Cosmic Rays Astrophysics: The Discipline, Its Scope, and Its Applications

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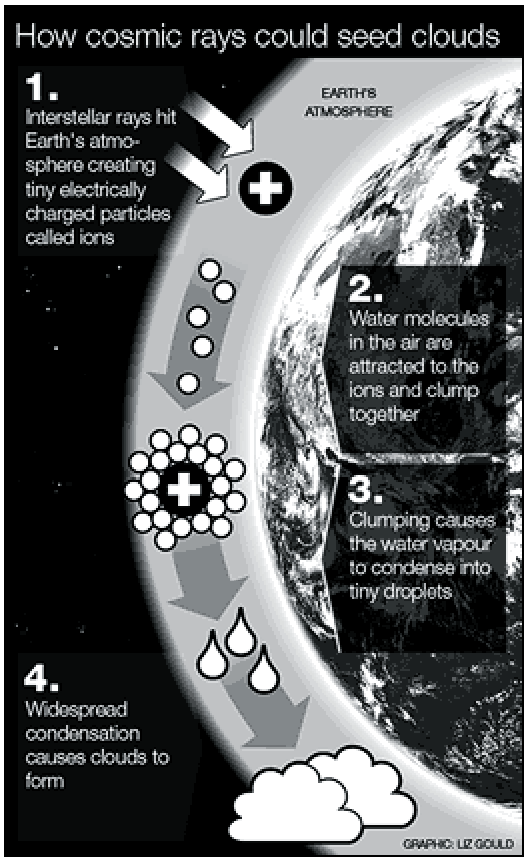
Main Points

- ✓A glimpse of cosmic rays astrophysics – *contexually*
- ✓ Cosmic rays astrophysics and Earth
- ✓Cosmic rays astrophysics and the heliosphere
- ✓ Applications

Motivation?

“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

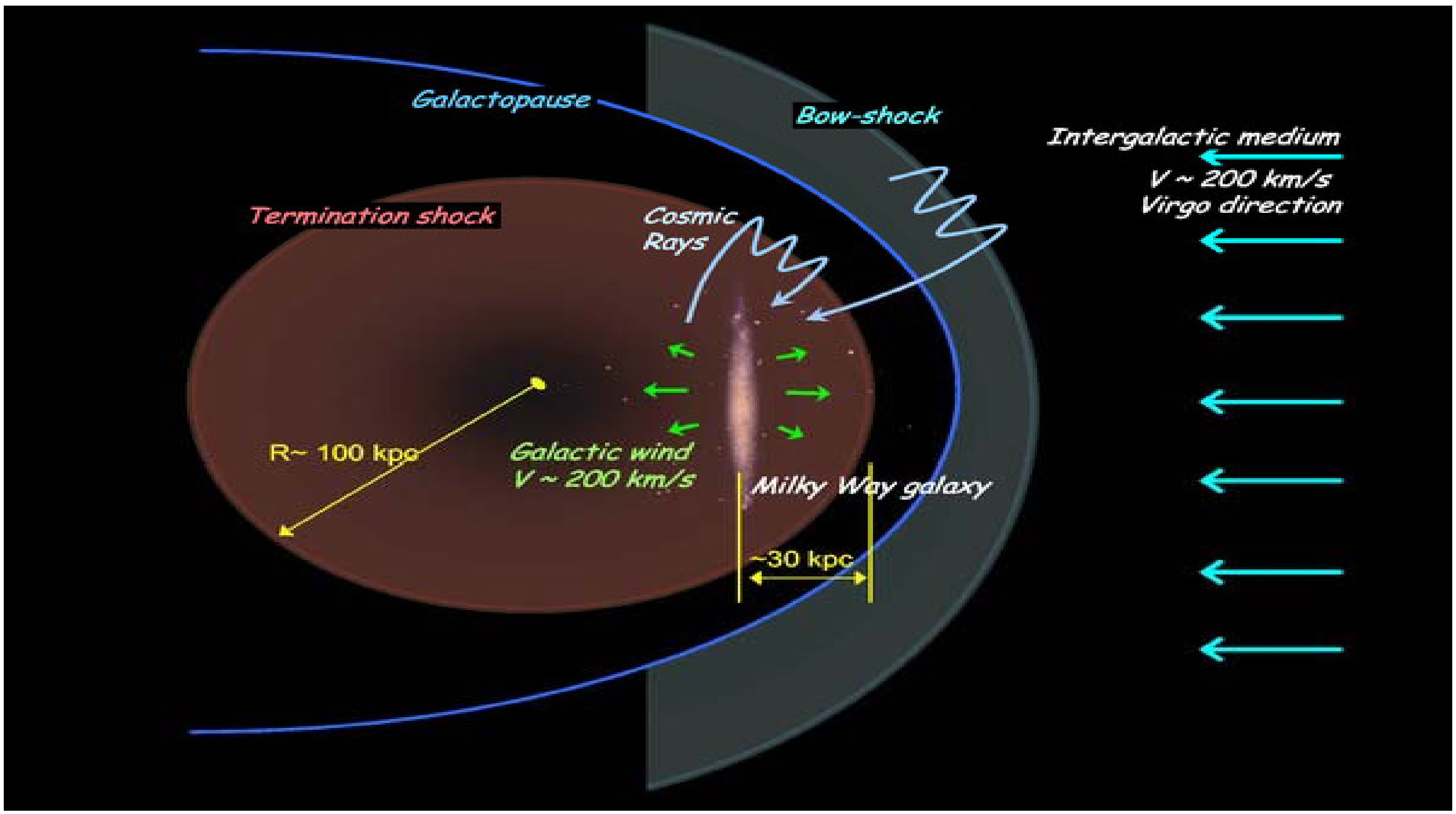
However, this recent conjecture goes farther!

Motivation?

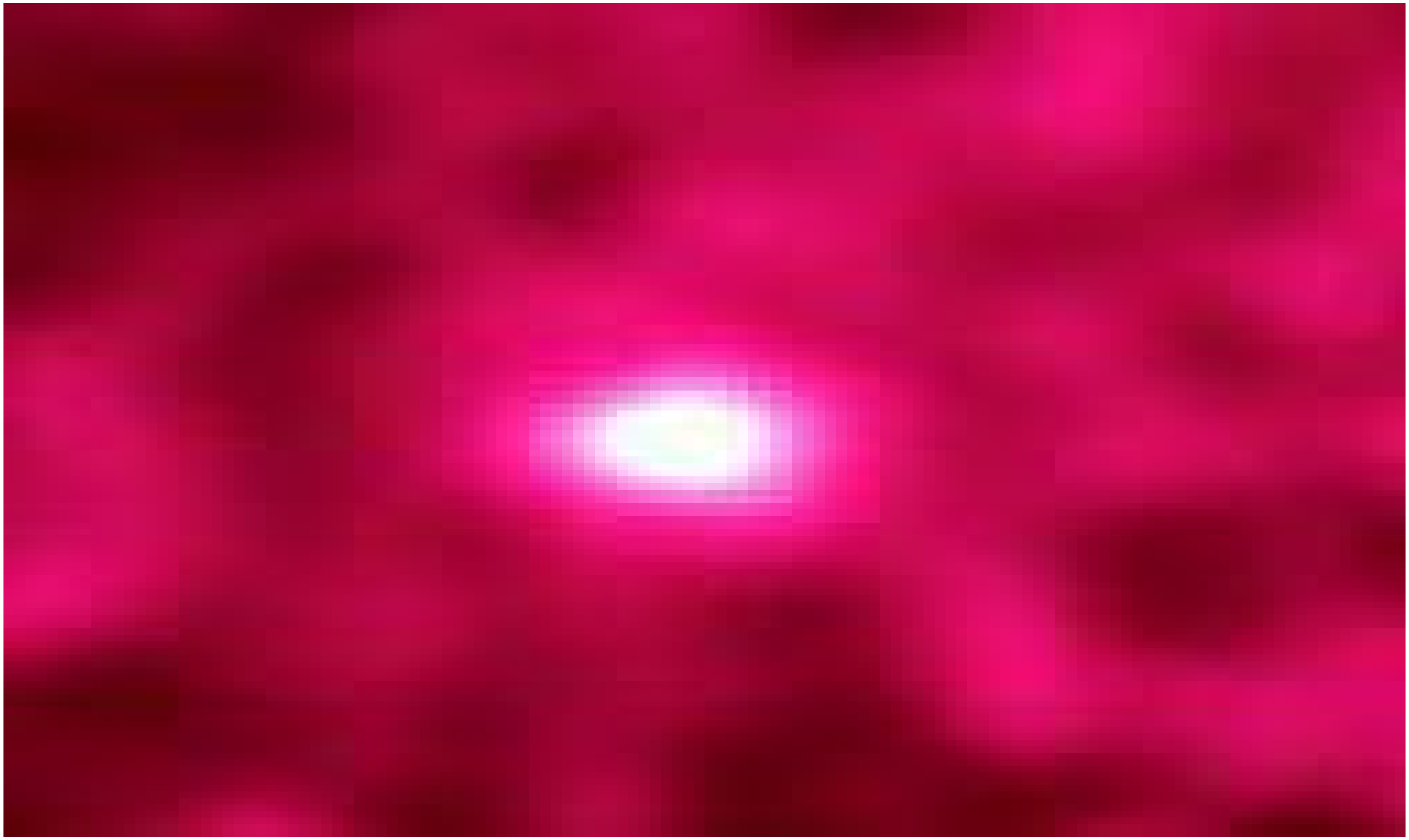
"Varying cosmic-ray flux may explain cycles of biodiversity"

By Bertram Schwarzschild, Physics Today

October 2007



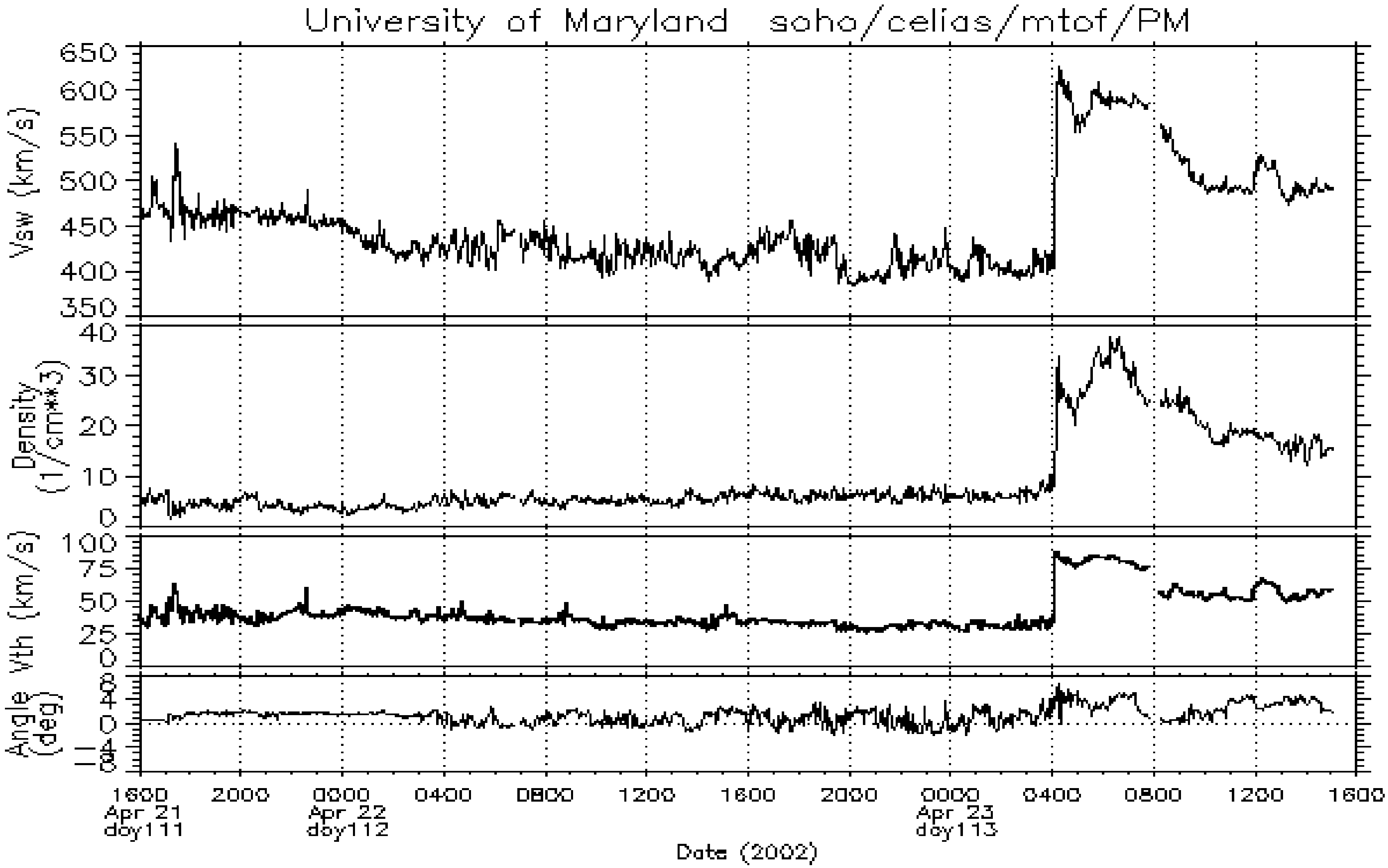
Motivation?



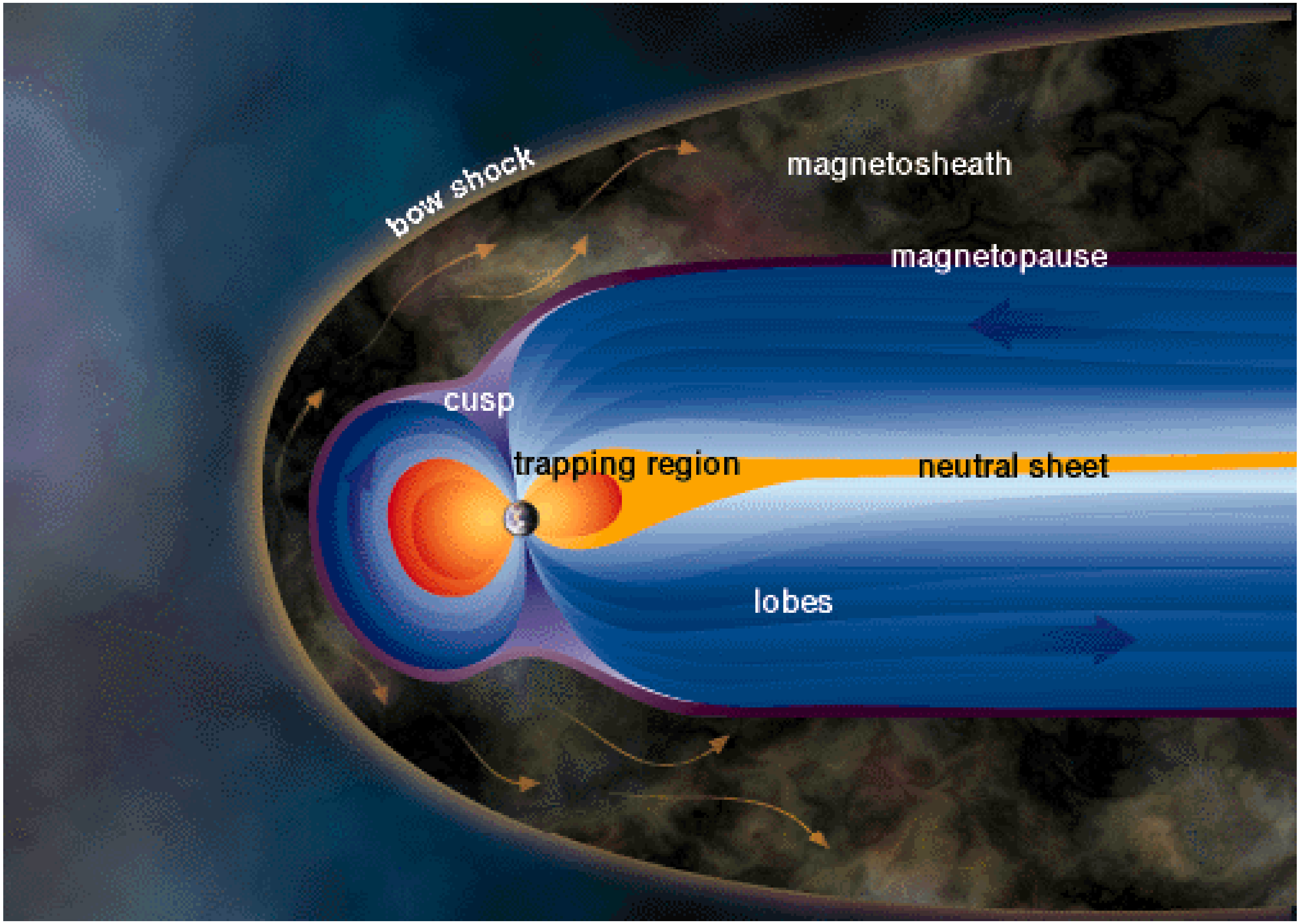
Gamma-ray picture of our moon illuminated by cosmic rays

Particle Environment

Two main sources of ionizing radiation:

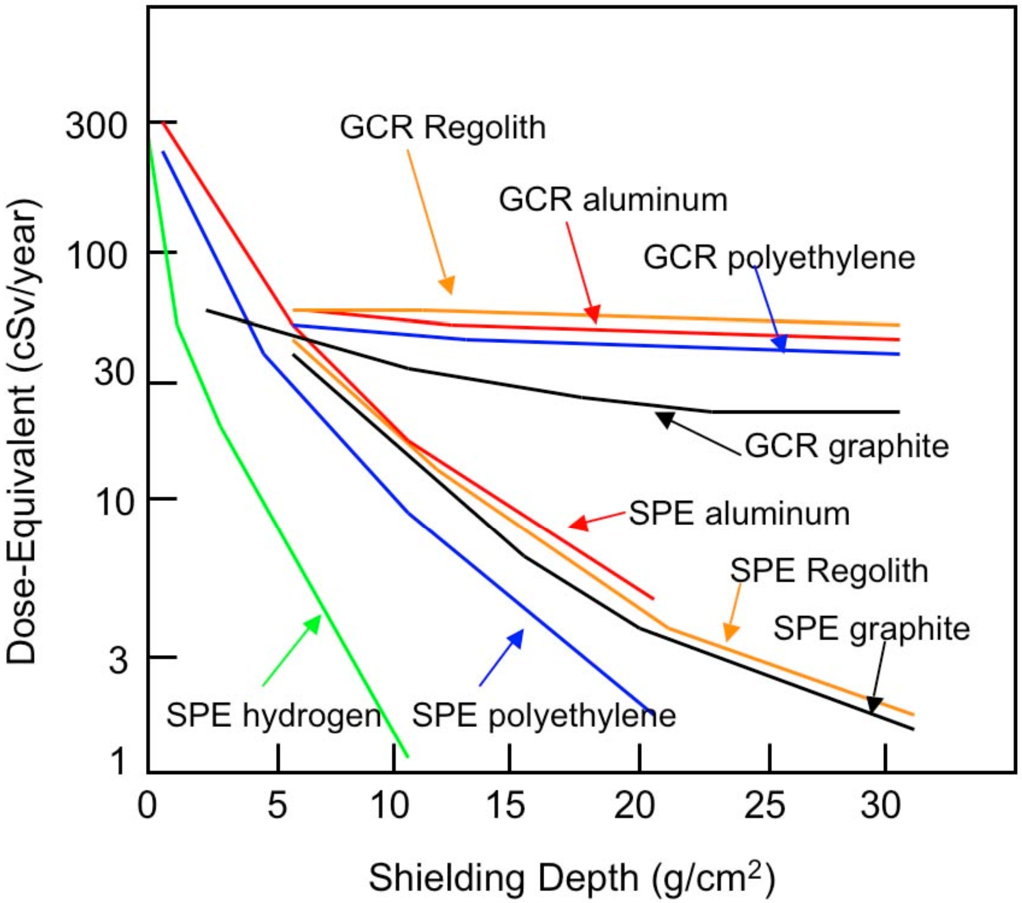


Expected Exposure Levels

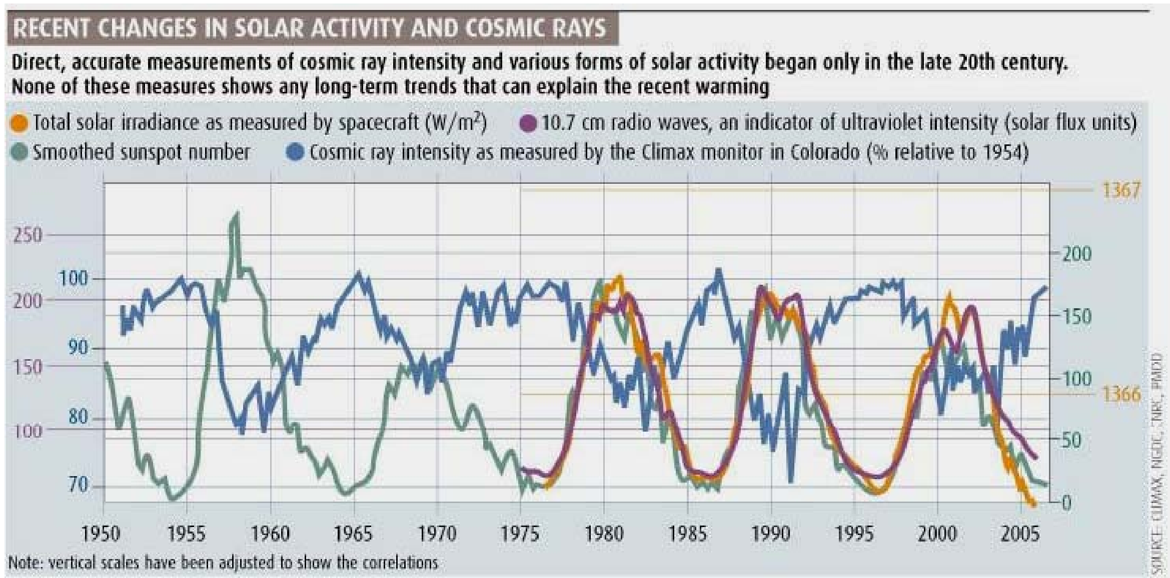


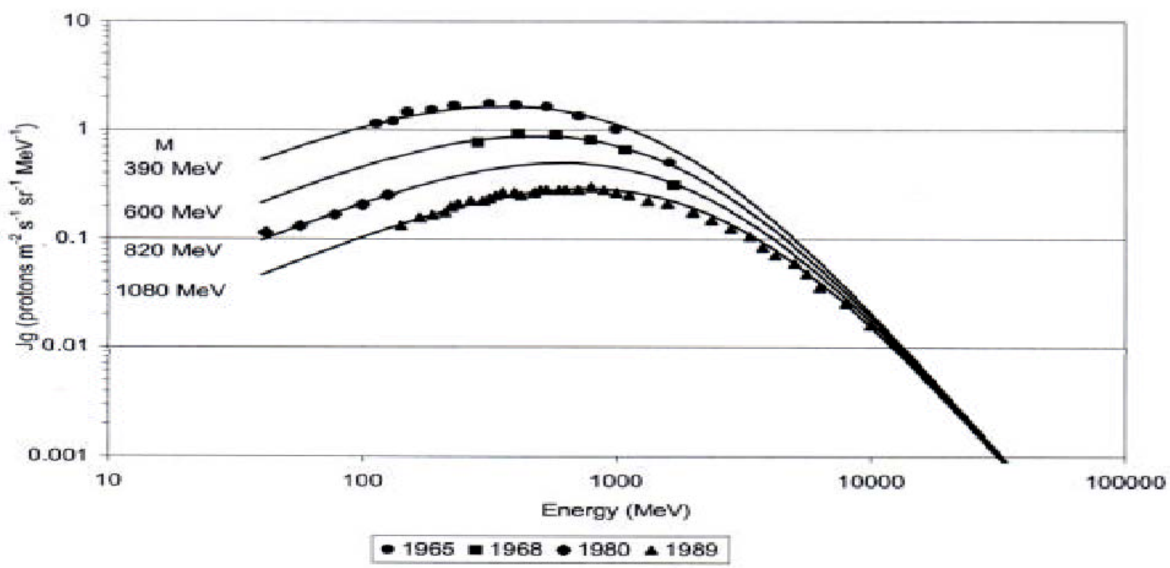
Transport of GCRs and SEPs

-Materials vary in their ability to shield against GCR nuclei
-**Polymeric based materials tend to be most effective** but their structural properties remain poor
-**Aluminum**, like all metals, is **a poor GCR shield**

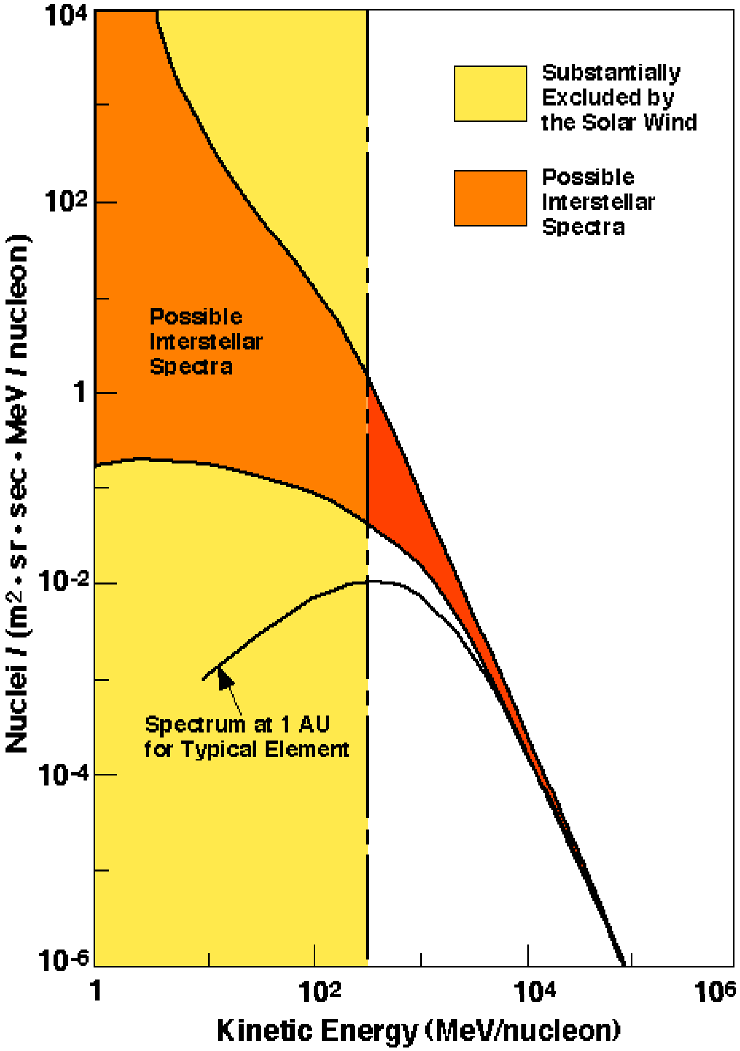


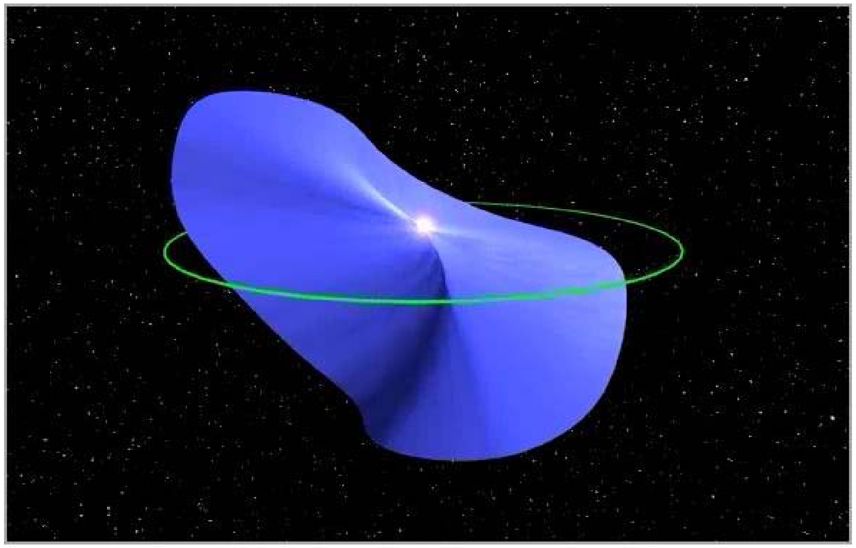
GCR near Earth: Solar Cycle Dependence





GCR near Earth: Modulation by the Sun



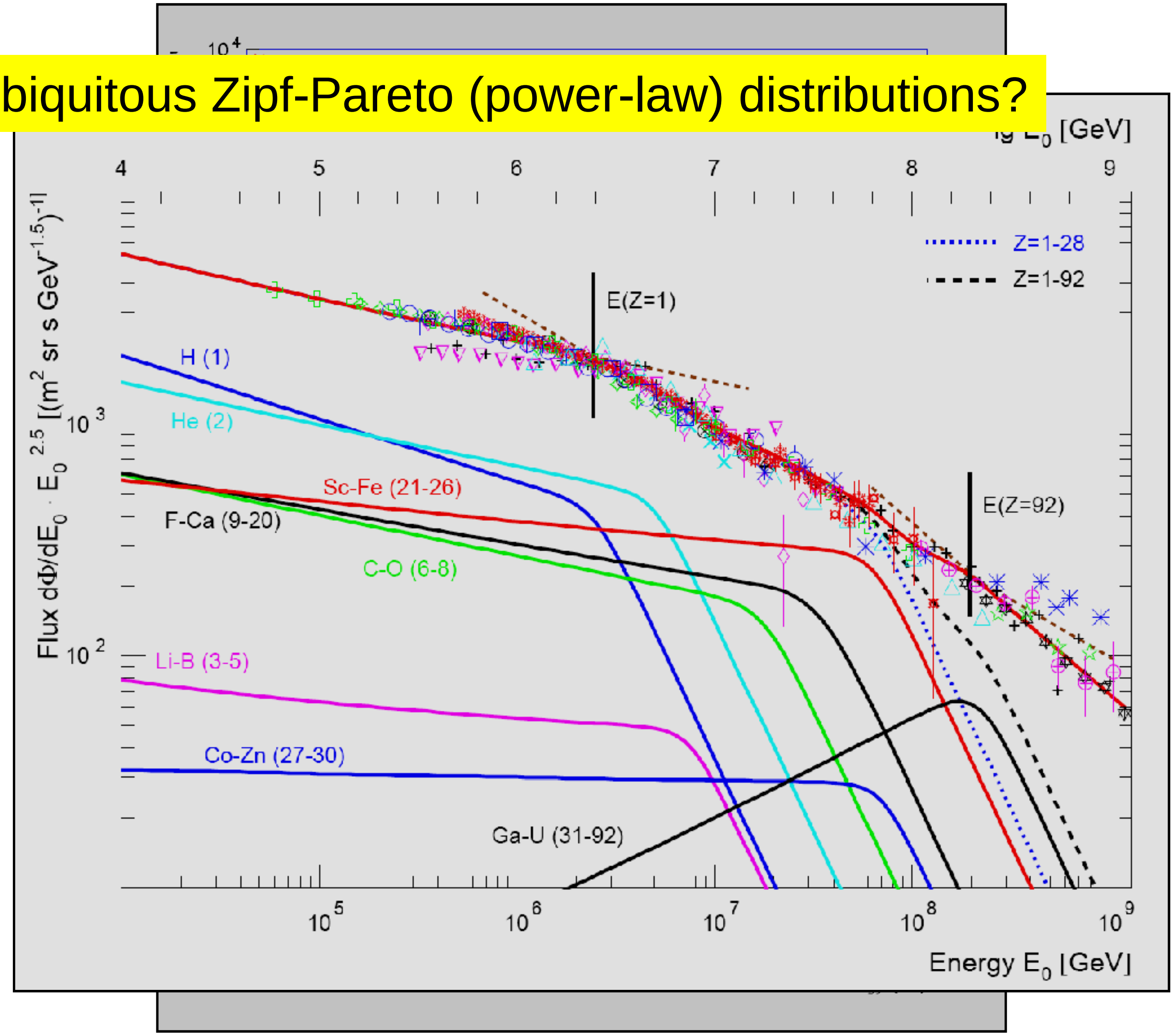


Heliospheric magnetic field is altered significantly between quiet Sun and active Sun conditions

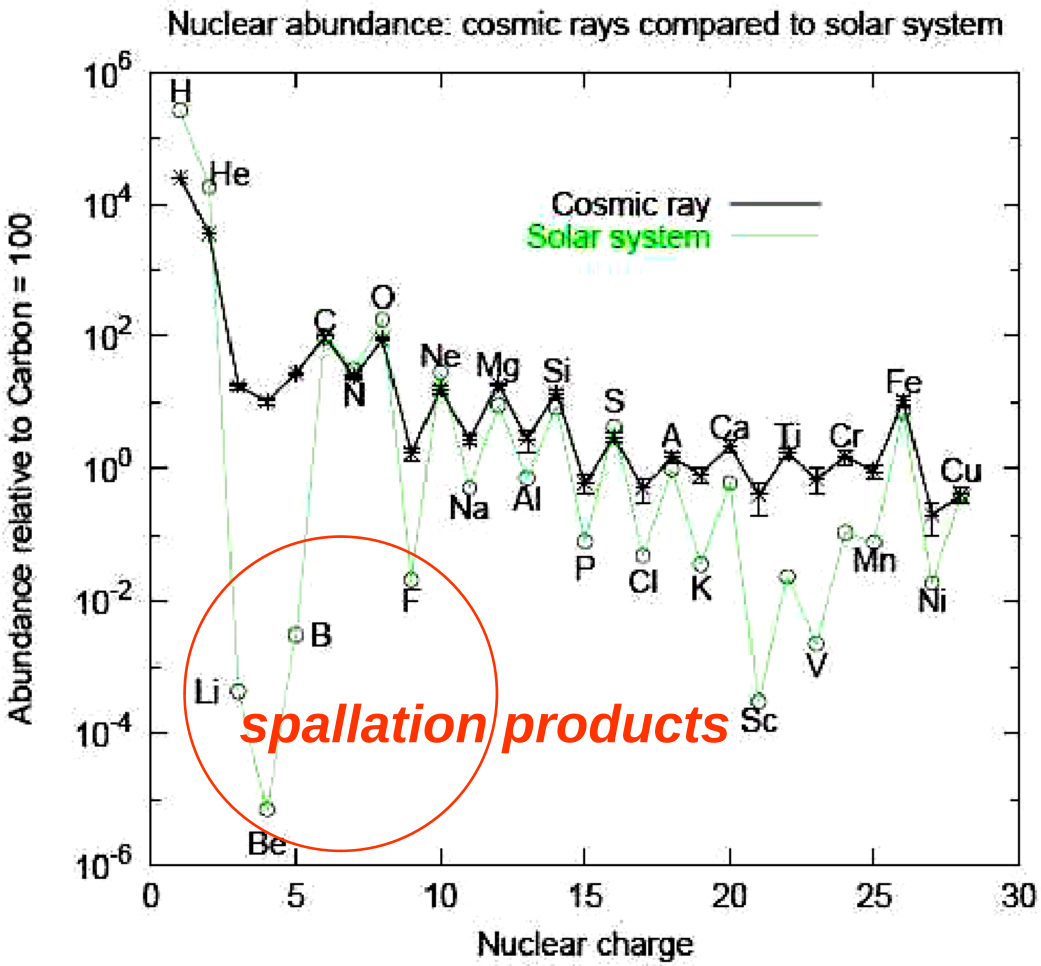
Simplified models can capture this variation with a single 'modulation parameter'

GCR near Earth: Observed Spectra

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



GCR near Earth: Observed Composition

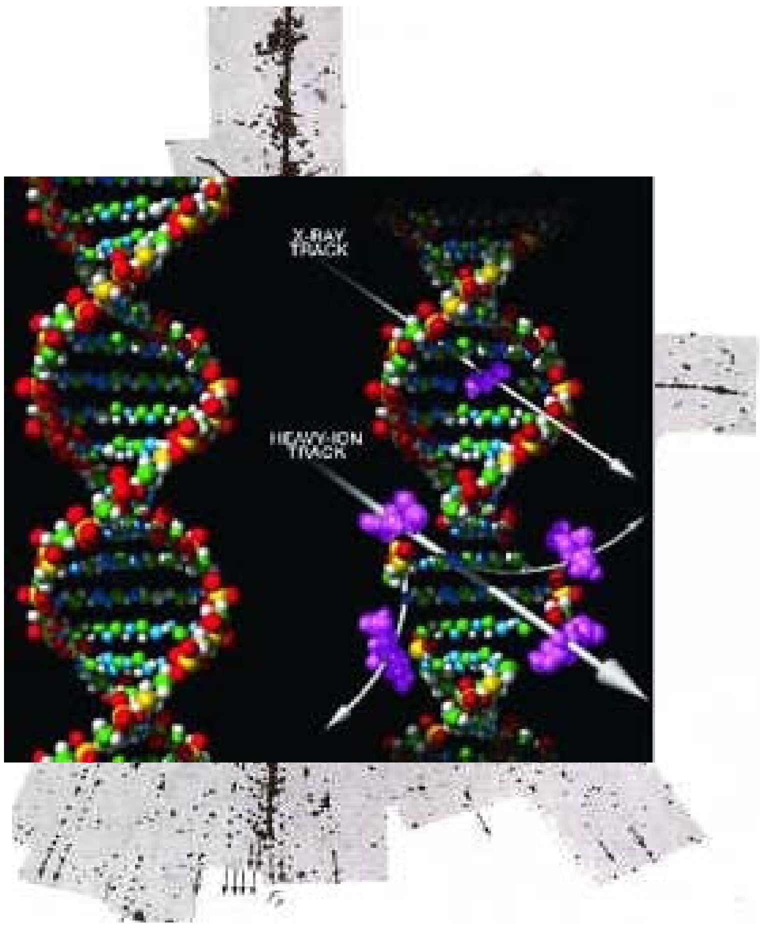


GCR composition is altered from their source composition due to propagation in the interstellar medium (ISM)

Mostly spallation reactions with the ISM's protons producing light secondaries like Li, Be, and B

These tell us much about the time GCRs spend and amount of matter they meet in the galaxy since their synthesis

GCR near Earth: Interactions



A Very Brief History of Cosmic Rays

1912 Victor Hess discovers “extra-terrestrial radiation”

1930s-1940s Discovery of protons; secondaries; pions

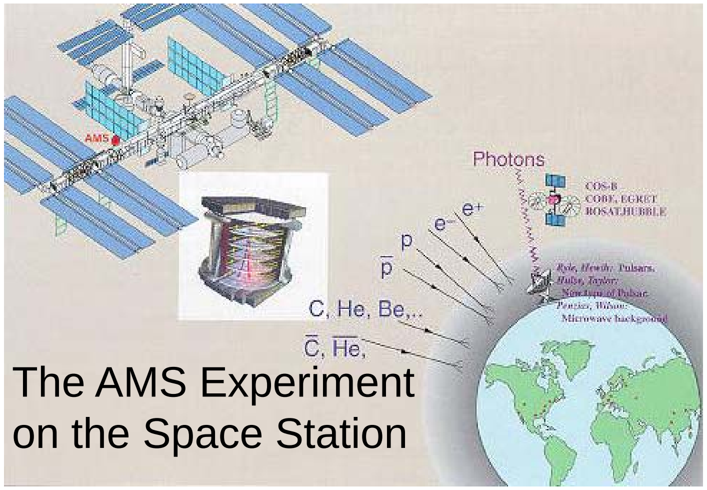
1948 Discovery of helium and heavier nuclei (up to Z=28)

1960s Discovery of “ultra-heavy” (Z>28) nuclei; electrons and positrons (x-ray astrophysics)

1970s Discovery of isotopes

1980s Age of cosmic rays; ISM properties

1990s+ Discovery of antiprotons; ACRs; GCRs with ultra high energies

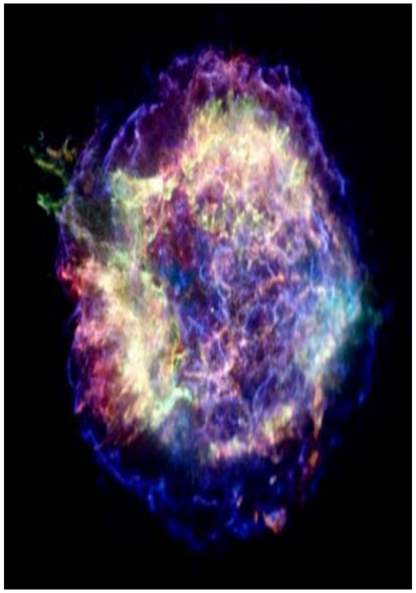


The AMS Experiment on the Space Station

A Glimpse of Cosmic Rays Astrophysics

Origin of cosmic rays:

- **-supernovae remnants ISM matter**
- **-nucleosynthesis $(4m_H - m_{He}) = 0.029\ m_H = 6\text{x}10^{14}$ J/kg**
- **-H, He, and CNO burning cycles**
- **-nuclei heavier than Ni are unstable**
- **-stable ones (e.g., Fe) can be accelerated**



Cassiopeia A

Acceleration of cosmic rays:

- **-first-ionization-potential differentiation**
- **-supernovae shock**
- **-First-order Fermi**

Transport of cosmic rays

- **-diffusive – tied to the galactic magnetic field**
- **-propagation effects (re-acceleration; spallation reactions; radioactive decay…)**

Modulation of cosmic rays

- **-cyclic**
- **-minor energy loss**

A Glimpse of Cosmic Rays Astrophysics

Theoretical Framework

Ginzburg-Syrovatskii Equation [also known as **Parker's 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 description for isotropic distribution functions

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

-It includes diffusive shock acceleration as well as solar modulation; <u>but not</u> Fermi's second-order acceleration process:

$$\frac{1}{p^2}\frac{\partial}{\partial p}\left\{p^2 D_{pp}\frac{\partial f}{\partial p}\right\}$$

Without a theory the facts are silent. *-A.J. Hayek*

GCR Acceleration

Fermi Second-Order Acceleration Mechanism

[E. Fermi, "On the Origin of the Cosmic Radiation," 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 particle's energy according to:

$$
\begin{aligned}
\frac{\langle \Delta E \rangle}{E} &\propto \left(\frac{V}{c}\right)^2 \quad \Longrightarrow \\
\frac{dE}{dt} &= rE \quad \Longrightarrow \\
f(E) &\propto E^{-\eta}; \quad \eta = 1 + (r\tau)^{-1}
\end{aligned}
$$

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

GCR Acceleration

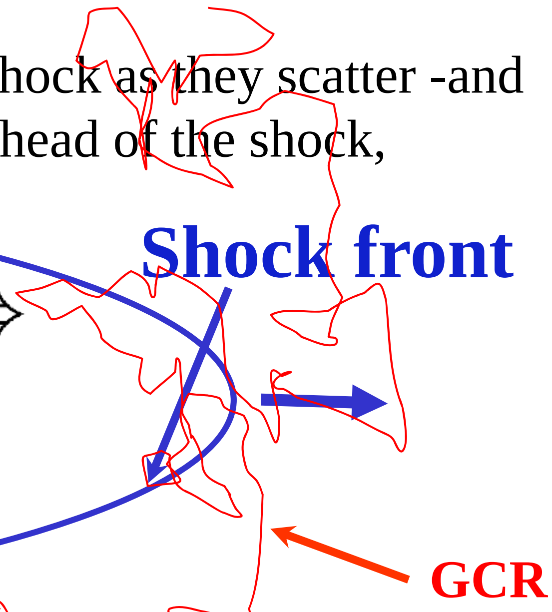
Fermi First-Order Acceleration Mechanism

[E. Fermi, "Galactic Magnetic Fields and the Origin of Cosmic Radiation," 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:

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

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

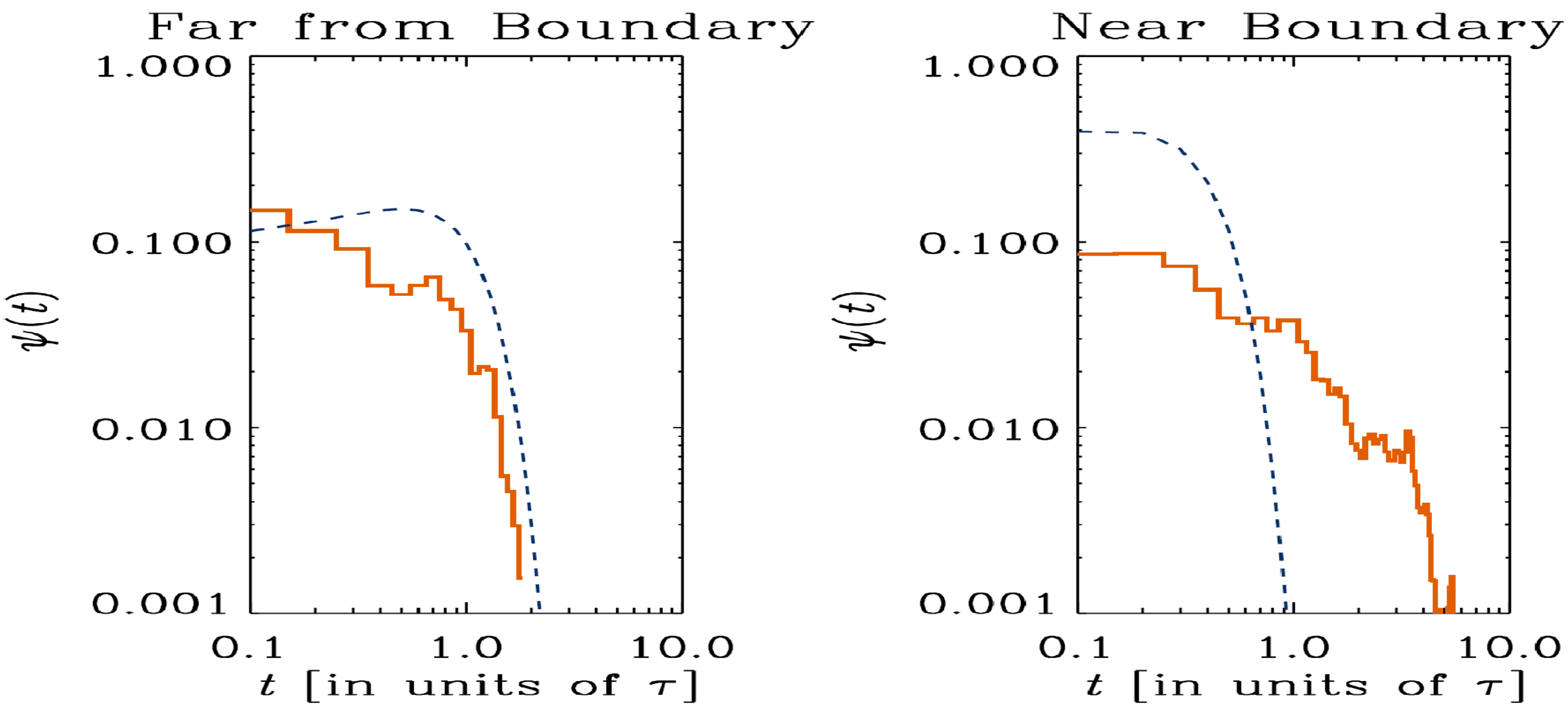
$$\langle t\rangle = \int_o^\infty t\phi(t)dt \ ; \ \frac{\sigma^2(t)}{\langle t\rangle^2} \sim \alpha \ ; \ \kappa \propto p^\alpha$$

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

DSA: No characteristic acceleration time!

GCR Acceleration: DSA

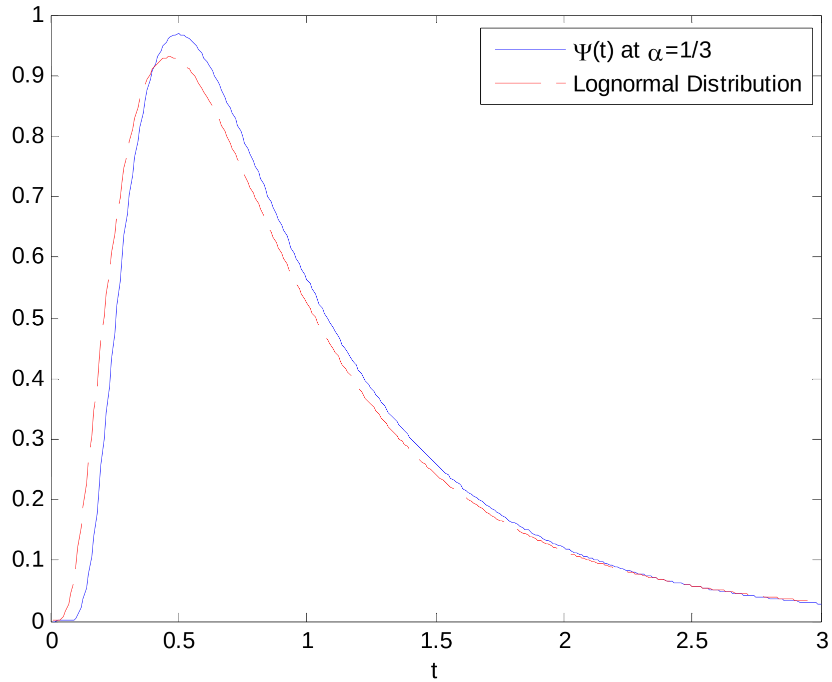
Dispersive Transport ?



A stochastic acceleration-time in the presence of a 'boundary' [in *p* and/or *t*] can be shown to result in a 'knee' like structure – almost quite naturally…

GCR Acceleration: DSA

Dispersive Transport ?



$$\psi(t) = \left(\bar{t}/t\right)^{3/2} \exp\left[\frac{\left(\bar{t}\right)^2 - \left(\bar{t}\right)^3/2t - t\;\bar{t}/2}{\overline{t^2}}\right] \Big/ \sqrt{2\pi\;\overline{t^2}}$$

GCR Acceleration: DSA

Standard transport theory –
Gaussian propagators

Dispersive transport –
Non-Gaussian propagators that are characterized by distributions with long (algebraic) tails, e.g., lognormal, Levy, Pareto

Medium such that a random walker is characterized by a transit-time distribution as well as a residence-time distribution