

Antimatter Harvesting in Space

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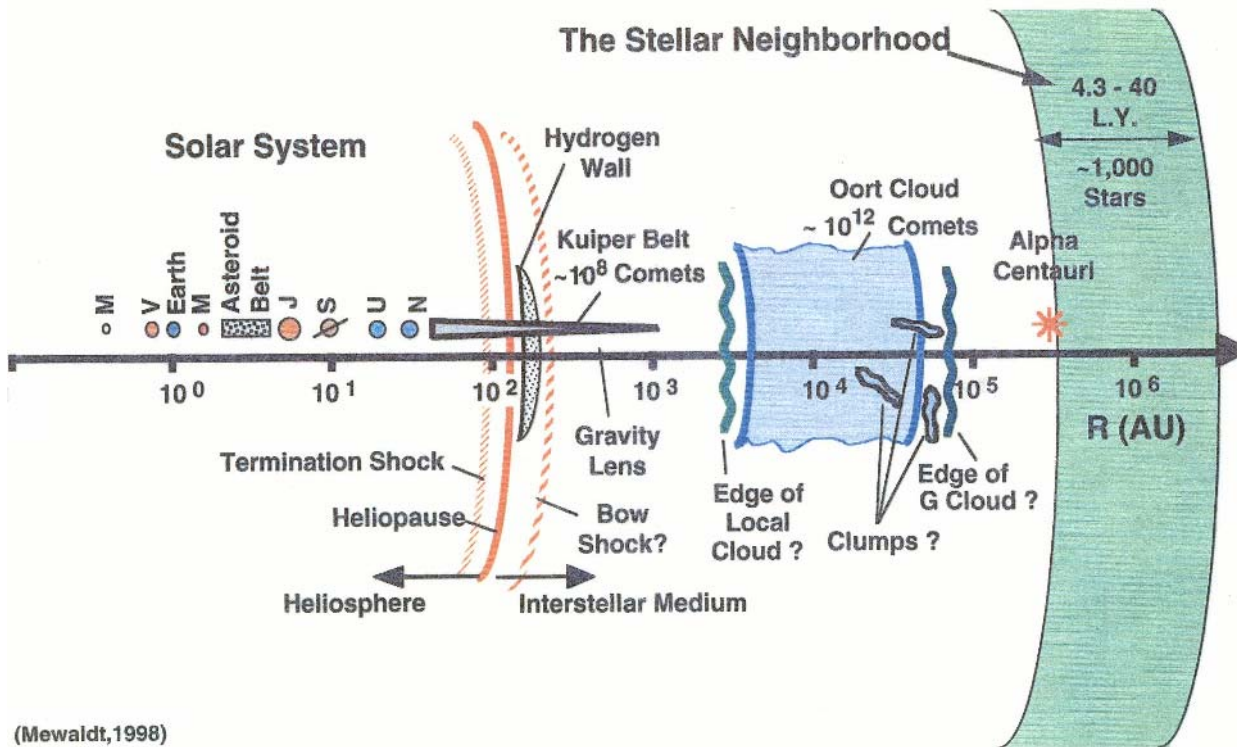
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NASA Exploration Vision



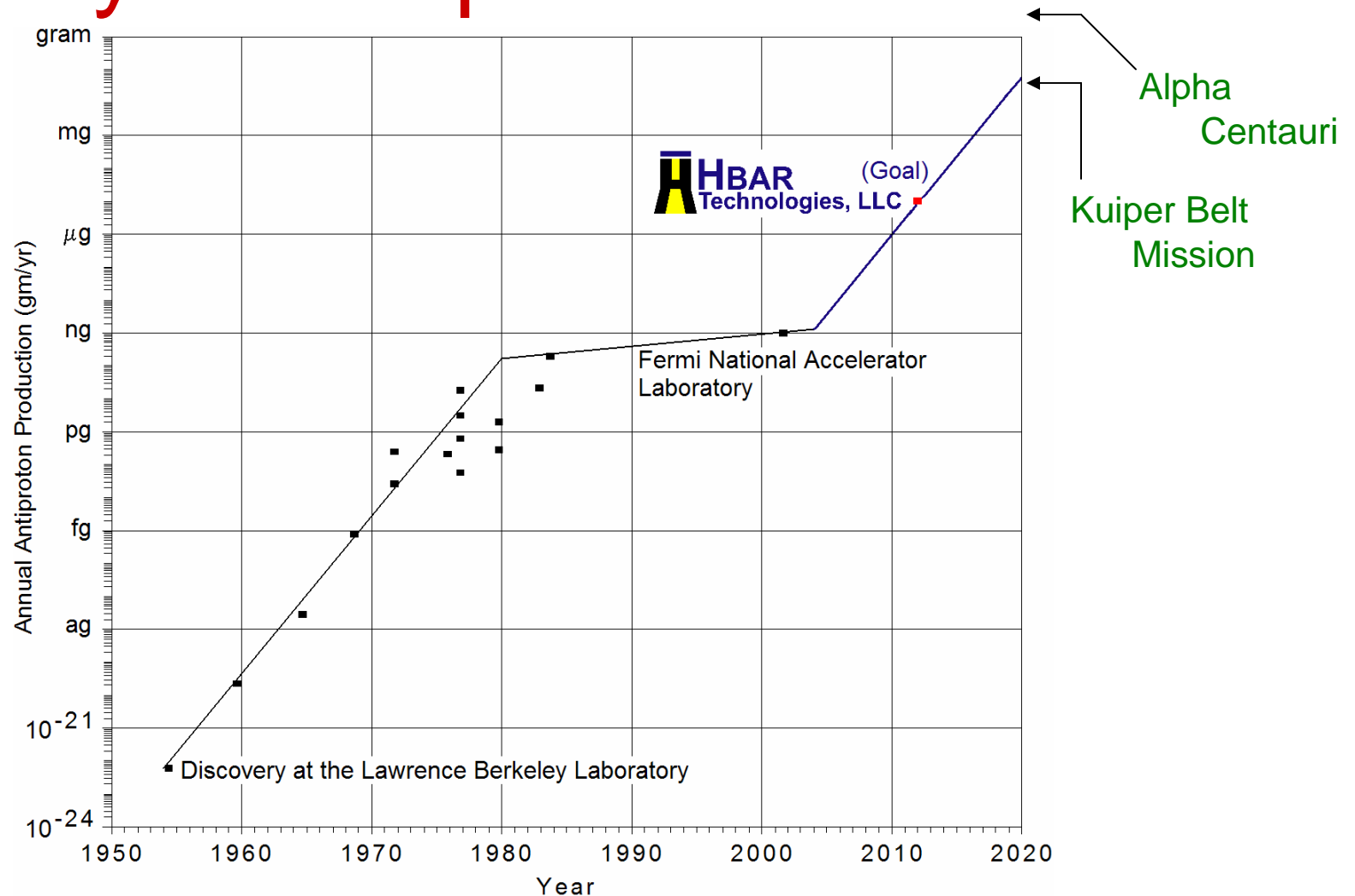
SCALE OF THE HELIOSPHERE AND THE LOCAL INTERSTELLAR MEDIUM



(Mewaldt, 1998)

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History of Antiproton Generation



Fermilab Overview

- The Main Injector accelerates protons to 120 GeV and directs them into the antiproton production target.
- The Antiproton Source accumulates and cools the antiprotons at a kinetic energy of 8 GeV.
- The Main Injector accelerates the antiprotons to 150 GeV and injects them into the Tevatron Collider.



Antiproton Production @ Fermilab

- Present: 10^{11} antiprotons/hour for 4500 hours per year
- Present: 27.4 M\$/year for purchase of all antiprotons
- Near Future: Agreement to purchase 1% of Fermilab production for an annual cost of 274 k\$, plus cost of construction, utilities, and safety oversight of the Hbar Technologies research facility on the Fermilab site.
- Cost per Treatment: Assuming 10^{10} antiprotons per “treatment”, the treatment cost is \$609 minus shipping.
- 2-3 Years: As our appetite for antiprotons increases, we will negotiate for a higher fraction of antiprotons.

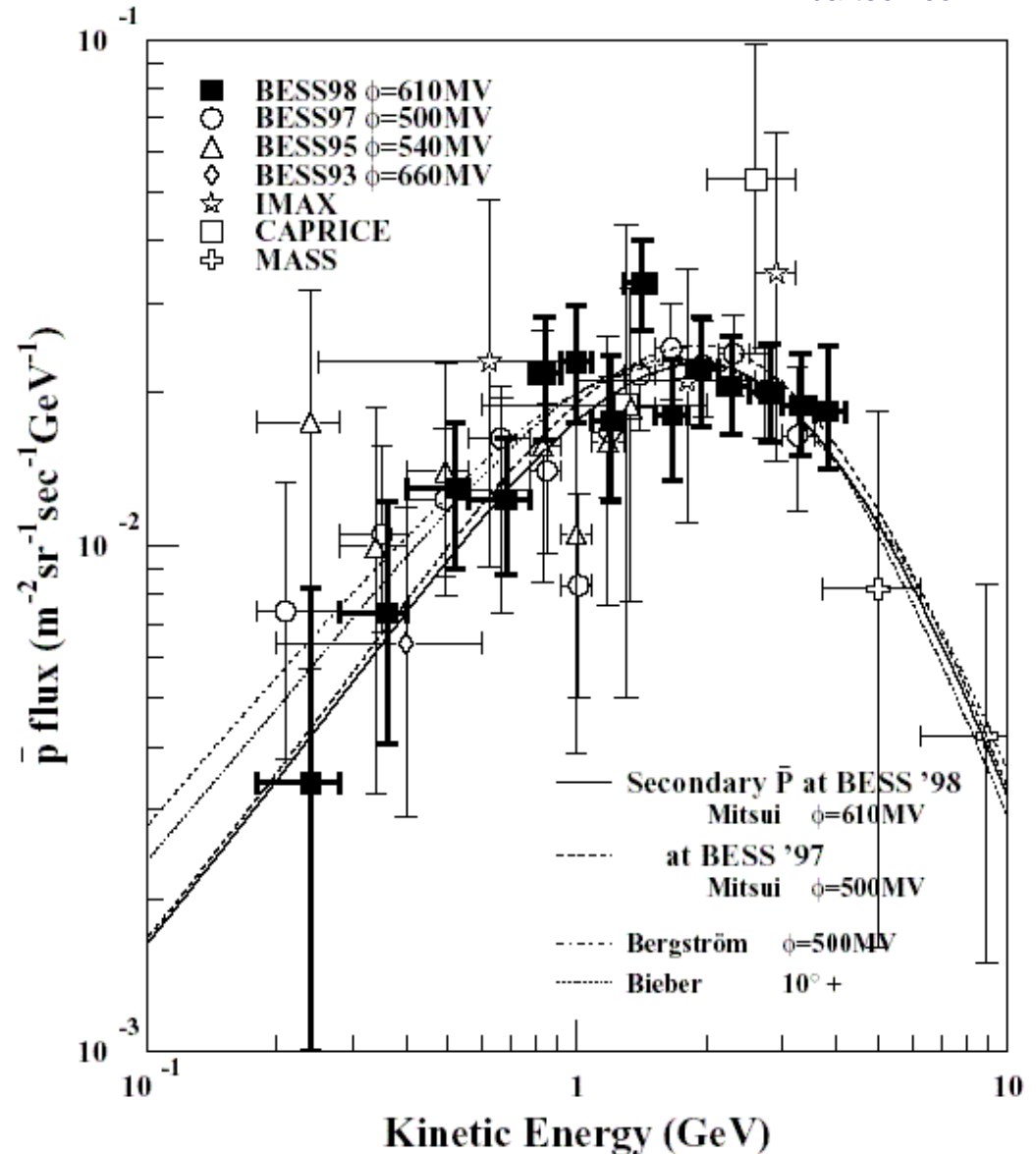
Antiproton Harvesting in Space

In the band of 1-2 GeV, the number of antiprotons between Mars and Venus is 80 g, out to Saturn there is 20 kg.

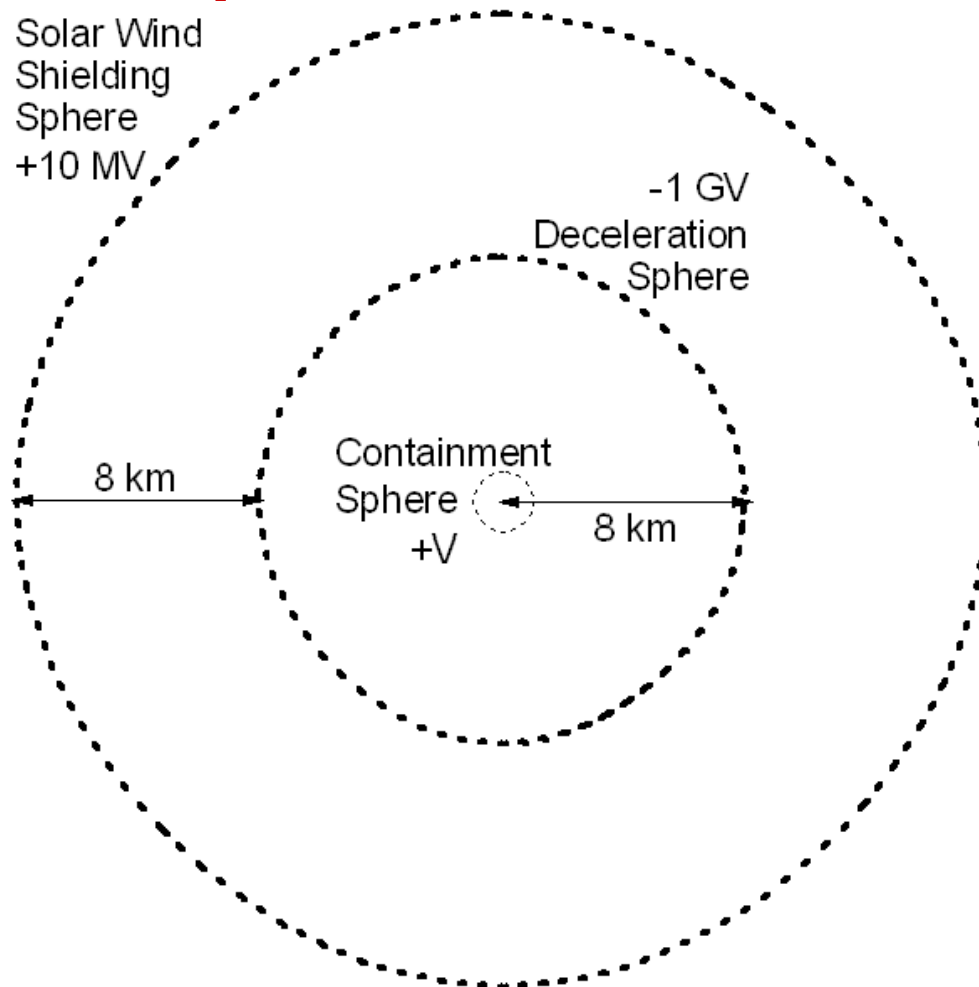
The flux of antiprotons in this energy range hitting the Earth's atmosphere is 3 mg/year.

***THIS IS THE ULTIMATE
RENEWABLE RESOURCE!***

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Spherical Harvester Geometry



Sketch of the initial spherical harvesting technology underlying the architecture proposed in this project.

The residual spread in antiproton kinetic energies is reduced by electron cooling and positron scattering within previously capture antihydrogen.

The scale of this geometry is to reproduce the current antiproton accumulation rate at Fermilab.

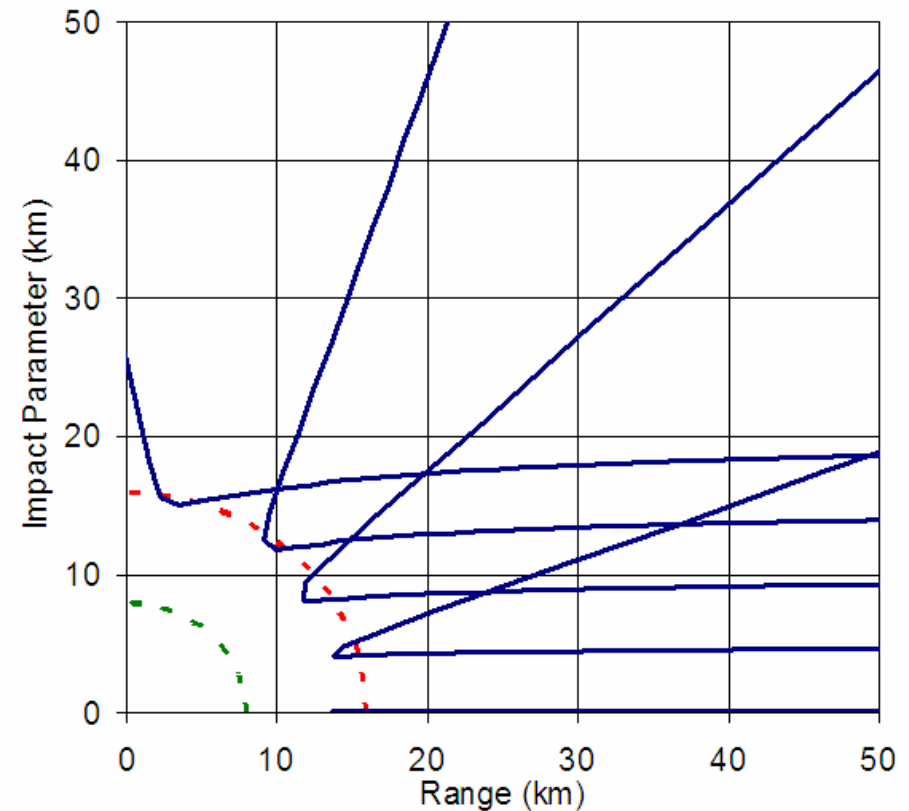
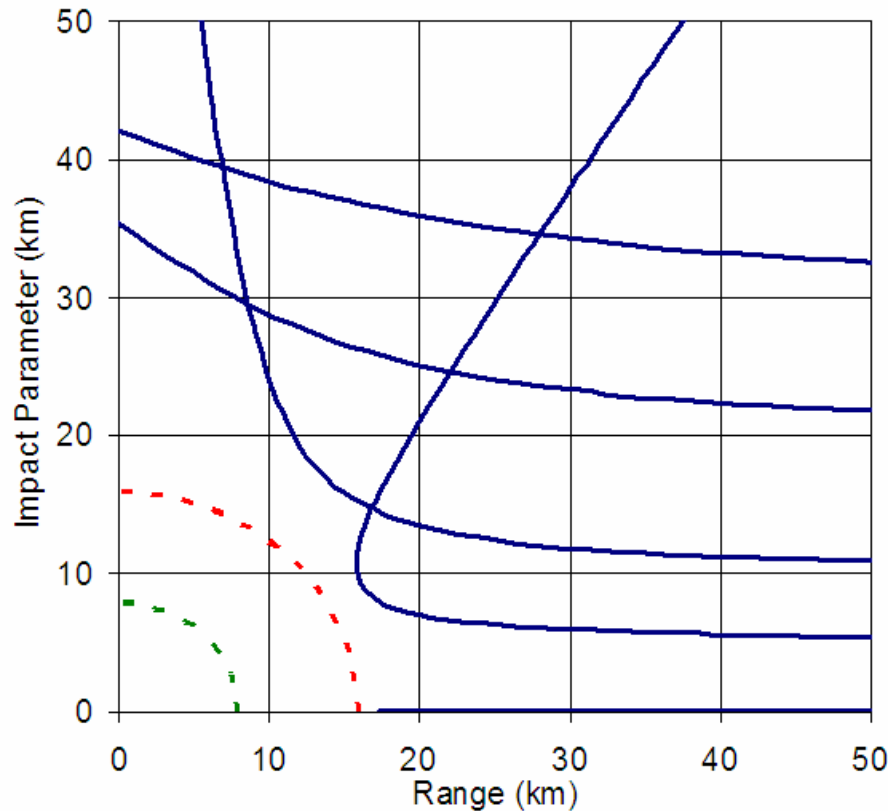
Antiparticle Trapping Primer

- The controlling legal authority for elementary particles moving in electromagnetic fields is *Louville's Theorem*. Basically, this theorem states that distributions of such particles act in 6-D phase space (three space coordinates, three velocity coordinates) as an incompressible fluid.
- You can compress the distribution in one or more phase space dimensions, but the distribution expands in at least one other phase space dimension to maintain a constant volume.
- The only way around Louville's Theorem is to take advantage of the particle nature of the distribution. This requires individual particle scattering or the statistical mechanical observations and manipulations of the distribution.

How to Get Cold Distributions?

- 1) Form the particles nearly at rest at the bottom of a potential well.
- 2) Thermodynamic contact with a cold gas [electron cooling, ionization (collisional) cooling].
- 3) Velocity dependent forces [optical molasses, photon absorption].
- 4) Stochastic cooling (measuring the mean of a statistically uncorrelated distribution of particles, and then correcting the mean offset to zero).

External Particle Deflection

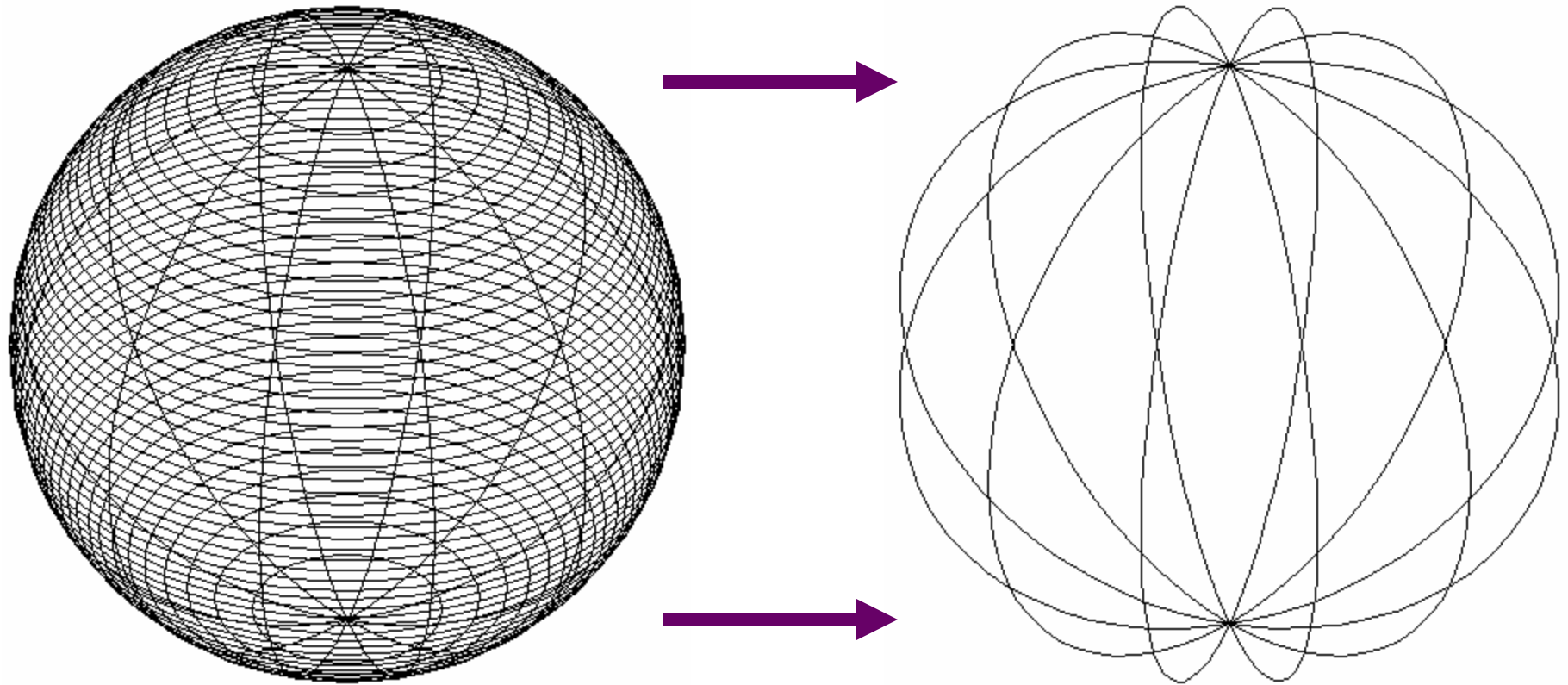


Calculation of the trajectories of 9 MeV solar protons (left) and solar electrons (right) in proximity to the repelling sphere (red) and decelerating sphere (green). Note that both signs of particles are diverted away from the antiprotons being cooled inside the decelerating sphere. Particles are incident on the harvester from the right.

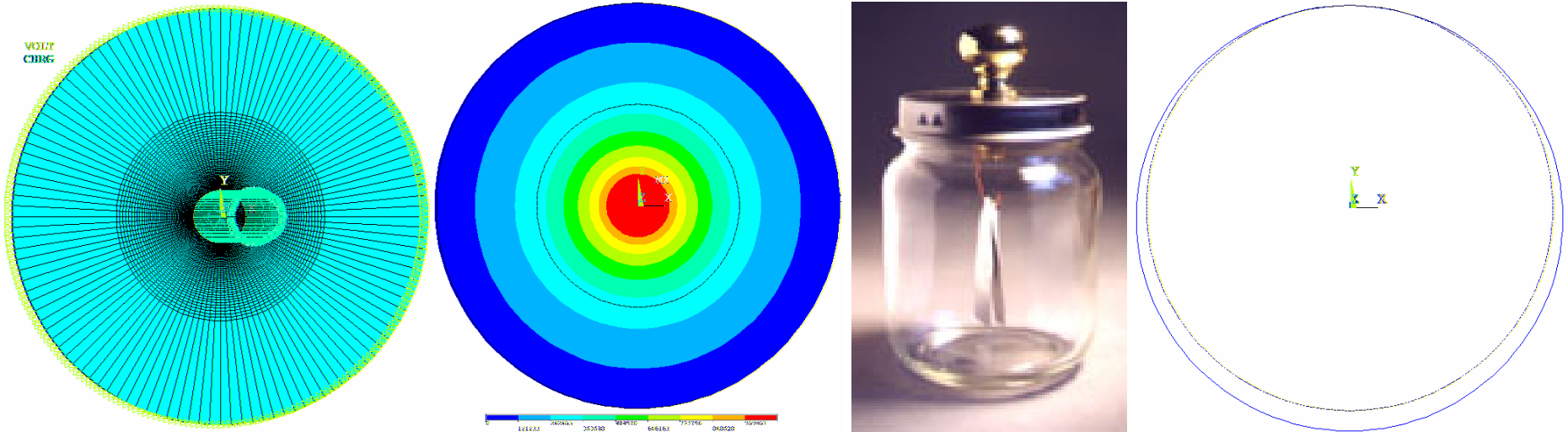
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What Have We Learned so Far during Phase I ???

Change in Sphere Fabrication

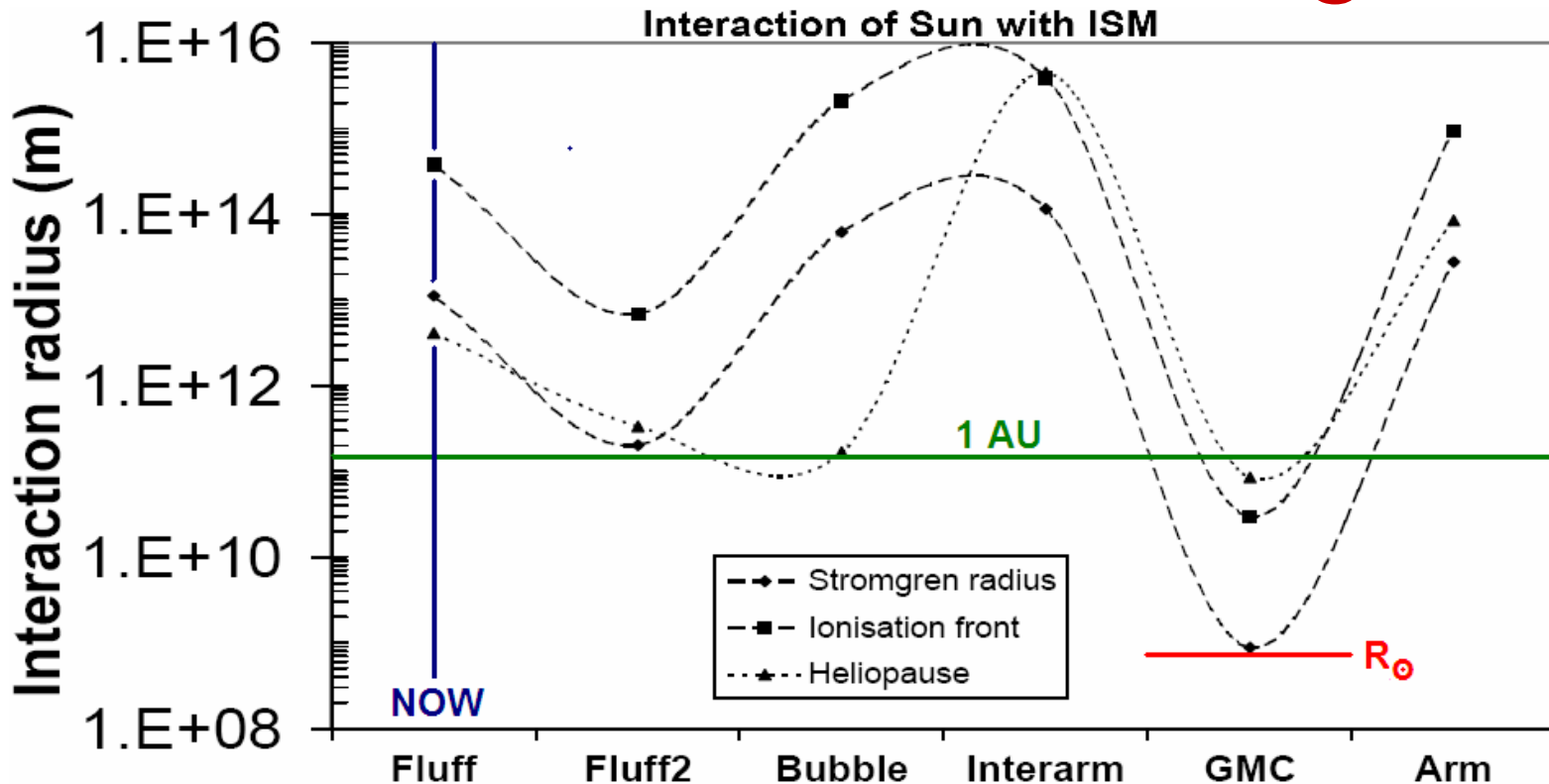


Single Wire Loop Calculations



| Parameter | Value |
|---|-------------------------|
| Newtonian Gravitational Constant G_N ($m^3/kg-s^2$) | 6.673×10^{-11} |
| Permittivity of Free Space ϵ_0 (F/m) | 8.854×10^{-12} |
| Wire radius a (m) | 1.0×10^{-5} |
| Density of titanium wire ρ (kg/m^3) | 4507 |
| Critical Voltage V_c (V) | 0.22 |

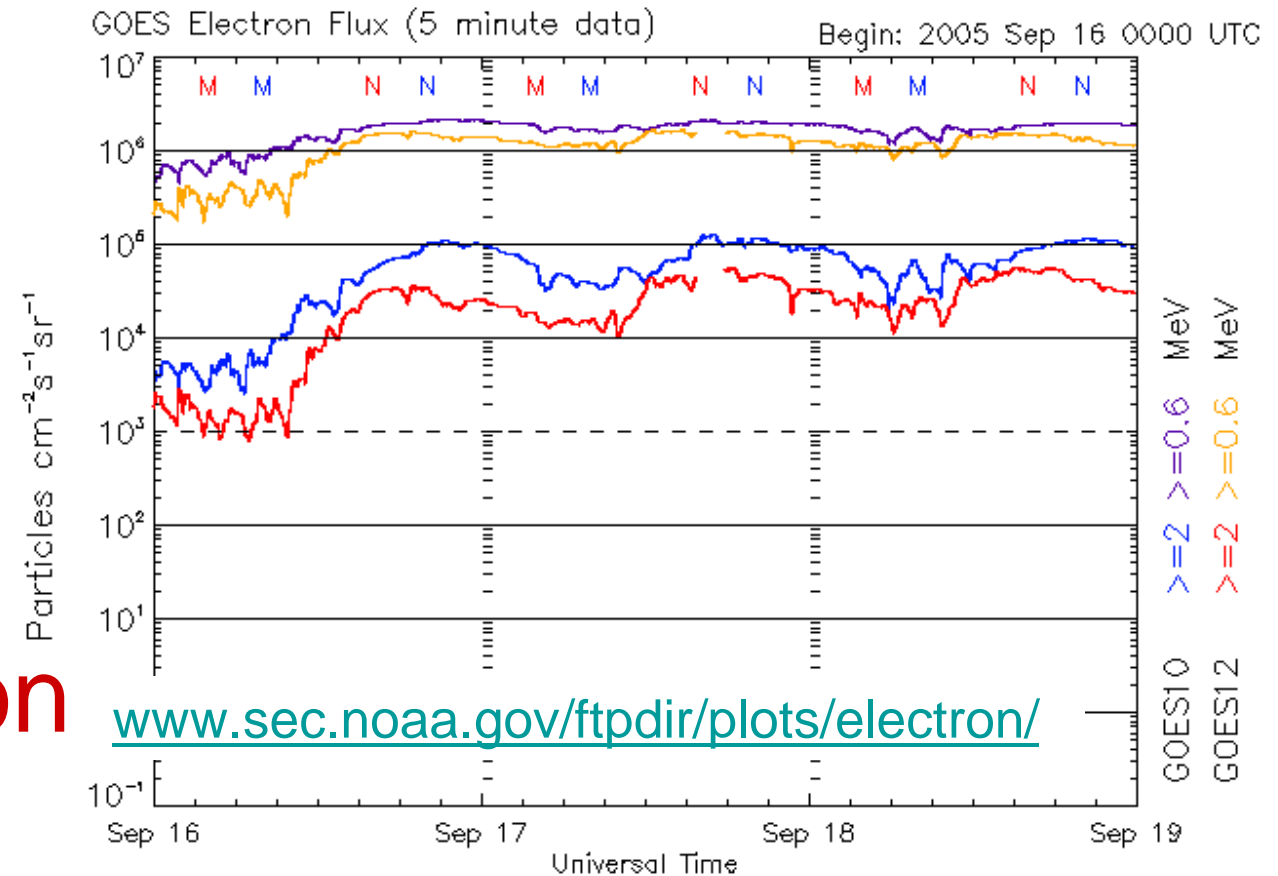
Neutral Gas Poisoning



Hydrogen gas is found in neutral atom form far from the sun. Closer to the sun, the solar ultraviolet photons ionize the hydrogen gas. The boundary between these two regions is called the Stromgren radius. Hypothesized variations with density in the local interstellar medium.

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Interaction with Solar Electrons: Power Consumption



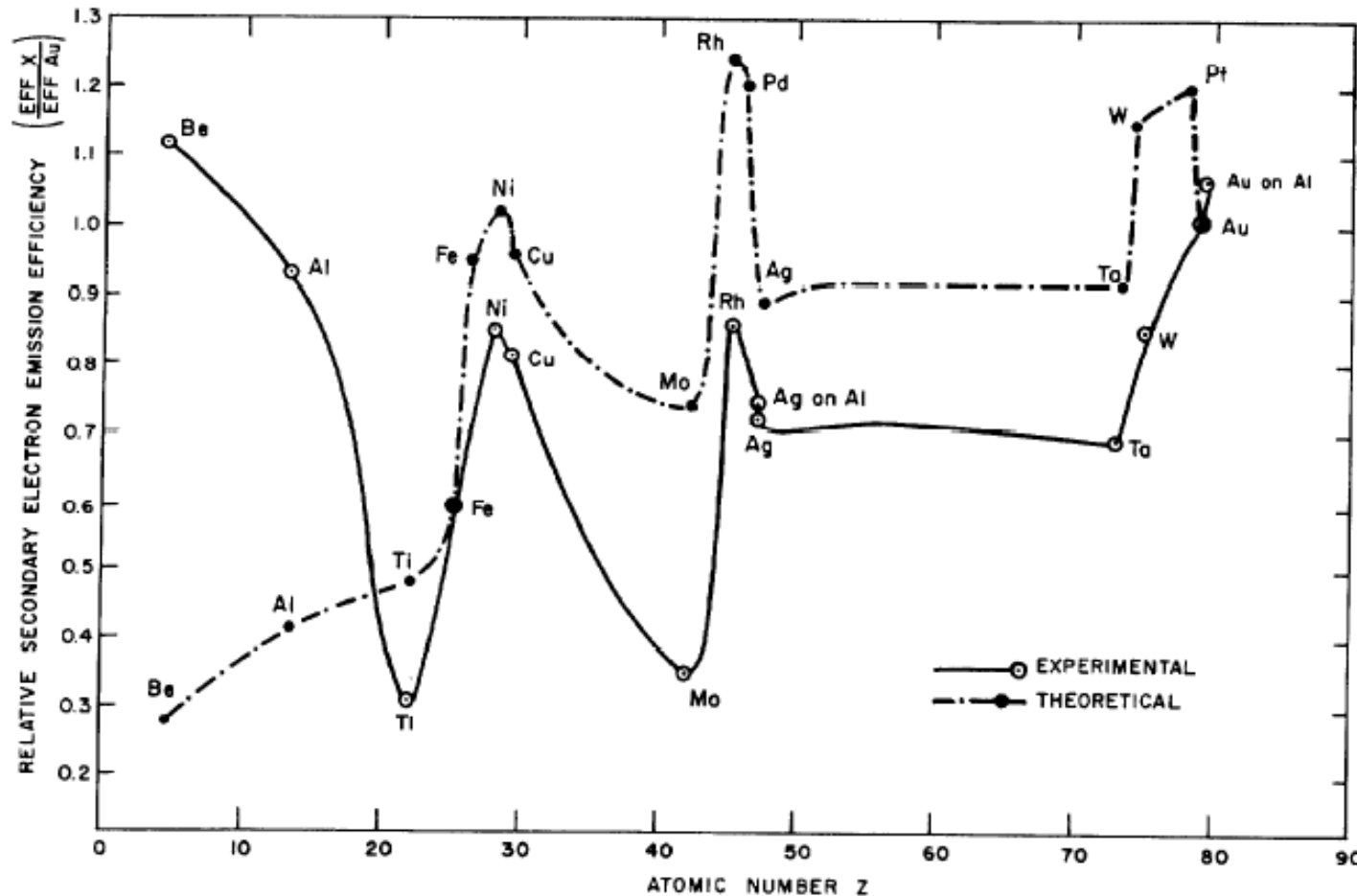
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NOAA/SEC Boulder, CO USA

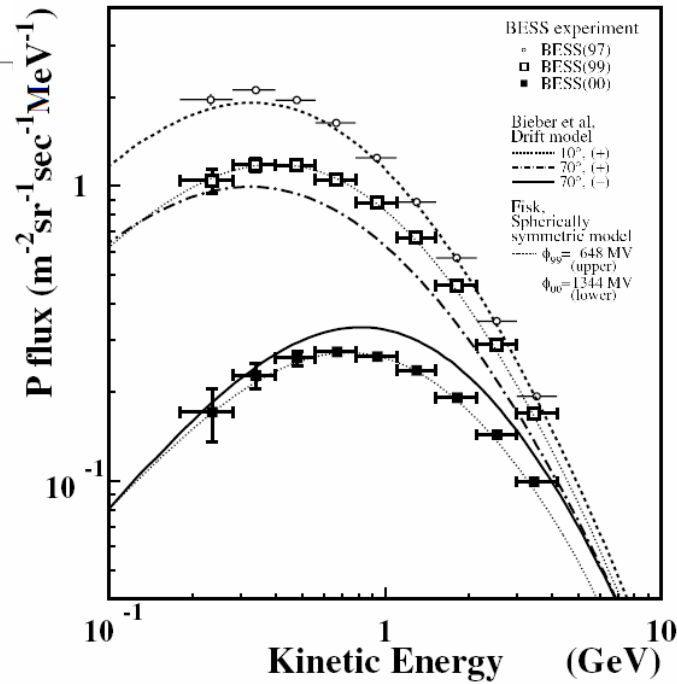
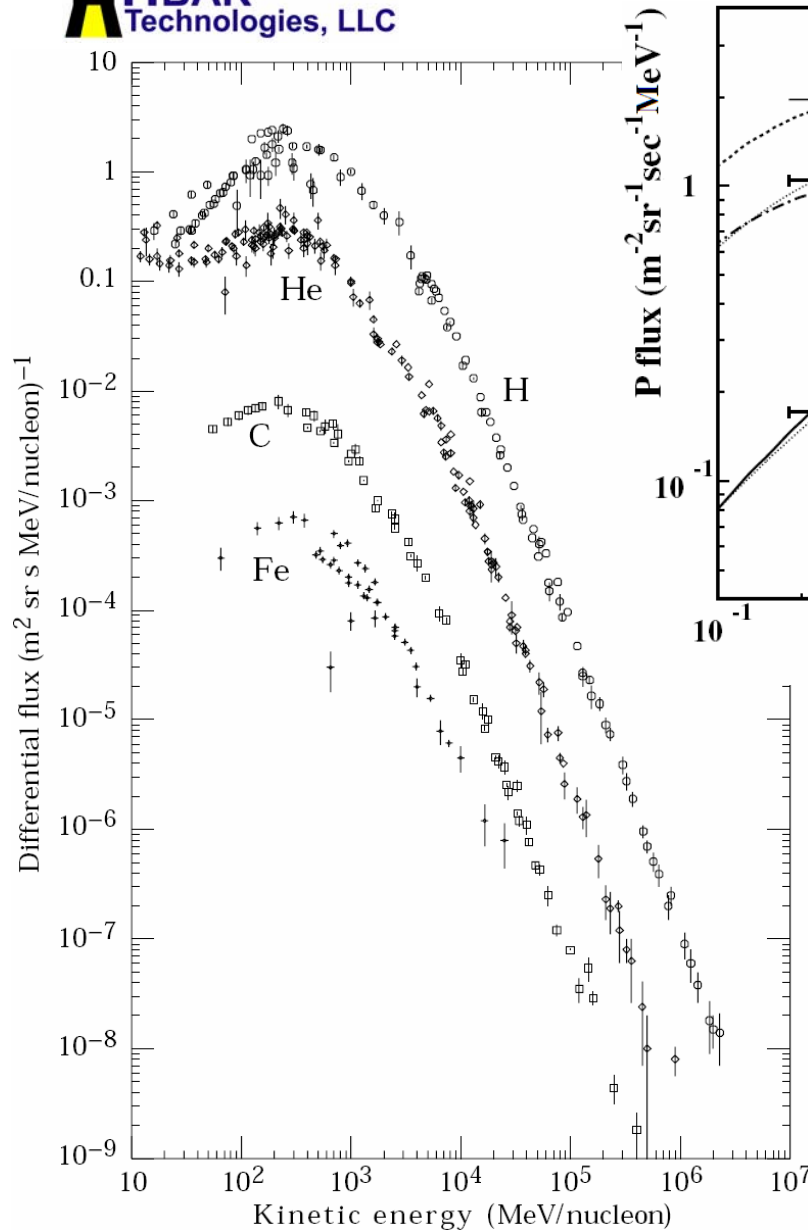
Assuming an electron flux of 10^{10} electrons/ $\text{m}^2\text{-s}$ at the harvester, and an outer sphere cross-sectional area of $8 \times 10^8 \text{ m}^2$, one obtains an incident current of 1.3 A. Multiplying by the probability of collision with the wires, the current to counteract this neutralization flux is $13 \mu\text{A}$. At 10 MV and 10% efficiency, the power is 1.3 kW.

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Reducing Power Consumption



Secondary electron emission coefficients for incident 70 MeV electrons on thin targets. Note that many candidate metals for wire are near unity.

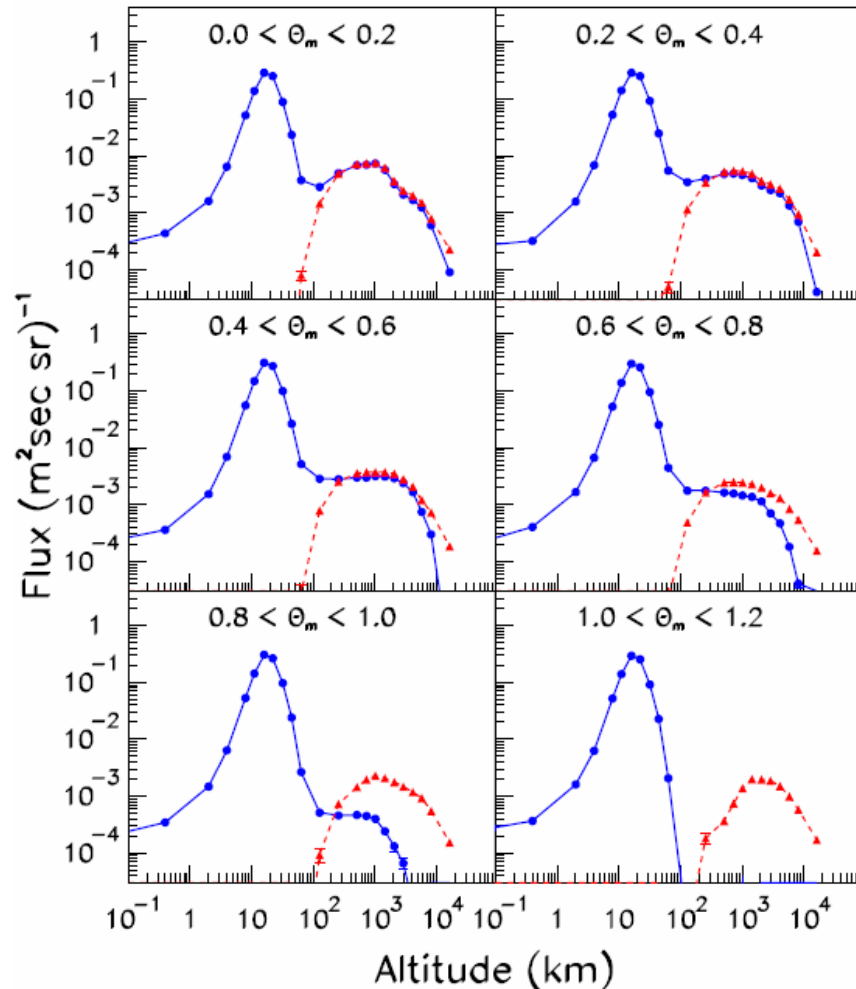


Cosmic ray flux for multiple ion species (left) and for hydrogen at various times (above) in the solar cycle. Note that the two plots have different kinetic energy units on the horizontal axis.

Cosmic Rays

High energy galactic cosmic rays will traverse the harvesters. But the entire cosmic ray spectrum extends down below 1 GeV, where the biasing of the electric potential outside of the outer sphere does deflect protons and heavier ions.

Operation Near Planets



Reproduced from Huang et. al., altitude dependence of cosmic-ray produced antiproton flux above the Earth in six latitude regions (in radians). The solid (blue) curves are for downward flowing antiprotons, while the dashed (red) curves are for upward propagating particles.

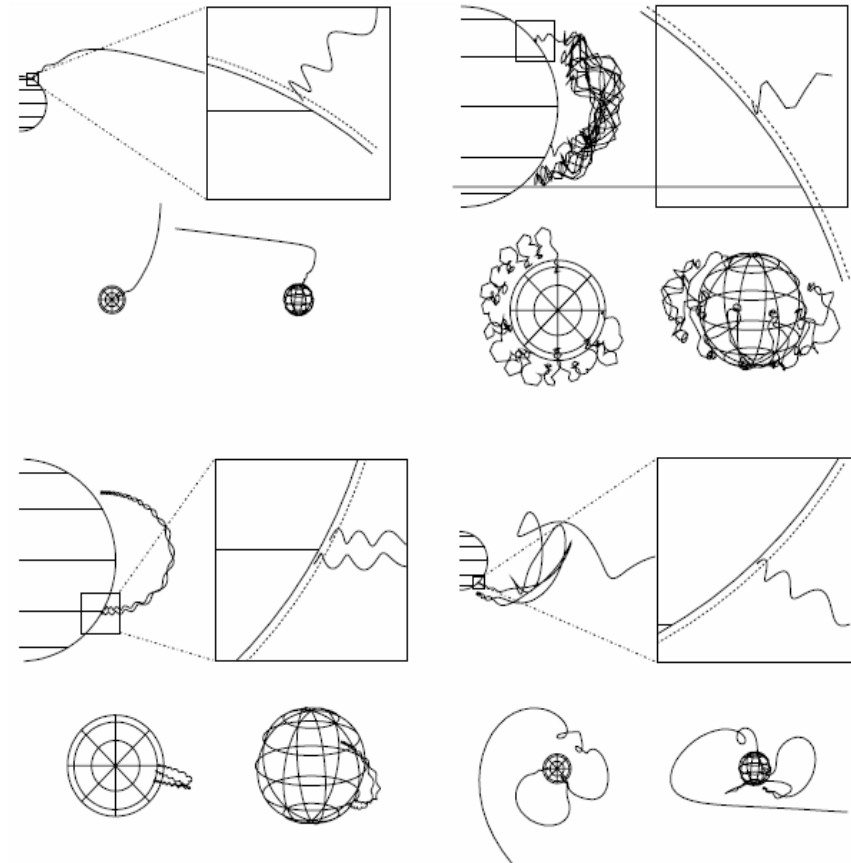
One of the interesting conclusions of this paper is that the antiproton flux at the Earth's surface is measurable. While a thousand times lower than the peak flux at 10 km, one could imagine a capture system that has a capture area 1000x larger than a space-borne harvester, laying out on the ground.

The absolute flux of cosmic-ray produced antiprotons at an altitude of 38 km is only 15-20% of the antiproton flux found propagating in space.

Operation in Magnetic Fields

The issue of planetary magnetic fields and their roles on antiproton propagation is also addressed by Huang et. al. The effect of multiple entries into the atmosphere during cyclotron oscillations on magnetic field lines was simulated. In the paper, they study trapped, semi-trapped, and non-trapped antiprotons.

There was no apparent advantage utilizing planetary magnetic fields. Given the added negative effects of harvester degradation due to atomic oxygen and orbital debris collisions, we conclude at this moment that operation of antiproton harvesters far from planetary bodies is preferable.

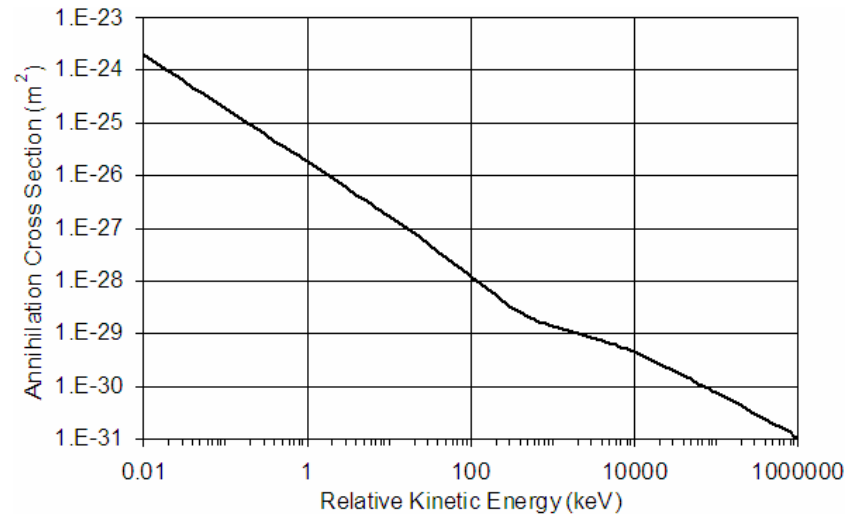


C. Y. Huang, L. Derome, and M. Buenerd,
Phys. Rev. D **68**, 053008 (2003)

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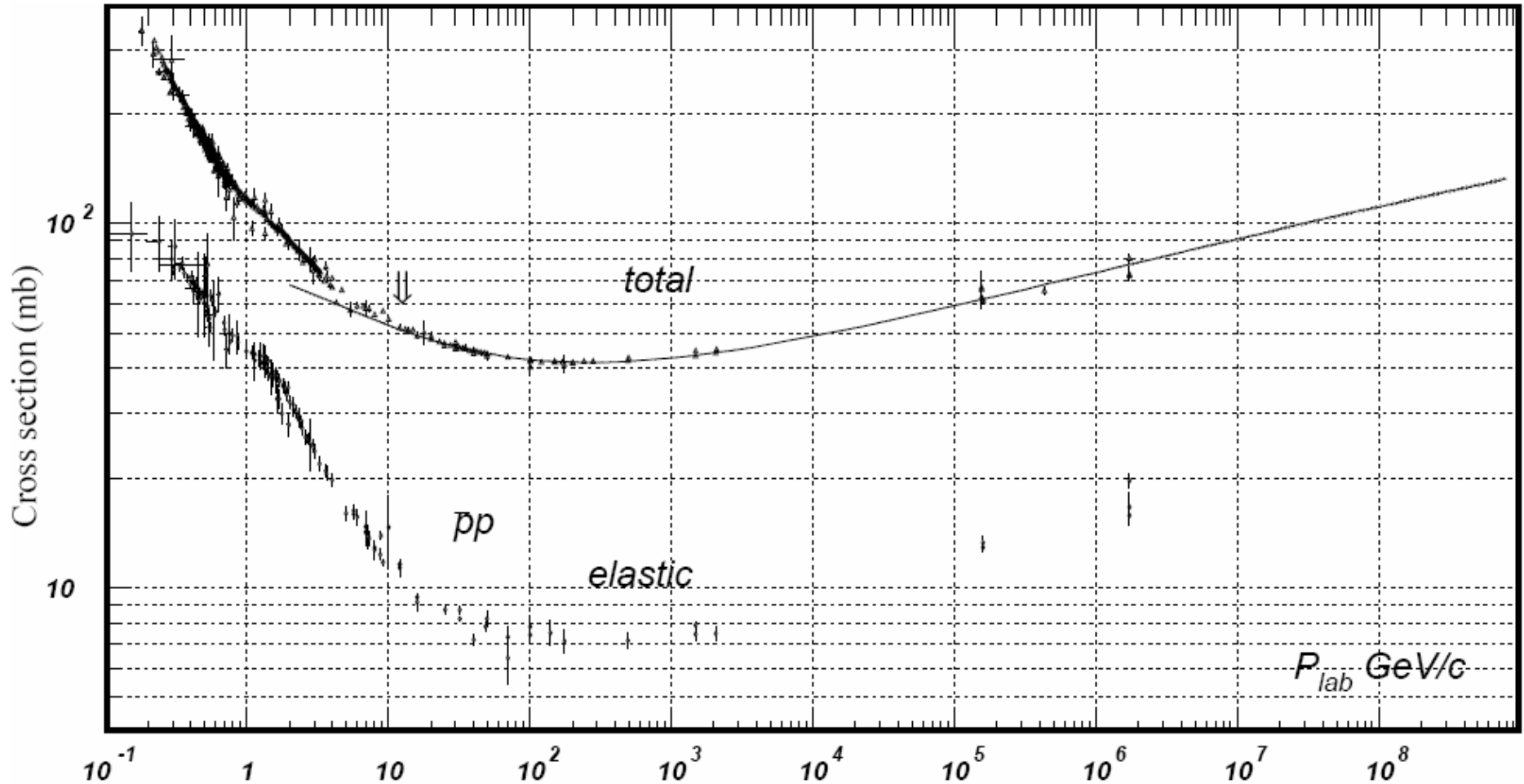
Cooling: Electron-Positron Plasma

Annihilation cross-section between a stationary electron and a moving positron of a given kinetic energy T .
Note that the cross-section decreases with a $1/T$ power law (except for the dip at 1 MeV).



| Parameter | Value |
|--|-------------------------|
| Spatially uniform electron cloud density ρ_q (m ⁻³) | 1.4×10^{26} |
| Permittivity of Free Space ϵ_0 (F/m) | 8.854×10^{-12} |
| Charge of the electron e (C) | 1.602×10^{-19} |
| Radius of the cloud R (m) | 8000 |
| Radial electric field at the electron cloud surface E_r (V/m) | 7×10^{21} |
| Electron cloud surface voltage V (V) | 3×10^{25} |

Cooling: Hydrogen Gas



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Conclusions

- We have studied some of the more obvious issues surrounding the feasibility of constructing antimatter harvesters in space.
- We look forward to studying a host of equally important issues in Phase II. Some of these issues are:
 - Shape stability under solar wind deflection
 - A comprehensive model of architecture performance, including issues addressed in both Phase I and Phase II
 - Deployment strategies and initial system cost estimate
 - Scalability assessment for much larger accumulation rates

The Adventure has Only Begun!