



# Extraction of Antiparticles Concentrated in Planetary Magnetic Fields

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# Alternate Title

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Natural supplies of antimatter in our solar system and the efficiency of 'mining' for use in space applications and missions.



## Antiprotons

<b>Value</b>	\$160 x 10 <sup>12</sup> /gram
<b>Supply</b>	10 <sup>-14</sup> kg/year (10 ng)

## Diamonds

<b>Value</b>	\$350/gram
<b>Supply</b>	26,000 kg/year

# Outline

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- Background
  - Production, storage and use
- Antimatter around the Earth
  - Physical processes yielding natural sources
  - Model limitations and improvements
- Antimatter in our Solar System
  - Comets and Jovian planets
- Collection and storage system
  - Performance and operation
- Summary

# Antimatter Annihilation

- Every particle has its antiparticle which will annihilate when they come in contact. The process releases  $E=mc^2$  worth of energy.



Fuel	Energy Density	Notes
Battery	$7.2 \times 10^5$ J/kg	Lithium Ion
Chemical	$1.4 \times 10^7$ J/kg	LO <sub>2</sub> /LH <sub>2</sub>
Fission	$8.2 \times 10^{13}$ J/kg	U <sup>235</sup>
Fusion	$3.4 \times 10^{14}$ J/kg	DT
Antimatter	$9.0 \times 10^{16}$ J/kg	$E=mc^2$

*Table 1- Relative energy density.*

- Antimatter represents the perfect 'battery' with an energy storage density 10 orders of magnitude better than chemical reactions and 3 orders of magnitude better than nuclear reactions.



# Antimatter Uses

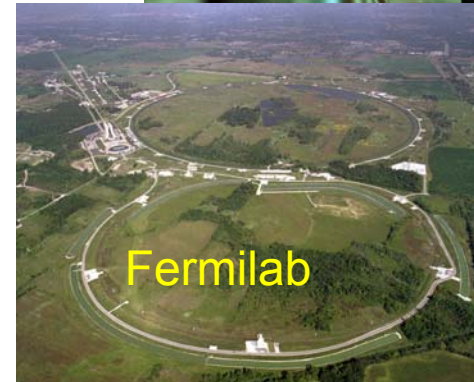
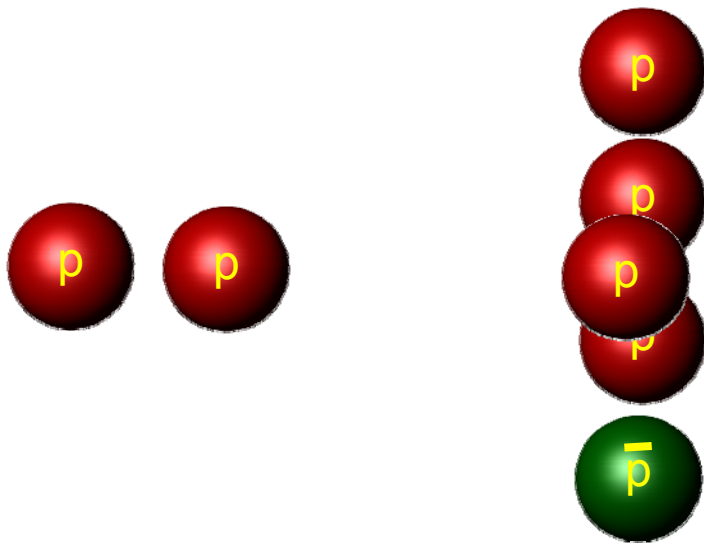
- **Applications for Antimatter**
  - Energy storage
  - Aggressive high  $\Delta V$  space exploration
    - Catalyst for nuclear reactions (nanogram – microgram range)
  - Medicine
    - Tumor treatment, medical diagnostics
  - Homeland Security
  - Basic Science



# Antimatter Production and Storage

Pair production energy threshold

$$E_{th} = m_p \left( 2 + \frac{4}{A} \right) = 5.6 \text{ GeV (p+p)} = 10^{-10} \text{ J}$$



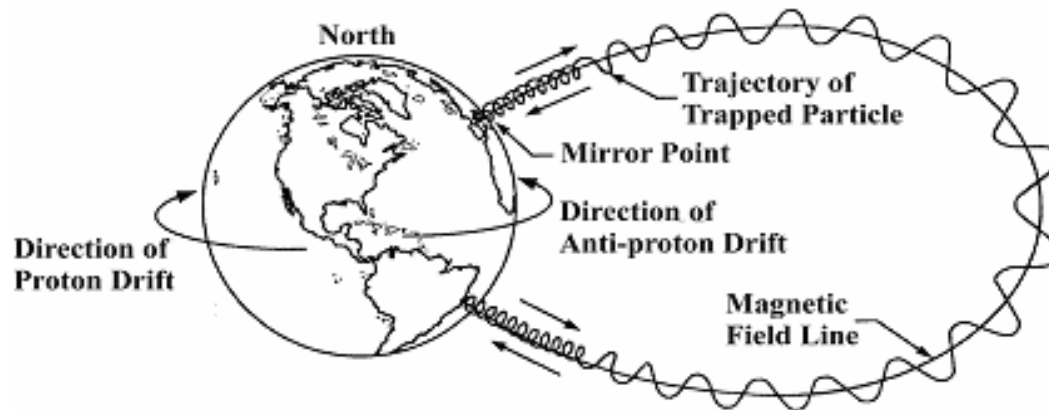
## Storage

- Very limited quantities stored for ~days to weeks.
- Annihilation losses due to vacuum limits
- Current technology  $\sim 10^{10} \text{ kg}/\mu\text{g}_{\text{stored}}$

# Interesting Questions

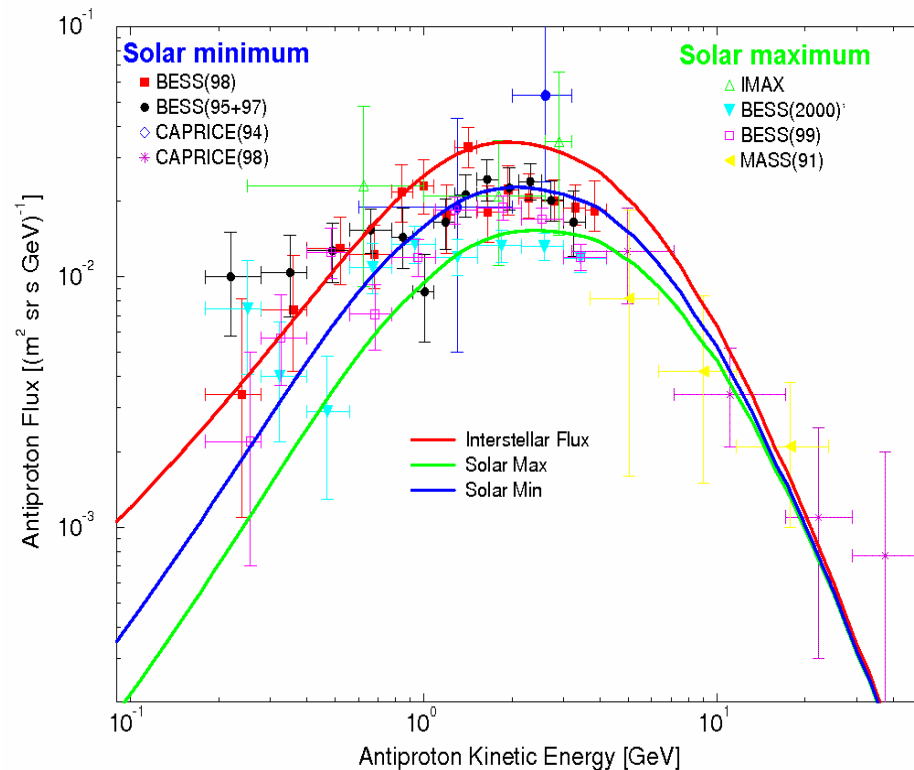
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- How much antimatter is present in the natural environment?
- How efficiently can it be collected?





# Natural Antiproton Background



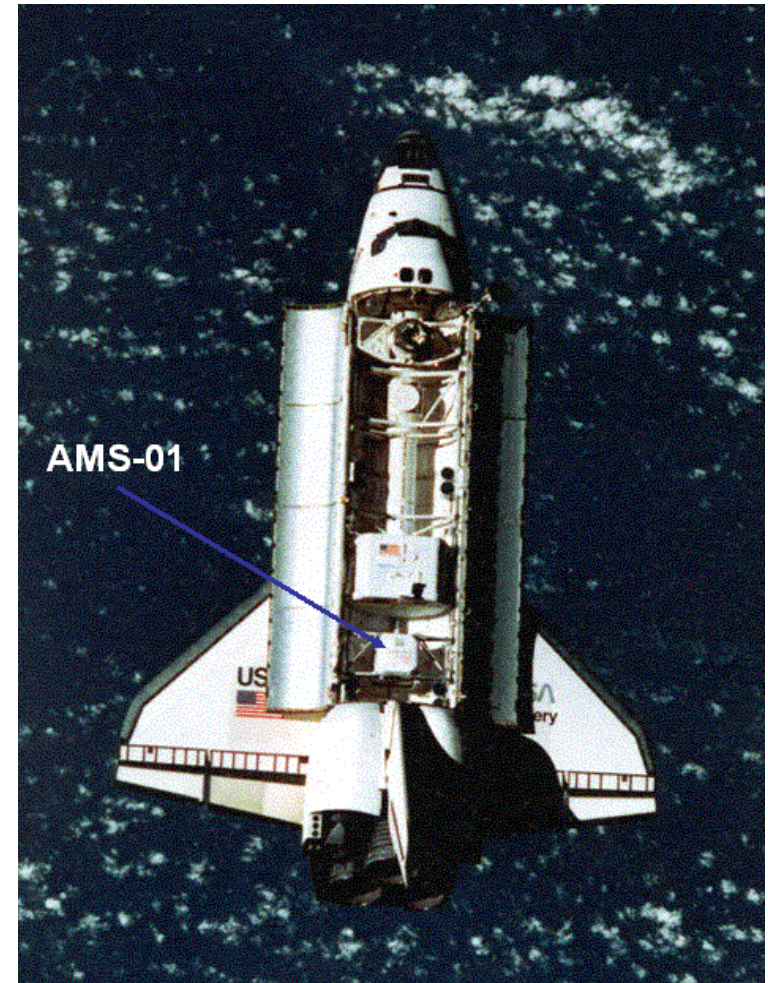
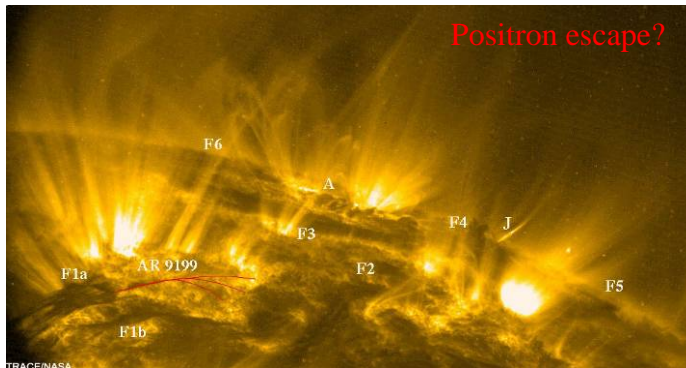
Planet	Yearly Impingement
Earth	0.004 kg
Jupiter	9.1 kg
Saturn	1.3 kg
Uranus	0.39 kg
Neptune	0.33 kg

*Yearly impingement of antiprotons on planetary magnetospheres. ( $1 \text{ GeV} < E < 10 \text{ GeV}$ )*

Antimatter is present in the natural space environment and surrounds us as a tenuous plasma. The local conditions around solar system bodies can increase the net flux substantially. I'll focus on this area during the presentation.

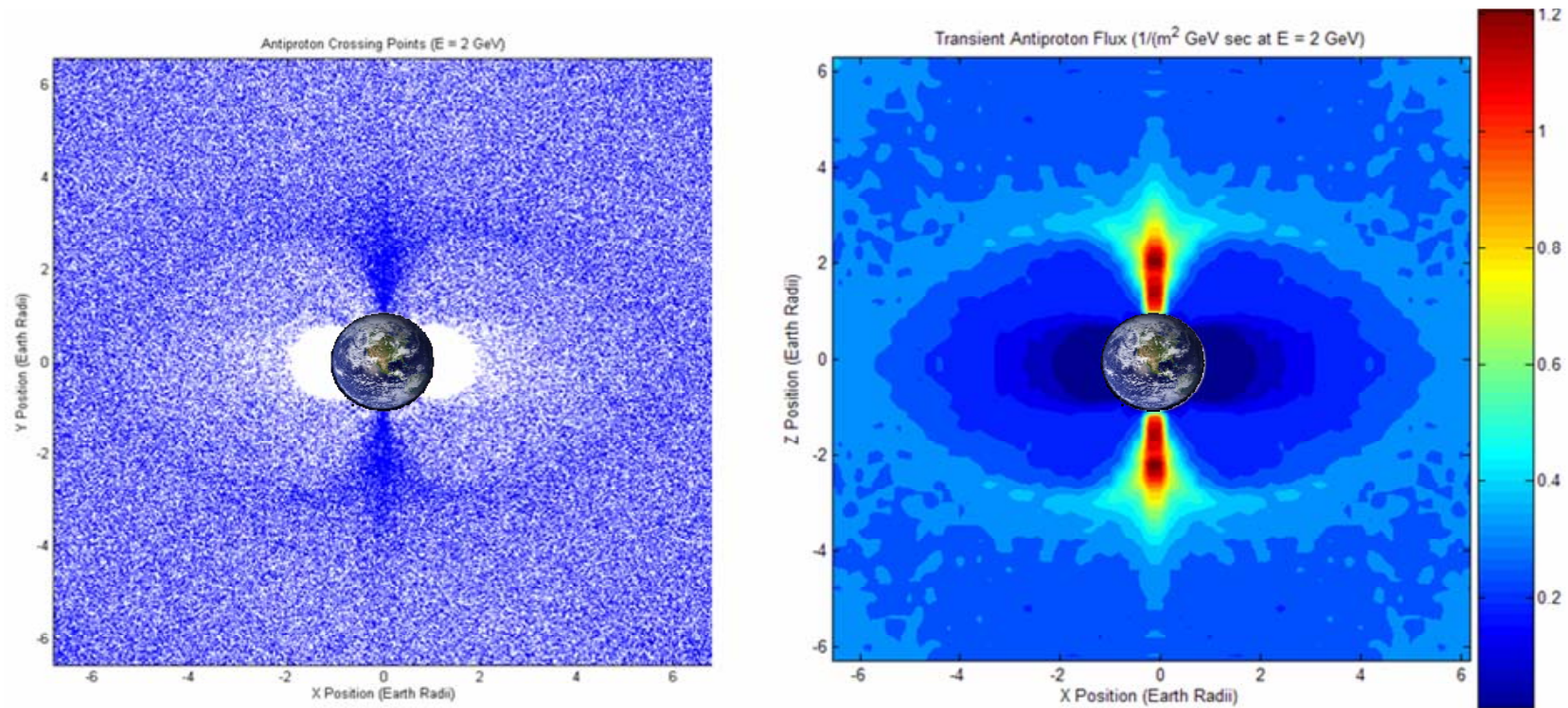
# Positron Background Flux

- Interesting positron measurements
  - GCR background
    - $e^+/e^- \approx 0.1$
  - Earth Orbit ( $L=1.05$ )
    - $e^+/e^- \approx 4$
    - Modeling part of phase II effort.
  - Solar Flares
    - RHESSI measured positron annihilation lines
    - Modeling part of phase II effort.





# Magnetospheric Focusing



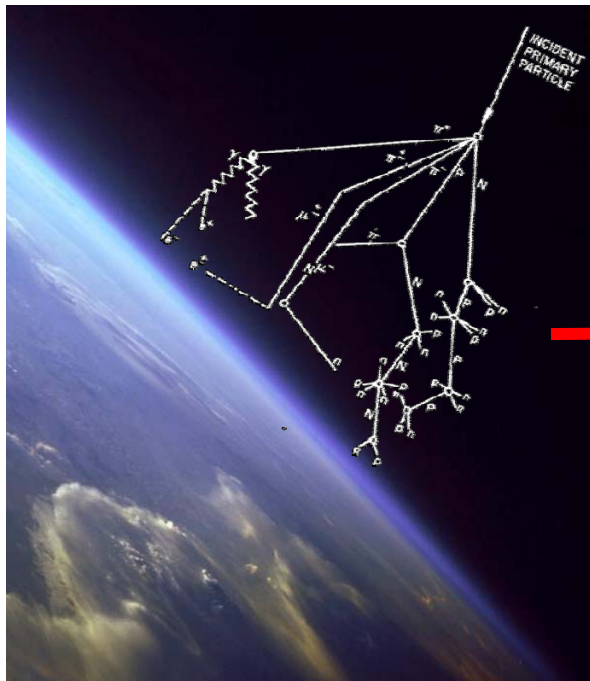
*Figure - Predicted antiproton flux in the vicinity of the Earth. (E=2 GeV)*

The magnetic field of the Earth will focus the interstellar flux. Though the flux is more intense near the poles, extraction would require a polar orbiting spacecraft which spends a large fraction of its orbit in the lower flux regions.

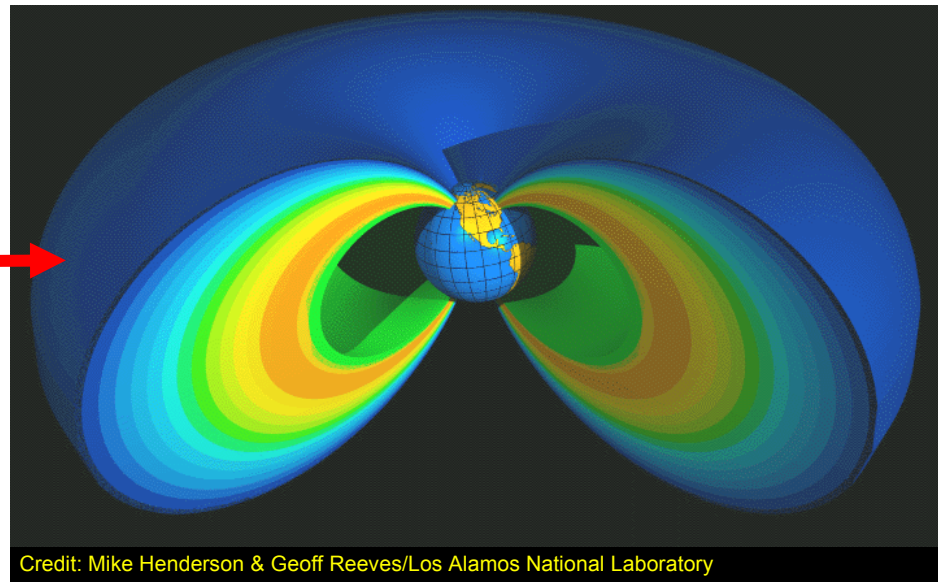
# In Situ Production and Trapping

Local production of antimatter within the Van Allen radiation belts

- Pair production and trapping in the exosphere
  - $p + p \rightarrow \bar{p} + p + p + p$
- Cosmic Ray Albedo Antineutron Decay
  - $p + p \rightarrow \bar{n} + n + p + p \rightarrow \bar{p} + \bar{e} + \text{neutrino} + p + p + n$



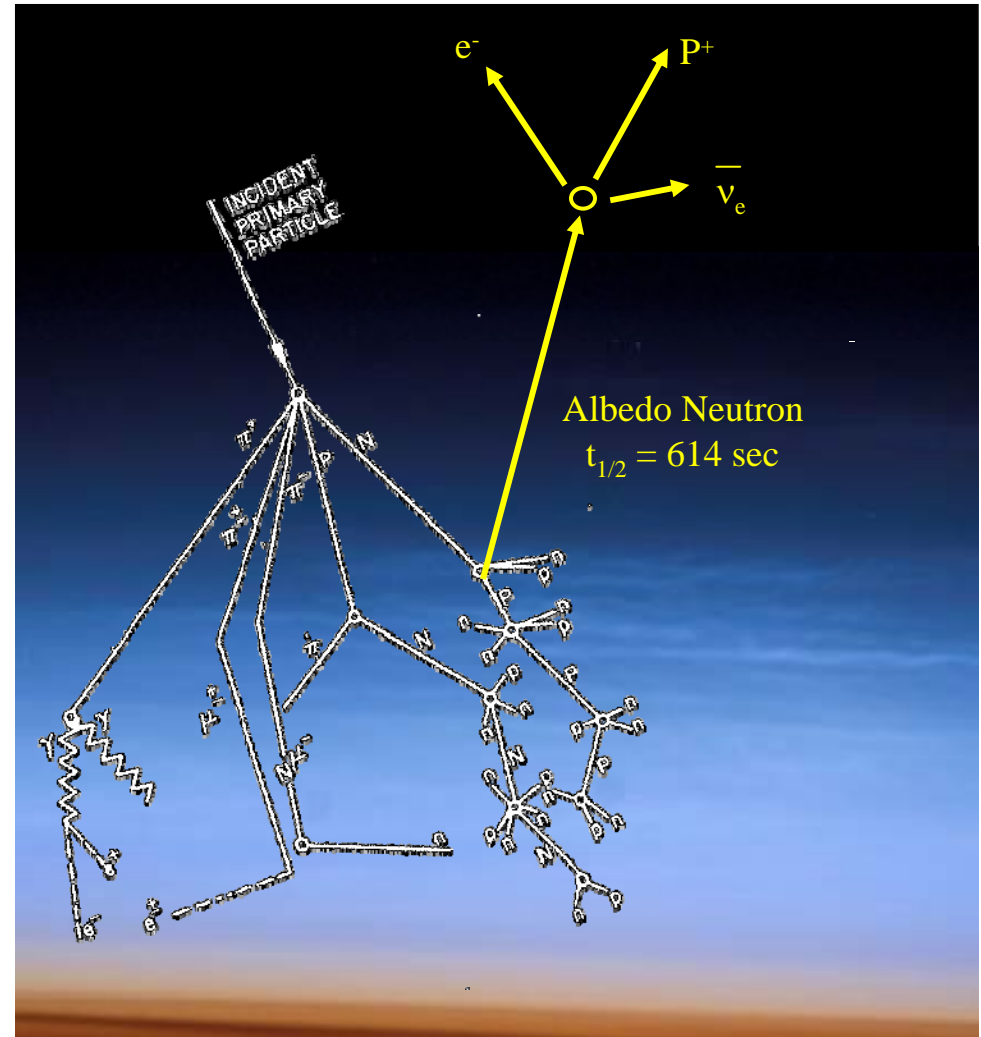
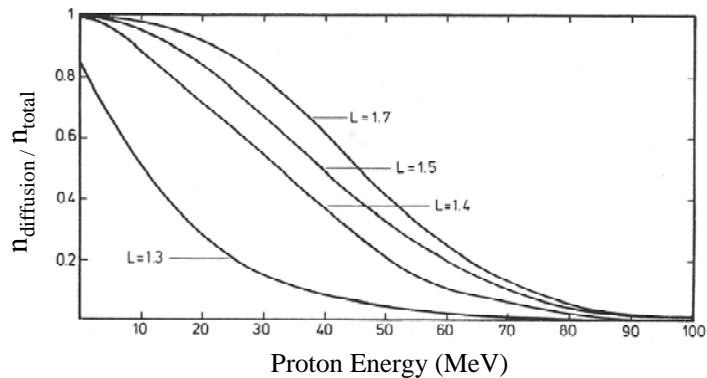
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Credit: Mike Henderson & Geoff Reeves/Los Alamos National Laboratory

# Proton Belt Source

- Diffusion of Solar Protons
  - Magnetic fluctuations allow low energy solar protons to diffuse inward
- Cosmic Ray Albedo Neutron Decay (CRAND)
  - Albedo neutrons decay within trapping region to populate the belts.
  - Primary generation source for high energy inner belt protons ( $E > 30$  MeV).





# Albedo Antineutrons

- Narrow downward angular distribution of GCR pair produced antineutrons generates limited numbers of albedo anti-neutrons.
- Significant loss in efficiency relative to neutron backscatter
  - Phase I Geant4 simulations
  - 1 albedo anti-neutron for every  $10^5$ - $10^9$  albedo neutrons.
- Antiproton source function reduced by this fractional efficiency

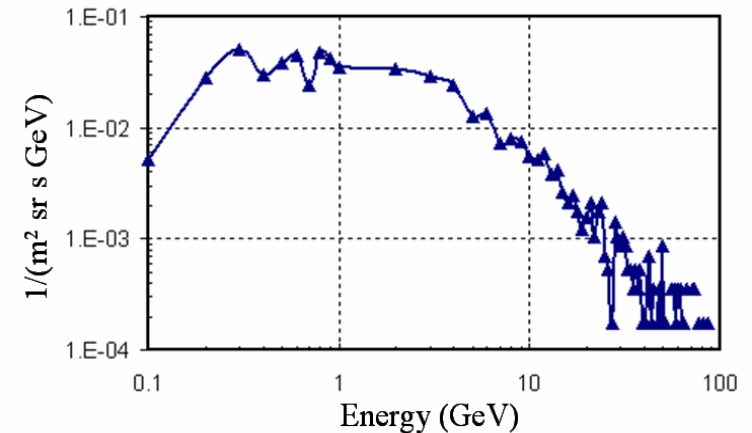
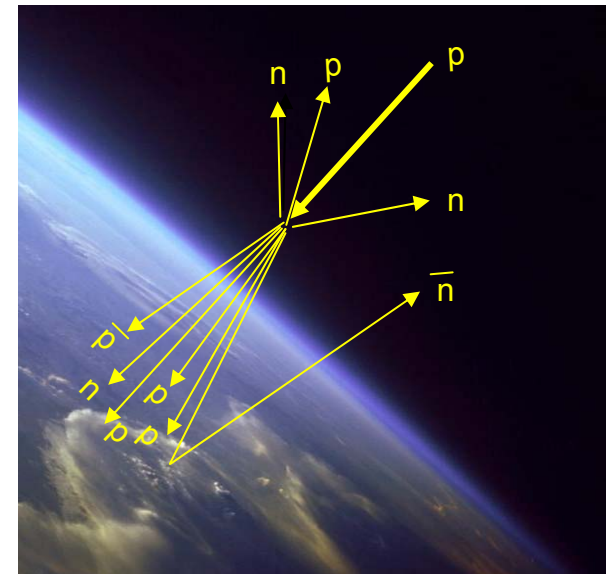


Figure – Production spectrum for antineutrons generated in the Earth's atmosphere.



# Atmospheric Annihilation

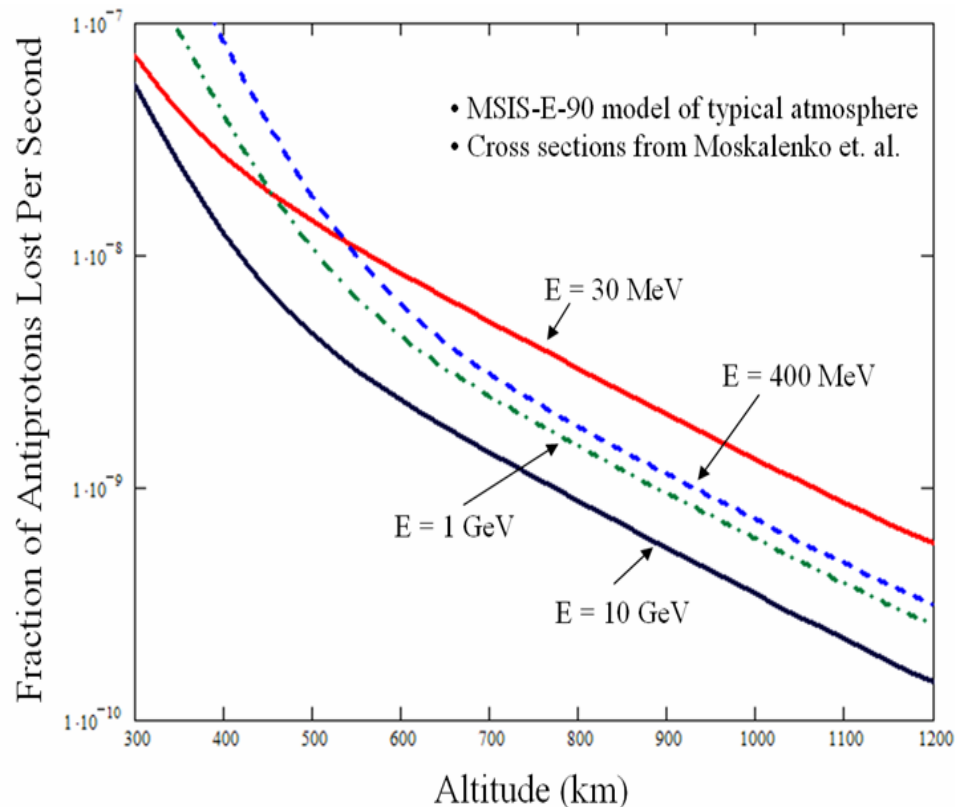


Figure – Fraction of antiprotons lost per second due to annihilation with the atmosphere. (Earth)

Antiparticles trapped in the Earth's radiation belt will annihilate, but only at a relatively low rate which enables large populations to form.

# Trapped Inner Belt Mass

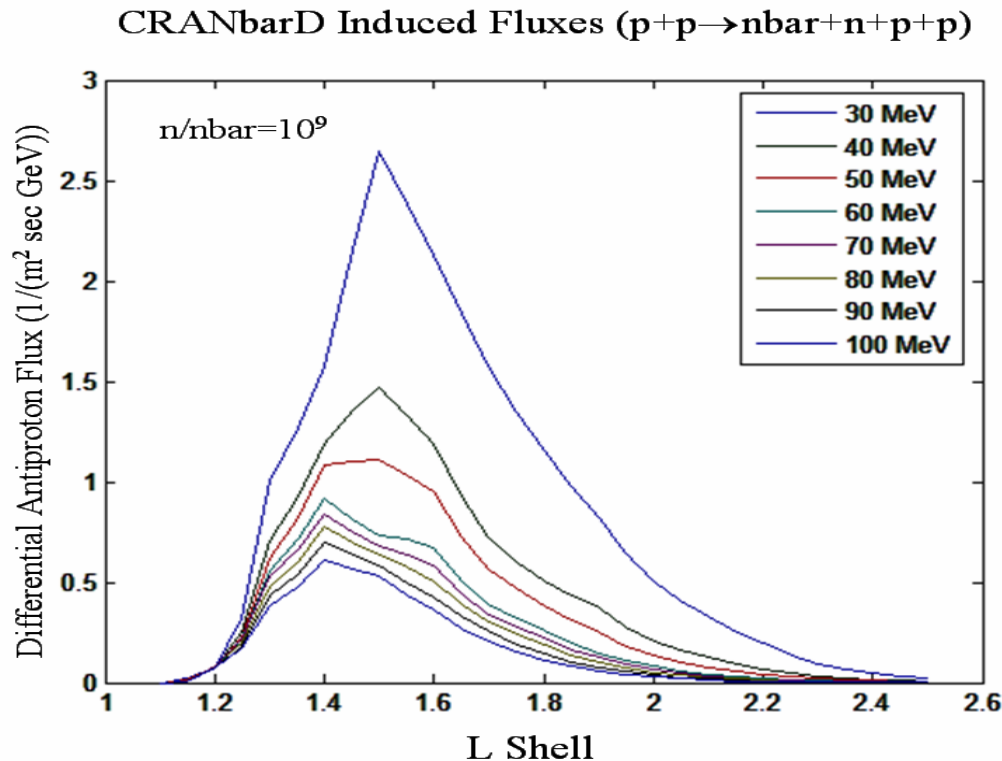


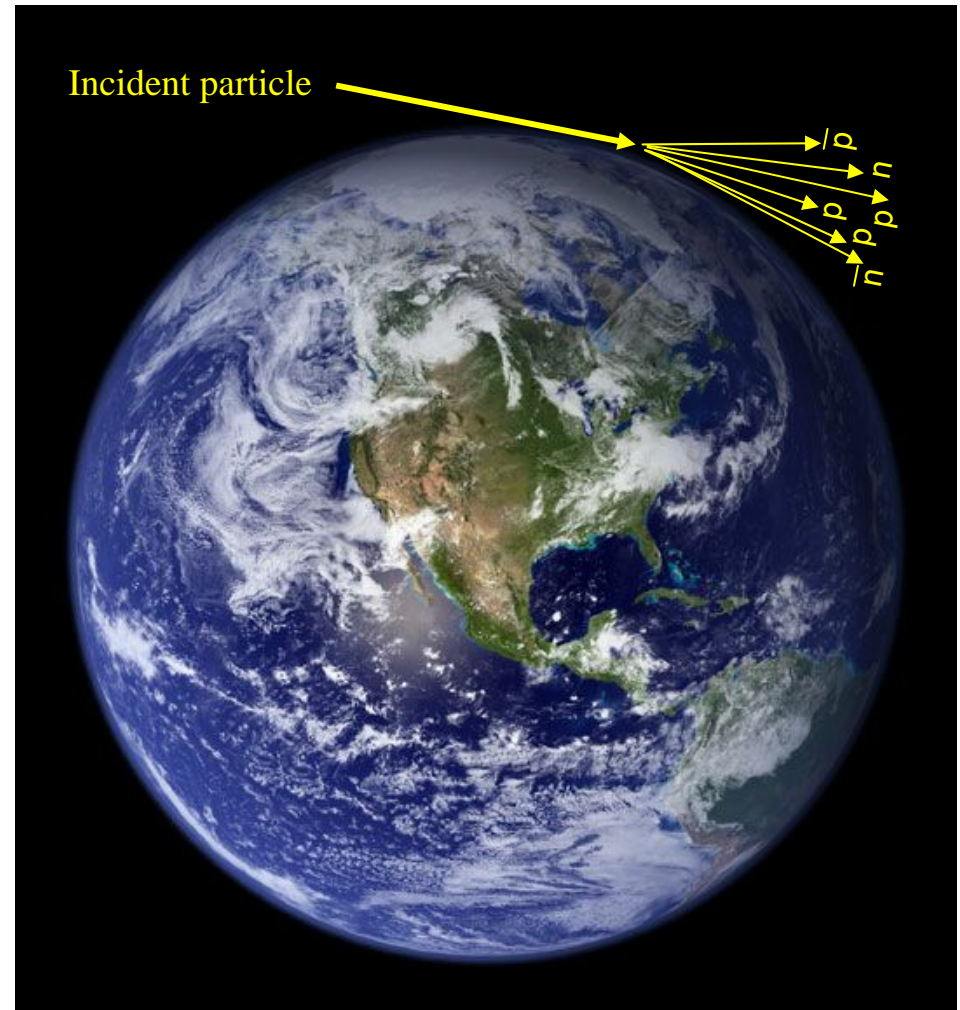
Figure – Estimated antiproton flux around Earth.

When integrated, the estimated quasi-static antiproton belt mass is conservatively estimated to be only about 0.25 nanograms around the Earth. This does not include antineutrons generated at an oblique angle to the atmosphere.

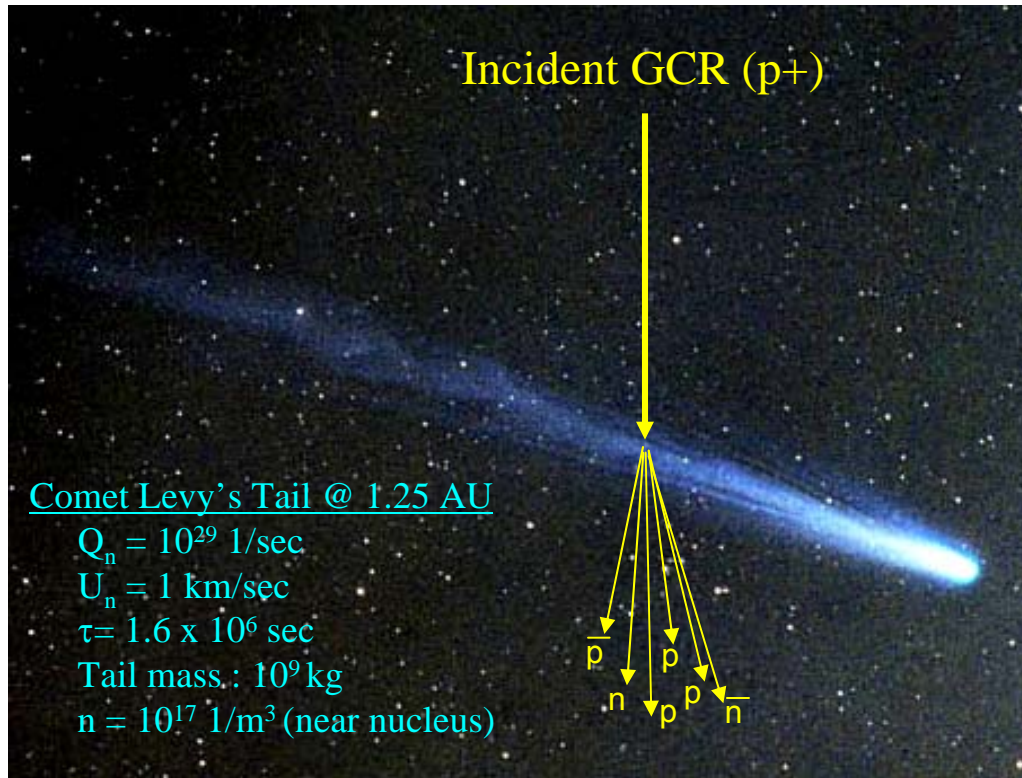
# Phase II Tasks

- Model shallow angle antineutron generation
  - Direct pass through with no need to backscatter in atmosphere.
  - Improved efficiency
- Model radiation belt physics directly instead of extrapolating from proton population

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial L} \left[ \frac{D_{LL}}{L^2} \frac{\partial f}{\partial L} \right] + \text{Sources} + \text{Losses}$$



# Pair Production in Comet Tails



## Comet number density model...

Gas production rate  $Q_n$

$$n(z, b) := \frac{Q_n}{4 \cdot \pi \cdot u_n \cdot (z^2 + b^2)} \cdot \exp\left(\frac{-\sqrt{z^2 + b^2}}{u_n \cdot \tau}\right)$$

Outflow speed  $u_n$

Ionization time constant  $\tau$

## Integrated cross section...

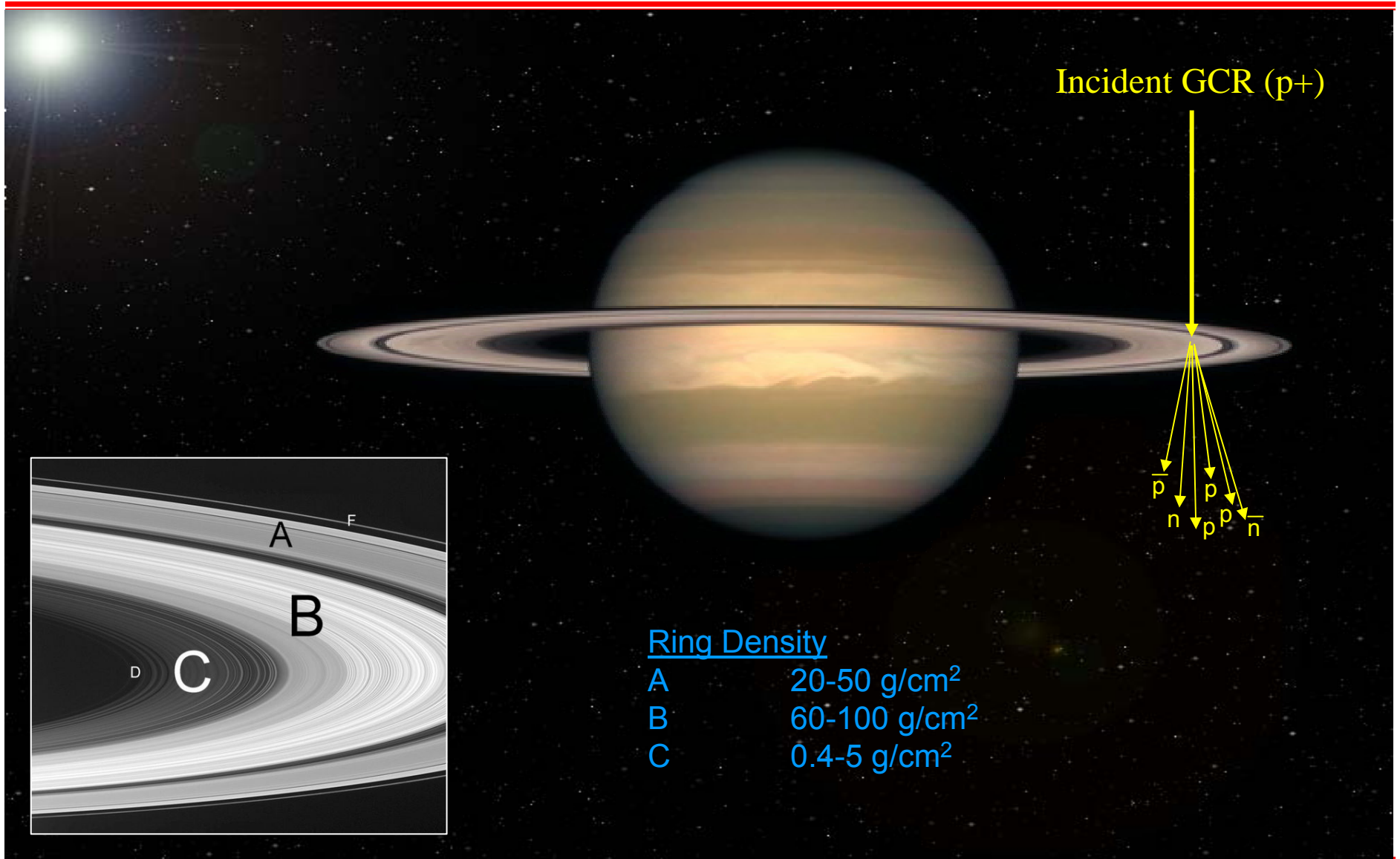
$$1 - 10 \mu\text{g}/\text{cm}^2$$

Comet tails are not dense enough to produce an appreciable antiproton flux beyond the background GCR already present in the vicinity.

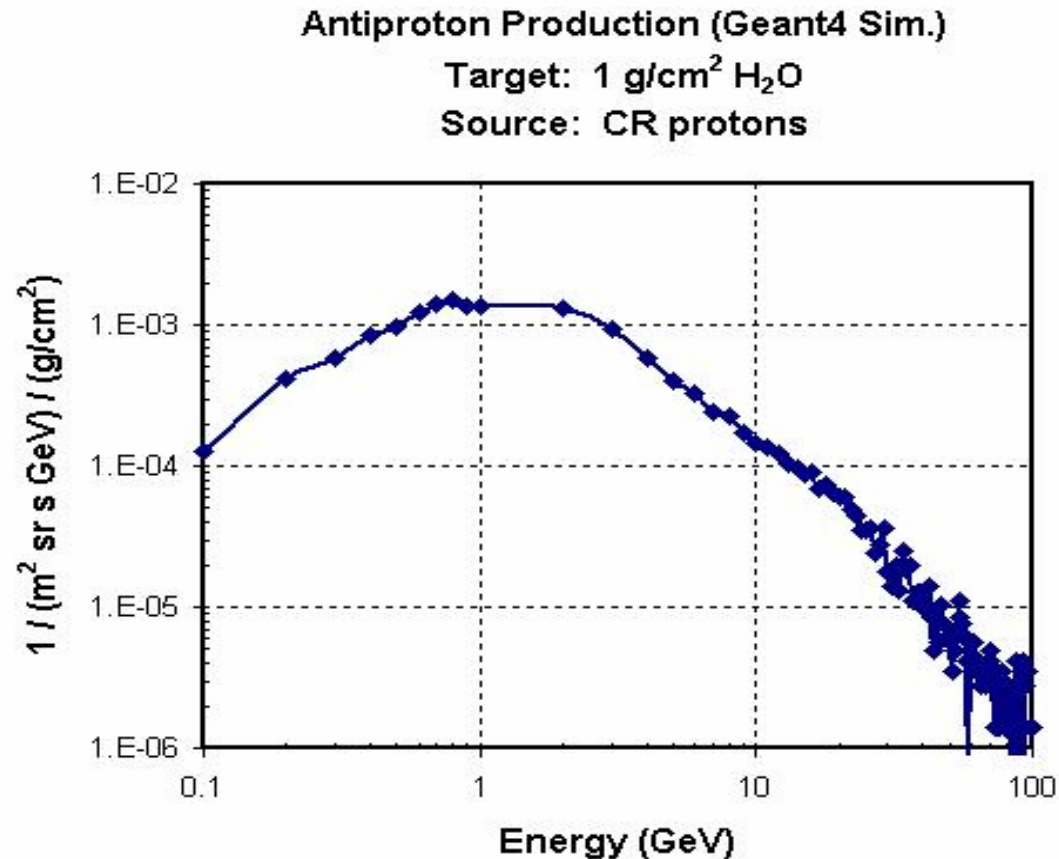
However, the ionized portion of the tail may have interesting secondary uses to assist in the collection of GCR antiprotons. (In situ plasma magnet)



# Saturn Ring Production



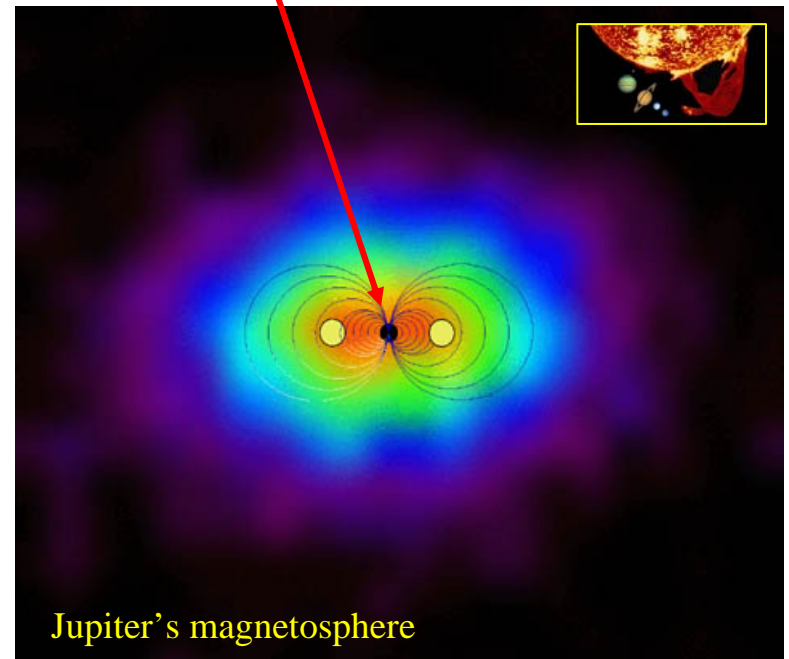
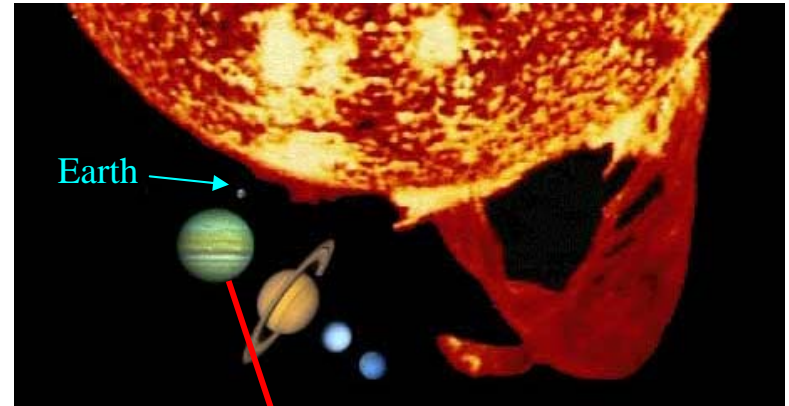
# Saturn Ring Production Spectrum



Ring source flux estimated to be about an order of magnitude larger than the background GCR flux but with a reduced angular distribution.

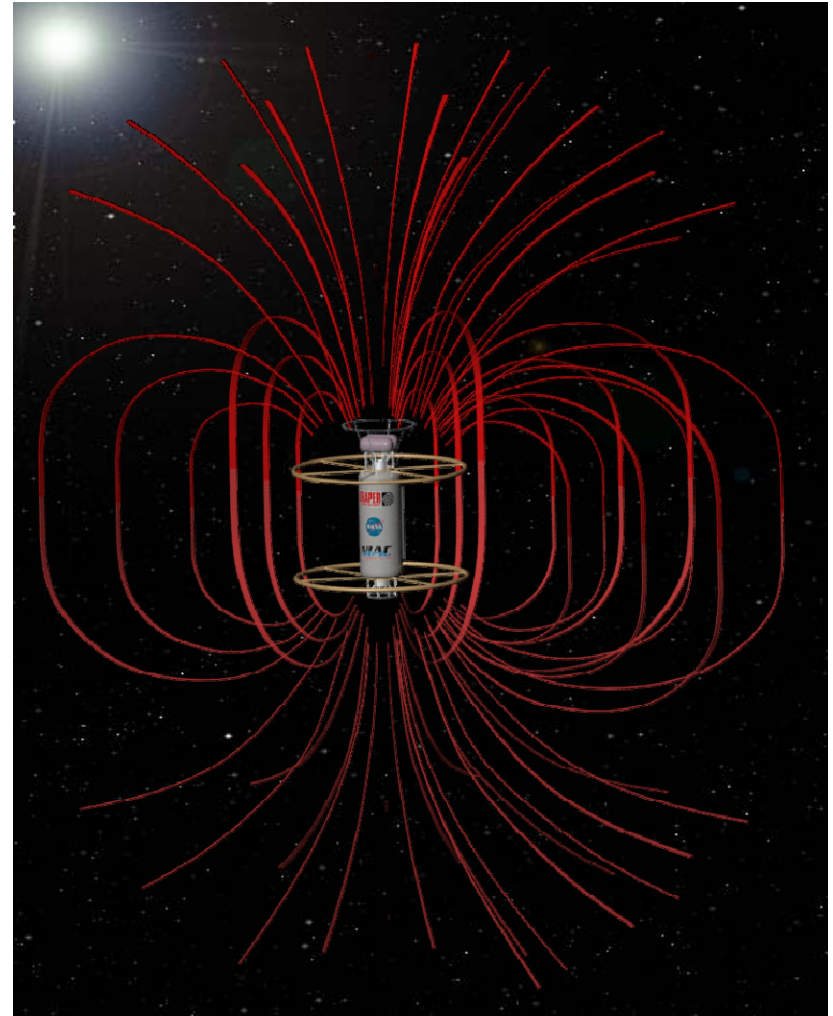
# Radiation Belt Scaling

- Jovian Scaling Factors
  - Major
    - Atmospheric interaction area
      - GCR flux interaction increase
    - Additional production targets
      - Rings and other structures
    - Magnetosphere size
      - Time of flight increase
- Phase I Extrapolations
  - Jupiter (1 ug trapped antiprotons)
    - Smaller supply than originally anticipated due to the cutoff of the GCR production spectrum by its large magnetic field.
  - Saturn (400 mg of trapped antiprotons)
    - Antineutrons generated in the A&B rings (20-100 gm/cm<sup>2</sup>, Nicholson and Dones, 1991) do not have to be backscattered for trapping which drastically increases the efficiency.
- Phase II Direction
  - Jovian magnetosphere modeling



# Magnetic Dipole Funnel

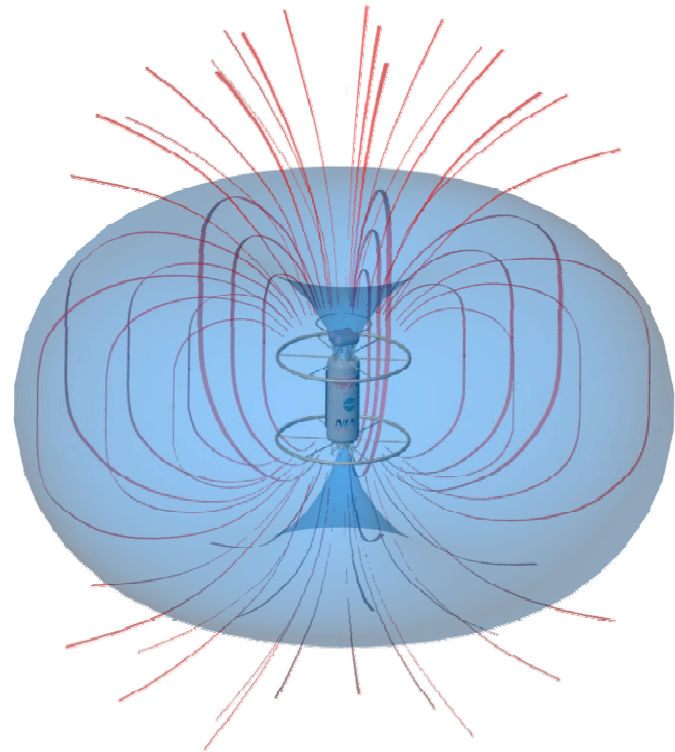
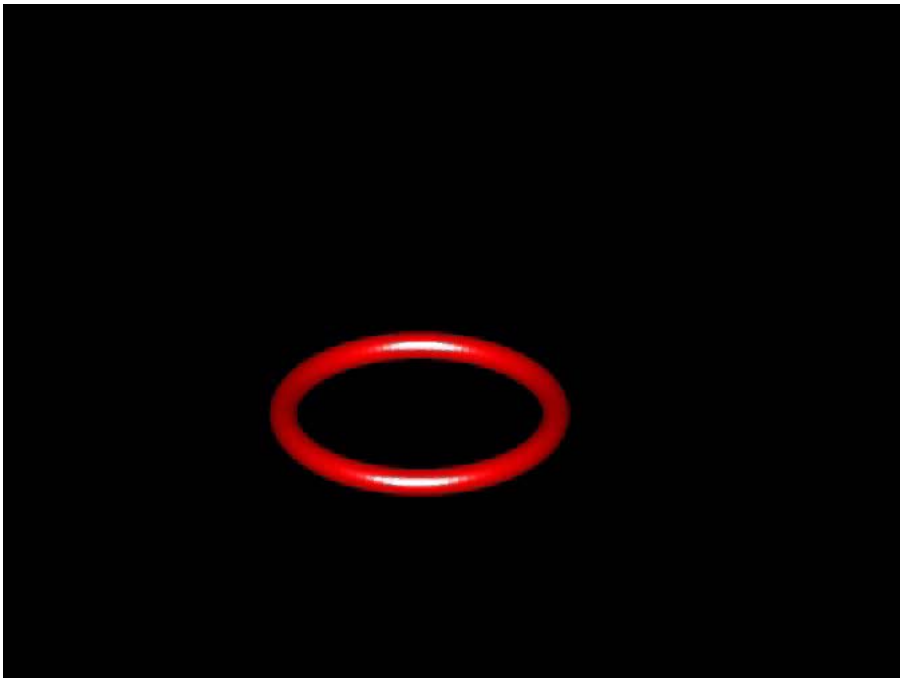
- Tantalizing evidence of natural concentrations of antimatter in our solar system
  - Concentrated but still very tenuous
- A magnetic scoop can be used to funnel the charged particles into a restricted volume and further concentrate them for collection and use.
  - Charged particles are concentrated as they follow magnetic field lines towards the dipole source.



# Artificial Magnetosphere

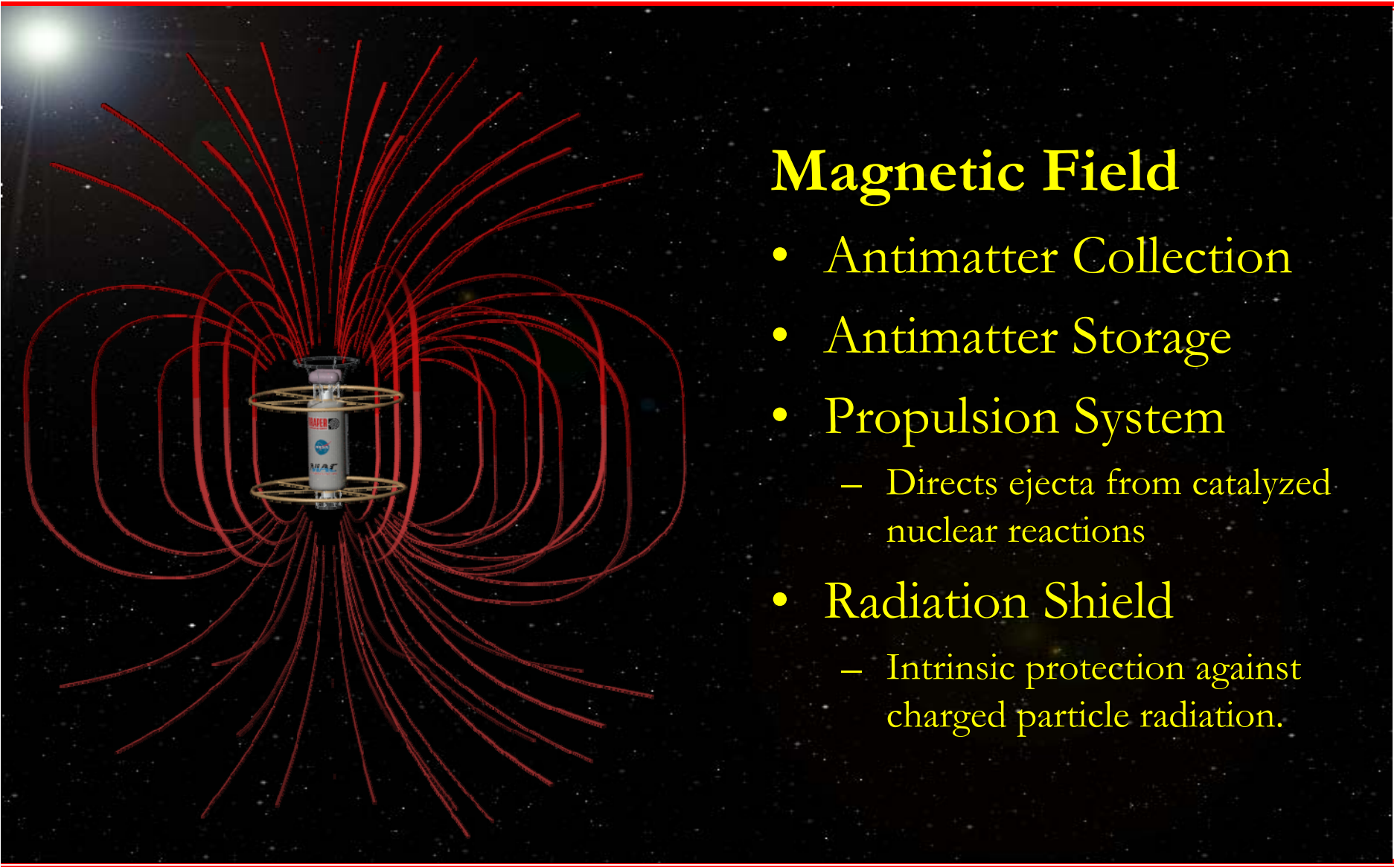
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- Particles can then be stored in an artificial magnetosphere that surrounds the spacecraft by transferring the particle to closed field lines.
  - Very low density  $\rightarrow 1 \text{ mg/km}^3 = 10^5 \text{ cm}^{-3}$





# Secondary Benefits of Dipole Field

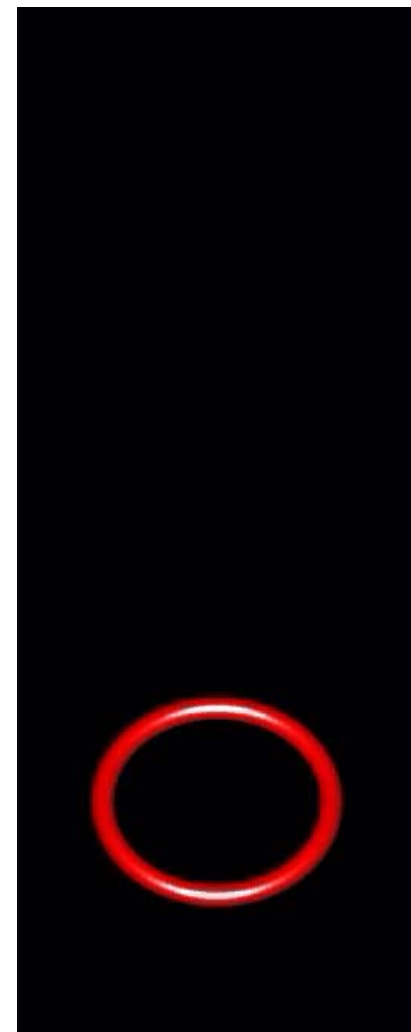
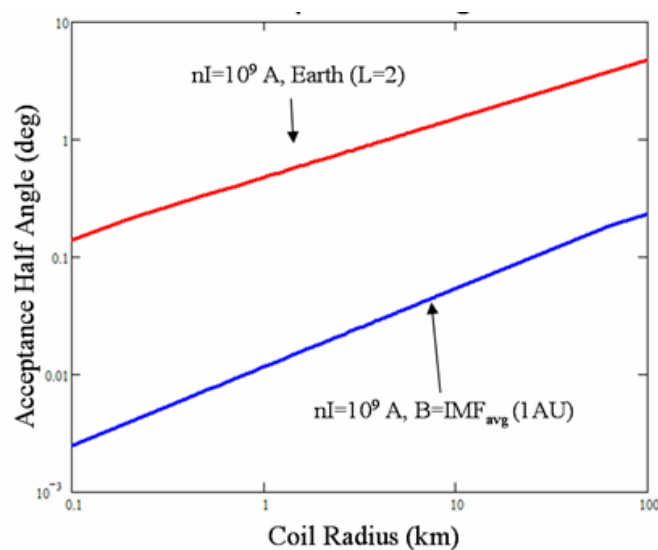
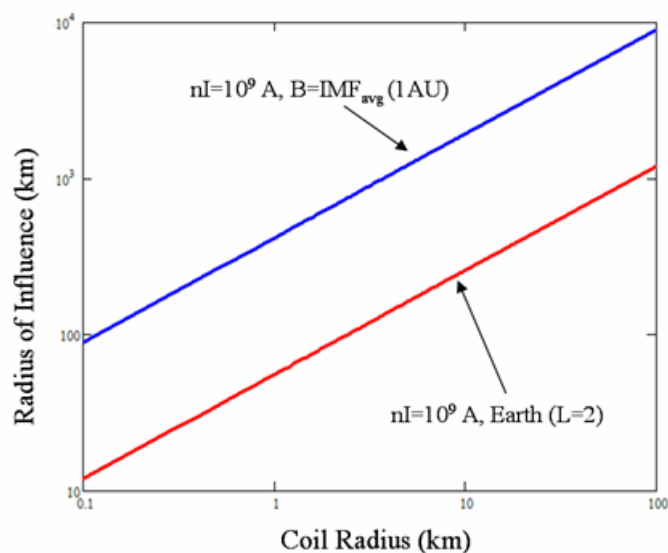


## Magnetic Field

- Antimatter Collection
- Antimatter Storage
- Propulsion System
  - Directs ejecta from catalyzed nuclear reactions
- Radiation Shield
  - Intrinsic protection against charged particle radiation.

# Phase I - Collection Limits

- Limit of magnetic influence restricts the potential antiproton collection region.
- Acceptance angle limits the collection efficiency
  - This can be improved by increasing the particle momentum
    - Apply E and/or RF fields
    - Efficiency scales linearly with final particle momentum
      - 2X p gives 2X angle
    - Feasible at lower energies but probably not at the GeV energy scale.



# Phase I - Collection Rate Estimates

- Mass values assume no flux concentration from planetary phenomena.
  - Background GCR flux only.
  - Multiply by relative integral flux to obtain planetary collection rates.
- Collection rate and efficiency (collection rate versus ring mass) increase with loop diameter.

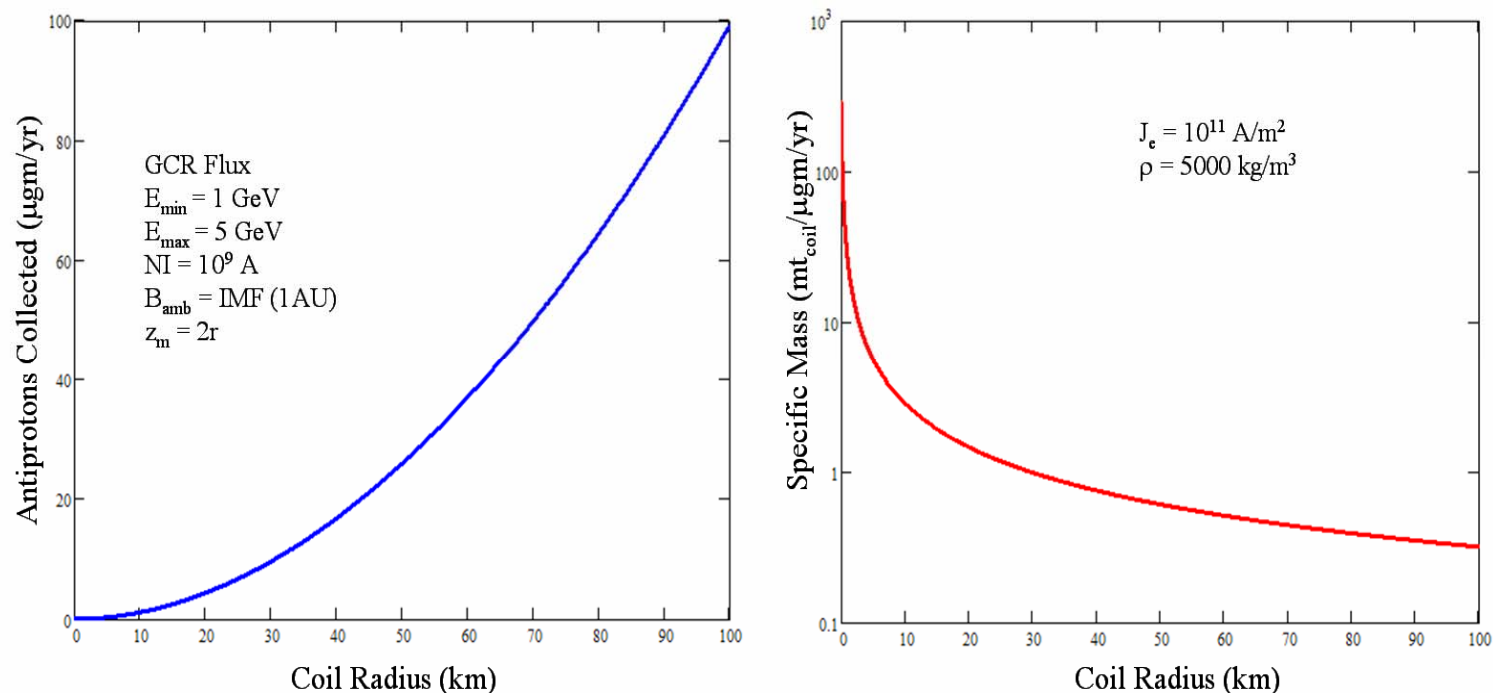
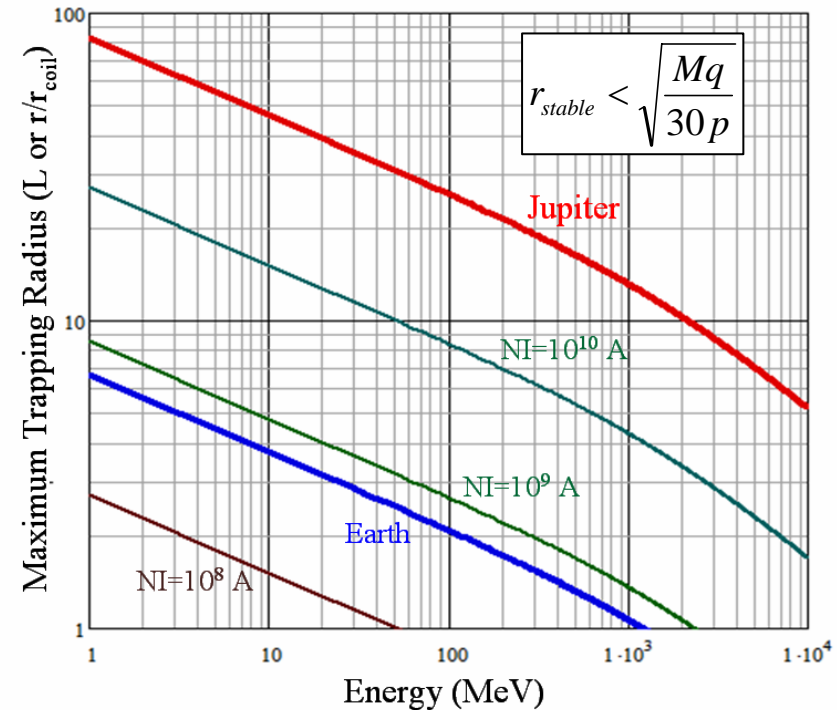
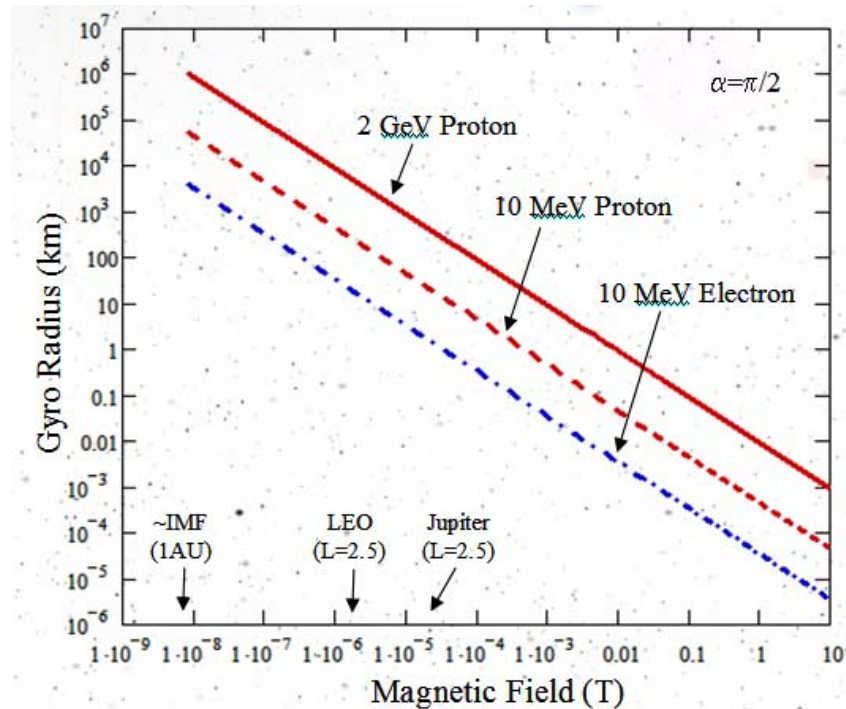


Figure – Antiproton collection rate based on the background interstellar GCR flux.

# Trap Stability Limits

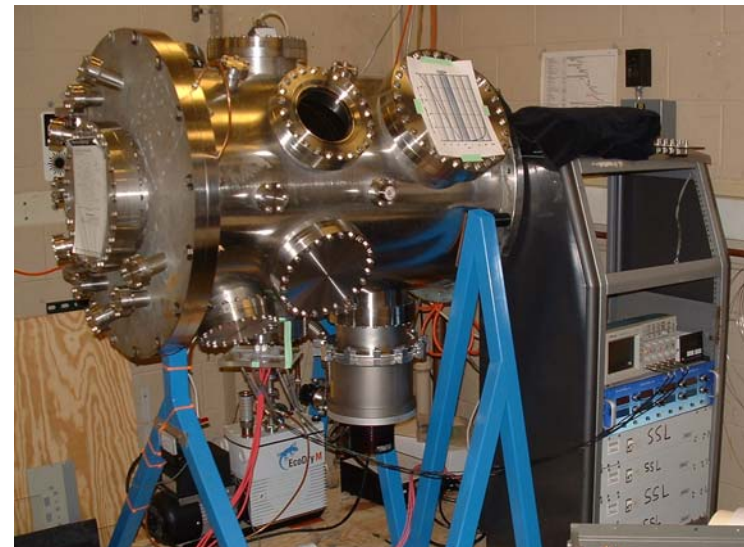
- Alfven stability criterion
  - Conservation of the first adiabatic invariant
  - Gyro radius  $\ll$  radius of curvature of the guiding center



# Phase II Activities (Scoop)

- Computational Modeling
  - Analytical validation
  - Trap design
  - Optimization
  - Stability analysis
- Experimental Verification
  - Scaled system experiment
- Technology Evaluation
  - Plasma magnet, etc...

Parameter	Full Scale	Experiment 1	Experiment 2
(Background B-field)	30 $\mu\text{T}$	2 $\mu\text{T}$	0.2 $\mu\text{T}$
(Amp-turns of current)	$10^9$ Amp-turns	725 amp-turns	72.5 Amp-turns
(Dipole influence radius)	27.6 km	30 cm	30 cm
(Radius of current flow)	1 km	1.1 cm	1.1 cm
(Larmor radius in core)	9.0 m	98 $\mu\text{m}$	98 $\mu\text{m}$
(Particle mass)	$1.67(10^{-27})$ kg	$1.0 (10^{-30})$ kg	$1.0 (10^{-30})$ kg
(Particle energy)	1000 MeV	1.4 eV	0.015 eV
(Particle charge)	$-1.6(10^{-19})$ C	$-1.6(10^{-19})$ C	$-1.6(10^{-19})$ C



MIT SSL Vacuum Chamber



# Summary / Conclusions

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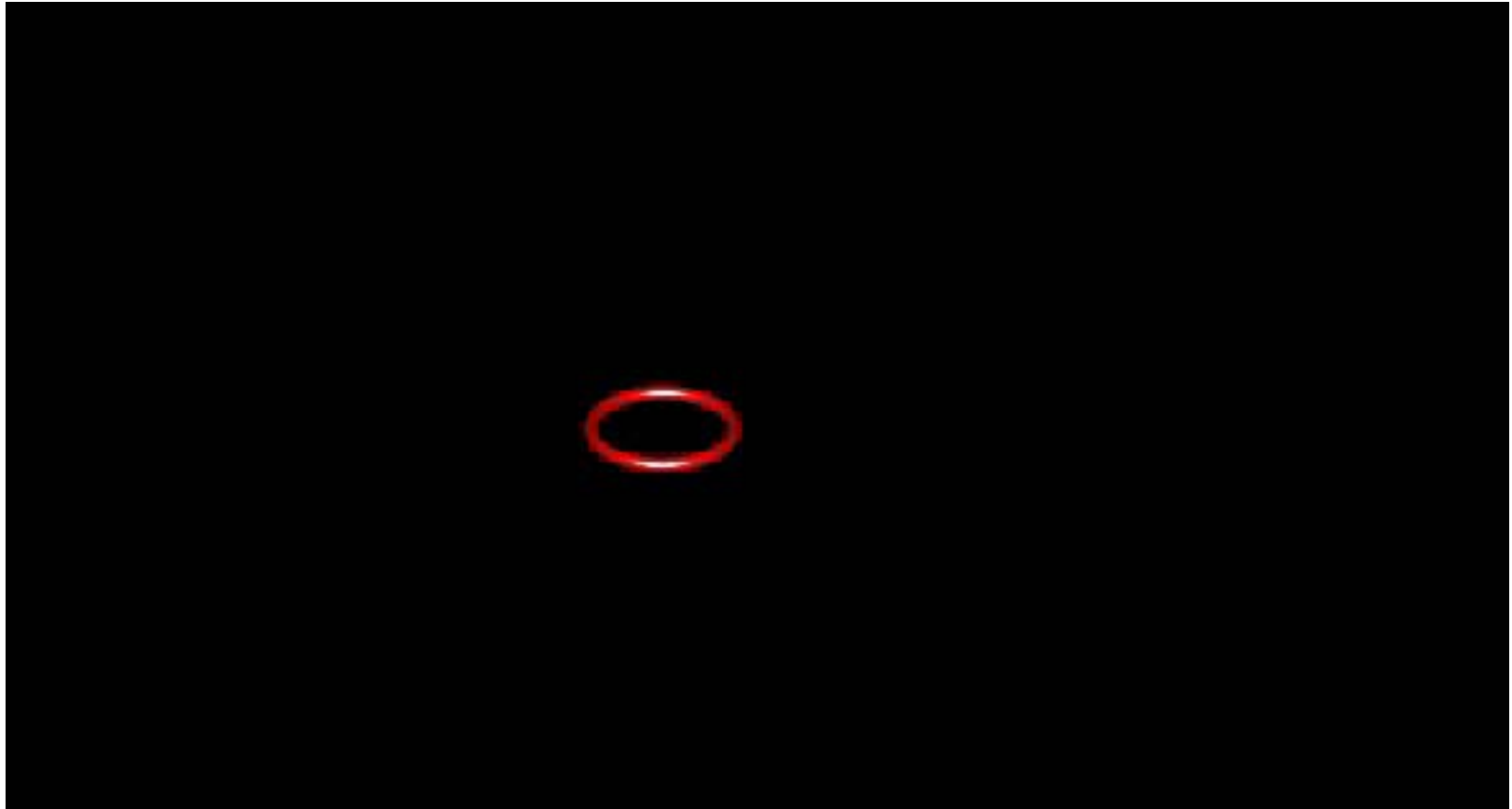
- **Natural Transient Antiprotons Fluxes**
  - **Earth's** magnetosphere is continuously impinged by a tenuous plasma of antiprotons from the GCR background. ( $\sim 4$  grams/yr)
  - **Jupiter's** magnetosphere is impinged by about 10 kg/yr of antiprotons though the flux remains very low
  - **Comet** tails do not generate a significant increase over the background GCR flux due to insufficient density
  - **Jupiter's Io torus** generates a negligible excess flux due to insufficient density
  - **Saturn's rings** are the best source of antiprotons in the solar system with a flux  $\sim 10X$  the GCR background.
- **Trapped Antiproton Populations**
  - **Earth** has a small (0.25 - 15 ng) trapped supply of antiprotons. The low level is due to inefficiencies in backscattering albedo antineutrons from the atmosphere. This may be a sufficient amount to enable bootstrap missions to Saturn for more exotic missions.
  - **Jupiter** has a smaller than anticipated trapped flux due to its magnetosphere shielding the atmosphere from the production spectrum
  - **Saturn** has the largest trapped antiproton supply in the Solar System (estimated at  $\sim 400 \mu\text{g}$ ) due to high antineutron production from GCR interactions with its ring system.
- **Antiproton Collection and Storage**
  - **A magnetic funnel** formed from passively cooled high temperature superconducting loops can be used to collect significant quantities of antiprotons from low background levels or in regions of high intensity local production.
  - **A magnetic bottle** formed from the same superconducting loops can be used to safely store antiprotons for long periods of time. Particles and antiparticles at various energies can coexist in the same device since the large trapped volume ( $\text{km}^3$  or more) and natural vacuum afforded by the space environment minimizes losses.
- **Phase II Objectives**
  - Full radiation belt models with improved source model simulations
  - Detailed models and design of magnetic collector
  - Experimental validation of design
  - System level analysis of feasibility

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# Backup Slides

# Chaotic Motion

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# Synchrotron Losses

- The energy radiated in one Larmor orbit is

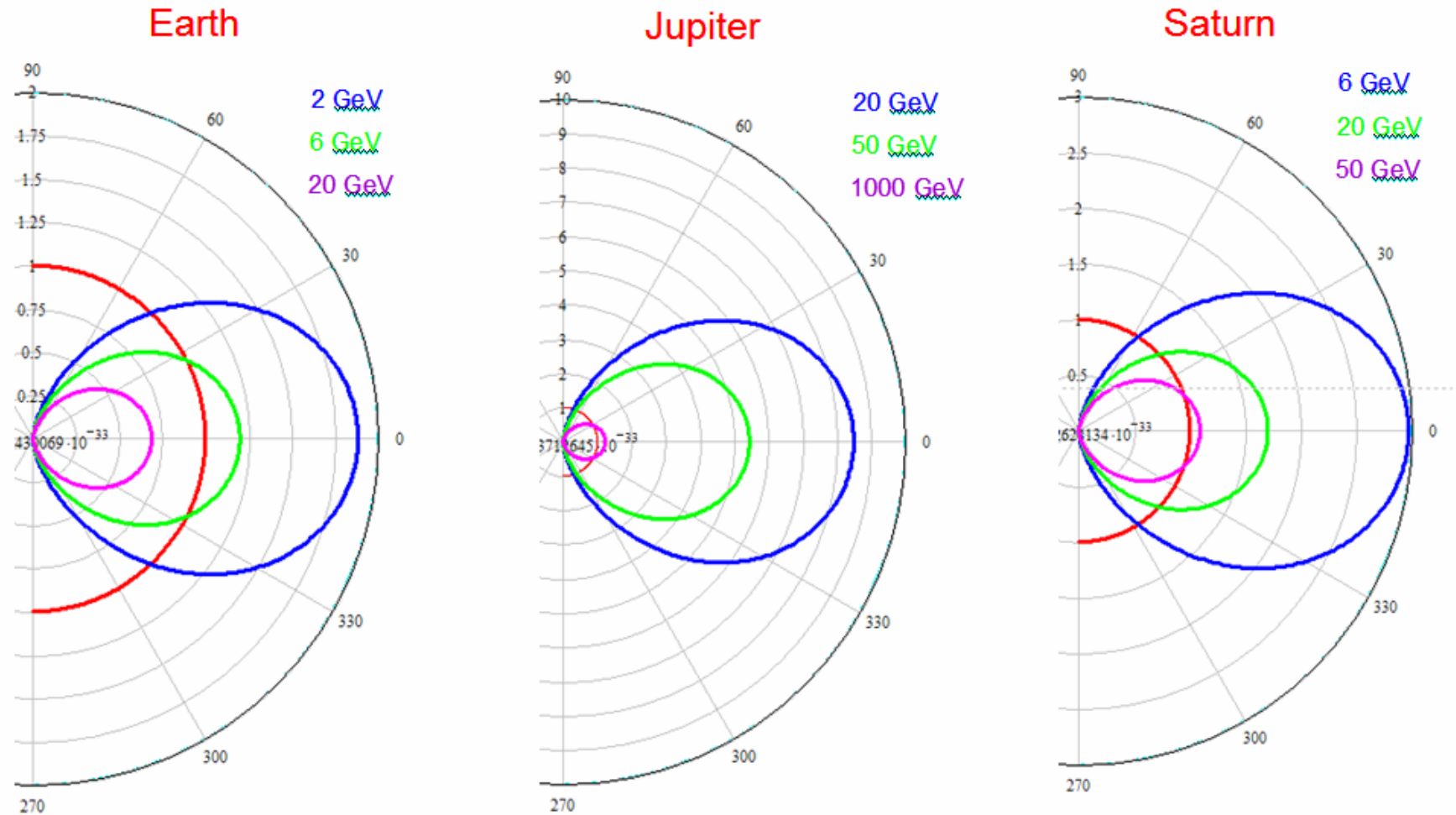
$$\frac{\Delta E}{E_k} = \frac{1}{\gamma - 1} \frac{E^3 B q^3}{3 \epsilon_0 m_0^5 c^9} \left( 1 - \frac{m_0^2 c^4}{E^2} \right)$$

- Electron fractional loss is independent of  $E_k$ 
  - $E_{k,n} = E_{k,0} (1 - \Delta E / E_{k,0})^n$
- Antiproton fractional loss is roughly linear in  $E_k$ 
  - $dE_k = (E \tau)^{-1} (a E_k^2 + b E_k) dt$

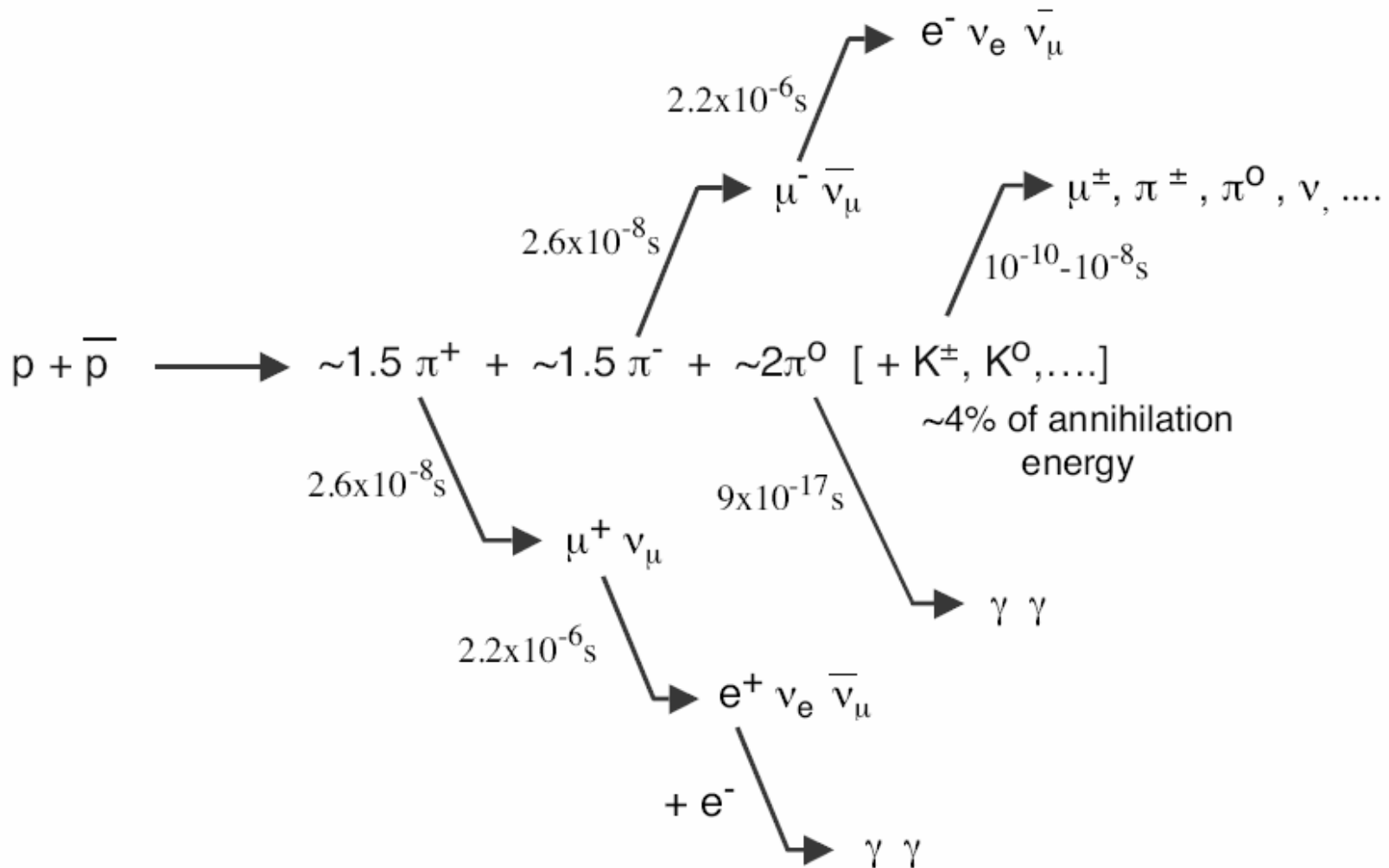
	Full Scale	Test Case 1	Test Case 2
<b>Particle</b>	Antiproton	Electron	Electron
<b>Throat B Field Intensity</b>	628.35mT	41.41mT	4.14mT
<b>Kinetic Energy</b>	1GeV	1.4eV	0.015eV
<b>Lifetime</b>	368.373 yrs	25.063 min	41.772 hrs



# Forbidden Regions

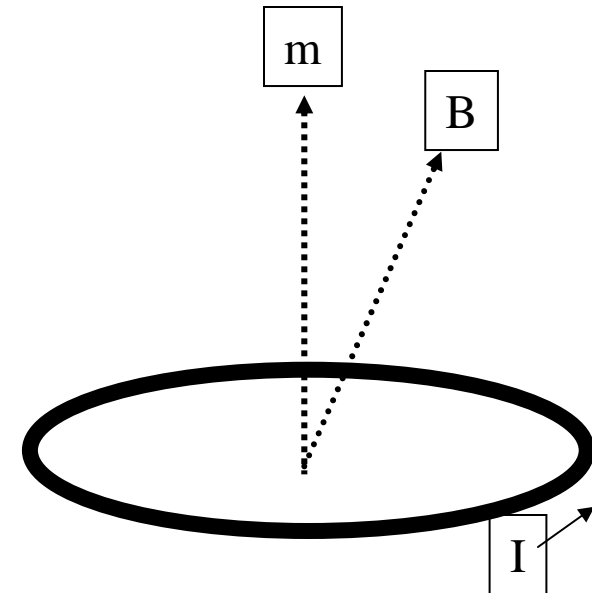


# Antiproton Annihilation Products



# Torque and Forces

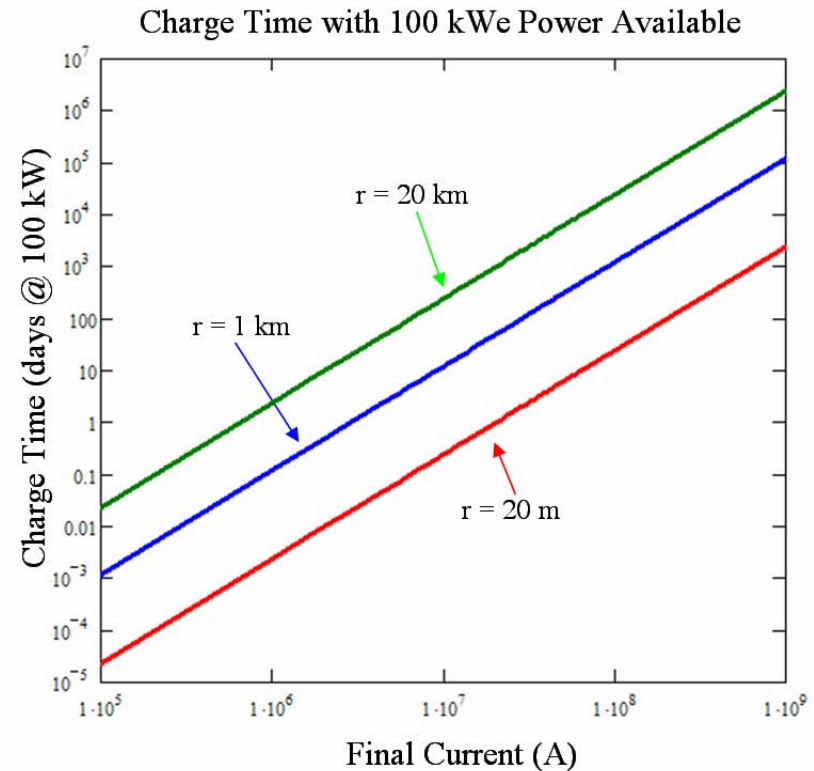
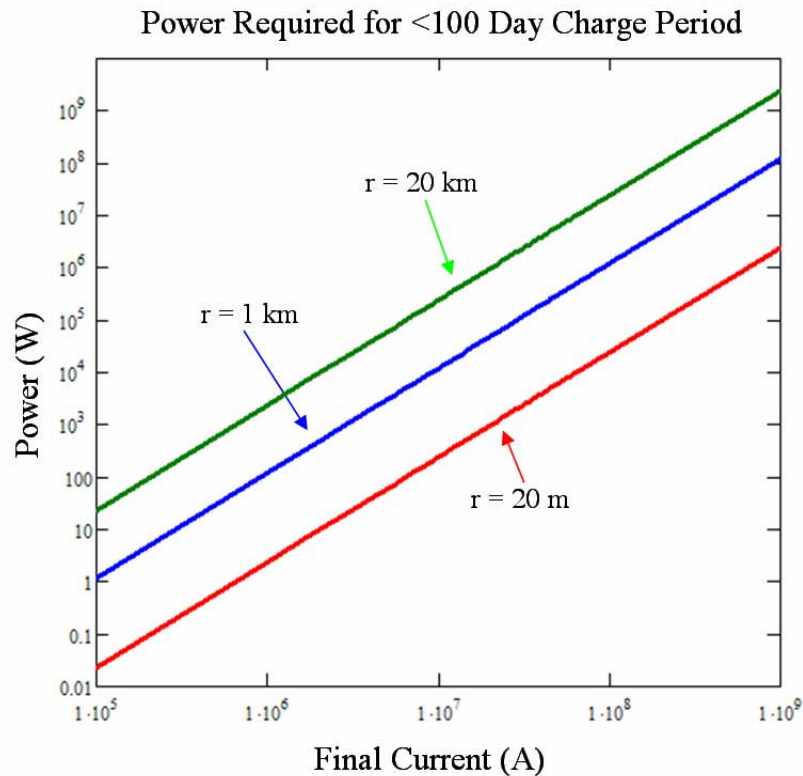
- Precession
  - A current loop experiences a torque when exposed to an ambient magnetic field
    - Wants to align loop with the local magnetic field lines
  - Loop will precess around the field lines if no damping is present
  - AC currents can eliminate the torque for non-aligned loops.
    - Makes trapping more difficult
- Translation
  - No net force in constant field
  - Some translation due to field gradients



$$\mathbf{m} = NIA$$

$$\text{Torque} = \mathbf{m} \times \mathbf{B}$$

# Power Requirements

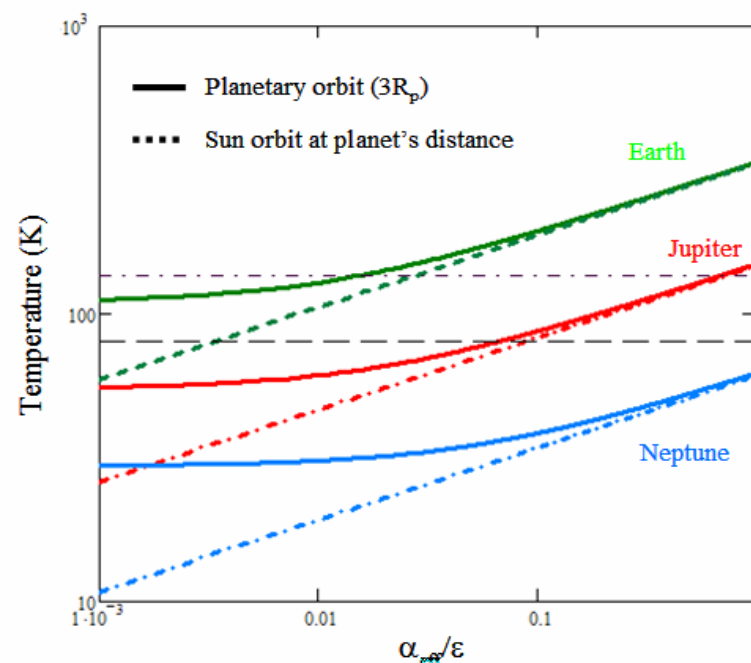


- Energy stored in the magnetic field



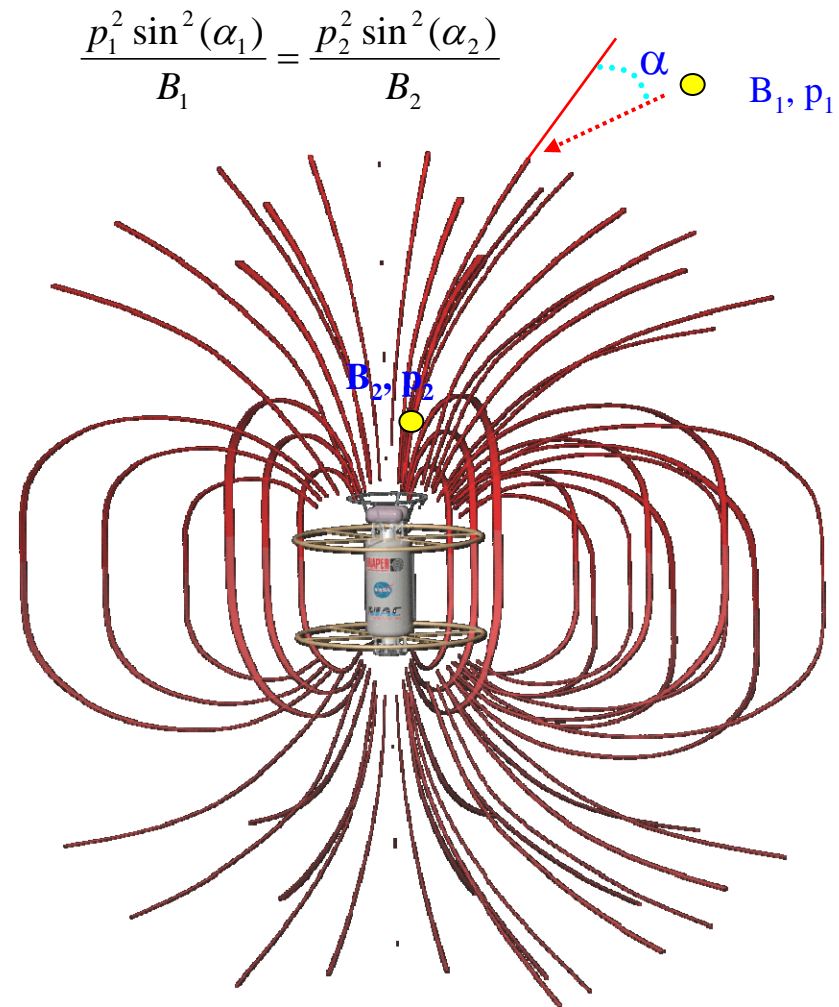
# Thermal Control

- Passive thermal cooling highly desirable for superconducting coils.
  - Coating only – doesn't require power input or cooling system hardware.
  - Leverages differential emissivity between visible and infrared bands.
- Multi-Layer Insulation (MLI) required to cool coils to superconducting temperatures in the Earth's vicinity.
- Second surface mirror coatings and multi-layer films potentially feasible for use at Jupiter and beyond.



# Antiproton Collection

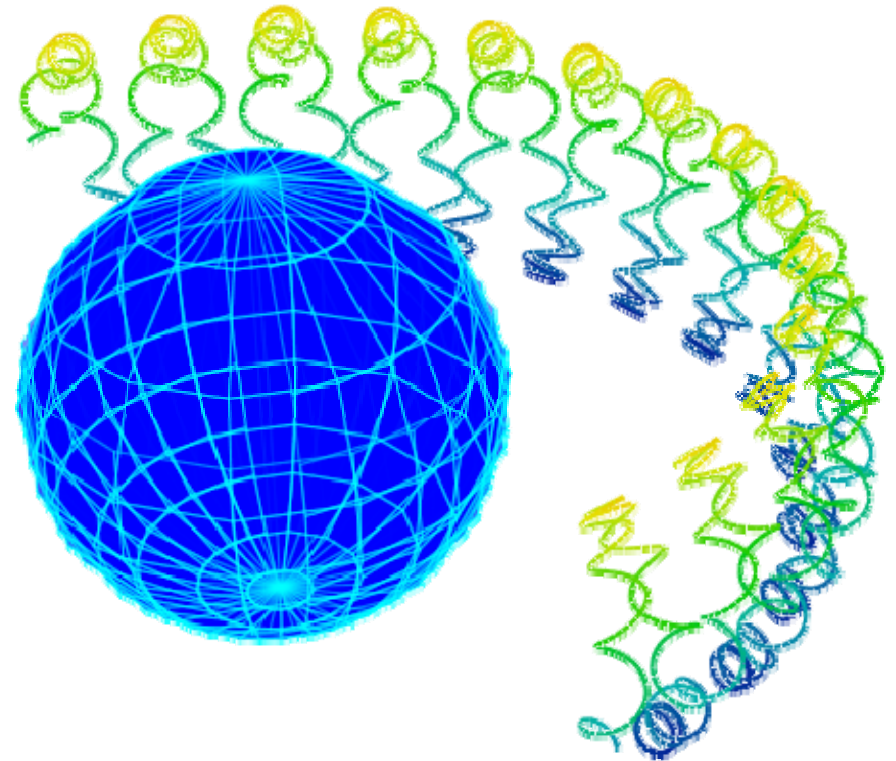
- Magnetic Scoop
  - Charged particles are concentrated as they follow magnetic field lines towards the dipole source.
- Scoop Efficiency
  - Limited by magnetic reflection & gyro radius limitations
    - Particles reflected when their pitch angle ( $\alpha$ ) reaches 90 deg
    - Gyro radius must be smaller than the radius of influence to ensure the particle does not spiral out of the field region before being trapped.
  - Related to relative magnetic field intensities and particle momentum.
    - Applied E and RF fields can be used to pull the particles towards the collector and extend the maximum obtainable acceptance angle.
- Collection
  - Particle can be collected (trapped in field) by degrading its energy and/or using a supplementary field (E-field easiest) to move the particle to a closed field line.
  - Restrictions on stable trapping based on particle momentum and field characteristics.



# Stable Trapping

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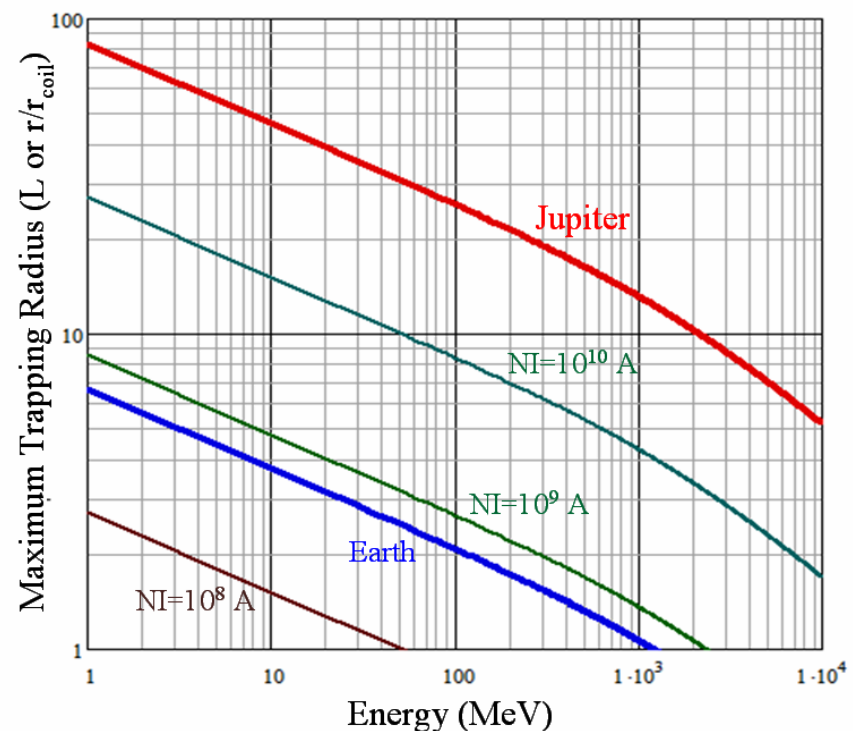
- Van Allen Radiation Belts
  - Protons and electrons trapped in the magnetic field of the Earth
  - Charged particles follow the magnetic field lines of the planet and bounce between the North and South magnetic poles.
- Three Characteristic Motions
  - Gyration (circular motion around field lines)
  - Bouncing (North/South reflection)
  - Drift (rotation around the planet)
- Characteristic Time Scales
  - (10 MeV proton trapped @  $L=2.5$ )
  - Gyration  $\sim 30$  ms
  - Bounce  $\sim 1$  sec
  - Drift  $\sim 100$  sec



# Trap Stability

- Traditional storage limits (space charge, Brillouin) for Penning traps not a major factor for antiprotons stored in the dipole magnetic field due to very low plasma density
  - $1 \text{ mg/km}^3 \rightarrow 10^5 \text{ 1/cm}^3$
- Alfven stability criterion
  - Based on the conservation of the first adiabatic invariant
  - Gyro radius should be  $\ll$  radius of curvature of the guiding center
- Limits the maximum particle energy for a given field strength

$$r_{stable} < \sqrt{\frac{Mq}{30p}}$$





# GCR Simulation

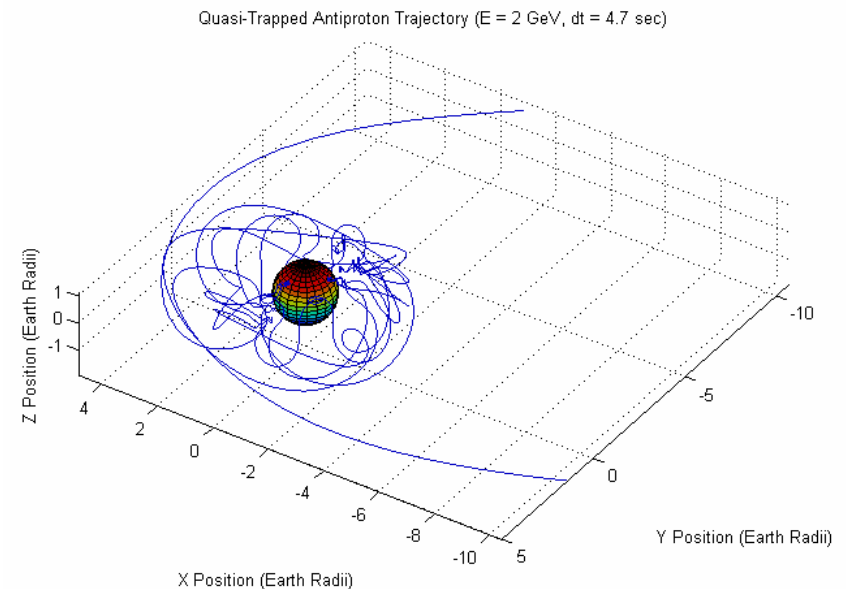
- Variable time step explicit Runge-Kutta ODE solver used to propagate high energy charged particles through the inner magnetosphere

- Integration of Lorentz equation

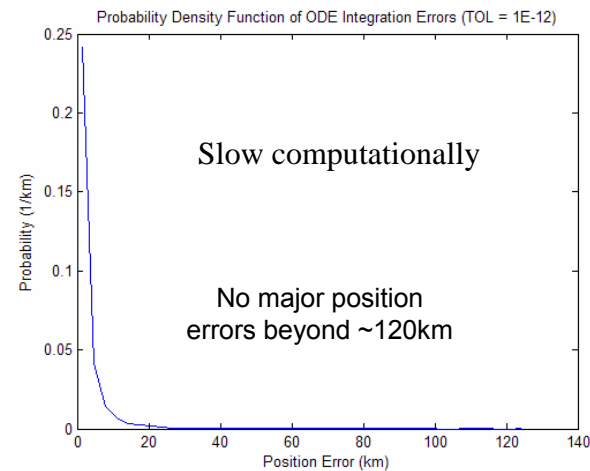
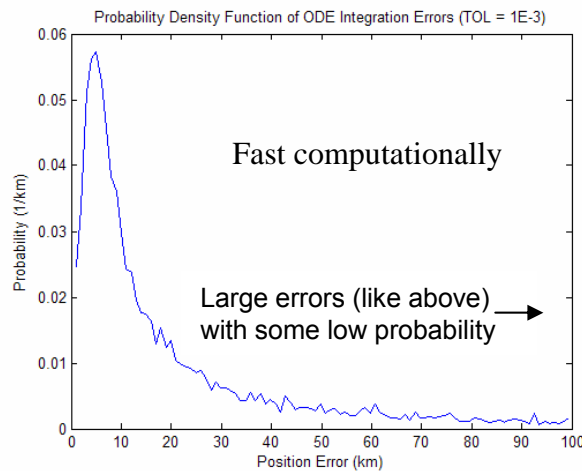
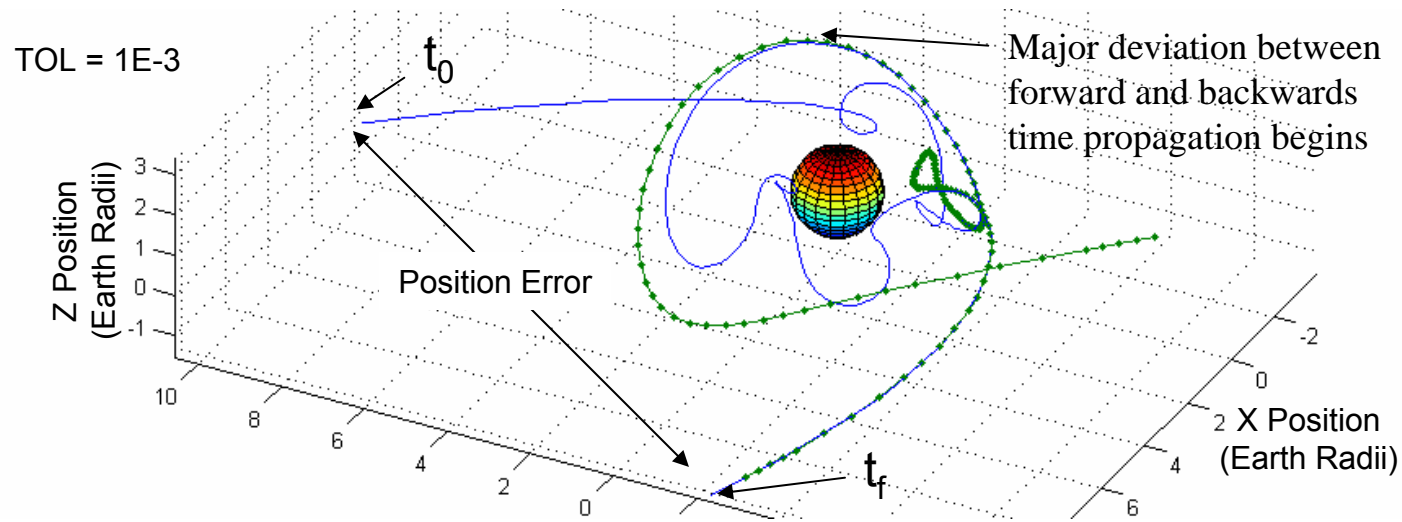
$$\frac{d\vec{p}}{dt} = q(\vec{V} \times \vec{B} + \vec{E})$$

- System of first order ODEs
  - Static inner field dipole model of Earth and Jupiter simulated.
    - E=0

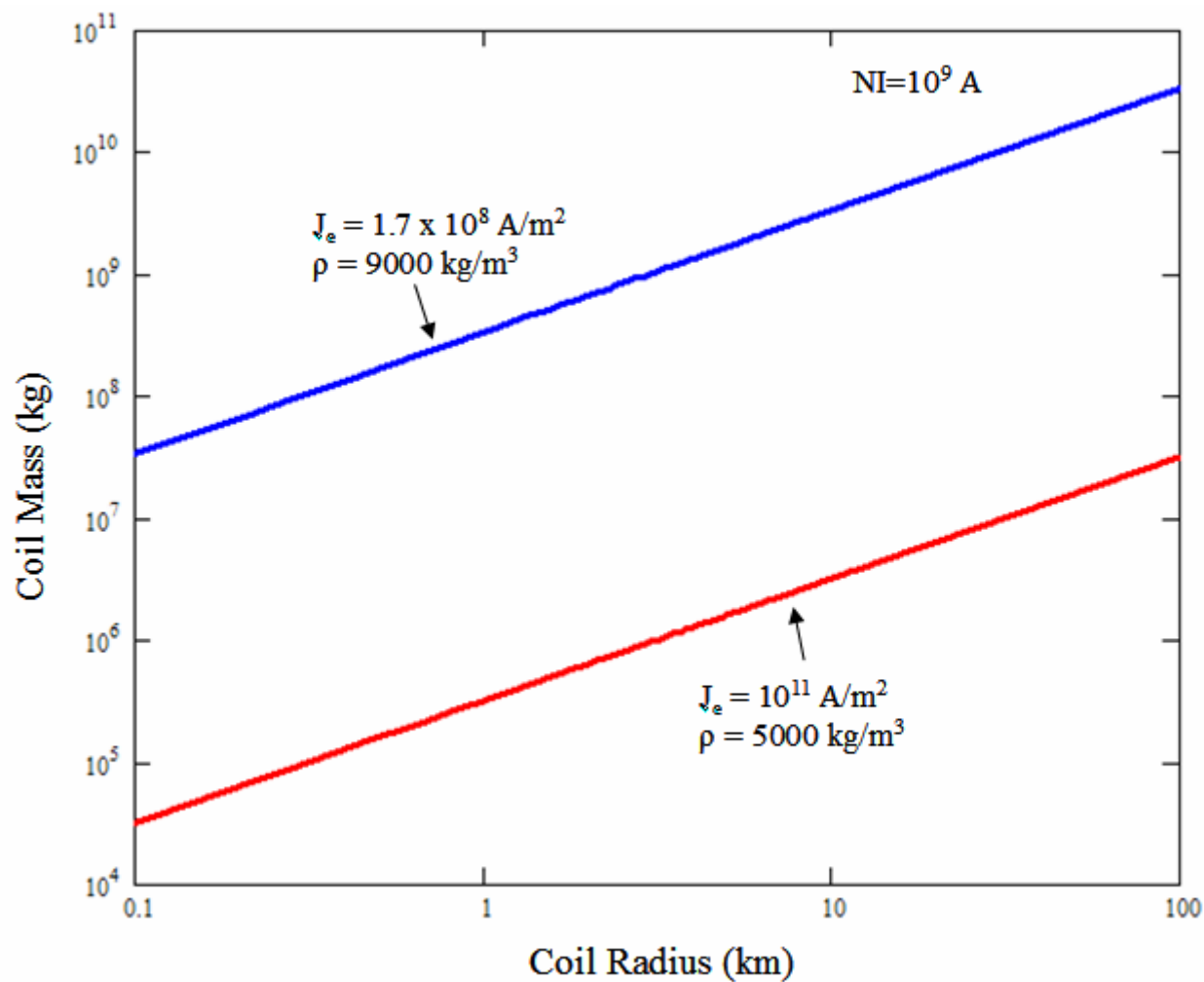
- Ability to expand on work first performed by Carl Stormer.
  - Modern desktop computers can duplicate 18000 hours (9 years) of graduate student work in about 3 seconds.



# Integration Error Tolerance



# Ring Mass



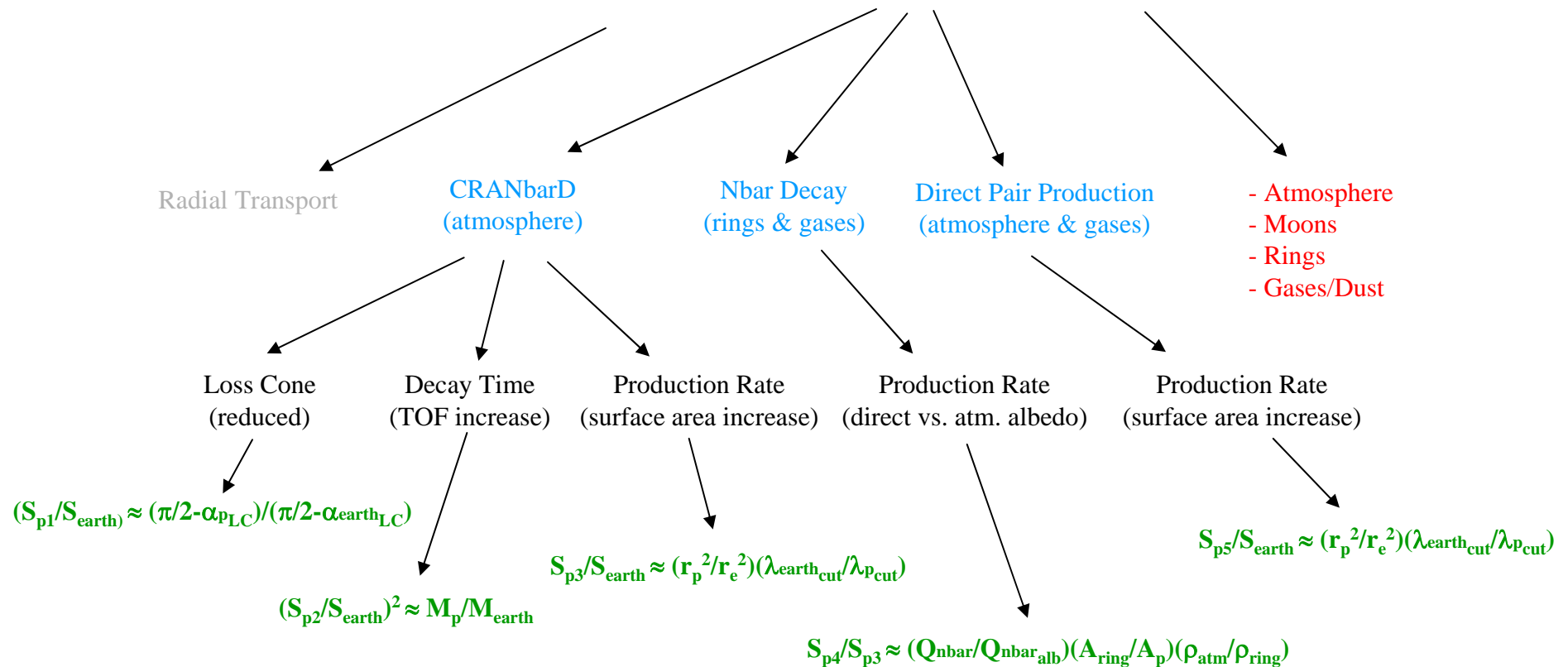
# Technology Development

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- Technology Gap : Low mass, high strength, long strand, ultra-high current loops
  - Requirement : High temperature superconductors with  $J_e > \sim 10^{10}$  A/m<sup>2</sup> at 90K and L>100m.
  - Priority : Essential for collecting from natural low flux antiproton background, highly desirable for systems with artificial augmentation.
- Technology Gap : In-orbit power
  - Requirement : Space qualified nuclear reactor with  $P \geq 100$  kWe
  - Priority : Highly valuable though solar power is potentially another option.
- Technology Gap : High efficiency, orbital antiproton generator
  - Requirement : Orbital particle accelerator with beam power = 200 GeV.
  - Priority : Essential for artificial augmentation, not needed if natural antiproton sources are used.
- Technology Gap : Passive cooling systems
  - Requirement : Reduced mass multi-layer thermal blankets for passive temperature control of large structures with  $T_{\max} < 90$ K at 1 AU.
  - Priority : Improvements in reducing mass or operating temperature valuable; reduces requirements on HTS.
- Technology Gap : Affordable Lift
  - Requirement : Reduced cost to orbit. (\$/kg)
  - Priority : Not required, but helpful.

# Jovian to Earth Radiation Belt Scaling

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial L} \left[ \frac{D_{LL}}{L^2} \frac{\partial f}{\partial L} \right] + Sources + Losses$$

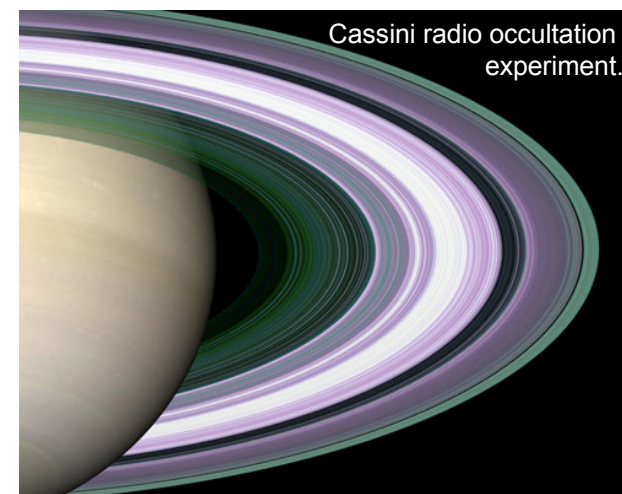


See backup slides for additional detail...



# Jovian Estimates

- Dominant Antiproton Source
  - Fraction of antineutrons which decay in Jovian magnetospheres.
- Jupiter
  - Smaller supply than originally anticipated due to the cutoff of the GCR production spectrum by its large magnetic field.
  - Approximately 1  $\mu\text{gm}$  spread throughout its magnetosphere.
- Saturn
  - Rings are the largest source of locally generated antiprotons in the solar system. Nearly a half milligram of antiprotons are trapped.
  - Primarily formed by the decay of ring produced antineutrons in the magnetosphere. Antineutrons generated in the A&B rings (20-100  $\text{gm}/\text{cm}^2$ , Nicholson and Dones, 1991) do not have to be backscattered for trapping which drastically increases the efficiency.
  - Rings are also a significant source of antiprotons which are directly produced but which are reabsorbed by the rings after one or more bounce periods.

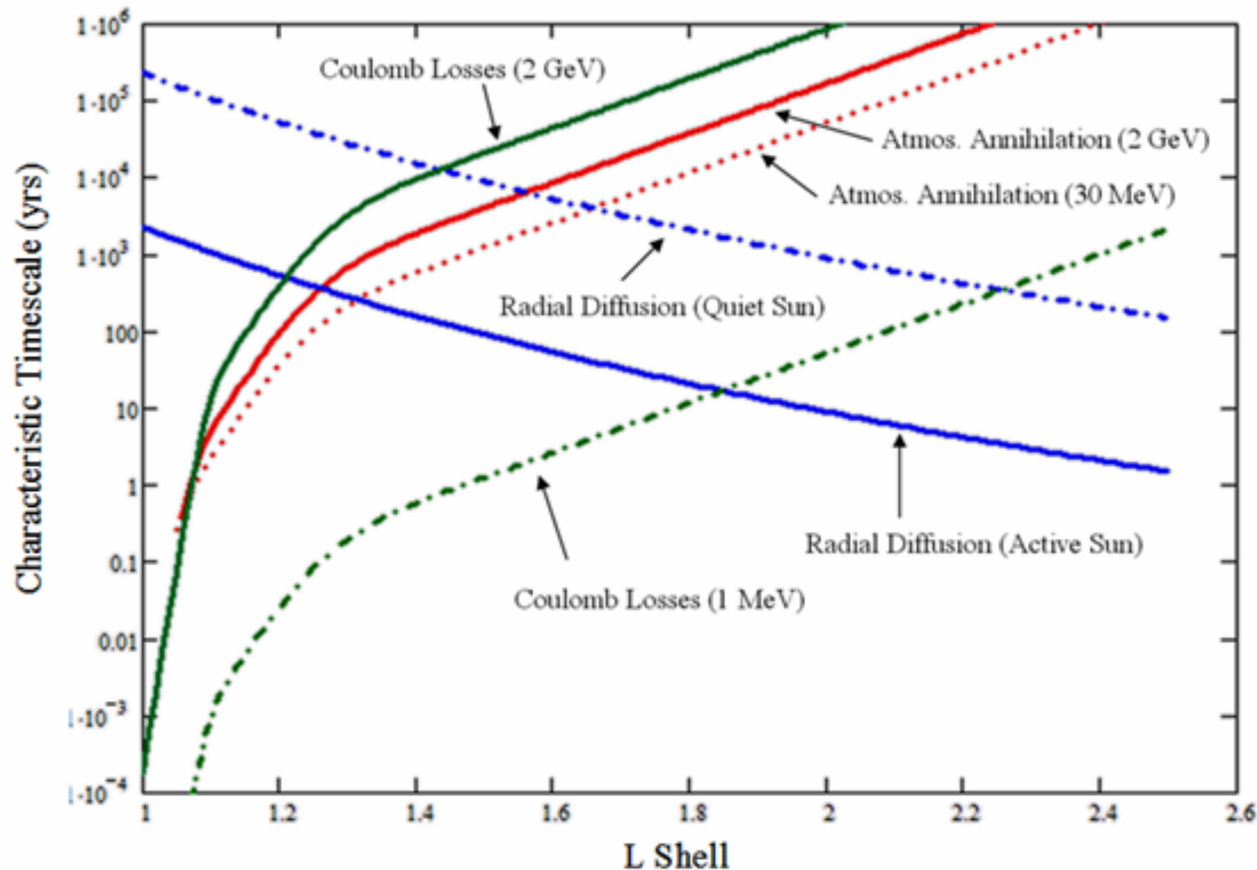


$$(S_p/S_{\text{earth}}) \approx (S_{p1}/S_{\text{earth}1}) (S_{p2}/S_{\text{earth}1}) (S_{p3}/S_{\text{earth}1}) + (S_{p4}/S_{\text{earth}1-3}) + (S_{p5}/S_{\text{earth}5})$$

	$S_{1-3}/S_{\text{earth}}$	$S_1/S_{\text{earth}}$	$S_2/S_{\text{earth}}$	$S_3/S_{\text{earth}}$	$S_4/S_{1-3}$	$S_5/S_{\text{earth}}$	Mass
	<i>Nbar Related</i>	<i>Loss Cone</i>	<i>Decay Time</i>	<i>Production Area</i>	<i>Rings (Nbar)</i>	<i>Direct Pbar</i>	<i>Trapped Pbar</i>
<b>Earth</b>	1	1	1	1	0	1	~0.25 ng
<b>Jupiter</b>	$> 6 \times 10^3$	$< 1.2$	~ 140	~ 45	~ 0	~ 45	~1 $\mu\text{gm}$
<b>Saturn</b>	$> 3 \times 10^3$	$< 1.2$	~ 25	~ 90	$10^3$ (?)	~ 90	~400 $\mu\text{gm}$
<b>Uranus</b>	$> 110$	$< 1.2$	~ 7	~ 15	~ 0	~ 15	~ 18 ng
<b>Neptune</b>	$> 75$	$< 1.2$	~ 5	~ 15	~ 0	~ 15	~ 13 ng

Note : Values shown are very coarse engineering estimates based on extrapolations only.

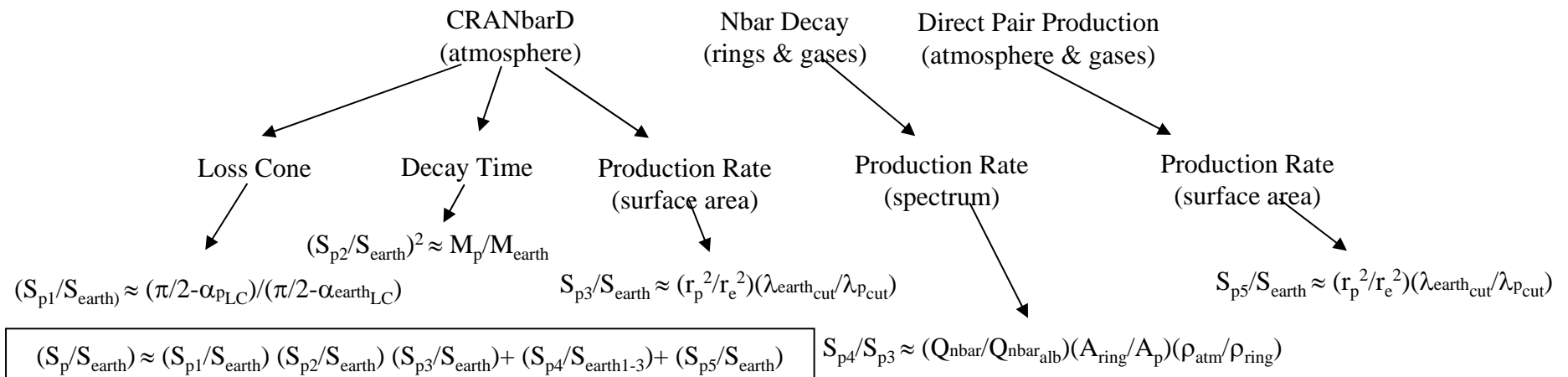
# Antiproton Loss Timescales



The antiproton radiation belt is replenished over the timescale of years ( $\ll 1$  ng/yr). Given these rates, the trapped Earth supply is unlikely to represent a practical source of antiprotons for 'mining'.

# Explanations & Jovian Estimates

- $S_1$  - Stronger magnetic fields increase the antineutron decay acceptance cone.
- $S_2$  - A greater percentage of the particles decay when path lengths (and flight times) are longer. The size of the trapping region is estimated by comparing the particle gyro radius to the radius of curvature of the field lines. Increasing the radius of curvature for the same field strength enables trapping over wider regions. This becomes non-linear and breaks down as the flight time approaches the particle's relativistic half life.
- $S_3$  - Antineutron pair production in the atmosphere increases with the available production area. Due to cutoff limitations, some portion of the source spectrum (GCR) may not strike the atmosphere, thus reducing the production rate. This limitation is primarily an issue near Jupiter where most of the production spectrum is cutoff at  $\lambda \sim 60$  deg.
- $S_4$  - Antineutrons produced in belts ( $\sim$ Saturn) or gases ( $\sim$ Io Torus) surrounding the planet do not need to be backscattered to decay within the belts. There is no analogous source for this around the Earth. The efficiency improves by with the relative path lengths and the inverse of the antineutron backscatter ratio. However, the Io torus and dust deposits are not thick enough ( $\text{g}/\text{cm}^2$ ) to produce significant antineutron fluxes.
- $S_5$  - Antiproton pair production in the atmosphere increases with the available production area. Due to cutoff limitations, some portion of the source spectrum (GCR) may not strike the atmosphere, thus reducing the production rate.



# Decay Time Scaling (S2)

The magnetic field at a distance  $x$  from the planet is proportional to,

$$B \propto \frac{M}{x^3}$$

where  $M$  is dipole moment of the planet. The maximum distance for stable trapping at a given energy (Larmor limits) can be given as the point where the gyro radius is equal to no more than 10% the radius of curvature. The radius of curvature is approximately  $x_{eq}/3$  so therefore,

$$\frac{x}{3} < 10 \frac{p}{Bq} \rightarrow x^2 < \frac{Mq}{30p} \rightarrow x_{max} \propto \sqrt{M}$$

Since the time of flight is related to the distance ( $d=vt$ ), the maximum flight time in a planetary magnetosphere is proportional to the square root of the planet's magnetic dipole moment. Relating this to flight times in the Earth's magnetosphere gives,

$$\frac{flighttime_p}{flighttime_{Earth}} = \sqrt{\frac{M_p}{M_{Earth}}}$$

Planet	Dipole Moment	Radius
Earth	$7.9 \times 10^{25}$ gauss cm <sup>3</sup>	6378 km
Jupiter	$1.5 \times 10^{30}$ gauss cm <sup>3</sup>	71492 km
Saturn	$4.3 \times 10^{28}$ gauss cm <sup>3</sup>	60268 km
Uranus	$3.8 \times 10^{27}$ gauss cm <sup>3</sup>	25559 km
Neptune	$2 \times 10^{27}$ gauss cm <sup>3</sup>	24764 km

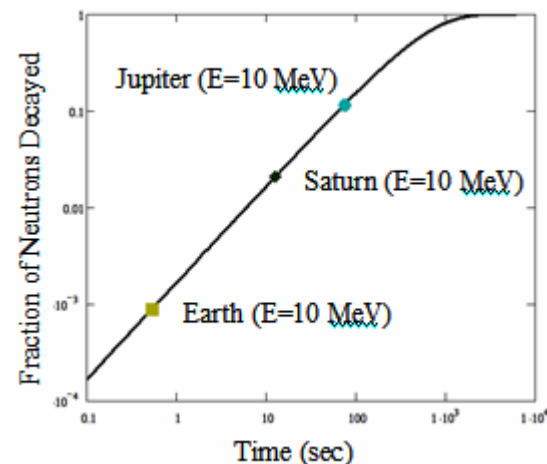
The number of neutrons that have decayed in the planet's rest frame after a time  $t$  is,

$$\frac{N_{decayed}}{N_0} = 1 - e^{-t/\tau_{1/2}}$$

where  $\tau_{1/2}$  is the neutron's relativistic half life ( $\gamma\tau_{1/2}$ ). When  $t \ll \tau_{1/2}$  the number of particles that decay within a planet's magnetosphere relative to the number at Earth can be simplified to,

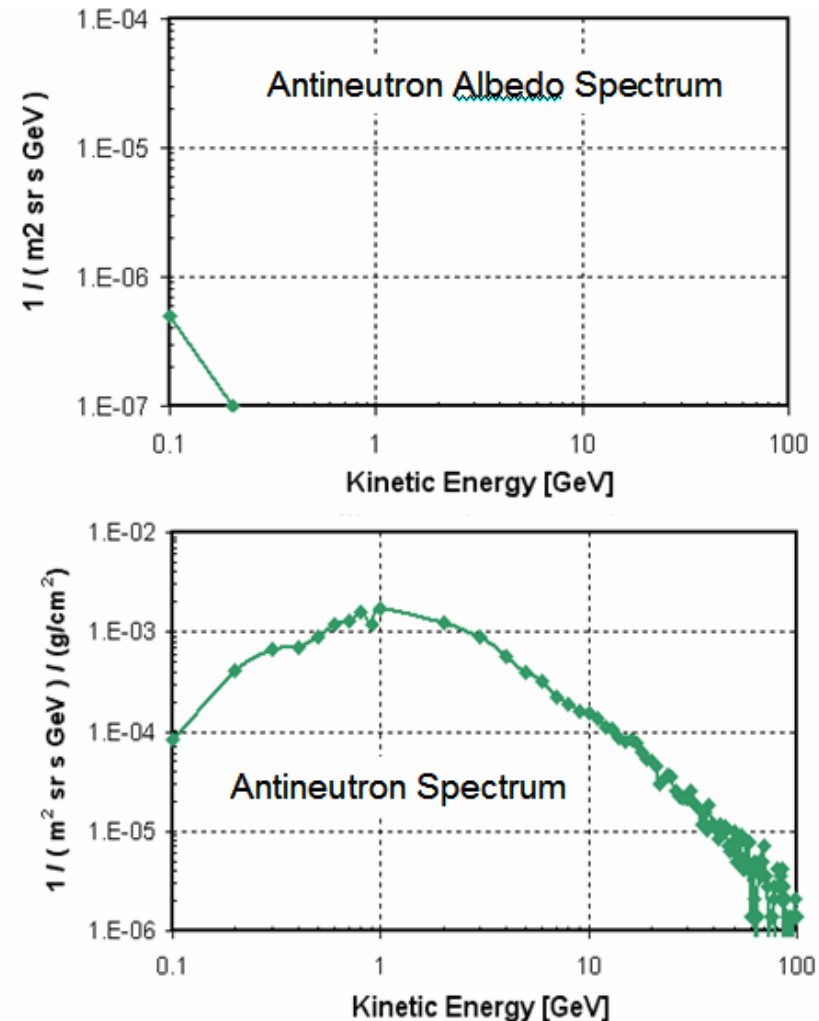
$$\frac{N_1}{N_2} \approx \frac{t_1}{t_2} \rightarrow \frac{N_p}{N_{Earth}} \approx \sqrt{\frac{M_p}{M_{Earth}}}$$

Note that this expression is energy independent. Therefore, planets with stronger magnetic fields can trap a greater number of decay products from albedo antineutrons since the longer transit times enable a larger percentage of them to decay while within the trapping region.



# Production Rate Scaling (S4)

- Atmospheric production of antiprotons via anti-neutron decay is inefficient because it relies on the backscatter of anti-neutrons.
- Antineutrons produced in rings or other structures can directly exit and travel into the magnetosphere where they decay. This process is much more efficient than relying on backscatter.
- At 100 MeV and a 5 g/cm<sup>2</sup> pass length, the differential antineutron flux is 900 times larger than the albedo flux.
- This needs to be scaled by the relative angular capture efficiency and the area over which the antineutrons are generated.





# Local Production Augmentation

- Optimization of the production process has been proposed numerous times before.
  - About four orders of magnitude improvement in energy efficiency appears feasible.
- Space based production
  - First proposed in 1987 by Haloulakos and Ayotte.
    - Offers certain intrinsic advantages for space propulsion, namely that the antiprotons do not have to be stored and transported from Earth.
- In Situ Trapping
  - Generator placed within magnetic bubble or magnetosphere will collect generated antiprotons with high efficiency.
  - Configuration enables wide angular distribution and energy ranges to be captured with minimal complexity.
  - Leverages high vacuum environment.

	<b>CERN</b>	<b>Fermilab</b>	<b>In Situ</b>
<i>Incident Proton Energy (GeV)</i>	26	120	200
<i>Generation Efficiency (pbar/p)</i>	0.4%	4.7 %	8.5%
<i>Angular Capture Efficiency</i>	20%	30%	100%
<i>Momentum Capture Efficiency</i>	1%	1.2%	85%
<i>Handling Efficiency</i>	5%	18%	80%
<i>Total Efficiency (pbar/p)</i>	$4 \times 10^{-7}$	$3 \times 10^{-5}$	0.058
<i>Overall Energy Efficiency</i>	$1.4 \times 10^{-9}$	$2.5 \times 10^{-8}$	$2.7 \times 10^{-4}$
<i>Rate at 100 kWe (Prometheus)</i>			9.5 $\mu$ g/yr
<i>Rate at 1 GWe</i>			95 mg/yr

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