

The **Geant 4** Simulation Toolkit

and its applications to medical and space science



Maria Grazia Pia
INFN Genova, Italy

H. Araujo, S. Chauvie, G.A.P. Cirrone, G. Cuttone, F. Foppiano, S. Guatelli, A. Howard,
J. Knobloch, E. Lamanna, F. Longo, A. Mantero, L. Peralta, P. Rodrigues, A. Trindade
for the Geant4 Collaboration

...with contributions from many **Geant 4** users

VIII Simulation Symposium
Hayama, 3-7 September 2001

What is Geant 4?

OO Toolkit for the simulation of next generation HEP detectors

*...of the current generation too
...not only of HEP detectors*

also...

An experiment of distributed software production and management

An experiment of application of rigorous software engineering methodologies and Object Oriented technology to the HEP environment

Born from the requirements of large scale HEP experiments

Geant3

- ✦ Fortran
- ✦ CERN product

inadequate for LHC experiments

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

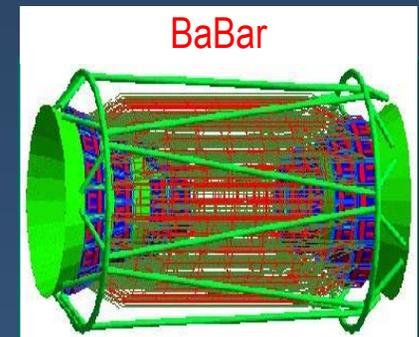
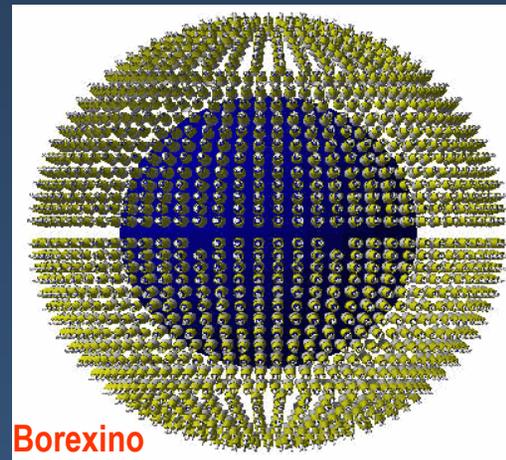
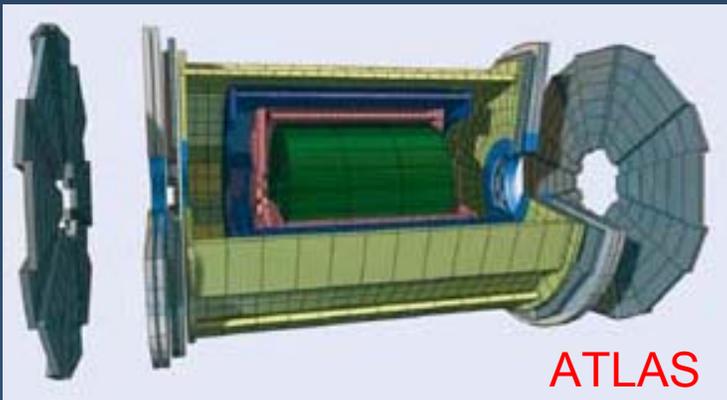
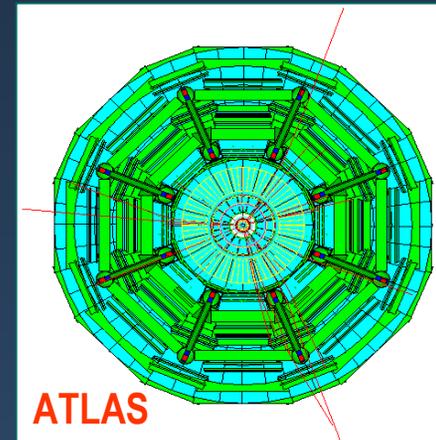
1st release: December 1998

2 new releases/year since then

Geant 4

Code and
documentation
publicly distributed
from www

- Run, event and track management
- PDG-compliant particle management
- Geometry and materials
- Tracking
- **Physics processes**
- Detector response
- User interface
- Visualisation
- Persistency





Geant4 Collaboration

Development, maintenance, distribution, user support of the Geant4 Toolkit



Laboratories

CERN, TJNL, KEK, SLAC, TRIUMF



Agencies

European Space Agency (ESA)



National Institutes

INFN (Italy), IN2P3 (France), PPARC (UK)



Research Institutes

Karolinska (Stockholm), LIP (Lisbon)

Lebedev (Moscow), Serpukov (Protvino), Budker (Novosibirsk)

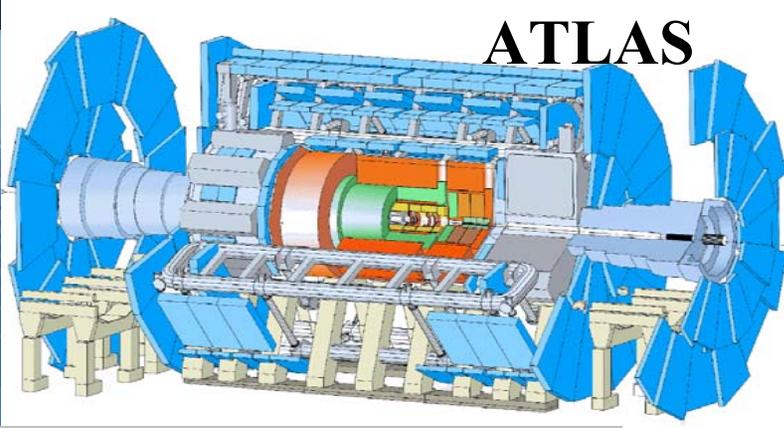


Universities

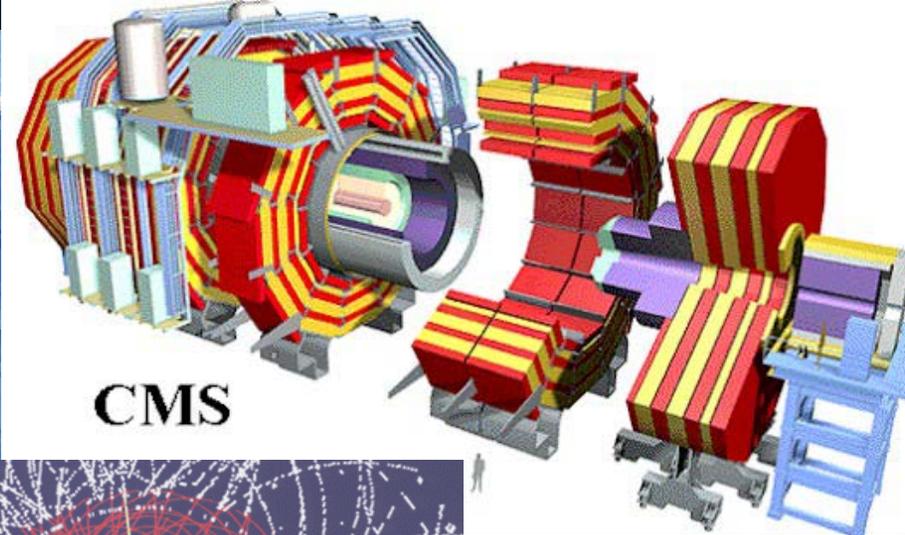
Barcelona (Spain), Cordoba (Argentina), Frankfurt (Germany), Helsinki (Finland), Northeastern (USA) etc.



Governed by a Memorandum of Understanding among the member parties



ATLAS



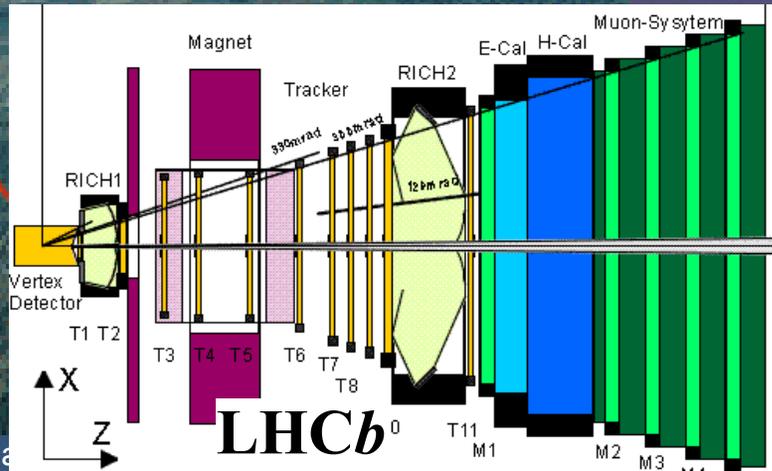
CMS



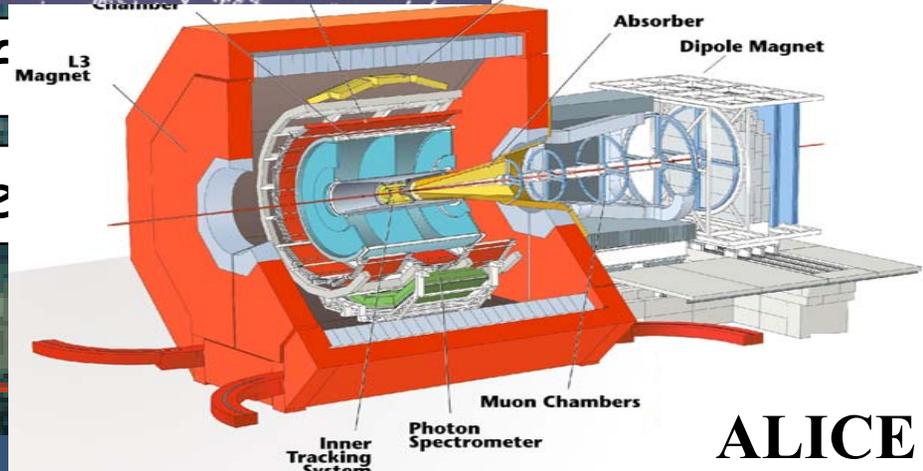
Storage
 Raw recording rate 0.1–1 GByte/s
 Accumulating at 5-8 PBytes/year

Complex physics, complex detectors...

Processing
 200,000 of today's fastest PCs

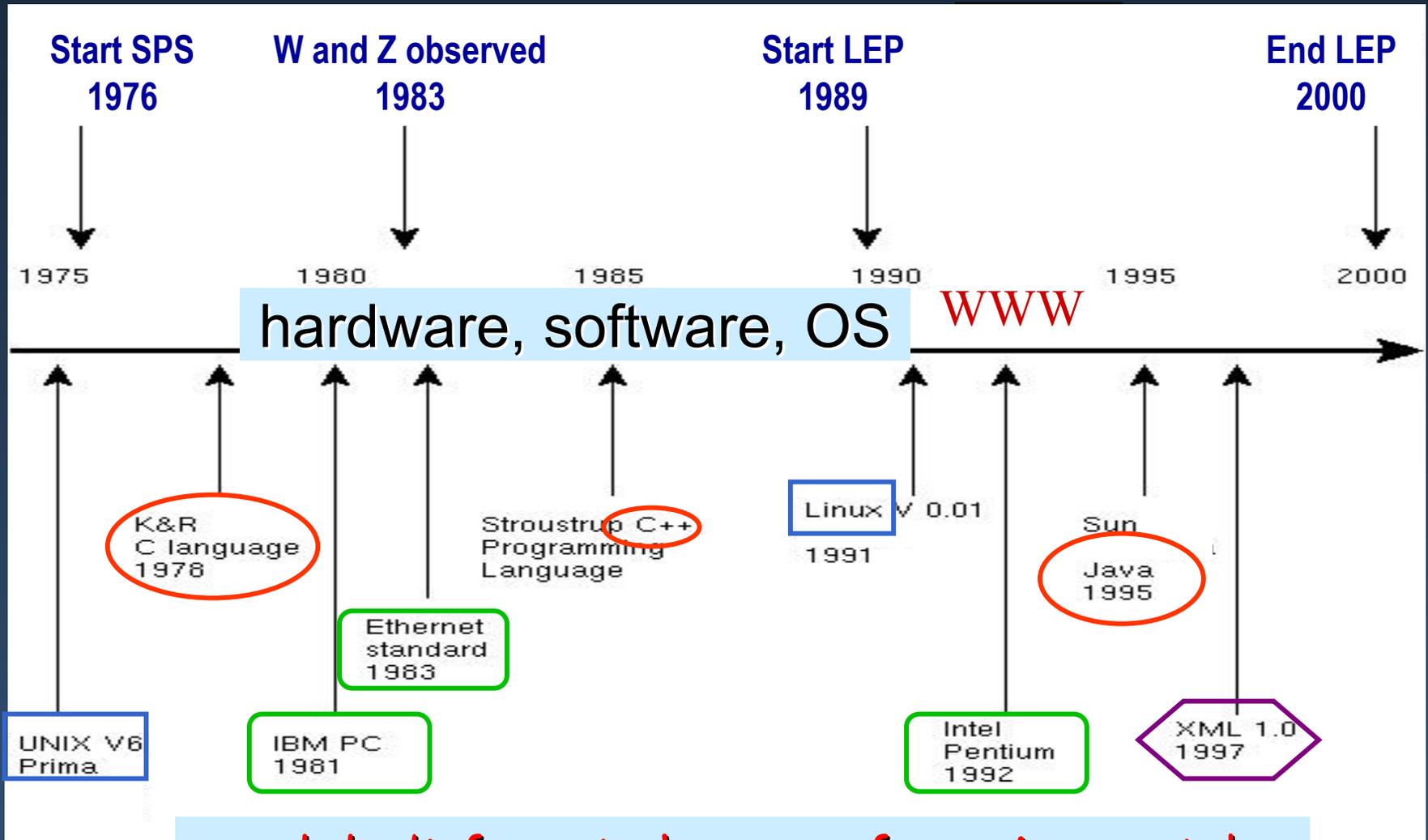


LHCb



ALICE

...in a fast changing computing environment



...and don't forget changes of requirements!

Evolution towards greater diversity  we must anticipate changes

Guidelines for physics

From the Minutes of LCB (LHCC Computing Board) meeting on 21 October, 1997:

“It was noted that experiments have requirements for **independent, alternative physics models**.

In Geant4 these models, differently from the concept of packages, allow the user to **understand** how the results are produced, and hence improve the **physics validation**.

Geant4 is developed with a modular architecture and is the ideal framework where existing components are integrated and new models continue to be developed.”

Physics in Geant4

Rich of diverse models

Transparent

Open to evolution

OO technology

Openness to **extension** and **evolution**

- new implementations can be added w/o changing existing code

Robustness and ease of **maintenance**

- **protocols** and well defined dependencies minimise coupling

Strategic vision



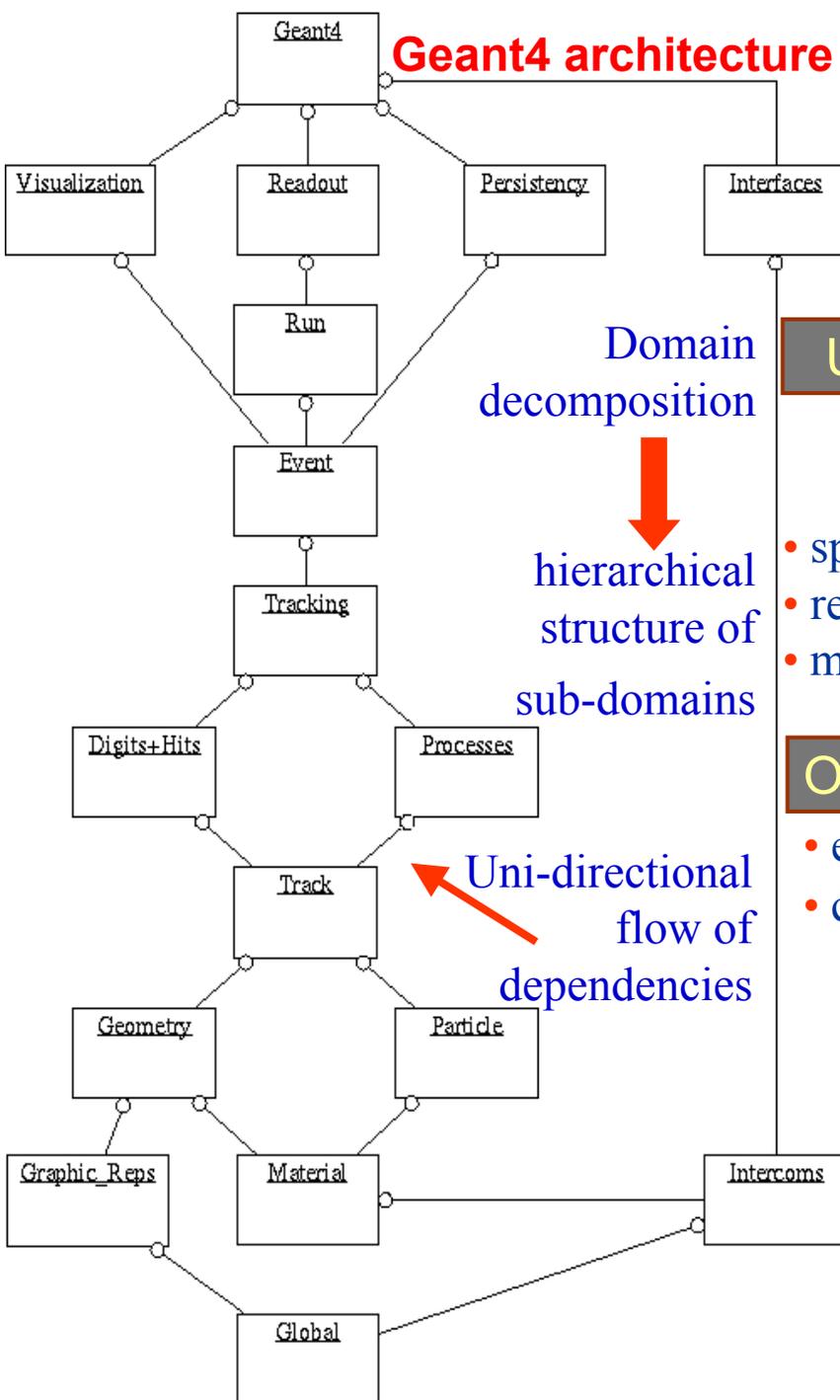
Toolkit

A set of compatible components

- each component is **specialised** for a specific functionality
- each component can be **refined** independently to great detail
- components can be **integrated** at any degree of complexity
- it is easy to provide (and use) **alternative** components
- the user application can be **customised** as needed

Software Engineering

plays a fundamental role in Geant4



User Requirements

- formally collected
- systematically updated
- PSS-05 standard

Software Process

- spiral iterative approach
- regular assessments and improvements
- monitored following the ISO 15504 model

Object Oriented methods

- OOAD
- use of CASE tools
- essential for distributed parallel development
- contribute to the transparency of physics

Quality Assurance

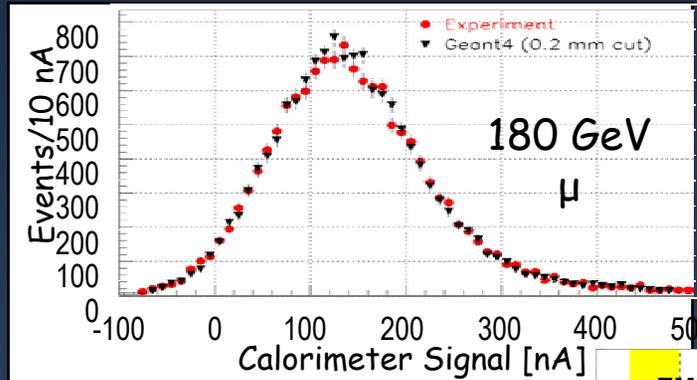
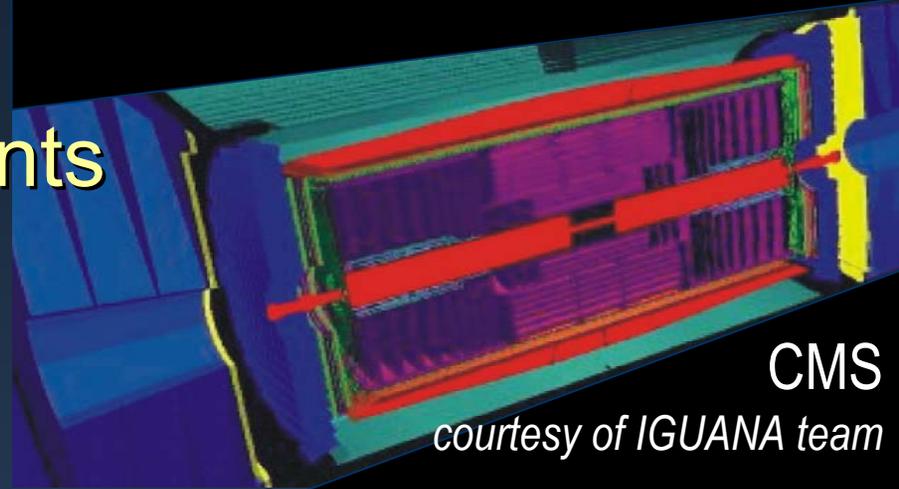
- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

Use of Standards

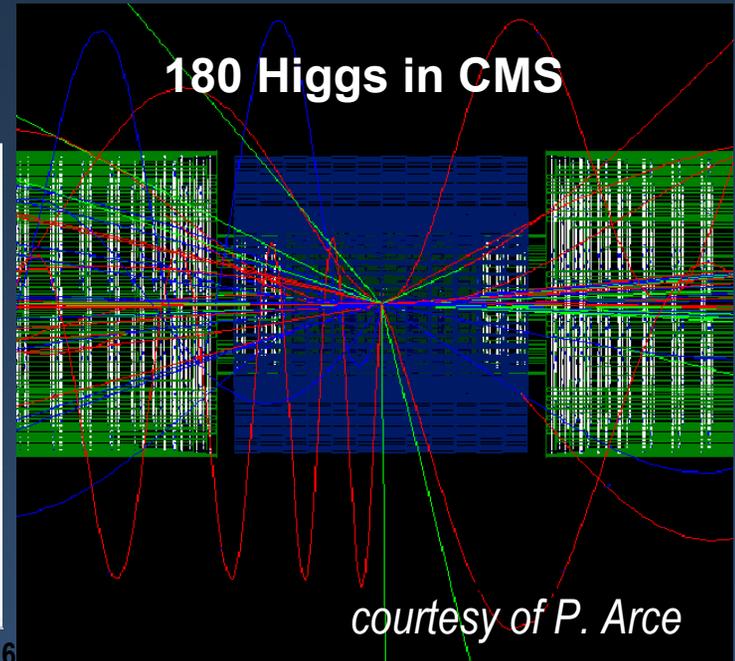
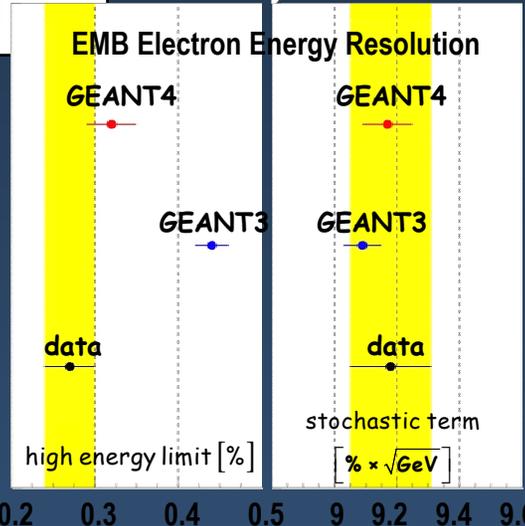
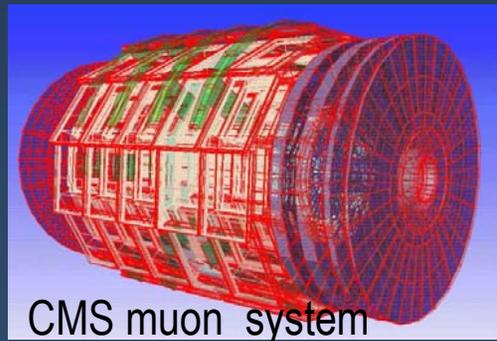
- de jure and de facto

Geant4 in LHC experiments

A few examples of usage...



Atlas,
courtesy of P. Loch



Geant4 is definitively a mature and useful product for large scale detector response simulations!

P. Loch (ATLAS experiment), Calor 2002 Conference



scientific...

Globalisation

Sharing requirements and functionality
across diverse fields

Requirements for LowE protons in **Geant 4**

GEANT4 LOW ENERGY ELECTROMAGNETIC PHYSICS

User Requirements Document

Status: in CVS repository

Version: 2.4

Project: Geant4-LowE

Reference: LowE-URD-V2.4

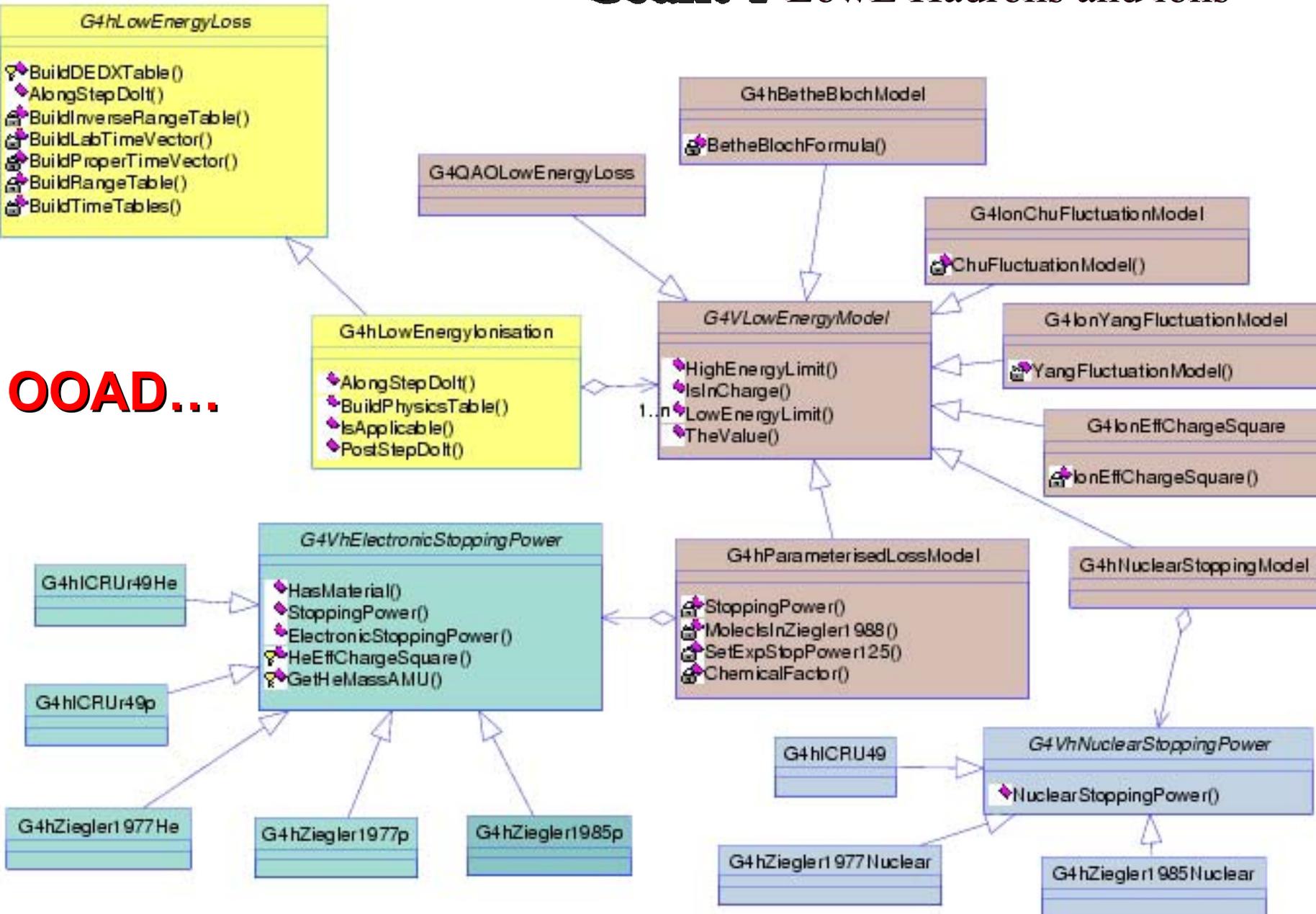
Created: 22 June 1999

Last modified: 26 March 2001

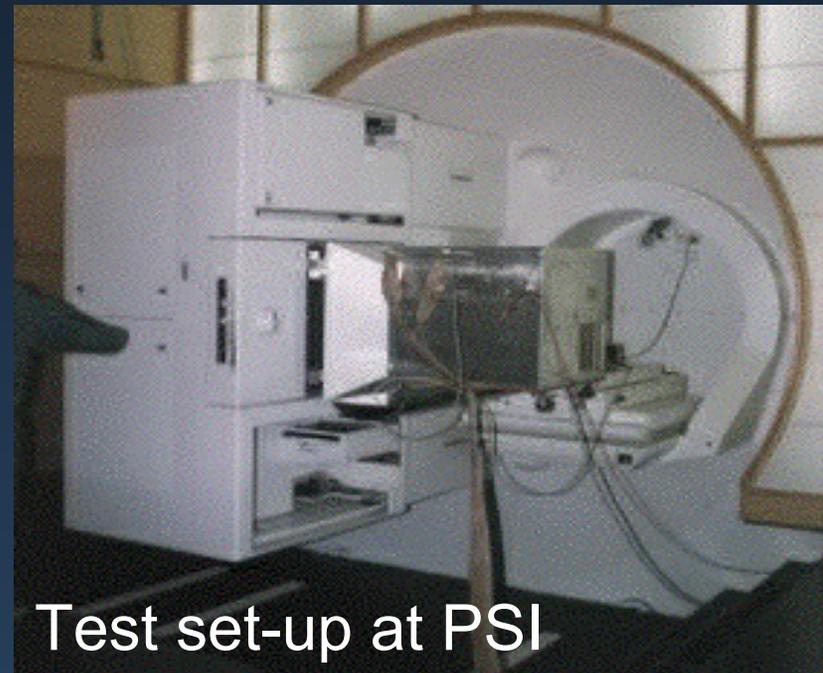
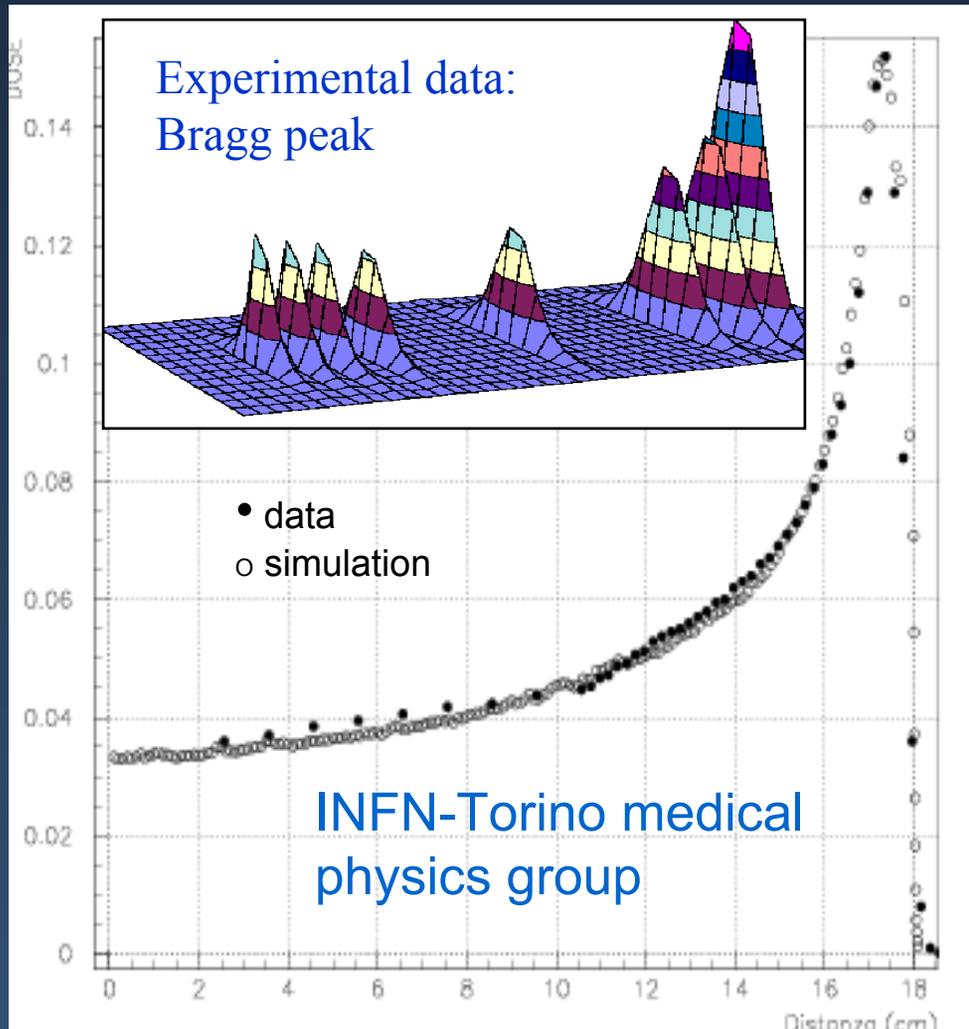
Prepared by: Petteri Nieminen (ESA) and Maria Grazia Pia (INFN)

- **UR 2.1** The user shall be able to simulate electromagnetic interactions of positive charged hadrons down to $E < 1$ KeV.
- **Need**: *Essential*
- **Priority**: *Required by end 1999*
- **Stability**: *T. b. d.*
- **Source**: *Medical physics groups, PIXE*
- **Clarity**: *Clear*
- **Verifiability**: *Verified*

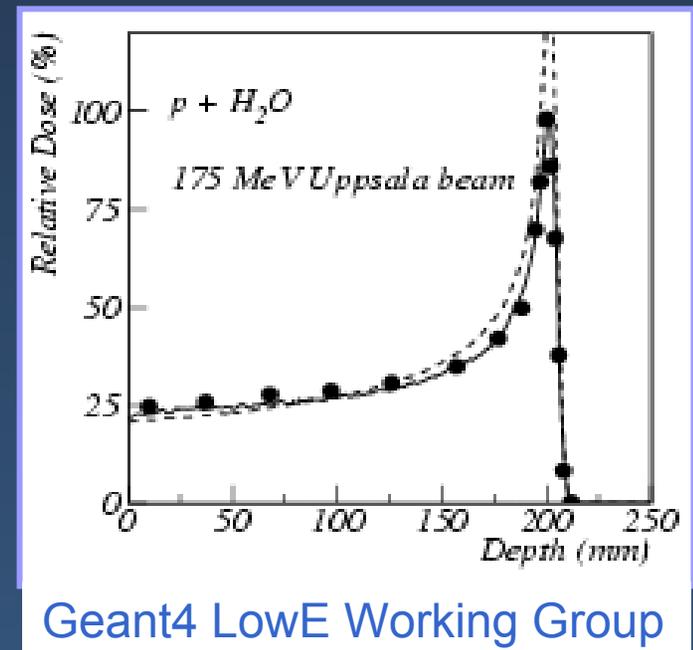
Geant 4 LowE Hadrons and ions



...and validation



Test set-up at PSI



Courtesy of R. Gotta,
Thesis

Chandra X-ray Observatory Status Update

September 14, 1999
MSFC/CXC
Press release



CHANDRA CONTINUES TO TAKE SHARPEST IMAGES EVER; TEAM STUDIES INSTRUMENT DETECTOR CONCERN

Normally every complex space facility encounters a few problems during its checkout period; even though Chandra's has gone very smoothly, the science and engineering team is working a concern with a portion of one science instrument.

The team is investigating a reduction in the energy resolution of one of two sets of X-ray detectors in the Advanced Charge-coupled Device Imaging Spectrometer (ACIS) science instrument.

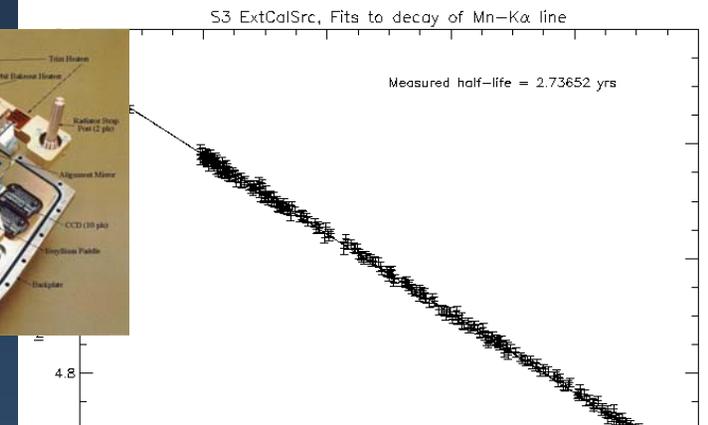
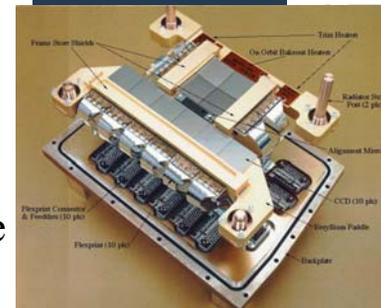
A series of diagnostic activities to characterize the degradation, identify possible causes, and test potential remedial procedures is underway.

The degradation appeared in the front-side illuminated Charge-Coupled Device (CCD) chips of the ACIS. The instrument's back-side illuminated chips have shown no reduction in capability and continue to perform flawlessly.

Maria Grazia Pia, 8th Simulation Symposium, Hayama

What could be the source of detector damage?

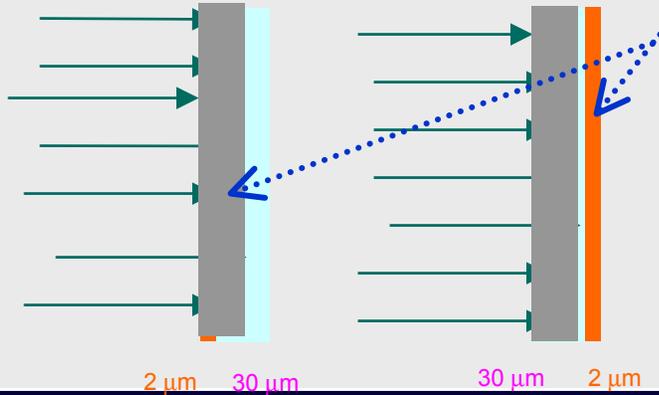
- Radiation belt electrons?
- Scattered in the mirror shells?
- Effectiveness of magnetic "brooms"?
- Electron damage mechanism? - NIEL?
- Other particles? Protons, cosmics?



"Analysis of ACIS calibration source data from the last 5 days has shown an unexplained degradation in the energy resolution of the front-side illuminated CCD chips of ACIS. The degradation is evident in data starting from 5 days ago and shows a change in the FWHM from approx 130 eV to 500 eV"

Operations CXO Status Report
Friday 9/10/99 10:00am EST

Active layer
Passive layer

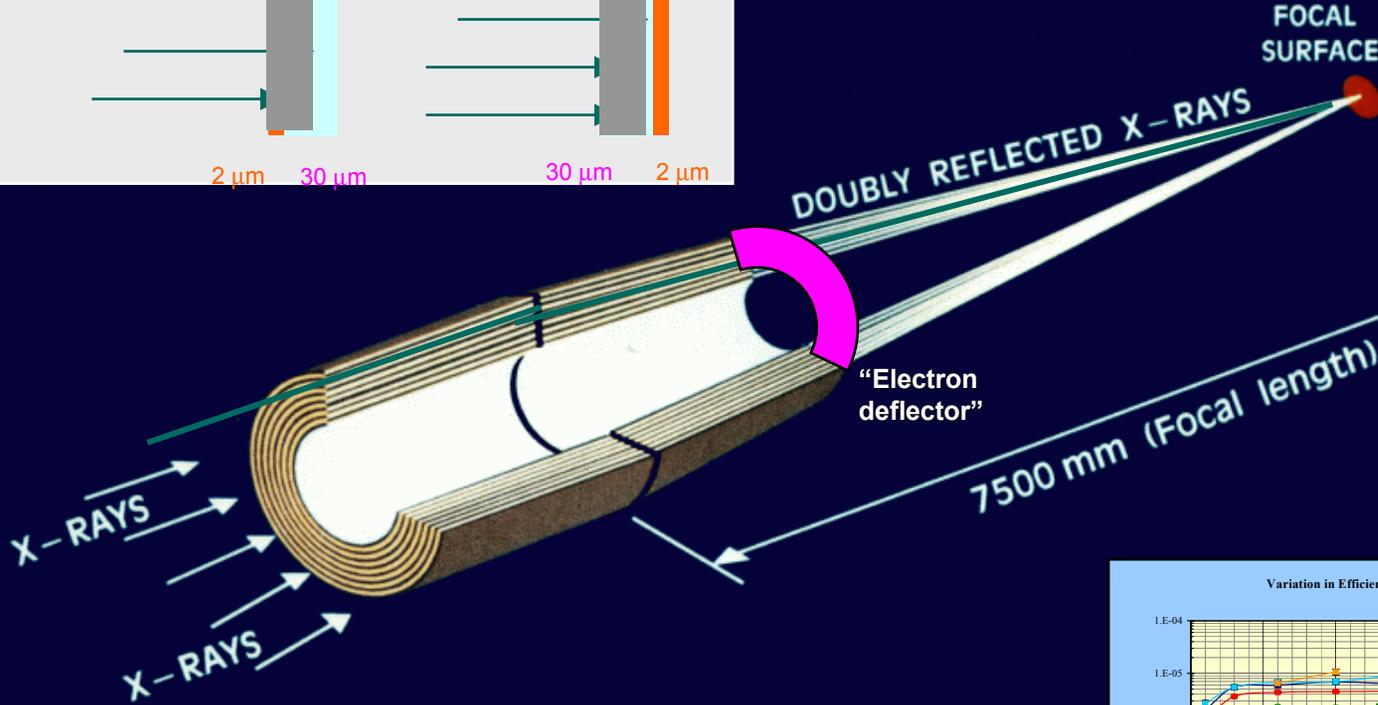


CCD displacement damage:
front vs. back-illuminated

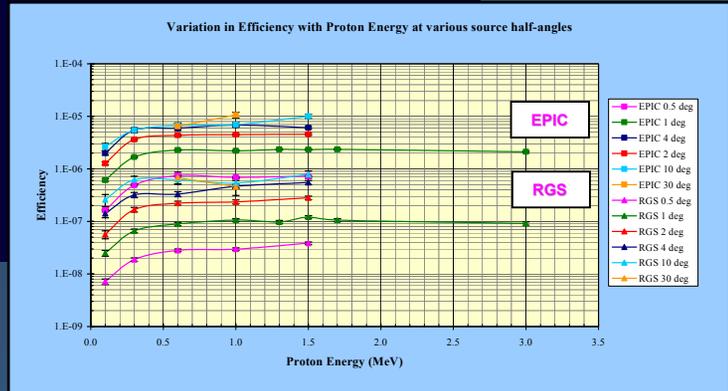
30 μm Si ⇒ ~1.5 MeV protons



Geant 4



Low-E (~100 keV to few MeV),
low-angle (~0°-5°) proton scattering

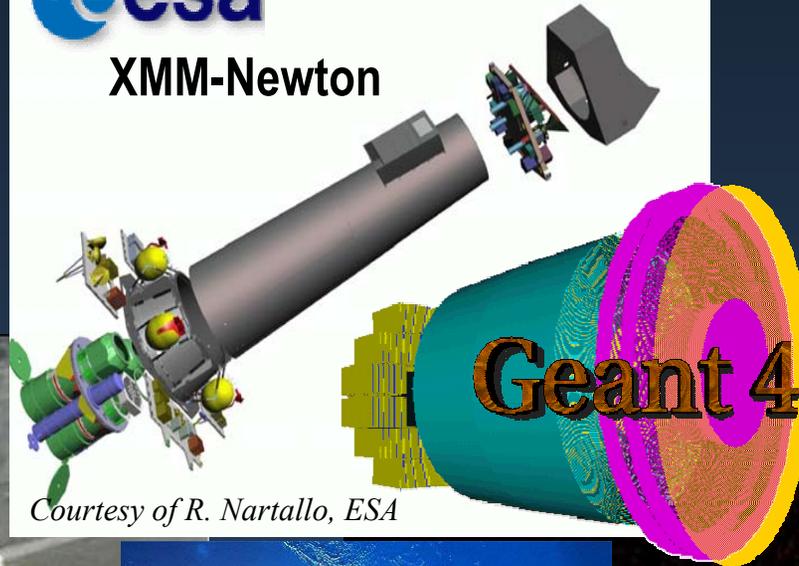


Courtesy of
ESA Space Environment
& Effects Analysis Section

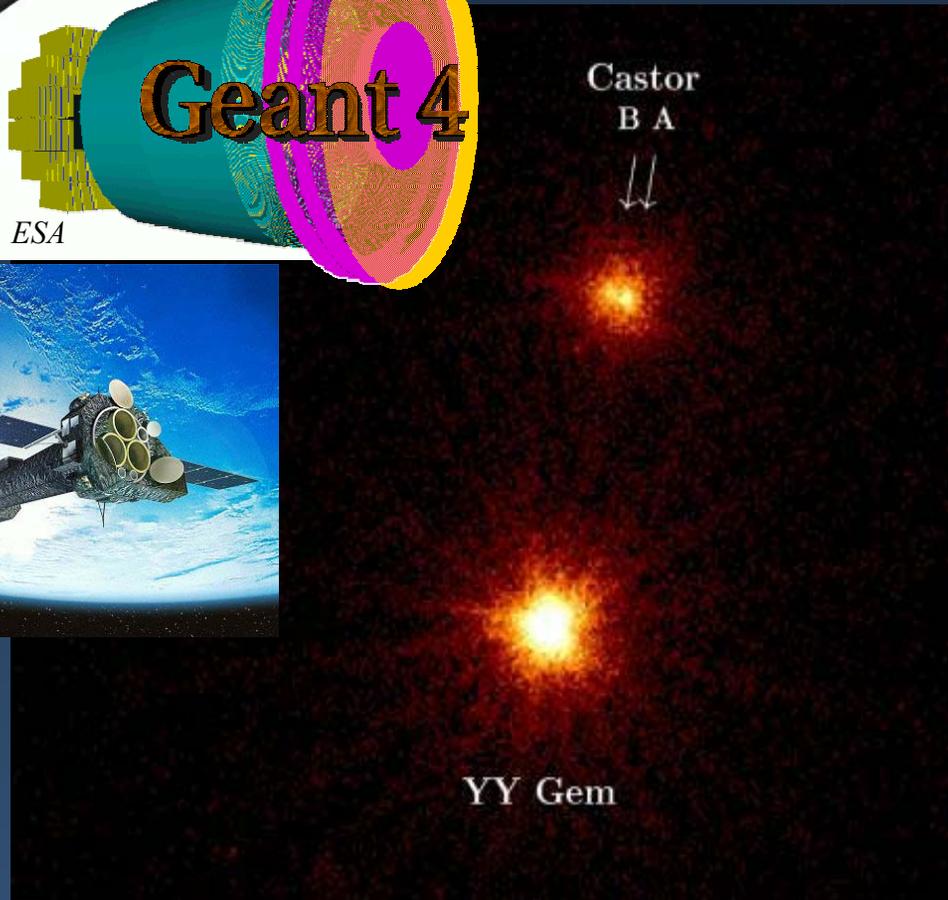
What happened next?



XMM-Newton



Courtesy of R. Nartallo, ESA



XMM was launched on 10 December 1999 from Kourou



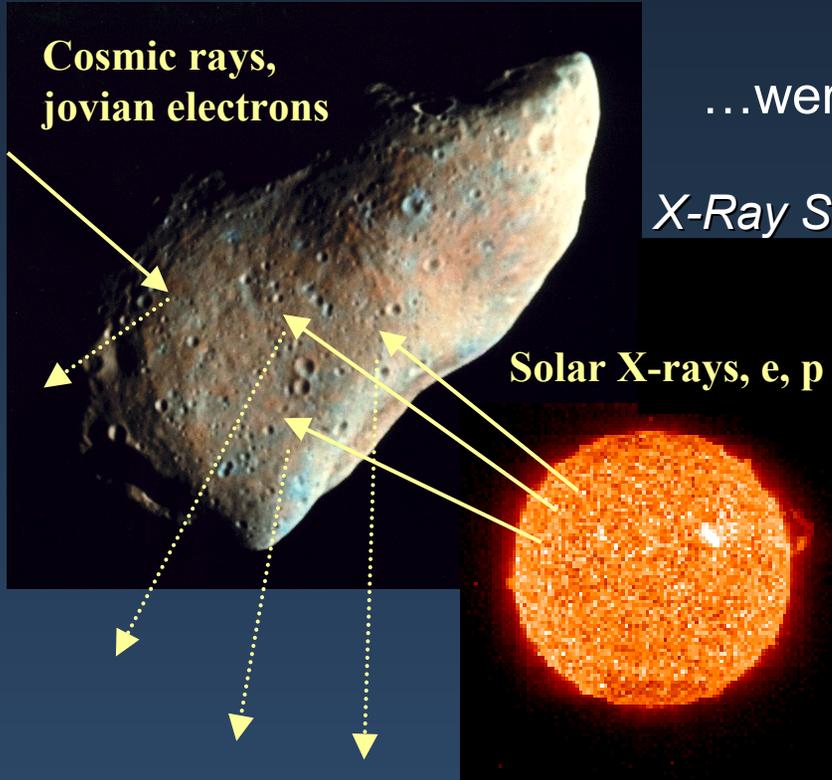
EPIC image of the two flaring Castor components and the brighter YY Gem

...and the other way round

Low energy e, γ extensions

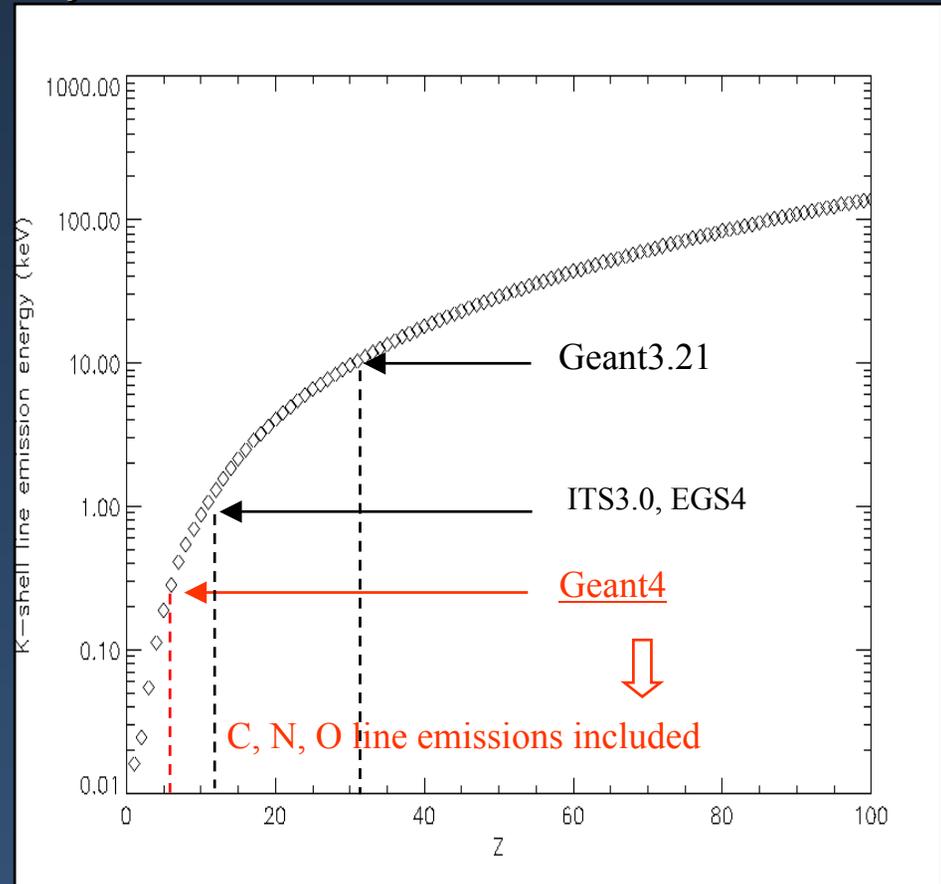
...were triggered by astrophysics requirements

X-Ray Surveys of Planets, Asteroids and Moons



Courtesy SOHO EIT

Induced X-ray line emission:
indicator of target composition
($\sim 100 \mu\text{m}$ surface layer)

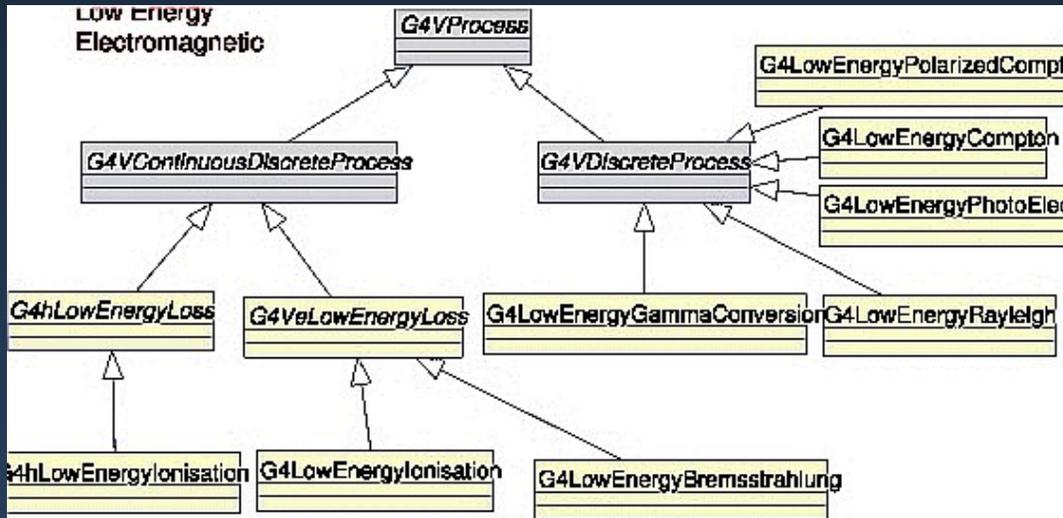


Geant 4 Low Energy Processes: e, γ

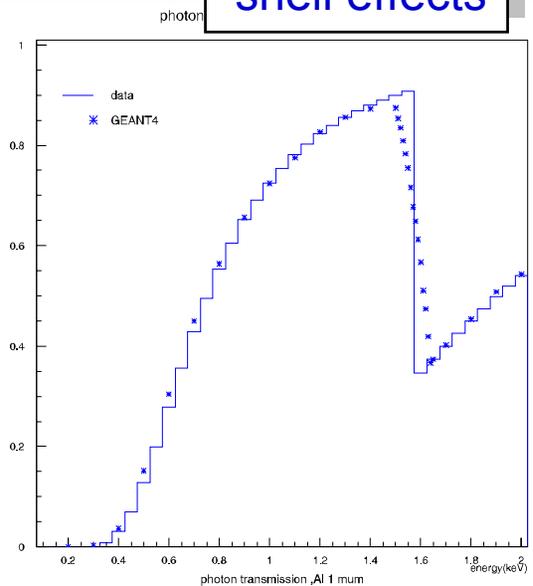
250 eV up to 100 GeV

New electromagnetic physics models

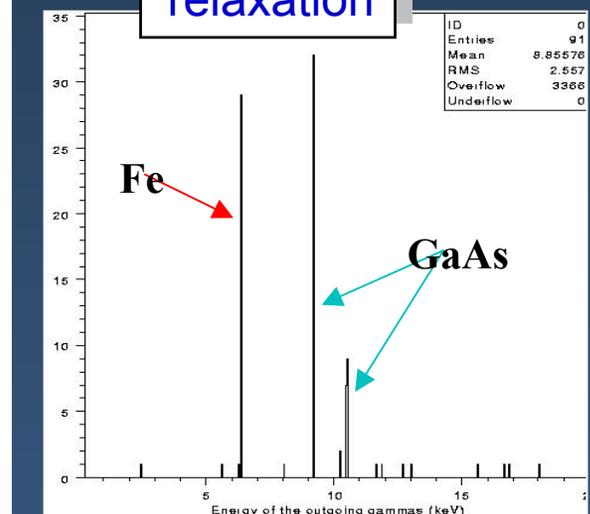
Based on EPDL97, EEDL and EADL evaluated data libraries



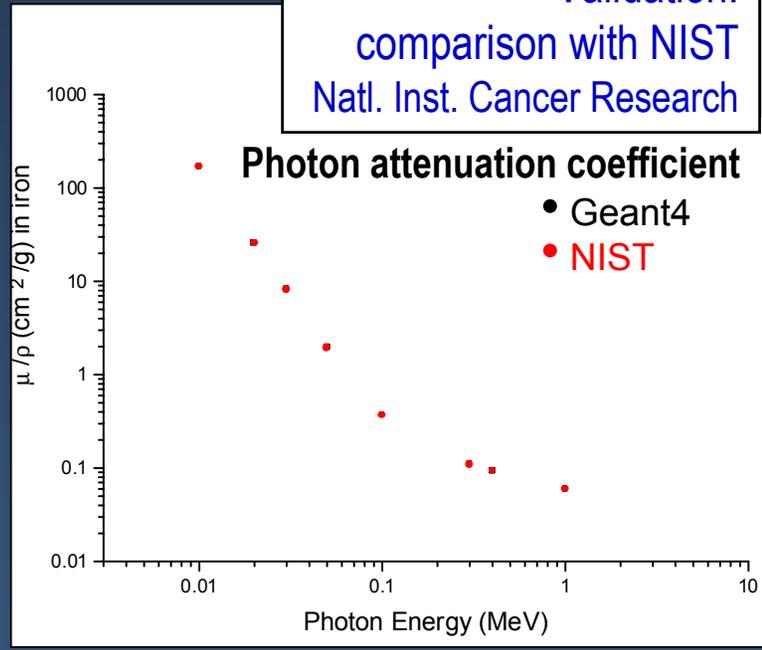
shell effects



Atomic relaxation



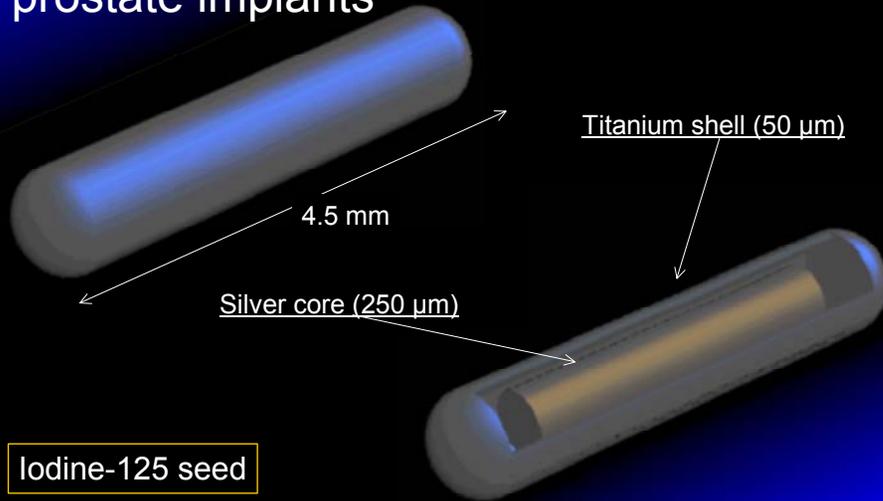
Validation: comparison with NIST Natl. Inst. Cancer Research



...the first user application

Titanium encapsulated ^{125}I sources in permanent prostate implants

Seed components



Exploiting X-ray fluorescence to lower the energy spectrum of photons (and electrons) and enhance the RBE

10 keV electron in water

GEANT4

R. Taschereau, R. Roy, J. Pouliot

keV/ μm

*Centre Hospitalier Universitaire de Quebec,
Dept. de radio-oncologie, Canada*

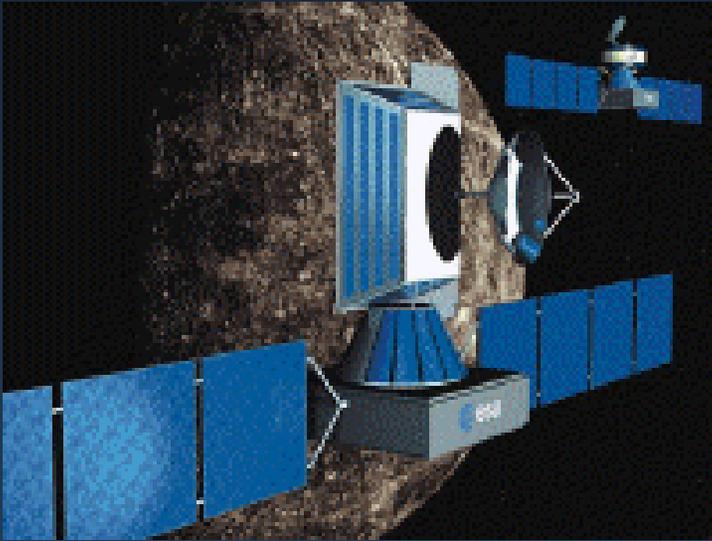
Univ. Laval, Dept. de Physique, Canada

*Univ. of California, San Francisco, Dept. of
Radiation Oncology, USA*

Terrisol

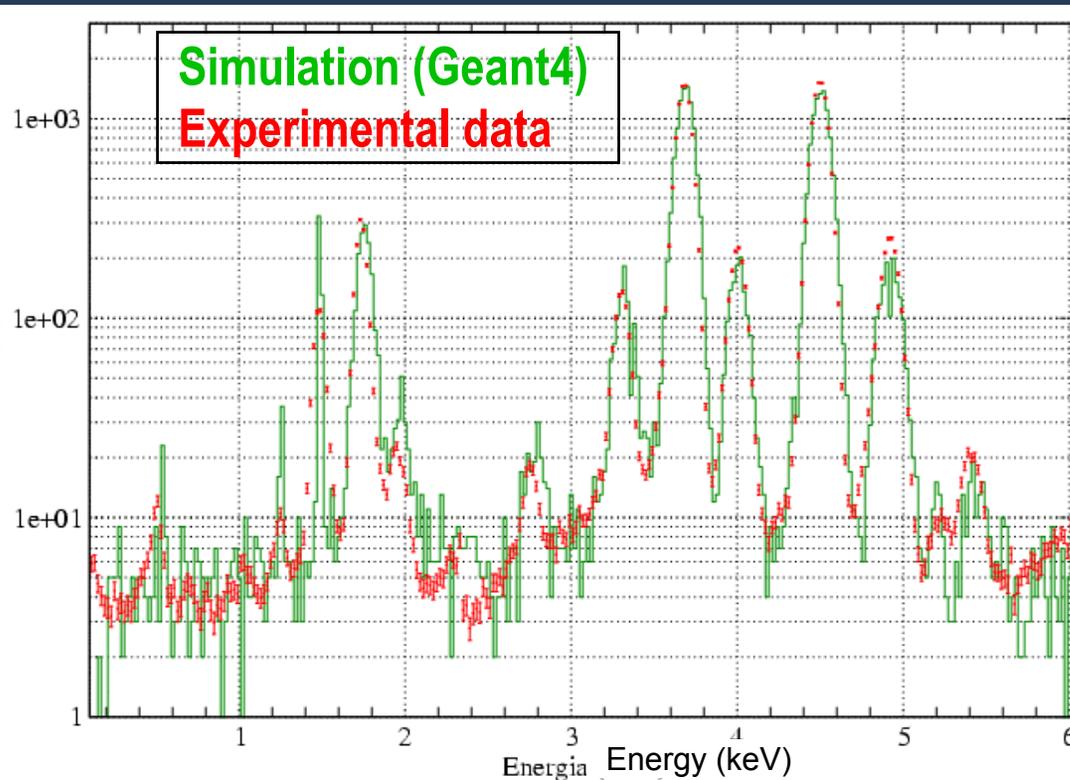
Maria Grazia Pia, 8th Simulation Symposium, Hayama

Distance (nm)



Bepi Colombo ESA mission to Mercury

Analysis of the elemental composition of Mercury crust through X-ray spectroscopy



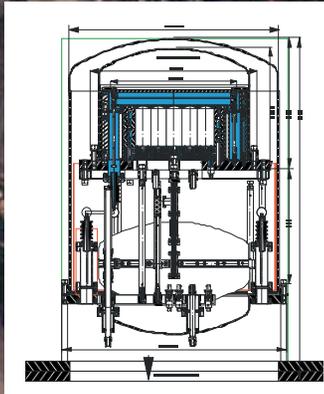
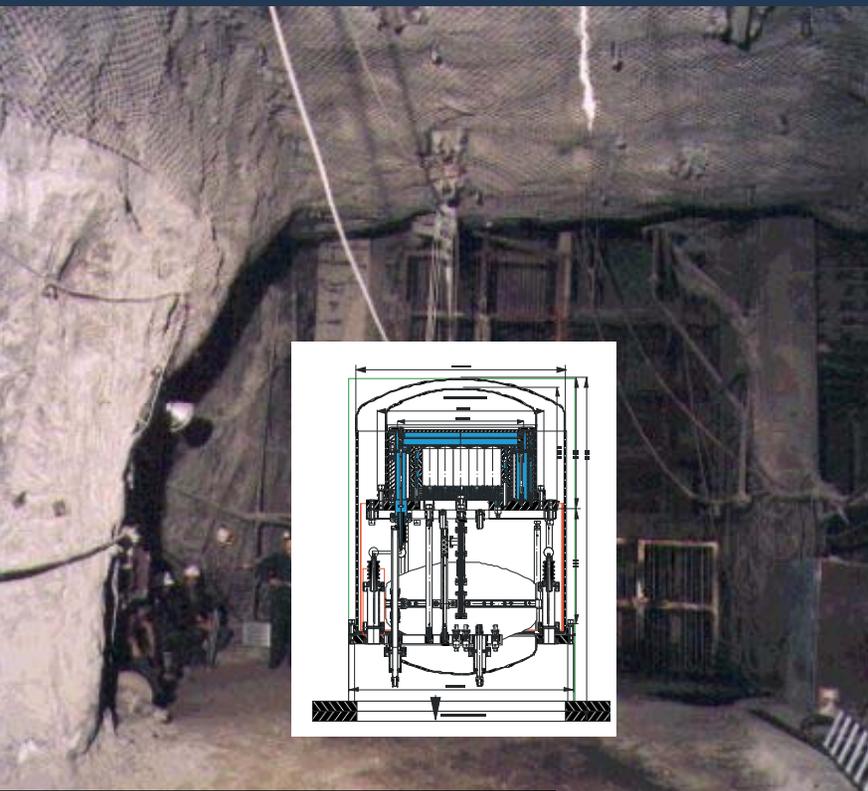
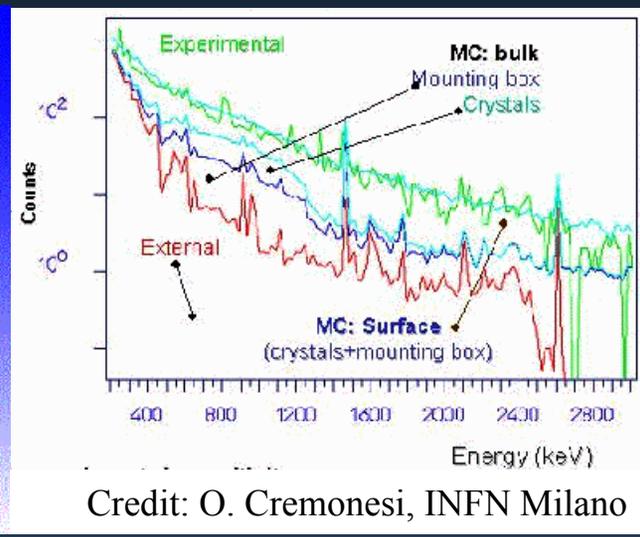
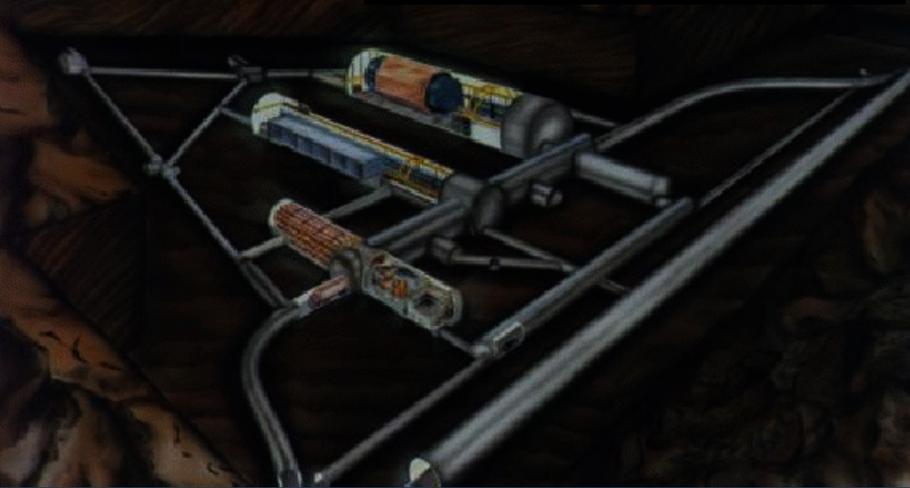
Fluorescent spectrum of Icelandic Basalt (“Mars-like”)



Experimental data:
courtesy of A. Owens, ESA
6.5 keV photon beam, BESSY

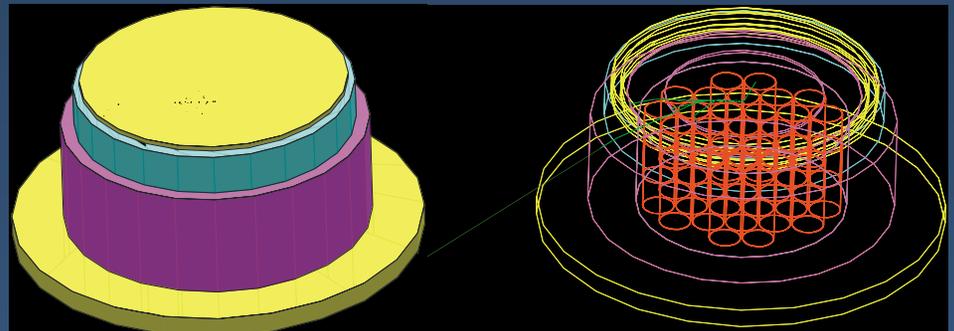
Anderson-Darling goodness
of fit test on various data sets:
compatibility 95% CL

Gran Sasso Laboratory



Back to HEP...

- Similar requirements on low energy physics from underground HEP experiments ~1 year later
- Recent interest on these physics models from LHC for precision detector simulation



Courtesy of H. Araujo and A. Howard, IC London

UKDM, Boulby Mine

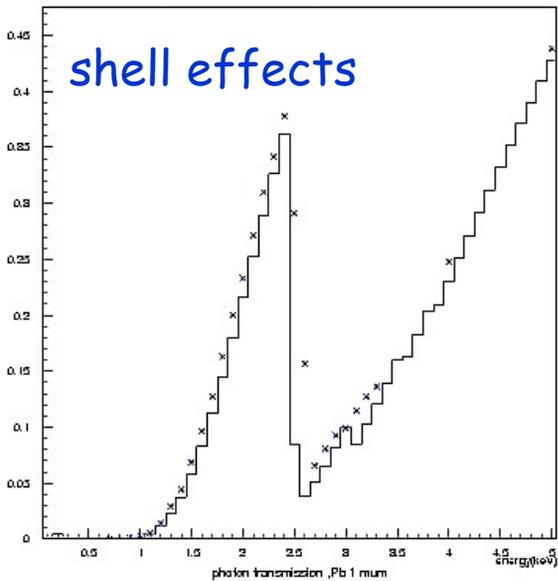
Medical Applications

Verification of conventional
radiotherapy treatment planning
(as required by protocols)

Investigation of innovative methods in radiotherapy

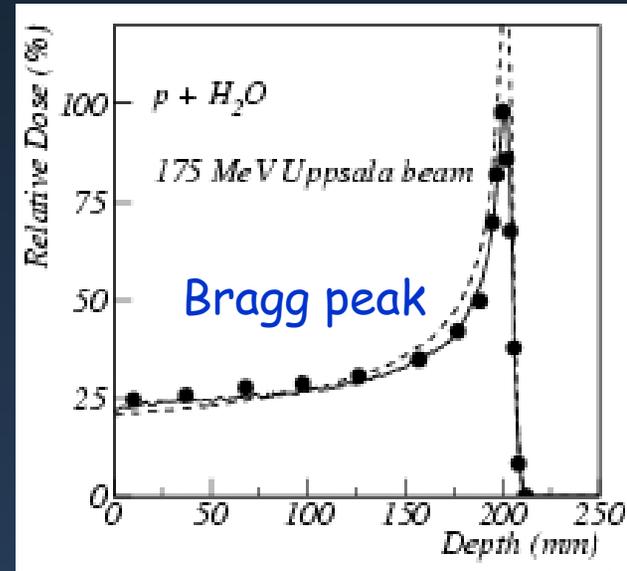
Radiodiagnostics





Physics requirements

Many new physics features w.r.t. Geant3



e,γ down to 250 eV

(EGS4, ITS to 1 keV, Geant3 to 10 keV)

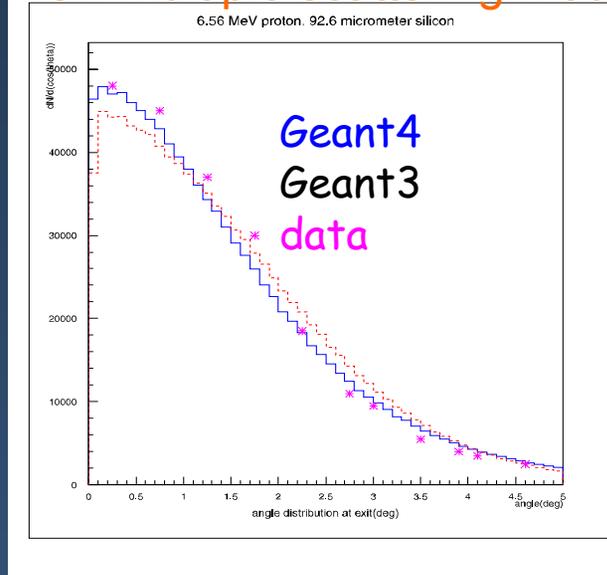
Based on EPDL97, EEDL and EADL evaluated data libraries

And much more:

- fluorescence
- radioactive decay
- hadronic models
- etc...

And much relevant functionality in other domains too, not only physics!

New multiple scattering model



Hadron and ion

electromagnetic models based on Ziegler and ICRU data and parameterisations

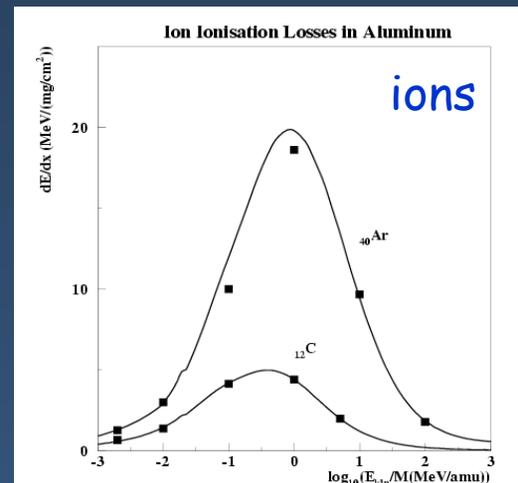
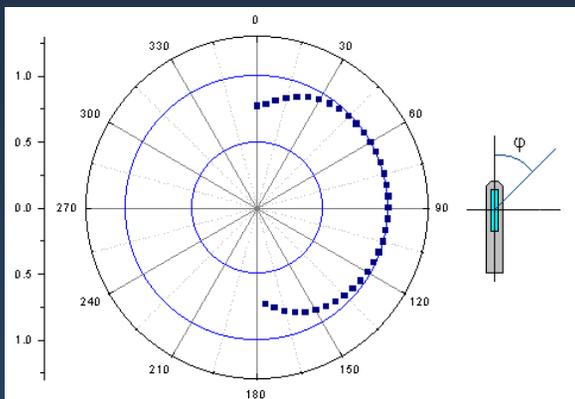


Figure 9: Ion electronic stopping power in aluminum. Points - the best fit on the data from Ref.[12], solid line - GEANT4 parameterisation. The accuracy of the data is about 5%.

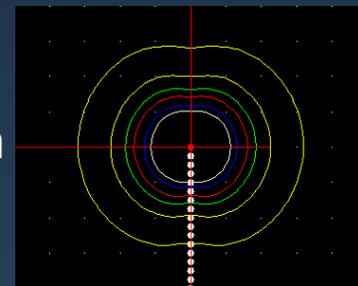
Endocavitary brachytherapy

Radioactive sources are used to deposit therapeutic doses near tumors, while preserving surrounding healthy tissues



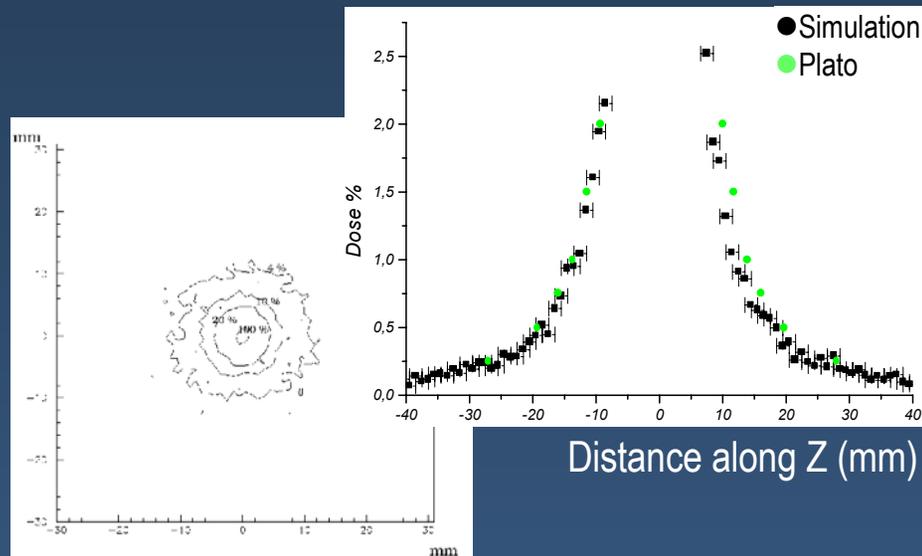
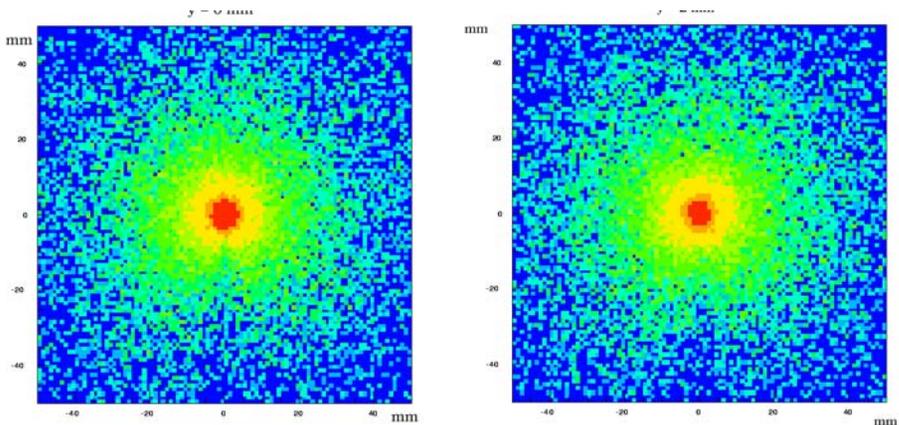
Source anisotropy

Plato-BPS treatment planning algorithm makes some crude approximation (ϕ dependence, no radial dependence)



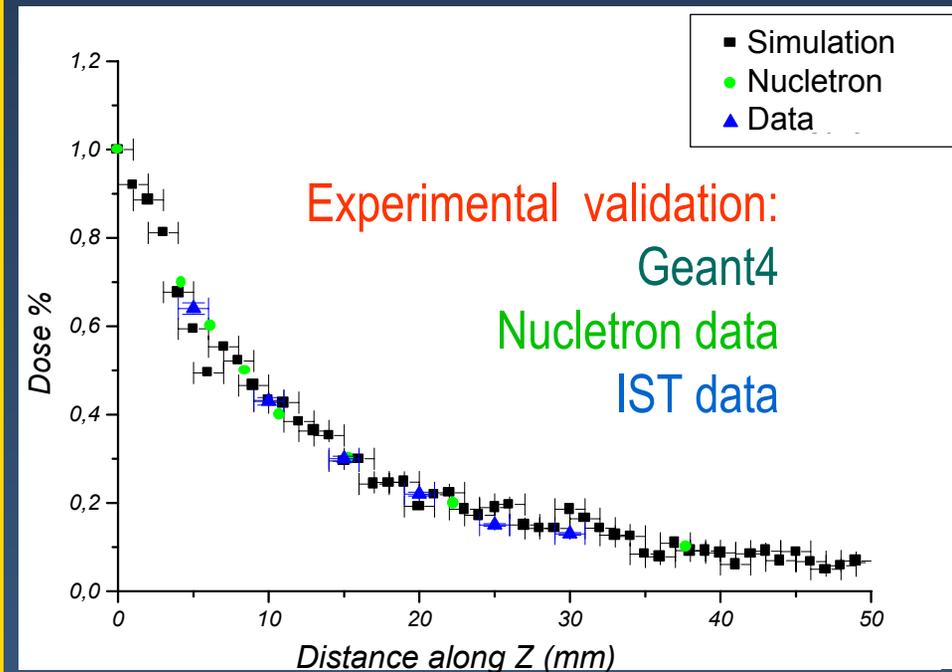
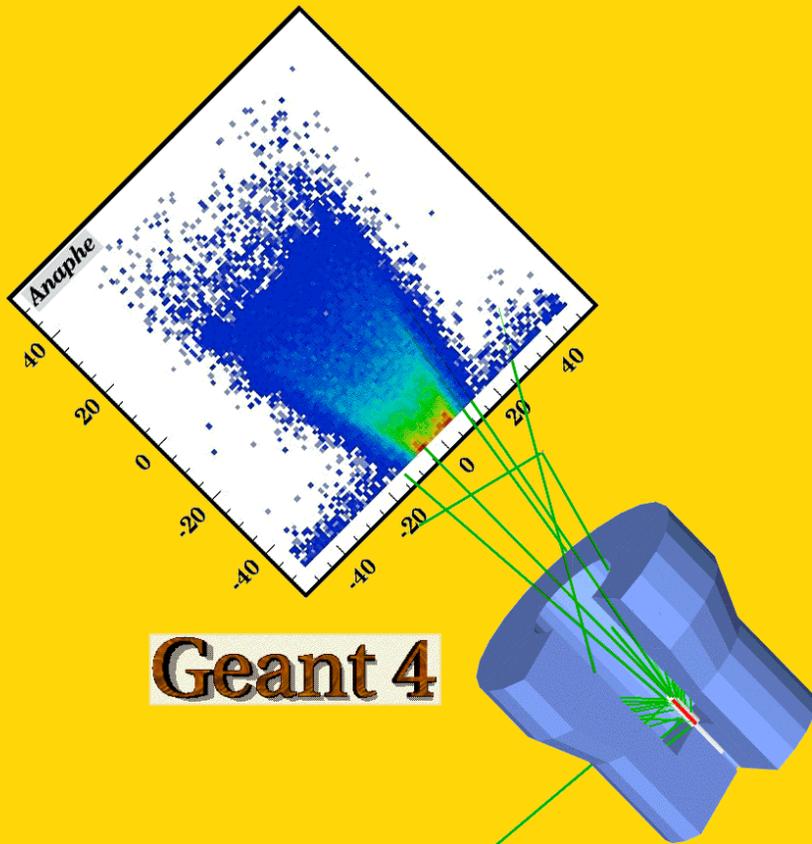
Precise dose distribution with Geant4

MicroSelectron-HDR Ir-192 source

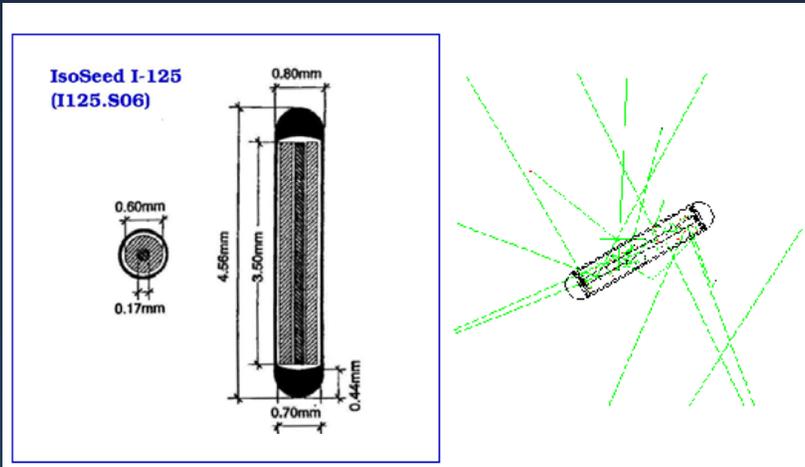


Superficial brachytherapy

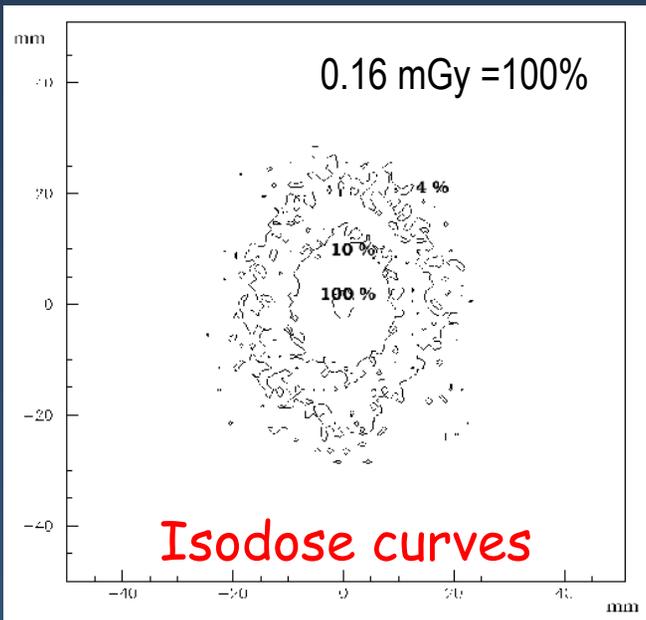
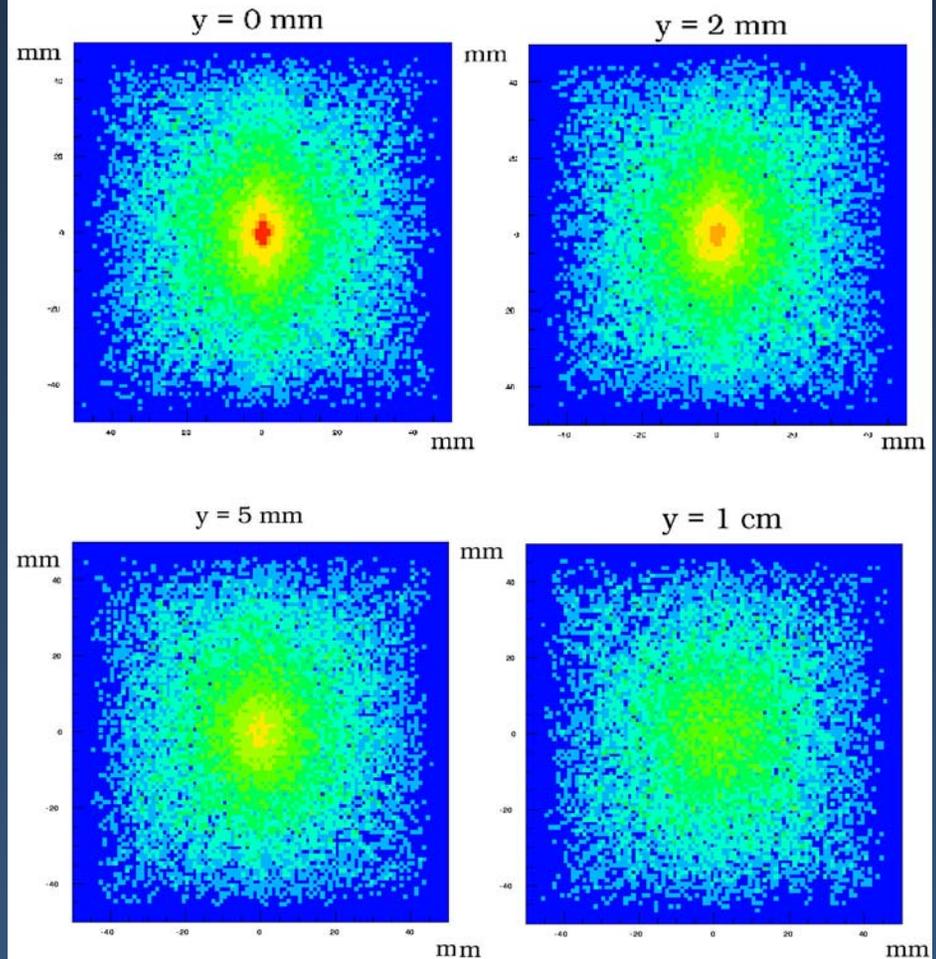
No commercial treatment planning software available



Interstitial brachytherapy

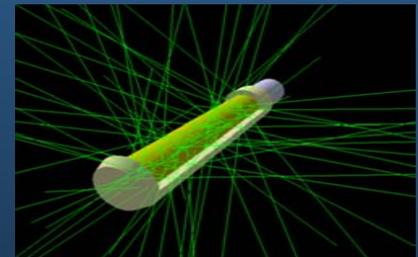
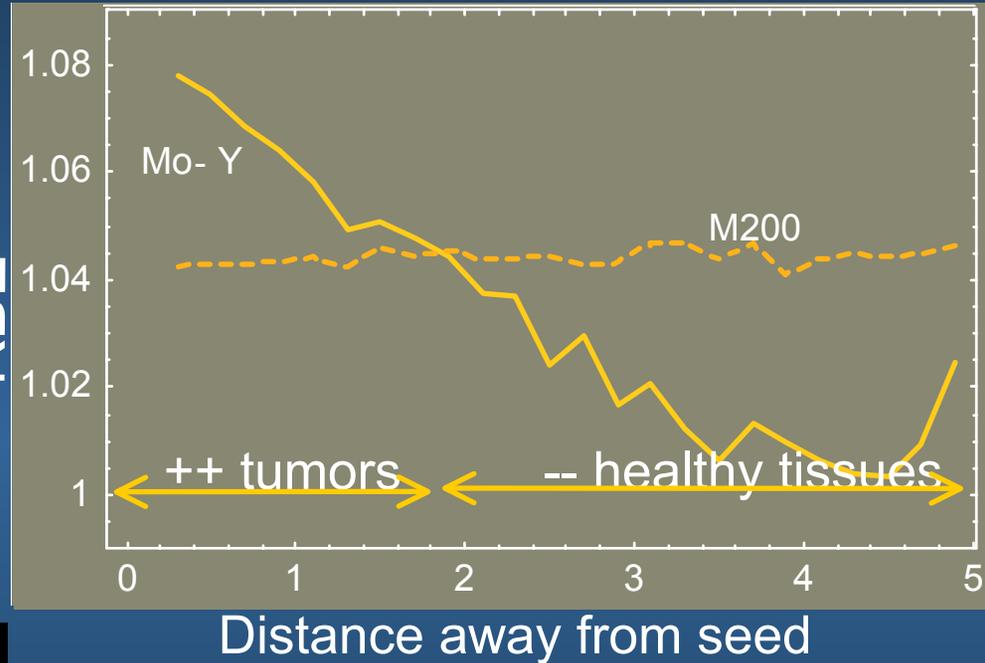
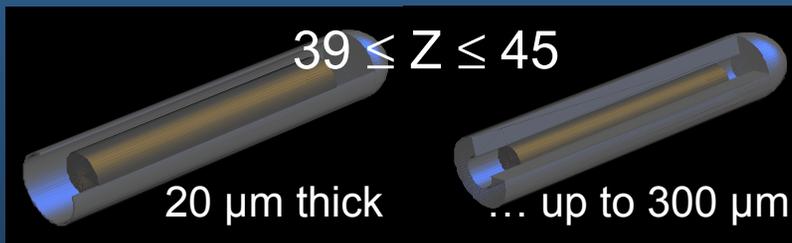
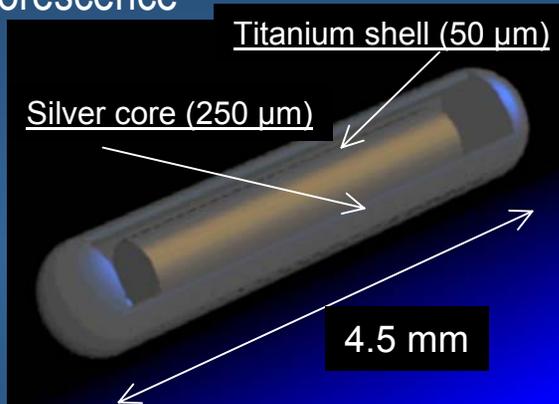


Bebig Isoseed I-125 source



RBE enhancement of a ^{125}I brachytherapy seed with characteristic X-rays from its constitutive materials

Goal: improve the biological effectiveness of titanium encapsulated ^{125}I sources in permanent prostate implants by exploiting X-ray fluorescence



Geant 4

R. Taschereau, R. Roy, J. Pouliot

Centre Hospitalier Universitaire de Québec, Dépt. de radio-oncologie, Canada

Univ. Laval, Dépt. de Physique, Canada

Univ. of California, San Francisco, Dept. of Radiation oncology, USA

GEANT4 Dose Calculation



Parameter selection

Geant 4

Central disk
Phase Space Data
CT Images

Beam A

Beam B

Beam X

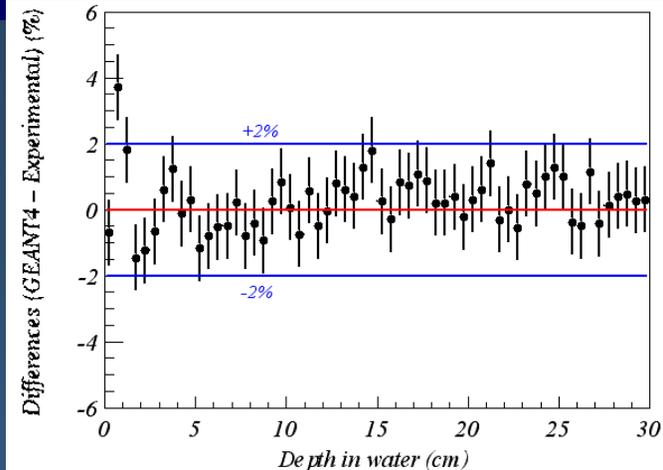
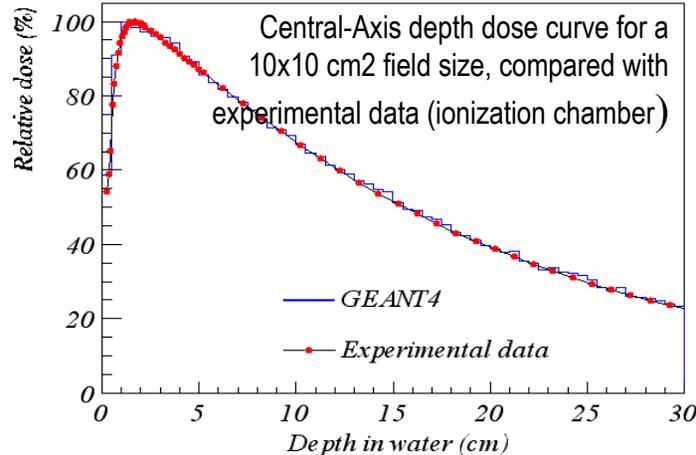
CPU #1

CPU #2

CPU #16

16-CPU FARM

Validation of phase-space distributions from a Siemens KD2 linear accelerator at 6 MV photon mode



M.C. Lopes ¹,
L. Peralta ²,
P. Rodrigues ²,
A. Trindade ²

¹ IPOFG-CROC Coimbra
Oncological Regional Center

² LIP - Lisbon

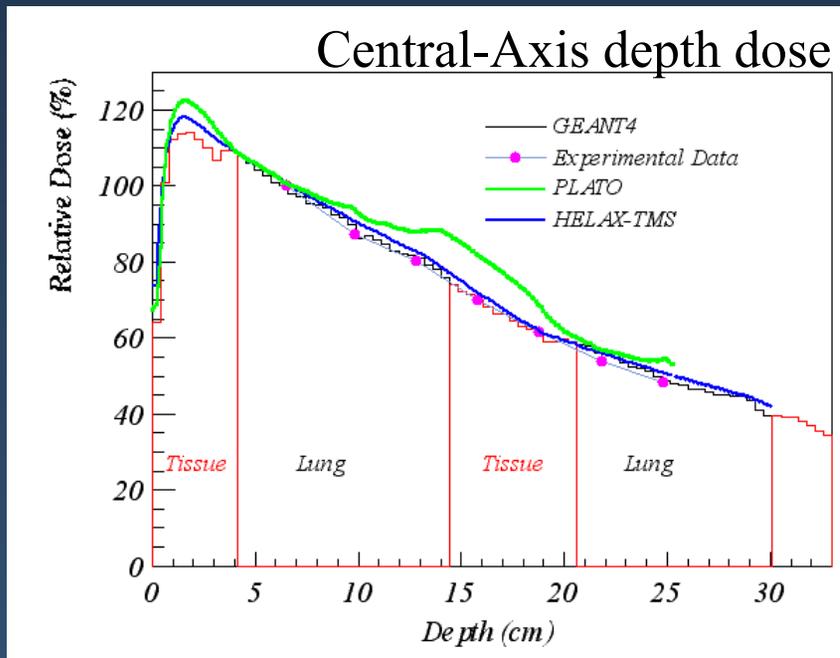
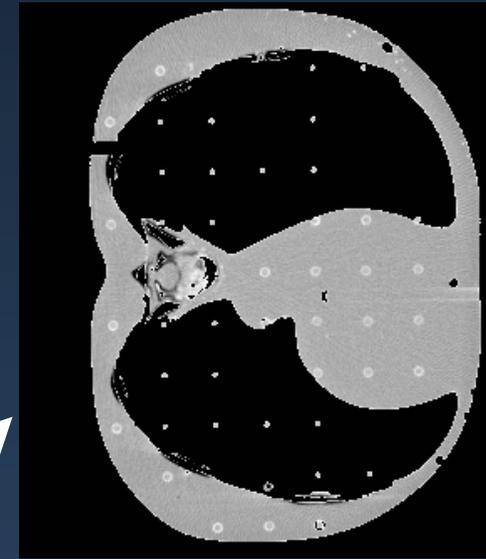
Comparison with commercial treatment planning systems

M. C. Lopes ¹, L. Peralta ², P. Rodrigues ², A. Trindade ²

¹ IPOFG-CROC Coimbra Oncological Regional Center - ² LIP - Lisbon

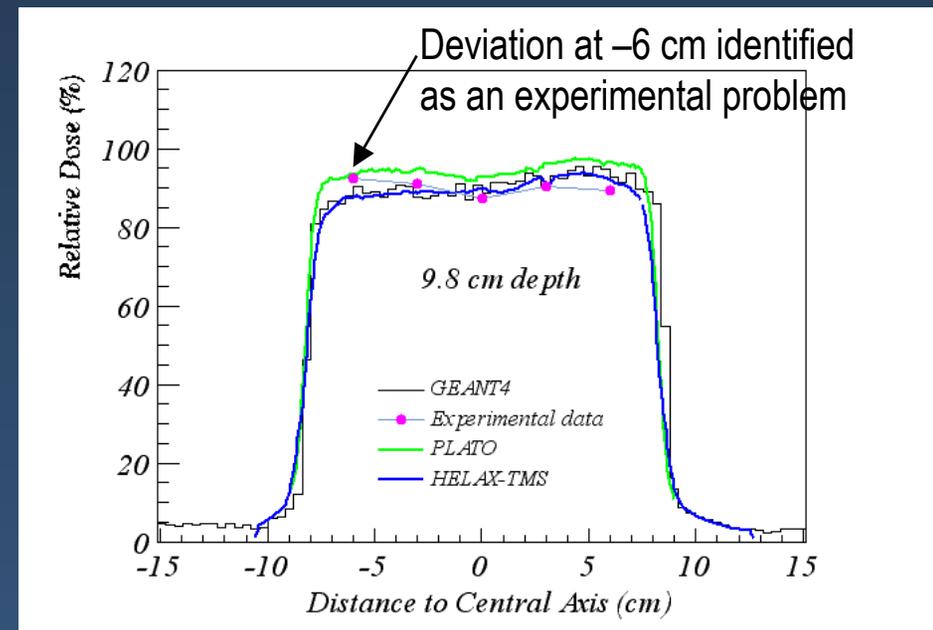
CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter

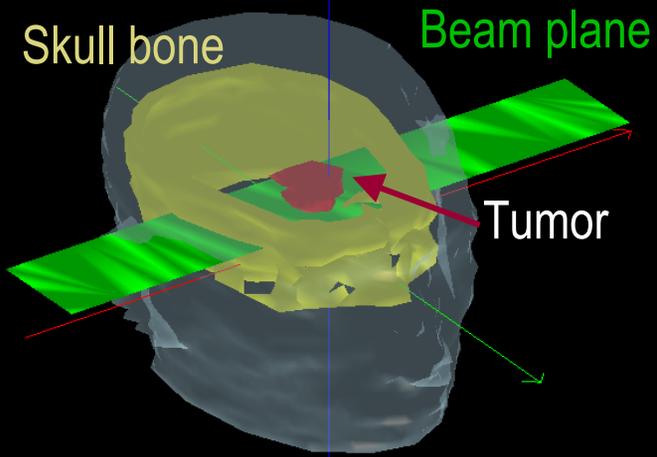
CT images used to define the geometry:
a thorax slice from a Rando anthropomorphic phantom



Profile curves at 9.8 cm depth

PLATO overestimate the dose at ~ 5% level





Head and neck with two opposed beams for a 5x5 and 10x10 field size

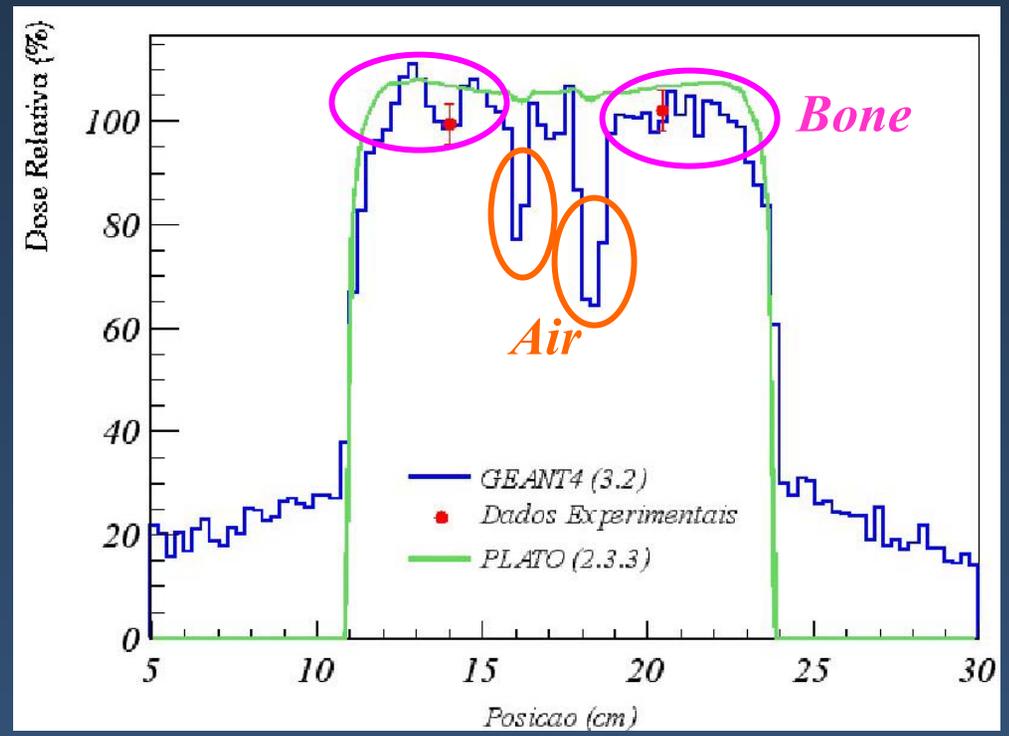
A more complex set-up

M. C. Lopes¹, L. Peralta², P. Rodrigues², A. Trindade²
¹ IPOFG-CROC Coimbra Oncological Regional Center - ² LIP - Lisbon

An off-axis depth dose taken at one of the slices near the isocenter

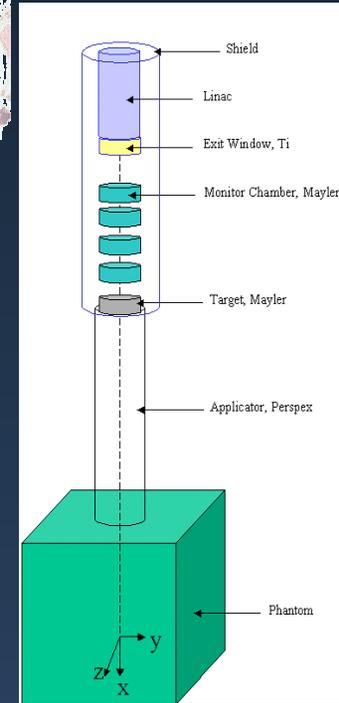
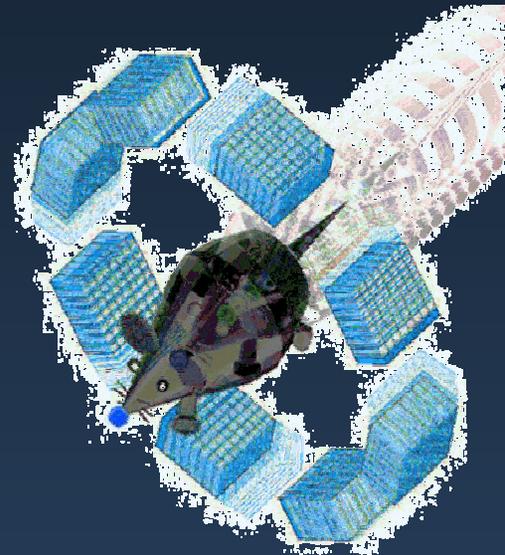
PLATO fails on the air cavities and bone structures and cannot predict accurately the dose to tissue that is surrounded by air

Deviations are up to 25-30%

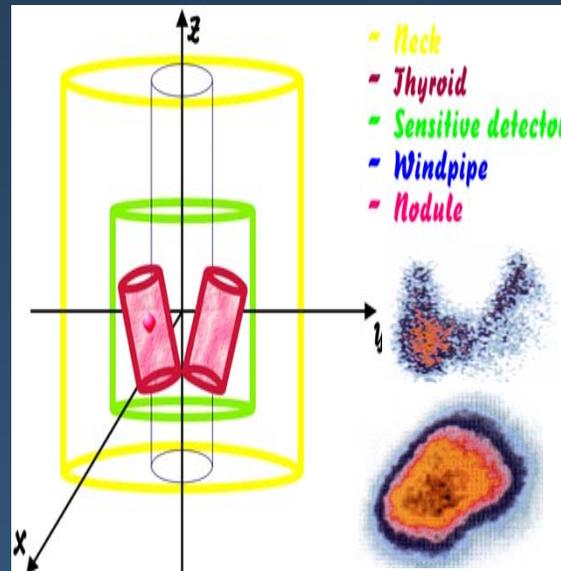
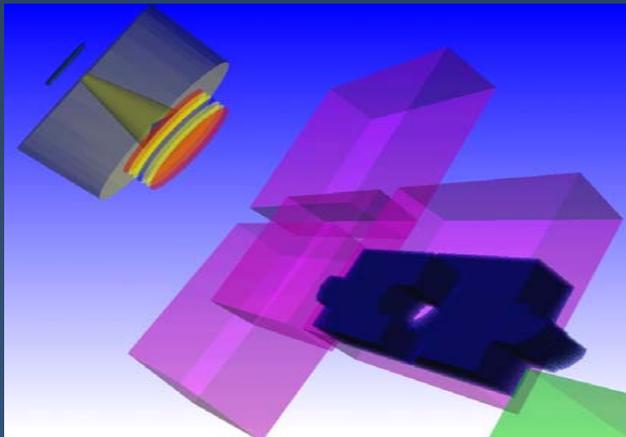


Other medical applications

- IORT (INFN Cosenza)
- Metabolic therapy (INFN Cosenza)
- IMRT (IRCC Candiolo)
- Design and optimisation of treatment heads
- Hadron therapy
- PET (GATE - ClearPET)
- etc.



no time to mention all...



Space Applications

Astronomy and astrophysics
Fundamental physics

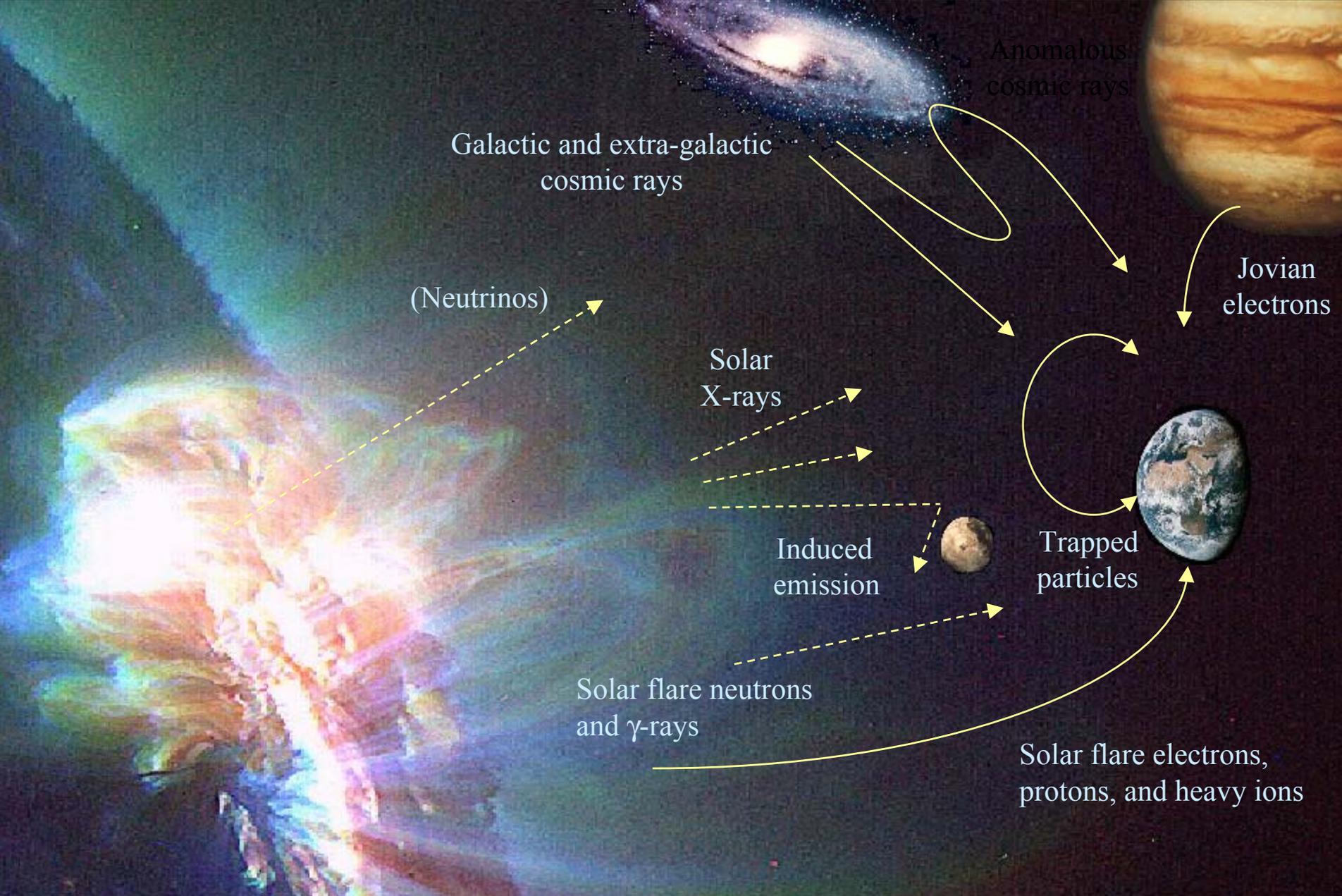
Effects of the space radiation environment
(shielding)

Effects on manned missions

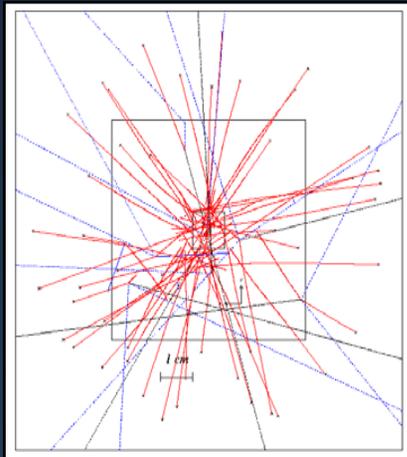
Space radiation environment

Photons: $\sim 300 \text{ eV} < E < 20 \text{ MeV}$
Electrons: $\sim 10 \text{ keV} < E < 20 \text{ MeV}$

Protons: $\sim 10 \text{ keV} < E < 20 \text{ MeV}$
Ions: $\sim 10 \text{ keV} < E < 20 \text{ MeV}$



Modules for space applications



Particle source and spectrum

General purpose source particle module

Delayed radioactivity



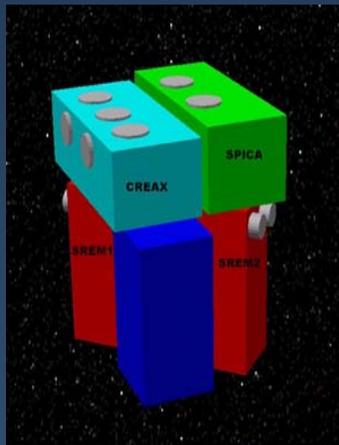
INTEGRAL and other science missions

Low-energy e.m. extensions



Geological surveys of solar system

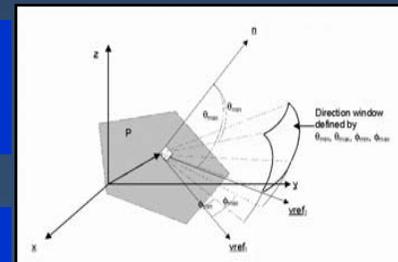
Geant 4



Instrument design purposes

CAD tool front-end

Sector Shielding Analysis Tool



Dose calculations

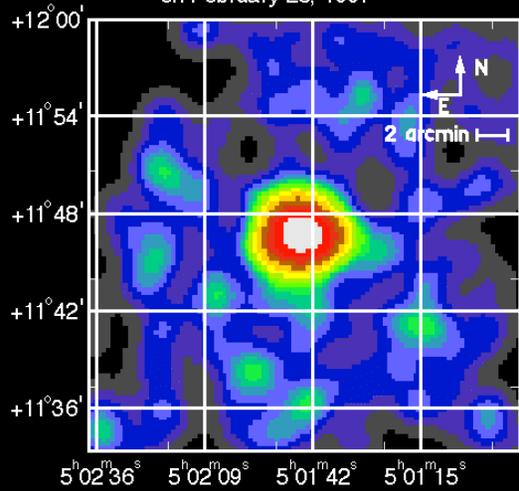
GeMAT Geant4-based Microdosimetry Analysis Tool

MULASSIS MULti-LAYer Shielding Simulation Software

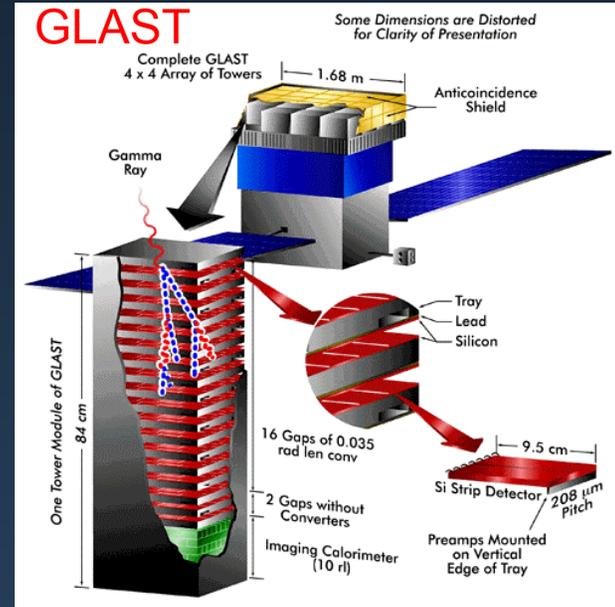
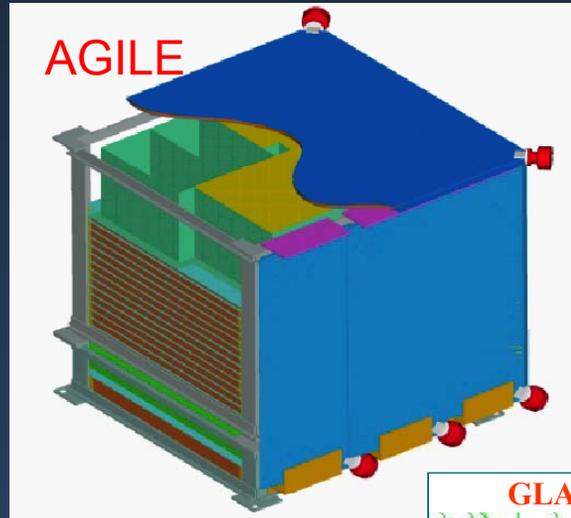
γ astrophysics

γ -ray bursts

BeppoSAX Observation of Gamma-Ray Burst on February 28, 1997

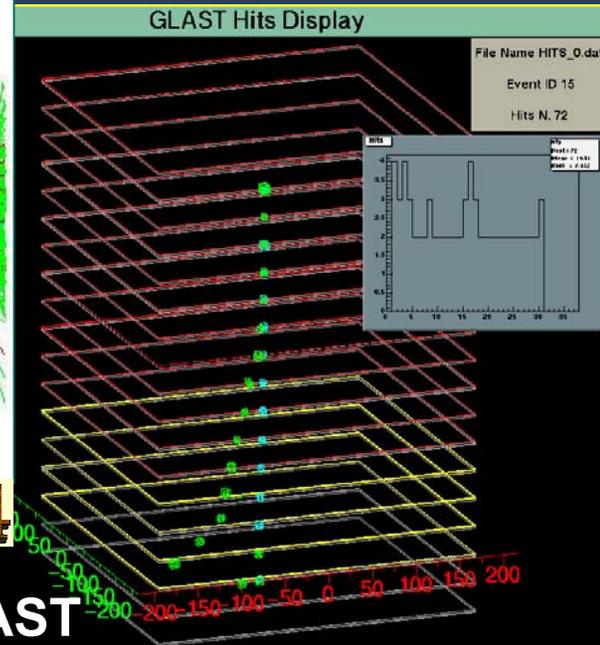
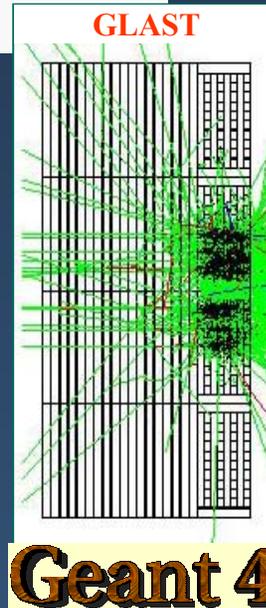


Courtesy of Fabrizio Fiore and the BeppoSAX Team

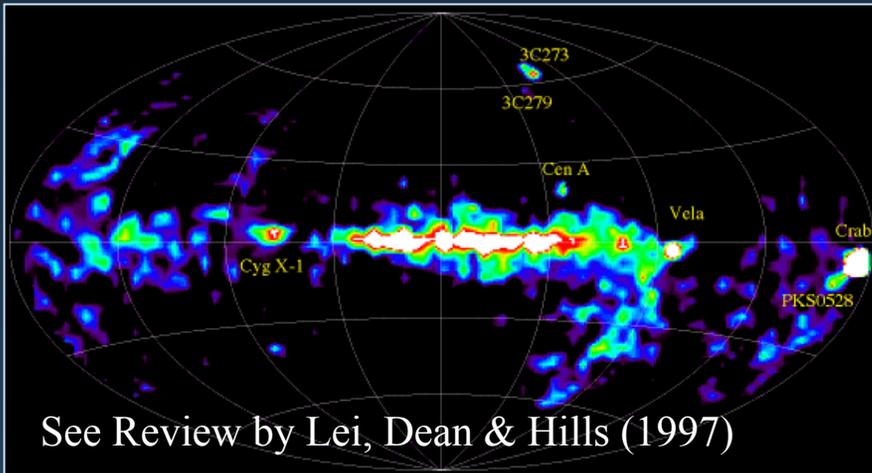


- γ conversion
- electron interactions
- multiple scattering
- δ -ray production
- charged particle tracking

Typical telescope:
Tracker
Calorimeter
Anticoincidence



Polarised Gamma Astrophysics



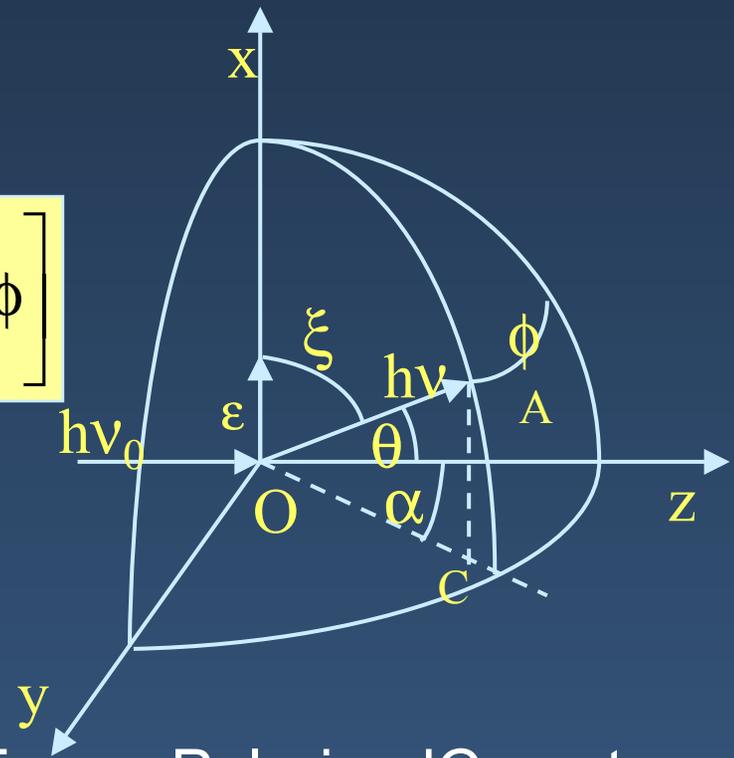
Compton astrophysics
(MeV region)

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{h\nu^2}{h\nu_0^2} \left[\frac{h\nu_0}{h\nu} + \frac{h\nu}{h\nu_0} - 2 \sin^2 \theta \cos^2 \phi \right]$$

- θ Polar angle
- ϕ Azimuthal angle
- ε Polarization vector

Geant 4

G4LowEnergyPolarizedCompton

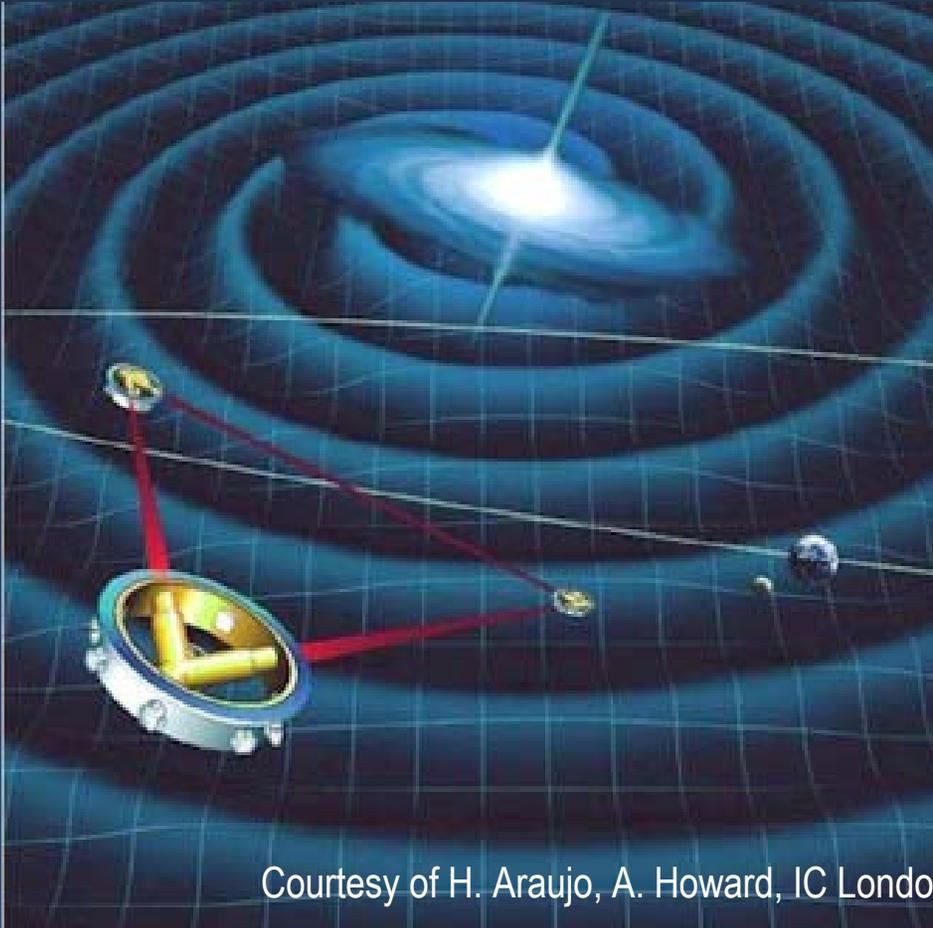


LISA (gravitational waves)

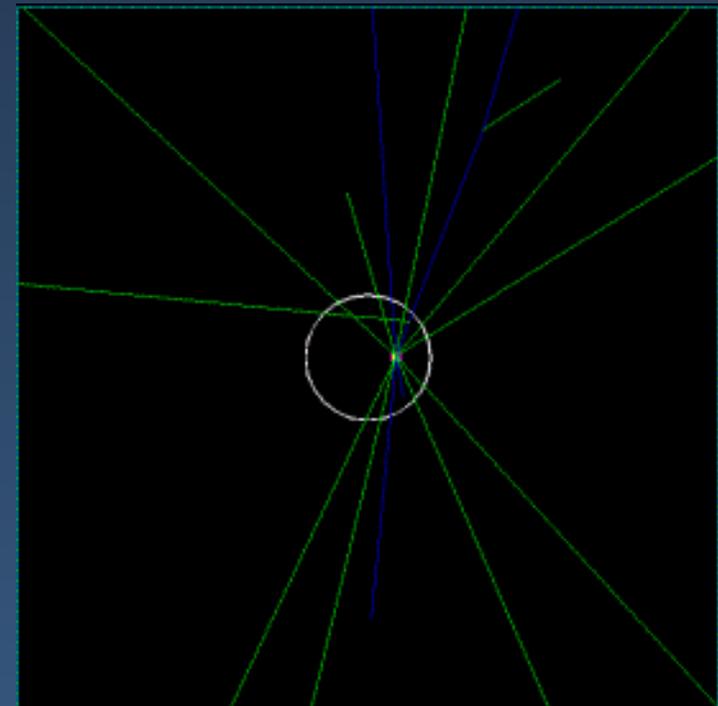
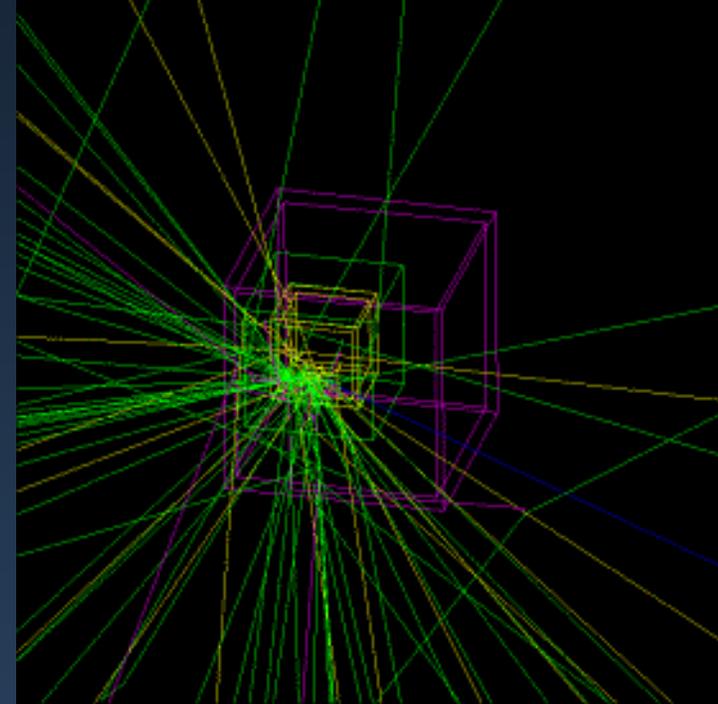
Geant4 relevant for evaluation of space charging effects

Very long base-line: 1 million km

Very high precision: $< 1\text{nm} - 1\text{pm}$ (!)



Courtesy of H. Araujo, A. Howard, IC London



Geant 4 - DNA

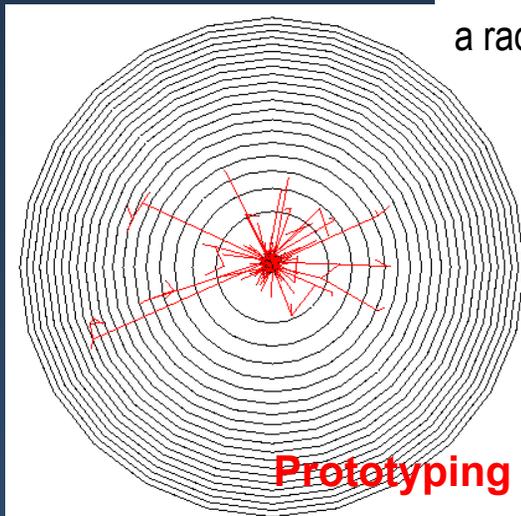
<http://www.ge.infn.it/geant4/dna/>

Study of radiation damage at the cellular and DNA level in the space radiation environment (*and other applications...*)

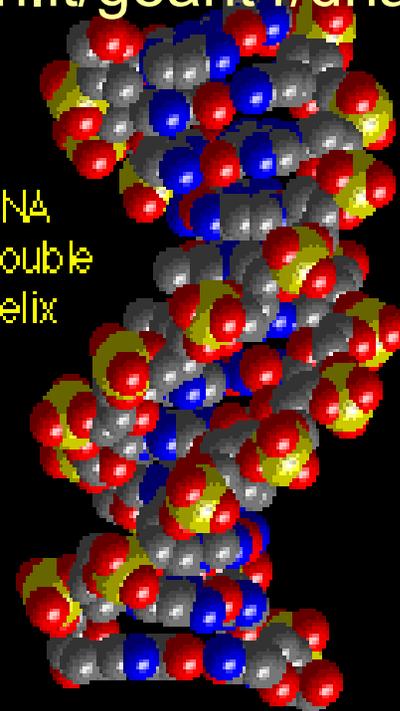
Multi-disciplinary Collaboration of

- astrophysicists/space scientists
- particle physicists
- medical physicists
- computer scientists
- biologists
- physicians

5.3 MeV α particle in a cylindrical volume
The inner cylinder has a radius of 50 nm



DNA
Double
Helix



- Relevance for space: astronaut and airline pilot radiation hazards, biological experiments
- Also in radiotherapy, radiobiology...



Technology transfer

Particle physics software aids space and medicine

Geant4 is a showcase example of technology transfer from particle physics to other fields such as space and medical science [...].

CERN Courier, June 2002

<http://cern.ch/geant4/>

<http://www.cern.ch/geant4-tt/>

<http://www.ge.infn.it/geant4/>

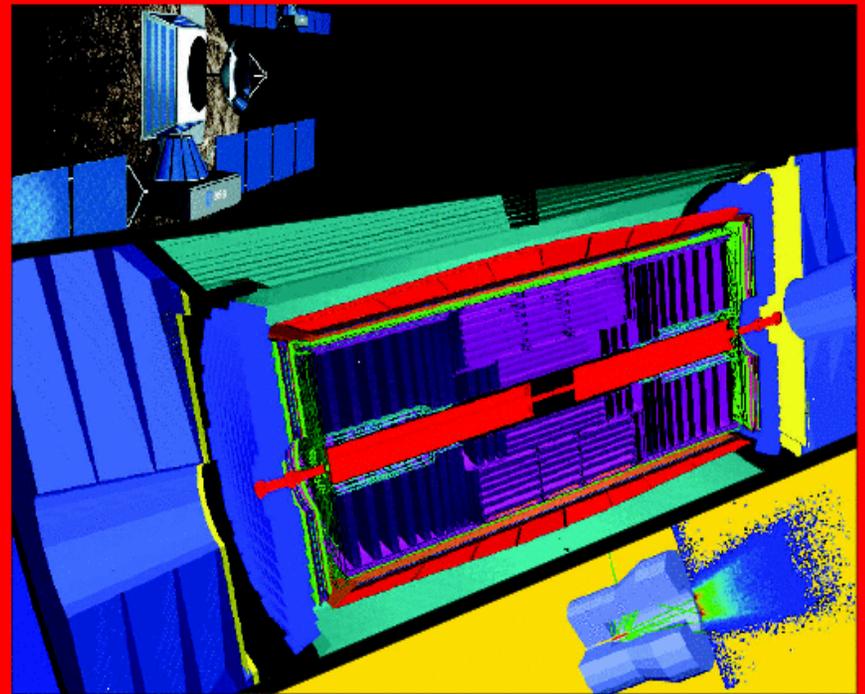
Maria.Grazia.Pia@cern.ch or pia@ge.infn.it

Maria Grazia Pia, 8th Simulation Symposium, Hayama

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 42 NUMBER 5 JUNE 2002



Simulation for physics, space and medicine

NEUTRINOS

Sudbury Neutrino Observatory confirms neutrino oscillation p5

TESLA

Electropolishing steers superconducting cavity to new record p10

COSMOPHYSICS

Joint symposium brings CERN, ESA and ESO together p15

Conclusions

Complexity of physics, detectors, environments

A rapidly changing computing environment

Similar requirements across diverse fields (HEP, astrophysics, medicine...)

The response:

- rigorous approach to software engineering
- OO technology
- powerful functionality, rich physics

Achieve:

- openness to extension and evolution
- maintainability over an extended time scale
- transparency of physics

Results:

- HEP, space science, medical physics...
- science + technology transfer

Thanks!

- CERN (J. Knobloch)
- ESA/ESTEC (*R. Nartallo, P. Nieminen, A. Owens, A. Peacock*)
- Imperial College, London (*H. Araujo, A. Howard*)
- INFN Cosenza (*F. Castrovillari, D. Cuce, E. Lamanna*)
- INFN LNS (*G.A.P. Cirrone, G. Cuttone*)
- INFN Torino (*S. Chauvie, R. Gotta, F. Marchetto, V. Rolando, A. Solano*)
- IST (*S. Agostinelli, F. Foppiano, S. Garelli, S. Guatelli, M. Tropeano*)
- Univ. Laval, Quebec (*L. Beaulieu, J.F. Carriere, R. Taschereau*)
- LIP (*L. Peralta, P. Rodrigues, A. Trindade*)
- PSI (*N. Crompton, P. Juelke*)
- Savona Hospital (*G. Ghiso, R. Martinelli*)
- Geant4 Collaboration
- Geant4 users (*too many to mention them all...*)
- **The Simulation Symposium Organizers**
- **Katsuya Amako (KEK)**