Geant4
- Past, Current and Future

Makoto Asai (SLAC SD/EPP)

May 3rd, 2017

Future Trends in Nuclear Physics Computing @ Jefferson Lab

SLAC NATIONAL ACCELERATOR LABORATORY
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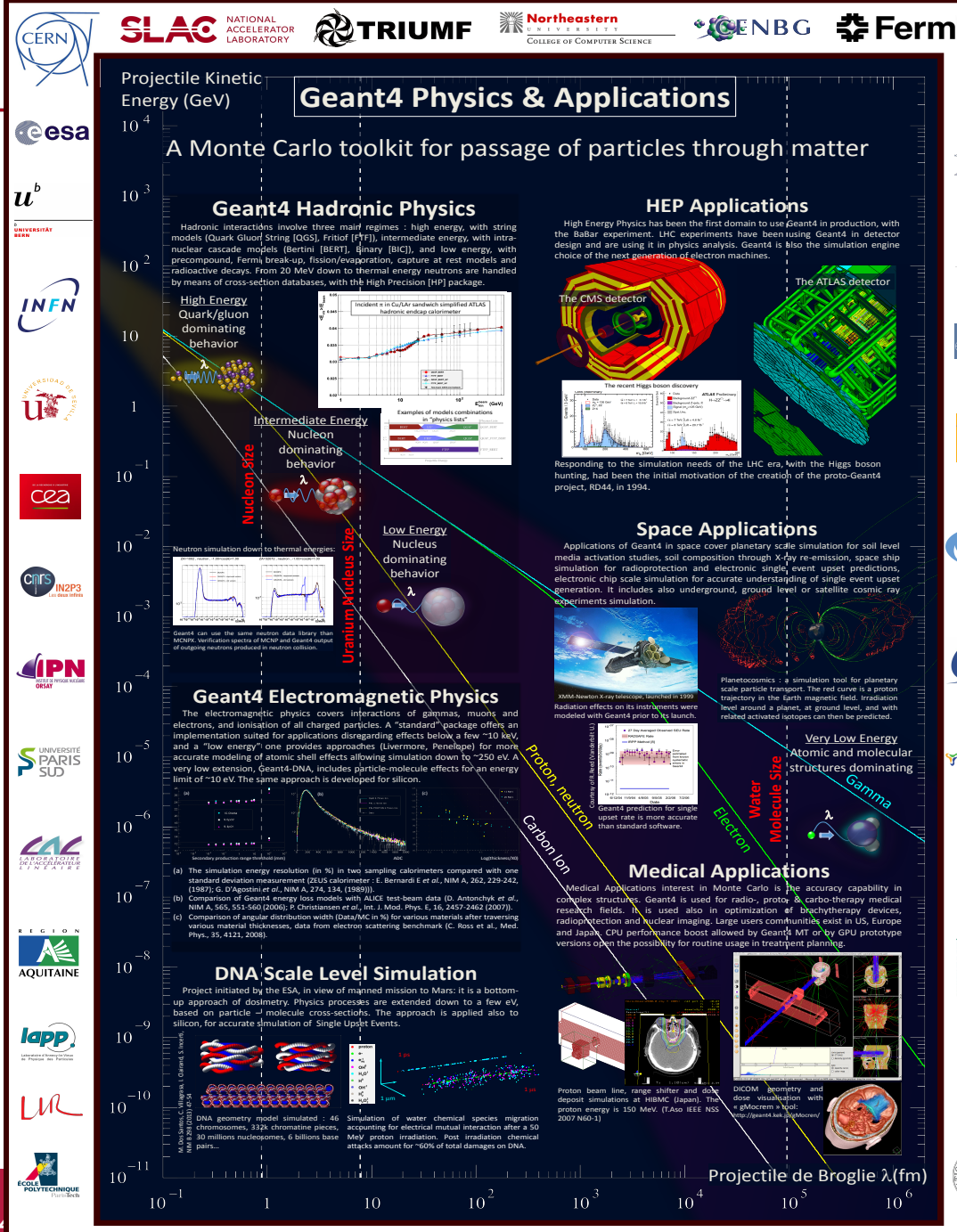
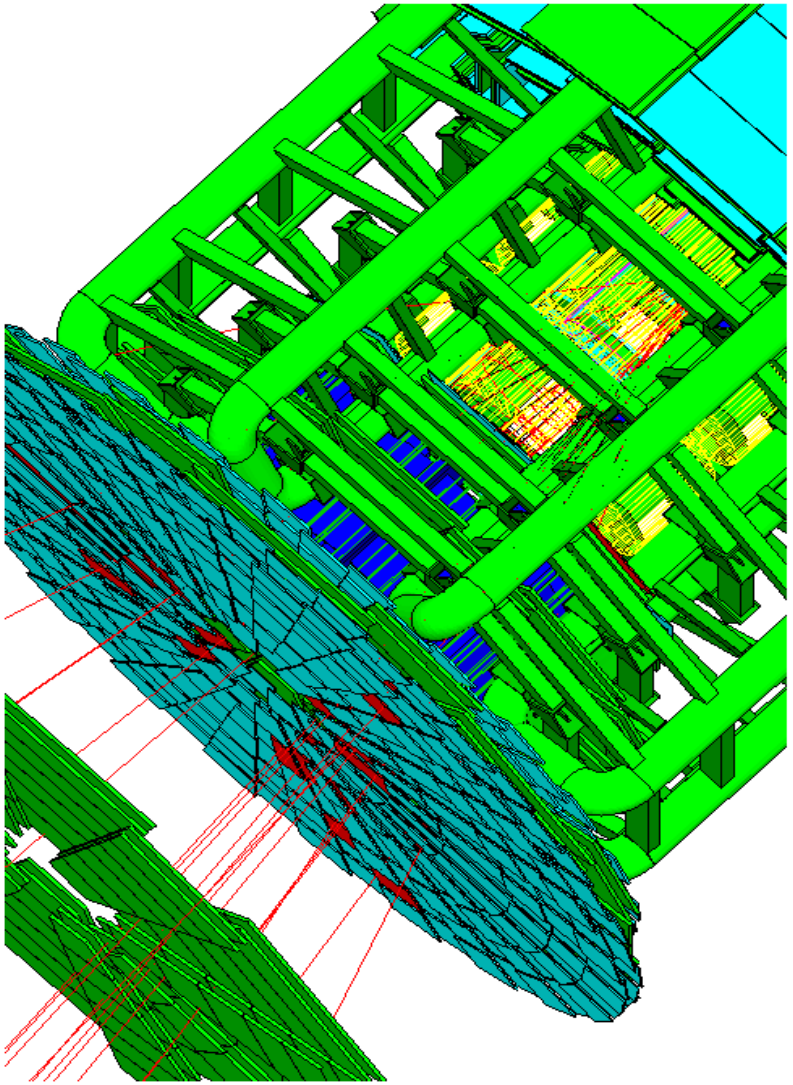
Contents

- Geant4 – past and present
- Recent and ongoing developments
- Future and opportunities

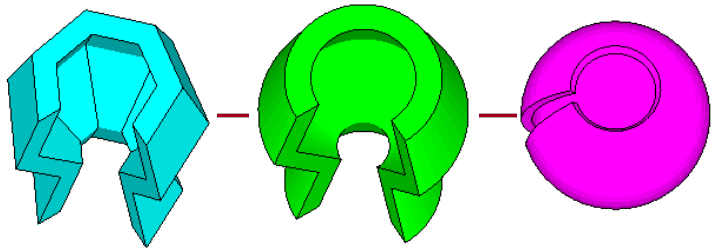


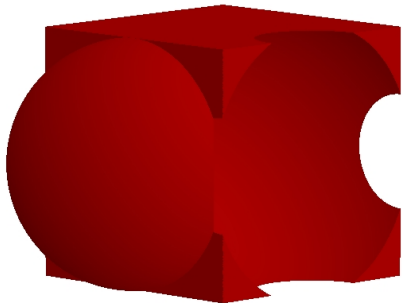
Key Geant4 functionalities

- Geant4 offers most, if not all, 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
- Thanks to the polymorphism mechanism of C++, the users can easily plug-in their extensions without interfering with the other part of Geant4.
- Extensive user guide documents and examples are provided.

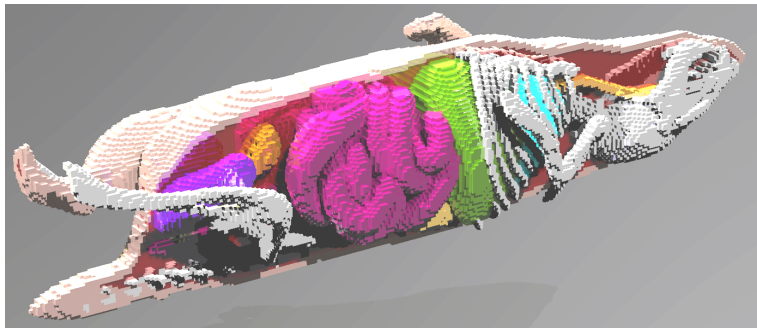


Key geometry capabilities



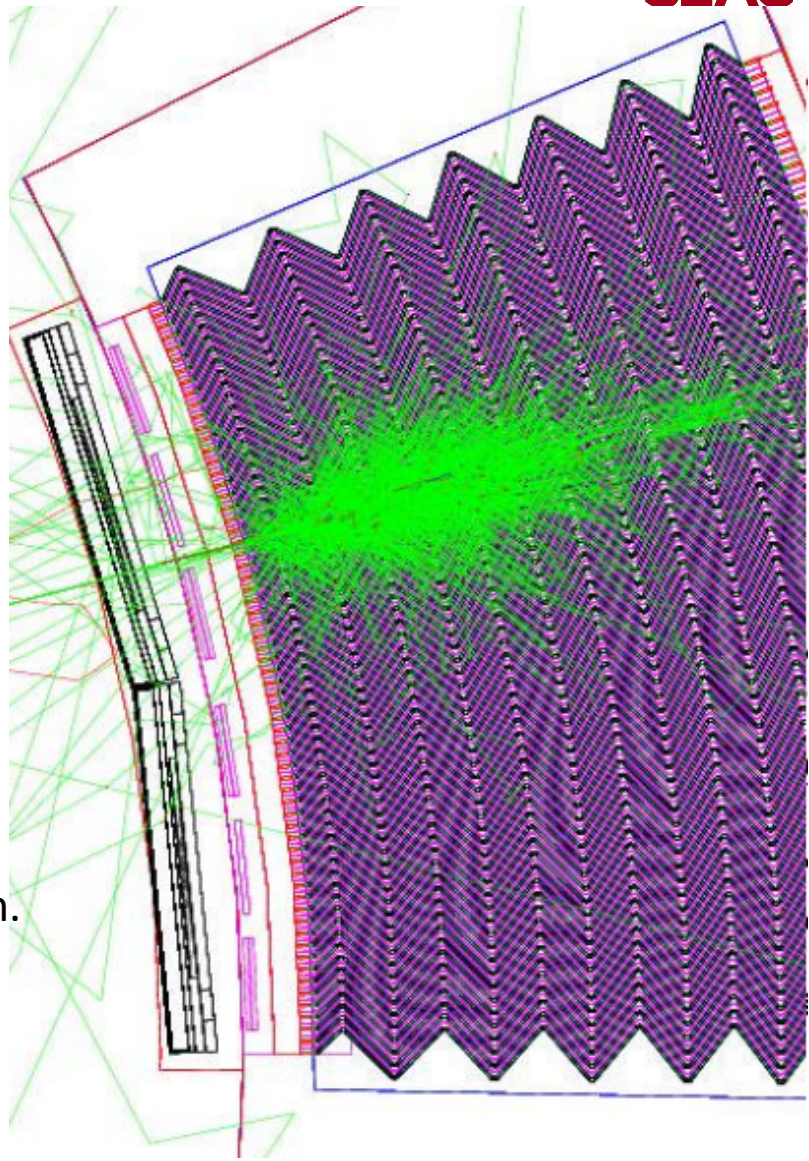


- Richest collection of shapes
  - CSG (Constructed Solid Geometry), Boolean operation, Tessellated solid, etc.
  - The user can easily extend
- Describing a setup as hierarchy or 'flat' structure
  - Describing setups up to billions of volumes
  - Tools for creating & checking complex structures
  - Interface to GDML and CAD
- Navigating fast in complex geometry model
  - Automatic optimization
- 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
- Geant4 provides sets of alternative physics models so that the user can freely choose appropriate models according to the type of his/her application.
  - For example, some models are more accurate than others at a sacrifice of speed.



Geant4 is a toolkit

- Everything is open to the user
  - Choice of physics processes/models
  - Choice of GUI/Visualization/persistency/histogramming options
- Geant4 is a toolkit.
  - A user may build a standalone application on top of Geant4.
    - Many examples in lots of different use-cases / user domains are provided to start with.
  - Geant4 may be used through “frameworks” or turn-key applications
    - E.g. Gaudi, ART, …
    - E.g. Topas, Spenvis, PlanetoCosmics, MRED…
- Geant4 has minimal dependencies to external libraries.
  - C++ and STL, cmake
  - Xerces-C, OpenGL, Qt, etc. for optional persistency/GUI/Visualization options

Geant4 History

R&D phase (RD44)

Production phase

- Early discussions, for example at CHEP 1994 @ San Francisco
  - "Geant steps into the future" R. Brun et al.
  - "Object oriented analysis and design of a GEANT based detector simulator" K. Amako et al.
- Dec '94 - CERN RD44 project start
- Apr '97 - First alpha release
- Jul '98 - First beta release
- Dec '98 - First Geant4 public release - version 1.0

- Several major architectural revisions
  - E.g. STL migration, "cuts per region", parallel worlds, **multithreading**

- Dec 4th, '15 – Geant4 version 10.2 release
  - Jan 27th, '17 - Geant4 10.2-patch03 release ← Retroactive patch release
- Dec 9th, '16 – Geant4 version 10.3 release
  - Feb 24th, '17 - Geant4 10.3-patch01 release ← Current version
- We currently provide one public release every year.

Geant4 – A Simulation Toolkit

CERN

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http://www.geant4.org/

KOBE UNIVERSITY Graduate School of Science

Science & Technology Facilities Council

富山高等専門学校 Toyama National College of Technology

S. Agostinelli et al.
Geant4: a simulation toolkit
NIM A, vol. 506, no. 3, pp. 250-303, 2003

JINR

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Физический институт имени П.Н.Лебедева Российской академии наук
Ф И А Н

RITSUMEIKAN

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

J. Allison et al.
Geant4 Developments and Applications
IEEE Trans. Nucl. Sci., vol. 53, no. 1, pp. 270-278, 2006

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Geant4 ASSOCIATES INTERNATIONAL Experts in Radiation Simulation

Scopus Preview

S. Agostinelli et al.

Geant4: a simulation toolkit

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

8720 documents have cited:

GEANT4 - A simulation toolkit

Agostinelli S., Allison J., Amako K., Apostolakis J., Araujo H., ...

(2003) *Nuclear Instruments and Methods in Physics Research, Sec... ...s and Associated Equipment*, 506 (3), pp. 250-303.

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Author name

- Banerjee, S. (840)
- Stugu, B. (812)
- Eigen, G. (811)
- Seiden, A. (808)
- Adye, T. (801)

Subject area

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GEANT4—a simulation toolkit

..., D Zschiesche, **Geant4** Collaboration - Nuclear instruments and ..., 2003 - Elsevier

Geant4 is a toolkit for simulating the passage of particles through matter. It includes a complete range of functionality including tracking, geometry, physics models and hits. The physics processes offered cover a comprehensive range, including electromagnetic,

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Geant4 developments and applications

J Allison, K Amako, J Apostolakis... - ... on Nuclear Science, 2006 - ieeexplore.ieee.org

Abstract: **Geant4** is a software toolkit for the simulation of the passage of particles through matter. It is used by a large number of experiments and projects in a variety of application domains, including high energy physics, astrophysics and space science, medical physics

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GATE, a Geant4-based simulation platform for PET integrating movement and time management

G Santin, D Strul, D Lazaro, L Simon... - ... Record, 2002 IEEE, 2002 - ieeexplore.ieee.org

Abstract: GATE, the **Geant4** Application for Tomographic Emission, is a simulation platform developed for PET and SPECT. It combines a powerful simulation core (the **Geant4** toolkit) and a large range of developments dedicated to nuclear medicine. In particular, it models

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Geant4 low energy electromagnetic physics

S Chauvie, S Guatelli, V Ivanchenko... - ... Record, 2004 IEEE, 2004 - ieeexplore.ieee.org

Abstract: The **Geant4** simulation toolkit includes a specialised package, implementing a precise treatment of electromagnetic interactions of particles with matter below 1 keV. The **Geant4** low energy electromagnetic package provides a variety of models describing the

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J. Allison et al.

Recent developments in Geant4

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

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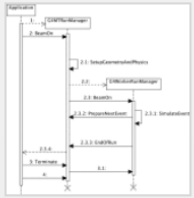

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 835, 1 November 2016, Pages 186–225

Recent developments in GEANT4

J. Allison[a, b], K. Amako[c, a], J. Apostolakis[d], P. Arce[e], M. Asai[f], T. Aso[g], E. Bagli[h], A. Bagulya[i], S. Banerjee[j], G. Barrand[k], B.R. Beck[l], A.G. Bogdanov[m], D. Brandt[n], J.M.C. Brown[o], H. Burkhardt[d], Ph. Canal[j],

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Highlights

- Multithreading resulted in a smaller memory footprint and nearly linear speed-up.
- Scoring options, faster geometry primitives, more versatile visualization were added.
- Improved electromagnetic and hadronic models and cross sections were developed.

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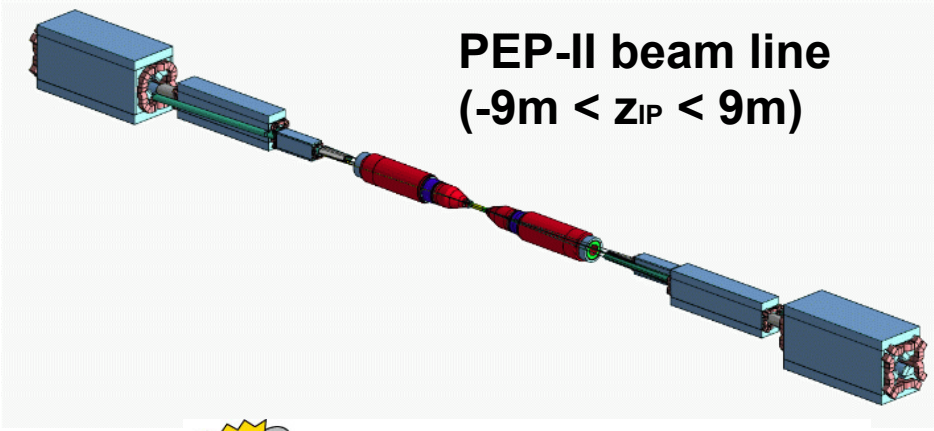
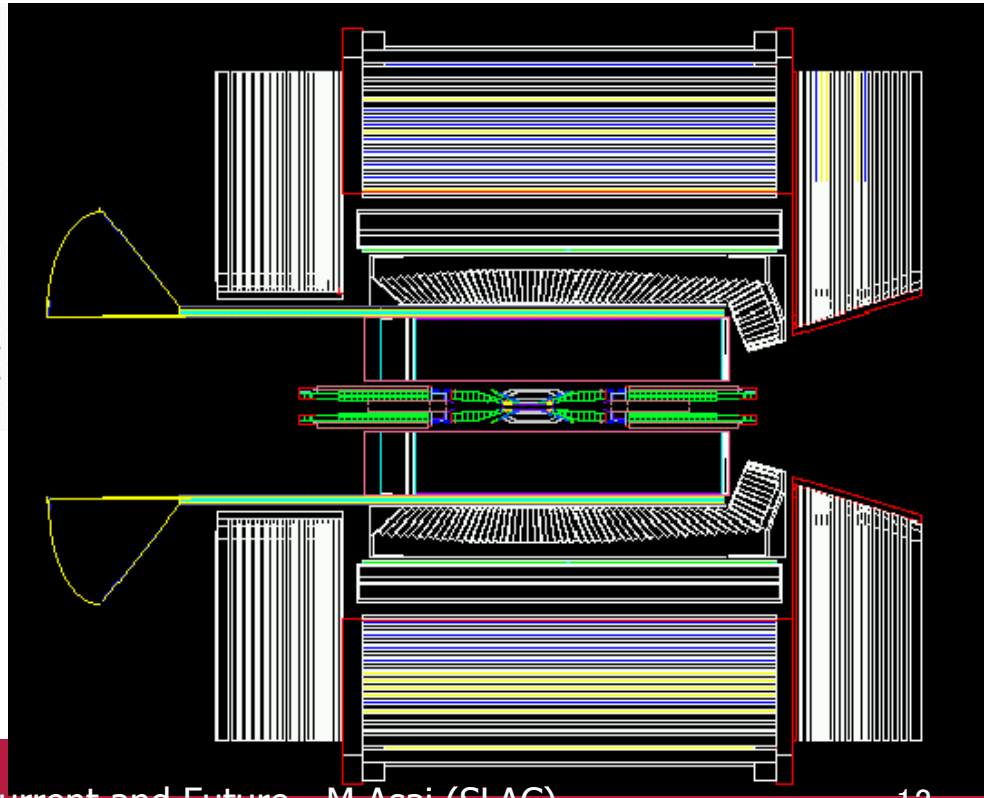
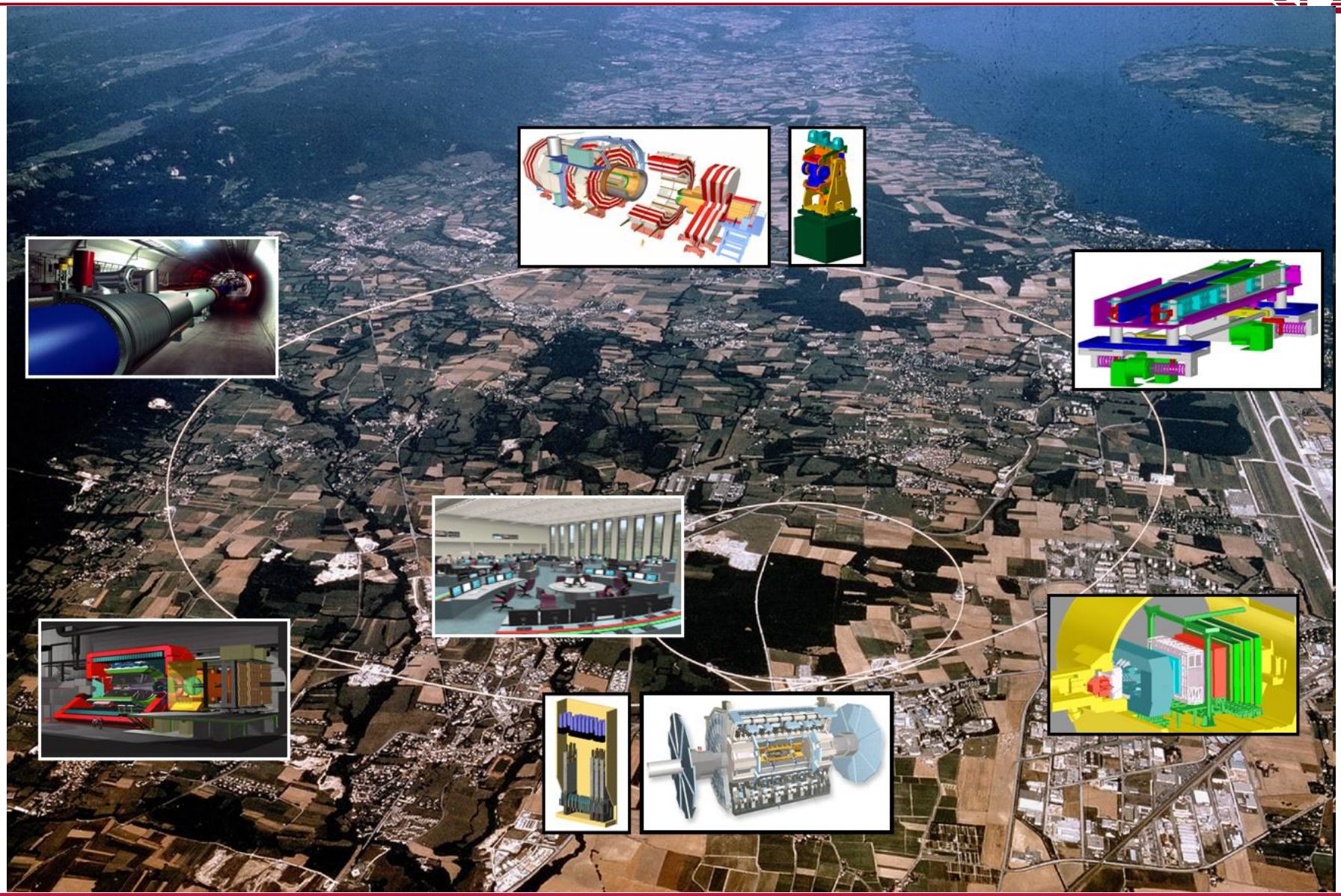
BaBar and Geant4

- BaBar is the pioneer HEP experiment in use of OO technology, and the first customer of Geant4. BaBar SW and Geant4 were in the R&D phase simultaneously.
  - During the R&D phase of Geant4, we acknowledge lots of valuable feedbacks provided by BaBar.
- BaBar started its simulation production in 2000 and had produced more than 10 billion events at more than 20 sites in Europe and North America.

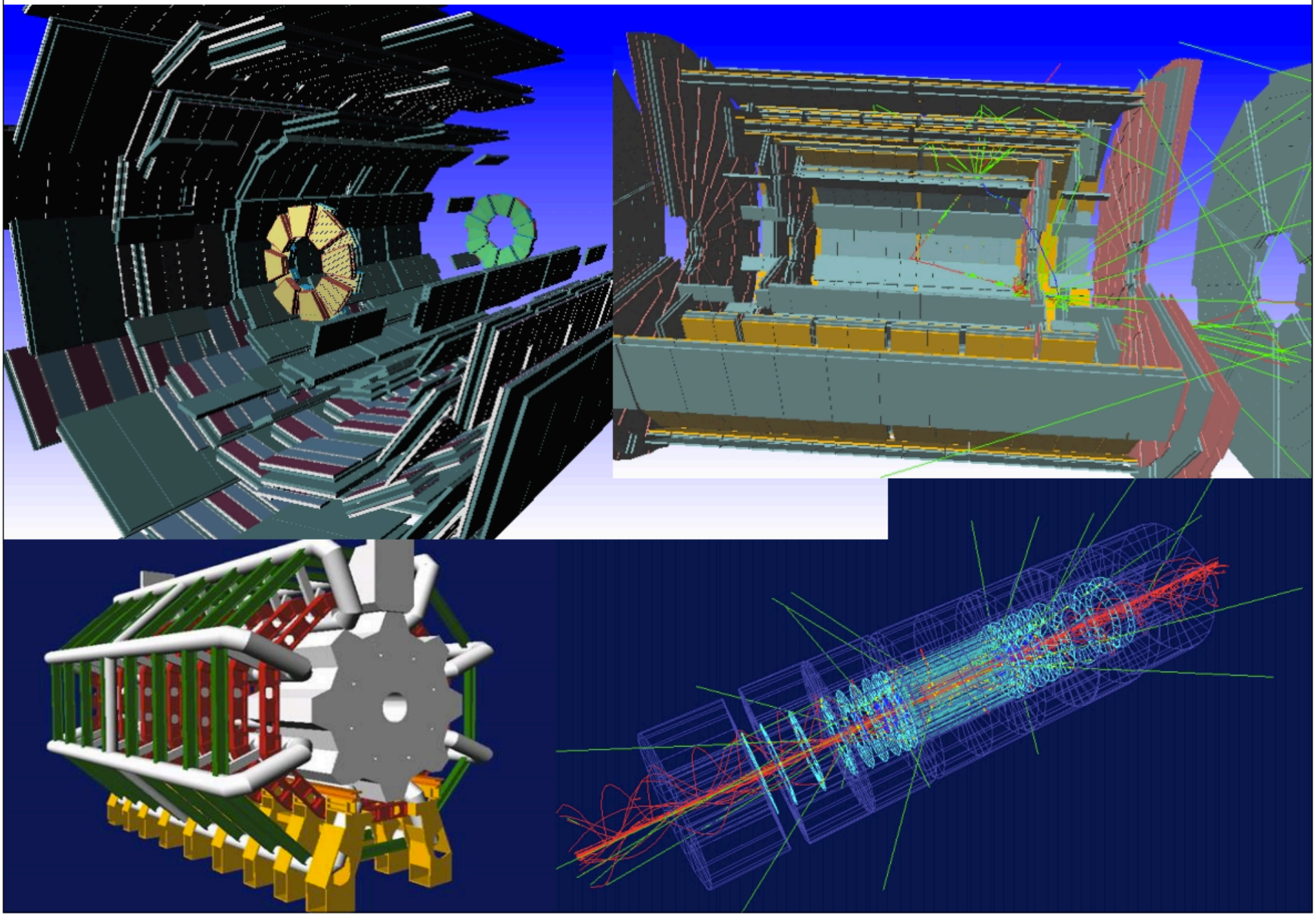




Large Hadron Collider (LHC) @ CERN



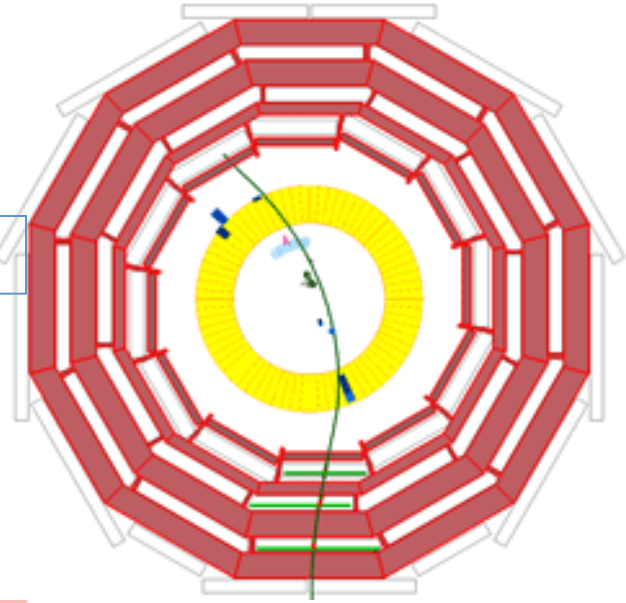
Geant4 in High Energy Physics (ATLAS at LHC)



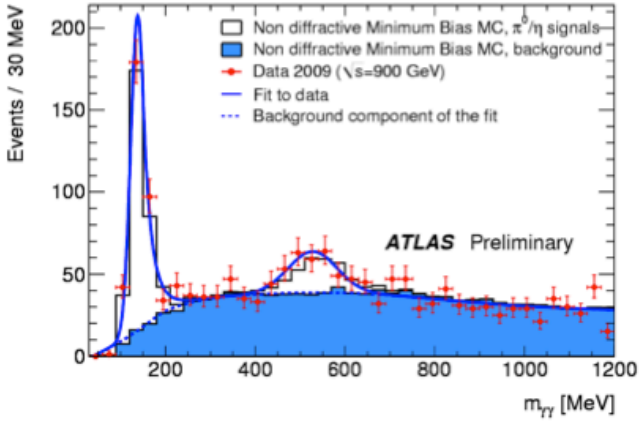
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

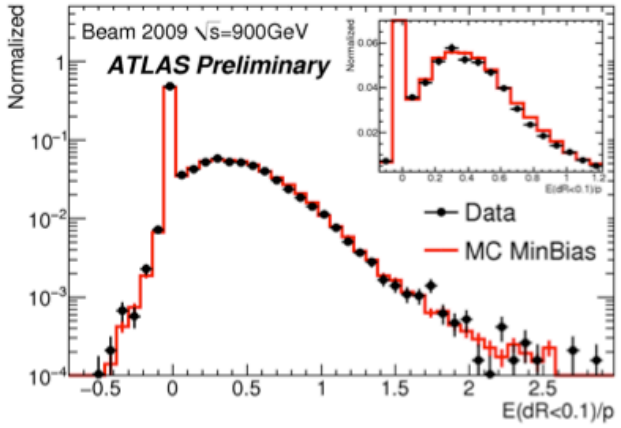
The π^0 mass is within 0.8 ± 0.6% of expectations.

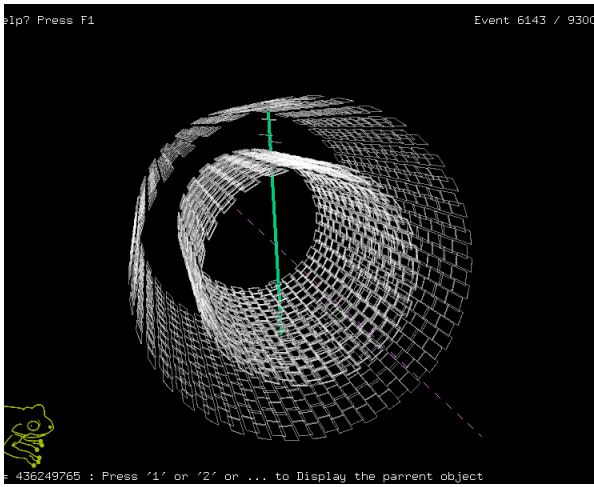
The η^0 mass is within 3 ± 2% of expectations.

The detector uniformity is better than 2%.

Response of the calorimeter to single isolated tracks. To reduce the effect of noise, topological clusters are used in summing the energy.

This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.





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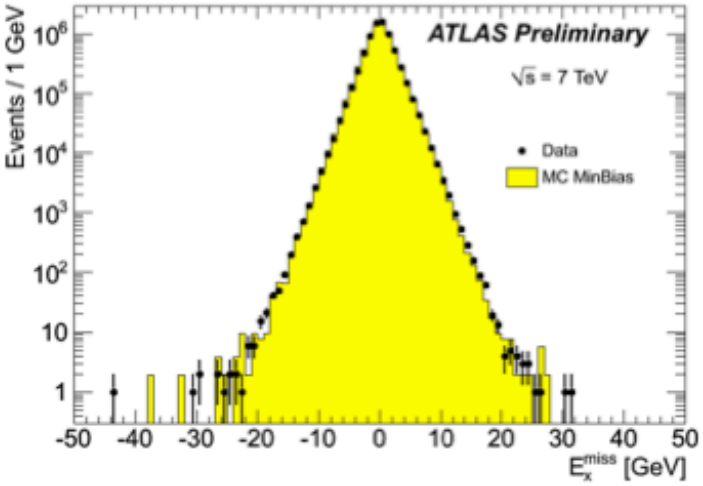
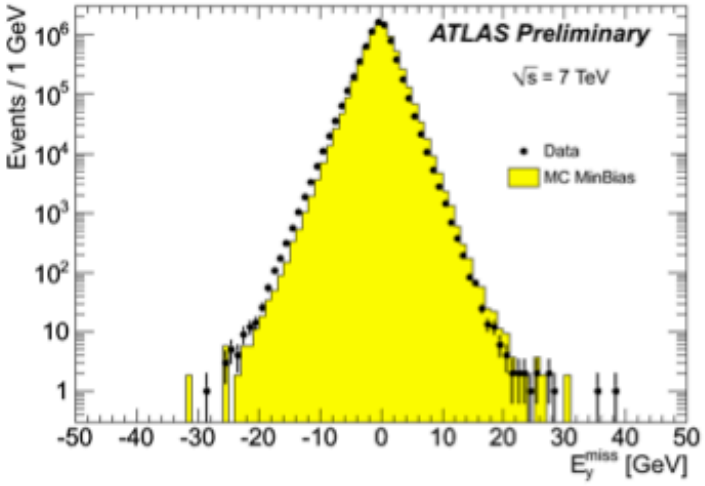
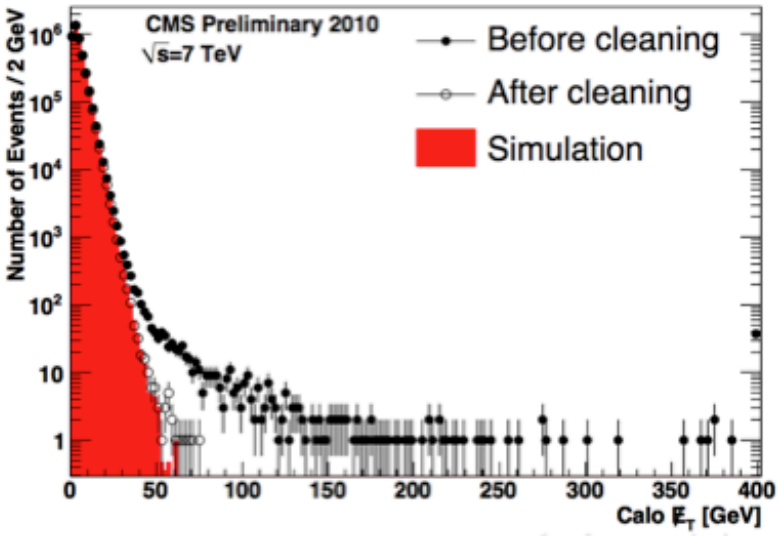
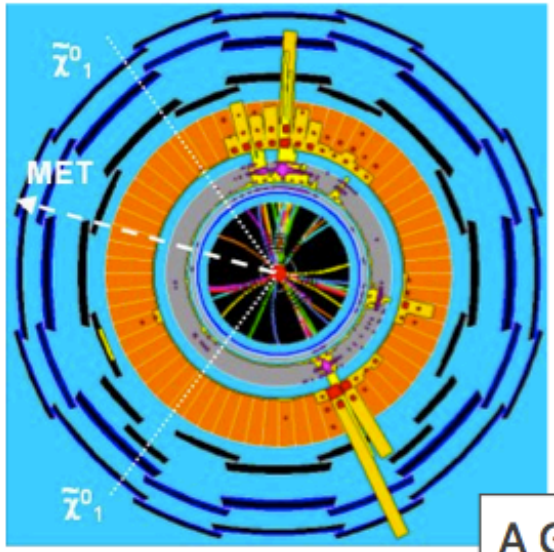








A GEANT4 event.

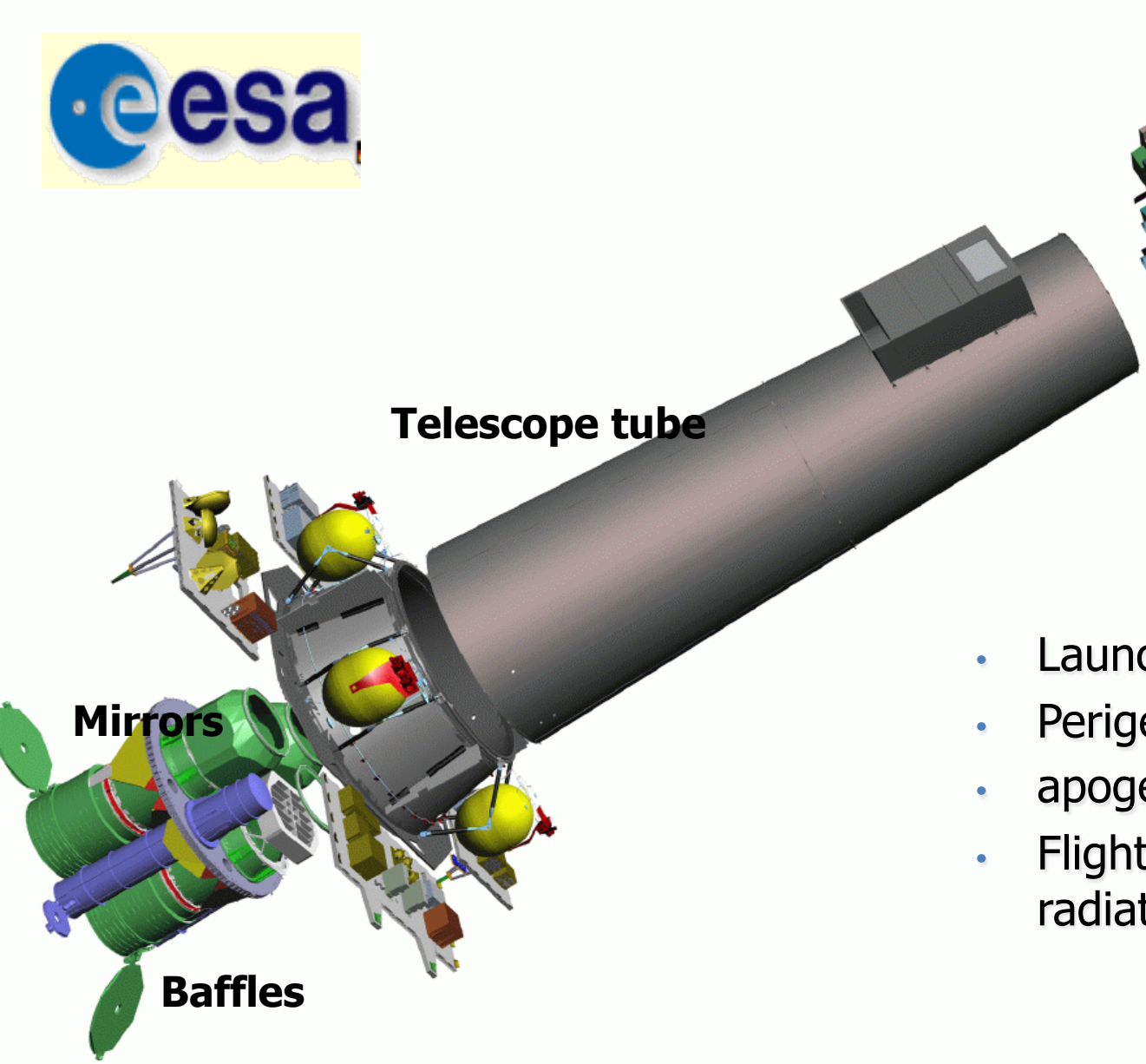
This is one of the hardest things to get right. MET incorporates everything measured in the detector and attempts to identify non-interacting particles, such as neutrinos or dark matter.

Agreement is astounding.

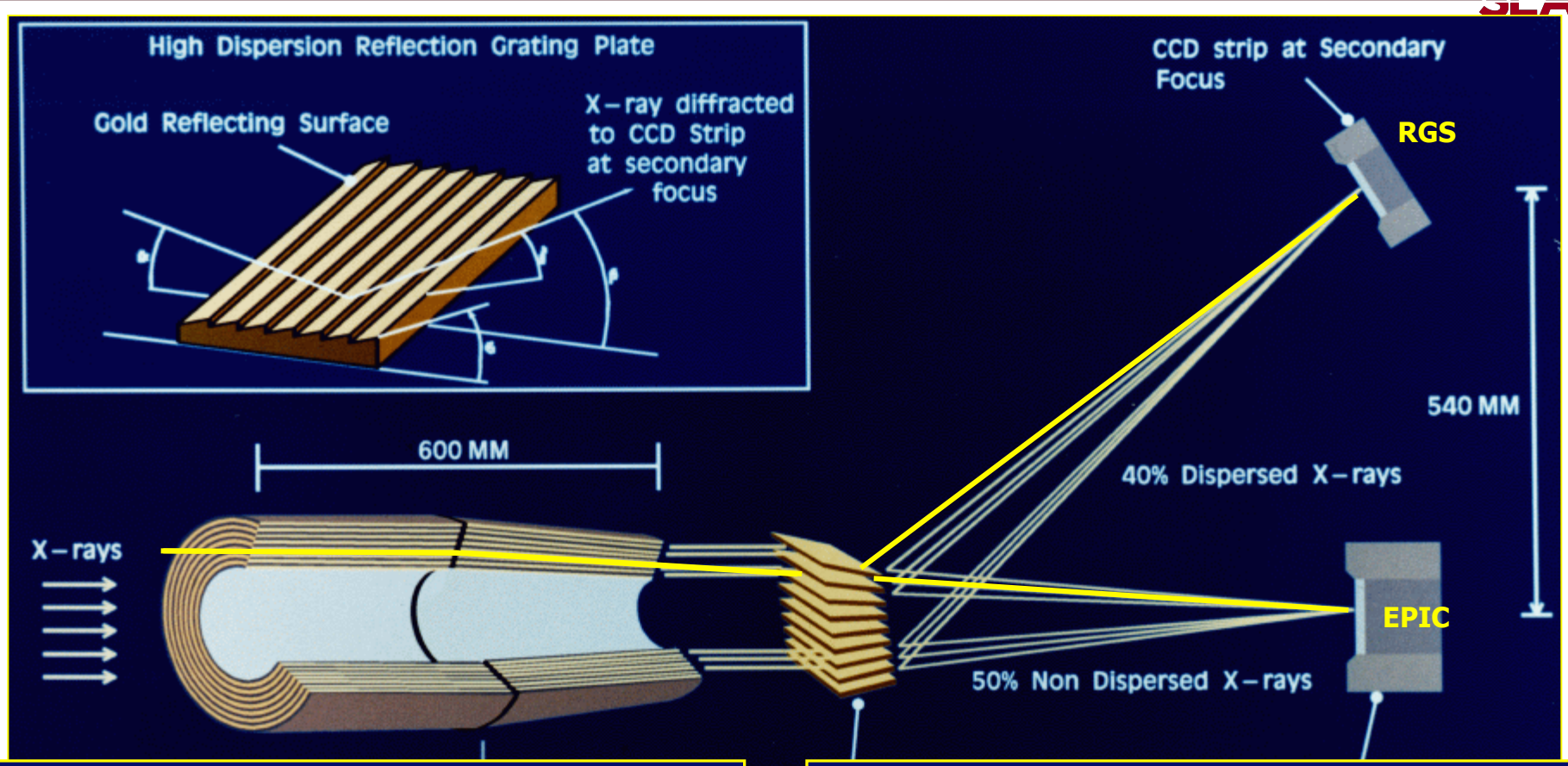
You can even see that the ATLAS detector is not quite centered – in both data and MC.

Both ATLAS and CMS plots are made from a tiny piece of the very earliest data.

T. LeCompte (ANL)



- Launch December 1999
- Perigee 7000 km
- apogee 114000 km
- Flight through the radiation belts



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

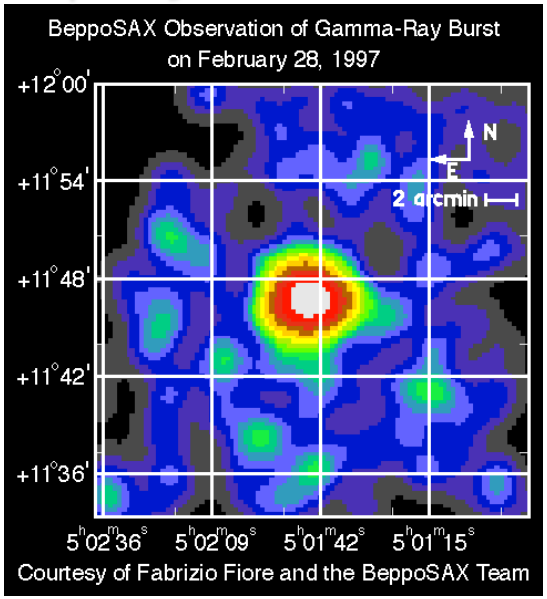
Obscure problem; not much analysed

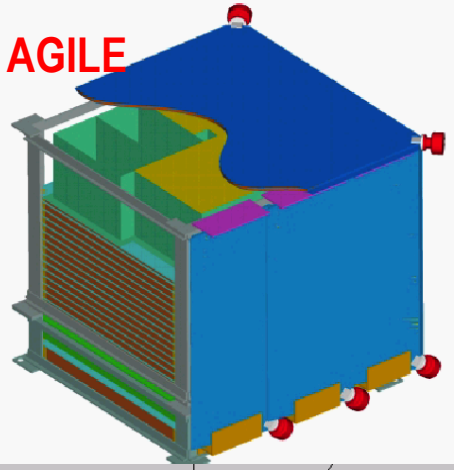
As the outcome of the simulation, beam shutter was introduced.

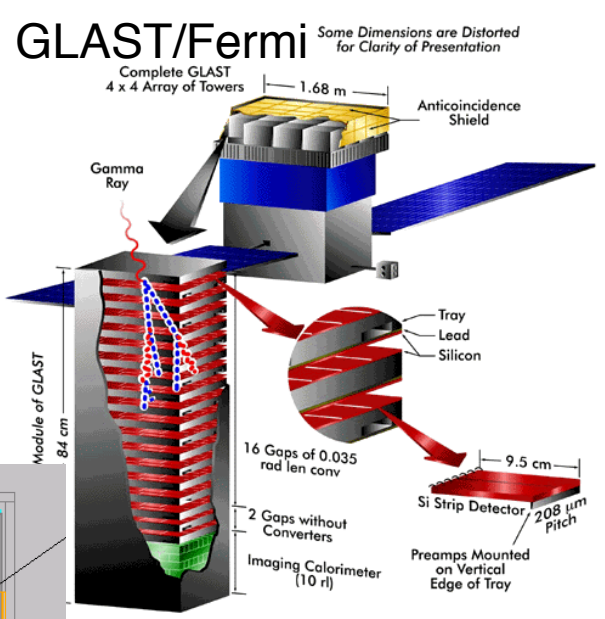
The shutter is closed while XMM is passing through the radiation belt.

γ astrophysics

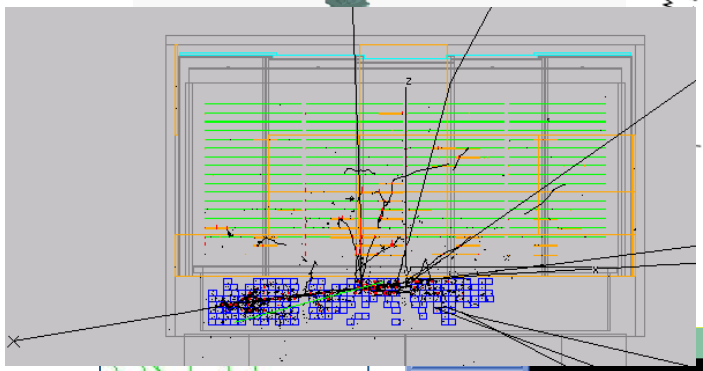
γ-ray bursts

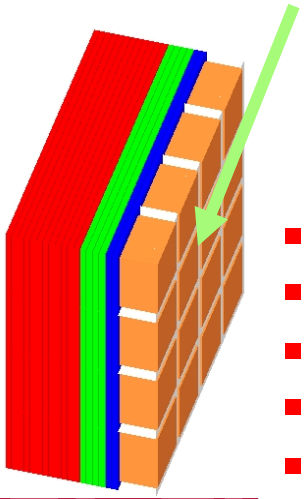






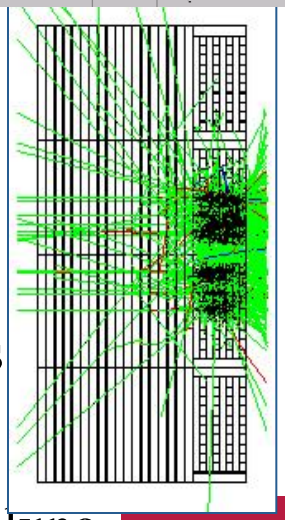
GLAST / Fermi

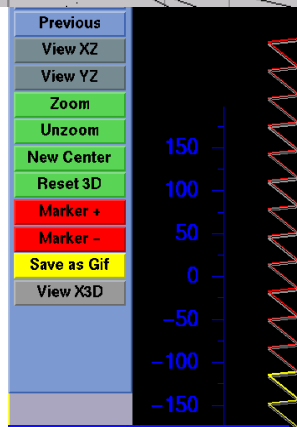


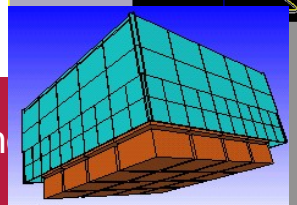


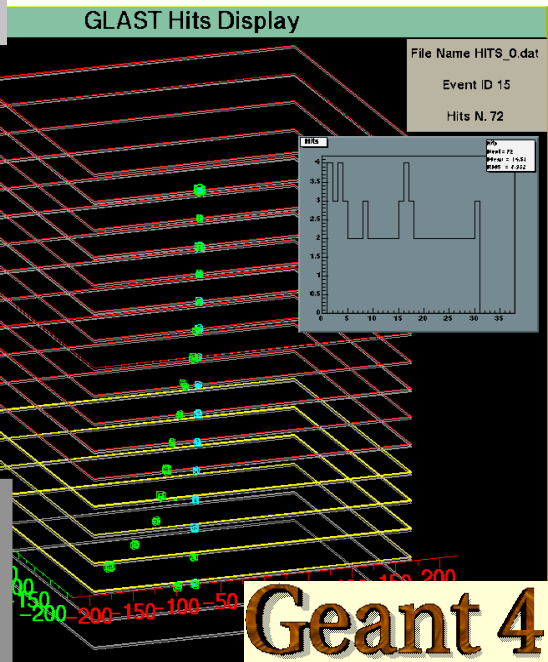
Typical telescope:
Tracker
Calorimeter
Anticoincidence

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



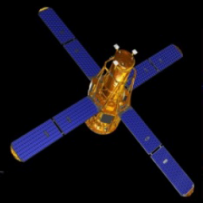






Geant4 in space


Akebono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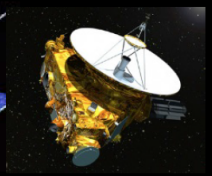
ACE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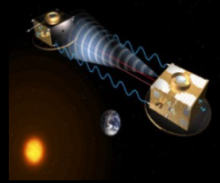
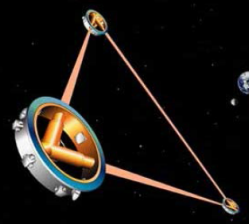

LISA Pathfinder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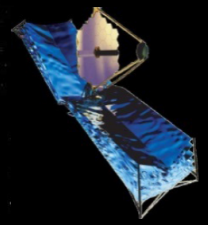
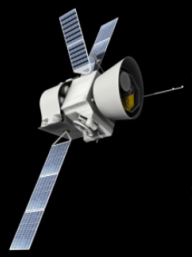
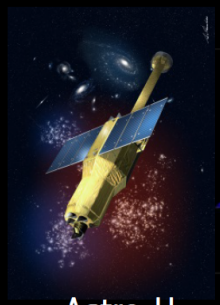

JWST


INTEGRAL


BepiColombo


Messenger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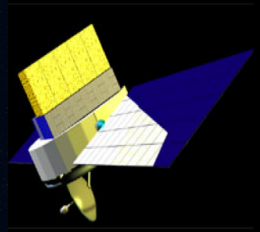
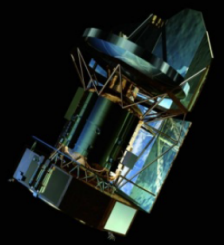

Fermi


SOHO


GAIA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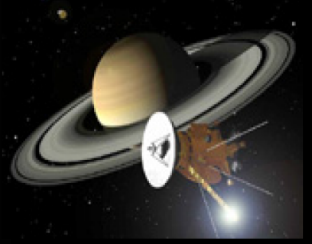

Cassini

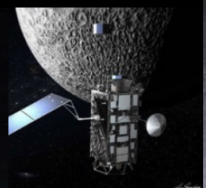

Suzaku


SWIFT


XMM-Newton


JUICE


JUNO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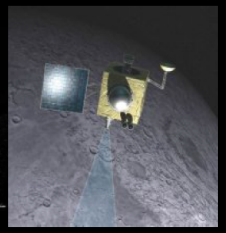
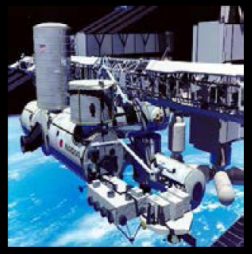

Chandrayaan-1


Chandrayaan-2


Columbus


EUSO


AMS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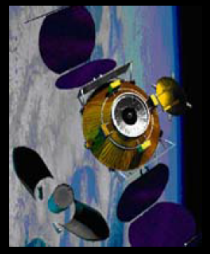
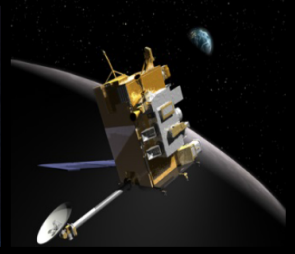

ConeXpress


Chang'e-1

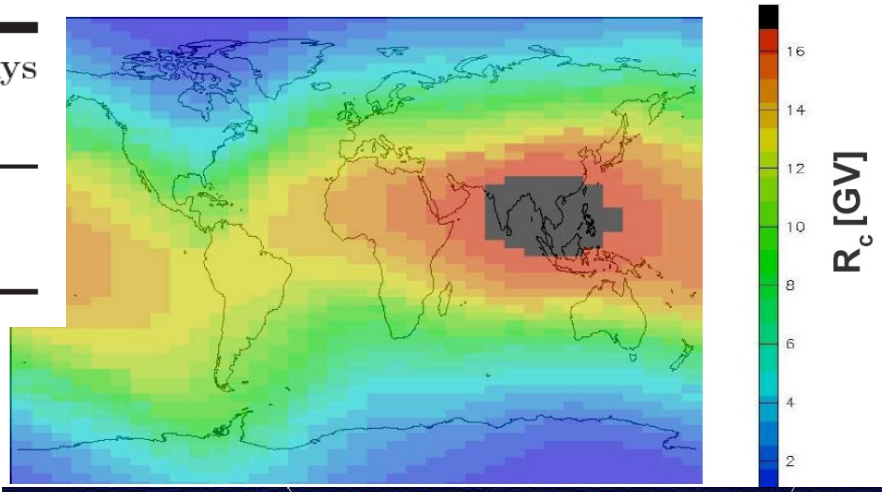

LRO

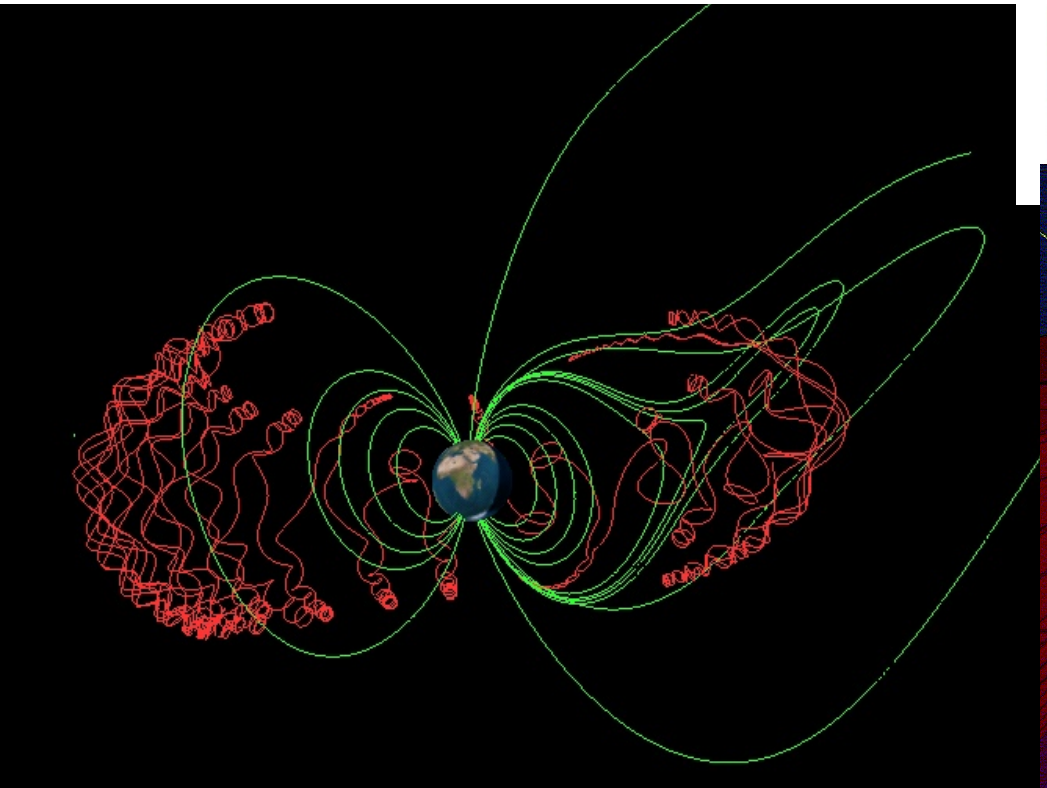
PlanetoCosmics
Geant4 simulation of Cosmic Rays in planetary Atmo-/Magneto- spheres

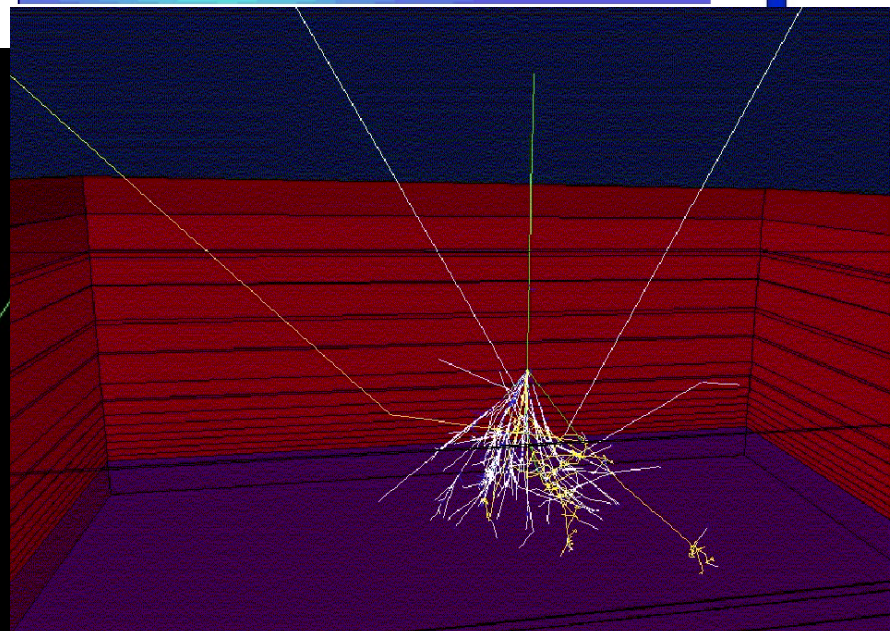
Geant4 Simulation of the Propagation of Cosmic Rays through the Earth's Atmosphere

L. Desorgher, E. O. Flückiger, M. R. Moser, and R. Bütikofer
Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland

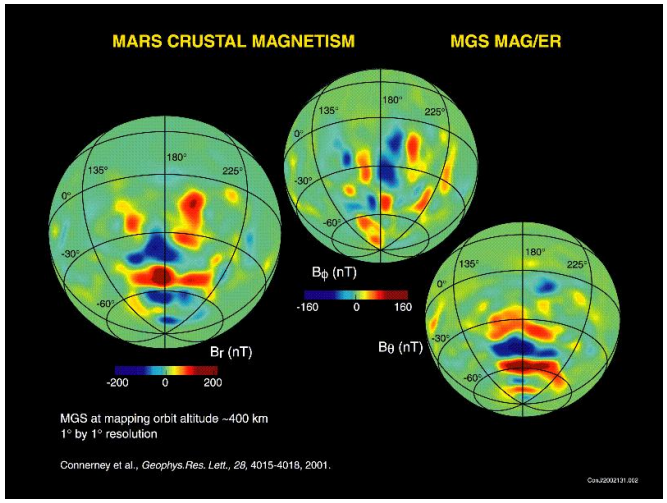
Cutoff Rigidities vs position

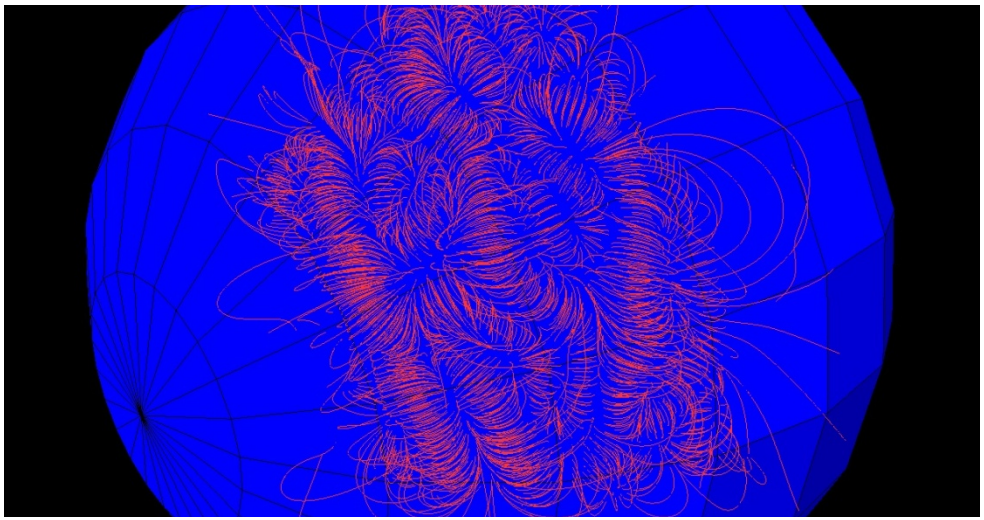




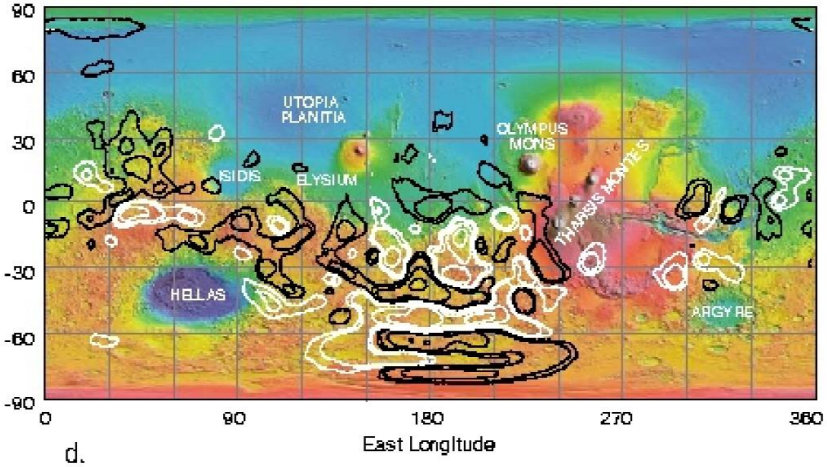


PlanetoCosmics
Mars field and atmosphere

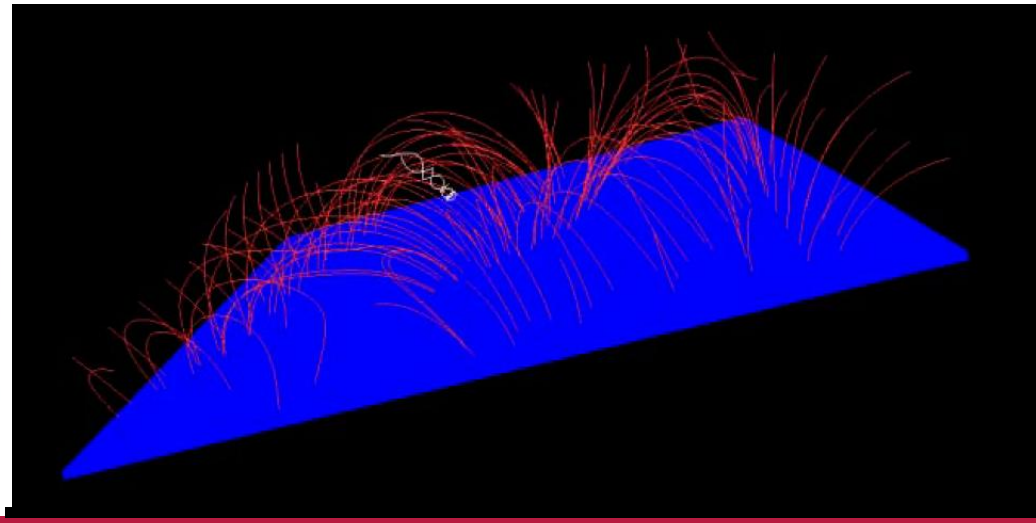




- NASA Mars GRAM2001 model



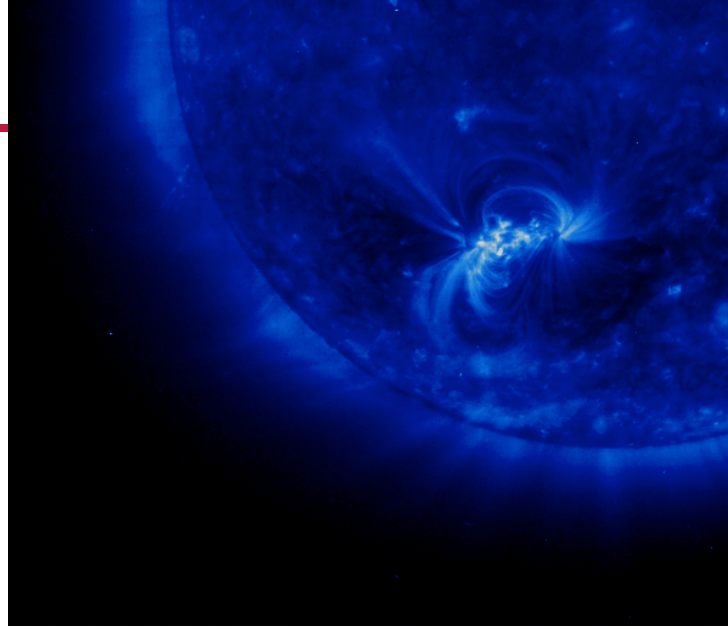
d.

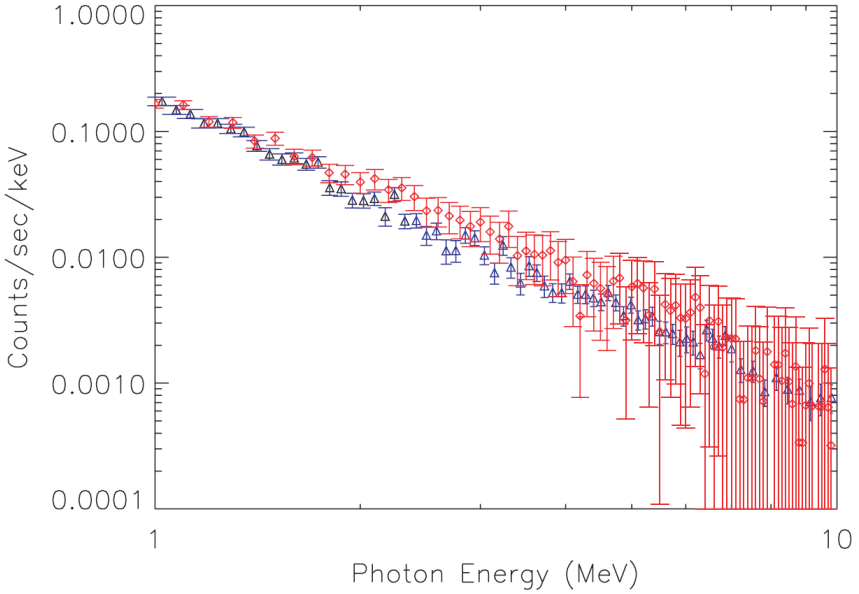


Solar event gamma-rays

- Electron Bremsstrahlung – induced gammas in solar flares
- Compton back-scattering

  → observable gamma-ray spectrum much softer than predicted by simple analytic calculations





Effects of Compton scattering on the Gamma Ray Spectra of Solar flares

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Mitsuhiro KOHAMA, Yukikatsu TERADA and Toru TAMAGAWA
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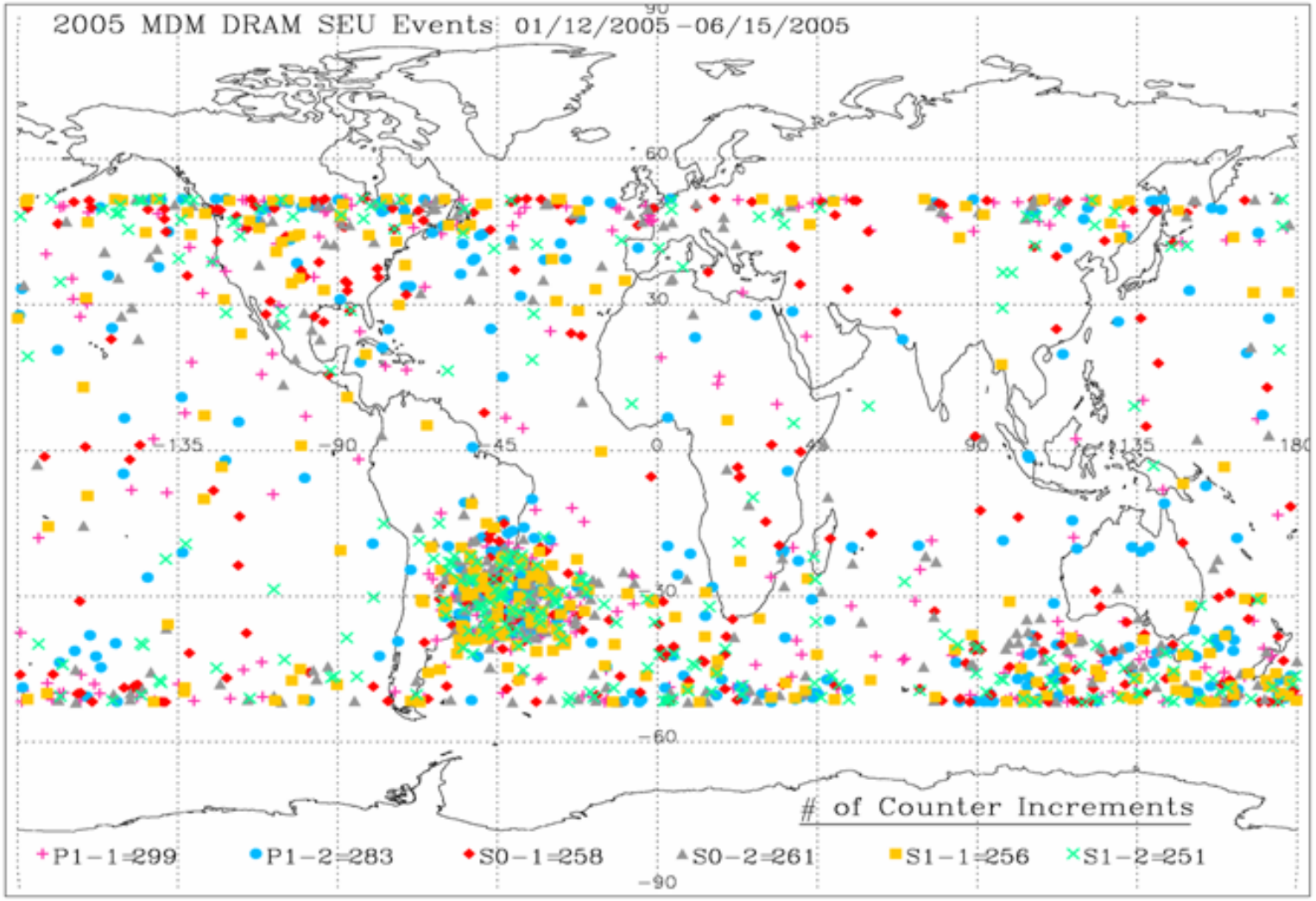
(Received ; accepted)

Abstract

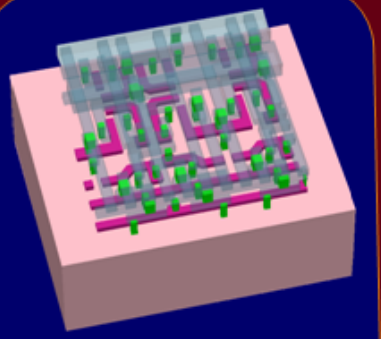
Using fully relativistic GEANT4 simulation tool kit, the transport of energetic electrons generated in solar flares was Monte-Carlo simulated, and resultant bremsstrahlung gamma-ray spectra were calculated. The solar atmosphere was ap-

ISS Single Event Upset Observations

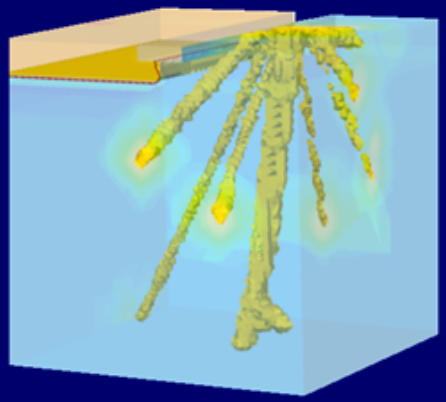


ISS Orbit

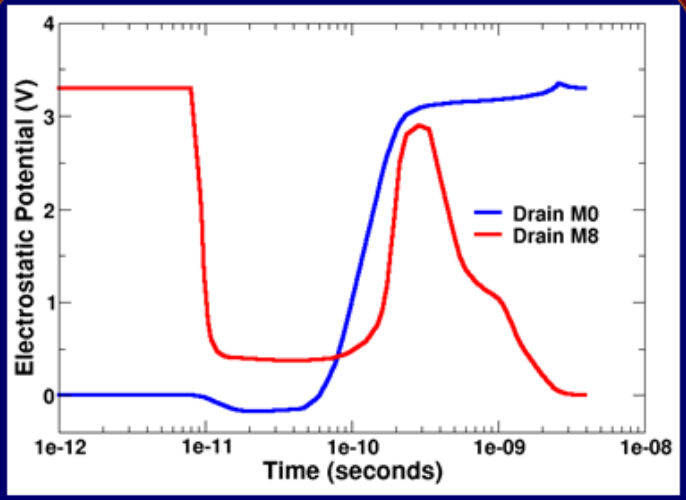
RADSAFE on SEE in SRAMs



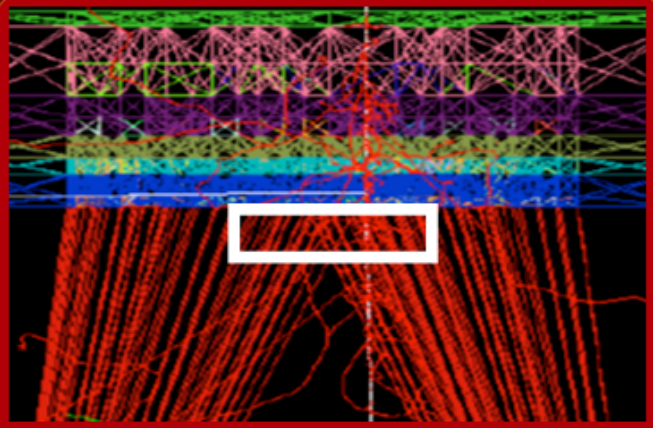
TCAD Cell Structure: SRAM Cell



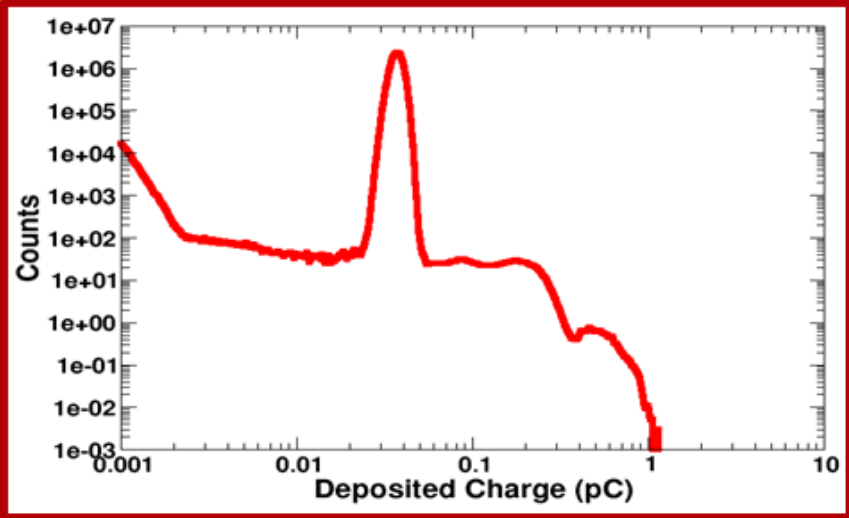
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset



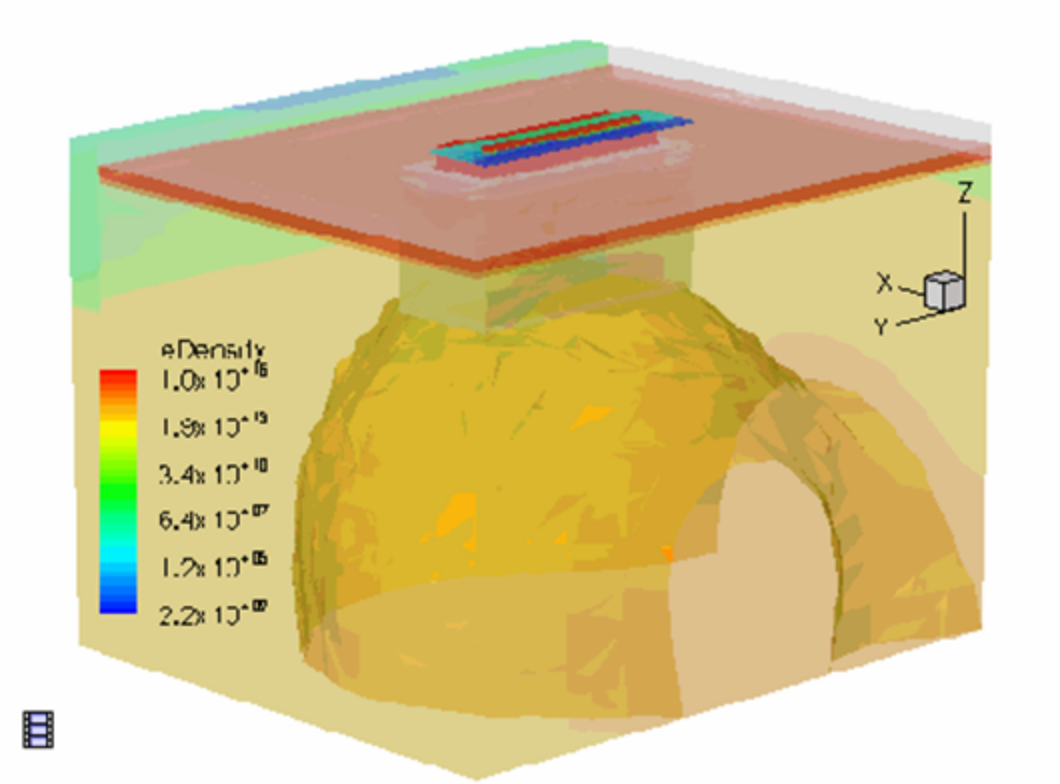
Geant4 Geometry and 523 MeV Neon Event

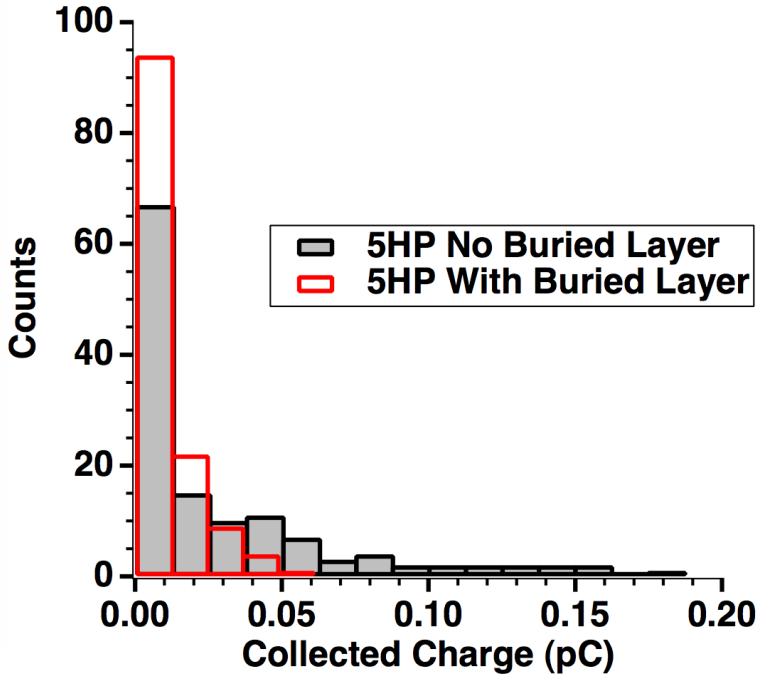


MRED Energy Deposition for 10^8 Events

Simulation of Radiation Events

- 63-MeV proton incident on a SiGe Heterojunction Bipolar Transistor (HBT)
- Iso-charge surfaces following a nuclear reaction



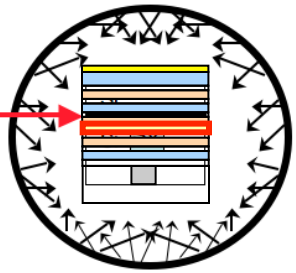


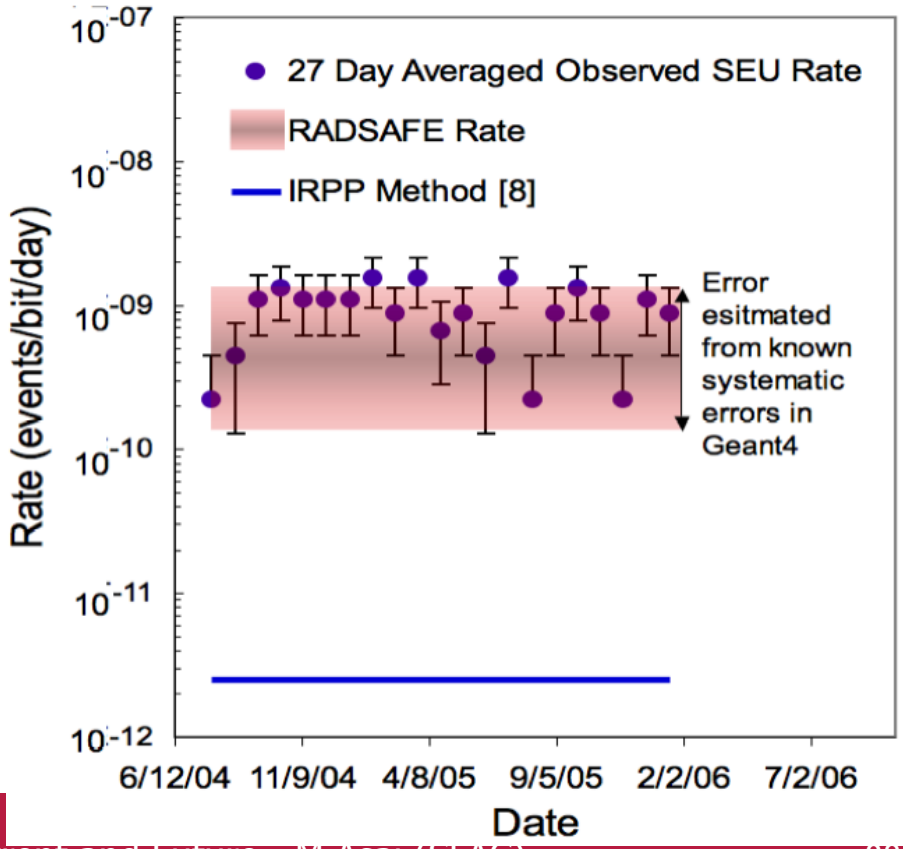
Courtesy of R.Reed (Vanderbilt U.)

Observed and Predicted SEU Rate for an SRAM

- SRAM used on NASA Messenger spacecraft
- Observed Average SEU Rate:
  - $1x10^{-9}$ Events/Bit/Day
- Vendor predicted rate using CREME96:
  - $2x10^{-12}$ Events/Bit/Day
  - Classical Method nearly a factor 500 lower than observed rate
- MRED rate (includes reaction products):
  - Between $1.3x10^{-10}$ and $1.3x10^{-9}$ Errors/Bit/Day

Multi-layered Stack

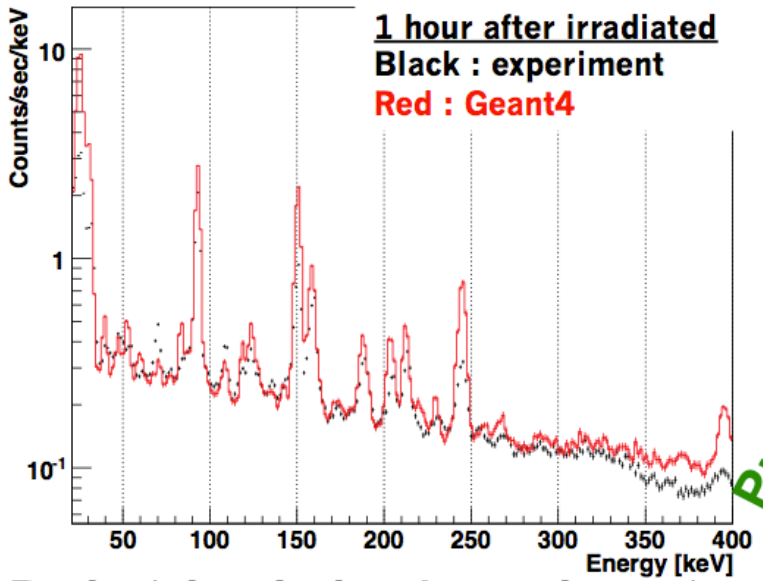




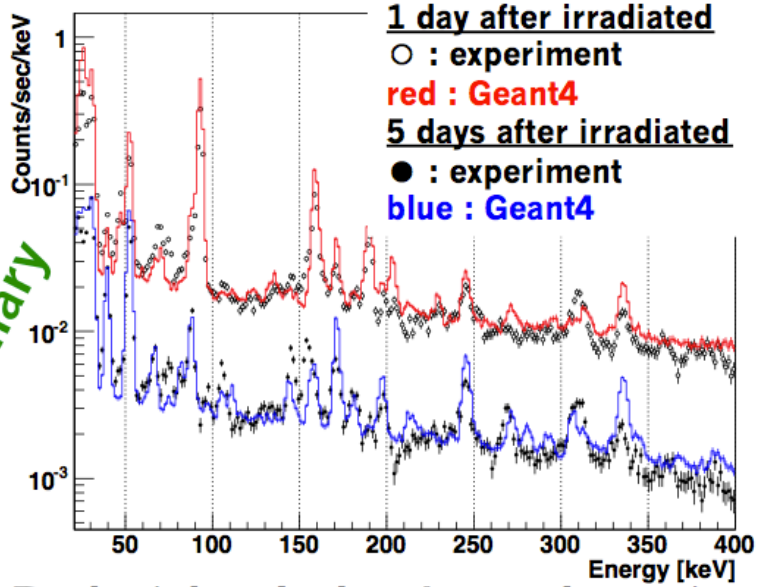
Courtesy of R.Reed (Vanderbilt U.)

Time evolution of the activation background

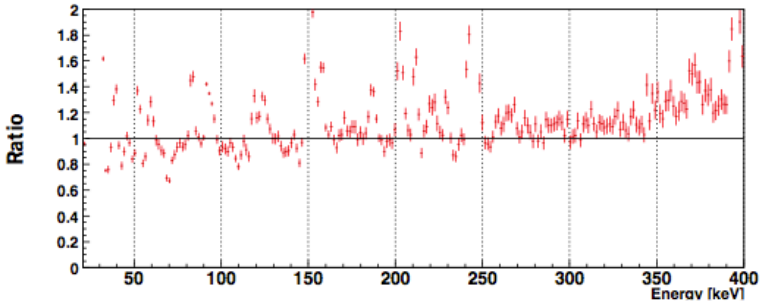
Comparison with Geant4



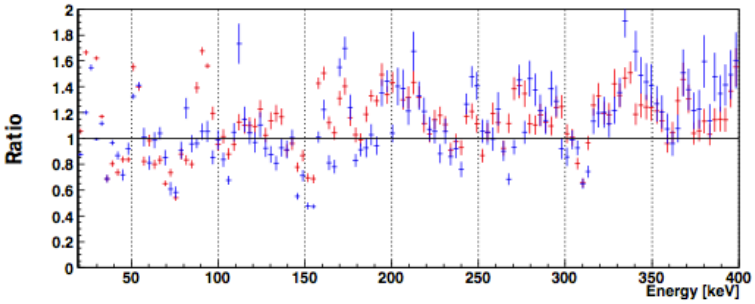
Preliminary



Ratio (simulation/experiment)



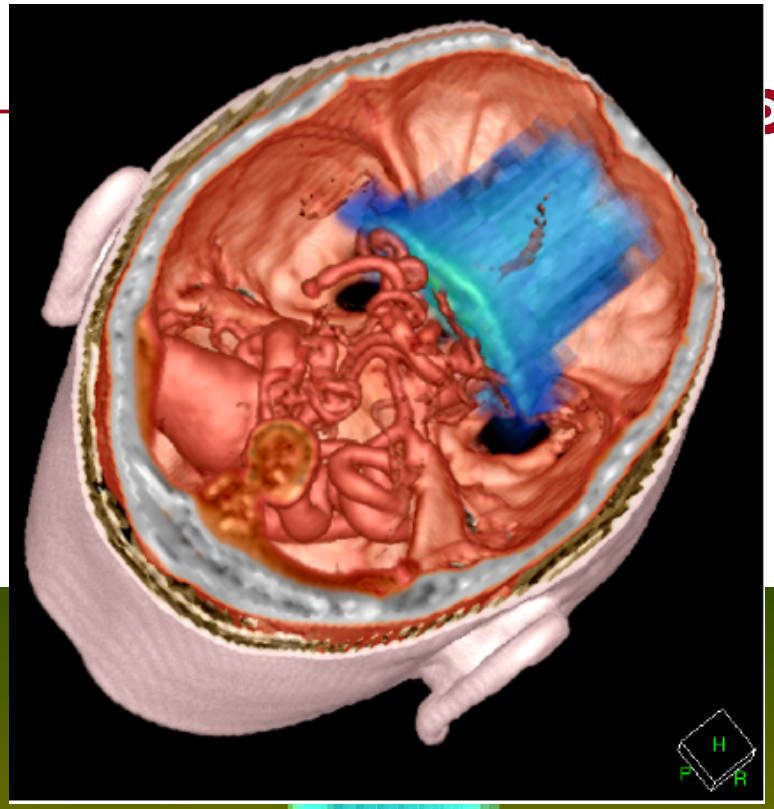
Ratio (simulation/experiment)

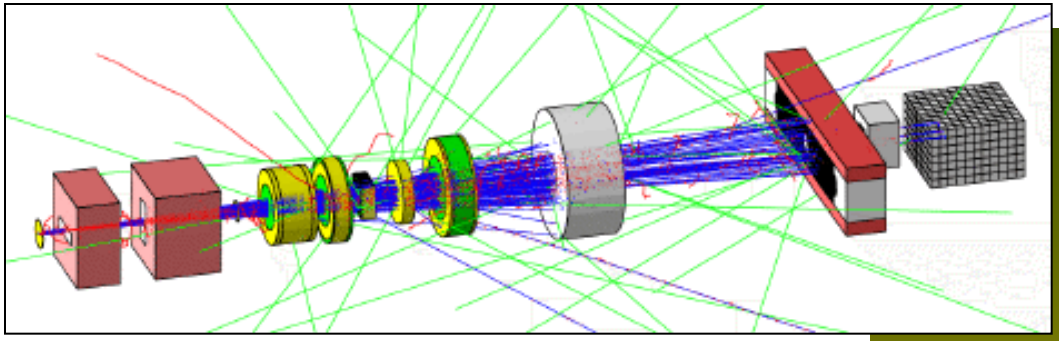


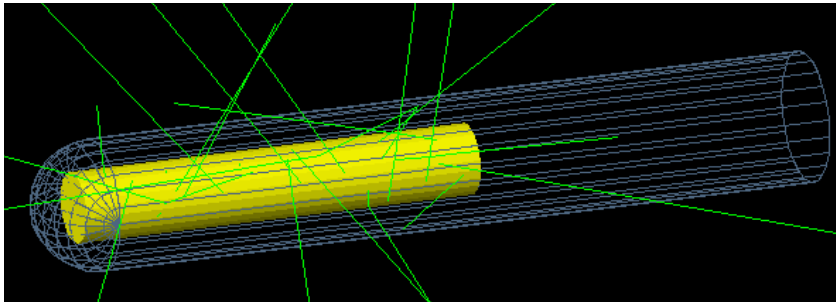
❖ Simulation results agrees with experimental data within a factor of two in terms of the line intensities

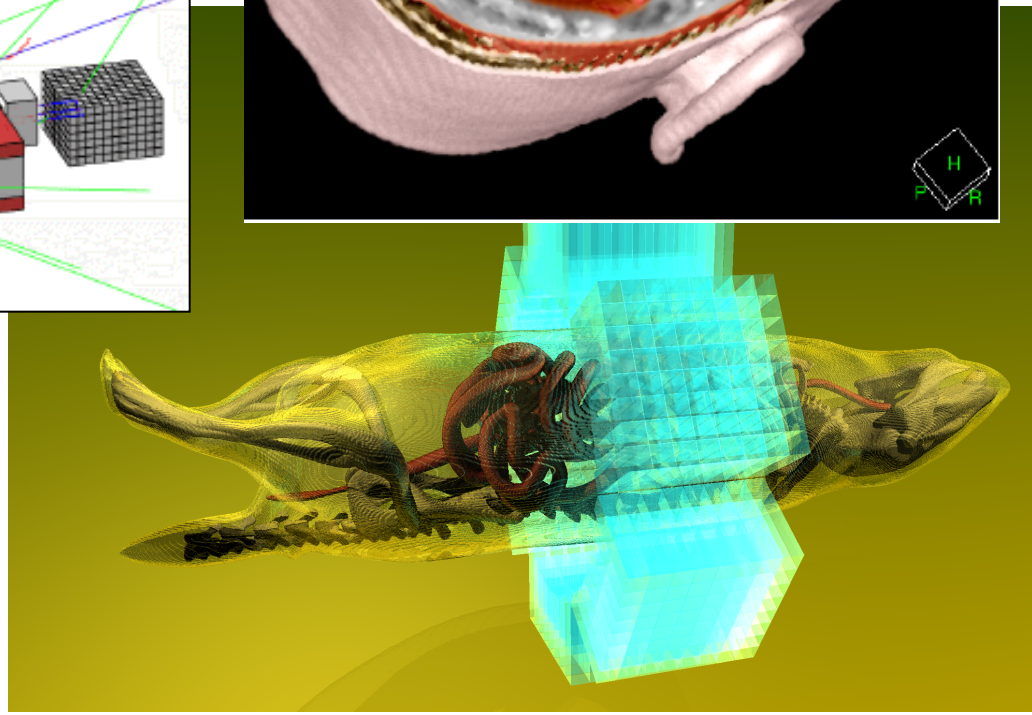
Geant4 @ Medical Science

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



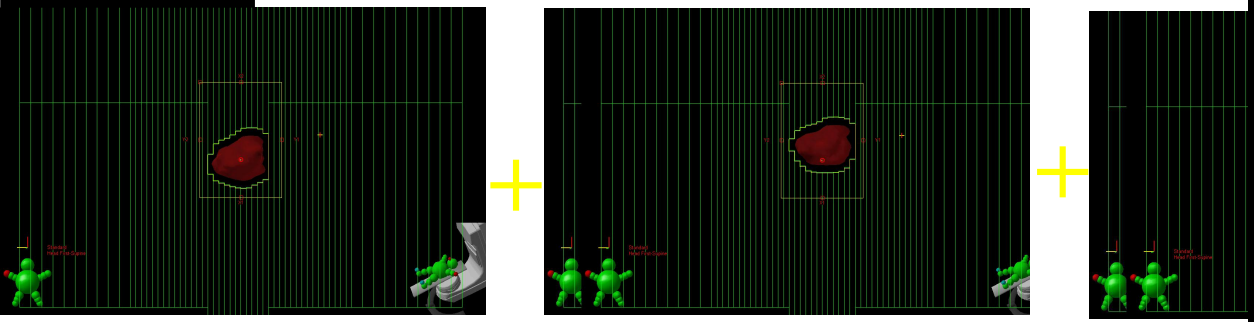


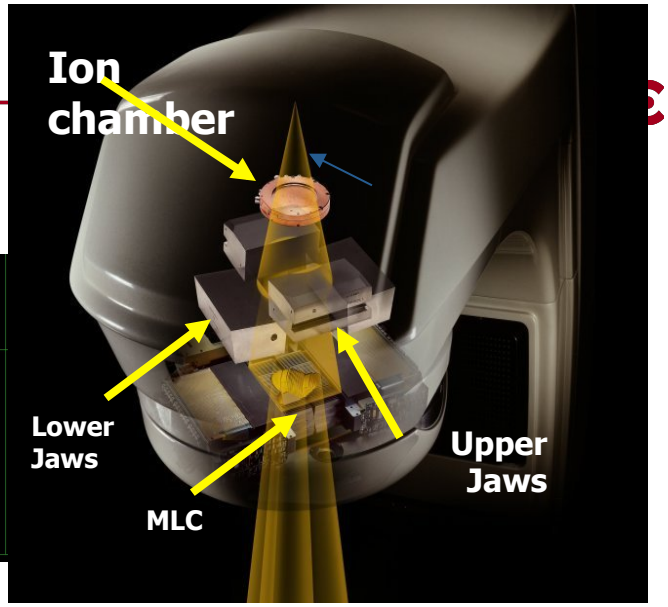




4D RT Treatment Plan

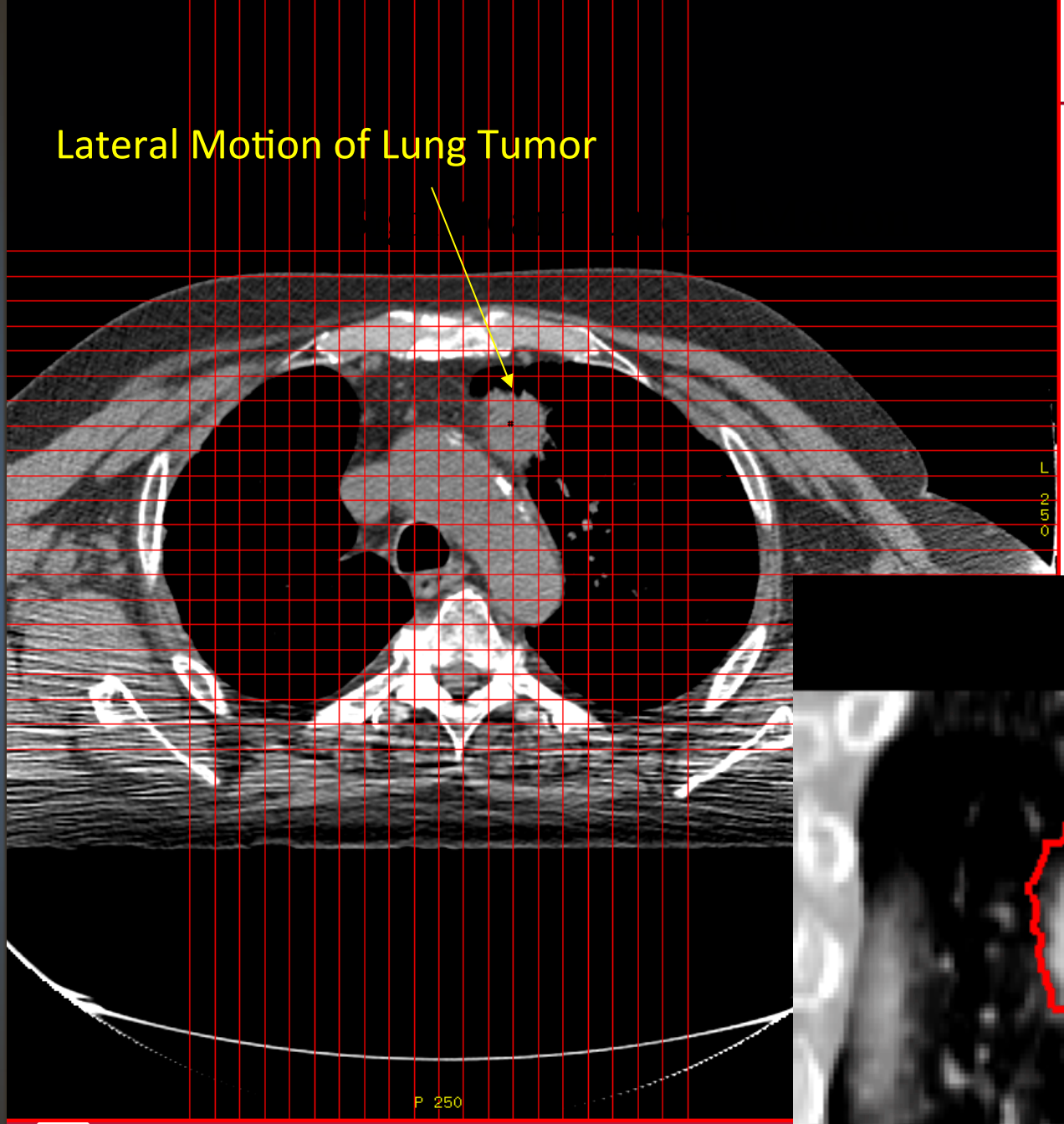
ource: Lei Xing, Stanford University

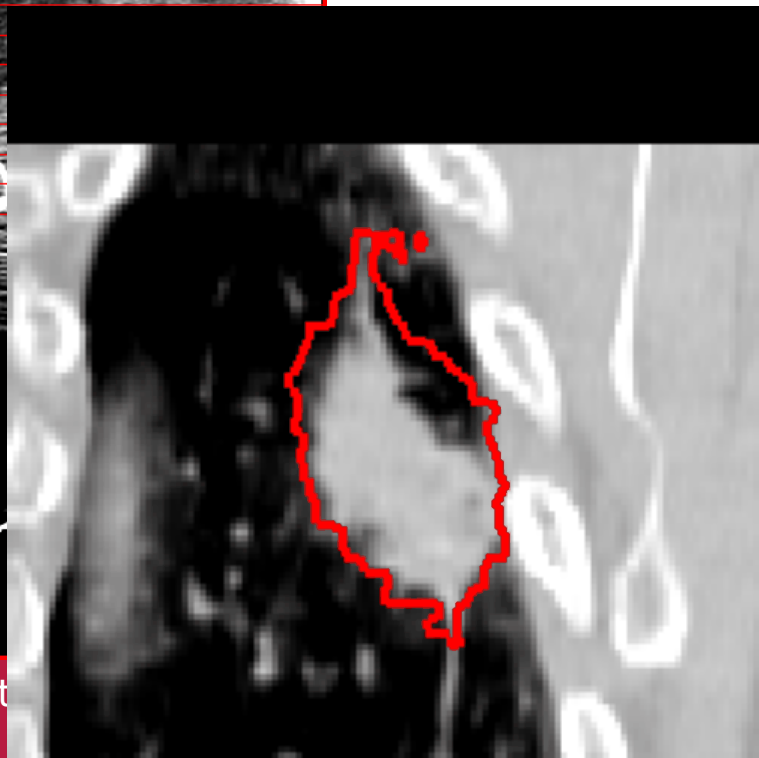




Y. Yang, S. Huq, L Xing, Med. Phys, 2006

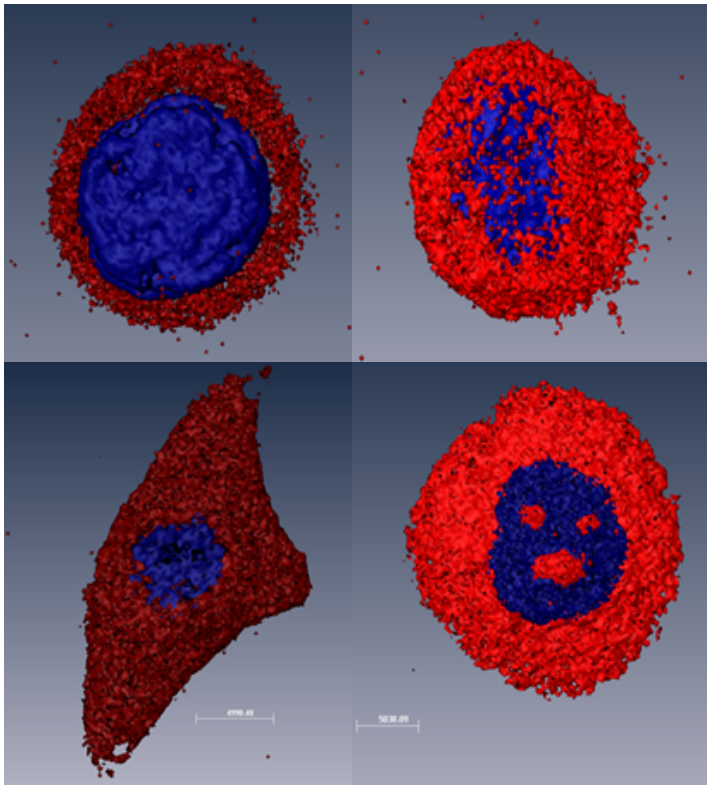
Lateral Motion of Lung Tumor

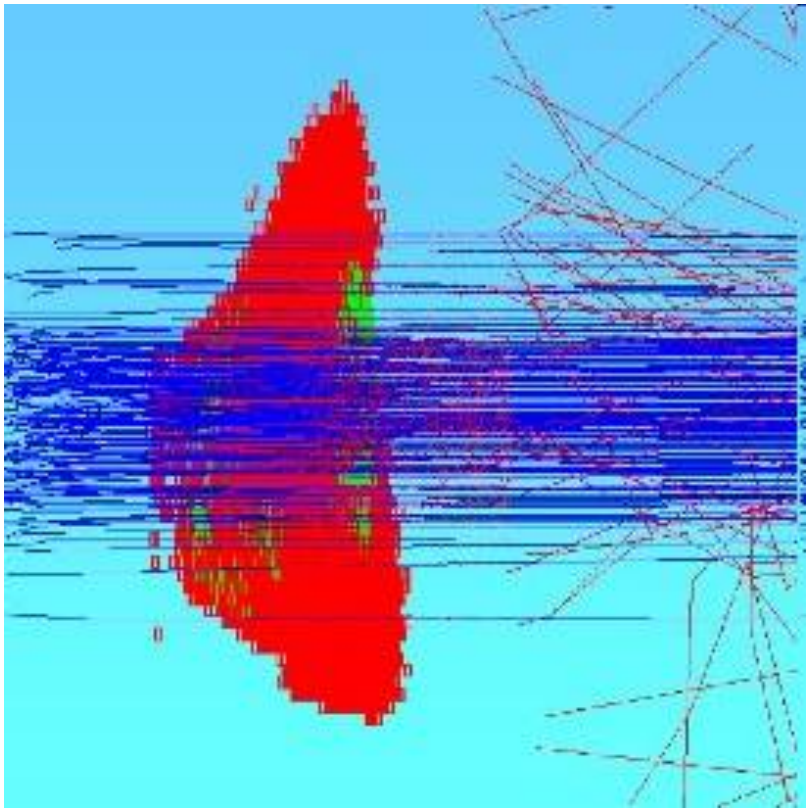




Single cell irradiation

- Example of single cell irradiation by 3 MeV alpha particles in a high-resolution cellular phantom
  - 4h or 24h incubated cell
  - 64 x 64 x 60 resolution
  - 0.36 x 0.36 x 0.16 μm^3 voxel size
- Full CENBG microbeam irradiation setup simulated

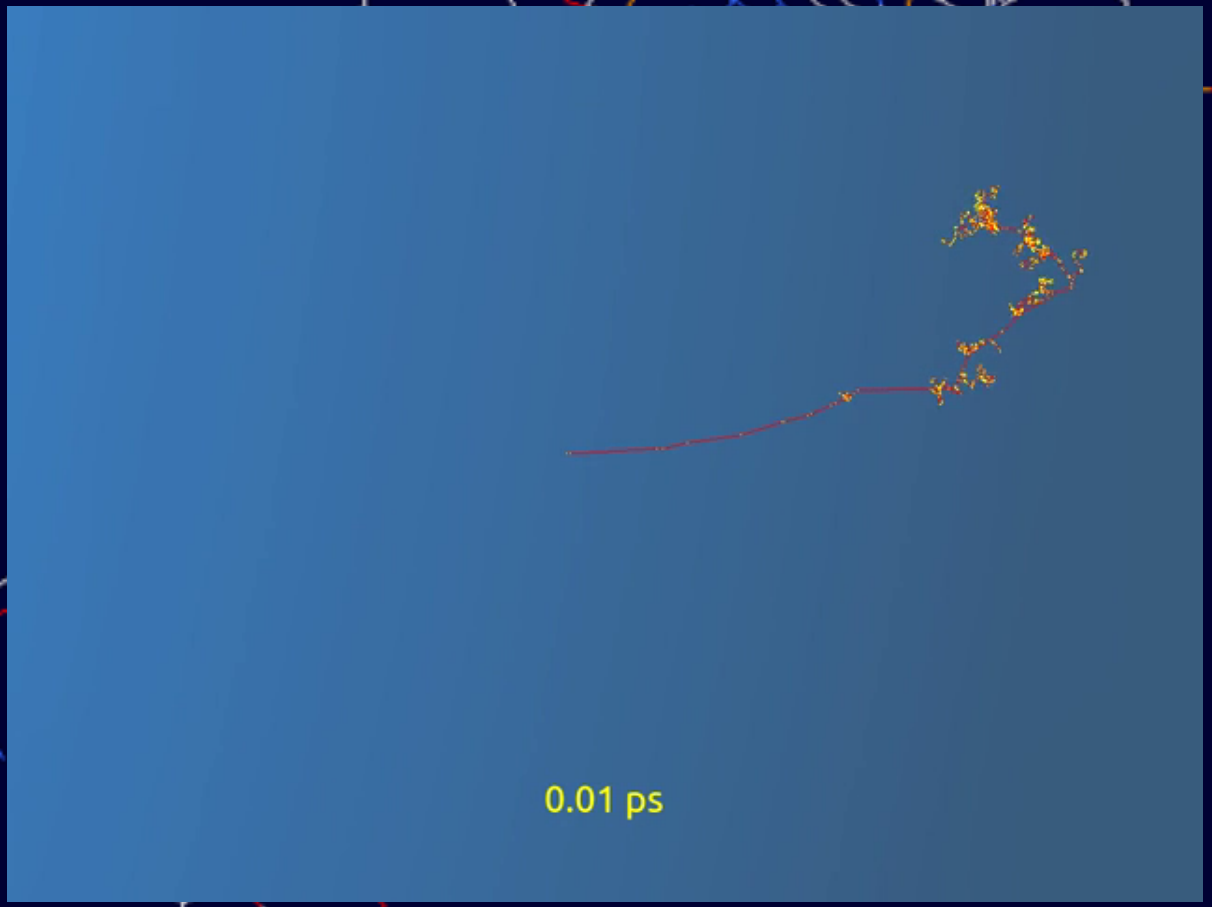




Courtesy of Sebasien Incerti (IN2P3-CNRS / CENBG)

DNA in Geant4

most common DNA conformation in cells



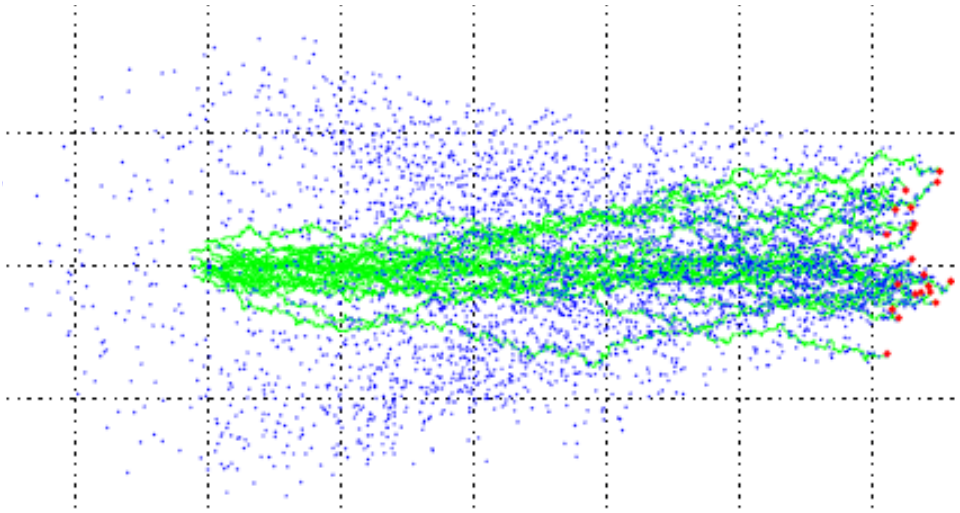
Conversion of ProteinDataBank-format file ▸ Geant4

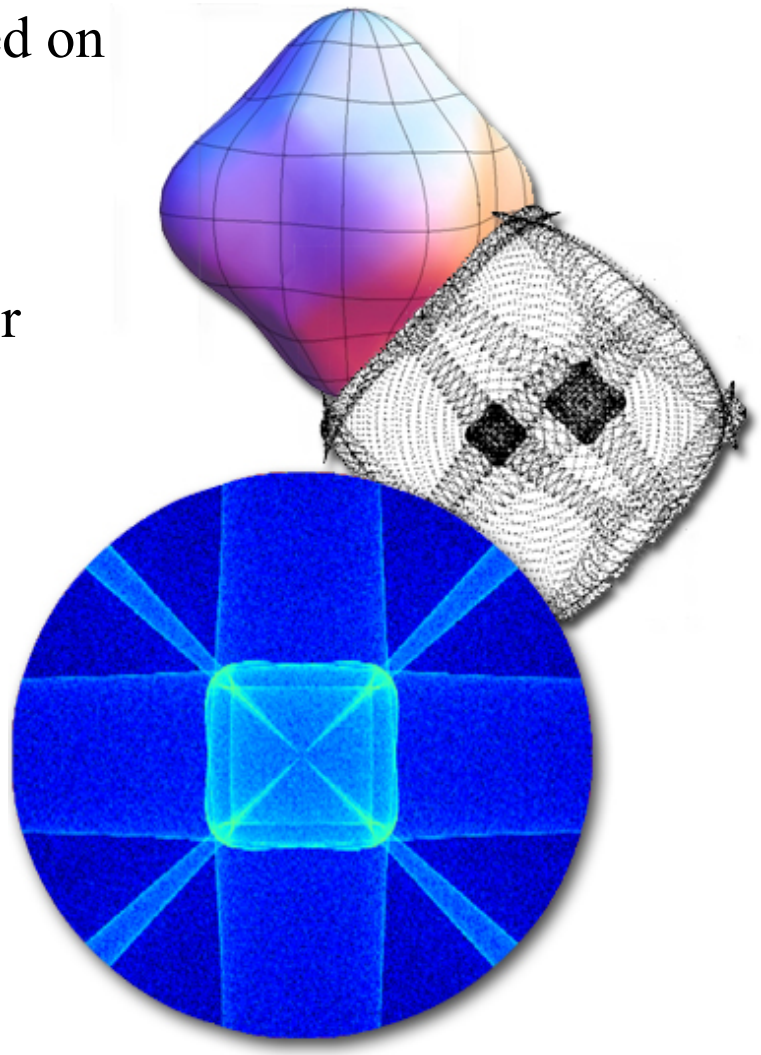
Courtesy of Sebasien Incerti (IN2P3-CNRS / CENBG)

Condensed Matter Physics in Geant4

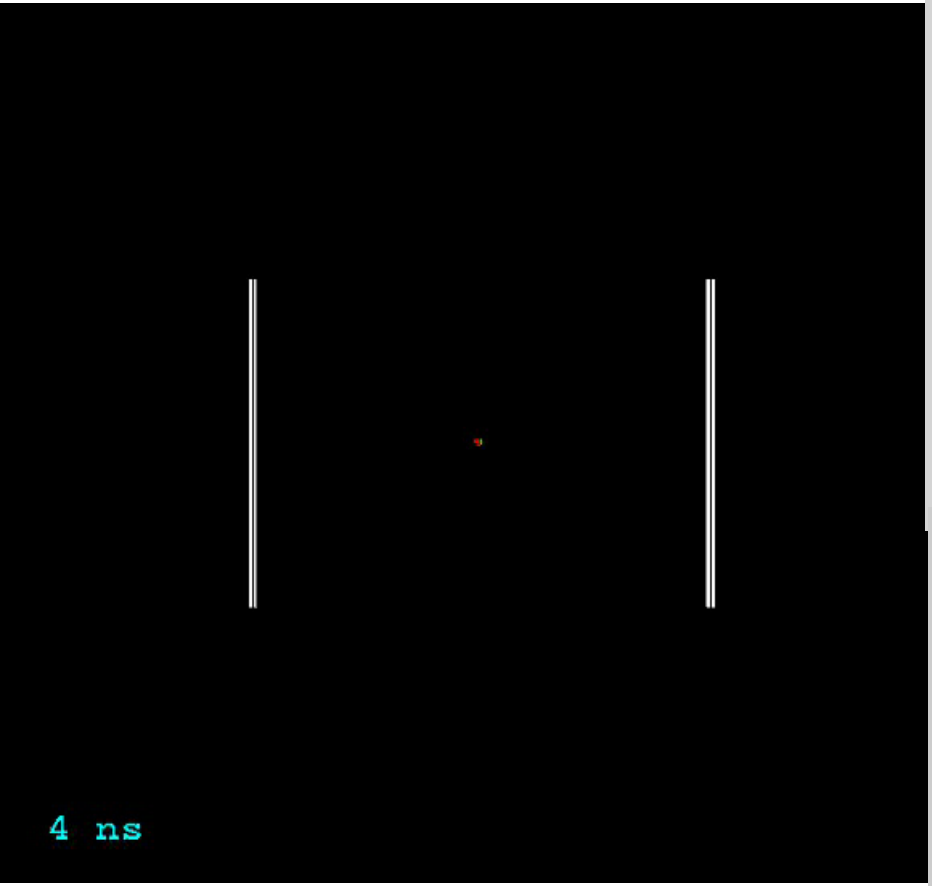
- Phonon propagation, including focusing based on elasticity tensor (right)

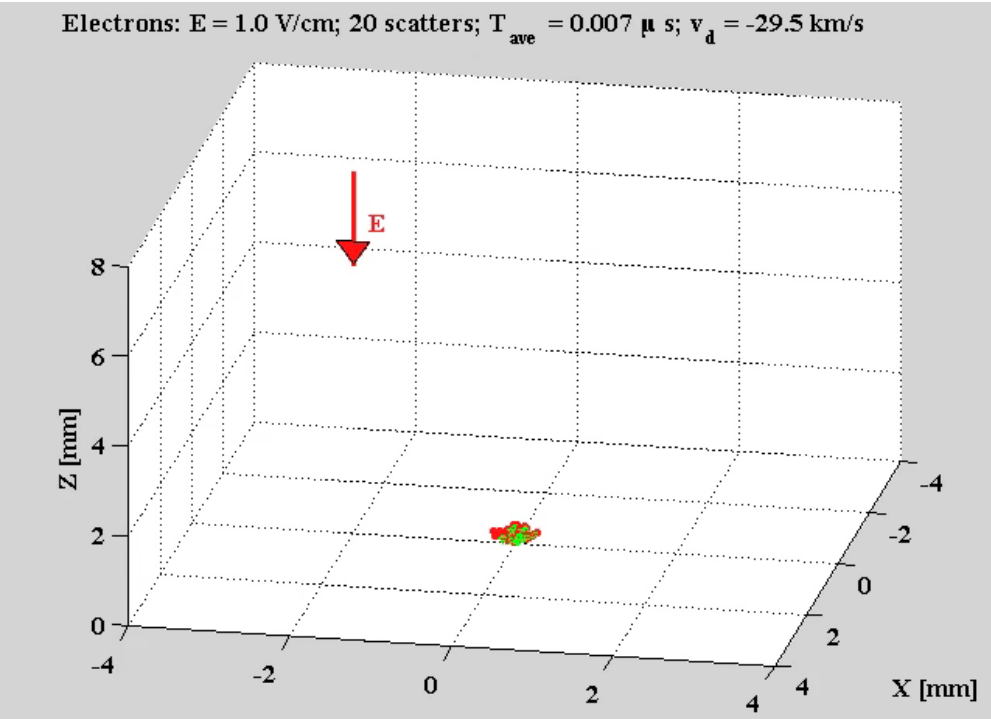
- e-/h+ transport, including conduction band anisotropy and Luke-Neganov emission, under development (below)

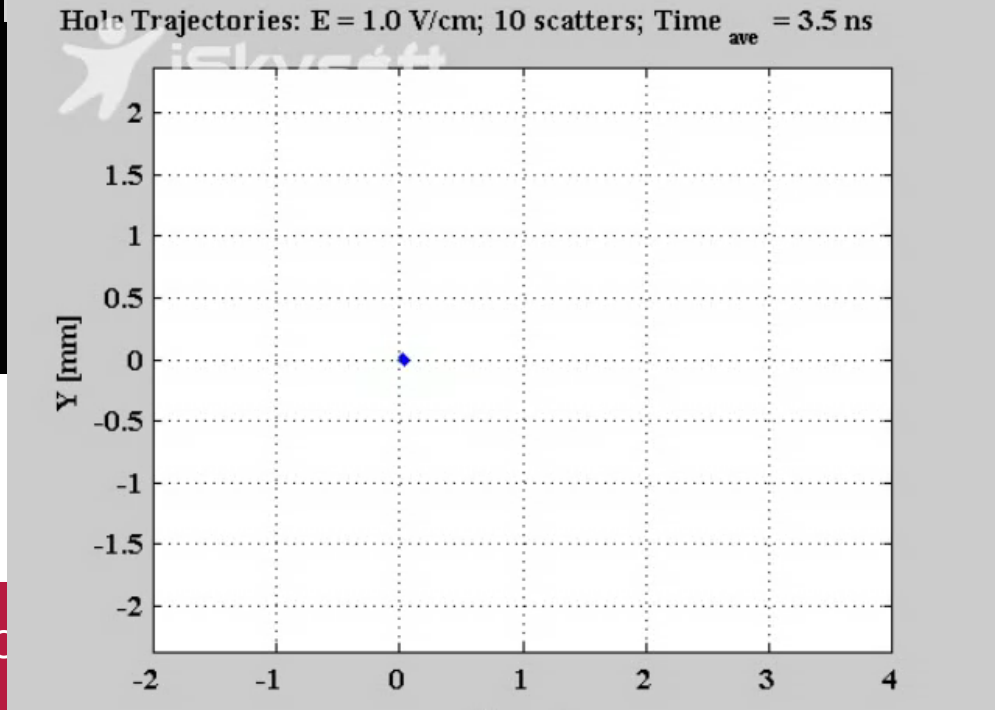




e-/h propagation with Luke phonon emission in Ge crystal

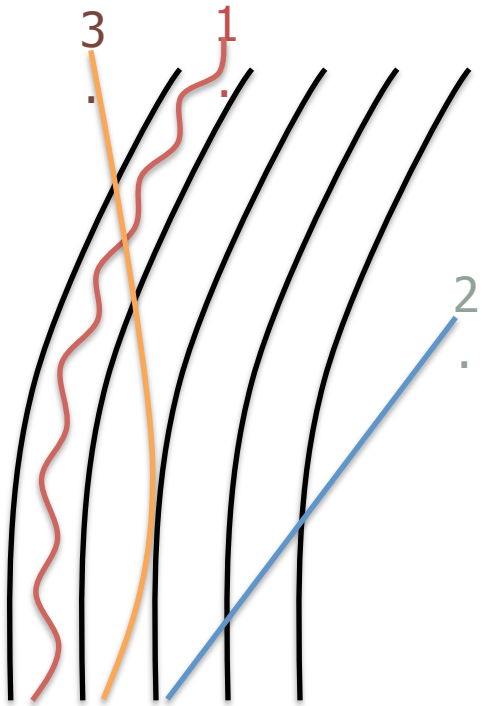


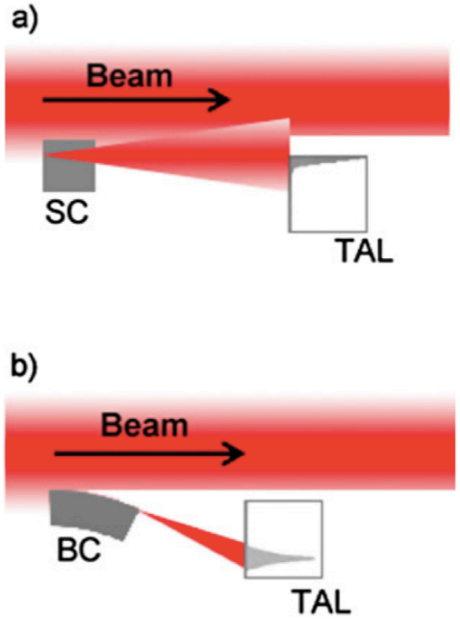


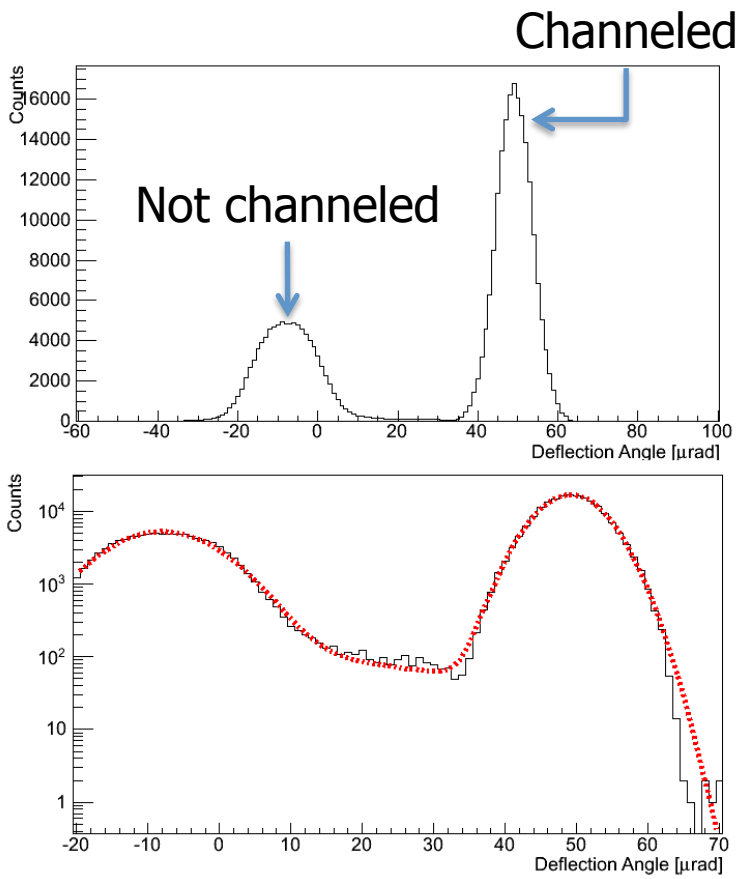


Bent crystal as a collimator

- Bent crystal can be used as a collimator to deflect particles of beam halo.
- This study will be extended for T-513 experiment at SLAC LCLS ESTB



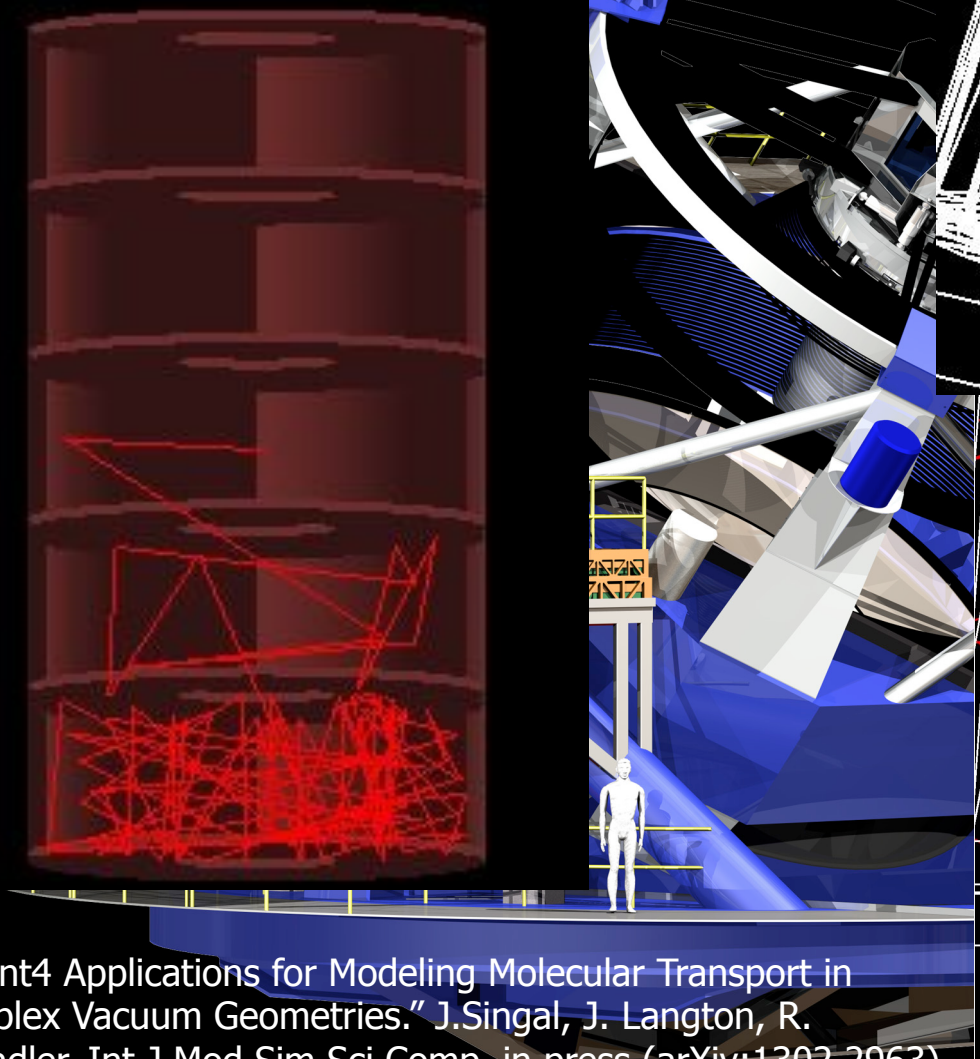


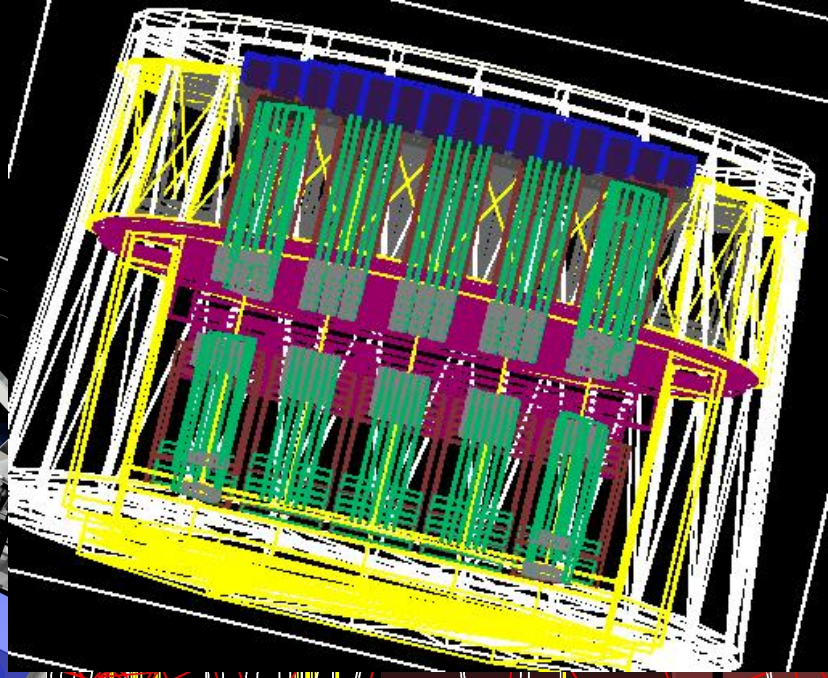


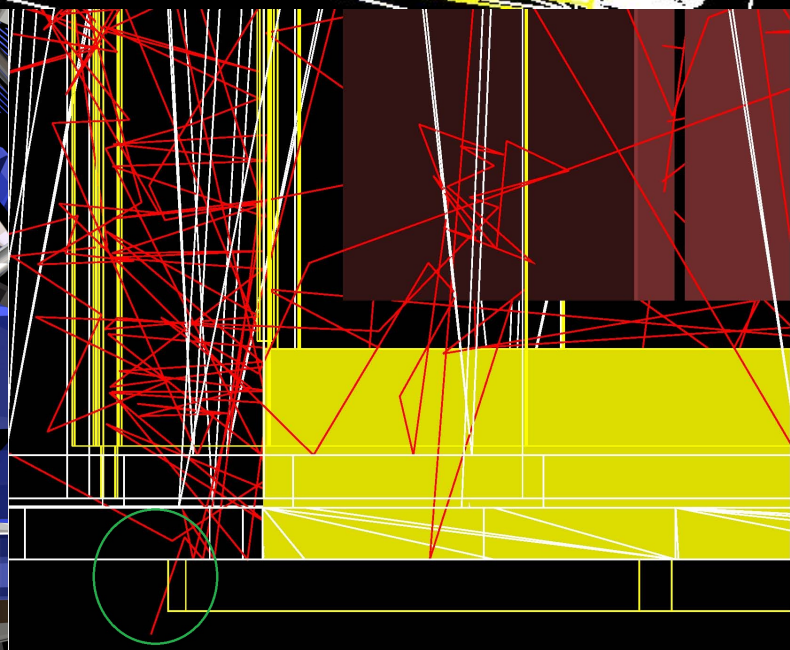
Enrico Bagli (INFN/Ferrara)

- W. Scandale et al., Phys. Lett. B 680 (2009) 129

LSST (Large Synoptic Survey Telescope)





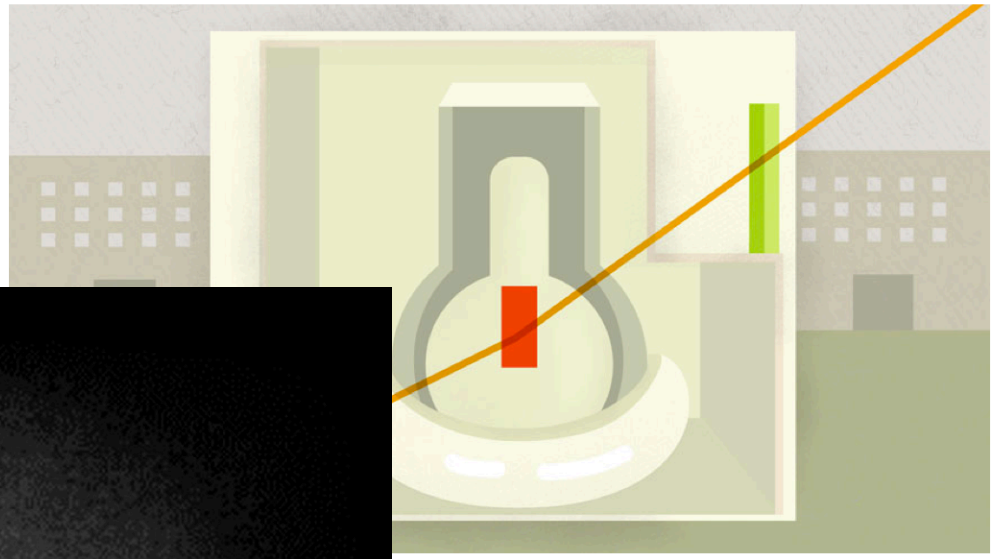


"Geant4 Applications for Modeling Molecular Transport in Complex Vacuum Geometries." J.Singal, J. Langton, R. Schindler, Int J Mod Sim Sci Comp, in press (arXiv:1302.2963)

symmetry of particle physics

Those exterior walls, made of concrete 10 feet thick, offer their own challenge. Based on computer simulations run with the particle physics software GEANT4, the walls are expected to reduce the resolution to about 30 centimeters.

In addition, the team must also prepare for the high radiation levels present just outside of the reactor units.



ors (shown here in green) on either side of
record the path of muons (represented by the
rough the reactor. By determining how the
ctors, scientists will compile the first picture of

with Shawna X.

As time ticks down to the restart of the Large Hadron Collider, scientists are making sure their detectors run like clockwork.

age

ELSEVIER

Journal of Environmental Radioactivity

Volumes 162–163, October 2016, Pages 118–128

Evaluating remediation of radionuclide contaminated forest near Iwaki, Japan, using radiometric methods

D.C.W. Sanderson[a], A.J. Cresswell[a], K. Tamura[b], T. Iwasaka[c], K. Matsuzaki[d]

[a] Scottish Universities Environmental Research Centre, East Kilbride, Glasgow G75 0QF, United Kingdom

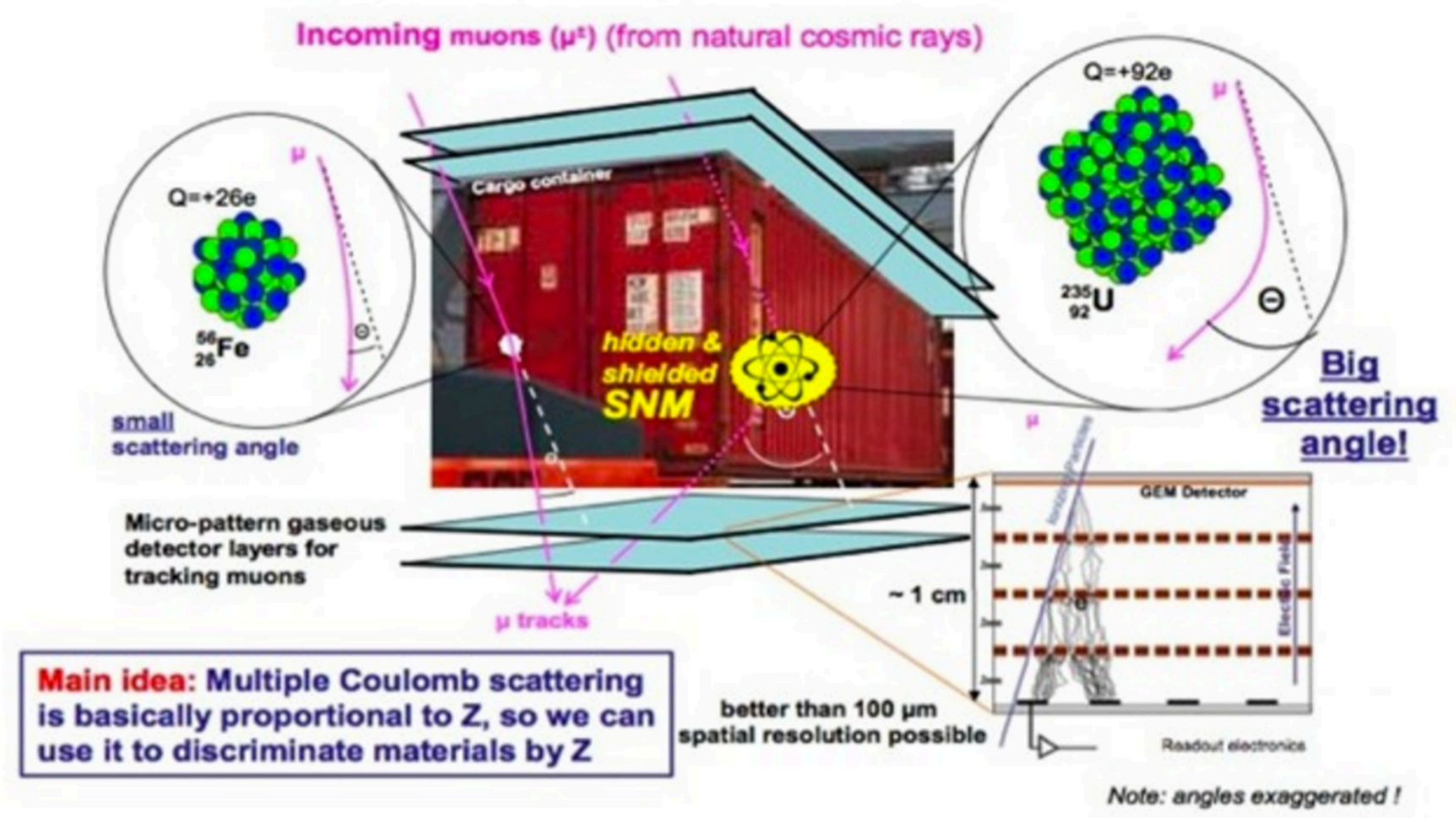
[b] Faculty of Life and Environmental Sciences, University of Tsukuba, Japan

[c] Miraishiko Inc., Kanegaya, Asahi-ku, Yokohama, Japan

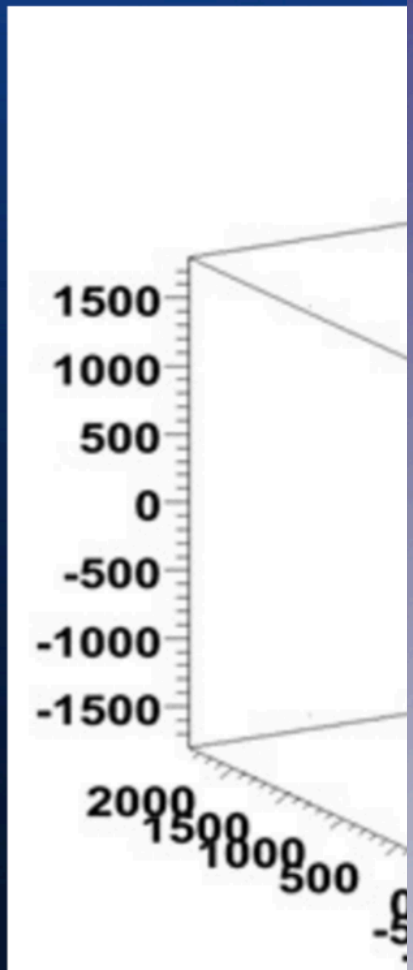
[d] Yunodakesansonai, Iwaki, Japan

Received 24 December 2015, Revised 10 May 2016, Accepted 15 May 2016, Available online 24 May 2016

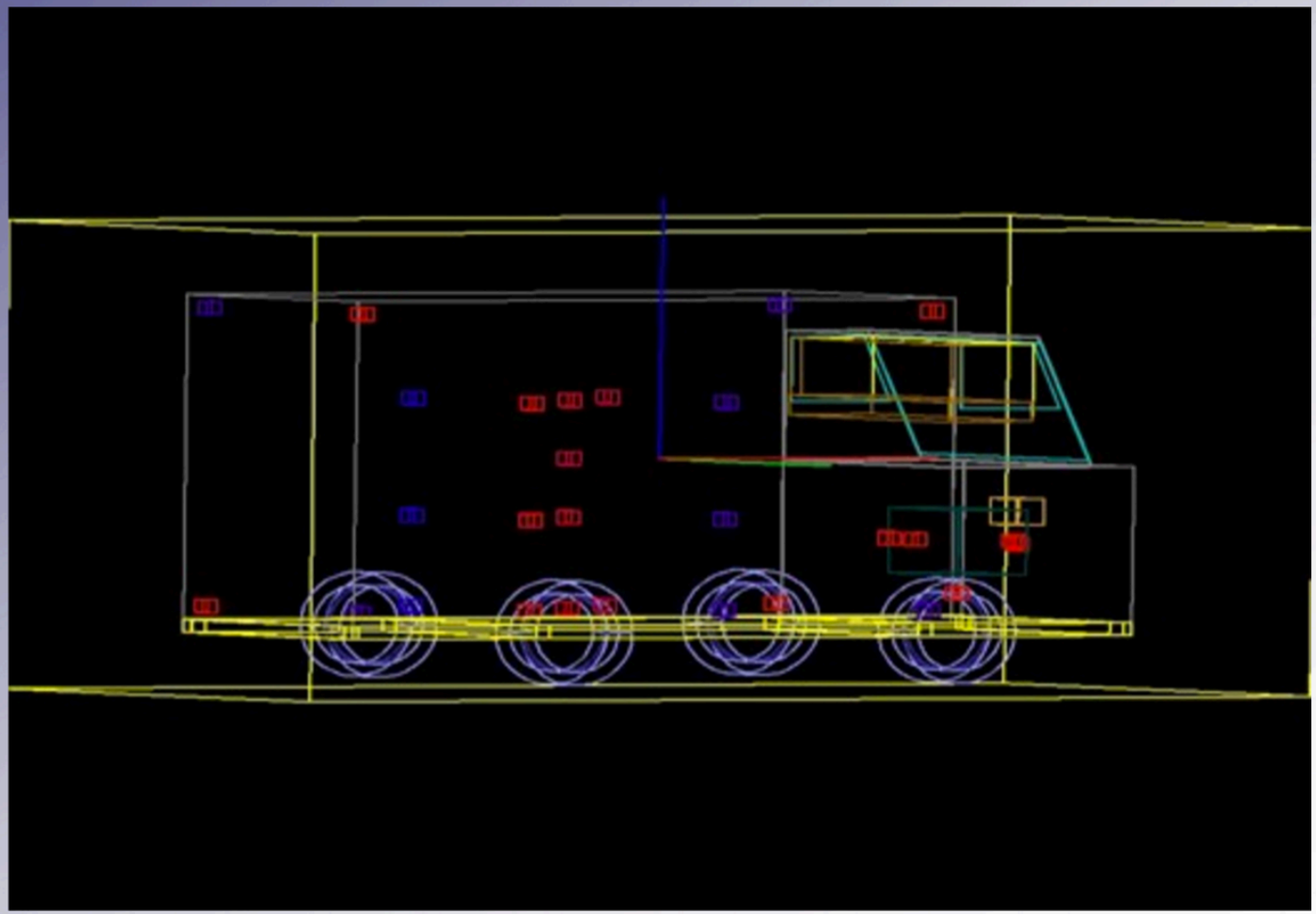
Muon tomography for nuclear threat detection



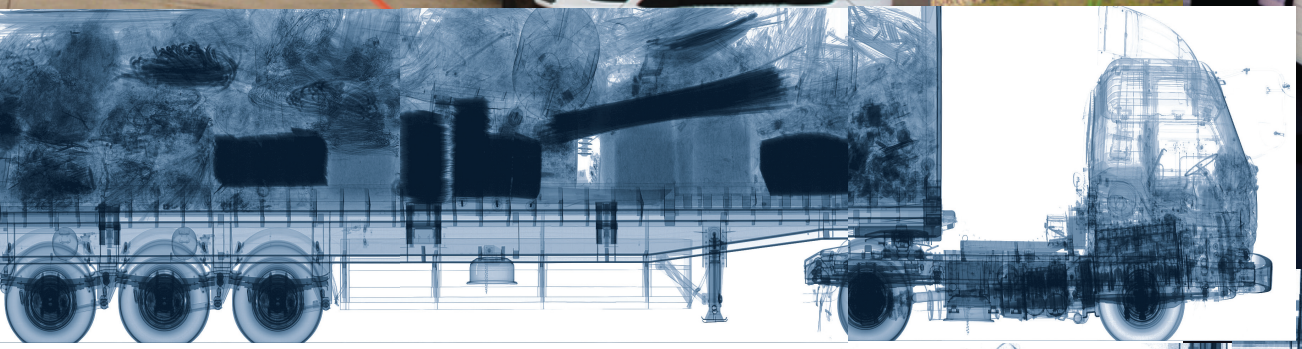
Muon tomography for nuclear threat detection

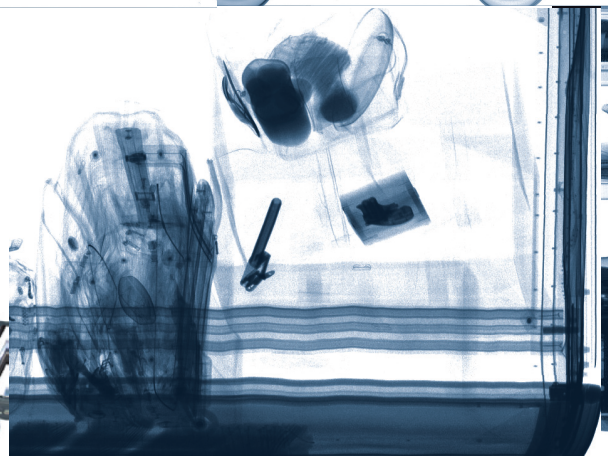


Simulated Truck
Red Boxes are Uranium
Blue are Lower Z Materials



Simulating x-ray cargo radiography





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Uncovering Special Nuclear Materials by Low-energy Nuclear Reac

P. B. Rose, A. S. Erickson ✉, M. Mayer, J. Nattress & I. Jovano

Scientific Reports **6**, Article number: 24388 (2016)
doi:10.1038/srep24388
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Applied physics | Imaging techniques

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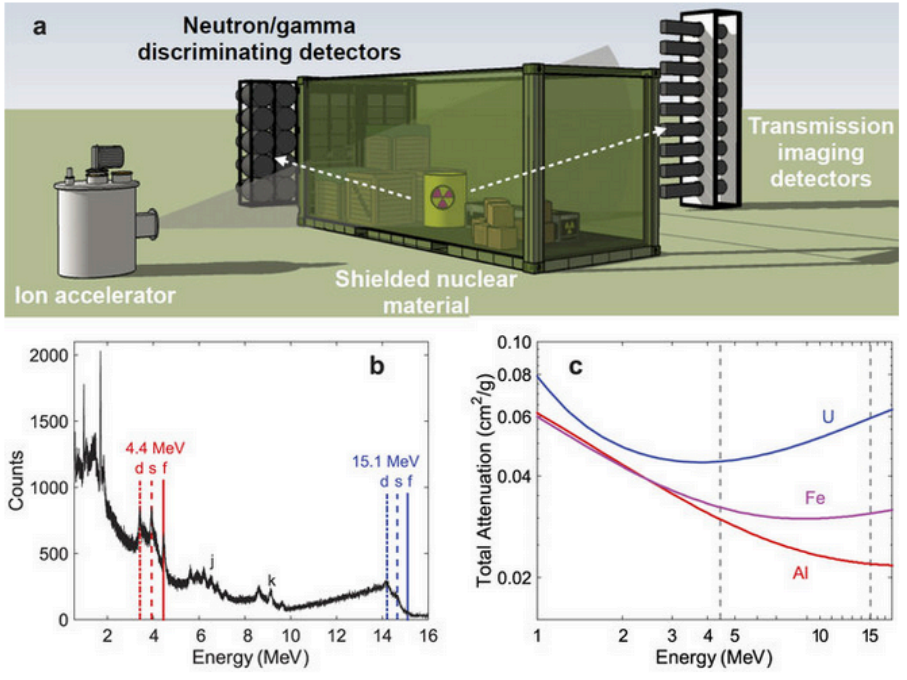
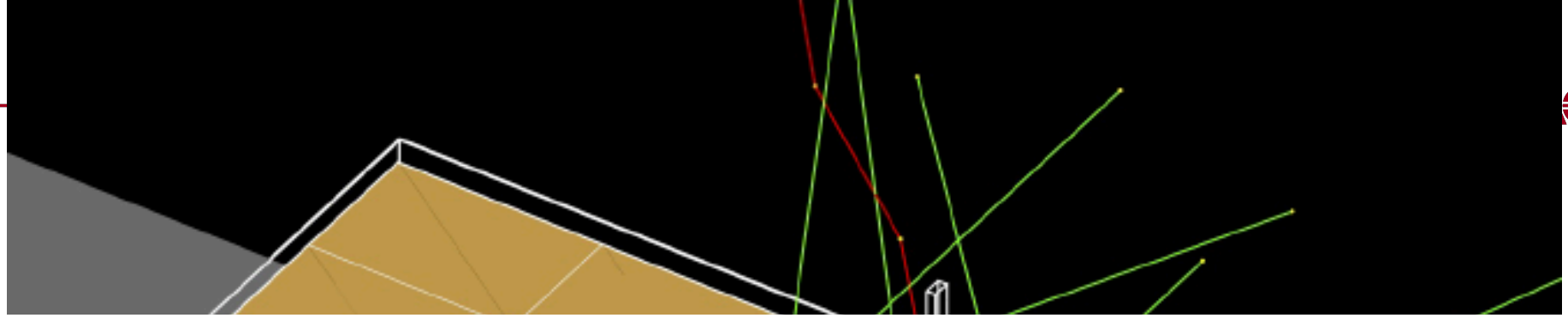
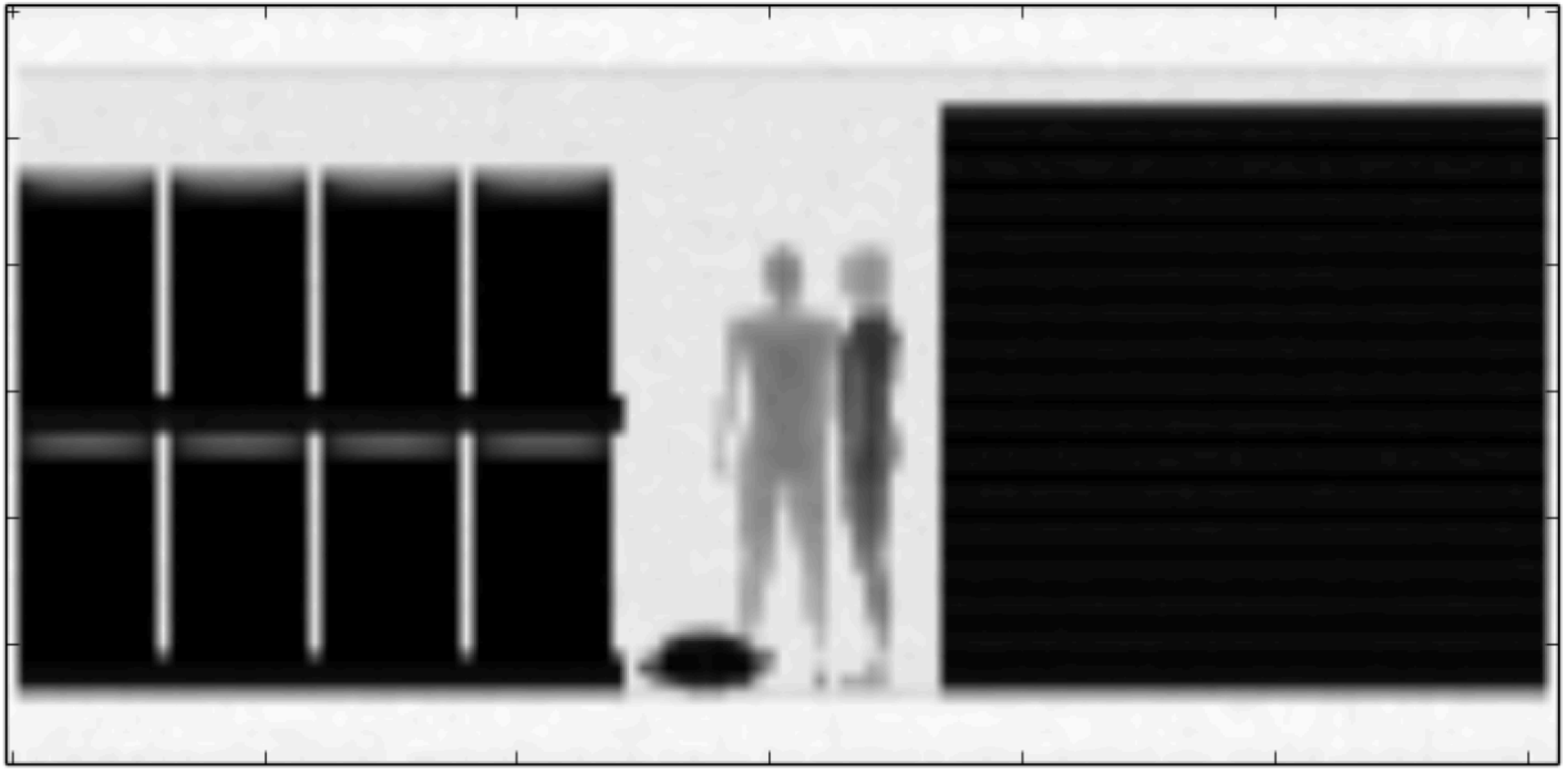
Figure 1: Illustration of the imaging method using a low-energy nuclear reaction radiation source.







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Postdoctoral position at the University of Alabama for work on EXO-200 and nEXO

University of Alabama - United States - Est. salary: $35,000 - $49,000 a year

The nuclear physics group at the University of Alabama invites applications for a postdoctoral position. The group plays a role in data analysis of the

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Postdoctoral Associate

Virginia Tech - Blacksburg, VA - Est. salary: $43,000 - $62,000 a year

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User demands / requirements are our driving force

- Geant4 has been evolved and its capability has been significantly extended in the past 20 years. They all are demanded / requested / motivated / inspired by our users.
  - Pre-packaged physics lists, cuts-per-region, low-energy EM physics, DNA physics and chemistry, parallel world, command-based scorers, various event biasing options, crystal structure, phonon, multithreading, to name just a few.
- Users demands are collected through lots of different communication channels.
  - HyperNews, requirement tracking system
  - Technical Forum and user workshops / tutorials
  - Emails, conferences, meetings
  - Direct involvement of G4 developers to experiments / user communities
  - Yearly work-plan is publicized to the users for their feedback.
    - http://geant4.cern.ch/support/planned_features.shtml
- We are learning NP requirements.
  - EIC Software Consortium
  - How about Technical Forum dedicated to NP?
  - Tutorial focused/emphasized on NP use-cases

Calorimetry for the High Energy Frontier

Lyon, France

2 - 6 October 2017

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- Important dates

Home

CHEF2017 is the second edition of the CHEF conferences series that started in 2013 with the goal to address the calorimeters at the energy frontiers in Physics. It also deals with the innovative concepts of calorimetry in nuclear, particles and astroparticles physics.

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E-mail address

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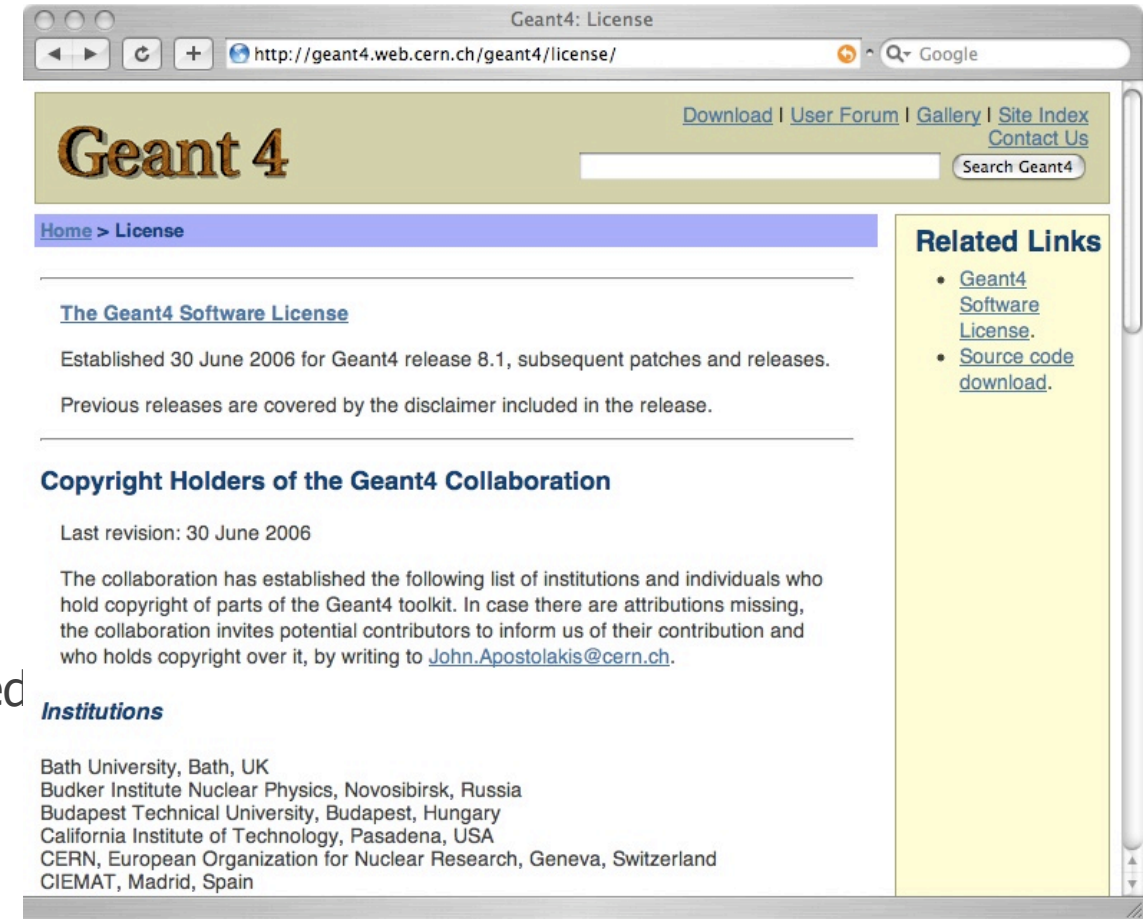
- Simple enough that you can read and understand it.

http://cern.ch/geant4/license/

Also available in the downloaded release code.



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Geant4 – Recent and on-going developments

Geant4 Software

Introduction

Geant4 is being used in many different fields where simulation of radiation passing through and interacting with matter is critical. User domains include: high energy and nuclear physics, medical physics and space engineering, shielding protection and more. Its abstract layers based on robust OO design enables flexibility and extendibility of the code, and its open-source code and open collaboration have allowed substantial extensions of the code. New features are constantly added to the code, while increasing attention is paid to improving software performance and robustness by employing cutting-edge software engineering technologies.

New physics

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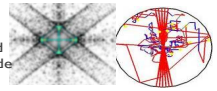
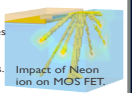


SuperCDMS Cryogenic Dark Matter Search seeks to directly detect dark matter. Geant4 models the caustic pattern in a Ge crystal (left) by tracking individual phonons (right)

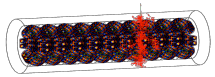
Reaction	Reaction rate (10^{10} M^{-1} s^{-1})
$H^{\bullet} + e^{-}_{aq} + H_2O \rightarrow OH^{-} + H_2$	2.65
$H^{\bullet} + {}^{\bullet}OH \rightarrow H_2O$	1.44
$H^{\bullet} + H^{\bullet} \rightarrow H_2$	1.20
$H_2 + {}^{\bullet}OH \rightarrow H^{\bullet} + H_2O$	4.17×10^{-3}
$H_2O_2 + e^{-}_{aq} \rightarrow OH^{-} + {}^{\bullet}OH$	1.41
$H_2O^{+} + e^{-}_{aq} \rightarrow H^{\bullet} + H_2O$	2.11
$H_2O^{+} + OH^{-} \rightarrow 2\,H_2O$	14.3
${}^{\bullet}OH + e^{-}_{aq} \rightarrow OH^{-}$	2.95
${}^{\bullet}OH + {}^{\bullet}OH \rightarrow H_2O_2$	0.44
$e^{-}_{aq} + e^{-}_{aq} + 2\,H_2O \rightarrow 2\,OH^{-} + H_2$	0.50

Reactions of radicals available in Geant4.

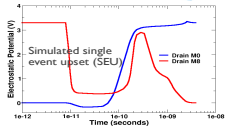
Geant4 performs mission critical studies of radiation and charging effects on spacecraft electronics.



Impact of Neon ion on MOS FET

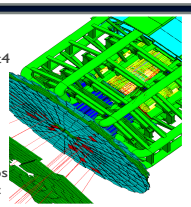


Energy depositions in DNA structure.



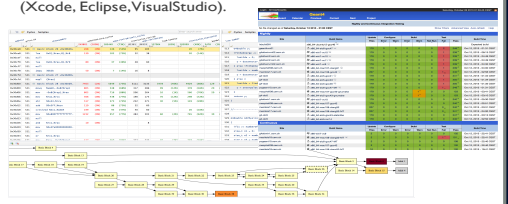
Geometry

The flexibility and extendibility of Geant4 design also enables handling rich collection of shapes including CSG (Constructed Solid Geometry), BREP (Boundary REPresented), Boolean operation, Tessellated solid, etc. and the user can easily add new shapes. Geant4 geometry navigation can deal with setups up to billions of volumes with automatic optimization. In addition, geometry models can be 'dynamic', i.e. changing the setup at run-time, e.g. "moving objects".



Software quality assurance

Geant4 uses modern tools to manage the code and improve code quality: from handling issues with JIRA to continuous testing integration with CTest/CDash, profiler based optimizations, Quality/Assurance (Coverity, Valgrind, etc.), and IDE integration (Xcode, Eclipse, VisualStudio).



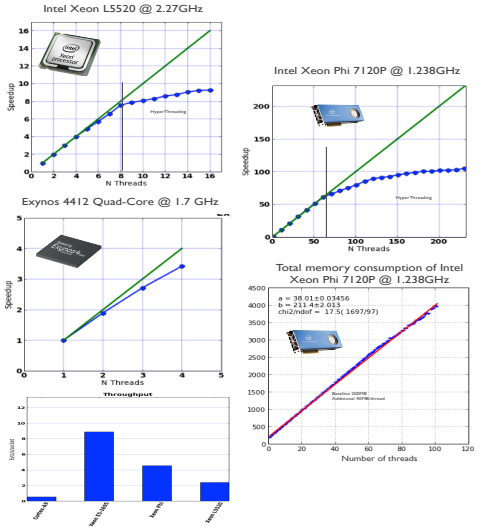
New era - Geant4 version 10 series

The next release of Geant4 – Version 10.0 (December 2013) will include event-level parallelism via multi-threading. To efficiently use new computing architectures the workload of a single job will be sub-divided to many worker threads each responsible for the simulation of one or more events. Current beta release has already shown good scalability on a number of different architectures: Intel Xeon servers, Intel Xeon Phi co-processors and low-power ARM processors

- Proof of principle
- Identify objects to be shared
- First testing
- API re-design
- Example migration
- Further testing
- First optimizations
- Further refinements

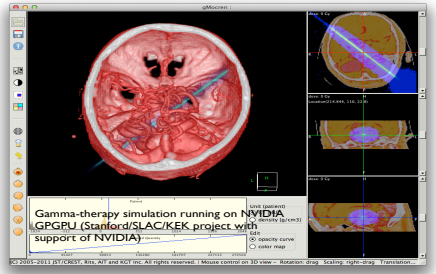
G4MT prototype-9.4 (2011) → G4MT prototype-9.5 (2012) → G4 10.0.beta (current) → G4 10.0 (Dec. 2013) → G4 10 series (2014~)

- MT code integrated into G4
- Production ready
- Public release



Investments for the future

Geant4 collaboration members are participating in various explorations of emerging technologies. These technologies include GPU/CUDA, OpenCL, OpenACC, vectorization, DSL, etc.



Geant4 version 10 series

- The release in 2013 was a major release.
  - Geant4 version 10 – release date : Dec. 6, 2013
- The highlight is its multi-threading capability.
  - The world first large-scale physics software fully multithreaded
- Geant4 version 10 series will be evolving.
  - Performance improvements (both in physics and computing)
  - Missing functionalities yet to be migrated to multithreading,
  - Additional APIs
  - Additional functionalities
  - New physics

- Proof of principle
- Identify objects to be shared
- First testing

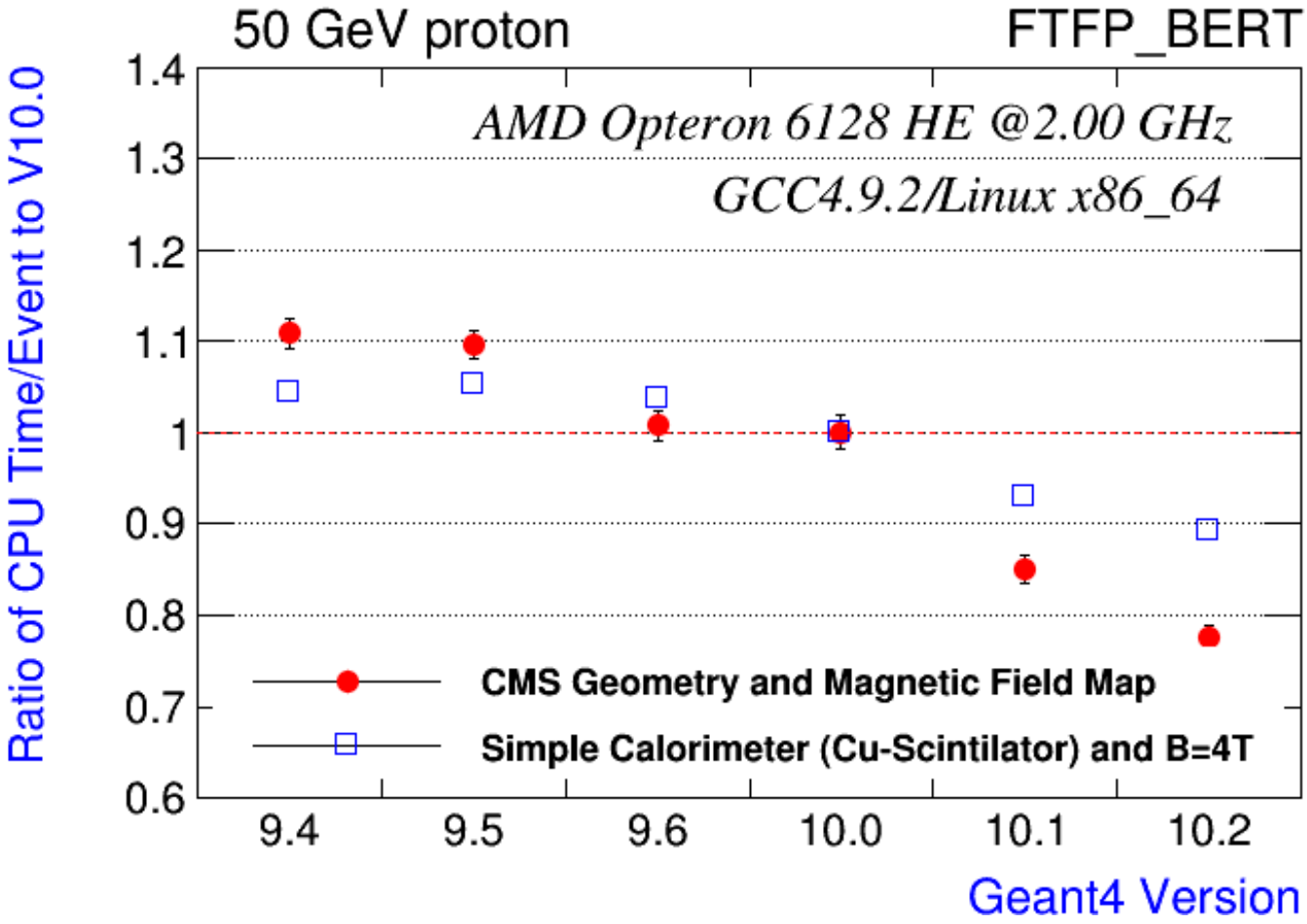
- MT code integrated into G4

- API re-design
- Example migration
- Further testing
- First optimizations

- Production ready
- Public release

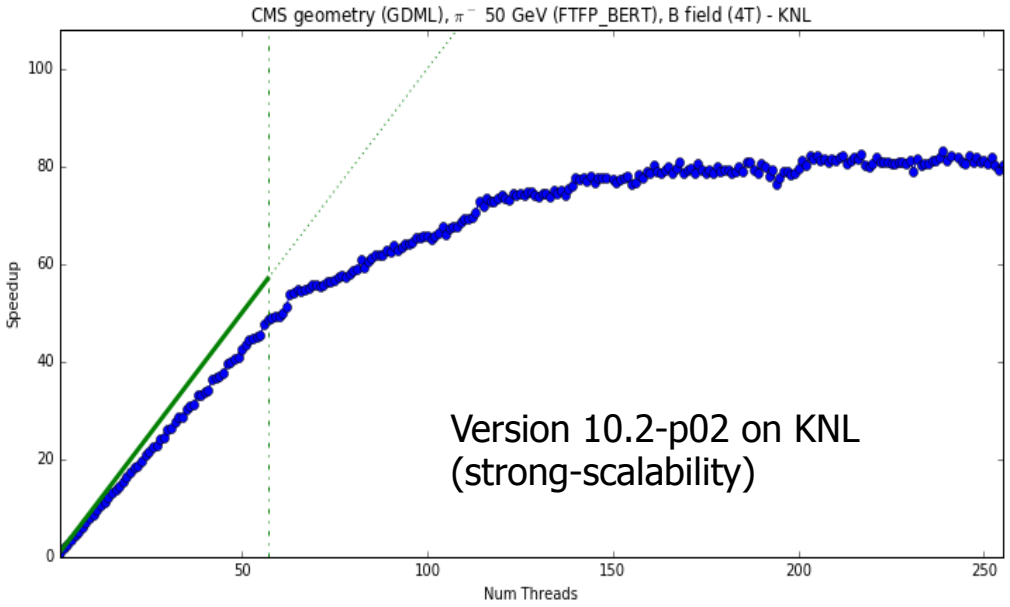
- Further refinements

We are making it faster!



ATLAS : "The 10% CPU improvement we gain from the move from G4 9.6 to 10.1 is invaluable to the collaboration."

Many core, many thread



- For three years we have provided support for running Geant4 on KNC.
  - ATLAS, CMS successfully multithreaded
- We will soon extend our support to KNL.
  - With KNL, thanks to x86 binary compatibility including the use of gcc, work-flow is tremendously simplified.

System	Time to completion (5k events)
Xeon E5-2620 @ 2.1 GHz (12 cores, 24 threads)	570 s
KNC (31s1P) @ 1.0 GHz (228 threads)	1000 s
KNL (7210, quadrant mode, MCDRAM only) @ 1.3 GHz (255 threads)	378 s (x3 improvement w.r.t. KNC)
KNL (shared library)	480 s (25% slower than static library)

More memory-efficient, more HPC friendly

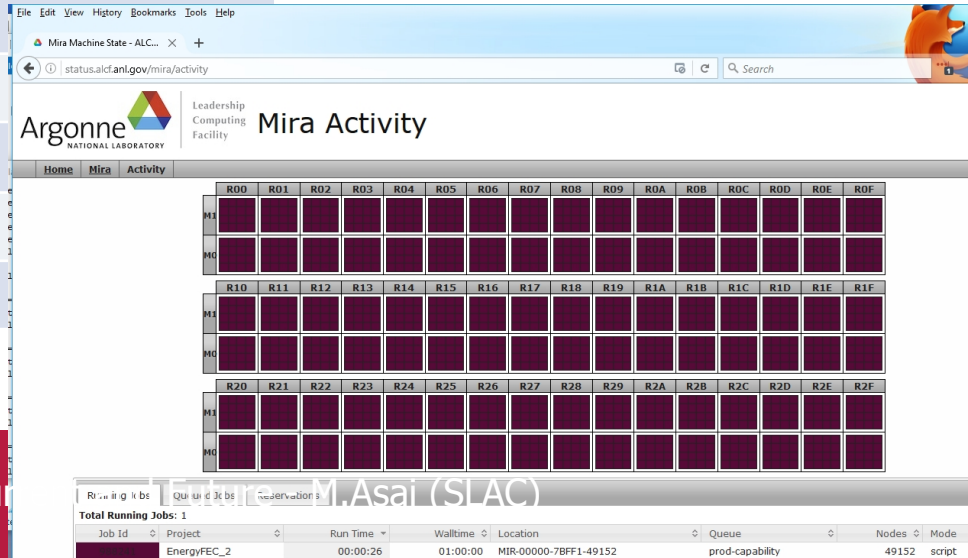
Version	Intercept	Memory/thread
9.6 (seq.)	113 MB	(113 MB)
10.0.p02-seq	170 MB	(170 MB)
10.0.p02-MT	151 MB	28 MB
10.3.beta-MT	148 MB	9 MB

Memory space required for Intel Xeon Phi 3120A
Full-CMS geometry (GDML), 4 Tesla field, 50 GeV pi- (FTFP_BERT)

# of CPU	# of threads	Speed-up factor	efficiency
10	80	79	98. 8%
20	160	158	98. 8%
40	320	317	99. 0%
80	640	626	97. 8%
160	1280	1251	97. 7%
320	2560	2297	89. 7%
640	5120	3555	69. 4%

Tachyon-2 supercomputer @ KISTI (South Korea)
FTFP_BERT physics validation benchmark

- Geant4 has successfully run with a combination of MT and MPI on Mira Bluegene/Q Supercomputer (@ANL) with all of its 3 million threads
  - Full-CMS geometry & field
- I/O is the limiting factor to scale large concurrent threads:
  - Granular input data files, output data/histograms, etc.
  - 2017 work item
  - Targeting also Cori @ NERSC



Geant4
– Future and opportunities

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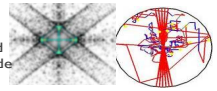
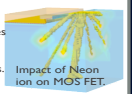


SuperCDMS Cryogenic Dark Matter Search seeks to directly detect dark matter. Geant4 models the caustic pattern in a Ge crystal (left) by tracking individual phonons (right)

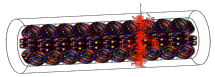
Reaction	Reaction rate (10^{10} M^{-1} s^{-1})
$H^{\bullet} + e^{-}_{aq} + H_2O \rightarrow OH^{-} + H_2$	2.65
$H^{\bullet} + {}^{\bullet}OH \rightarrow H_2O$	1.44
$H^{\bullet} + H^{\bullet} \rightarrow H_2$	1.20
$H_3^+ + {}^{\bullet}OH \rightarrow H^{\bullet} + H_2O$	4.17×10^{-3}
$H_2O_2 + e^{-}_{aq} \rightarrow OH^{-} + {}^{\bullet}OH$	1.41
$H_2O^+ + e^{-}_{aq} \rightarrow H^{\bullet} + H_2O$	2.11
$H_2O^+ + OH^{-} \rightarrow 2\,H_2O$	14.3
${}^{\bullet}OH + e^{-}_{aq} \rightarrow OH^{-}$	2.95
${}^{\bullet}OH + {}^{\bullet}OH \rightarrow H_2O_2$	0.44
$e^{-}_{aq} + e^{-}_{aq} + 2\,H_2O \rightarrow 2\,OH^{-} + H_2$	0.50

Reactions of radicals available in Geant4.

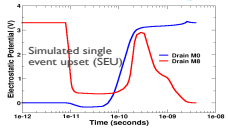
Geant4 performs mission critical studies of radiation and charging effects on spacecraft electronics.



Impact of Neon ion on MOS FET

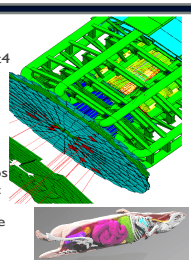


Energy depositions in DNA structure.



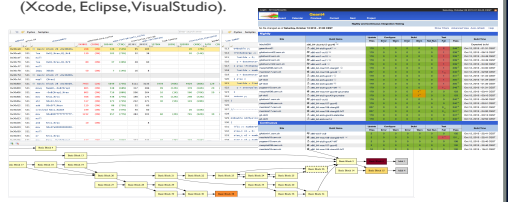
Geometry

The flexibility and extendibility of Geant4 design also enables handling rich collection of shapes including CSG (Constructed Solid Geometry), BREP (Boundary REPresented), Boolean operation, Tessellated solid, etc. and the user can easily add new shapes. Geant4 geometry navigation can deal with setups up to billions of volumes with automatic optimization. In addition, geometry models can be 'dynamic', i.e. changing the setup at run-time, e.g. "moving objects".



Software quality assurance

Geant4 uses modern tools to manage the code and improve code quality: from handling issues with JIRA to continuous testing integration with CTest/CDash, profiler based optimizations, **Quality/Assurance (Coverity, Valgrind, etc.)**, and IDE integration (Xcode, Eclipse, VisualStudio).



New era - Geant4 version 10 series

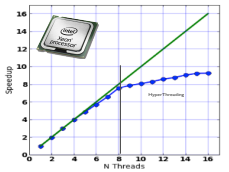
The next release of Geant4 – Version 10.0 (December 2013) will include event-level parallelism via multi-threading. To efficiently use new computing architectures the workload of a single job will be sub-divided to many worker threads each responsible for the simulation of one or more events. Current beta release has already shown good scalability on a number of different architectures: Intel Xeon servers, Intel Xeon Phi co-processors and low-power ARM processors

- Proof of principle
- Identify objects to be shared
- First testing
- API re-design
- Example migration
- Further testing
- First optimizations
- Further refinements

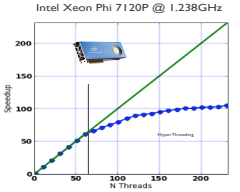
G4MT prototype-9.4 (2011) → G4MT prototype-9.5 (2012) → G4 10.0.beta (current) → G4 10.0 (Dec. 2013) → G4 10 series (2014~)

- MT code integrated into G4
- Production ready
- Public release

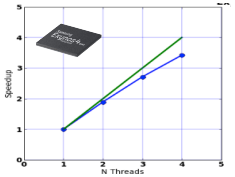
Intel Xeon L5520 @ 2.27GHz



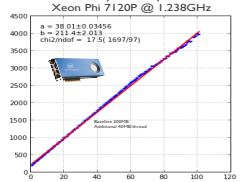
Intel Xeon Phi 7120P @ 1.238GHz



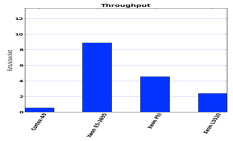
Exynos 4412 Quad-Core @ 1.7 GHz



Total memory consumption of Intel Xeon Phi 7120P @ 1.238GHz

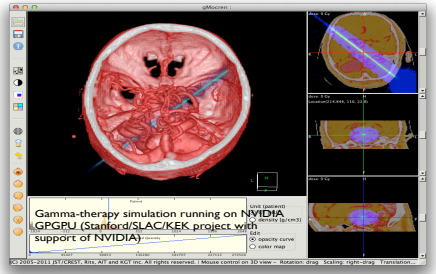


Throughput



Investments for the future

Geant4 collaboration members are participating in various explorations of emerging technologies. These technologies include GPU/CUDA, OpenCL, OpenACC, vectorization, DSL, etc.



New physics – new opportunities

- Physics of O(100TeV)
- Neutrino interactions
  - Should come with enriched event biasing options
- Electron/hole drift in semiconductor
- More phonon physics
- Channeling effects and physics with crystal structure in general
  - X-ray diffraction
- Single atom irradiation
- Target material polarization
- Chemical reactions of radicals in DNA-scale
- New domains ?

- Note : Geant4 kernel is robust enough over 20 years of evolution. This stability enables risk-free extensions to new physics.

New computing trends

- HPC and cloud friendliness
  - Combining MPI and MT
  - Smart data collection from millions of threads
- Code re-engineering
  - Geant Vector Prototype (Geant-V) project
    - VecGeom solid library, EM physics
  - Splitting transportation process
- GPU as a co-processor
  - Off-loading some calculations to GPU, e.g. EM physics, thermal neutron physics, DNA physics and chemical processes, etc.

- Will be integrated into Geant4 with (hopefully) minimum API changes

To sum up

- Geant4 is a general purpose Monte Carlo simulation tool for elementary particles passing through and interacting with matter. It finds quite a wide variety of user domains including high energy and nuclear physics, space engineering, medical applications, material science, radiation protection and security.
- After 20 years with several architectural evolutions, Geant4 is still steadily evolving.
  - Latest evolution was Geant4 version 10.0 released in December 2013 that is the first fully multithreaded large-scale physics software in the world.
- Given Geant4 is nowadays mission-critical for many users including all LHC experiments, space missions, medical applications, etc., Geant4 is to be kept maintained and still evolving for at least next decade.
- User's demands / requirements are our driving force.
  - May the Force be with Geant4!