Activation, background and signal to noise ratio simulations for CubeSats

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Topics

- 1. Signal to noise ratio simulations:
  - CAMELOT CubeSat (bigger “version” of GRBAlpha)
  - Detector response included
  - Simulation of all background sources
  - Simulation of transient astrophysical sources (sGRB, lGRB etc)

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- 2. Activation simulations:
  - HERMES CubeSat, THESEUS satellite
  - Developed a custom method, ~100x faster than direct MC
  - Understand short term activation → how long the satellite is “blind” after a passing
  - Understand how the background increases after years in orbit

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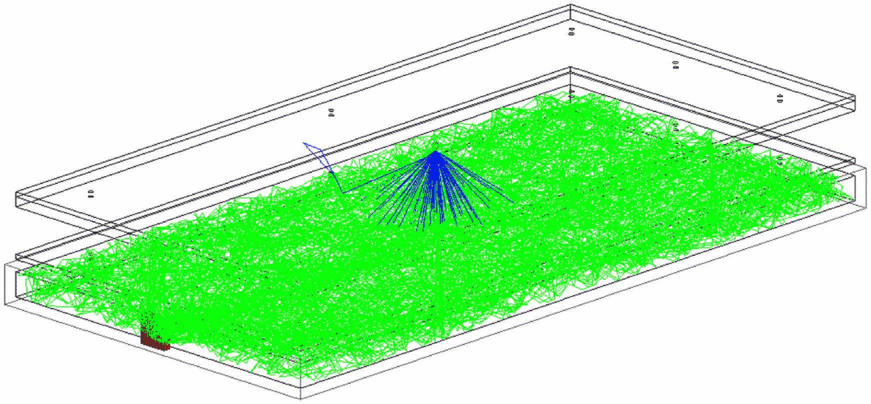
  - Understand how the background increases after years in orbit
- We have shared the source code for 1. and will share 2. so other projects don’t have to start from scratch
- Satellite geometry is replaceable easily → the work can be reproduced for other missions in a few weeks time → saving lot of man power

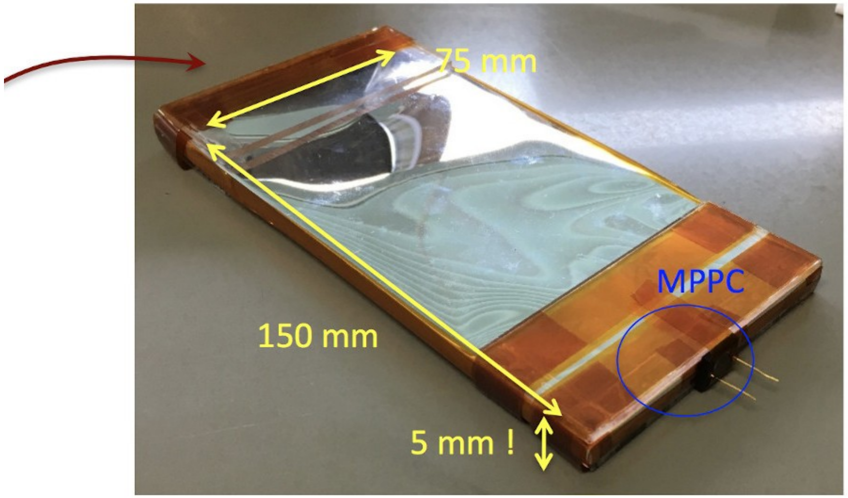
Signal to noise ratio simulations

- Why?
  - We wanted to understand what SNR and detection rate we should expect.
  - Can we detect TGFs?
  - How thick should the detector casing be to maximize SNR
- Geant4 simulation framework
- Satellite model can be importad as a CAD model (.stl)

Calibrating detectors

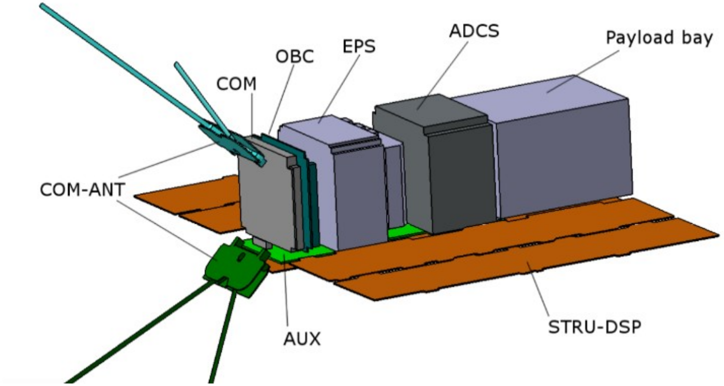
- Measurements done with 241 Am source collimated to irradiate different positions on the scintillator (read by single MPPC) at Hiroshima Uni.
- To obtain optical parameters of scintillators (absorption length, reflectivity of the surface) and to validation the Geant4 simulation framework.

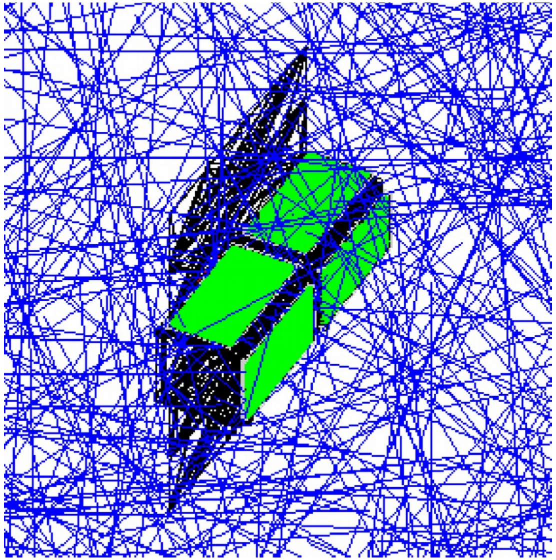




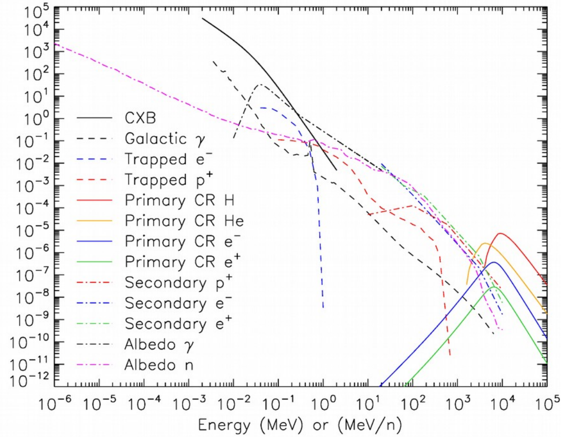
The model

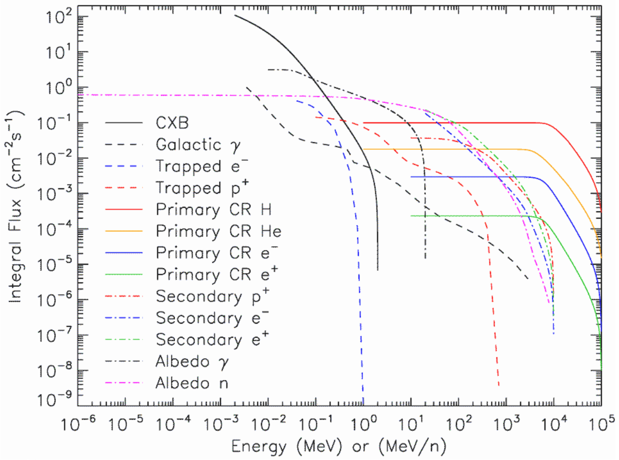
- Full Monte Carlo simulation in Geant4 including optical photon tracking, satellite structure and expected X-ray/particle background. Details in Galgóczi et al. 2021, arXiv:2102.08104
- Code on GitHub (https://github.com/ggalgoczi/szimulacio/tree/master/Bck_4.10.6)
- Outside SAA and for latitude < 50°, i.e. in the regions favourable for GRB detections





Background simulations

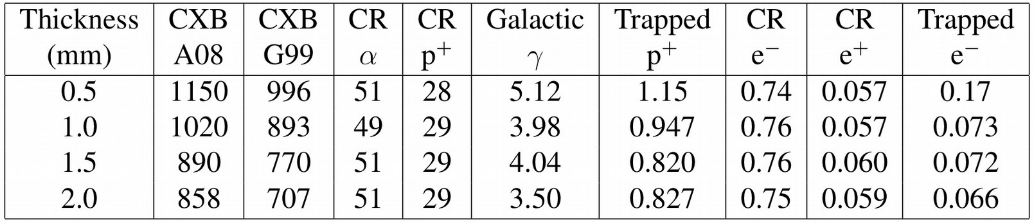




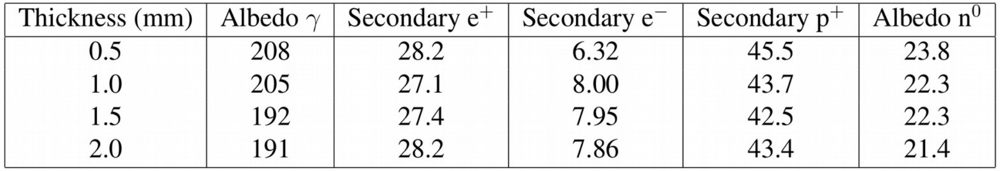
Al housing

Ajello+ 2008

Gruber+ 1999



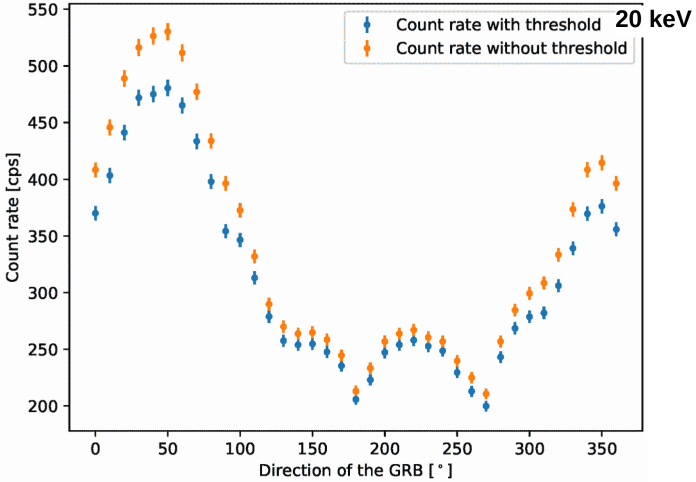
Thickness (mm)	CXB A08	CXB G99	CR α	CR p^+	Galactic γ	Trapped p^+	CR e^-	CR e^+	Trapped e^-
0.5	1150	996	51	28	5.12	1.15	0.74	0.057	0.17
1.0	1020	893	49	29	3.98	0.947	0.76	0.057	0.073
1.5	890	770	51	29	4.04	0.820	0.76	0.060	0.072
2.0	858	707	51	29	3.50	0.827	0.75	0.059	0.066

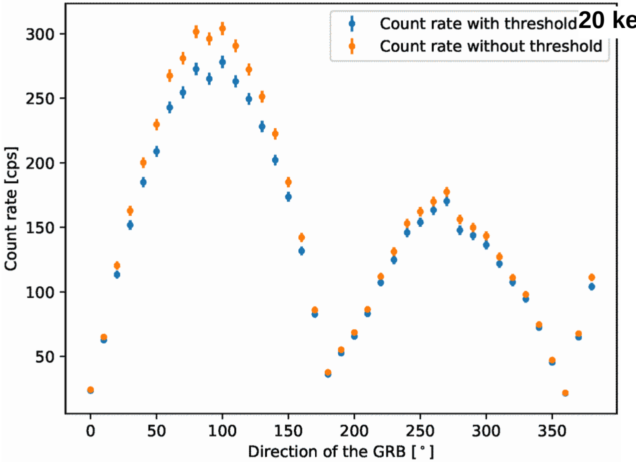


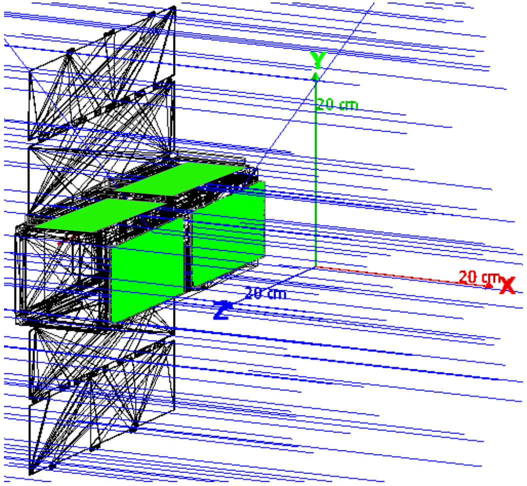
Thickness (mm)	Albedo γ	Secondary e^+	Secondary e^-	Secondary p^+	Albedo n^0
0.5	208	28.2	6.32	45.5	23.8
1.0	205	27.1	8.00	43.7	22.3
1.5	192	27.4	7.95	42.5	22.3
2.0	191	28.2	7.86	43.4	21.4

- **Background detection count rate (cps)** for different Al detector housing thickness for E>20 keV
- For a detector with sensitivity ~keV to ~MeV the most important external background is CXB and Earth's X-ray/gamma-ray albedo when outside of SAA and polar regions

Expected signal to noise ratio

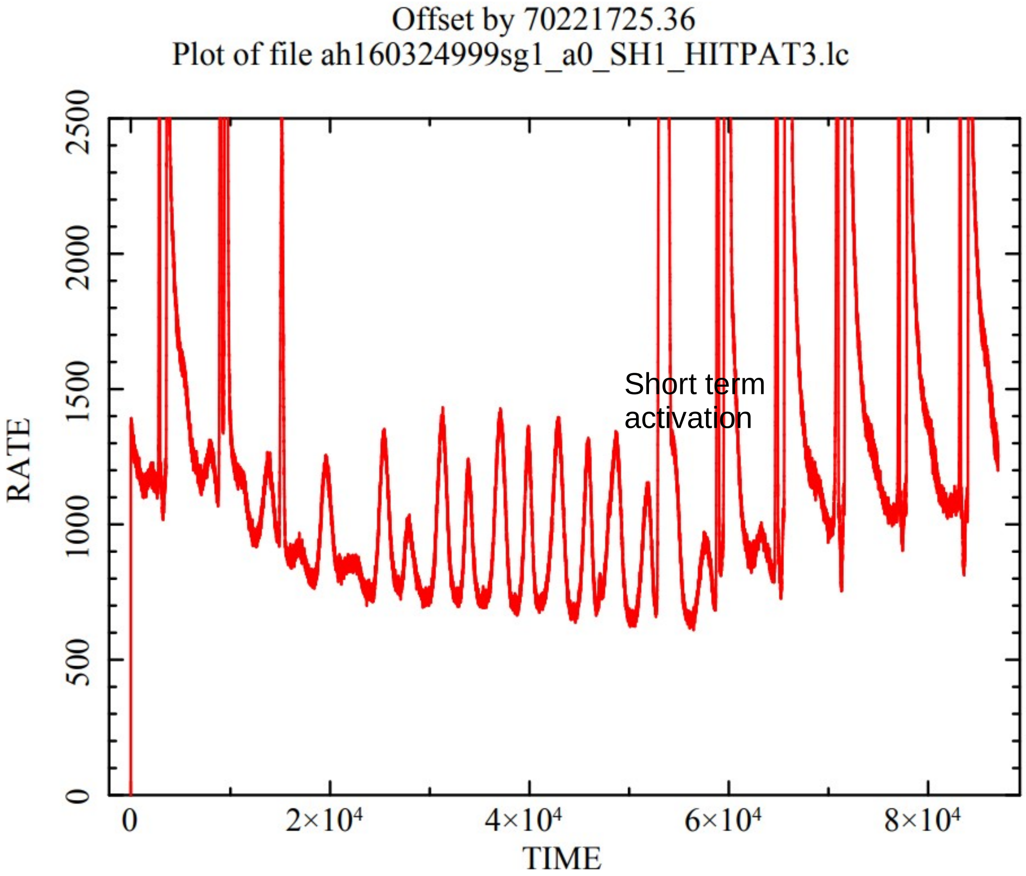






- Medium 1.024s-peak spectrum of sGRB was used
- 2 mm of Al for detector housing thickness
- For direction with highest eff. area the detection SNR are:
  - **sGRB SNR = 9-13** (64, 256, 1024 ms exposure)
  - **lGRB SNR = 8-20** (64, 256, 1024, 4096 ms exposure)
  - **SGR SNR = 140** (0.2 s exposure)
  - **TGFs are also detectable**

Role of activation

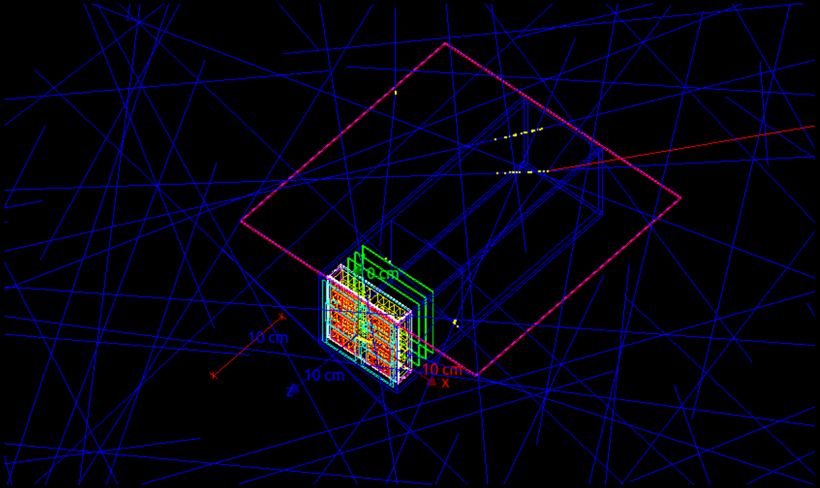


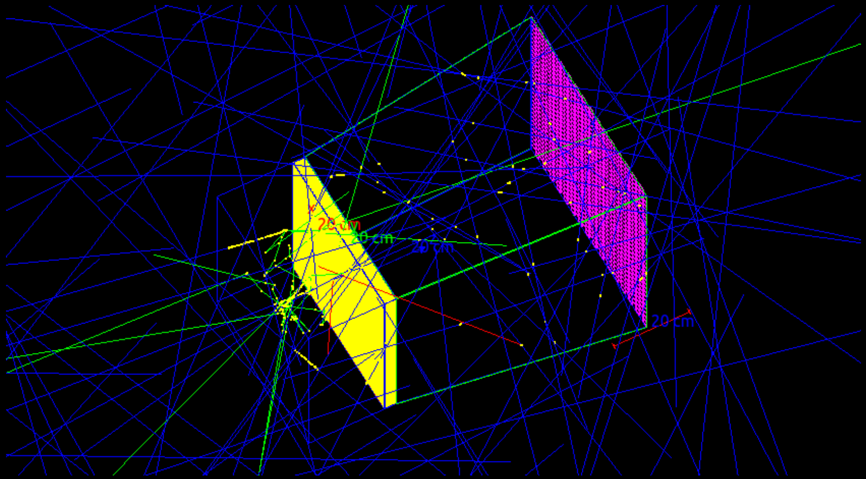
Short term
activation

How to determine activation?

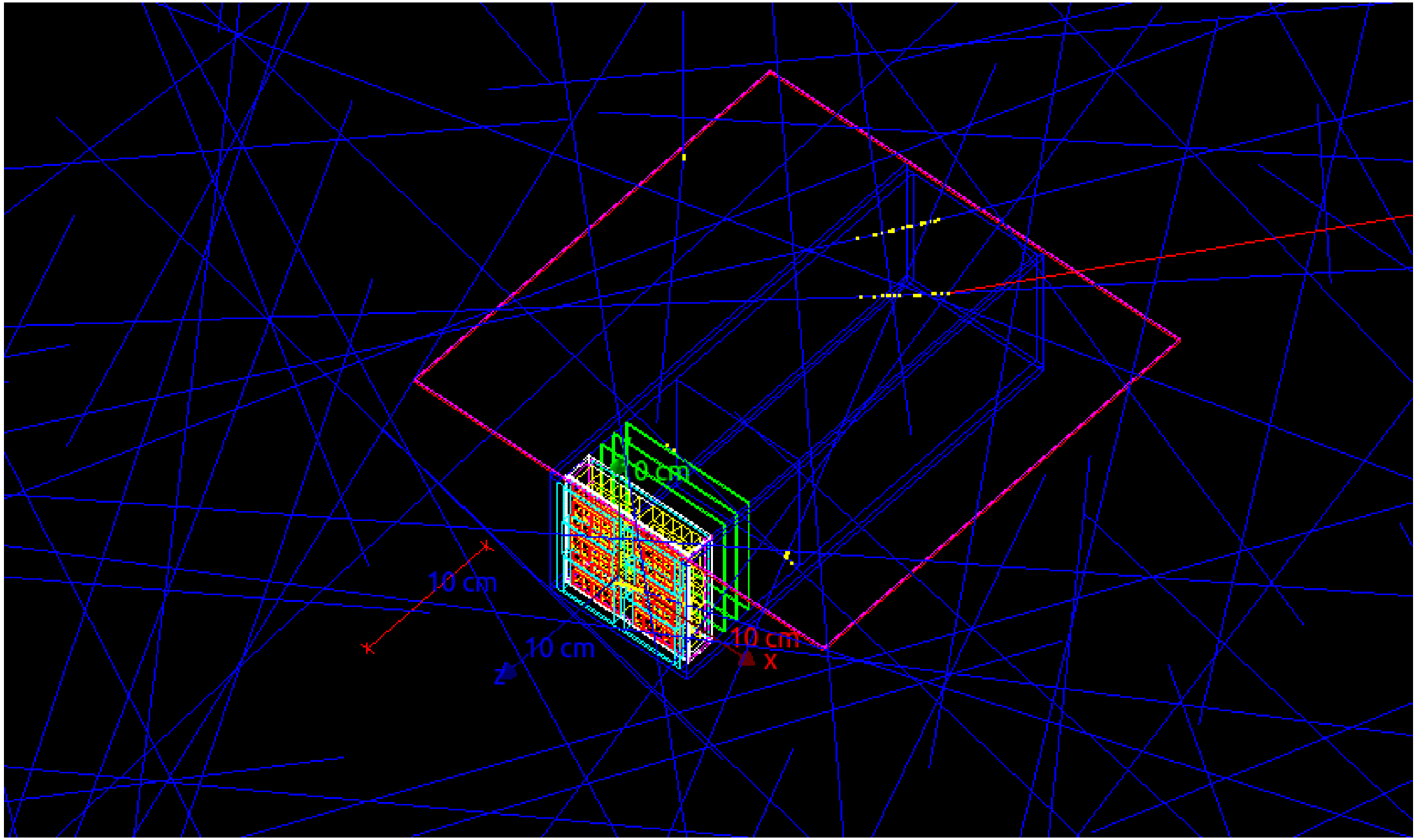
- Problem with direct MC approach:
  - Each SAA passing should be simulated ~independently (10 000 simulations)
  - ~10-100 year of computational time with enough statistics
- Solution:
  - Decouple the simulation into 3 steps (arXiv:2101.03946)
    - Determine the produced isotopes with MC
    - Calculate the number of isotopes left from each SAA passing (analitical, very fast!) → Sum up the isotopes left from all SAA passings
    - Simulate the detector response to these isotopes

HERMES & THESEUS





1. step: isotope production



1. step: isotope production

30 volumes:

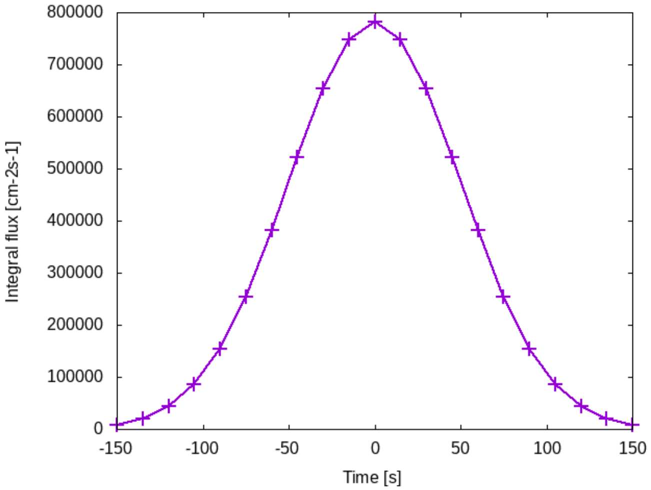
experimentalHall_phys
scint_container_phys
coll_container_phys
bus_sideXp_phys
bus_sideXm_phys
bus_sideYp_phys
bus_sideYm_phys
bus_sideZm_phys
sdd_container_phys
optCoupler_phys
crystalBox_sideZm_phys
shielding_sideZm_phys
crystalBox_sideXp_phys
shielding_sideXp_phys
Etc.

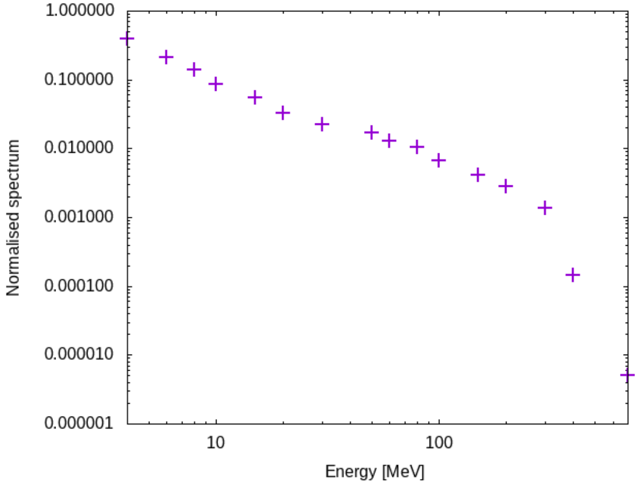
A műhold anyagai [g]:

EffectiveAluminiumSolid	1093.5
G4_Al	510.113
G4_STAINLESS-STEEL	378.613
G4_SILICON_DIOXIDE	83.52
G4_W	61.2997
FR4	51.5027
Silicone	8.748
GAGG (each crystal)	8.35121
G4_Si	0.0440234
Polymide	0.011583

Input spectrum

- 4 -700 MeV protons
- Inside SAA Gaussian time profile is assumed
- Energy spectrum from AP9 model





Results of step 1

- Number of produced isotopes
- For each volume independently
- For each energy band independently
- Eg. 100 MeV protons, the 6 most abundant isotopes in GAGG

Name	Normed number to 100 000 cm^{-2} fluence
O15	67699.3
Ga68	68916.9
Ga67	71839.1
Tb154	74030.8
Tb155	88155.1
Tb153	89372.8

2nd step: Build decay chains and sole Bateman eq.

- To analitically calculate number of isotopes for a given decay time:
  - Build the decay chains
  - Solve Bateman eq.

    $$N_n(t) = \sum_{i=1}^{n}\left[N_i(0)\times\left(\prod_{j=i}^{n-1}\lambda_j\right)\times\left(\sum_{j=i}^{n}\left(\frac{e^{-\lambda_j t}}{\prod_{p=i,p\neq j}^{n}(\lambda_p-\lambda_j)}\right)\right)\right]$$

    - For all volumes
    - For all energy bands
    - For ~all SAA passings
- Sum the results to get how much activity we have

2nd step results

- Lot of decay chains → eg. 700 MeV: 1 844 382 decay chain
- Long decay chains:
  - eg. Hf156 → Yb152 → Tm152[482.320] → Tm152 → Er152[1715.400] → Er152 → Ho152[179.400] → Ho152 → Dy152[3500.000] → Dy152 → Tb152[256.930] → Tb152 → Gd152[2880.670] → Gd152 → Sm148 → Nd144
- C++
- 4 hours of computation time (most time for 400 and 700 MeV energy bands)

2nd step results

- 100 MeV in scintillator

Activity [mBq]

Eu149	0.1691
Zn65	0.2145
Ga68	0.4014
Ge68	0.4100
Gd151	0.5584
Gd153	0.8577

- 20 MeV in scintillator

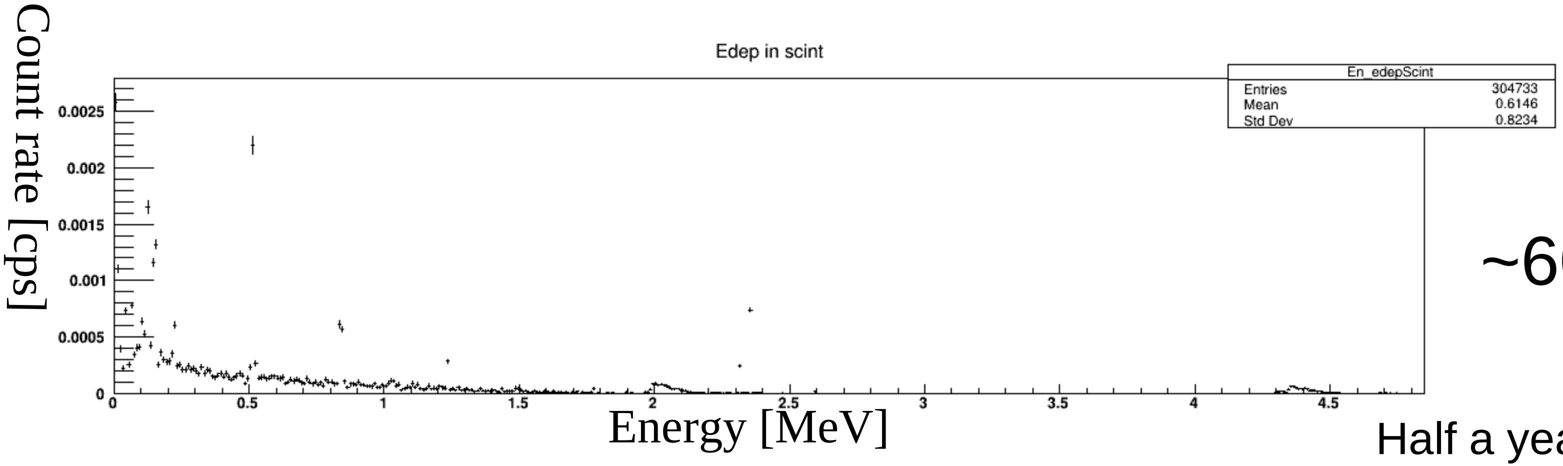
Activity [Bq]

Ge69	1.54e-35
Tb156	5.85e-14
Tb155	1.55e-13
Ge71	2.67e-08
Ga68	1.92e-05
Ge68	1.96e-05

3rd step

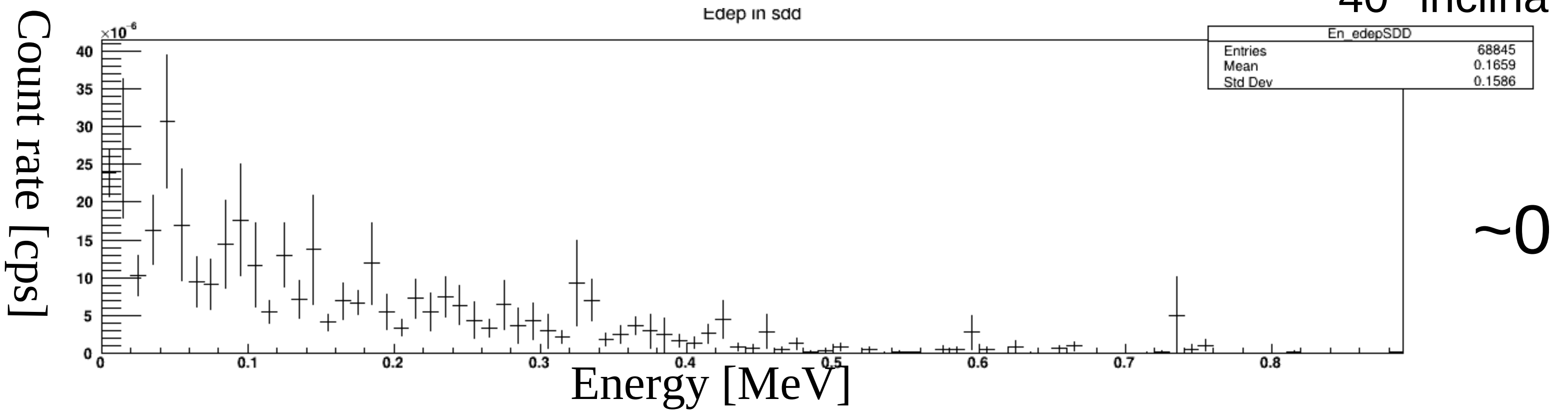
- Simulate the detector response → Which isotopes deposit energy inside the detectors above threshold?
- Simulate each isotope one by one in each volume
- Norm the detector response by the activity of the given isotope
- By summing up the energy deposition histograms, we can get we would actually measure due to activation

3rd step results



~60 cps

Half a year in space
40° inclination



~0.2 cps

Summary

- Signal to noise ratio simulations:
  - Applied to CAMELOT
  - Simulated all background components and potential targets
  - Chosen best aluminum thickness
- Activation simulations:
  - Applied to HERMES
  - After half a year in orbit, background would be 60 cps due to activation
- Both simulations were designed in a way that the models of the satellites are replaceable easily
- If there is interest we might make the simulations more user friendly