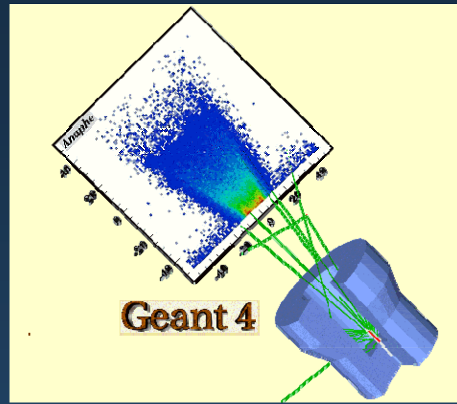
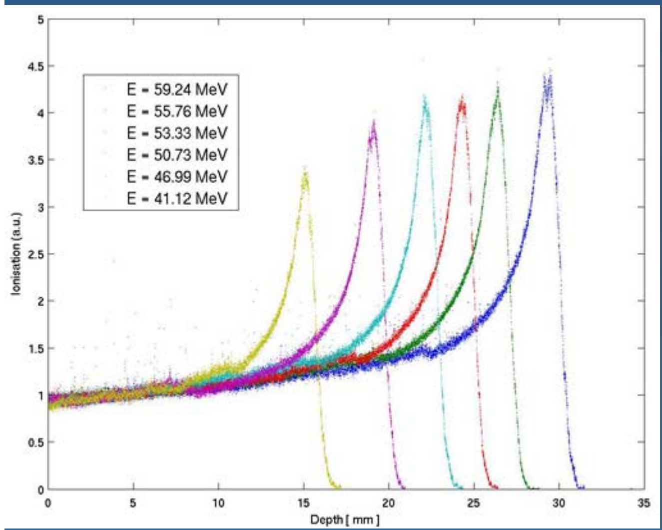


Fine simulation for heavy ion therapy

NIRS – MedAustron Joint Symposium
Innsbruck, 26 February 2006



Maria Grazia Pia
Maria.Grazia.Pia@cern.ch

http://cern.ch/geant4
http://www.ge.infn.it/geant4

Geant 4

Object Oriented Toolkit for the simulation of particle interactions with matter

also…

An experiment of distributed software production and management

An experiment of application of rigorous software engineering methodologies and object oriented technology to the particle physics environment

Born from the requirements of large scale HEP experiments

Widely used not only in HEP

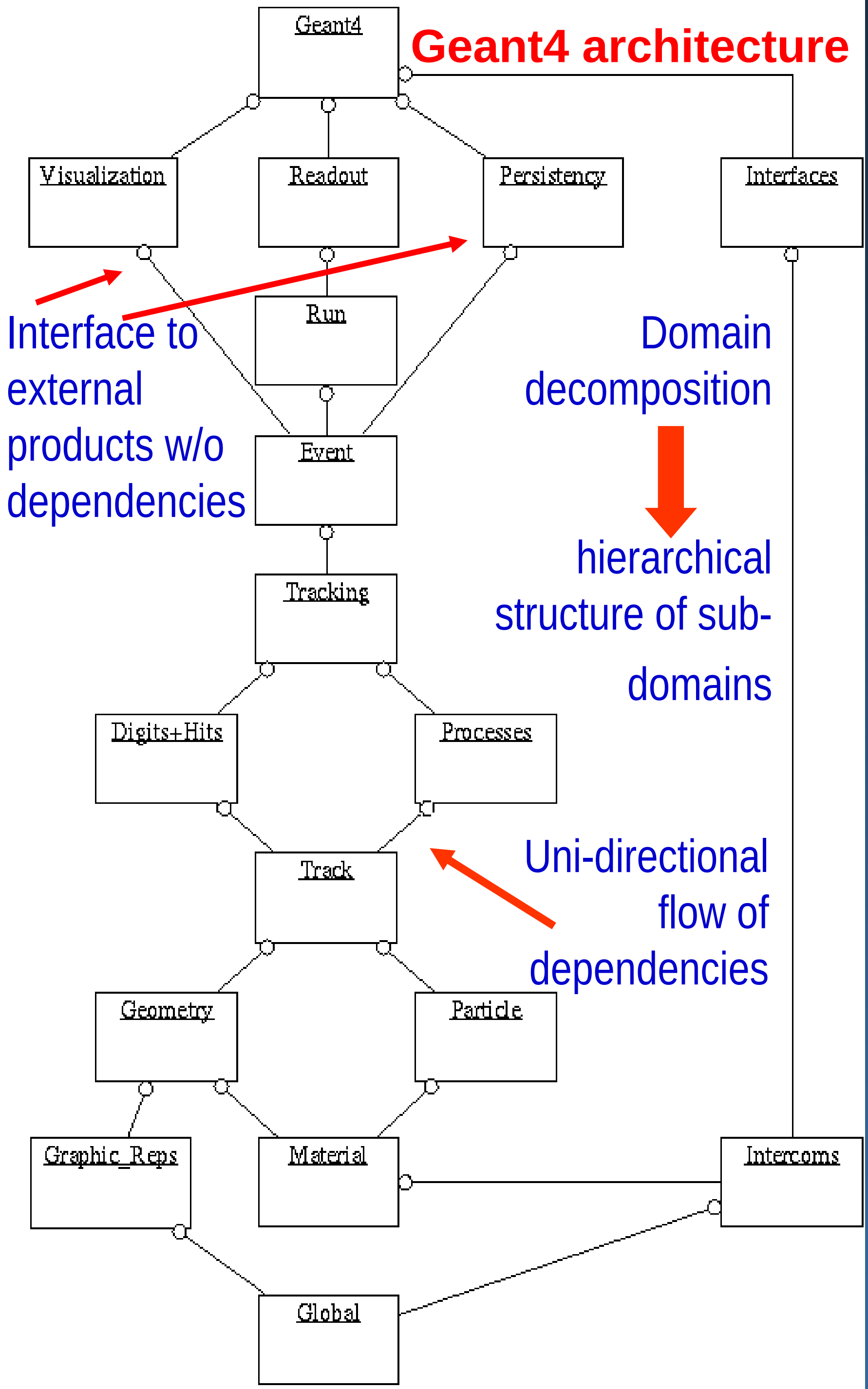
- Space science and astrophysics
- Medical physics, medical imaging
- Radiation protection
- Accelerator physics
- Pest control, food irradiation
- Landmining, security
- etc.

- Technology transfer

R&D phase: **RD44**, 1994 - 1998

1st release: December 1998

2 new releases/year since then

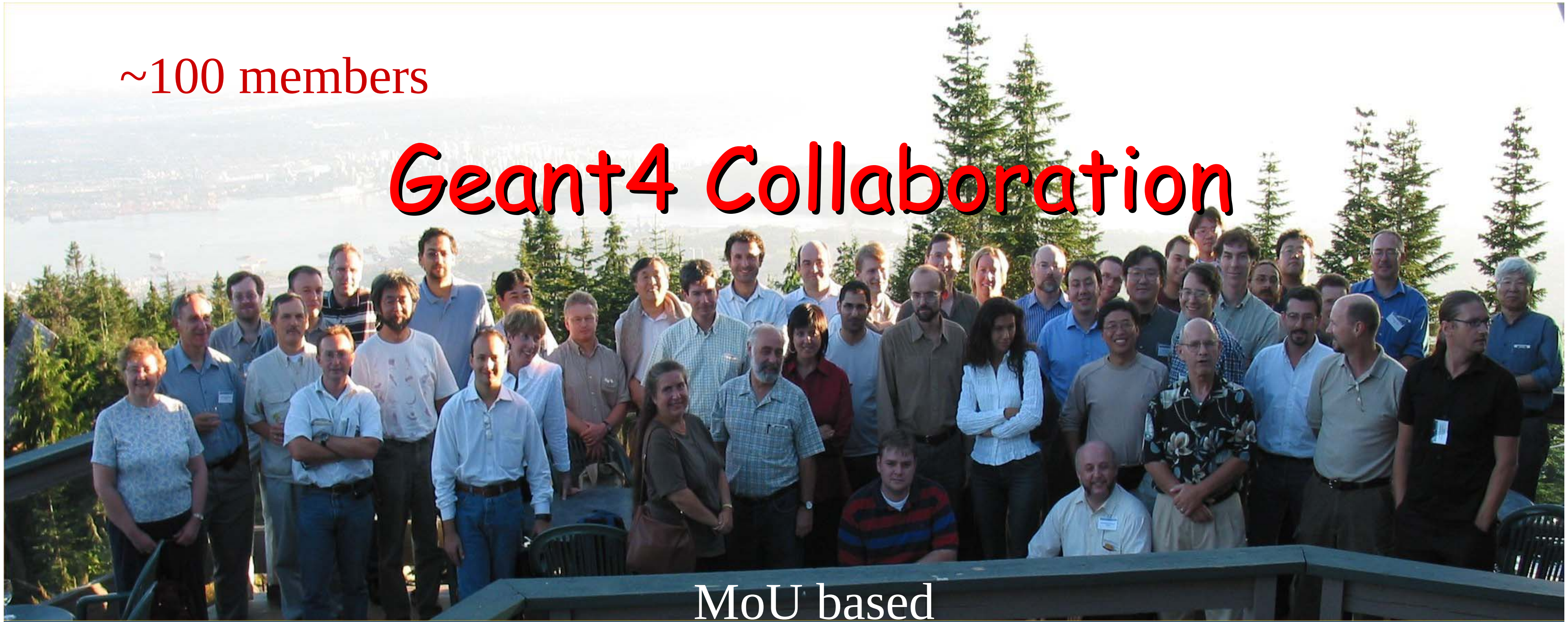


Geant 4 in a nutshell

- Rigorous software engineering
  - Iterative-incremental software process
  - Object oriented methods
  - Quality assurance
- Geometry
  - Powerful and versatile geometry modelling
  - Multiple solid representations handled through the same abstract interface
  - Simple placements, parameterised volumes, replicas, assembly-volumes etc.
  - Boolean operations on solids
- Physics independent from tracking
- Subject to rigorous, quantitative validation
- Electromagnetic physics
  - Standard, Low-Energy, Muon, Optical etc.
- Hadronic physics
  - Parameterised, data-driven, theory-driven models
- Interactive capabilities
  - Visualisation, UI/GUI
  - Multiple drivers to external systems
- **Open source**, freely downloadable from the web site (http://cern.ch/geant4)

~100 members

Geant4 Collaboration



MoU based

Development, Distribution and User Support of Geant4

Major physics laboratories:
CERN, KEK, SLAC, TRIUMF, TJNL

European Space Agency:
ESA

National Institutes:
INFN, IN2P3, PPARC

+ several groups at Universities

scientific…

Globalisation

Sharing requirements and functionality across diverse fields

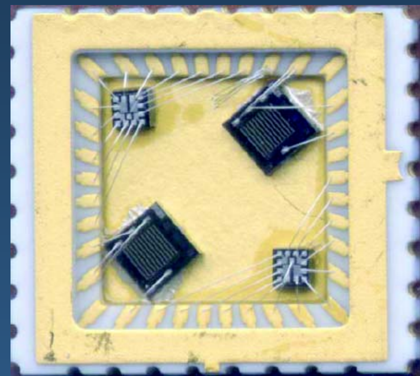
Dosimetry with Geant4

Wide spectrum of physics coverage, variety of physics models
Precise, quantitatively validated physics
Accurate description of geometry and materials

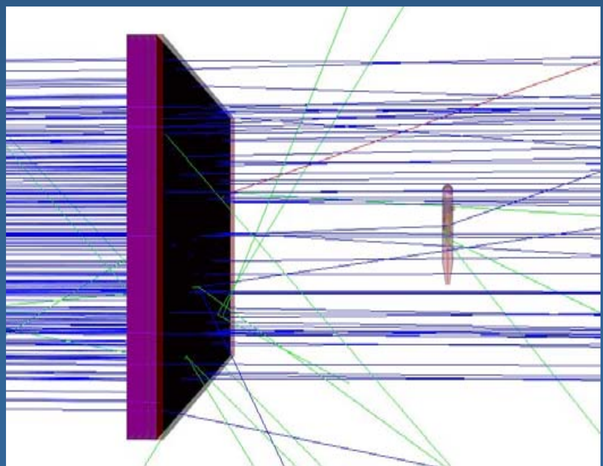
Multi-disciplinary application environment

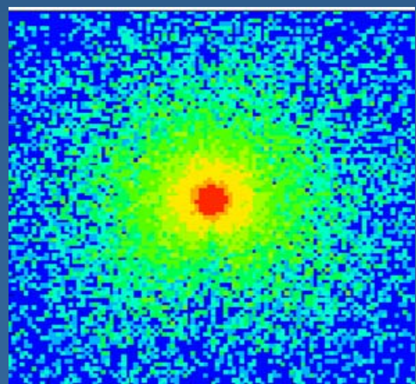
Space science

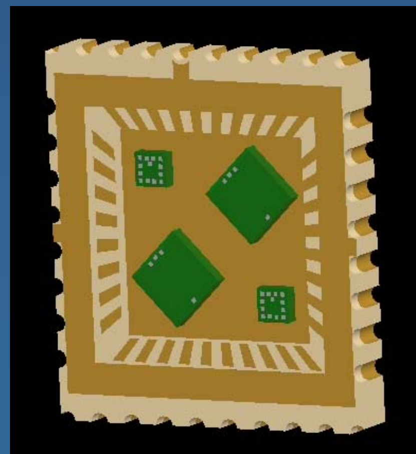
Radiotherapy



Effects on components

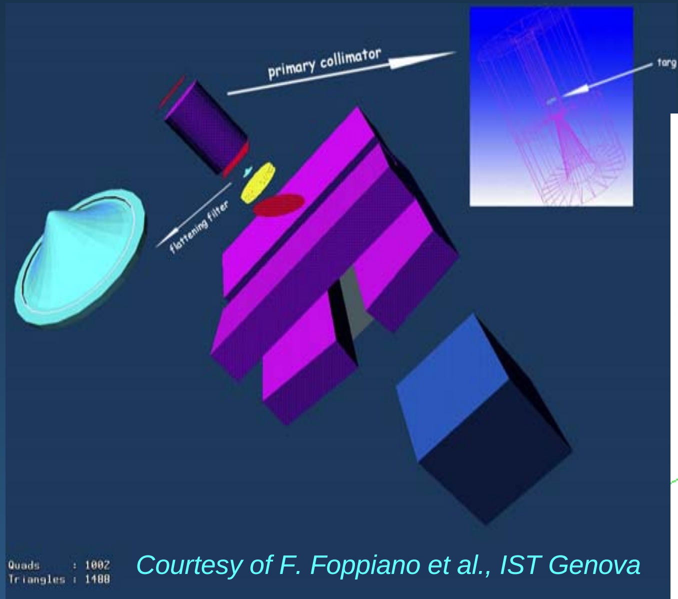






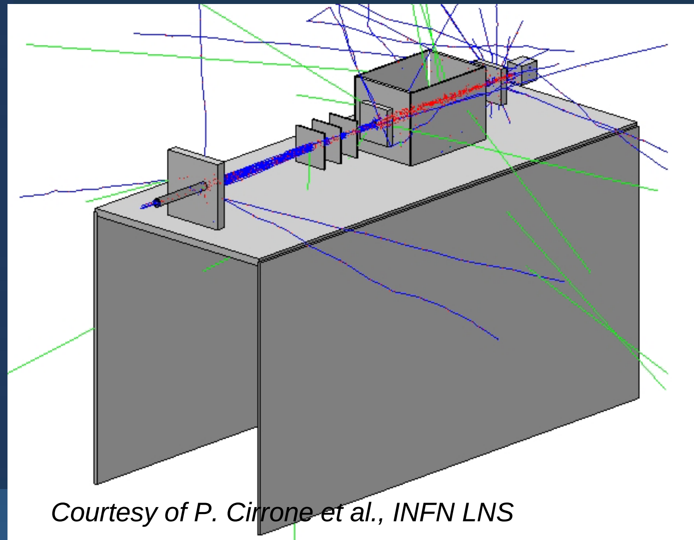
Geant 4

Dosimetry in Medical Applications

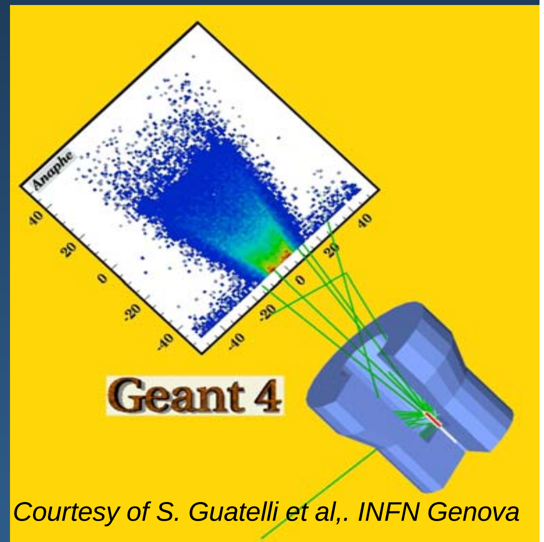


Courtesy of F. Foppiano et al., IST Genova

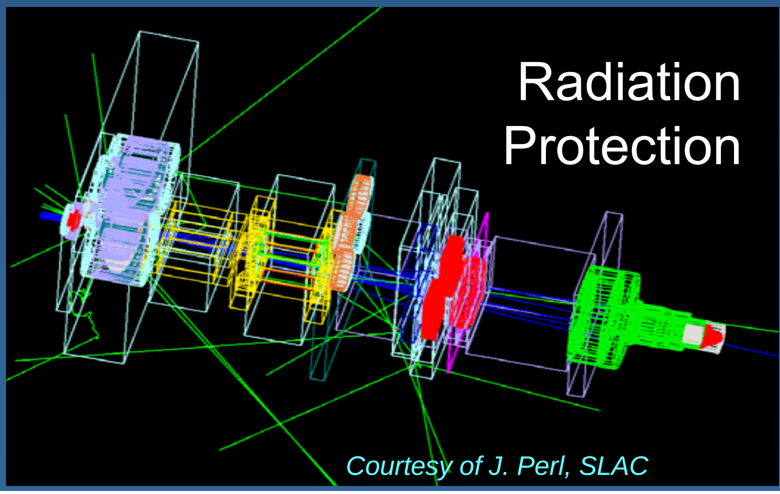
Radiotherapy with external beams, IMRT


Courtesy of P. Cirrone et al., INFN LNS

Hadrontherapy

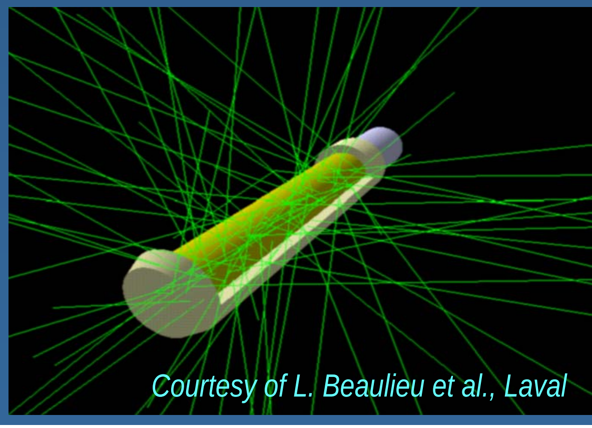


Courtesy of S. Guatelli et al,. INFN Genova


Radiation Protection

Courtesy of J. Perl, SLAC

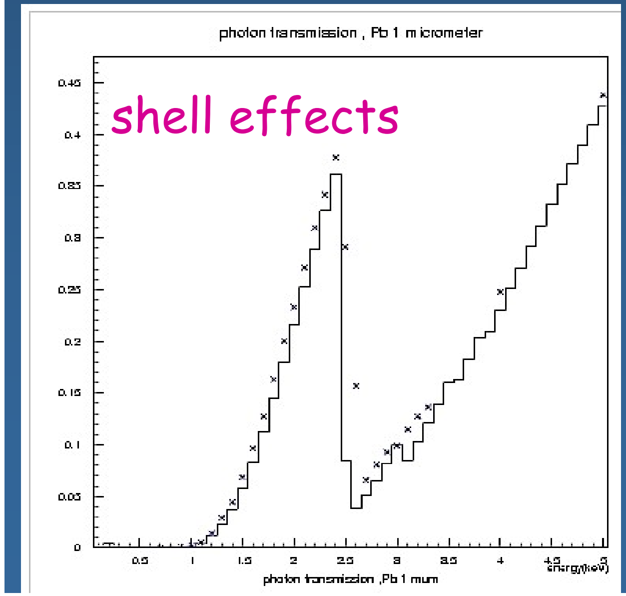
Brachytherapy


Courtesy of L. Beaulieu et al., Laval

Precise dose calculation

Geant4 Low Energy Electromagnetic Physics package

- Electrons and photons (250/100 eV < E < 100 GeV)
  - Models based on the Livermore libraries (EEDL, EPDL, EADL)
  - Penelope models
- Hadrons and ions
  - Free electron gas + Parameterisations (ICRU49, Ziegler) + Bethe-Bloch
  - Nuclear stopping power, Barkas effect, chemical formulae effective charge etc.
- Atomic relaxation
  - Fluorescence, Auger electron emission, PIXE



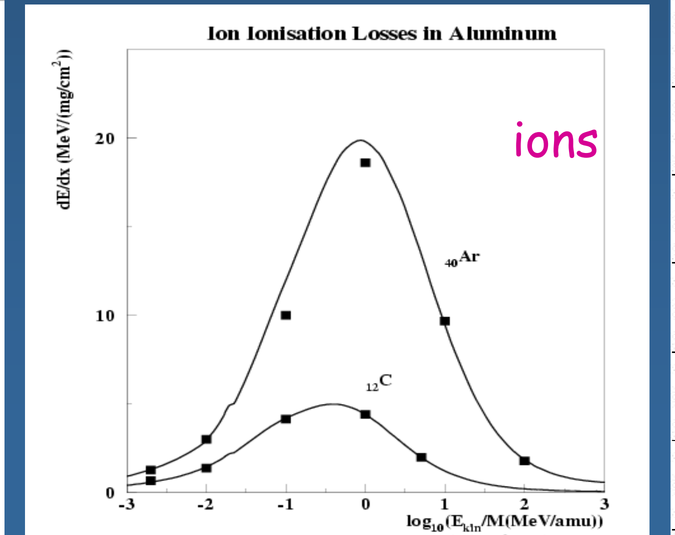
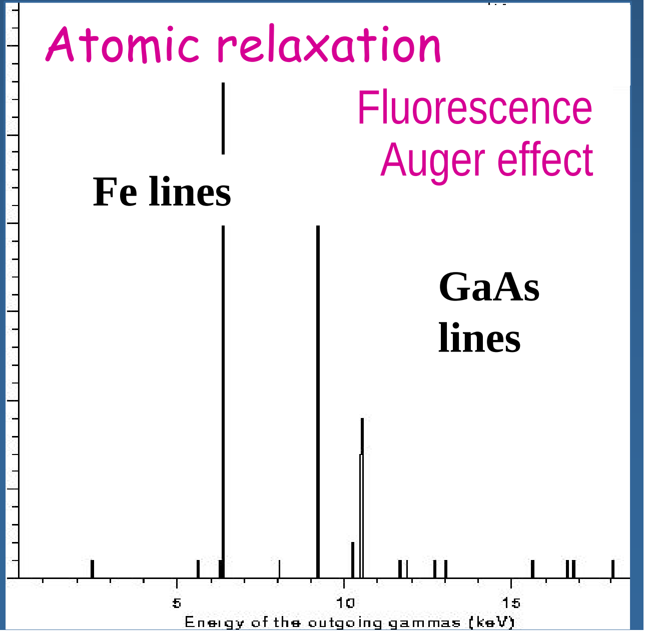


Figure 9: Ion electronic stopping power in aluminum. Points - the best fit on the data from Ref.[12], solid line - GEANT4 parameterisation. The accuracy of the data is about 5 %.



Validation

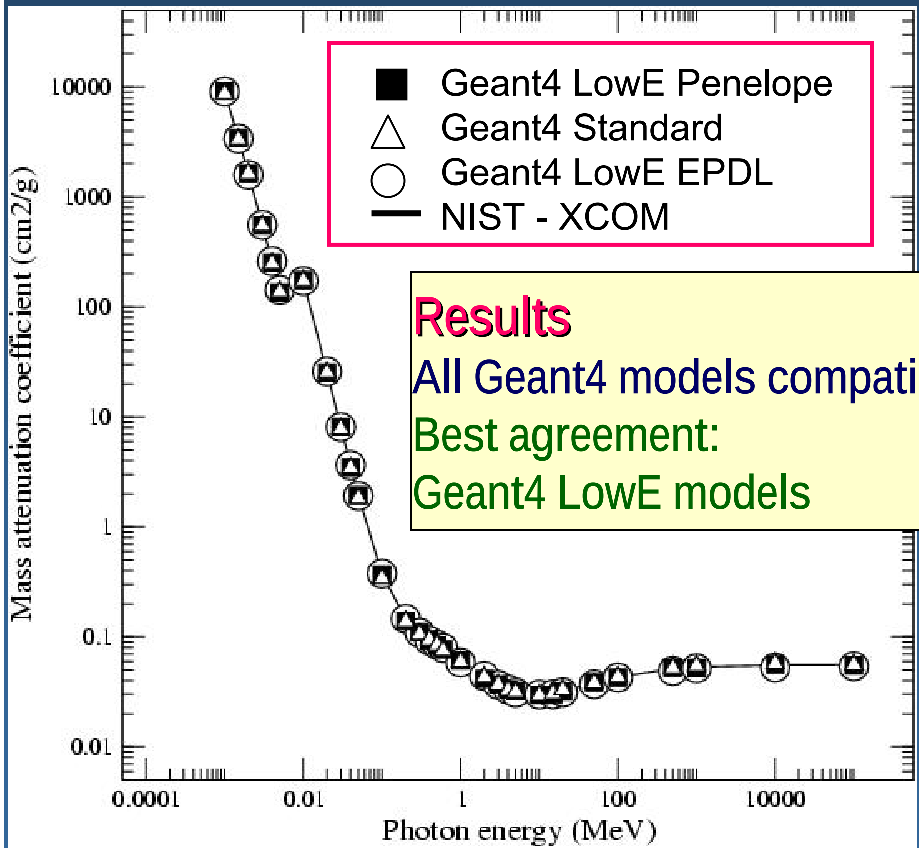
Huge, ongoing effort for systematic, quantitative validation

K. Amako, S. Guatelli, V. N. Ivanchenko, M. Maire, B. Mascialino, K. Murakami, P. Nieminen, L. Pandola, S. Parlati, M.G. Pia, M. Piergentili, T. Sasaki, L. Urban

Comparison of Geant4 electromagnetic physics models against the NIST reference data

IEEE Trans. Nucl. Sci., Vol. 52, Issue 4, Aug. 2005, pp. 910-918

Mass attenuation coefficient in Fe

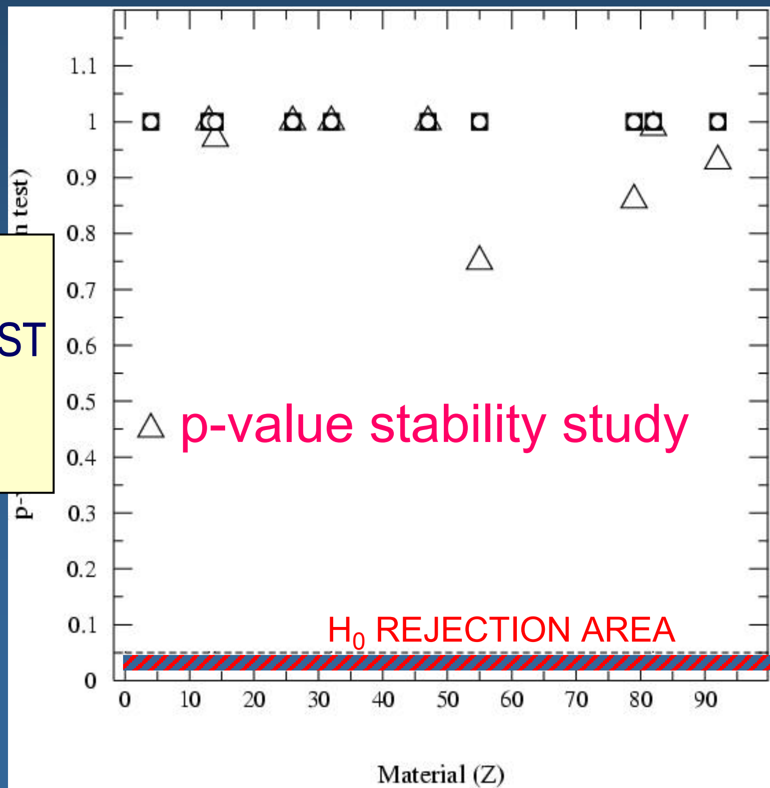


Results

All Geant4 models compatible with NIST

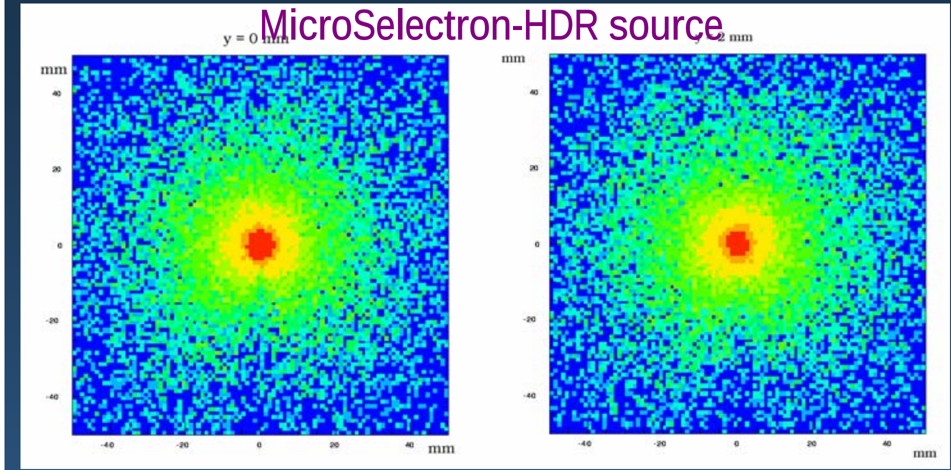
Best agreement:

Geant4 LowE models

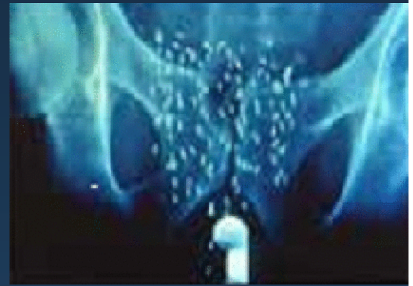


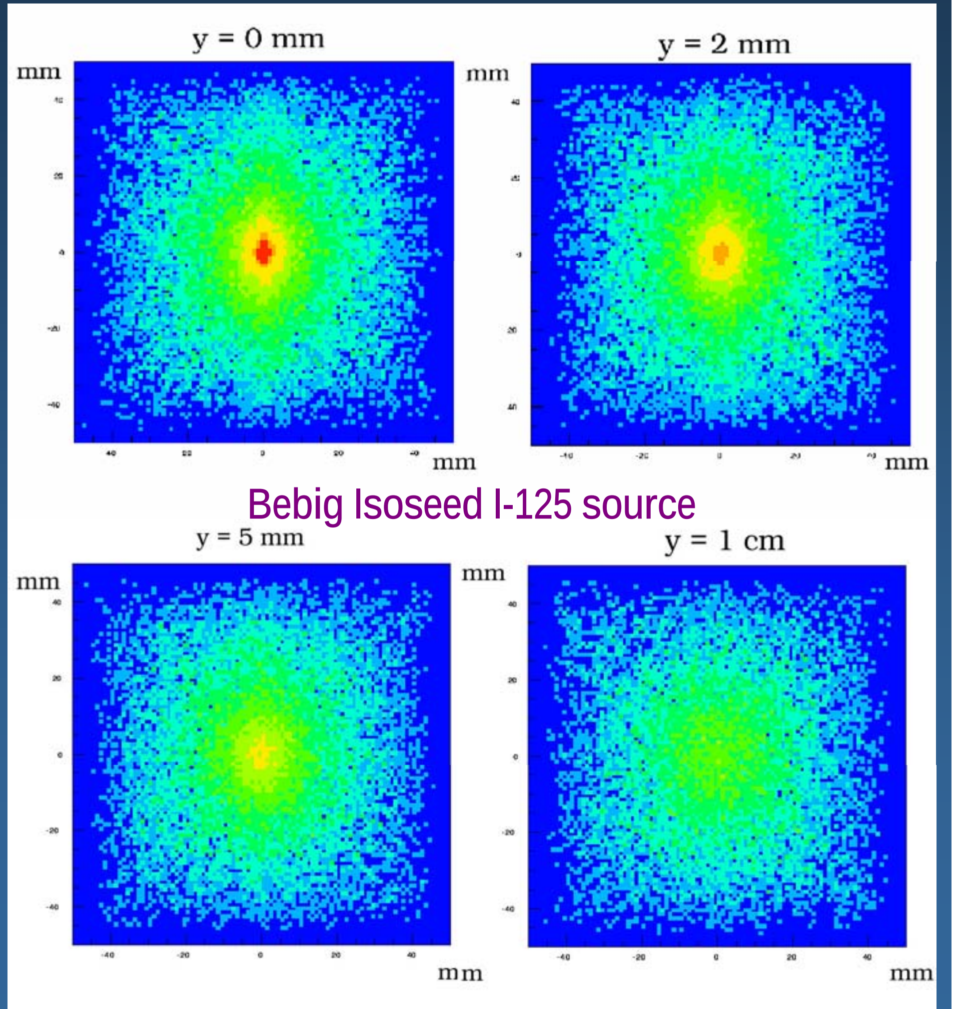
△ p-value stability study

Endocavitary brachytherapy

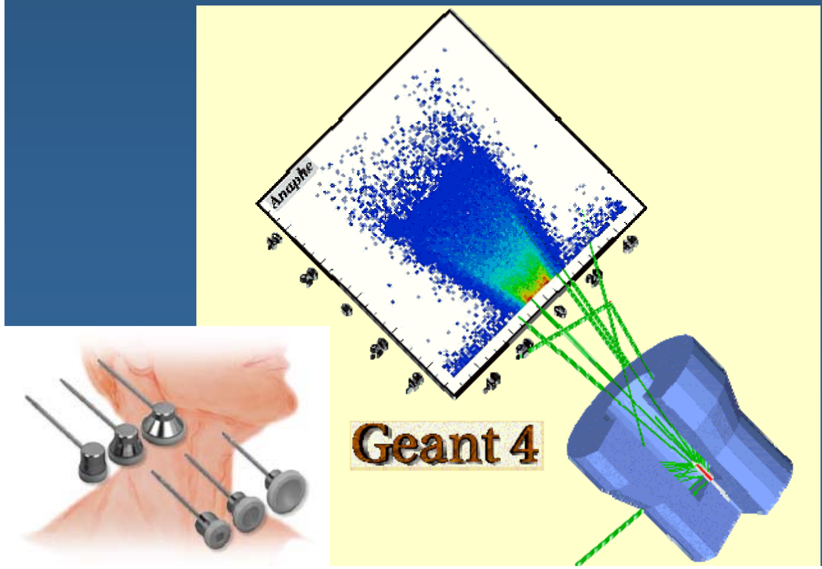


Interstitial brachytherapy

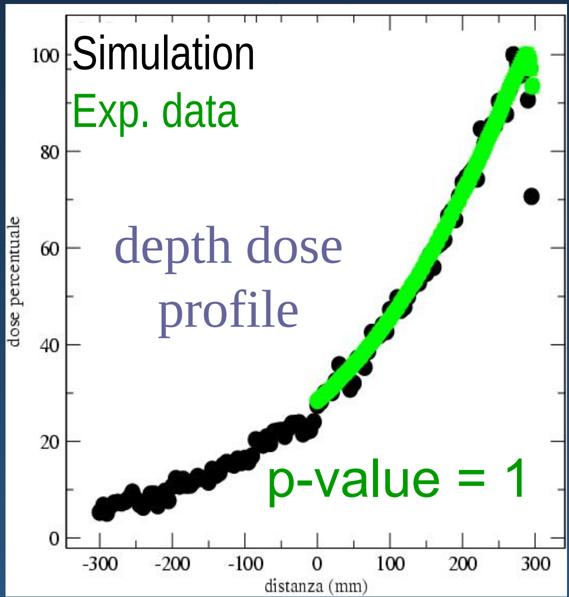


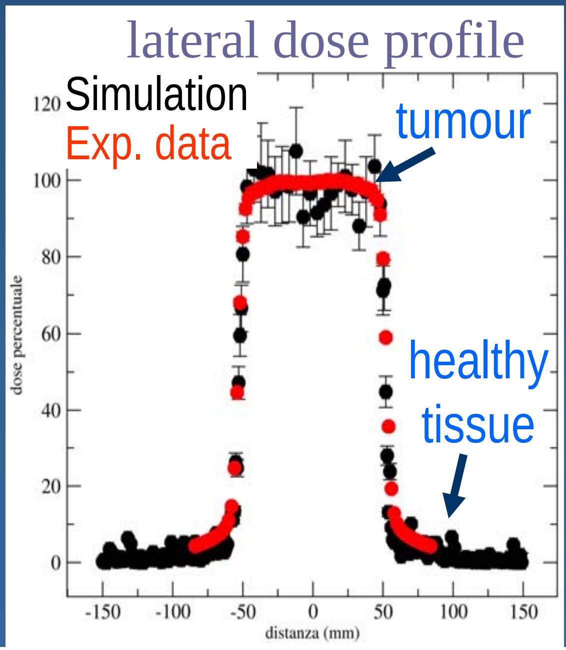


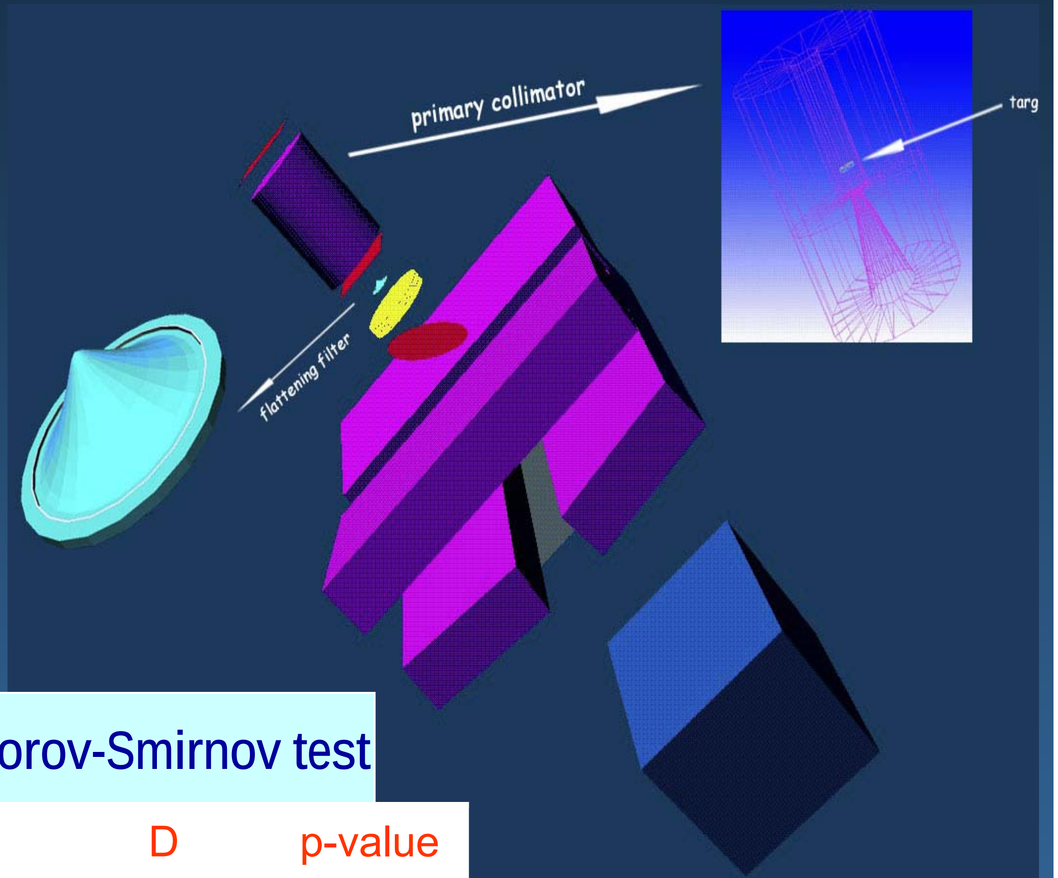
Superficial brachytherapy



A medical accelerator for IMRT



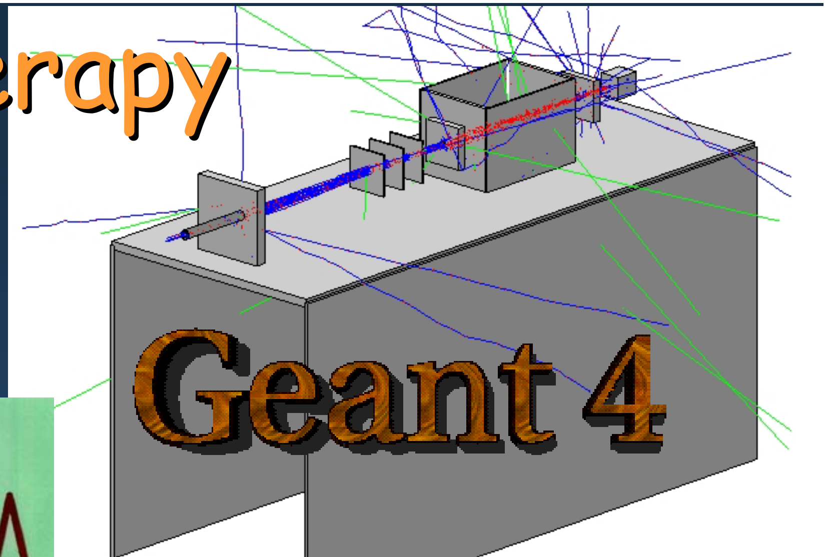




Kolmogorov-Smirnov test

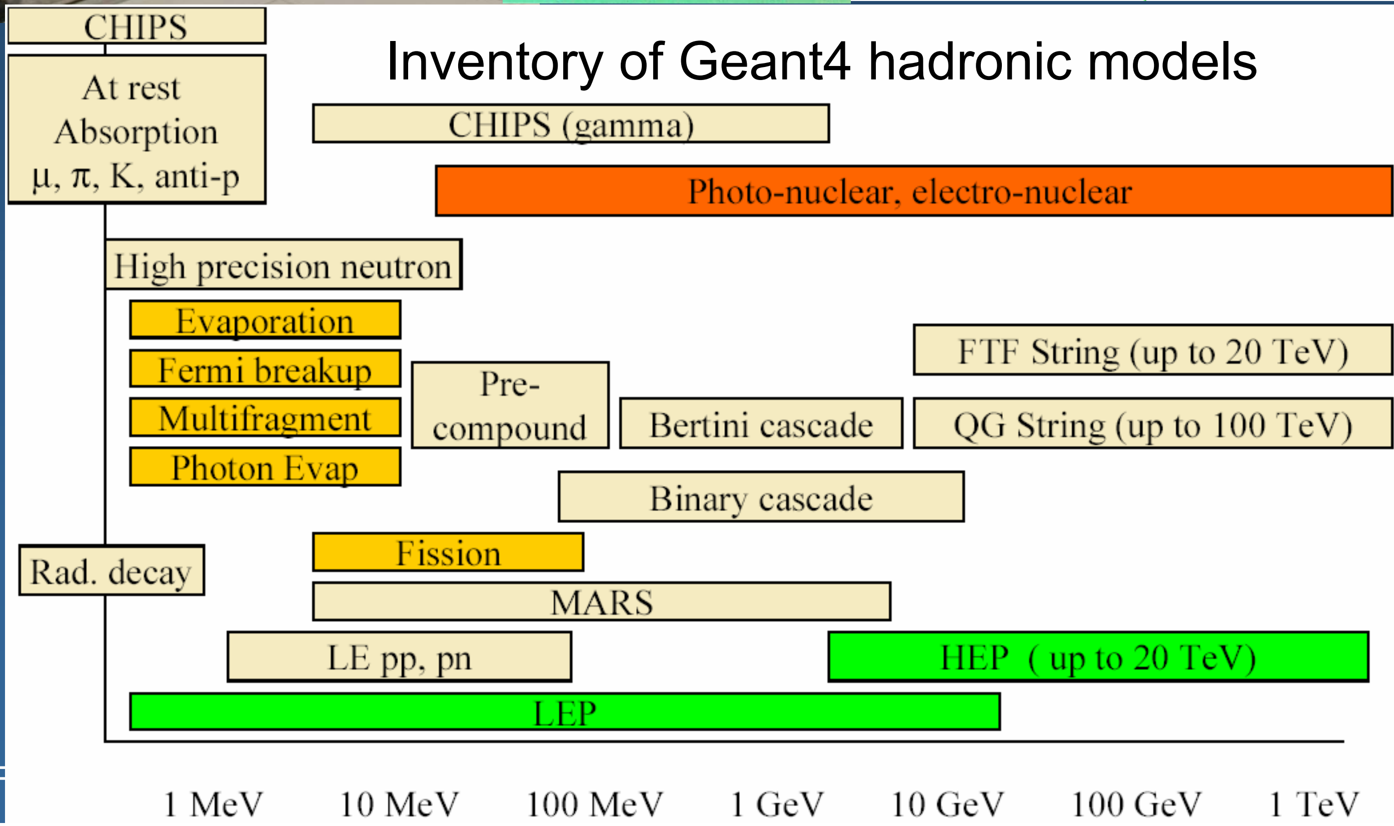
range	D	p-value
-84 ÷ -60 mm	0.385	0.23
-59 ÷ -48 mm	0.27	0.90
-47 ÷ 47 mm	0.43	0.19
48 ÷ 59 mm	0.30	0.82
60 ÷ 84 mm	0.40	0.10

Hadrontherapy



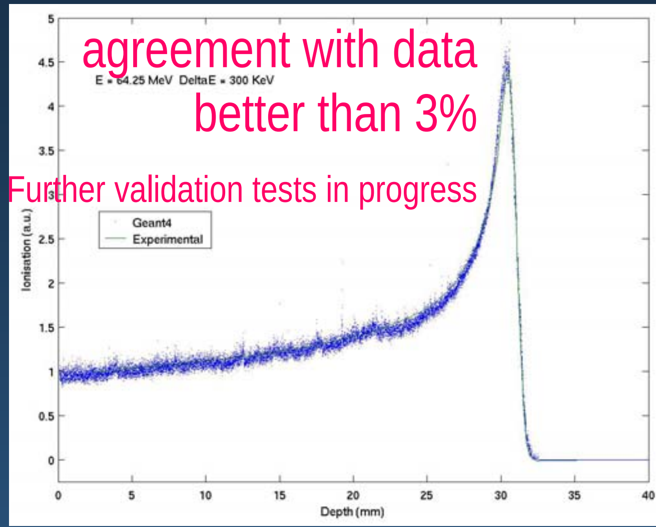
Courtesy of P. Cirrone, LNS, Catania

Inventory of Geant4 hadronic models



Dosimetry: protons and ions

WHOLE PEAK (N_1=149 N_2=66)	Cramer – von Mises test	Anderson – Darling test
Test statistics	0.06	0.499375
p-value	0.79	0.747452
Electromagnetic only	0.52	0.443831



agreement with data better than 3%

Further validation tests in progress

G.A.P. Cirrone, G. Cuttone, F. Di Rosa, S. Guatelli, A. Heikkinen, B. Mascialino, M. G. Pia, G. Russo

Validation of Geant4 Physics Models for the Simulation of the Proton Bragg Peak

In preparation, to be submitted to IEEE Trans. Nucl. Sci.

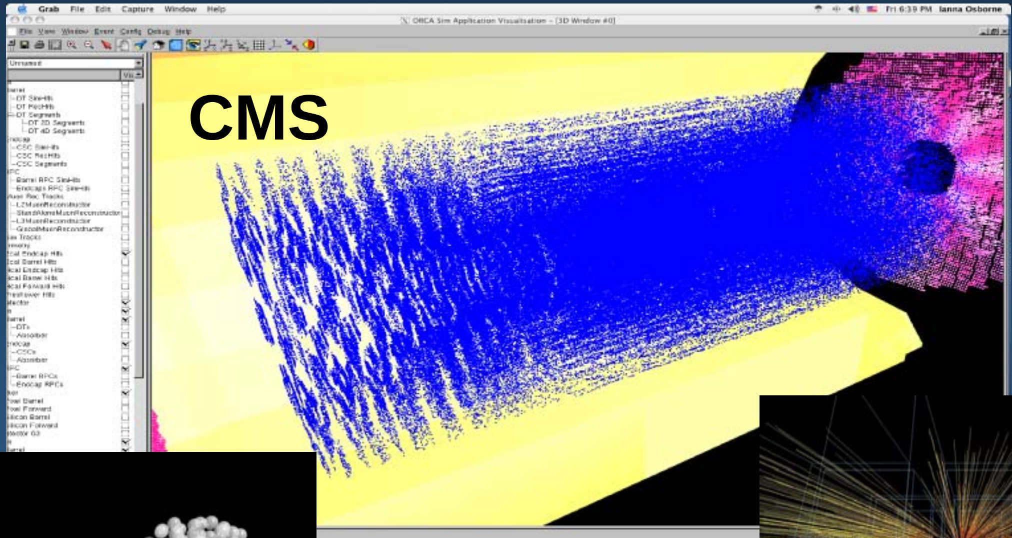
See talk at CHEP06, Mumbai, 13-17 February 2006

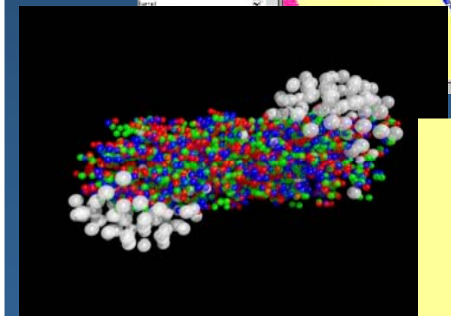
Severals papers published by user groups (Japan, US, Europe…)

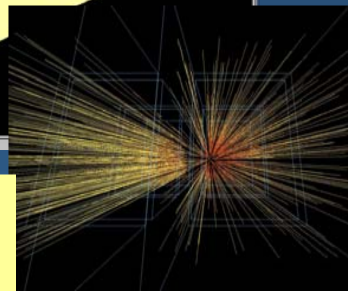
Heavy ion beams

NIRS N. Kanematsu, M. Komori - Nagoya K. Niwa, T.Toshito, T.Nakamura, T.Ban, N.Naganawa, S.Takahashi - Uchu-ken M.Ozaki - Kobe S. Aoki - Aichi Y.Kodama - Naruto H.Yoshida - Ritsumei S.Tanaka - SLAC M. Asai, T. Koi - Tokyo N.Kokubu - Gunma K. Yusa - Toho H.Shibuya, R.Ogawa, A. Shibazaki, T.Fukushima - KEK K. Amako, K.Murakami, T. Sasaki

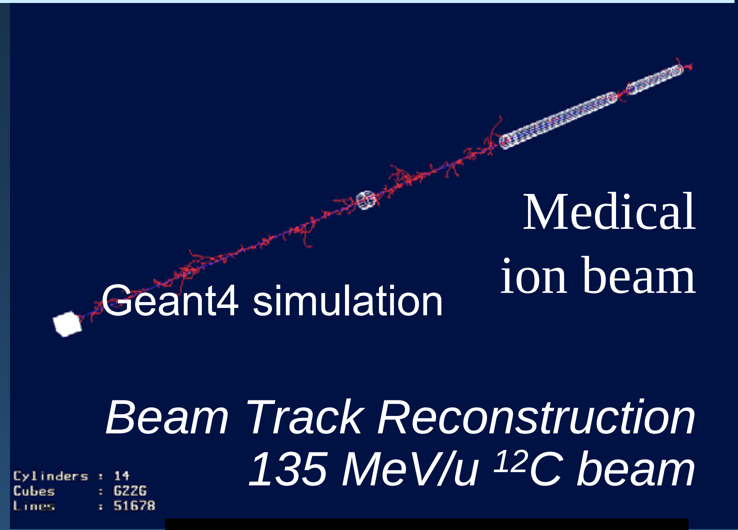
~ 180 minutes to simulate 1 event with 55K generator tracks

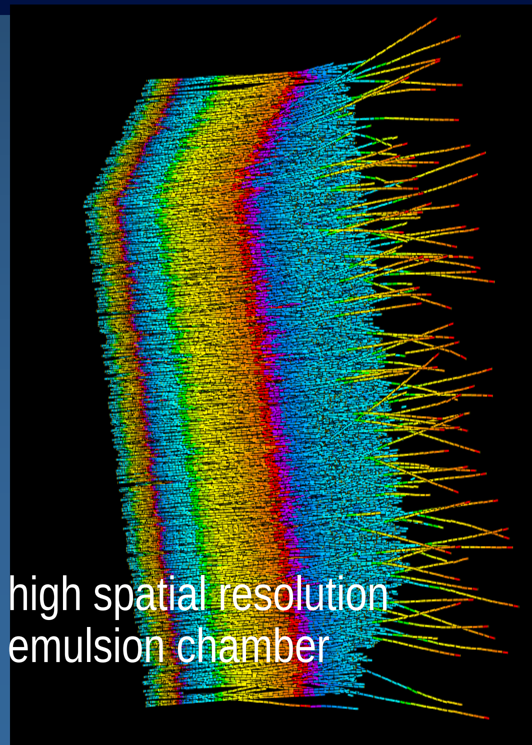






Events with > 50000 particles/event in detector acceptance





See more in K. Amako's talk

Exotic Geant4 applications…

FAO/IAEA International Conference on
Area-Wide Control of Insect Pests:

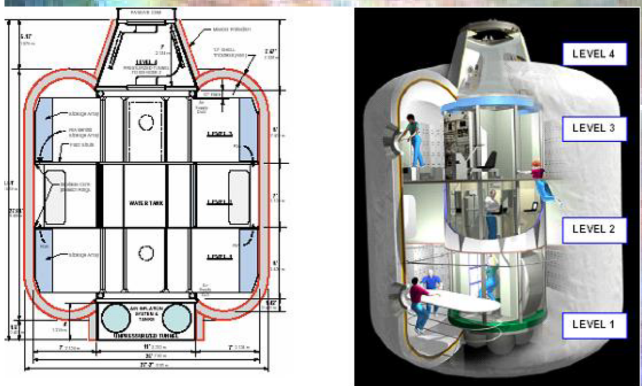
Integrating the Sterile Insect
and Related Nuclear and Other Techniques

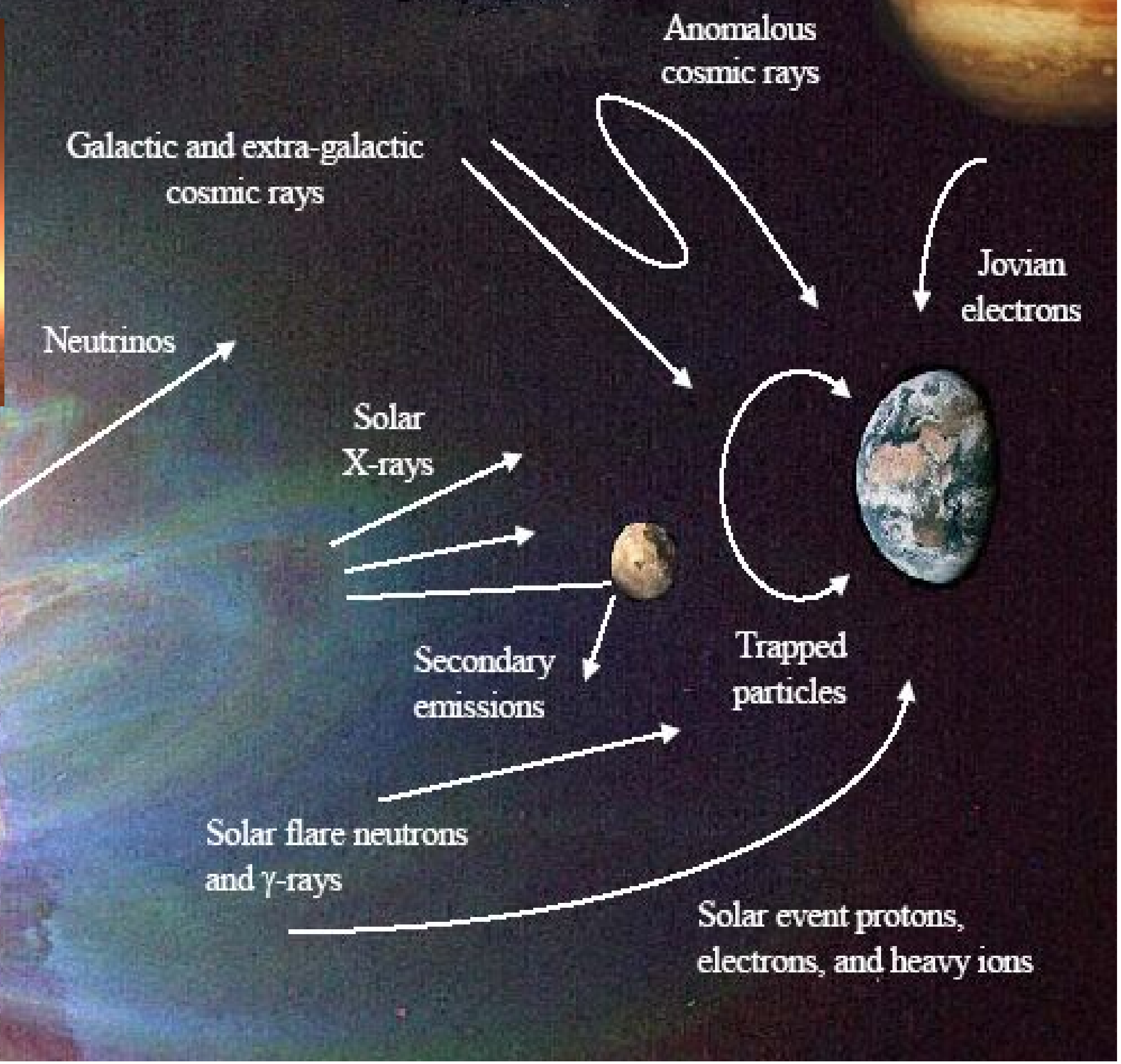
Vienna, May 9-13, 2005

K. Manai, K. Farah, A.Trabelsi, F. Gharbi and O. Kadri (Tunisia)

Dose Distribution and Dose Uniformity in Pupae Treated by the Tunisian Gamma Irradiator Using the GEANT4 Toolkit

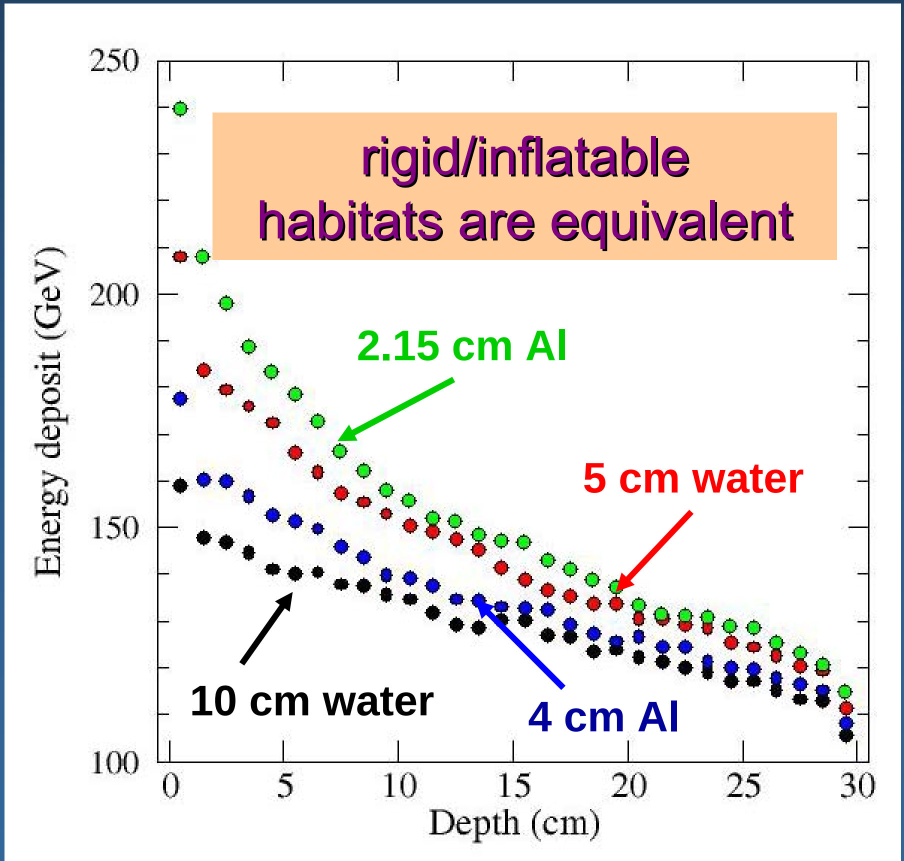
Radiation protection for interplanetary manned missions

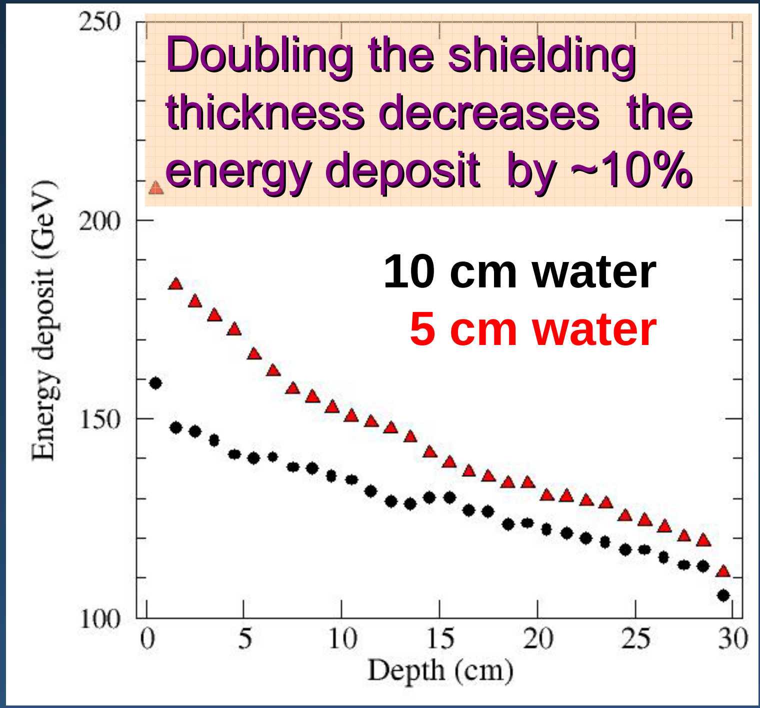


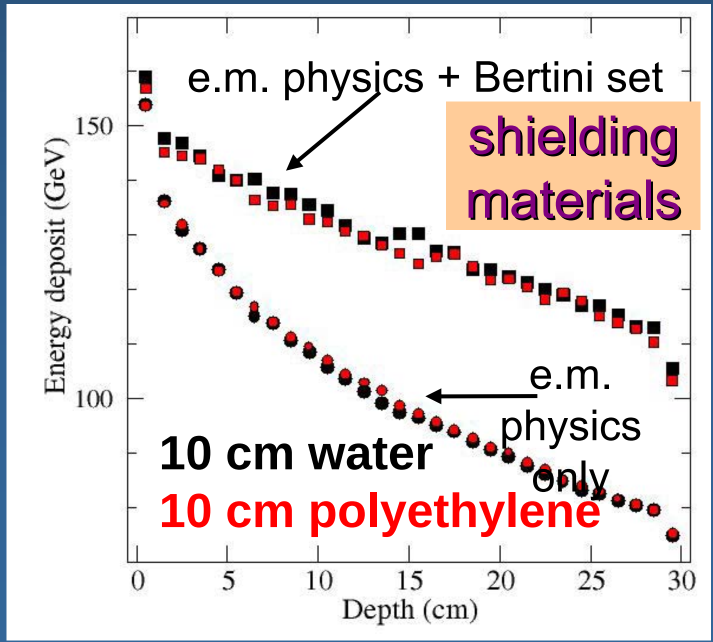


Geant 4

S. Guatelli et al., Geant4 Simulation for interplanetary manned missions,
to be submitted to IEEE Trans. Nucl. Sci.



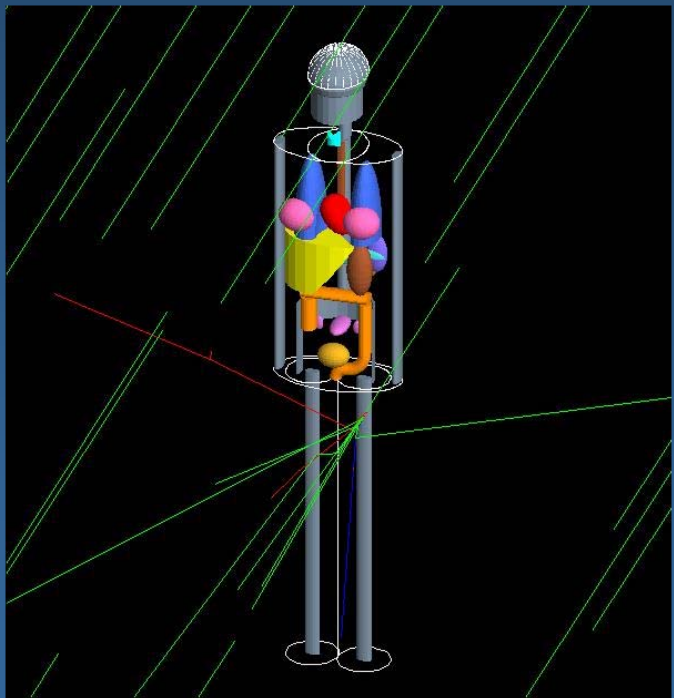




A major concern in radiation protection is the
dose accumulated in organs at risk

Geant 4

Anthropomorphic Phantoms

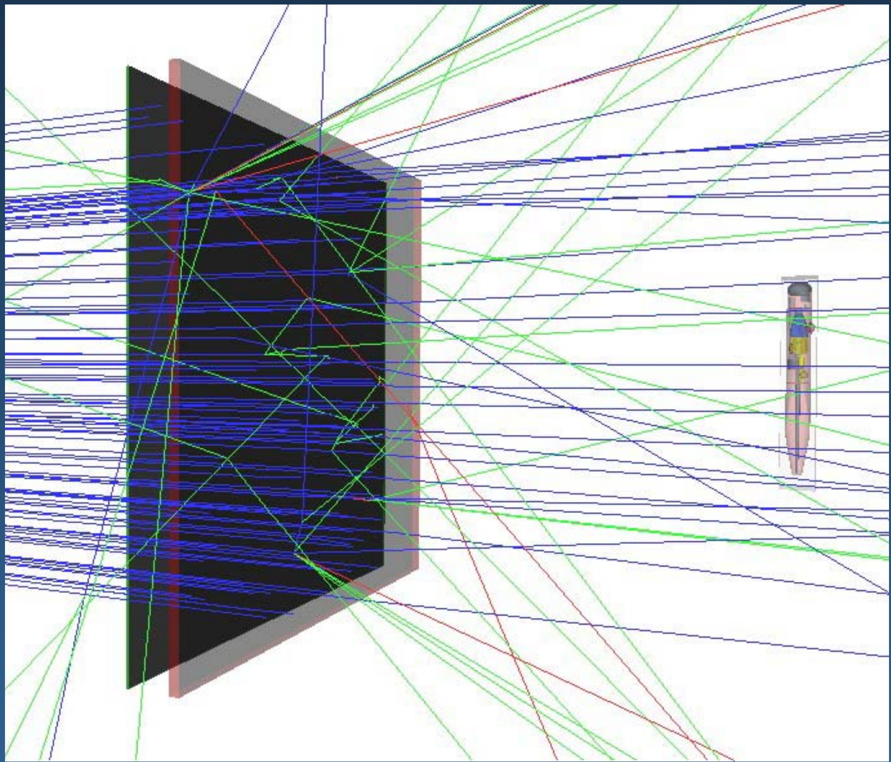


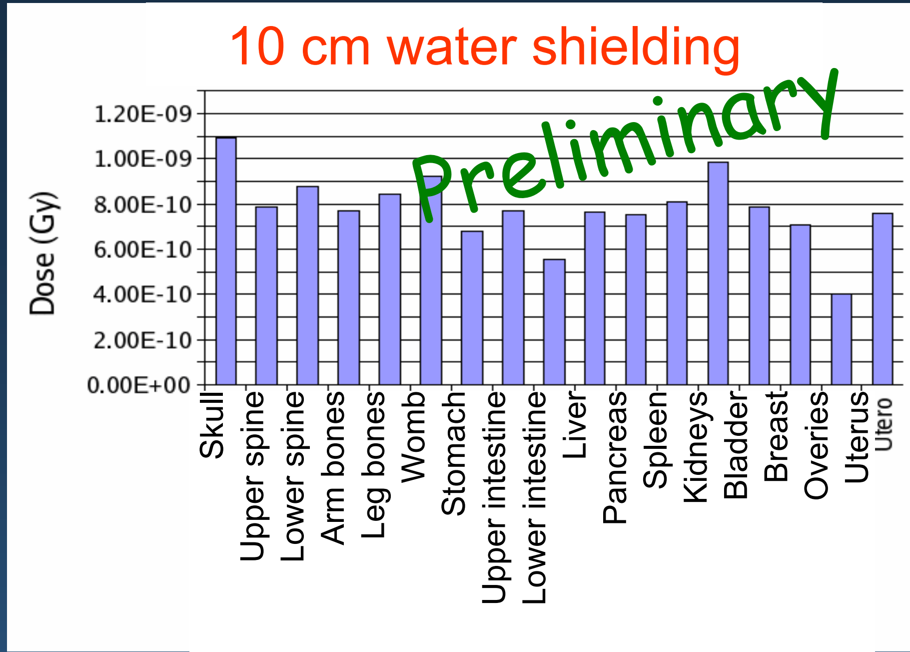
- Development of anthropomorphic phantom models for Geant4
  - evaluate dose deposited in critical organs
- Original approach
  - analytical and voxel phantoms in the same simulation environment

Analytical phantoms
Geant4 CSG, BREPS solids
Voxel phantoms
Geant4 parameterised volumes

GDML
for geometry description storage

Radiation exposure of astronauts





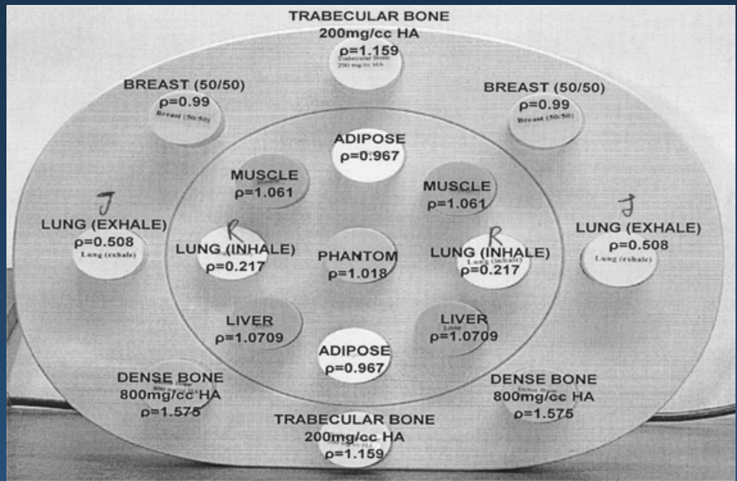
Dose calculation in critical organs

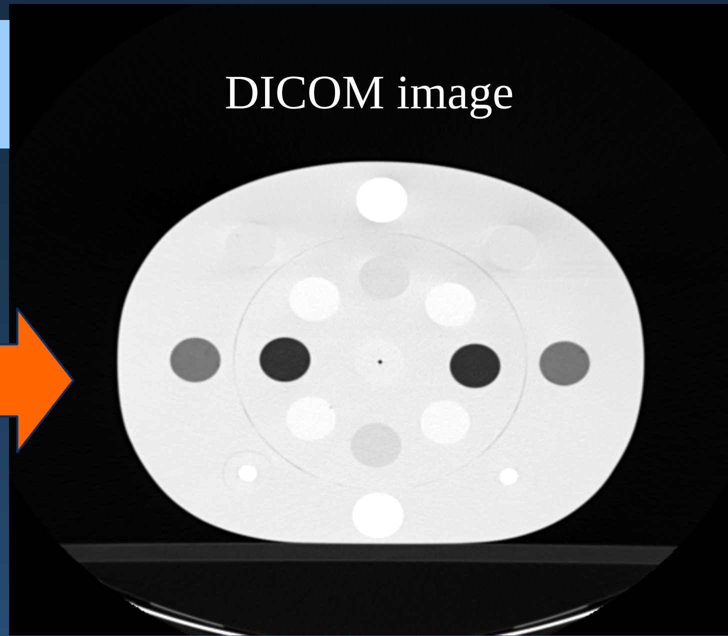
Effects of external shielding
self-body shielding

Geant 4

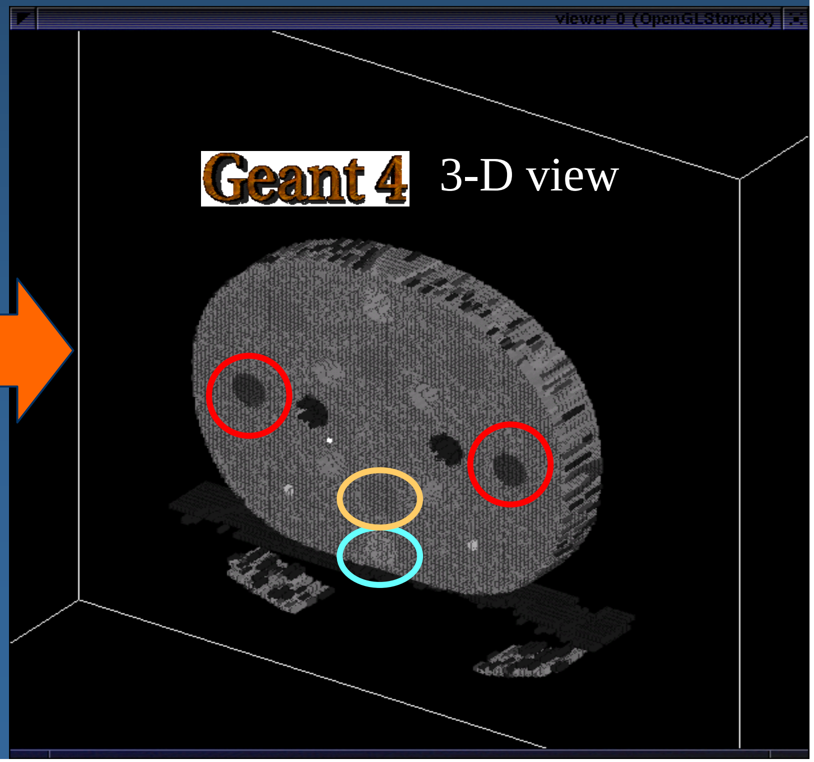
opens new ground for
precise dose calculation and
TBI optimisation

Geant4-DICOM interface





- Reading image information
- Transformation of pixel data into densities
- Association of densities to a list of materials
- Defining the voxels
  - Geant4 parameterised volumes
  - parameterisation function: material



CENTRE DE RECHERCHE
Pavillon L'Hôtel-Dieu
Centre hospitalier universitaire de Québec
UNIVERSITÉ LAVAL
L. Archambault, L. Beaulieu, V.-H. Tremblay

Comparison with commercial treatment planning systems

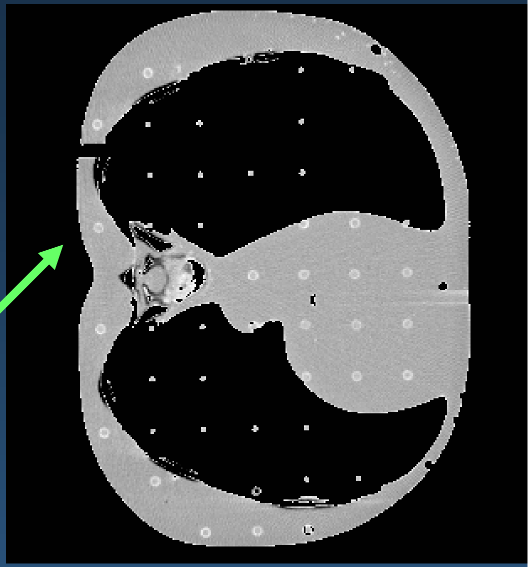
M. C. Lopes [1], L. Peralta [2], P. Rodrigues [2], A. Trindade [2]
[1] IPOFG-CROC Coimbra Oncological Regional Center - [2] LIP - Lisbon

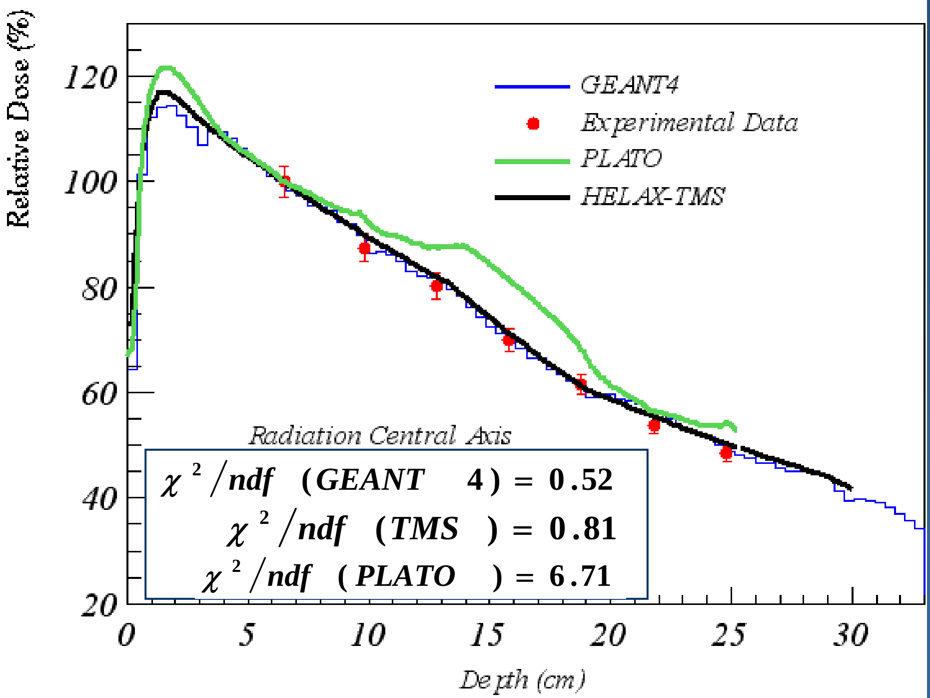
Siemens KD2 linear accelerator,
6 MV photon mode

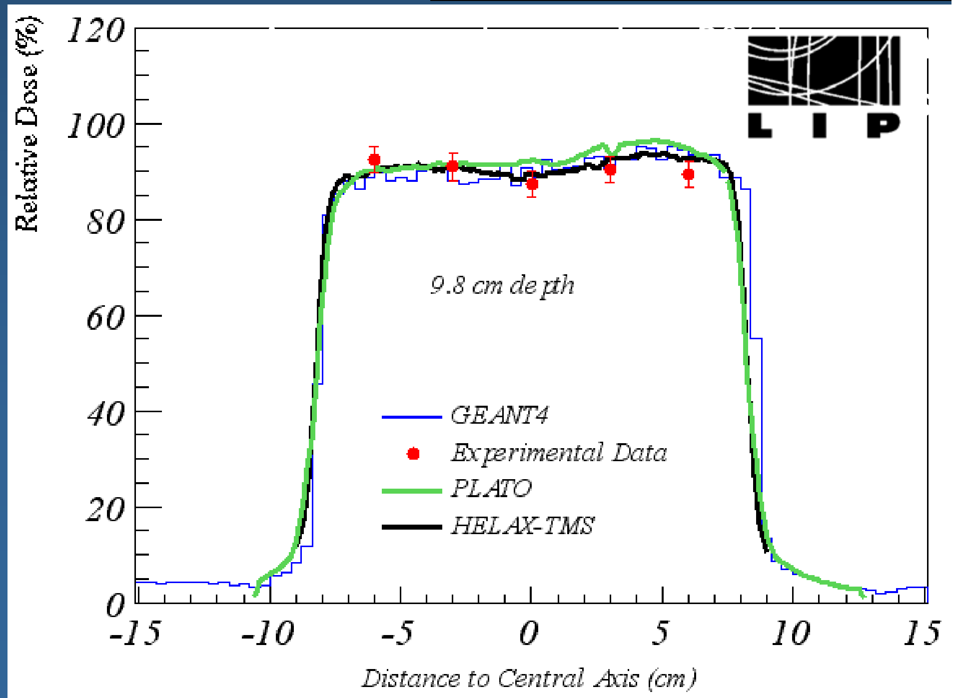
CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter

CT images used to define the geometry:

a thorax slice from a Rando anthropomorphic phantom







Speed of Monte Carlo simulation

Speed of execution is often a concern in Monte Carlo simulation

Often a trade-off between precision of the simulation and speed of execution

Typical use cases

Semi-interactive response

- Detector design
- Optimisation
- Oncological radiotherapy

Very long execution time

- High statistics simulation
- High precision simulation

Methods for faster simulation response

Fast simulation (analytical methods)

Variance reduction techniques (event biasing)

Inverse Monte Carlo methods

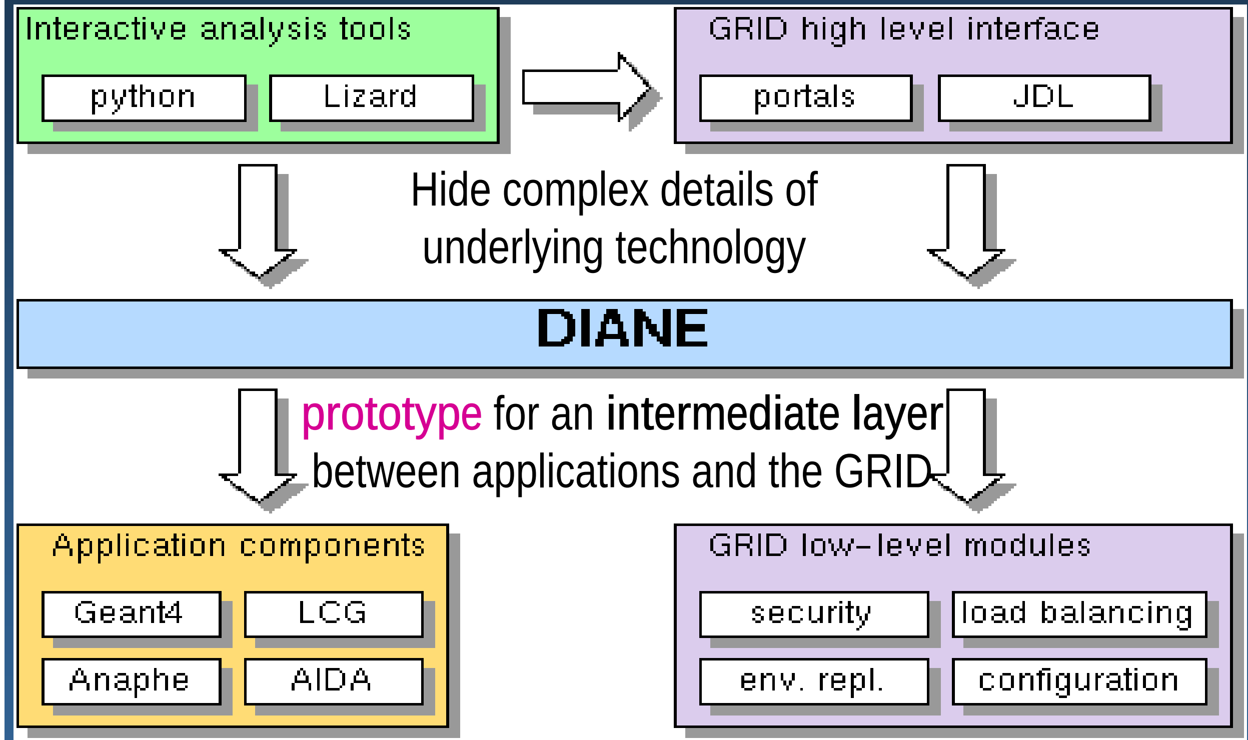
Parallelisation

S. Guatelli, A. Mantero, P. Mendez Lorenzo, J. Moscicki, M. G. Pia

Geant4 simulation in a distributed computing environment

In preparation, to be submitted to IEEE Trans. Nucl. Sci.

See talk at CHEP06, Mumbai, 13-17 February 2006



Sequential
1 machine: ~ 4h 38'

Local PC farm (Taipei)
29 machines: ~ 12'

GRID
27 machines: ~ 25'
(preliminary)

Same code

Master-Worker
architectural pattern

http://cern.ch/DIANE

Parallel cluster processing

– make fine tuning and customisation easy
– transparently using GRID technology
– **application independent**

File Edit View Favorites Tools Help

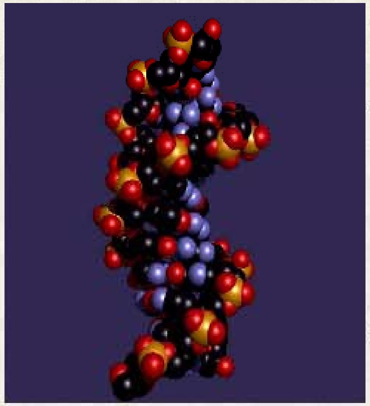
http://www.ge.infn.it/geant4/dna

Go Links

Geant 4 DNA

- Home
- Requirements
- Documents
- Talks
- Papers
- Meetings
- Team
- Geant4
- Geant4-INFN
- Geant4 LowE Physics
- Useful links

Simulation of Interactions of Radiation with Biological Systems at the Cellular and DNA Level

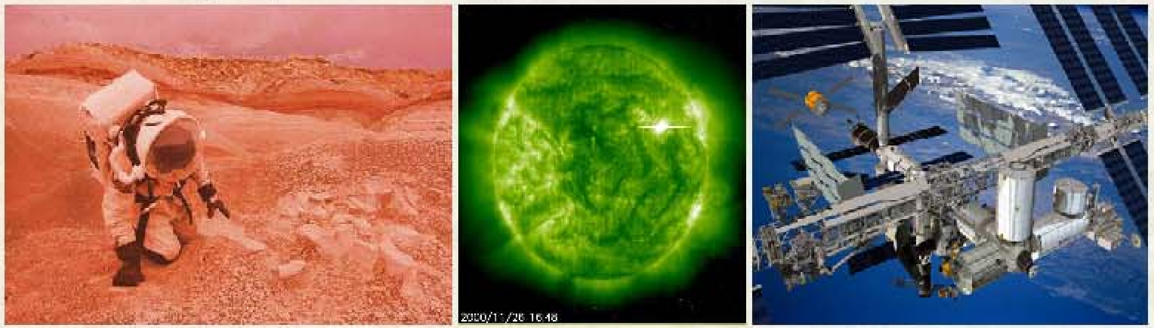


Estimating **cancer risk for human exposures to space radiation** is a challenge which involves a wide range of knowledge in physics, chemistry, biology and medicine.

Traditionally, the biological effects of radiation are analysed in top-bottom order, i.e. evaluation of the absorbed macroscopic radiation dose at a given location in the biological tissue is translated to the degree of danger it presents, and dose limits are consequently set that are considered to be acceptable.

A novel approach, based on the new-generation object-oriented **Geant4** Monte Carlo Toolkit, proceeds in a reverse order, from bottom to top, by analysing the nano-scale effects of energetic particles at the cellular and DNA molecule level.

This project is sponsored by the European Space Agency (ESA) and is pursued by a multidisciplinary European team of biologists, physicians, physicists, space scientists and software engineers.



Pictures courtesy of ESA

Geant 4 DNA

The concept of “dose” fails at cellular and DNA scales

It is desirable to gain an understanding to the processes at all levels *(macroscopic vs. microscopic)*

- “Sister” activity to Geant4 Low-Energy Electromagnetic Physics
  - Follows the same rigorous software standards
- International (open) collaboration
  - ESA, INFN *(Genova, Torino)*, IN2P3 *(CENBG, Univ. Clermont-Ferrand)*
- Simulation of nano-scale effects of radiation at the DNA level
  - Various scientific domains involved
    - medical, biology, genetics, physics, software engineering
  - Multiple approaches can be implemented with Geant4
    - RBE parameterisation, detailed biochemical processes, etc.
- First phase: 2000-2001
  - Collection of user requirements & first prototypes
- Second phase: started in 2004
  - Software development & open source release

Cellular level

Theories and models for cell survival

TARGET THEORY MODELS
- Single-hit model
- Multi-target single-hit model
- Single-target multi-hit model

MOLECULAR THEORY MODELS
- Theory of radiation action
- Theory of dual radiation action
- Repair-Misrepair model
- Lethal-Potentially lethal model

Geant4 approach: variety of models all handled through the same abstract interface

in progress

Geant 4

Critical evaluation of the models

Requirements
Problem domain analysis

Analysis & Design
Implementation
Test

Experimental validation of Geant4 simulation models

DNA level

Low Energy Physics extensions

- Specialised processes down to the eV scale
  - at this scale physics processes depend on material, phase etc.
  - in progress: Geant4 processes in water at the eV scale
  - β-release winter 2006
- Processes for other material than water to follow
  - interest for radiation effects on components

Current status

	Electrons	Protons (H+)	Hydrogen (H)	Alpha (He++)	He+	He
Elastic	Brenner (7.5 - 200 eV) Emfietzoglou (> 200 ev)	Negligible effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect
Excitation	Emfietzoglou Born (7 ev – 10 keV)	Miller and Green Born (100 eV – 10 MeV)	Negligible effect	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)
Charge decrease	Not pertinent to this particle	Dingfelder (100 eV – 2 MeV)	Not pertinent to this particle	In progress	In progress	Not pertinent to this particle
Charge increase	Not pertinent to this particle	Not pertinent to this particle	Miller and Green Dingfelder (0.1 Kev – 100 MeV)	Not pertinent to this particle	In progress	In progress
Ionization	In progress	Rudd (0.1 - 500 keV) In progress (> 500 keV)	Rudd (0.1 – 100 MeV)	In progress	In progress	In progress

Cross sections

	Electrons	Protons (H+)	Hydrogen (H)	Alpha (He++)	He+	He
Elastic	Brenner (7.5 - 200 eV) Emfietzoglou (> 200 ev)	Negligible effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect
Excitation	Emfietzoglou Born (7 ev – 10 keV)	Miller and Green Born (100 eV – 10 MeV)	Negligible effect	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)
Charge decrease	Process not pertinent to this particle	Dingfelder (100 eV – 2 MeV)	Process not pertinent to this particle	In progress	In progress	Process not pertinent to this particle
Charge increase	Process not pertinent to this particle	Process not pertinent to this particle	Miller and Green Dingfelder (0.1 Kev – 100 MeV)	Process not pertinent to this particle	In progress	In progress
Ionization	In progress	Rudd (0.1 - 500 keV) In progress (> 500 keV)	Rudd (0.1 – 100 MeV)	In progress	In progress	In progress

Process kinematics

	Electrons	Protons (H+)	Hydrogen (H)	Alpha (He++)	He+	He
Elastic	Brenner (7.5 - 200 eV) Emfietzoglou (> 200 ev)	Negligible effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect
Excitation	Emfietzoglou Born (7 ev – 10 keV)	Miller and Green Born (100 eV – 10 MeV)	Negligible effect	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)
Charge decrease	Process not pertinent to this particle	Dingfelder (100 eV – 2 MeV)	Process not pertinent to this particle	In progress	In progress	Process not pertinent to this particle
Charge increase	Process not pertinent to this particle	Process not pertinent to this particle	Miller and Green Dingfelder (0.1 Kev – 100 MeV)	Process not pertinent to this particle	In progress	In progress
Ionization	In progress	Rudd (0.1 - 500 keV) In progress (> 500 keV)	Rudd (0.1 – 100 MeV)	In progress	In progress	In progress

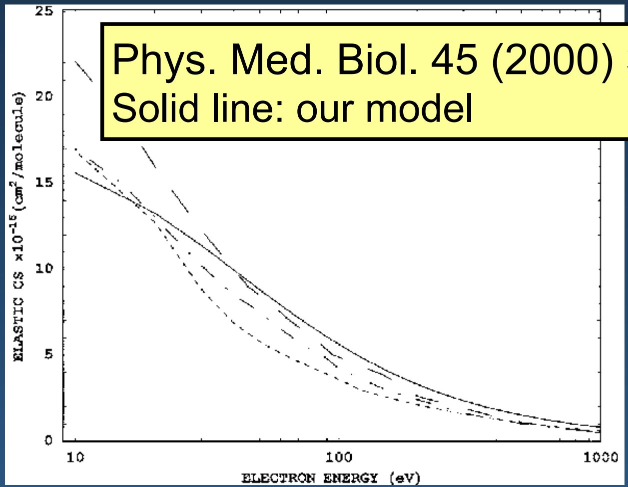
Final state generation

	Electrons	Protons (H+)	Hydrogen (H)	Alpha (He++)	He+	He
Elastic	Brenner (7.5 - 200 eV) Emfietzoglou (> 200 ev)	Negligible effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect
Excitation	Emfietzoglou Born (7 ev – 10 keV)	Miller and Green Born (100 eV – 10 MeV)	Negligible effect	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)	Miller and Green (1 keV – 15 MeV)
Charge decrease	Process not pertinent to this particle	Dingfelder (100 eV – 2 MeV)	Process not pertinent to this particle	In progress	In progress	Process not pertinent to this particle
Charge increase	Process not pertinent to this particle	Process not pertinent to this particle	Miller and Green Dingfelder (0.1 Kev – 100 MeV)	Process not pertinent to this particle	In progress	In progress
Ionization	In progress	Rudd (0.1 - 500 keV) In progress (> 500 keV)	Rudd (0.1 – 100 MeV)	In progress	In progress	In progress

Elastic scattering

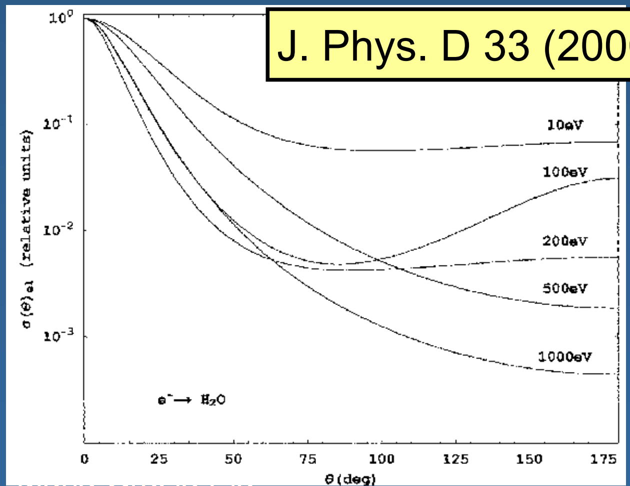
- Total cross section

Phys. Med. Biol. 45 (2000) 3171-3194
Solid line: our model

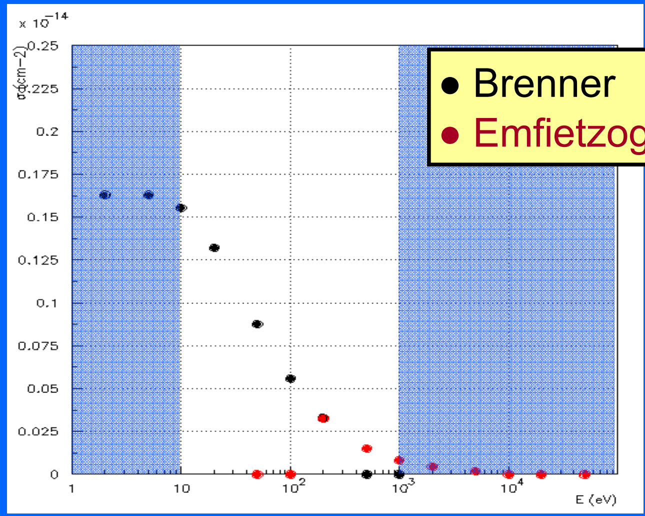


- Angular distribution

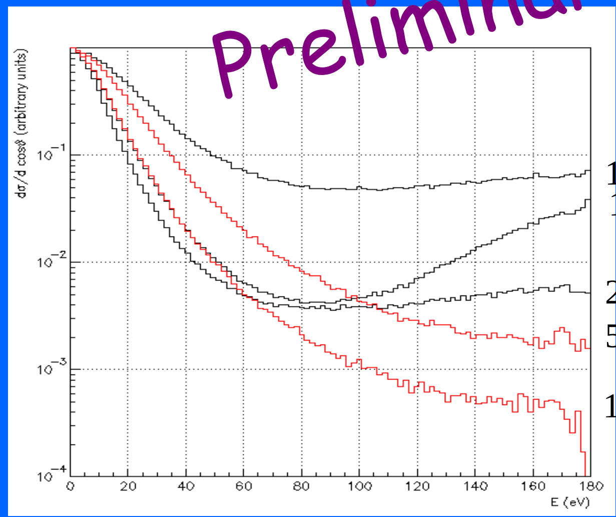
J. Phys. D 33 (2000) 932-944



Geant 4



Preliminary



Geant 4 for medicine

- Macroscopic level
  - calculation of dose
  - already feasible with Geant4
  - develop useful associated tools
- Cellular level
  - cell modelling
  - processes for cell survival, damage etc.
- DNA level
  - DNA modelling
  - physics processes at the eV scale
  - bio-chemical processes
  - processes for DNA damage, repair etc.

Complexity of

software, physics and biology

addressed with an iterative and incremental software process

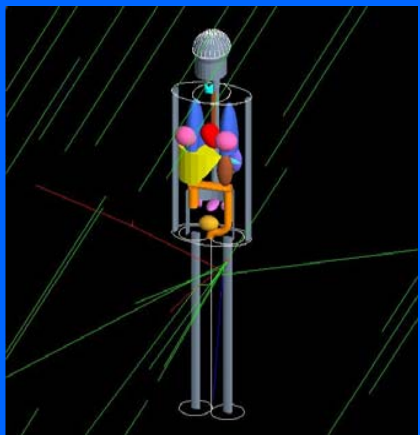
↓

Parallel development at all the three levels

(domain decomposition)

Scenario
for Mars (and earth…)

Geant4 simulation
treatment source
+
geometry from CT image
or
anthropomorphic phantom



Dose in
organs at risk

Phase space input
to nano-simulation

Geant4 simulation
with biological
processes at cellular
level (cell survival,
cell damage…)

Oncological risk to
astronauts/patients

Geant4 simulation with
physics at eV scale
+
DNA processes

Conclusions

- Geant4 offers powerful geometry and physics modelling in an advanced computing environment
- Wide spectrum of complementary and alternative physics models

- Multi-disciplinary applications of dosimetry simulation
- Precision of physics, validation against experimental data

- Geant4-DNA: extensions for microdosimetry
  - physics processes at the eV scale
  - biological models

- Multiple levels addressed in the same simulation environment
  - conventional dosimetry
  - processes at the cellular level
  - processes at DNA level

- OO technology in support of physics versatility: openness to extension, without affecting Geant4 kernel

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Phys. Med. Biol. **48** No 18, 3021-3042

…and many more in other journals

Meditations…

CHEP 2001, Beijing, China
Computing in High Energy Physics

- HEP computing has a potential for technology transfer
  - not only the WWW…
  - not only Geant4…
- The role of HEP: expertise, but also reference
  - Physics and software engineering expertise
  - Reference to many small groups and diverse activities
- Technology transfer: collaboration rather than colonisation
  - Valuable contributions from the medical domain (requirements, testing, rigorous methodologies…)
  - New resources into projects of common interest
  - Avoid the “colonial” attitude