



Introduction to Geant4

Geant = « GEometry And Tracking »

Geant4 PHENIICS & IN2P3 Tutorial,

16 – 20 May 2022,

Orsay

Marc Verderi

LLR, Ecole polytechnique

Credits

- Material in this presentation is from many sources
- And in particular from Makoto Asai presentations

Layout

- **Geant4 Overview**
 - Geant4 & its key functionalities
 - Key geometry capabilities
 - Physics models in Geant4
 - Geant4 – Brief history
 - Geant4 Collaboration
- **Geant4 Application Domains**
 - Large Hadron Collider (LHC) @ CERN
 - Geant4 in Space
 - Geant4 in Medical Science
 - Geant4 in Homeland Security
 - Geant4 in Other fields
- **Geant4 Toolkit Philosophy**

Geant4 Physics & Applications
A toolkit for Monte Carlo simulation of passage of particles in matter

Geant4 Hadronic Physics
Hadronic interaction modeling involves three main regimes: high energy, with string models (Quark/Gluon String (QGS), Friiof (FTF)), intermediate energy, with intra-nuclear cascade models (Bertini (BERI), Binary (BIC), Liège (INCL++)), and low energy, with precompound, Fermi break-up, fission/evaporation, capture at rest models and radioactive decays. Below 20 MeV, down to thermal energy neutrons are handled by means of cross-section databases, with the High Precision (HP) package. This approach has been recently extended to charged particles.

Geant4 Electromagnetic Physics
The electromagnetic physics covers interactions of gammas, muons and electrons, and ionization of all charged particles. A "low energy" approach, an implementation suited for applications disregarding effects below a few ~ 10 keV, and a "low energy" one provides approaches (Livermore, Penelope) for more accurate modeling of atomic shell effects allowing simulation down to ~ 250 eV. A very low extension, Geant4 DNA, includes particle-molecule effects for an energy limit of ~ 10 eV. The same approach is developed for silicon.

Geant4 DNA Scale Level Simulation
The ESA initiated a DNA scale level simulation, in view of manned mission to Mars. A bottom-up approach of dosimetry is adopted. Physics processes are extended down to a few eV, based on particle-molecule cross-sections. The approach is also applied to silicon, for accurate simulation of Single Upset Events.

Geant4 Medical Applications
Medical Applications interest in Monte Carlo is the accuracy capability in complex structures. Geant4 is used in radio-, proton & carbo-therapy medical research fields. It is also utilized in optimization of brachytherapy devices, radiotherapy and nuclear imaging. Large users communities exist in US, Europe and Japan. CPU performance boost allowed by Geant4 MT for by GPU prototype versions open the possibility for routine usage in treatment planning.

Geant4 Space Applications
Applications of Geant4 in space cover planetary scale simulation for soil level media activation studies, soil composition through X-ray re-emission, space ship simulation for radioprotection and electronic single event upset predictions, electronic chip scale simulation for accurate understanding of single event upset generation. It includes also underground, ground level or satellite cosmic ray experiments simulation.

Geant4 HEP Applications
High Energy Physics has been the first domain to utilize Geant4 in production, with the BaBar experiment at SLAC. The CERN LHC experiments used Geant4 for detector design and now for physics analysis. Geant4 is the simulation engine choice of the next generation of electron machines.

Geant4 Homeland Security Applications
Homeland security applications of Geant4 are rather new, with the simulation of X-ray scanning systems developed for airports or the simulation of systems for large devices like cargos, trucks...

Projectile Kinetic Energy (GeV) vs. **Projectile de Broglie λ (fm)**

High Energy Quark/gluon dominating behavior
Intermediate Energy Nucleon dominating behavior
Low Energy Nucleus dominating behavior
Neutron simulation down to thermal energies
Uranium Nucleus Size
Very Low Energy Atom and molecule dominating behavior

Proton, Neutron, Carbon, Ion
Water, Electron, Molecule Size
Gamma

The CMS detector
The ATLAS detector
The High Luminosity in 2022
AMM-Neutron X-ray telescope, launched in 1999
Planetocosmos - a simulation tool for planetary scale particle transport

(a) The simulation energy resolution (in %) in two sampling calorimeters compared with one standard deviation measurement (DELTA) values: L. Bernini et al., NIMA, 202, 229-242, (1987); G. D'Agostini et al., NIMA, 274, 134, (1989).
(b) Comparison of Geant4 energy loss models with ALICE SiD beam data (D. Antonelli, et al., NIMA, 345, 555-560 (2009); P. Christensen et al., HEP, J. Most Phys. E, 16, 2457-2462 (2007)).
(c) Comparison of angular distribution width (Data/MC in %) for various materials after traversing various material thicknesses, data from electron scattering benchmark (C. Ross et al., Med. Phys., 35, 4121, 2008).

Geant4 can use the same reaction data library than MCNPX, verification against MCNP and general purpose of outgoing neutrons produced in neutron collision.
Geant4 prediction for single upset rate is more accurate than standard software of the domain.

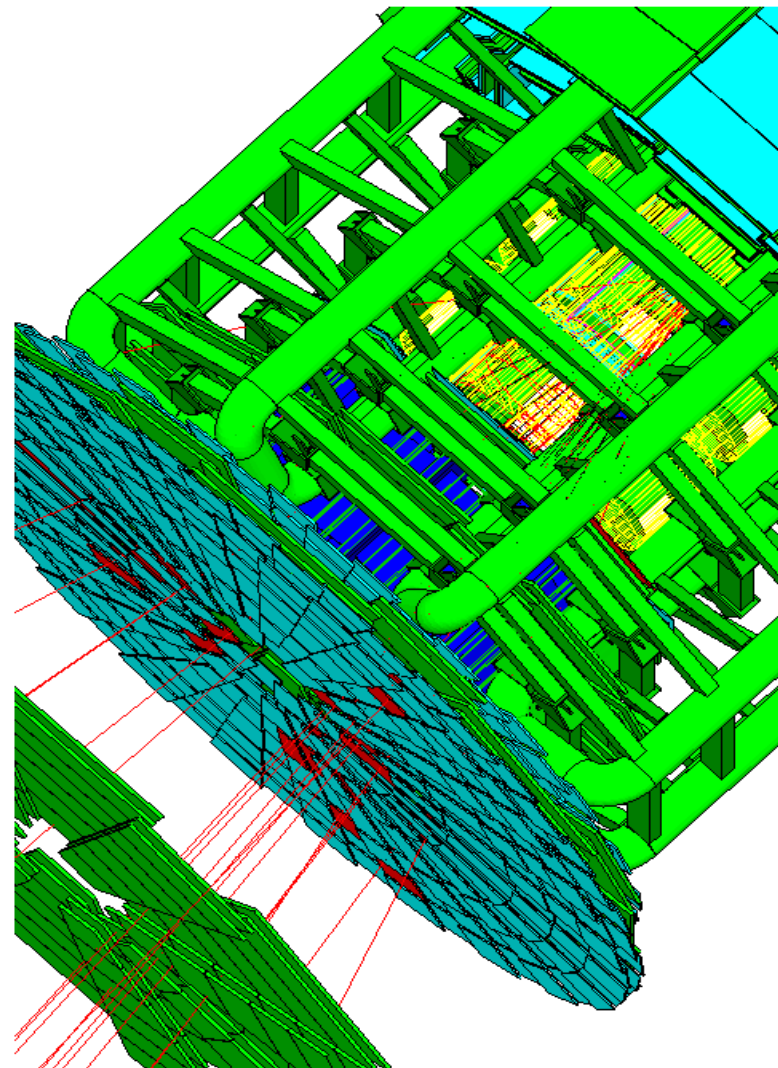
Proton beam line, range shifter and dose deposit simulations at HIMAC (Japan).
A MCeren dipse display in DICOM geometry <http://geant4.kan.gsi.jp/MCeren/>

DNA geometry model simulated: 46 Simulation of water chemical species migration accounting for electrical mutual interaction after a 50 million protons/cm², 5 billion base pairs...
Most proton irradiation, Post irradiation chemical attacks amount for ~60% of total damages on DNA.

Geant4 Overview

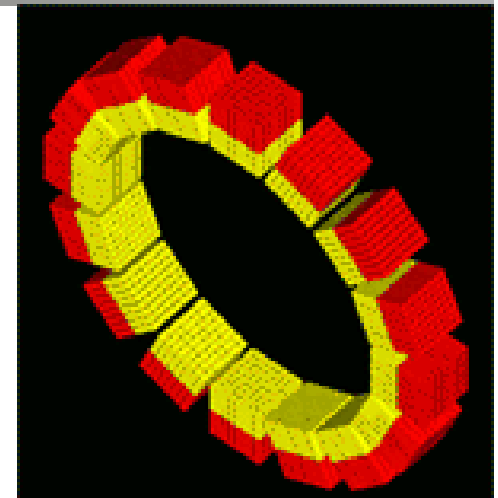
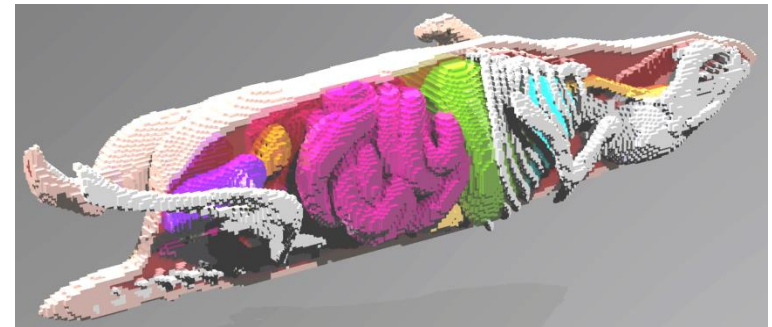
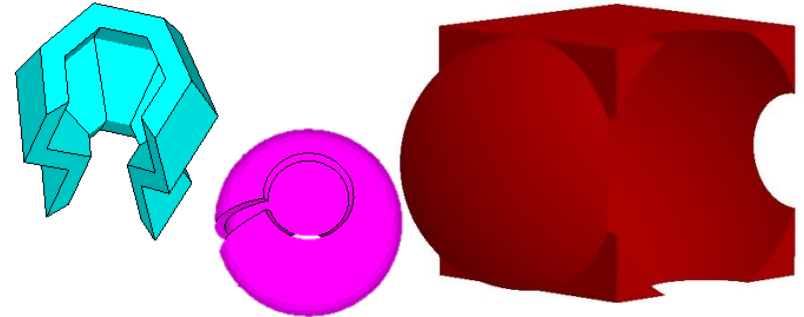
Geant4 & its key functionalities

- General purpose Monte Carlo toolkit for simulating the passage of elementary particles through and interacting with matter.
- Wide variety of user domains
 - high energy and nuclear physics,
 - space engineering
 - medical applications
 - material science
 - radiation protection and security.
- Geant4 offers lots of the functionalities required for the simulation of elementary particle and nucleus passing through and interacting with matter.
 - Kernel
 - Geometry and navigation
 - Physics processes
 - Scoring
 - GUI and Visualization drivers
- Users can easily plug-in their extensions without interfering with the other parts of Geant4.
- Extensive user guide documents and examples are provided.



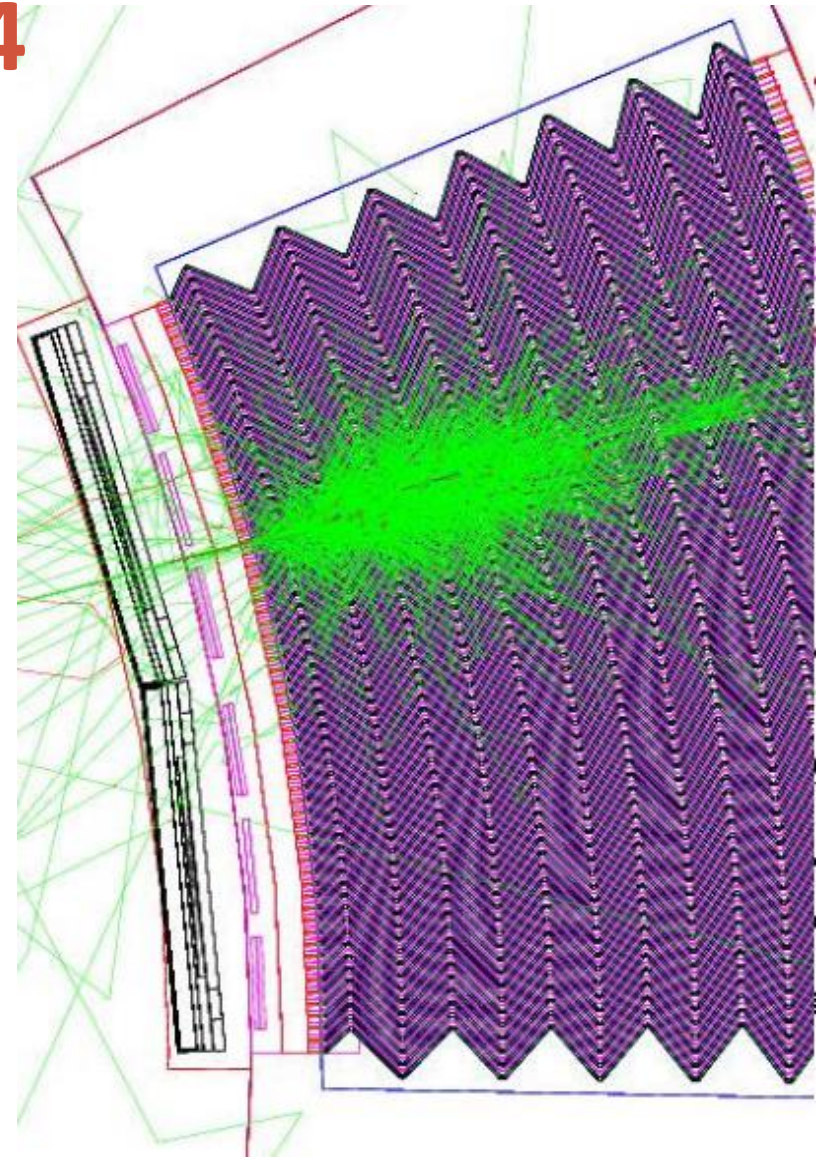
Key geometry capabilities

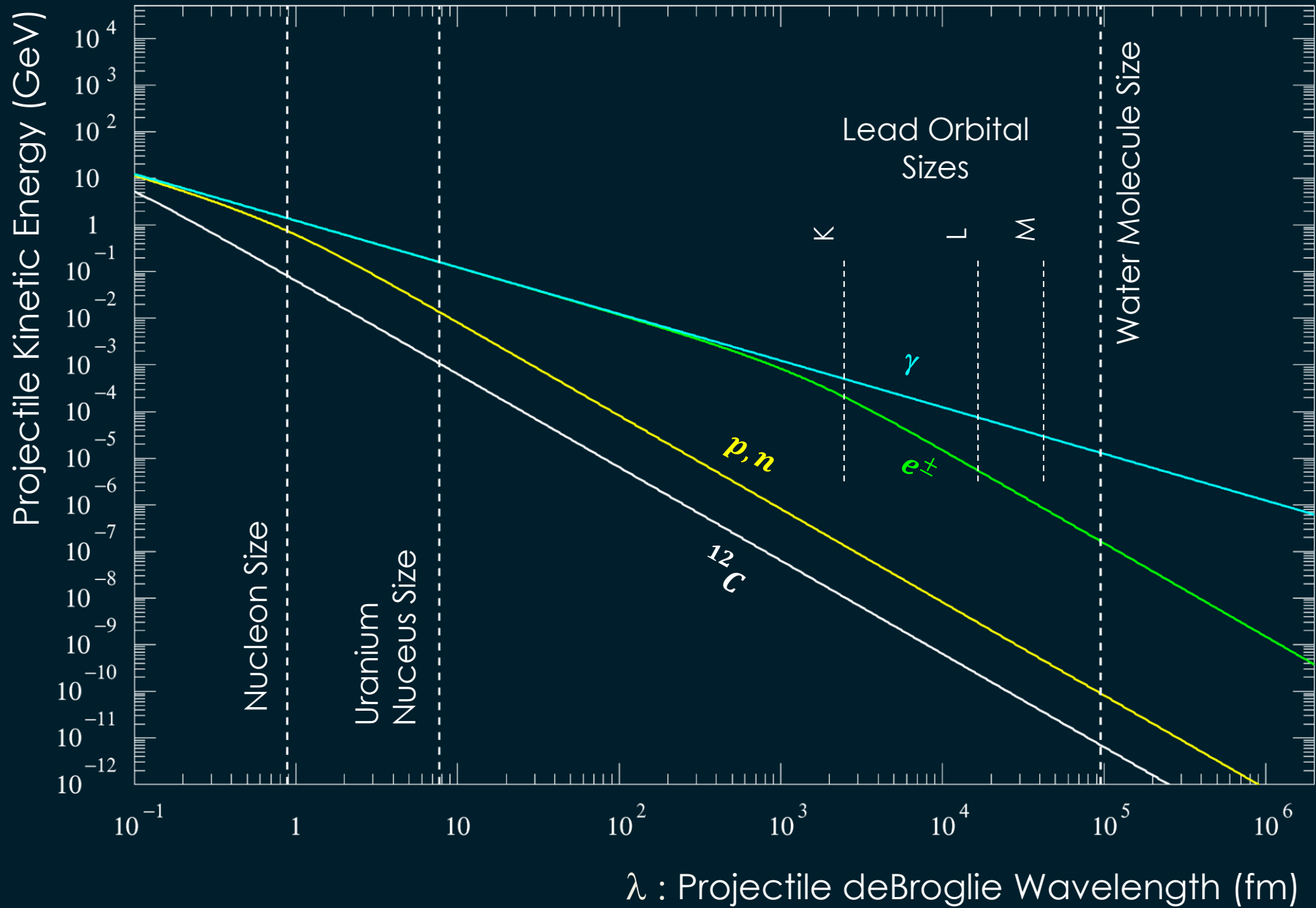
- Richest collection of shapes
 - CSG (Constructed Solid Geometry), Boolean operation, Tessellated solid, etc.
 - The user can easily extend
- Geometry structure described as hierarchy of volumes (or as 'flat' in some cases)
 - Describing setups up to billions of volumes
 - Tools for creating & checking complex structures
 - Some interface to CAD
- Navigating fast in complex geometry
 - Automatic optimization performed
 - Based on a virtual 3D grid with limited #volumes per grid cell & fast logic for finding adjacent cells
- Geometry models can be 'dynamic'
 - Changing the setup at run-time
 - e.g. "moving objects"

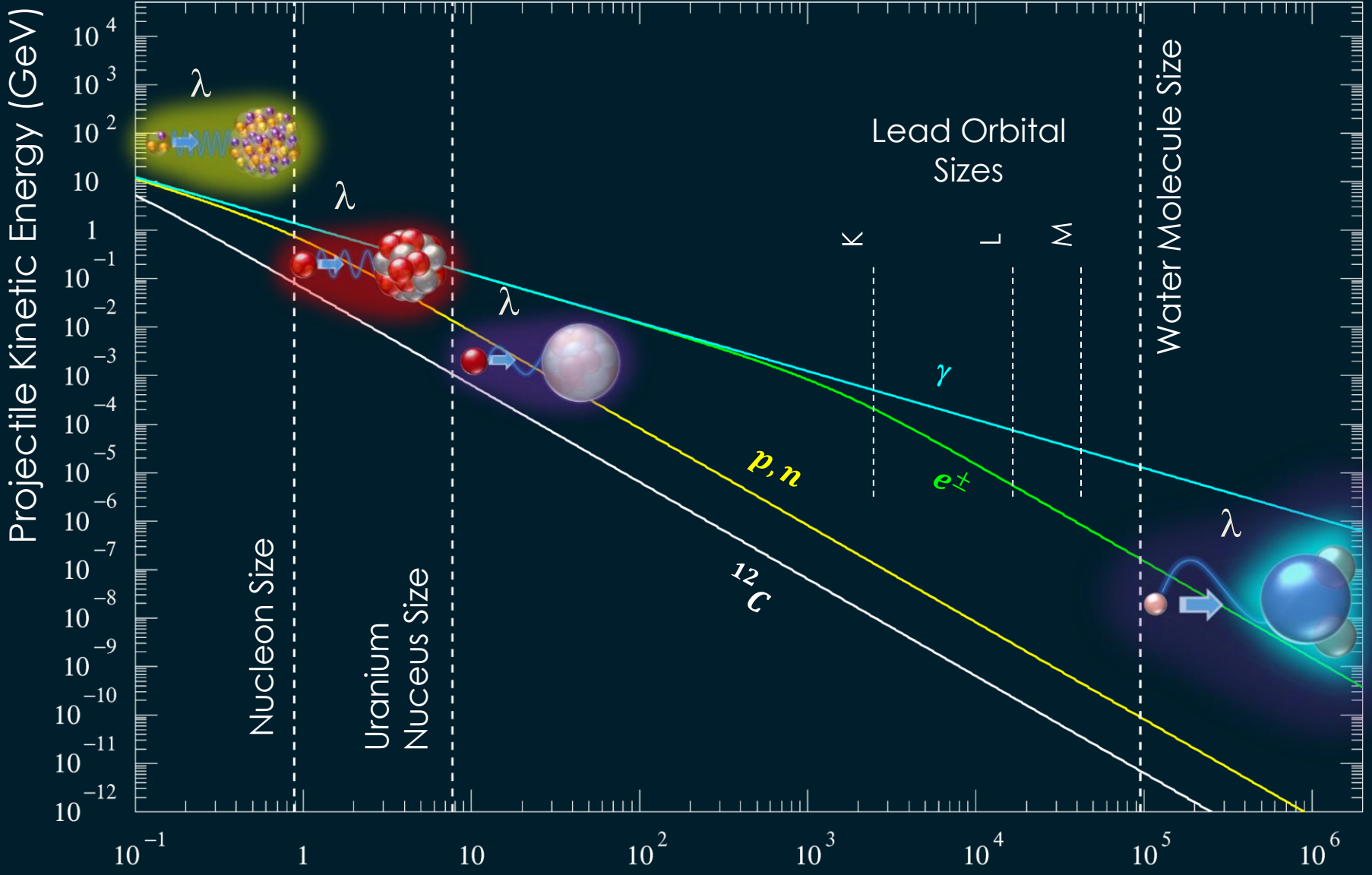


Physics models in Geant4

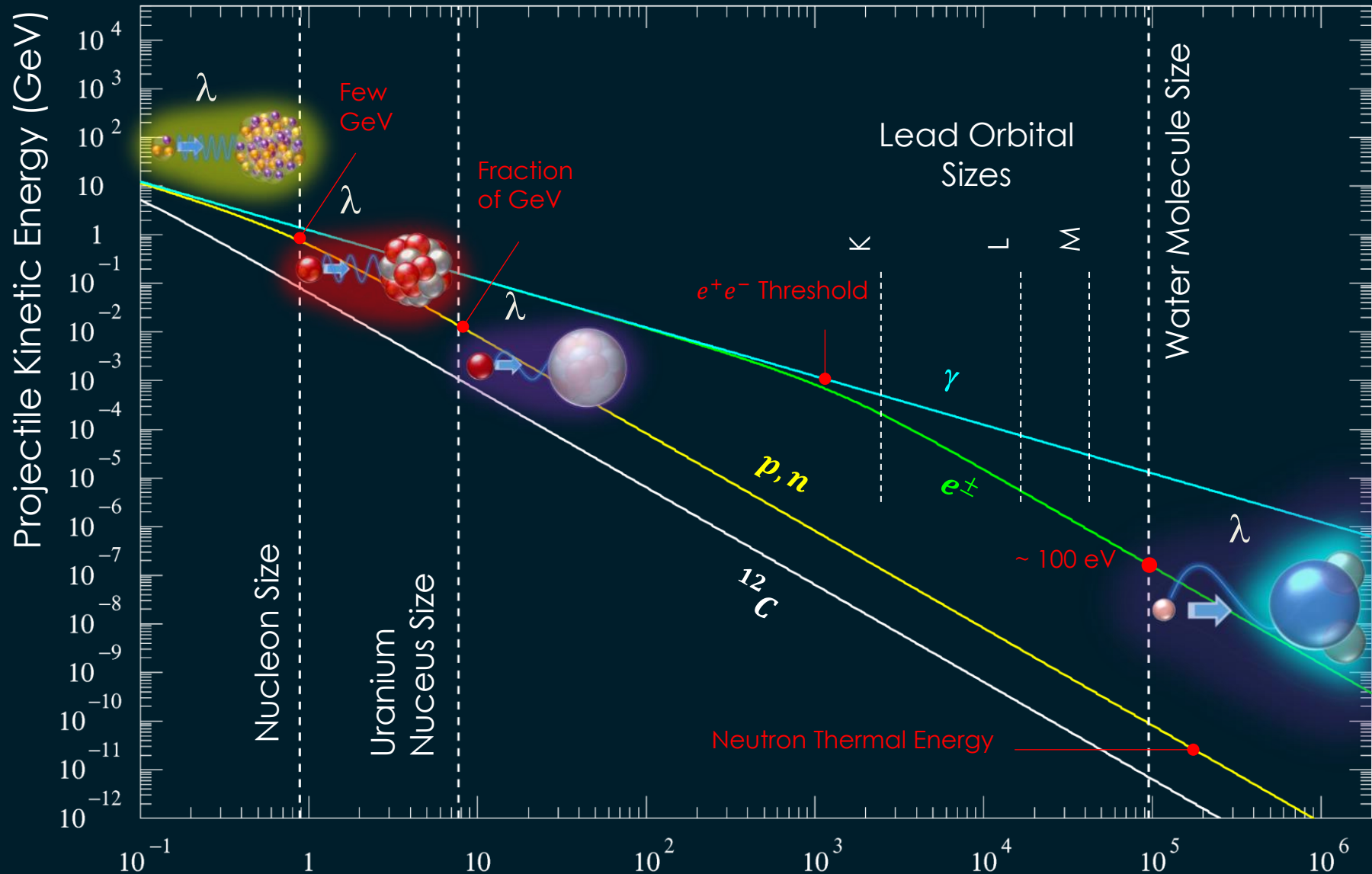
- Geant4 offers
 - Electromagnetic processes
 - Hadronic and nuclear processes
 - Photon/lepton-hadron processes
 - Optical photon processes
 - Decay processes
 - Shower parameterization
 - Event biasing techniques
 - And you can plug-in more
- Wide set of physics models provided
 - Complementary models with different energy range applicability
 - That can be combined to cover a wide range
 - Competing models with same energy range applicability
 - That can be selected by the user







λ : Projectile deBroglie Wavelength (fm)

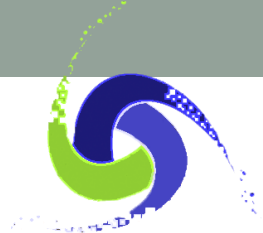


λ : Projectile deBroglie Wavelength (fm)

Geant4 – Brief history

- **Dec 1994 - Project start**
 - RD44 project : assess OO benefit for detector simulation, to respond to complex needs of LHC and other fields.
- Apr 1997 - First alpha release
- Jul 1998 - First beta release
- **Dec 1998 - First Geant4 public release - version 1.0**
- ...
- Several major evolutions: migration STL, “cuts per region”, parallel worlds...
- ...
- **Dec 6th 2013 : Geant4 version 10.0**
 - **First version with multi-threading -ie parallelism- support in production**
- ...
- Dec 4th, 2020 - Geant4 version 10.7 release
 - ...
 - 19th Nov 2021 – Geant4 10.6-patch03 release
- **Dec 10th 2021 : Geant4 version 11.0**
 - **Evolve from multi-threading to tasking**
 - **Mar 8th, 2022 - Geant4 11.0-patch01 release**
- We currently provide one public release per year.
 - Announced on Collaboration Web pages and mailing list
 - **please subscribe !** ([🔔 geant4](#) → [user support](#) → [mailing list subscription](#))

 **Current version**



GEANT4 collaboration

A SIMULATION TOOLKIT



<https://geant4.web.cern.ch/>



Geant4: a simulation toolkit

S. Agostinelli *et al.*

NIM A, vol. 506, no. 3, pp. 250-303, 2003



Laboratoire d'Annecy-le-Vieux de Physique des Particules

Geant4 Developments and Applications

J. Allison *et al.*

IEEE Trans. Nucl. Sci., vol. 53, no. 1, pp. 270-278, 2006

u^b

UNIVERSITÄT BERN



Recent Developments in Geant4

J. Allison *et al.*

NIM A, vol. 835, pp. 186-225, 2016



Northeastern UNIVERSITY

COLLEGE OF COMPUTER SCIENCE



~130 members, ~30 FTE

Two of your lecturers, Igor is missing

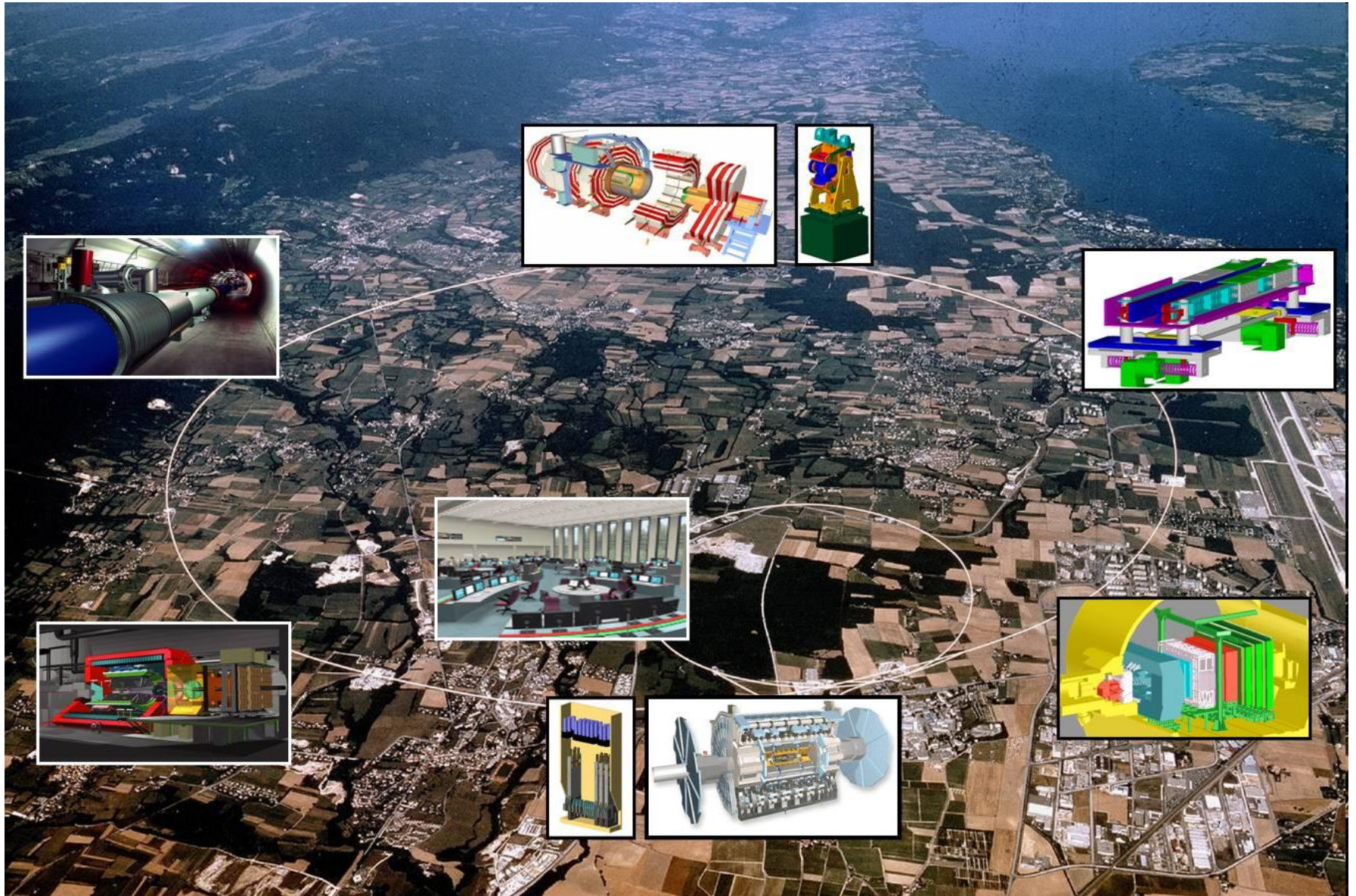


- An international collaboration
 - >100 active members
 - 19 countries

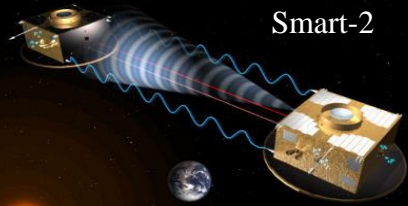
Geant4 application domains

not exhaustive

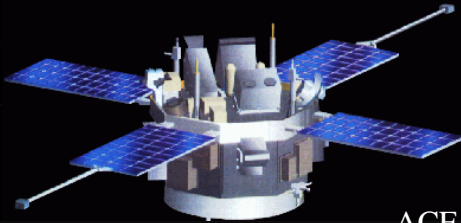
Large Hadron Collider (LHC) @ CERN



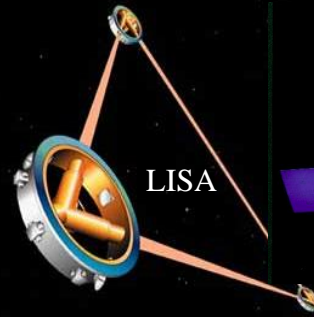
Geant4 in Space



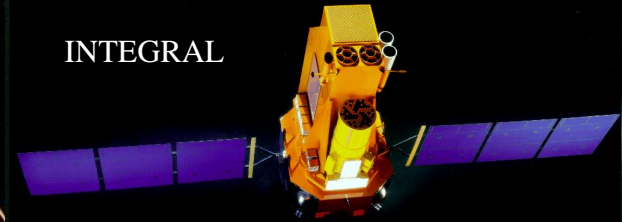
Smart-2



ACE



LISA



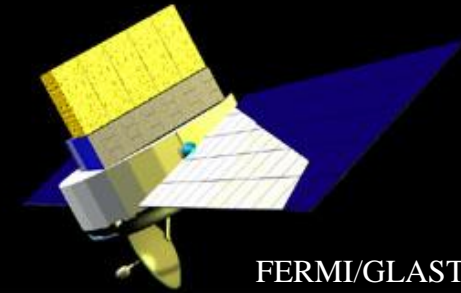
INTEGRAL



Cassini



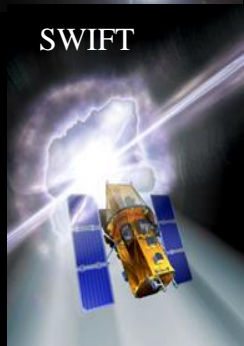
Bepi Colombo



FERMI/GLAST



Herschel



SWIFT



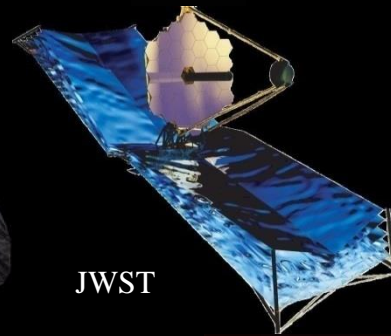
Astro-E2



XMM-Newton



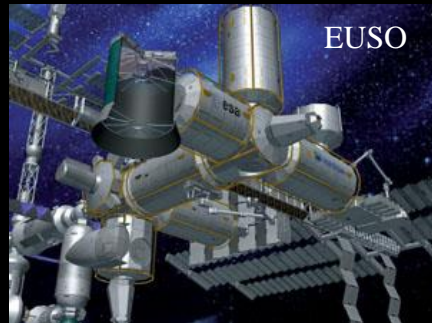
GAIA



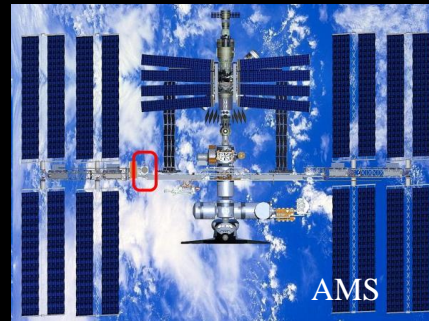
JWST



ISS Columbus



EUSO

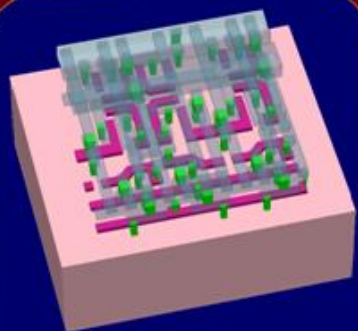


AMS

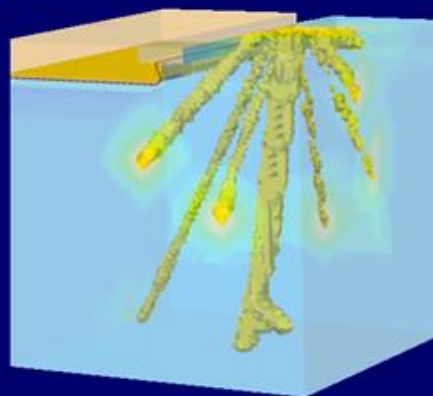


MAXI

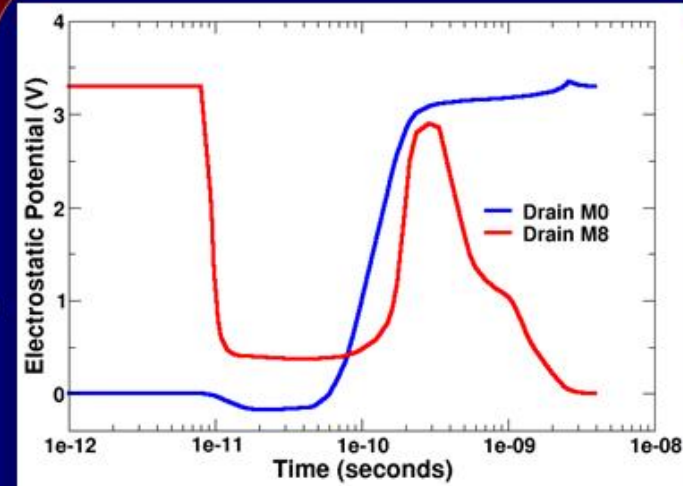
RADSAFE on SEE in SRAMs



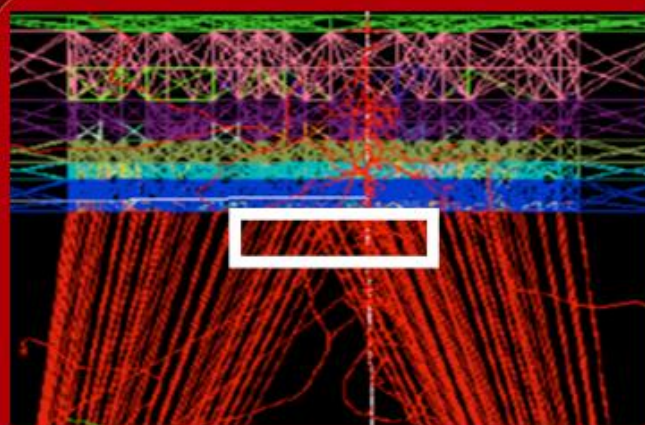
TCAD Cell Structure: SRAM Cell



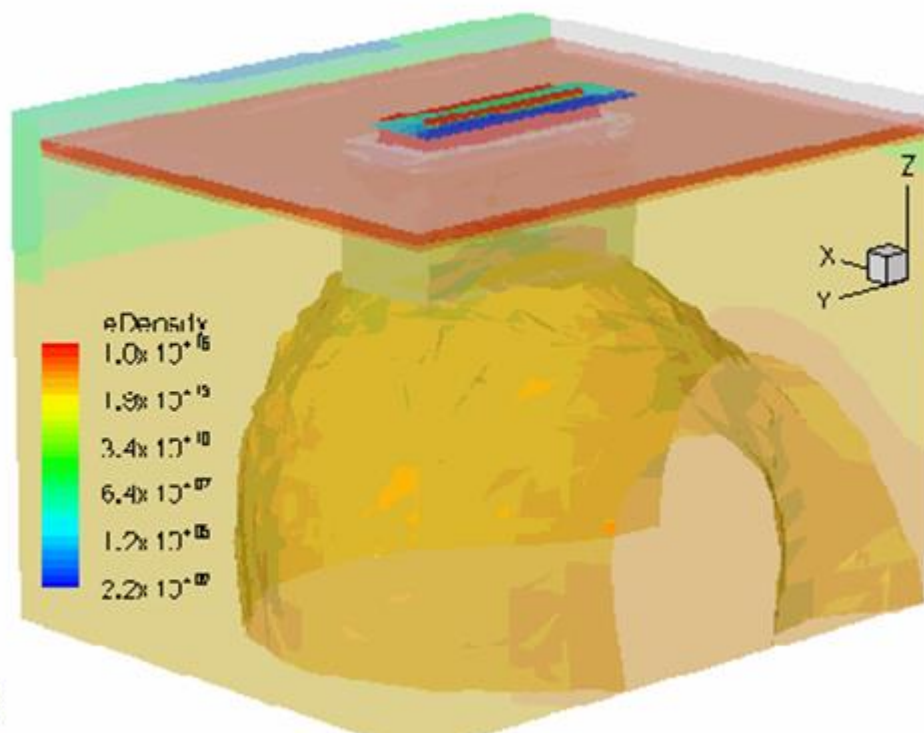
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset

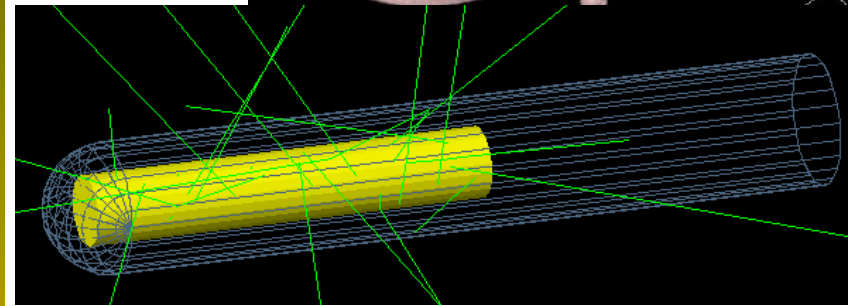
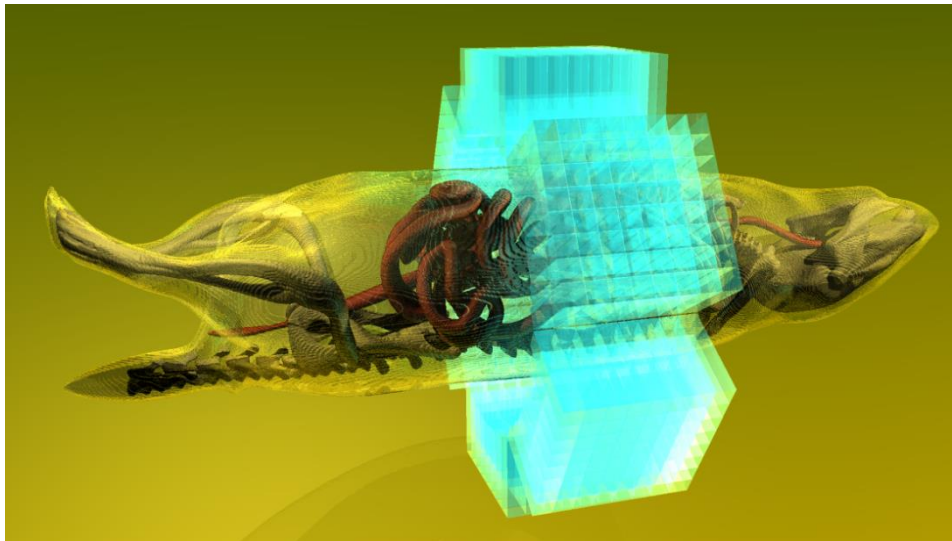
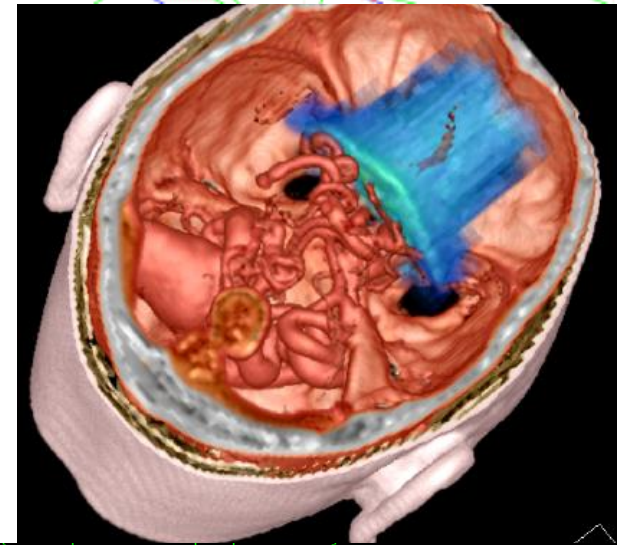
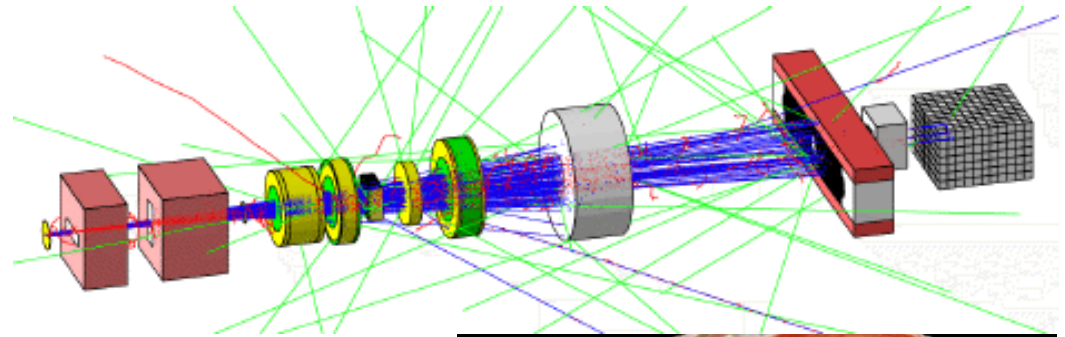


Geant4 Geometry and 523 MeV Neon Event



Geant4 in Medical Science

- Four major use cases
 - Beam therapy
 - Brachytherapy
 - Imaging
 - Irradiation study





Tool for Particle Simulation

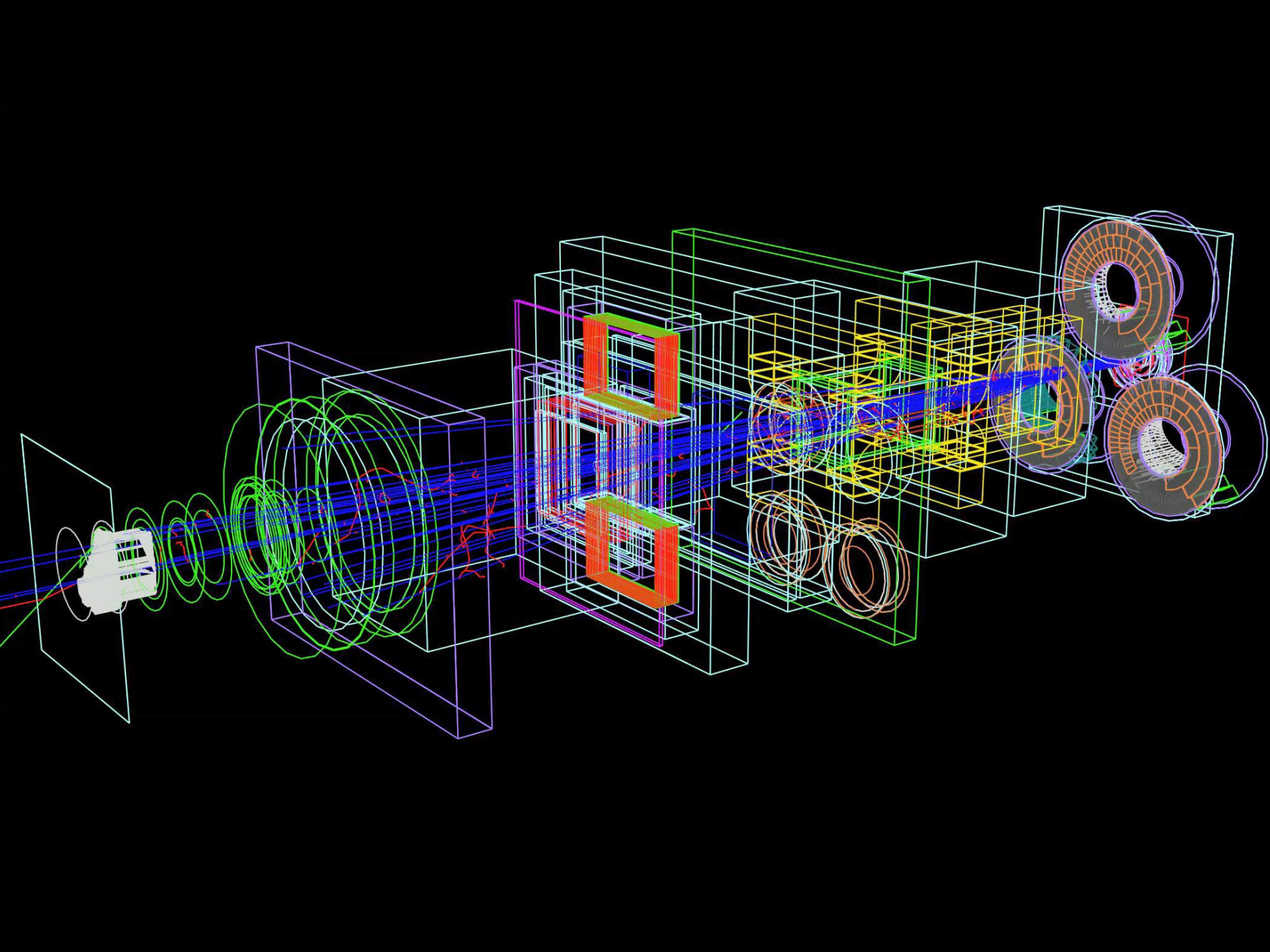
Joseph Perl - SLAC National Accelerator Laboratory

Bruce Faddegon, José Ramos - University of California San Francisco

Jungwook Shin – St Jude Children’s Research Hospital

Harald Paganetti, Jan Schümann - Massachusetts General Hospital





Head and Neck Study - Dose

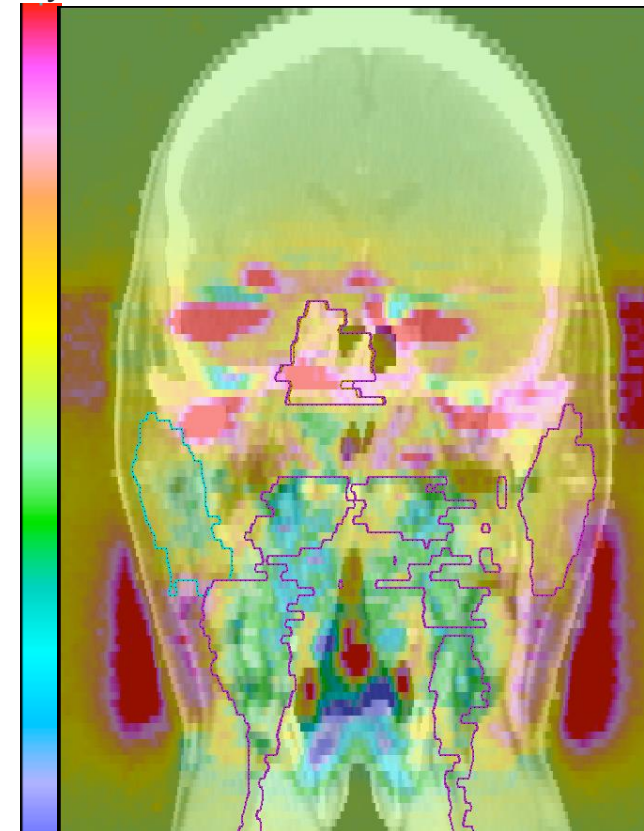
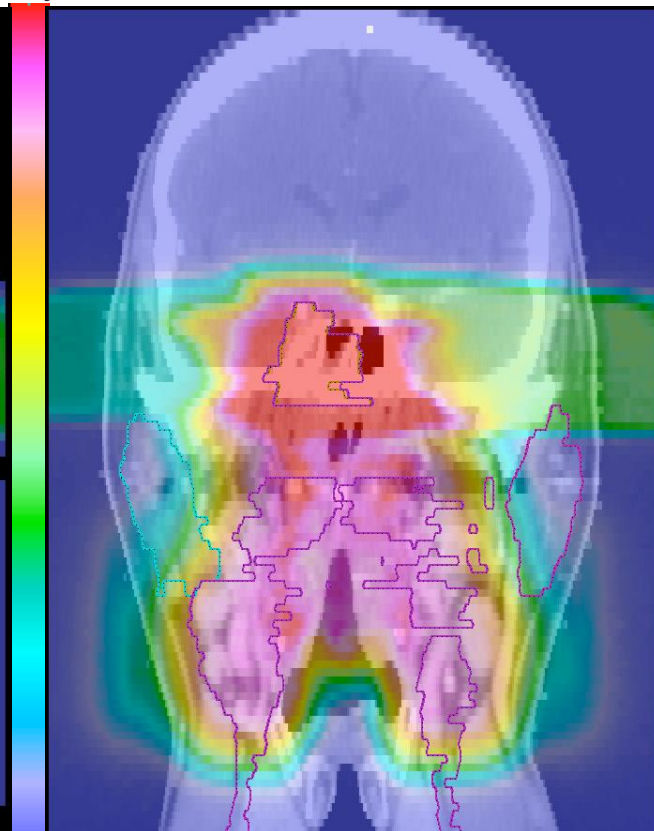
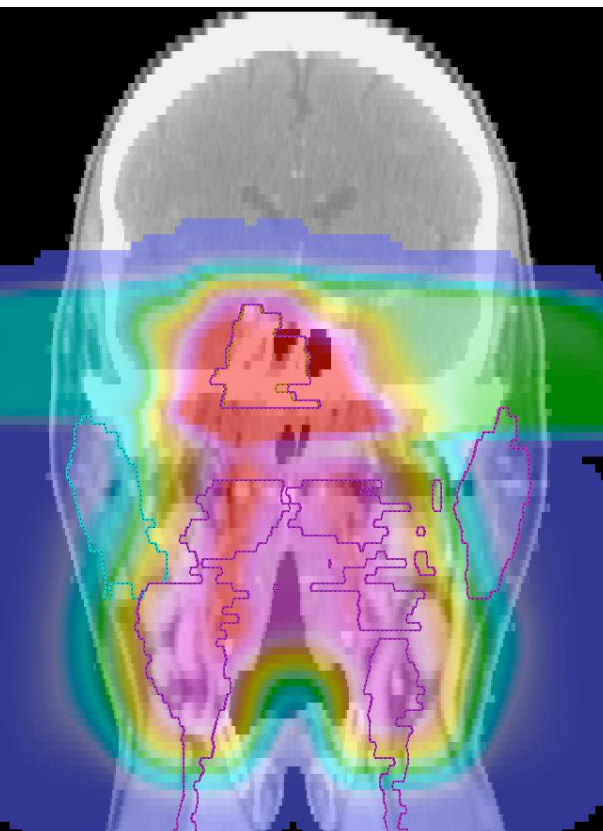
TPS - Pencil Beam

65 Gy

TOPAS - Monte Carlo

5 Gy

Difference



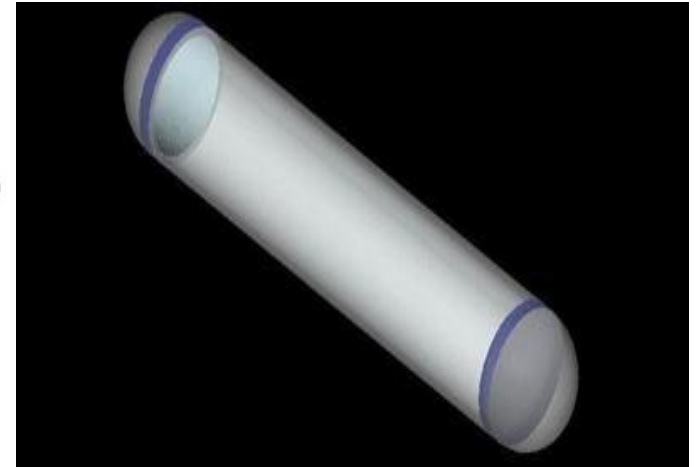
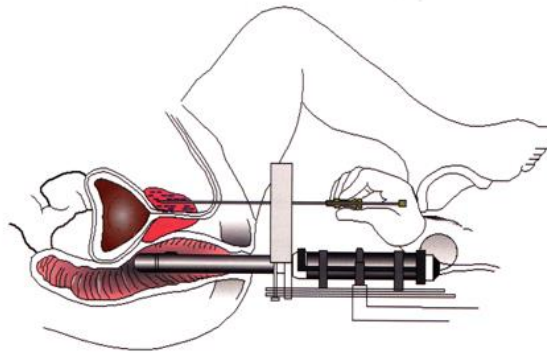
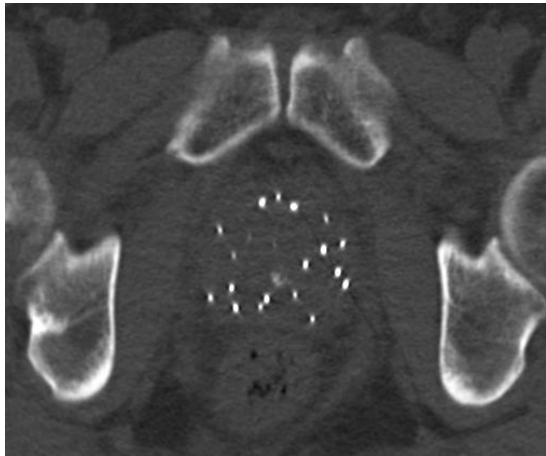
0

- 5 Gy

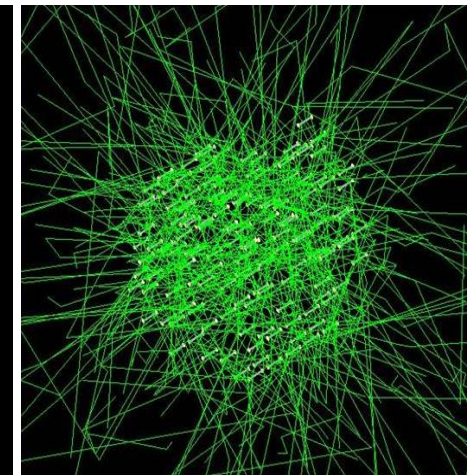
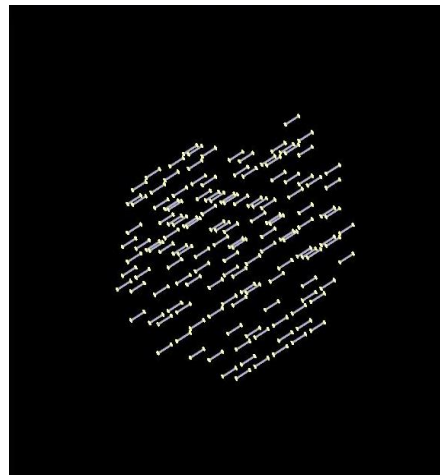
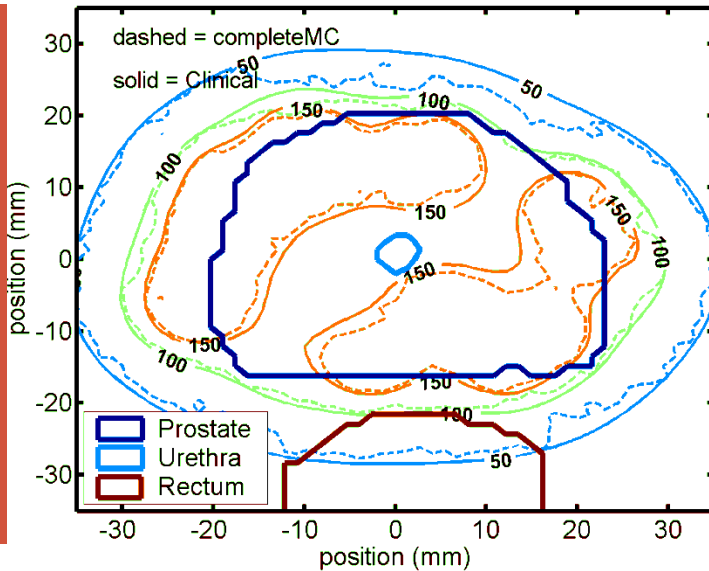
10 beams (6 directions + 4 boost)

Prostate brachytherapy

Jean-François Carrier, CHUM

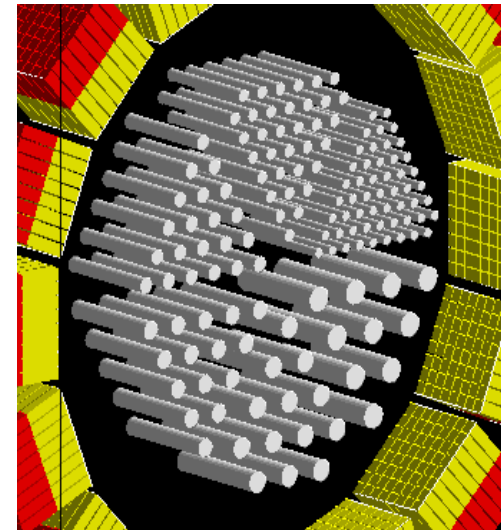


Carrier et al., IJROBP (68), 2007 pp. 1190-1198



GATE: Geant4 Application for Tomography Emission

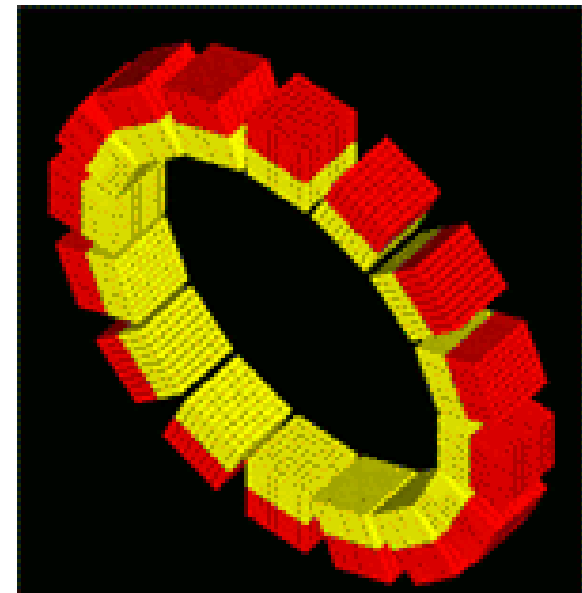
- Toolkit for Imaging applications
- based on the Geant4 toolkit
- easier to use for Imaging applications
- <http://www.opengatecollaboration.org>



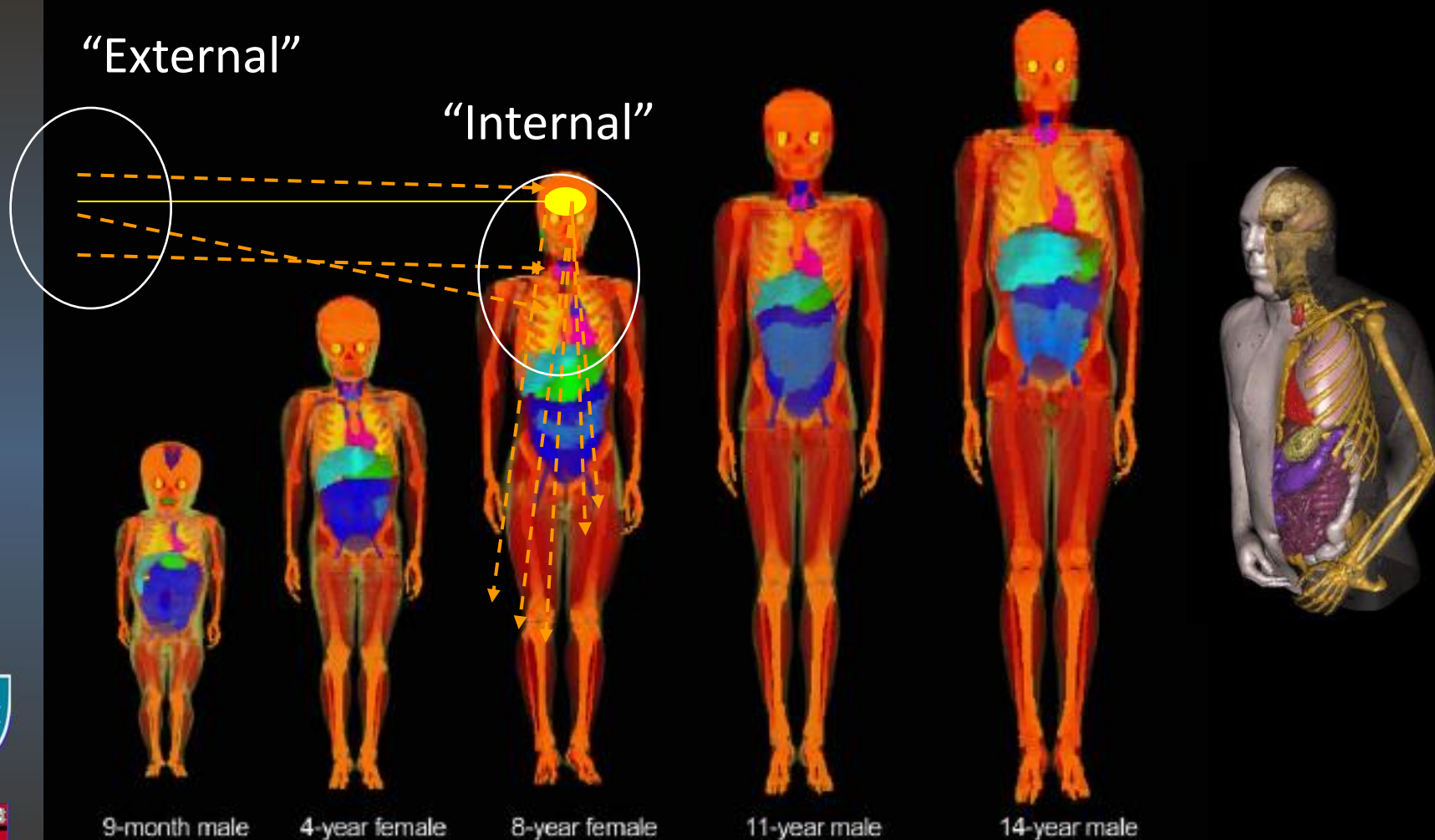
Source: Irene Buvat, INSERM/CHU

Triple-head gamma camera

S. Staelens
Uni Ghent



Neutron radiation issue in proton therapy



Phantoms implemented in Geant4 with dose calculation environment at MGH

Geant4 in Homeland Security : simulating x-ray cargo radiography





Los Alamos National Laboratory undergraduate research assistant inside a muon tomography machine.

Courtesy of: Los Alamos National Laboratory

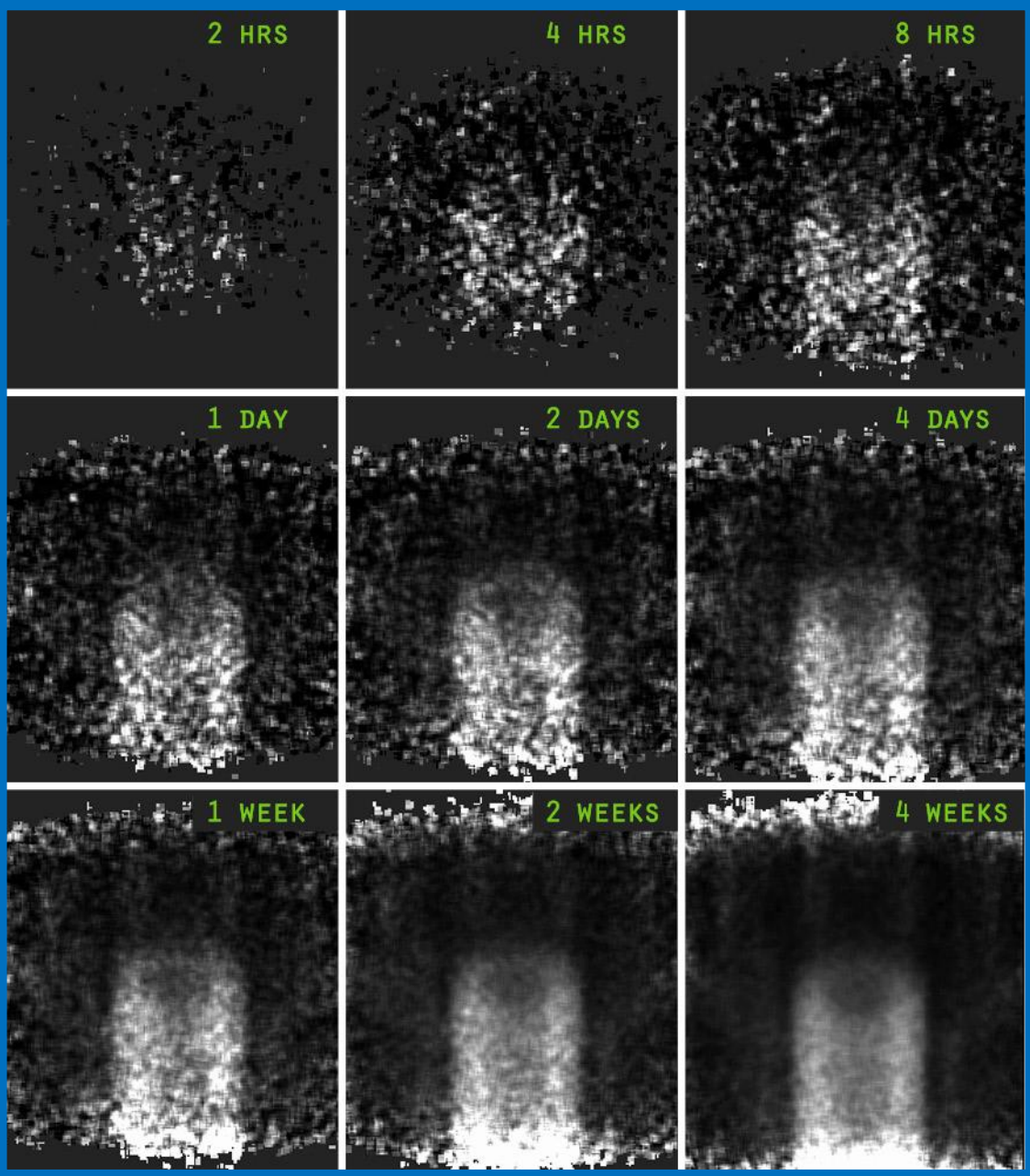


feature
August 28, 2014

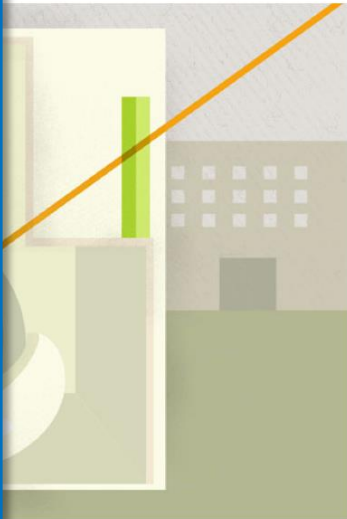
Particle physics

Cosmic rays can help us see the interior of the nucleus.

<https://www.symmetrymagazine.org/article/august-2014/particle-physics-to-aid-nuclear-cleanup>



Those exterior walls, made of concrete 10 feet thick, offer their own challenges. With the particle physics techniques used to reduce the resolution to a few centimeters, the high radiation levels...



... (green) on either side of the muons (represented by the orange line). By determining how the muons are deflected, they will compile the first picture of the interior.

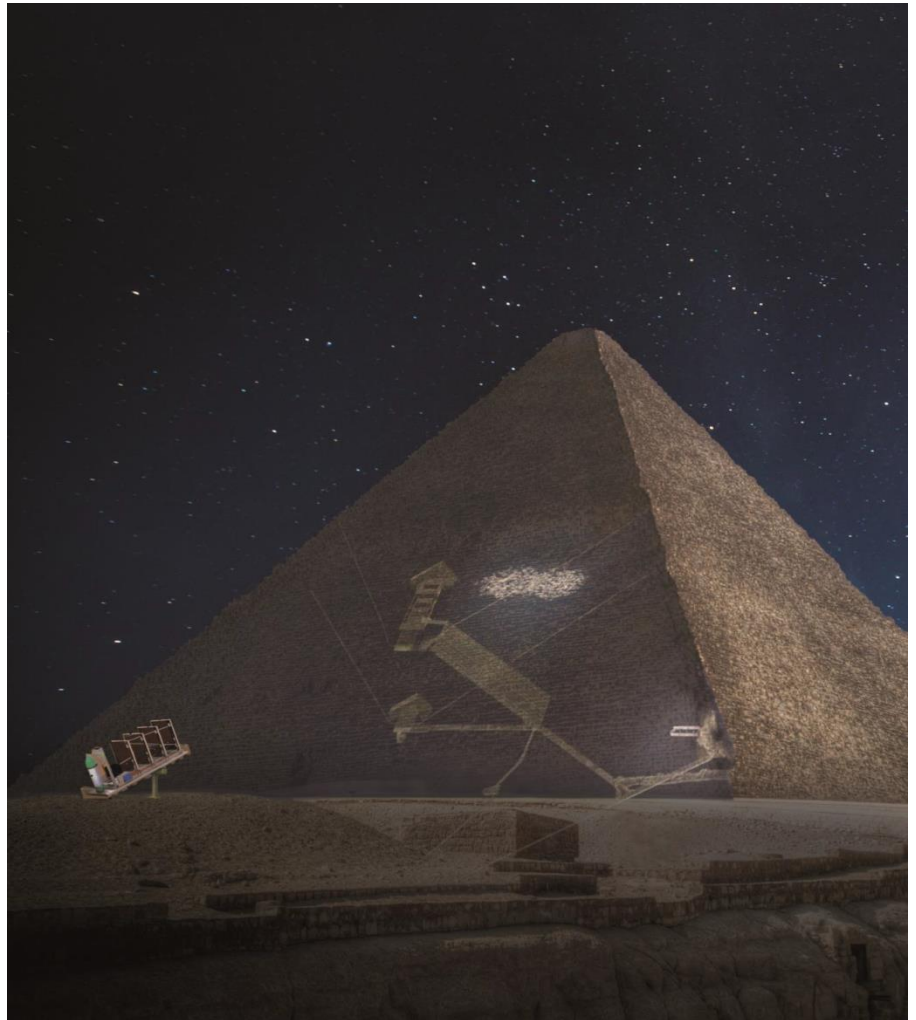
... turning the clock at the Large Hadron Collider, scientists are making sure their detectors run like clockwork.

Archeology

- Same “muography” technique used in the recent discovery of a big void in the Great Pyramid
- Geant4 used in the simulation of the muon detection system



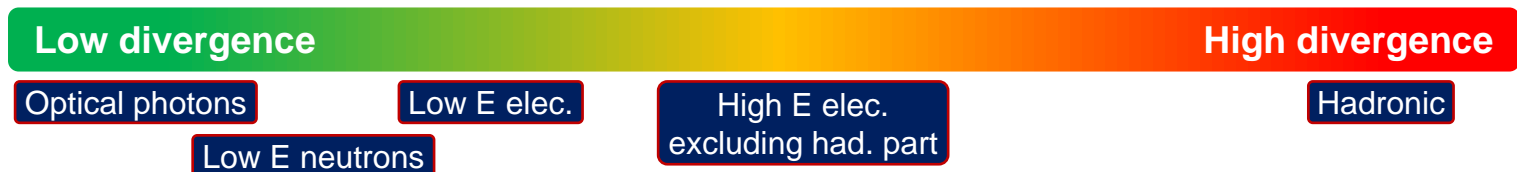
- Images : courtesy of D. Attié & S. Procureur



Geant4 on GPU ?

Can Geant4 run on GPU ?

- We have often the question “can Geant4 run on GPU ?”
 - Underlying hope : GPUs are fast, so running Geant4 on GPU would be fast !
 - Not that simple...
- GPU are fantastic to treat « **many very similar things** » « **behaving almost the same** »
 - Typical example and original motivation : optical photons
 - The treatment can be done in parallel, applying the same calculation to a set of data.
 - And this can be repeated calculation after calculation if the set of data is not destroyed by these calculations.
 - In other words, **no divergences** appear in the data set : the data set remains of « the same nature ».
 - GPUs are designed to make these parallel calculations efficiently, and they are performing nicely !
- But with a Monte Carlo like Geant4:
 - « **many very similar things** » → « **many very different things** » !
 - Many type of particles !
 - « **behaving almost the same** » → « **behaving not at all the same** » !
 - Interactions of particles are very different from one type to another
 - Even particles of same type can undergo very different interactions ! } → **Source of plenty of divergences !**
- Usage of GPU limited *a priori* to some « sectors », strongly linked to their divergences:



- Net gain of that ?
 - Great for medical applications (demonstrated) : low E elec. in simple geometries.
 - But for HEP and complicated geometries: **ongoing R&D**, first responses expected in a time scale of one year.

Geant4 toolkit philosophy

The Toolkit philosophy

- **Geant4 is not an application**
 - applications : eg powerpoint, root, etc.

Geant4 is a toolkit

- Which means:
 - **Geant4 provides tools / components**
 - Many of them are defined from abstract classes
 - All are open to the users (☞ you)
 - **You build your own application selecting the Geant4 components you need**
 - Either selecting ready to use tools
 - Or building your own, if needed, from the base abstract classes
 - **You instantiate the components in your own main program**
 - That you then compile and link
- You need a minimal knowledge of the Geant4 structure
 - And of the Geant4 base classes and existing tools
- Which is all what this tutorial is about !

