# The Space Radiation Environment

*TRISH* Red Risk School Seminar Series
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For the Lawyers…..

The views expressed in this presentation are my own and do not necessarily reflect those of Loma Linda University or NASA.

# Outline

- Introduction
- Properties of Charged Particles
- Charged Particle Radiobiology
- Damage to Electronics
- Space Environment
- NASA Health Risks

# Primary Hazards to Humans during Space Flight

**Decreased gravity**

- *Bone Loss, Muscle Atrophy, Reduced Immune Function, Fluid-Shifts*

**Isolation/confinement/altered light-dark cycles**

- *Sleep Issues, Psychological Stress*

**Hostile/closed environment**

- *Atmosphere, Microbes, Dust, Habitability*

**Distance from Earth**

- *Autonomy, Food Systems/Nutrition, Clinical Medicine*

**Increased radiation**

- *Cancer, CNS, Cardiovascular and Degenerative Changes, Acute Risks*


Image Credit: NASA/Pat Rawlings, SAIC

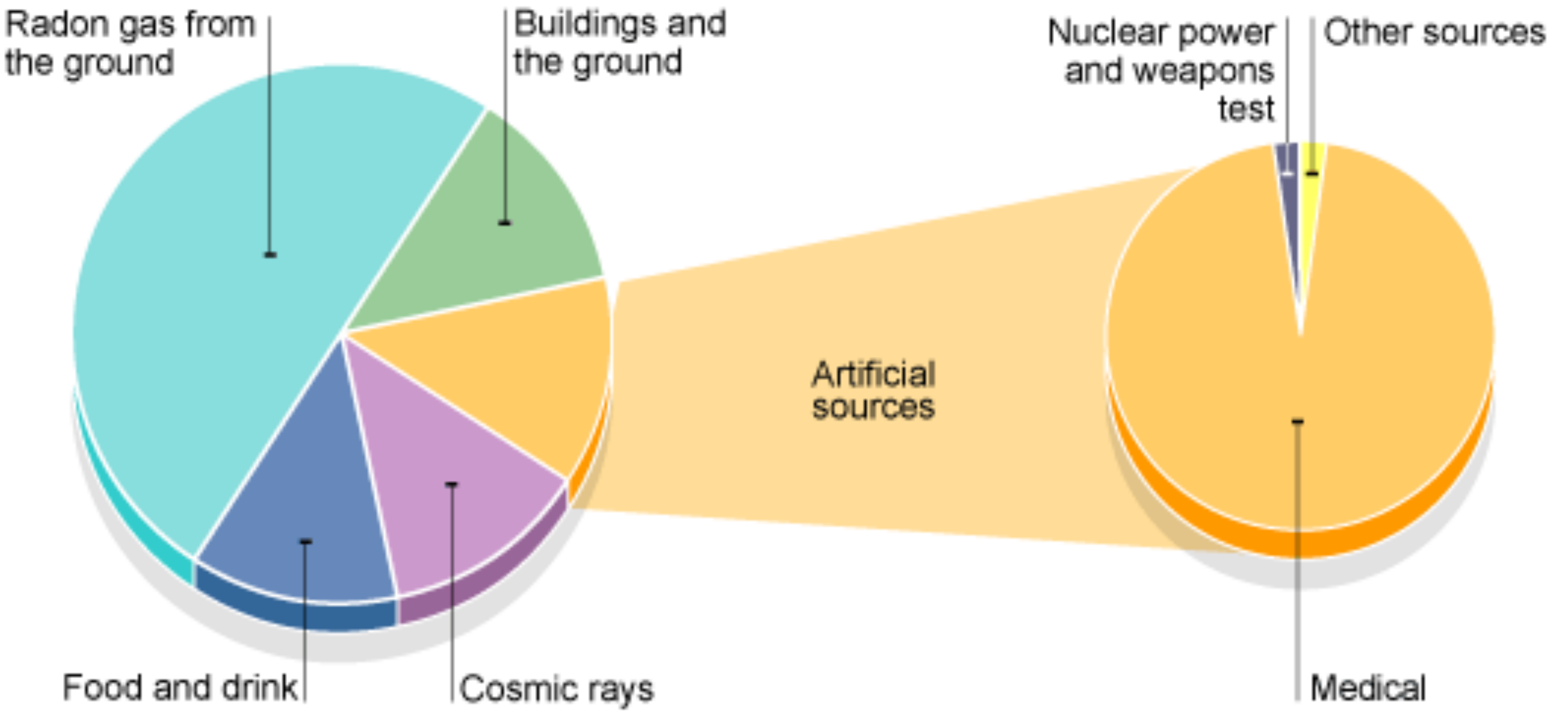
Modified from L Simonsen

# The Space Radiation Problem

- Space radiation is comprised of high-energy protons, heavy ions and secondary particles produced in shielding
- Unique damage to biomolecules, cells, and tissues occurs from charged particles that is qualitatively distinct from photons
- No human data to estimate risk from heavy ions
- Animal and cell models must be applied or developed to estimate cancer, CNS risks, and other risks
- Strategies to mitigate risks must be developed and implemented

# Background Radiation Exposure

## ≈ 3.60 mSv / year (w/o Medical Exposures)

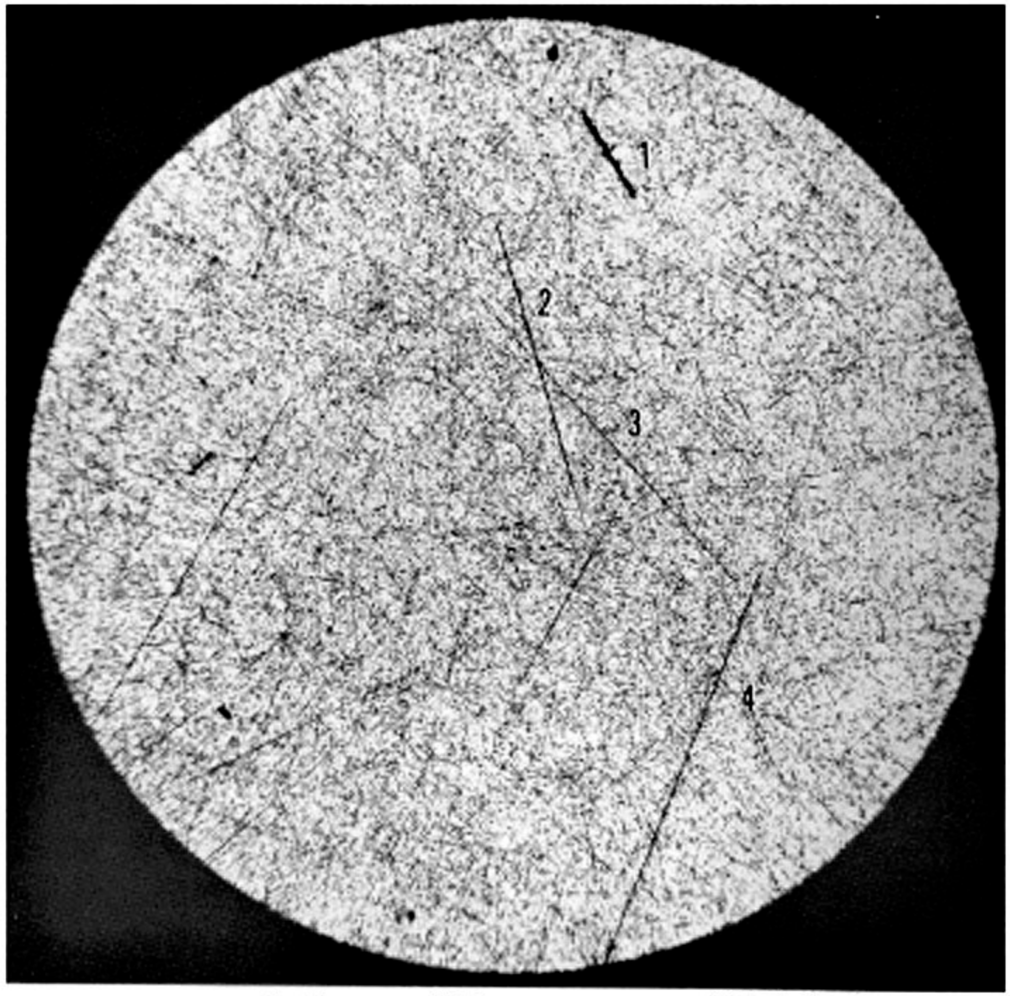



Chest X-ray ~ 0.1 mSv; Mammogram ~ 2.5 mSv; CT Scan ~ 30 – 100 mSv
Space Station Annual Dose ~ 0.1 Sv; A-Bomb Dose ~ 1- 4 Sv; RT 20 – 90 Sv

http://www.bbc.co.uk/schools/gcsebitesize/science/add_ocr_gateway/radiation/radioisotopesrev1.shtml

N Metting, DOE Low Dose Program

# A Snapshot of the Space Radiation Field
## Cosmic Ray Tracks from Apollo 17




1.5 mm

~ 1.5 mm Microscope Field

8A-11 (Film bag) 43.0/122.6 Apollo 17

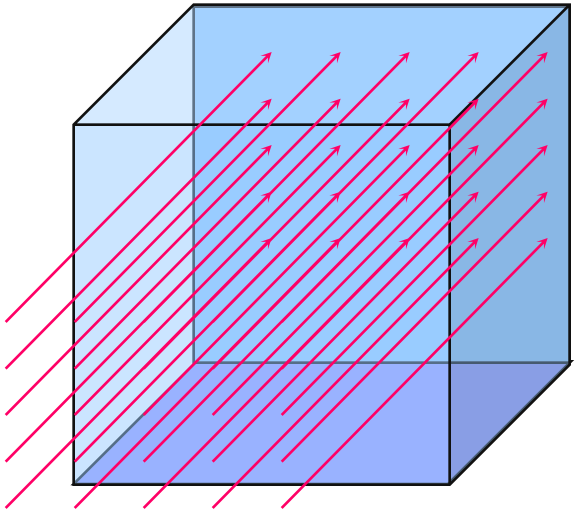
Schaefer & Sullivan, 1976

# Properties of Charged Particles

# The Fundamental Concept of Dose is Insufficient

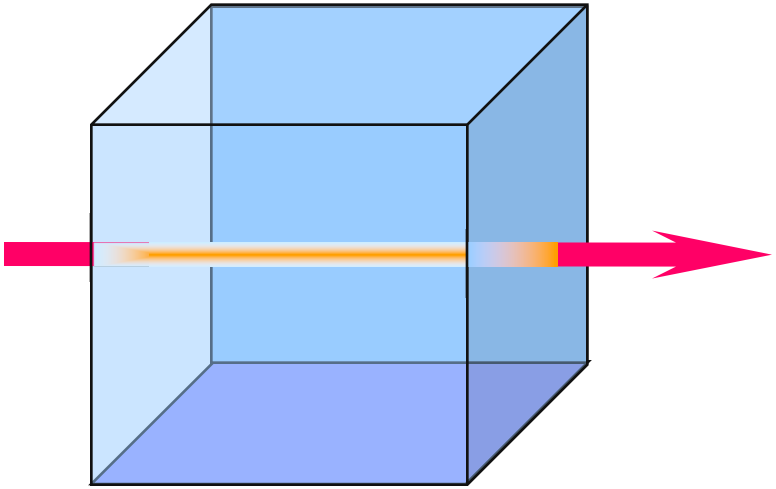
- Dose is defined as energy absorbed per unit mass
  *(irrespective of the spatial distribution of the absorbed energy)*

**1 Dose Unit**



**Low LET radiation deposits energy in a uniform pattern**

**1 Dose Unit**



**High LET radiation deposits energy in a non-uniform pattern**

# Physical Quantities

- HZE = High charge (Z) and energy (E)
- Dose (D) = Energy absorbed in bulk matter [How Much]
  - D = F x LET (1 Gy = 1 J/kg = 100 rad)
- Fluence (F) = number of particles per unit area (#/cm$^2$) [How Many]
- Linear energy transfer (LET) = rate of energy loss in bulk matter (keV per micron of track length) [How Intense]
- Range (R) = average distance travelled before ion stops
- Relative Biological Effectiveness (RBE) = ratio of doses of ion to gamma rays to produce identical biological effect [How Effective]

Radiation Protection Concepts

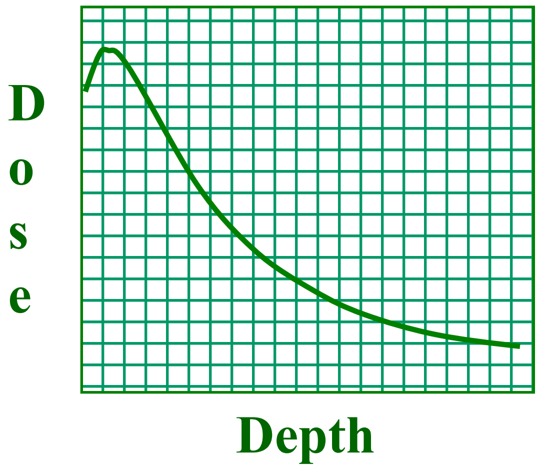
- Quality Factor (Q) = committee assigned value of RBE for human radiation protection
- Dose Equivalent (H) = D x Q (1 Sv = 100 rem)
- Risk = model quantity, not a measured value

# Energy Loss by Radiation in Matter

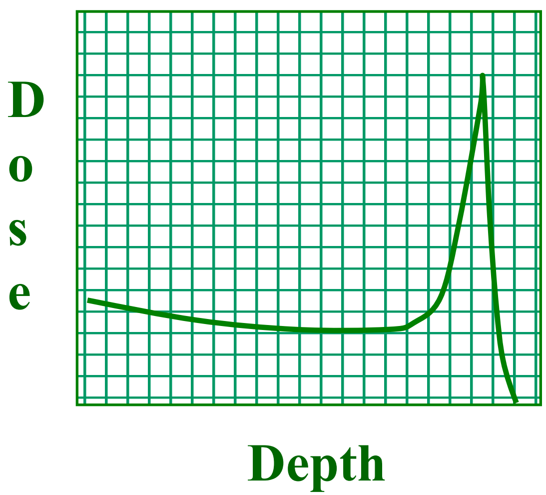
- **Photons** (Exponential attenuation)
  - $N(x)/N_o = e^{-\mu x}$
    - $N(x)/N_o$ is fraction of photons left at depth x
    - $\mu$ is linear attenuation coefficient
- **Charged Particles** (Bragg Curve, LET)
  - $1/\rho(dE/dx) = 4\pi r_o^2 N_e z^2 m_o c^2/\beta^2 \left[\ln(2m_o c^2\beta^2/I(1-\beta^2)) - \beta^2 - \Sigma_i(c_i/Z)\right]$
    - $N_e$ is electrons per gram of medium, $\rho$ is density of medium, $\beta$ is v/c, $z$ is charge of particle and $I$ is ionization constant of medium
    - The important component is : $dE/dx \propto z^2/\beta^2$

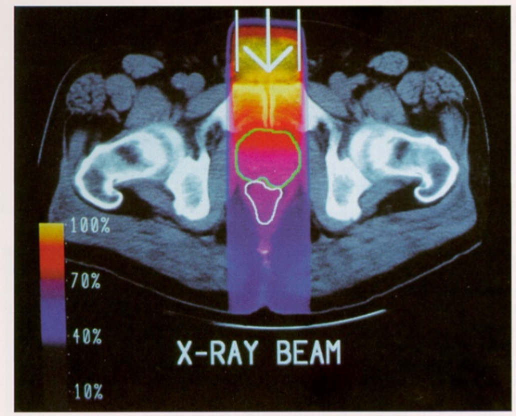
# Photon and Proton: Dose vs. Depth

X-rays &
Gamma Rays:
Exponential

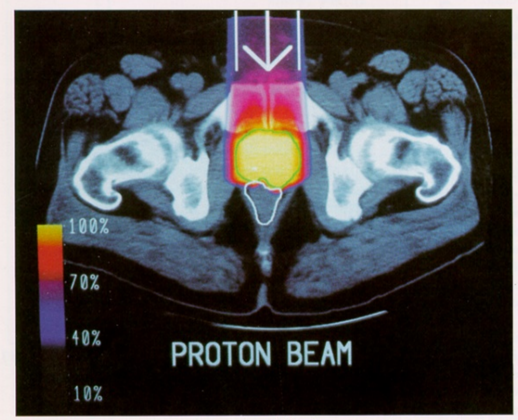



Protons:
Bragg
Curve



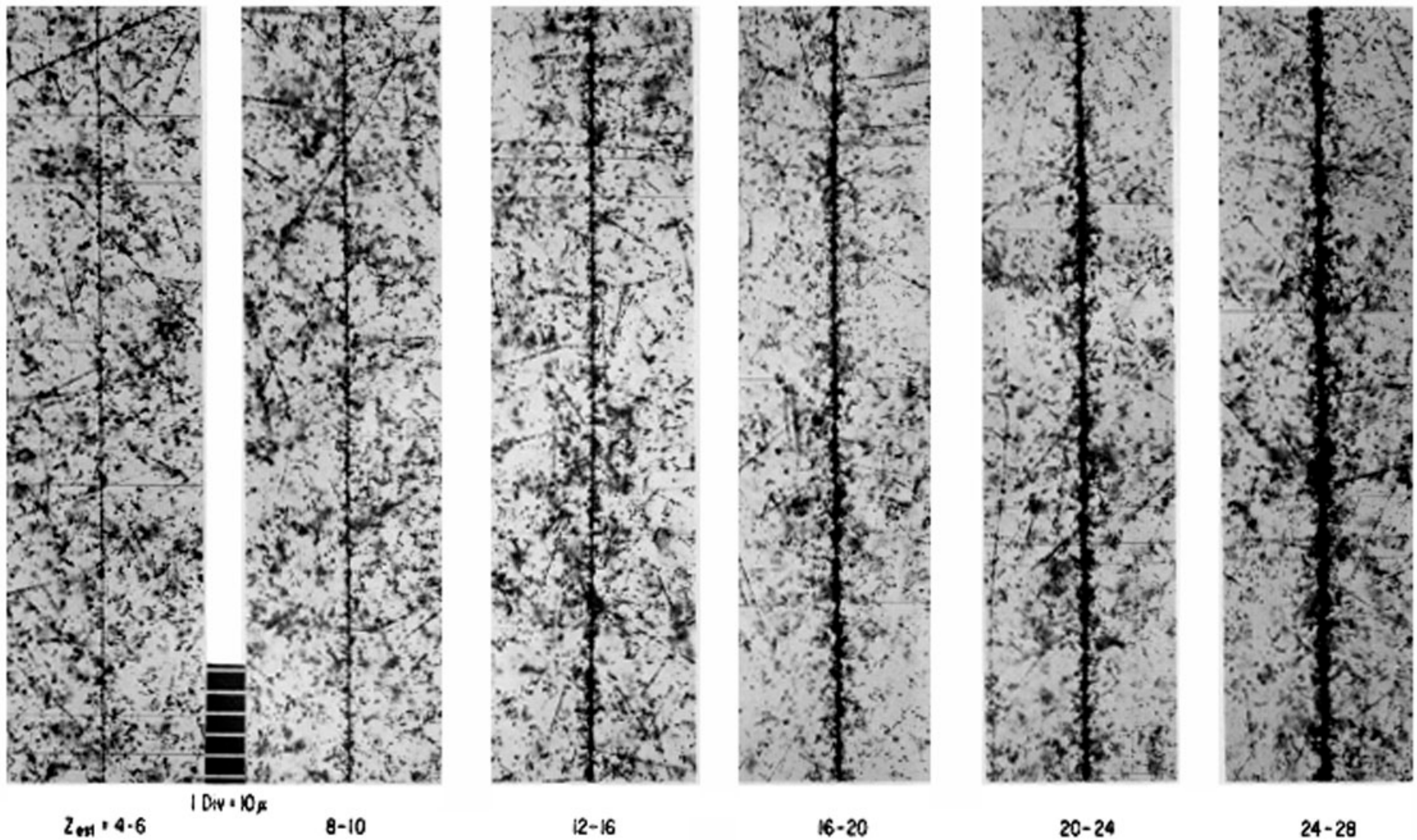




A single 18 MeV x-ray beam entering from the front. The central circle represents the prostate gland. The irregular structure outlined in white below the prostate gland represents the rectum. A single x-ray beam entering from above deposits most of its energy within the small bowel and bladder before reaching the tumor.




A proton beam deposits its maximum energy within the tumor in the prostate gland, minimizing the dose to the small bowel and bladder.

# Ionization Density and LET Varies with $Z^2$

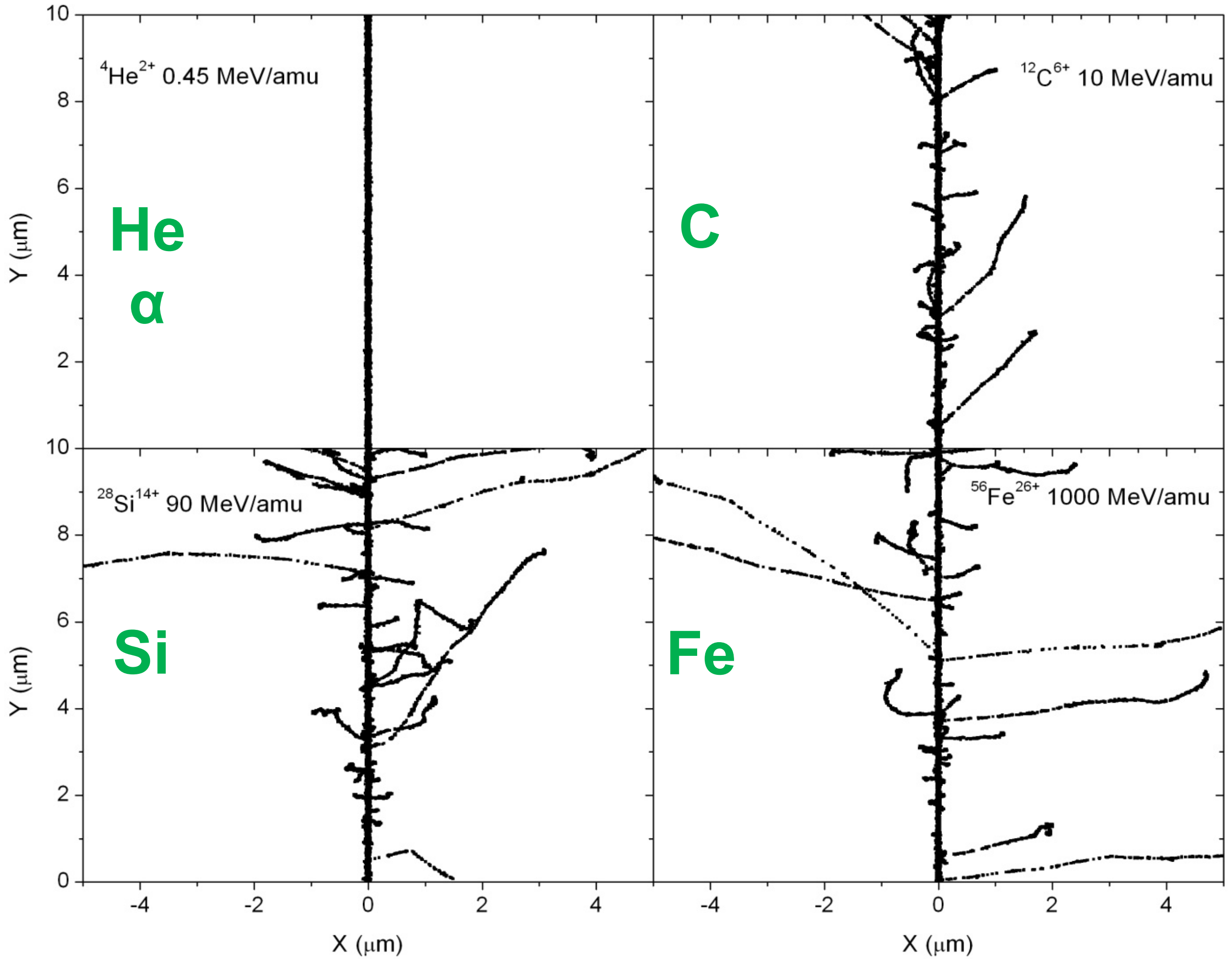



High Energy Sections of HZE Particle Tracks in Ilford G.5 Emulsion Flown on Apollo 8

Schaefer & Sullivan, 1976

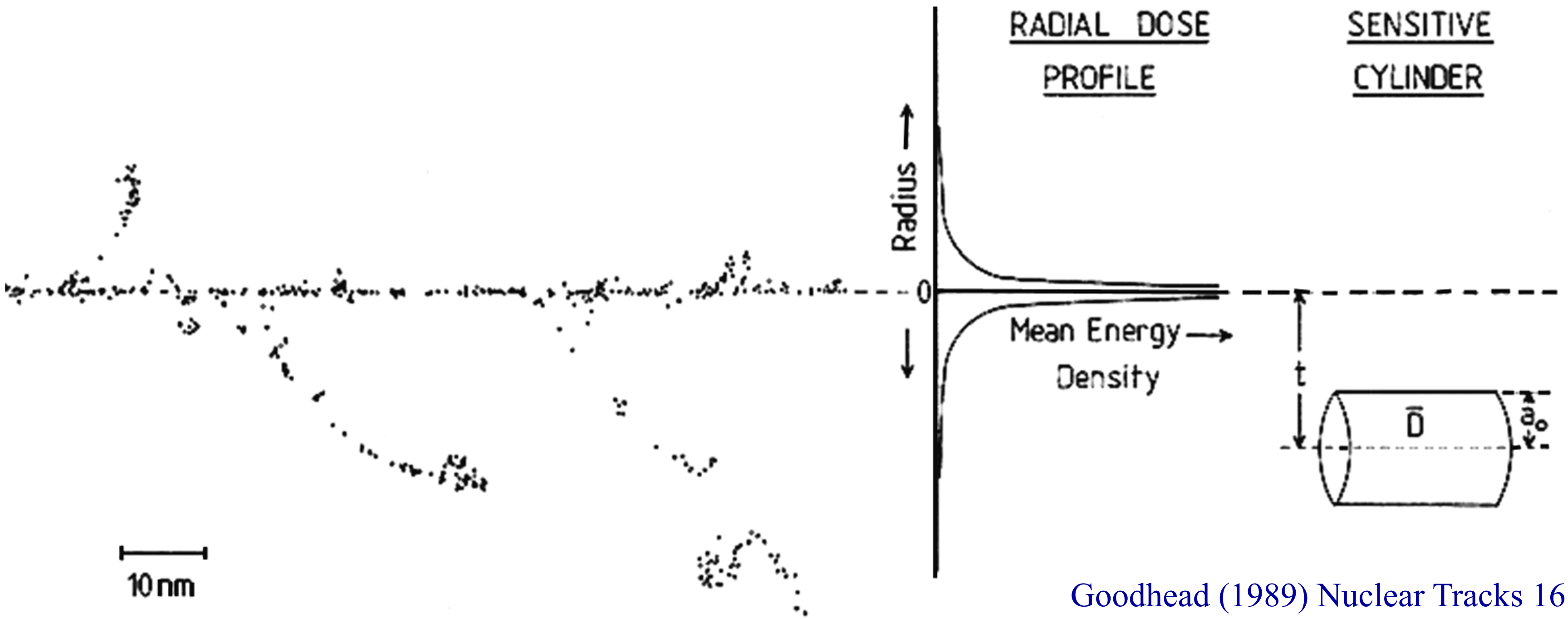
# Tracks of LET = 150 keV/micron Ions

## LET is useful but insufficient to describe track structure




Plante and Cucinotta

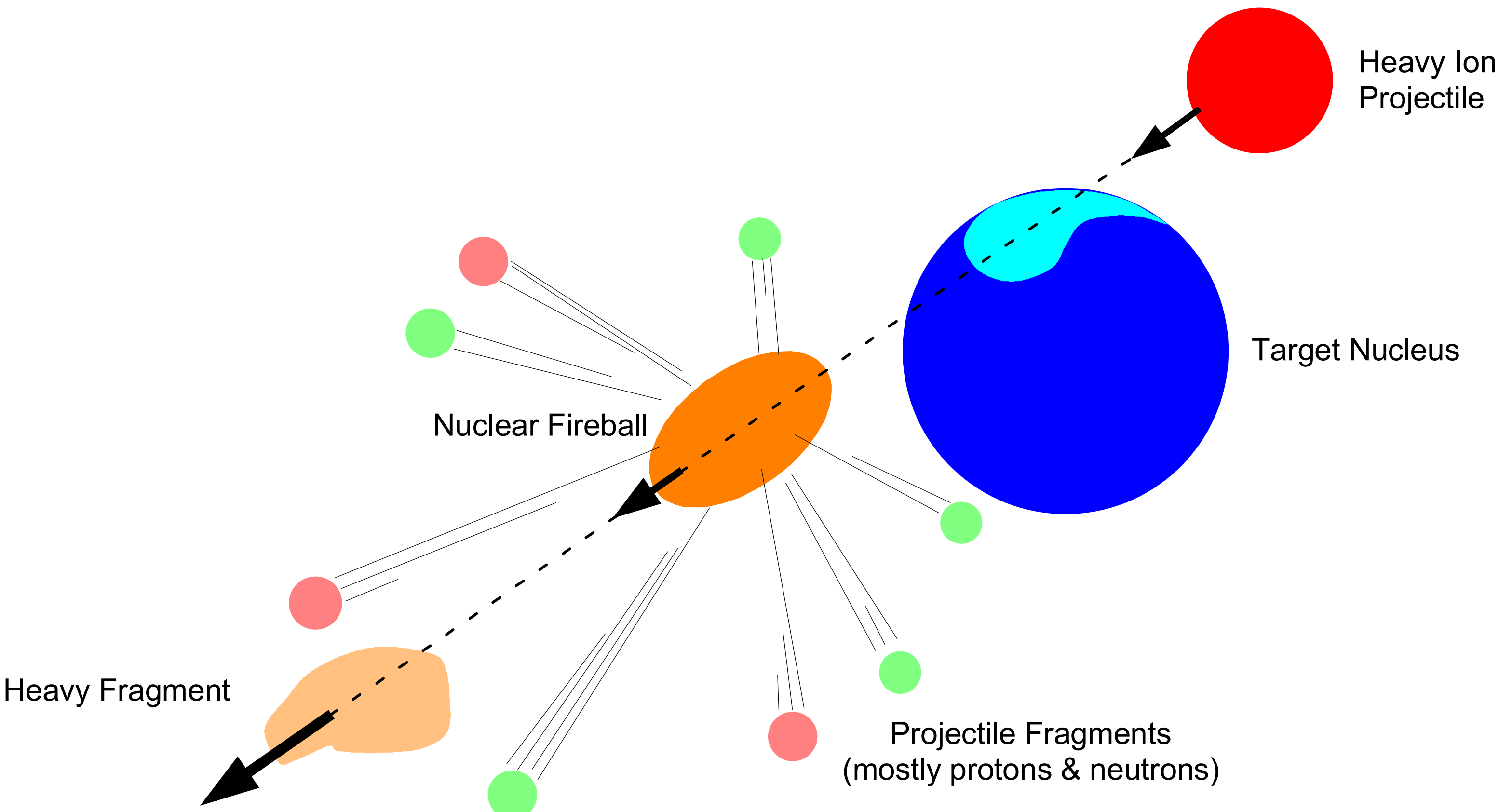
# Radial Dose Distribution of a Track



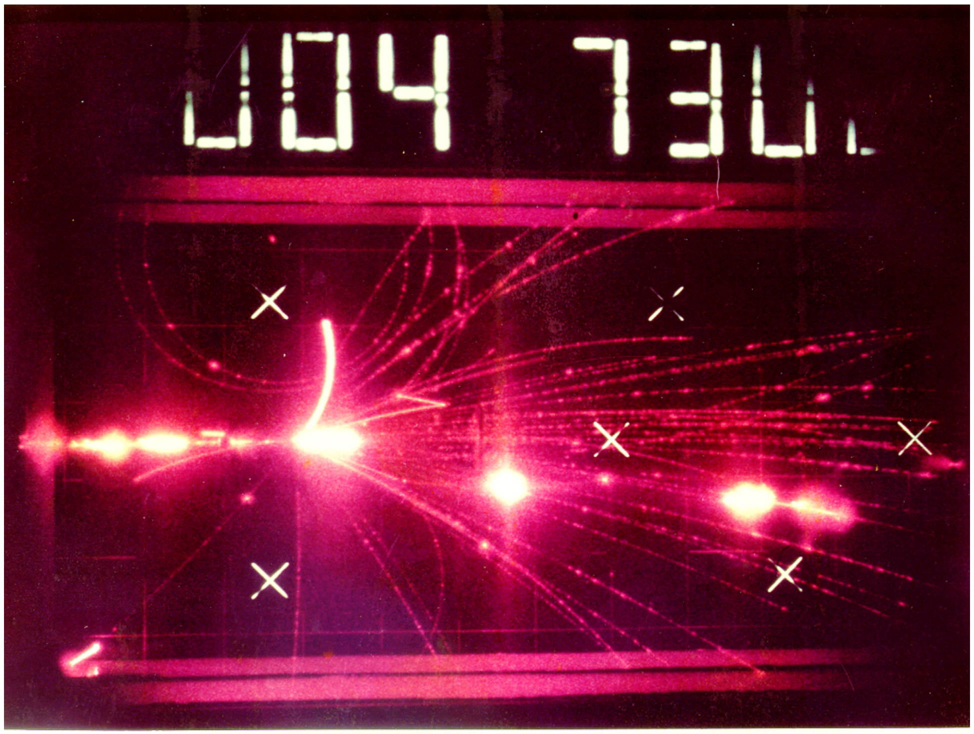
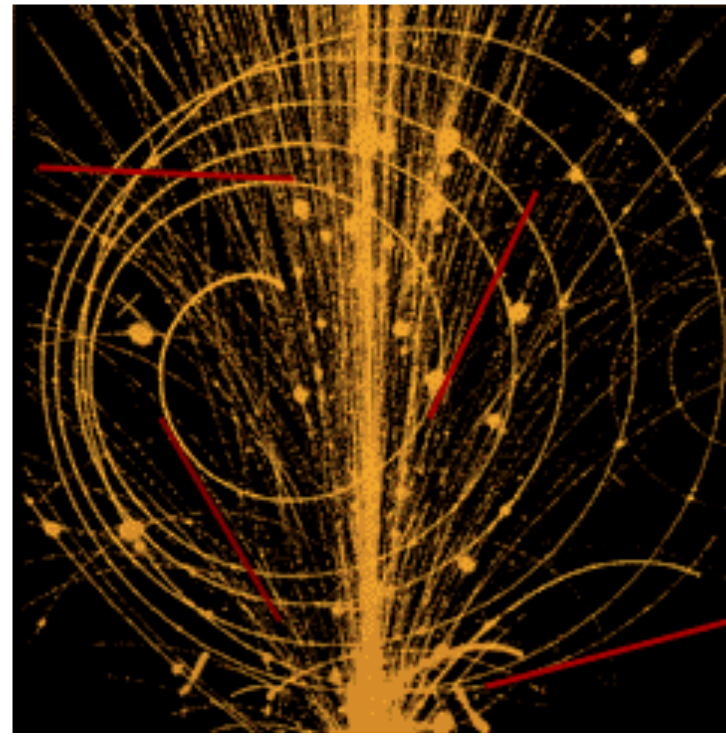

Goodhead (1989) Nuclear Tracks 16: 177

A 500 MeV/n particle can produce delta electrons of range 1 - 5 mm (100 -500 cell diameters) in water

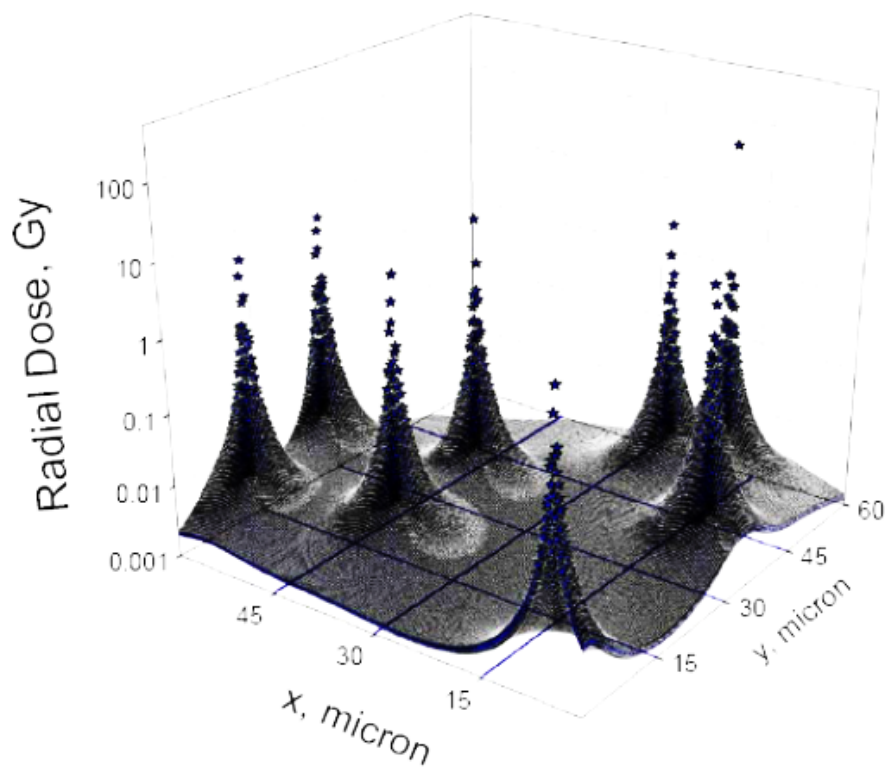
# Nuclear Interactions: Projectile Fragmentation

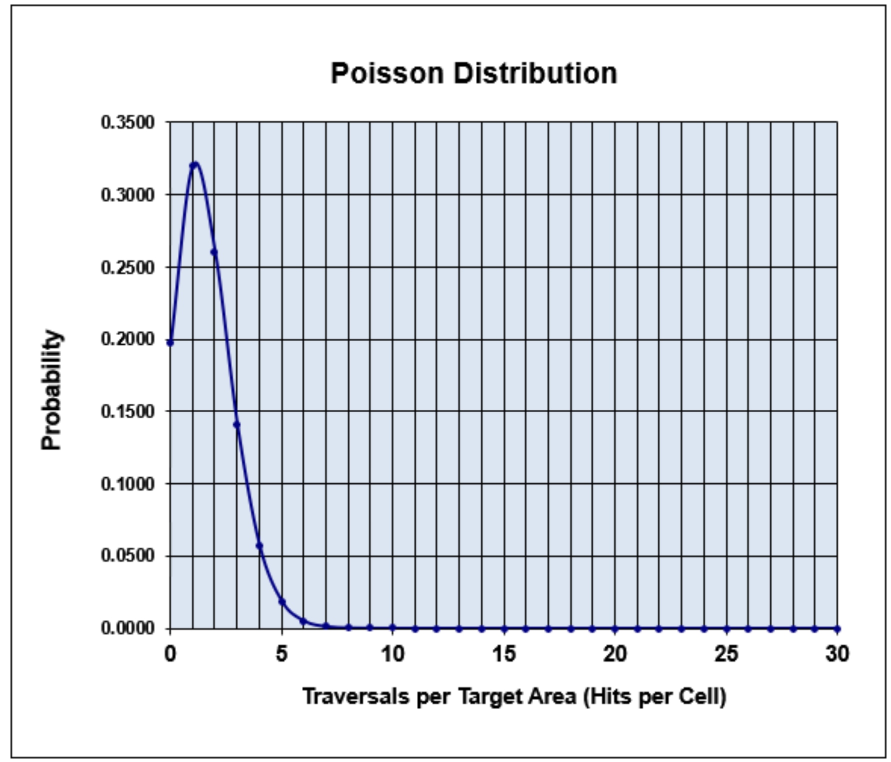


# Charged Particles Can Create Secondary Particles through Nuclear Reactions

# Exposures on a Microscopic Scale



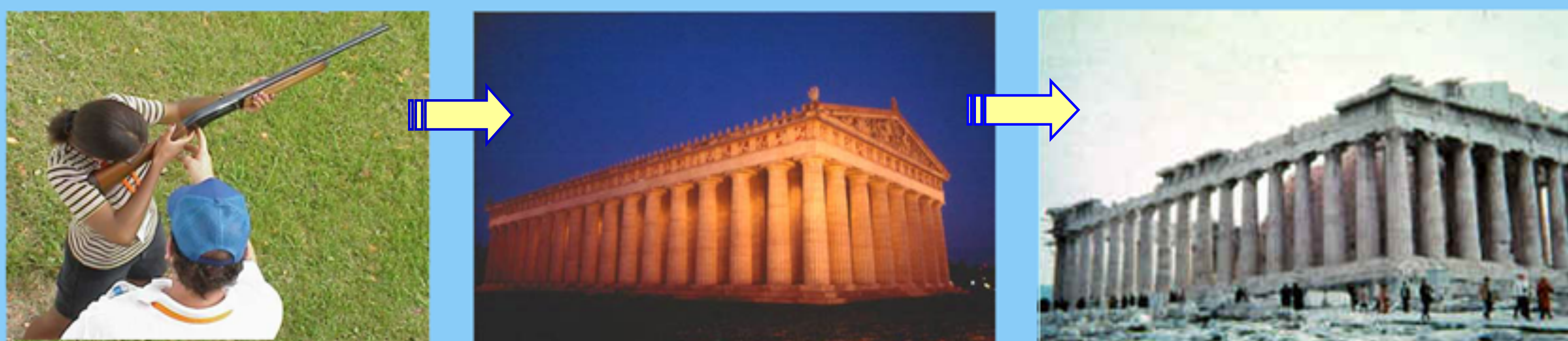




$^{56}$Fe 1000 MeV/n, LET 151 keV/µm. Dose 50 cGy. Cell (nucleus) area 100 µm$^2$

Dose = Fluence (average) x LET

# Charged Particle Radiobiology

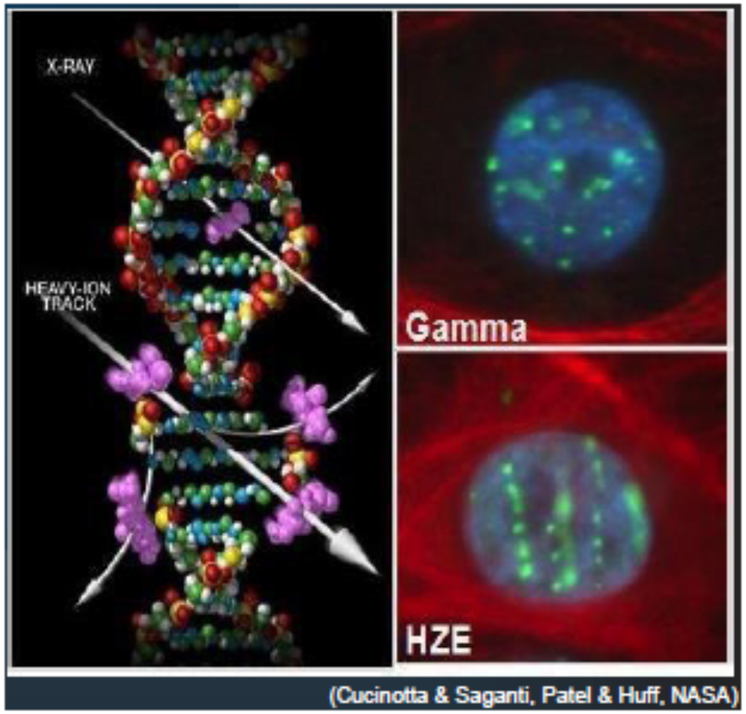
# An Analogy for Structured Energy Deposition and its Consequences

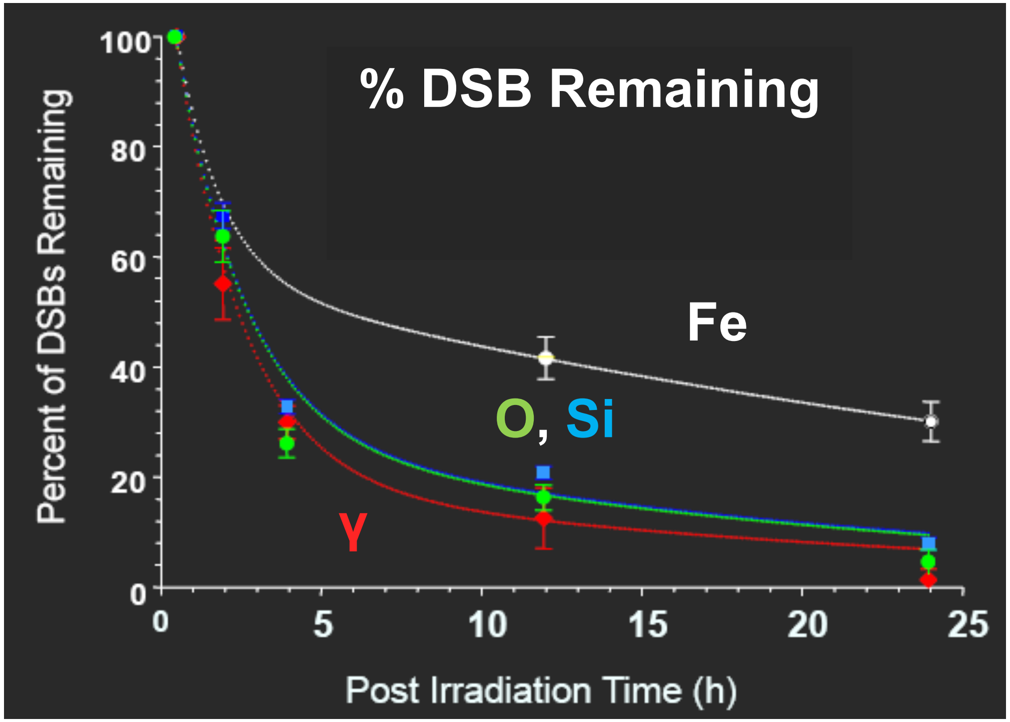


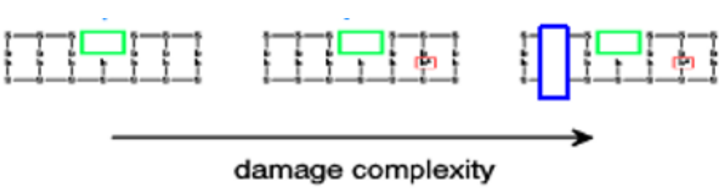
Low LET radiation produces isotropic damage to organized targets.

High LET radiation produces correlated damage to organized targets.

# DNA Damage




**Simple** **Complex** **Clustered**

Less effective DNA repair

Higher rate of residual lesions

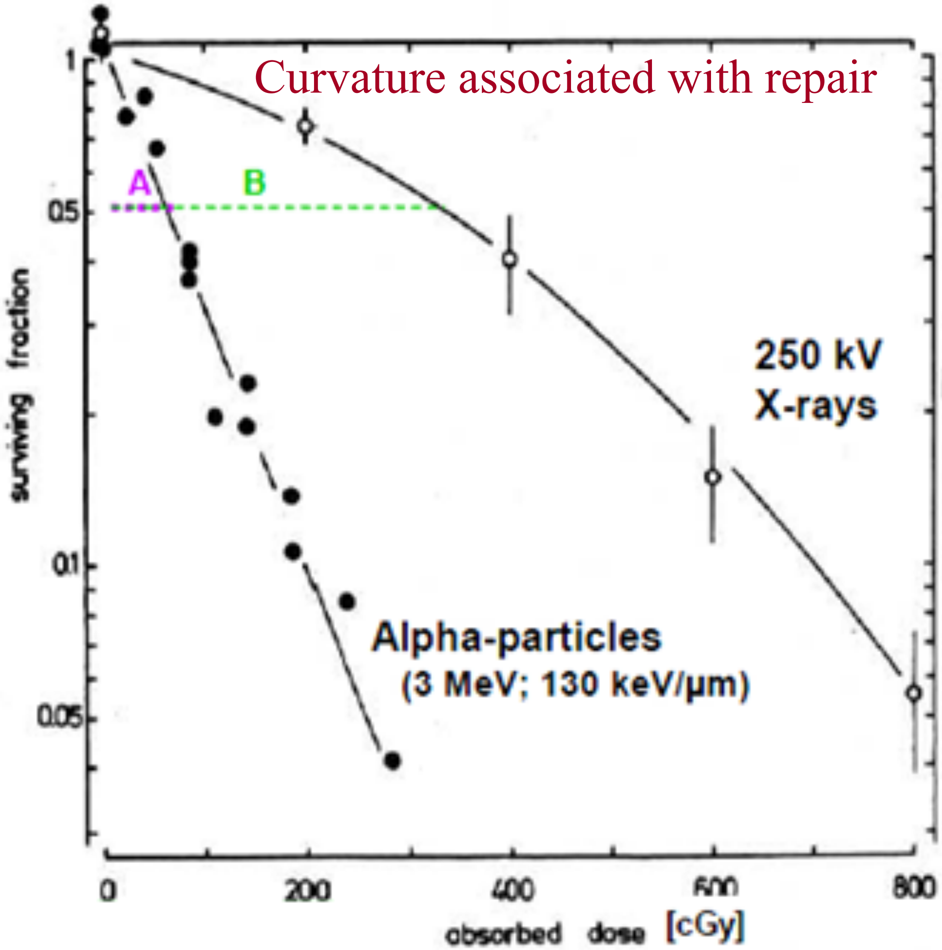
Genomic instability

Enhanced cell killing

Modified from M Story

# Cell Survival and RBE Concept

V79 Cells $^{238}$Pu α vs X-rays




Relative Biological Effectiveness (RBE)

= Ratio of doses that produce same biological effect

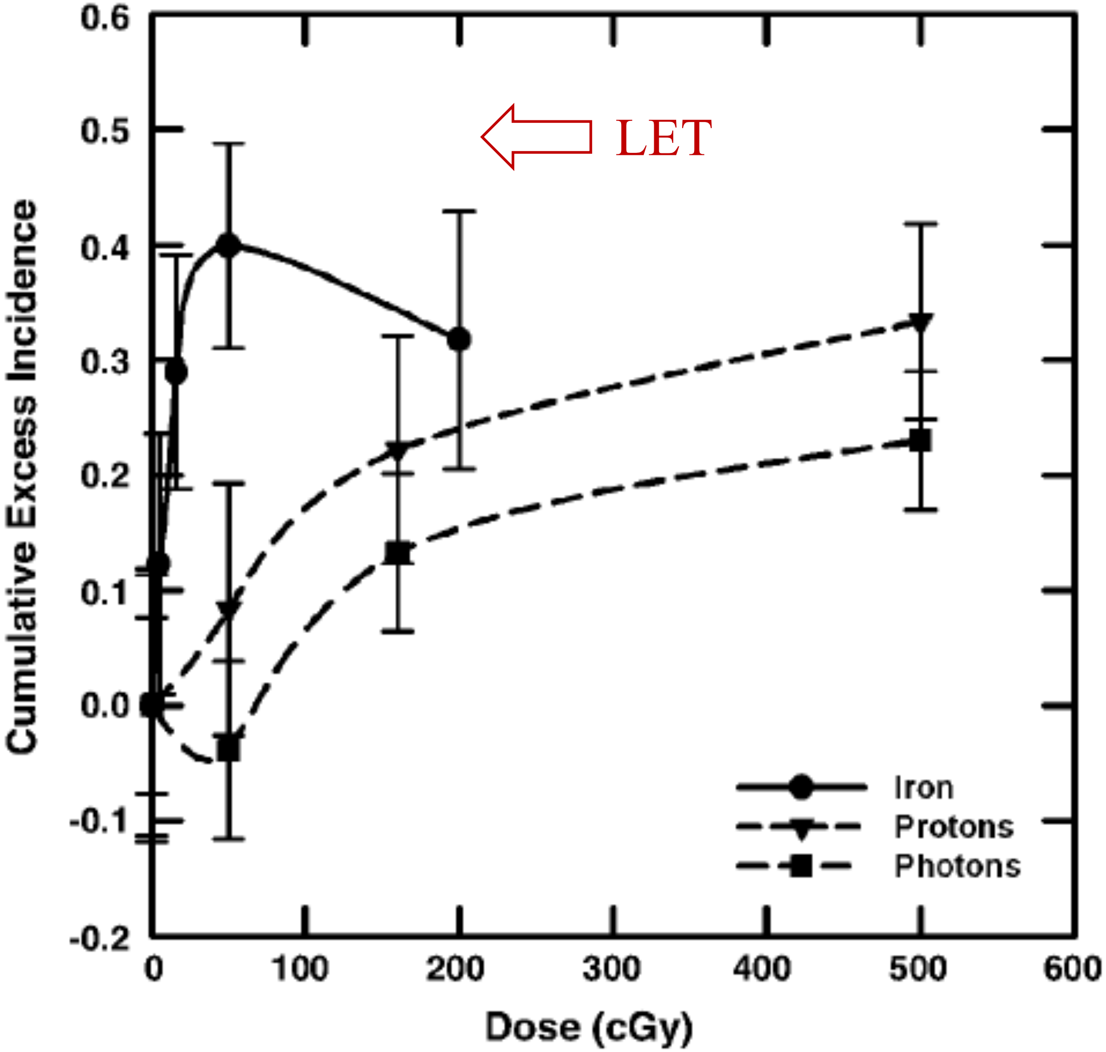
Varies with dose.

For 50% Survival
RBE for alpha Particles
**Dose B** ÷ **Dose A** ~ 5

Modified from D Goodhead and Radiat Res 92: 343 (1982)

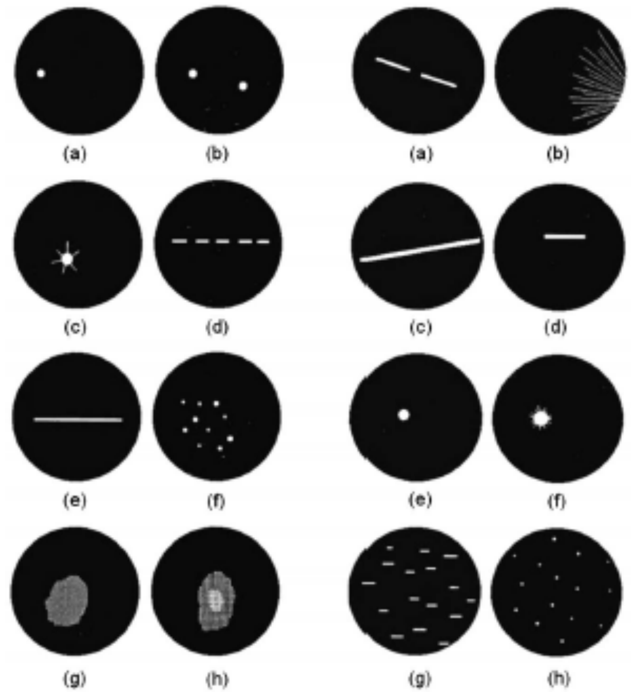
# Mammary Tumor Induction in Rats

## Gamma rays, Protons and Iron Particles




Dicello et al. (2004)

# Light Flash Illusions from Single Particles

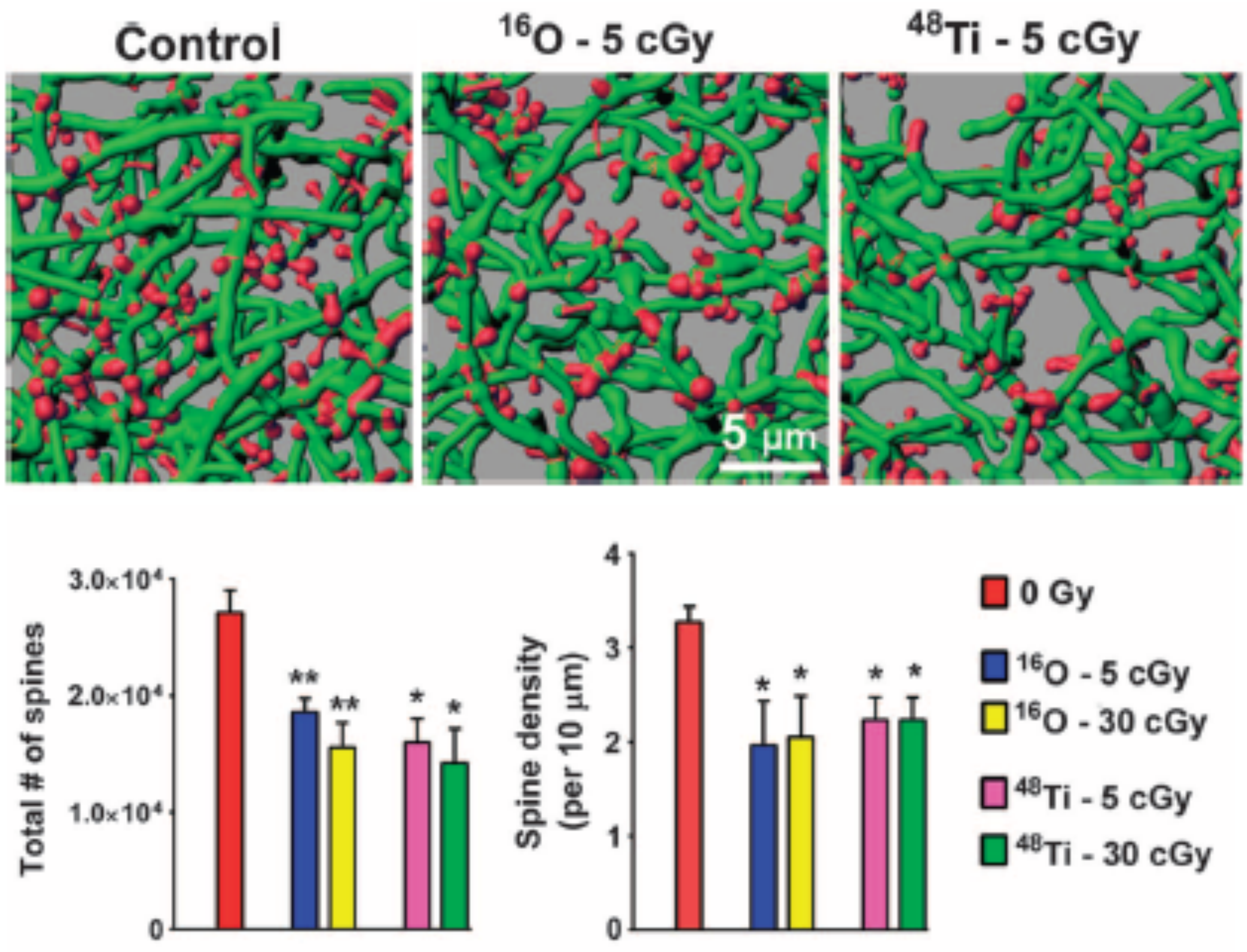



Sketches by Astronauts

ALTEA Experiment

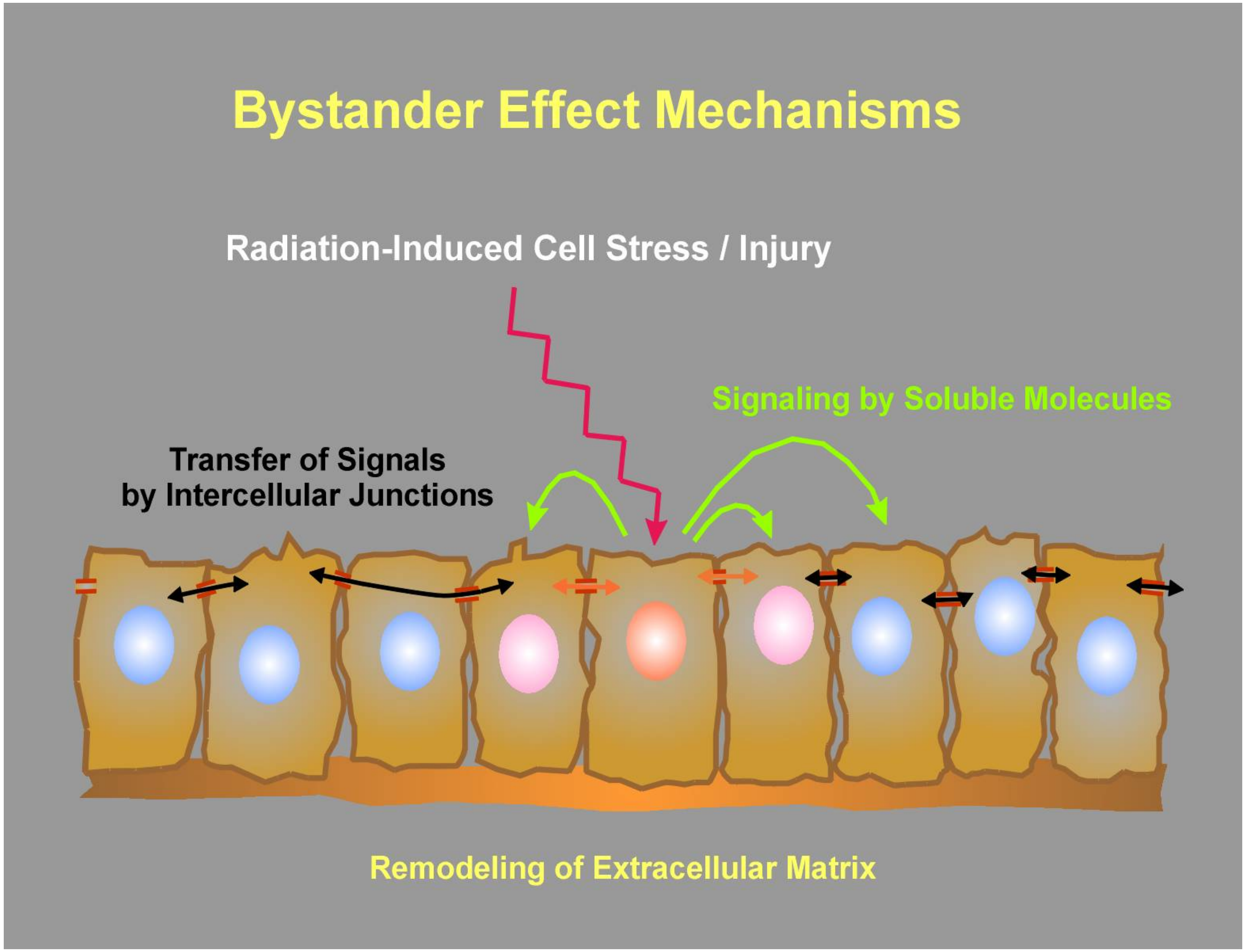
L Narici. New Journal of Physics 10 (2008) 075010
W.G. Sannita et al. Vision Research 46 (2006) 2159–2165

# Neuronal Branching and Spine/Synapse Loss




Mouse. Dendritic Spine # and Density. $^{16}$O and $^{48}$Ti ions. 8 weeks post IR.
Parihar et al.

# The Bystander Effect



# The Biology Is Complicated

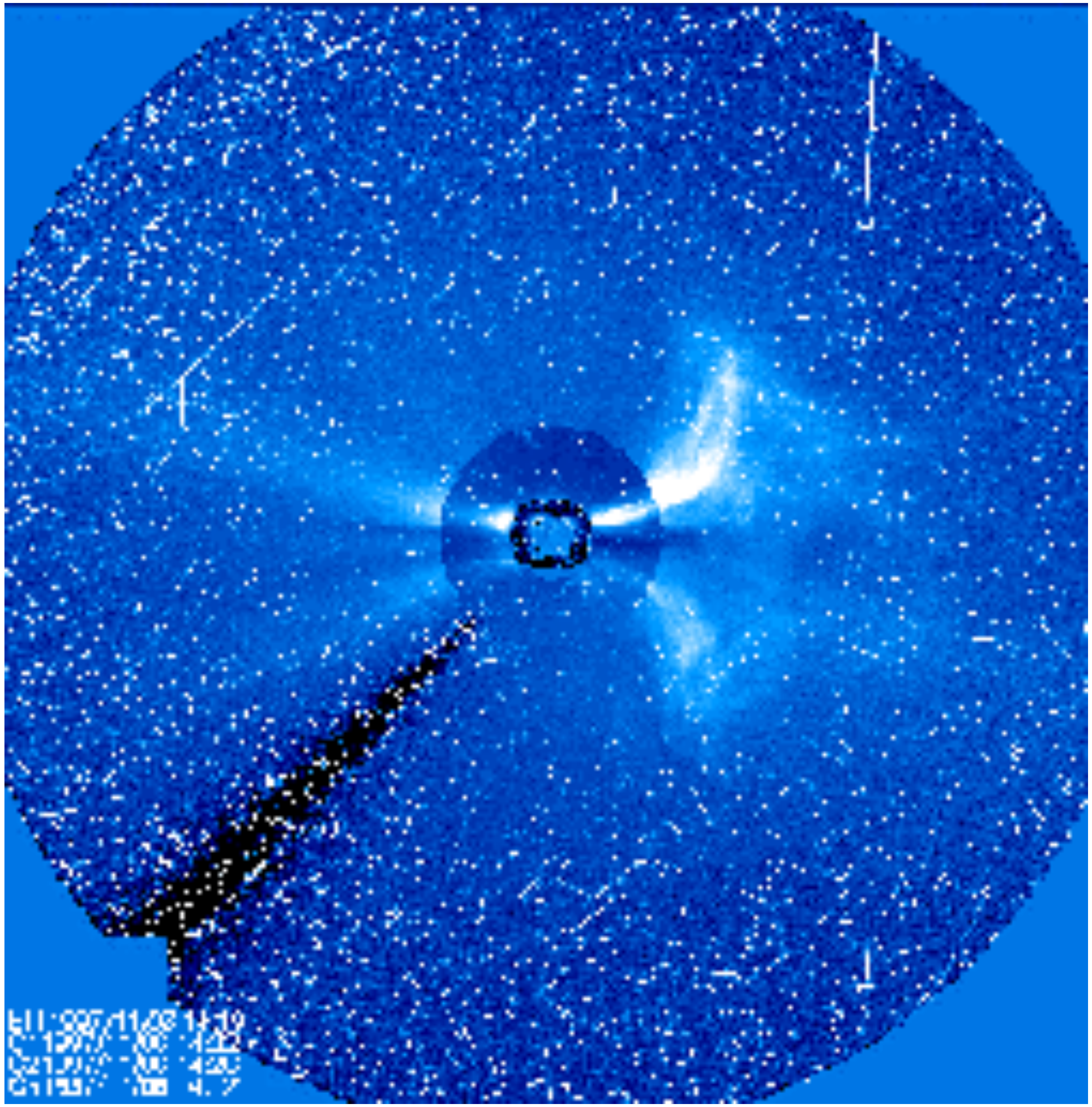
- Dose Responses Are Not All Linear
  - U-Shaped
- Particle Effects May Be Unique
  - Effects may trend oppositely
  - Quality factors very hard to define
- Mixed Particle Exposures May Not Produce Simple Additive Responses
- Sequential Exposures Don't Produce Simple Additive Responses
- Dose Rate Effects Unclear for Particles
  - What are the biological time constants?

# GCR Damage to Electronics

Single Event Upsets
Single Event Latch-ups
Single Event Gate Ruptures

# Examples of Single Event Upsets

SOHO / LASCO Satellite Imager



# GCR Damage to Electronics

## Single Event Upsets, Latchups & Gate Ruptures

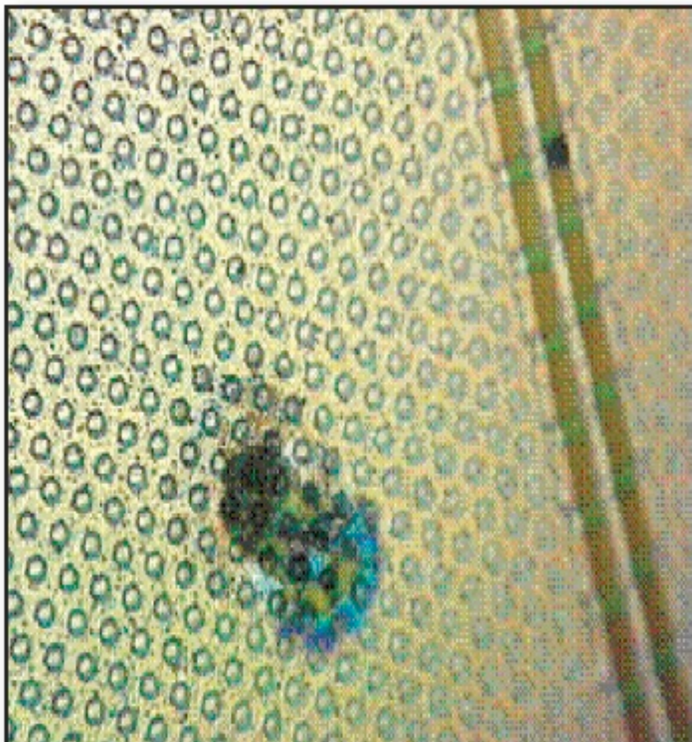


**Figure 6.** Photograph of a catastrophic SEGR in a power MOSFET causing functional failure.

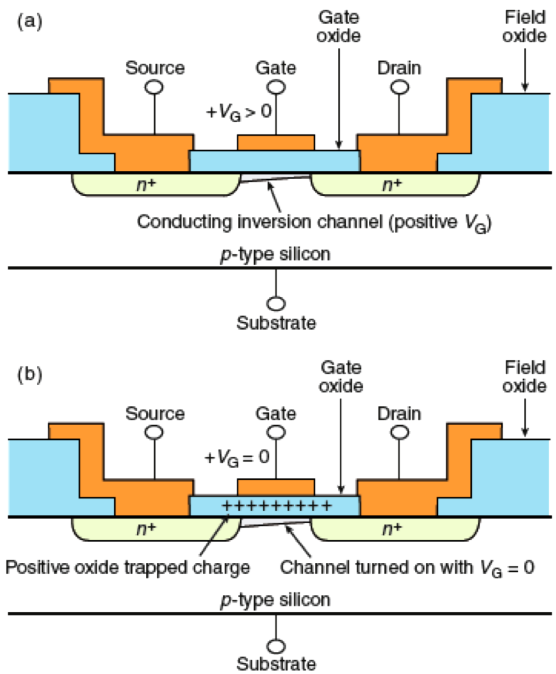
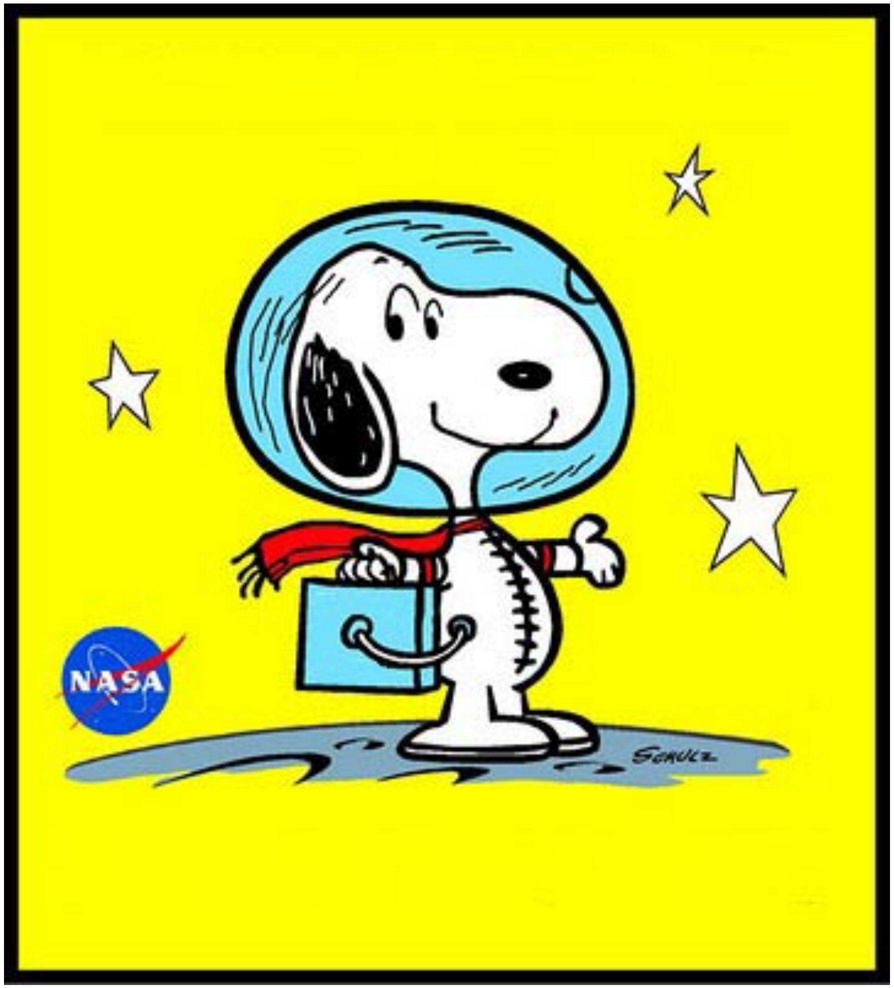



**Figure 1.** Schematic of an *n*-channel MOSFET illustrating the basic effect of total ionization-induced charging of the gate oxide. Normal operation (a) and postirradiation (b) show the residual trapped positive charge (holes) that produces a negative threshold voltage shift.

Harsh Environments: Space Radiation Environment, Effects, and Mitigation.
R. Maurer et al. Johns Hopkins APL Technical Digest , Volume 28, Number 1 (2008)

# Space Radiation Environment



# Human Environments in Space

Present

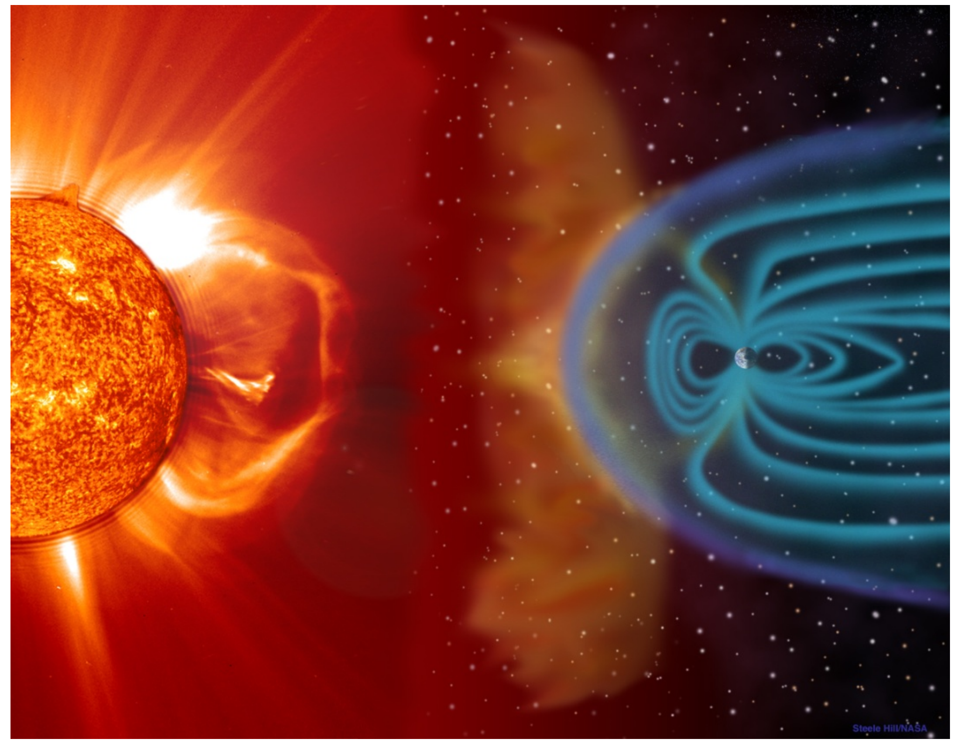
Future

# Proposed Updates to Design Reference Missions

| DRM Categories | Mission Type and Duration | Gravity Environment | Radiation Environment | Earth Return |
|---|---|---|---|---|
| **Low Earth Orbit** | Short (<30 days) | microgravity | LEO-Van Allen | 1 day or less |
| | Long (>30 days) | microgravity | LEO-Van Allen | 1 day or less |
| **Lunar Surface** | Short (<30 days) | 1/6 g | Deep space | 5 days |
| | Long (>30 days) | 1/6 g | Deep space | 5 days |
| **Lunar Orbital** | Short (<30 days) | microgravity | Deep space | 5 days |
| | Long (>30 days) | microgravity | Deep space | 5 days |
| **Mars** | Preparatory (<365 days) | microgravity | Deep Space | Days-Weeks |
| | Planetary (≥365 days) | microgravity & 3/8 g | Mars | Mission duration |

# Complex Space Radiation Field

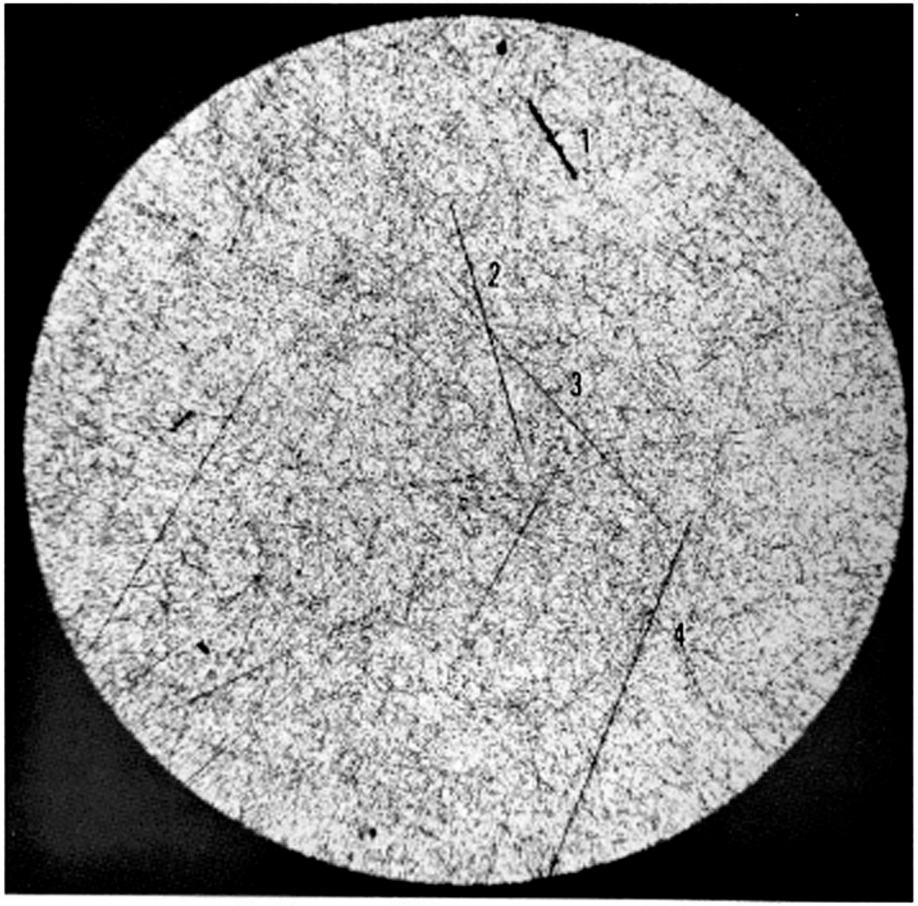
## Three Main Sources



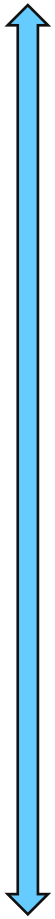

Sources Outside and Inside the Solar System

# Space Radiation Environment is Dominated by Charged Particles

*Example: Cosmic Ray Tracks from Apollo 17*



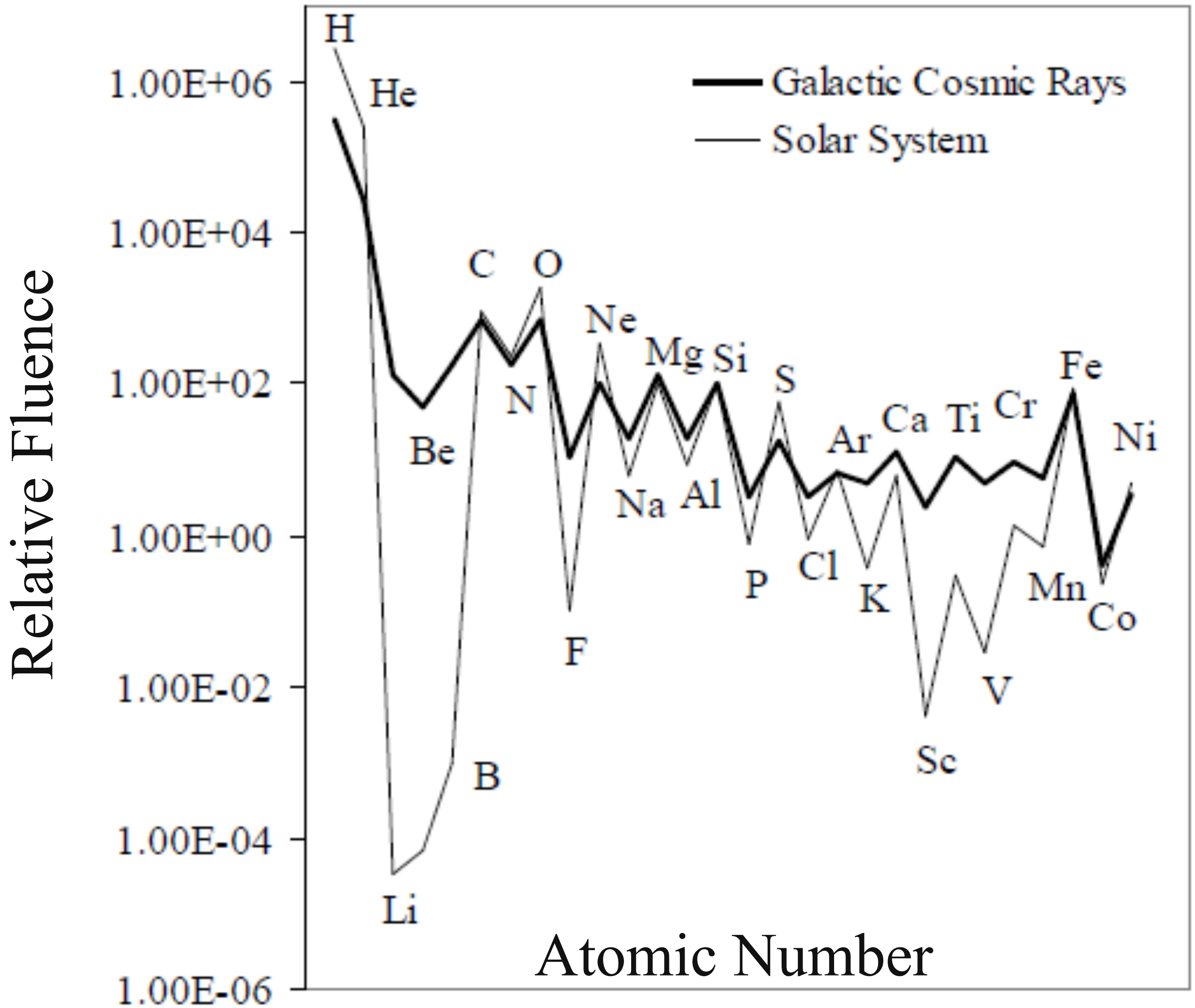

~ 1.5 mm Microscope Field
8A-11 (Film bag) 43.0/122.6 Apollo 17




Schaefer & Sullivan, 1976

# Galactic Cosmic Rays

# GCR Abundance

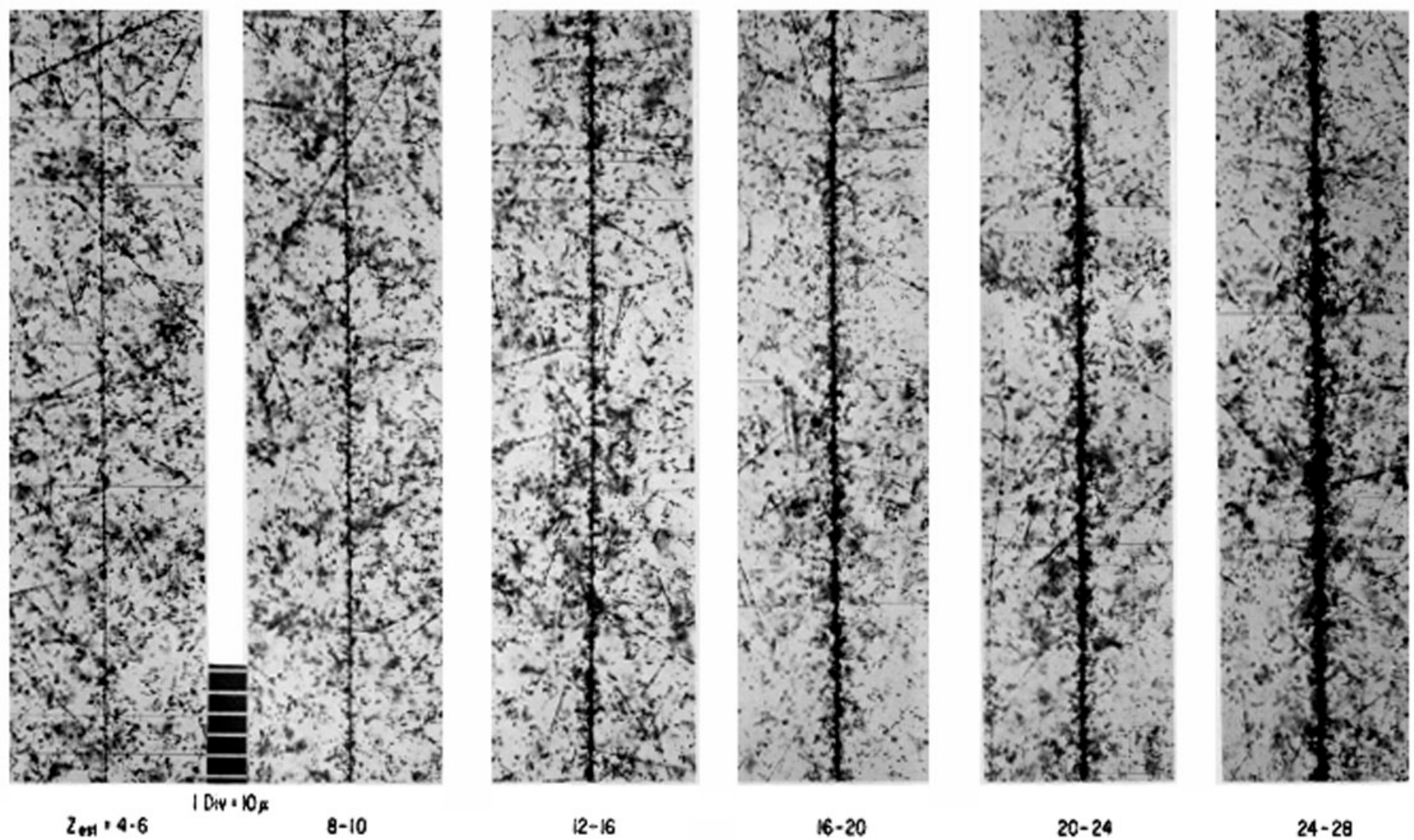



85% H
13% He
2% Z > 2

Nat. Res. Council (2008) Managing Space Radiation Risk in the New Era of Space Exploration

# Cosmic Ray Tracks from Apollo 8

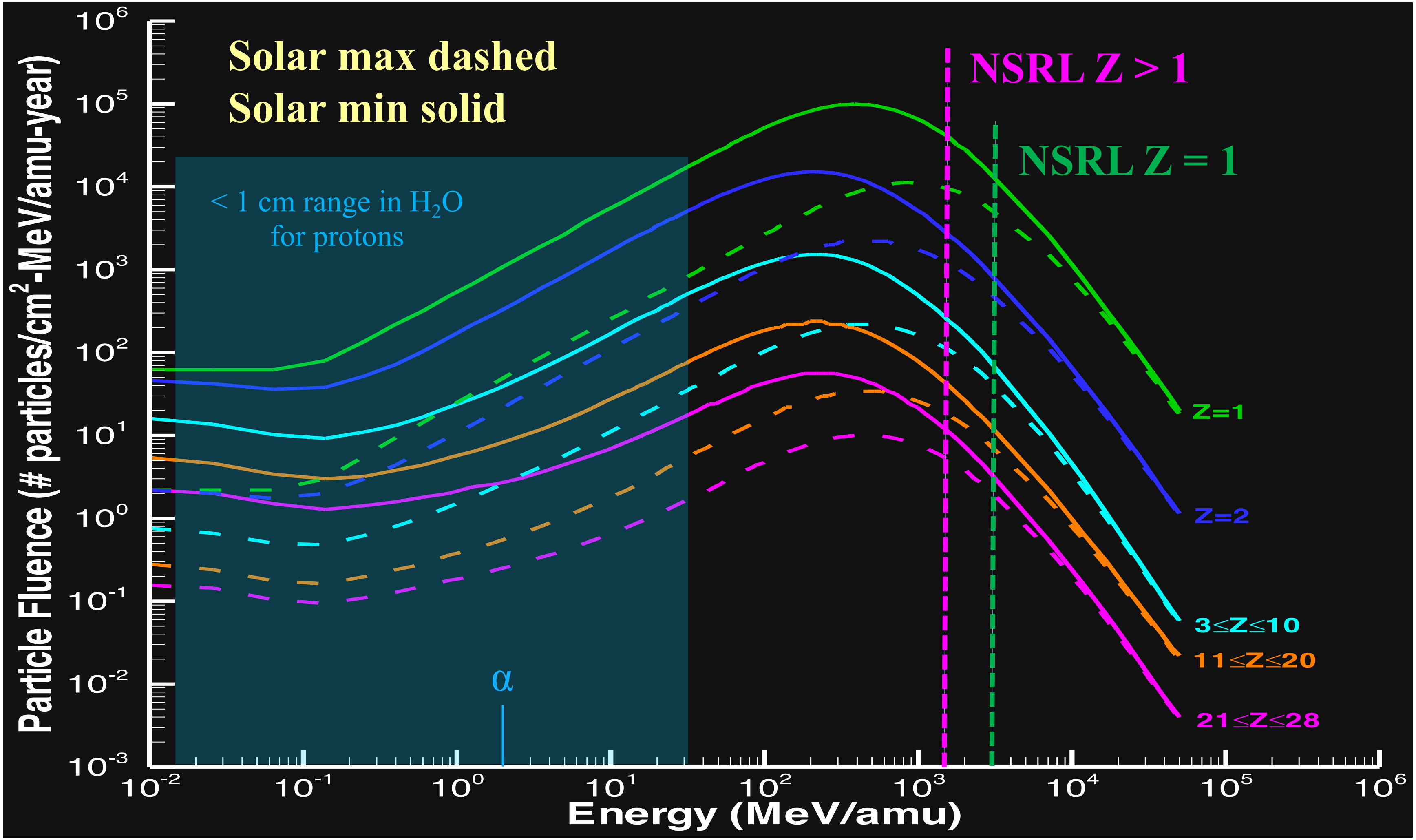
## Track Width Varies with $Z^2$




High Energy Sections of HZE Particle Tracks in Ilford G.5 Emulsion Flown on Apollo 8

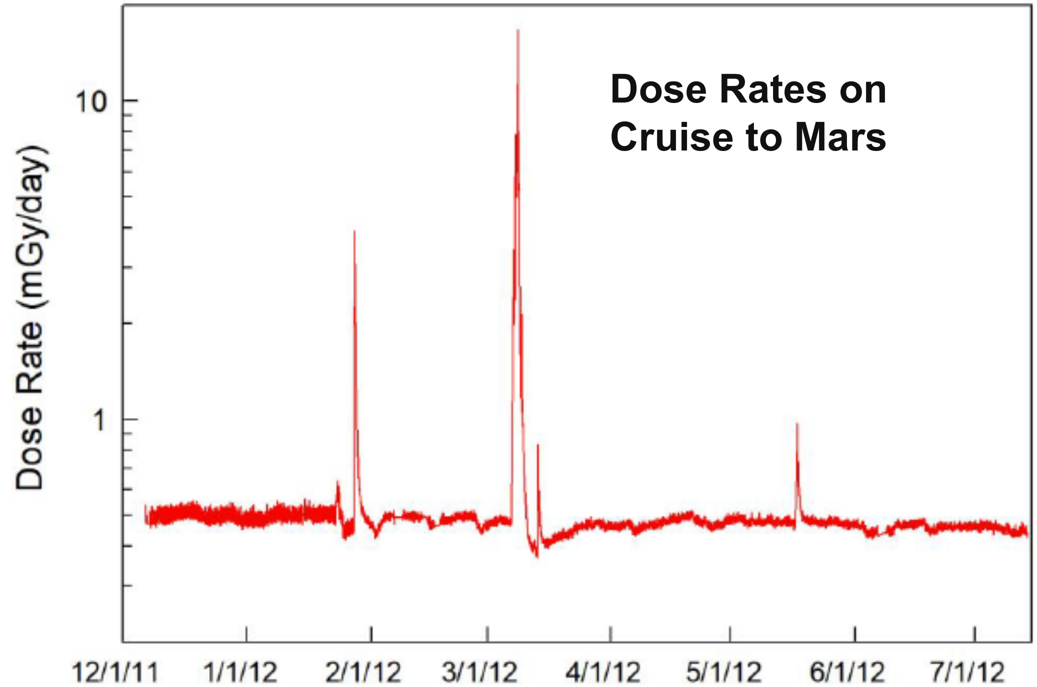
Schaefer & Sullivan, 1976

# Free Space GCR Environments at 1 AU



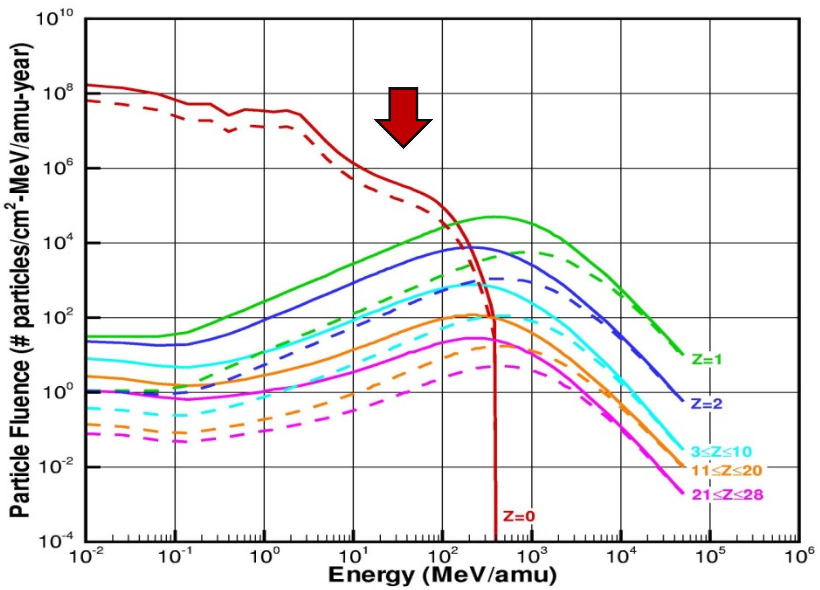

Modified from: M. S. Clowdsley, G. DeAngelis, J. W. Wilson, F. F. Badavi, and R. C. Singleterry

# Dose Rates Observed During Mars Mission: MSL



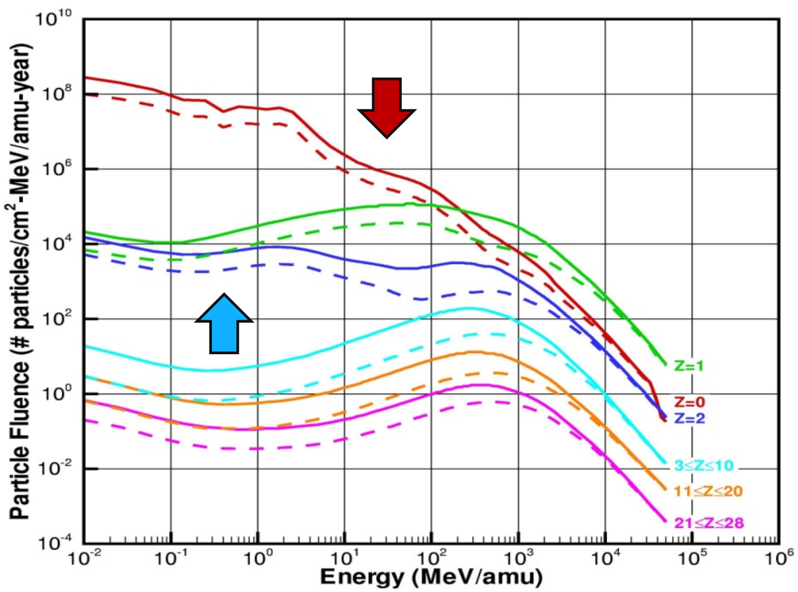

•Near-constant GCR + five SPE events
• SPE events contribution to total dose ~ 5%
•Average GCR absorbed dose rate 0.45 mGy/day

# The Deep Space GCR Environment is Modified in the Lunar and Mars Environments




Lunar GCR Environment

Neutron Component




Mars Surface GCR Environment

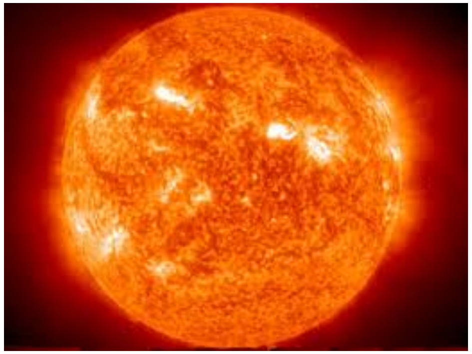
Neutron Component

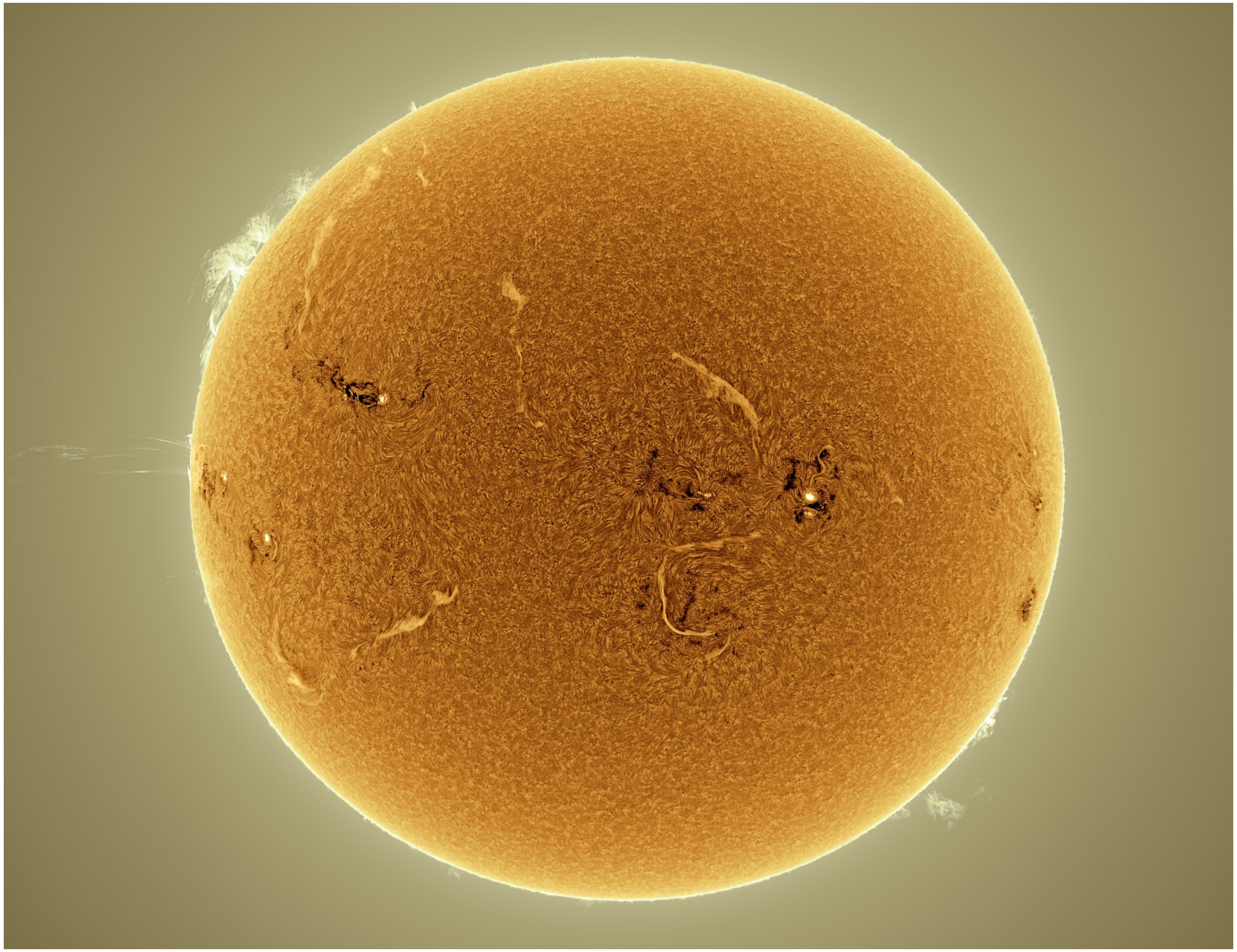
Atmospheric Shielding $2^o$'s

Cucinotta

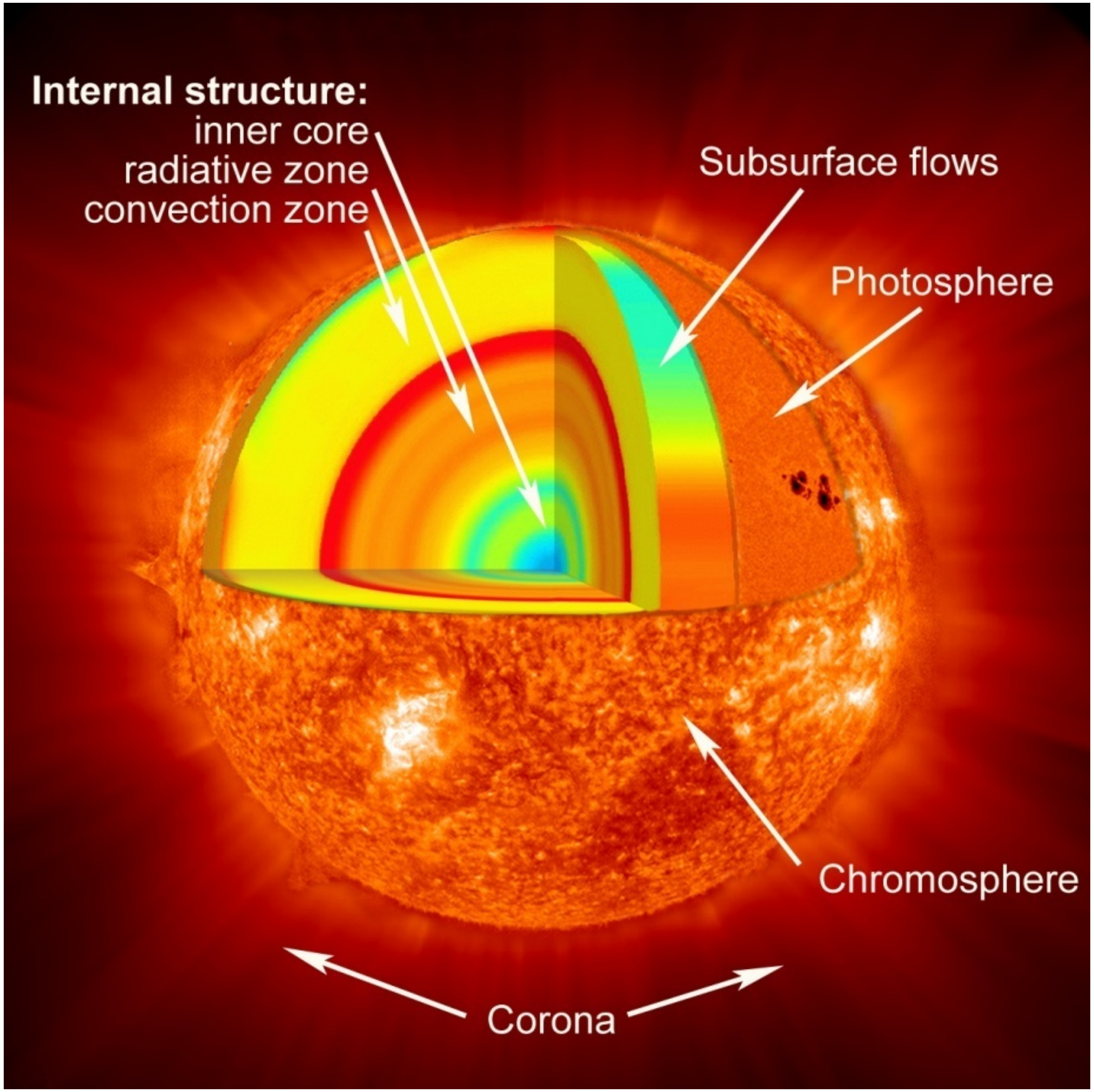
# The Sun

# The Sun is Composed Primarily of H & He Plasma



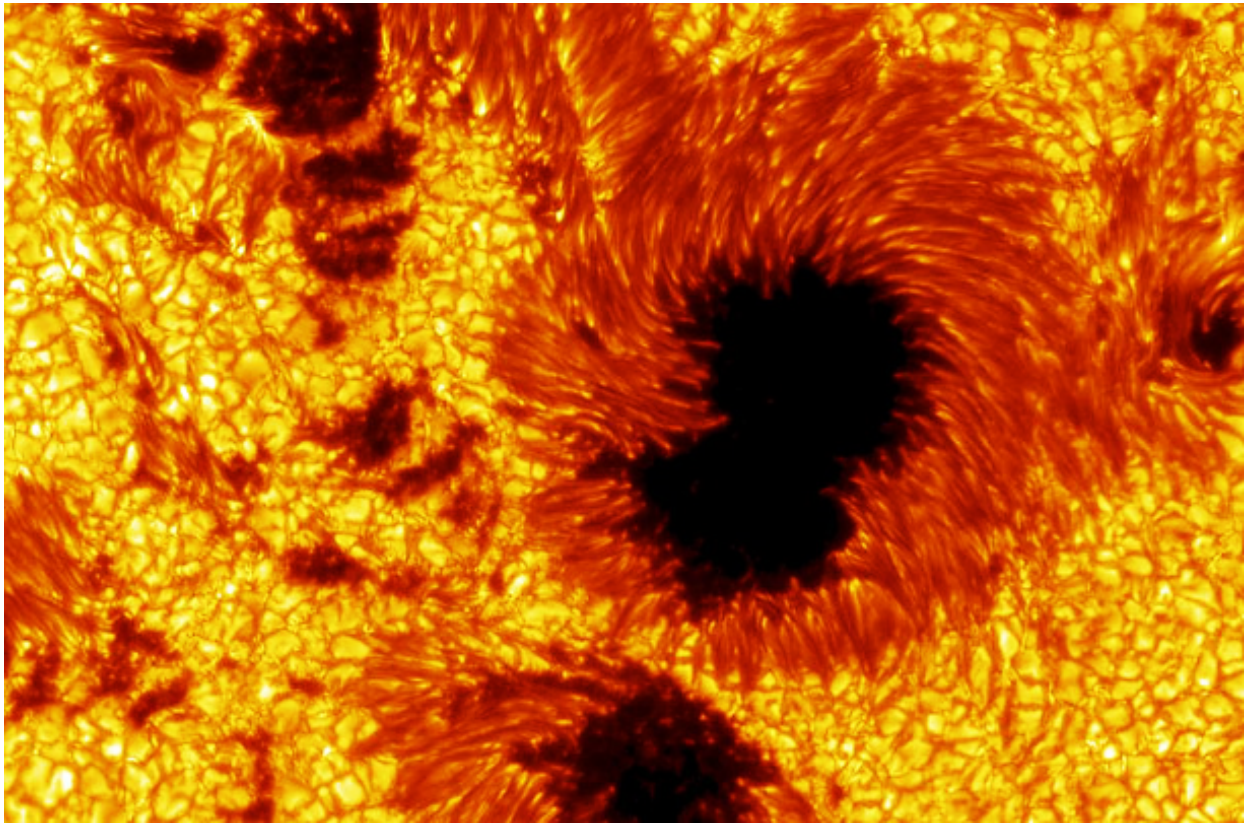


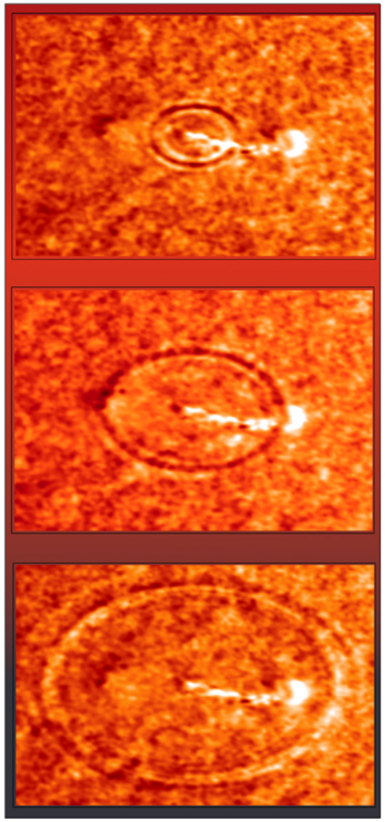
# Sun Structure




NOAA

# High Resolution Views of a Sunspot and a Solar "Quake"

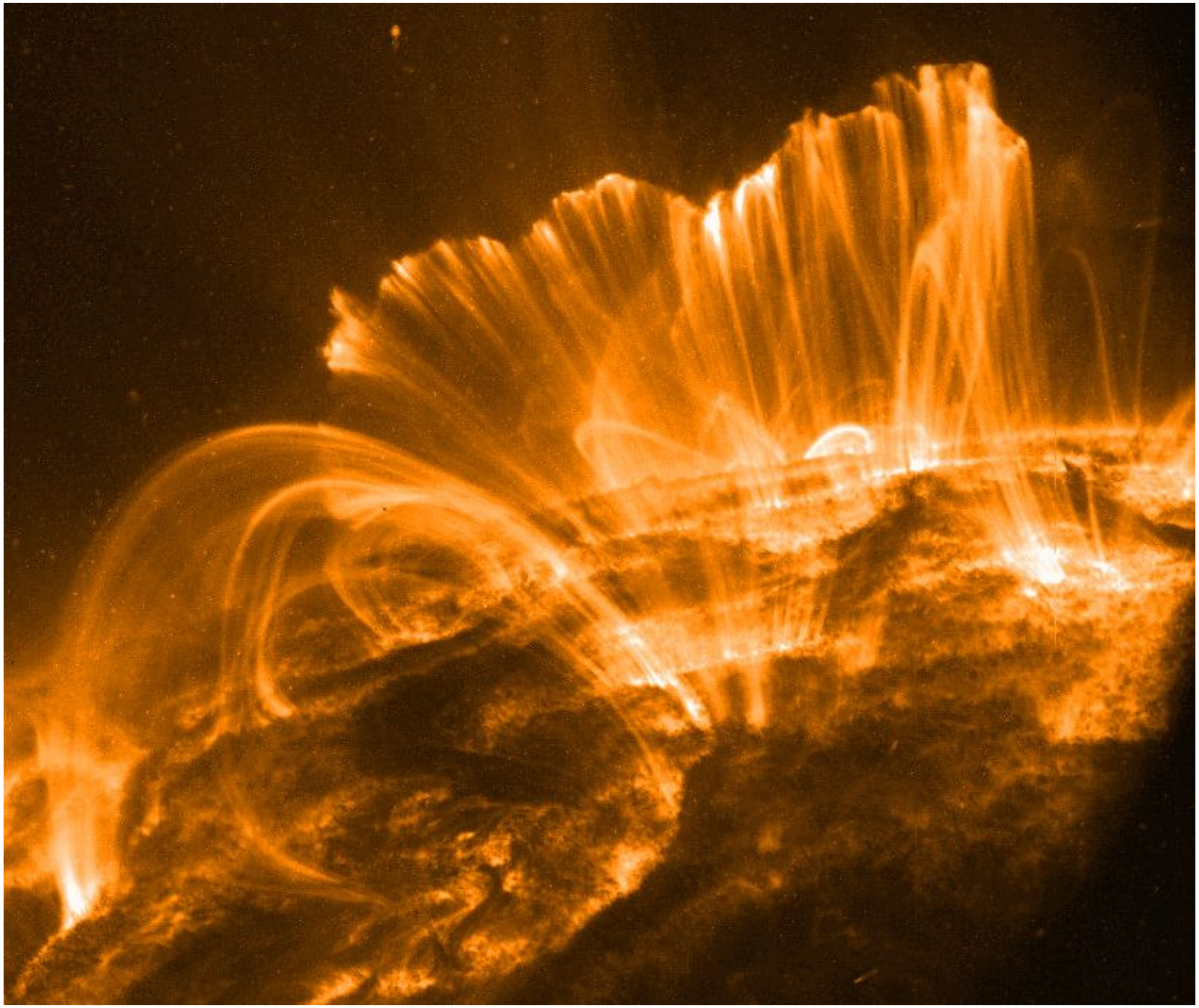




Solar Quake Sequence

NOAA

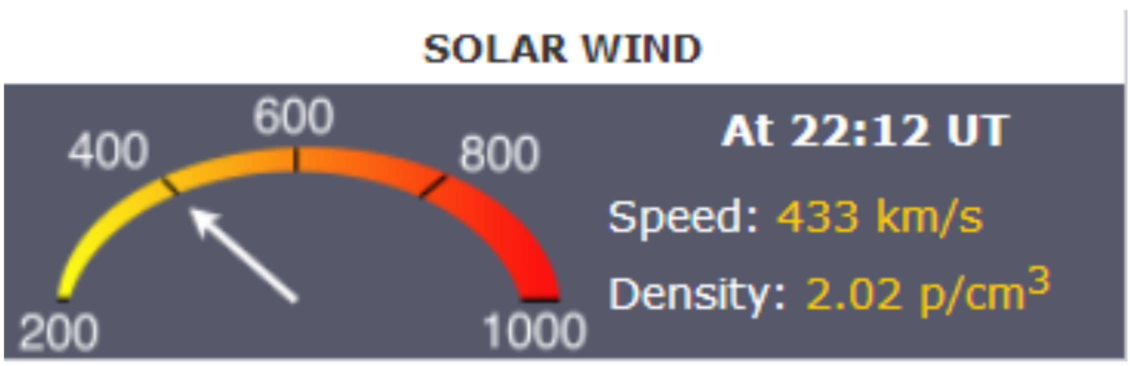
# Plasmas Generate and Follow Magnetic Field Lines



NASA

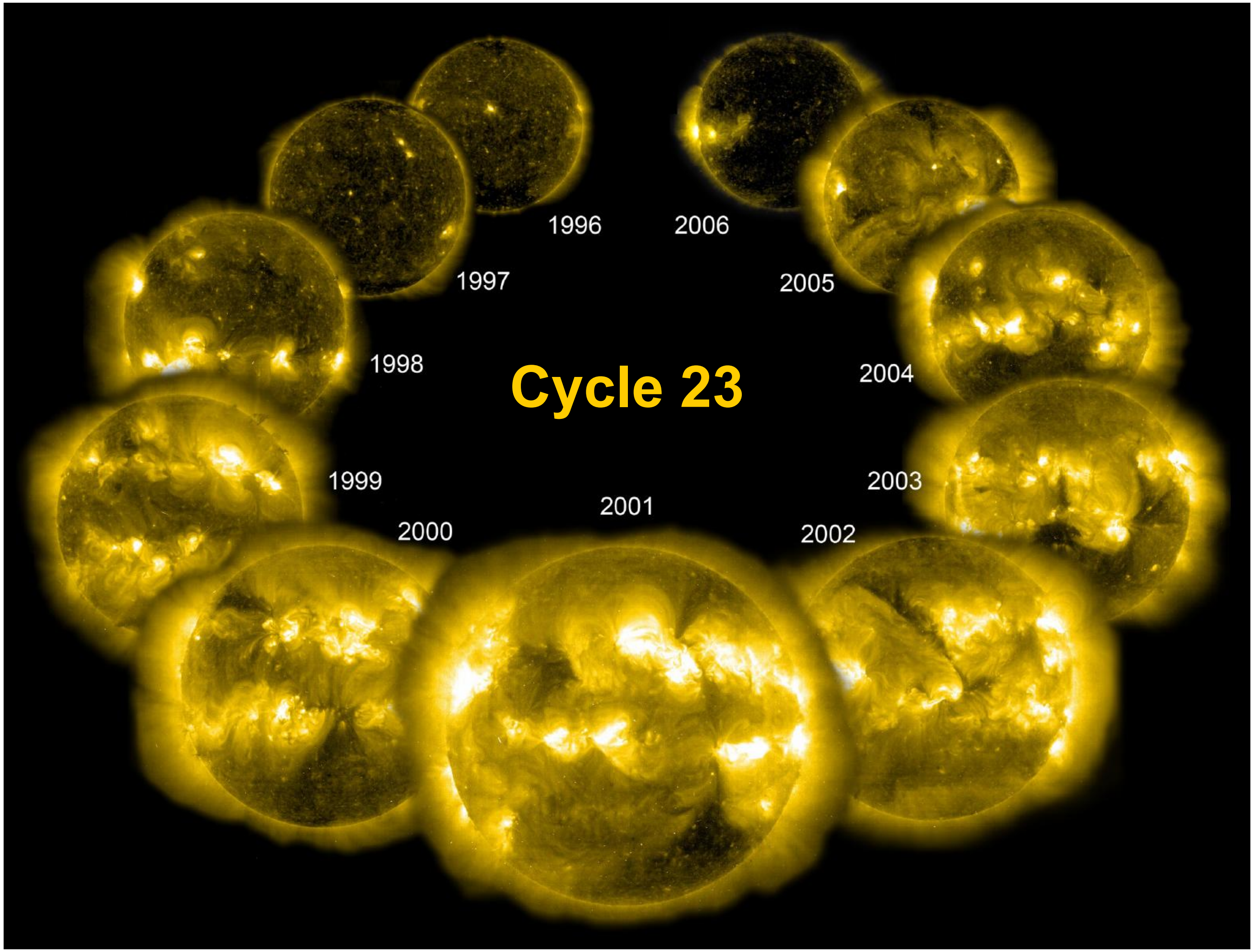
# Solar Wind

- Stream of charged particles from Sun's Corona
  - Protons, electrons & heavier ions at a density of ~ 1 to 30 per $cm^3$
- Magnetized plasma
- Detected at > 10 billion km from Earth by Pioneer and Voyager spacecraft
- Interface with interstellar space
- Velocity: ~300 - 900 km/sec
- Energy: 0.5 to 2.0 keV/n

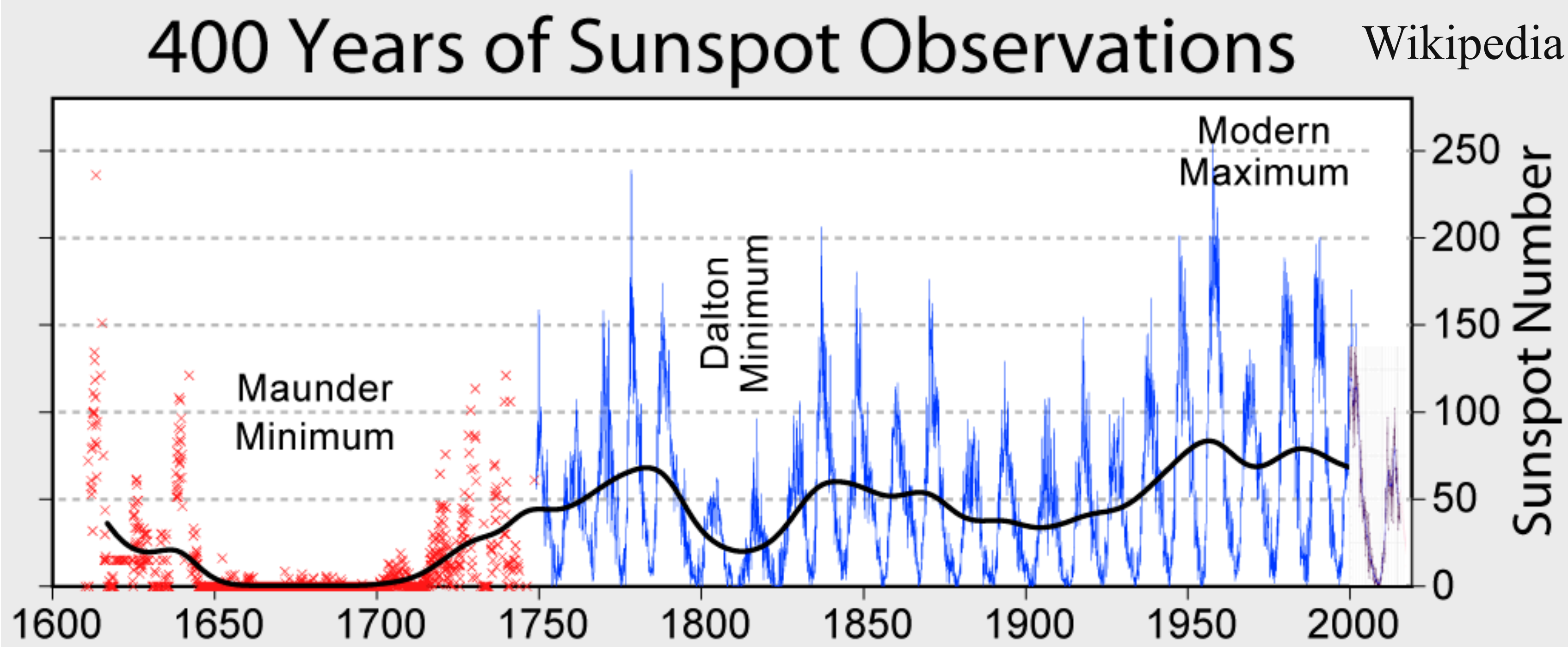


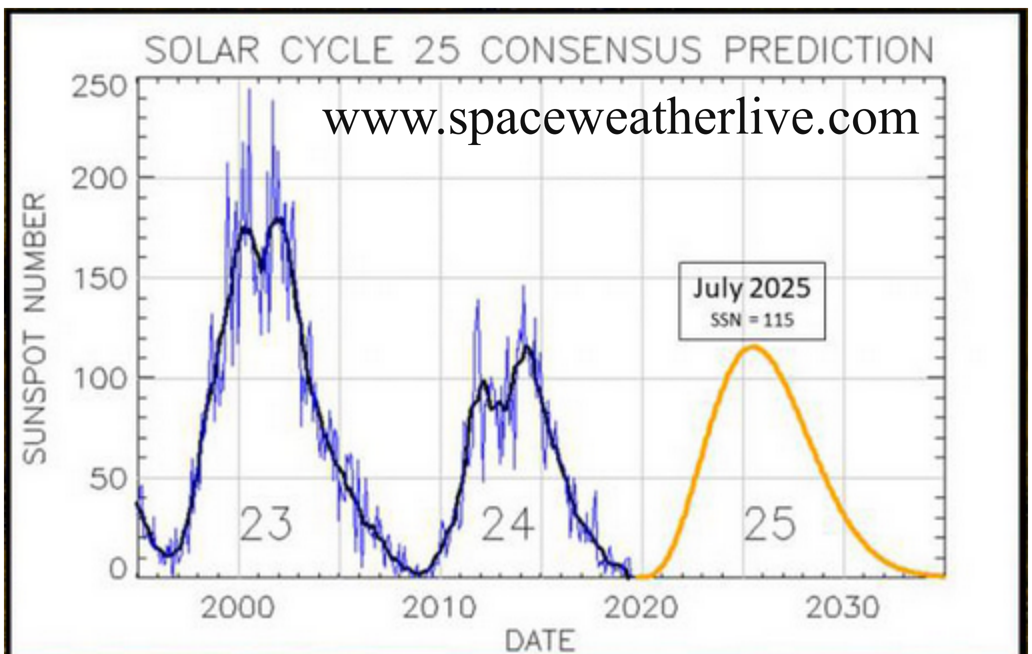

Typical solar wind
April 26, 2020
sohowww.nascom.nasa.gov

# Solar Cycle: 11-Year Variation in Luminosity Accompanied by Magnetic Field Reversal

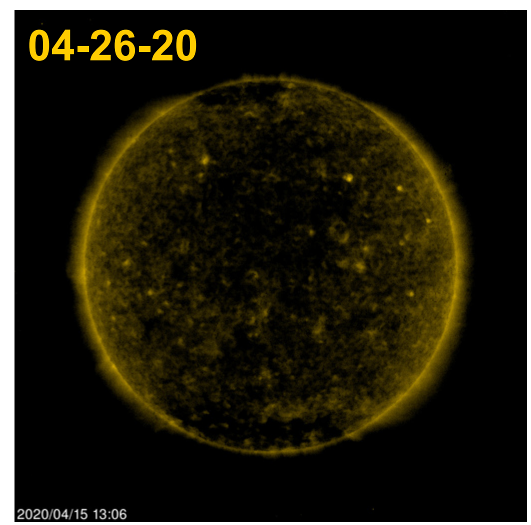



SOHO




The Sun Now: 284 nm



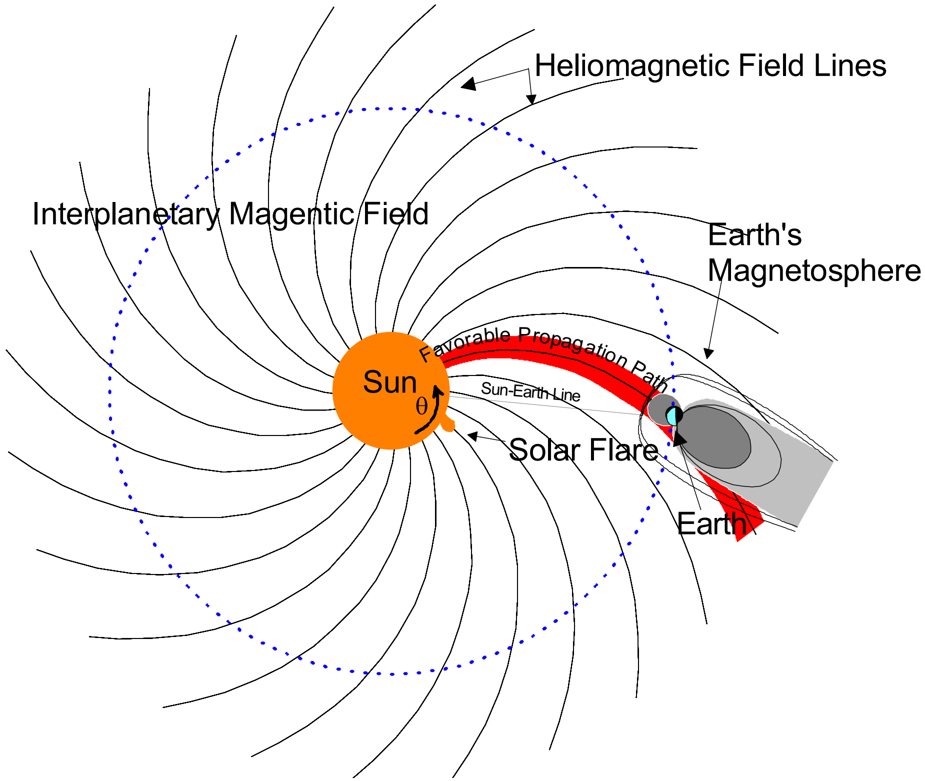

sohowww.nascom.nasa.gov

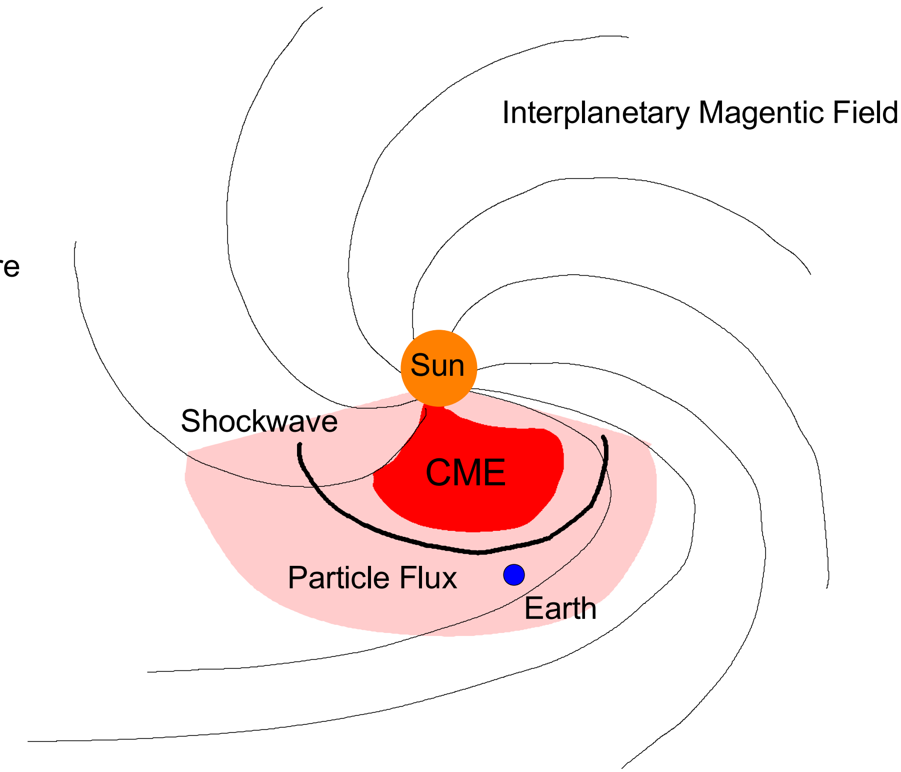
# Solar Particle Events

# Solar Particle Events

- Increased levels of protons and heavier ions
- Energies
  - Protons 100’s of MeV
  - Heavier ions – 100’s of GeV
- Abundances depend on radial distance from Sun
- Partially ionized species have greater ability to penetrate magnetosphere
- Frequency a function of solar cycle

# There Are Two Main Types of SPEs
## Impulsive (Flares) and Gradual (CMEs)



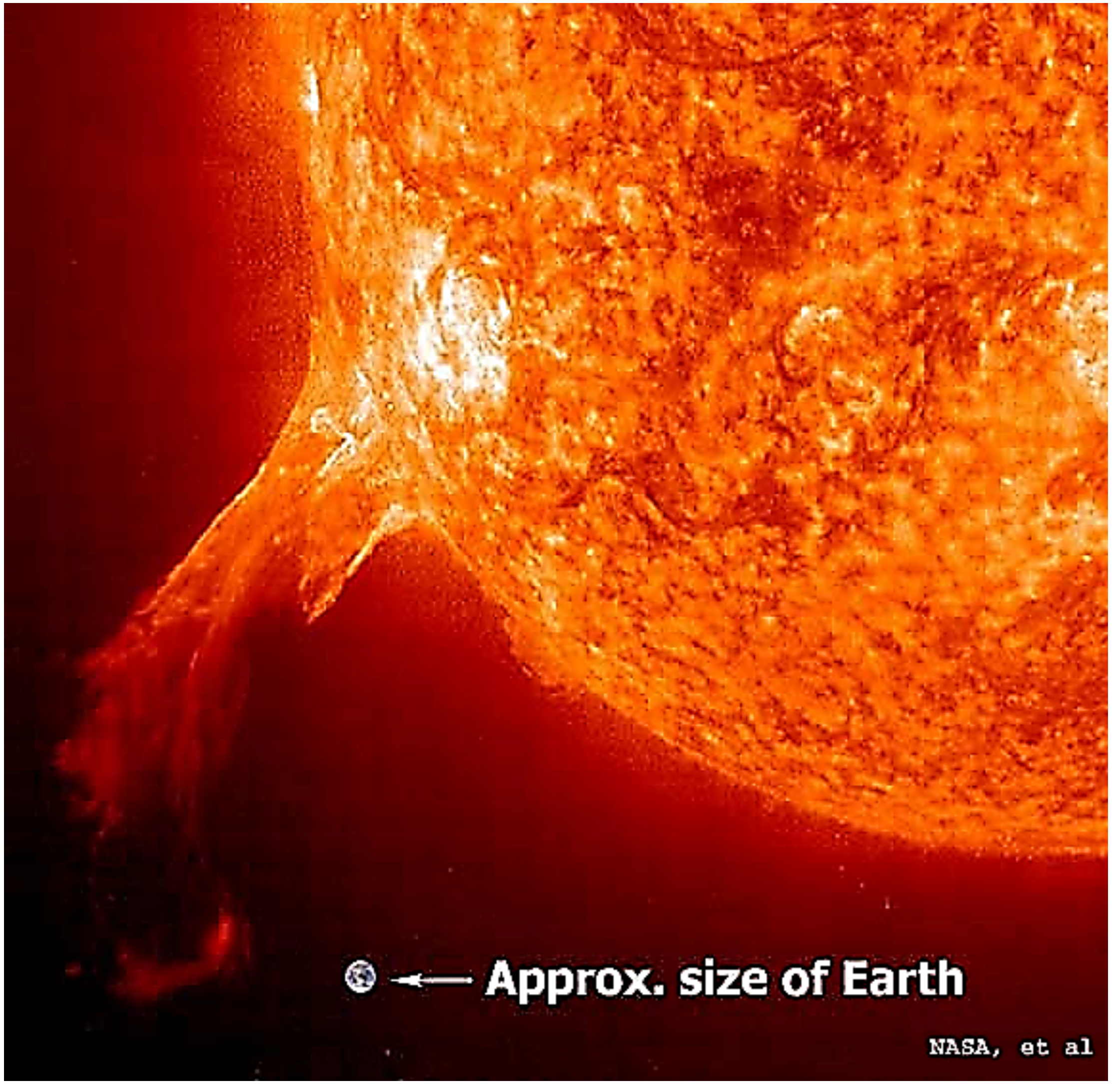

- Impulsive ~ 1000/year
  - Flare accelerated
  - Composition of flare plasma
- Gradual ~ 10/year
  - Coronal mass ejection driven shocks
  - Same composition as corona and solar wind

E.R. Benton, OSU

# Solar Flare (Impulsive Event)

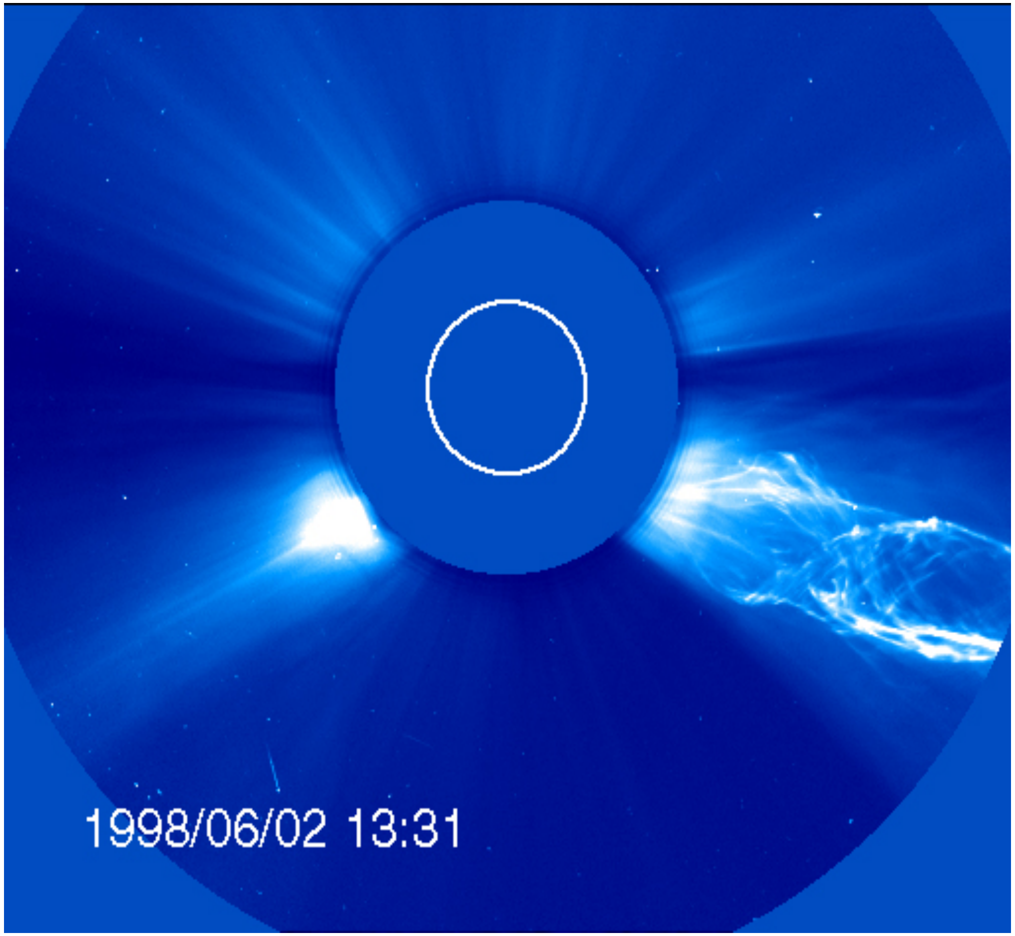
Particles arrive at Earth within minutes if field lines aligned.

Energy of particles is determined by events at Sun atmosphere



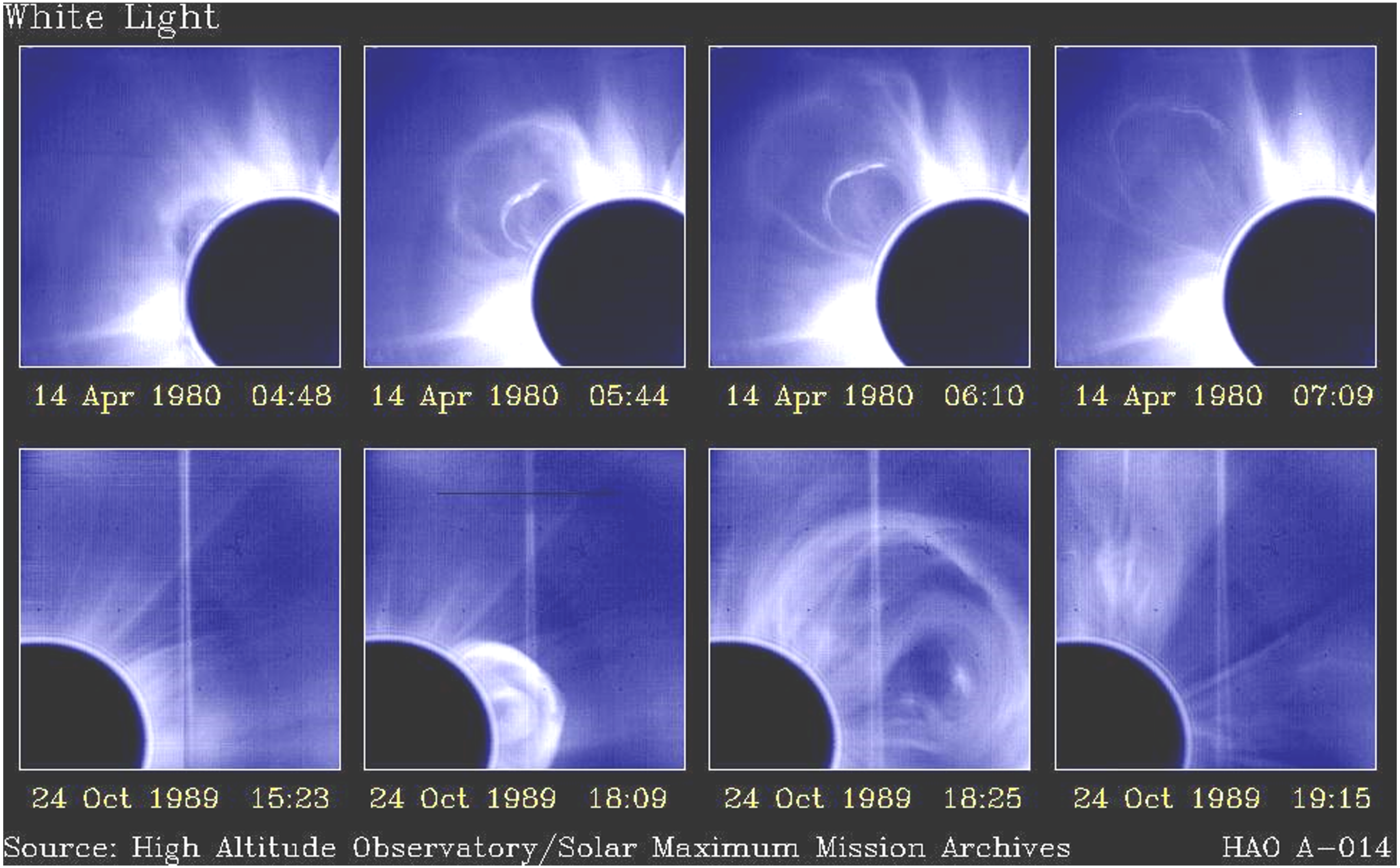
# Coronal Mass Ejections (Gradual Events)

- Bubble of gas and magnetic field
- Ejects ~$10^{17}$ g of matter
- Shock wave accelerates particles enroute to 3000 km/s vs 400 km/s for solar wind
- Reaches Earth after ~ 1 day
- Associated with magnetic storms
- Proton rich solar events 10 x worse than flares

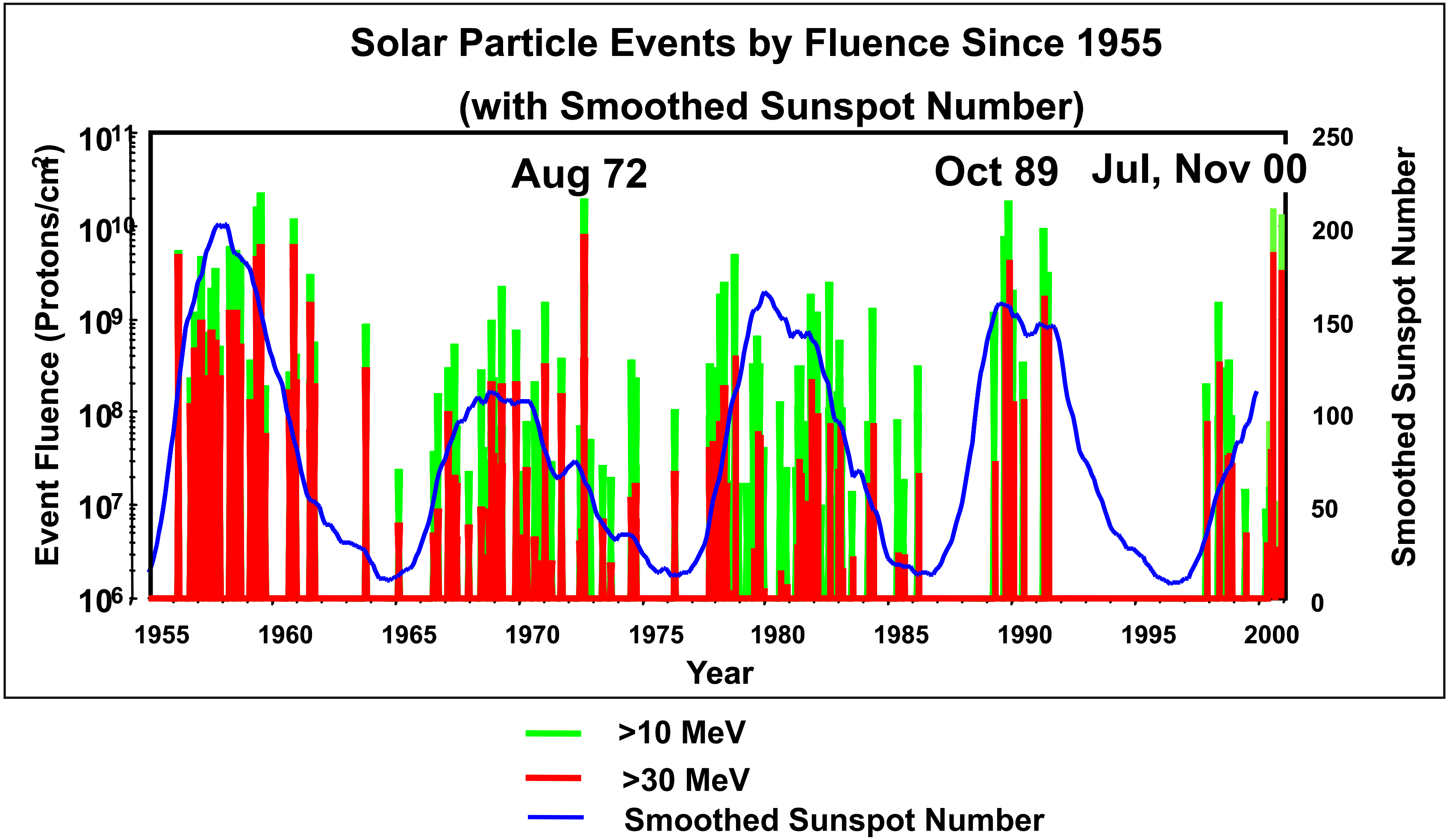


# Coronal Mass Ejections

## April 14, 1980 & October 24, 1989

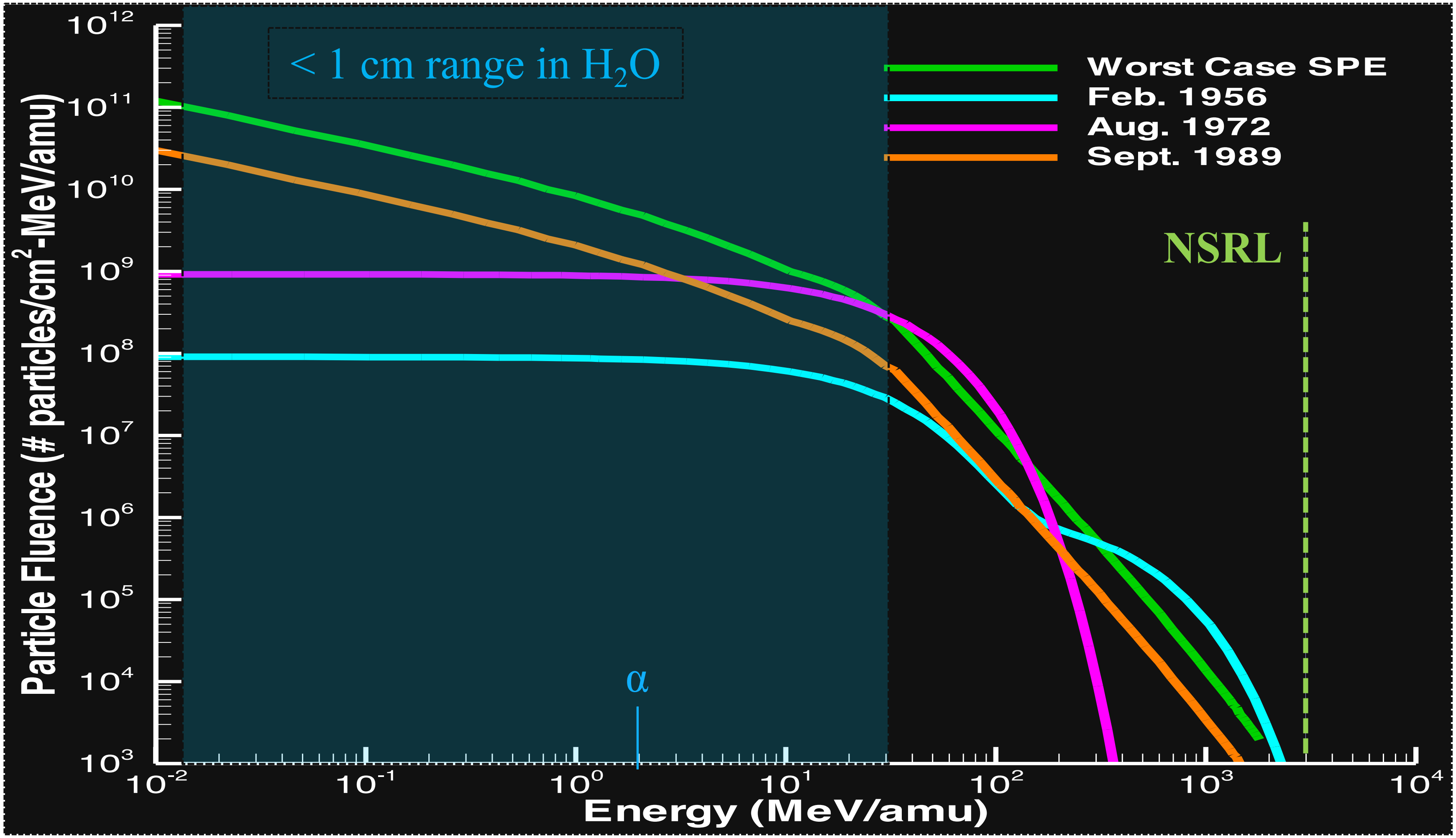


# Probability of Occurrence Varies with Solar Cycle



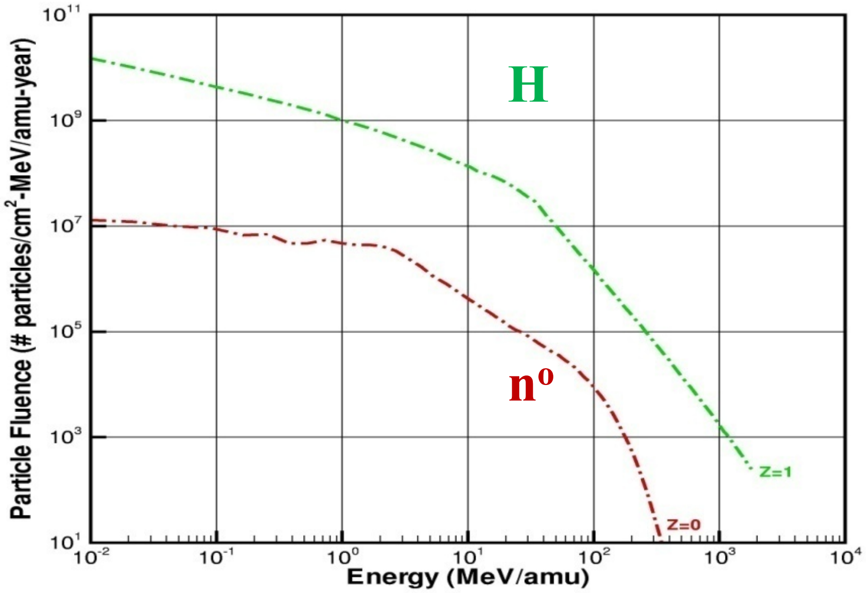

R Turner, ANSER, Inc.

# Free Space SPE Proton Spectra at 1 AU

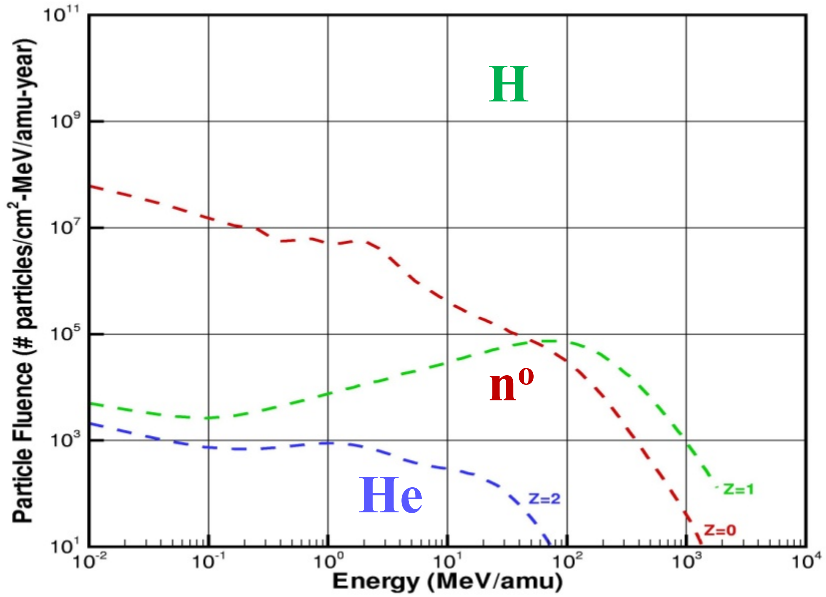



Modified from: M. S. Clowdsley, G. DeAngelis, J. W. Wilson, F. F. Badavi, and R. C. Singleterry

# The Deep Space SPE Environment is Modified in the Lunar and Mars Environments




Sept. 29, 1989 SPE On
Lunar surface




Sept. 29, 1989 SPE On
Martian surface

Cucinotta

# Time Course of August 1972 CME

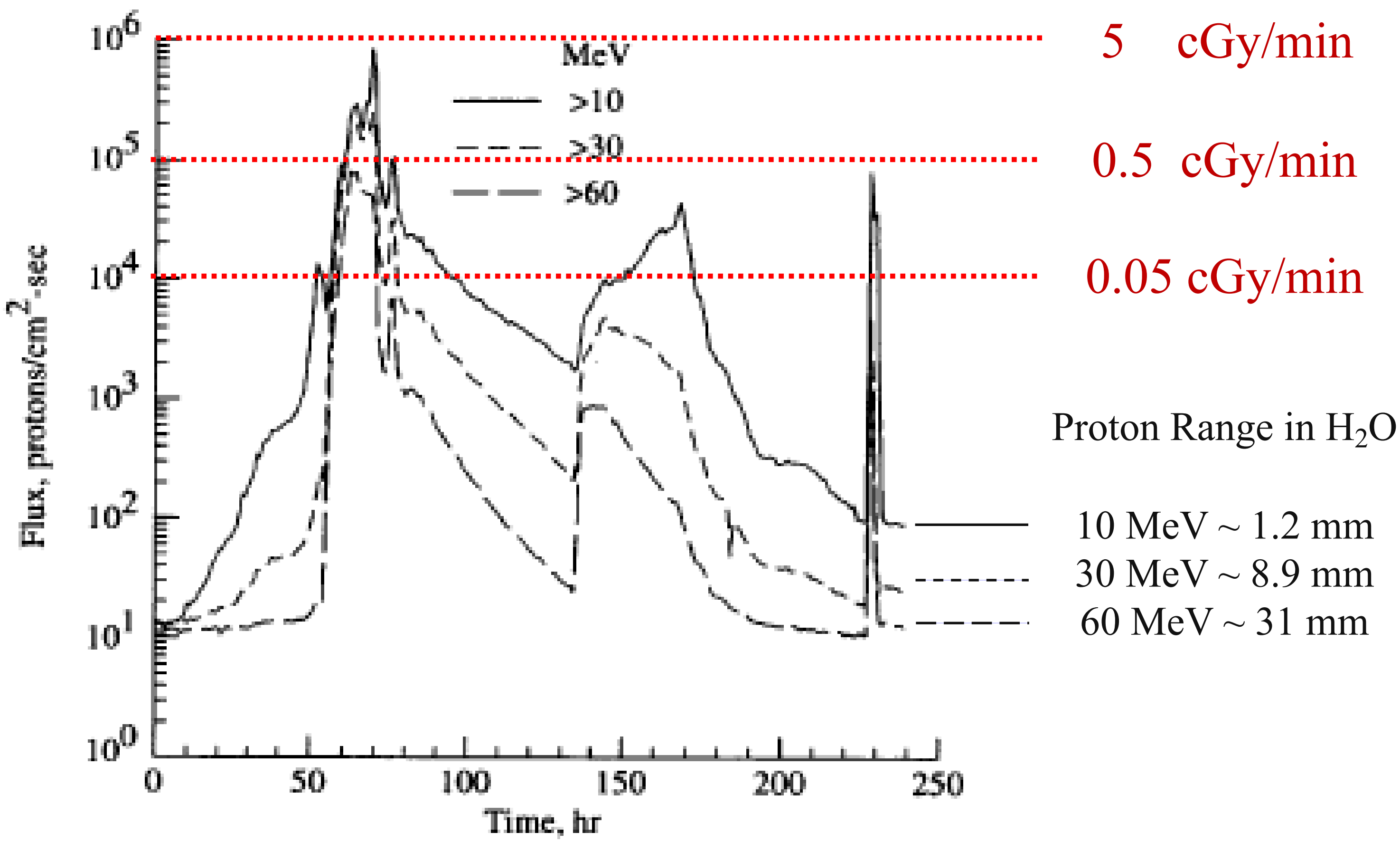



Figure 4. Measured intensities at 1 au of solar event of August 2–11, 1972.

Wilson et al. (1997) Exposures to Solar Particle Events in Deep Space. NASA TP3668

# Cumulative Size Distribution of SPEs

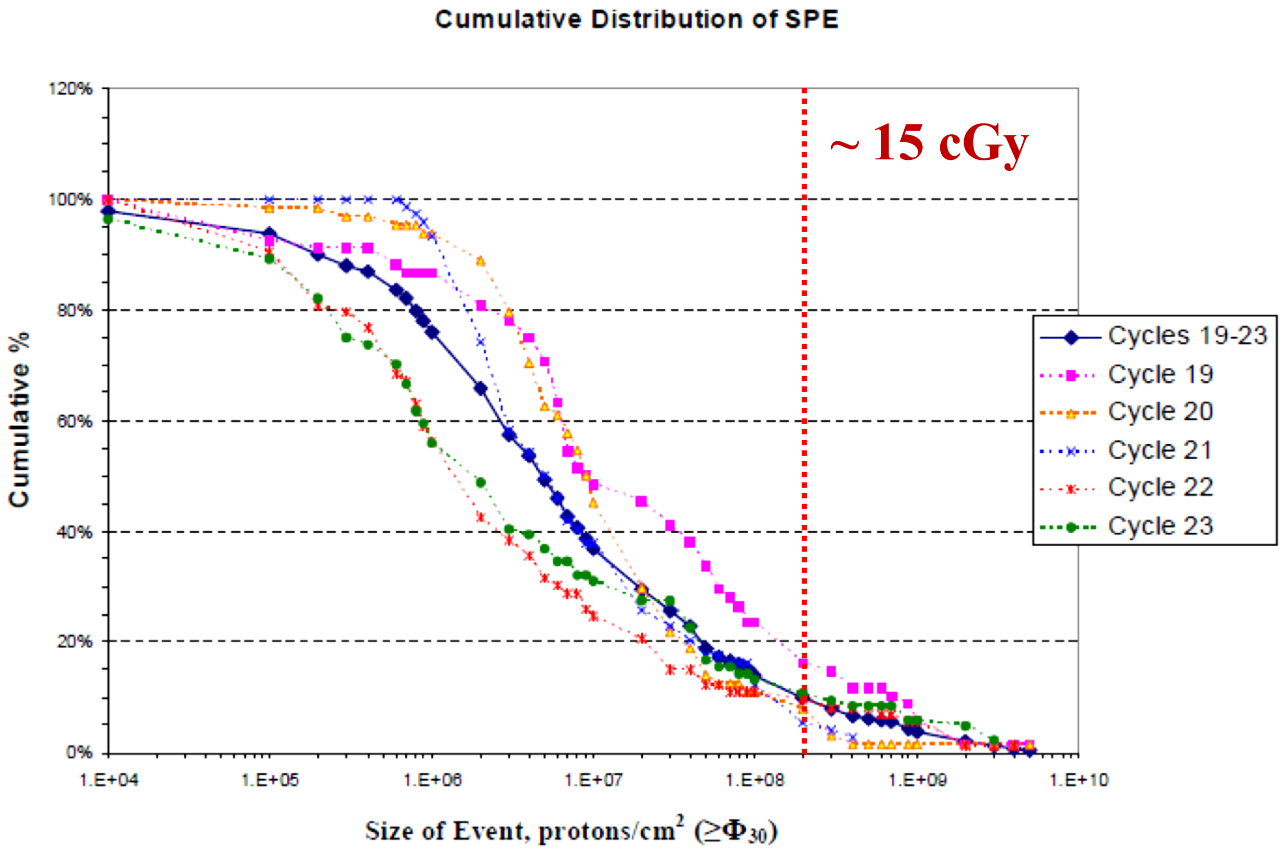



FIGURE 2-9. Cumulative Distribution of SPE. SOURCE: F. Cucinotta, NASA. "Radiation risk assessments for lunar missions-shielding evaluation criteria", Presented to the committee on December 12, 2006.

~ 10% of SPE's Result in Cumulative Doses (BFO) > 15 cGy

Nat. Res. Council (2008) Managing Space Radiation Risk in the New Era of Space Exploration

# Potential SPE Exposures

A modest SPE under nominal shielding in deep space

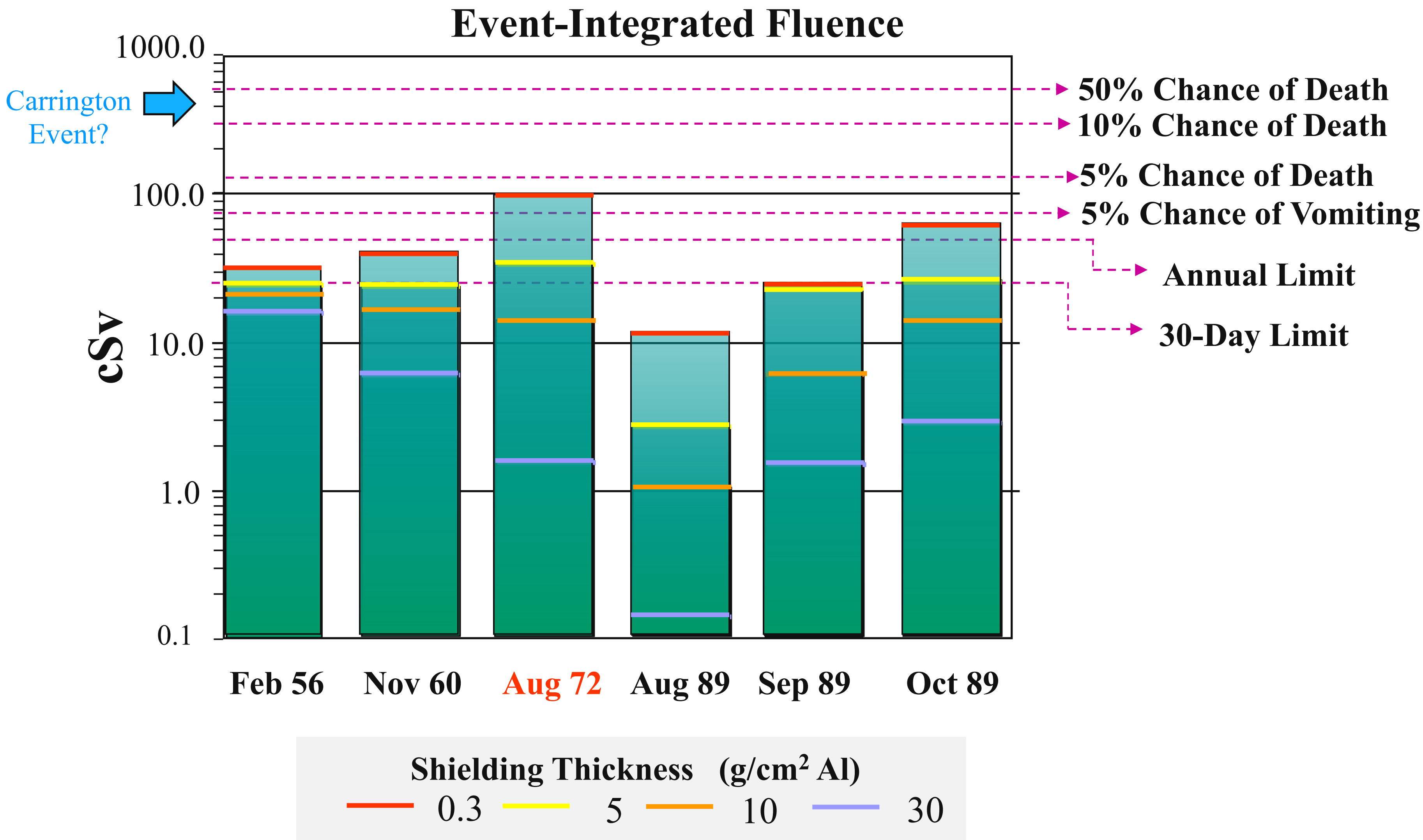
Will be on the order of 1-10 cSv (BFO)
Equals 10 to 250 days on orbit in ISS
Equals one month GCR dose on the way to Mars

Equals 100 to 1000 chest x-rays
Equals 3-30 years annual dose for public

An astronaut on EVA can get 3 to 5 times the shielded dose

# How Bad Can an SPE Be?

## Lunar Surface-EVA BFO Dose Equivalent (cSv)



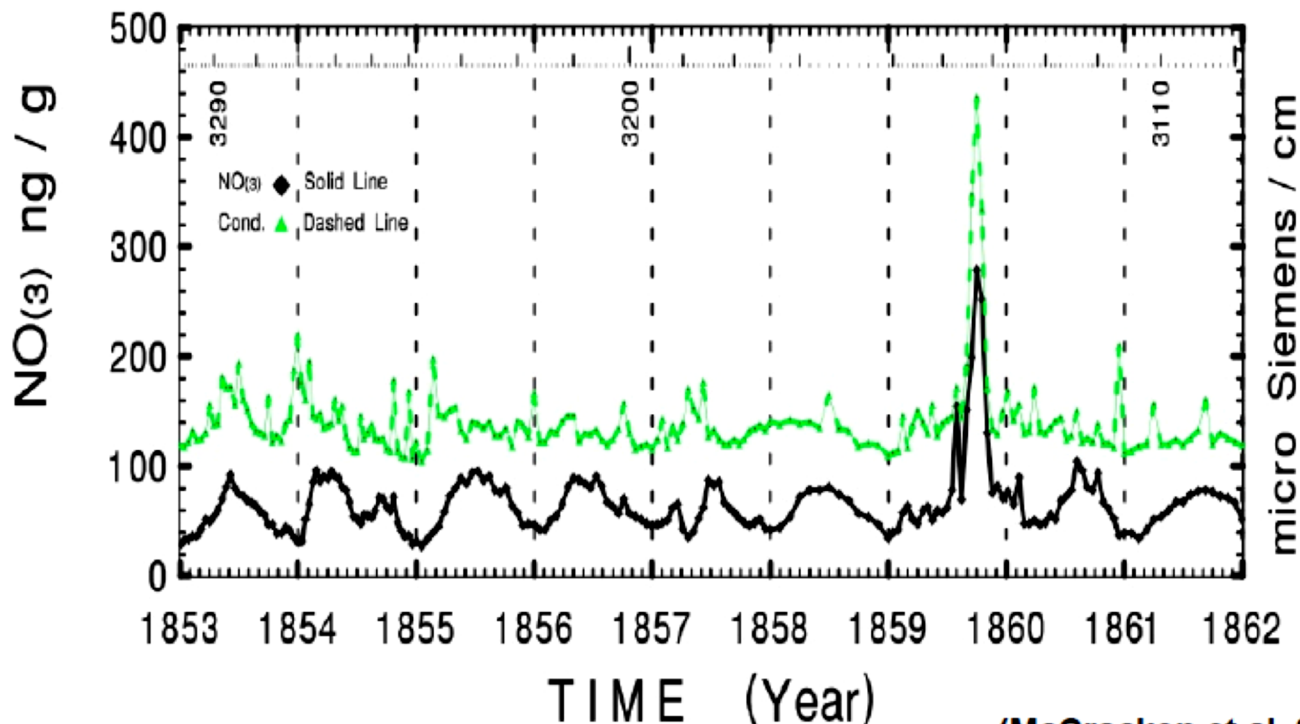

Modified from R. Turner

# Largest Observed CME

## "Carrington Event" 9/1/1859

**The largest event in the ice-core record occurred at 1859.75, in close correlation with the September 1 1859 white light flare seen by Carrington.**

**The fluence was conservatively estimated to be 19 x $10^9$ protons/cm$^2$ with >30 MeV; ~4 times the fluence of the Aug. 1972 event**




**(McCracken et al. 2001)**

Dose derived from nitrate concentration in Greenland Ice Cores

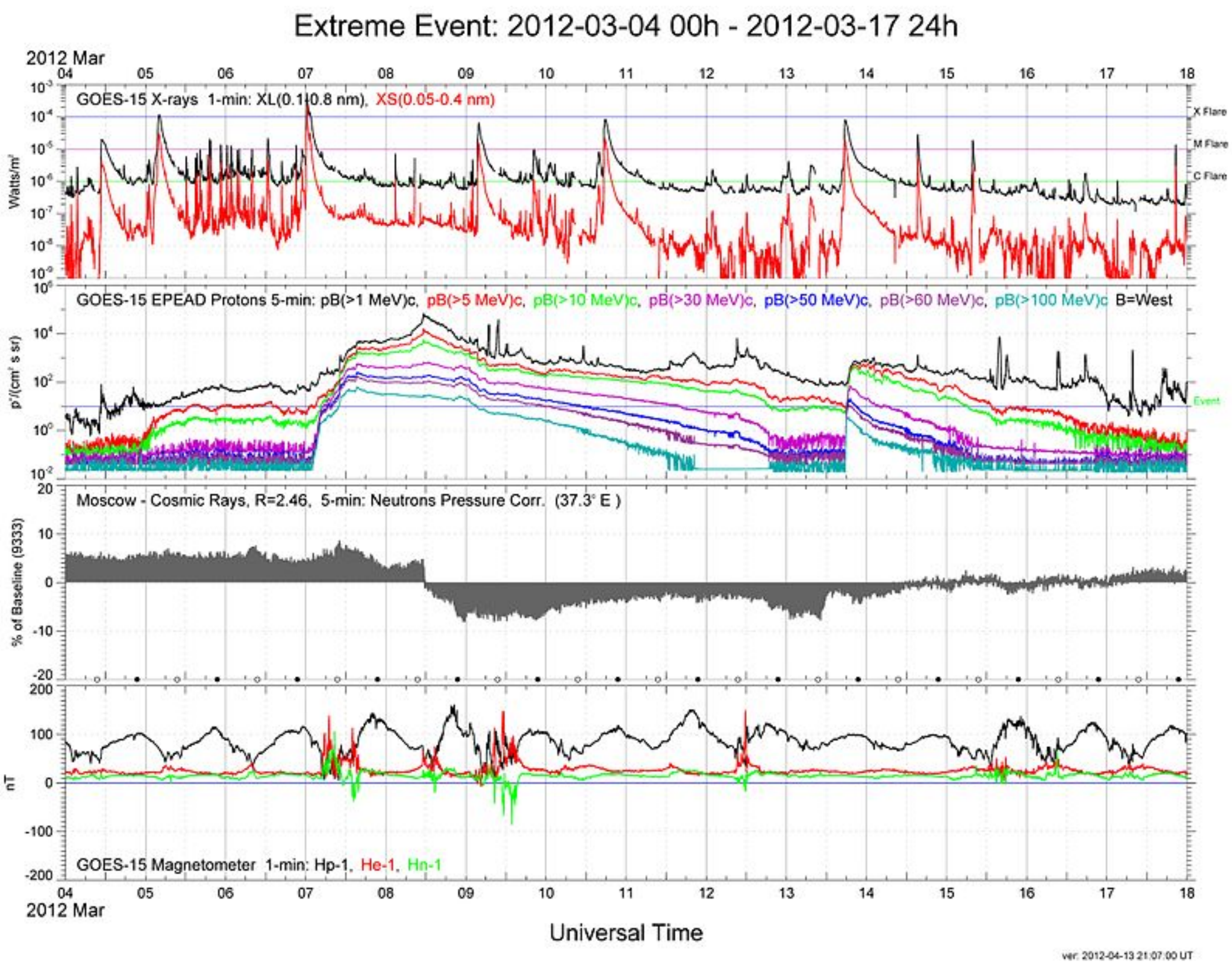
# Space Weather Prediction

X-rays

Protons

Neutrons

Mag. Field

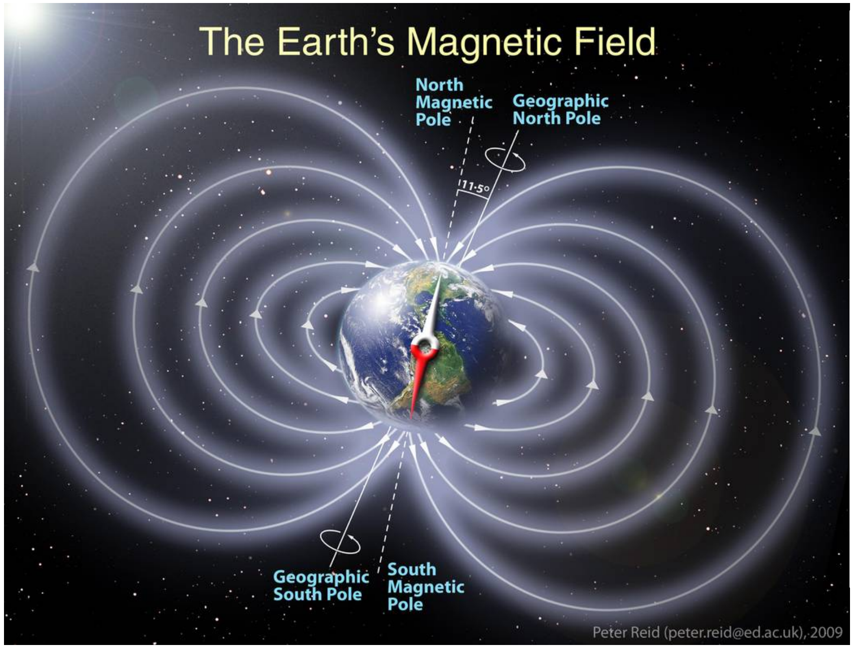


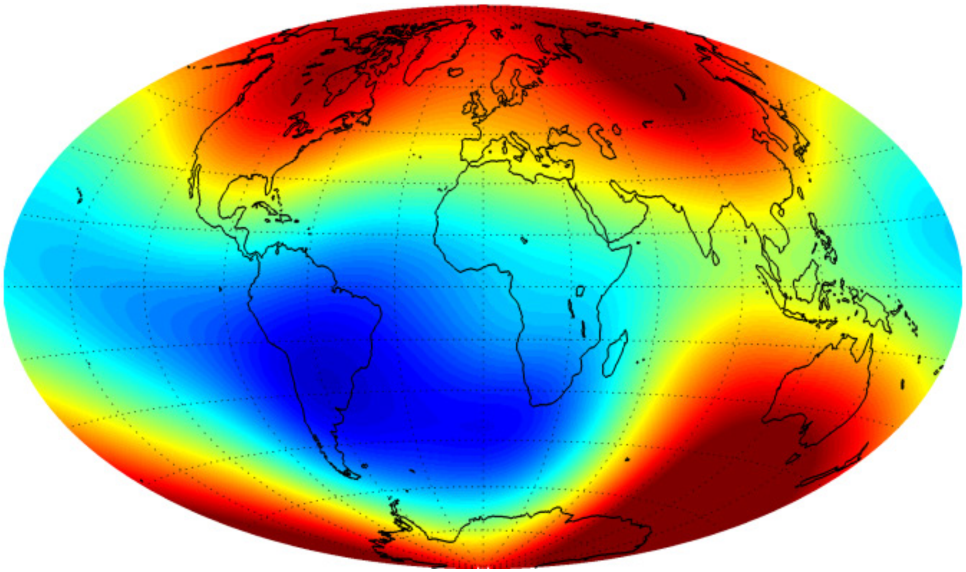

GOES Satellites

http://www.swpc.noaa.gov

# Geomagnetic Field and Trapped Radiation Belts

# Earths Magnetic Field



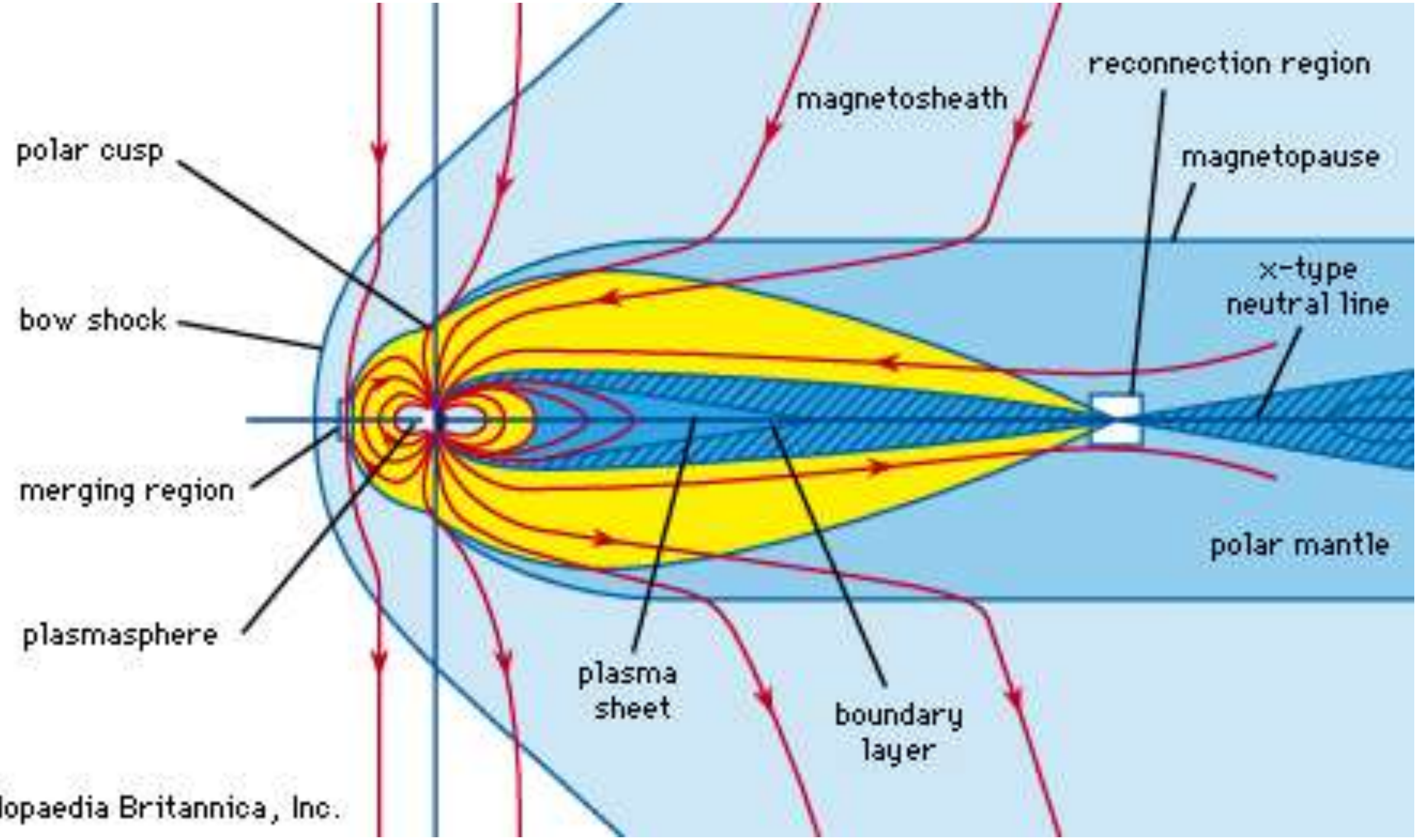



Approximately Dipolar Field
0.5 Gauss ($5 \times 10^{-5}$ Tesla)
Magnetic South is at Geographic North

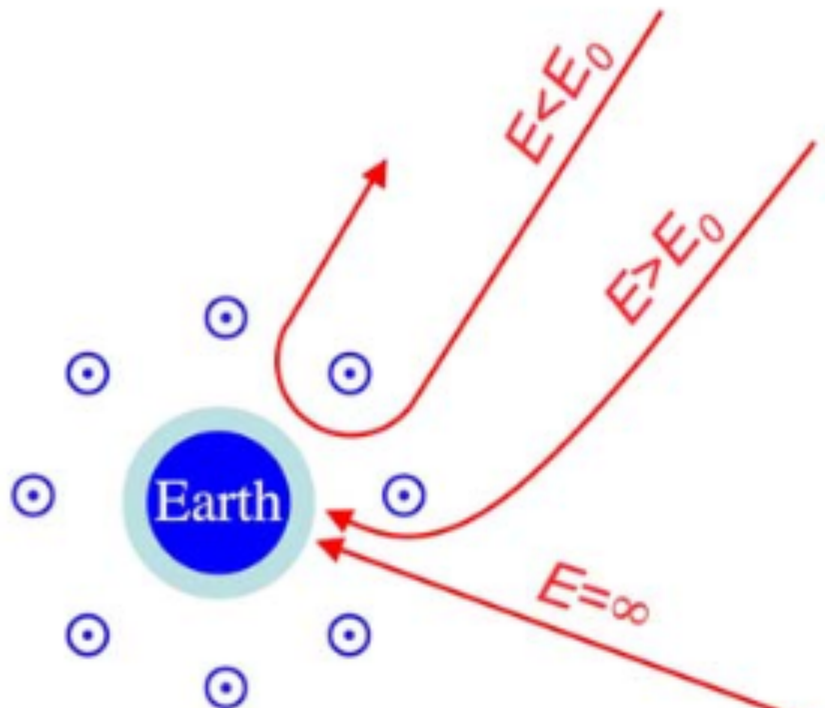
Field Strength at Surface (2014)
Red is strong, Blue is Weak

NASA

# Modification of Geomagnetic Field by Solar Interactions



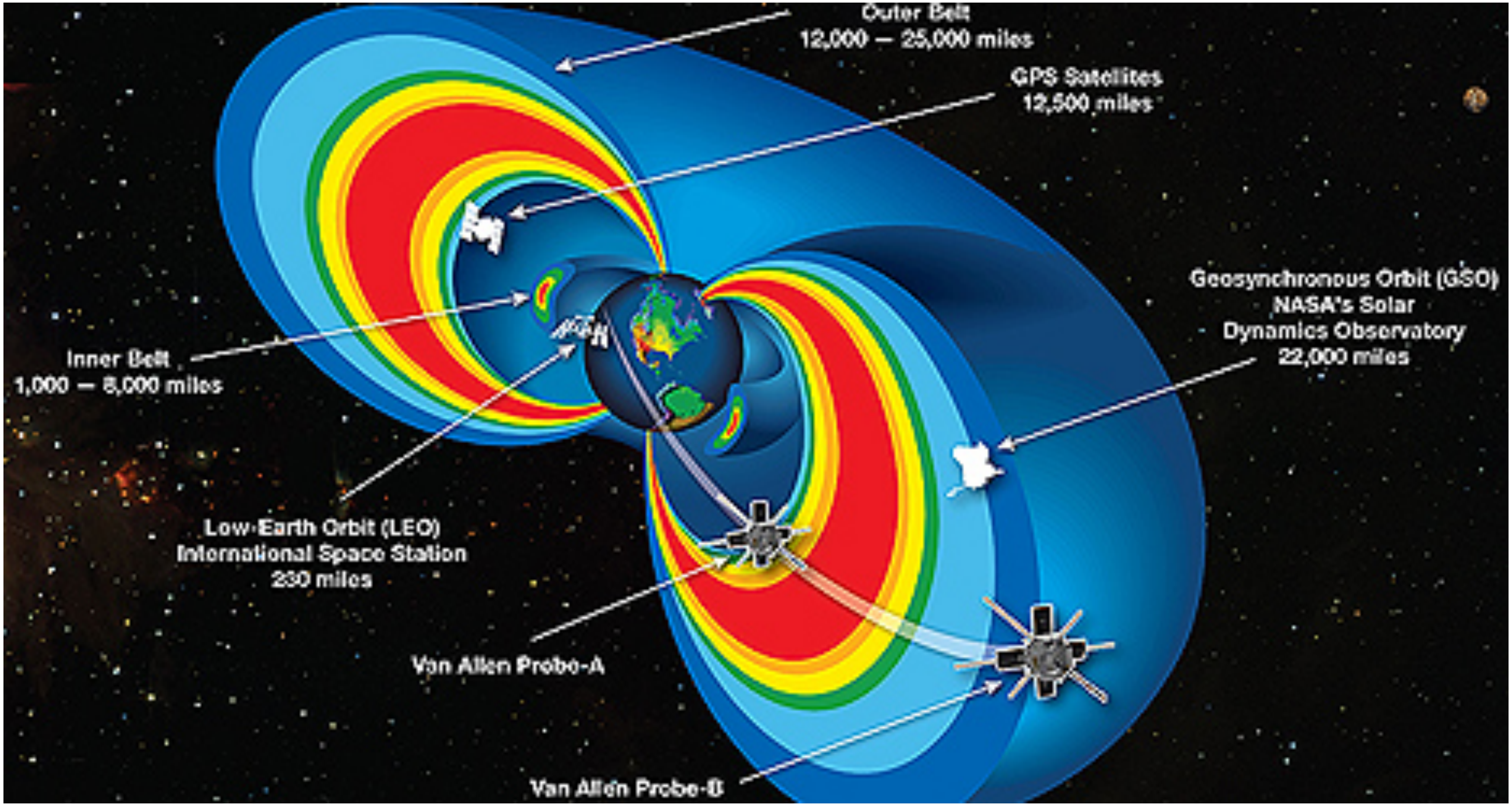
# Cosmic Ray Trajectories in the Geomagnetic Field




There are three types of orbits, depending on the energy of the incoming particle.

$E_o$ is Geomagnetic Cutoff Energy in the Range of ~ 1 – 10 GeV (not GeV/n).

# Van Allen Radiation Belts



# Van Allen Belt Particles

- Components:
  - Protons: E ~ 0.04 to 500 MeV
  - Electrons: E ~ 0.04 to 7 MeV
    - Stopped by 6 mm of Al
  - Heavier Ions: E Low
- Location of peak levels is E dependent
  - Peaks at ~1500 nm
- Lowest point ~ 200 nm over South Atlantic
- Location of populations shifts with time
- Average counts vary slowly with solar cycle
- Counts may increase by orders of magnitude with magnetic storms

# Variations in Solar Luminosity Affect the Trapped Belt Spectrum

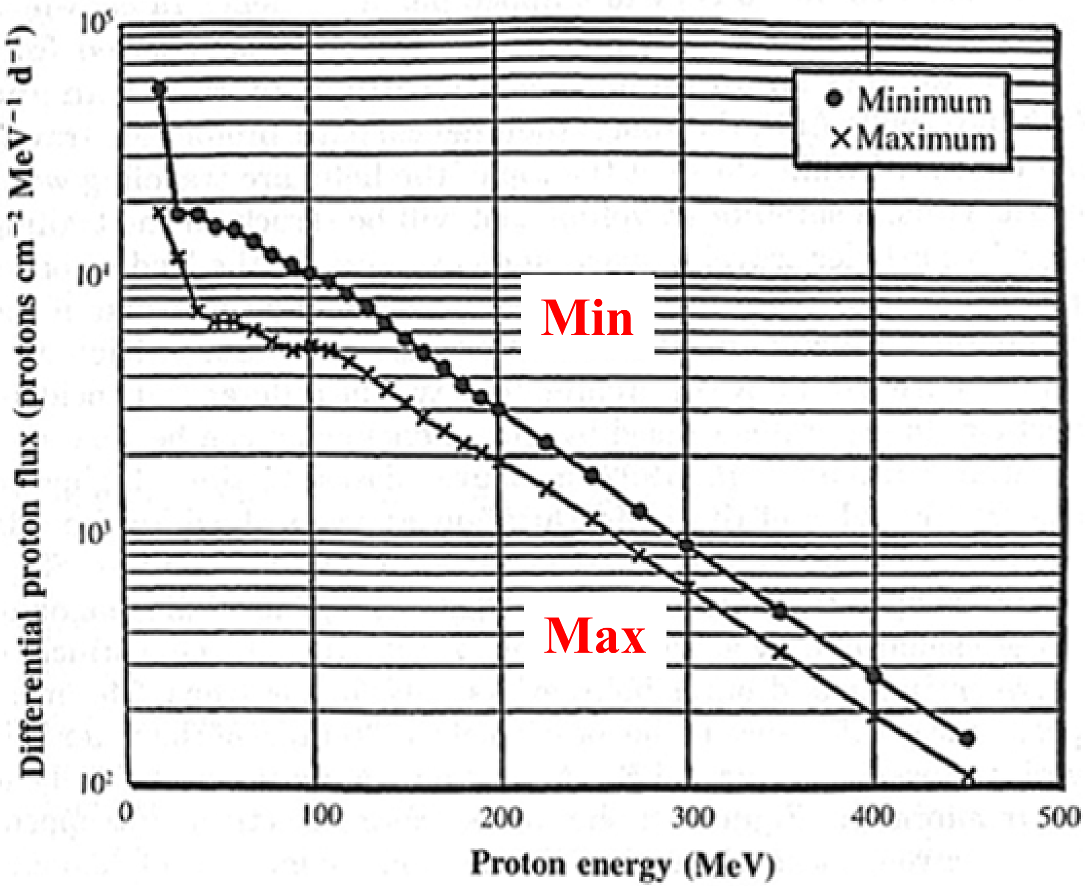



**Fig. 3.3.** Trapped-belt proton spectrum for the ISS orbit (51.6 degrees inclination, 470 km altitude) using AP-8 models for solar maximum and minimum (Atwell, 1999)[5].

Solar Minimum
vs.
Solar Maximum

Counter-intuitive
Nomenclaturee

# Temporal Variations

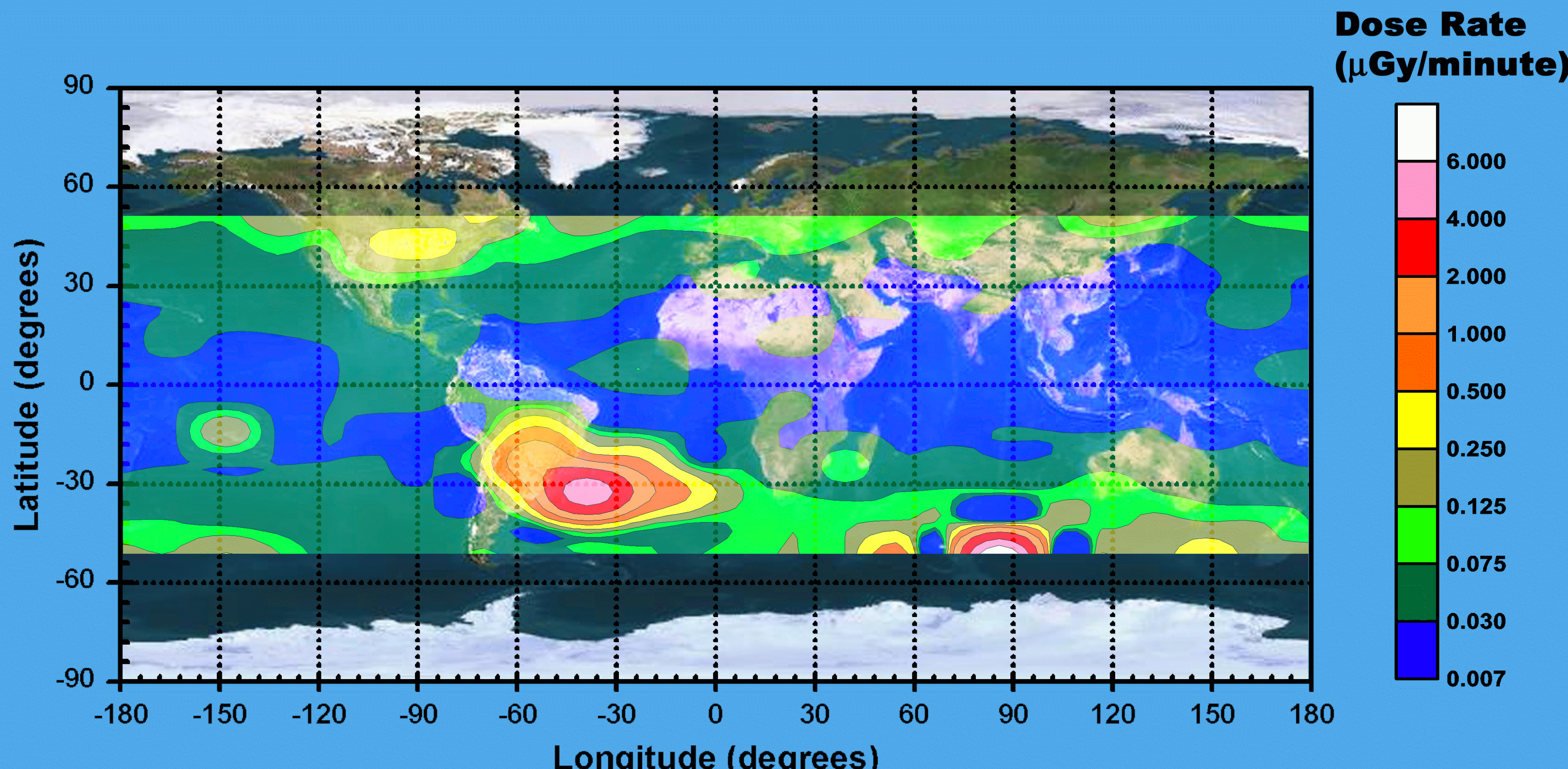
## Protons

- Fairly Stable
  - Highest levels at solar max
  - Lowest levels at solar min
  - ~ 6% change per year
  - ~2-fold difference between solar min and max
- Geomagnetic field shift changes location
  - ~6 degrees westward shift in longitude in 20 years
- Particle increases at outer edge may create new belts with magnetic storms

## Electrons

- Cycles with solar cycle
  - Highest at solar max
  - Lowest at solar minimum
- Inner Zone fairly stable
- Outer Zone varies by $10^2$ to $10^6$ fold
  - Solar cycle variations masked
  - Local time variations due to magnetic field distortion
  - 27 day variation due to solar rotation
  - Sensitive to magnetic storms

# Dose Rate Measured by JSC Tissue Equivalent Proportional Counter




**Inclination = 51.6 degrees**
**Altitude ~ 340 kilometers**
**December 10-22, 2006**

**Shuttle - STS-116**
**TEPC - Dose Rate**

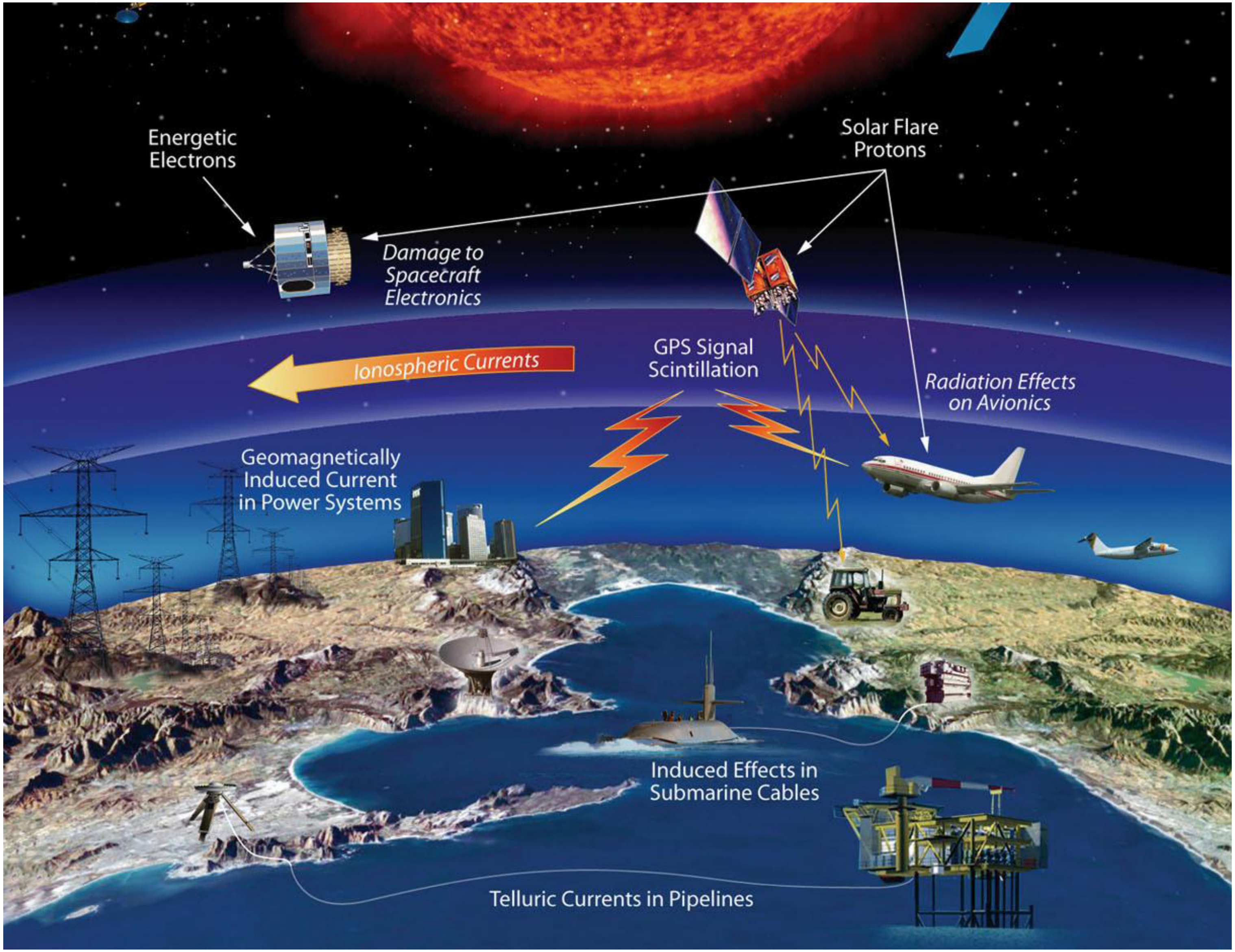
E.R. Benton, OSU

# Aurorae

## Interaction of SPE with Geomagnetic Field and Upper Atmosphere

http://www.sec.noaa.gov

# Terrestrial Effects of Large CME’s



# Shielding

# Shielding by Geomagnetic Field

Flux vs energy for Fe nuclei

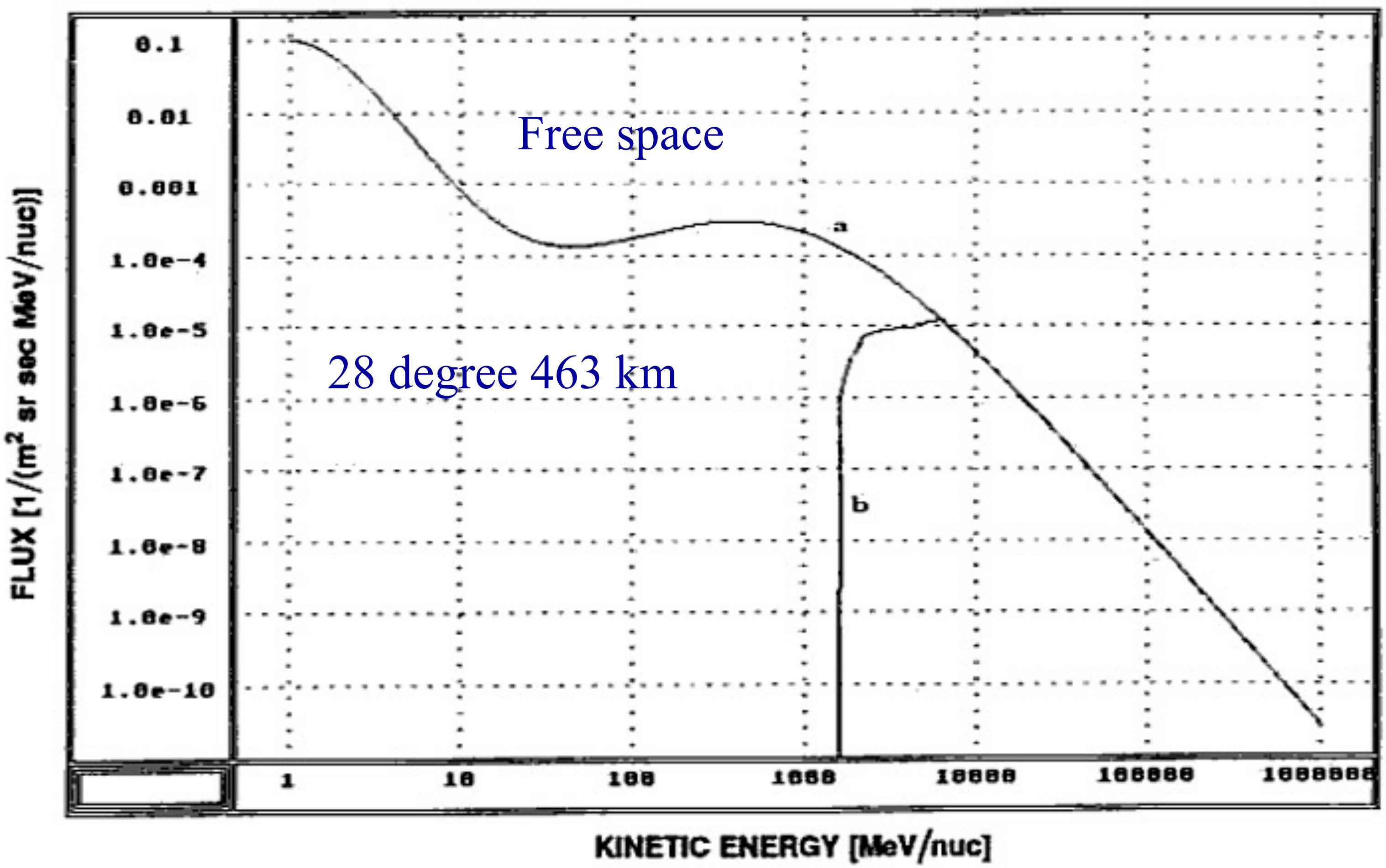



Figure 18. Differential Energy Spectrum for Iron Nuclei in 1984.3, a) Outside the Geomagnetic Field, b) 24 hours Average for LDEF Orbit (28 Degree Inclination, Circular Orbit at 463 km Altitude).

# Earth's Atmosphere

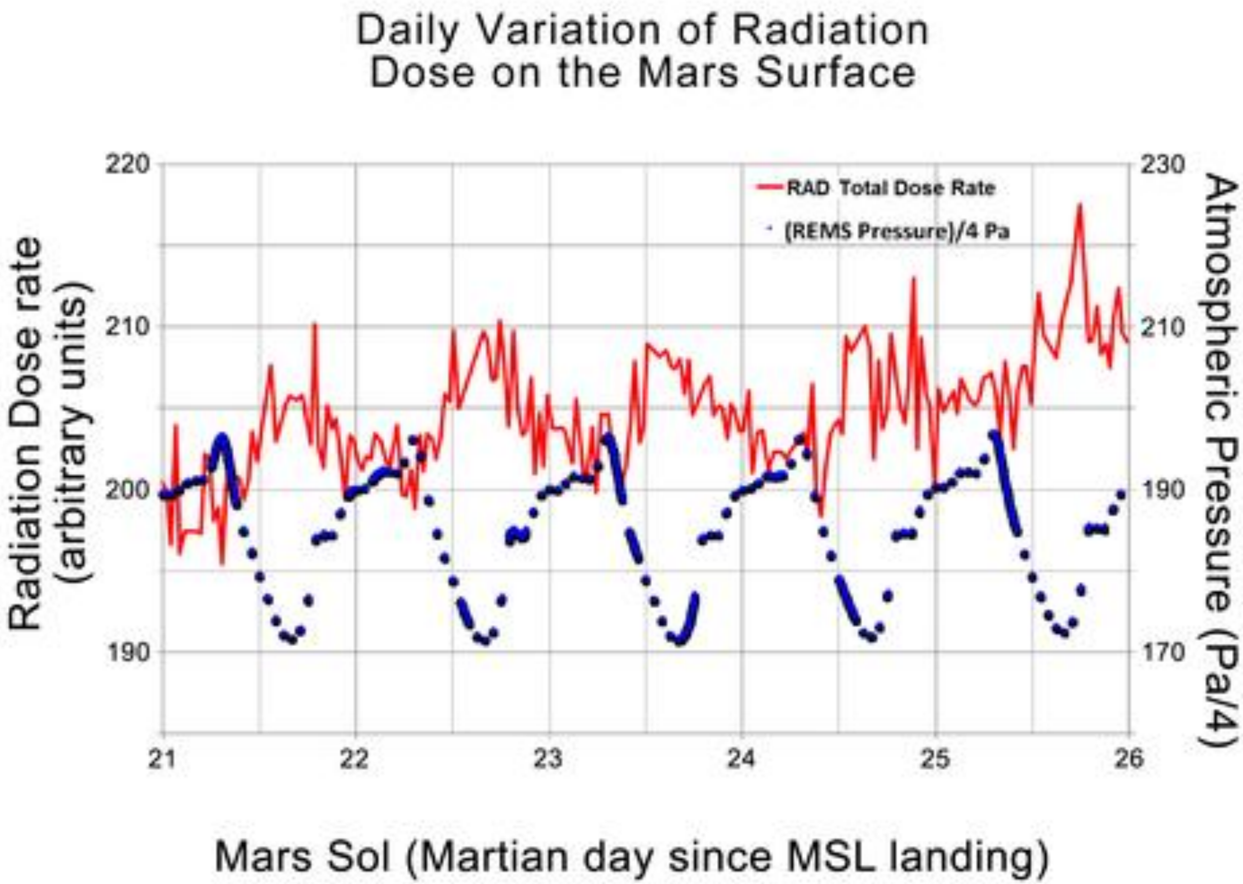
100 km thick at avg. density 0.0012 $g/cm^3$

Shielding Thickness ~ 240 $g/cm^2$

**~ 2.4 m Water, 21 cm Lead**

*Changes w Solar Cycle*

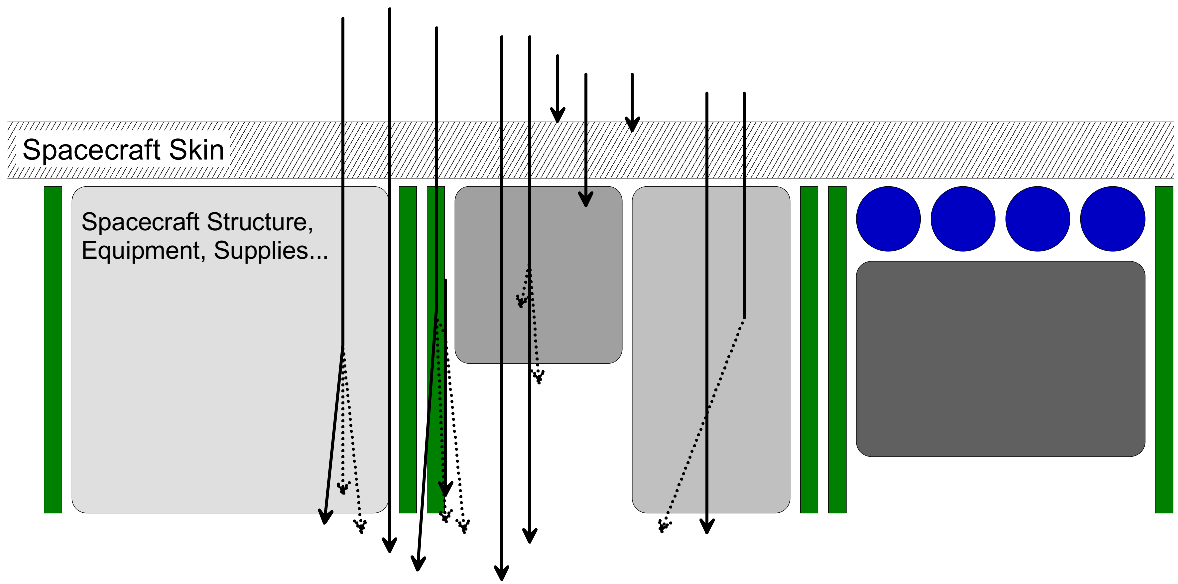
# Mars Surface Dose (MSL)
## Reflects Daily Atmosphere Density Changes




D Hassler Southwest Research Institute / NASA MSL

# Production of Secondary Particles by Spacecraft Materials

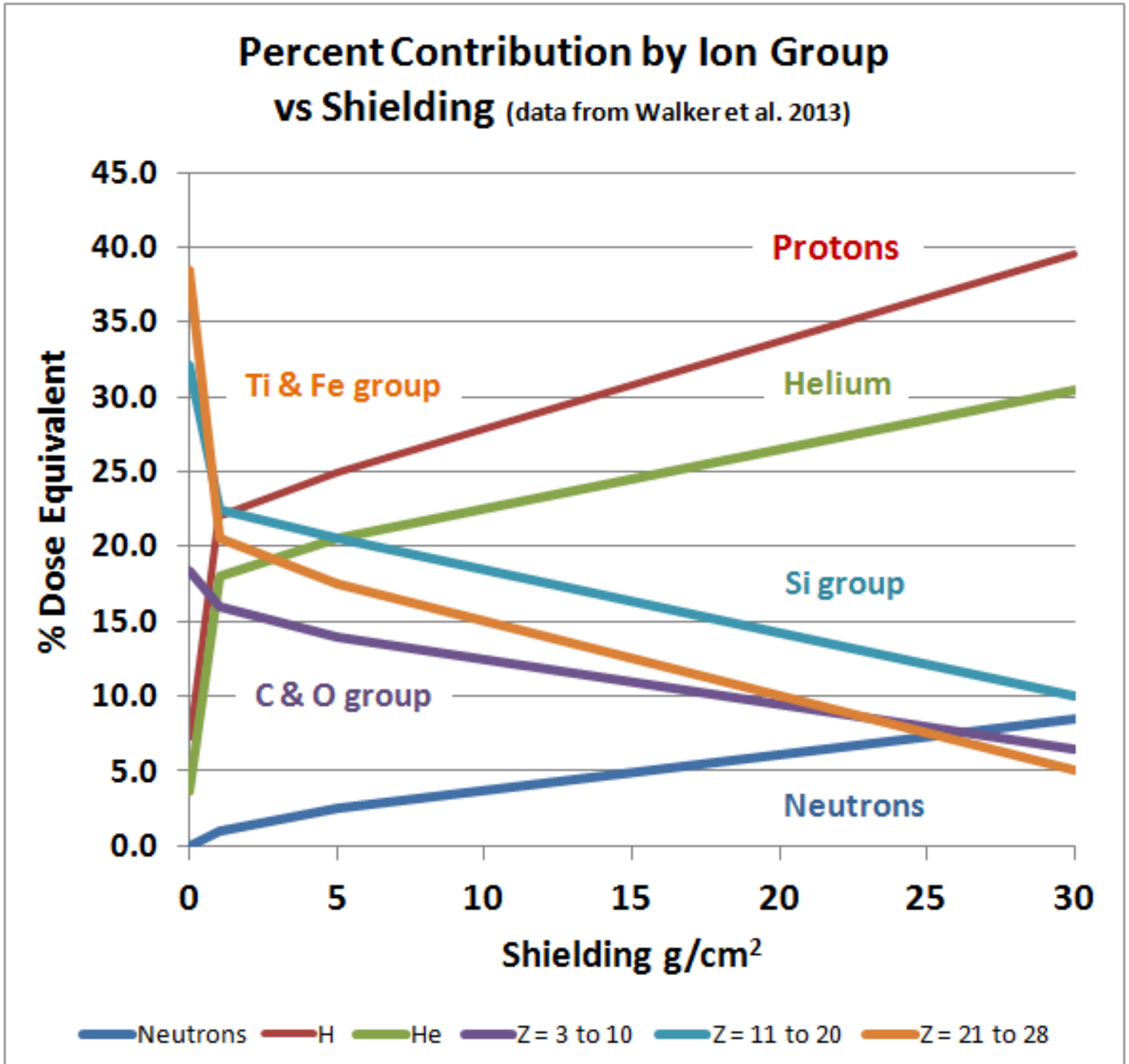
**Primary Particles (protons, He nuclei, & heavy ions)**




**Secondary Particles**

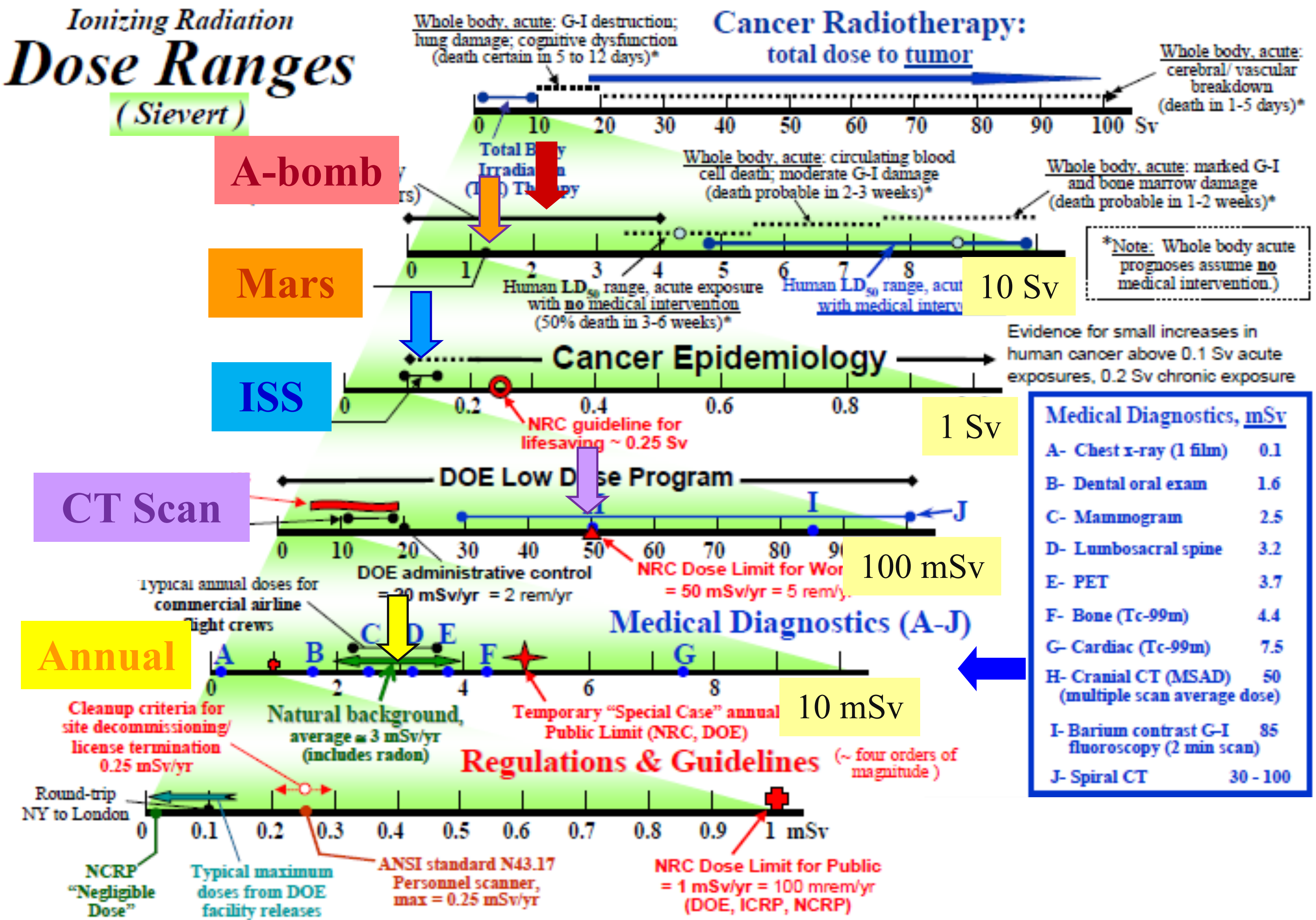
| | |
|---|---|
| $\pi^0, \pi^\pm$, $\mu^\pm$, $e^\pm$, $\gamma$, etc. | nuclear interactions, pair production, etc. |
| neutrons | nuclear interactions |
| protons | elastic scattering |
| | inelastic |
| recoil nuclei | proton and HZE induced target fragmentation |
| projectile fragments | HZE projectile fragmentation |

# Spacecraft Dose Equivalent Composition as Function of Shielding



# Exposures

# Doses in Context: Powers of Ten




| Medical Diagnostics, mSv | |
|---|---|
| A- Chest x-ray (1 film) | 0.1 |
| B- Dental oral exam | 1.6 |
| C- Mammogram | 2.5 |
| D- Lumbosacral spine | 3.2 |
| E- PET | 3.7 |
| F- Bone (Tc-99m) | 4.4 |
| G- Cardiac (Tc-99m) | 7.5 |
| H- Cranial CT (MSAD) (multiple scan average dose) | 50 |
| I- Barium contrast G-I fluoroscopy (2 min scan) | 85 |
| J- Spiral CT | 30 - 100 |

Radiology

Modified from N Metting

# Exposure Rules of Thumb

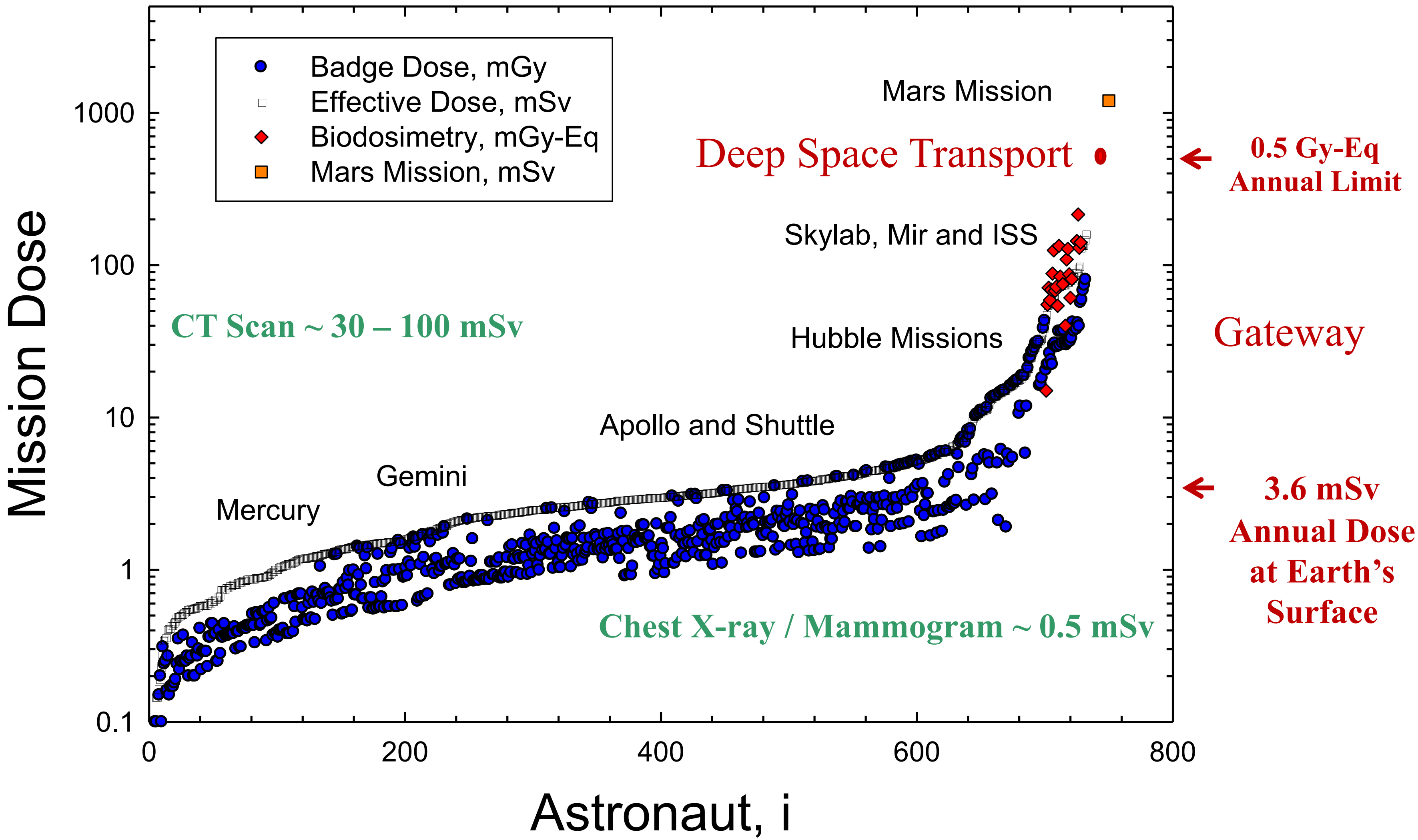
- A mammalian cell nucleus (100 $\mu m^2$) is traversed by a particle on average:
  - Protons: Once every 3 days
  - Helium: Once every 3 weeks
  - $Z > 2$ ion: Once every 3 months

- Mars mission exposure: ≈ 200:100:50:50:50
  - Protons ≈ 200 mGy
  - Helium ≈ 100 mGy
  - $Z = 3$ to 9 ≈ 50 mGy
  - $Z > 9$ ≈ 50 mGy
  - Neutrons ≈ 50 mGy

  - Total 0.445 mGy/day or 1.8 mSv/day
    - » MSL RAD

# NASA Crew Doses

## (Dose-rates ~1.5 mSv/d, Deep Space)




Modified from Simonsen and Cucinotta et al. Radiat Res (2008)

# Projected Exposures Mapped to 2019 DRMs

| 2016 DRM | BFO Dose (mGy) | 2019 DRM |
|---|---|---|
| LEO6 | 30-60 | LEO Short |
| LEO12 | 60-120 | LEO Long |
| Sortie | 15-20 | Lunar Orbital/Surface Short |
| Lunar Visit/Hab | 100-120 | Lunar Surface Long |
| Deep Space Hab | 175-220 | Lunar Orbital Long/Mars Preparatory |
| Planetary | 300-450 | Mars Planetary |

- Dose ranges encompass span of mission architectures and MSL measurements
  - Doses are highly dependent on crew, vehicle, and missions parameters
  - Mars dose equivalent 1050 – 1200 mSv
- 1989 SPE series ~98 mGy (additional)
  - Female BFO
  - 20 g/cm$^2$ aluminum vehicle

# NASA's Health Risks

# Categories of Space Radiation Risks

Four categories of radiation risk of concern to NASA

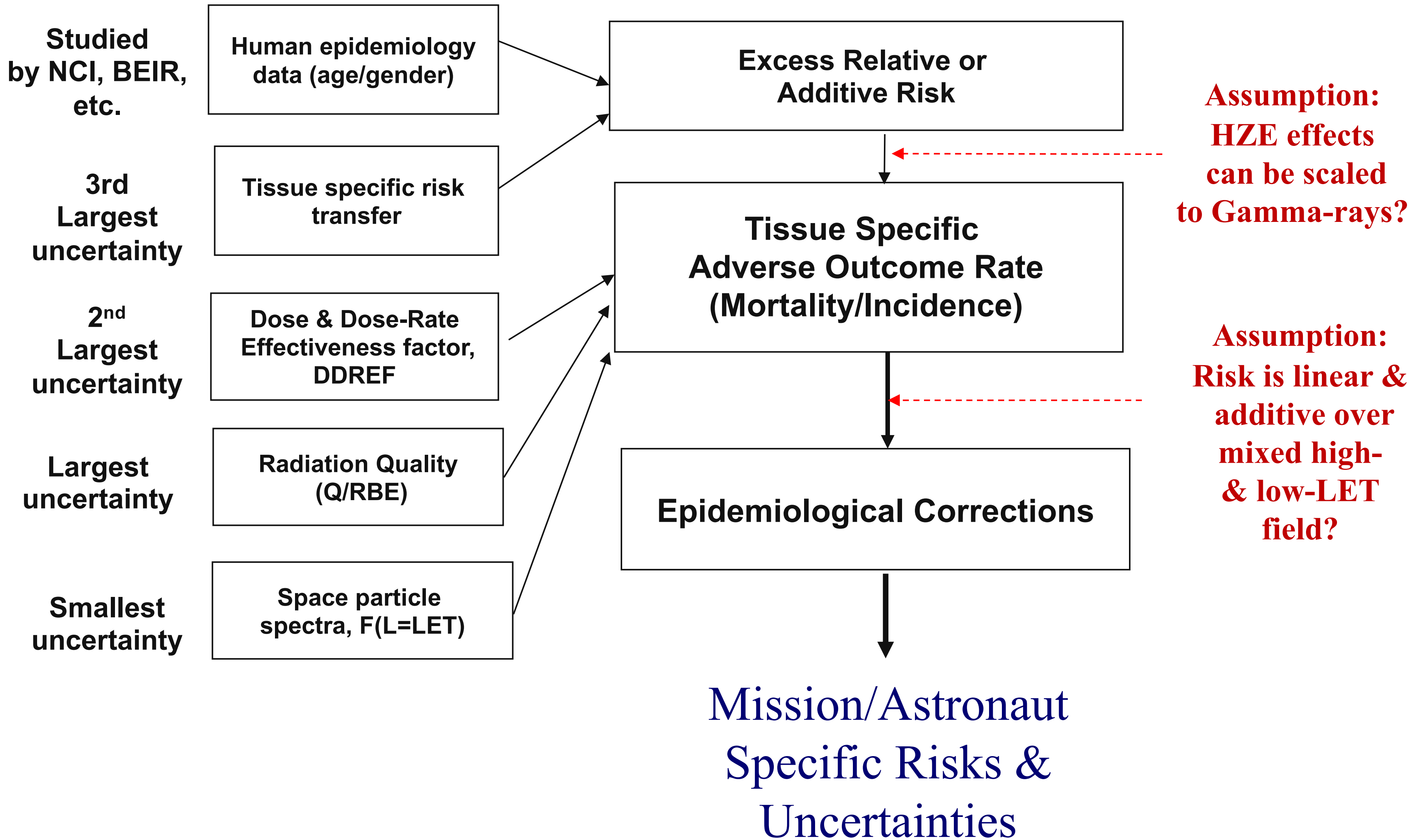
- Carcinogenesis (morbidity and mortality risk)
- Acute and Late Central Nervous System (CNS) risks
  - Immediate or late functional changes
- Chronic & Degenerative Tissue Risks
  - Cataracts, heart-disease, etc.
- Acute Radiation Risks – ARS, sickness or death

Caveat: Other spaceflight stressors also contribute to risk and combinatorial effects are largely unknown

# Risk Assessment

- Astronauts are radiation workers.
- NASA and astronauts enter into informed consent agreement
- Risk management follows "ALARA" principle
- Time – Distance – Shielding mitigation approaches
- Unavoidable exposure
- Risk – benefit analysis
- Acceptable risks
  - To Crew
  - To Family
  - To Society (NASA represents the public)
- 3% Lifetime mortality occupational risk benchmark

# Risk Projection Strategy




Adapted from F. Cucinotta

# Mortality Risk at Solar Minimum

(20 g/cm$^2$ Aluminum Shielding)

REID (Risk of Exposure Induced Death from all causes).
1 – 13% Range for Mars Missions – Avg. 2 – 4%.

| Mission | D, Gy | H, Sv | % REID | 95% CI |
|---|---|---|---|---|
| | | *Males* | | |
| Lunar (180 d) | 0.06 | 0.14 | 0.56 | [0.19,1.92] |
| Mars (600 d) | 0.36 | 0.87 | 3.2 | [1.0,10.5] |
| Mars (1000 d) | 0.41 | 0.96 | 3.4 | [1.1,11.0] |
| | | *Females* | | |
| Lunar (180 d) | 0.06 | 0.14 | 0.68 | [0.21,2.4] |
| Mars (600 d) | 0.36 | 0.87 | 3.9 | [1.2, 12.8] |
| Mars (1000 d) | 0.41 | 0.96 | 4.1 | [1.4, 14.4] |

# NASA Permissible Exposure Limits

NASA-STD-3001, Volume 1. Limits for lens, circulatory system, and central nervous system are imposed to limit or prevent risks of degenerative tissue diseases

**Table 4—Dose limits for short-term or career non-cancer effects (in mGy-Eq. or mGy) Note RBE's for specific risks are distinct as described below.**

| *Organ* | *30 day limit* | *1 Year Limit* | *Career* |
|---|---|---|---|
| Lens* | 1000 mGy-Eq | 2000 mGy-Eq | 4000 mGy-Eq |
| Skin | 1500 | 3000 | 4000 |
| BFO | 250 | 500 | Not applicable |
| Heart** | 250 | 500 | 1000 |
| CNS*** | 500 | 1000 | 1500 |
| CNS*** ($Z \geq 10$) | - | 100 mGy | 250 mGy |

*Lens limits are intended to prevent early (< 5 yr) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (> 5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.

**Heart doses calculated as average over heart muscle and adjacent arteries.

***CNS limits should be calculated at the hippocampus.

# Current Integrated Mitigation Strategy

- Pre-Mission
  - Mission planning – trajectory, duration, habitat/vehicle design
    - Radiation Exposure and risk assessment
    - Trajectory planning to reduce time spent in the radiation belts
  - Crew assignment
    - Permissible mission duration assessment
    - Medical screening
- In-Mission
  - SPE storm shelter or shielding garment as available
  - Continuous operational radiation monitoring and alarming
  - Space weather assets monitoring and forecasting
  - Appropriate tailoring of medical capabilities for DRMs
- Post-Mission
  - Medical follow-up
  - Standard clinical therapies

# Research Challenges to Increase Safe Days

- **Radiation quality effects on biological damage**
    - Qualitative and quantitative differences between space radiation compared with x-rays or gamma-rays
- **Dependence of risk on dose and low dose-rates encountered in space**
    - Biology of repair, cell, and tissue regulation
- **Extrapolation from experimental data to humans**
- **Individual radiation sensitivity**
    - Genetic, dietary and healthy worker effects
- **Quantifying synergistic modifiers of risk from other spaceflight factors**
- Research solicitations focused on understanding and quantifying these uncertainties to increase safe days in space, inform standards, and identify/validate biomarkers and medical countermeasures for risk mitigation

# Biological Rationale for Multi-ion GCR Simulations

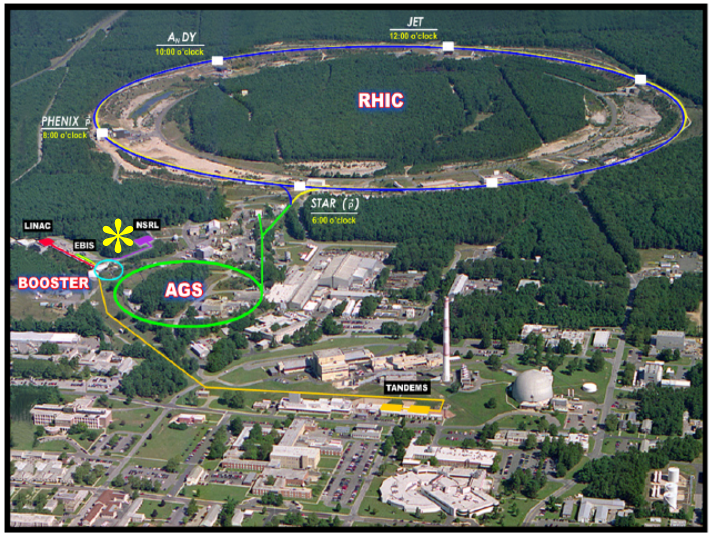
- Dose responses are not all linear
- Particle effects may be unique
- Effects may be antagonistic
- Mixed particle exposures may not produce simple additive responses
- Dose rate effects unclear for particles

- Insufficient time and resources for reductionist approach alone

# GCR sim's at Brookhaven National Laboratory

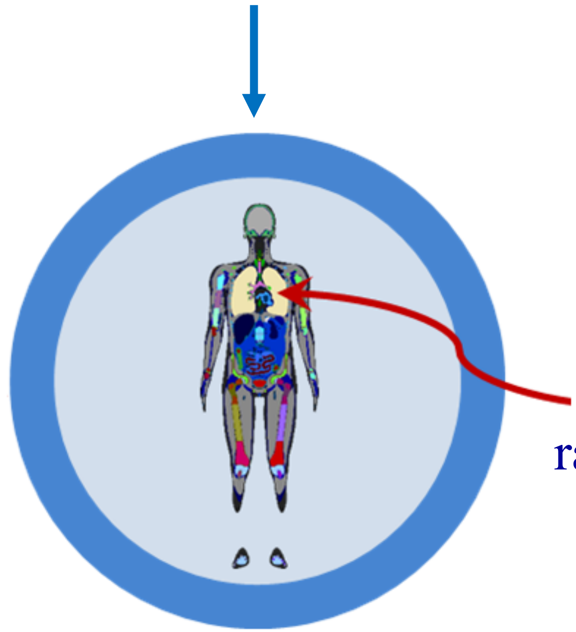
## 33 and 6 ion/energy combinations

**Brookhaven National Laboratory**




**NASA Space Radiation Laboratory** *

**Spacecraft Shielding**



**Local Field:**
biological
samples
experience
radiation field as
if they were
located here.

**Free Space**

# Summary

- Complex field of charged particles that varies spatially and temporally
- Energy deposition patterns (tracks) lead to unique, and less repairable biological effects.
- GCR, solar wind and trapped belts relatively constant dose rate
- Typical deep space exposures 0.45 mGy or 1.5 mSv per day
- Solar Cycle changes spectrum and fluence ~ 2-fold
- ~ 1 Sv Exposure for a Mars mission
  - Exceeds current safety limits
- SPEs Capable of ~1 Sv to deep tissues and ~6 Sv to skin
- SPEs variable over hours to a few days
  - Peak dose rate ~5 cGy/min
  - Unpredictable occurrence varies with solar cycle
- Risks and mitigation strategies identified
  - Biological uncertainty greatest component
  - Ongoing research including GCR simulation

# Thank-You for Your Attention

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Thank-you to my many colleagues and sponsors