41st Space Congress

Progress Toward Electrostatic Radiation Shielding of Interplanetary Spacecraft

Strategies, Concepts and Technical Challenges of Human Exploration Beyond Low Earth Orbit

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Space Radiation: A Key Challenge

- We **cannot** explore the solar system until the space radiation problem has been solved
- Three principle sources of space radiation

Galactic Cosmic Radiation (GCR)

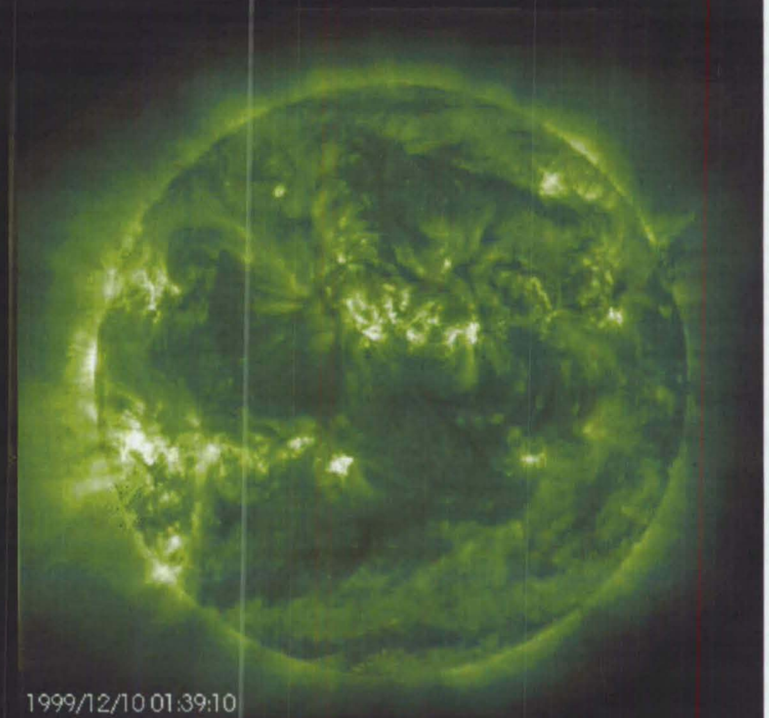
- Charged particles accelerated in the shock waves surrounding supernovae
- Ever-present, low-level flux of high-energy particles
- Large cumulative dose over the course of a mission
- Penetrate our solar system isotropically

Solar Particle Events (SPEs)

- Particles accelerated by solar phenomena
- Sporadic
- High flux when it does occur
- Lower-energy spectrum than GCR
- Approximately isotropic flux due to magnetic interactions in the solar system

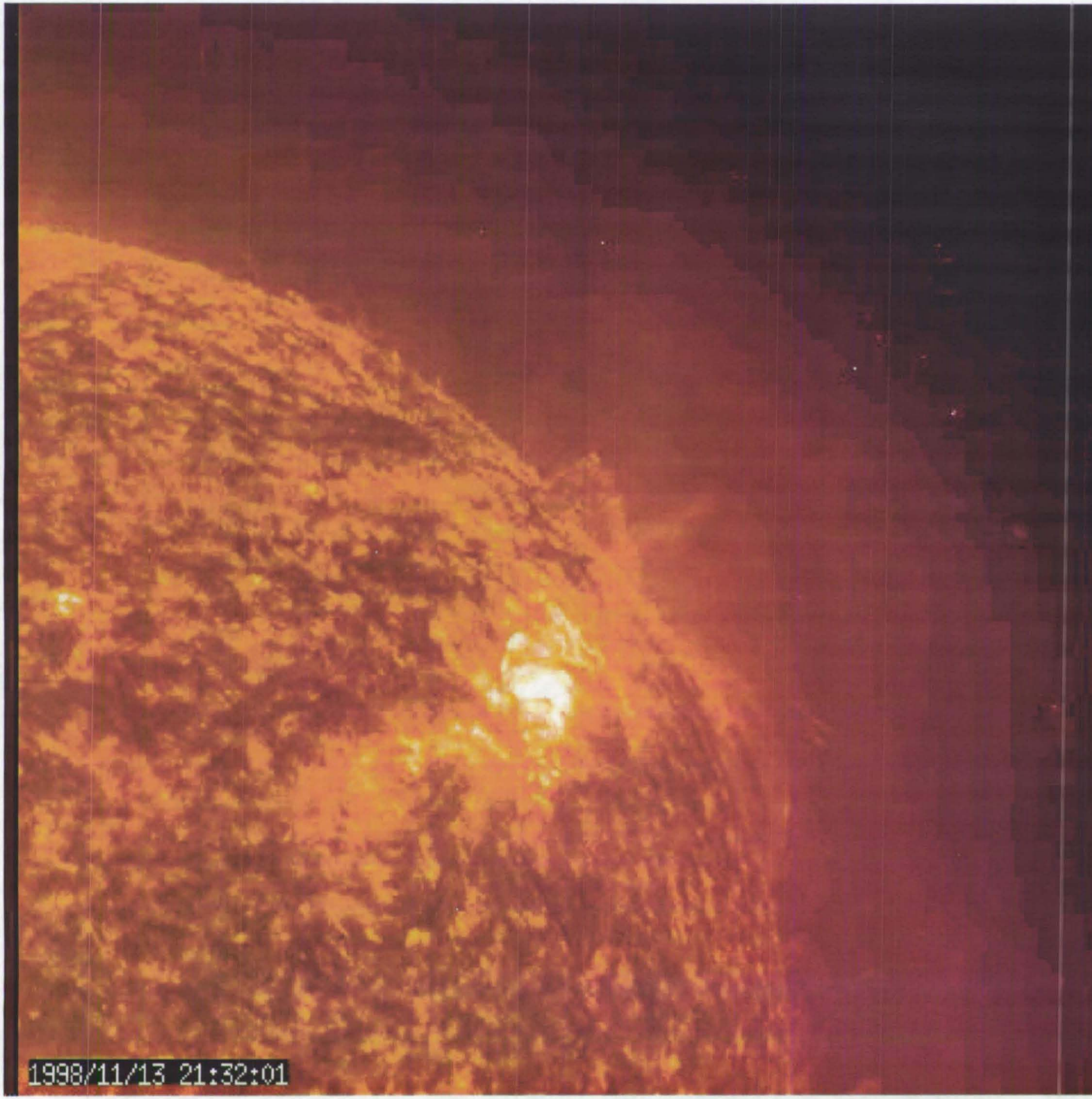
2 Types of SPEs

- Impulsive
  - Occur over a period of several hours
  - Associated with Solar Flares
- Gradual
  - Occur over a period of several days
  - Associated with Coronal Mass Ejections



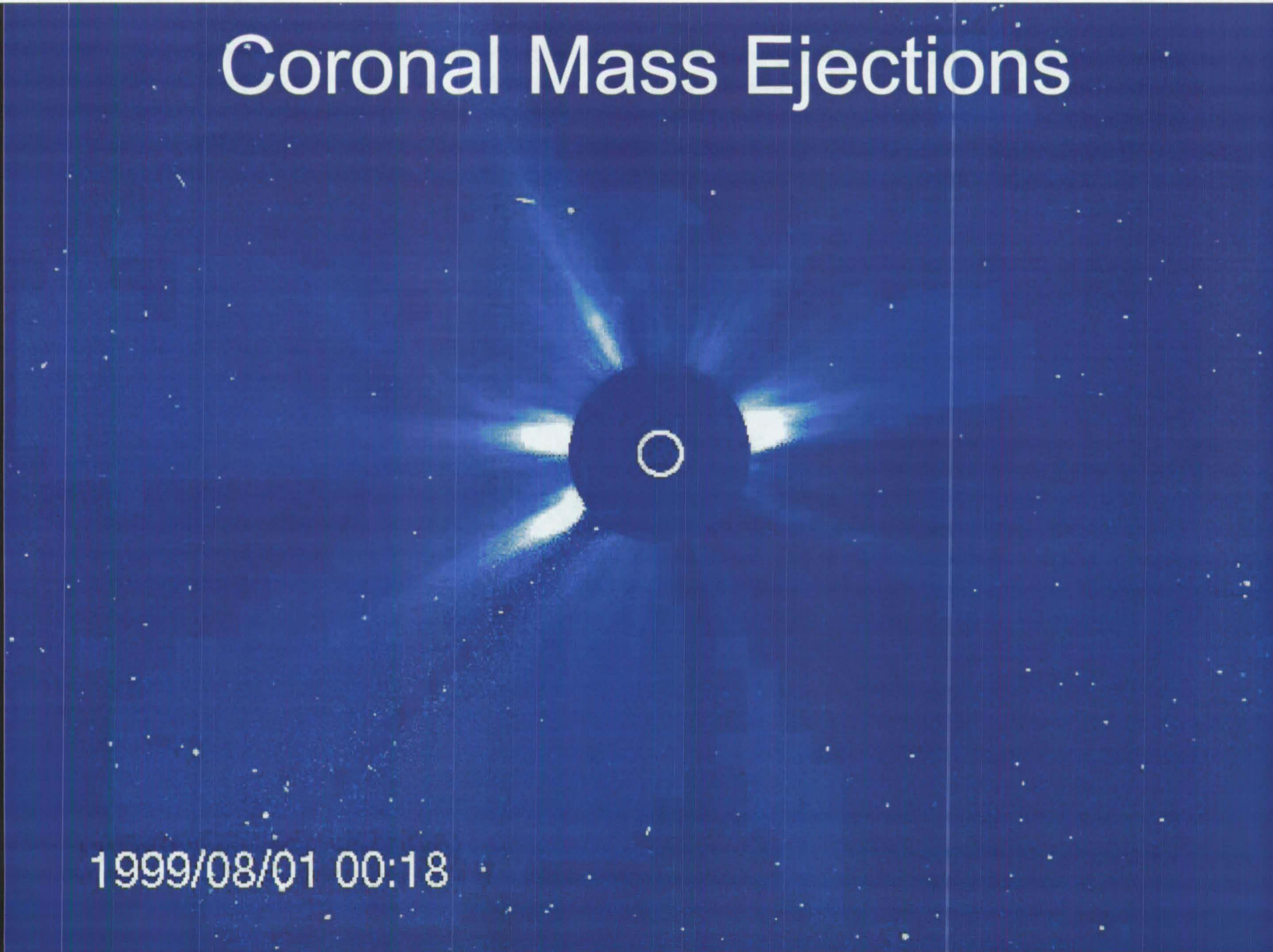
SOHO (ESA/NASA)

Solar Flares



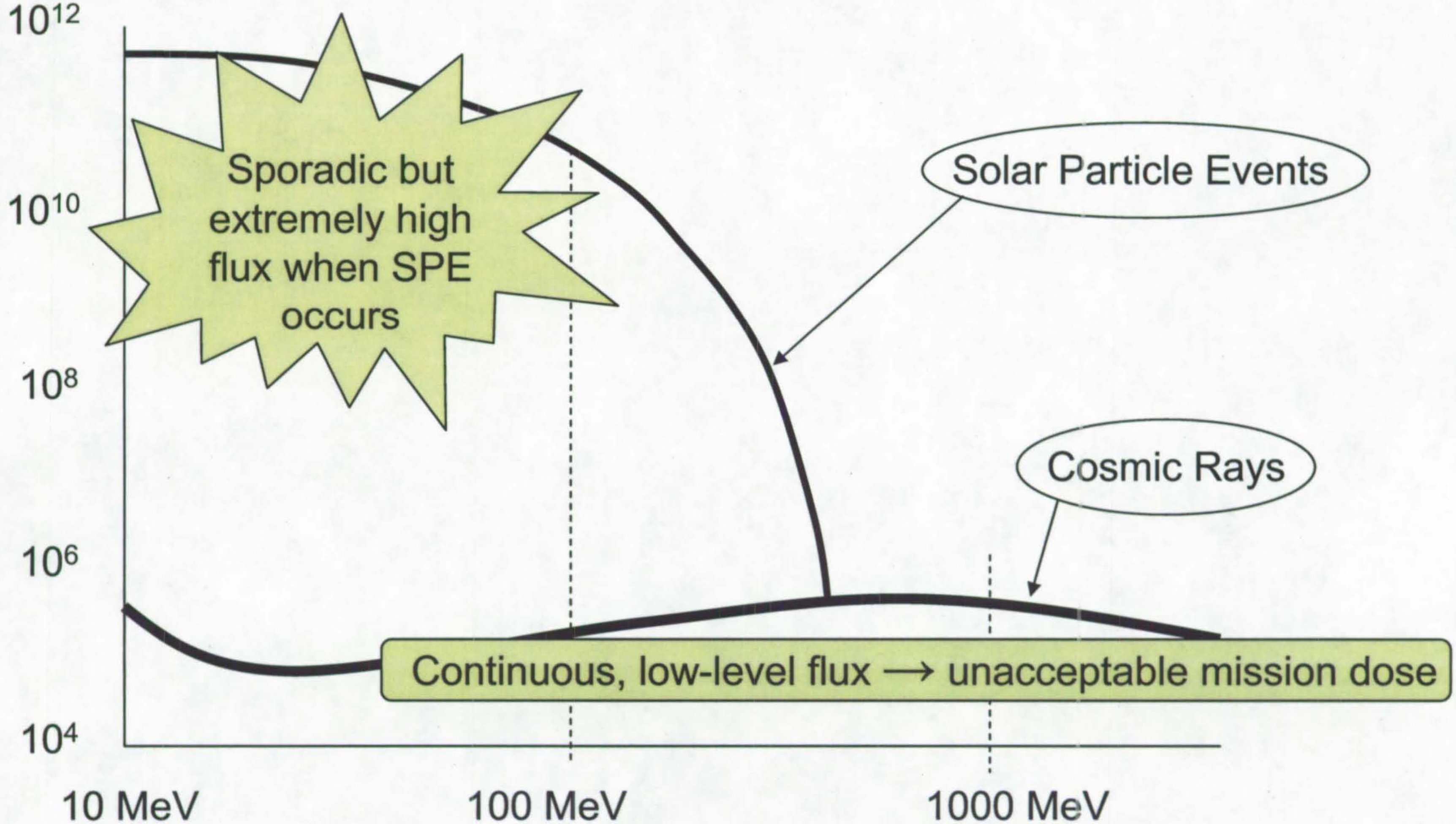
SOHO (ESA/NASA)

Coronal Mass Ejections



SOHO (ESA/NASA)

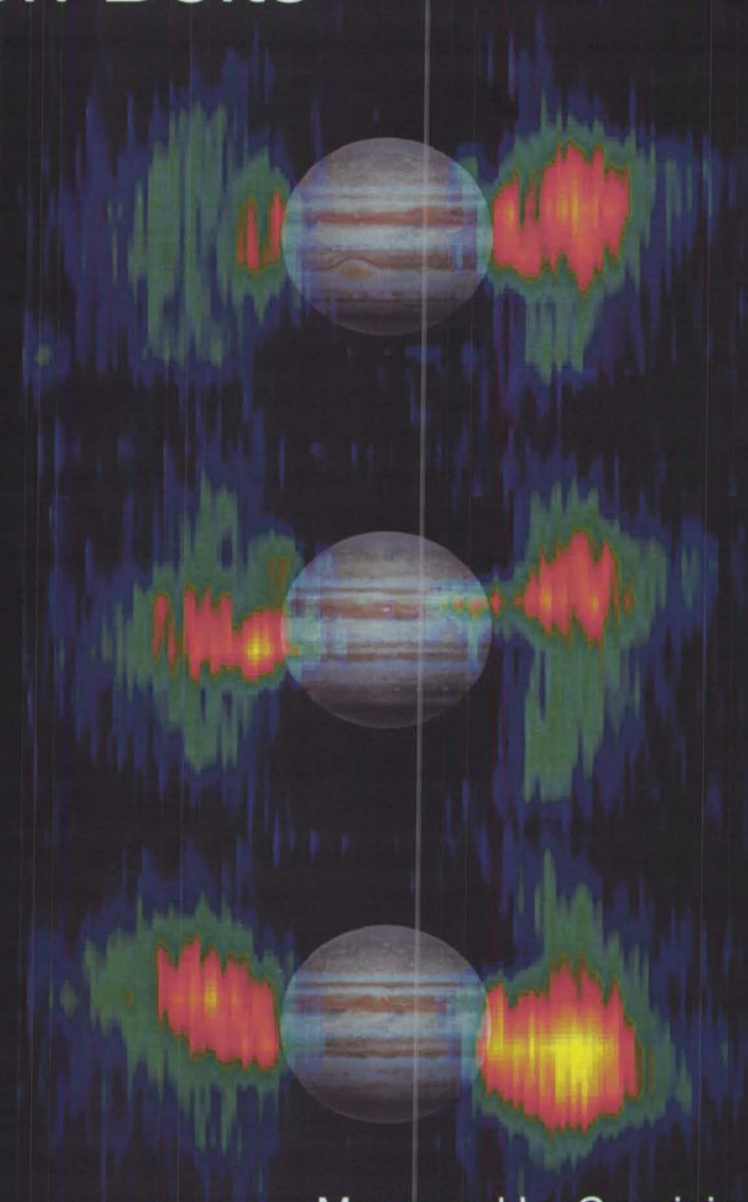
Space Radiation Spectrum



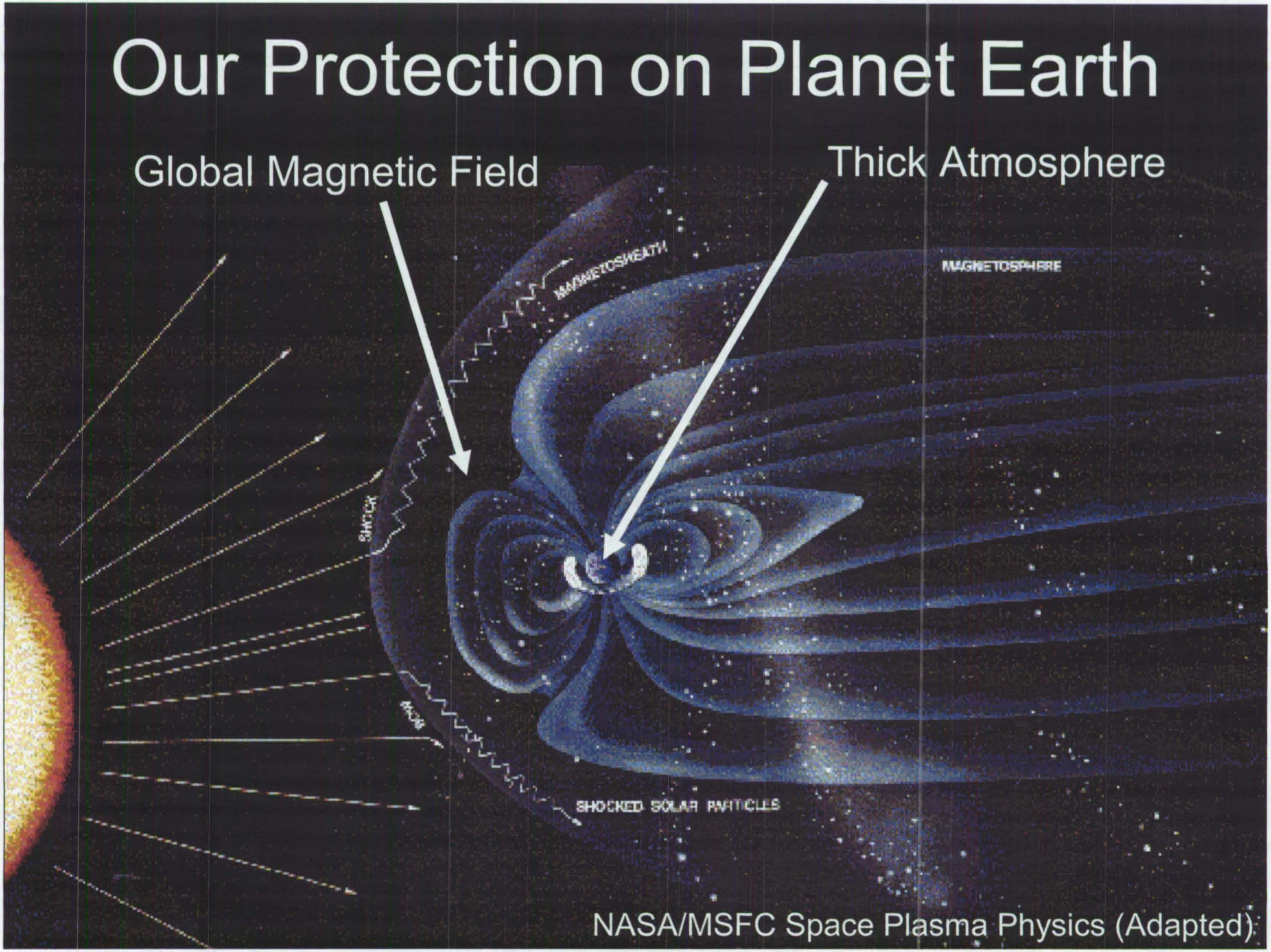
Ref. Silberberg *et al.*, 1984

Planetary Radiation Belts

- Earth
- Jupiter and other giant gas planets
  - Significant radiation belts
  - Especially bad at Europa



Measured by Cassini spacecraft
Image courtesy JPL


Our Protection on Planet Earth
Global Magnetic Field
Thick Atmosphere
MAGNETOSHEATH
MAGNETOSPHERE
SHOCK
SHOCKED SOLAR PARTICLES
NASA/MSFC Space Plasma Physics (Adapted)

Effects in Spaceflight

- Biological Effects
  - Delayed: cumulative effects of total dose
  - Acute: immediate effects of intense exposure
    - A single SPE may be lethal
- Electronic Effects

Passive (Material) Shielding

- The most successful method, to date
- Foams or other materials on outside of spacecraft
- The spacecraft structure, itself
- Consumables placed strategically
  - food
  - drinking water

Passive Shielding, continued

- Problems
  - Spacecraft Mass may become excessive
  - Secondary radiation
  - Some radiation gets through, *which is not acceptable during the high flux of SPEs*
- “Storm-Shelter approach”

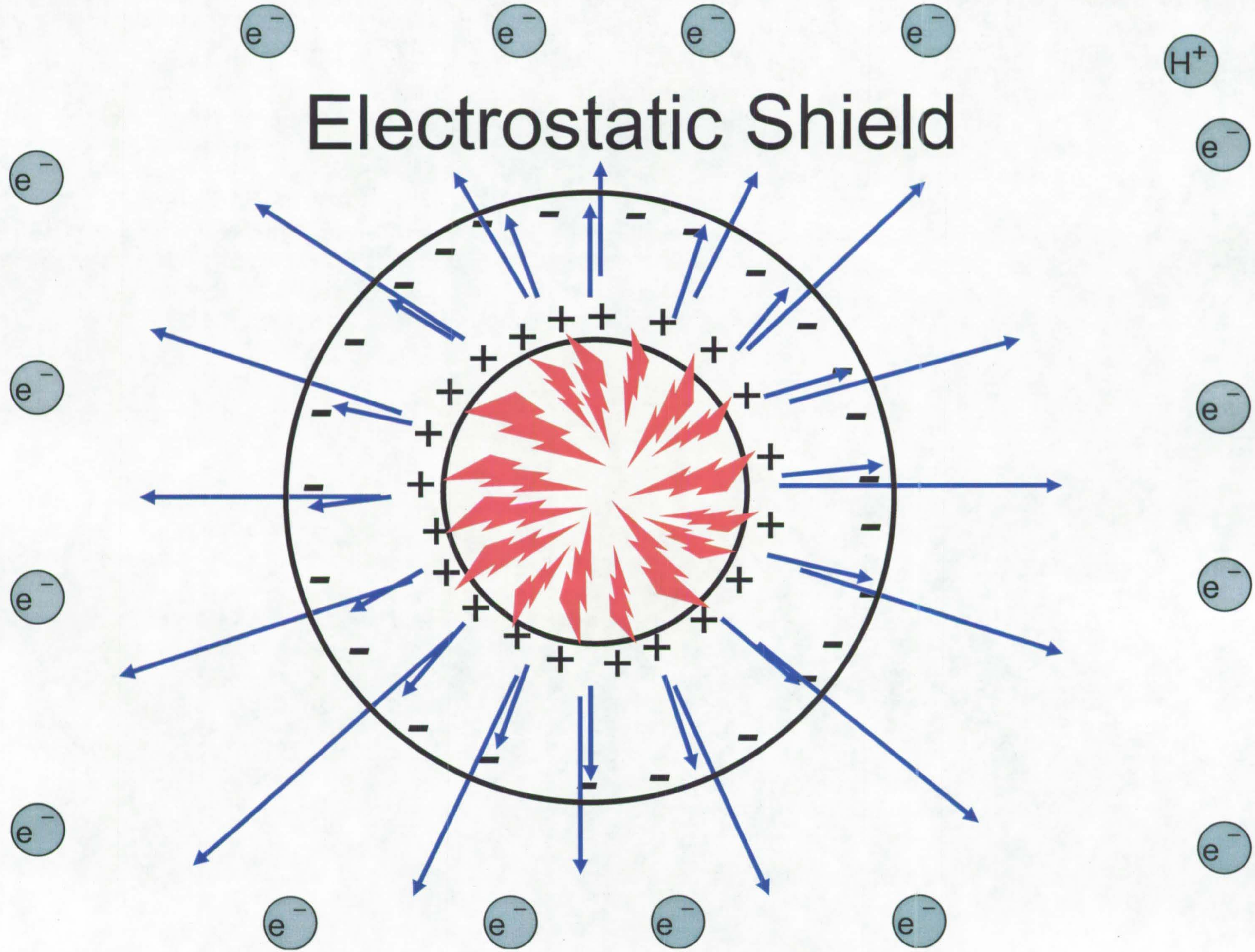
Problems with Storm Shelters

- Excessive time in cramped quarters
  - Gradual SPE may last 4 or 5 days
  - Psychologically and physically distressing
- Provides no protection for spacecraft electronics
  - May suffer irreparable damage resulting in eventual loss of mission and crew
- Crew unable to attend to the spacecraft
  - During the precise time when it needs the *most* attention (due to radiation effects)
  - May need quick response to manage spacecraft

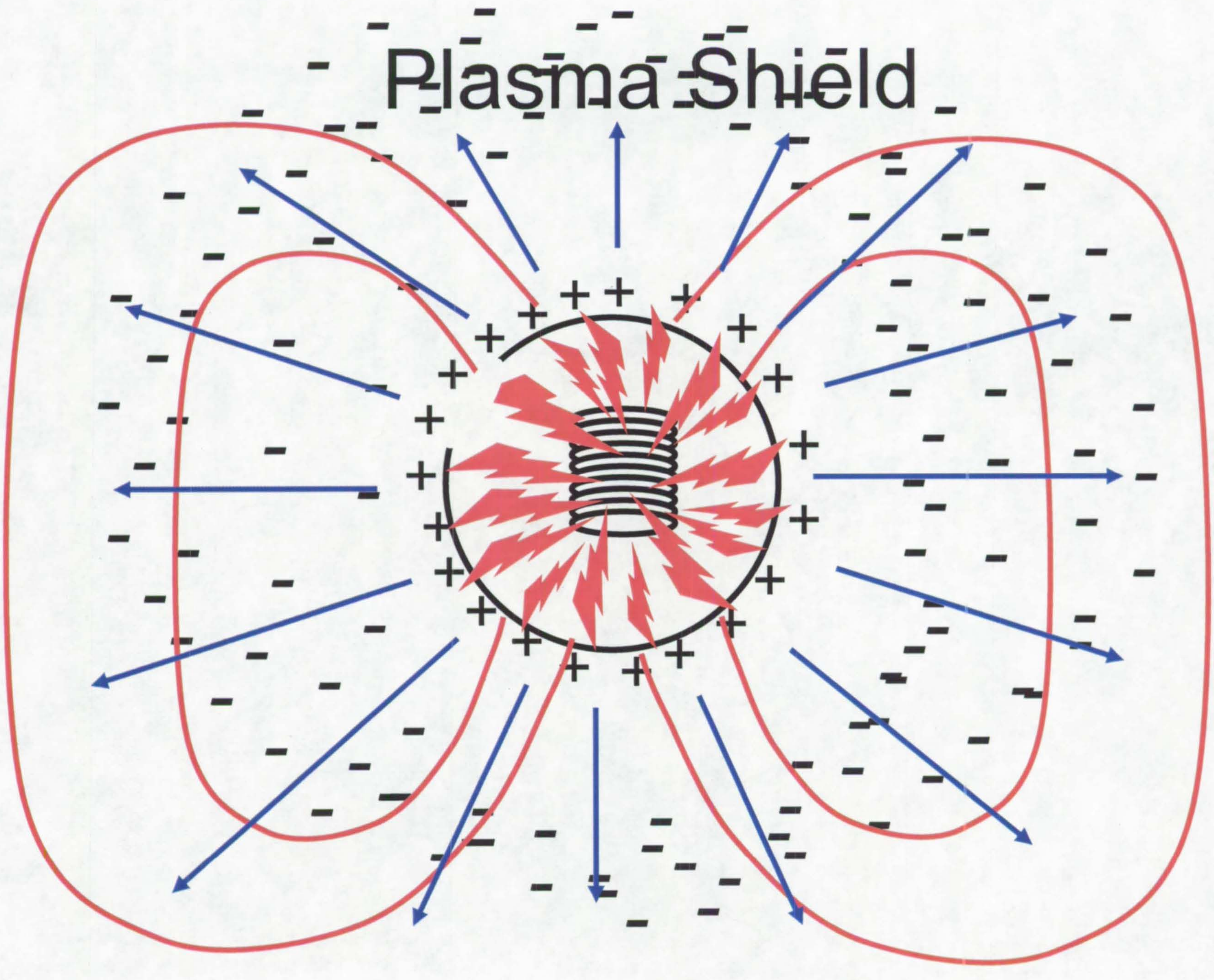
Magnetostatic Shield

- Attempt to mimic the shielding due to Earth's magnetic field
- Requires heavy, superconducting coils to produce sufficient magnetic field
- Hazard that coil could explode under the energy of the fields
- Better to use the mass of the coil as foam on the outside of the spacecraft

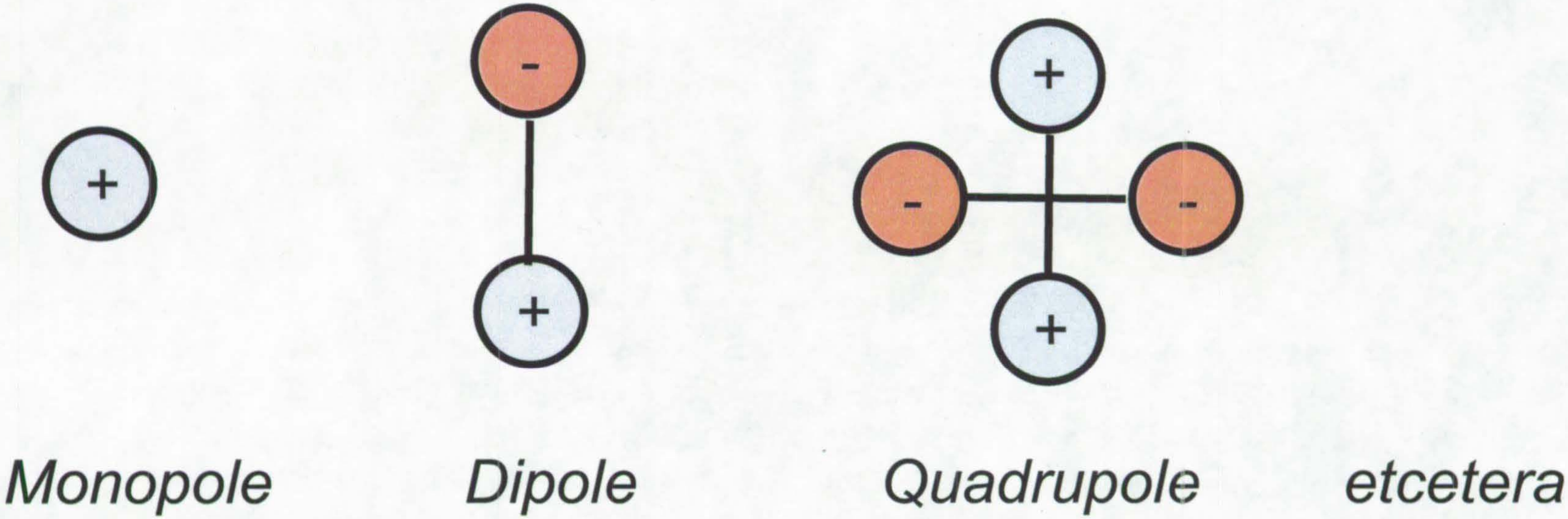
Electrostatic Shield



Plasma Shield



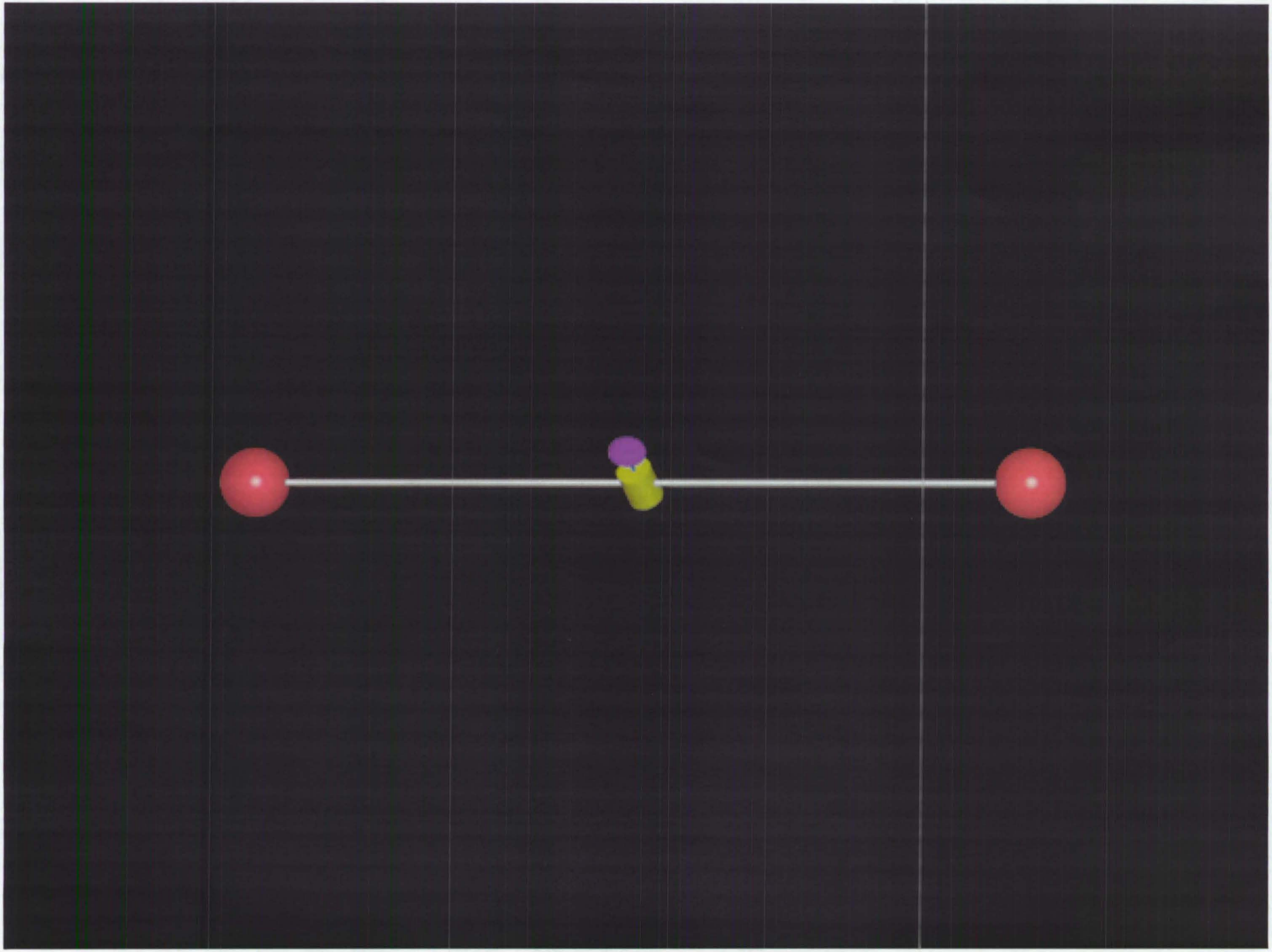
Multipole Expansions

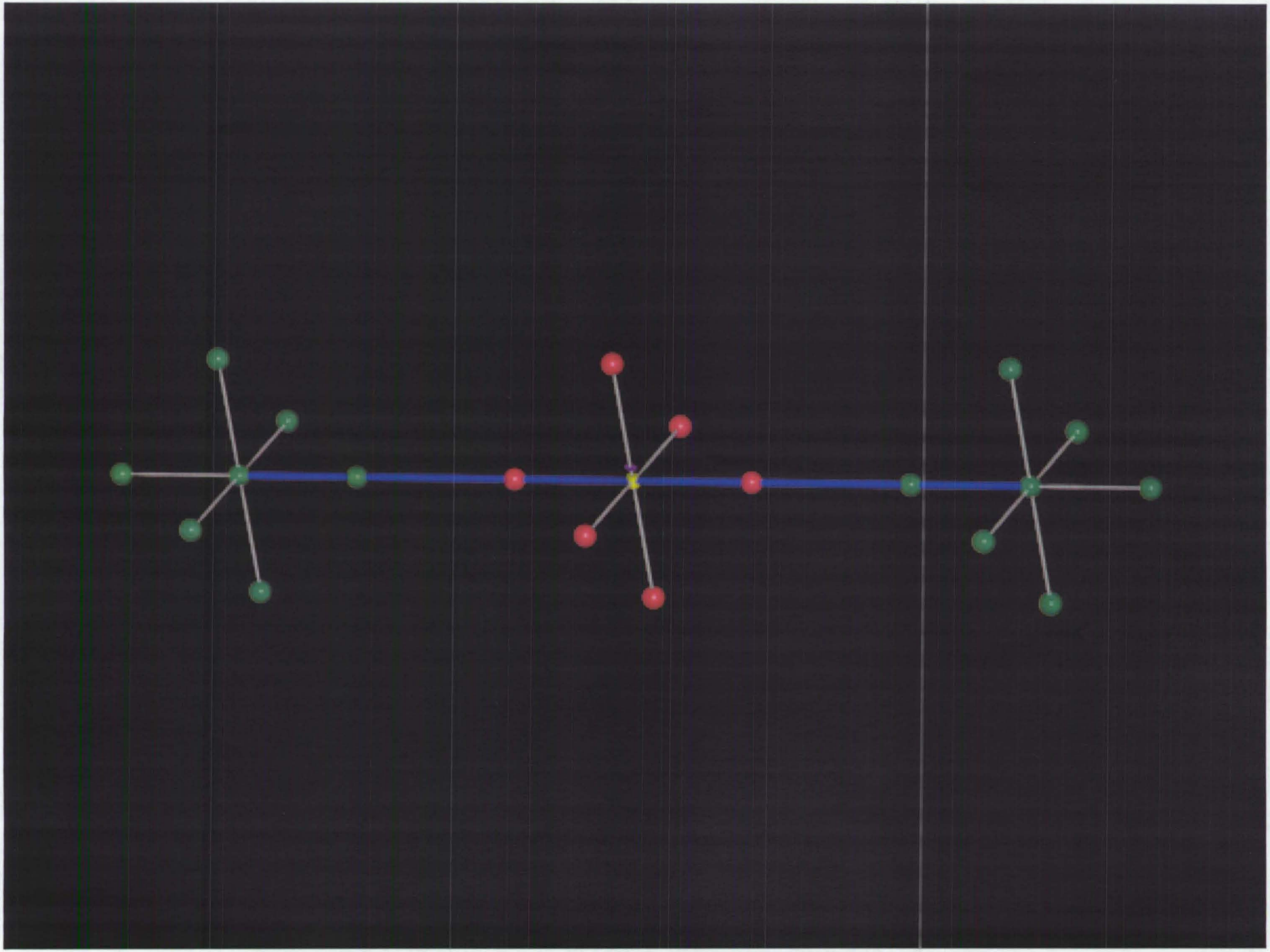


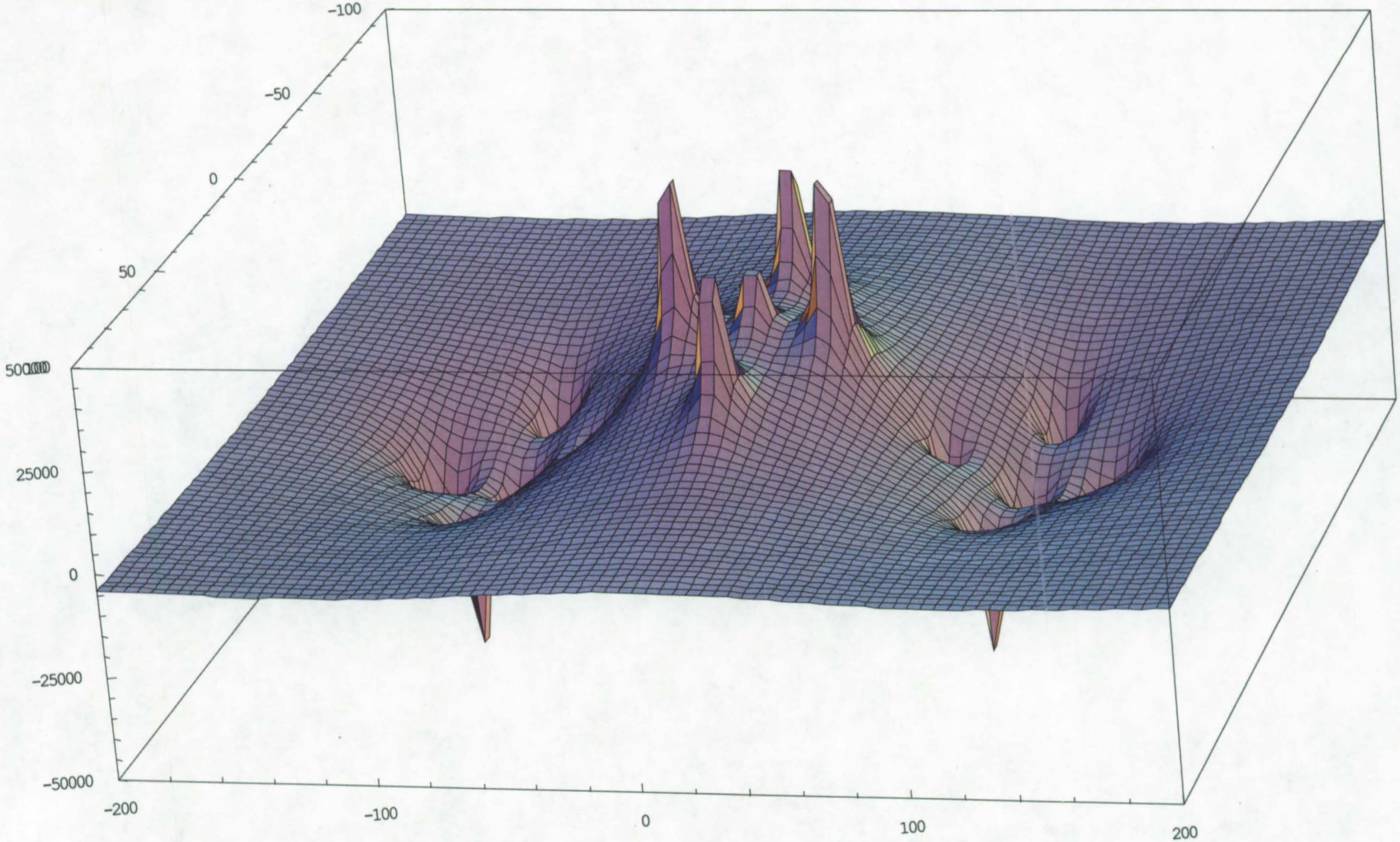
- An arbitrarily-complex electric field can be described as an infinite sum of these terms

Multipole Electrostatic Shield

- Each term in the multipole expansion falls off with respect to distance more quickly than the previous term
  - Monopole term dominates far away
  - Higher-order terms dominate in close
- Assign different functions to different terms
- Result: Spherical zones of protection to repel both protons and electrons
  - But no charges need to be physically deployed around the spacecraft

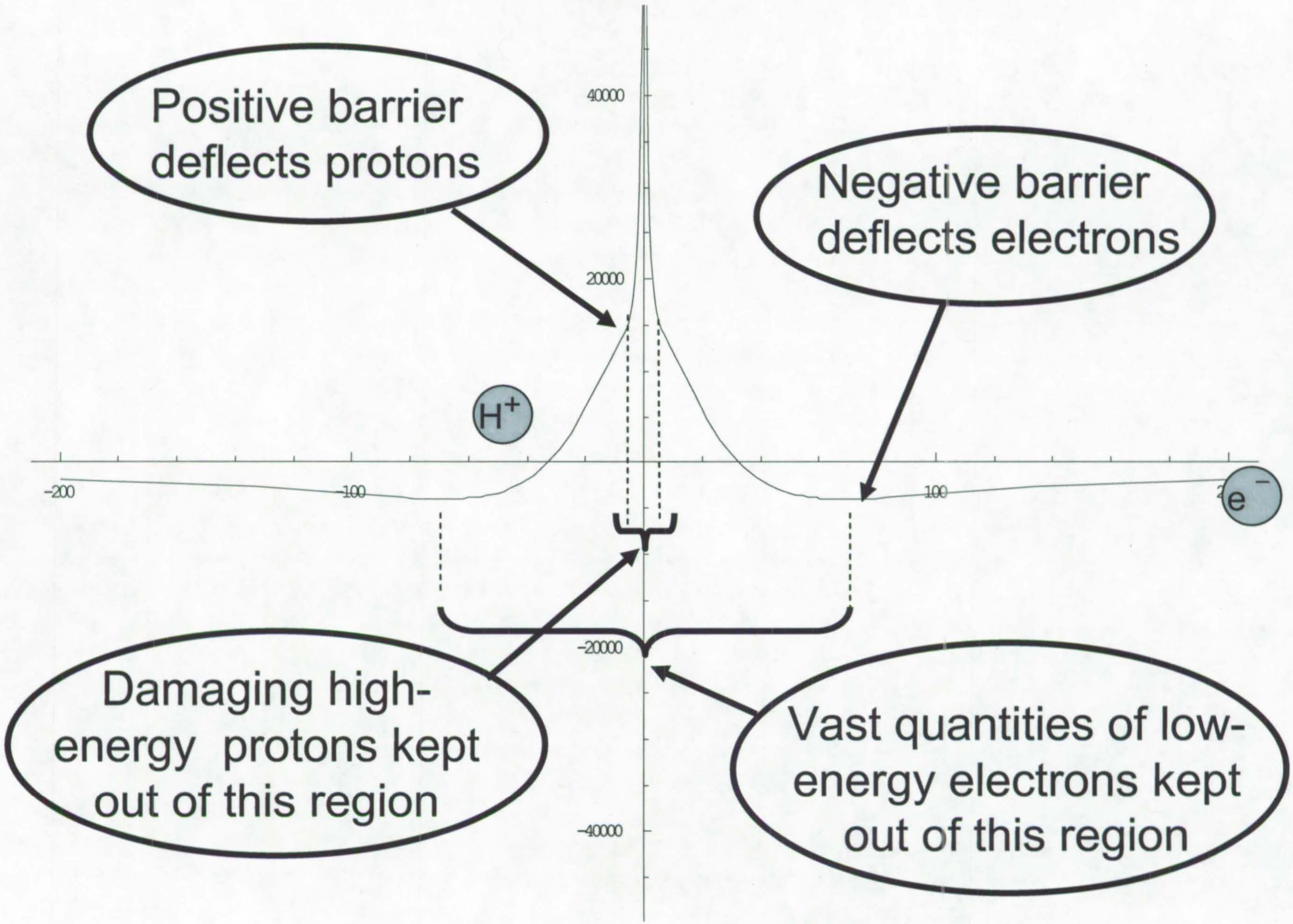






-100
-50
0
50
50000
25000
0
-25000
-50000
-200
-100
0
100
200

$$\Phi(x=\xi, y=\xi, z=\xi)$$



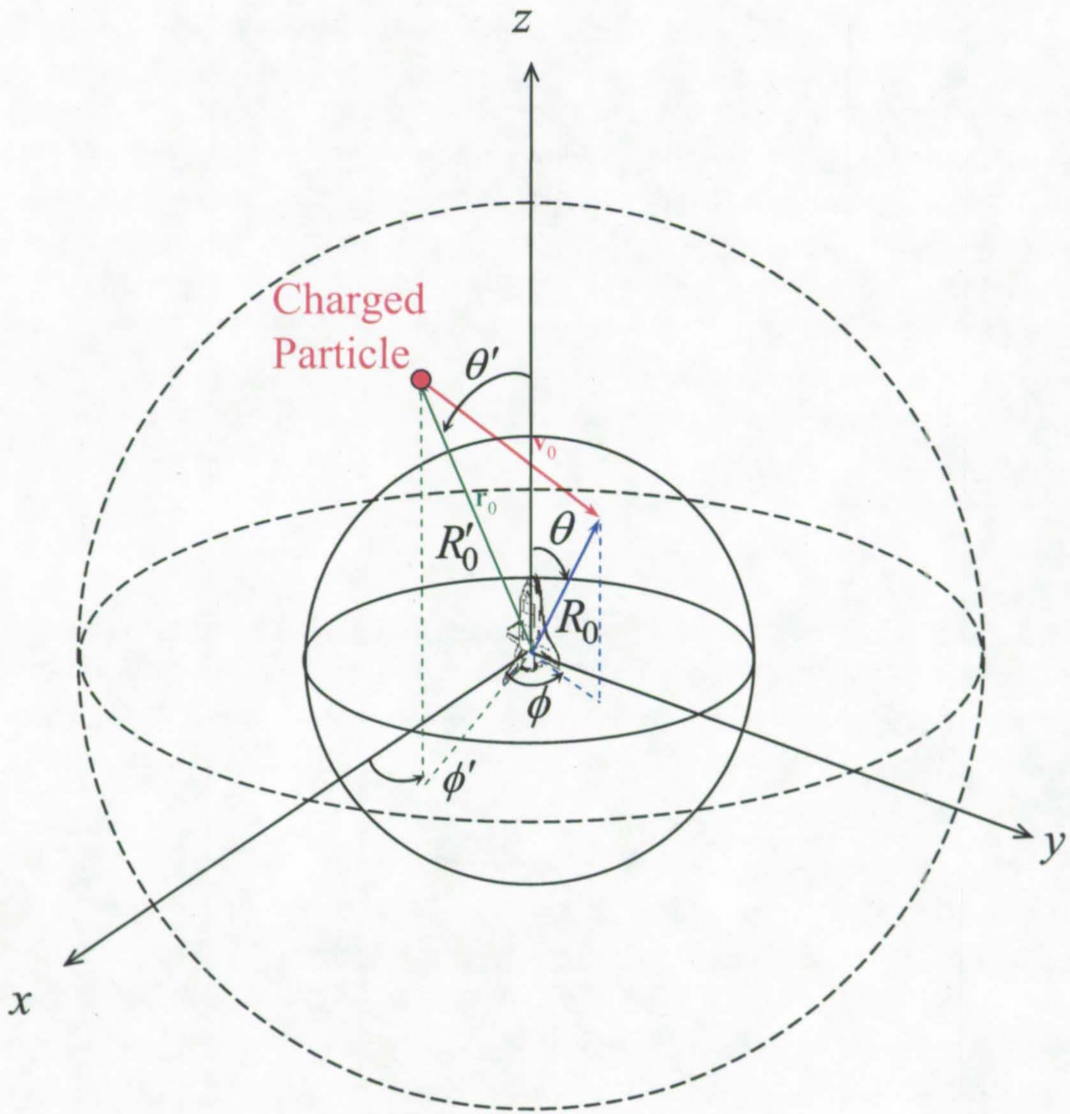


Diagram of Isotropic Radiation, Showing
Initial State of Charged Particle.

A bunch of math…

$$A_x = \left(c_{23}c_{32}E_x - c_{22}c_{33}E_x - c_{13}c_{32}E_y + c_{12}c_{33}E_y + c_{13}c_{22}E_z - c_{12}c_{23}E_z\right)Q$$
$$A_y = \left(-c_{23}c_{31}E_x + c_{21}c_{33}E_x + c_{13}c_{31}E_y - c_{11}c_{33}E_y - c_{13}c_{21}E_z + c_{11}c_{23}E_z\right)Q$$
$$A_z = \left(c_{22}c_{31}E_x - c_{21}c_{32}E_x - c_{12}c_{31}E_y + c_{11}c_{32}E_y + c_{12}c_{21}E_z - c_{11}c_{22}E_z\right)Q$$

$$Q\mathbf{E}(\mathbf{r}) = \dot{\mathbf{p}} = \frac{d}{dt}(\gamma\, m_0 \mathbf{v})$$
$$= \gamma\, m_0\left(\dot{\mathbf{v}} + \gamma^2 \frac{\mathbf{v}\cdot\dot{\mathbf{v}}}{c^2}\mathbf{v}\right)$$

$$\mathbf{E}(\mathbf{r}) = \sum_{i=1}^{N} V_i R_i \frac{\mathbf{r}-\mathbf{r}_i}{\left|\mathbf{r}-\mathbf{r}_i\right|^3}$$

$$\mathbf{v}_0 = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = v_0 \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix}$$

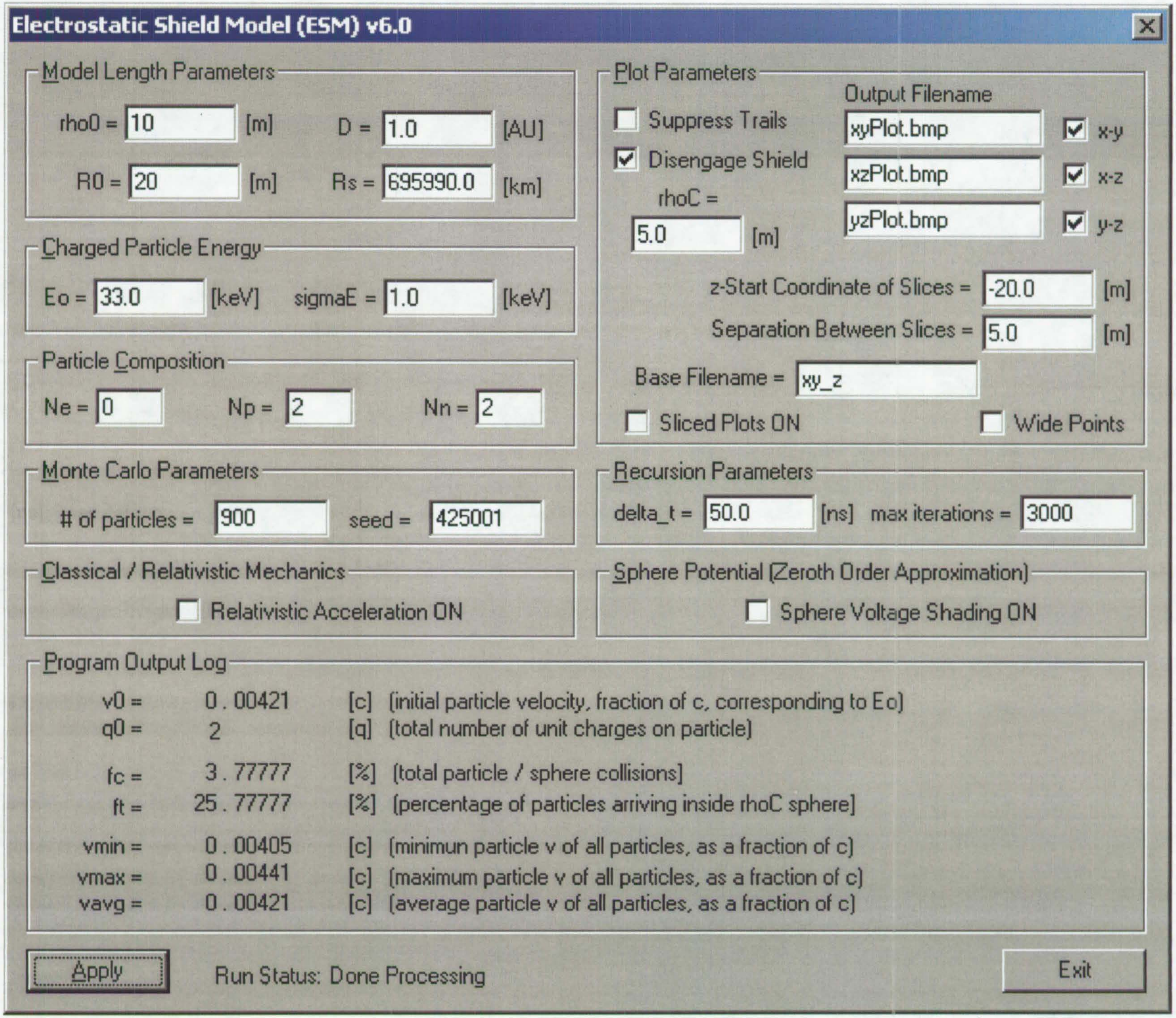
$$\gamma \equiv \left(1 - v^2 / c^2\right)^{-1/2}$$

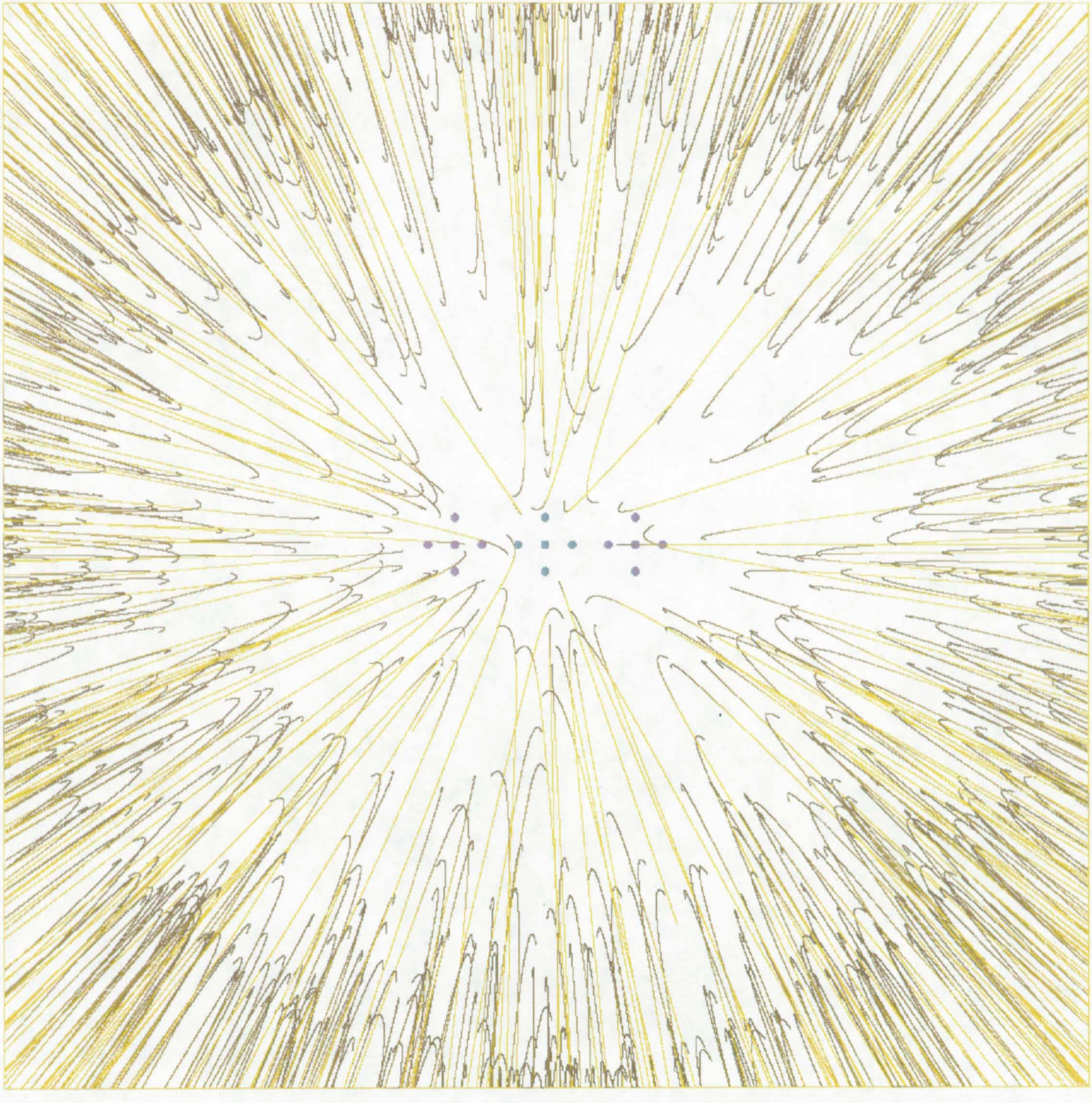
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

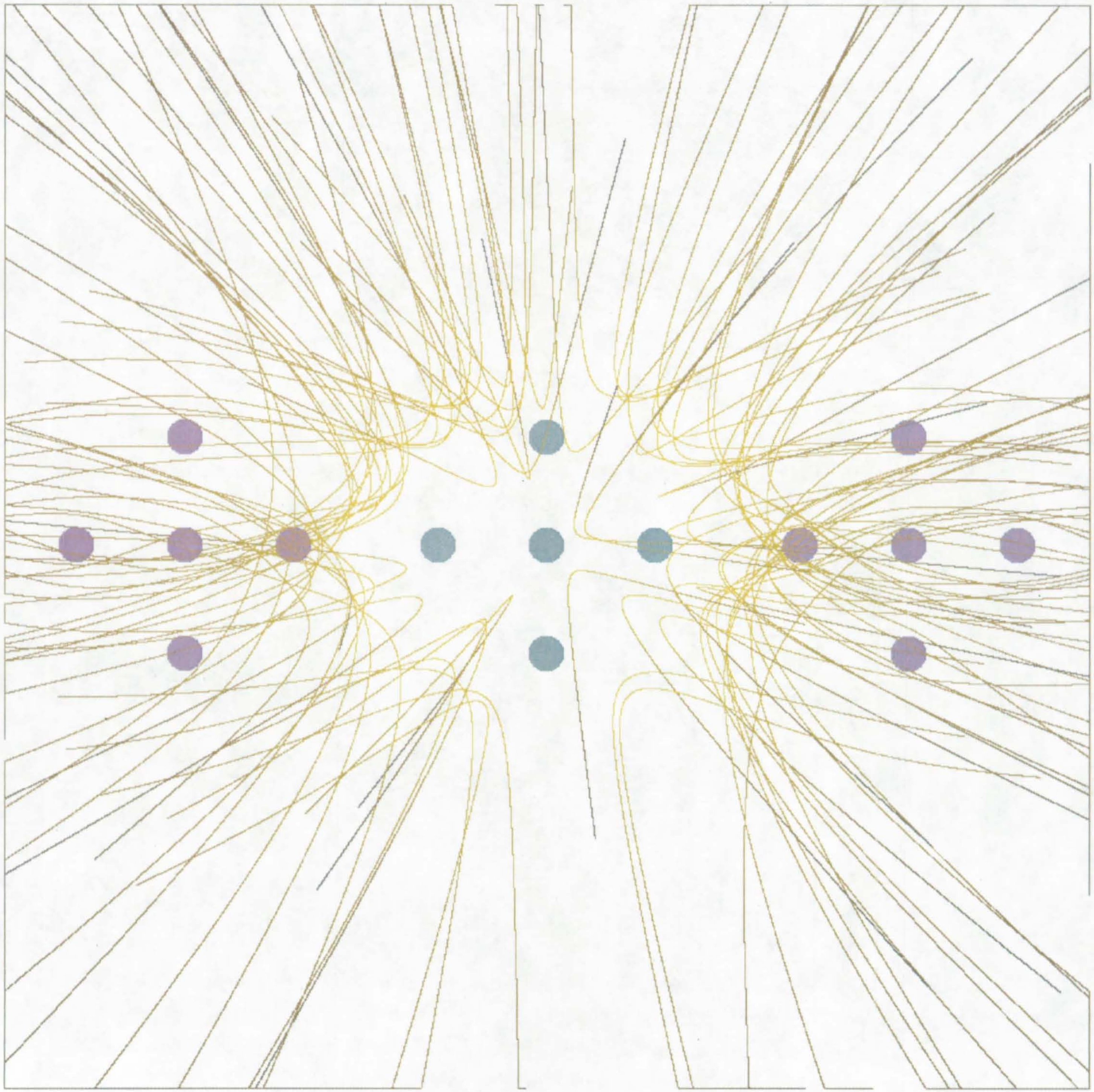
$$\alpha \equiv \frac{R_0 \sin\theta\cos\phi - R_0' \sin\theta'\cos\phi'}{\left\|\begin{pmatrix} R_0 \sin\theta\cos\phi - R_0' \sin\theta'\cos\phi' \\ R_0 \sin\theta\sin\phi - R_0' \sin\theta'\sin\phi' \\ R_0 \cos\theta - R_0' \cos\theta' \end{pmatrix}\right\|} \qquad \beta \equiv \frac{R_0 \sin\theta\sin\phi - R_0' \sin\theta'\sin\phi'}{\left\|\begin{pmatrix} R_0 \sin\theta\cos\phi - R_0' \sin\theta'\cos\phi' \\ R_0 \sin\theta\sin\phi - R_0' \sin\theta'\sin\phi' \\ R_0 \cos\theta - R_0' \cos\theta' \end{pmatrix}\right\|}$$

$$\gamma \equiv \frac{R_0 \cos\theta - R_0' \cos\theta'}{\left\|\begin{pmatrix} R_0 \sin\theta\cos\phi - R_0' \sin\theta'\cos\phi' \\ R_0 \sin\theta\sin\phi - R_0' \sin\theta'\sin\phi' \\ R_0 \cos\theta - R_0' \cos\theta' \end{pmatrix}\right\|}$$

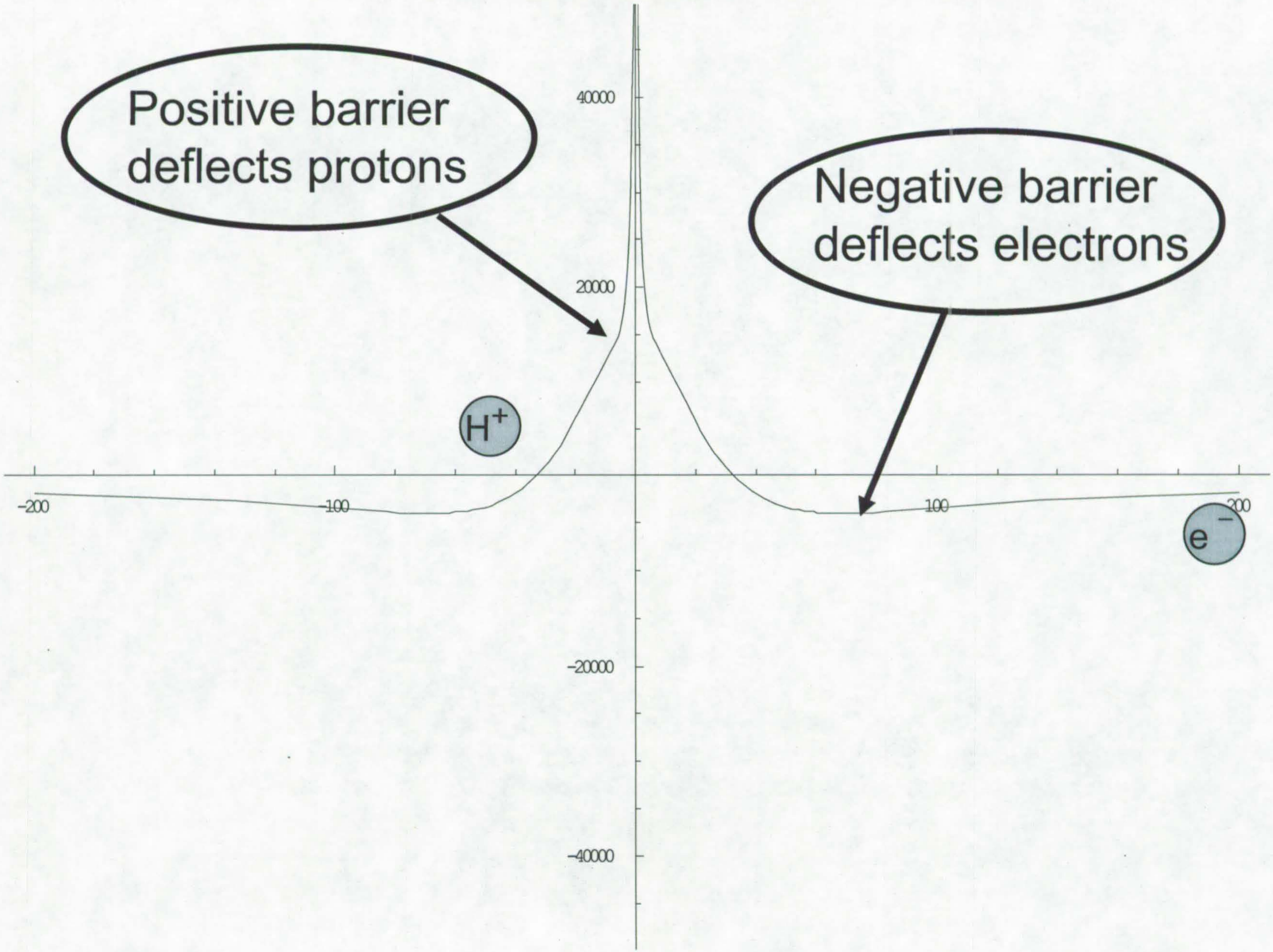
$$\mathbf{r}_0 = R_0' \begin{pmatrix} \sin\theta'\cos\phi' \\ \sin\theta'\sin\phi' \\ \cos\theta' \end{pmatrix} \qquad v_0 = \frac{\sqrt{2}T}{m_0 c}\left(\sqrt{1 + \left(\frac{m_0 c^2}{T}\right)^2} - 1\right)^{1/2}$$


Electrostatic Shield Model (ESM) v6.0
Model Length Parameters
rho0 = 10 [m]
D = 1.0 [AU]
R0 = 20 [m]
Rs = 695990.0 [km]
Charged Particle Energy
Eo = 33.0 [keV]
sigmaE = 1.0 [keV]
Particle Composition
Ne = 0
Np = 2
Nn = 2
Monte Carlo Parameters
# of particles = 900
seed = 425001
Classical / Relativistic Mechanics
Relativistic Acceleration ON
Plot Parameters
Output Filename
Suppress Trails
xyPlot.bmp
x-y
Disengage Shield
xzPlot.bmp
x-z
rhoC =
5.0 [m]
yzPlot.bmp
y-z
z-Start Coordinate of Slices = -20.0 [m]
Separation Between Slices = 5.0 [m]
Base Filename = xy_z
Sliced Plots ON
Wide Points
Recursion Parameters
delta_t = 50.0 [ns]
max iterations = 3000
Sphere Potential (Zeroth Order Approximation)
Sphere Voltage Shading ON
Program Output Log
v0 = 0.00421 [c] (initial particle velocity, fraction of c, corresponding to Eo)
q0 = 2 [q] (total number of unit charges on particle)
fc = 3.77777 [%] (total particle / sphere collisions)
ft = 25.77777 [%] (percentage of particles arriving inside rhoC sphere)
vmin = 0.00405 [c] (minimun particle v of all particles, as a fraction of c)
vmax = 0.00441 [c] (maximum particle v of all particles, as a fraction of c)
vavg = 0.00421 [c] (average particle v of all particles, as a fraction of c)
Apply
Run Status: Done Processing
Exit





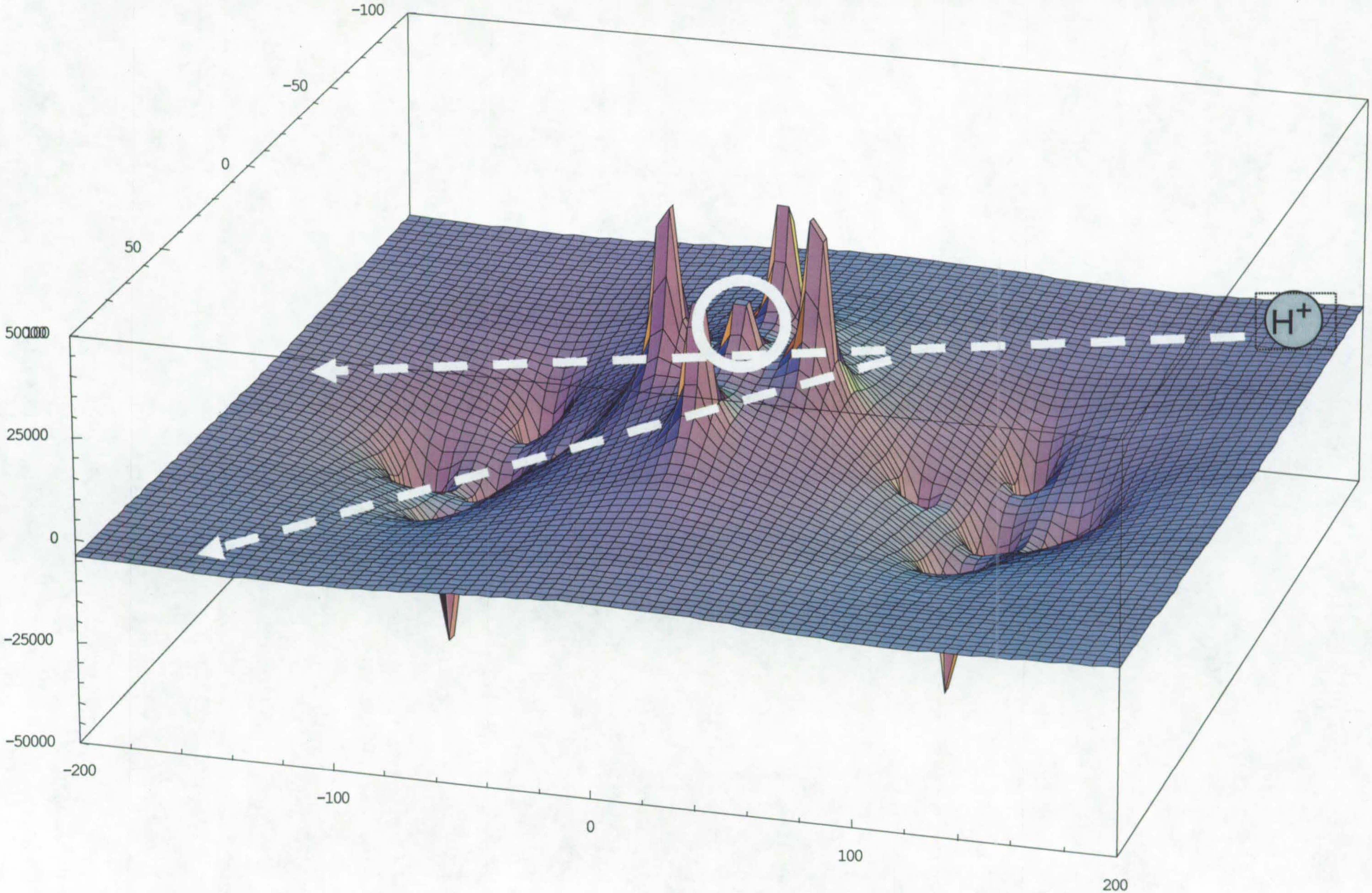
$$\Phi(x=\xi, y=\xi, z=\xi)$$



Cutoff Energy

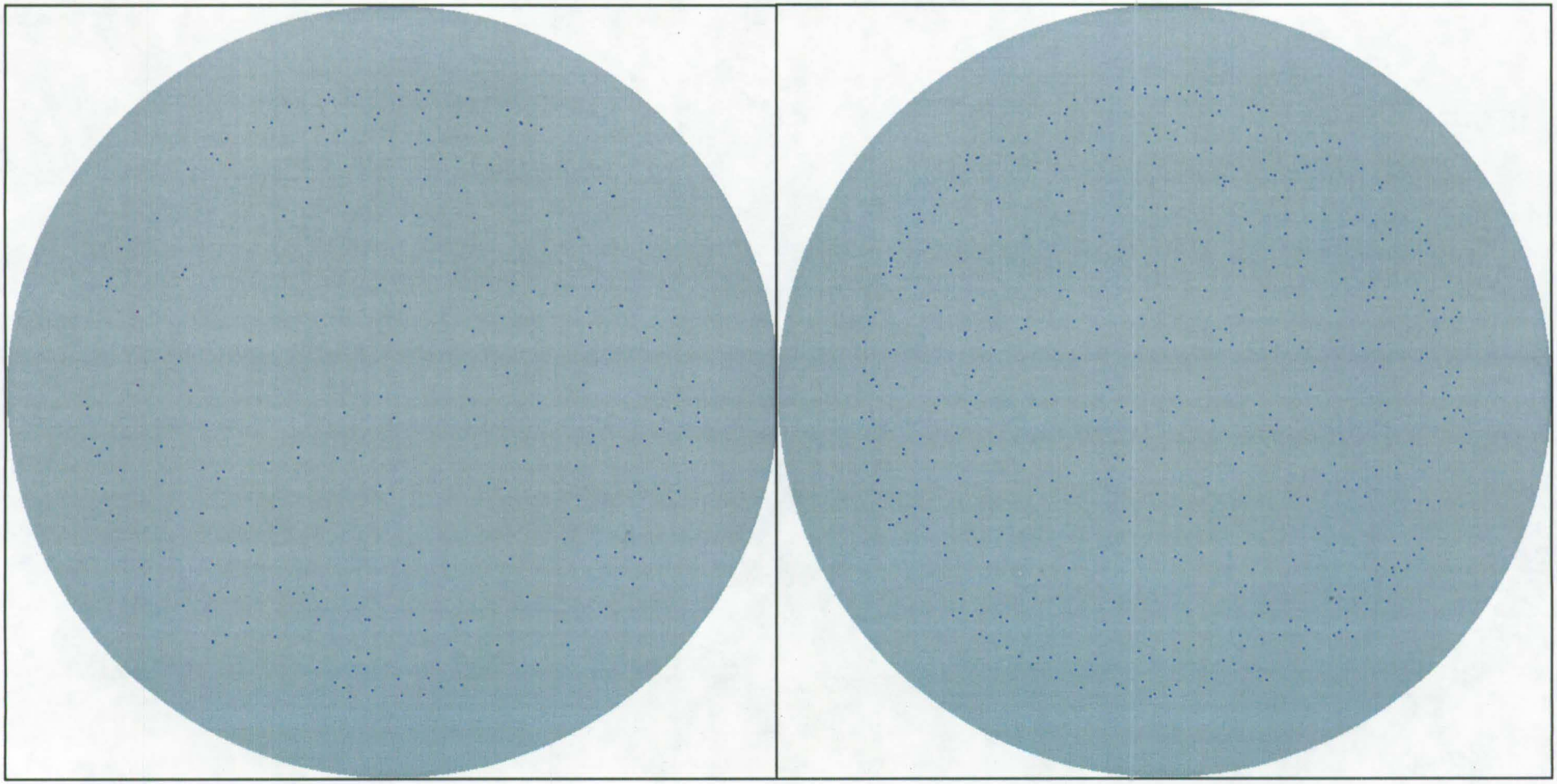
- All particles unable to get over the “hump” are deflected
  - The hump’s magnitude is the cutoff energy
- Particles with energy above cutoff may strike the spacecraft
  - But many are *turned slightly* and therefore “miss” the spacecraft
  - The number that “miss” is a function of energy

Deflection of Over-Cutoff Particles

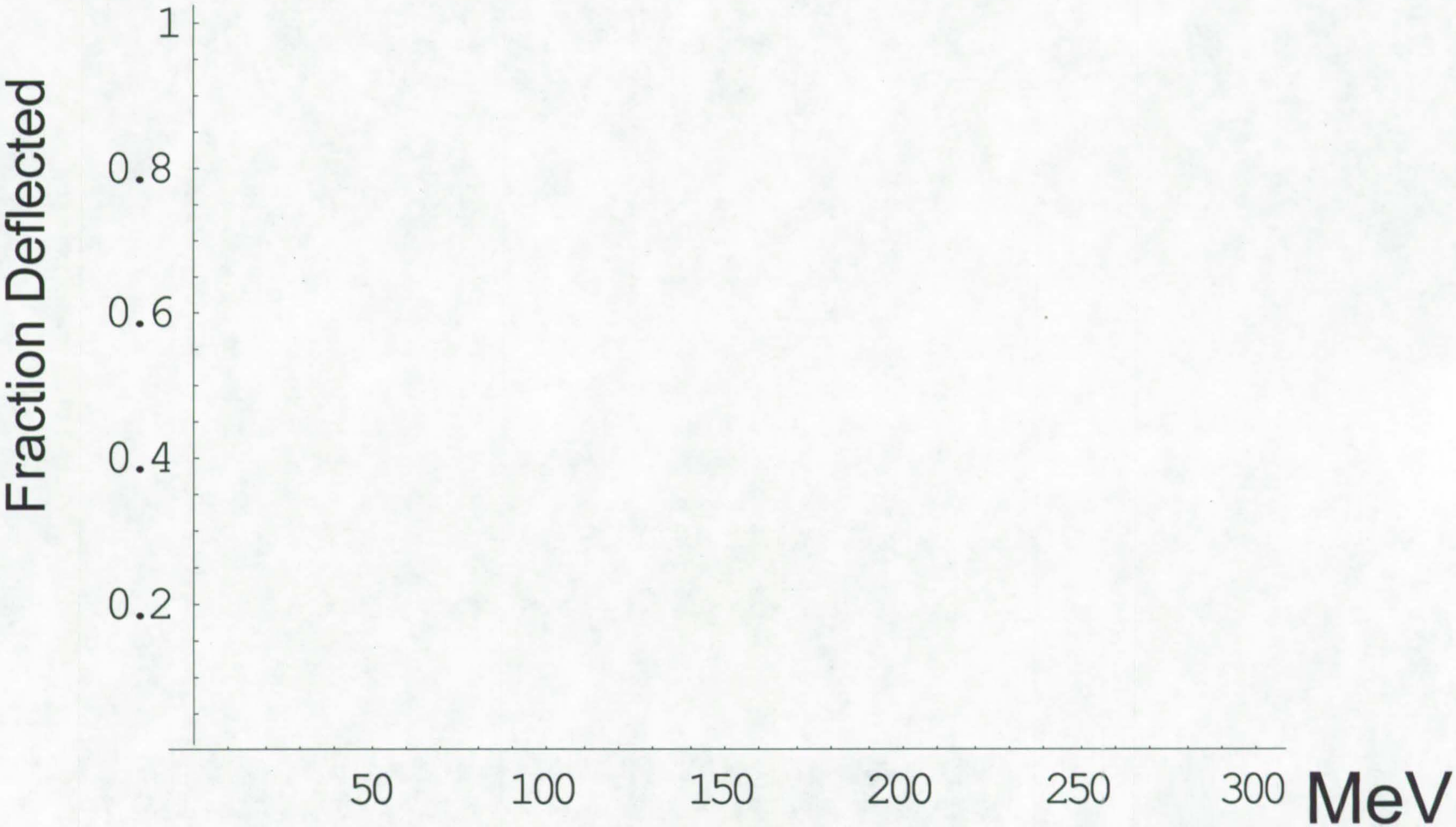


Above Cutoff Energy

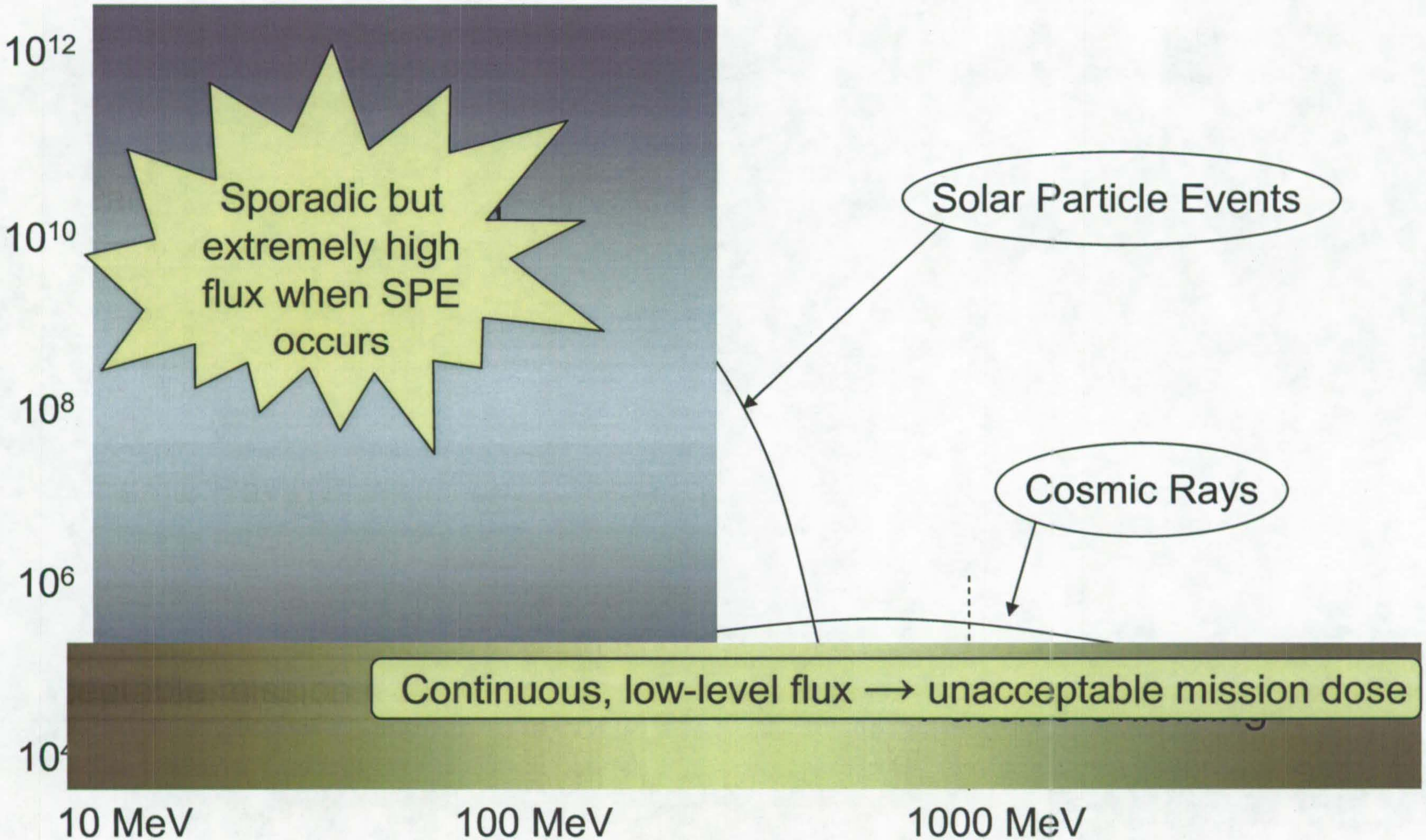
Increased Penetration with Increased Particle Energy



Shield Efficiency
as a Function of Particle Energy



Space Radiation Spectrum



Ref. Silberberg *et al.*, 1984

Maximizing Cutoff Energy

- Geometry of Shield
  - Arrangement of Spheres
  - Bigger Spheres
  - More Spheres

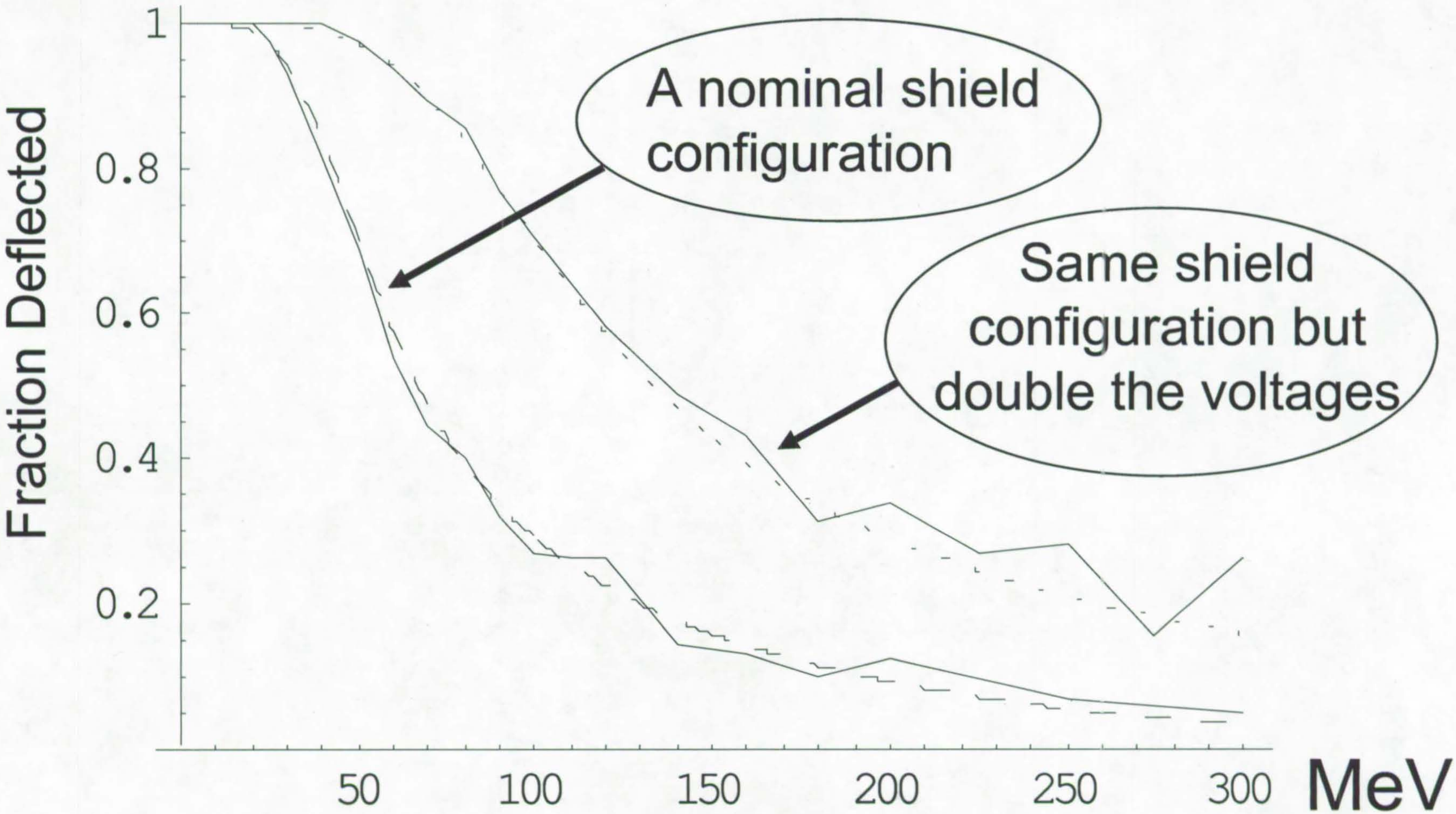
These affect shielding efficiency, but not cutoff energy

- ***Higher Voltage!***

Developing higher-voltage, space-based power supplies is the key technology challenge

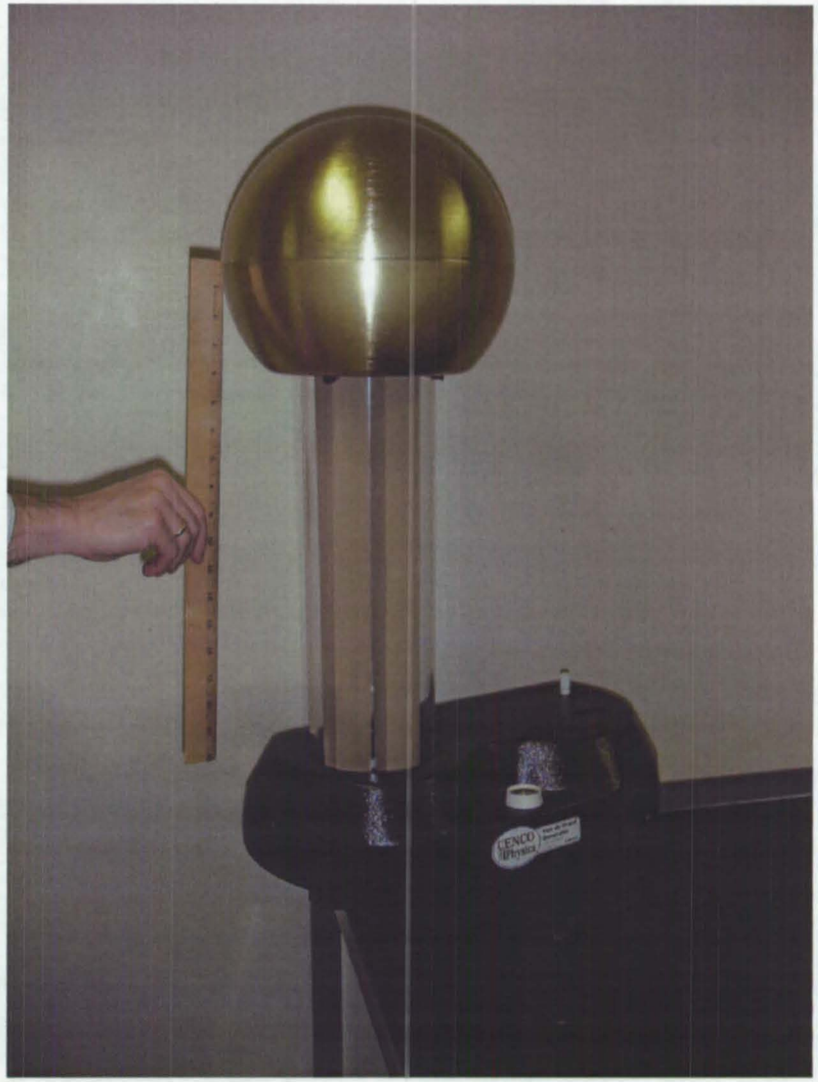
Shield Efficiency

as a Function of Particle Energy



Power Supplies

- Van de Graaf generators
  - 10 to 20 MV for particle accelerators
    - *But very large!*
  - 500 kV for inexpensive desktop versions
    - Limited by charge bleed-off into the atmosphere



Achievable Voltages

- Take advantage of the space environment
- No atmosphere
  - Breakdown voltage in space is 20 to 30 times higher than on Earth
  - *Should achieve 10 – 15 MV in space with a small power supply*
- No gravity or ground plane
  - Easier spatial arrangement
  - Daisy-chaining 7 – 10 small power supplies along an insulating truss can achieve over 100 MV

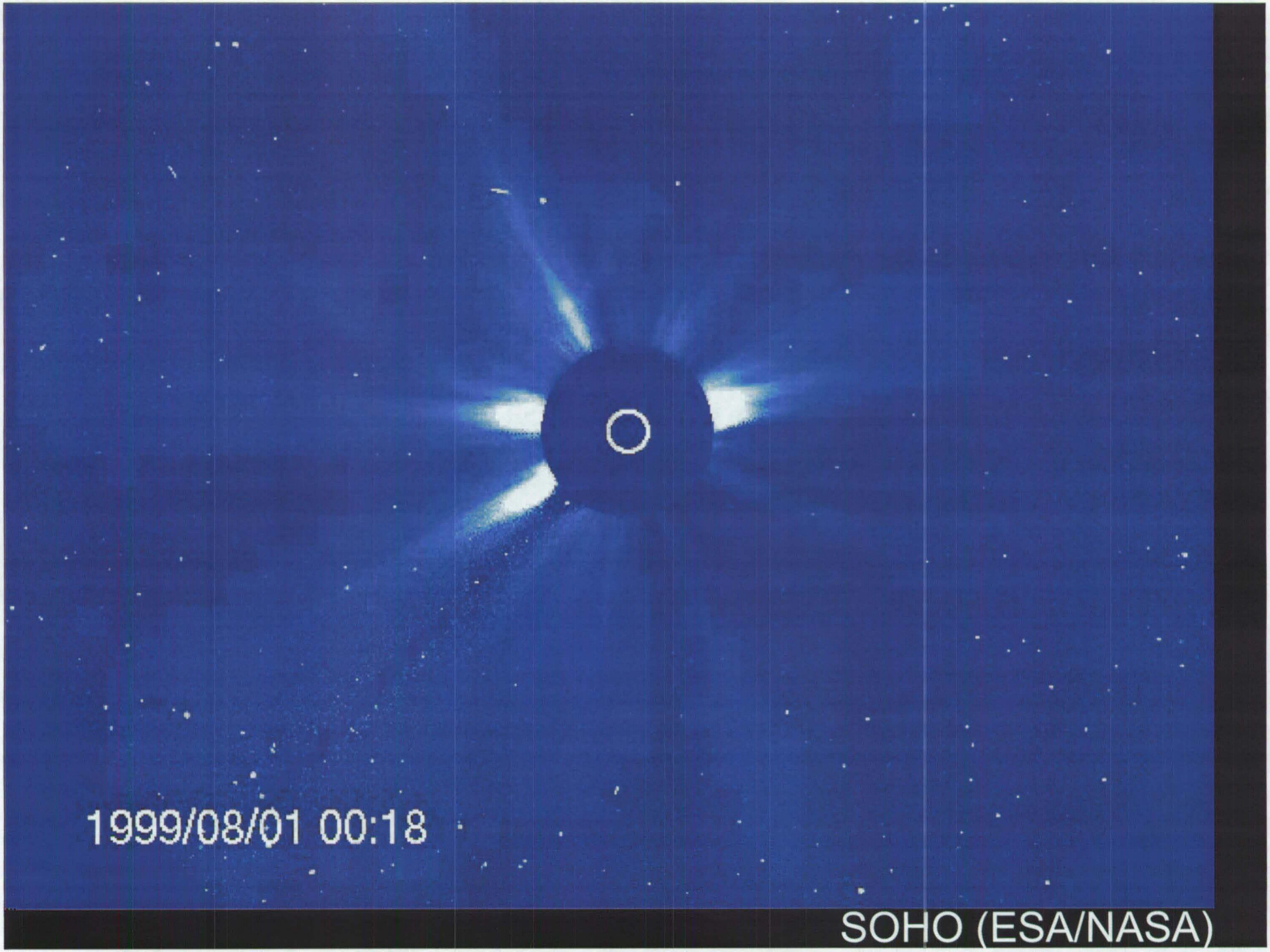
Integration with the Spacecraft

- Ion Thrusters
  - Ion exhaust cannot escape radiation shield
  - Incompatible with electrostatic shield!
- Strategy
  - Use passive shielding only, except during SPEs
  - Also use electrostatic shield in planetary orbit

Conclusion

- The radiation problem is a serious obstacle to solar system exploration
- Electrostatic shielding was previously dismissed as unworkable
  - This was based on the false assumption that radial symmetry is needed to provide isotropic protection
- KSC recently demonstrated the feasibility of asymmetric, multipole electrostatic shielding

- ***Combined with passive shielding it might solve the radiation problem***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