X SEMINAR ON SOFTWARE FOR NUCLEAR, SUBNUCLEAR AND APPLIED PHISICS

Porto Conte, Alghero, Italy
3 - 7 June 2013

A Geant 4 introduction

Geant 4 tutorial course

INFN
Geant4

The Geant4 toolkit

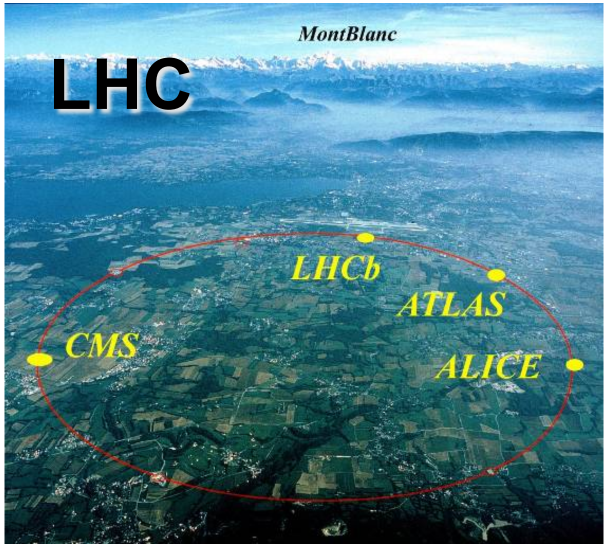
Geant 4 ⇨ *Geometry and Tracking*

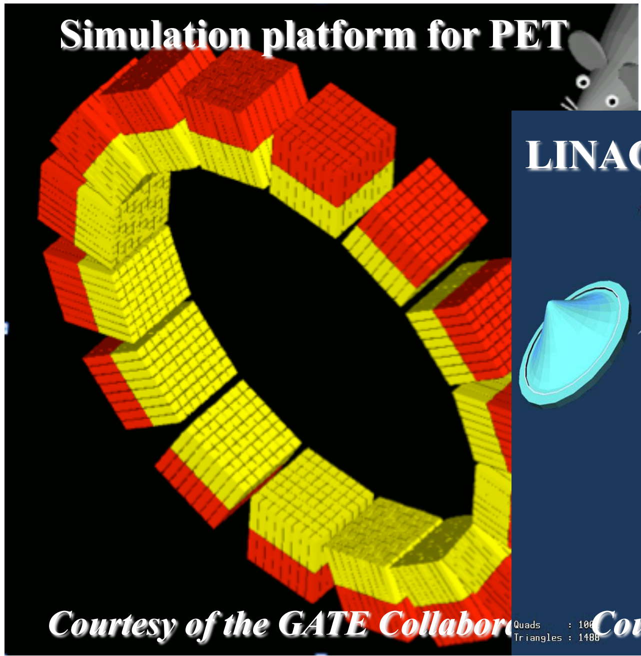
Object Oriented Toolkit (C++) born for the simulation of large scale HEP experiments at CERN (Geneva)

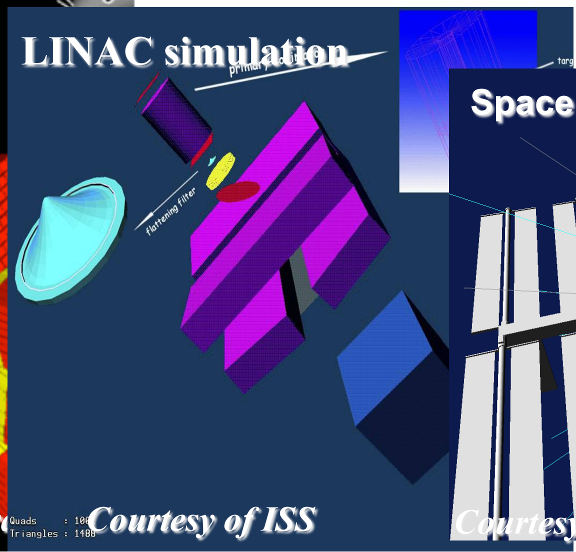
Agostinelli S. et al., GEANT4-a simulation toolkit, Nucl. Inst. And Methods in Phys. Res. A 506, 250-303 (2003)

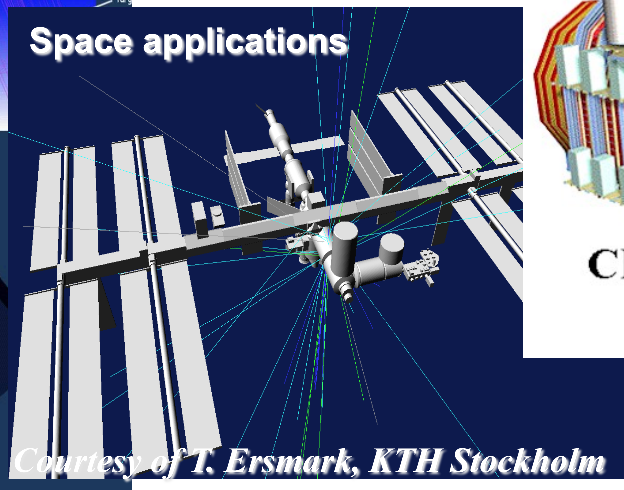
http://geant4.web.cern.ch/geant4

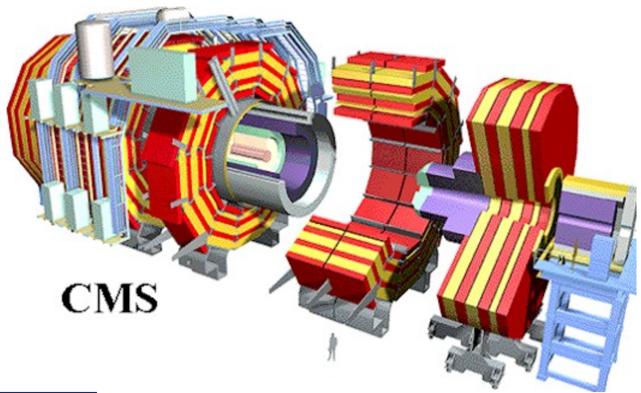
R&D phase: **RD44**, 1994 - 1998
1st release: December 1998
2 new releases/year since then











The Monte Carlo method

It is a **mathematical approach**
using a sequence of random numbers
to solve a problem

"If we are interested in a parameter of, i.e., an equation:

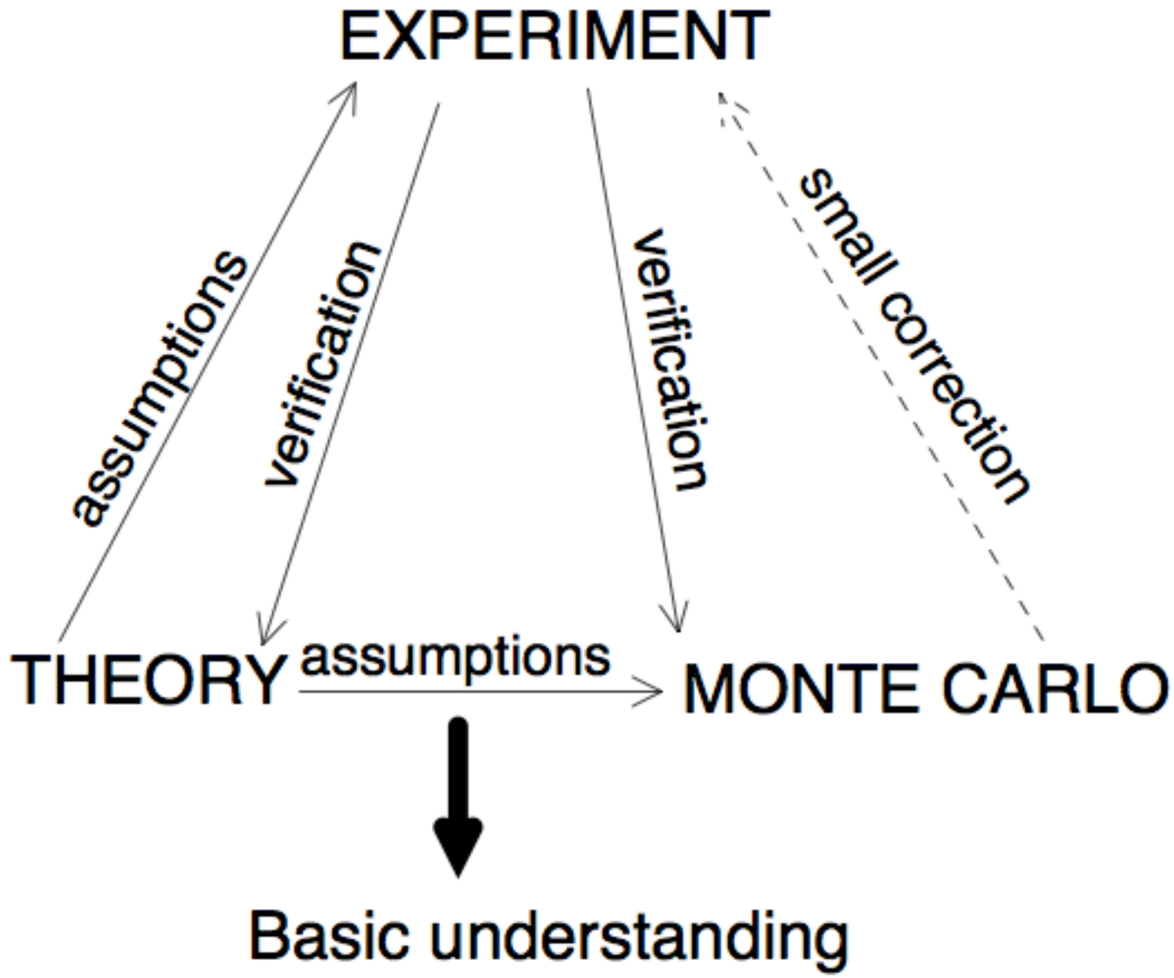
we must construct a big number of this equations, using

different random numbers, and

estimate the parameter and its variance"

A. F. Bielajew, 2001

The Monte Carlo method

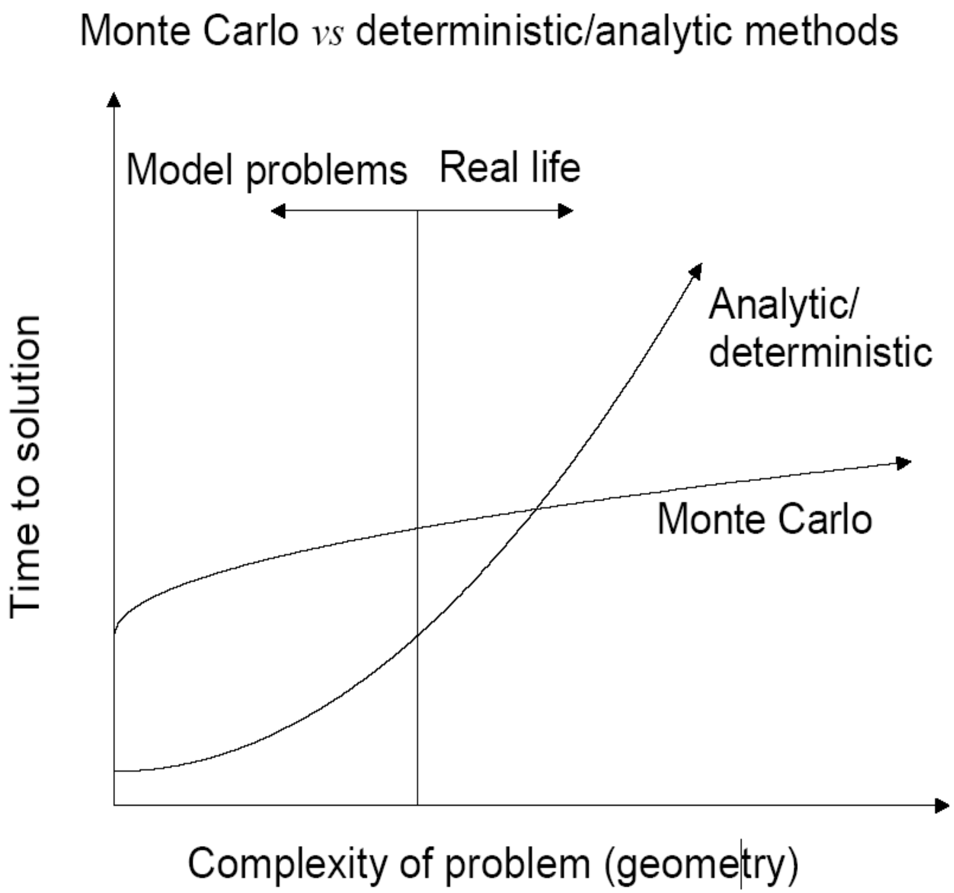


The Monte Carlo method

- Particles are tracked one-by-one, step-by-step and, after a reasonable number, the correct information can be extracted

- MC is very time consuming but
  - .... sometime necessary and
  - ....with many advantages

The Monte Carlo method

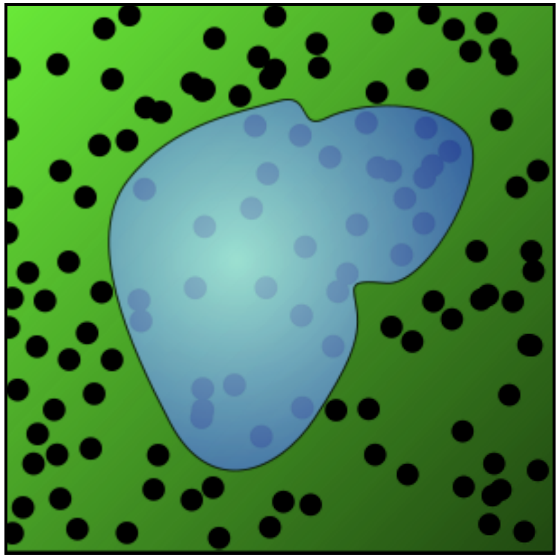


Plot from Alex F. Bielajew, 2001

Mathematical proofs exist demonstrating that

MC is the most efficient way of estimate quantity in 3D when compared to first-order deterministic method

A simple example



$$\text{area of object} =$$

$$= \text{area of rectangle} \times \frac{\text{number of points inside object}}{\text{total number of points in rectangle}}$$

The name *"Monte Carlo"* was popularized by physics researchers Stanislaw Ulam, Enrico Fermi, John von Neumann, and Nicholas Metropolis, among others; the name is a reference to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money to gamble. The use of randomness and the repetitive nature of the process are analogous to the activities conducted at a casino.

Geant4 and the Geant4 Collaboration

Monte Carlo codes on the market

- MCNP (neutrons mainly)
- Penelope (e- and gamma)
- PETRA (protons)
- EGSnrc (e- and gammas)
- PHIT (protons/ions)
- FLUKA (any particle)

Geant4

-GEometry ANd Traking

- Geant4 - a simulation toolkit
  Nucl. Inst. and Methods Phys. Res. A, **506** 250-303

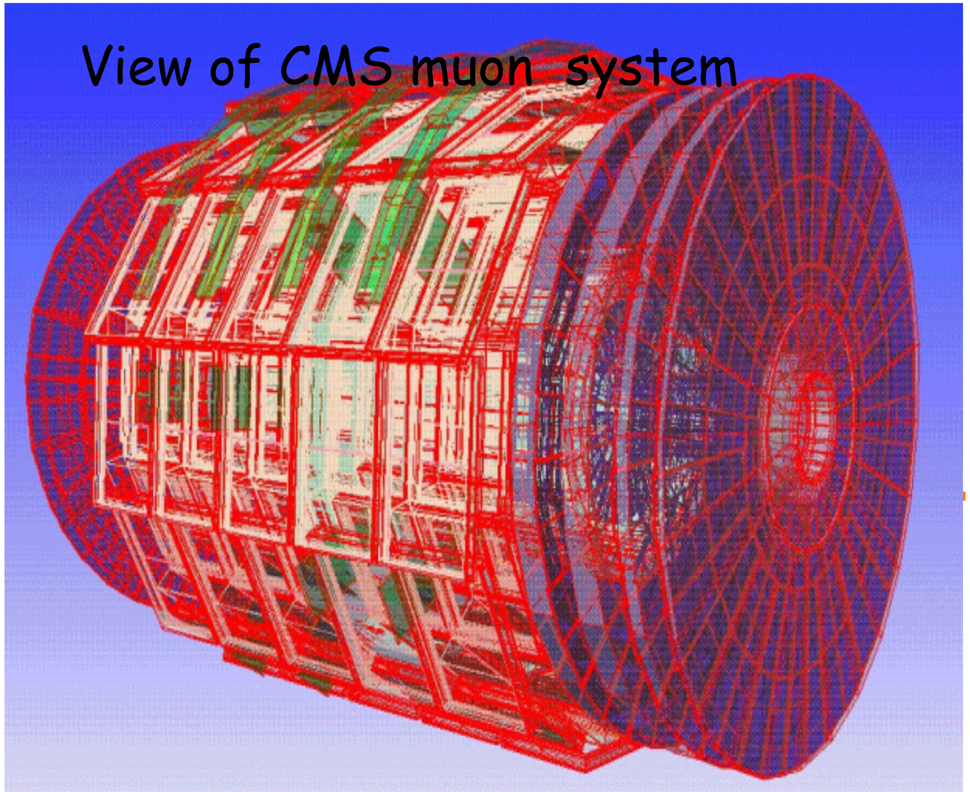
- Geant4 developments and applications
  Transaction on Nuclear Science **53**, 270-278

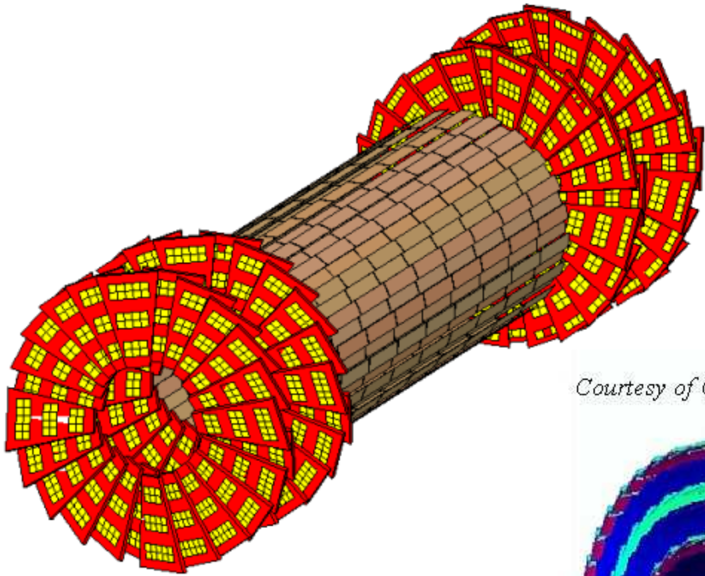
Facts about Geant 4

- Developed by an International Collaboration
  - Established in 1998
  - Approximately 100 members, from Europe, US and Japan
  - **http://geant4.cern.ch**
- Written in C++ language
  - Takes advantage from the Object Oriented software technology
- Open source
- Typically two releases per year
  - Major release, minor release, beta release

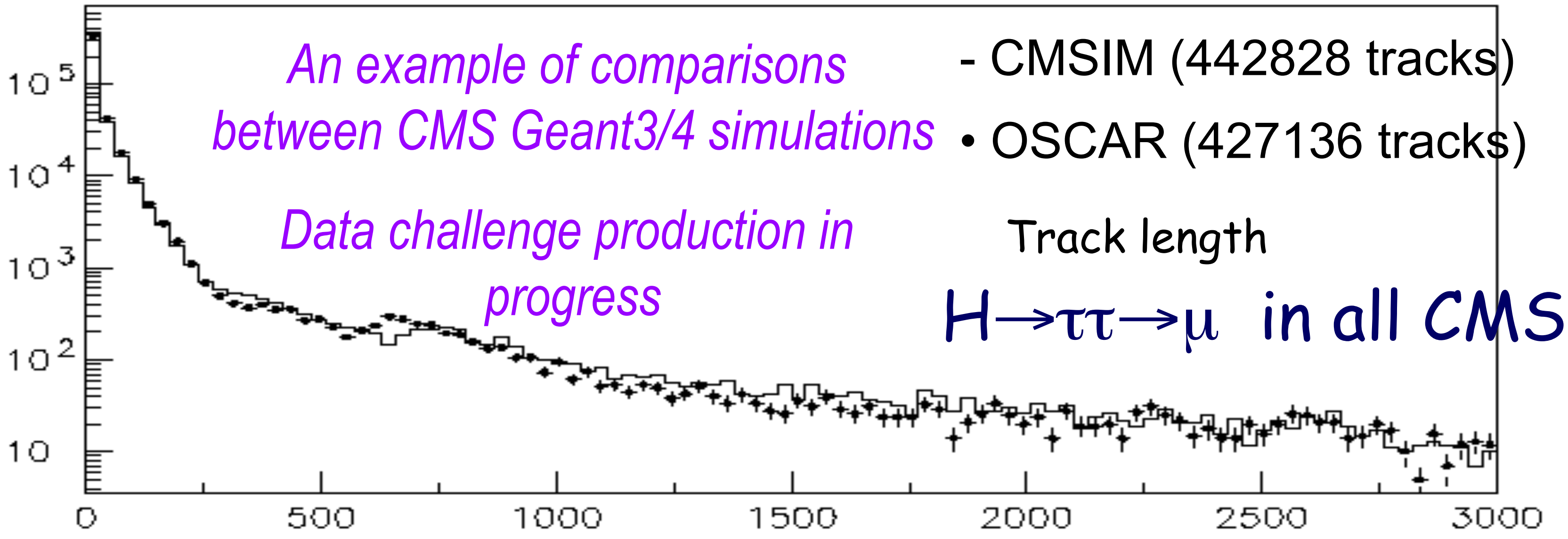
Geant4 applications

CMS





View of CMS pixel detector



An example of comparisons between CMS Geant3/4 simulations

Data challenge production in progress

- CMSIM (442828 tracks)
• OSCAR (427136 tracks)

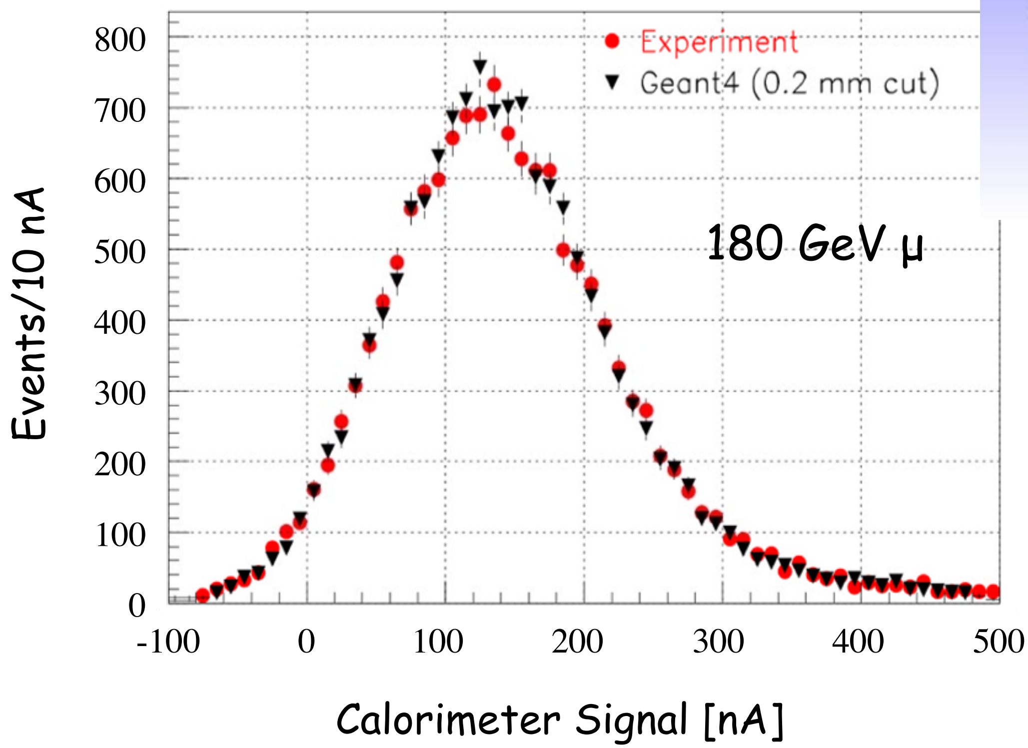
Track length

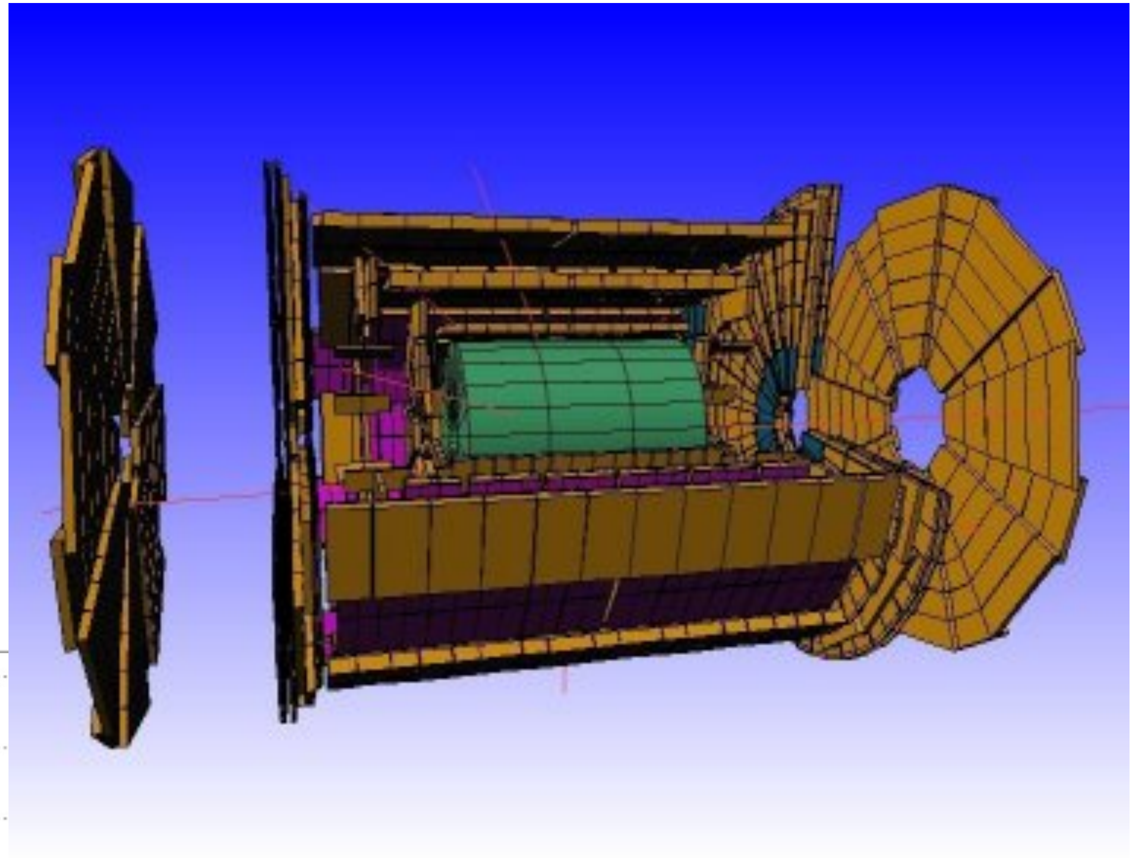
$H \rightarrow \tau\tau \rightarrow \mu$ in all CMS

ATLAS

Extensive comparisons with test beam data

(activity in progress)



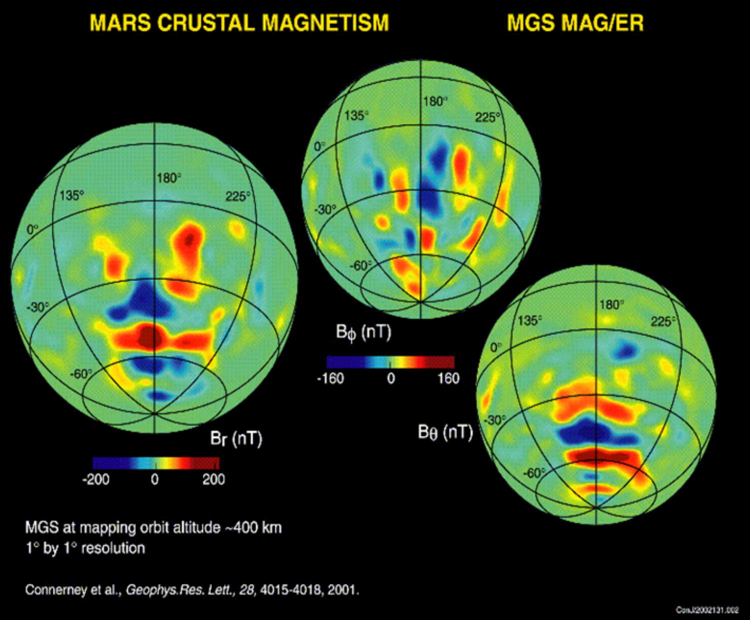


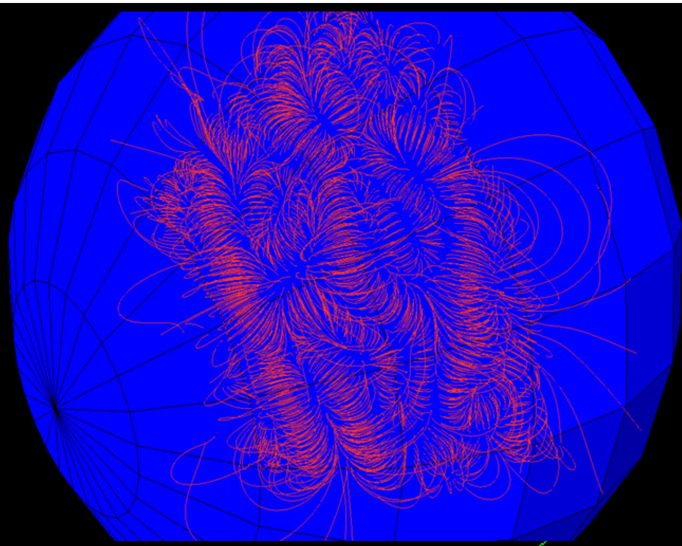
HEC Testbeam: Muon Response Comparisons

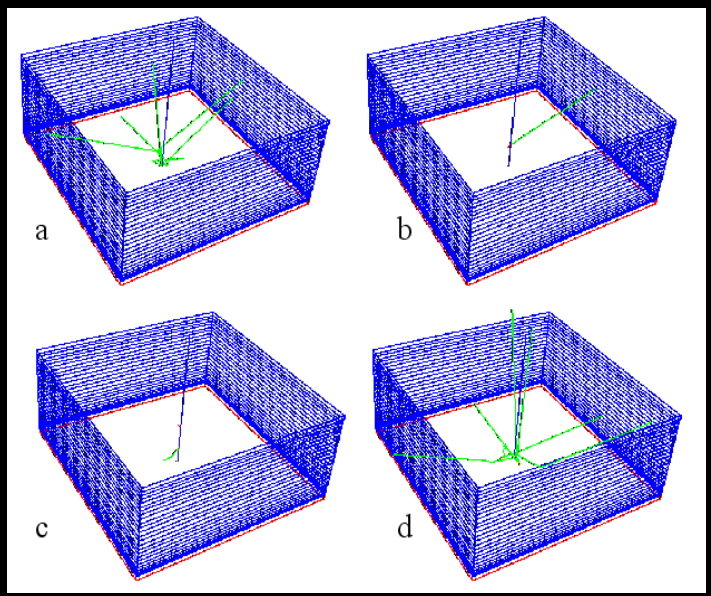
Courtesy of ATLAS Collaboration

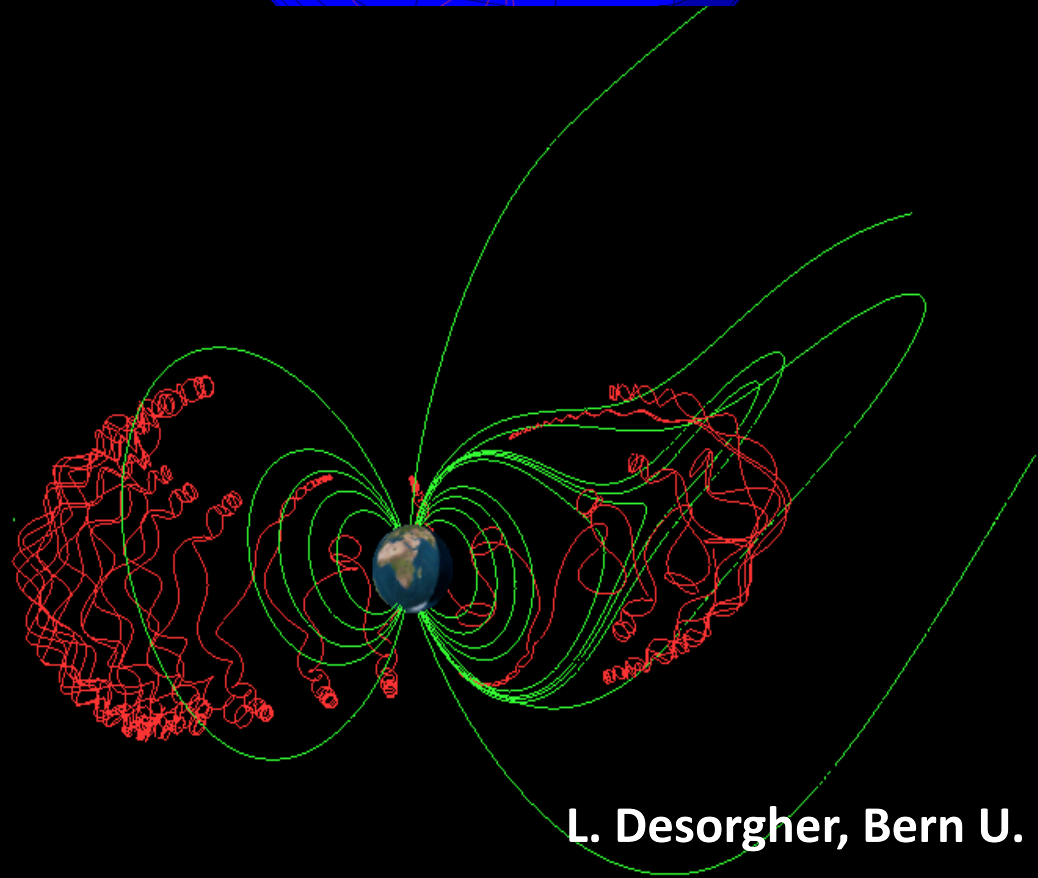
Space applications and Astrophysics

Planetary radiation environments



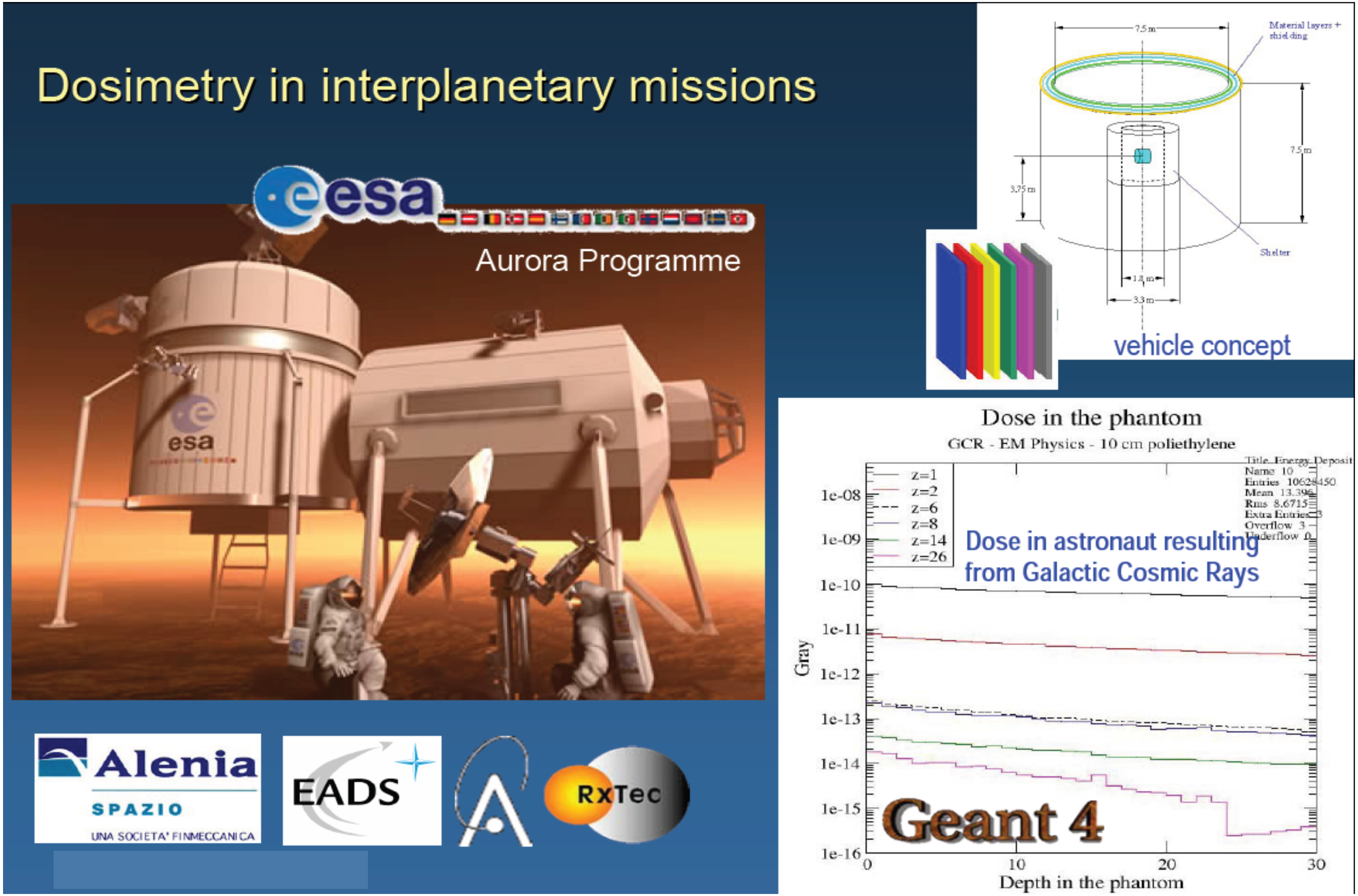




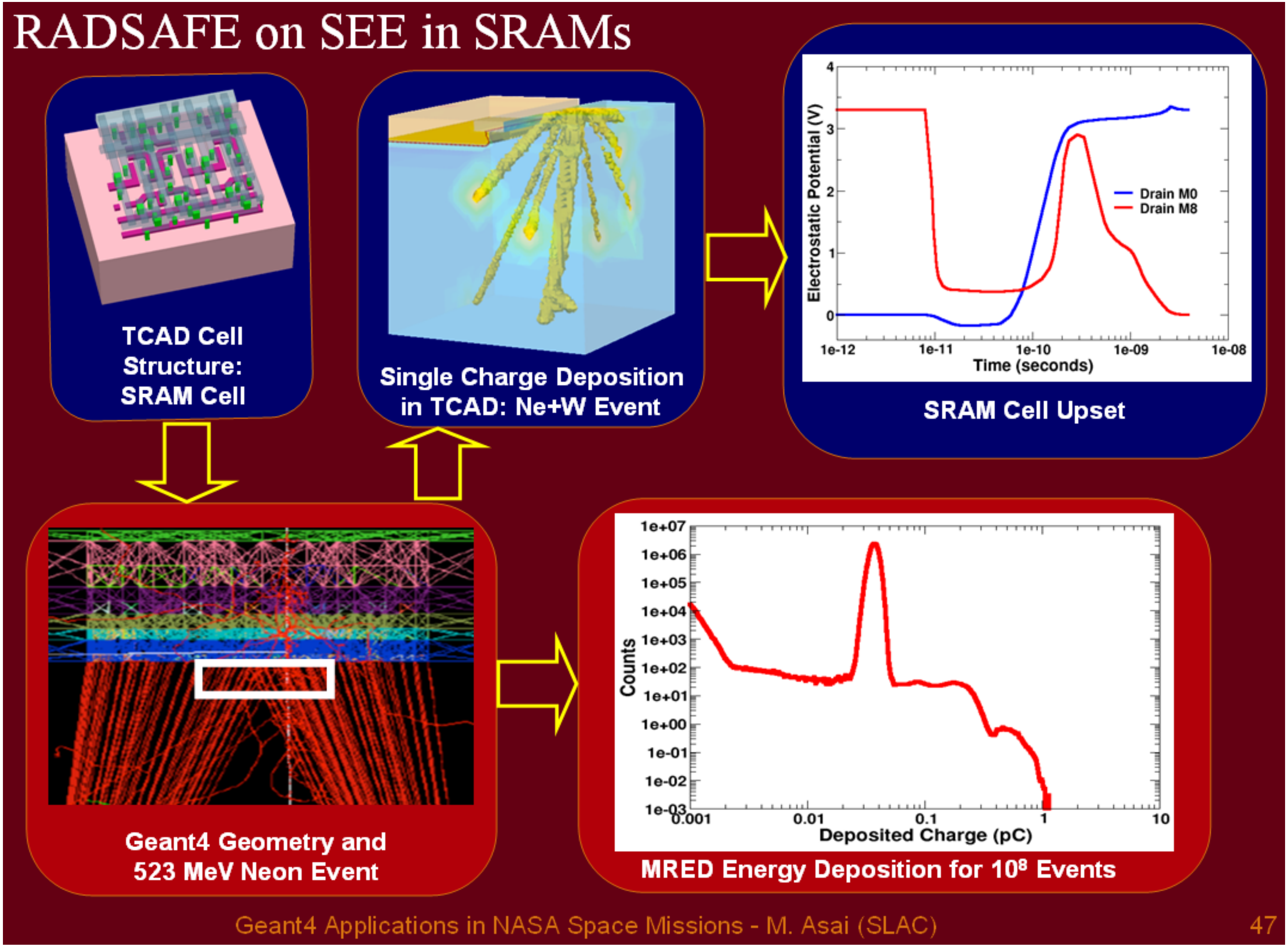


L. Desorgher, Bern U.

Dosimetry in interplanetary missions

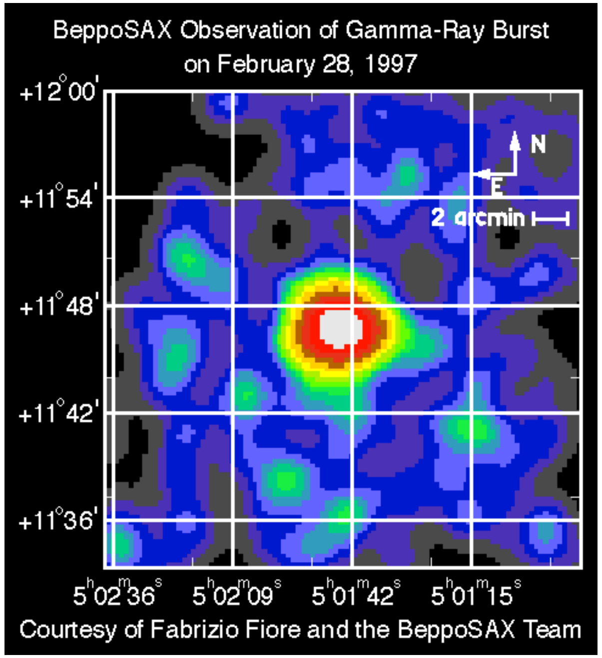


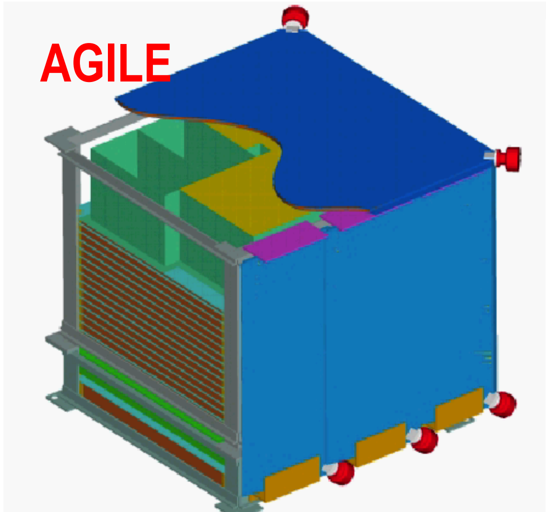
Radiation damage

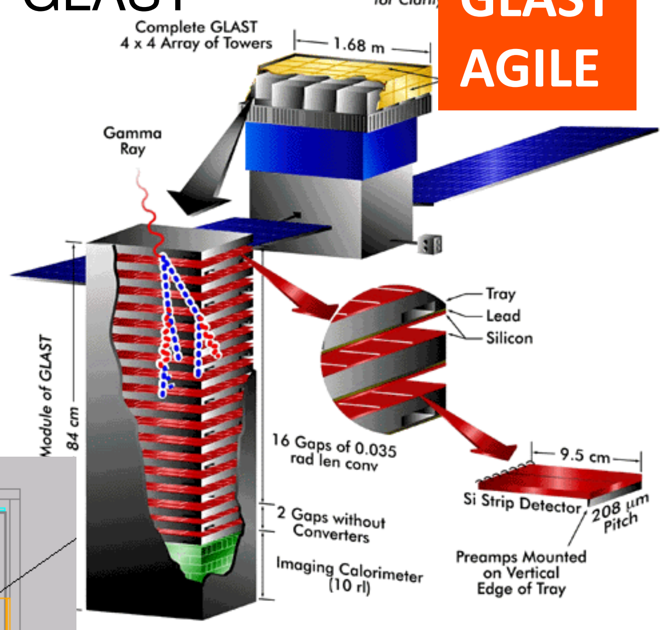


γ astrophysics

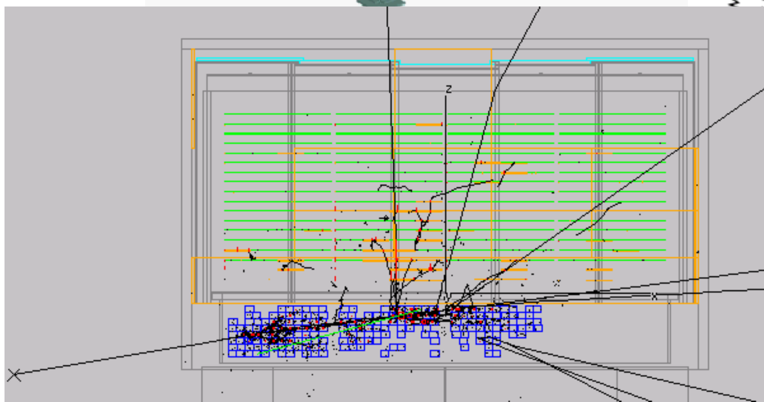
γ-ray bursts







GLAST
AGILE



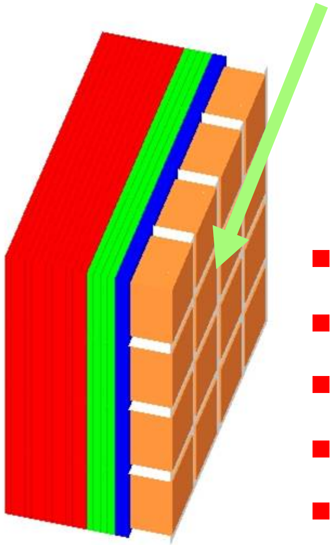
GLAST

Typical telescope:

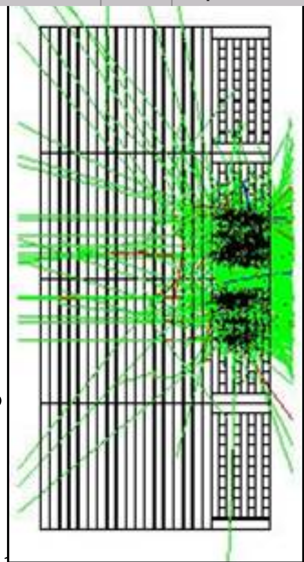
Tracker

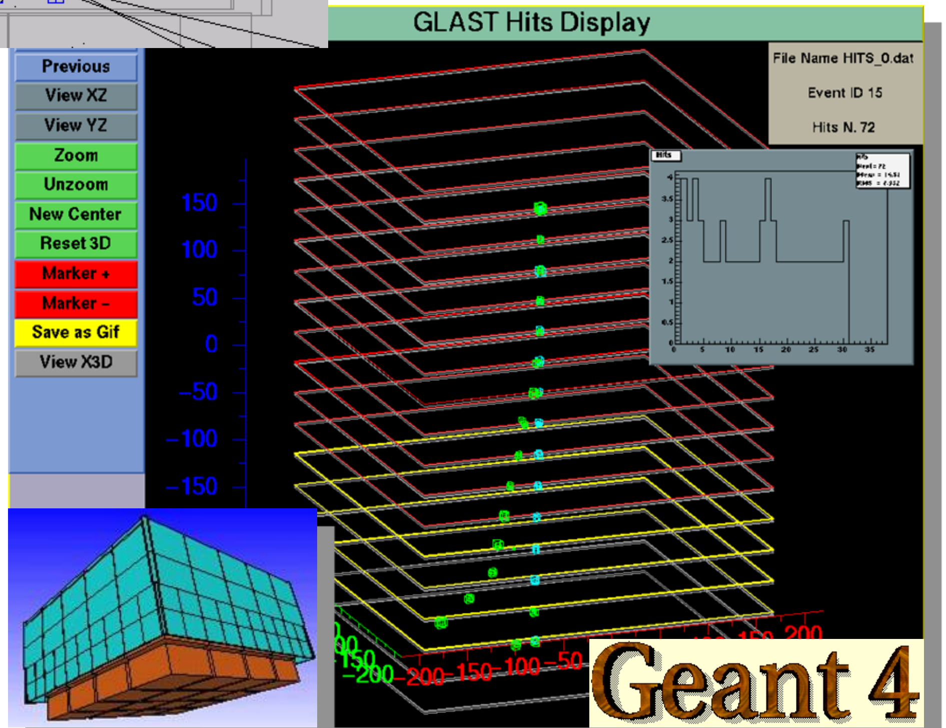
Calorimeter

Anticoincidence



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





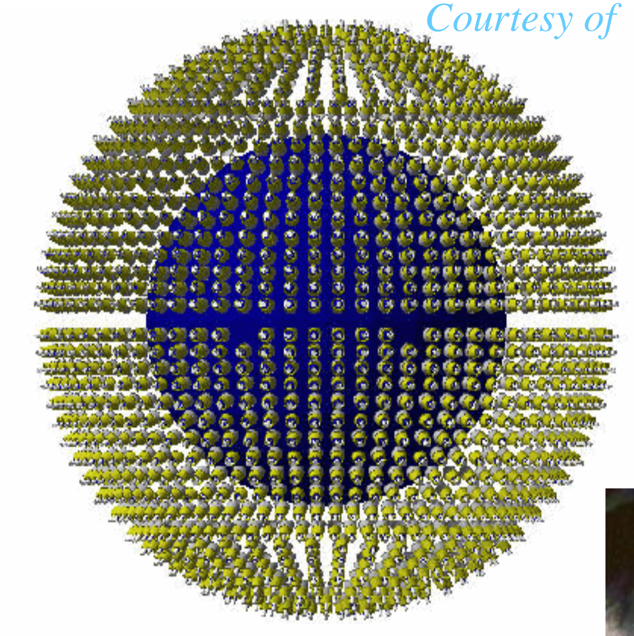
Underground astroparticle experiments

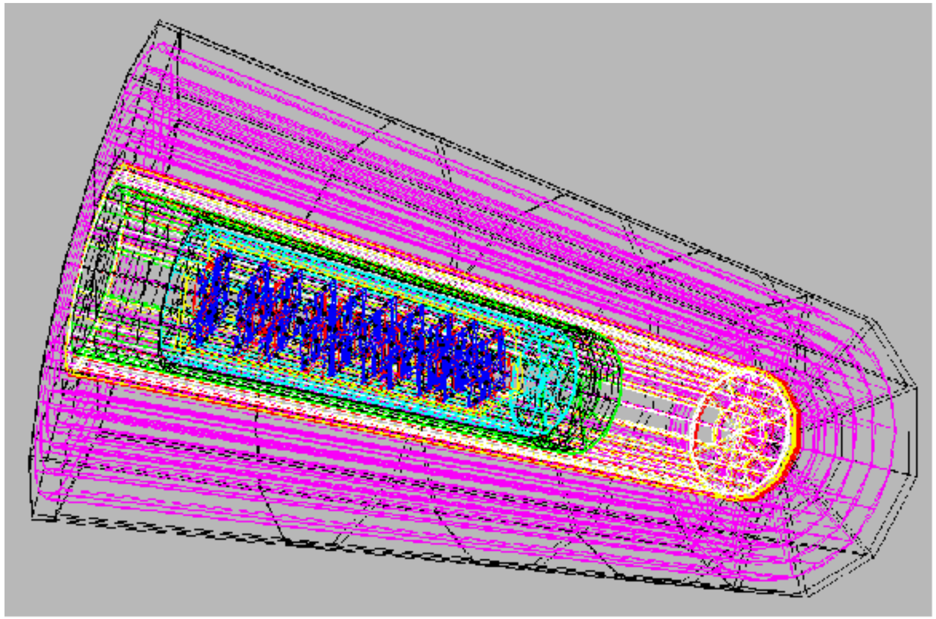
Geant 4

unique simulation capabilities:

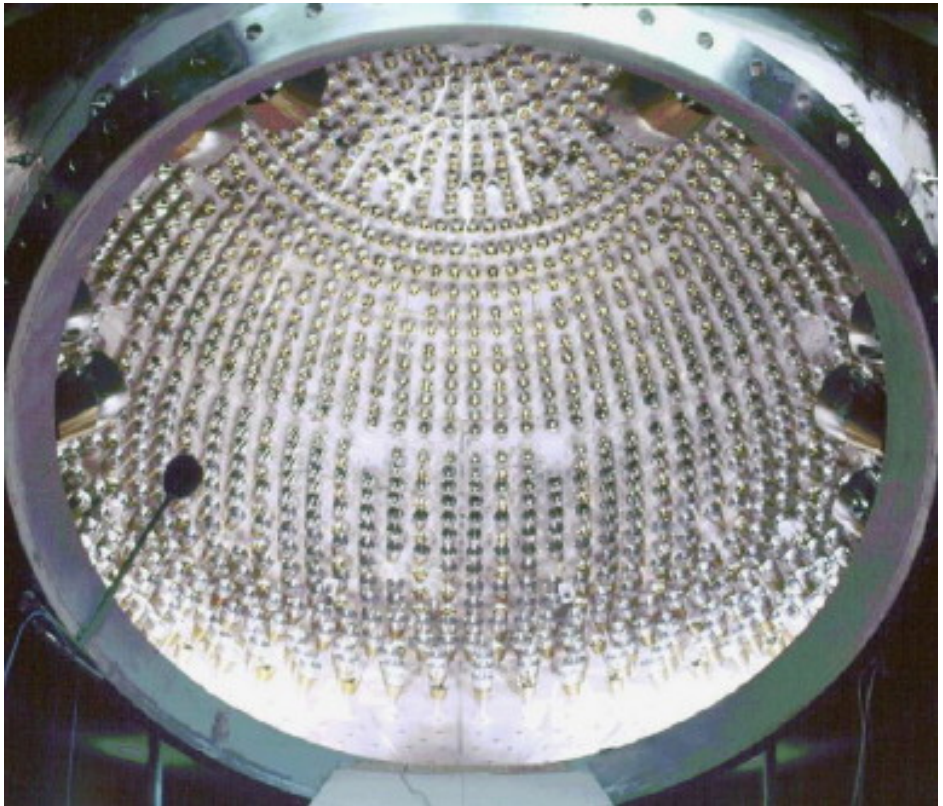
- lowE physics
- fluorescence
- radioactivity
- neutrons
- etc..

Courtesy of Borexino



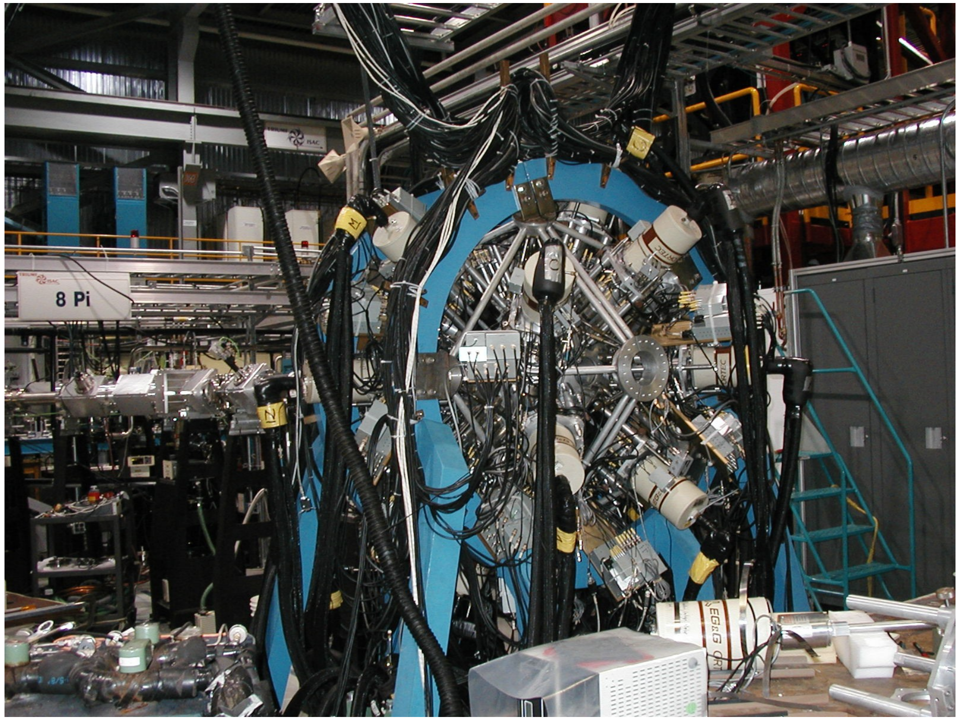


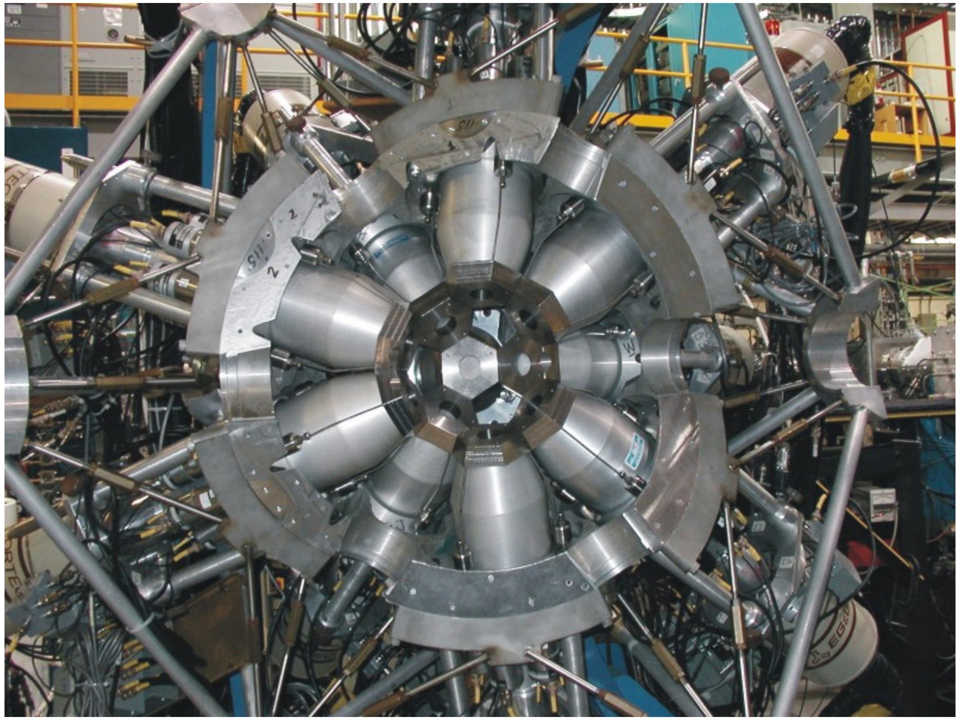
credit Oliviero Cremonesi

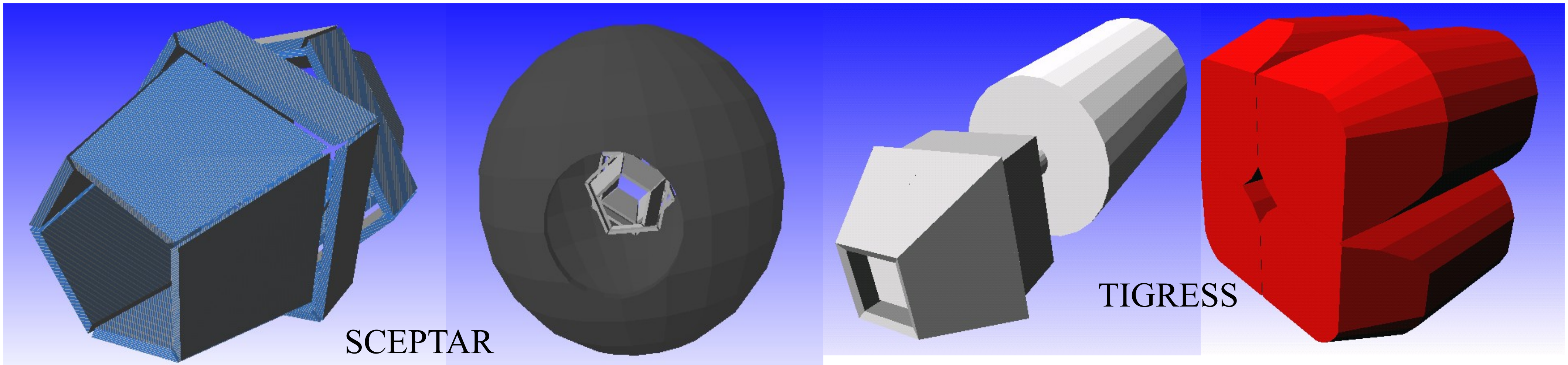


Nuclear Spectroscopy at TRIUMF

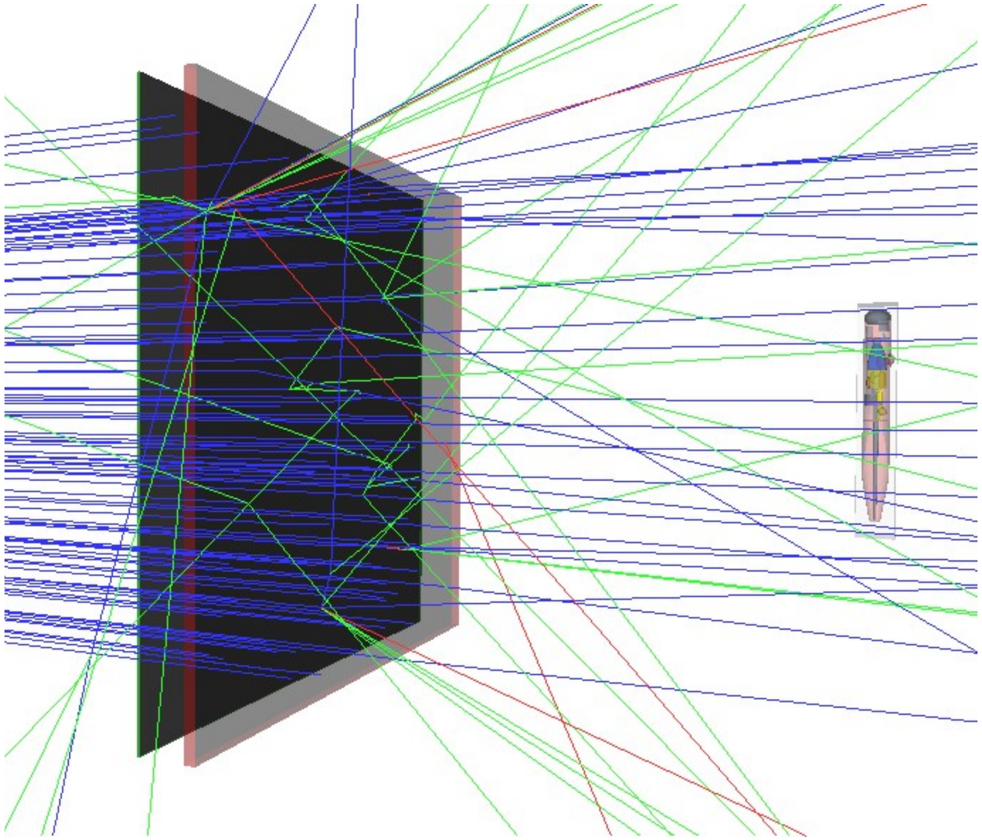
- gamma spectrometer with beams of radioactive nuclei
- Used with TRIUMF’s Isotope Separator and ACcelerator

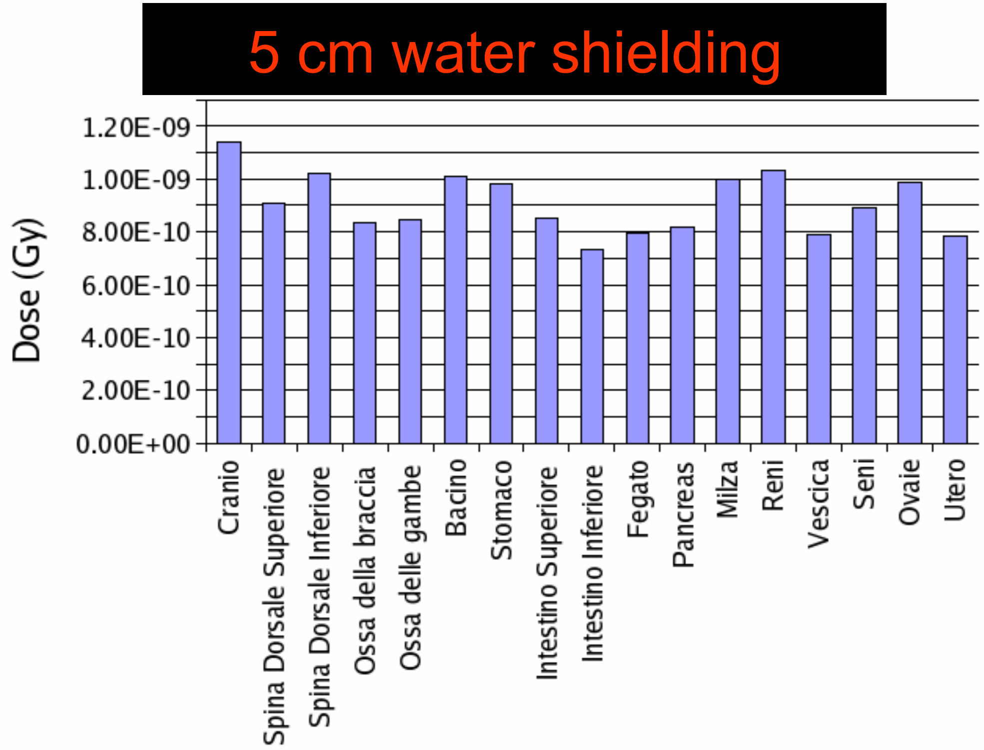


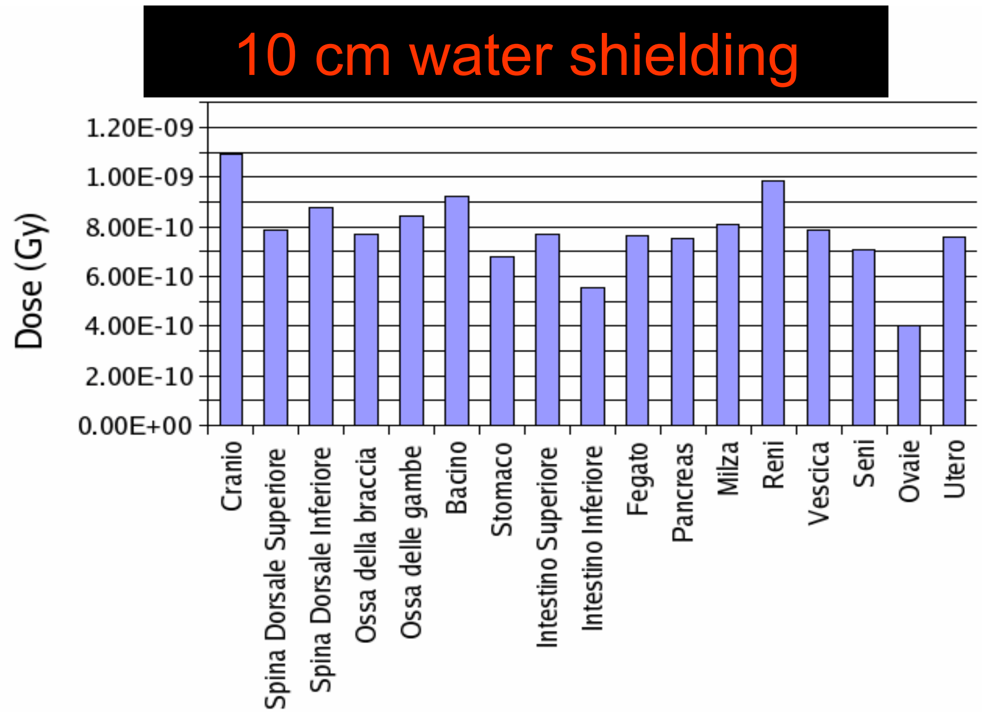




Radiation Protection







Dose calculation in critical organs

Effects of external shielding

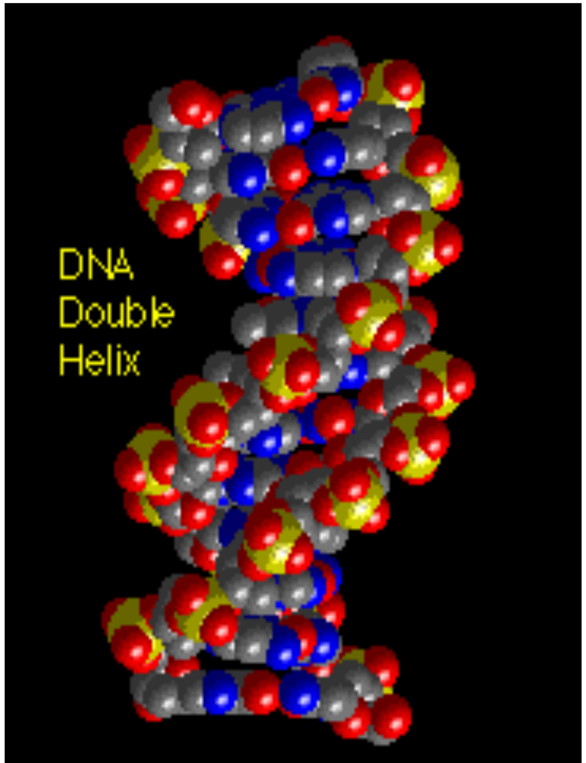
Self-body shielding

Medical applications

Geant4-DNA project

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

- Context :
  - modelling very low energy EM Physics processes for the simulation of radiation effects at the molecular level (« Geant4 DNA »)
- Purpose of the microdosimetry advanced example :
  - show to users how to implement very low energy EM Physics processes in a Geant4 application
  - contains a full PhysicsList



- Relevance for space: astronaut and airline pilot radiation hazards, biological experiments (ESA)
- Applications in radiotherapy, radiobiology…

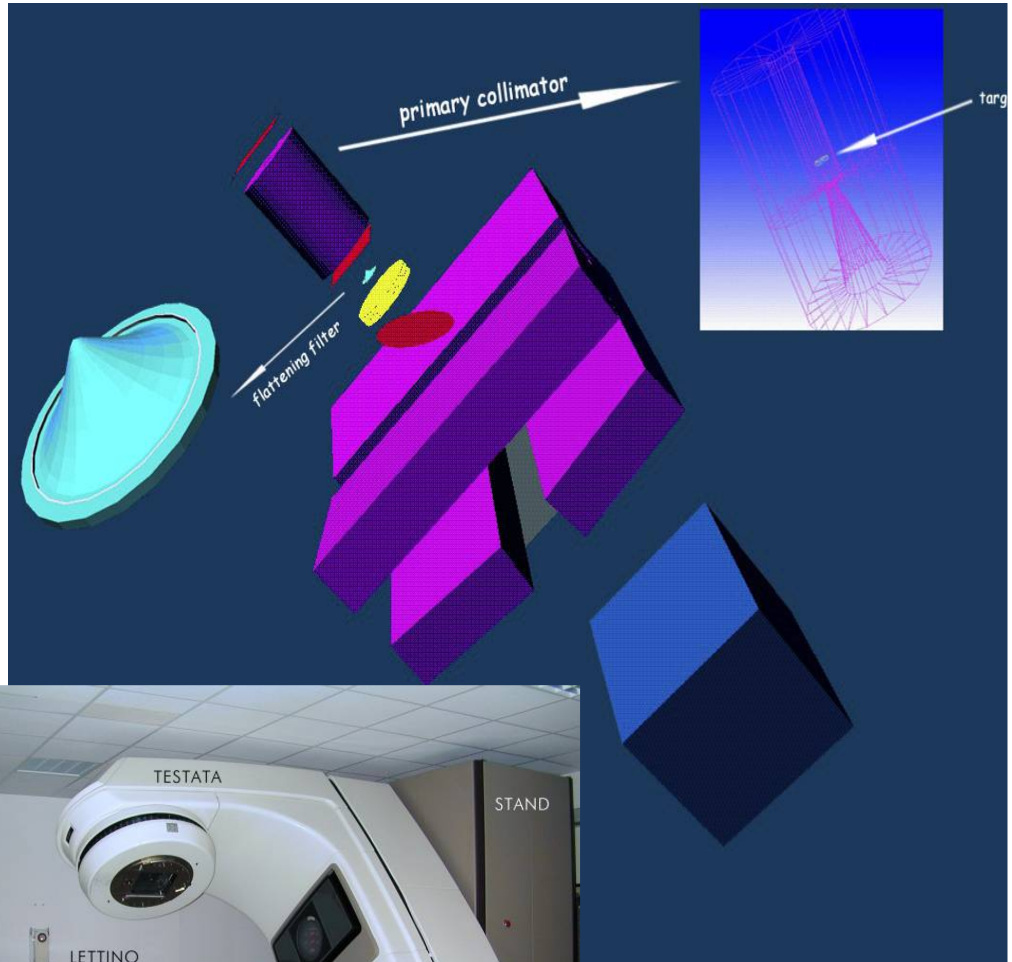
MEDICAL_LINAC example

Medical Linac for IMRT

- Simulation tool which determines the dose distributions resulting from the head of a linear accelerator used for **IMRT**

- Many algorithms were developed to estimate dose distributions, but even the most sophisticated ones resort to some approximations

- These approximations might affect the outcome of dose calculation, especially in a complex treatment planning as IMRT

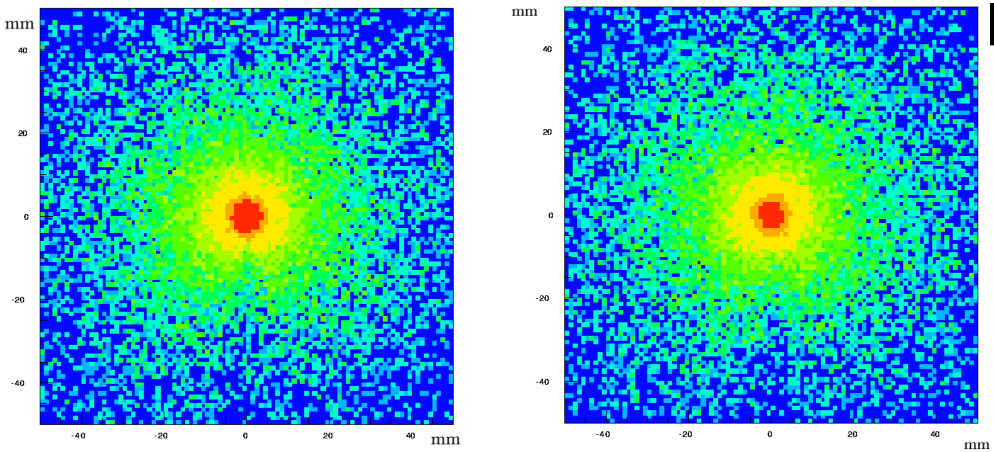


Brachyterapy example

Dosimetry

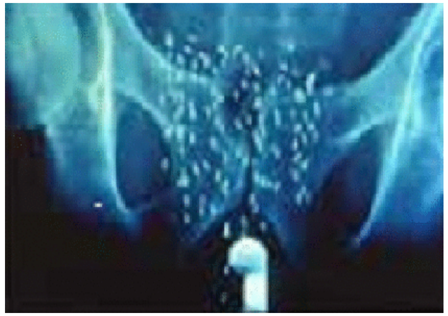
Endocavitary brachytherapy

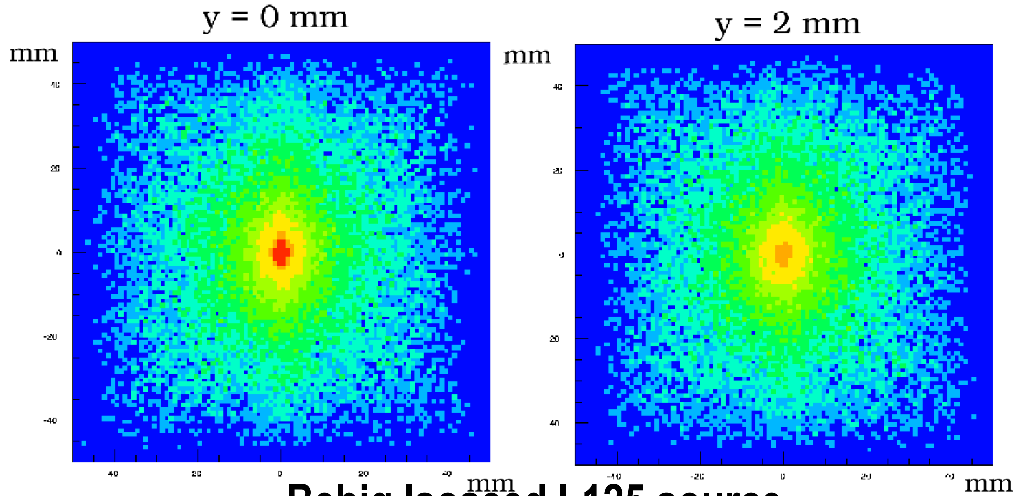
MicroSelectron-HDR source



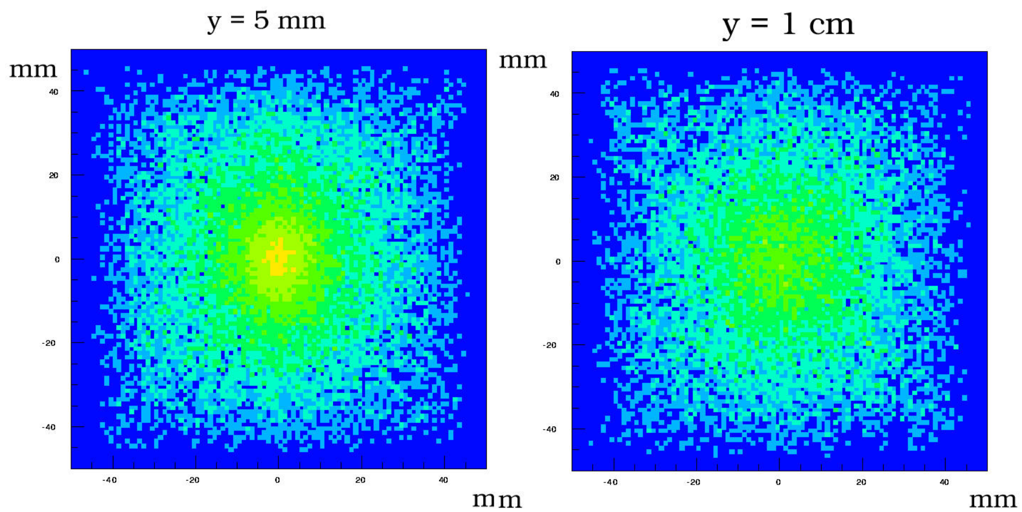
Dosimetry

Interstitial brachytherapy

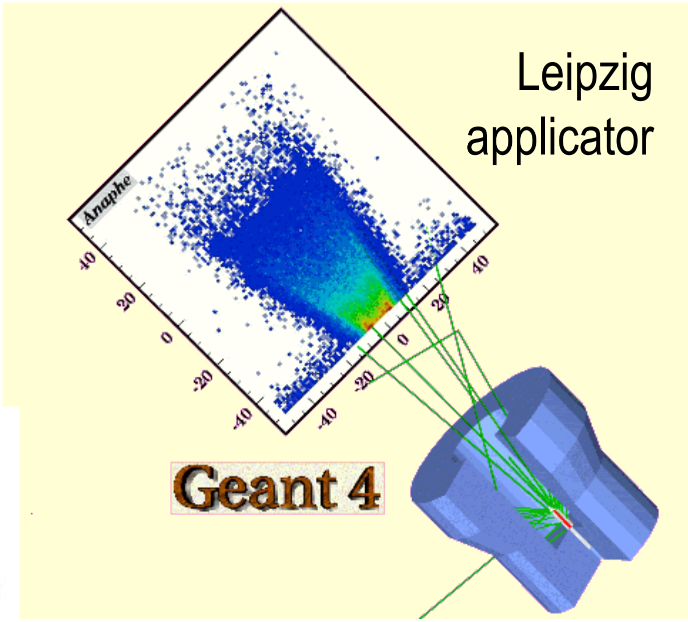




Bebig Isoseed I-125 source



Superficial brachytherapy



Leipzig applicator

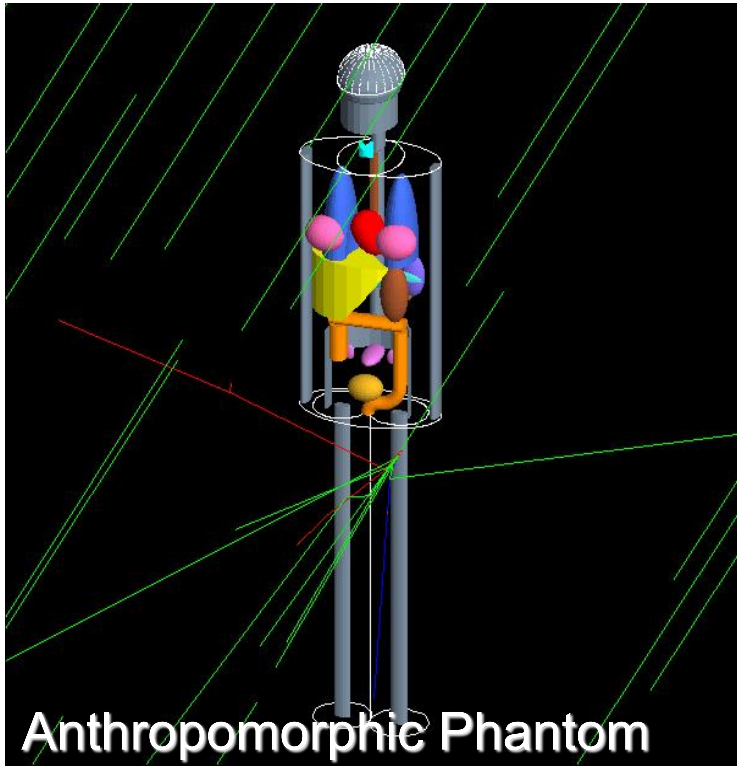
HUMAN_PHANTOM example

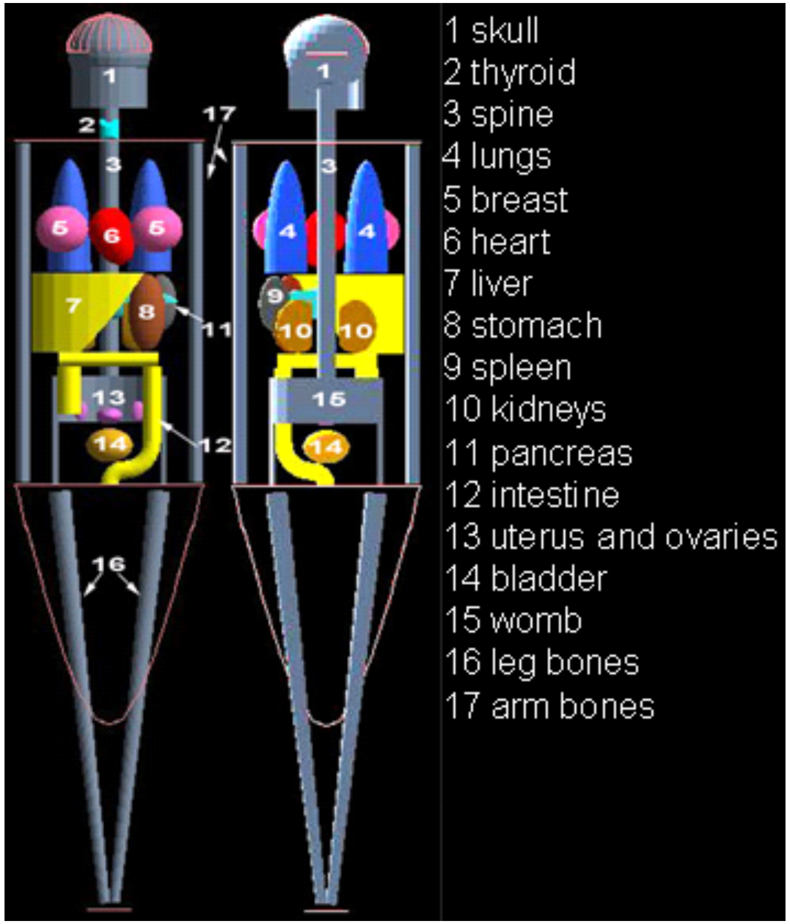
Total Body Irradiation

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

geant4_installDir/examples/advanced/human_phantom

Development of anthropomorphic phantoms with Geant4 for the evaluation of the dose deposited in critical organs

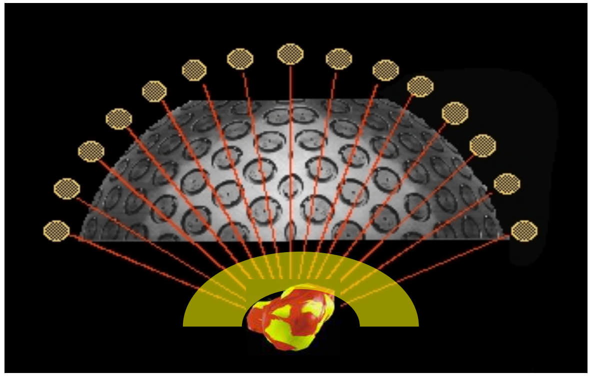




GammaKnife application

*Stereotactic Radiosurgery with **Gamma Knife** is used to treat brain disorders which are often inaccessible for conventional surgery → one single high dose session*

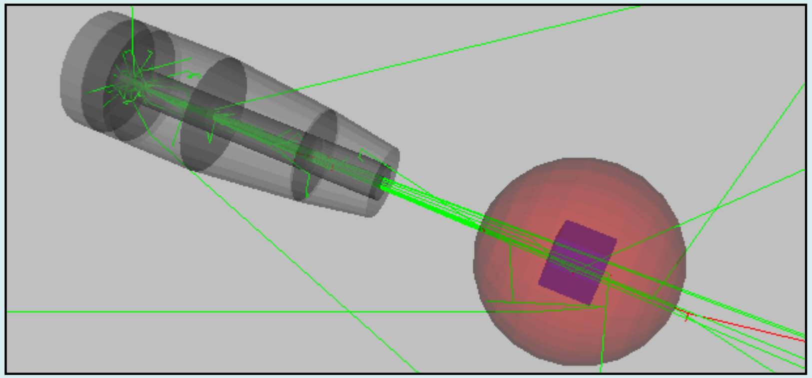
201 ^{60}Co sources in a hemispherical arrangement

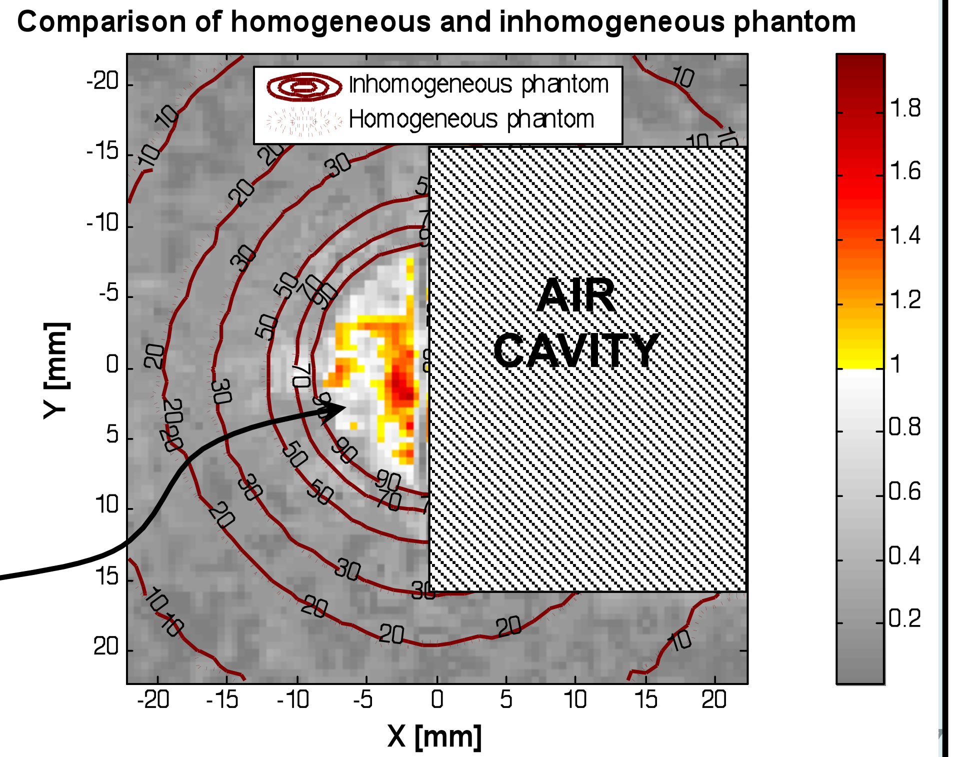


Gamma ray beams converge through a collimator system to a common focal point (isocentre)

The Treatment Planning System neglects material inhomogeneities for dose calculation in the target

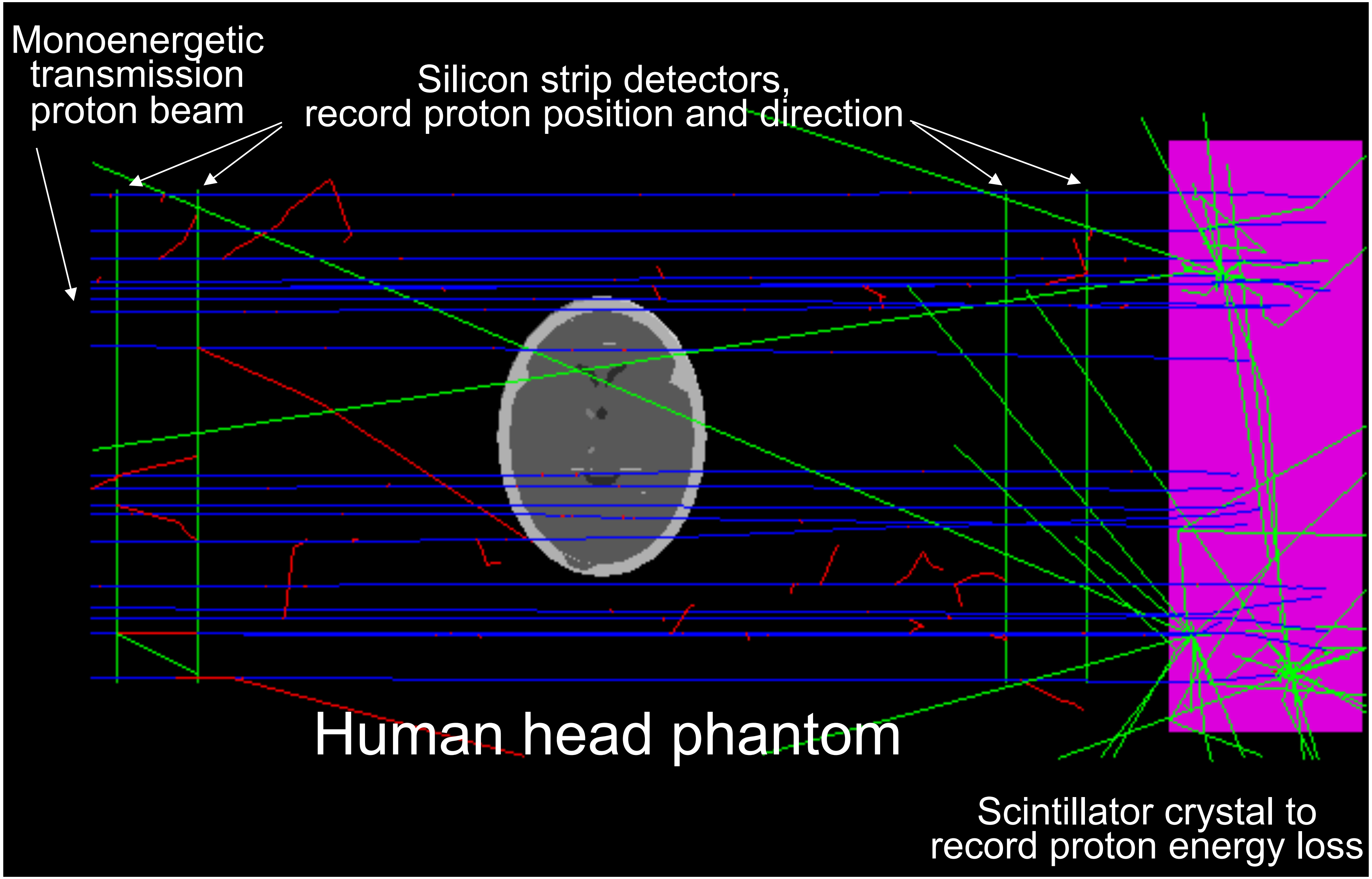
Geant4 simulation for the TPS verification in presence of different density materials





differences up to 4% in the dose distributions

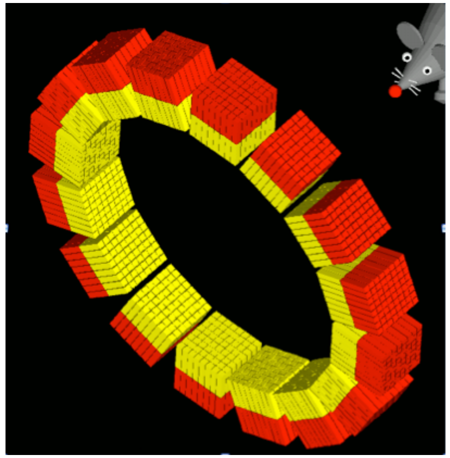
Proton Computed Tomography



GATE

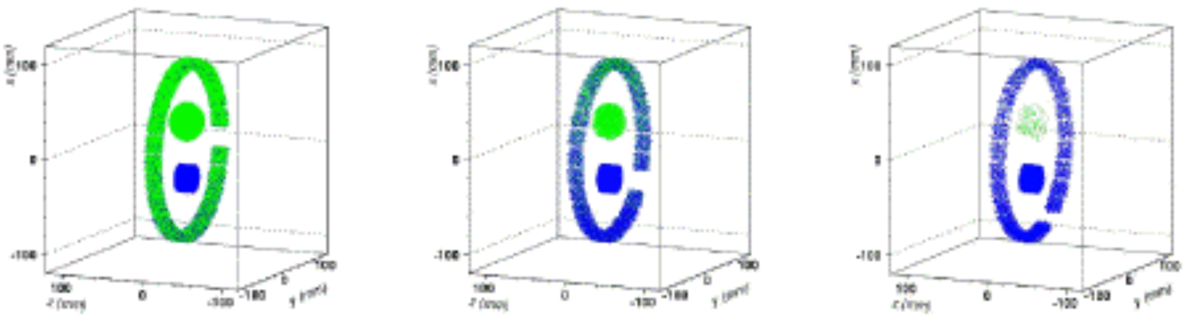
Geant4 Application for Tomographic Emission (GATE)

GATE Collaboration



- Accurate description of **time-dependent phenomena** such as source or detector movement
- Realistic simulations of data acquisitions in time thanks to the ability to **synchronize all time-dependent components**
- Modeling of the detector response: **use of digitization**
- Use of **decay module** to model the source decay kinetic

Simulation of the decay of O-15 (in green) and C-11 (in blue) sources throughout 3 time frames

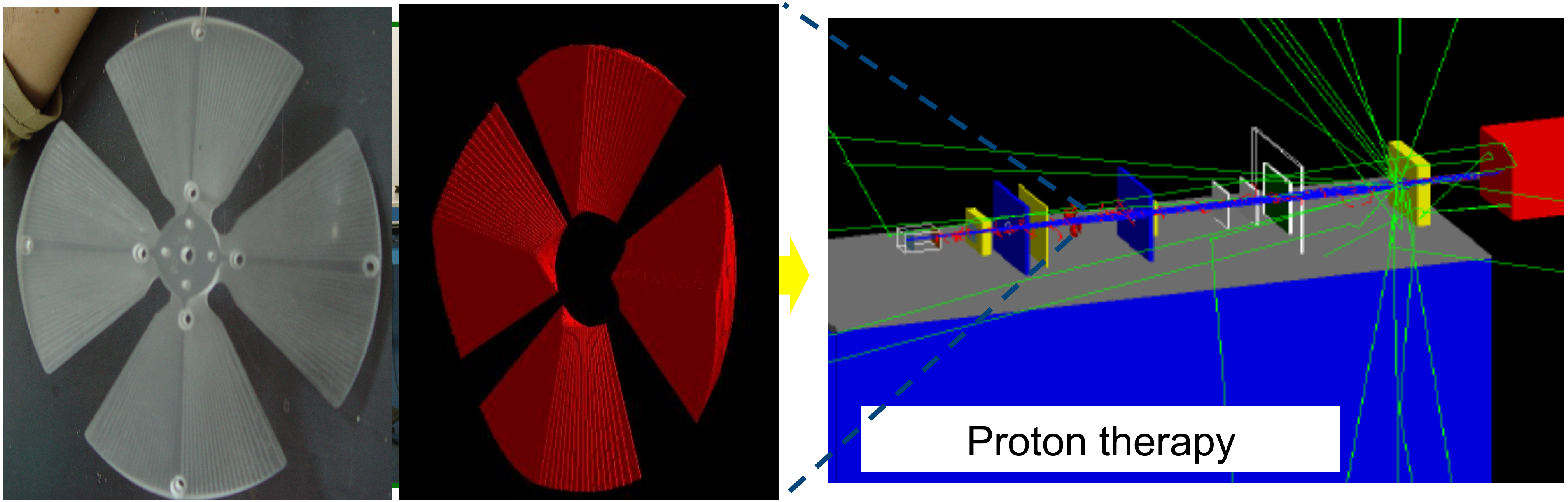


0 - 2 min   7 - 9 min   14 - 16 min

http://www-lphe.epfl.ch/~PET/research/gate/

HADRONTHERAPY example

CATANA (Centro di AdroTerapia e Applicazioni Nucleari Avanzate) is the first Italian facility for the treatment of ocular tumours



- General geometric proton beam line configuration
- 3D dose distribution calculation using a sensitive detector with cubic voxels

geant4_installDir/examples/advanced/hadrontherapy

**G.A.P. Cirrone, G. Cuttone et al., Implementation of a New Monte Carlo - GEANT4 Simulation Tool for the Development of a Proton Therapy Beam Line, IEEE Trans. Nucl. Sci., vol. 52, no. 1, pp. 262-265, Feb. 2005.*

Geant4 Advanced Examples

Wide experimental coverage:

- ✓HEP
- ✓Space science/astrophysics
- ✓Medical physics
- ✓Radiobiology
- ✓Detector technologies

Wide Geant4 coverage

- ✓Geometry features
- ✓Magnetic field
- ✓Physics (EM and hadronic)
- ✓Biological processes
- ✓Hits & Digis
- ✓Analysis
- ✓Visualisation, UI

Advanced example Working Group:

- **WG mission:**
  - Investigate, evaluate and demonstrate the Geant4 capabilities in various experimental domains
  - Identify requirements for further Geant4 improvements and extension in new domains
  - Provide connection between developers and users
- **Users interested in publishing an example can submit his/her request**

The Geant4 example categories

- Under `../geant4.9.6-install/share/Geant4-9.6.0/examples`:
  - Basic examples
    - Most typical use-cases Geant4 application (keeping simplicity and easy of use)
  - Novice examples
    - Applications ranging from non-interacting particle to very complex detectors simulation
  - Extended examples (Demonstration of Geant4 specific usage)
    - Electromagnetic
    - Analysis
    - Biasing
    - Visualization
    - ....
  - Advanced examples (Simulation of real experimental set-up or devices)
    - Brachytherapy
    - Gammaray_telescope
    - Medical_linac
    - Hadrontherapy

Thanks for your attention