Simulating Gamma-Ray Telescopes in Space Radiation Environments with Geant4:

Detector Activation

Andreas Zoglauer

University of California at Berkeley, Space Sciences Laboratory, Berkeley, USA

Georg Weidenspointner

Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

MPI Halbleiterlabor, München, Germany

Steven E. Boggs

University of California at Berkeley, Space Sciences Laboratory, Berkeley, USA

Which telescopes do we want to simulate?

Gamma-ray Telescopes

Reproduce & improve background knowledge of past and current instruments:

→ optimize data analysis and sensitivity of those instruments

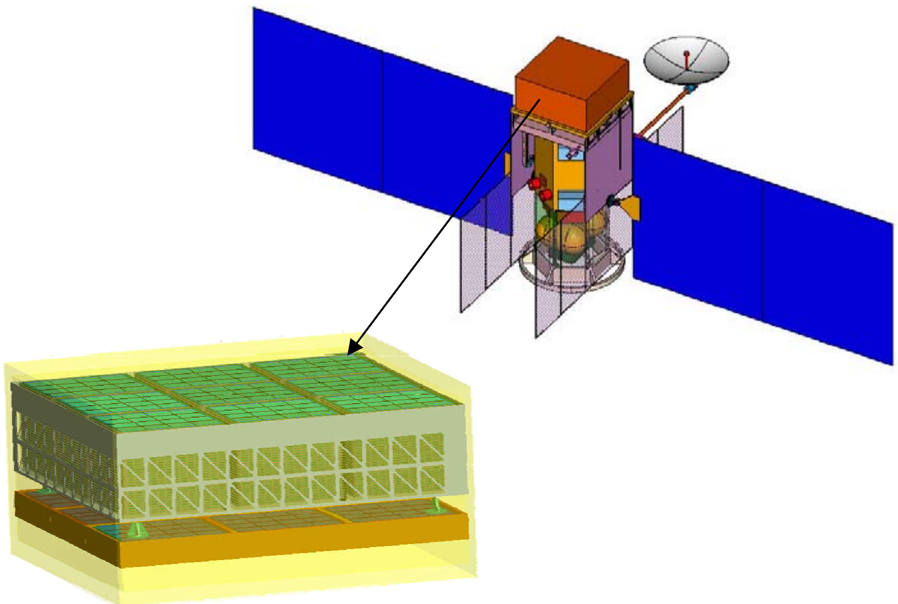
CGRO/COMPTEL: 0.7-30 MeV

INTEGRAL/SPI: 0.02 – 8 MeV

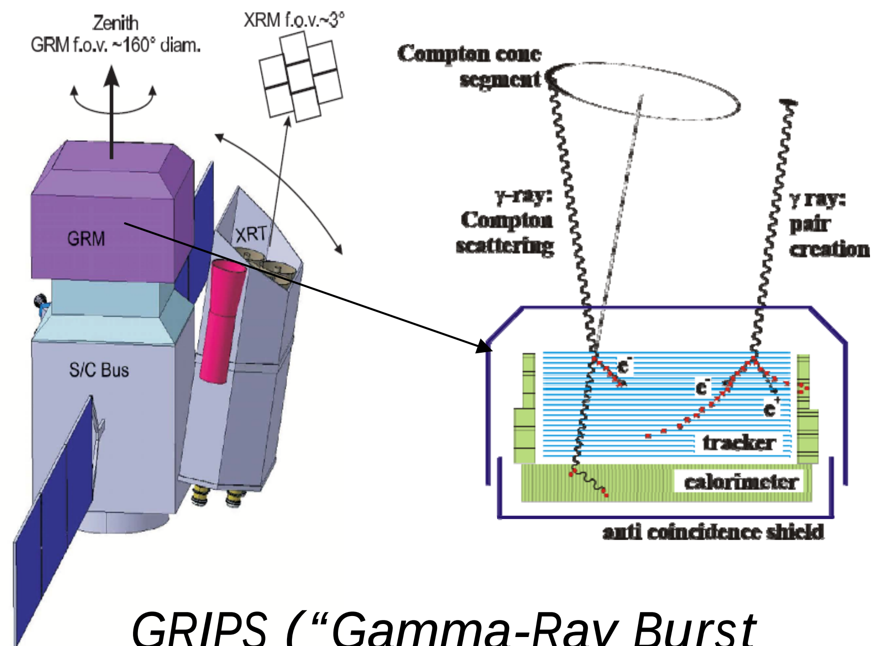
But also: Suzaku, Swift, etc.

Future Gamma-ray Telescopes

Estimate & optimize the performance of future soft-to-medium gamma-ray telescopes:



ACT ("Advanced Compton Telescope"): 0.2-10 MeV



GRIPS ("Gamma-Ray Burst Investigations via Polarization and Spectroscopy"): 0.2 – 50 MeV

But also: NeXT, NuSTAR, eROSITA, XEUS, GRI, etc.

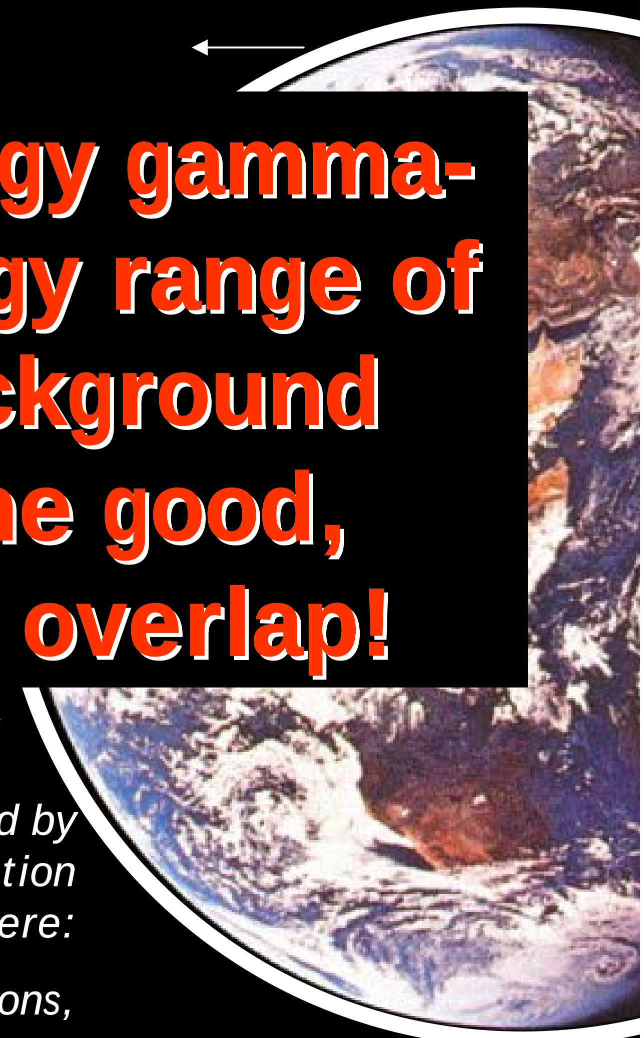
Which background components do we need to simulate?

The Space Radiation Environment

Sun through solar flares: photons, charged particles

Radiation belts:

Trapped protons (SAA) & resulting activation, electrons



For soft-to-medium energy gamma-ray telescopes, the energy range of the deposits of the background events and those of the good, "astrophysical" events overlap!

Cos

- Electrons
- Positrons

For some applications cosmic photons are also background

Secondaries induced by cosmic ray interaction with upper atmosphere:

Albedo photons, neutrons, electron, positrons

What are the requirements for the simulation engine?

Simulation requirements I

- *Photon interactions (250 eV – 1 TeV)*
  - **Polarized Compton scattering (including subsequent Compton scatters) with Doppler broadening**
  - **Polarized gamma conversion (at least down to a few MeV) including conversion on electrons**
  - Rayleigh scattering (taking care of polarization)
  - Photo effect
  - Photo nuclear reaction (e.g. Giant Dipole Resonance)
  - Atomic de-excitation
- *Electron interactions (250 eV – 1 TeV)*
  - Energy loss via ionization (must work for thin media!)
  - Molière scattering (must work for thin media!)
  - Bremsstrahlung
  - Delta rays
  - Møller scattering
- *Positron interactions (250 eV – 1 TeV)*
  - see electrons
  - Bahaba scattering instead of Møller scattering

Simulation requirements II

- *Proton interactions (up to 1 TeV)*
  - Ionization and scattering
  - Bremsstrahlung
  - Spallation
  - Capture
  - Nuclear de-excitation
- *Alpha particles interactions*
  - See protons (including capture!!)
- *Ion interactions (up to Fe)*
  - See alpha

Important for activation:

- Interaction cross sections for ALL isotopes
- Correct generation of radioactive isotopes
- Handle all channels of de-excitations and decays

Simulation requirements III

- *Neutron interactions (thermal – 1 TeV)*
  - Elastic scattering
  - Inelastic scattering
  - Neutron capture
  - Etc.

Important for activation:

- Interaction cross-sections for all isotopes
- Generation of correct radioactive isotopes in the correct amount
- Handle all channels of de-excitations and decays

Simulation requirements IV

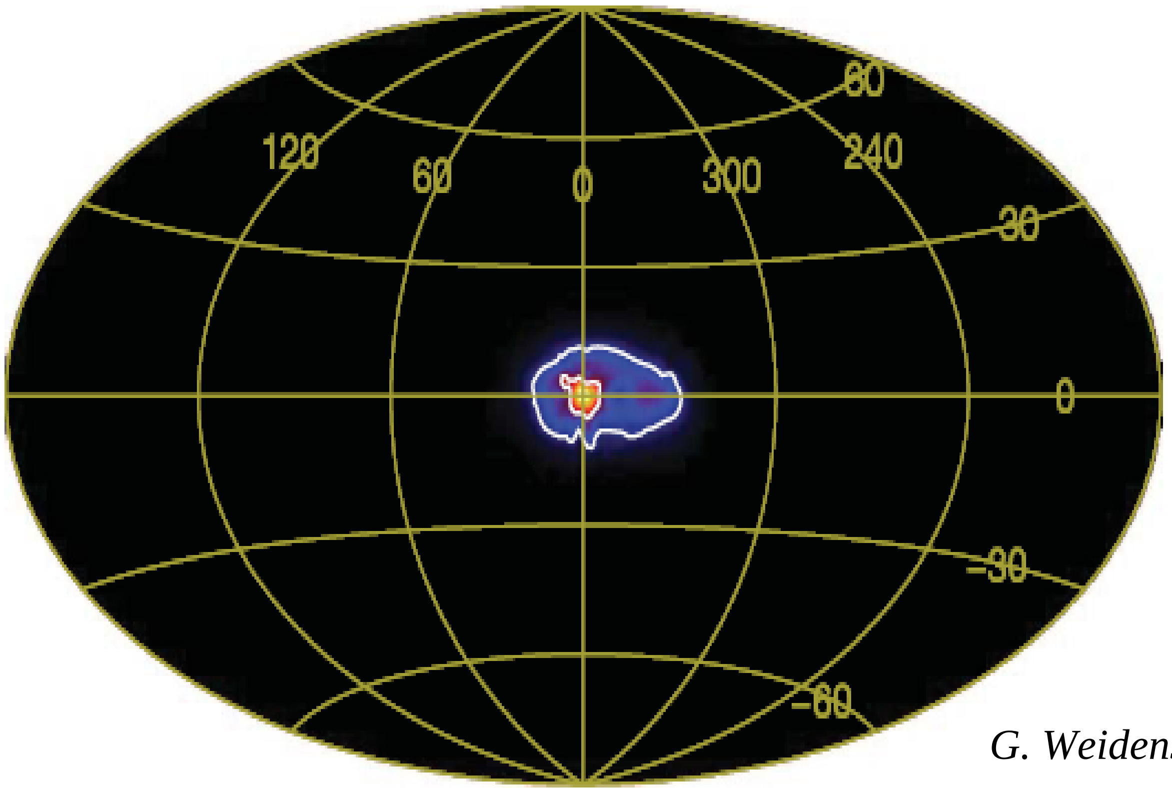
- *For generated radioactive isotopes:*
  - Handle radioactive decay including all possible decay channels & branching ratios
  - Correctly handle de-excitation, meta-stable states, etc.
  - Distinguish between PROMPT (within detectors coincidence window) and DELAYED de-excitation and radioactive decay
  - Determine build-up of radioactive elements over mission life

Many elements already included in Geant4

Missing:

Pipeline for simulating activation

Why is activation so important?



G. Weidenspointner, 2008

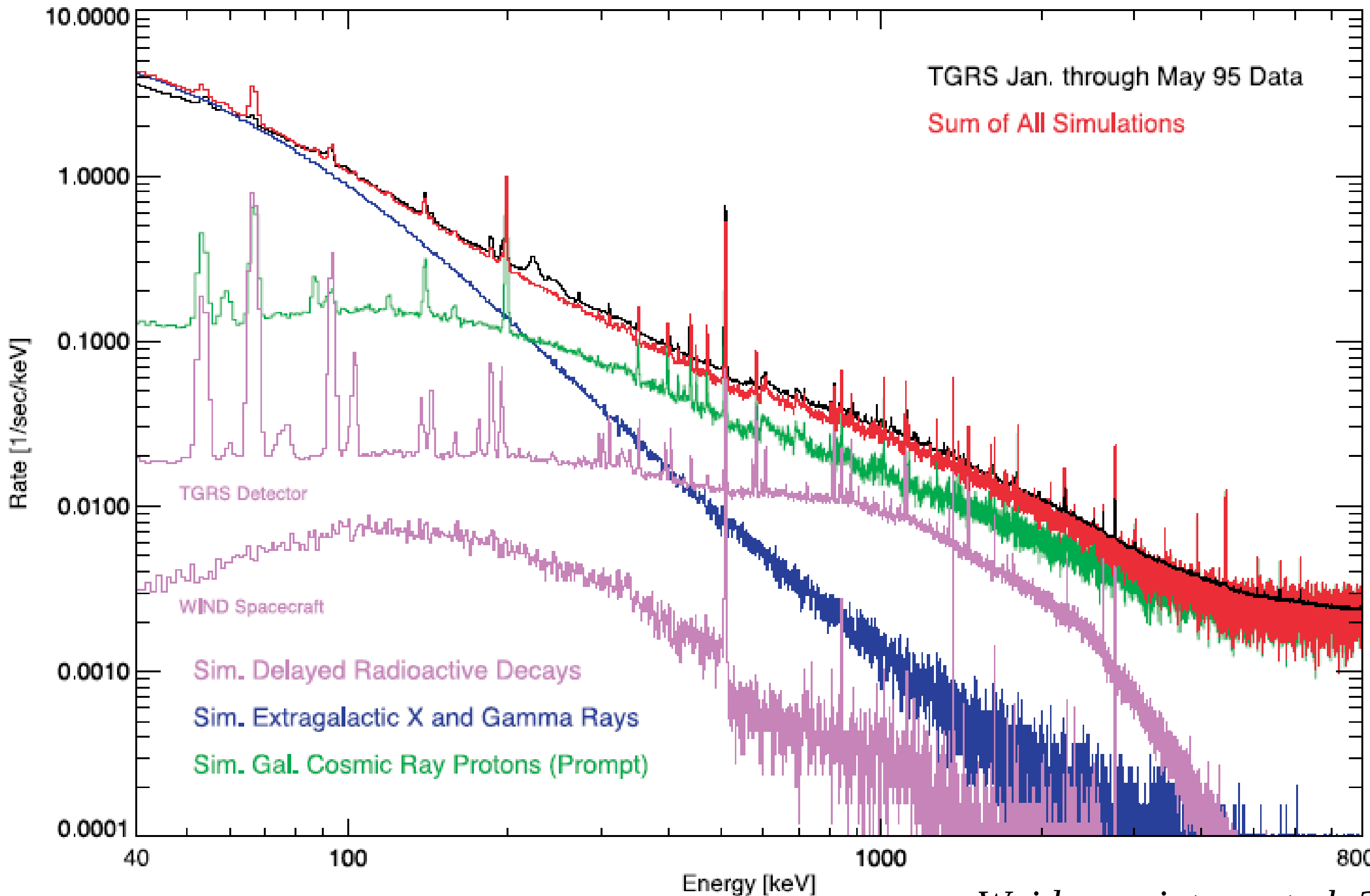
Many lines of high astrophysical interest, such as 511 keV (positron annihilation) or 1809 keV (^{26}Al – tracer for star creation regions) are also produced by radioactive decays induced by activation!

History:
Simulations with MGGPOD

MGGPOD

- *What is MGGPOD?*
  - Monte-Carlo suite consisting of the Fortran tools MGEANT (Geant3), GCALOR, PROMPT, ORIHET & DECAY
  - Designed for background simulation of gamma-ray telescopes
  - Main reference: Weidenspointner et al. 2005
- *Advantages:*
  - Verified & working!
- *Disadvantages:*
  - Base libraries (Geant3, GCalor) no longer supported
  - Unstable and undebuggable (ZEBRA data structures) …
  - Not all required physics processes, cross sections, etc. included

MGGPOD verification



Weidenspointner et al. 2005

Good agreement between measurement and simulation for TGRS, Integral and RHESSI

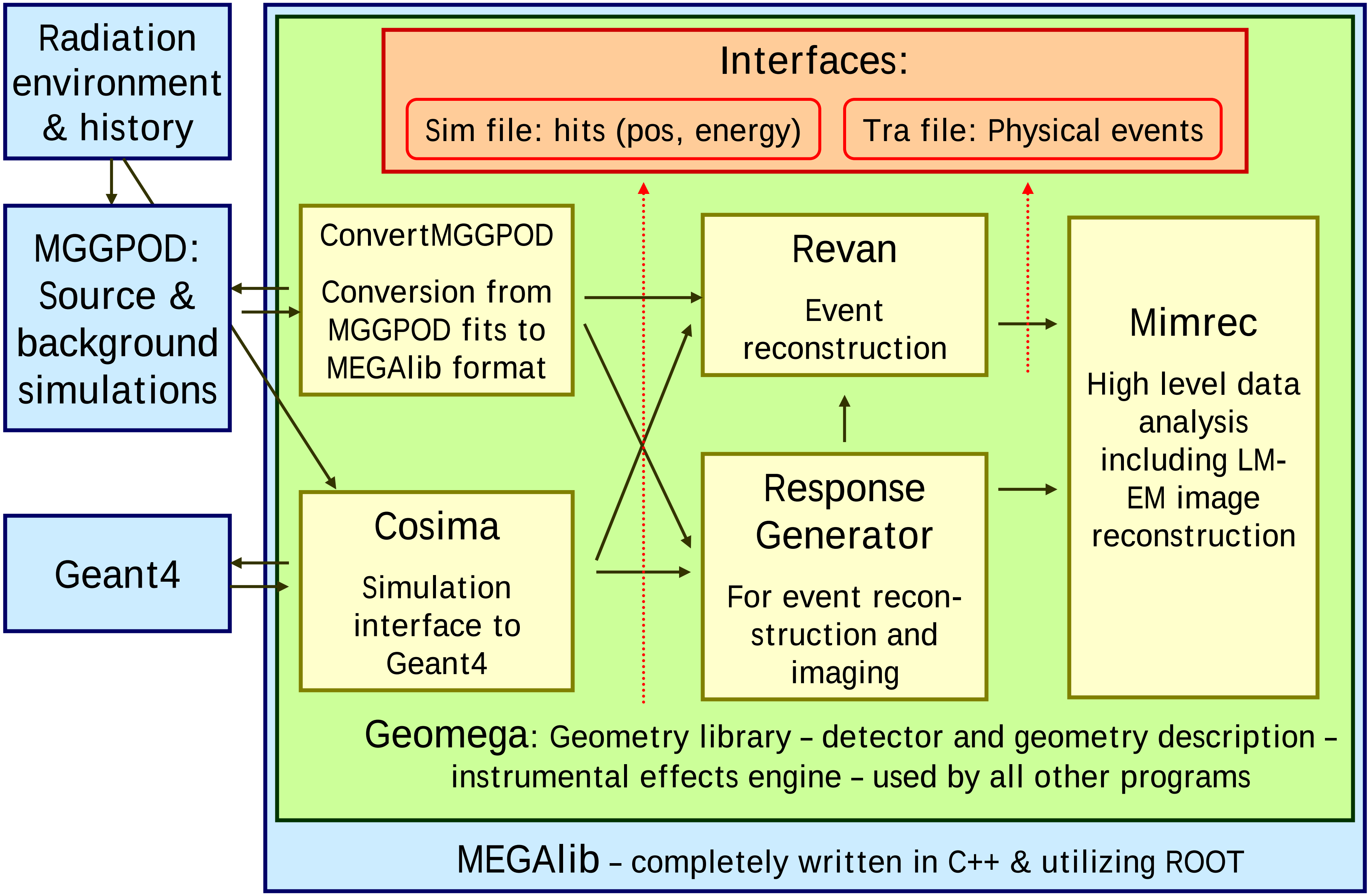
Switching to Geant4:

Integrate Activation Pipeline into "Cosima"

Cosima is the Geant4 simulation tool of the MEGAlib package, the "Medium Energy Gamma-ray Astronomy library" designed for simulating and analyzing Compton telescopes

Available from: http://www.mpe.mpg.de/MEGA/megalib.html

MEGAlib layout



Basic simulation strategy for activation

3-step process:

Simulate incidence radiation and collect generated nuclei

↓

Determine decay chains and activation per nucleus and volume after N sec of constant irradiation

↓

Simulate decay of radioactive isotopes

Step 1: Simulate initial interactions

Initial information:

- Radiation environment for protons, neutron, etc. from e.g. Marc Kippen's ACTtools

Geant4 simulation:

- Physics lists: EM: Livermore low-energy (G4LECS extension), hadrons: QGSP-BIC-HP, radioactive decay
- Simulate initial particles (including secondaries, etc.)
- For all generated nuclei: allow initial de-excitation.
- Take care of meta-stable states & immediate decays:
  - Define detector-dependent time window Δt (e.g. coincidence window):
    - If part of the de-excitation takes longer than Δt, generate a new event for this track
    - If the next decay of the initially generated nucleus happens within time window keep it, if it happens later store the nucleus and kill its (Geant4) track

Step 2: Determine activation

Initial information:

- List of initially generated nuclei per instrument volume
- Total simulation time (“exposure”)

Activation determination:

- Determine nucleus-generation rate
- Determine all possible decay chains per generated initial nucleus (from G4RadioactiveDecay → G4DecayTable → G4VDecayChain)
- Determine activation per volume and nucleus after time T of constant irradiation for each decay chain:
  - Set of coupled differential equations
  - Direct solution for up to 5 elements in chain, numerical solution for larger chains

Step 3: Simulate decays

Initial information:

- Activation per nucleus and volume

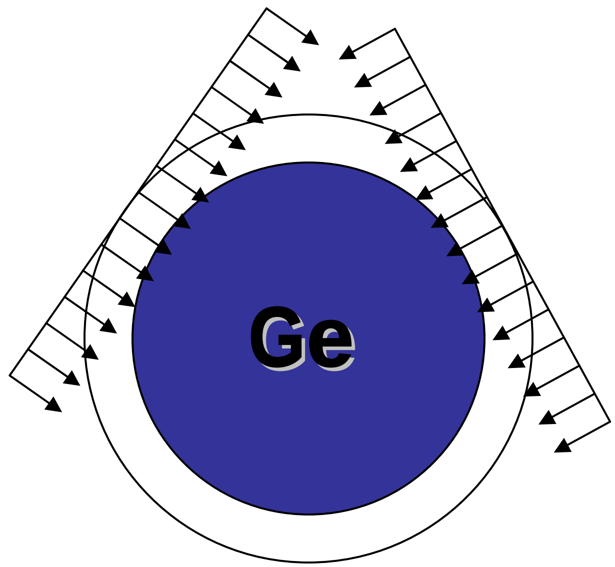
Simulation:

- Randomly choose one of the nuclei according to their activation
- Randomly position the start nucleus within its volume (take care it's not in a daughter volume)
- Let it decay and de-excite
  - Take care of meta-stable states and immediately following decays
    - Handling of meta-stable states as in step 1
    - If the next decay of the initially generated nucleus happens within the time window then keep it (but ignore the next started from the list of the same isotope and volume type), otherwise kill the track, since this event is already in event list.

Some preliminary results

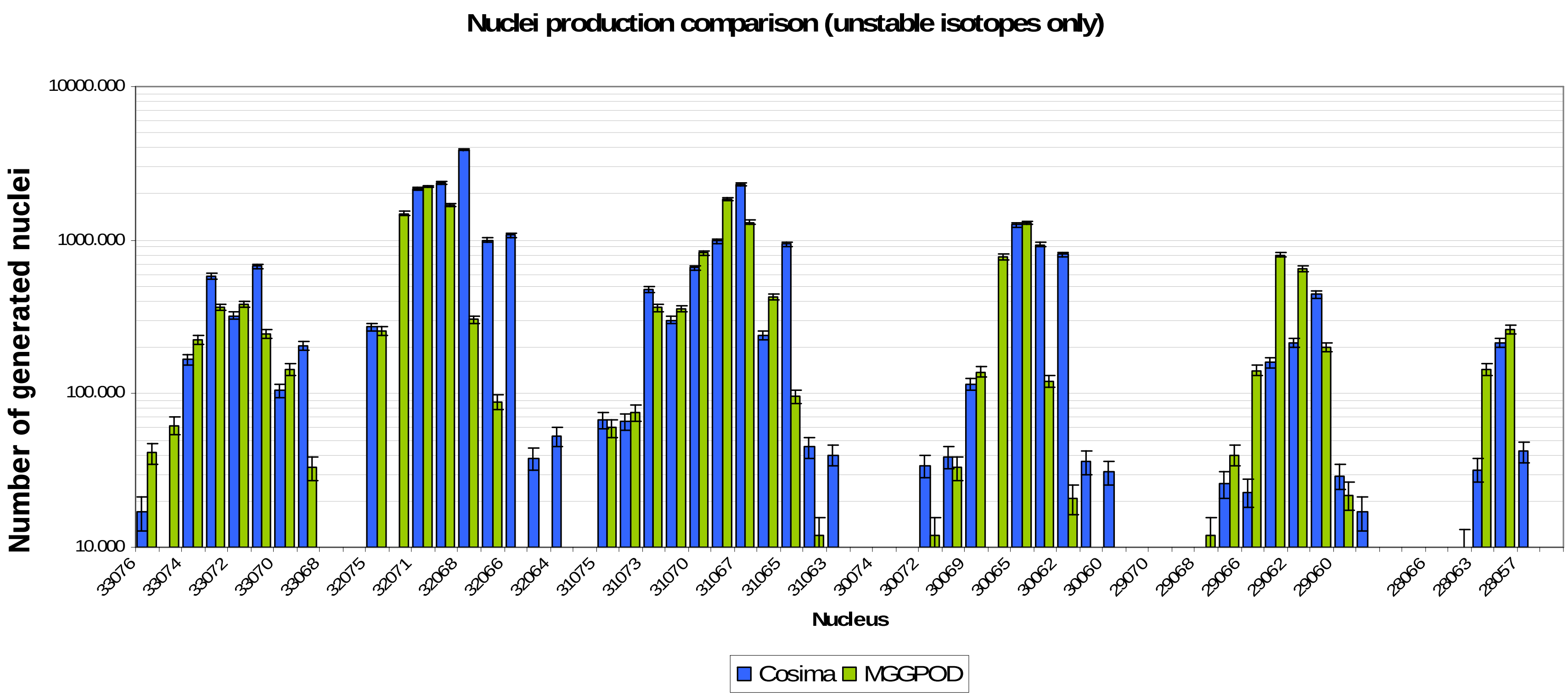
Simulation setup

Simulation of 200 MeV protons irradiating isotropically a Germanium sphere with radius 2 cm:



Identical simulation have been performed with Cosima & MGGPOD!

Step 1: Generated Nuclei

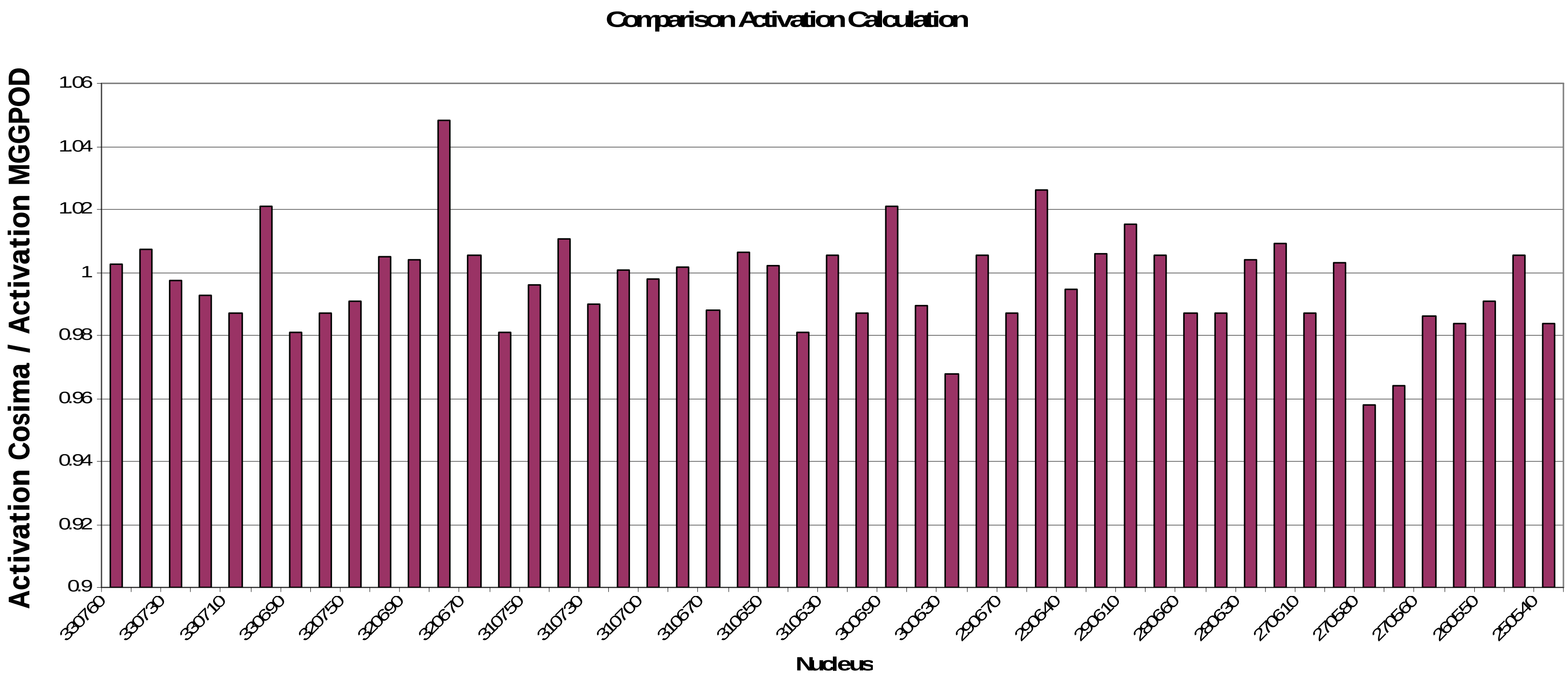


Differences:

- Average deviation: Factor 2.2
- Geant4 produces more nuclei with low neutron numbers compared to MGGPOD for e.g. Ge & Zn
- MGGPOD produces more Cu

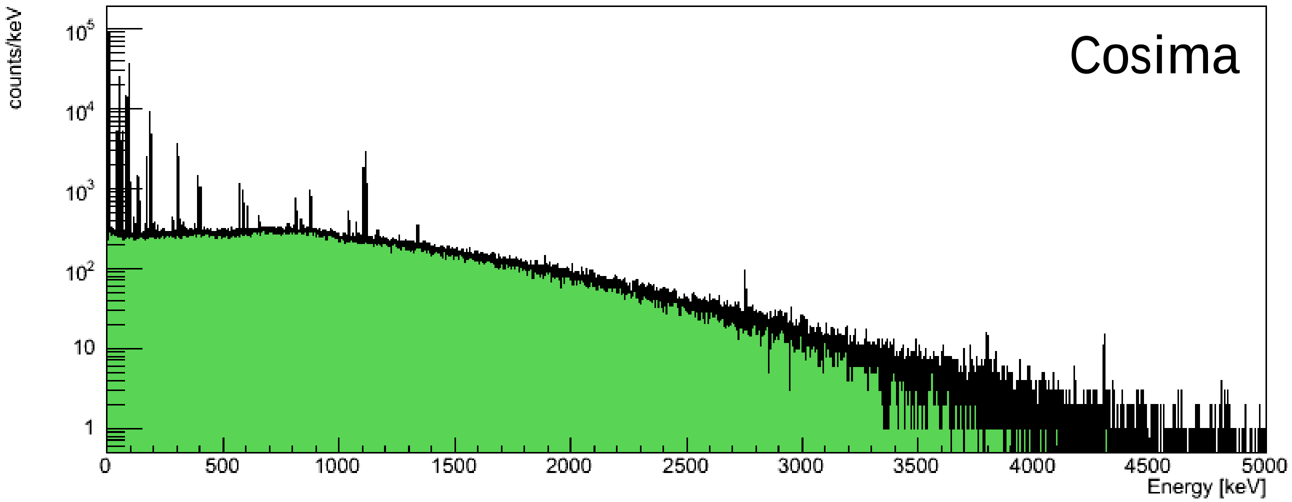
Step 2: Activation determination

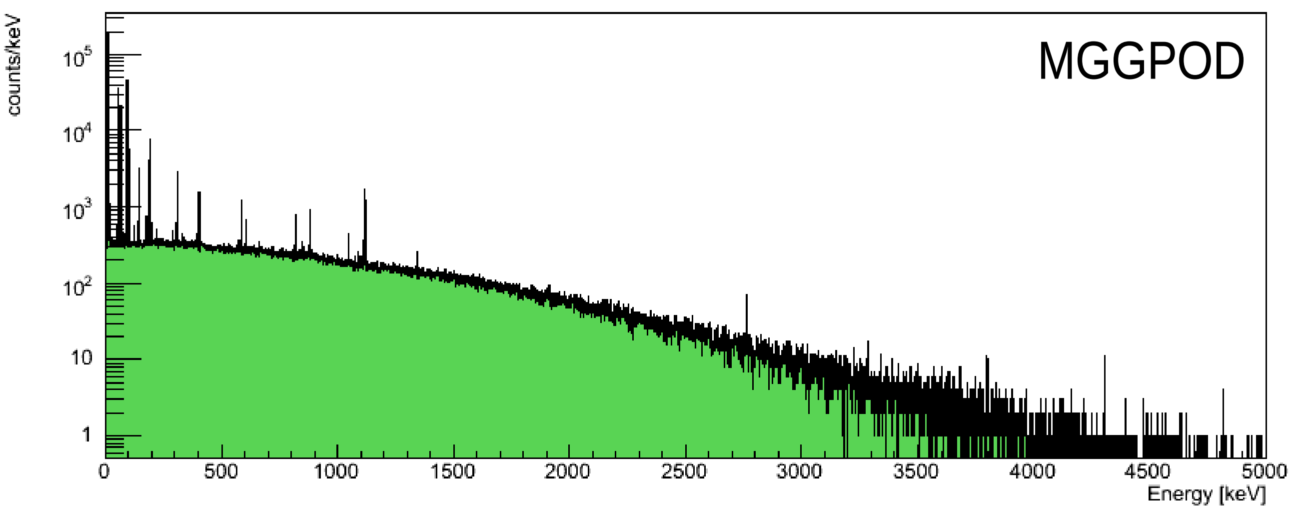
For both Cosima and MGGPOD the Cosima input rates were used!



Reasonable agreement, detailed differences are still under investigation

Step 3: Decay spectra



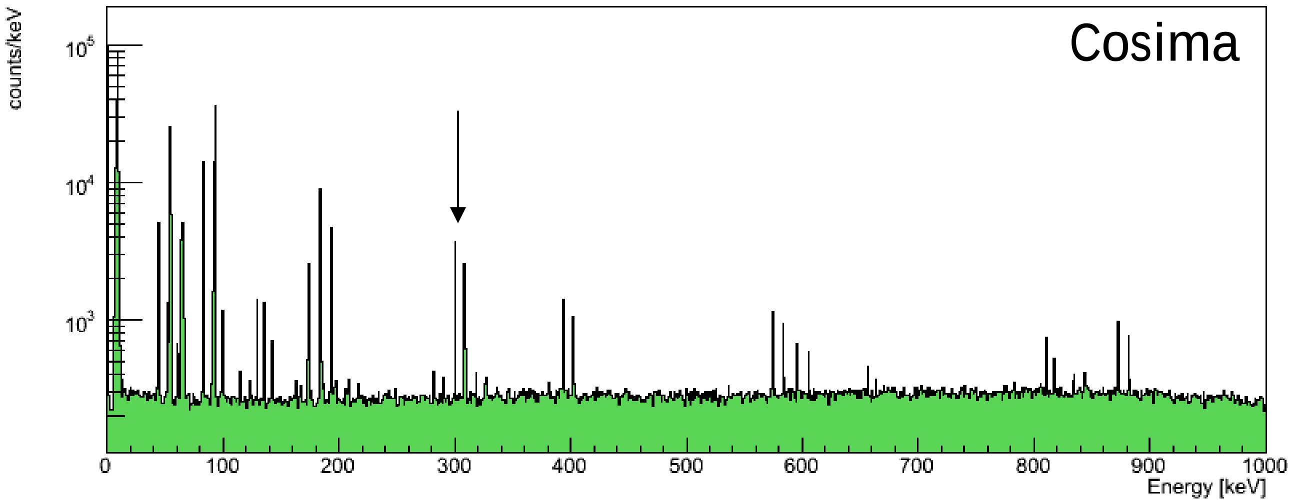


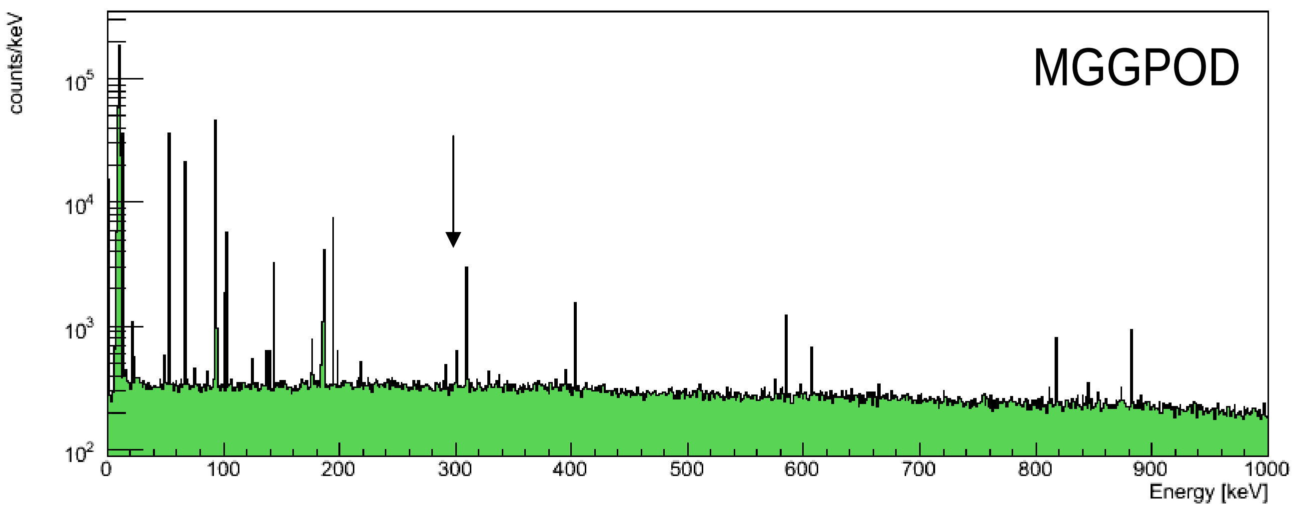
Input isotope lists are identical!!

Big picture:

Rather similar

Step 3: Decay spectra - details



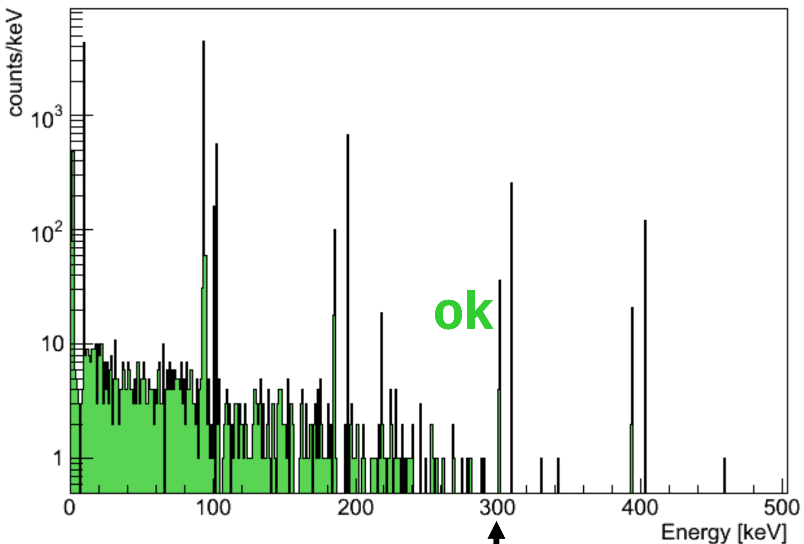


Differences:

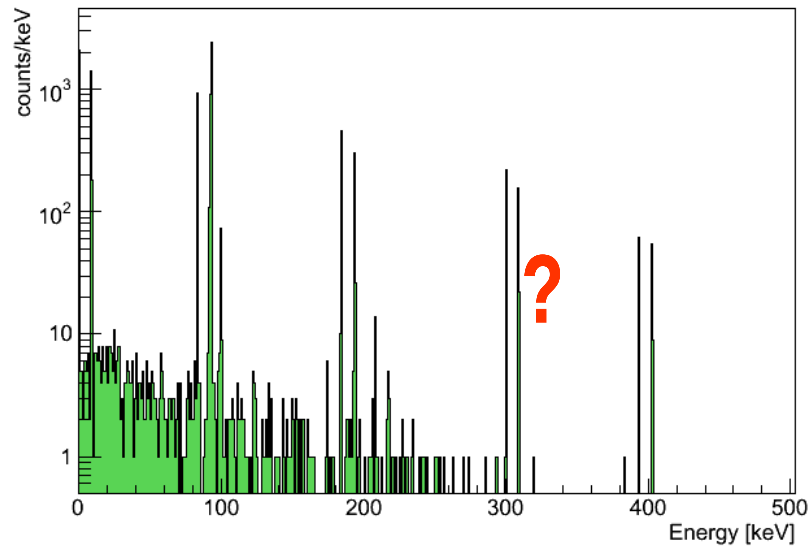
- Line ratios
- Background slope

Step 3: $^{67}Ga \rightarrow {}^{67}Zn$ (EC)

MGGPOD



Geant4 9.1



^{67}Zn (394 keV → 93 keV)
+ L-shell-γ + K-shell-γ

Ratios:

TGRS (measured):	~ 1:8	MGGPOD simulated:	~ 1:7
Geant4 data files:	~ 1:9	Geant4 simulated:	~ 6:5

Summary & Future

Summary:

- Activation pipeline implemented in Cosima
- However, non-negligible differences between MGGPOD & Cosima have been found

Future tasks & validations:

- Identify and – if necessary - resolve differences between Geant4 & MGGPOD
- Compare different proton & neutron energies as well background spectra
- If successful, simulate existing satellites: TGRS, Integral, COMPTEL

If comparisons are successful, a new release of Cosima with integrated activation will be made publicly accessible at:

http://www.mpe.mpg.de/MEGA/megalib.html