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Feb 28th, 7:30 AM - 8:30 AM

Spacecraft Radiation Shielding by a Dispersed Magnetic Field Array

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Spacecraft Radiation Shielding Using Dispersed Superconducting Loops

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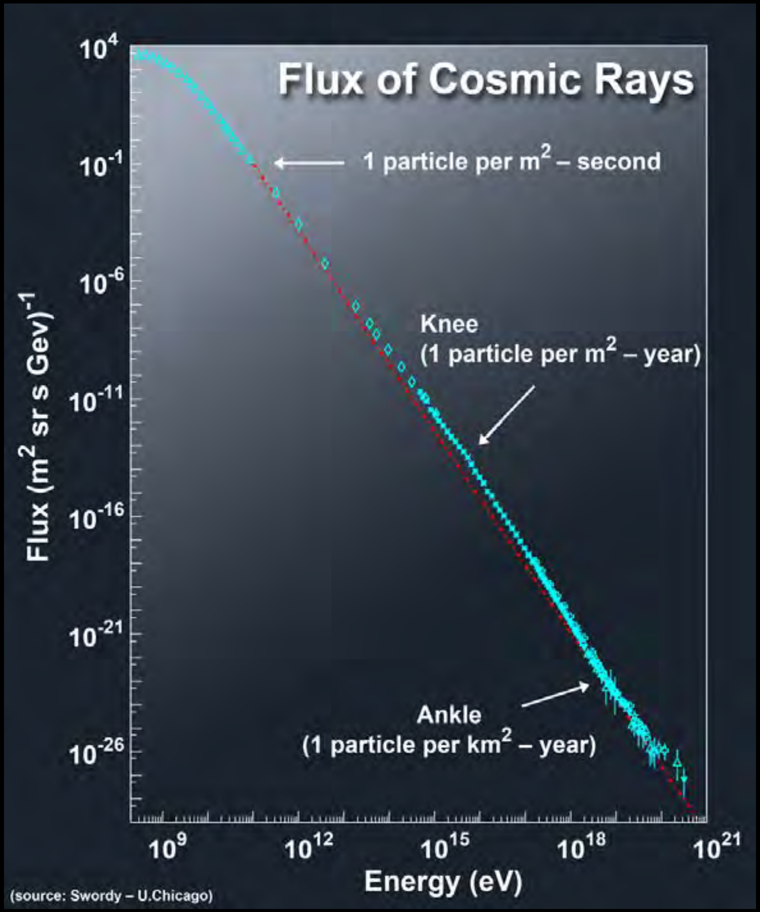
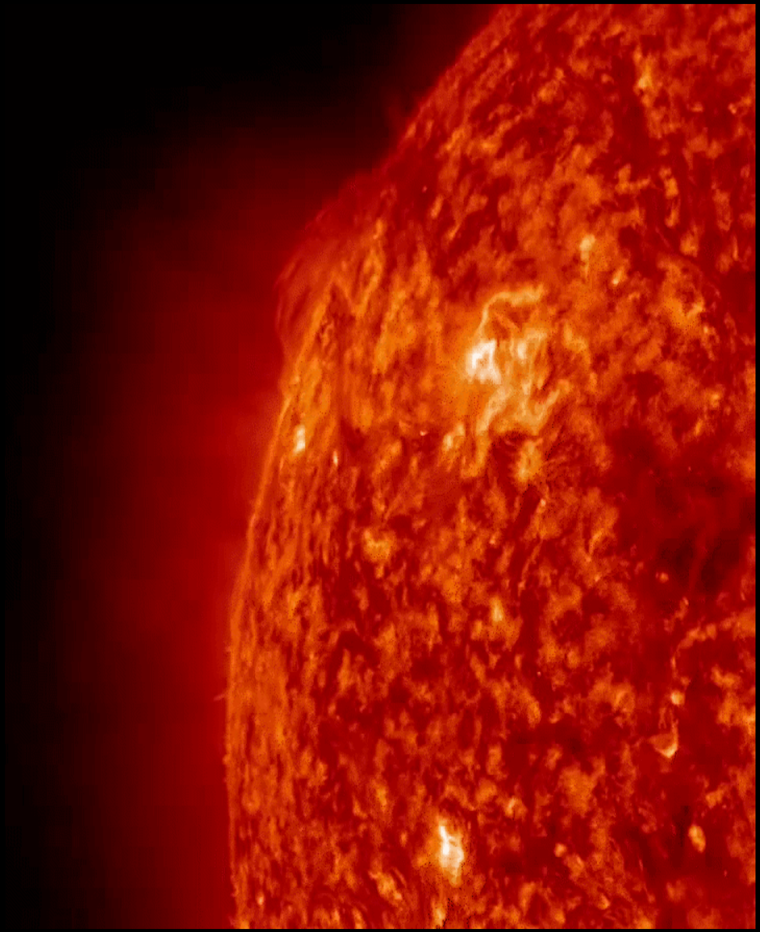
[1]OrangeWave Innovative Science, LLC

[2]Florida Institute of Technology

Interplanetary Radiation Environment





Galactic Cosmic Rays (GCRs)

Isotropic and *constant*
1—1000 GeV
Protons ←→ Fe

Solar Particle Events (SPEs)

Isotropic and *intermittent*
1—1000 MeV
protons, H, He, C, Si, Fe

Radiation Threat

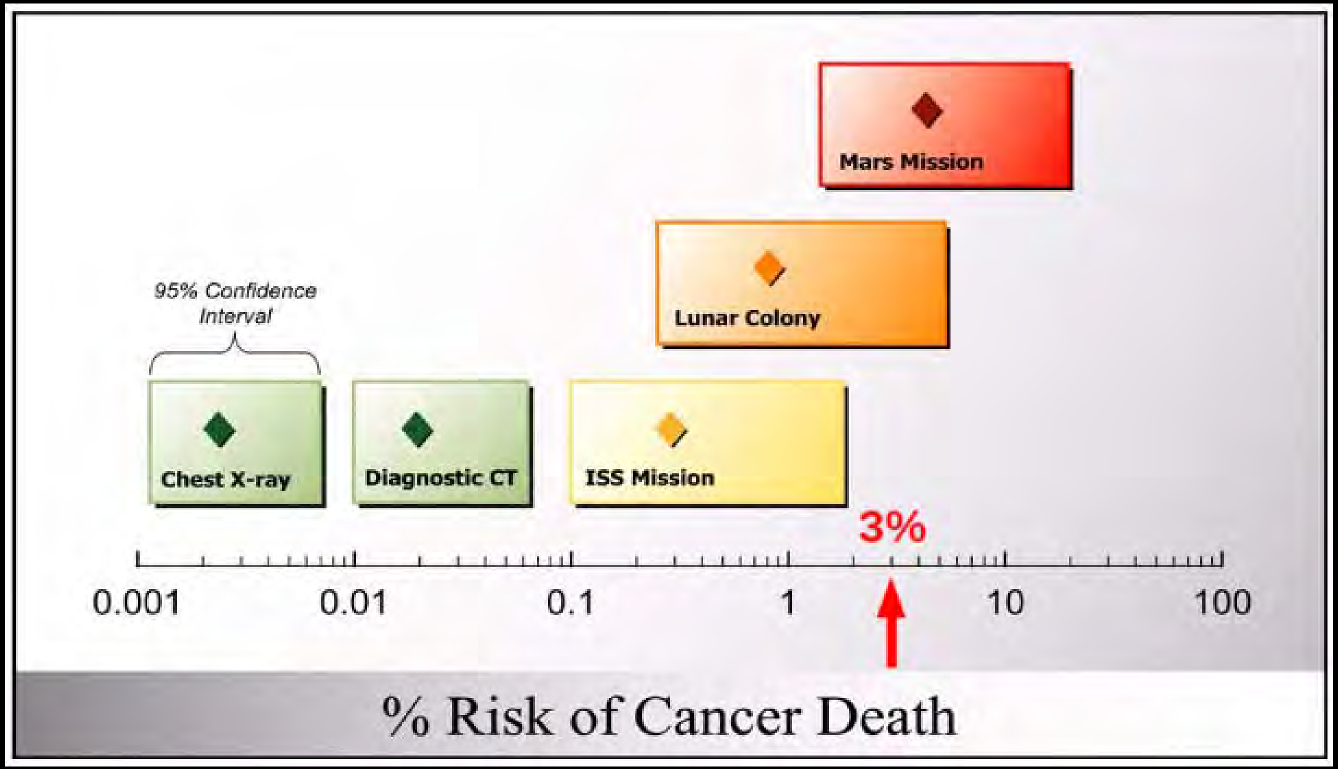
Radiation Exposure Induced Death (REID)

NASA Standard of **<3%** increase (95% confidence)

Table 4-1. *Example Career Effective Dose Limits in Units of milli-Sievert (mSv) for 1-year Missions and Average Life-loss for an Exposure-induced Death for Radiation Carcinogensis (1 mSv = 0.1 rem)*

	E(mSv) for 3% REID (Ave. Life Loss per Death, yr)	
Age, yr	**Males**	**Females**
25	520 (15.7)	370 (15.9)
30	620 (15.4)	470 (15.7)
35	720 (15.0)	550 (15.3)
40	800 (14.2)	620 (14.7)
45	950 (13.5)	750 (14.0)
50	1,150 (12.5)	920 (13.2)
55	1,470 (11.5)	1,120 (12.2)

Radiation Threat



"The NASA **PELs** for fatal cancer risk may be exceeded for several lunar scenarios including a large SPE, cumulative career exposure, and mission length dependent on crew age and gender. In addition, the NASA PELs for fatal cancer risk are projected to be violated under all possible Mars scenarios at this time."

-NASA Human Research Roadmap

Curiosity Rover

253-day cruise to Mars

SPEs

GCRs

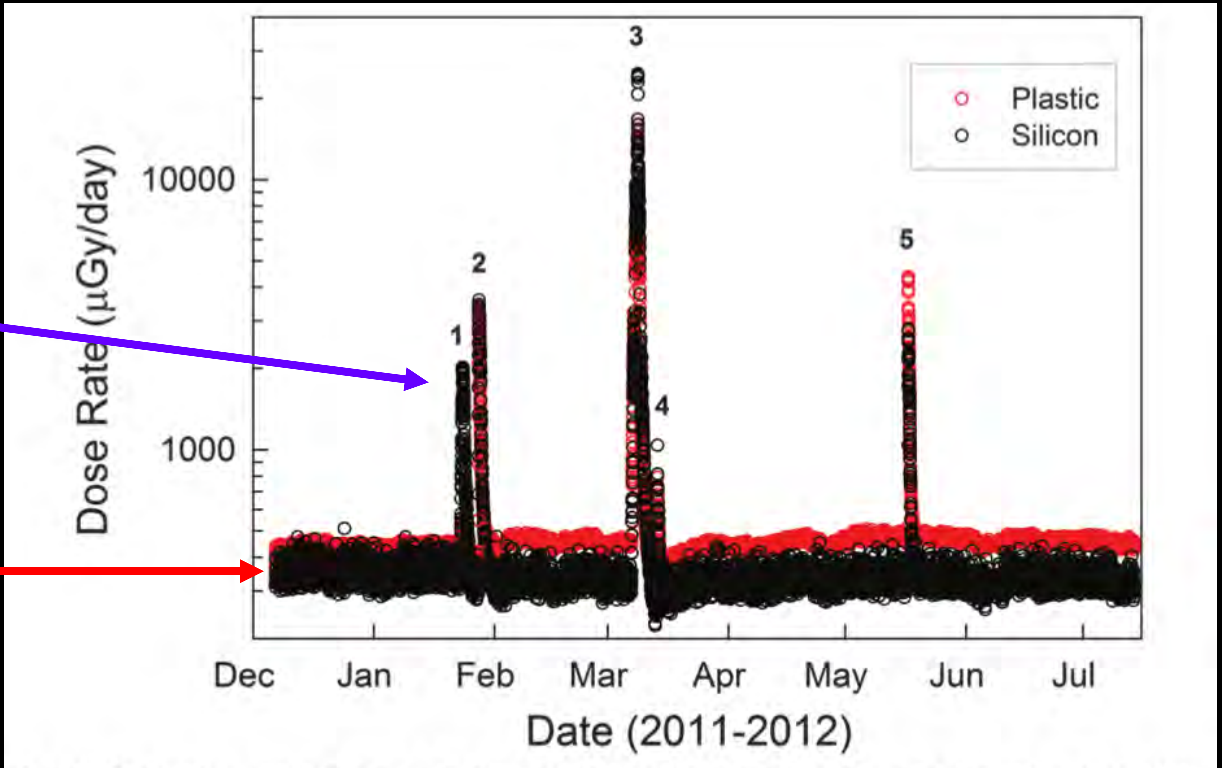


Fig. 1. Dose rates recorded in a silicon detector (black circles) and in a plastic scintillator (red circles) during the MSL's cruise to Mars.

Shortest round-trip: 660±120 mSv

Why magnetic shielding?

Threat Mitigation

Deal with consequences

- Molecular/DNA level
- Enterade
- Not a “showstopper”

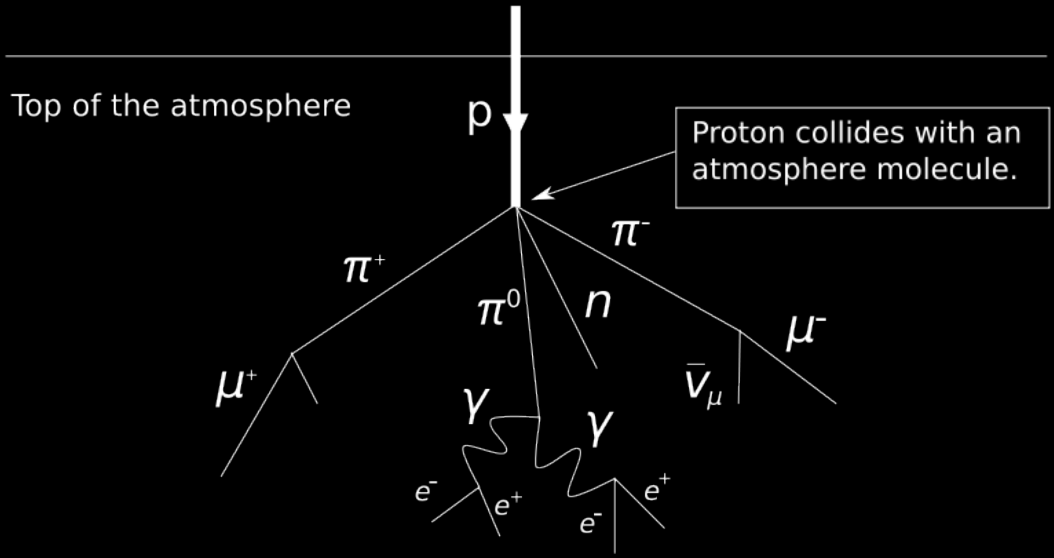
Prevention

- Absorption
- Deflect

NSBRI

Absorption - Material Shielding

Secondary particles *increase* exposure



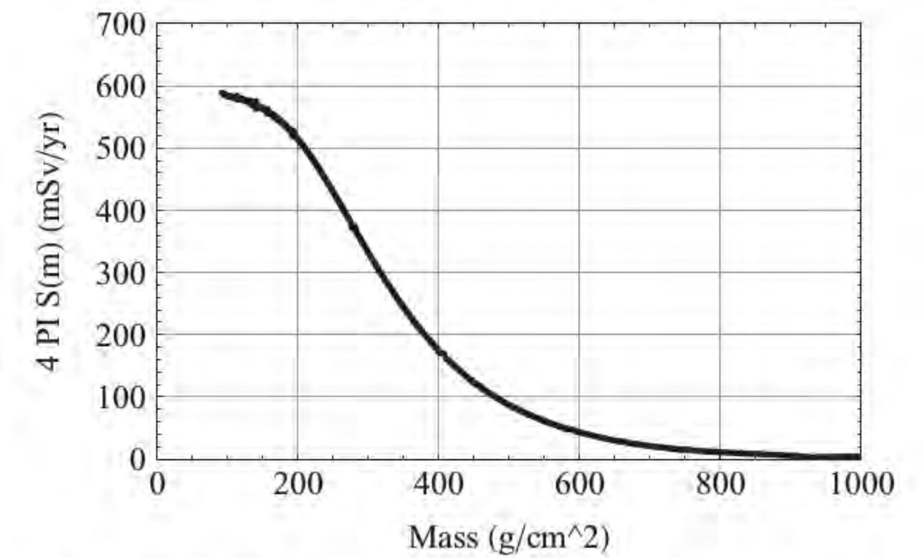
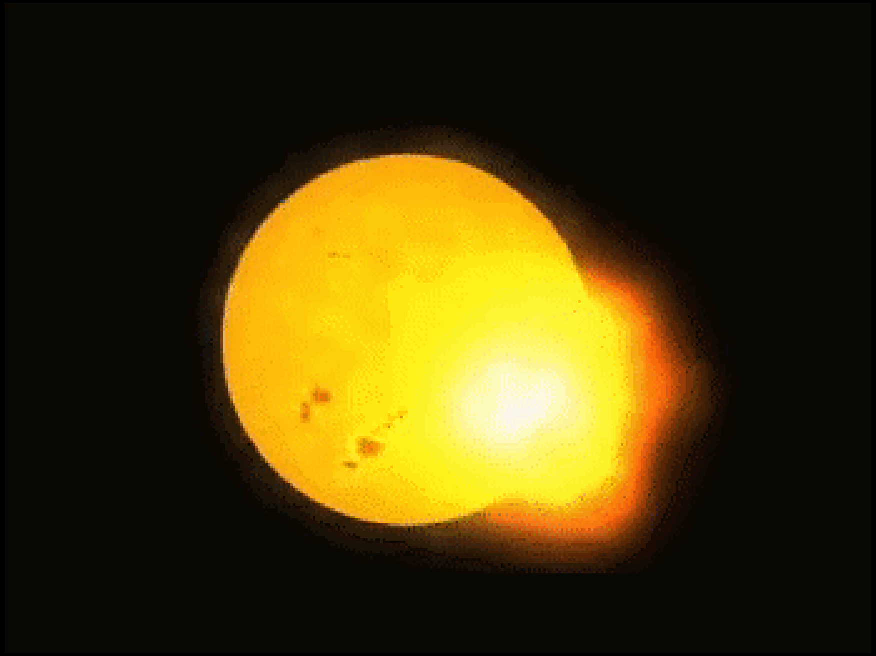


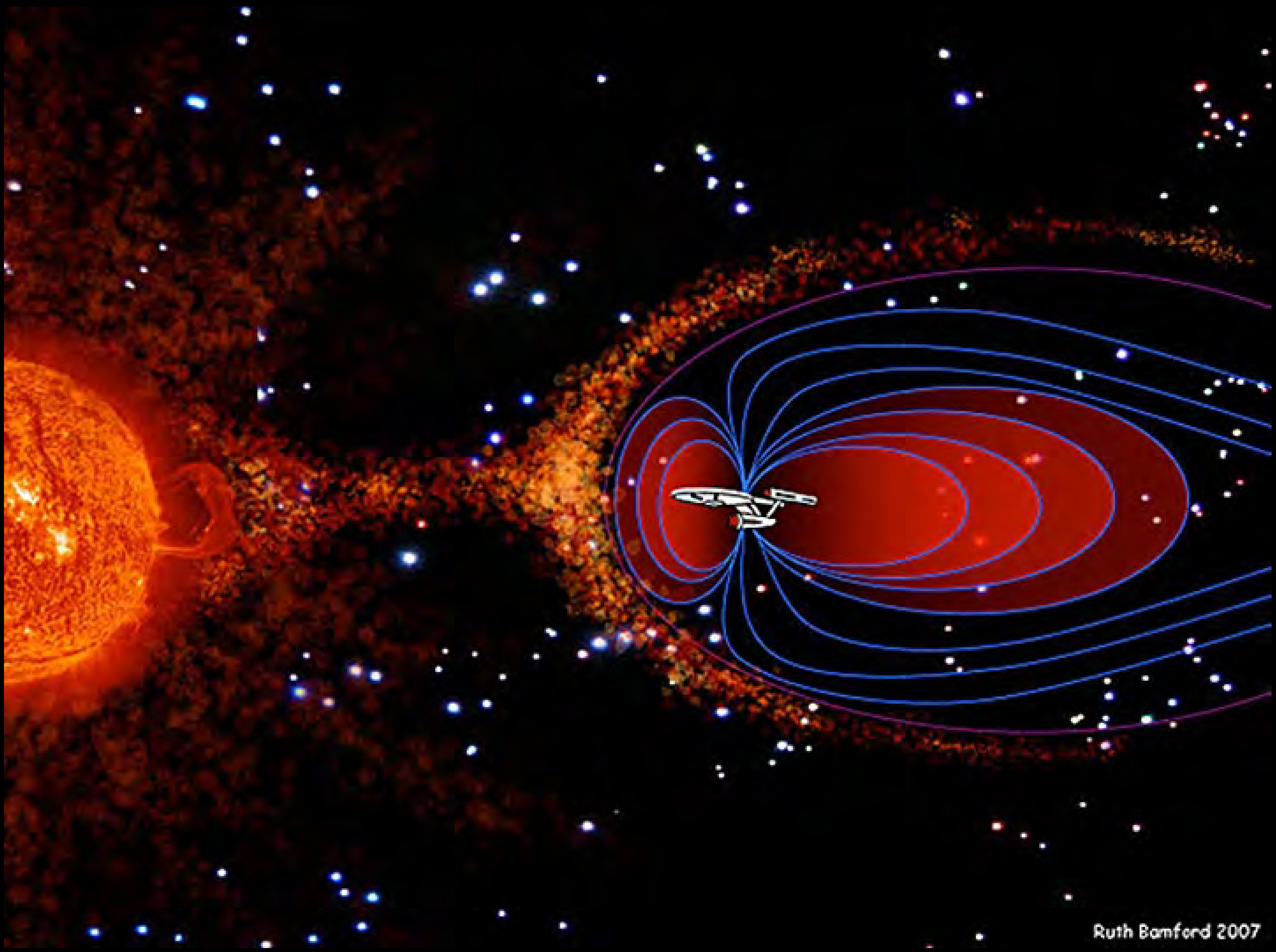
Fig. 5. This plot shows the atmospheric radiation shielding function at the 06/09 solar minimum,

Youngquist et al. (2014)

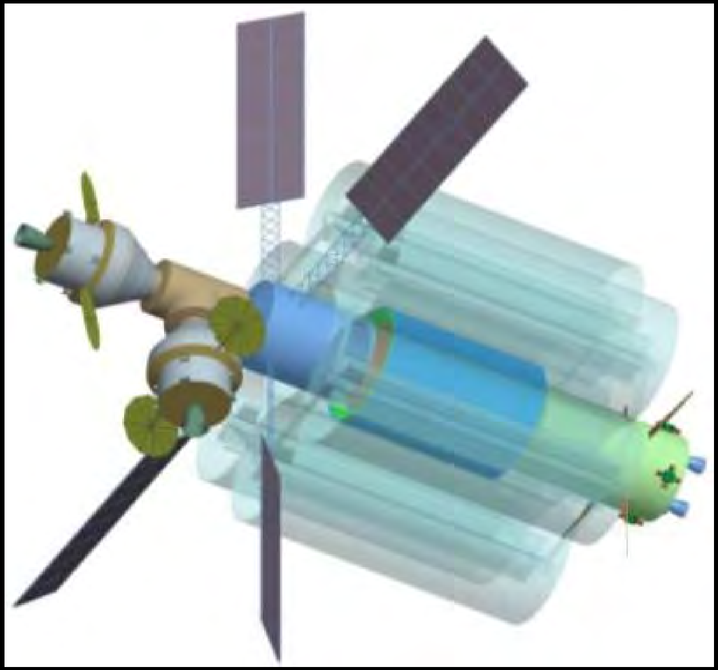
Deflection - Mimic Earth's Shield



Magnetic Shielding

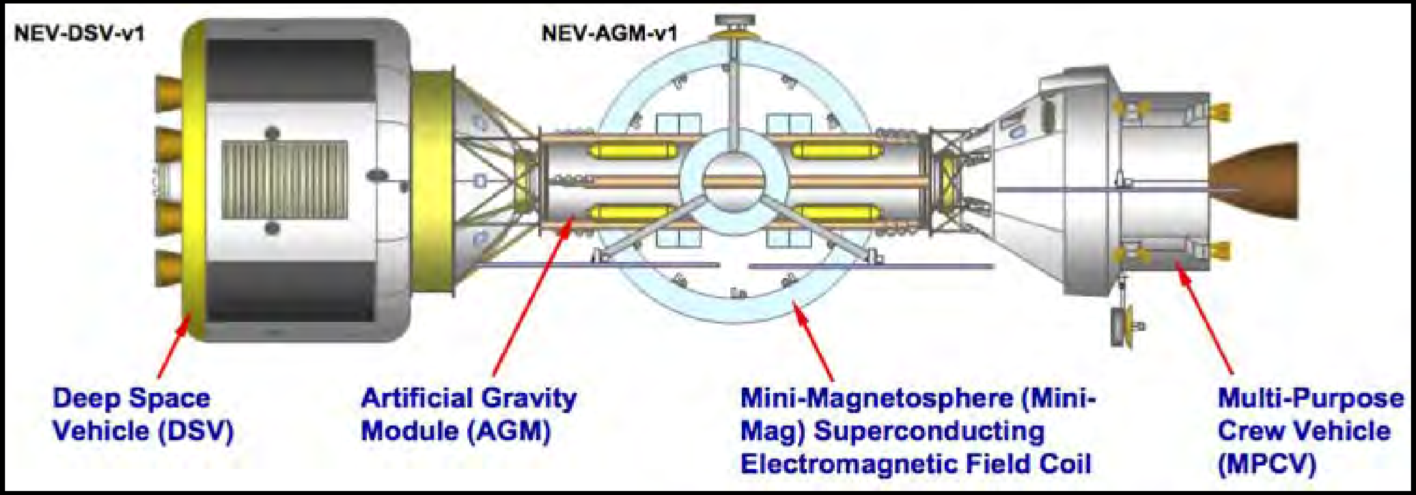


Previous Designs



Kervendal, E., Kirk, D., Meinke, R. (2006)

Superconducting magnets attached directly to spacecraft

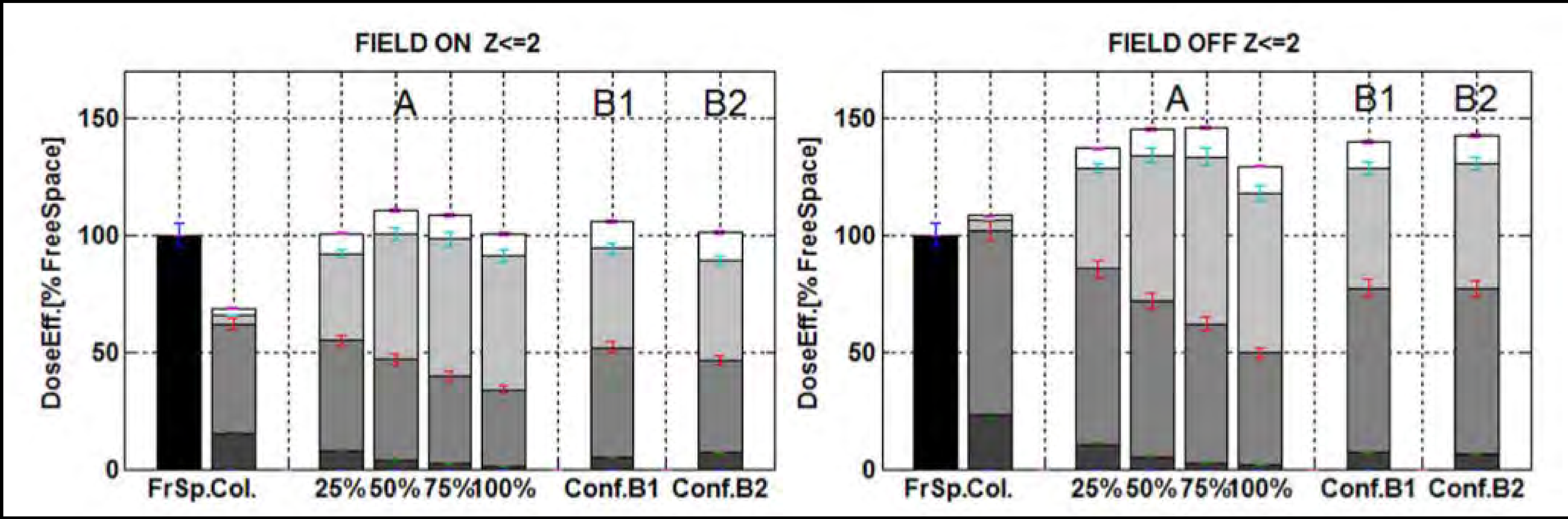


Bamford, R. A., et al. (2014)

Drawbacks

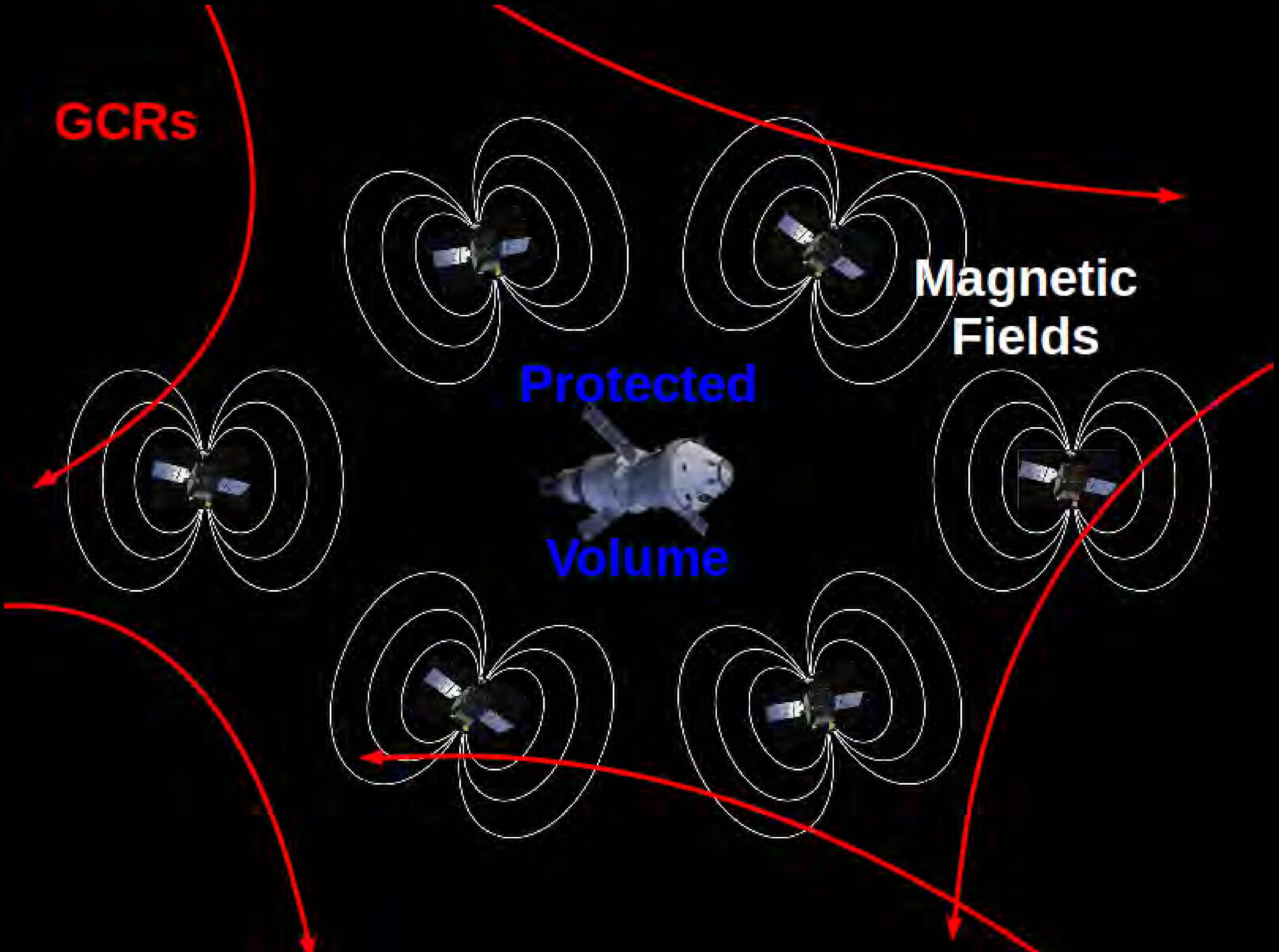
- Thermal management of superconductors
- Danger of quench in proximity of habitat
- Hinders EVAs
- Re-designing Orion

Increase of secondary radiation! (Vuolo et al. 2014)



New Concept

New Concept

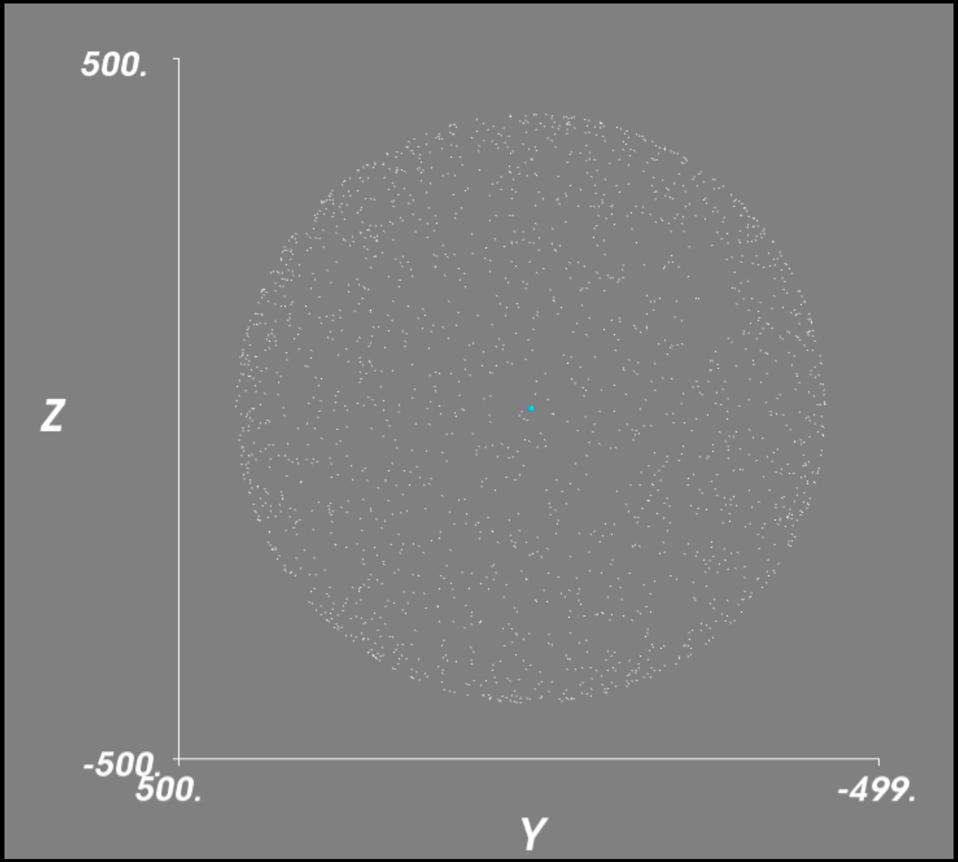


Goals

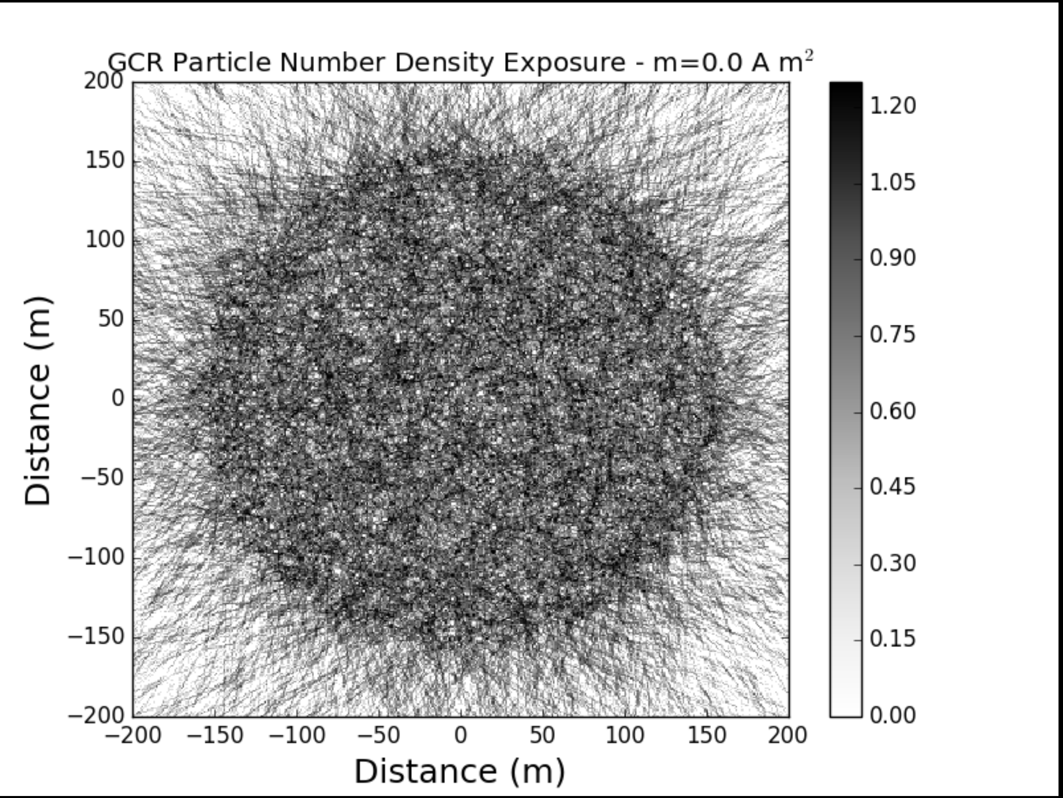
1. Optimize Design
2. First approximation
3. Good News
4. Great News
5. Bad News

Better solution?

Create Isotropic Environment



$$-1 < \cos\theta < 1$$
$$0 < \phi < 2\pi$$



Equation of Motion

$$\frac{d\vec{u}}{dt} = \frac{300}{E_n[\mathrm{MeV}]}\frac{Z}{A}(\vec{u} \times \vec{B}[T])$$

Energy space

Particle Advancement

$$u[n+1] = u[n] + a \cdot dt$$

$$r[n+1] = r[n] + u[n+1] \cdot dt$$

4th order Runge Kutta

Form of the Magnetic Shield

$$B_x = \frac{Cxz}{2\alpha^2\beta\rho^2}\left[(a^2+r^2)E(k^2) - \alpha^2 K(k^2)\right]$$

$$B_y = \frac{Cyz}{2\alpha^2\beta\rho^2}\left[(a^2+r^2)E(k^2) - \alpha^2 K(k^2)\right]$$

$$B_z = \frac{C}{2\alpha^2\beta}\left[(a^2-r^2)E(k^2) + \alpha^2 K(k^2)\right]$$

CIRCULAR CURRENT LOOPS

Exact magnetic field solutions outside conductor

(Simpson et al. 2001)

magnetic moment $\mu = IA$

Remove particles that hit loops $r_{cs} < R^2 + a^2 - 2a(R^2 - z^2)^{1/2}$

Energy loss $P = \frac{dE_n}{dt} = \frac{\mu_0 q^2 \gamma^6 u_0^2}{6\pi c}\left[c^4 a'^2 + |\vec{n} \times c^2 \vec{a}'|^2\right]$

High Temperature Superconductors

YBCO

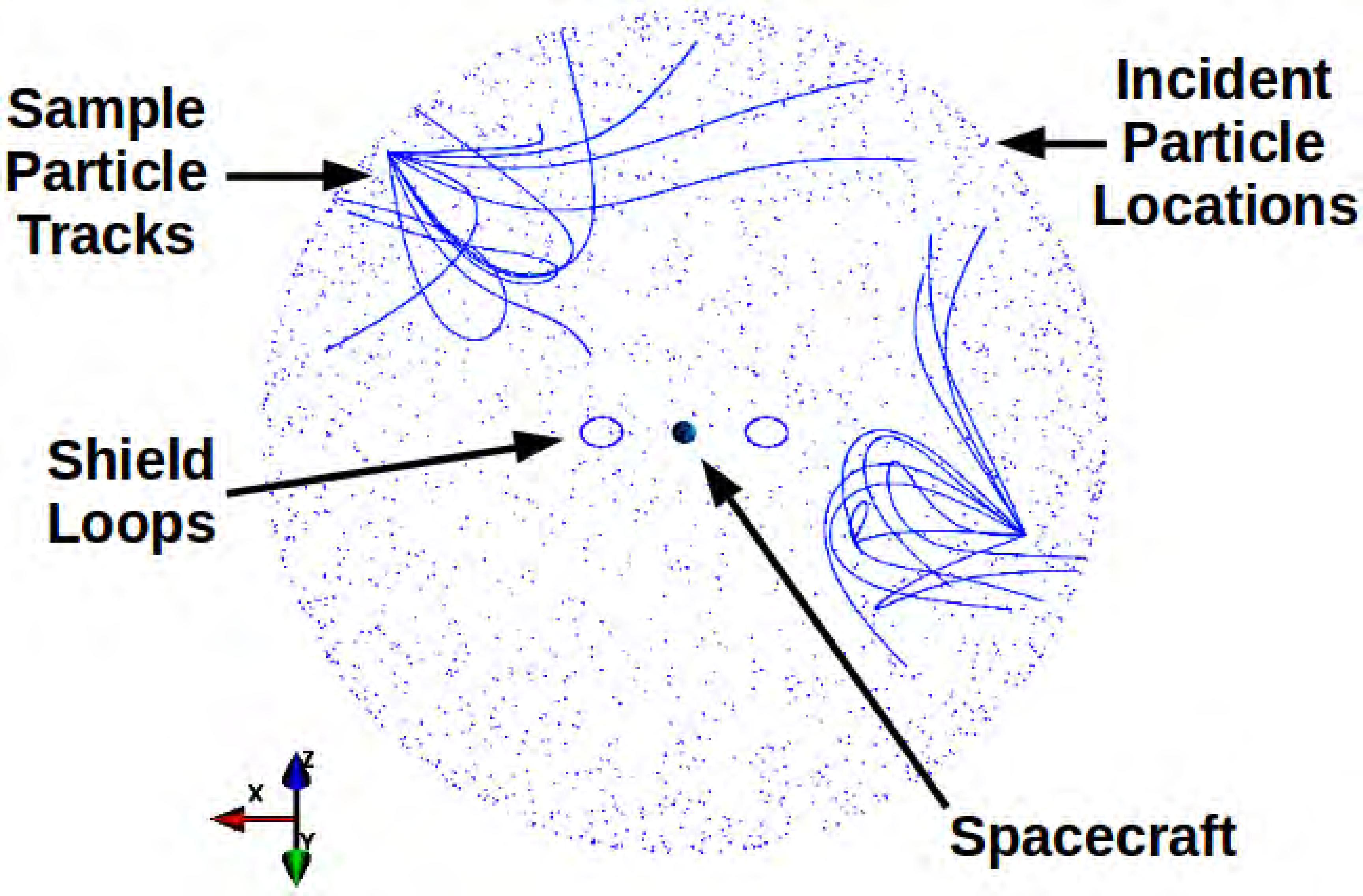
I = 300 A
J_e = 50 kA/cm^2
T_c = 90 K
T_o = 40-50 K

Loop dimensions

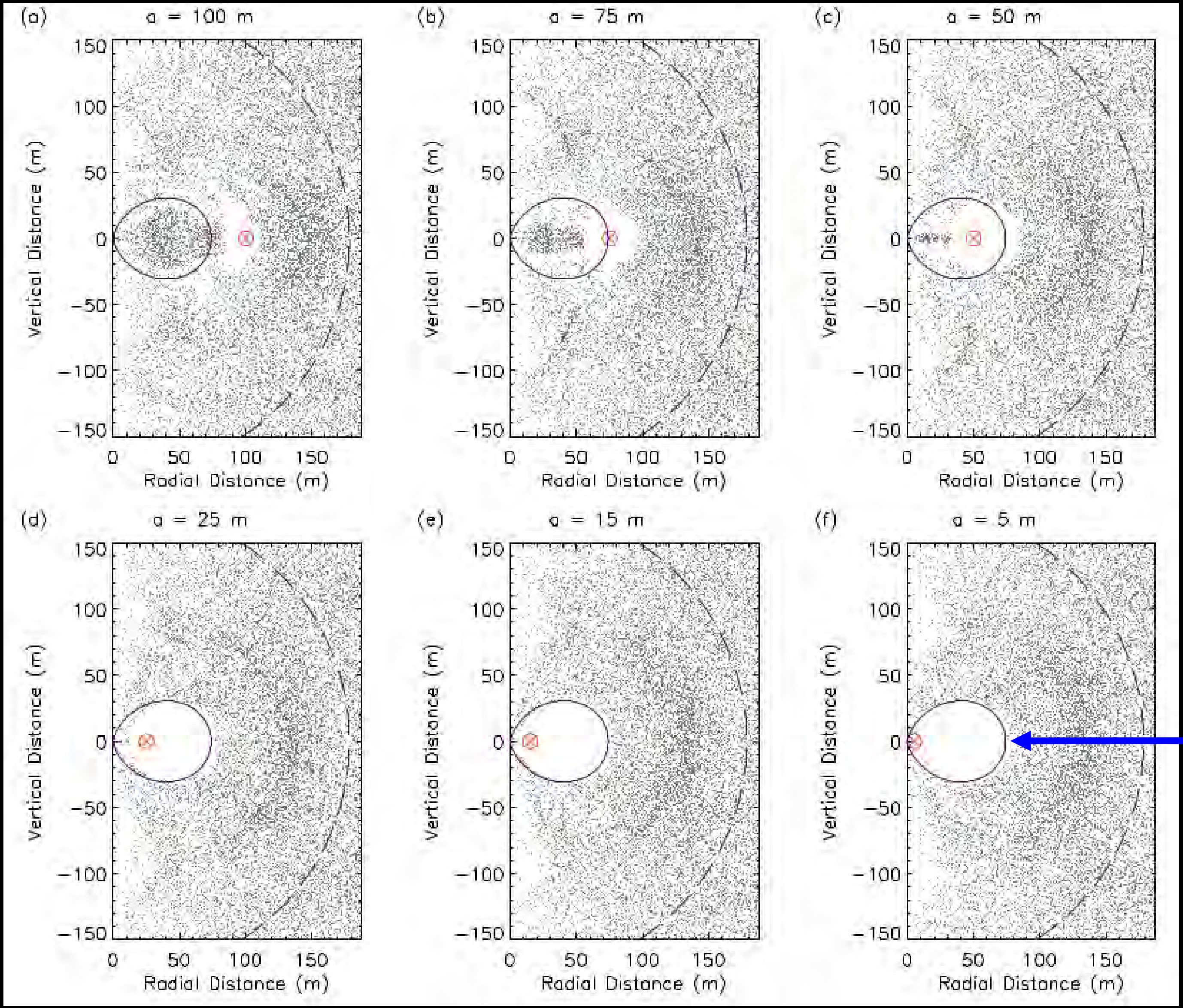
$$r_{cs} = \sqrt{\frac{\mu}{\pi^2 a^2 J_e}}$$

$$m = \frac{2\mu\rho}{aJ_e}$$

Configuration



Dispersed Shield – Large Loops



Shepherd & Kress (2007)

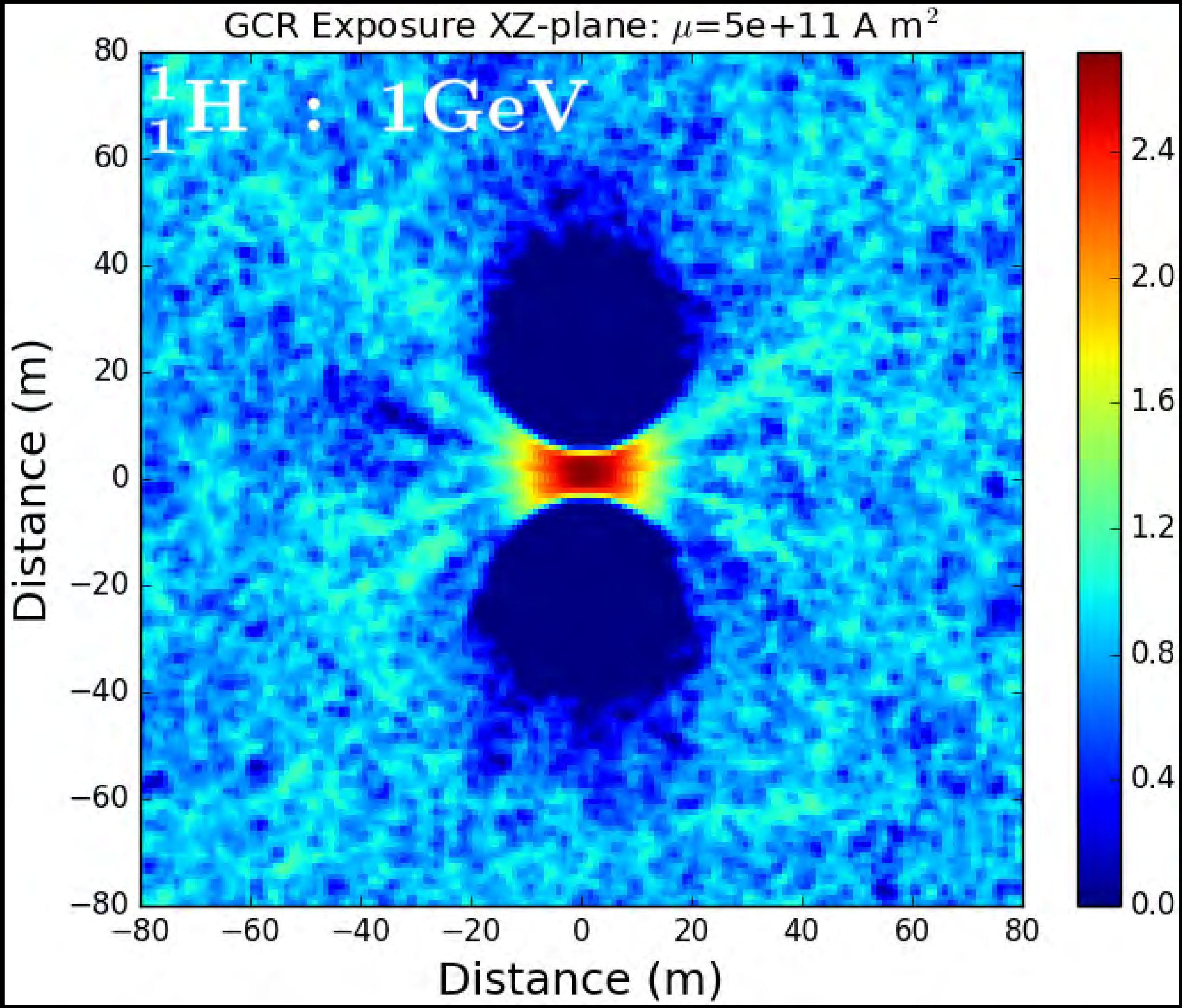
$\mu = 1.1\text{x}10^{13}$ A m^2

"Forbidden Zone"

Single Loop Simulations

1 GeV protons

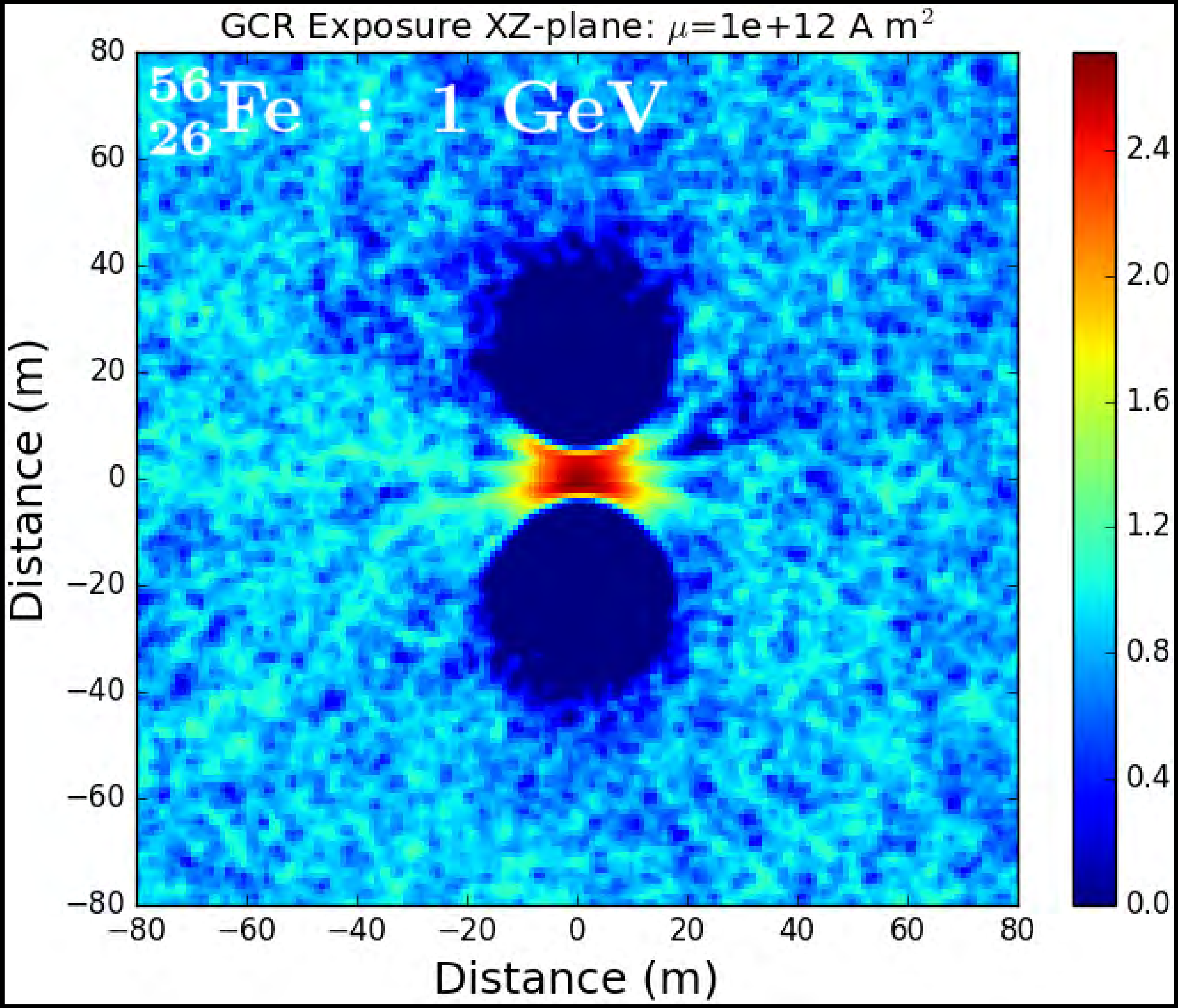
***a* = 10 m**



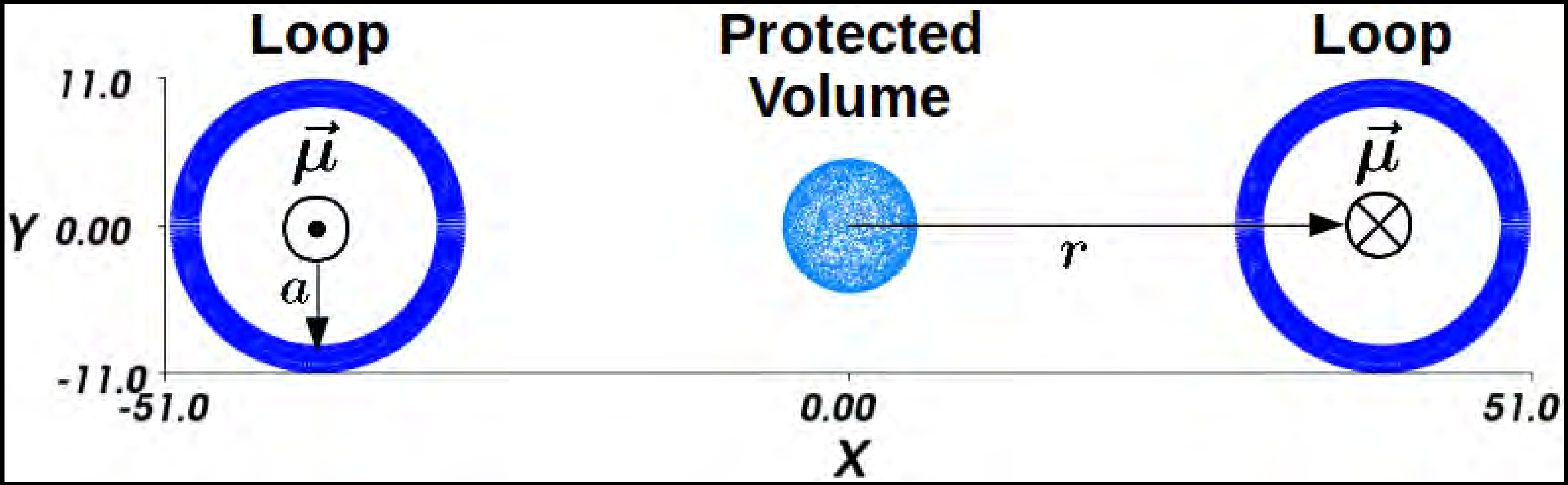
Single Loop Simulations

1 GeV
iron nuclei

***a* = 10 m**

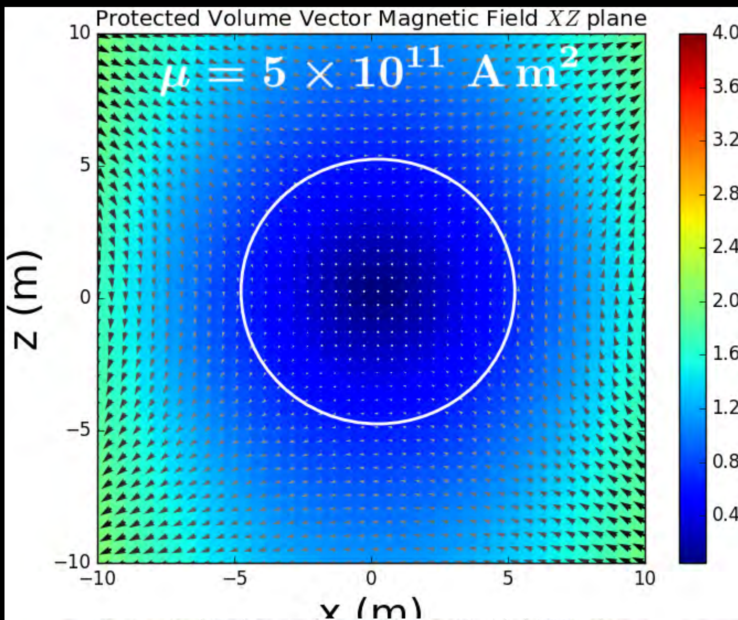


First Approximation

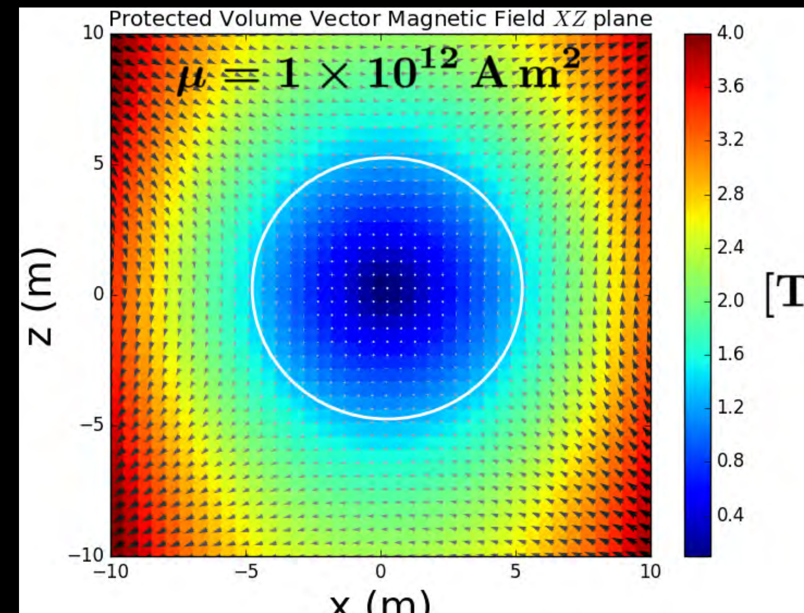


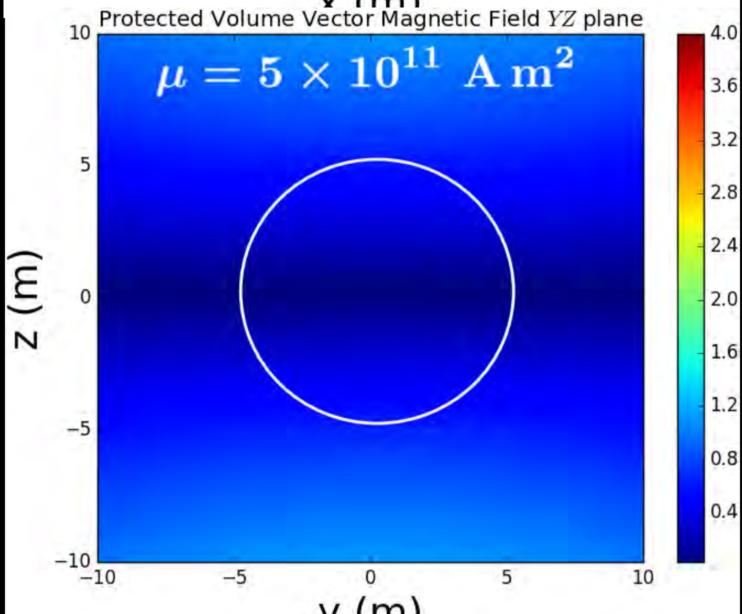
Two-loop magnetic “null”

Magnetic Field Environment

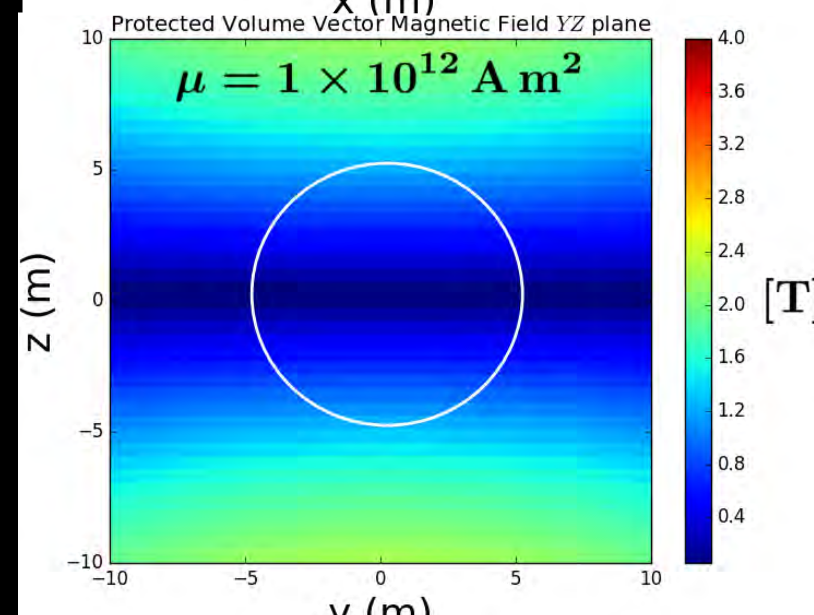


Deflect protons

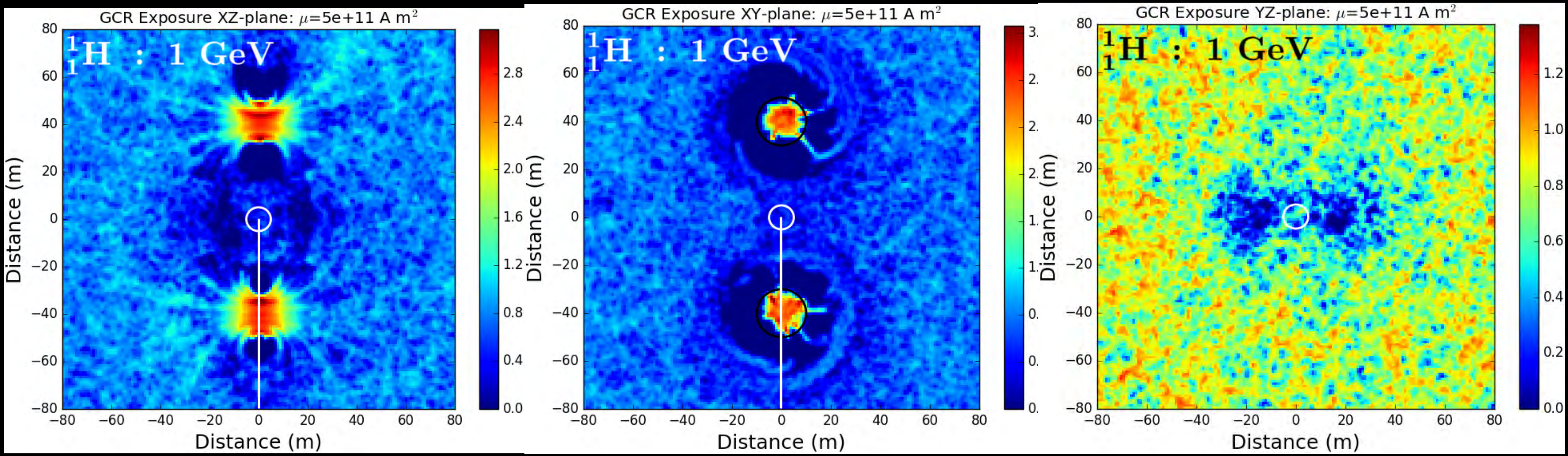




Deflect iron nuclei

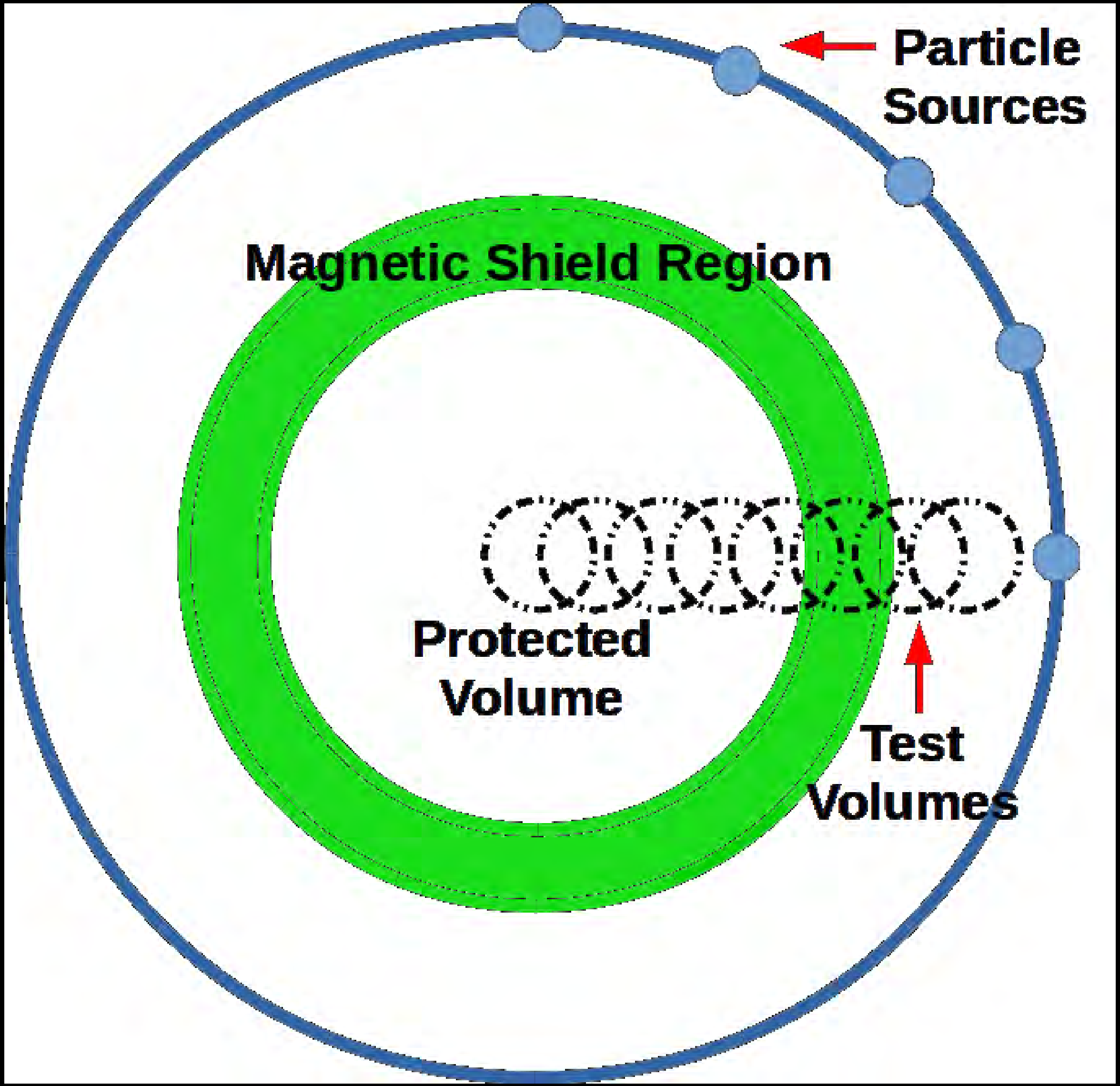


Simulations



Good news!

Diagnostics

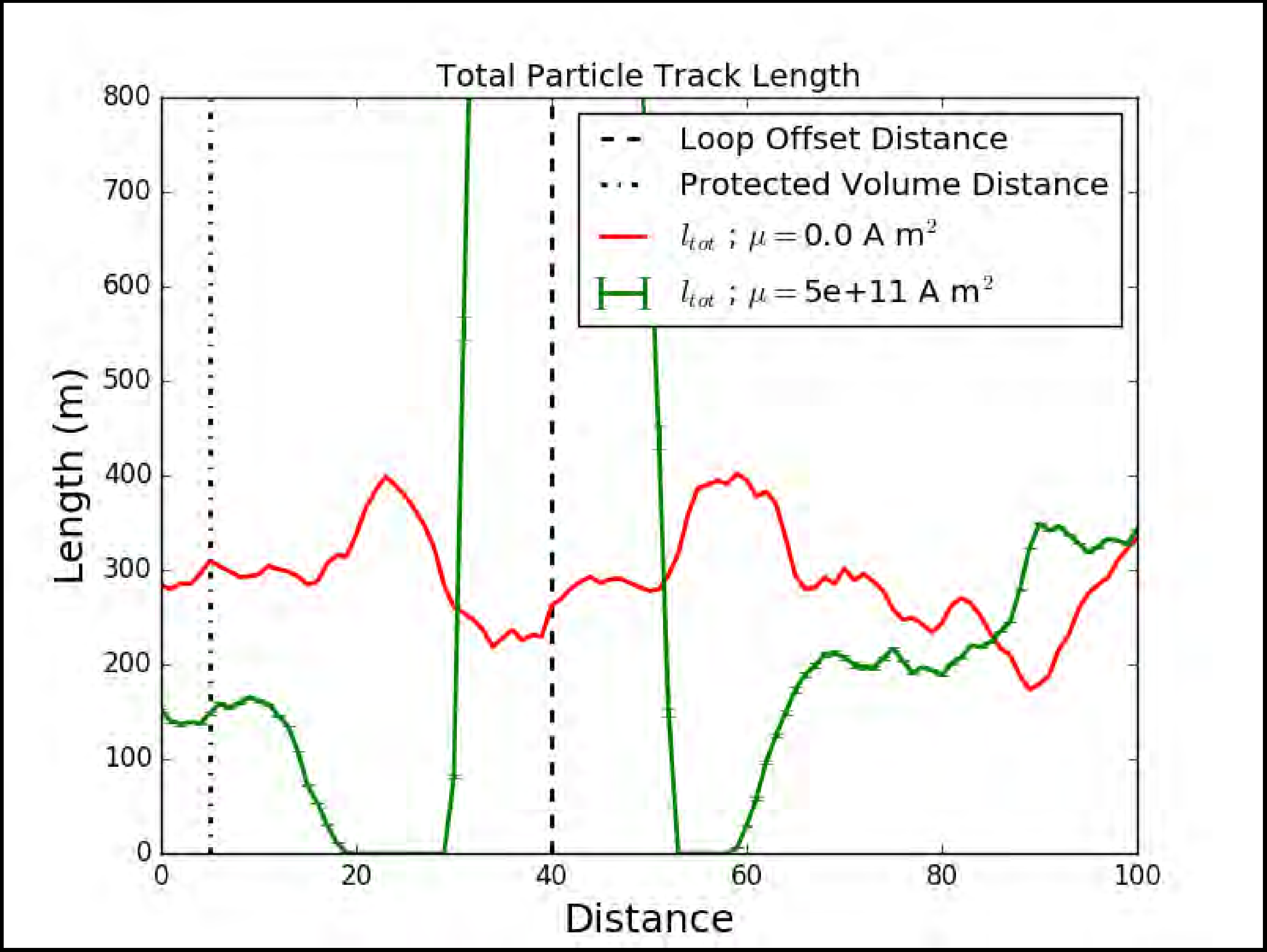


Track

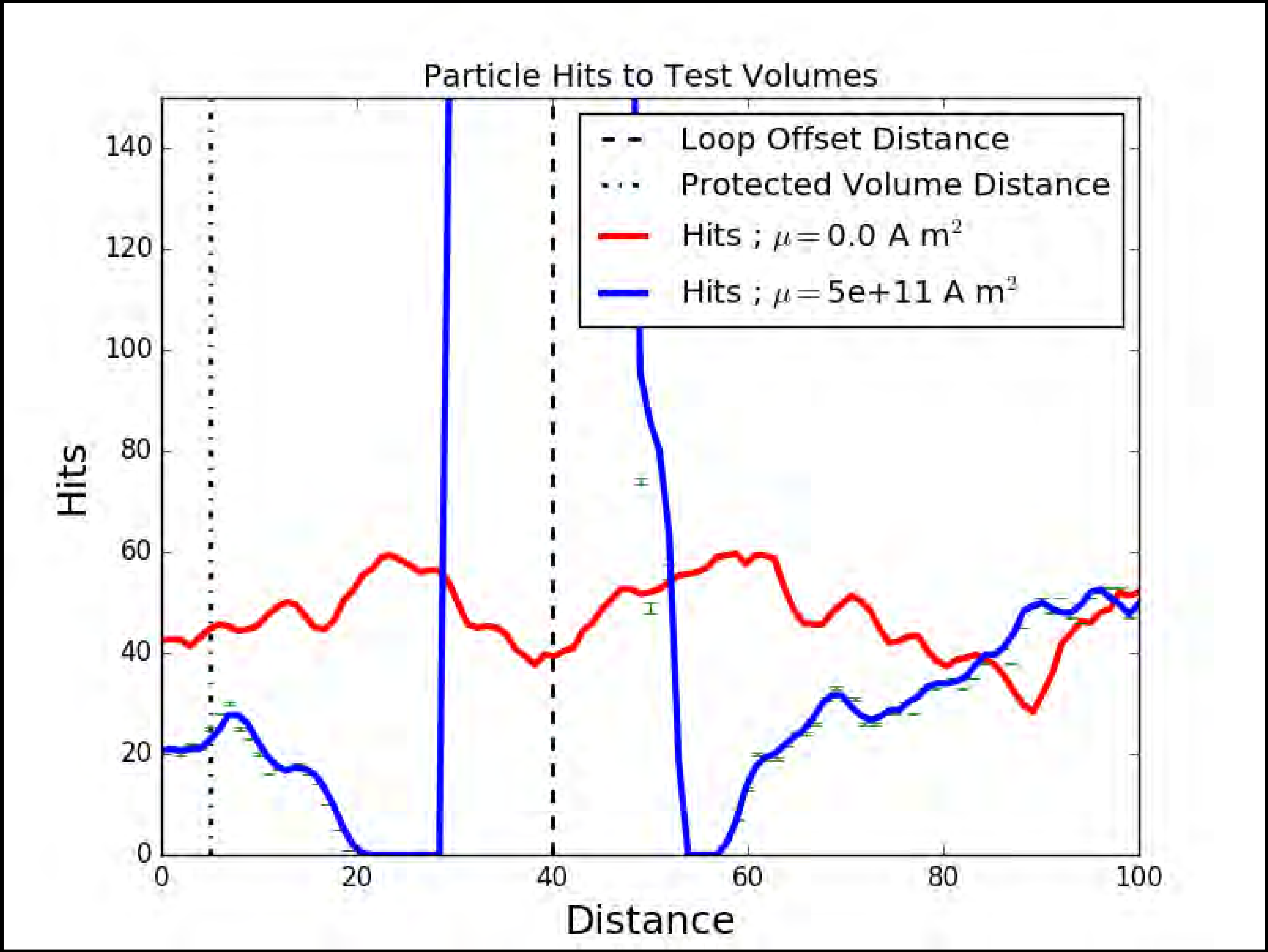
- Number of entering particles

- Total track length

Diagnostics



Diagnostics



Diagnostics

Protected Volume

Ion	μ (A m^2)	n_{avg}	% Reduction	$l_{tot-avg}$ (m)	% Reduction
$^{1}_{1}$H	0	44 ± 0	–	290 ± 0	–
$^{1}_{1}$H	5×10^{11}	22 ± 0	$50 \pm 0\%$	142 ± 1	$51 \pm 1\%$
$^{56}_{26}$Fe	0	55 ± 0	–	349 ± 0	–
$^{56}_{26}$Fe	1×10^{12}	15 ± 0	$73 \pm 0\%$	100 ± 1	$71 \pm 1\%$

Great news!

Superconducting Loop Properties

Simulation Loops

μ (A m^2)	a (m)	r_{cs} (m)	Mass (kg)	I (A)	B_{max} (T)
5×10^{11}	10	1.02	1.84×10^6	1.59×10^9	323
1×10^{12}	10	1.44	3.67×10^6	3.18×10^9	559

Bad news :(

NASA SLS Block 2 Payload = 130,000 kg

Alternative Loop Properties

μ (A m^2)	w (μm)	J_e (A m^{-2})	r_{cs} (m)	Mass (kg)	I (A)	B_{max} (T)
5×10^{11}	3.50	7.14×10^9	0.27	1.26×10^5	1.59×10^9	1068
1×10^{12}	1.75	14.29×10^9	0.27	1.26×10^5	3.18×10^9	2136

Optimization

1. "Decentralize" magnetic energy

- *more* dispersed = more loops

2. Reduce overall loop *I*, *B*, mass

3. Maximize the use of "forbidden zones"

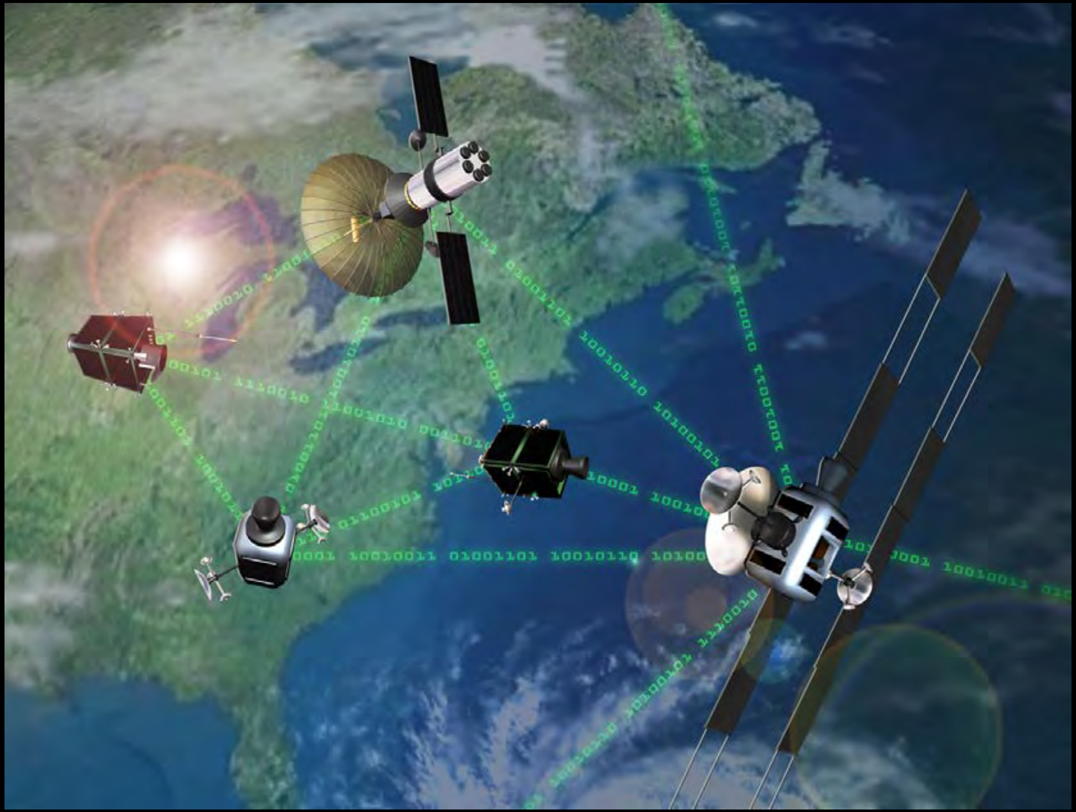
Further use of superconductors?

Superconductors in Space

- Superconducting magnetic energy storage (SMES)

- Docking and stability (magnetic levitation)

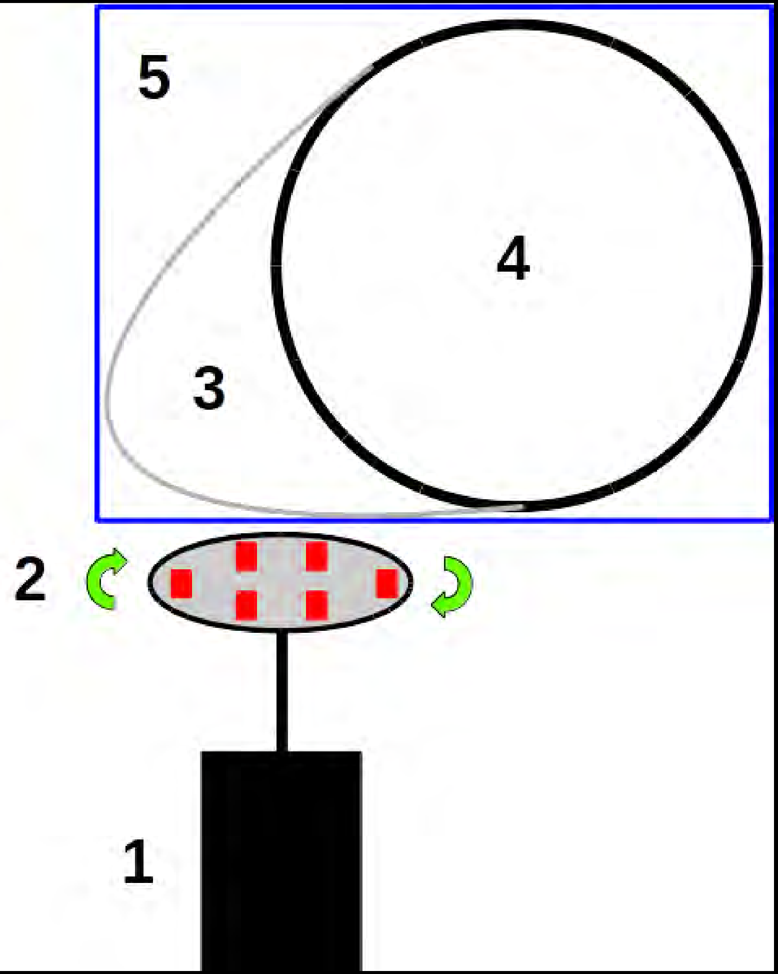
- Motors and MRIs



Charging Superconductors

Flux pumps

1. DC Motor
2. Rotor with Permanent Magnets (Red)
3. HTS Stator Loop With Soldered Joints
4. HTS Main Loop
5. Thermally Isolated Assembly



Conclusions

- Radiation mitigation is required for long duration exploration of space by humans

- Dispersed magnetic shield concept *works*, but needs *optimization*

- Synergistic combination of material shielding, magnetic shielding, and efficient propulsion

Thank You

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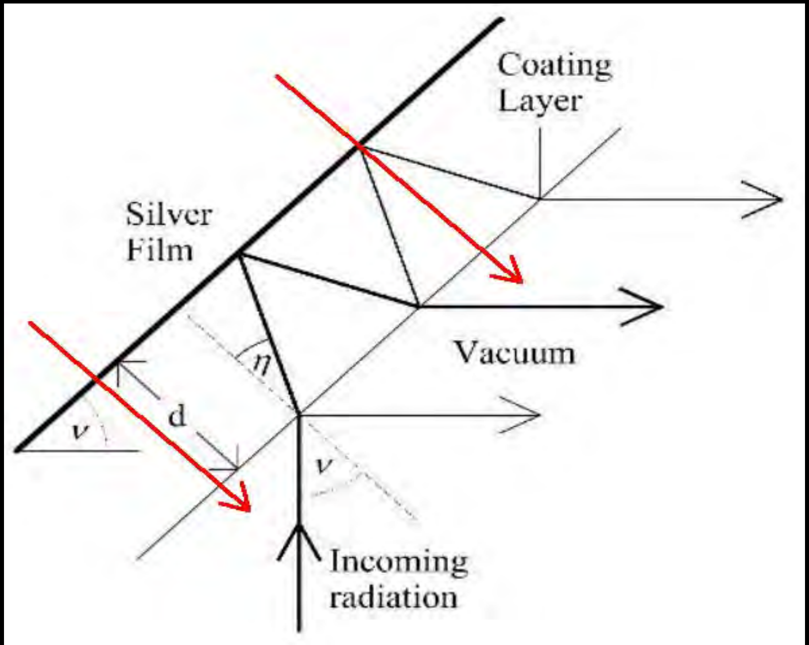
Thermodynamics



Youngquist & Nurge (2016)

$$J = \sigma A(T^4 - T_0^4)$$

<u>Cryogenic Select Surfaces</u>

$$\Delta E = C\Delta T + \sigma A(T^4 - T_0^4)\Delta t$$

Reflects 99.9% solar irradiance

Attenuation coefficient $\alpha = \frac{J}{J_0}$

Transmits long infrared radiation from interior

$$J = \frac{\Delta E}{\Delta t}$$

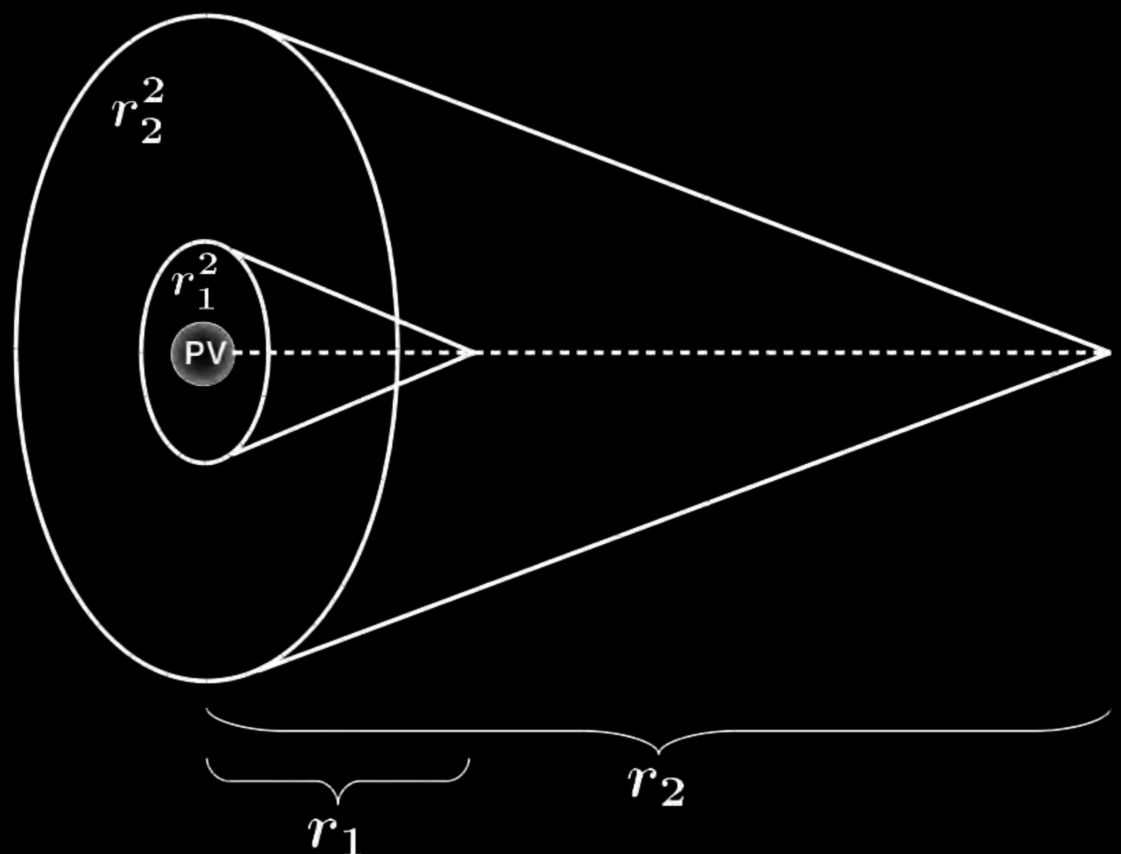
<u>**Limits of passive cooling**</u>

Result: Cryogenic temperatures below 50K

Secondary Particle Threat

$$\Omega_{PV} = \oint F_{\Omega} d\phi$$

$$\Omega_{PV} = \frac{A_{PV}}{r_{off}^2} \oint d\phi$$



Other Solution?

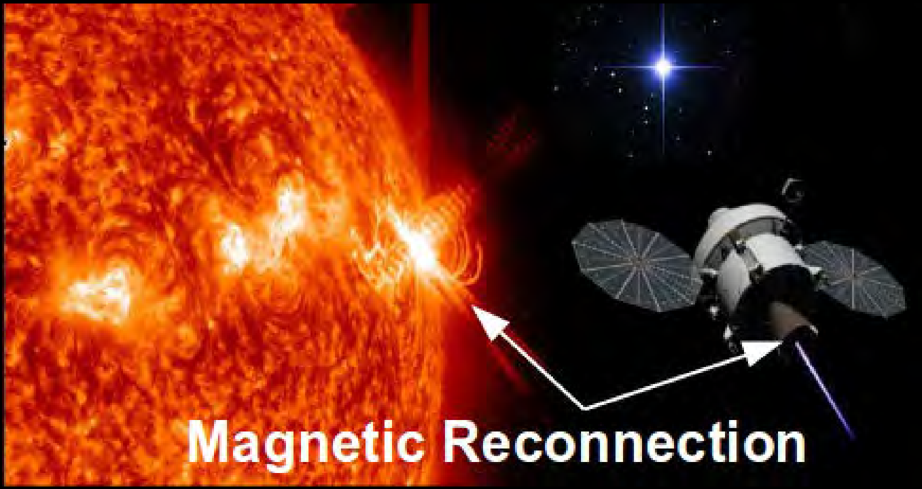
In the absence of a radiation shield – reduce exposure *time*

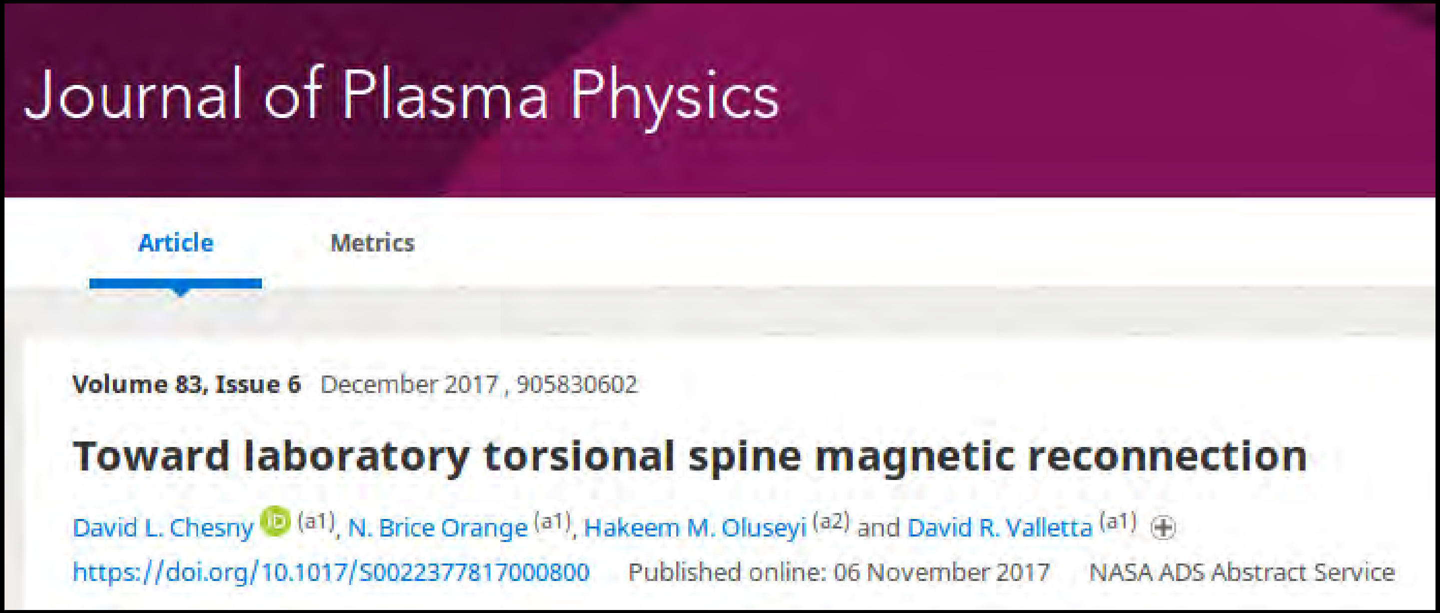
Increase thrust!

$$T = \dot{m} v_{ex}$$

What is the most efficient particle acceleration process in the solar system?

Magnetic Reconnection

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Toward laboratory torsional spine magnetic reconnection

David L. Chesny [a1], N. Brice Orange [a1], Hakeem M. Oluseyi [a2] and David R. Valletta [a1]

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