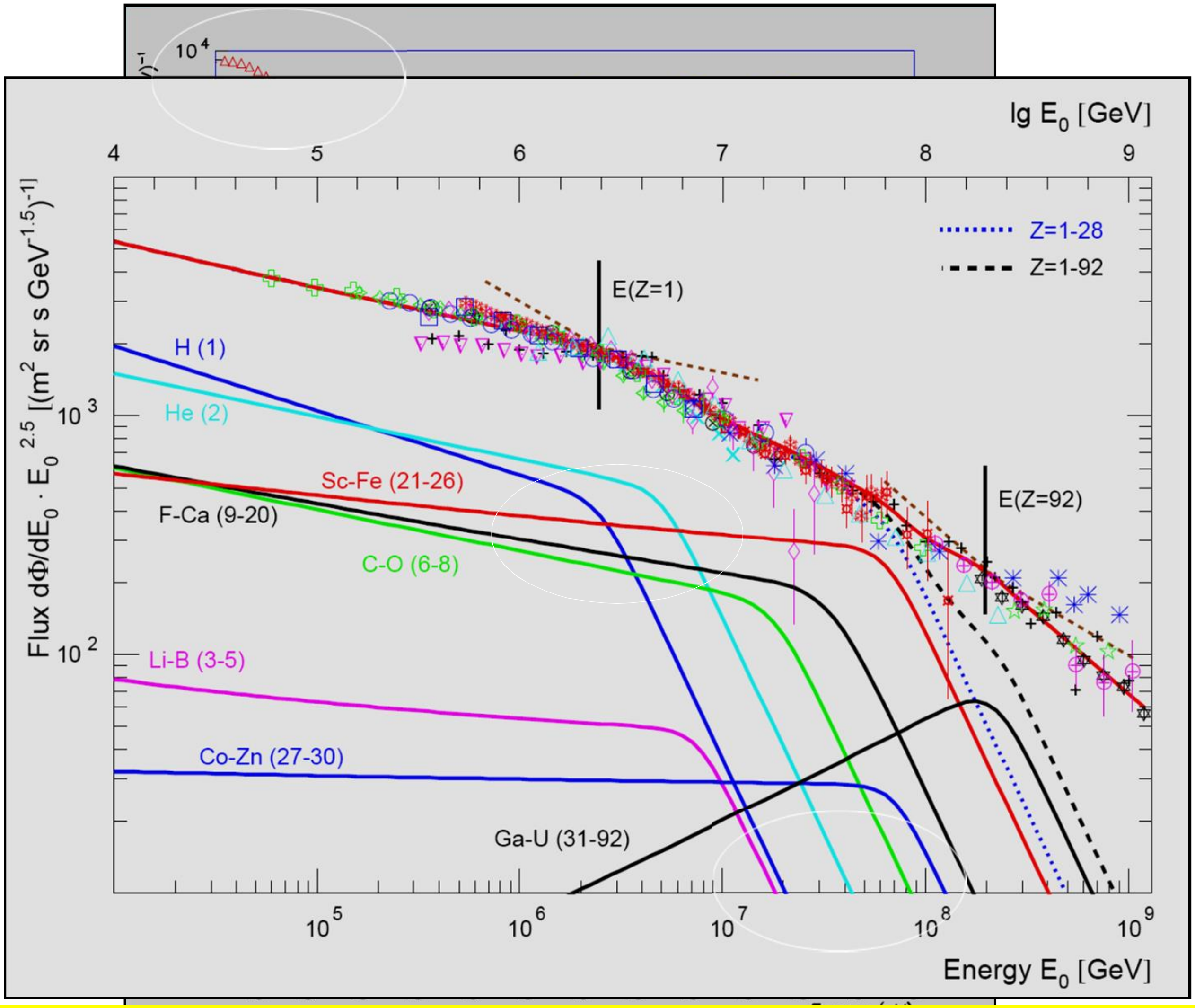
## *"Varying cosmic-ray flux may explain cycles of biodiversity"*

**By Bertram Schwarzschild, Physics Today**

October 2007

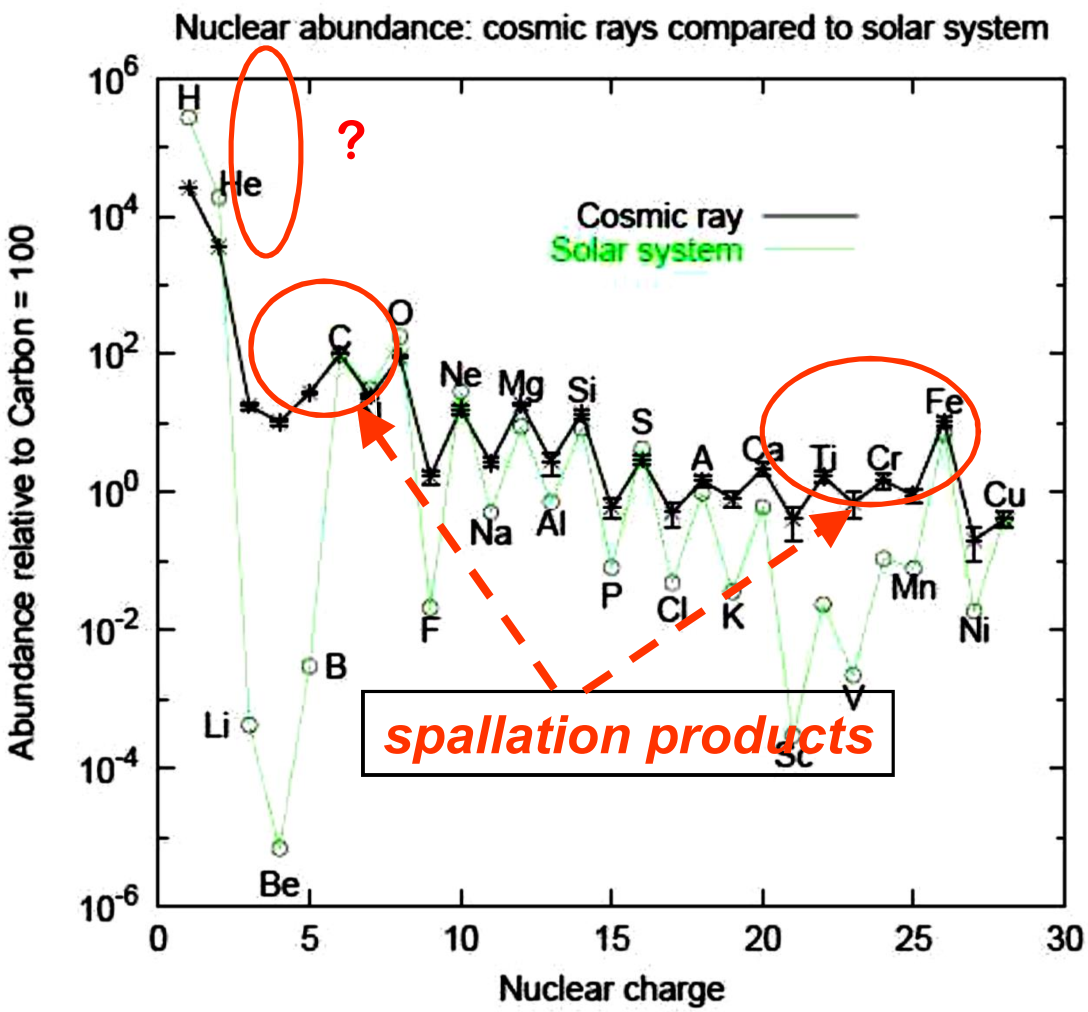


# **GCR near Earth:** Observed Spectra



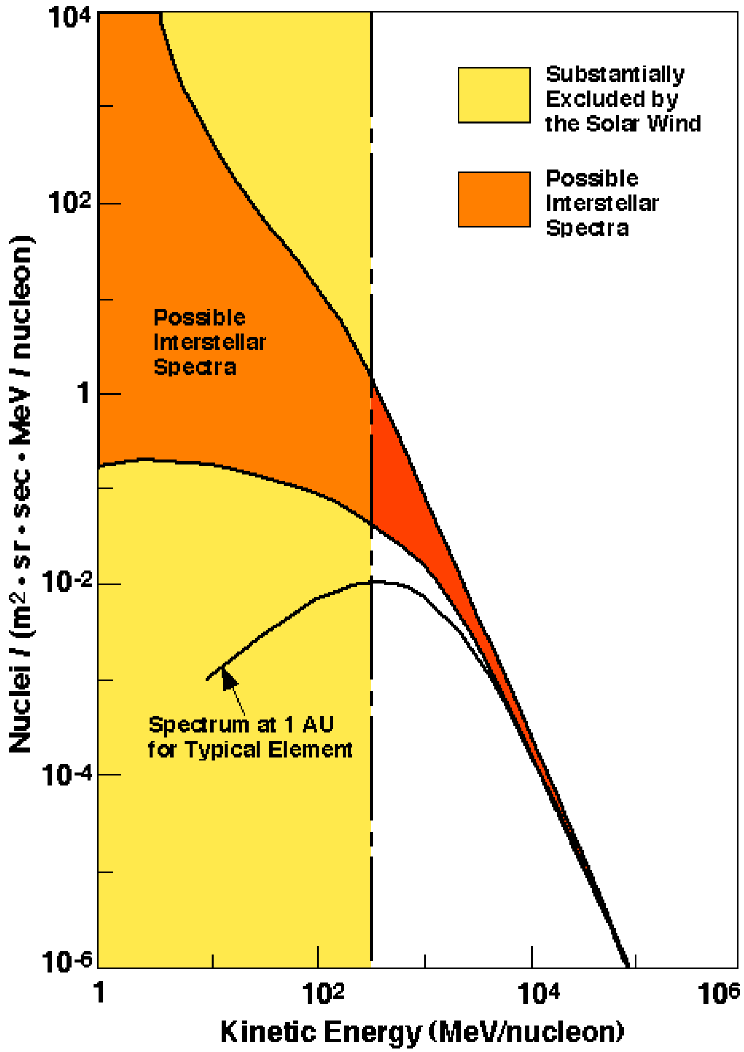

The ubiquitous Zipf-Pareto (power-law) distributions?

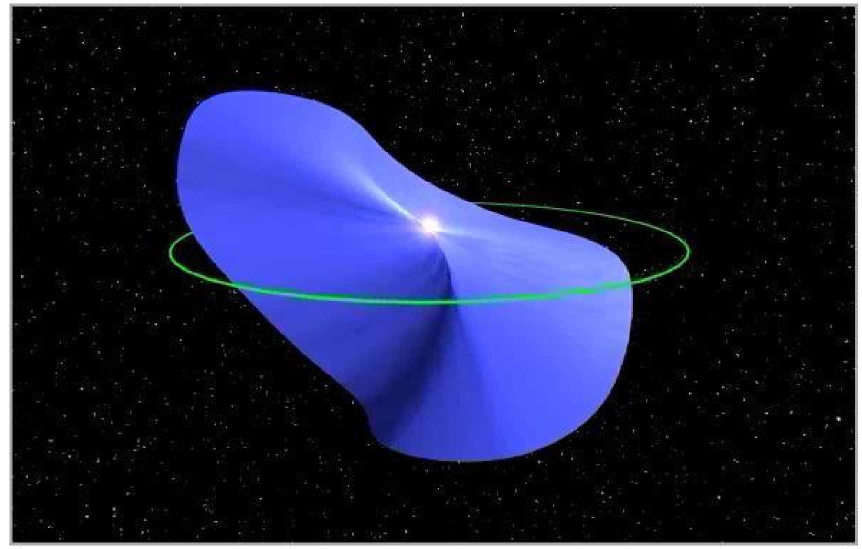
# GCR near Earth: Observed Composition




- GCR composition is altered from their source composition due to propagation in the interstellar medium (ISM)
- Mostly spallation reactions with the ISM's protons producing secondaries like the light nuclei Li, Be, and B, and sub-Fe group
- These tell us much about the time GCRs spend and amount of matter they meet in the galaxy since their synthesis and acceleration at their source(s)

# **GCR near Earth:** Modulation by the Sun

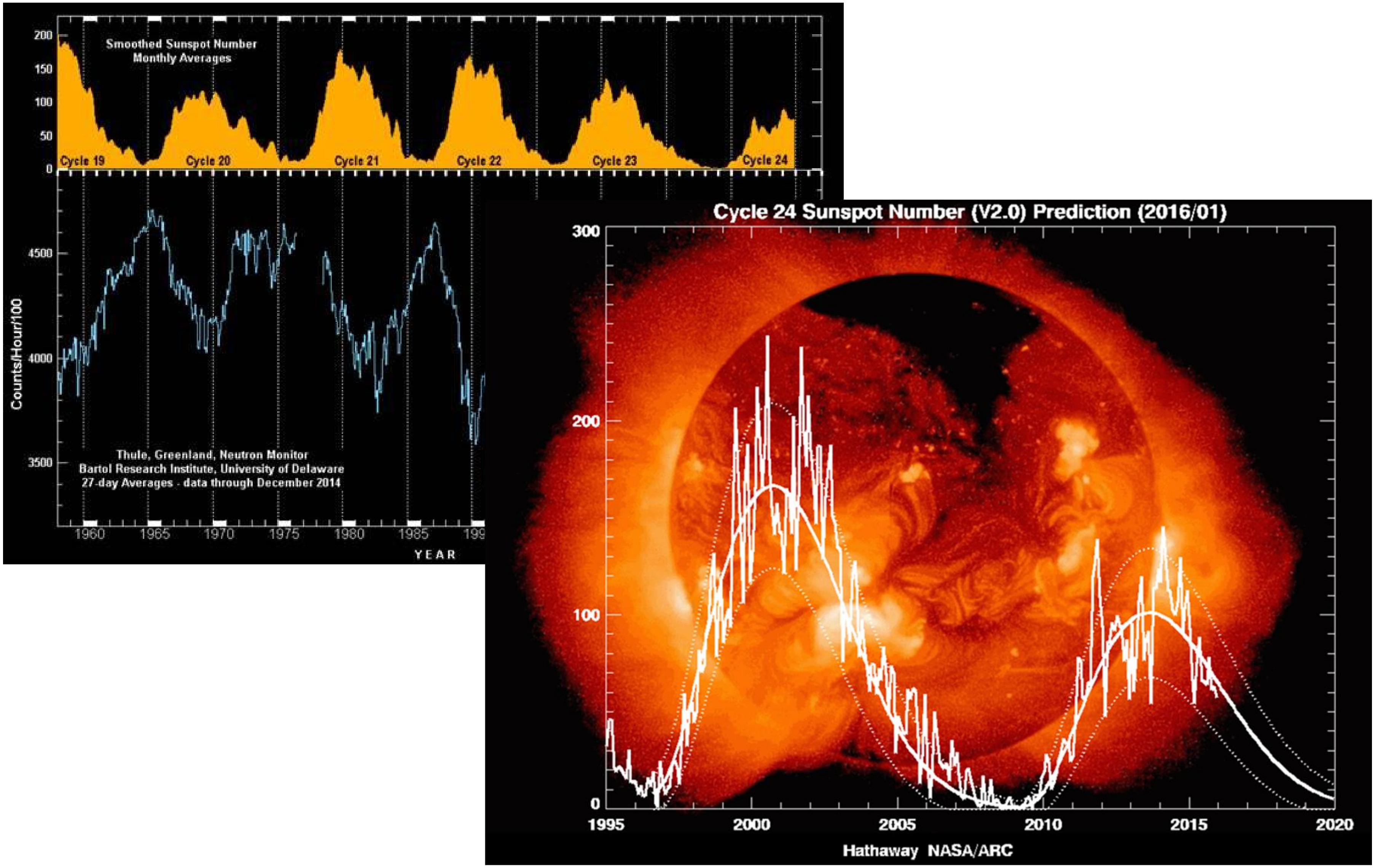


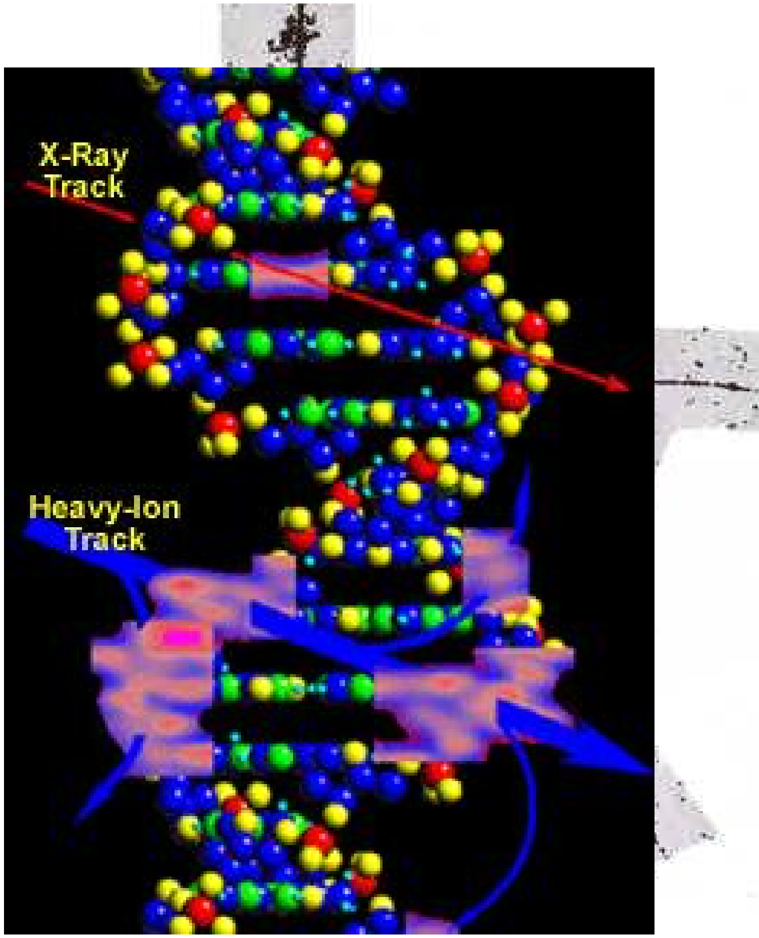
Heliospheric magnetic field is altered significantly between quiet Sun (Solar minimum) and active Sun (Solar maximum) conditions

Simplified models can capture this variation with a single ómodulation parameterô

# **GCR near Earth**: Solar Cycle Dependence



# **GCR near Earth:** Interactions




# **Typical Expected Dose levels:** Lunar Surface Mission

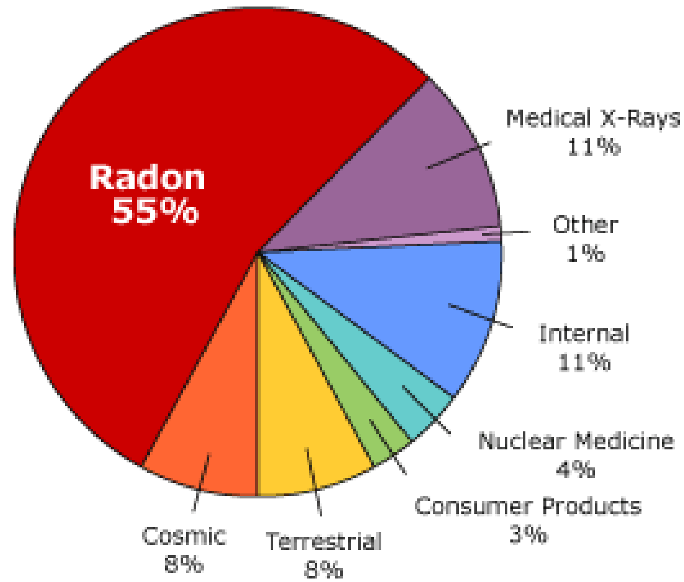
TABLE I: 1999 NCRP-recommended dose limits by organ and exposure duration.

| Limit (cSv) | Bone Morrow | Eye | Skin |
|---|---|---|---|
| 30-day Exposure | 25 | 100 | 150 |
| Annual | 50 | 200 | 300 |
| Career | 50-300 | 400 | 600 |

TABLE II: Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

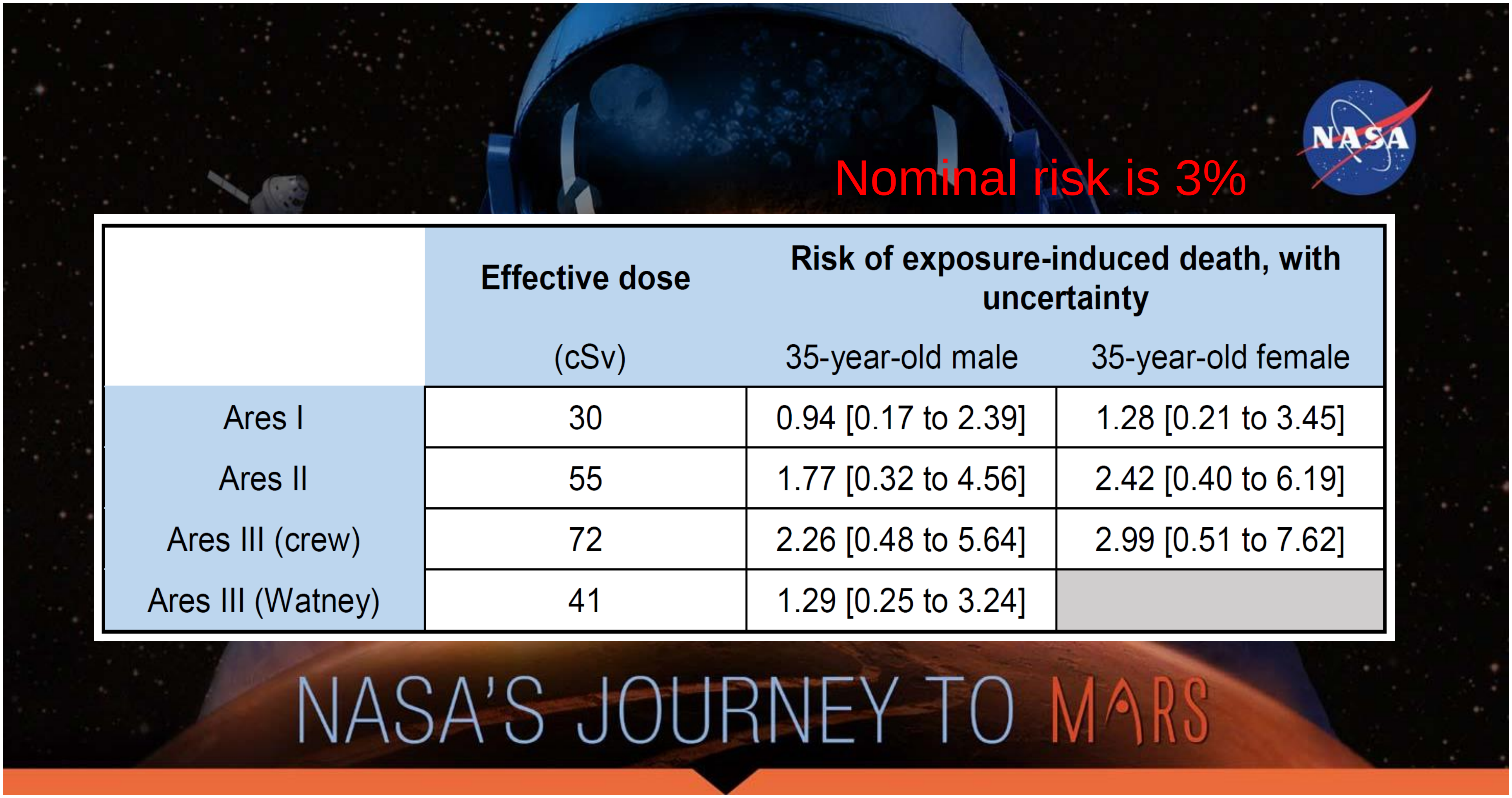
| Duration (days) | GCR (cSv) | SEP (cSv) | Mission (cSv) |
|---|---|---|---|
| 10 | 0.3/0.8 | 7.5/20.5 | 7.8/21.3 |
| 30 | 1.0/2.5 | 7.5/20.5 | 8.5/23.0 |
| 180 | 6.0/15.0 | 7.5/20.5 | 13.5/35.5 |
| 360 | 12.0/30.0 | 7.5/20.5 | 19.5/50.5 |

Surface expected levels vs. recommended limits




Distribution of terrestrial exposure of few cSv/yr

# **Typical Expected Dose levels:** Mars Mission




Nominal risk is 3%

| | Effective dose (cSv) | Risk of exposure-induced death, with uncertainty 35-year-old male | 35-year-old female |
|---|---|---|---|
| Ares I | 30 | 0.94 [0.17 to 2.39] | 1.28 [0.21 to 3.45] |
| Ares II | 55 | 1.77 [0.32 to 4.56] | 2.42 [0.40 to 6.19] |
| Ares III (crew) | 72 | 2.26 [0.48 to 5.64] | 2.99 [0.51 to 7.62] |
| Ares III (Watney) | 41 | 1.29 [0.25 to 3.24] | |

From: ñThe Radiation Threat to ôthe martianöõ, by R. Turner; http://www.anser.org/docs/The_Radiation_Threat_to_the_Martian.pdf

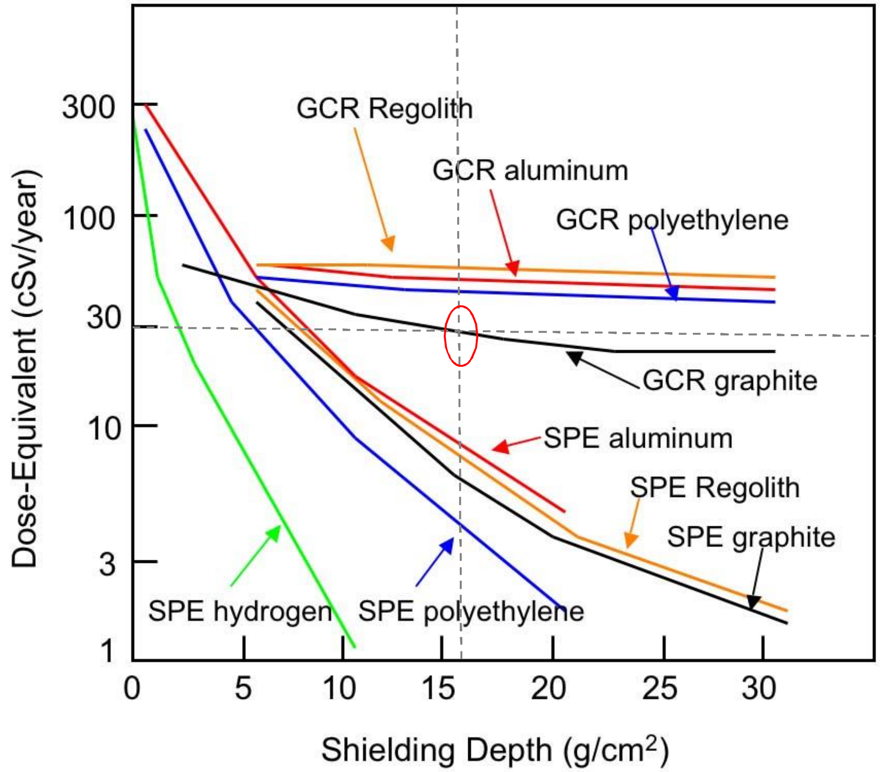
# **Shielding Effectiveness:** How good?, how certain?

Materials vary in their ability to shield against GCR nuclei

**Polymeric based materials tend to be most effective** - but their structural and safety properties remain poor or poorly known

**Aluminum**, like all metals, is **a poor GCR shield**

**Regolith** is not that much better either!




Recall, $1^2 + 1^2 + 1^2 + . . . +1^2$ (26 times) is << $26^2$

# A Physicist's View of Basic Processes


**Particles** & **Fields**

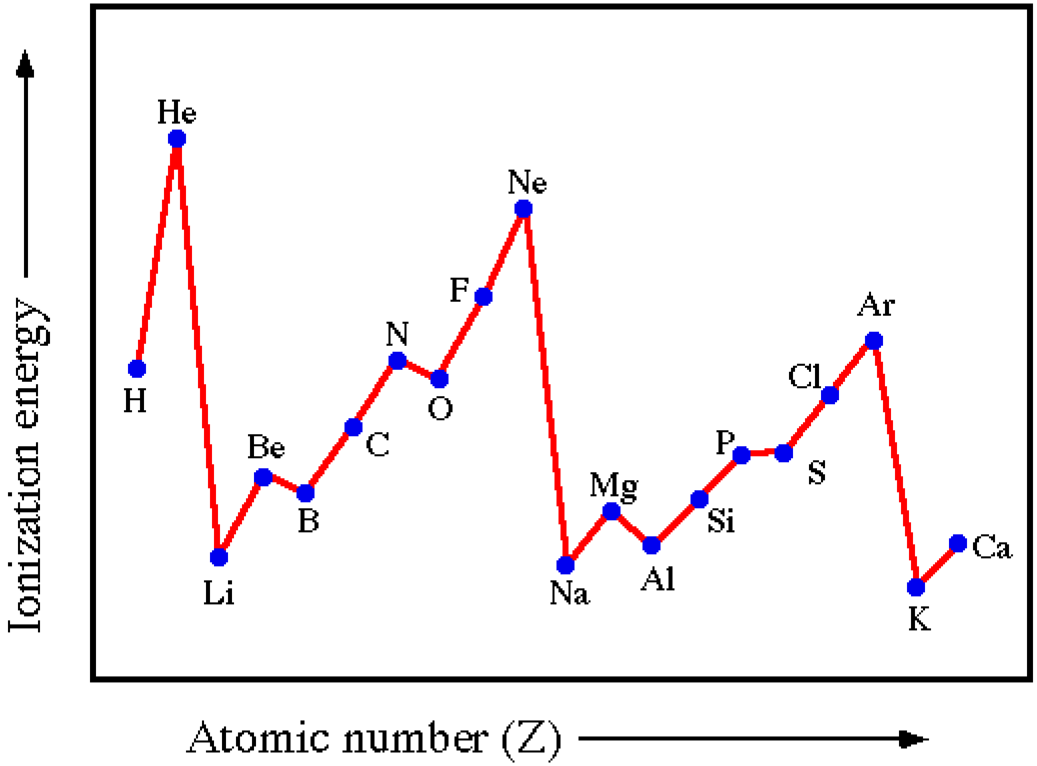
*plus*é some (or sum, óΣô) rules!

# A Glimpse of Cosmic Rays Astrophysics

Origin of cosmic rays:

supernovae remnants & ISM matter

explosive nucleosynthesis:

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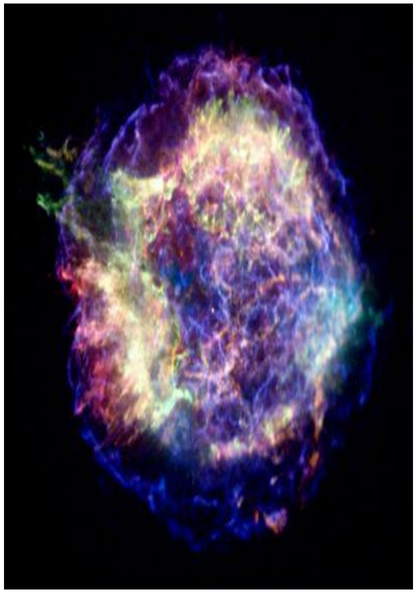


tions;

Modulation of cosmic rays:

cyclic (dynamically coupled to the heliosphere);

minor energy loss

SCO OB2

# A Glimpse of Cosmic Rays Astrophysics

## Theoretical Framework

Ginzburg-Syrovatskii Equation:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial \ell n(p)} + Q$$

-This equation is the basis of most theoretical/computational work on cosmic rays transport and acceleration

-It is a statistical (kinetic) description for isotropic distribution functions

-It applies to energetic particles whenever their speed >> Alfvén speed, if scattering (diffusion) is faster than macroscopic timecales

-Usual Without a theory the facts are silent. *-F.A. Hayek* d plasmas

# GCR Acceleration

Fermi Second-Order Acceleration Mechanism

[E. Fermi, ñOn the Origin of the Cosmic Radiation,ò Phys. Rev. 75, 1169 (1949)]

Collisions between an already energetic particle and a moving, massive cloud will on average result in an increase in the particleôs energy according to:

$$\frac{\langle \Delta E \rangle}{E} \propto \left(\frac{V}{c}\right)^2 \Longrightarrow$$

$$\frac{dE}{dt} = rE \Longrightarrow$$

$$f(E) \propto E^{-\eta}; \quad \eta = 1 + (r\tau)^{-1}$$

Problem is that the rate of energy increase is too small!

The great tragedy of science is the slaying of an elegant theory by ugly facts. *-Thomas Huxley*

# GCR Acceleration

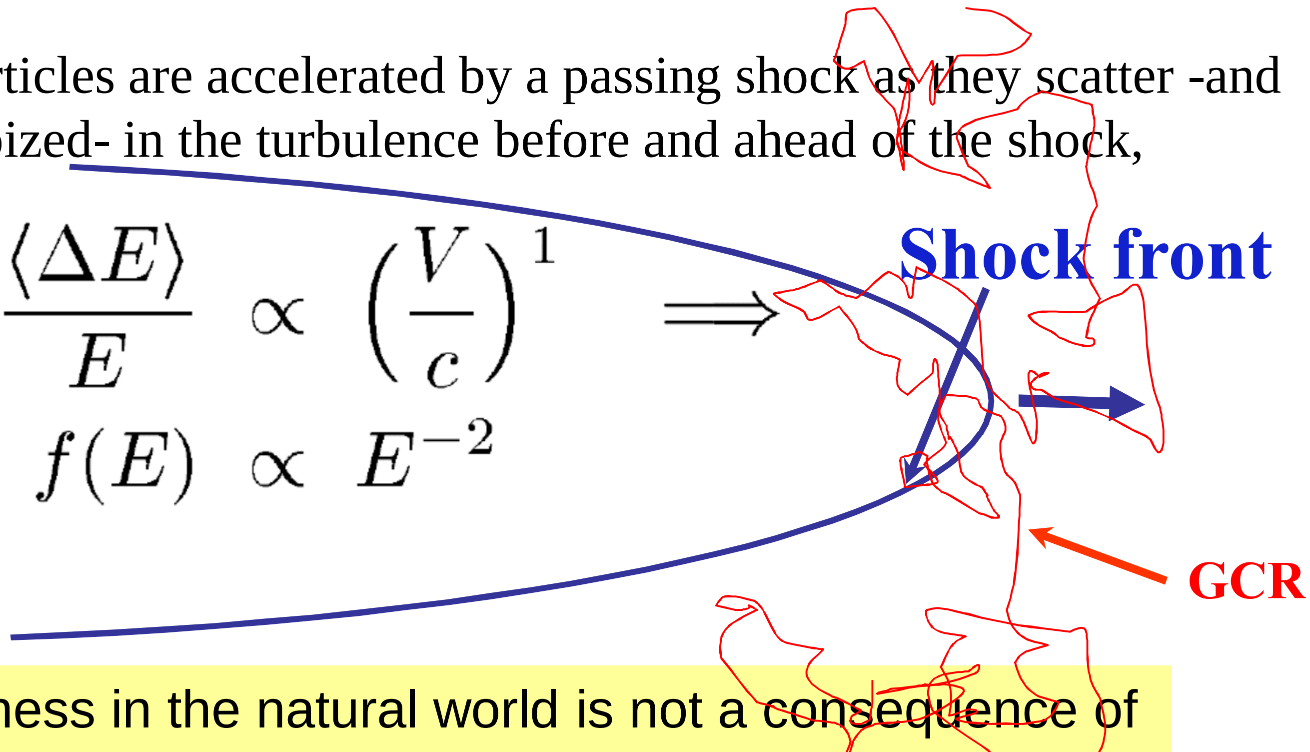
Fermi First-Order Acceleration Mechanism

[E. Fermi, ñGalactic Magnetic Fields and the Origin of Cosmic Radiation,ò Astrophys. J. 119, 1 (1954)]

Energetic particles are accelerated by a passing shock as they scatter -and get isotropized- in the turbulence before and ahead of the shock,

$$\frac{\langle \Delta E \rangle}{E} \propto \left(\frac{V}{c}\right)^1 \Longrightarrow$$

$$f(E) \propto E^{-2}$$




All the richness in the natural world is not a consequence of complex laws, but arises from the repeated applications of simple laws. *-L.P. Kadanoff*

# GCR Acceleration

Diffusive shock acceleration (DSA) theory:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[\kappa(x,p)\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{\partial u}{\partial x}p\frac{\partial f}{\partial p}$$

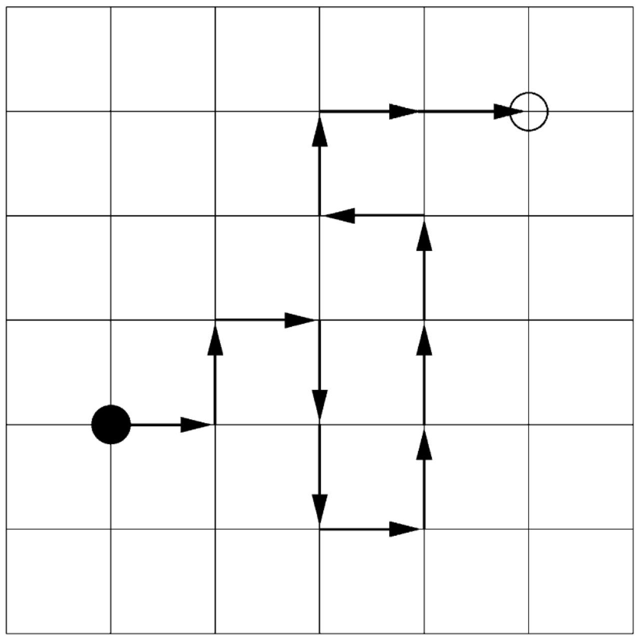
$$f(p,t)\Big|_{x=o} \propto \left(\frac{p}{p_o}\right)^{-q} \cdot \int_o^t \psi(t',p,p_o)Q(p_o,t-t')dt'$$

$$\langle t\rangle = \int_o^\infty t\phi(t)dt \ ; \ \frac{\sigma^2(t)}{\langle t\rangle^2} \sim \alpha \ ; \ \kappa \propto p^\alpha$$

Only for $\alpha \approx 0$ is the accel.-time PDF sharp ;
$\alpha$ is typically 1/4 to 1/2 !

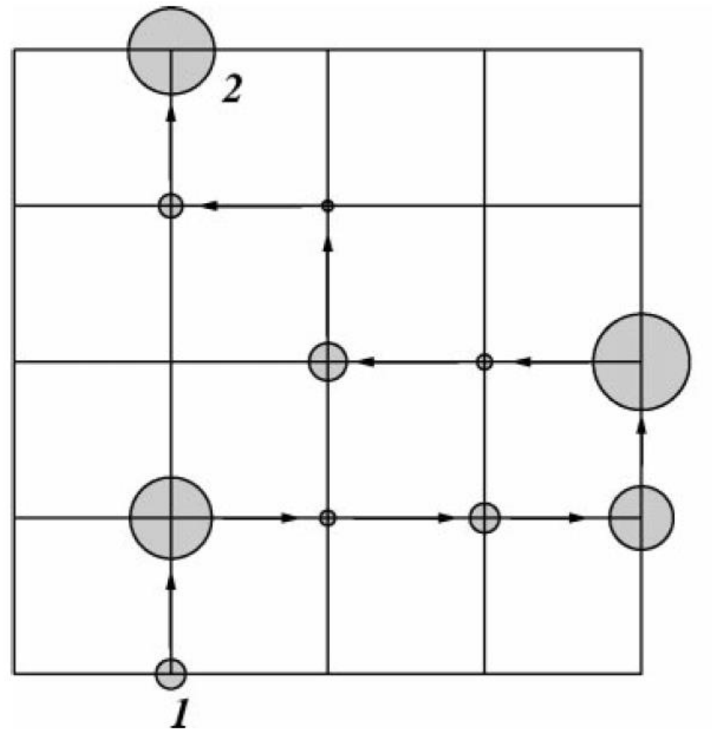
DSA: No characteristic acceleration time!

# Anomalous Transport [?]



**Brownian Motion in 2D**

Gaussian statistics;
central limit theorem;
well-behaved PDFs




**Continuous Time Random Walk**

Non-Gaussian statistics;
generalized transport equation;
fractional derivatives;
PDFs with long (algebraic) tails!

From Metzler & Klafter, *Physics Reports* **339** (2000)

# Space Radiation at Marshall

- Monitoring & Detection

  charged particles;

  neutrons

- Forecasting

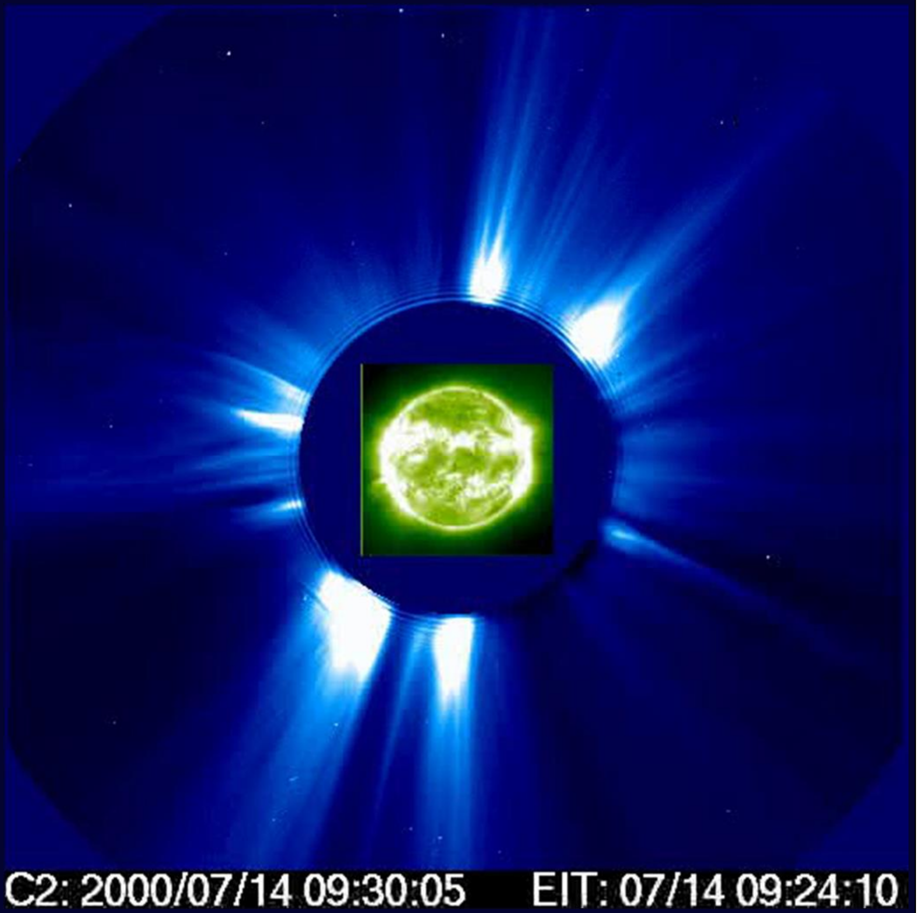
  flares; CMEs

- Modeling & Simulation

  propagation; effects; risk

- Radiation-Smart Structures

  Solutions




***Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event***

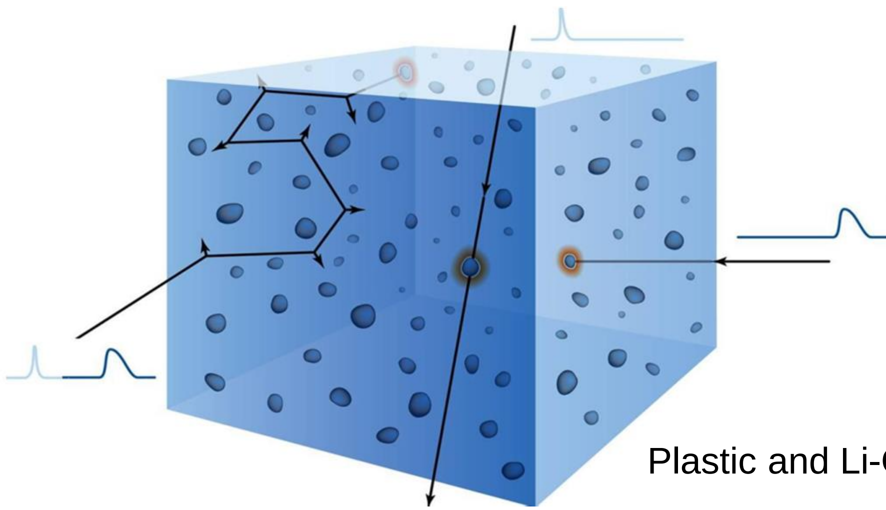
# **Space Radiation:** Monitoring & Detection

**Advanced Neutron Spectrometer (ANS):** is a new instrument technique being developed to meet NASAȸ requirements to monitor the radiation exposure due to secondary neutrons for future crewed missions:

$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$
$Q = 4.78$

$n + Gd \rightarrow Gd^{*} + \gamma$
$Q = [0,2]$

$n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$
$Q = 2.73$ (93%)
or 2.25 (7%)

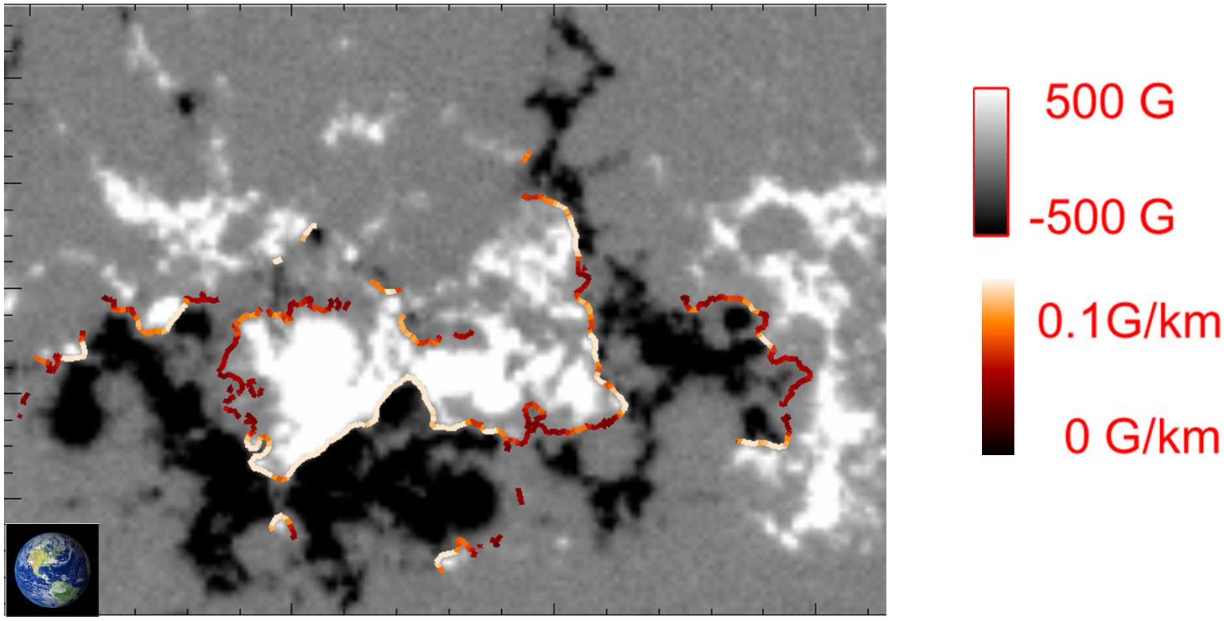


Plastic and Li-Gd-B scintillator

*Planned for an ISS flight demonstration in 2017*

# **Space Radiation:** Forecasting (Mag4)

**Mag4:** Marshall developed an automated prediction system that downloads and analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and then automatically converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events




**A magnetogram of an active region on the Sun**

# **Mag4:** A Comparison of Safe and Not Safe Days

June 26, 2013

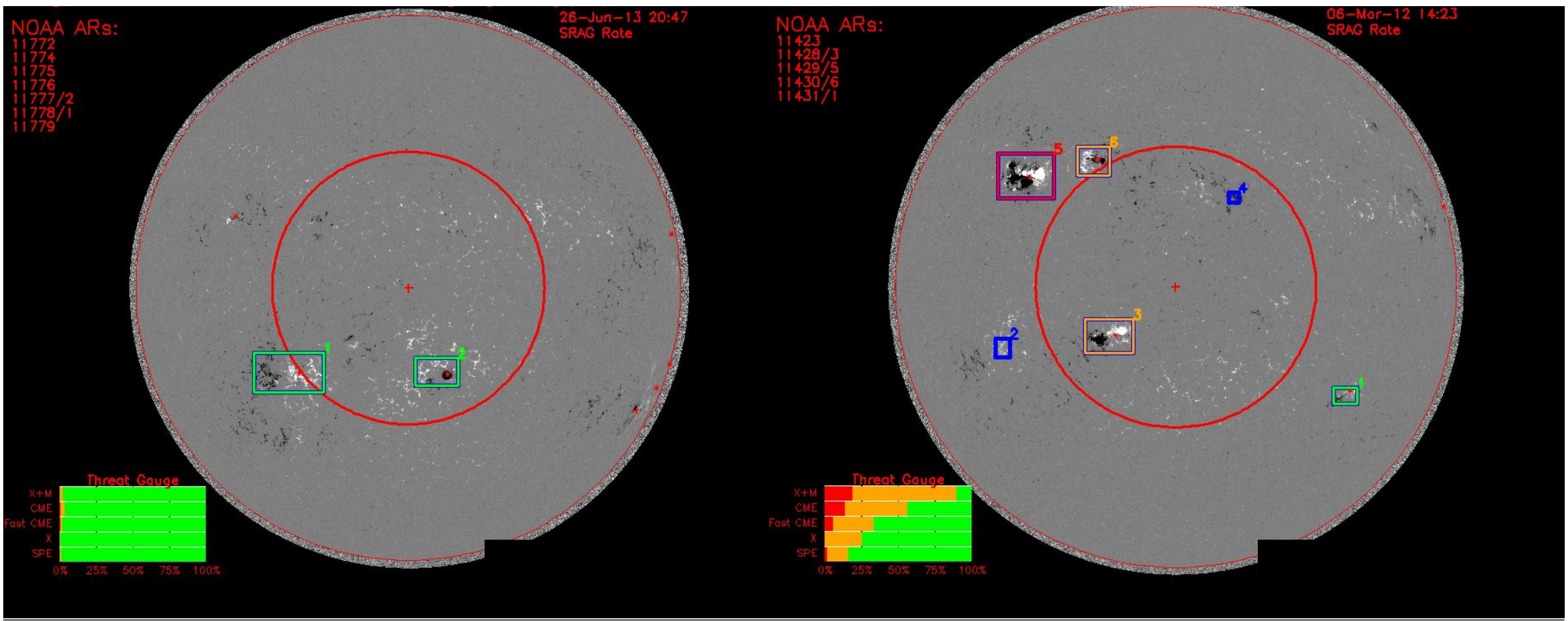
C1, C1.5 flares

March 7, 2012

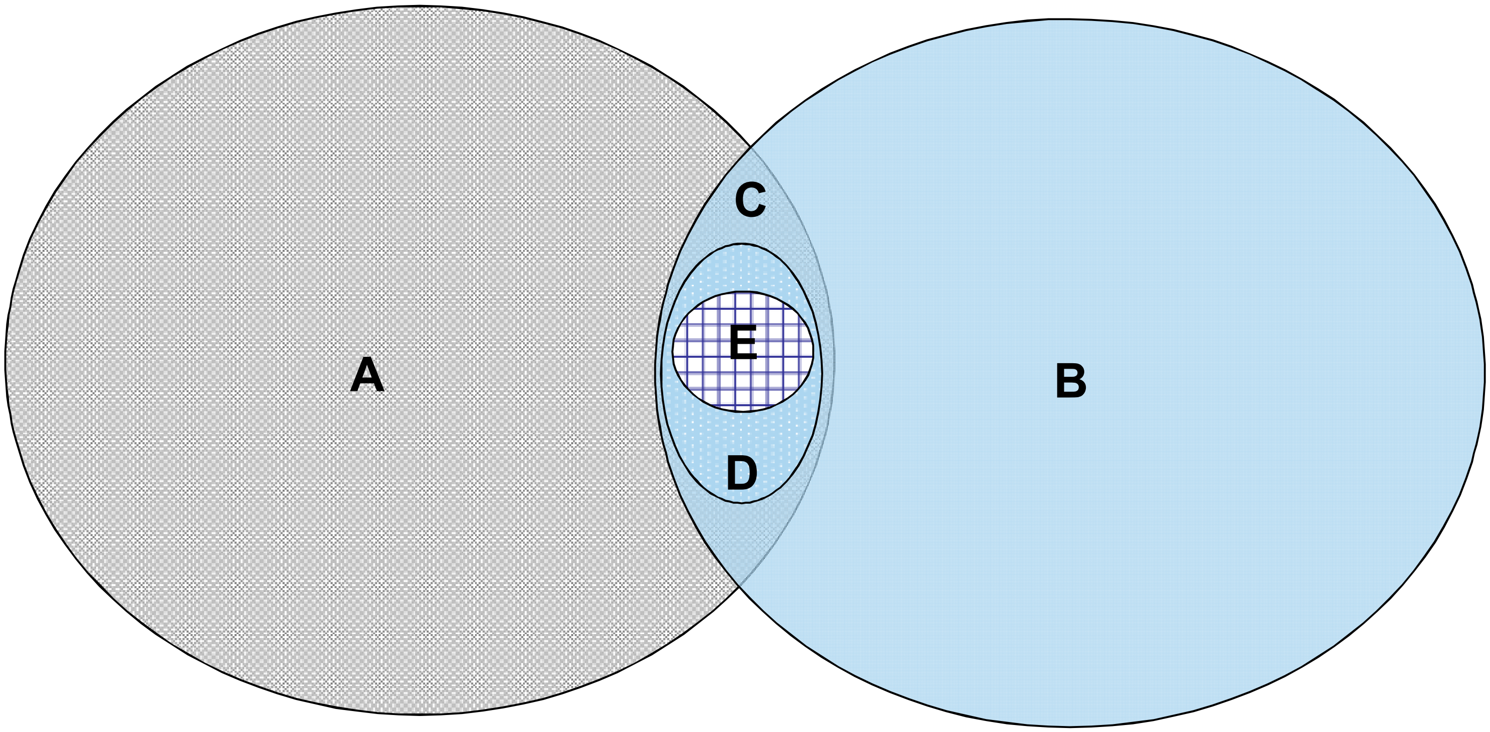
X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches 6530 φarticle flux unitô>10 MeV



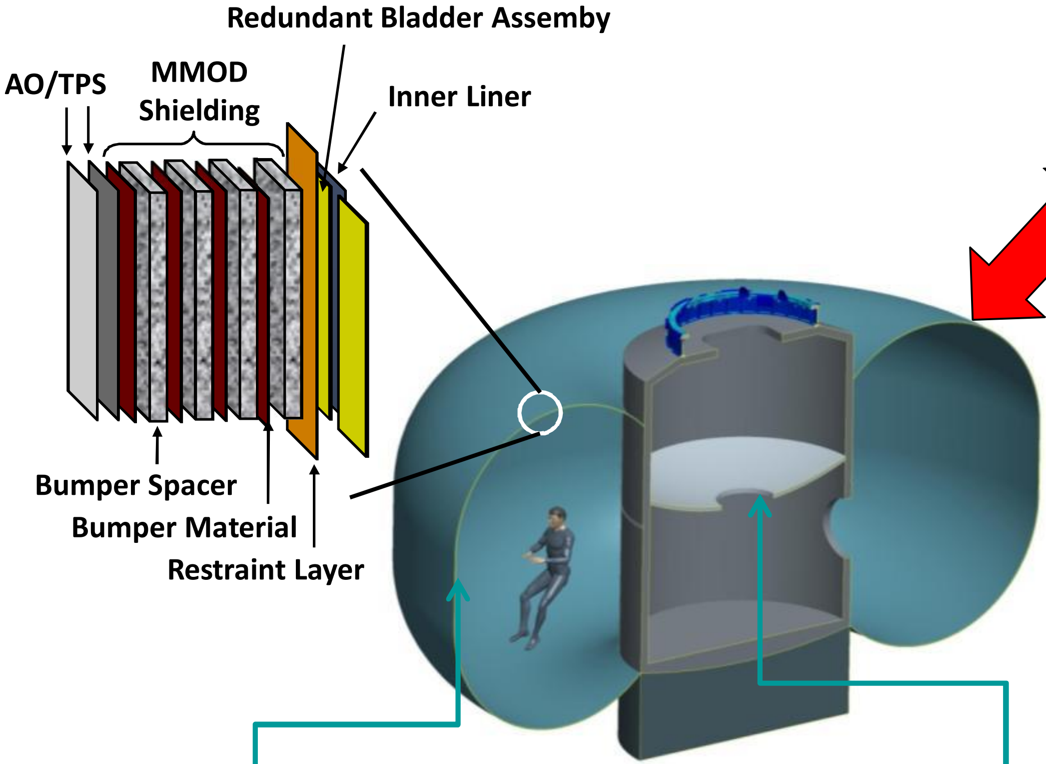
# Radiation-Smart Structures and Designs




**A**: Adaptive Structures
**B**: Sensory Structures
**C**: Controlled Structures
**D**: Active Structures
**E**: Intelligent Structures

# Radiation-Smart Structures and Designs

Smart Materials: Multi-functional




Smart Designs: Optimized

radiation shielding will most likely focus on MMOD shielding materials and core

# Prototyping radiation-smart designs

Å **Contour Crafting**: A new technology developed at the University of Southern California for robotic and autonomous construction; allows for versatile design options & construction materials

Å Space applications focusing on remote lunar base construction, MMOD and radiation protection solutions

Å Terrestrial applications for forward construction capability for military and for rapid, disaster relief efforts (FEMA)

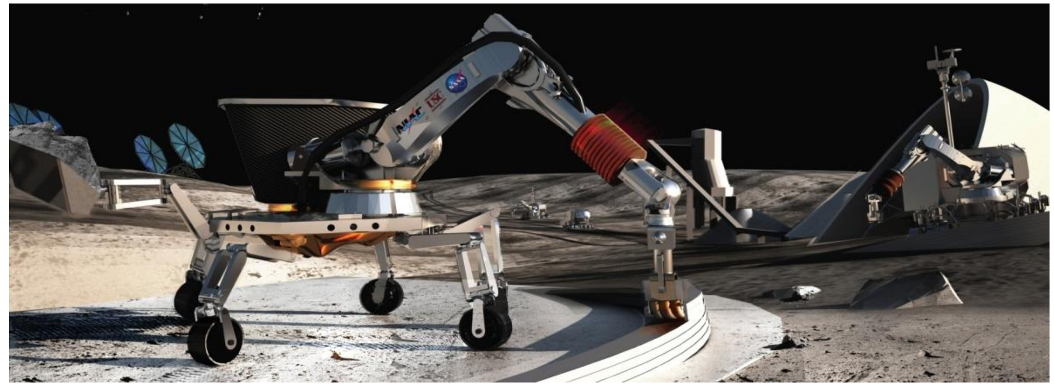
# **Built-In Protection:** (A New Paradigm)

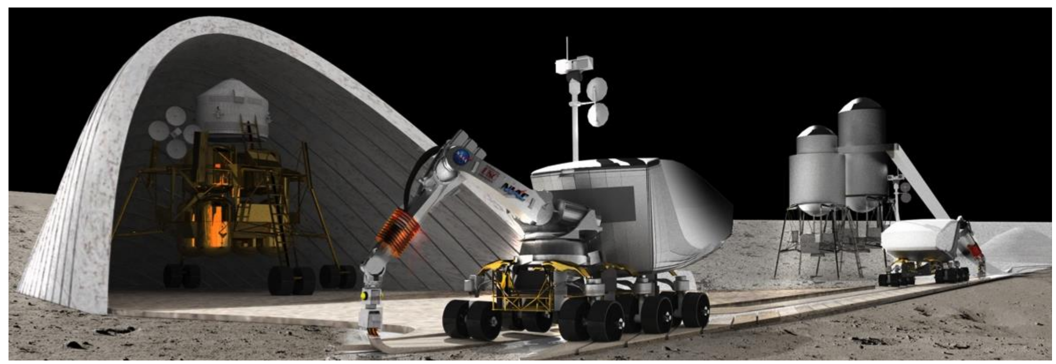
-NASA in collaboration with DoD, academia, and the private sector is embarking on a new and radical way in looking at the challenges and solutions of space-radiation exposure; from the ógroundsô up!

-Marshall is at the heart of this ónew paradigmô shaping

-Space-radiation protection solutions and strategies have evolved on many pathsé

é but they may be converging on a few!





# *Where to go for more info…*

- NASA HQ and centersô websites all have lots of information and leads; for example:
- **http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html**

- University physics, geophysics, astronomyé departments; for example:
- **http://www.srl.caltech.edu/**

- National laboratories; for example:
- **http://www.ngdc.noaa.gov/stp/SOLAR/COSMIC_RAYS/cosmic.html**

- Other space agencies; for example:
- **http://www.esa.int/esaSC/index.html**

- Professional societies for example:
- **http://cosparhq.cnes.fr/**