# FLUKA: Status & Capabilities

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# FLUKA

- Is A Fully Integrated Transport Code…
  - (Attempts To do All Relevant Physics Internally)
  - Accuracy v. Data ≥ all other existing general codes…
- Inherently Includes Magnetic Field Transport…
- Is Widely Used at Accelerators Around the World for Shielding Calculations and Simulations…
- Is Widely Used for Simulation of Sea-Level Cosmic Rays due to Extensive Air Showers.
- An Evolving, Supported Code…

# Heavy Ions in FLUKA

- Heavy Ion (Nucleus- Nucleus) Interactions are embedded within FLUKA
  - > 5 GeV/A – Done — Using DPMJET 3.0 Event Generator
  - < 5 GeV/A – Evolving (Both Target AND Projectile Matter)
    - *Current Solution – Use Heavily Modified version of rQMD 2.4 (relativistic Quantum Molecular Dynamics) Event Generator*
    - *Development Work in Progress – Improved versions of existing rQMD Models & Developing a New Hamiltonian Molecular Dynamics (HMD) Model*
  - <100 MeV/A (Inelastic)– Evolving… Inserting BME Model
- Be Careful about claims that GEANT4 also has a heavy ion capability… This recent claim is NOT comparable to the capabilities embedded within FLUKA…

# Some Recent NASA-Related FLUKA Results

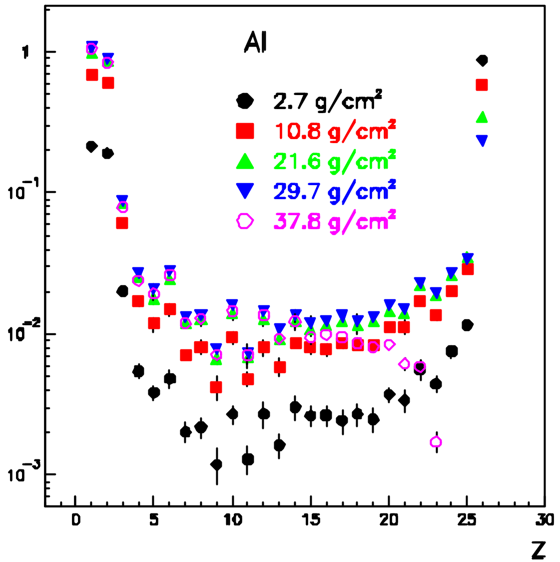
- Simulations of the NSRL "1" GeV/A Fe Runs
- Introduction of Voxel Geometries and Human Phantom models…
- Estimates of Space Radiation Biological Doses
- Variable Density Mediums as a mechanism to simulate micro-porous media (Bone & Lung)

# My Goal in This Talk …Is to Convince You That:

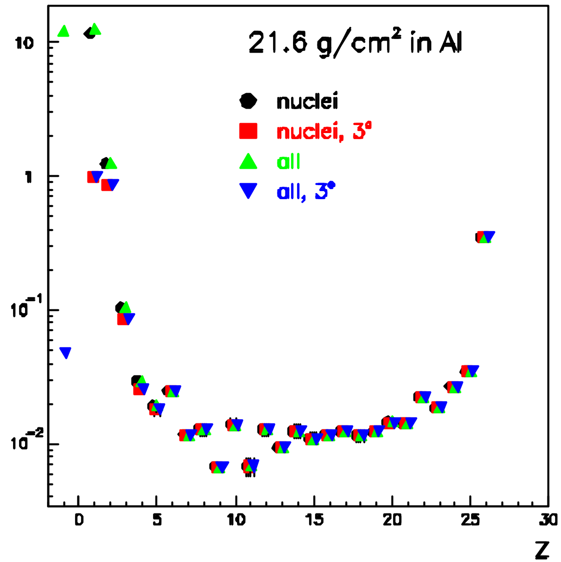
- FLUKA is ready for use
- New Tools are being added all the time to make it easire to use.
- It is an excellent tool for simulating accelerator experiments, and has substantial advantages over other codes and techniques
- We are ready to teach you how to use it!

# Fragment Spectrum from FLUKA for an "Ideal" Beam for 1 GeV/A Fe-Al Simulations

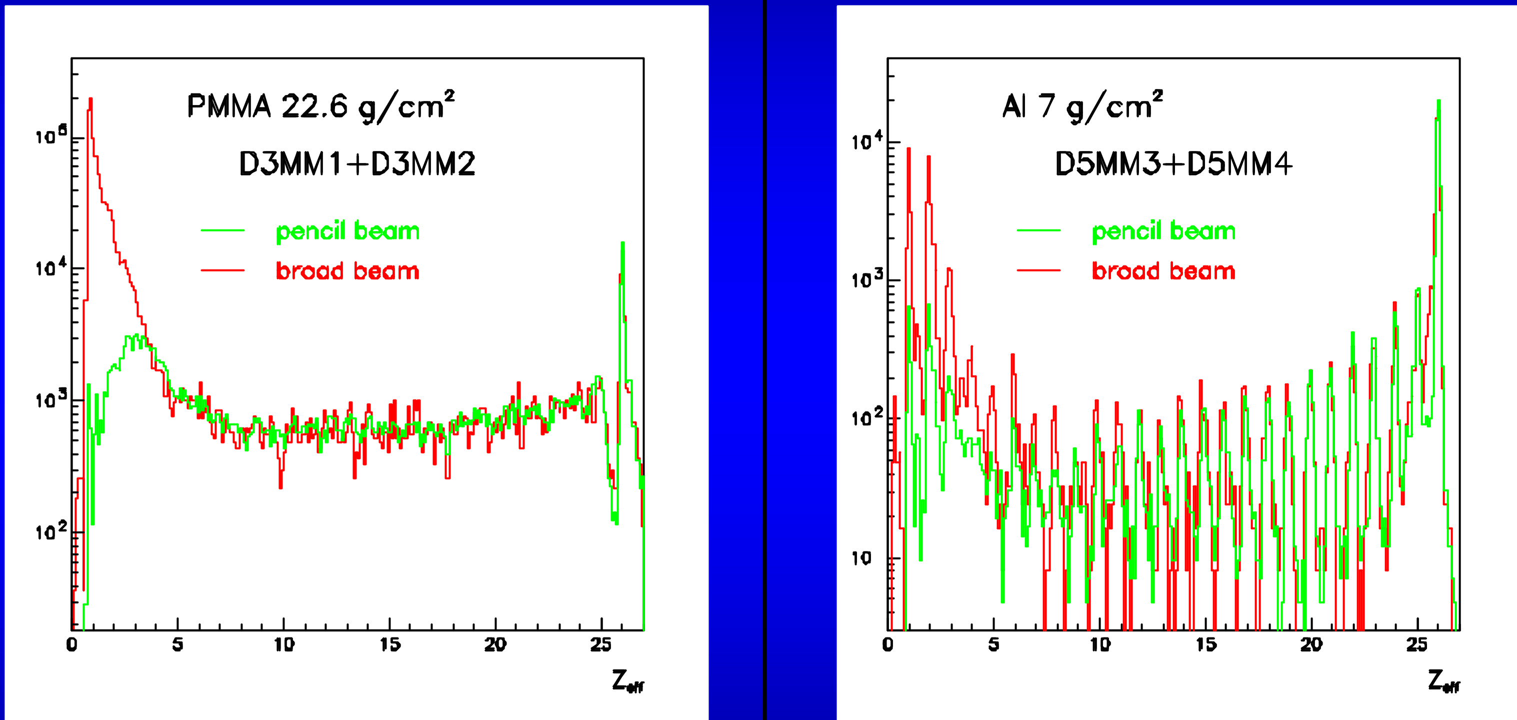
Fragments as a function of Depth




"All" & 3 Degree Detectors

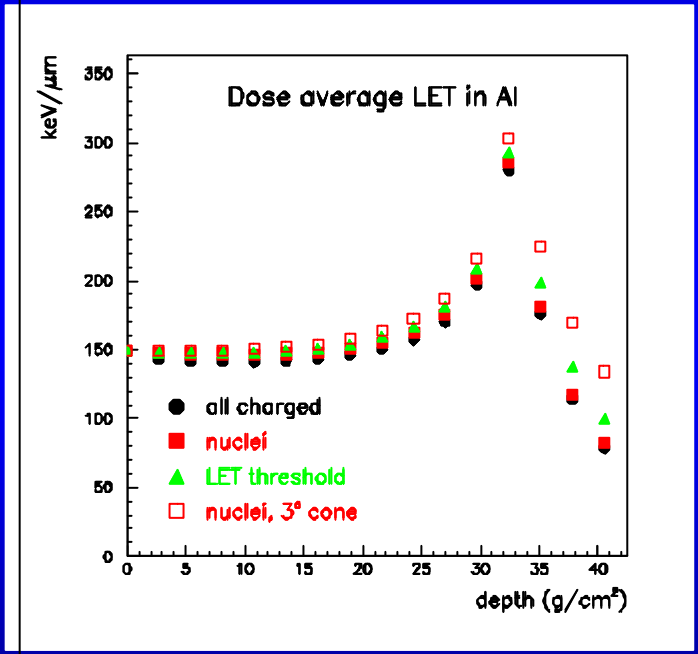


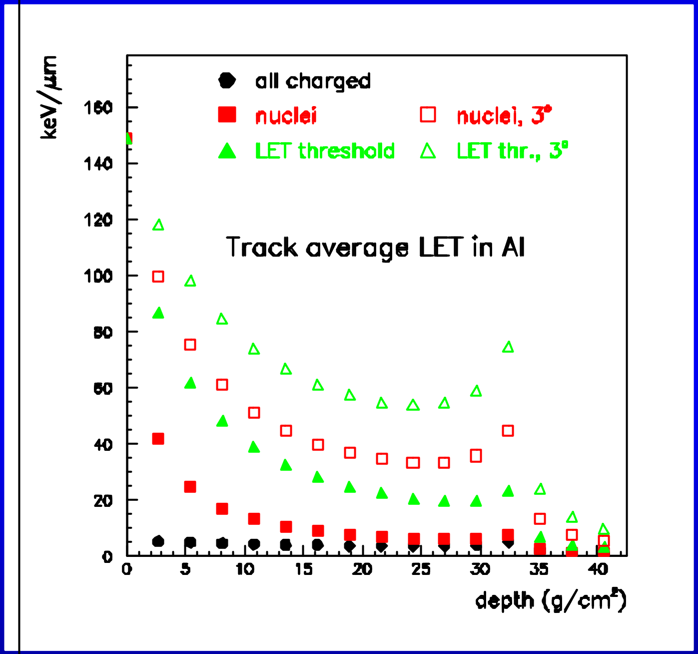
# Beam/Detector Size Effects



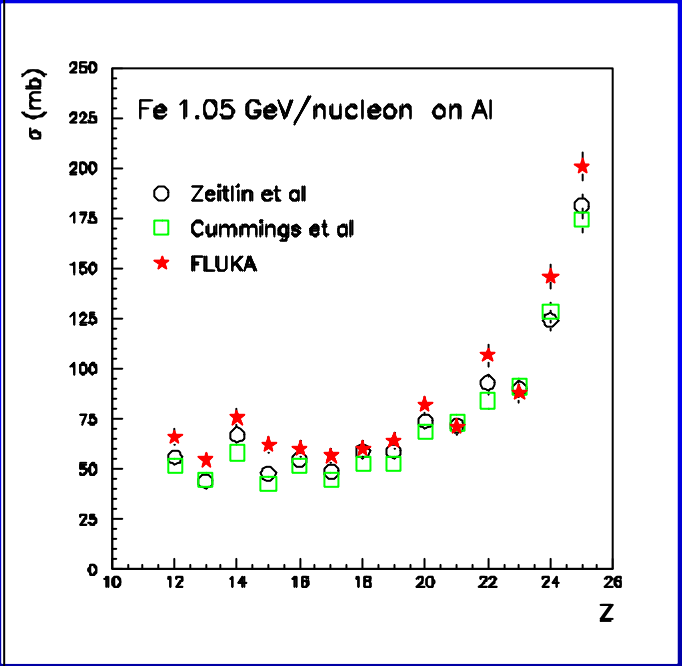

Pencil v. 7 cm Radius Beam on Nominal Zeitlin Setup with Simple Cuts

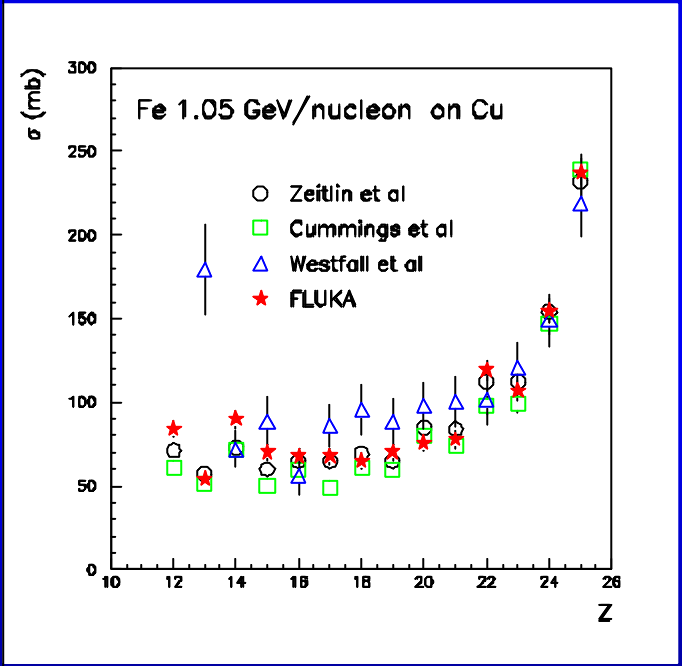
# "Track Average LET" is Problematic [Dependent on Detector Details]



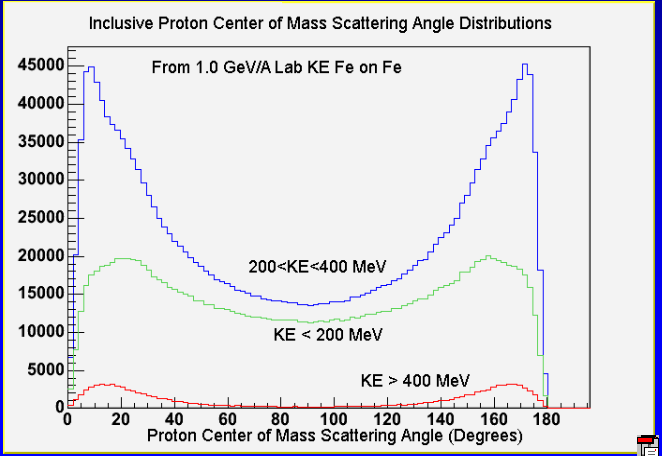
# FLUKA v. Published 1.05 GeV/A Fe

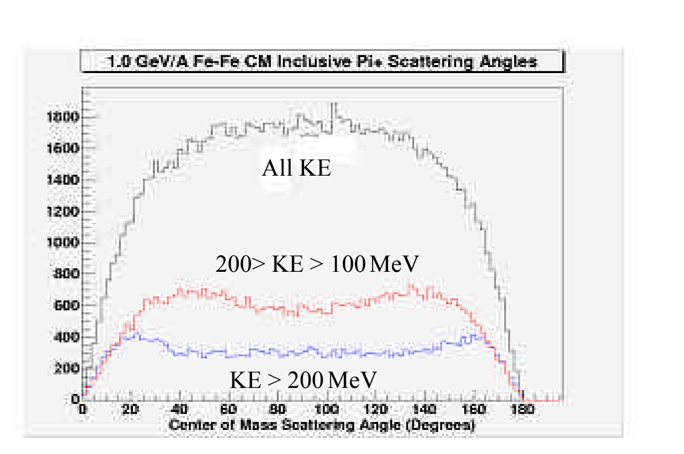


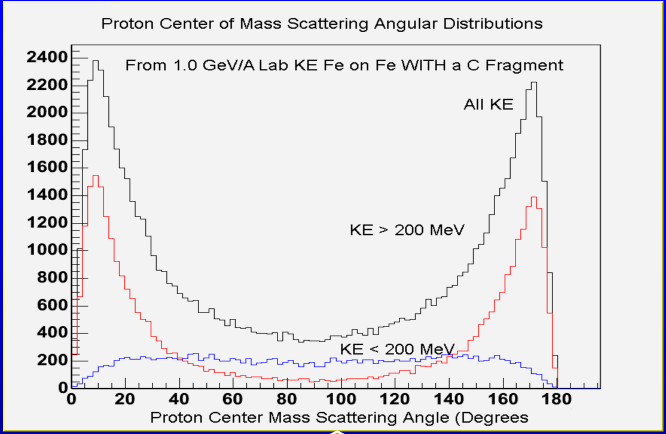
# FLUKA/rQMD 1.0 GeV/A (Lab KE) Fe – Fe
# CM Proton and Pion Angular Distributions

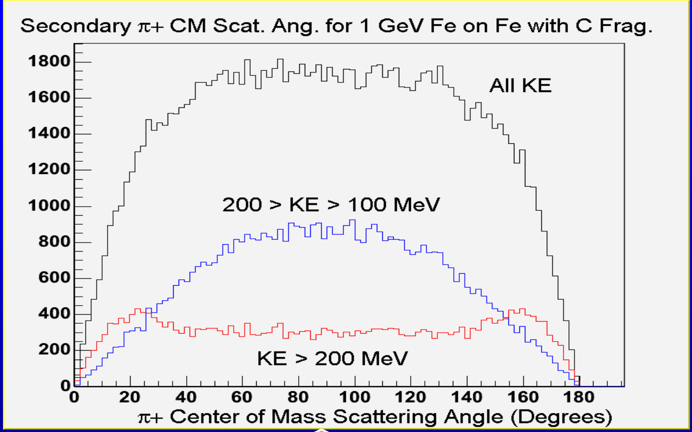
Inclusive




w/Carbon Fragment



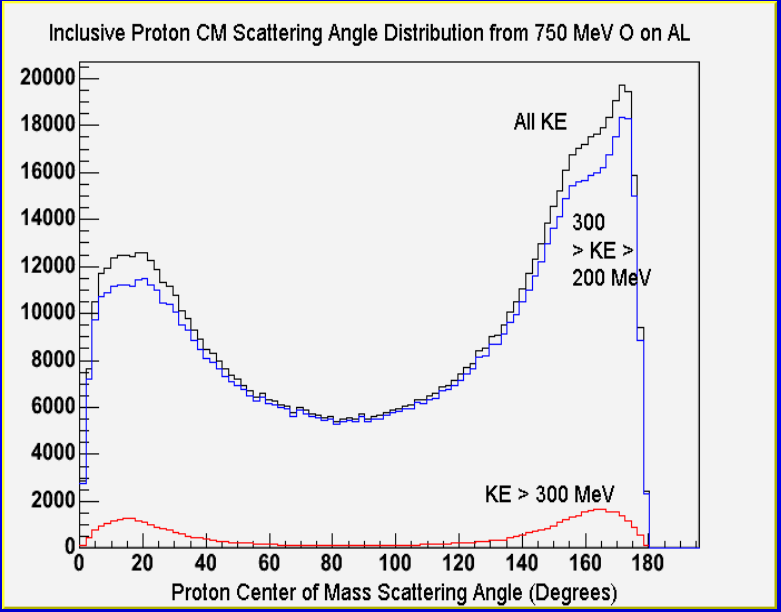




Protons

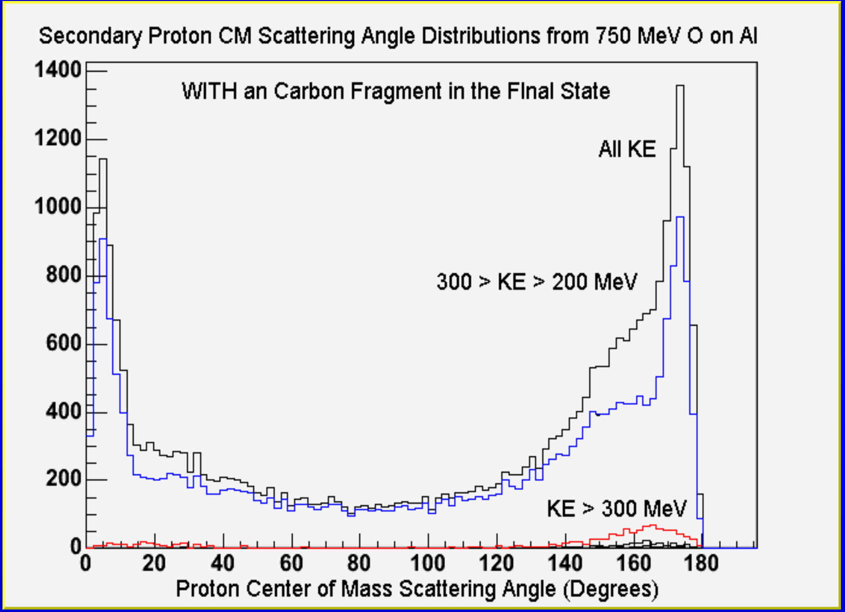
π+

Pions DO matter behind Thick Targets
BUT are REALLY Needed for Physics

# FLUKA/rQMD Event Generator
# 750 MeV/A Oxygen on Aluminum
# Proton CM Scattering Angle Distributions



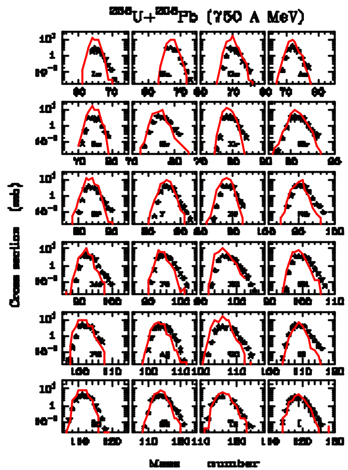

Inclusive Spectra




Only Events with a C Fragment
In the Final State

# FLUKA Fits to GSI Data

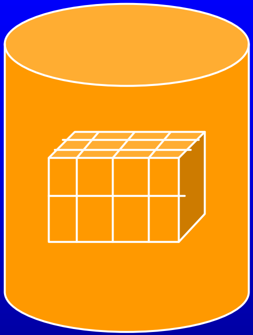
FLUKA: fragmentation results




Fragment charge cross sections for 750 MeV/n U ions on Pb. Data (stars) from J. Benlliure, P. Armbruster et al. Eur. Phys. J A 2, 193-198 (1998)). Fission products have been excluded like in the experimental analysis.

# Voxel Geometries in FLUKA

- FLUKA can embed voxel volumes within its normal combinatorial geometry.
- Embedded voxel volume is currently limited to a Regular Parallelepiped region.
- Transport through the voxels is optimized and efficient…
- Raw CT-Scan outputs can be imported directly!

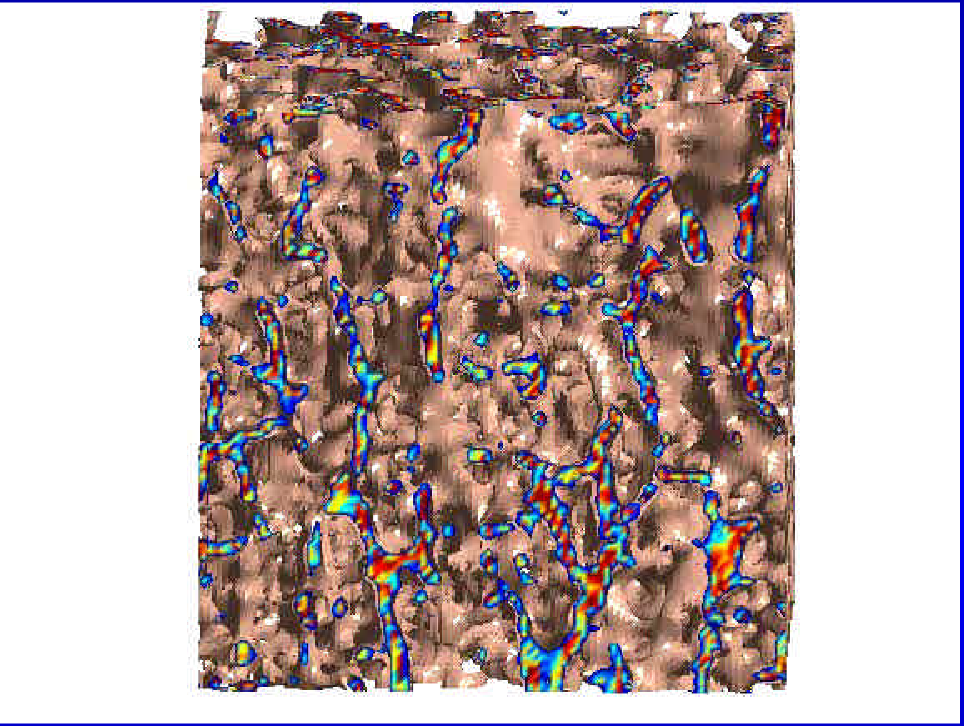


"Golem" Whole-Body CT-Scan-GSF Munich

# CT-Scan Voxels in FLUKA

- CT-Scans only give voxel density values that are proportional to electron density…
- For use in FLUKA (and all Monte Carlo transport codes), each individual voxel must have a material composition assigned…
- In addition, voxels containing porous material (like bone or lung tissue) are problematic due to the variation of effective pathlengths for different traversing tracks.
  - Solution: Introduce VARIBLE DENSITY Materials

# Trabecular Bone



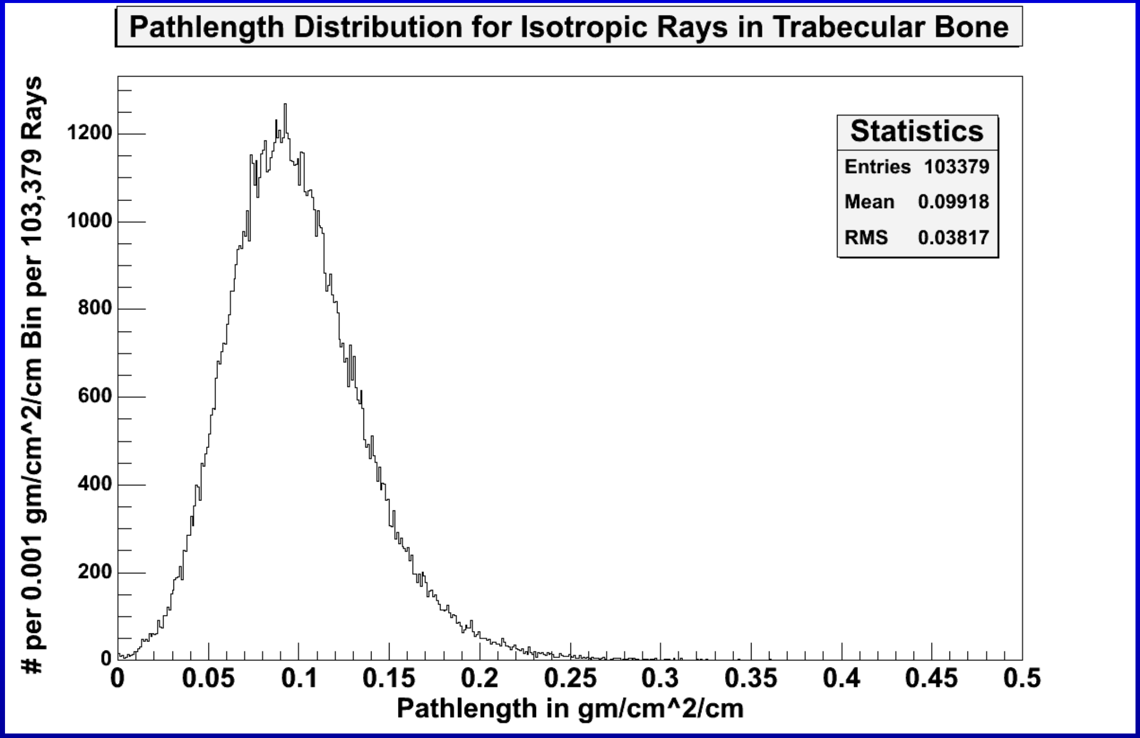
Data from 40 μm Voxel CT-Scans from M. Leibschner

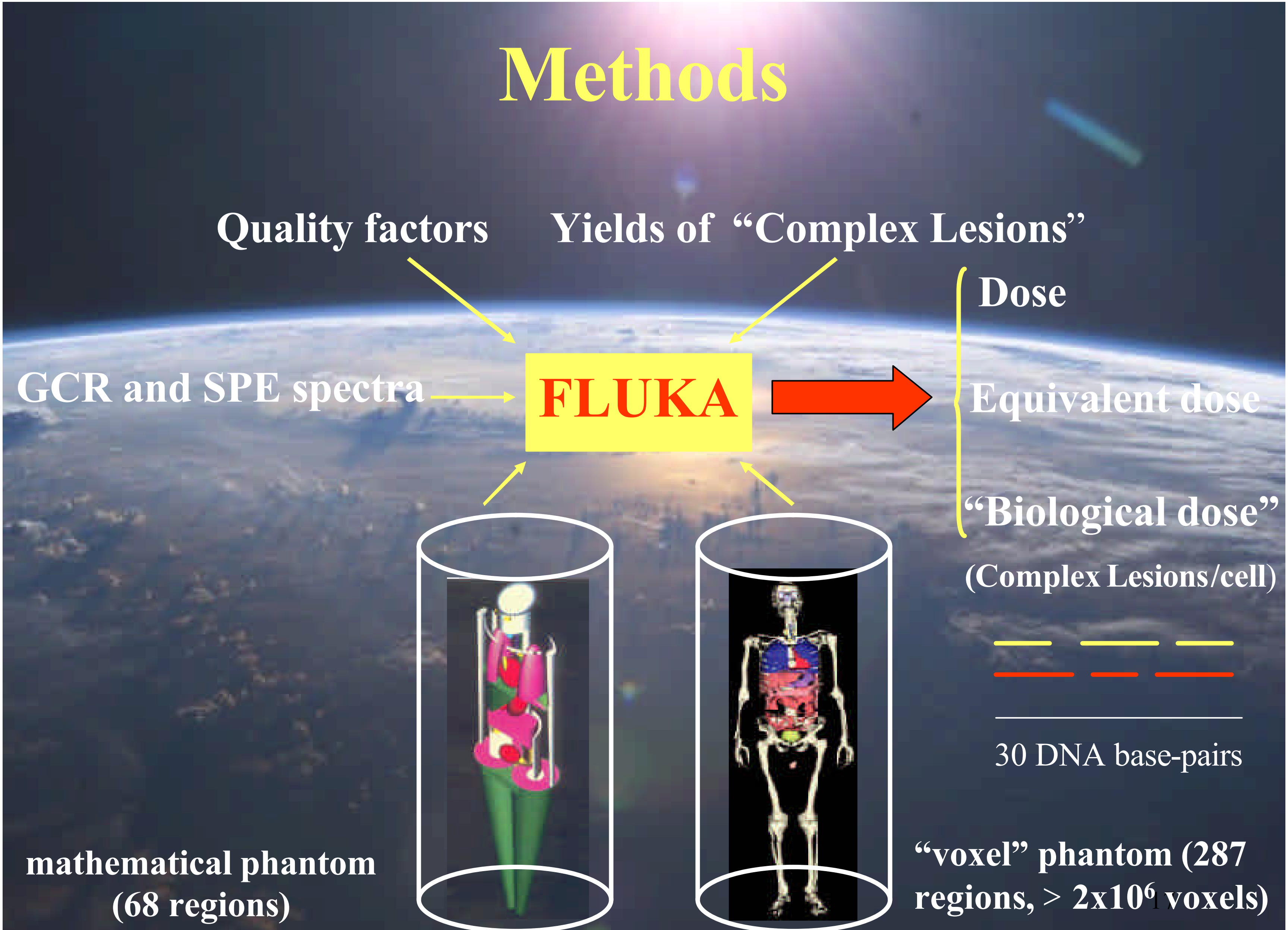
~10% Voxels are Hard Bone (ρ ~ 1.9)
~90% is marrow…

There is an asymmetry along the longitudinal axis of the bone…

Human bone is mostly Trabecular Bone with ~1-2 mm of Hard Bone shell.

# Using FLUKA "Rays" to Determine the Isotropic Pathlength Distributions in Trabecular Bone



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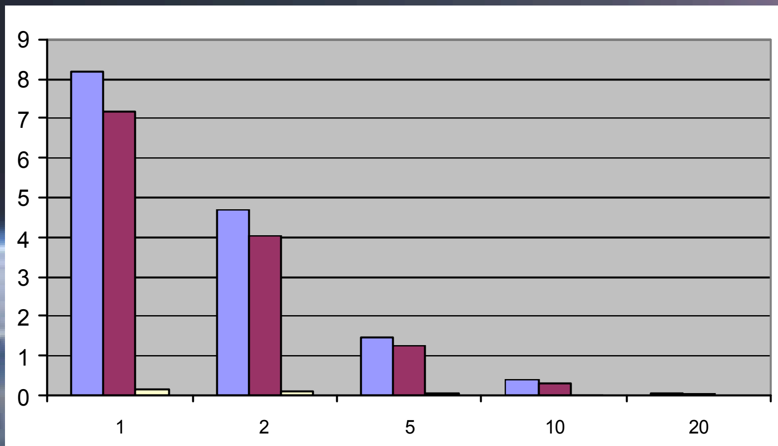
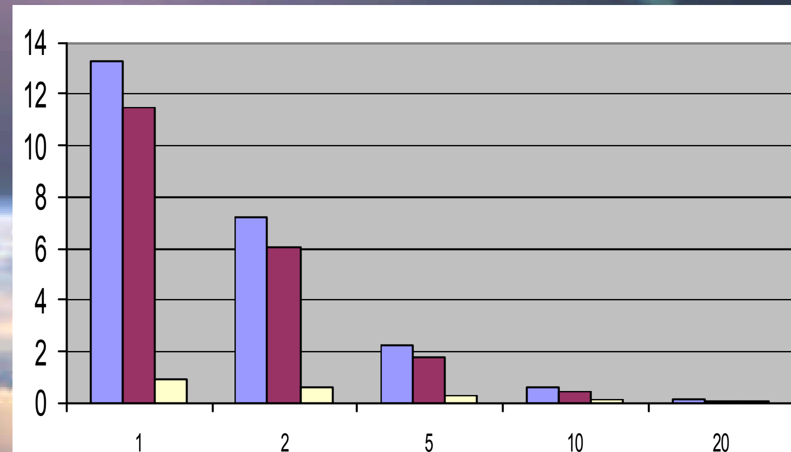
# August 1972 SPE - skin doses

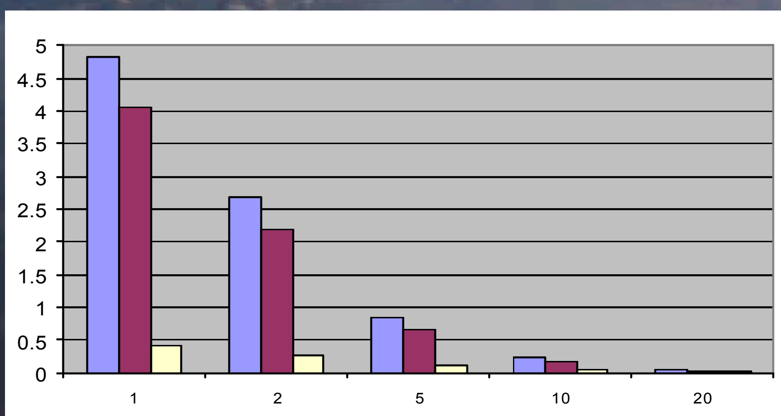
## skin dose (Gy)




## skin equivalent dose (Sv)




## skin "biological" dose (CLs/cell)




- dramatic dose decrease with increasing shielding (from 13.3 to 0.62 Sv in the range 1-10 g/cm$^2$)
- major contribution from primary protons (the role of nuclear reaction products is not negligible only for equivalent and "biological" dose)
- similar trends for equivalent and "biological" dose



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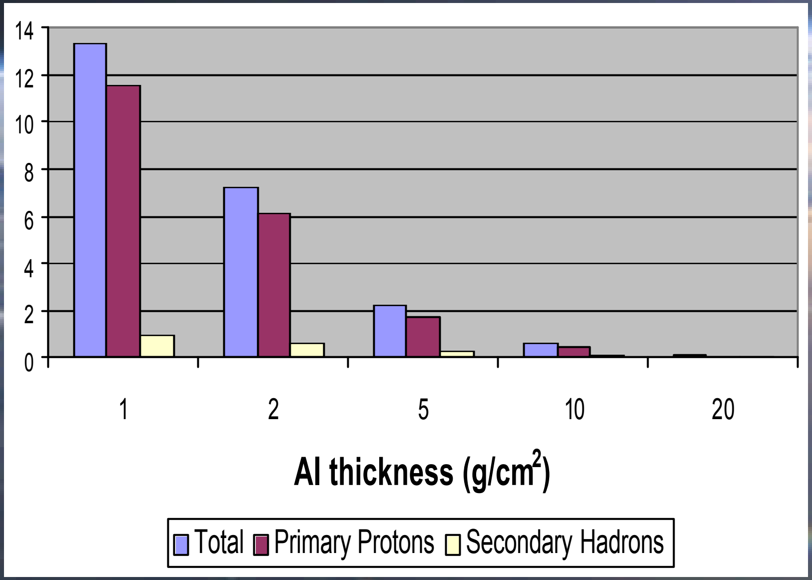
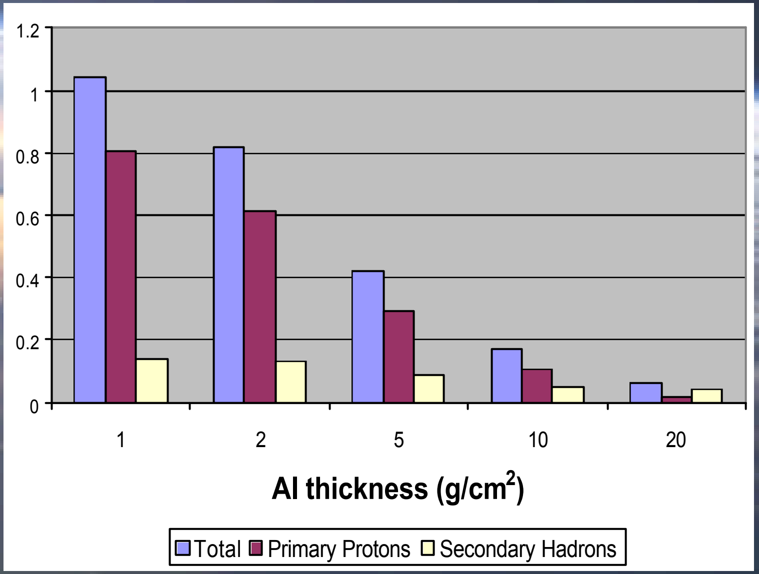
# August 1972 SPE - skin vs. internal organs

## Equivalent dose to skin (Sv)




## Equivalent dose to liver (Sv)




- much lower doses to liver than to skin (e.g. 1.0 vs. 13.3 Sv behind 1 g/cm$^2$ Al )
- larger relative contribution of nuclear reaction products for liver than for skin (e.g. 14% vs. 7% behind 1 g/cm$^2$ Al)



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# August 1972 SPE - comparison to NCRP limits

| Al shield ($g/cm^2$) | Skin | | Lens | | BFO | |
|---|---|---|---|---|---|---|
| | *Erma* | *Golem* | *Erma* | *Golem* | *Erma* | *Golem* |
| 1 | 13.31 | 11.63 | 6.89 | 8.01 | 1.80 | 2.76 |
| 2 | 7.25 | 6.57 | 4.90 | 5.81 | 1.32 | 1.95 |
| 5 | 2.23 | 2.11 | 1.60 | 1.79 | 0.62 | 0.88 |
| *10* | *0.62* | *0.60* | *0.56* | *0.42* | *0.25* | 0.33 !!! |

***NCRP limits for 30 days LEO missions: 1.5, 1.0 and 0.25 Gy-Eq for skin, lens and BFO, respectively Þ a 10 $g/cm^2$ Al storm shelter would provide adequate protection***



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# Aug. 1972 and Oct. 1989 SPEs -Effective Dose (Sv)

| Al shield | August 1972 *(Erma)* | | | October 1989 *(Erma)* | | |
|---|---|---|---|---|---|---|
| *(g/cm²)* | E | E* | $E^*_{NASA}$ | E | E* | $E^*_{NASA}$ |
| 1 | 2.04 | 1.35 | 1.31 | 1.11 | 0.78 | 0.78 |
| 2 | 1.43 | 0.95 | 0.94 | 0.79 | 0.55 | 0.58 |
| 5 | 0.63 | 0.43 | 0.52 | 0.42 | 0.30 | 0.33 |
| 10 | 0.23 | 0.17 | 0.27 | 0.20 | 0.15 | 0.18 |

- large contribution (33-50%) from gonads, especially with small shielding
- E* values (by neglecting gonads) very similar to those calculated with the BRYNTRN code and the CAM phantom *(Hoff et al. 2002, J. Rad. Res. 43)*



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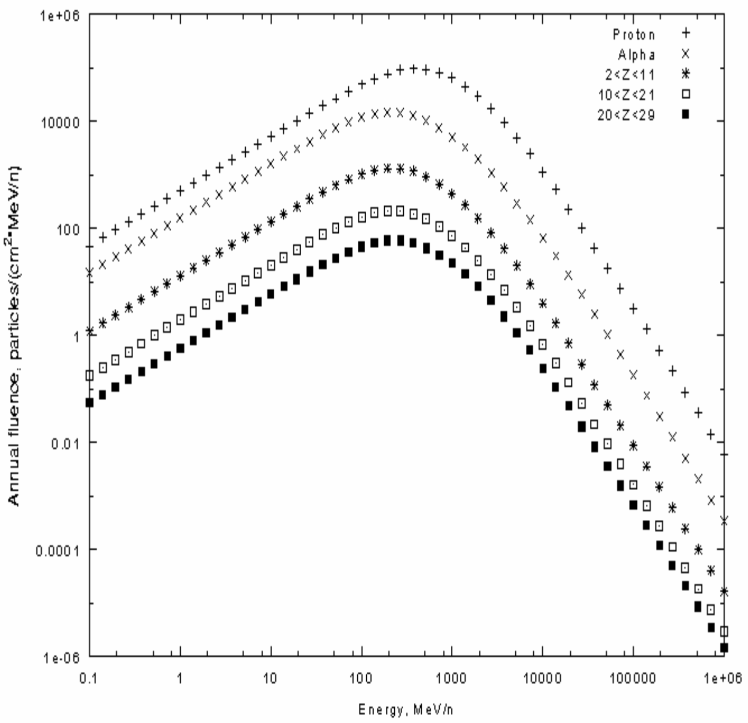
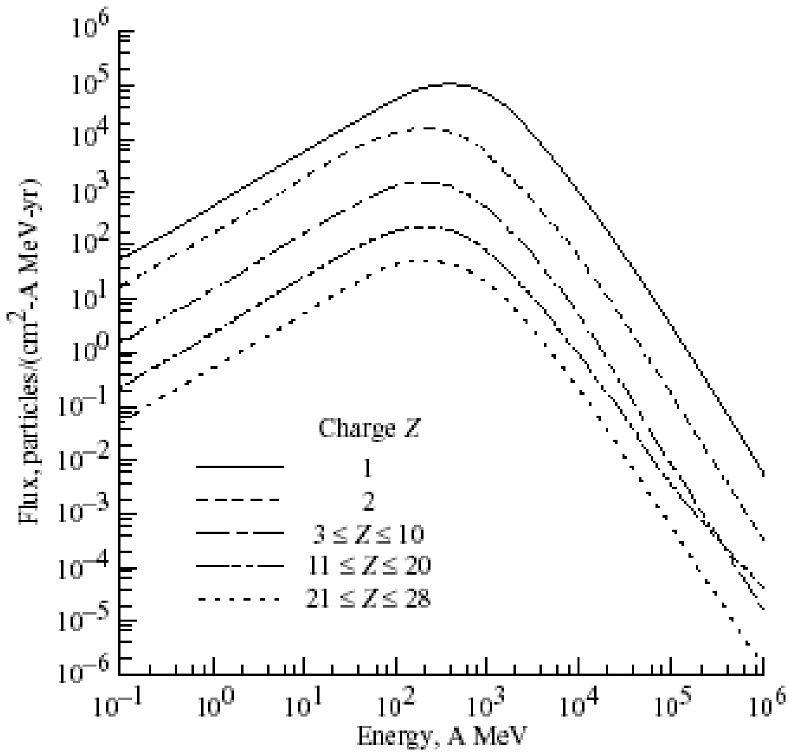
# Galactic Cosmic Rays (solar min)

**This work (F=465 MV)**

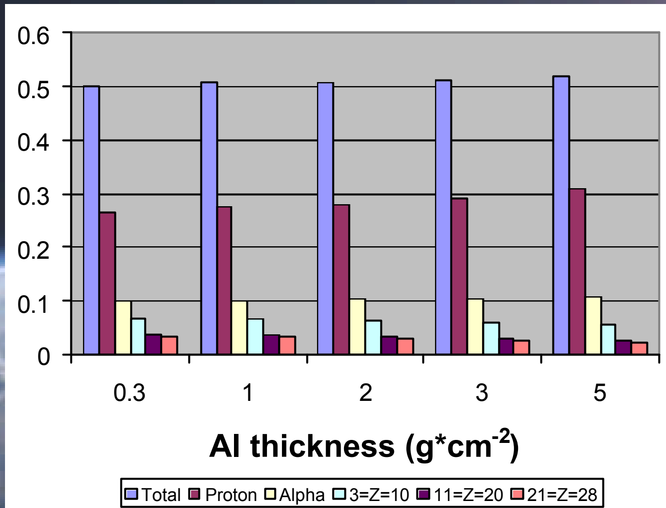



**Wilson et al. 1995** *(NASA TP 3495)*

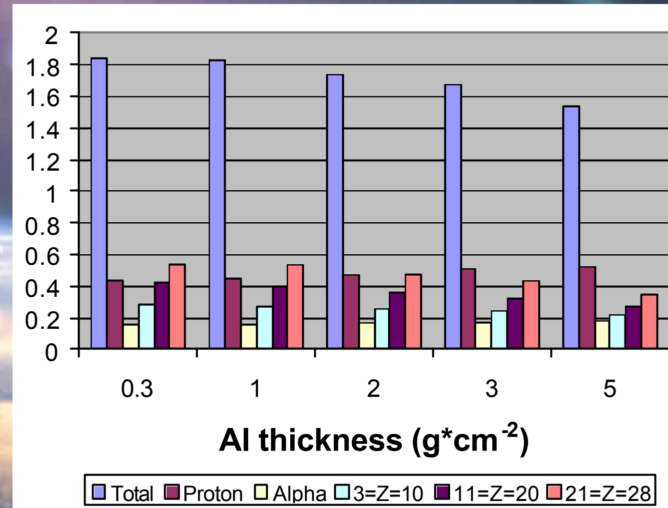


# GCR at solar min. (F=465 MV) - skin doses

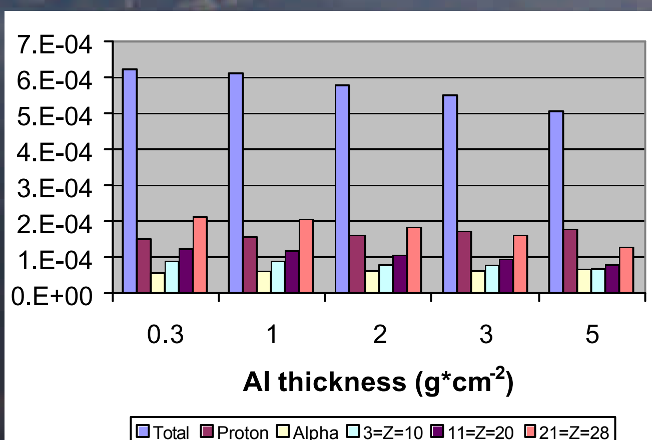
## Skin Dose [mGy/d]




## Skin Equivalent Dose [mSv/d]




## Skin "Biological" Dose [(CL/cell)/d]




- roughly constant skin dose (decrease in heavy-ion contribution balanced by increase in light-ion contribution) with increasing shielding, decrease of skin equivalent and "biological" doses starting from 2 g/cm$^2$
- much larger relative contribution of heavy ions for the skin equivalent and "biological" dose than for the skin dose



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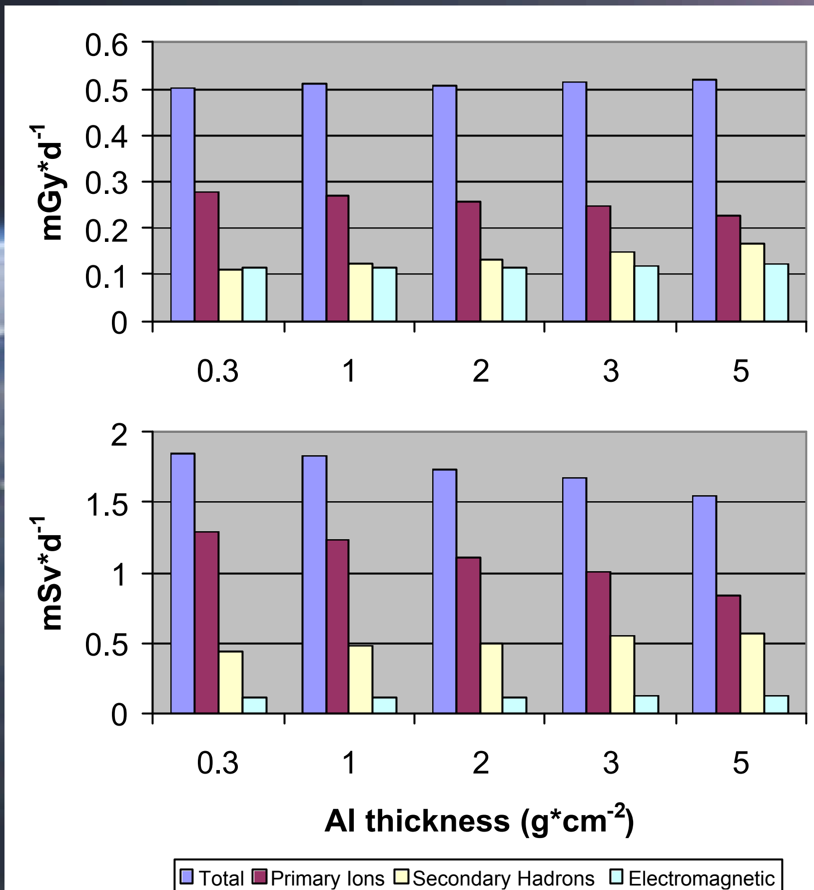
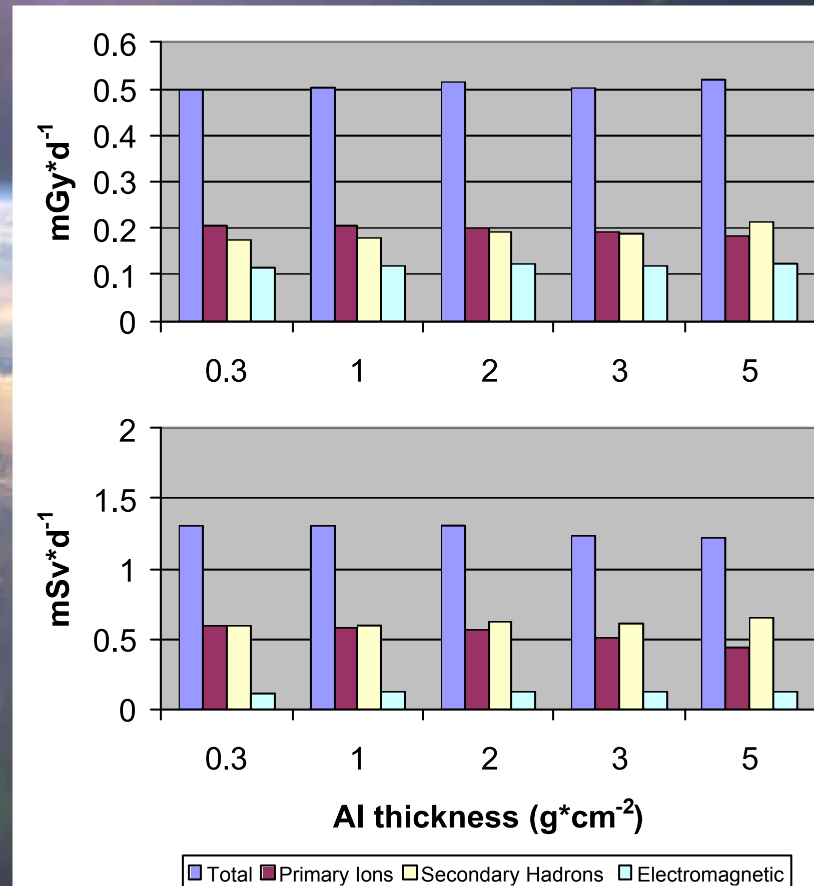
# GCR at solar min. (F=465 MV) - skin vs. internal organs

## skin




## liver




**With respect to skin, internal organs have 1) similar dose (~0.5 mGy/day) but smaller equivalent dose (~ 1.3 vs. 1.7 mSv/day); 2) larger relative contributions from nuclear interaction products**

# GCR at solar min. - Annual Effective Dose (Sv)

| Al (g/cm²) | This work (male) | This work (female) | This work (no gonads) | Hoff et al. (male) | Hoff et al. (no gonads) |
|---|---|---|---|---|---|
| 0.3 | 0.47 | 0.43 | 0.37 | | |
| 1 | 0.47 | 0.44 | 0.38 | 0.49 | 0.37 |
| 2 | 0.46 | 0.41 | 0.35 | 0.47 | 0.36 |
| 3 | 0.43 | 0.41 | 0.35 | 0.44 | 0.33 |
| 5 | 0.42 | 0.42 | 0.34 | 0.39 | 0.30 |

- large contribution from gonads, especially with small shielding (30% at 2 g/cm²)
- results very similar to those calculated with the HZETRN code and the CAM model *(Hoff et al. 2002, J. Rad. Res. 43)*

*NCRP recommendations for LEO ⇒ a 2-year mission to Mars at solar minimum would allow to respect the career limits for males of at least 35 years-old (limit: ≥ 1 Sv) and females of at least 45 (limit: ≥ 0.9 Sv)*



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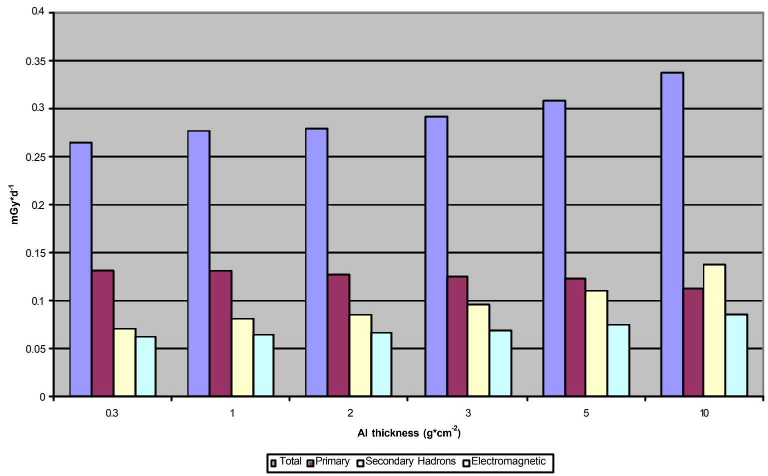
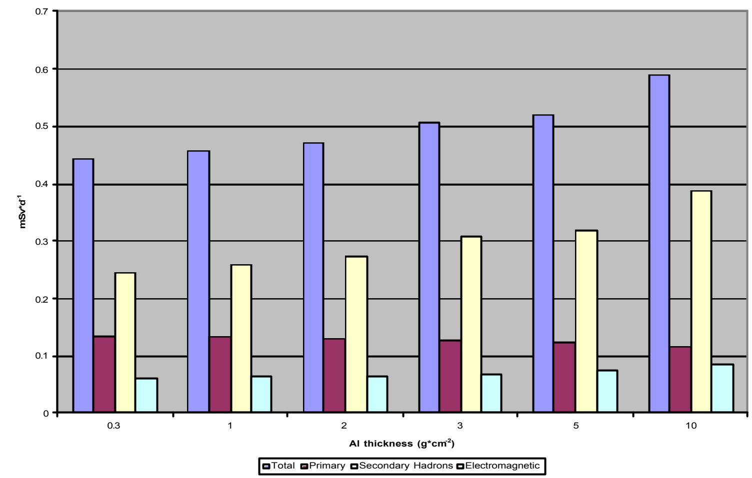
# GCR proton component - skin doses

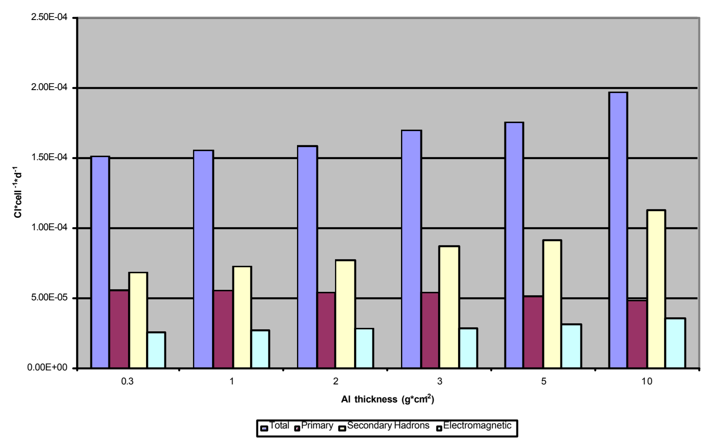
## Skin Dose [mGy/d]




## Equivalent Dose [mSv/d]



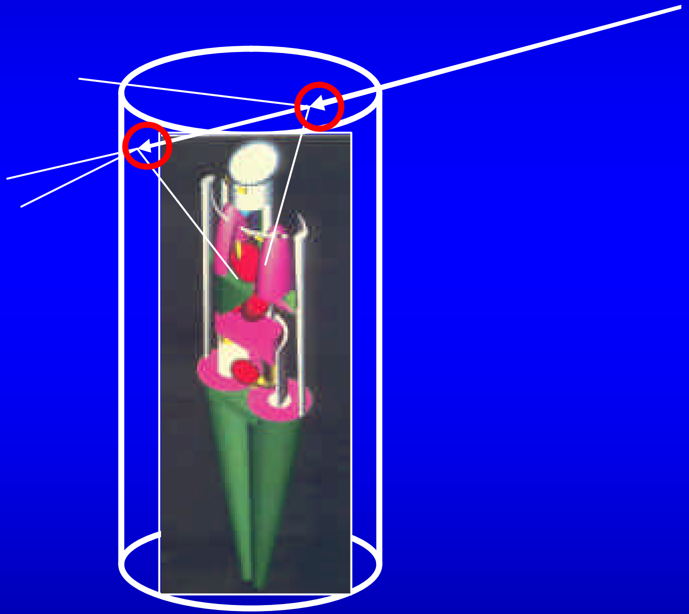

## "Biological" Dose [(CL/cell)/d]




- increase of proton doses (all dose types) with Al shielding thickness
- large role of nuclear reaction products, especially for equivalent and "biological" dose

# Proposed FLUKA "Sensitivity" Study

- Use existing model with Solar Min GCR
- Score each upstream interaction cross section (Proj.-Tar.-Frag.-E) that is included in a path that contributes to a Dose endpoint.
- Score for all 4 endpoints:
  - Dose
  - Dose Equivalent
  - Effective Dose Equivalent and
  - "Biological" Dose…
- Simulate Various "Spacecraft" wall materials and wall thicknesses…



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Fee $300 ($350 after Nov. 15, 2004)

Free for members of the NASA SRSP

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# Web Sites…

- FLEUR-*S* <http://www.cern.ch/~fleur>
  – Project status and publications—Downloads soon!
- FLUKA <http://www.fluka.org>
  – Download manuals and software (Linux, Unix,VMS)
- ROOT <http://root.cern.ch>
  – Download tutorials and software (Linux, Unix, Windows, Mac)

# The End

# August 1972 SPE

**Integral fluence (p cm$^{-2}$)**

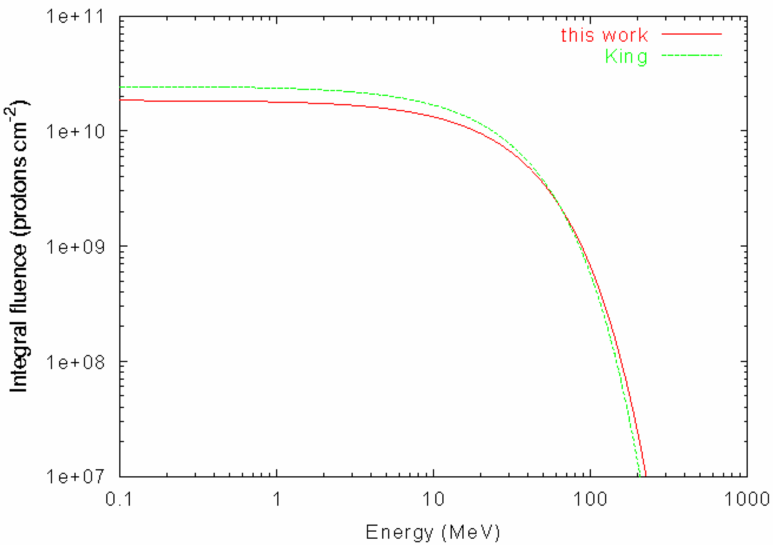
this work: $\Phi = 6.6\text{x}10^8 \exp[-(E-100)/30]$

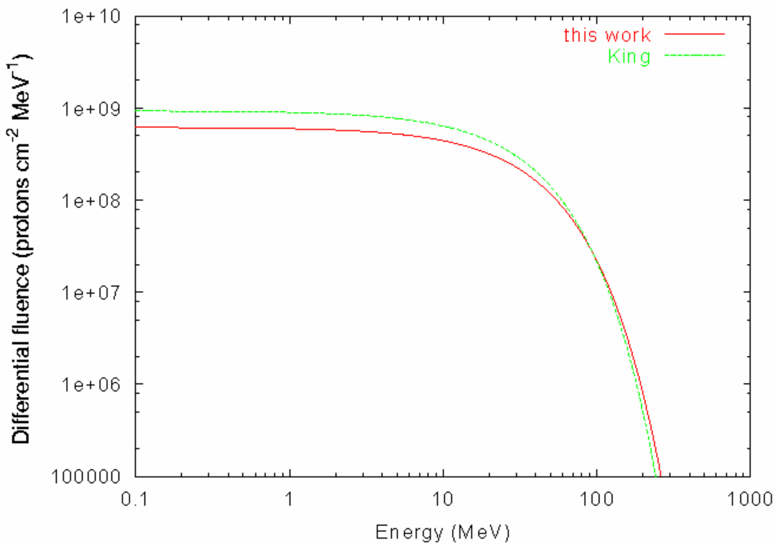
King: $\Phi = 7.9\text{x}10^9 \exp[-(E-30)/26.5]$

**Differential fluence (p cm$^{-2}$ MeV$^{-1}$)**

$d\Phi = 2.2\text{x}10^7 \exp[-(E-100)/30]dE$

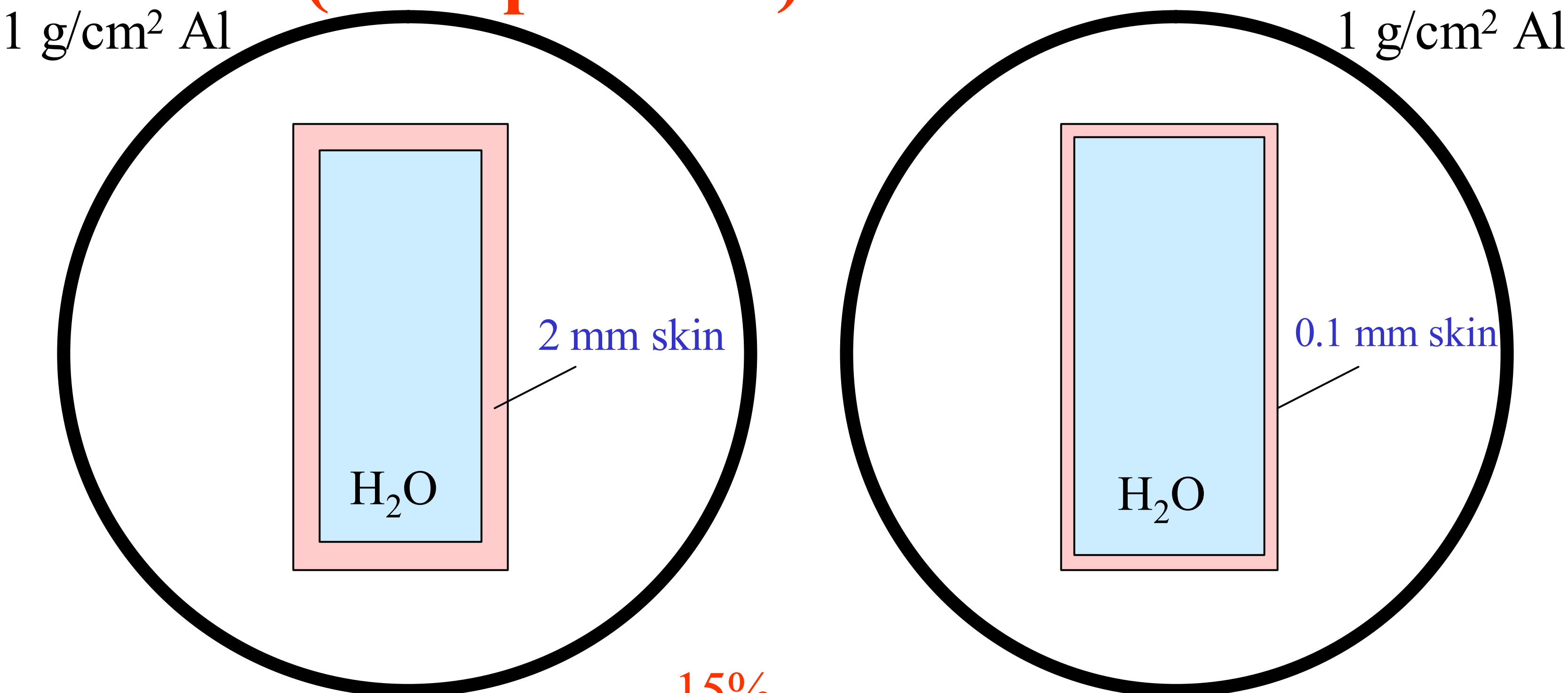
$d\Phi = 3.0\text{x}10^8 \exp[-(E-30)/26.5]dE$




*Protons with energy > 10 MeV: $1.32\text{x}10^{10}$ (this work), $1.68\text{x}10^{10}$ (King's spectrum) Þ factor 1.3*

# Aug. 1972 SPE -role of skin thickness (and spectrum) for skin doses



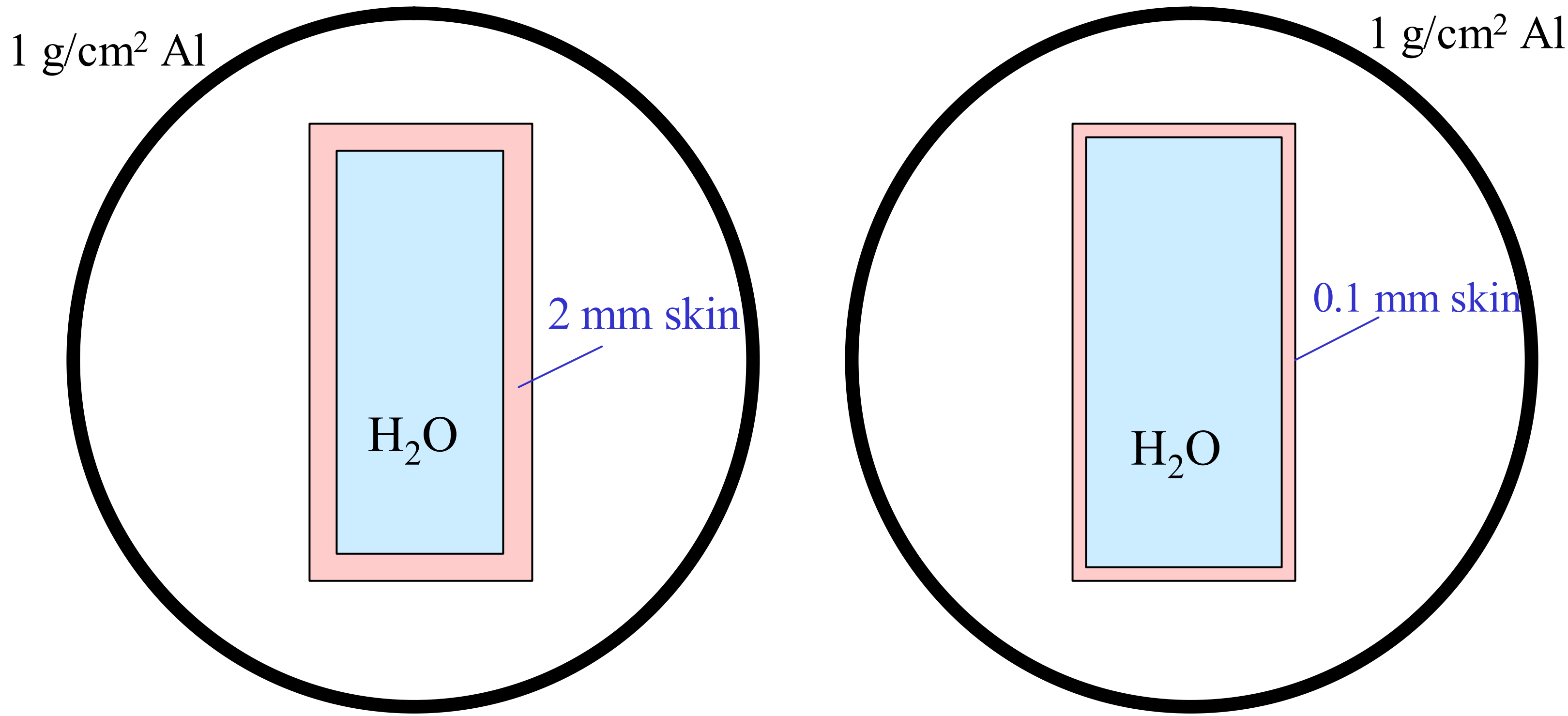

present spectrum: *10.6 Gy* → 15% → present spectrum: *12.2 Gy*

present spectrum: *10.6 Gy* → 67% → King spectrum: *17.7 Gy*

King spectrum: *13.1 Gy* → 35% → King spectrum: *17.7 Gy*

(Townsend et al. 1991: *15 Gy*; Wilson et al. 1999: *21.2 Gy*)

# GCR at solar min. -role of skin thickness for proton vs. alpha-particle contribution to skin equivalent doses




Proton/alpha = *2.25*

Proton/alpha = *1.3*

(Wilson et al.: *1.11*)

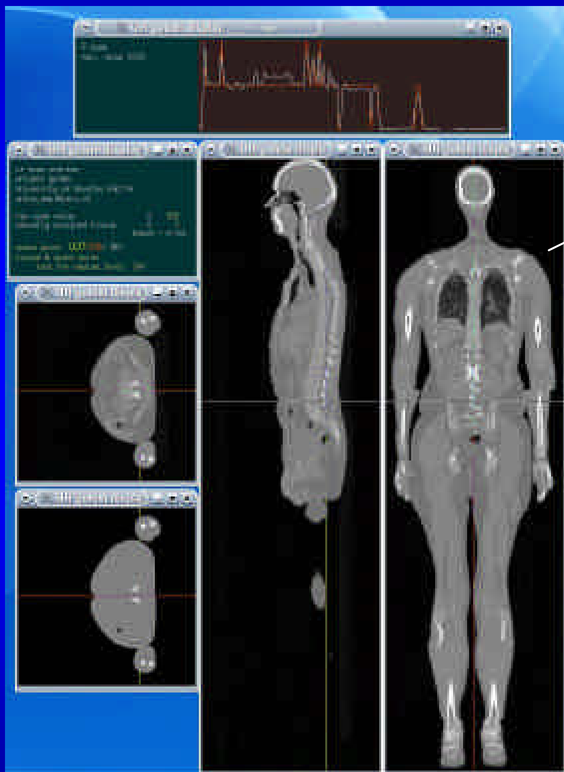
# Philosophical Overview

- The Overarching GOAL is to Provide the Ability to Assess the RISKS (Primarily to Humans) Associated with the Exposure to Space Radiation for All Foreseeable Regimes…
- This Inherently Includes Estimates of the UNCERTAINTY in those ASSESSMENTS…
- IT IS DANGEROUS TO FOCUS ON A SINGLE HUMAN OR ORGANIZATIONAL CUSTOMER! (…Although Specifically Identifiable Individuals and Organizations will use the CAPABILITIES that we will Develop…
- The CUSTOMER is a TASK—Providing the ABILITY to ENABLE the ASSEMENT OF RISK…

# Automated Algorithms to assign Material Compositions to CT-Scans (…A Well-Known Pattern Recognition Problem)

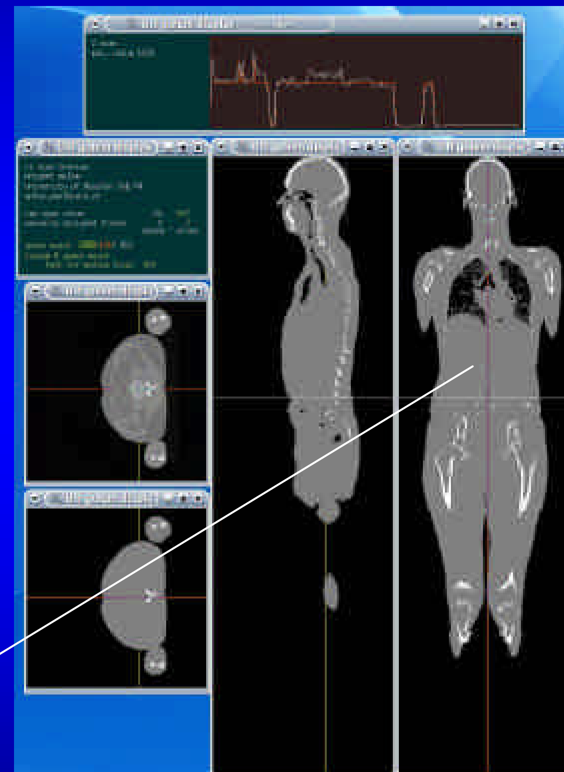
- The algorithm will identify 4 material types of voxels in human CT-Scans: Generic Soft Tissue, Hard Bone, Trabecular Bone, and Lung Tissue. (The individual voxel densities are still preserved).
- The identification is based simply on density and geographic situation.
- Voxels are forced into one of the 4 material types, even when it is a "boundary" voxel that is likely to be a combination of types (e.g. Soft Tissue-Hard Bone)

# Assigning Voxel Types with “Golem”



Original

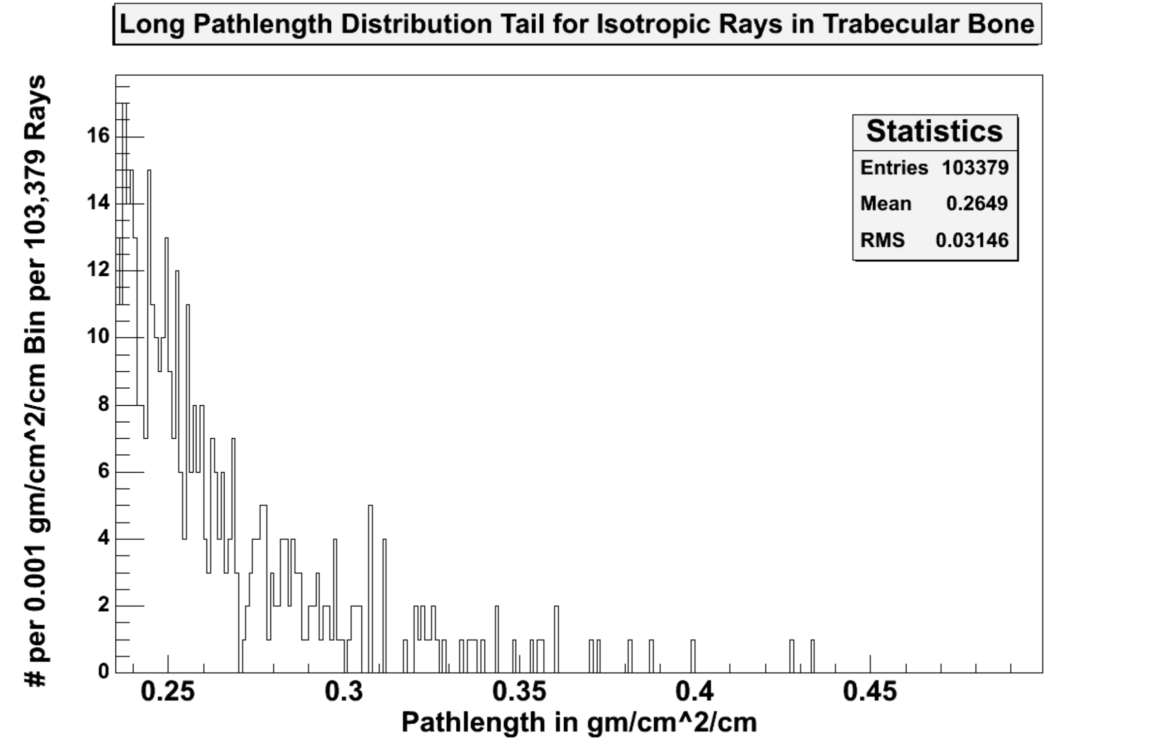
Material Types
Assigned



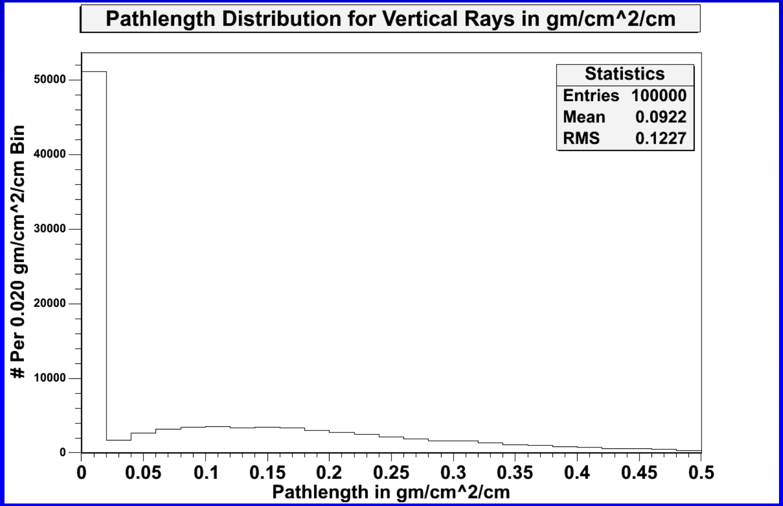
# Dealing with Porous Tissue Trabecular Bone

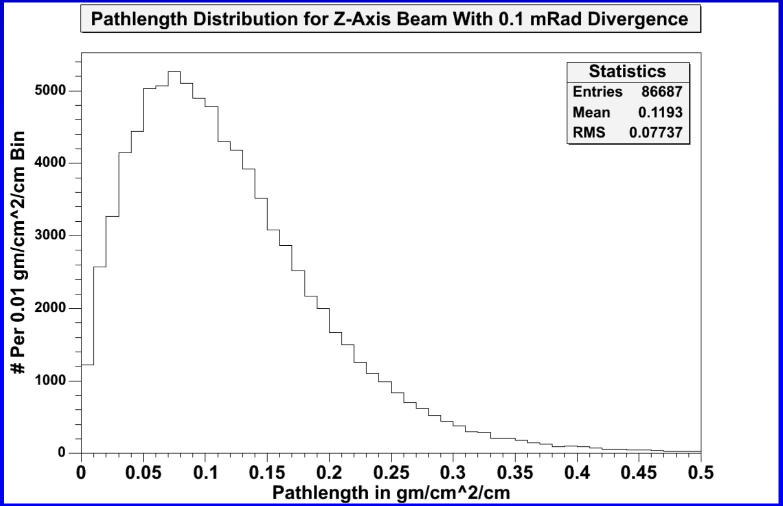
- Traversal of porous tissue by radiation is subject to a considerable variation in pathlength (in gm/cm$^2$).
- Approximation as a homogeneous average gives rise to a considerable error in such predictions as the spread in the subsequent Bragg peak.
- To deal with the problem of the variation in pathlengths within porous media where the porosity is too small as a practical matter, to be measured and included in detail within transport codes, FLUKA is implementing a special new type of material type with a variable *DENSITY*.
- In variable density materials, FLUKA will randomly select a density from a given distribution.
- Thus, we need to develop models of the pathlength distributions in these media

# Trabecular Bone
# Isotropic Long Pathlength Tail



# Pathlength Asymmetries along the Longitudinal Axis of Trabecular Bone

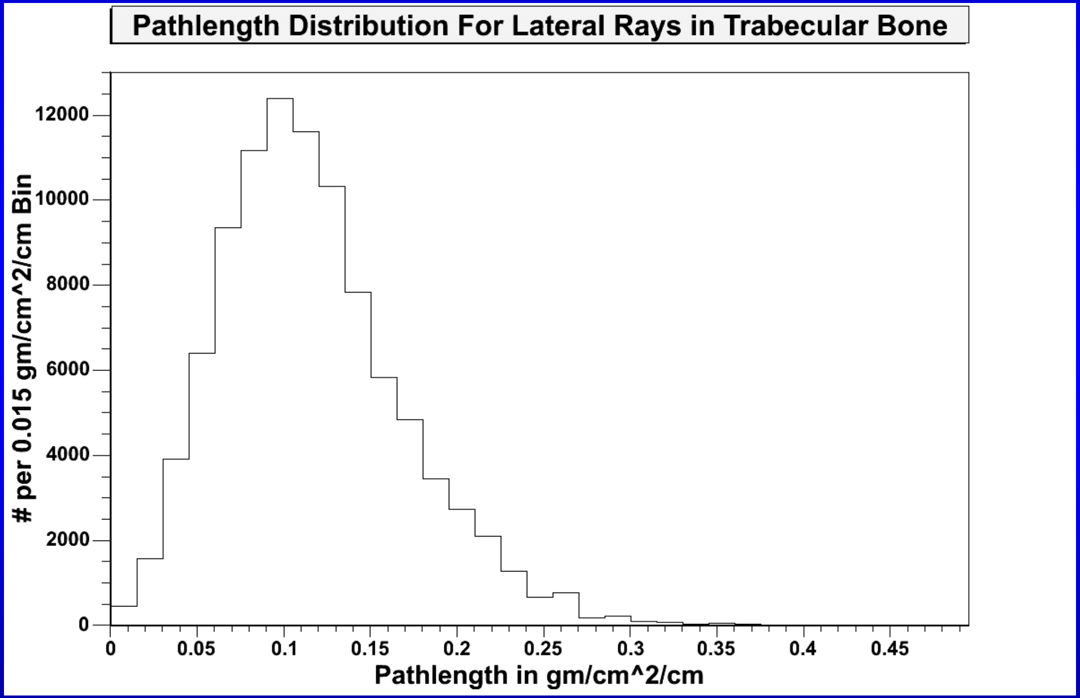



Pathlength distribution for “Rays” Parallel to longitudinal axis…

Pathlength distribution for “Rays” with a divergence of 100 mRadians Around the longitudinal axis…

# Pathlength Distribution for "Rays" Parallel to an Axis Perpendictular to the Longitudinal Axis of Trabecular Bone



# Future (Currently Funded) FLUKA Development

- ***Continue to Upgrade Event Generators w.r.t. DATA, and Benchmark against DATA.***
- Extend Event Generators Down to Threshold
- Continue to Improve GUI Tools for Backend Analysis and Front-end Run Setup…
- Make Releases Available to the Community
- Improve Current Geometry Input & Current GUI-based Visualization Tools
- ***Aid the Current Accelerator Program Analysis***
- ***Work on Establishing a Useful Abscissa for the Biologists***
  - ***"Track Average LET" Issues….***

# FLUKA – Useful Things That are Currently ***Unfunded***…

- Manpower to solve the Long Term **CAD** to Monte Carlo Geometry Input Issue (≥ 1 FTE)
  - This can be through the FLUKA Project or Independently…
  - All Transport Codes have a Common Universal need… (Transform .dxf formats into Combinatorial Combinations of Quadratic Primatives)
- Manpower (1 FTE) to develop Formal Web-Based User Tutorial Tools (Similar to the ones that exist at FNAL for ROOT…)

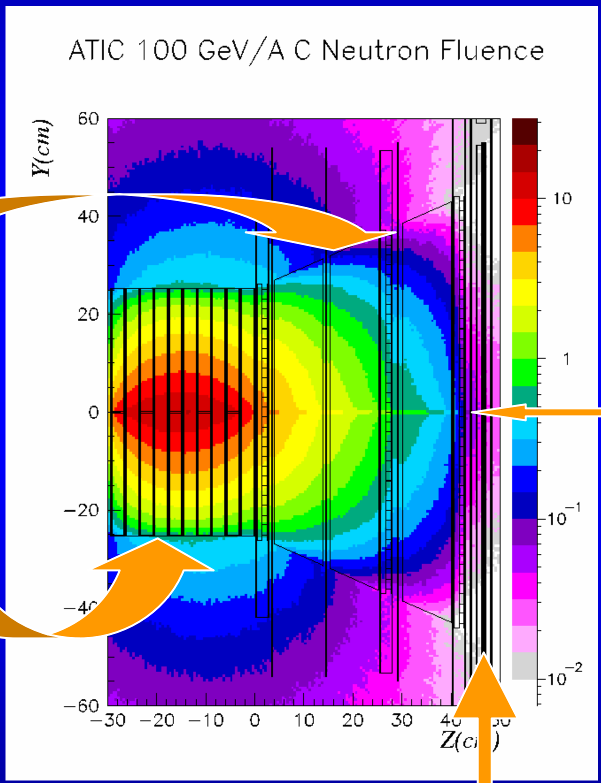
# A Simulation of the ATIC Cosmic Ray Balloon Experiment with a Version of FLUKA that now has the DPMJET 3.0 Event Generator

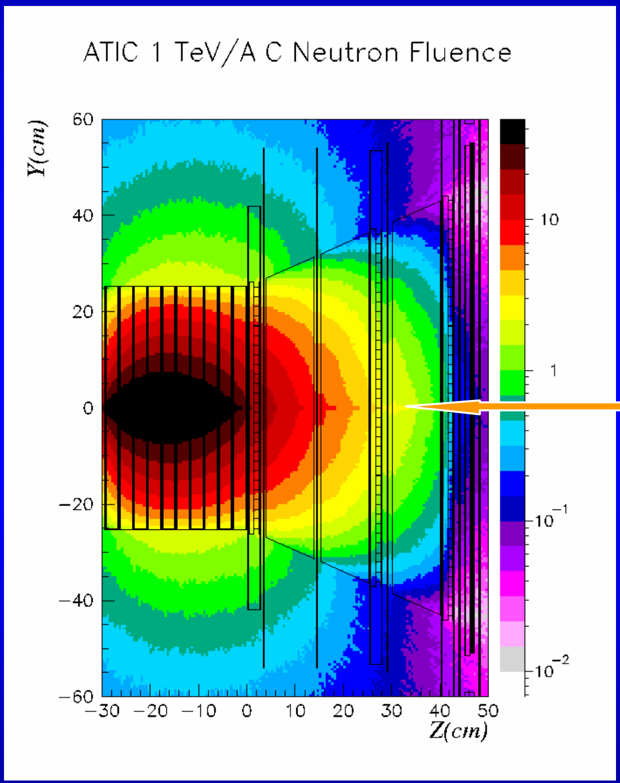
100 GeV/A Incident Carbon

1 TeV/A Incident Carbon

C Targets

BGO




Incident Beam

Si Detectors

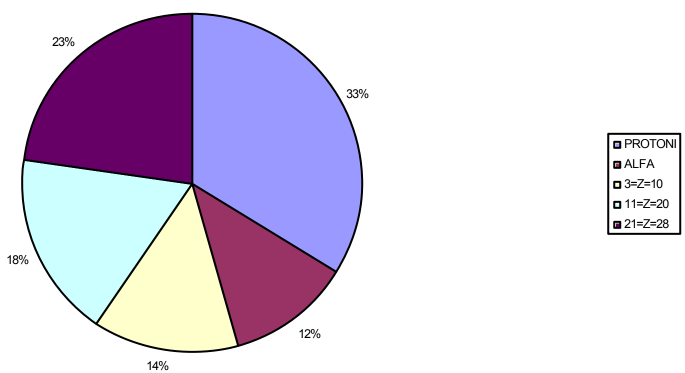
Predicted n fluences from a central C beam incident on the ATIC cosmic ray balloon expt. apparatus

WRMISS – Vienna
September 2004 - Pinsky

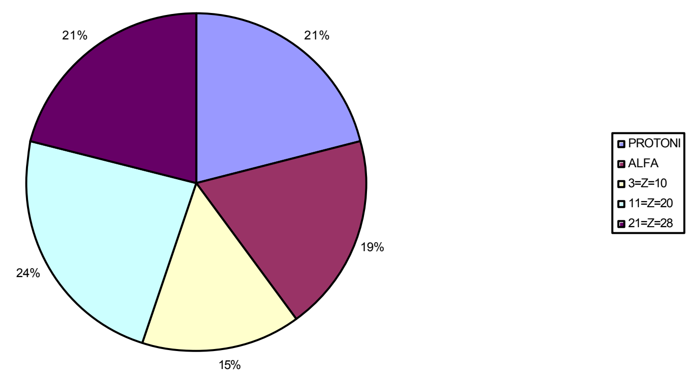
# GCR at solar min. - relative contribution of the different spectrum components

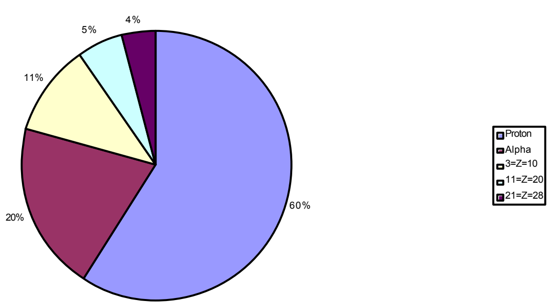
## *(skin equivalent dose behind 5 g/cm$^2$ Al)*

### This work



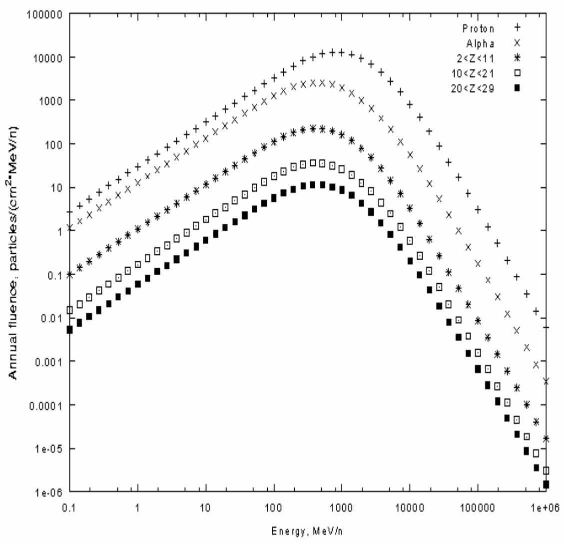

### Wilson et al.



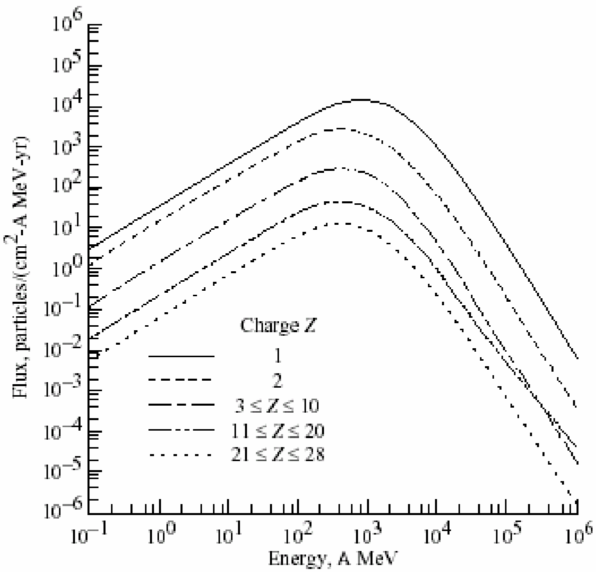



# GCR differential spectra at solar max

**This work** (F=1440 MV)




**Wilson et al.** (1981 solar max)




(b) GCR ion flux for 1981 solar maximum.

# GCR - comparison with skin dose results obtained with HZETRN+CAM *(Wilson et al. 1997, NASA TP 3682)*

| Al Shield (g/cm$^2$) | Solar min. (mGy/d) | | Solar max. (mGy/day) | |
|---|---|---|---|---|
| | This work | Wilson et al. | This work | Wilson et al. |
| 1 | 0.51 | 0.56 | 0.16 | 0.19 |
| 5 | 0.52 | 0.57 | 0.17 | 0.20 |
| 10 | 0.53 | 0.56 | 0.19 | 0.21 |
| 20 | 0.56 | 0.55 | 0.23 | 0.21 |



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## **The FLUKA Monte Carlo code** *(Þ A. Ferrari's talk)*

- hadron-hadron and hadron-nucleus interactions 0-100 TeV
- nucleus-nucleus interactions 5 GeV/u-10,000 TeV/u (DPMJET)
- electromagnetic and μ interactions 0-100 TeV
- neutron multigroup transport and interactions 0-20 MeV

- nucleus-nucleus interactions below 5 GeV/u down to 100 MeV/u (by coupling with the RQMD 2.4 code)

- parallel development of an original non-relativistic QMD code down to ~ 20 MeV/u

## 5.2 Acquire Essential Biomedical Data

### Ground Research

- Answer critical questions developed by the scientific community
  - Propagation of radiation through matter (radiation transport)
  - . . .

## 5.3 Develop Shielding Materials

. . .

20

### 5. Elements

**5.1 Simulate Space and Planetary Radiation Environments**

Construct and operate ground facilities at Brookhaven and Loma Linda University Medical Center

**5.2 Acquire Essential Biomedical Data**

**Ground Research**

- Answer critical questions developed by the scientific community
  - Propagation of radiation through matter (radiation transport)
  - Carcinogenesis
  - Central nervous system effects
- Develop genetic screening
- Predict biological effects of protons and HZE components of space radiation
  - Update radiation limits for long-term radiation effects
- Conduct clinical research—treatment in case of exposure, pharmacological agents

**Space Research**

- Support efforts that may lead to increased ability to forecast and characterize SPE with adequate response times and low false alarm rates
  - Update radiation limits for prompt radiation effects
- Coordinate emergency medical response for unplanned exposures (for example, during EVA)
- Coordinate international agreements on managing radiation risk on ISS
- Provide measurements of the space radiation environment (monitoring and dosimetry)
  - Robotic precursor missions
  - Shuttle and Station dosimetry
- Validate ground-based model predictions
- Utilize the ISS to establish interaction between radiation and hypogravity effects

**5.3 Develop Shielding Materials**

**Ground Research**

- Determine shielding properties of novel materials
- Incorporate biological effects of protons and HZE particles into the biological characterization of shielding

**Space Research**

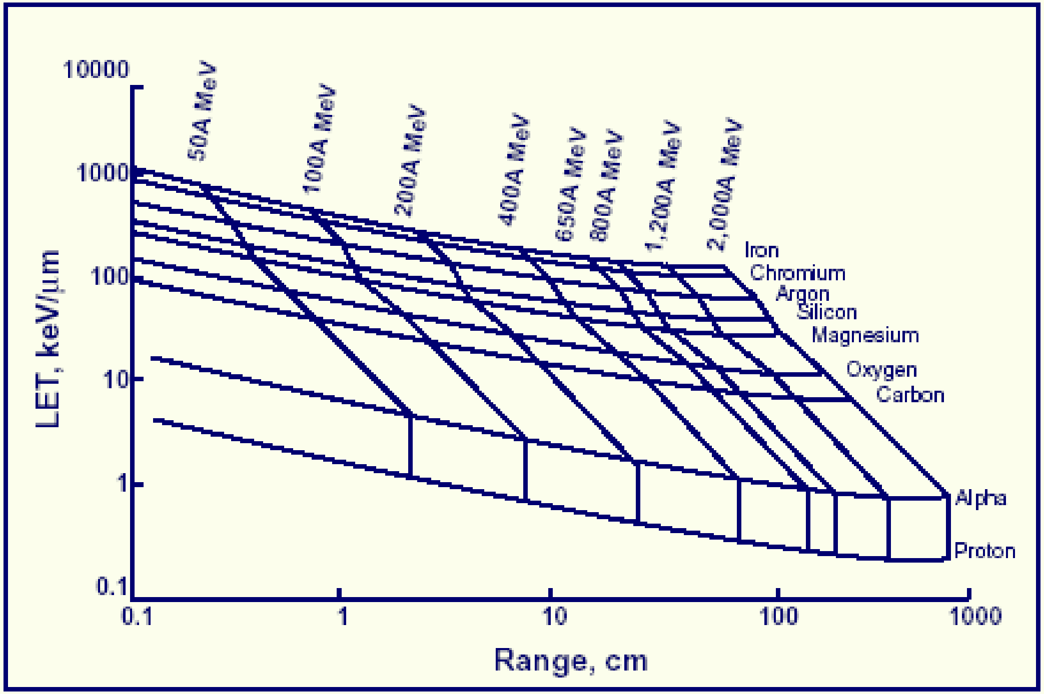
- Validate ground-based model predictions

**5.4 Incorporate Biomedical and Materials Requirements Into Mission Design**

- Standardized mission design tools (radiation transport, dosimetry, and so on)
- International protocols based on ALARA for dose measurements and monitoring
- Strategy to develop, review, accept, and implement flight rules
- Emergency response procedures for unplanned radiation exposures

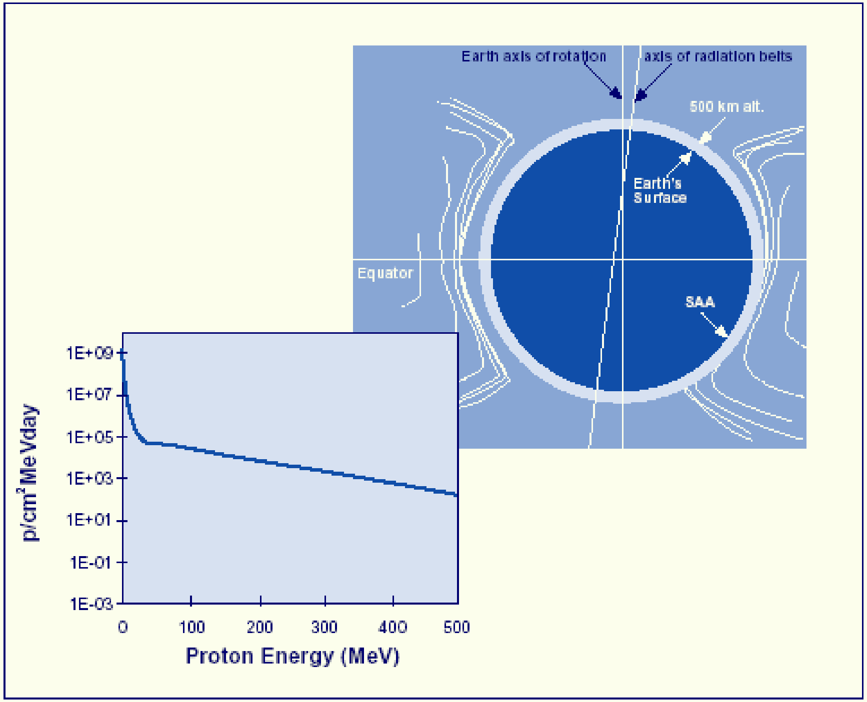
ELEMENTS

## Figure E.3. LET Versus Range




From NASA SPP

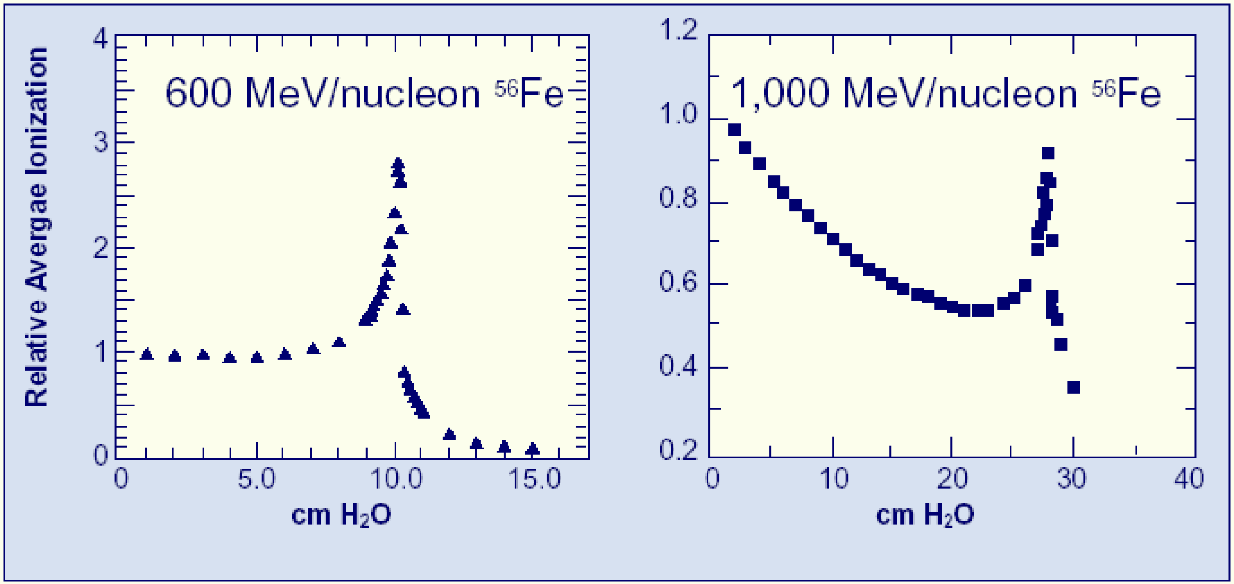
Figure D.7. Energy Distribution of Trapped Protons and South Atlantic Anomaly






From NASA SPP

Figure E.2. Bragg Curves for Monoenergetic Iron Beams

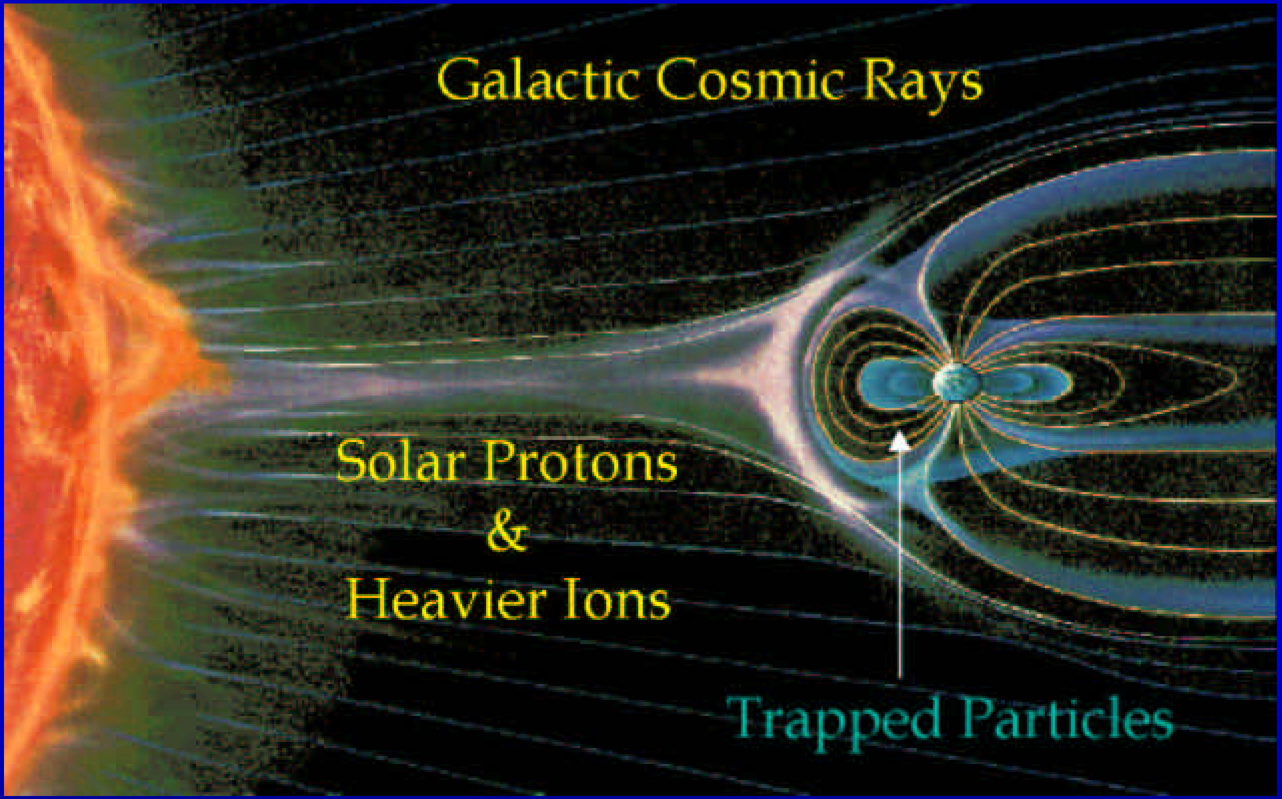



From NASA SPP

# The Technique

- We CANNOT Empirically Determine ALL of the needed Physics Cross Sections!
- We MUST Develop Reliable Physics-Based Models of the Cross Sections that are Applicable Over the Relevant Ranges of Parameters…
- The Models MUST Be Benchmarked with DATA!
- The Ultimate Task of Risk Assessment ALSO Requires Modeling of the Biological Aspects of EACH Relevant Regime of Radiation Exposure.

# We Also Need to Model Relevant Space Radiation Sources

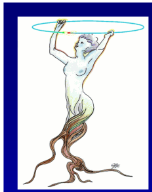



+ Albedos Caused by These Sources

From J. Barth
NASA/GSFC

# What CROSS SECTION DATA Do We Need?

- More is Better than Less (…And a more efficient Use of the Precious Beam Time!)
- Complete Fragmentation Spectra…
  - All Nuclear Fragments down to INDIVIDUAL Nucleons… (Lighter Ions Dominate Thick Shields)
  - Wider Angular Acceptances, Especially for Light Projectiles & Fragments… (The details are Kinematic, but try for 30° - - 10° may still be OK but Pixelization is Required…)
  - Double Differential "Type" Information on the Nucleons and Alphas… (Try for 30° Here, Too, and even crude E)
  - Pion Double Differential "Type" Information.
  - CENTRALITY information is very useful if possible…



# AND…

- Some Measurements at Higher Energies…
  - Up through 3-5 GeV/A where Pion Production becomes significant…
- Thin Target Measurements…
  - Thick Target Measurements are Useful Tools to Validate Your Model, BUT ONLY WHEN YOU ARE CLOSE TO SUCCESS.
- Exclusive Measurements…
  - The CENTRALITY of the collision is important…
  - This Comes for "FREE" more or less from the hardware standpoint... The cost is in the ANALYSIS!
- SO, Share the Analysis with the Modelers…

# Some Details…

- Use Transport Codes to SIMULATE the Measurement DATA STREAM…
- Use Transport Codes to Begin Defining the Abscissa for the Biologists Ground-Based Work.
- Share Cross Section Models to See Where They DIFFER from ONE and OTHER!
  - This will suggest fruitful measurements…

# So, Why do we need more work in this area?

- Prior codes and models used to evaluate Space Radiation shielding are not as accurate as we can hope to achieve now, and have not included all the relevant physics.
  - NRA 01-OBPR-05 recognized the need for a decade-long effort in data taking and modeling to obtain models accurate to 25% in any single channel.

# Radiation Transport – Monte Carlo

- Why use Monte Carlo techniques?
  - Easier to accurately represent details in the physics and the real-world 3-D geometric configurations…
  - Easier to estimate errors due to simplifying assumptions…
  - Produces specific detailed (event by event) results…
- Why *not* use Monte Carlo techniques?
  - Long computation times… [*but* ideally suited for parallel processing techniques…]