Geant 4

Version 10.1-p01

Kernel I

Makoto Asai (SLAC)

Geant4 Tutorial Course

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- Geant4 kernel
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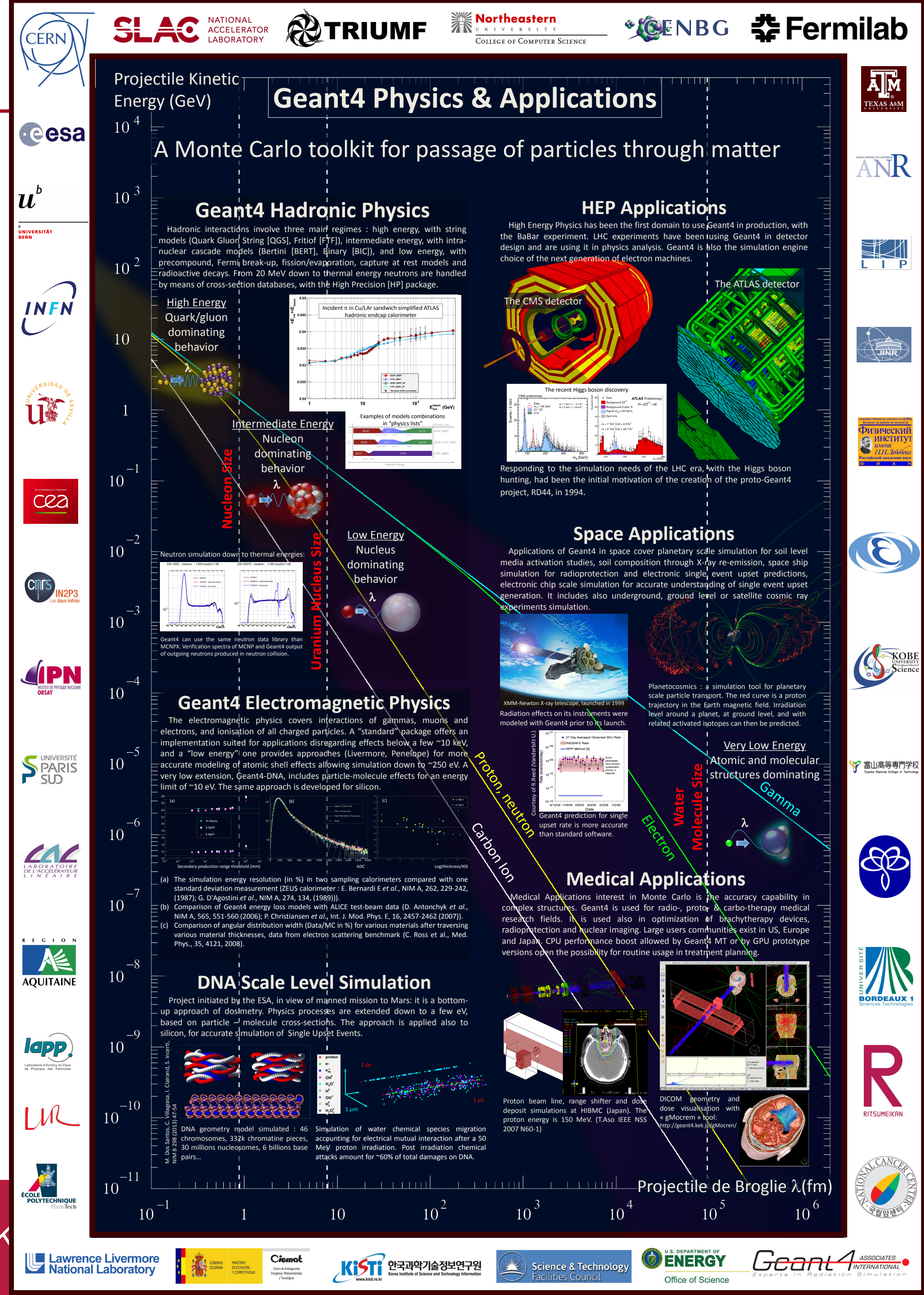


Geant 4

Version 10.1-p01

General introduction and brief history

Geant4

- 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.
- In order to meet wide variety of requirements from various application fields, a large degree of functionality and flexibility are provided.
- Geant4 has many types of geometrical descriptions to describe most complicated and realistic geometries
  - CSG, Tessellated and Boolean solids
  - Placement, replica, divided, parameterized, reflected and grouped
  - XML/GDML/CAD interfaces
- Everything is open to the user
  - Choice of physics processes/models
  - Choice of GUI/Visualization/persistency/histogramming options

Physics in Geant4

- It is rather unrealistic to develop a uniform physics model to cover wide variety of particles and/or wide energy range.
- Much wider coverage of physics comes from mixture of theory-driven, parameterized, and empirical formulae. Thanks to polymorphism mechanism, both cross-sections and models (final state generation) can be combined in arbitrary manners into one particular process.
- Geant4 offers
  - EM processes
  - Hadronic processes
  - Photon/lepton-hadron processes
  - Optical photon processes
  - Decay processes
  - Shower parameterization
  - Event biasing techniques
  - And you can plug-in more

Physics in Geant4

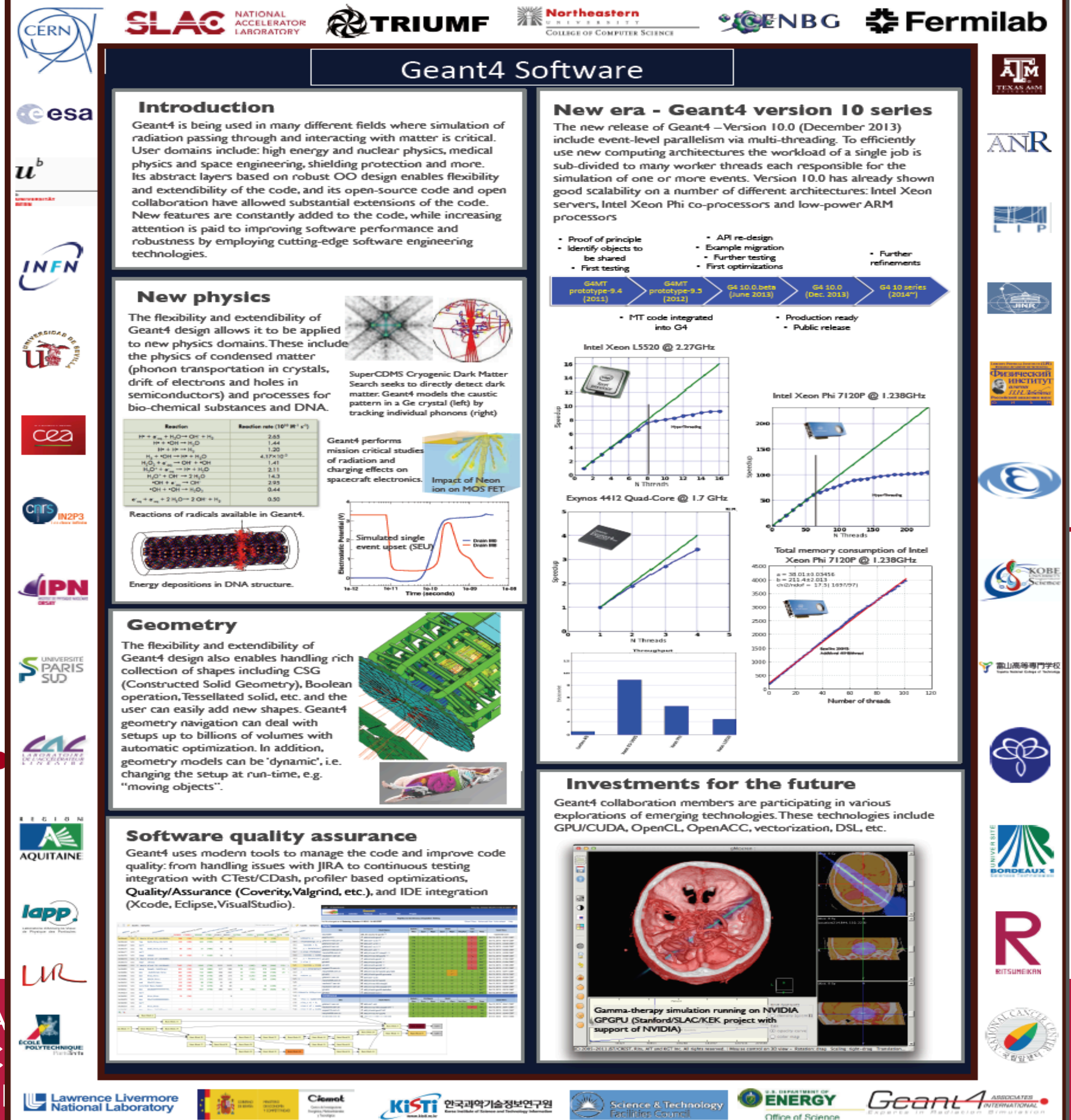
- Each cross-section table or physics model (final state generation) has its own applicable energy range. Combining more than one tables / models, one physics process can have enough coverage of energy range for wide variety of simulation applications.
- Geant4 provides sets of alternative physics models so that the user can freely choose appropriate models according to the type of his/her application.
  – In other words, it is the user's responsibility to choose reasonable set of physics processes/models that fits to his/her needs.
  – For example, some models are more accurate than others at a sacrifice of speed.
- Primarily, the user's task is choosing a "pre-packaged" physics list, that combines physics processes and models that are relevant to a typical application use-cases.
  – If "pre-packaged" physics lists do not meet your needs, you may add or alternate some processes/models.

Geant4 – Its history

- Dec '94 - Project start
- Apr '97 - First alpha release
- Jul '98 - First beta release
- Dec '98 - First Geant4 public release - version 1.0
- …
- Nov 30th, '12 – Geant4 version 9.6 release
  - Feb 4th, '15 - Geant4 9.6-patch04 release ← Retroactive patch release
- Dec 6th, '13 – Geant4 version 10.0 release
  - Mar 6th, '15 - Geant4 10.0-patch04 release ← Retroactive patch release
- Dec 5th, '14 – Geant4 version 10.1 release
  - Apr 1st, '15 - Geant4 10.1-patch01 release ← Current version

- We currently provide one public release every year.
  - Beta releases are also available.
  - Release announcements on Collaboration Web pages and through the announcement mailing list

What’s new in Geant4 version 10



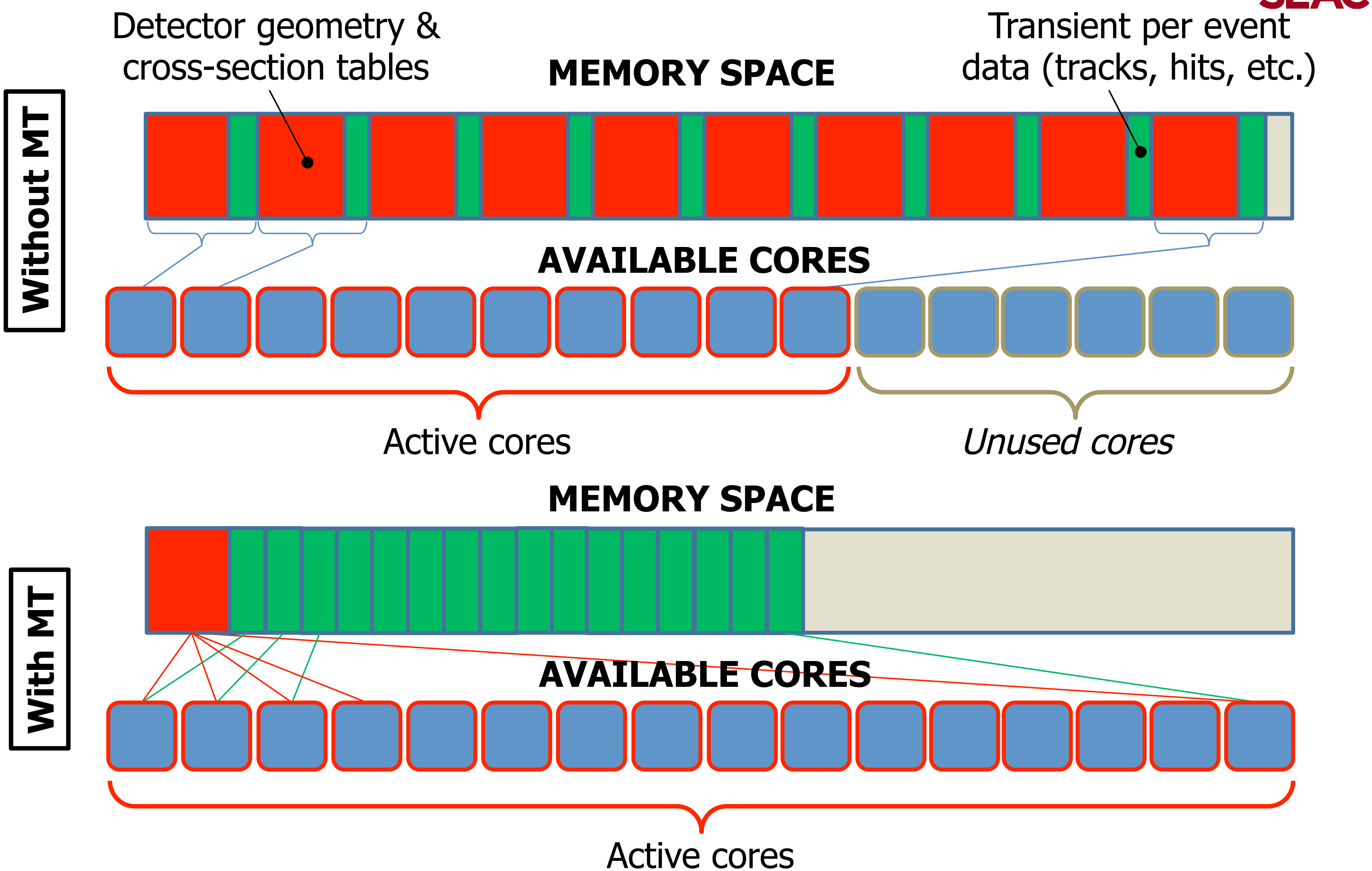
Geant4 Version 10 Series

- Major release Geant4 version 10.0 was released on December 6th, 2013.
  - The first major release since June 2007.
- There are several highlighted features including
  - Multithreading capability with event parallelism
  - Isomer production
  - Enhancements in biasing options
  - Introduction of phonon transport with a new concept of crystal
  - Support for GNUmake and LHEP and CHIPS physics models are ceased
- Version 10.1 released on December 5th, 2014 has lots of improvements in both physics and computing aspects.
- Release of version 10.2 is scheduled on December 4th, 2015

G4MT prototype-9.4 (2011)	G4MT prototype-9.5 (2012)	G4 10.0 (2013)	G4 10.1 (2014)	G4 10 series (2015~)
• Proof of principle • Identify objects to be shared • First testing	• MT code integrated into G4	• Production ready • Public release	• Memory reduction • First optimizations	• Further refinements

Geant4 version 10 series

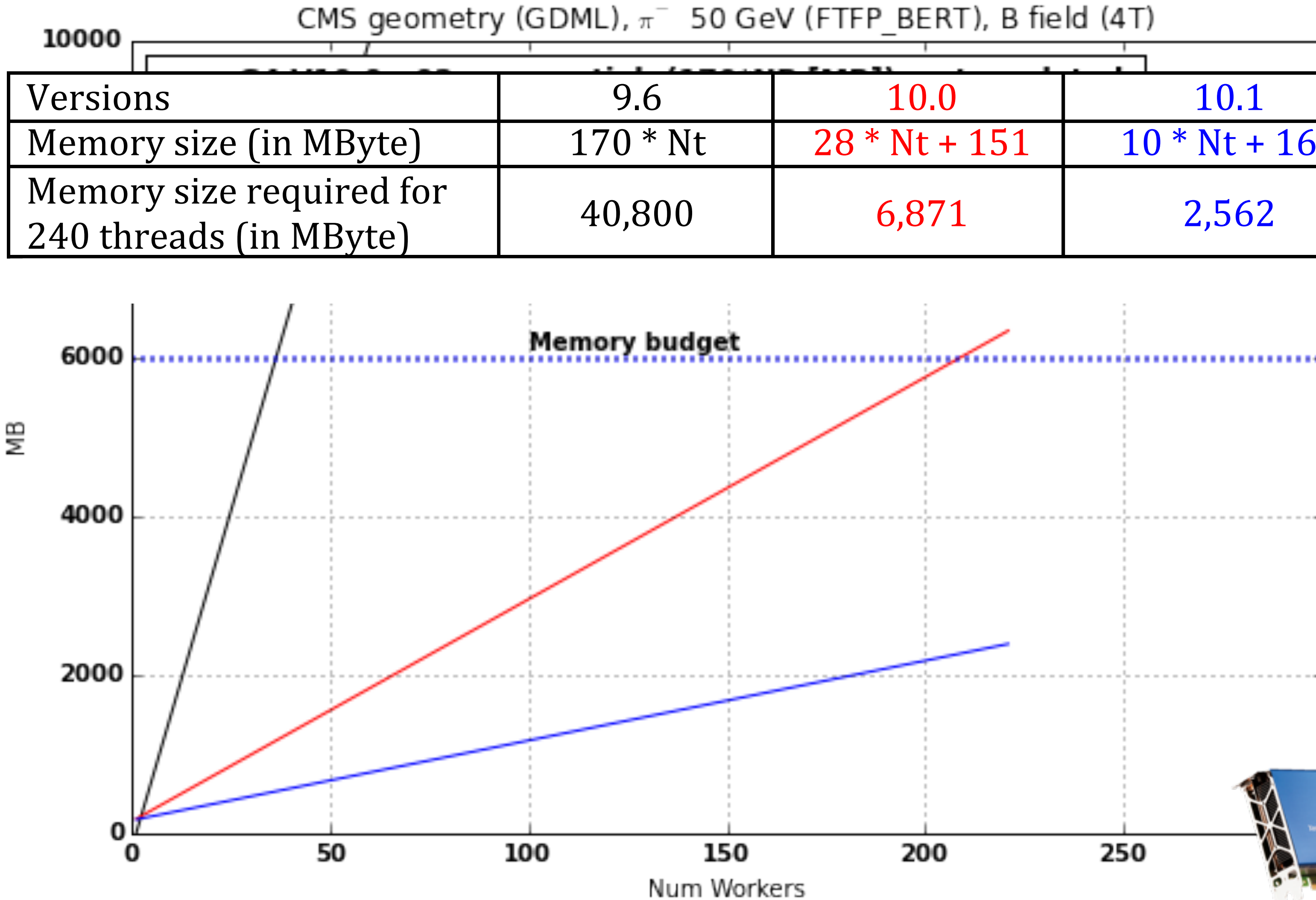
- Major release of version 10.0 was made on December 6th, 2013.
- One of the highlights of 10 series is its Multithreading capability.
  - Event-level parallelism with memory sharing over threads
  - Geant4 became the first HEP general-purpose software to be fully multithreaded
- 10.0 also included other developments, in particular:
  - Introduction of isomers
  - Alternative low energy neutron model G4LEND
    - Direct interface to GIDI (General Interaction Data Interface)
  - Consolidation of MSC in Electromagnetic physics
  - Decommission of obsolete physics models such as LHEP
  - Extension of event biasing capability to allow process occurrence and final state production biasing
  - Introduction of phonon transport with a new concept of crystal
  - New GUI/Vis built on Qt
    - Note: All these features are available with or without multithreading.
- Next release
  - 10.2 : December 4th, 2015 (planned)



Detector geometry & cross-section tables
MEMORY SPACE
Transient per event data (tracks, hits, etc.)
Without MT
AVAILABLE CORES
Active cores
Unused cores
MEMORY SPACE
With MT
AVAILABLE CORES
Active cores

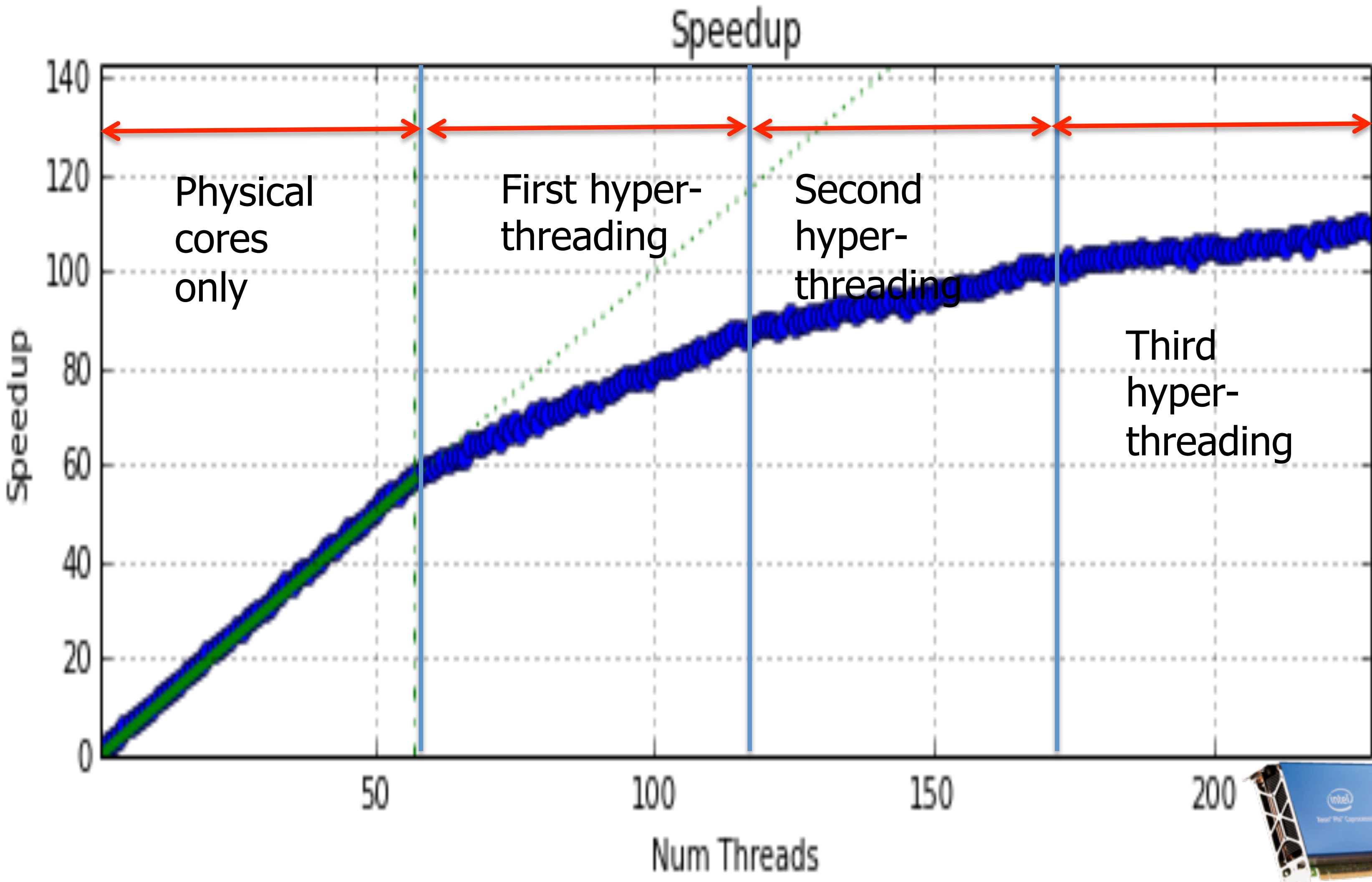
Memory consumption on Intel Xeon Phi

Versions	9.6	10.0	10.1
Memory size (in MByte)	170 * Nt	28 * Nt + 151	10 * Nt + 162
Memory size required for 240 threads (in MByte)	40,800	6,871	2,562



Intel Xeon Phi™ 3120A

Scalability on Intel Xeon Phi



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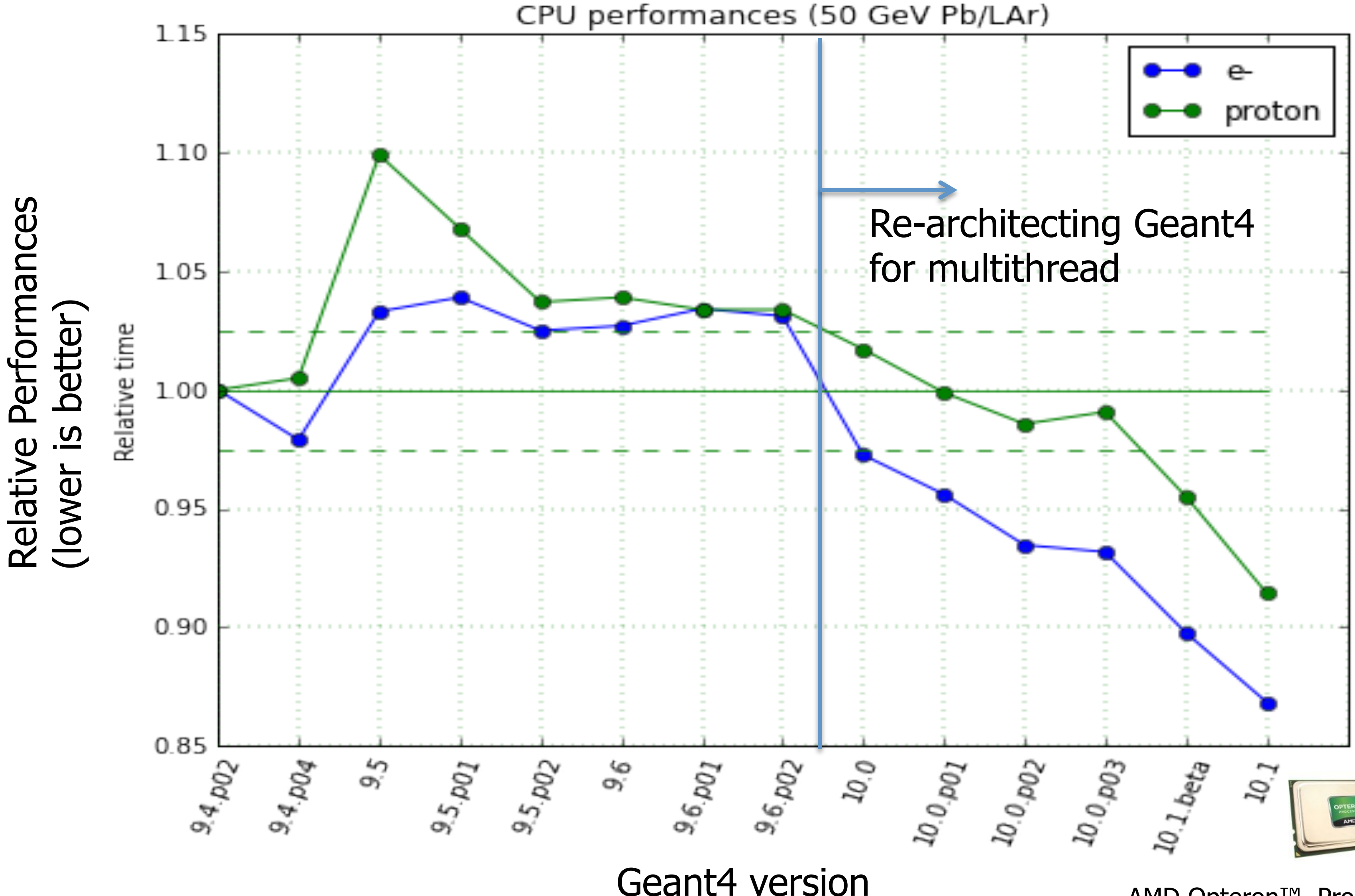
Throughput in sequential mode



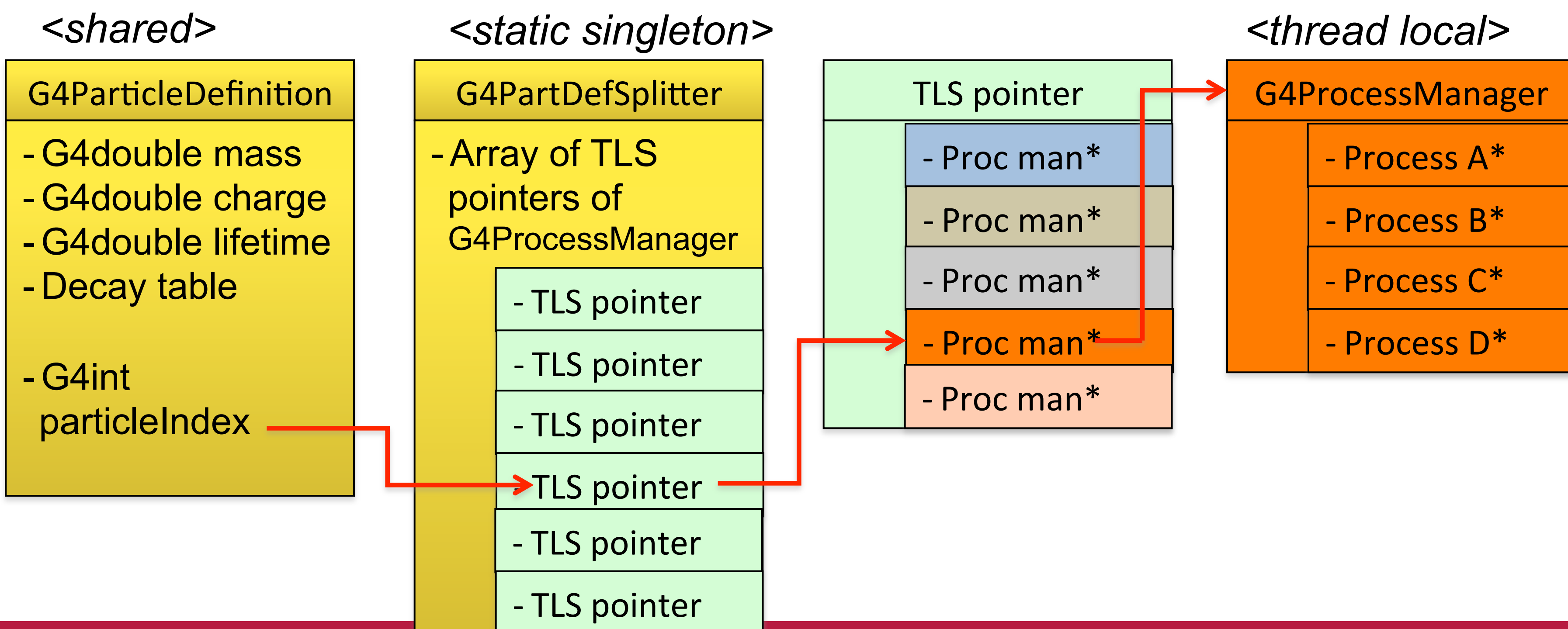
AMD Opteron™ Processor 6128

Geant4 multi-threading : event-level parallelism

- This choice minimizes the changes in user-code
  - Maintain API changes at minimum
- All Geant4 code has been made thread-safe.
  - Thread-safety implemented via Thread Local Storage
- Most memory-consuming parts of the code (geometry, physics tables) are shared over threads.
  - "Split-class" mechanism: reduce memory consumption
    - Read-only part of most memory consuming classes are shared
    - Enabling threads to write to thread-local part
- Particular attention to create "lock-free" code: linearity (w.r.t. #threads) is the metrics we are concentrating on for the v10.0 release.

Split class – case of particle definition

- In Geant4, each particle type has its own dedicated object of G4ParticleDefinition class.
  - Static quantities : mass, charge, life time, decay channels, etc.,
    - To be shared by all threads.
  - Dedicated object of G4ProcessManager : list of physics processes this particular kind of particle undertakes.
    - Physics process object must be thread-local.



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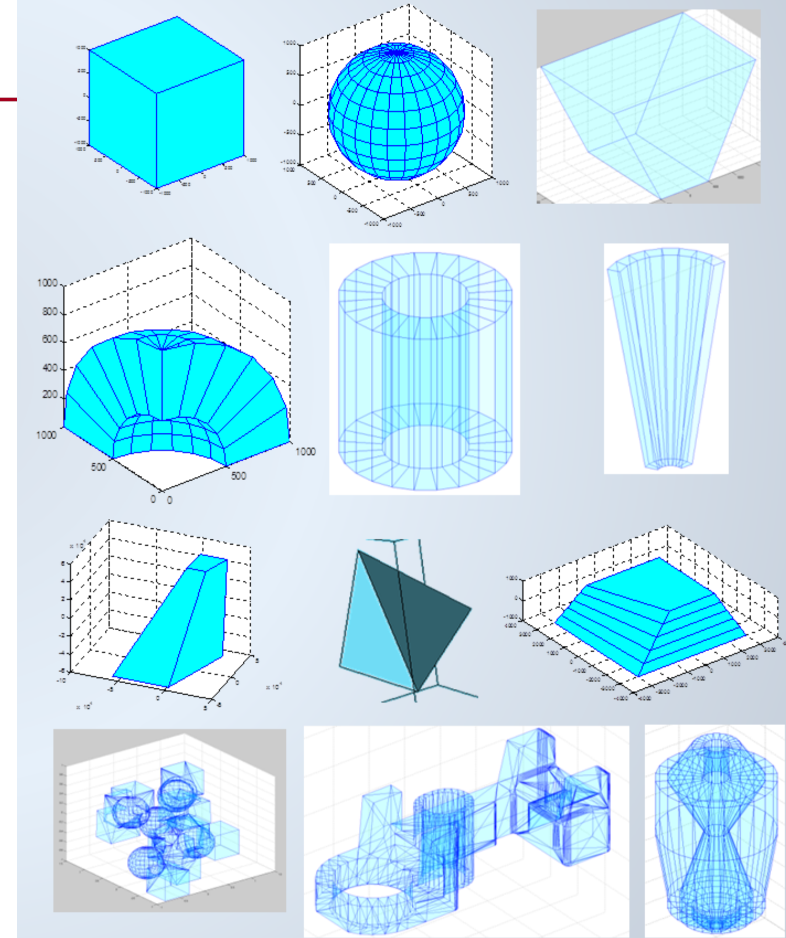
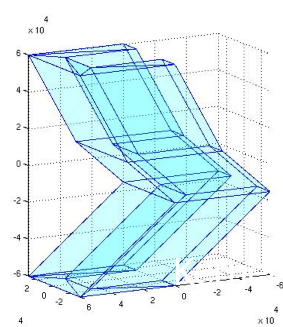
User's code migration

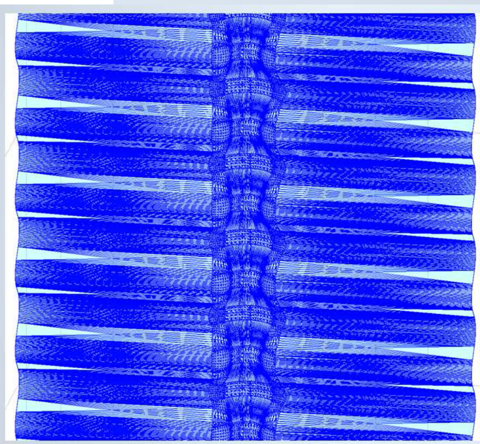
- If you have a running code with version 9.6 and you want to stick to sequential mode, you do not need to migrate. It should run with version 10.0.
  - Except for a few obsolete interfaces that you had already seen warning messages in v9.6.
- Migration of user's code to multi-threading mode of Geant4 version 10.0 should be fairly easy and straightforward.
  - Migration guide is available.
  - Geant4 users guides are updated with multi-threading features.
  - Many examples have been migrated to multi-threading.
  - Geant4 tutorials based on version 10.0 has already started.
- G4MTRunManager collects run objects from worker threads and "reduces".
- Toughest part of the migration is making user's code thread-safe.
  - It is always a good idea to clearly identify which class objects are thread-local.
- Every file I/O for local thread is a challenge
  - Input : primary events : examples are offered in the migration guide.
  - Output : event-by-event hits, trajectories, histograms

New features in geometry

- New command-based geometry overlap checks
  - Built-in check with random points on surfaces
  - Resolution and tolerance are tunable
- Introduction of gravity field and magnetic field gradient
- Optional new AIDA Unified Solid library
  - Optimized implementation of a large number of primitives and constructs
  - For example, the time required to compute intersections with the tessellated solid was dramatically reduced.
- Several new shapes including extruded solid
- New multi-union structure
  - Replace multiple use of binary Boolean unions
  - Far better performance for combining more than O(10) unions





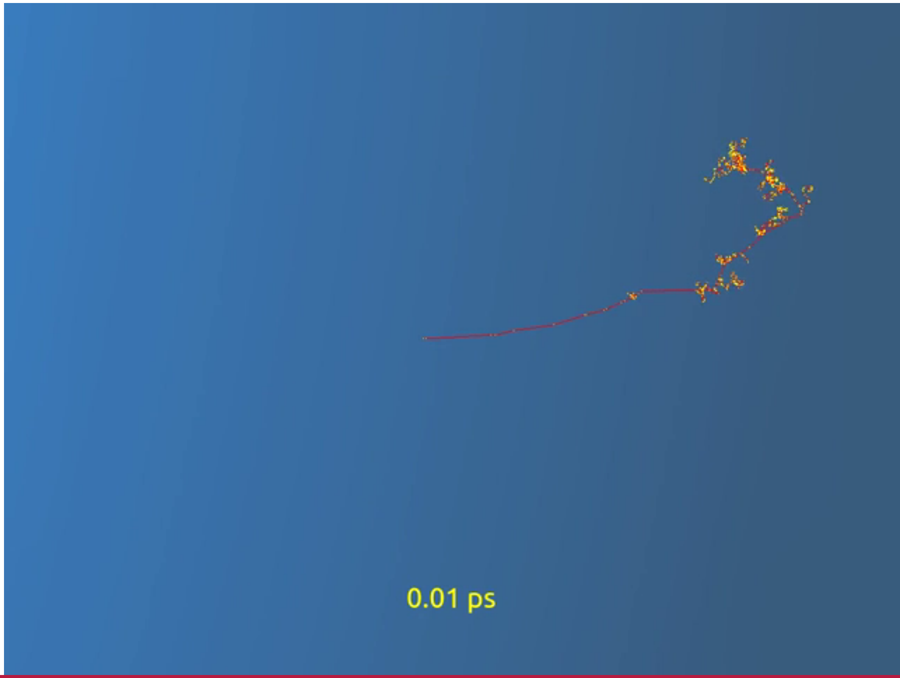


Method	Speedup
Inside	2423x
DistanceToIn	1334x
DistanceToOut	1976x

Information	Value
Number of facets	164.149
Number of voxels	100.000
Memory saved compared with original Geant4	22% (51MB)

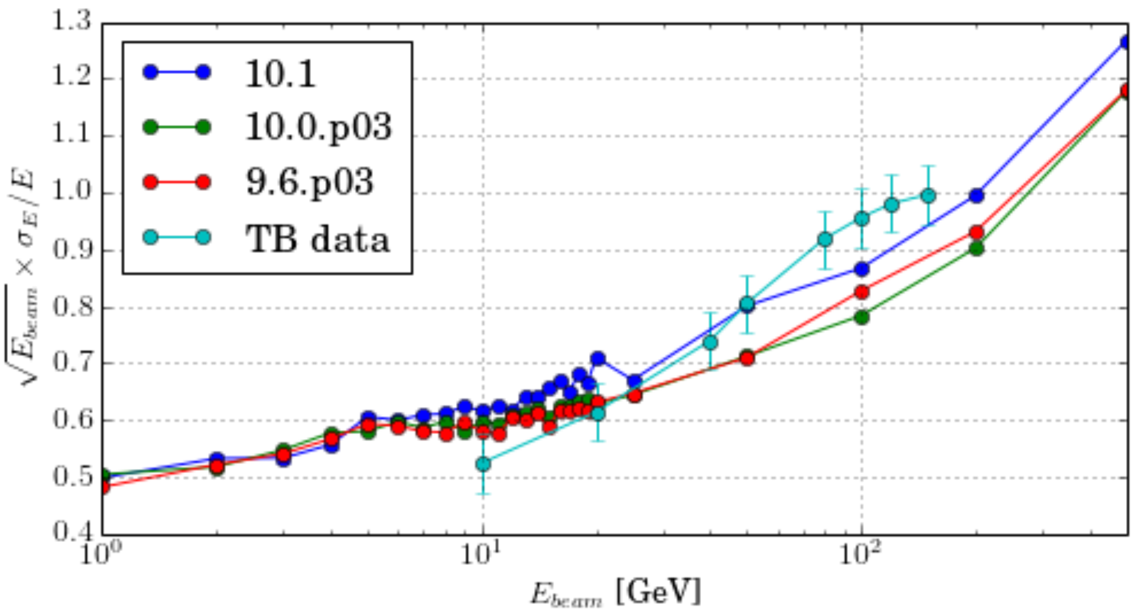
New features in EM physics

- Multiple/single scattering
  - Introduction of optional displacement on geometrical boundary
  - New G4LowEWenzalVIModel for low-energy applications
- Gamma processes
  - Photo-effect and Compton cross-sections at low-energy integrated
- High-energy models
  - Improvements in gamma->muons, positron->hadrons and positron->muons
  - Synchrotron radiation for all particle types
- Atomic de-excitation
  - New alternative fluorescence dataset (Bearden)
- New radiolysis process for water and silicon
  - Physics stage followed by physico-chemical and chemical stage
- Introduction of phonon transport with a new concept of crystal
- Channeling effect in straight and bent crystal
- Lots of code refinements along with MT

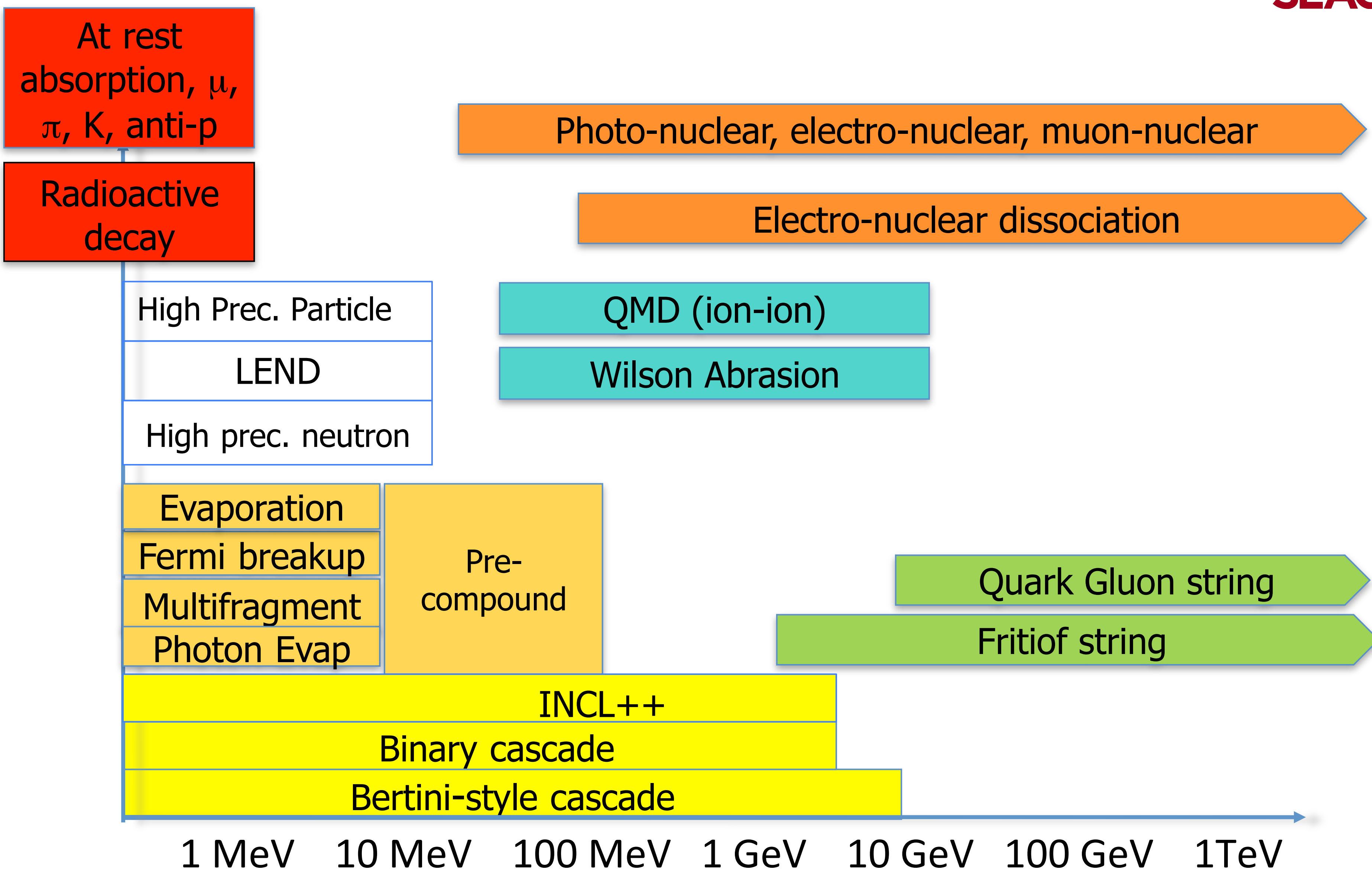


New features in hadronic physics

- FTFP_BERT is now the recommended physics list for most of high-energy use-cases
- Generation of Isomer (a.k.a. metastable nuclides)
  - by default lifetime > 1nsec
- Neutron_HP is extended to Particle_HP to cover p, d, t, α
- Alternative low-energy neutron model with GND (Generalized Nuclear Data) format
- Liege intra-nuclear cascade model (INCLXX) extended up to 20 GeV
- FTF model extended to nucleus-nucleus and antinucleus-nucleus interactions
- Radioactive decay redesigned with rare decay channels
- New hadron stopping models based on Bertini
- Decommission of LHEP and CHIPS models

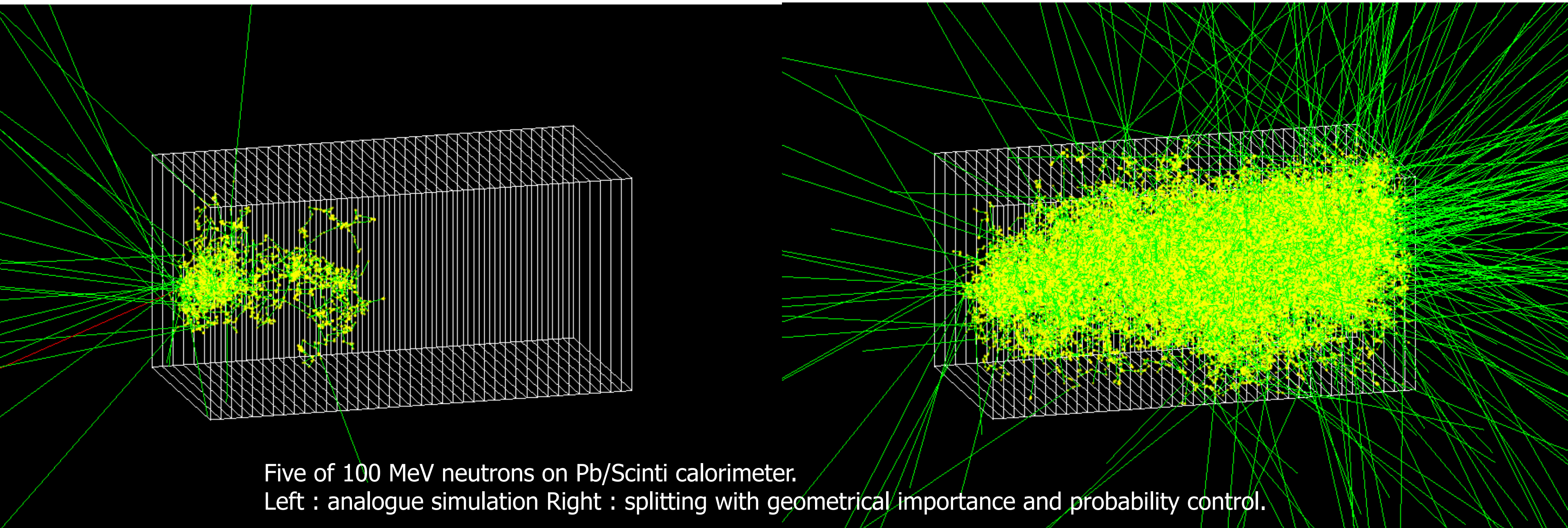


Hadronic Model Inventory



New biasing scheme

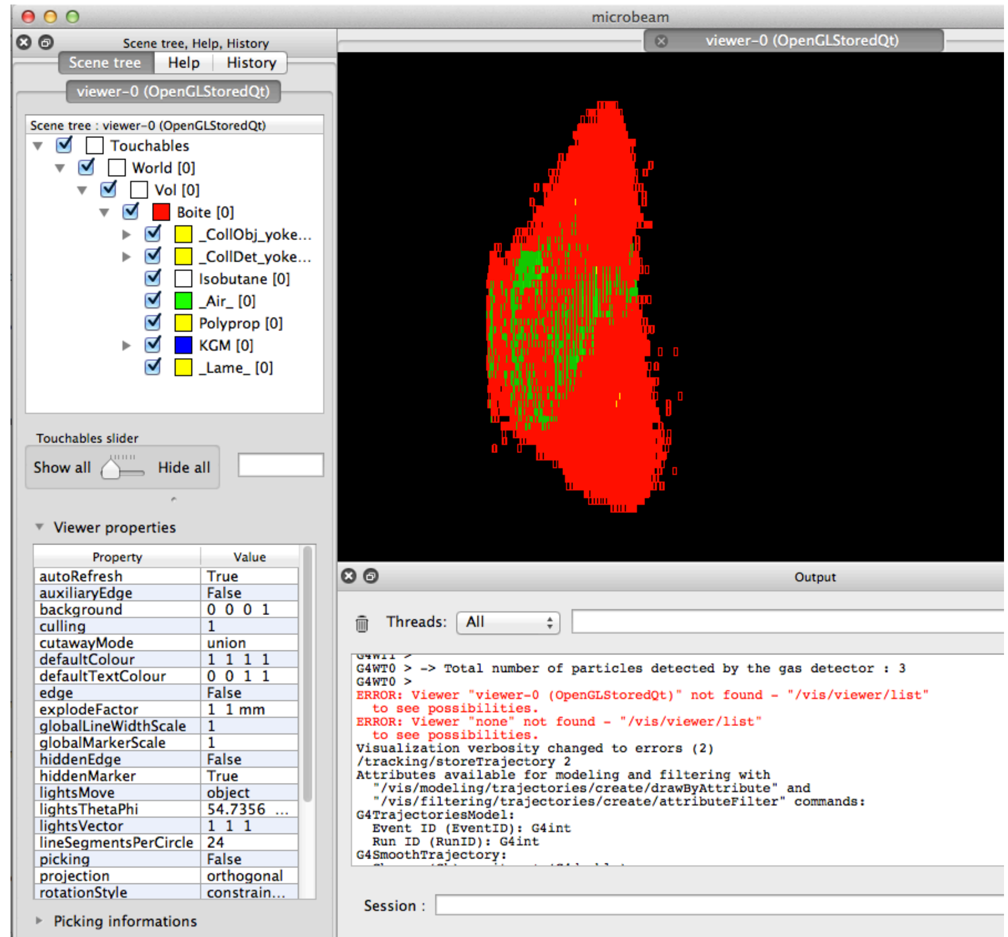
- Event biasing (a.k.a. variance reduction) scheme has been fully revised at version 10.
- It allows treating many biasing options in coherent manner.
- Such options include:
  - Physics process biasing : alters physics process
    - Cross-section biasing, forced interaction, forced passage, etc.
    - Biasing final products of an interaction, e.g. distribution
  - Non-physics biasing : alters the transportation of particle
    - Geometrical importance, splitting / Russian roulette, weight window, etc.
- Easily extensible to new (or user-defined) options
- Well-integrated with built-in scoring functionalities.
- New examples are available.

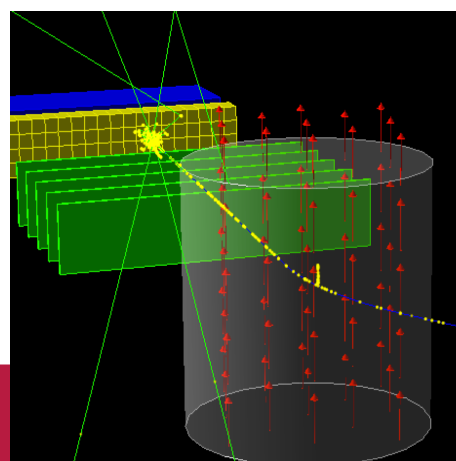


Five of 100 MeV neutrons on Pb/Scinti calorimeter.
Left : analogue simulation Right : splitting with geometrical importance and probability control.

New features in analysis, GUI and visualization

- New built-in fully-multithreaded histogramming tool
  - 1-D and 2-D histograms and scatter plots, n-tuples
  - Data format compatible with ROOT, XML, AIDA, CSV
    - Extensible to other format
- GUI and visualization
  - New Qt driver with OpenGL
    - Viewer properties and picking panel, dock-able widgets
    - Multithread output filtering
  - More than 30% faster drawing on OpenGL
  - Magnetic field lines





Geant4 version 10 series

- Geant4 version 10 series.
  - Performance improvements (both in physics and computing)
    - E.g. Memory size required per thread for full LHC/CMS will be reduced to half 28MB (v10.0) → < 10MB (v10.1)
  - Missing functionalities yet to be migrated to multithread are arriving
    - E.g. Real-time visualization in multithreaded mode with v10.2
  - Additional APIs
    - E.g. Better “integratability” with TBB (Intel® Threading Building Blocks), and also
    - Smoother integration of MPI (Message Passing Interface) and MT, in particular for merging results
  - Additional functionalities
    - E.g. More biasing options
  - New physics
    - E.g. Multi-TeV hadronics, neutrino physics, channeling effects in crystal

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Geant4 – A Simulation Toolkit

http://www.geant4.org/

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

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

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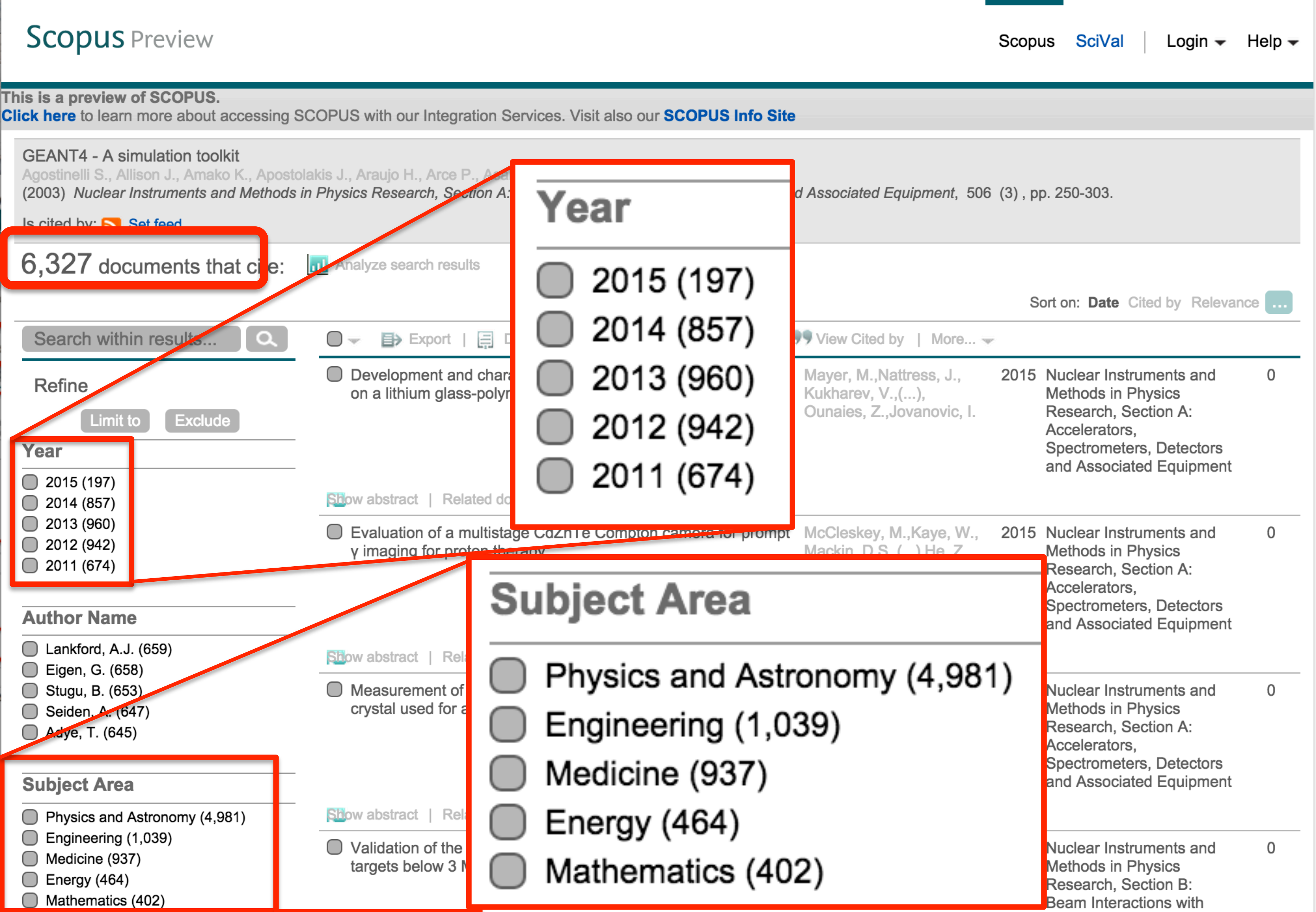
   Agostinelli, S.; Allison, J.; Amako, K.; Apostolakis, J.; Araujo, H.; Arce, P.; Asai, M.; Axen, D.; Banerjee, S.; Barrand, G.; Behner, F.; Bellagamba, L.; Boudreau, J.; Broglia, L.; Brunengo, A.; Burkhardt, H.; Chauvie, S.; Chuma, J.; Chytracek, R.; Coope
   Cited by Scopus (6327)

2. **An XML-based communication protocol for accelerator distributed controls**
   Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 586, Issue 3, March 2008, Pages 444-451
   Catani, L.
   Cited by Scopus (1)

3. **Birks@? scaling of the particle light output functions for the EJ 299-33 plastic scintillator**
   Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 768, December 2014, Pages 141-145
   Nyibule, S.; Toke, J.; Henry, E.; Schroder, W.U.; Acosta, L.; Auditore, L.; Cardella, G.; De Filippo, E.; Francalanza, L.; Giani, S.; Minniti, T.; Morgana, E.; Pagano, E.V.; Pirrone, S.; Politi, G.; Quattrocchi, L.; Russotto, P.; Trifiro, A.; Trimarchi, M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2014 (857)
2013 (960)
2012 (942)
2011 (674)
Author Name
Lankford, A.J. (659)
Eigen, G. (658)
Stugu, B. (653)
Seiden, A. (647)
Adye, T. (645)
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GEANT4—a simulation toolkit   inspirehep.net **[PDF]**
…, 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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J Allison, K Amako, J Apostolakis… - 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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We present the development of GATE, the **Geant4** Application for Tomographic Emission, as a new general purpose simulation platform for PET and SPECT applications. Built on top of the **Geant4** simulation toolkit, it provides multiple new features with the objective to ease **...**
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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, with newly developed software components dedicated to nuclear medicine. In particular, it **...**
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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

Geant 4

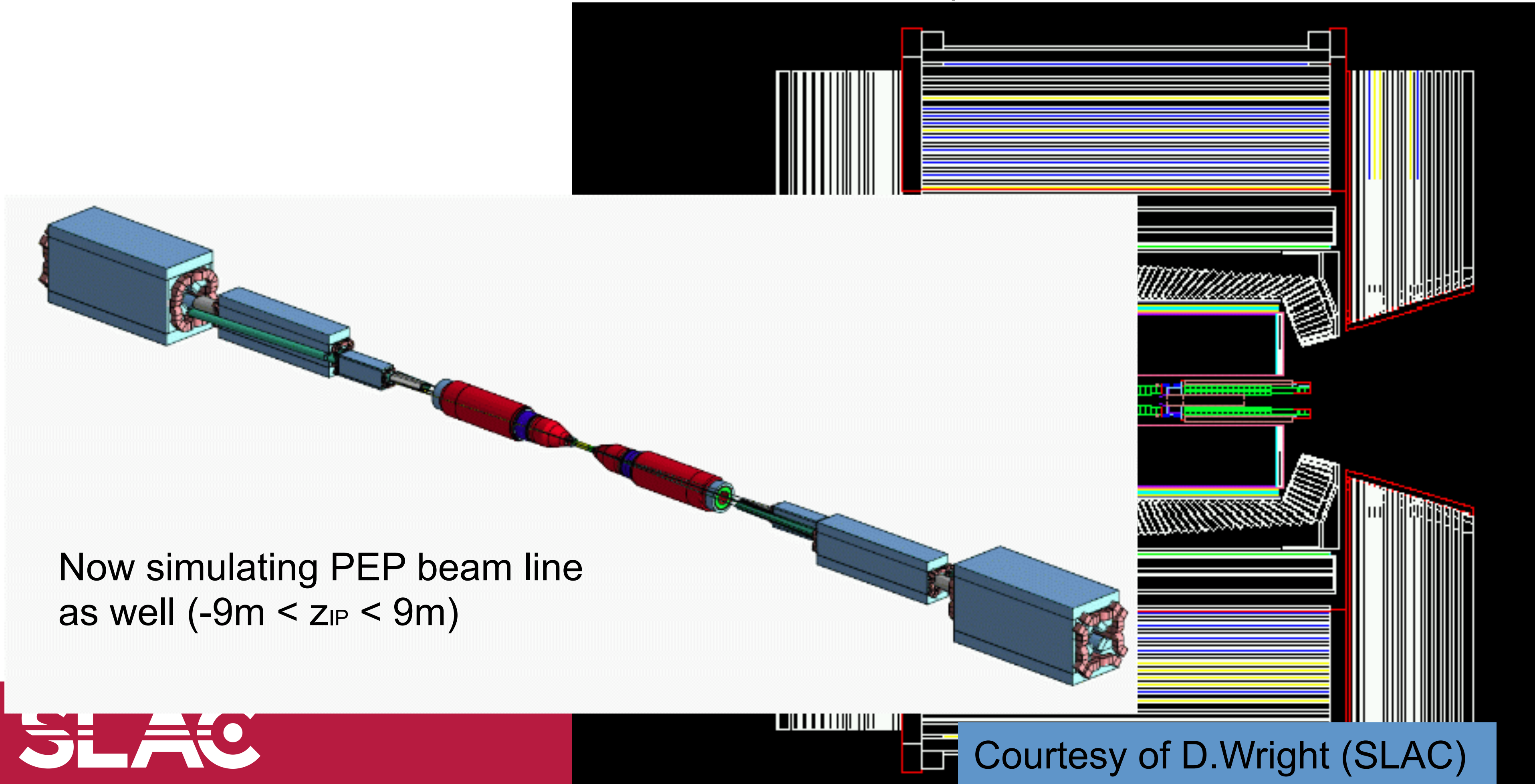
Version 10.1-p01

Highlights of Users Applications

To provide you some ideas how Geant4 would be utilized…

BaBar

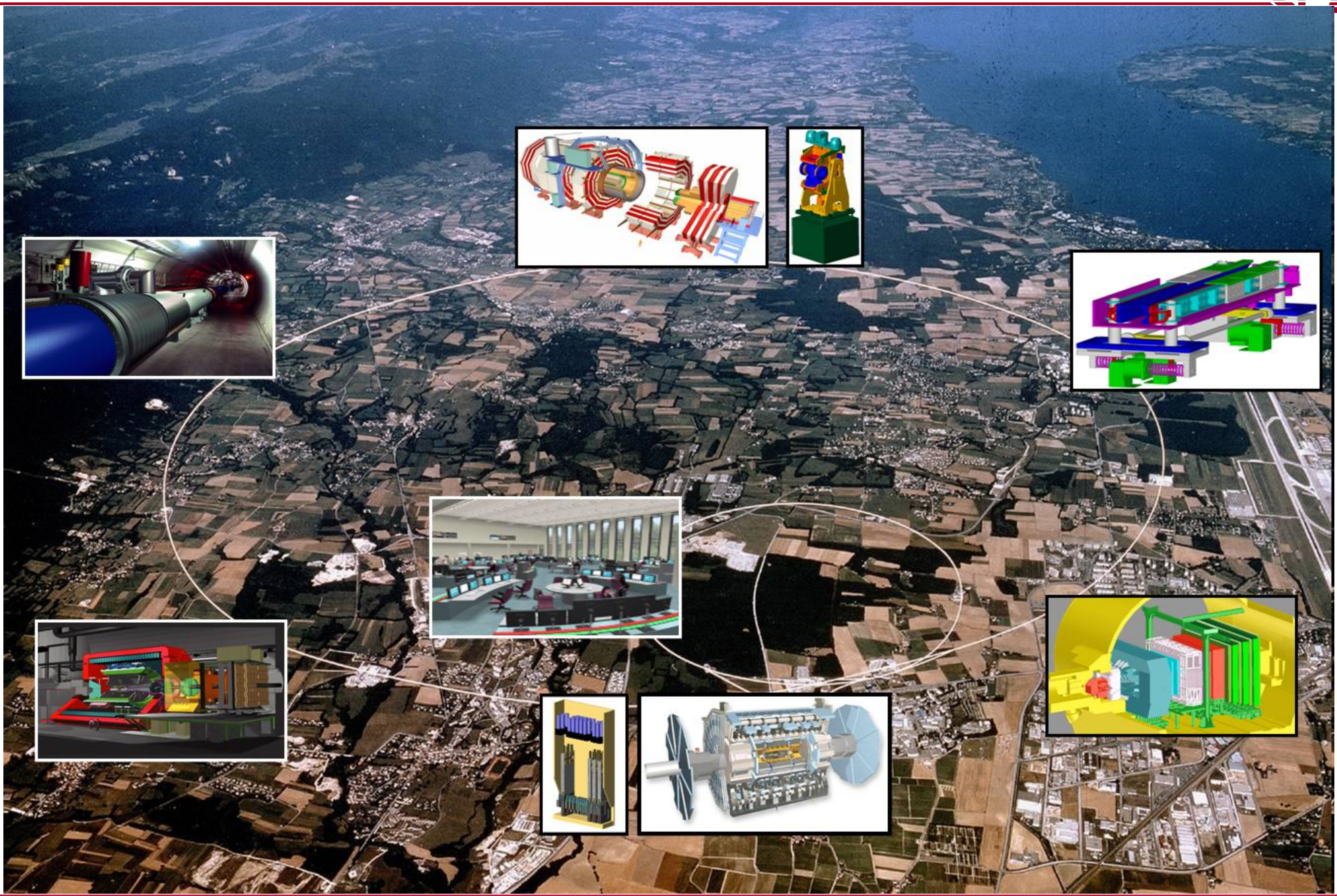
- BaBar at SLAC is the pioneer experiment in HEP in use of Geant4
  - Started in 2000
  - Simulated ~$2*10^{10}$ events so far
  - Produced at 20 sites in North America and Europe



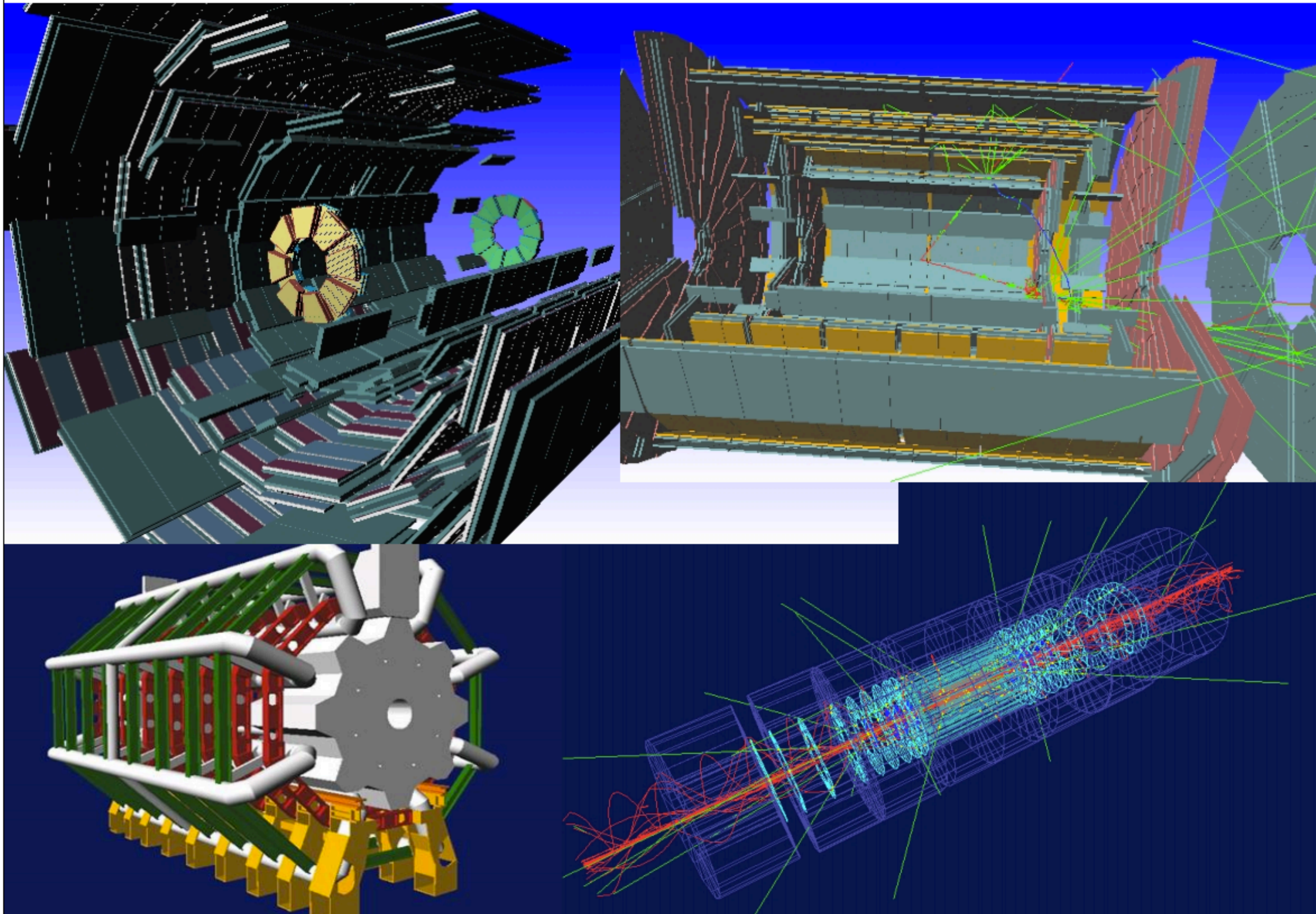
Now simulating PEP beam line as well ($-9m < z_{IP} < 9m$)

Courtesy of D.Wright (SLAC)

Large Hadron Collider (LHC) @ CERN



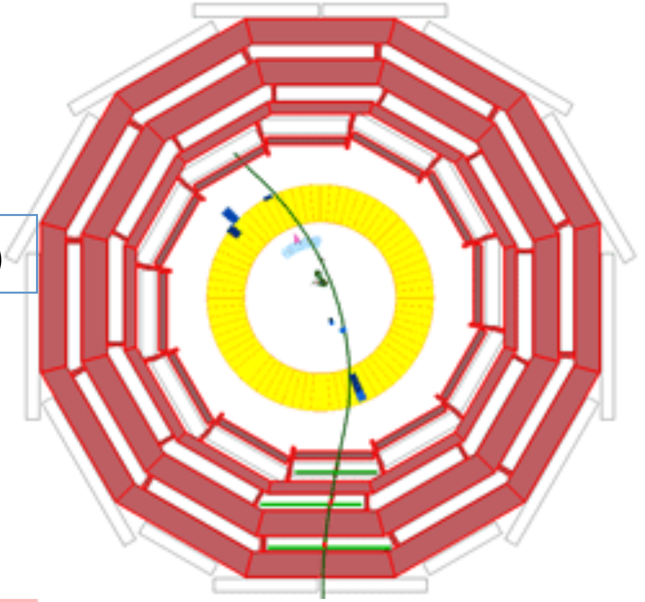
Geant4 in High Energy Physics (ATLAS at LHC)



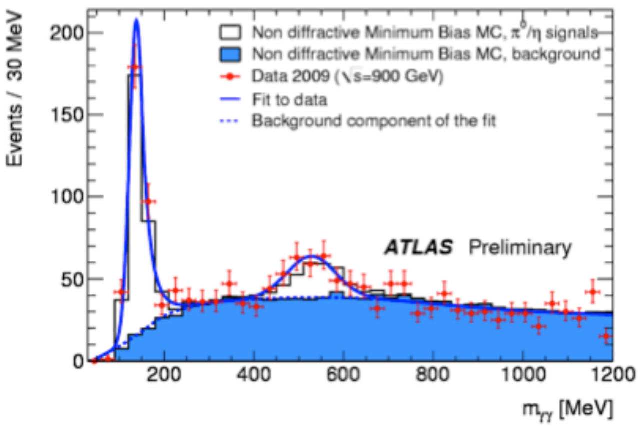
Geant4 has been successfully employed for

- Detector design
- Calibration / alignment
- First analyses

T. LeCompte (ANL)



GEANT4 Comparisons with the Calorimeters



Invariant mass of pairs of well-isolated electromagnetic clusters.

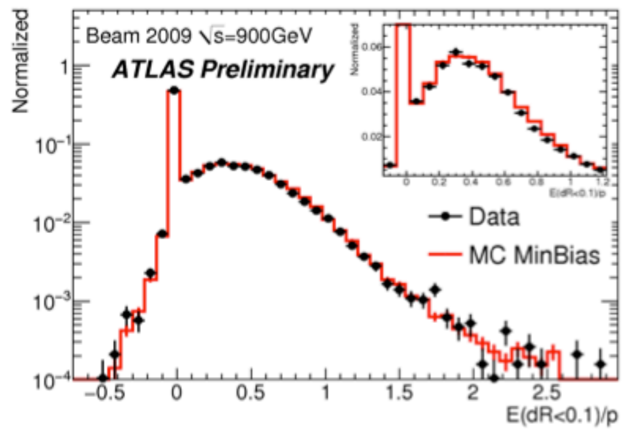
The π^0 mass is within 0.8 ± 0.6% of expectations.

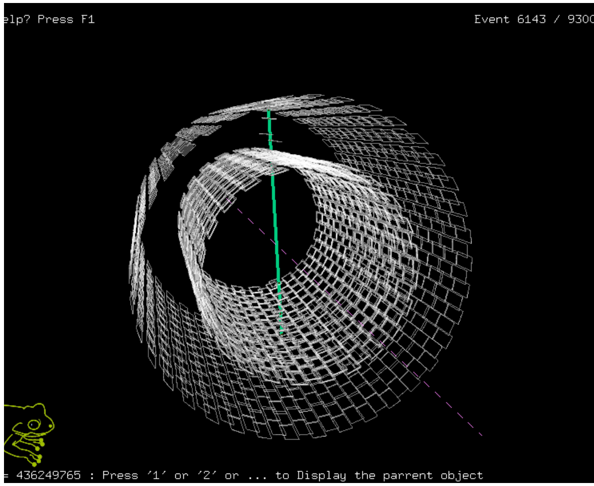
The η^0 mass is within 3 ± 2% of expectations.

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.

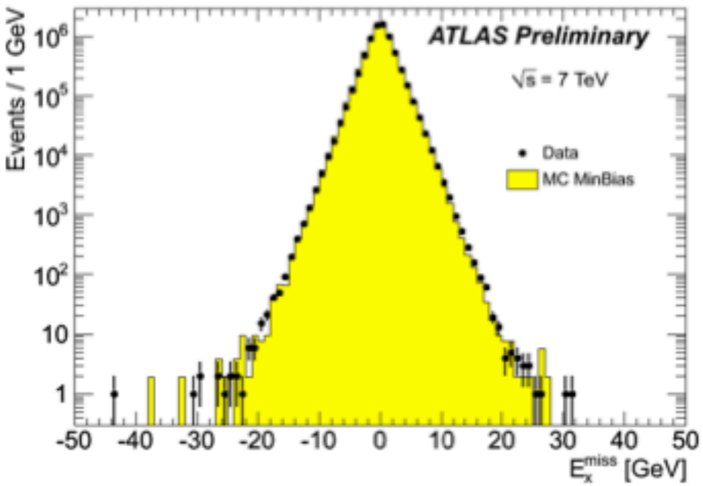
This plot agreed better than we ever expected. (I sent the student who made it back to make sure that they didn't accidentally compare G4 with G4.

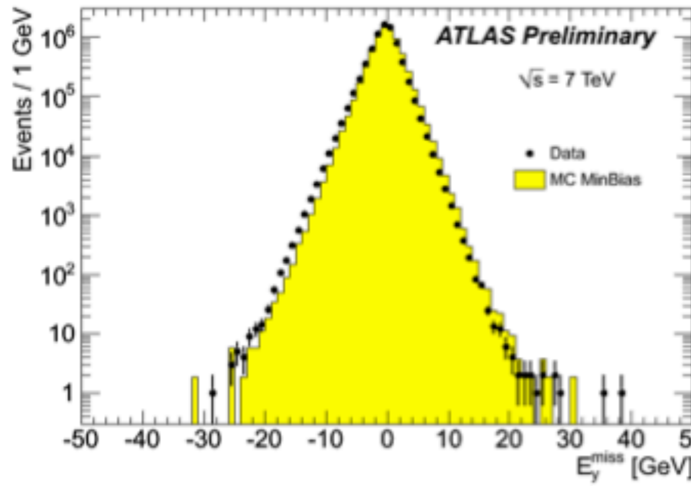




Figures from CMS

Missing E_T

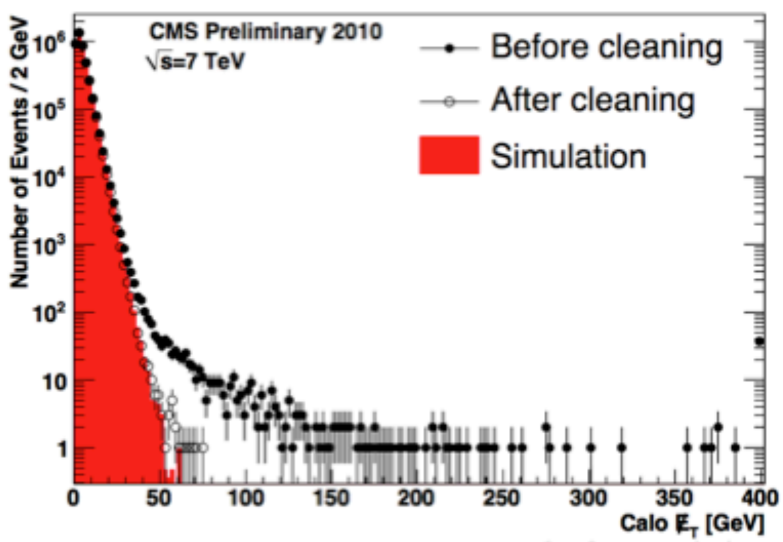


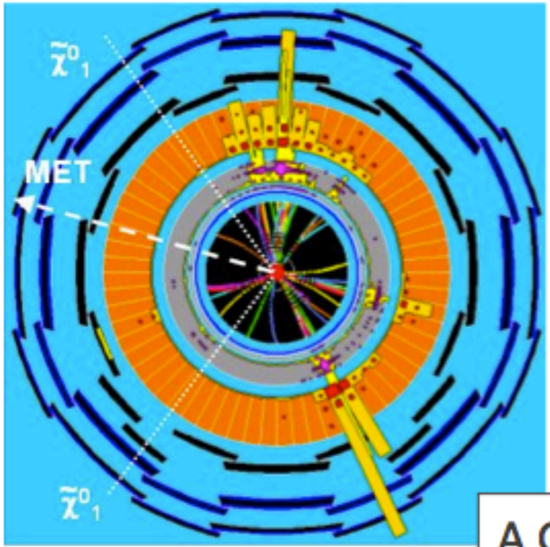


This is one of the hardest things to get right. MET incorporates everything measured in the detector and attempts to identify non-interacting particles, such as neutrinos or dark matter.

Agreement is astounding.

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



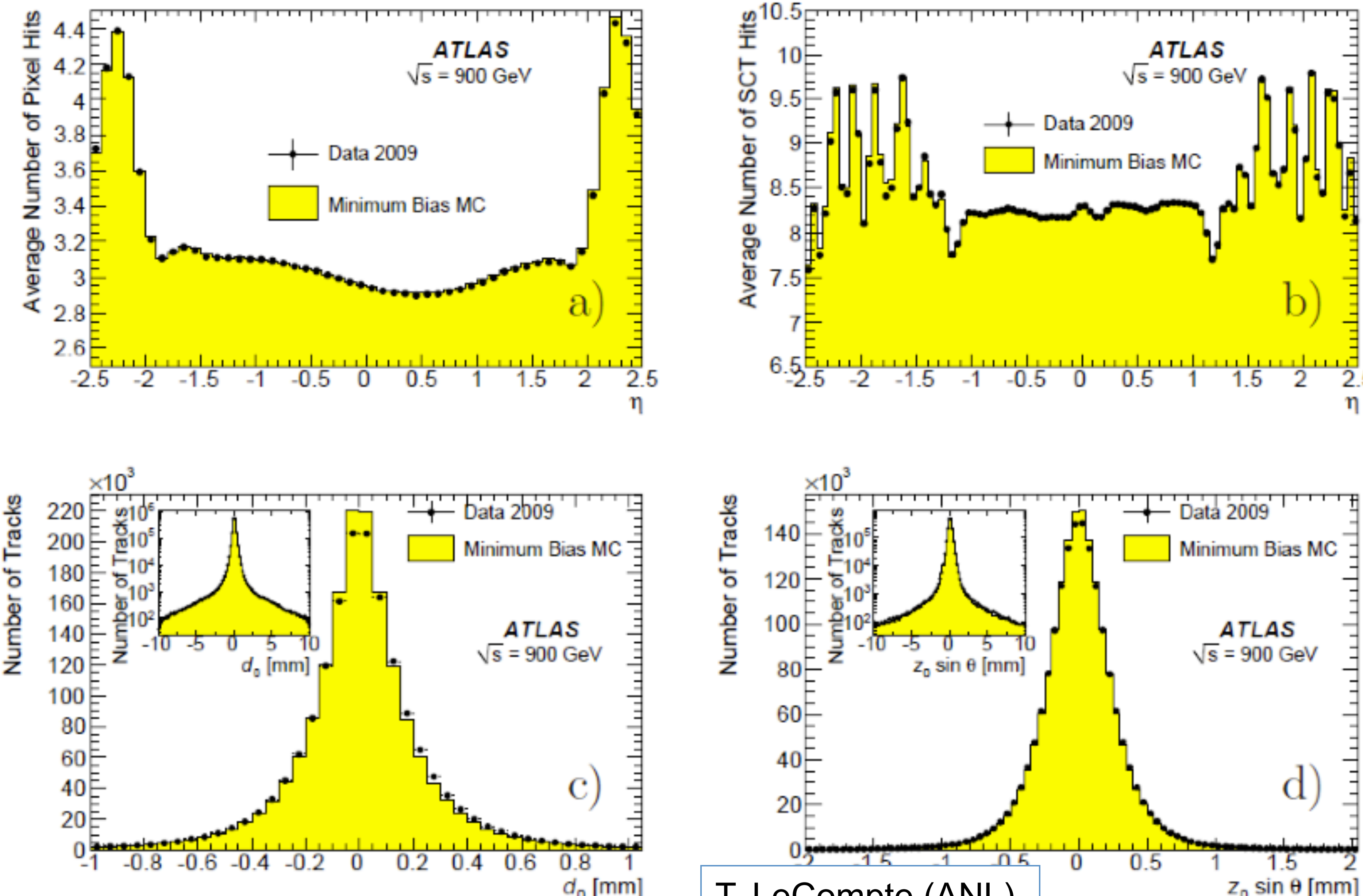


A GEANT4 event.

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

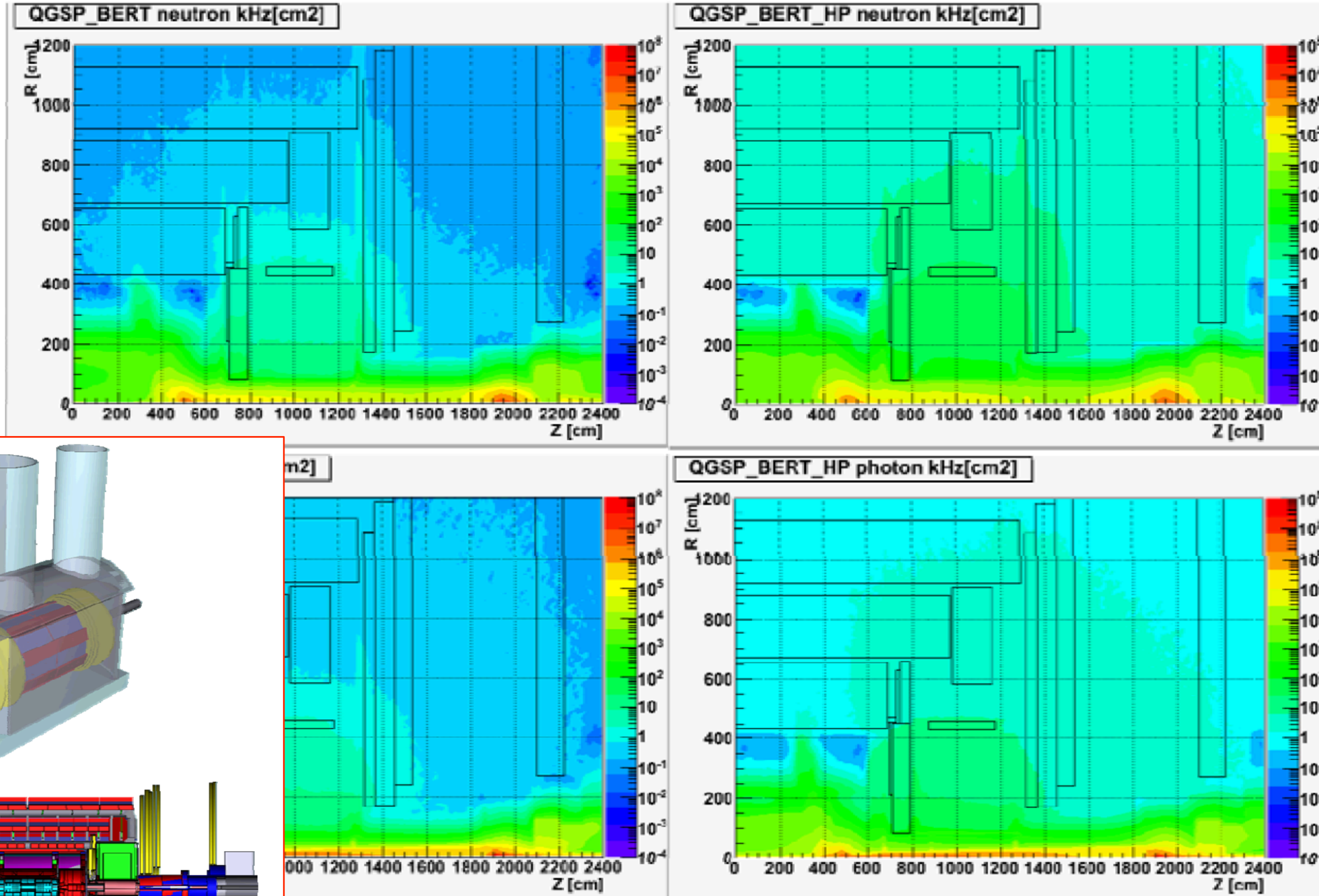
T. LeCompte (ANL)

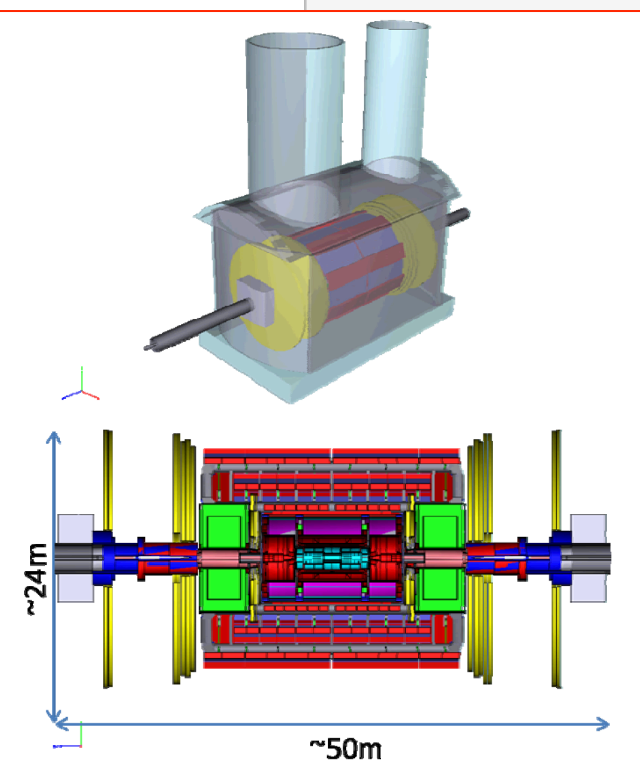
Data and simulation agreements



T. LeCompte (ANL)

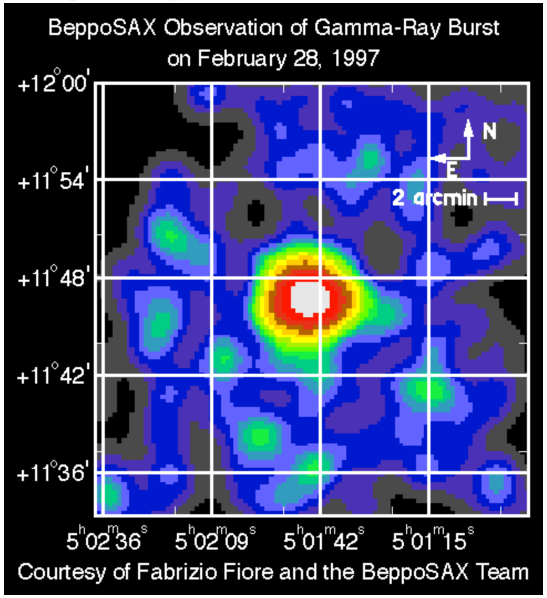
ATLAS cavern background study

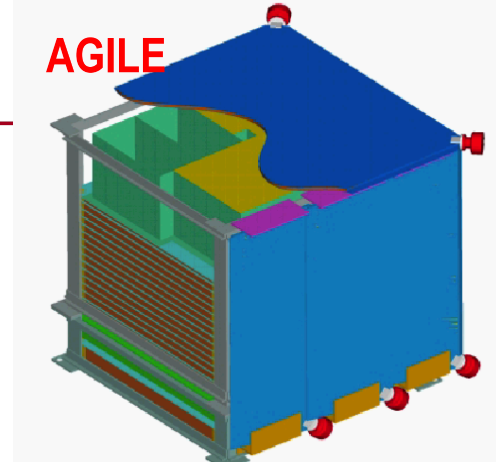


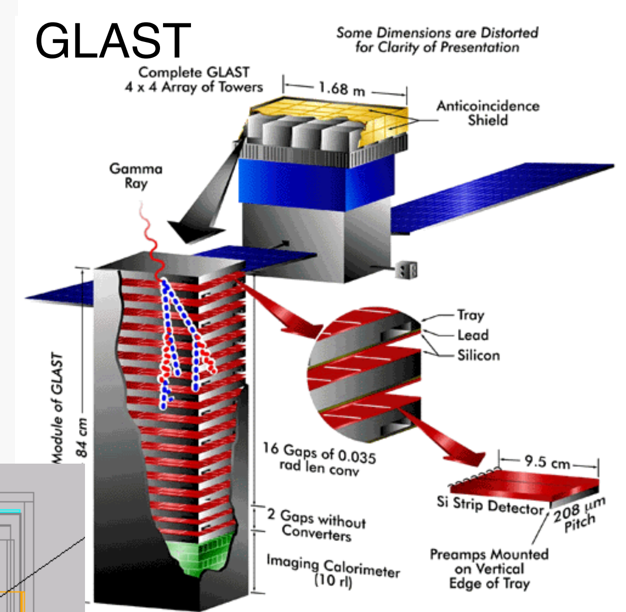


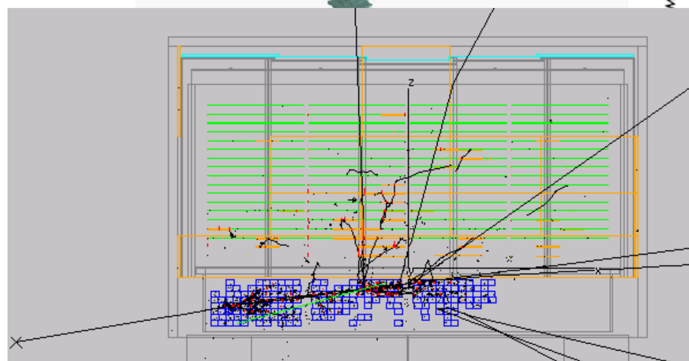
γ astrophysics

γ-ray bursts

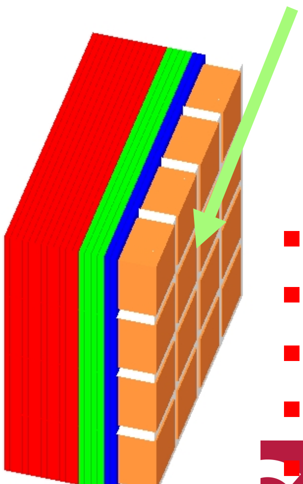






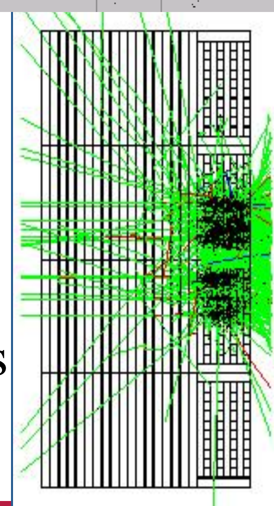


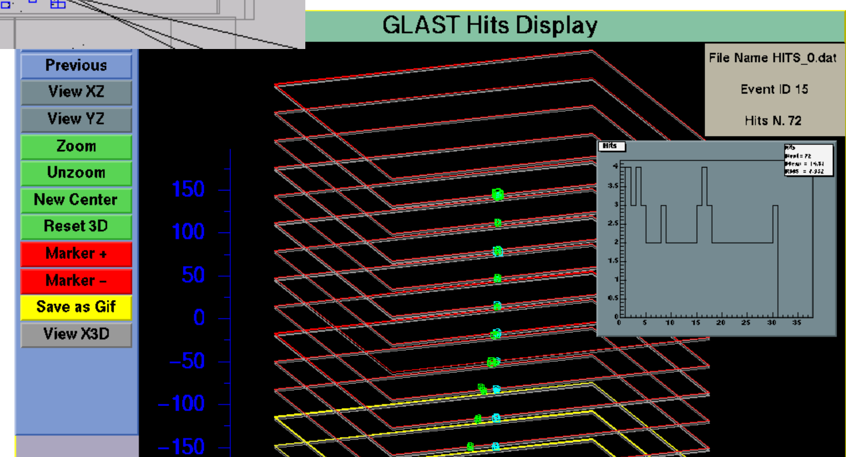
GLAST

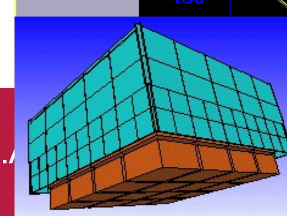


Typical telescope:
- *Tracker*
- *Calorimeter*
- *Anticoincidence*

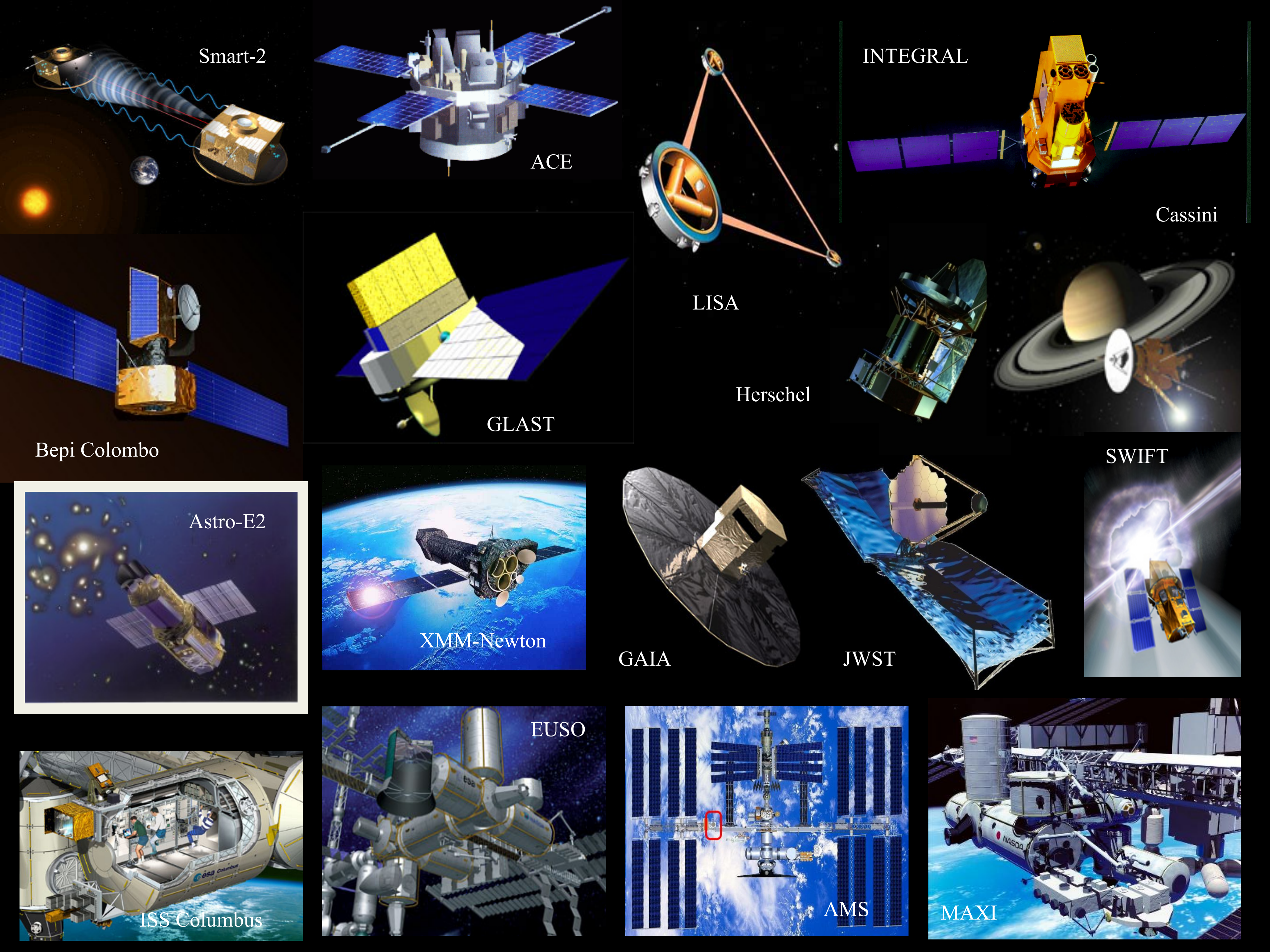
- γ conversion
- electron interactions
- multiple scattering
- δ-ray production
- charged particle tracking





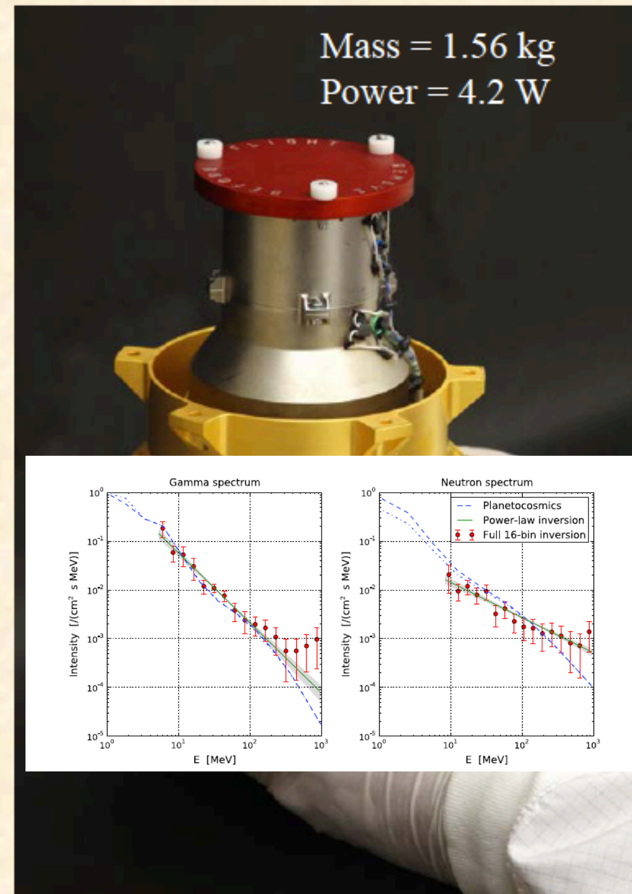


Geant 4

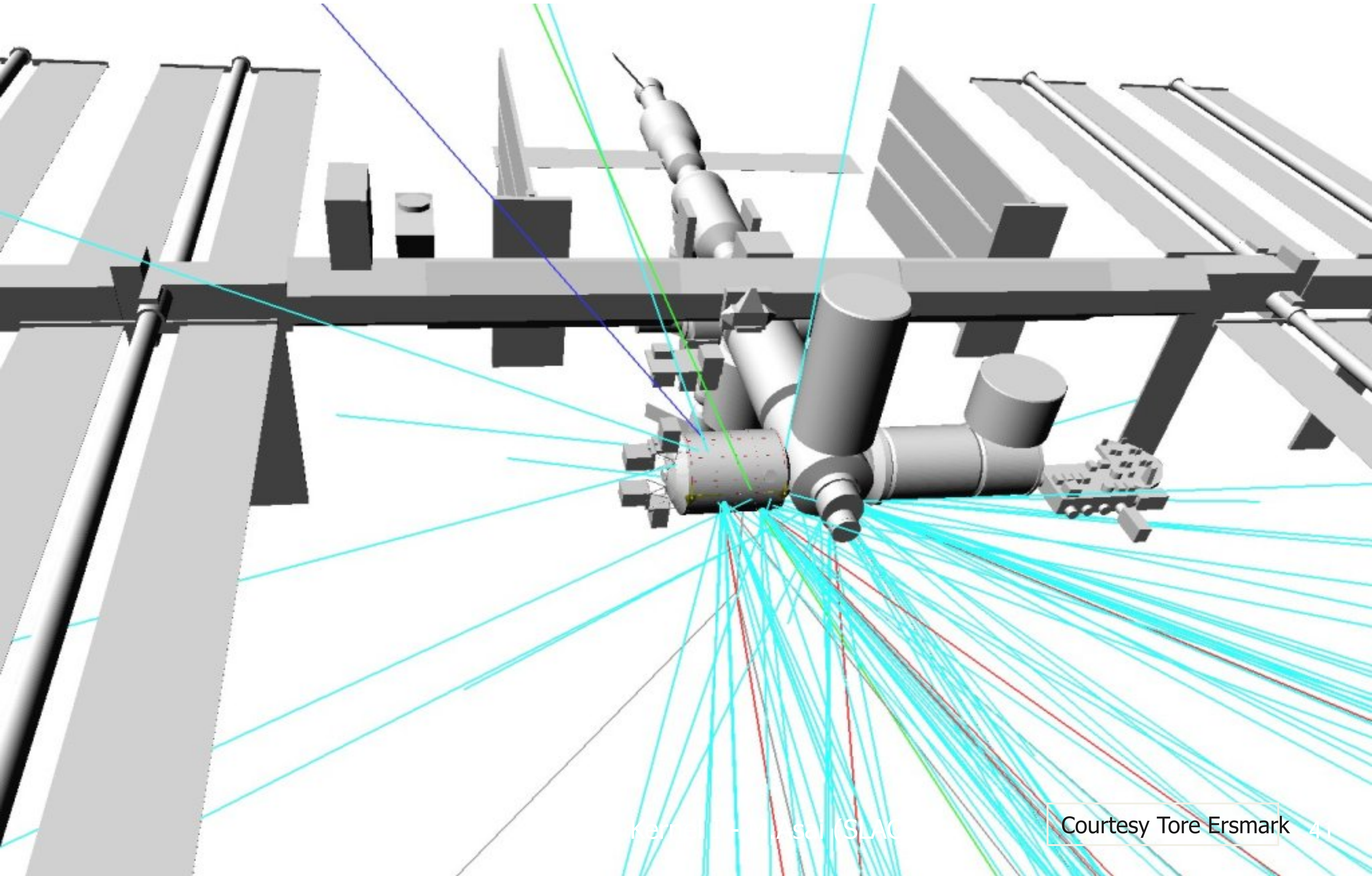

Smart-2
ACE
LISA
INTEGRAL
Cassini
Bepi Colombo
GLAST
Herschel
SWIFT
Astro-E2
XMM-Newton
GAIA
JWST
EUSO
ISS Columbus
AMS
MAXI

MSL Radiation Assessment Detector (RAD)

- RAD is a compact, highly capable radiation analyzer to characterize the full spectrum of space radiation (both charged & neutral particle).
- MSL RAD is currently characterizing the radiation environment on the surface of Mars.



International Space Station



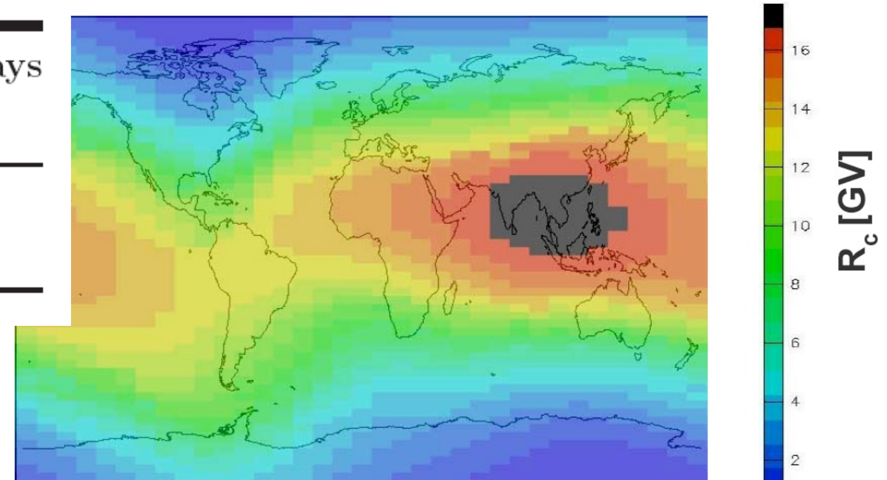
PlanetoCosmics
Geant4 simulation of Cosmic Rays in planetary Atmo-/Magneto- spheres

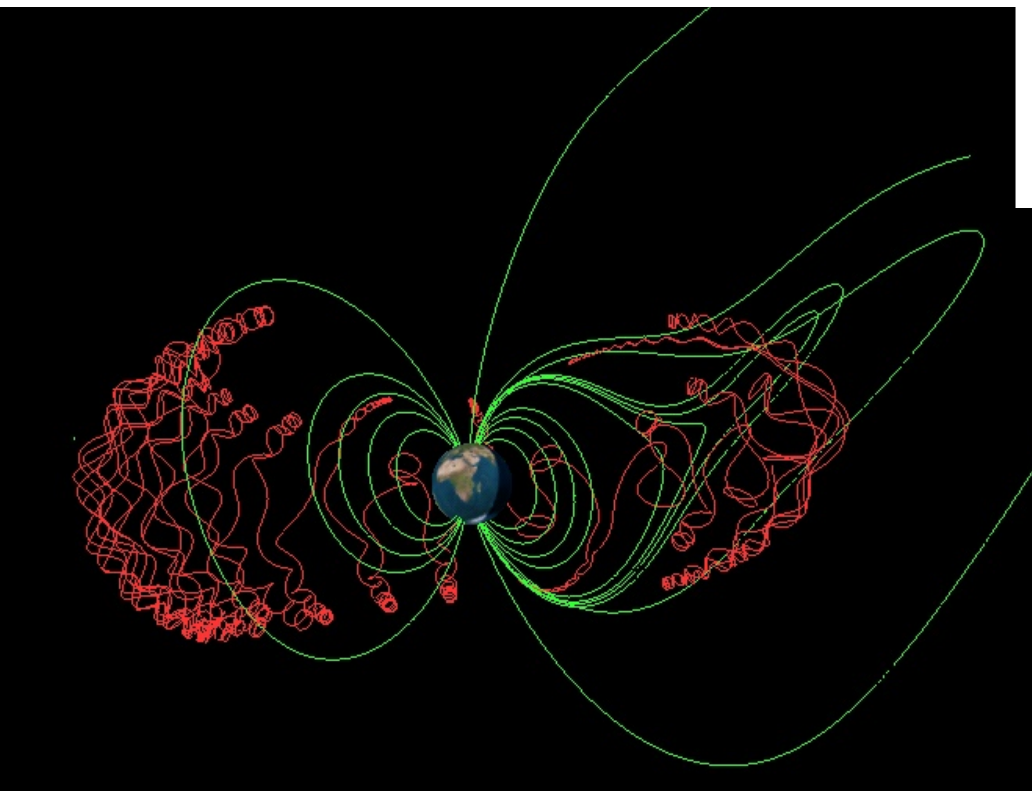
28th International Cosmic Ray Conference — 4277

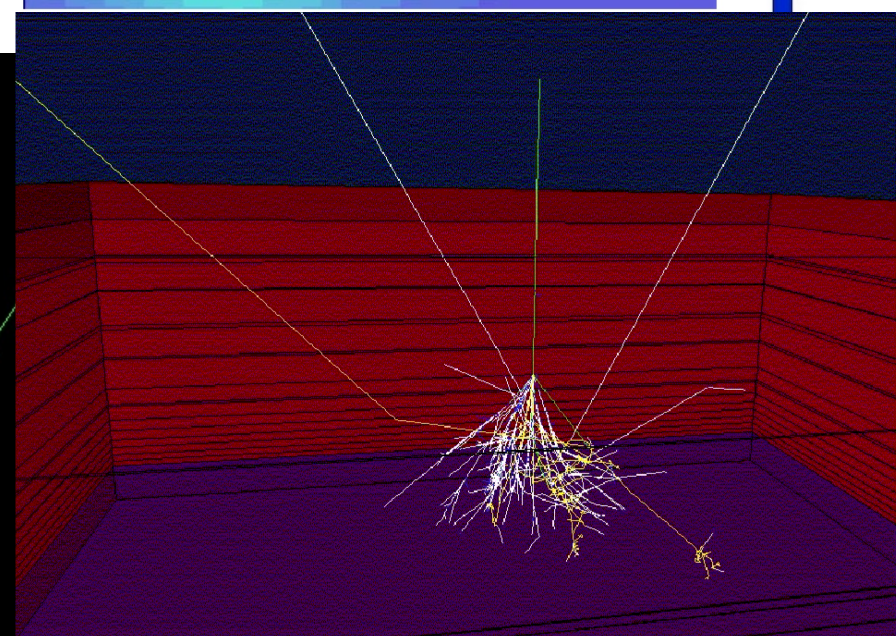
Geant4 Simulation of the Propagation of Cosmic Rays through the Earth's Atmosphere

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

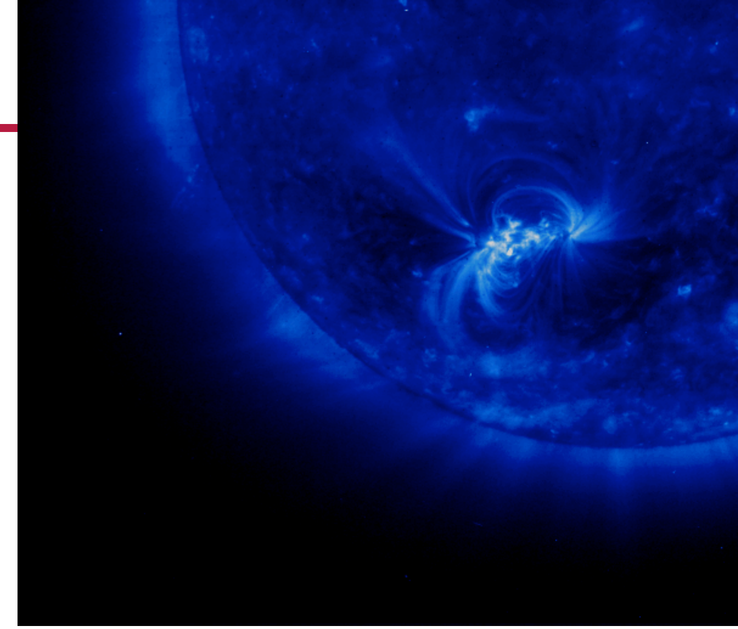
Cutoff Rigidities vs position



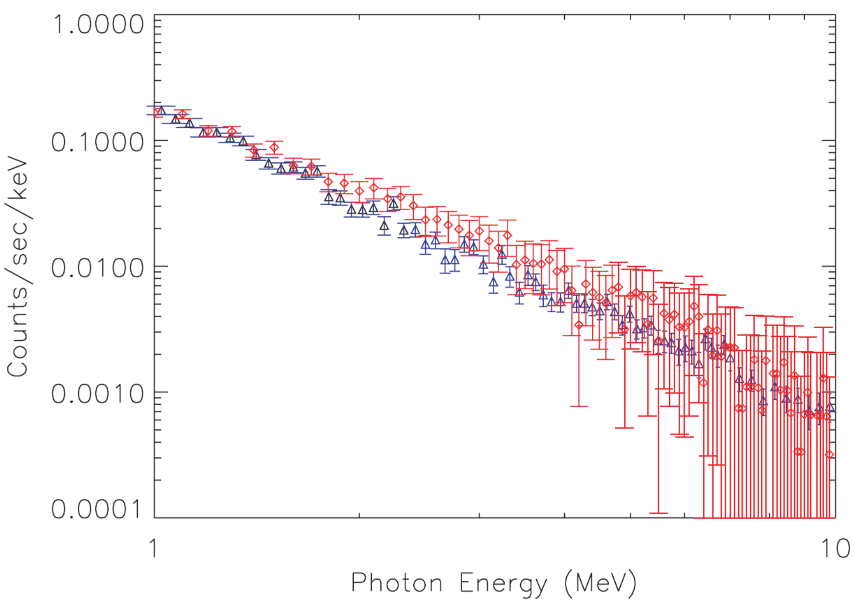




Solar event gamma-rays



- 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

Jun'ichi KOTOKU

National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, JAPAN

junichi.kotoku@nao.ac.jp

Kazuo MAKISHIMA[1] and Yukari MATSUMOTO[2]

Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo, 113-0022

and

Mitsuhiro KOHAMA, Yukikatsu TERADA and Toru TAMAGAWA

RIKEN (Institute of Physical and Chemical research), Wako-shi, Saitama

[1] *Also at RIKEN*

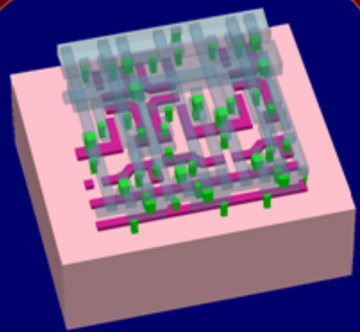
[2] *Present address: Mitsubishi Electric Co., Ltd.*

(Received ; accepted)

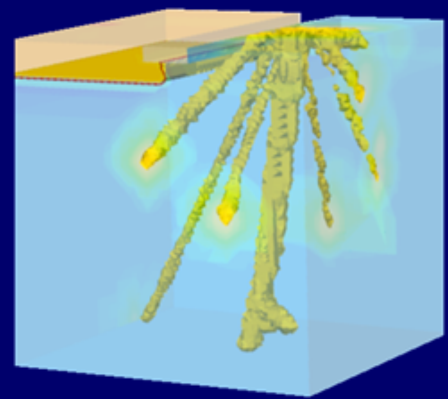
Abstract

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-

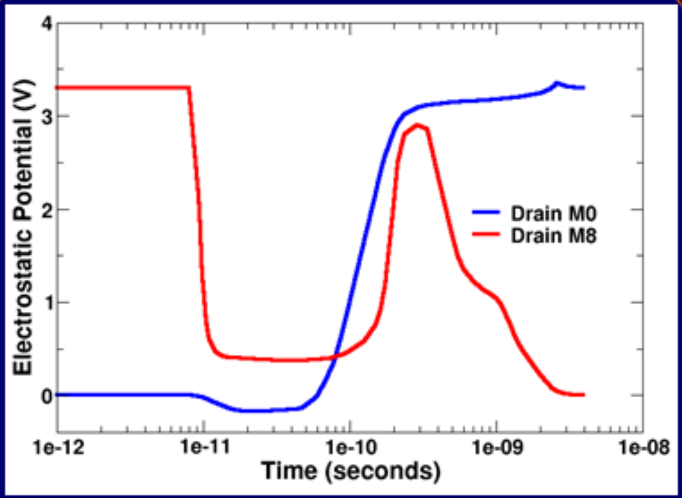
RADSAFE on SEE in SRAMs



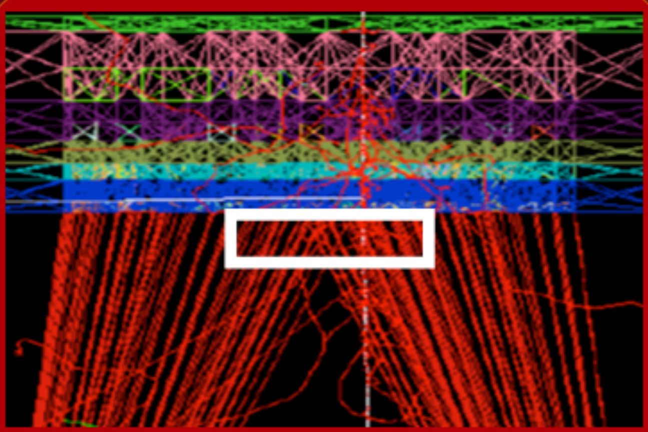
TCAD Cell Structure: SRAM Cell



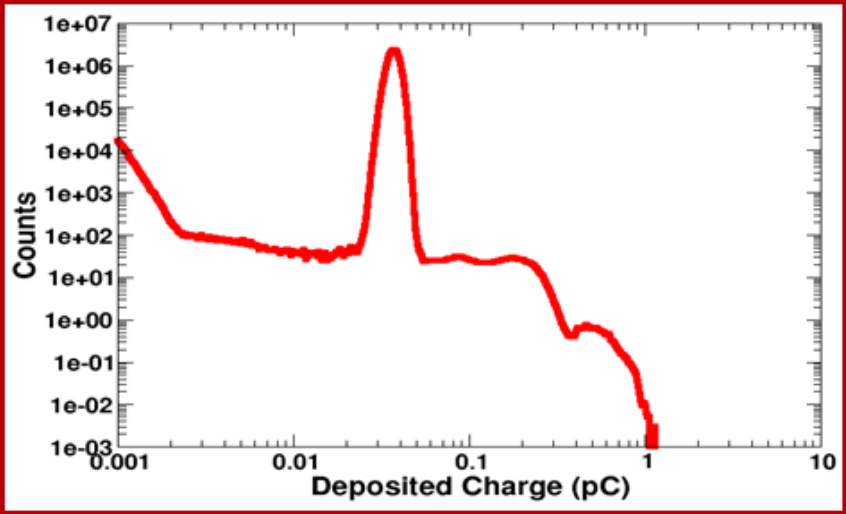
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset

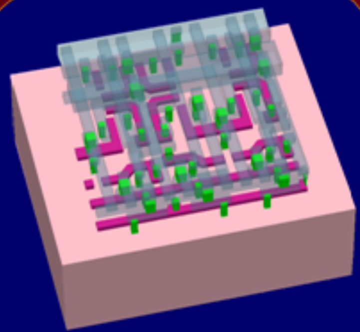


Geant4 Geometry and 523 MeV Neon Event

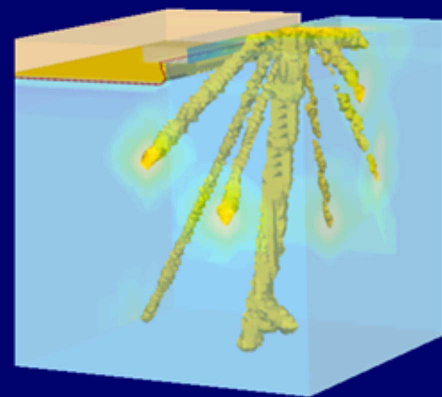


MRED Energy Deposition for 10^8 Events

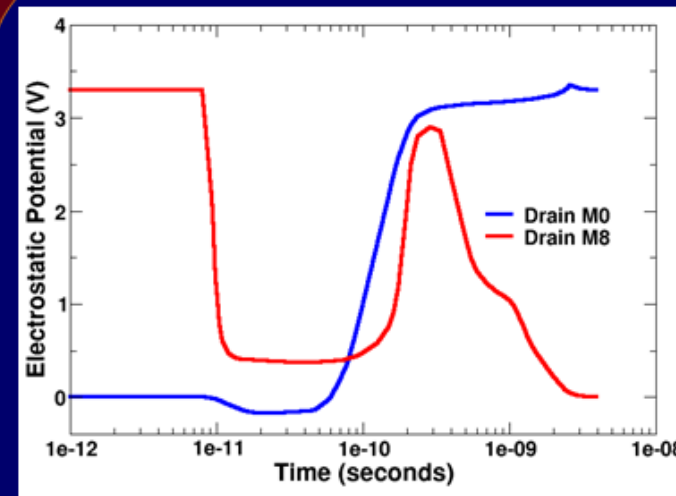
RADSAFE on SEE in SRAMs



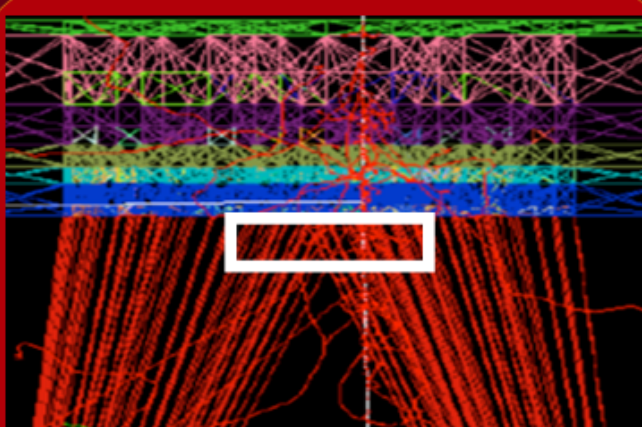
TCAD Cell Structure: SRAM Cell



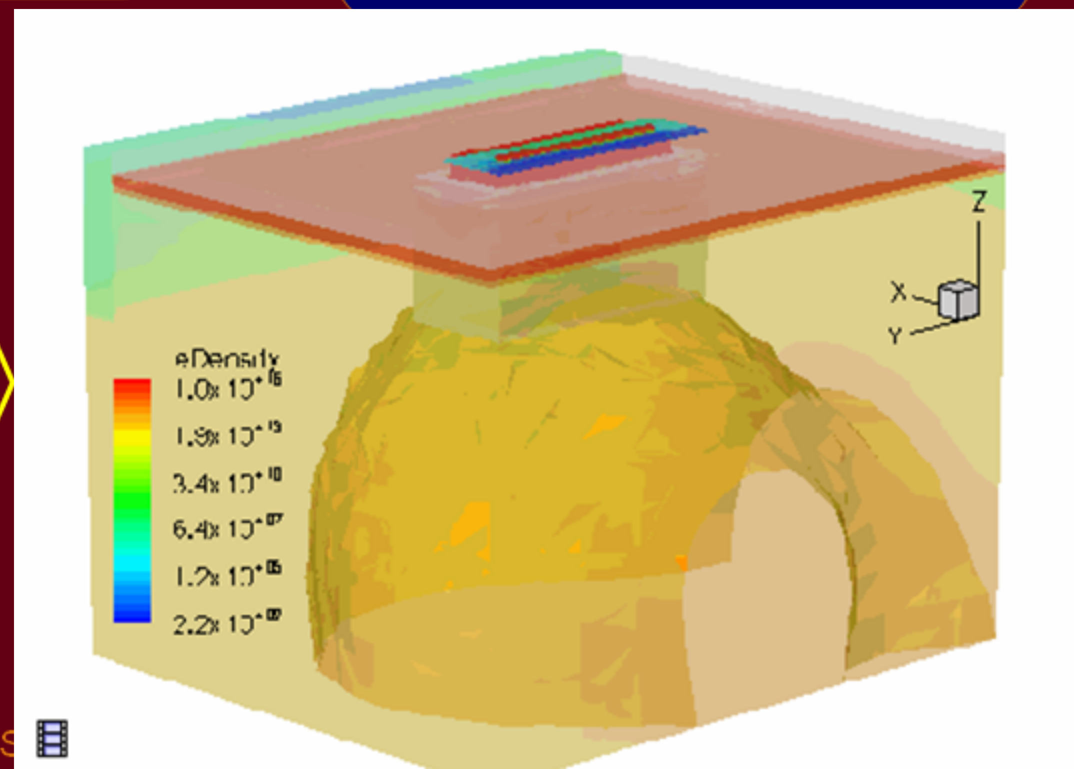
Single Charge Deposition in TCAD: Ne+W Event



SRAM Cell Upset

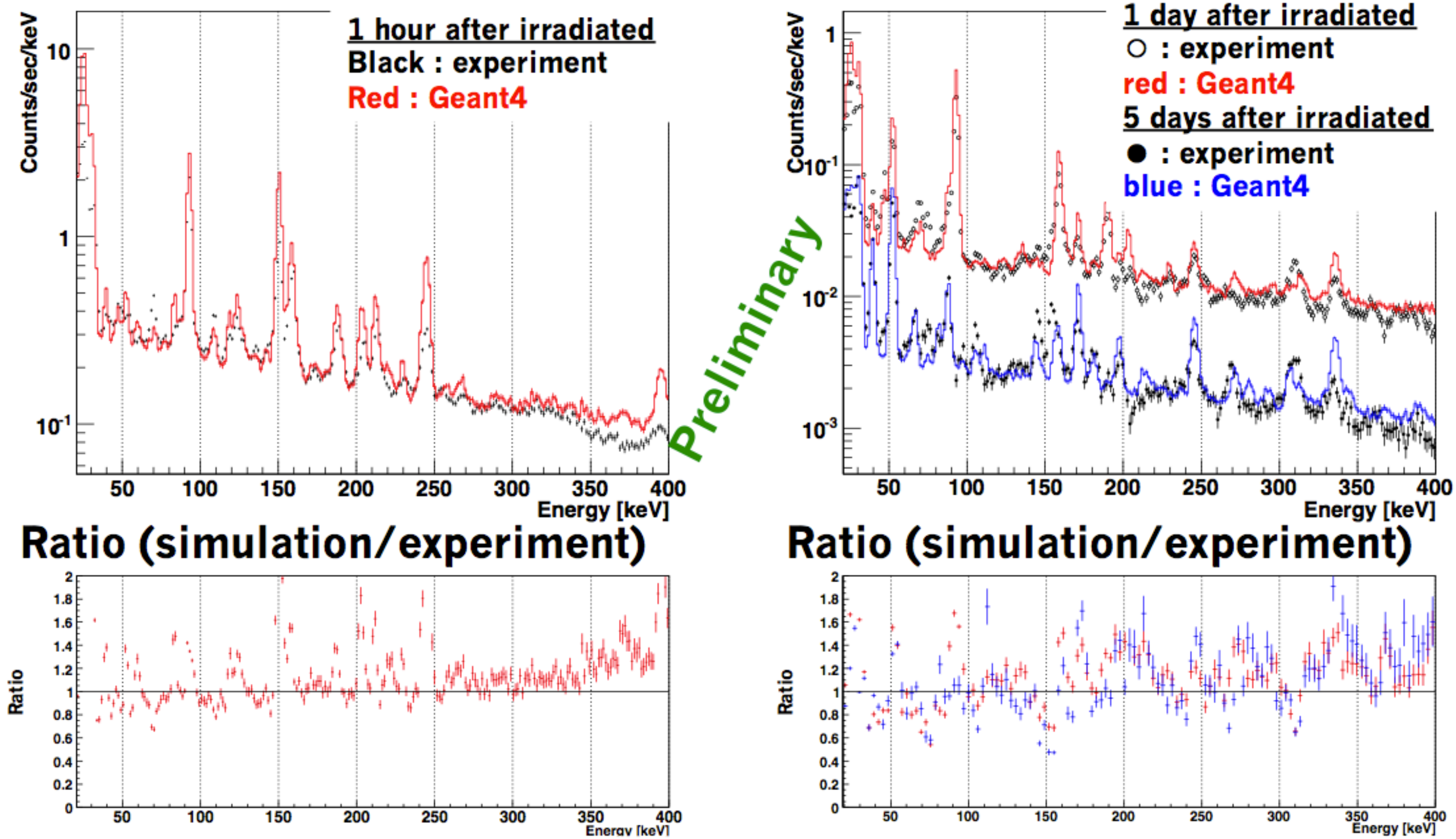


Geant4 Geometry and 523 MeV Neon Event



Time evolution of the activation background

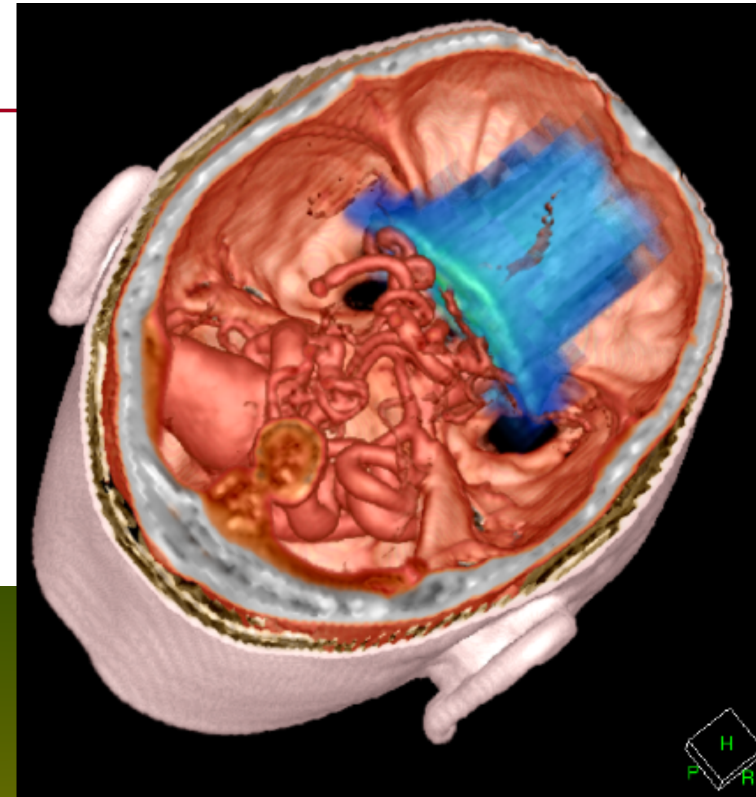
Comparison with Geant4

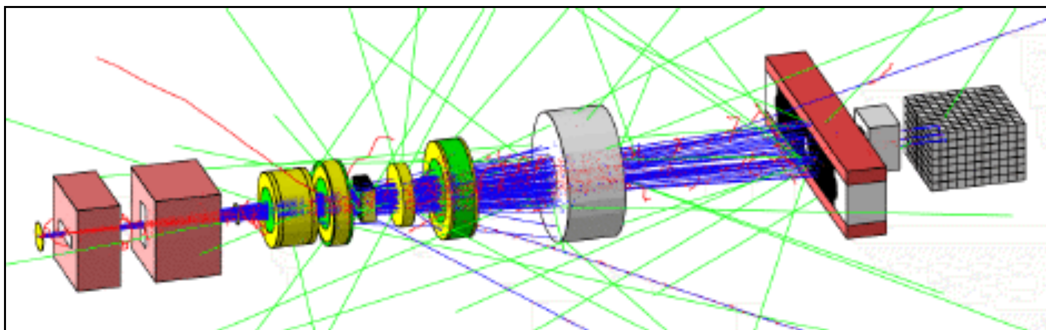


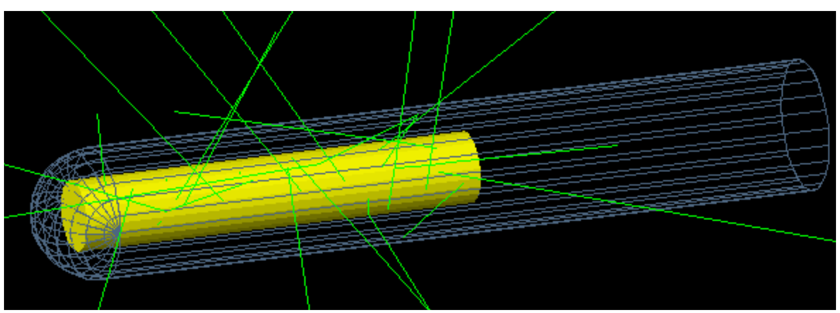
❖ Simulation results agrees with experimental data within a factor of two in terms of the line intensities

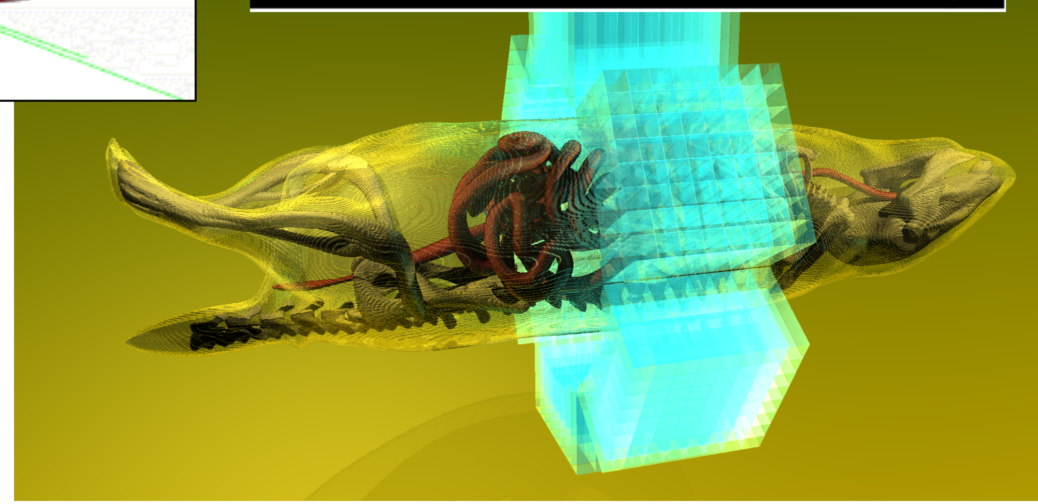
Geant4 @ Medical Science

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









Varian TrueBeam

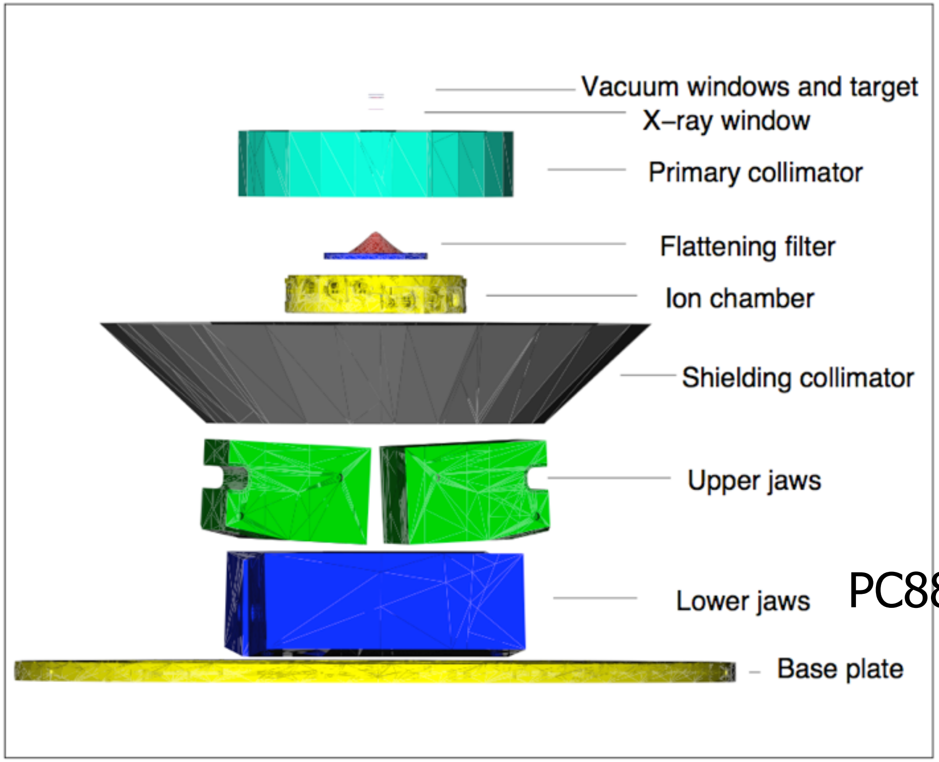


FIG. 3: Visualization of the treatment head components using OpenInventor in Geant4. All the components have been imported in Geant4 as GDML input files.

PC88339

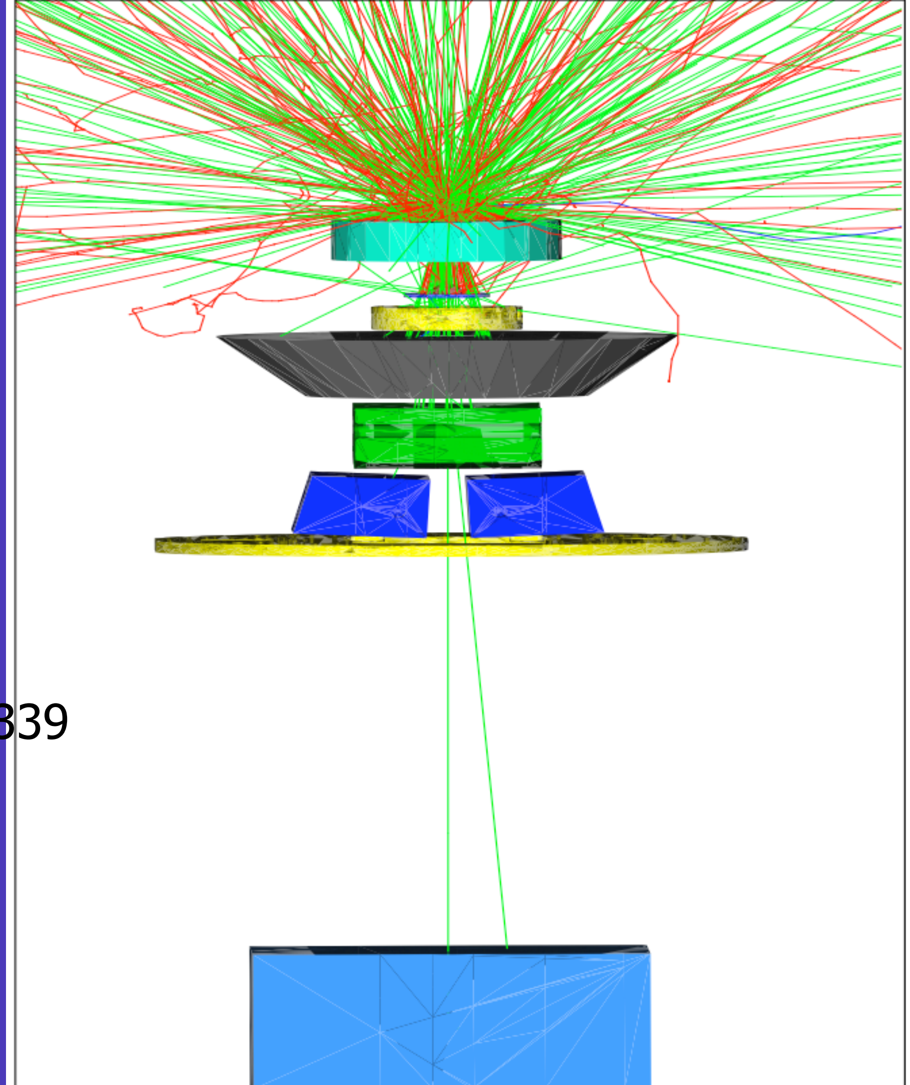


FIG. 4: Visualization of Geant4 particle trajectories along the treatment head components using OpenInventor. Electrons are photons shown in red and green, respectively. Field size was set to $10 \times 10\text{cm}^2$ and SSD to 100 cm. Note that for proprietary reasons, the appearance of some of the components in this figure has been modified.

Linking Computer-Aided Design (CAD) to Geant4-based Monte Carlo Simulations for Precise Implementation of Complex Treatment Head Geometries

Magdalena Constantin, Dragos E. Constantin, Paul J. Keall - Stanford Univ
Anisha Narula, Michelle Svatos - Varian Medical Systems
Joseph Perl - SLAC

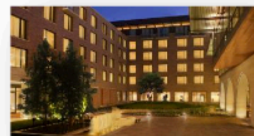
Phys. Med. Biol. 55 N211 doi: 10.1088/0031-9155/55/8/N03

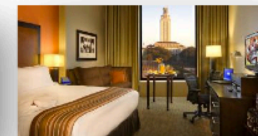
Varian Developer Workshop 2.0

Pre-AAPM meeting, Thursday-Friday

July 17-18, in Austin on the UT campus.

AT&T Executive Conference Center





Tentative Agenda

- **Wed July 16**

evening: reception. Guru "Hackathon" kickoff: cross-institutional teams coding projects throughout event

- **Thur July 17 Newbie Track:** Intro to our Research Tools

am: TrueBeam Developer Mode intro with customer talks & panel, What's New in DevMode, VirtuaLinac Cloud-Based Monte Carlo App
pm: iTools Reconstruction Toolkit, Eclipse API Suite intro, customer talks & panel, What's New in APIs

- **Fri July 18 Intermediate Track:** Hands on exercises. Bring laptops!

am: Eclipse API, Veritas xml-builder GUI for DevMode exercise, VirtuaLinac exercise
pm: Open-Source tools for RadOnc including Python, Enthought, DicomPyler, modifying Veritas. Panel. Guru Show & Tell

- **(Sat July 19 is the Varian User Meeting & AAPM committees)**
- Poster viewing during breaks: bring 4x4 hard copies or e-poster

C dress code.

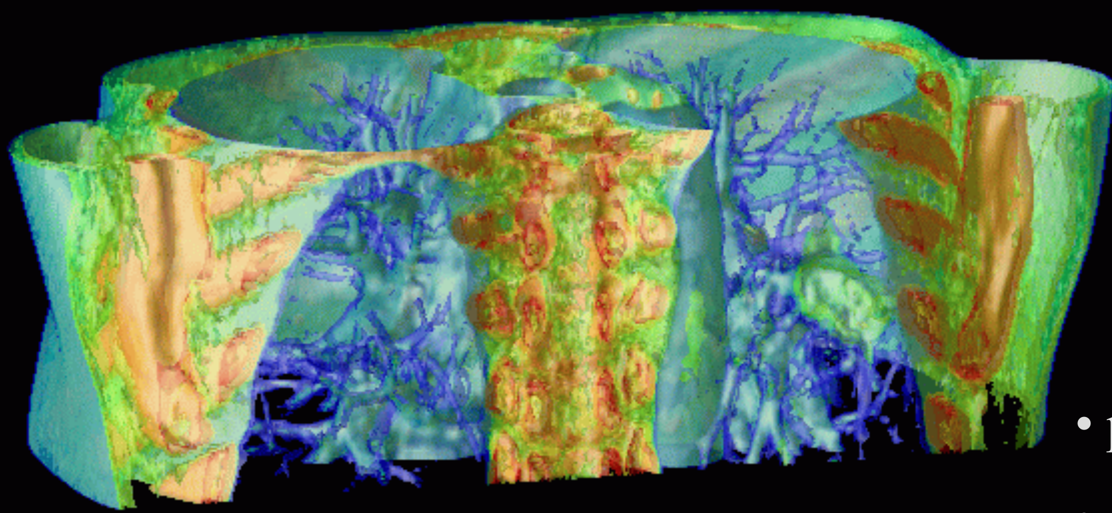
VirtuaLinac : web-based cloud Geant4 application for medical linac. At this event, more than 100 users simultaneously executed Geant4-based simulations. They use Amazon cloud.

- Breathing Patient -

4D Patient

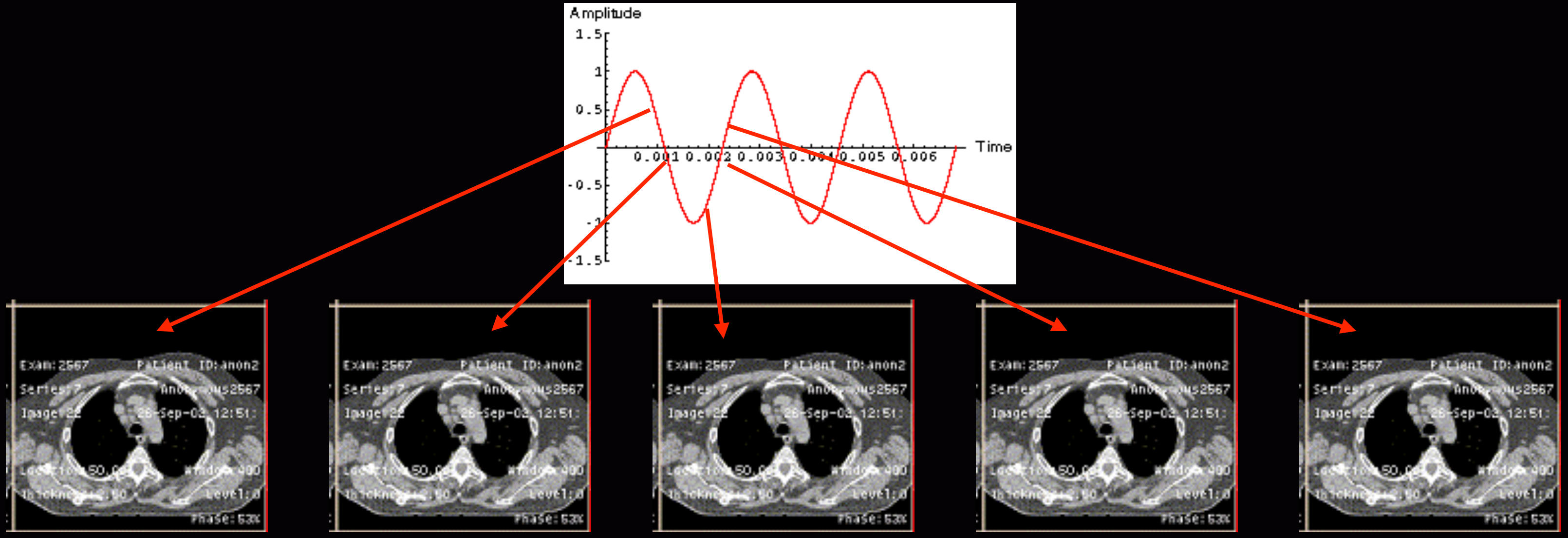
© Eike Rietzel

R

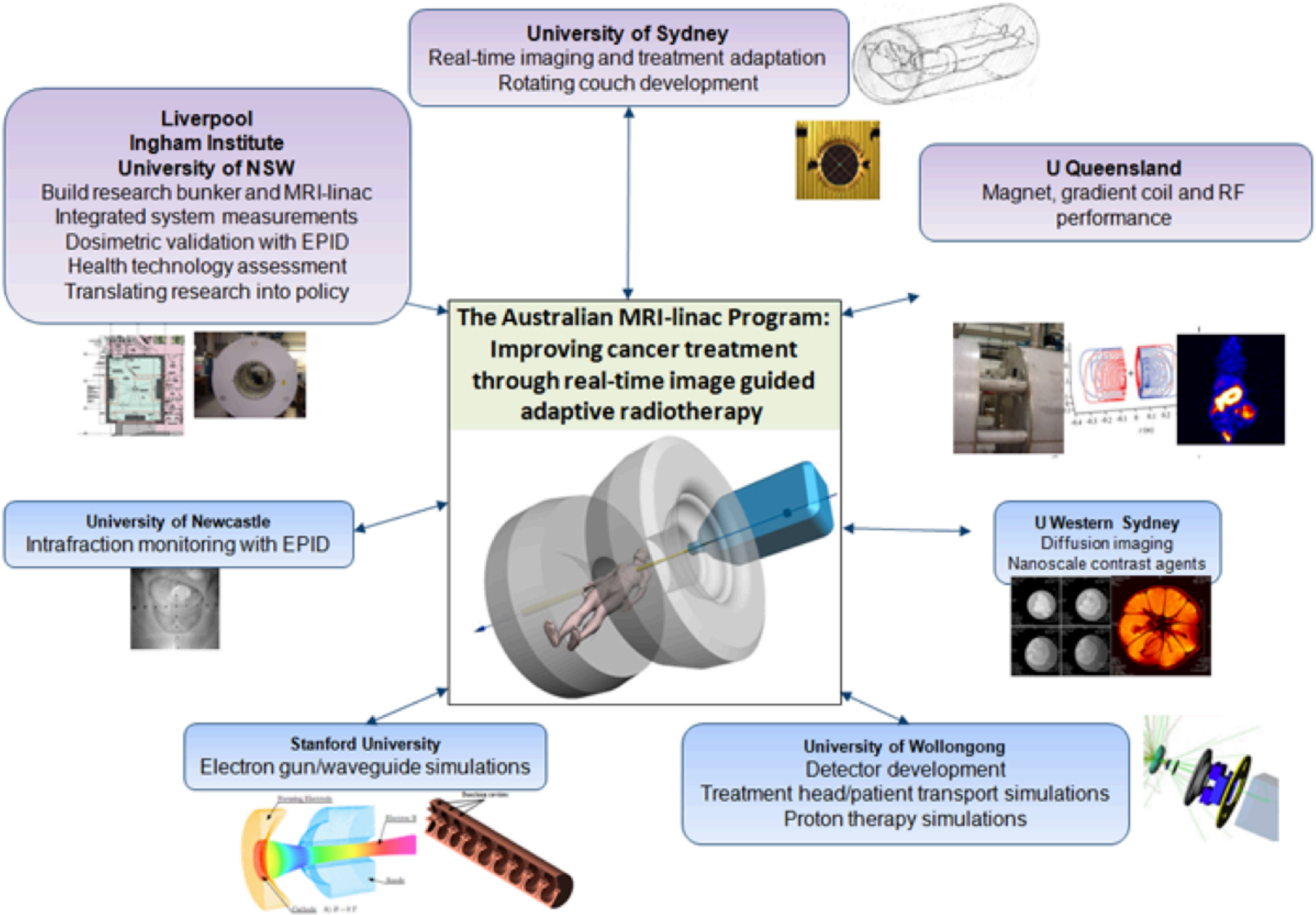


L

- posterior view
- posterior cut



MRI-Linac

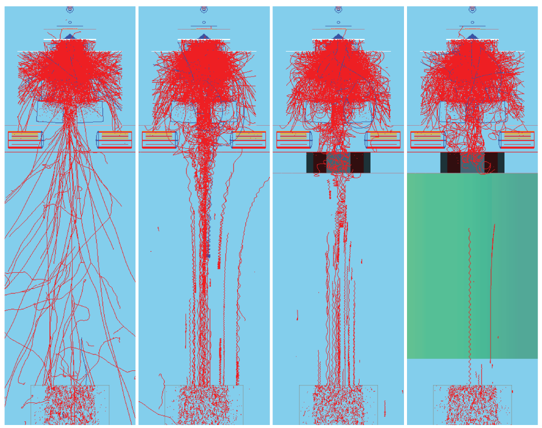


University of Sydney
Real-time imaging and treatment adaptation
Rotating couch development
Liverpool
Ingham Institute
University of NSW
Build research bunker and MRI-linac
Integrated system measurements
Dosimetric validation with EPID
Health technology assessment
Translating research into policy
U Queensland
Magnet, gradient coil and RF performance
The Australian MRI-linac Program:
Improving cancer treatment through real-time image guided adaptive radiotherapy
University of Newcastle
Intrafraction monitoring with EPID
U Western Sydney
Diffusion imaging
Nanoscale contrast agents
Stanford University
Electron gun/waveguide simulations
University of Wollongong
Detector development
Treatment head/patient transport simulations
Proton therapy simulations

Medical Physics

AVAILABLE ONLINE—See http://www.medphys.org May 2014 Volume 41, Number 5

The International Journal of Medical Physics Research and Practice



GEANT 4 Monte Carlo simulation of the impact of 1 T MRI magnetic field on contaminant electron surface dose for a fixed beam-line MRI-Linac combination. The central axis of the 6 MV photon beam is aligned with the cylindrical symmetry axis of the magnetic field with a source-isocenter distance of 160 cm. The tracks of 10,000 charged particles sampled from the phase space file at the base of flattening filter are shown for a 20x20 cm^2 field size. (a) B = 0 T (no magnetic field); (b) B= 1 T MRI with conventional air beam path; (c) B = 1 T with optimal electron contamination deflector (ECD); (d) B = 1 T with optimal ECD and 71 cm thick helium gas reservoir (green rectangle). Clearly, the MRI field with unmodified beam path introduces a large surface-dose hotspot in the field center which is effectively mitigated by the ECD with helium beam path.

[Figure 7 from Oborn, Kolling, Metcalfe, Crozier, Litzenberg, and Keall, ``Electron contamination modeling and reduction in a 1 T open bore inline MRI-linac system,'' Med. Phys. 41, 051708 (15pp.) (2014)].

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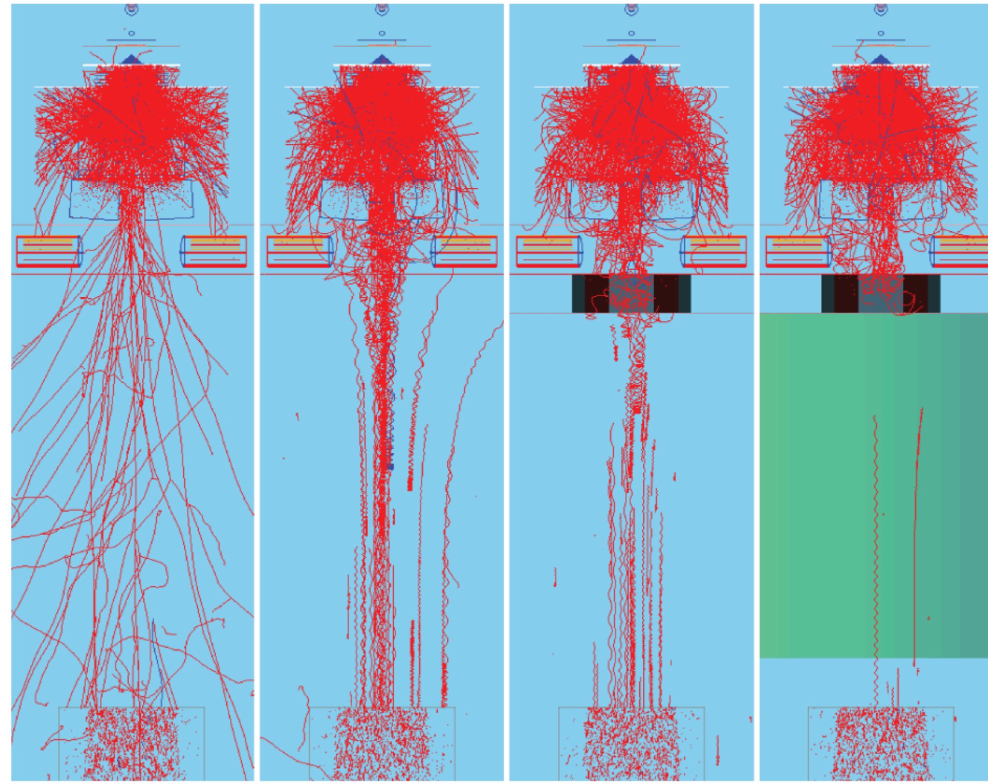
***Medical Physics* is a hybrid gold open-access journal.**



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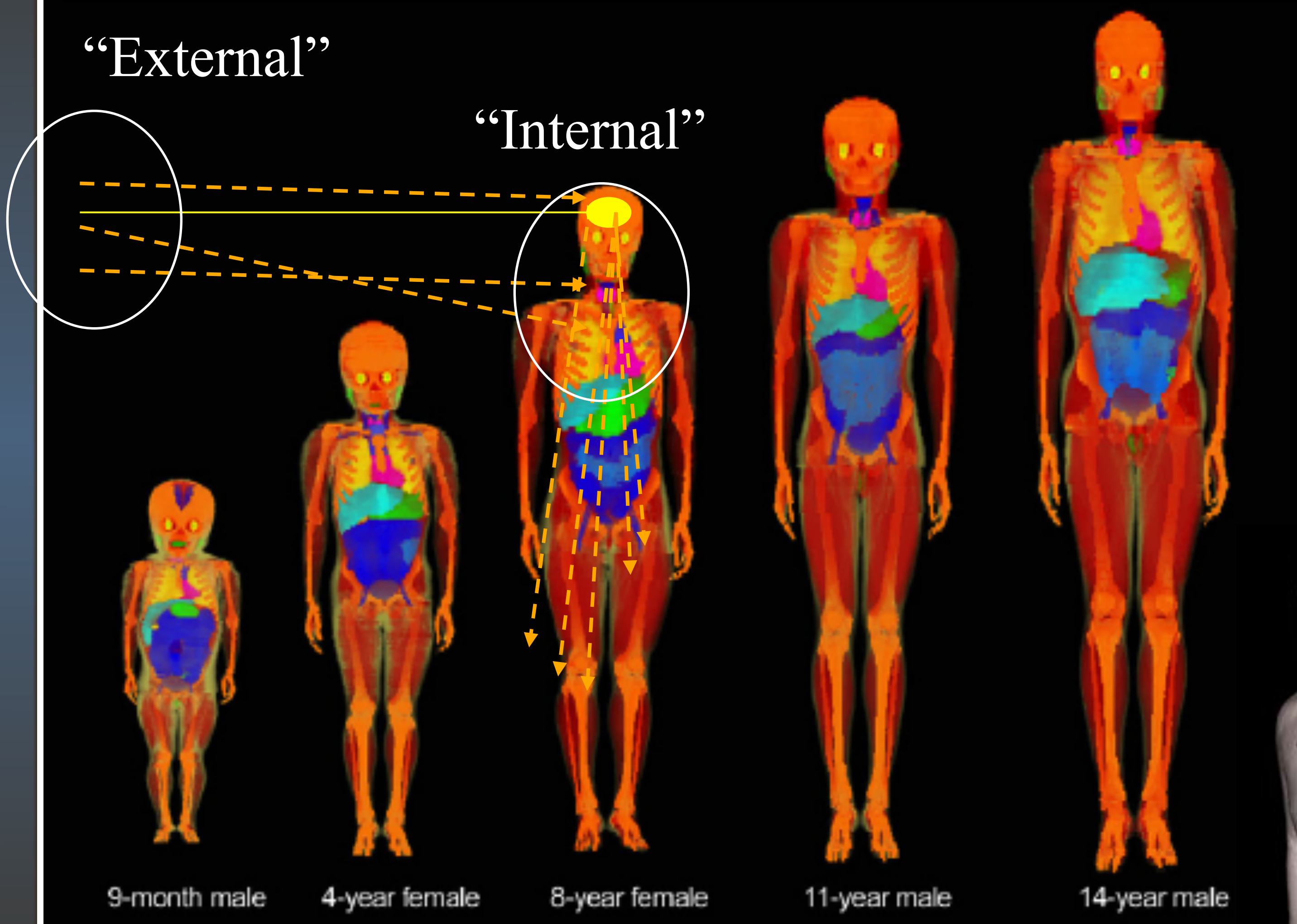
[Figure 7 from Oborn, Kolling, Metcalfe, Crozier, Litzenberg, and Keall, ``Electron contamination modeling and reduction in a 1 T open bore inline MRI-linac system,'' Med. Phys. 41, 051708 (15pp.) (2014)].

The risk associated with neutron radiation in proton therapy

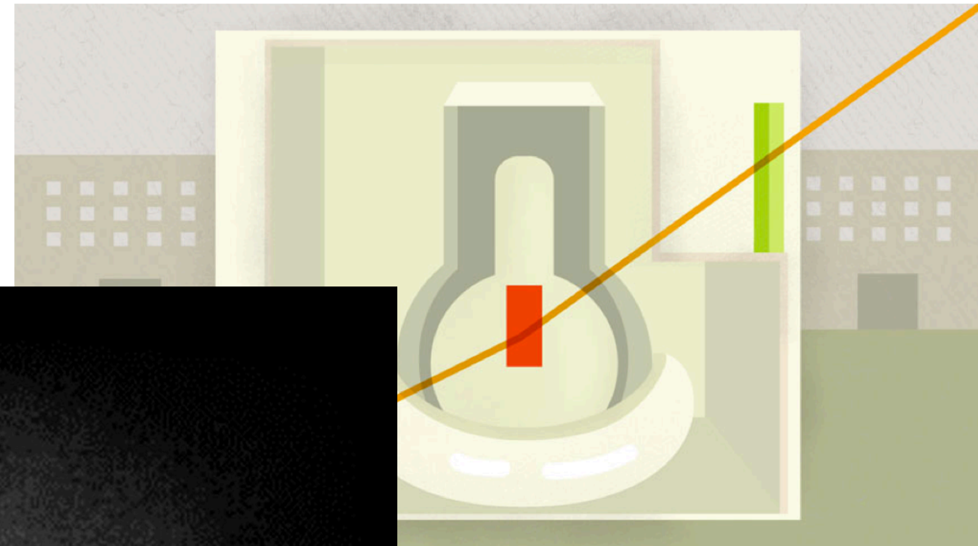


Phantoms implemented into the Geant4 Monte Carlo dose calculation environment at Mass. Gen. Hosp.

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 hrough the reactor. By determining how the ectors, scientists will compile the first picture of

with Shawna X.

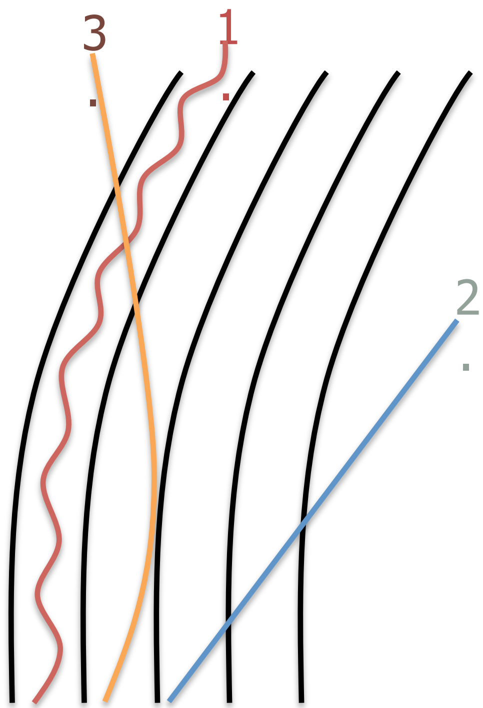
age

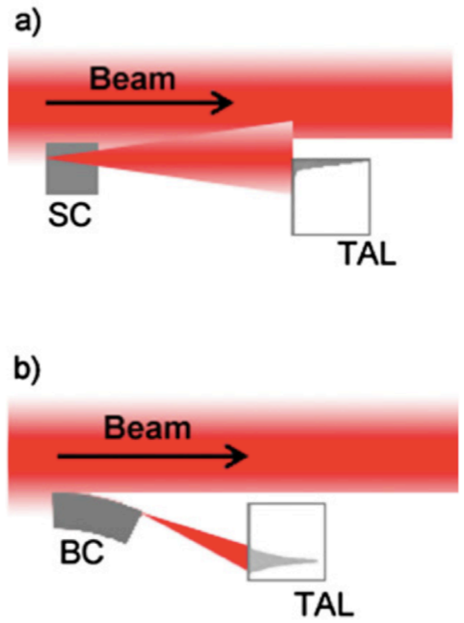
As time ticks down to the restart of the Large Hadron Collider, scientists are making sure their detectors run like clockwork.

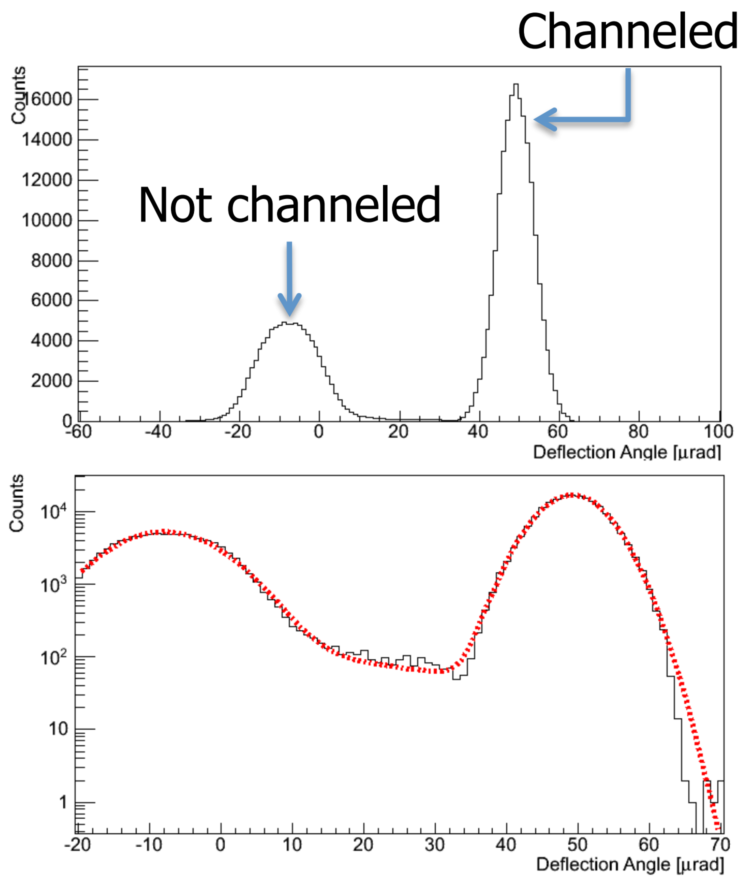
Simulating x-ray cargo radiography

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





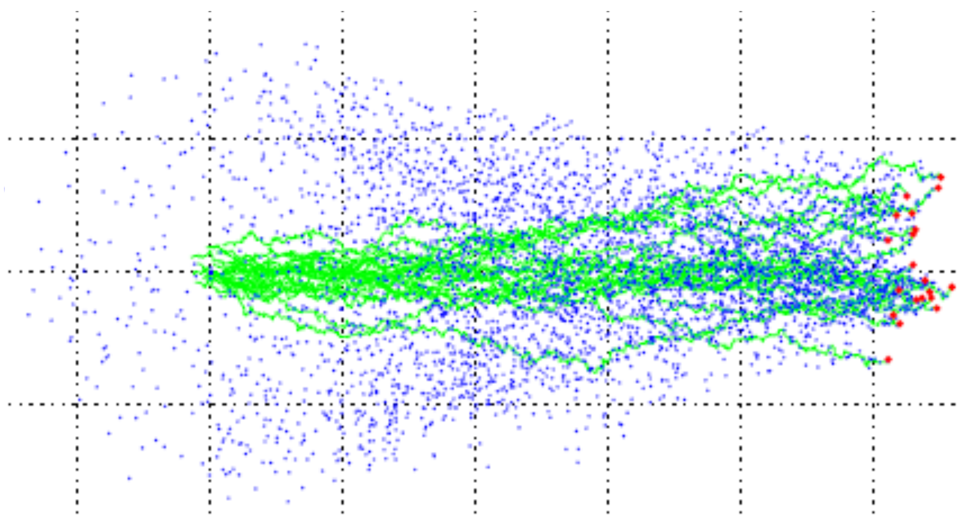


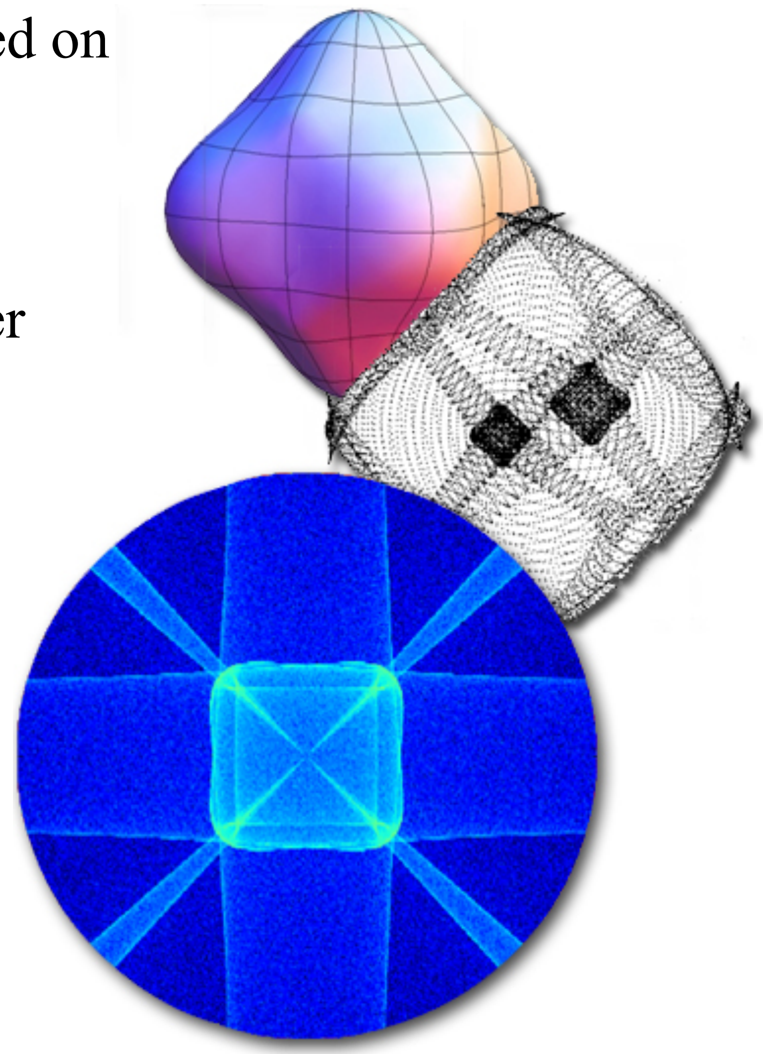
Enrico Bagli (INFN/Ferrara and SLAC)

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

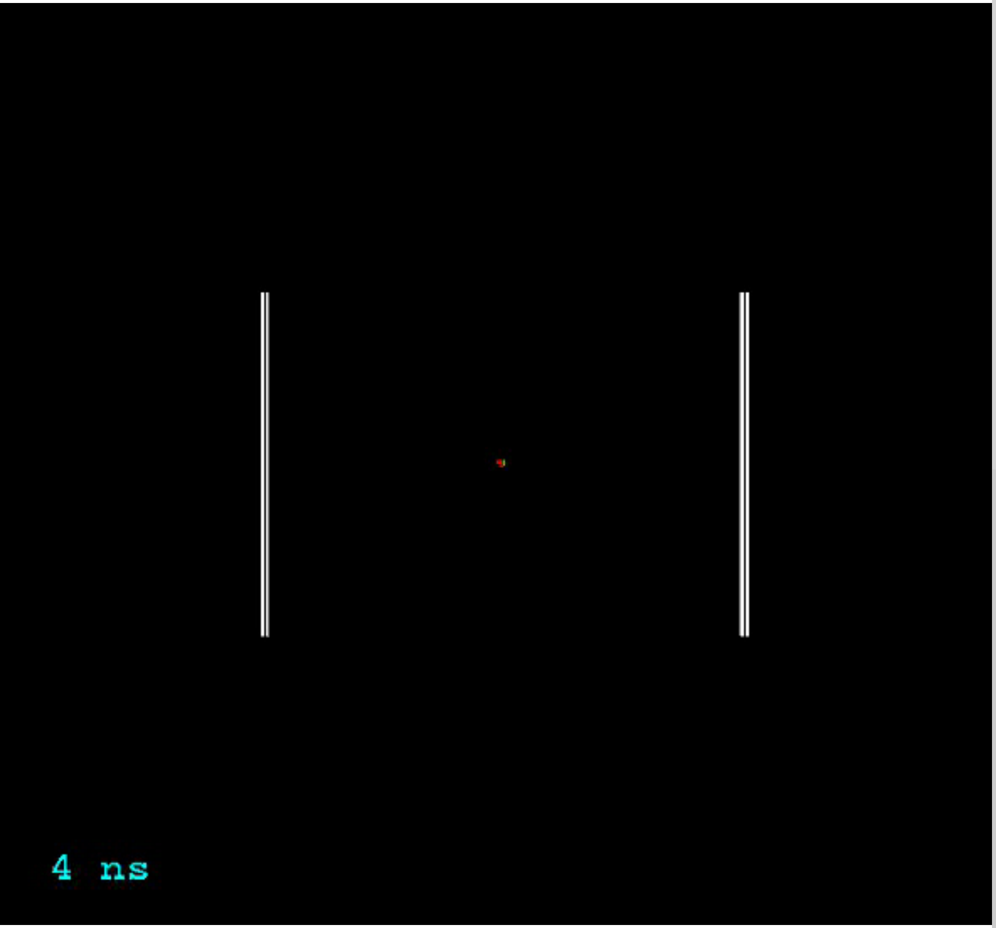
Condensed Matter Physics in Geant4

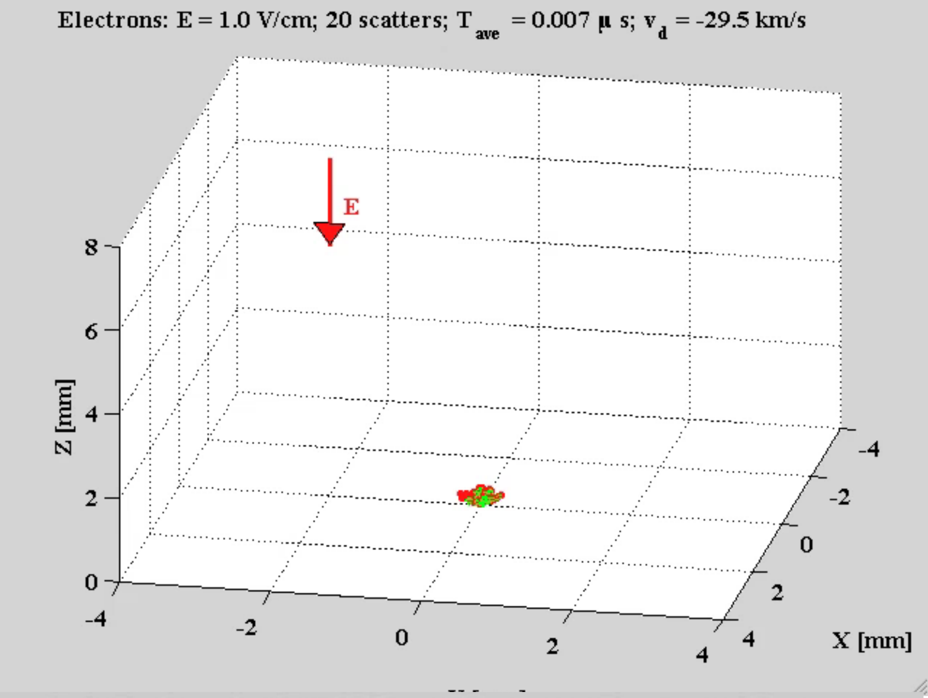
- Phonon propagation, including focusing based on elasticity tensor (right)
- e-/h+ transport, including conduction band anisotropy and Luke-Neganov emission, under development (below)

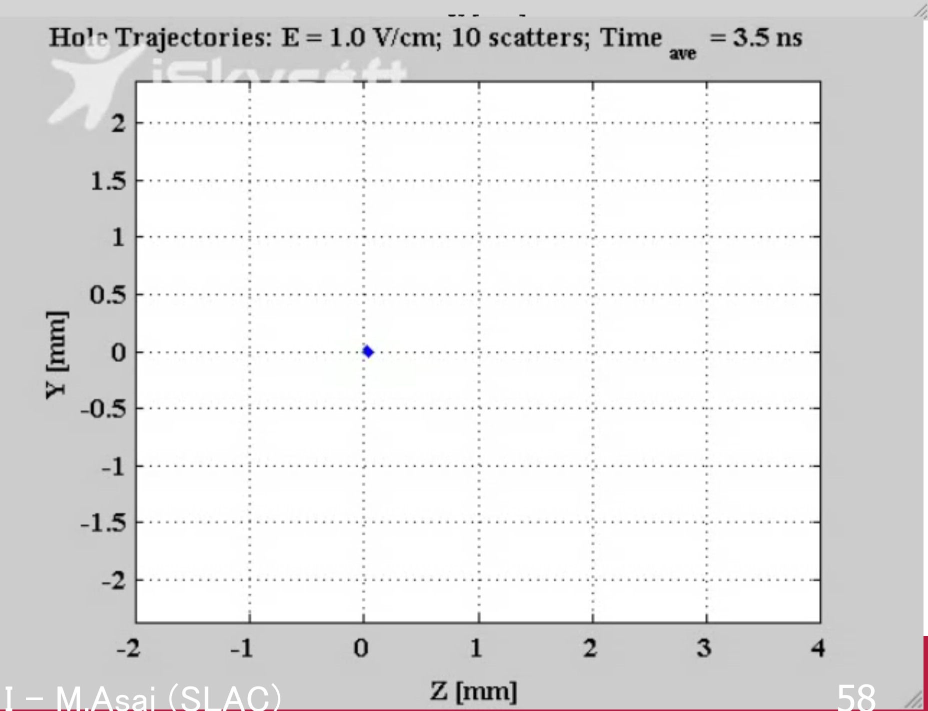




e-/h propagation with Luke phonon emission in Ge crystal







Geant4

Version 10.1-p01

Geant4 license

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- Makes clear the user's wide-ranging freedom to use, extend or redistribute Geant4, even as part of some for-profit venture.
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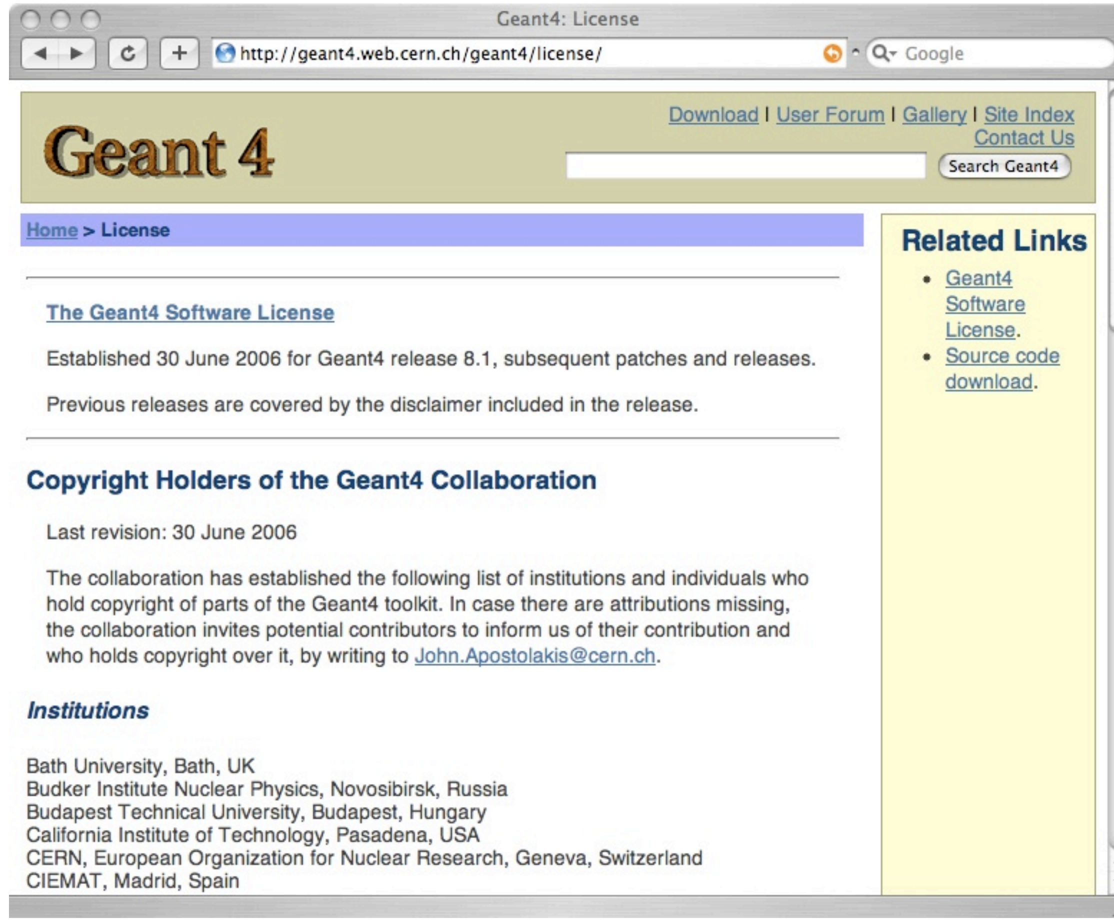
- http://cern.ch/geant4/license/



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Geant 4

Version 10.1-p01

Basic concepts and kernel structure

Terminology (jargons)

- Run, event, track, step, step point
- Track ←→ trajectory, step ←→ trajectory point
- Process
  - At rest, along step, post step
- Cut = production threshold
- Sensitive detector, score, hit, hits collection,

Run in Geant4

- As an analogy of the real experiment, a run of Geant4 starts with "Beam On".
- Within a run, the user cannot change
  – detector setup
  – settings of physics processes
- Conceptually, a run is a collection of events which share the same detector and physics conditions.
  – A run consists of one event loop.
- At the beginning of a run, geometry is optimized for navigation and cross-section tables are calculated according to materials appear in the geometry and the cut-off values defined.
- G4RunManager class manages processing a run, a run is represented by G4Run class or a user-defined class derived from G4Run.
  – A run class may have a summary results of the run.
- G4UserRunAction is the optional user hook.

Event in Geant4

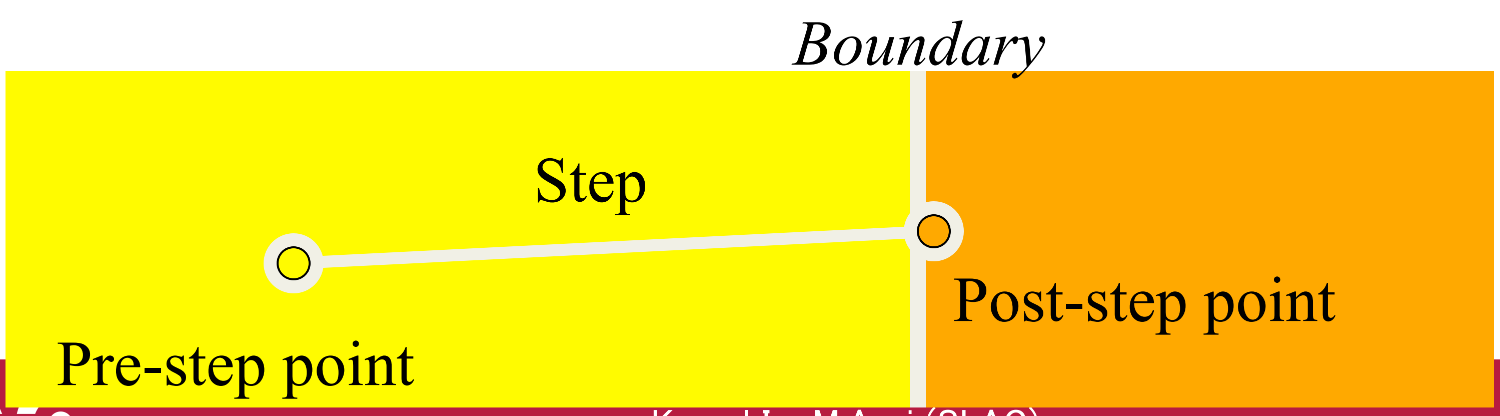
- An event is the basic unit of simulation in Geant4.
- At beginning of processing, primary tracks are generated. These primary tracks are pushed into a stack.
- A track is popped up from the stack one by one and "tracked". Resulting secondary tracks are pushed into the stack.
  - This "tracking" lasts as long as the stack has a track.
- When the stack becomes empty, processing of one event is over.
- G4Event class represents an event. It has following objects at the end of its (successful) processing.
  - List of primary vertices and particles (as input)
  - Hits and Trajectory collections (as output)
- G4EventManager class manages processing an event. G4UserEventAction is the optional user hook.

Track in Geant4

- Track is a snapshot of a particle.
  - It has physical quantities of current instance only. It does not record previous quantities.
  - Step is a "delta" information to a track. Track is not a collection of steps. Instead, a track is being updated by steps.
- Track object is deleted when
  - it goes out of the world volume,
  - it disappears (by e.g. decay, inelastic scattering),
  - it goes down to zero kinetic energy and no "AtRest" additional process is required, or
  - the user decides to kill it artificially.
- No track object persists at the end of event.
  - For the record of tracks, use trajectory class objects.
- G4TrackingManager manages processing a track, a track is represented by G4Track class.
- G4UserTrackingAction is the optional user hook.

Step in Geant4

- Step has two points and also “delta” information of a particle (energy loss on the step, time-of-flight spent by the step, etc.).
- Each point knows the volume (and material). In case a step is limited by a volume boundary, the end point physically stands on the boundary, and it logically belongs to the next volume.
  - Because one step knows materials of two volumes, boundary processes such as transition radiation or refraction could be simulated.
- G4SteppingManager class manages processing a step, a step is represented by G4Step class.
- G4UserSteppingAction is the optional user hook.



Trajectory and trajectory point

- Track does not keep its trace. No track object persists at the end of event.
- G4Trajectory is the class which copies some of G4Track information. G4TrajectoryPoint is the class which copies some of G4Step information.
  - G4Trajectory has a vector of G4TrajectoryPoint.
  - At the end of event processing, G4Event has a collection of G4Trajectory objects.
    - /tracking/storeTrajectory must be set to 1.
- Keep in mind the distinction.
  - G4Track ←→ G4Trajectory, G4Step ←→ G4TrajectoryPoint
- Given G4Trajectory and G4TrajectoryPoint objects persist till the end of an event, you should be careful not to store too many trajectories.
  - E.g. avoid for high energy EM shower tracks.
- G4Trajectory and G4TrajectoryPoint store only the minimum information.
  - You can create your own trajectory / trajectory point classes to store information you need. G4VTrajectory and G4VTrajectoryPoint are base classes.

Particle in Geant4

- A particle in Geant4 is represented by three layers of classes.
- G4Track
  - Position, geometrical information, etc.
  - This is a class representing a particle to be tracked.
- G4DynamicParticle
  - "Dynamic" physical properties of a particle, such as momentum, energy, spin, etc.
  - Each G4Track object has its own and unique G4DynamicParticle object.
  - This is a class representing an individual particle.
- G4ParticleDefinition
  - "Static" properties of a particle, such as charge, mass, life time, decay channels, etc.
  - G4ProcessManager which describes processes involving to the particle
  - All G4DynamicParticle objects of same kind of particle share the same G4ParticleDefinition.

Tracking and processes

- Geant4 tracking is general.
  - It is independent to
    - the particle type
    - the physics processes involving to a particle
  - It gives the chance to all processes
    - To contribute to determining the step length
    - To contribute any possible changes in physical quantities of the track
    - To generate secondary particles
    - To suggest changes in the state of the track
      - e.g. to suspend, postpone or kill it.

Processes in Geant4

- In Geant4, particle transportation is a process as well, by which a particle interacts with geometrical volume boundaries and field of any kind.
  - Because of this, shower parameterization process can take over from the ordinary transportation without modifying the transportation process.
- Each particle has its own list of applicable processes. At each step, all processes listed are invoked to get proposed physical interaction lengths.
- The process which requires the shortest interaction length (in space-time) limits the step.
- Each process has one or combination of the following natures.
  - AtRest
    - e.g. muon decay at rest
  - AlongStep (a.k.a. continuous process)
    - e.g. Celenkov process
  - PostStep (a.k.a. discrete process)
    - e.g. decay on the fly

Cuts in Geant4

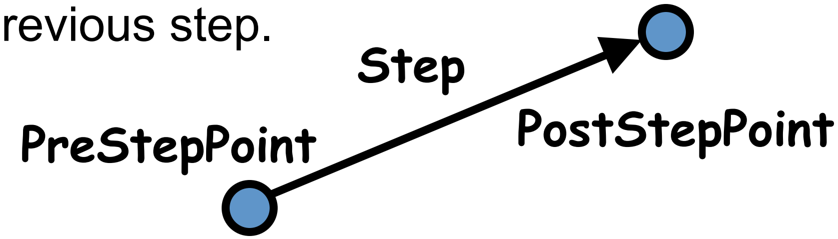
- A Cut in Geant4 is a production threshold.
  - Not tracking cut, which does not exist in Geant4 as default.
    - All tracks are traced down to zero kinetic energy.
  - It is applied only for physics processes that have infrared divergence
- Much detail will be given at later talks on physics.

Track status

- At the end of each step, according to the processes involved, the state of a track may be changed.
  - The user can also change the status in UserSteppingAction.
  - Statuses shown in green are artificial, i.e. Geant4 kernel won't set them, but the user can set.
- fAlive
  - Continue the tracking.
- fStopButAlive
  - The track has come to zero kinetic energy, but still AtRest process to occur.
- fStopAndKill
  - The track has lost its identity because it has decayed, interacted or gone beyond the world boundary.
  - Secondaries will be pushed to the stack.
- fKillTrackAndSecondaries
  - Kill the current track and also associated secondaries.
- fSuspend
  - Suspend processing of the current track and push it and its secondaries to the stack.
- fPostponeToNextEvent
  - Postpone processing of the current track to the next event.
  - Secondaries are still being processed within the current event.

Step status

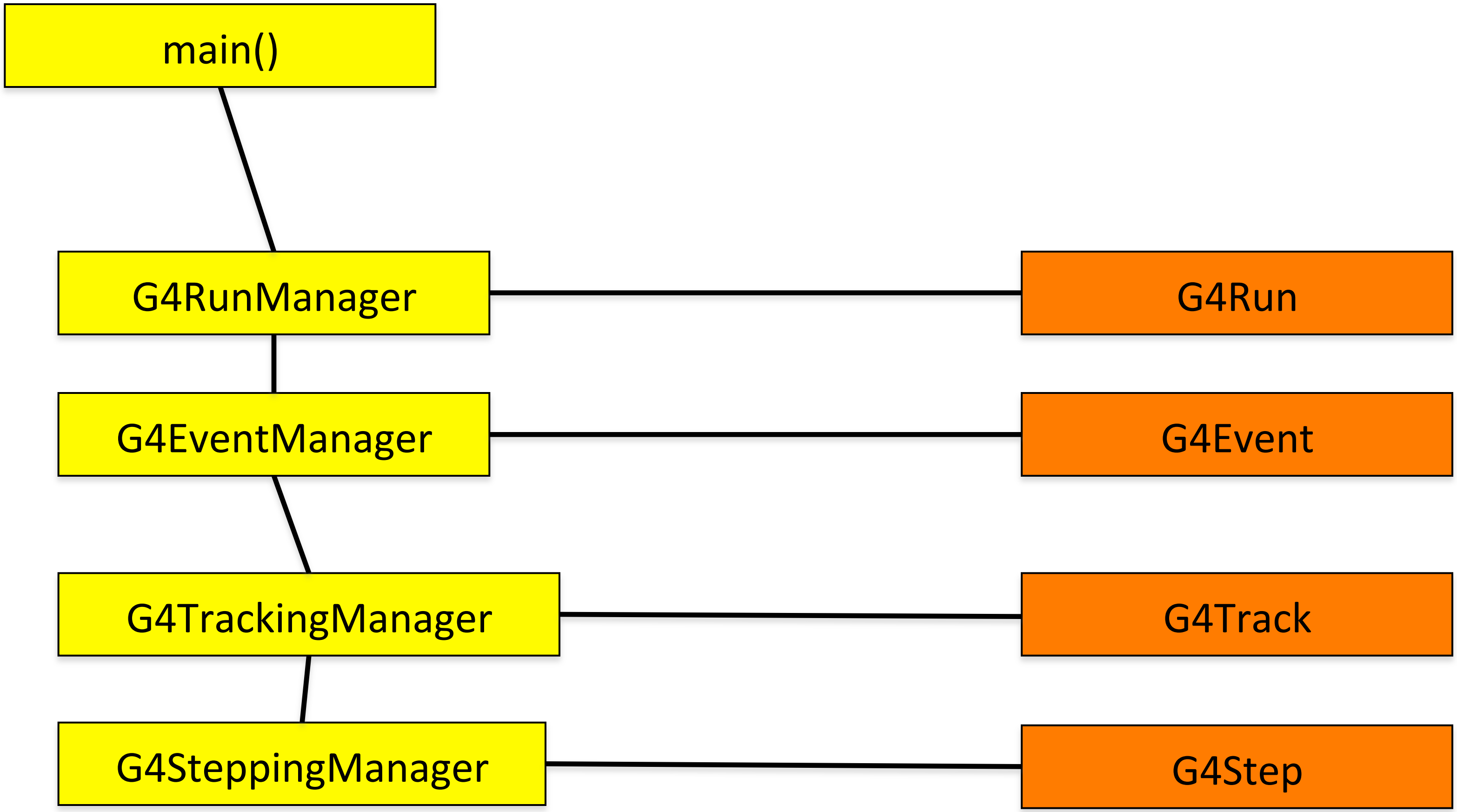
- Step status is attached to G4StepPoint to indicate why that particular step was determined.
  - Use “PostStepPoint” to get the status of this step.
  - “PreStepPoint” has the status of the previous step.



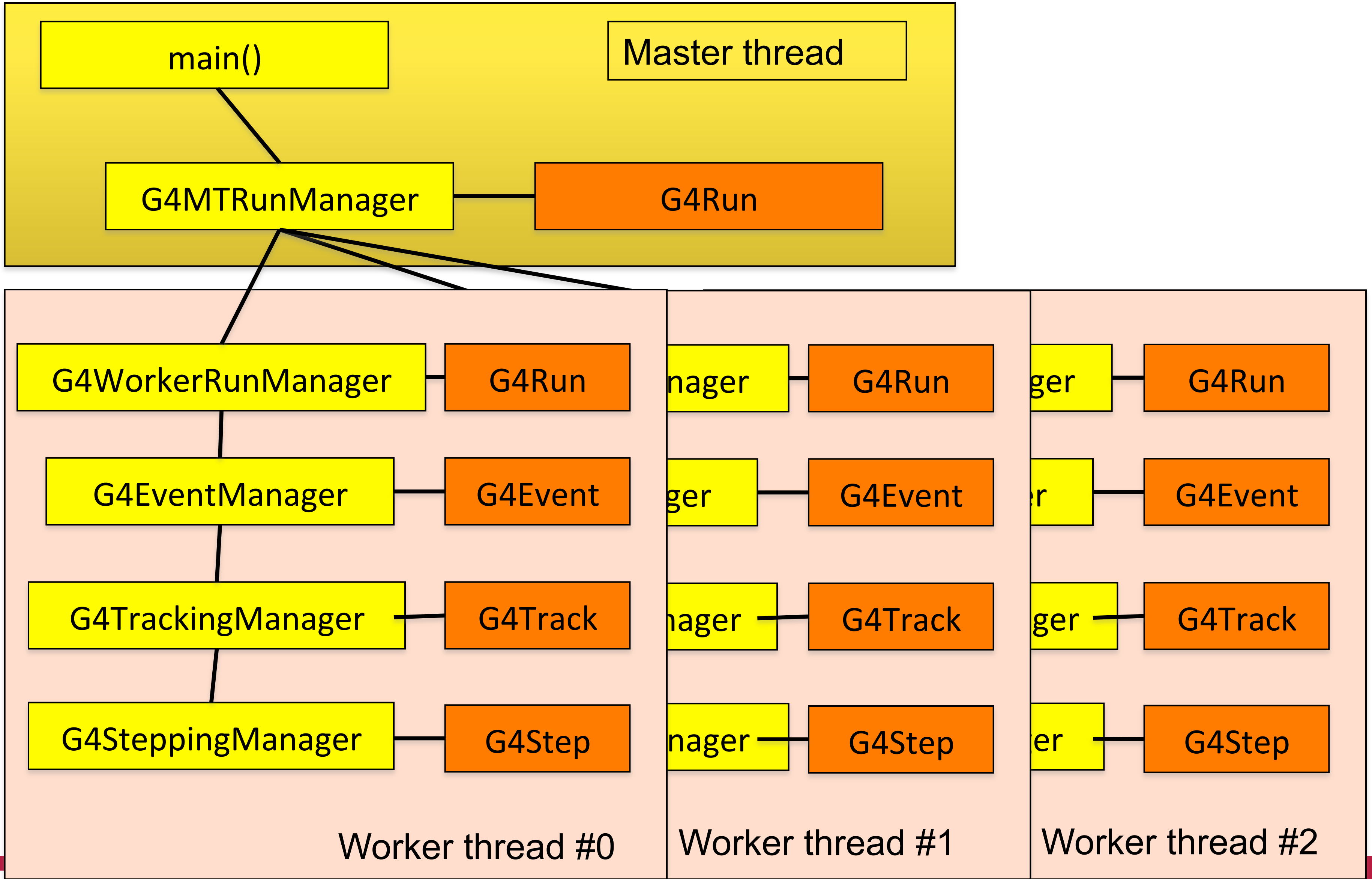
- fWorldBoundary
  - Step reached the world boundary
- fGeomBoundary
  - Step is limited by a volume boundary except the world
- fAtRestDoItProc, fAlongStepDoItProc, fPostStepDoItProc
  - Step is limited by a AtRest, AlongStep or PostStep process
- fUserDefinedLimit
  - Step is limited by the user Step limit
- fExclusivelyForcedProc
  - Step is limited by an exclusively forced (e.g. shower parameterization) process
- fUndefined
  - Step not defined yet

- If you want to identify the first step in a volume, pick fGeomBoudary status in PreStepPoint.
- If you want to identify a step getting out of a volume, pick fGeomBoundary status in PostStepPoint

Sequential mode



Multi-threaded mode



Shared? Thread-local?

- In the multi-threaded mode, generally saying, data that are stable during the event loop are shared among threads while data that are transient during the event loop are thread-local.
- In general, geometry and physics tables are shared, while event, track, step, trajectory, hits, etc., as well as several Geant4 manager classes such as EventManager, TrackingManager, SteppingManager, TransportationManager, FieldManager, Navigator, SensitiveDetectorManager, etc. are thread-local.
- Among the user classes, user initialization classes (G4VUserDetectorConstruction, G4VUserPhysicsList and newly introduced G4VUserActionInitialization) are shared, while all user action classes and sensitive detector classes are thread-local.
  - It is not straightforward (and thus not recommended) to access from a shared class object to a thread-local object, e.g. from detector construction to stepping action.
  - Please note that thread-local objects are instantiated and initialized at the first *BeamOn*.
- To avoid potential errors, it is advised to always keep in mind which class is shared and which class is thread-local.

Extract useful information

- Given geometry, physics and primary track generation, Geant4 does proper physics simulation "silently".
  - You have to do something to extract information useful to you.
- There are three ways:
  - Built-in scoring commands
    - Most commonly-used physics quantities are available.
  - Use scorers in the tracking volume
    - Create scores for each event
    - Create own Run class to accumulate scores
  - Assign G4VSensitiveDetector to a volume to generate "hit".
    - Use user hooks (G4UserEventAction, G4UserRunAction) to get event / run summary
- You may also use user hooks (G4UserTrackingAction, G4UserSteppingAction, etc.)
  - You have full access to almost all information
  - Straight-forward in sequential mode, but do-it-yourself

Unit system

- Internal unit system used in Geant4 is completely hidden not only from user's code but also from Geant4 source code implementation.
- Each hard-coded number must be multiplied by its proper unit.

```
radius = 10.0 * cm;
kineticE = 1.0 * GeV;
```

- To get a number, it must be divided by a proper unit.

```
G4cout << eDep / MeV << " [MeV]" << G4endl;
```

- Most of commonly used units are provided and user can add his/her own units.
- By this unit system, source code becomes more readable and importing / exporting physical quantities becomes straightforward.
  - For particular application, user can change the internal unit to suitable alternative unit without affecting to the result.

G4cout, G4cerr

- G4cout and G4cerr are *ostream* objects defined by Geant4.
  - G4endl is also provided.

```
G4cout << "Hello Geant4!" << G4endl;
```

- Some GUIs are buffering output streams so that they display print-outs on another window or provide storing / editing functionality.
  - The user should not use std::cout, etc.
- The user should not use std::cin for input. Use user-defined commands provided by intercoms category in Geant4.
  - Ordinary file I/O is OK.

G4cout in multithreaded mode

- By default, every G4cout string is displayed on the screen in the order as it is generated.
  - A line made by a worker thread is preceded by the worker identifier.
- It is not very readable if lines of several worker threads interleave.

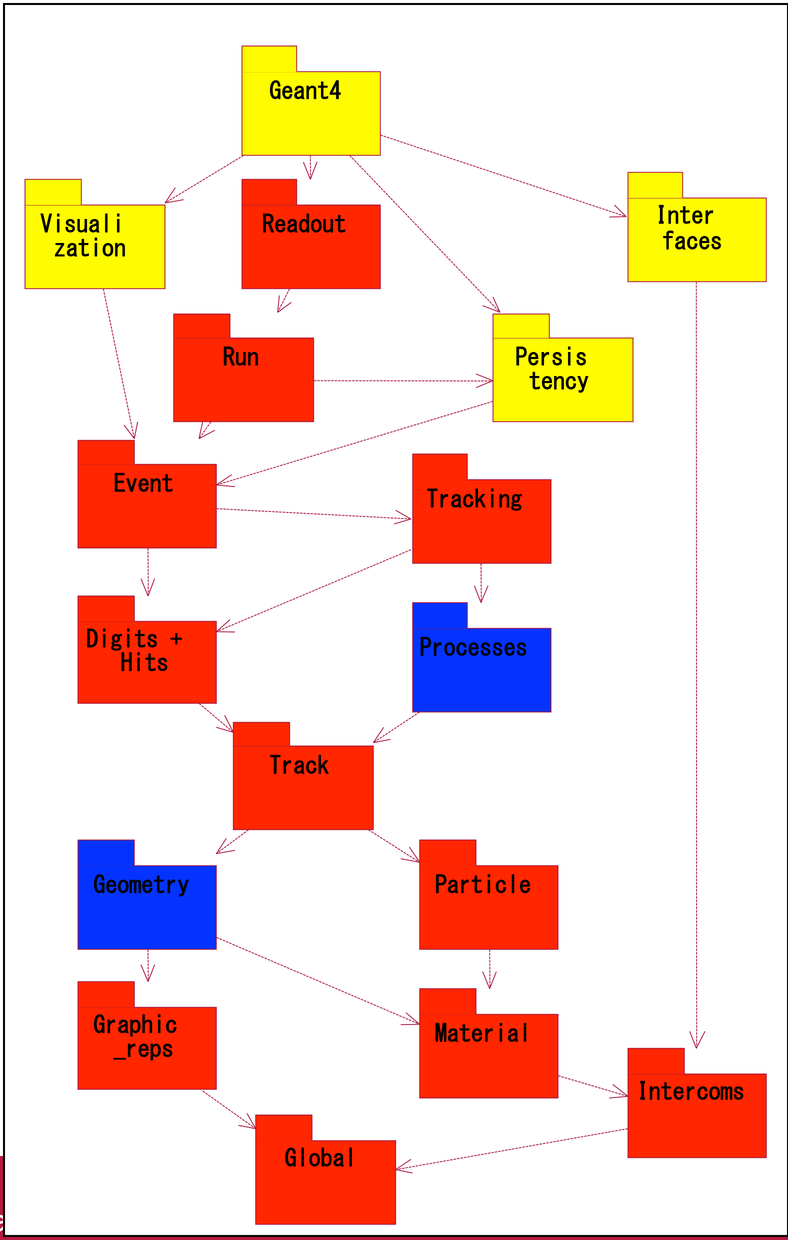
  /control/cout/ignoreThreadsExcept <threadID>
  - Omit cout from worker threads except the specified one.
  - If specified thread ID is greater than the number of threads, no cout is displayed from worker threads. -1 to reset.

  /control/cout/useBuffer <true/false>
  - Send cout stream to a buffer dedicated to each worker thread.
  - The buffered text will be printed at the end of the job for each thread at a time, so that output of each thread is grouped.

  /control/cout/setCoutFile <fileName> <appendFlag>
  - Send G4cout stream to a file dedicated to a thread.
  - If append flag is true output is appended to the existing file, otherwise file output is overwritten.
  - To return to a display output, use special file name "**Screen**".

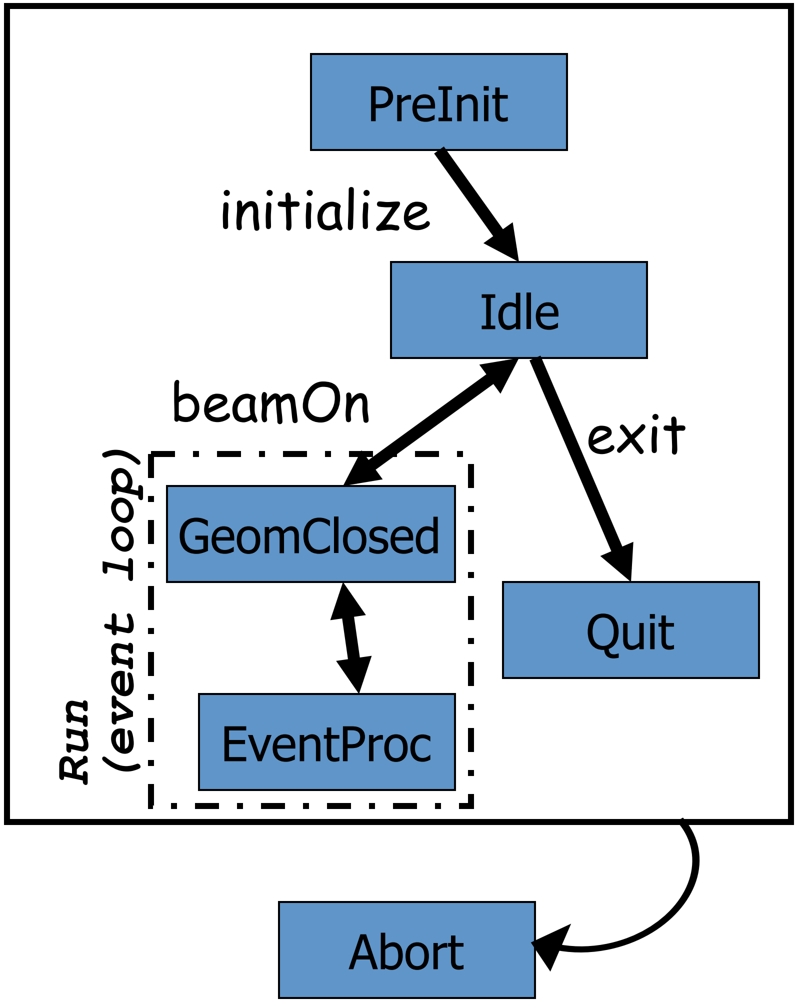
Geant4 kernel

- Geant4 consists of 17 categories.
  - Independently developed and maintained by WG(s) responsible to each category.
  - Interfaces between categories (e.g. top level design) are maintained by the global architecture WG.
- Geant4 Kernel
  - Handles run, event, track, step, hit, trajectory.
  - Provides frameworks of geometrical representation and physics processes.



Geant4 as a state machine

- Geant4 has six application states.
  - G4State_PreInit
    - Material, Geometry, Particle and/or Physics Process need to be initialized/defined
  - G4State_Idle
    - Ready to start a run
  - G4State_GeomClosed
    - Geometry is optimized and ready to process an event
  - G4State_EventProc
    - An event is processing
  - G4State_Quit
    - (Normal) termination
  - G4State_Abort
    - A fatal exception occurred and program is aborting



Note: Toggles between GeomClosed and EventProc occur for each thread asynchronously in multithreaded mode.

Geant 4

Version 10.1-p01

User classes

To use Geant4, you have to…

- Geant4 is a toolkit. You have to build an application.
- To make an application, you have to
  - Define your geometrical setup
    - Material, volume
  - Define physics to get involved
    - Particles, physics processes/models
    - Production thresholds
  - Define how an event starts
    - Primary track generation
  - Extract information useful to you
- You may also want to
  - Visualize geometry, trajectories and physics output
  - Utilize (Graphical) User Interface
  - Define your own UI commands
  - etc.

User classes

- main()
  - Geant4 does not provide *main().*
- Initialization classes
  - Use G4RunManager::SetUserInitialization() to define.
  - Invoked at the initialization
    - G4VUserDetectorConstruction
    - G4VUserPhysicsList
    - G4VUserActionInitialization
- Action classes
  - Instantiate in your G4VUserActionInitialization.
  - Invoked during an event loop
    - G4VUserPrimaryGeneratorAction
    - G4UserRunAction
    - G4UserEventAction
    - G4UserStackingAction
    - G4UserTrackingAction
    - G4UserSteppingAction

Note : classes written in red are mandatory.

The main program

- Geant4 does not provide a *main*().
- In your *main(),* you have to
  - Construct G4RunManager (sequential mode) or G4MTRunManager (multithreaded mode)
  - Set user mandatory initialization classes to RunManager
    - G4VUserDetectorConstruction
    - G4VUserPhysicsList
    - G4VUserActionInitialization
- You can define VisManager, (G)UI session, optional user action classes, and/or your persistency manager in your *main()*.

Describe your detector

- Derive your own concrete class from G4VUserDetectorConstruction abstract base class.
- In the virtual method *Construct()*, that is invoked in the master thread (and in sequential mode)
  - Instantiate all necessary materials
  - Instantiate volumes of your detector geometry
- In the virtual method *ConstructSDandField()*, that is invoked in each worker thread (and in sequential mode)
  - Instantiate your sensitive detector classes and field classes and set them to the corresponding logical volumes and field managers, respectively.

Select physics processes

- Geant4 does not have any default particles or processes.
  - Even for the particle transportation, you have to define it explicitly.
- Derive your own concrete class from G4VUserPhysicsList abstract base class.
  - Define all necessary particles
  - Define all necessary processes and assign them to proper particles
  - Define cut-off ranges applied to the world (and each region)
- Primarily, the user's task is choosing a "pre-packaged" physics list, that combines physics processes and models that are relevant to a typical application use-cases.
  - If "pre-packaged" physics lists do not meet your needs, you may add or alternate some processes/models.
  - If you are brave enough, you may implement your physics list.

Generate primary event

- This is the only mandatory user action class.
- Derive your concrete class from G4VUserPrimaryGeneratorAction abstract base class.
- Pass a G4Event object to one or more primary generator concrete class objects which generate primary vertices and primary particles.
- Geant4 provides several generators in addition to the G4VPrimaryParticlegenerator base class.
  - G4ParticleGun
  - G4HEPEvtInterface, G4HepMCInterface
    - Interface to /hepevt/ common block or HepMC class
  - G4GeneralParticleSource
    - Define radioactivity

Optional user action classes

- All user action classes, methods of which are invoked during “Beam On”, must be constructed in the user’s *main*() and must be set to the RunManager.
- G4UserRunAction
  - G4Run* GenerateRun()
    - Instantiate user-customized run object
  - void BeginOfRunAction(const G4Run*)
    - Define histograms
  - void EndOfRunAction(const G4Run*)
    - Analyze the run
    - Store histograms
- G4UserEventAction
  - void BeginOfEventAction(const G4Event*)
    - Event selection
  - void EndOfEventAction(const G4Event*)
    - Output event information

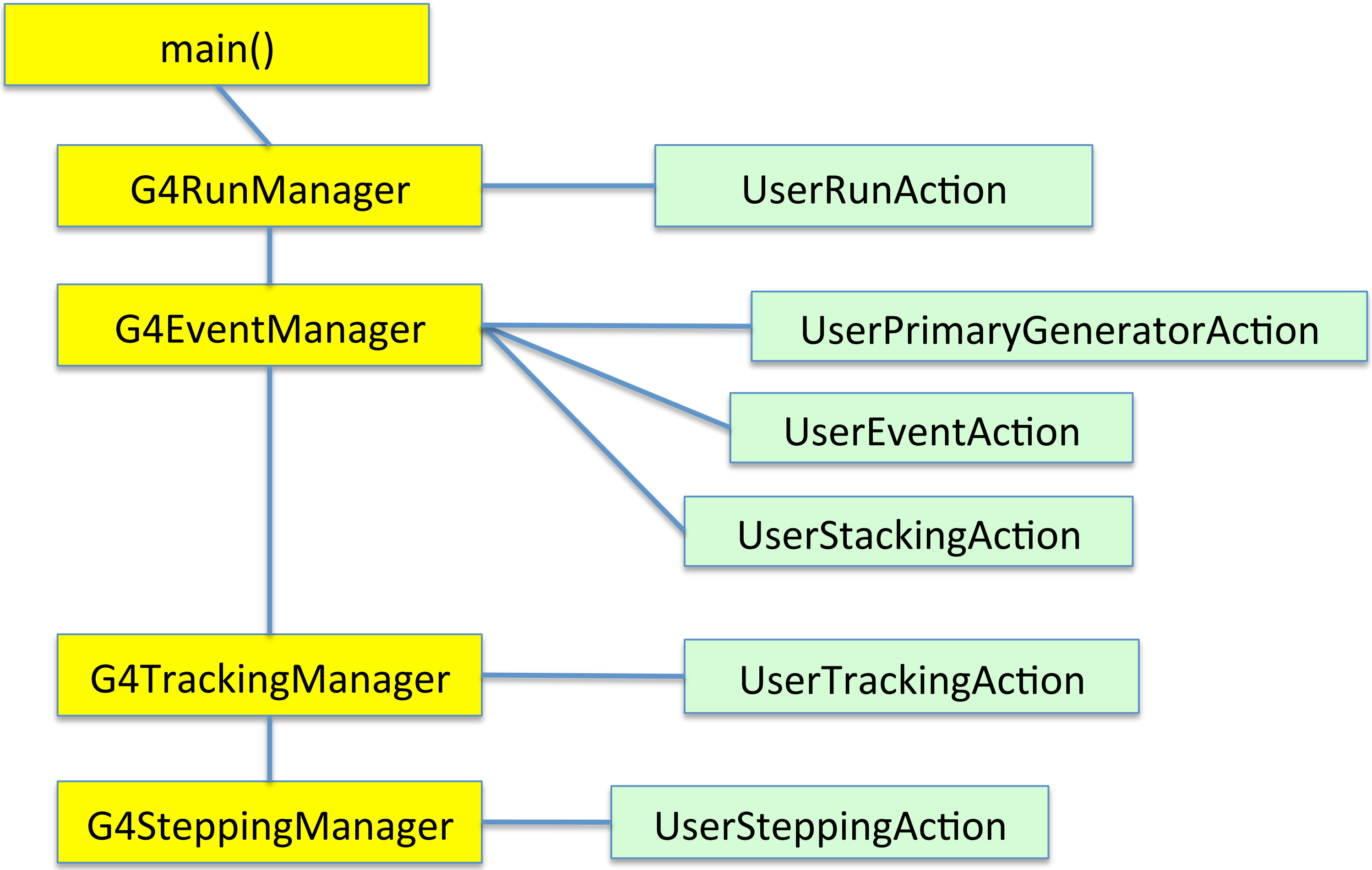
Optional user action classes

- G4UserStackingAction
  - void PrepareNewEvent()
    - Reset priority control
  - G4ClassificationOfNewTrack ClassifyNewTrack(const G4Track*)
    - Invoked every time a new track is pushed
    - Classify a new track -- priority control
      - Urgent, Waiting, PostponeToNextEvent, Kill
  - void NewStage()
    - Invoked when the Urgent stack becomes empty
    - Change the classification criteria
    - Event filtering (Event abortion)

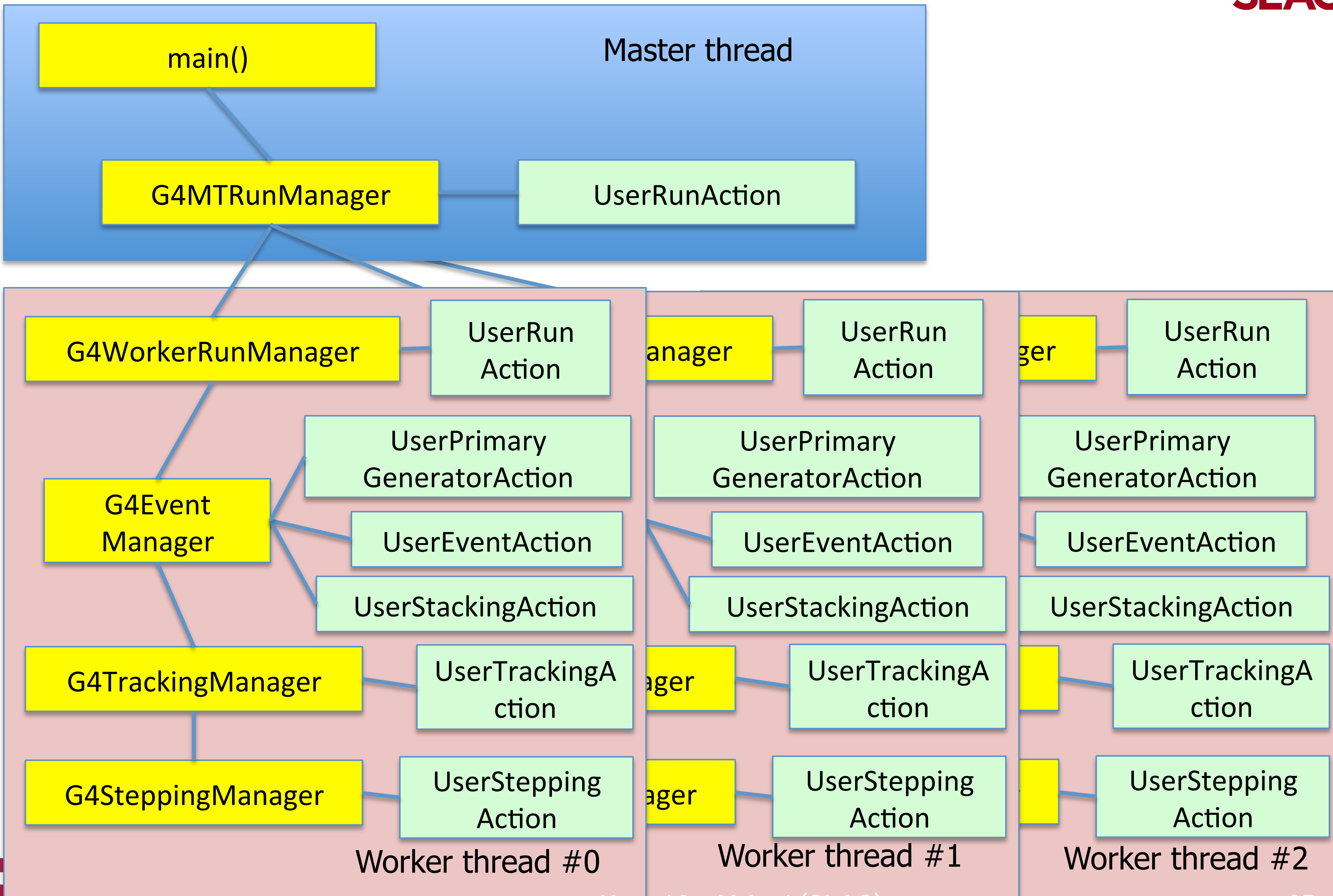
Optional user action classes

- G4UserTrackingAction
  - void PreUserTrackingAction(const G4Track*)
    - Decide trajectory should be stored or not
    - Create user-defined trajectory
  - void PostUserTrackingAction(const G4Track*)
    - Delete unnecessary trajectory
- G4UserSteppingAction
  - void UserSteppingAction(const G4Step*)
    - Kill / suspend / postpone the track
    - Draw the step (for a track not to be stored as a trajectory)

Sequential mode



Multi-threaded mode



Instantiate user action classes

- G4VUserActionInitialization has two virtual methods.
- *Build()*
  - Invoked at the beginning of each worker thread as well as in sequential mode
  - Use *SetUserAction()* method to register pointers of all user actions.
  - In multithreaded mode, all user action class objects instantiated in this method are thread-local.
    - User run action instantiated in this method is for thread-local run
- *BuildForMaster()*
  - Invoked only at the beginning of the master thread in multithreaded mode
  - Use *SetUserAction()* method to register pointer of user run action for the global run.

Let me remind you…

- Define material and geometry
  - → G4VUserDetectorConstruction
    - Material and Geometry lectures
- Select appropriate particles and processes and define production threshold(s)
  - → G4VUserPhysicsList
    - Physics lectures
- Instantiate user action classes
  - → G4VUserActionInitialization
    - Hands-on
- Define the way of primary particle generation
  - → G4VUserPrimaryGeneratorAction
    - Primary particle lecture
- Define the way to extract useful information from Geant4
  - → G4VUserDetectorConstruction, G4UserEventAction, G4Run, G4UserRunAction
  - → G4SensitiveDetector, G4VHit, G4VHitsCollection
    - Scoring lectures