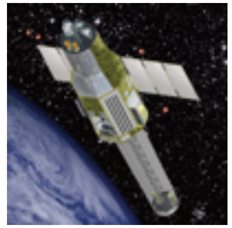
Development and Verification of the Response Function for the BGO Active Shields onboard ASTRO-H

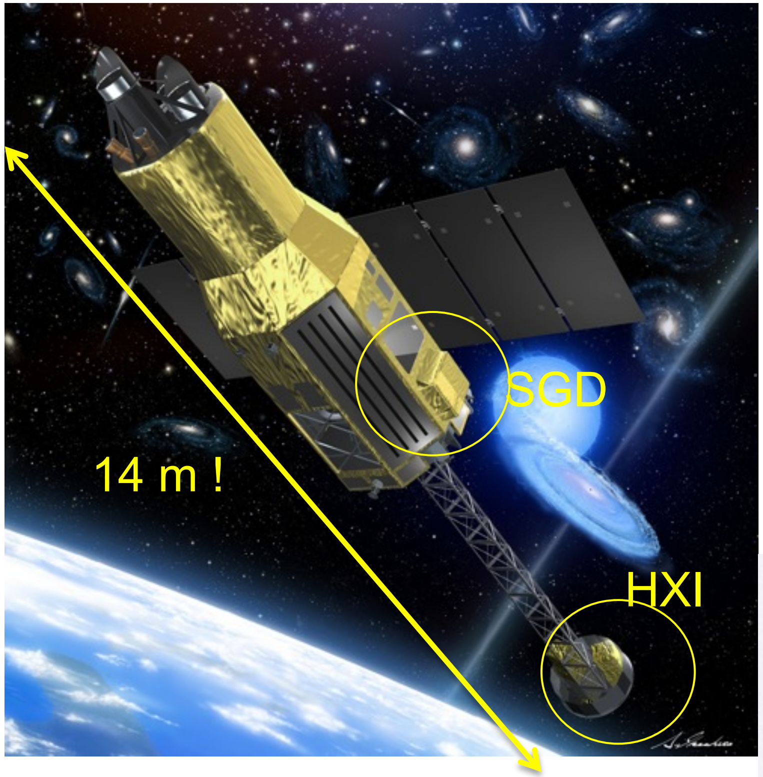
Masanori Ohno (Hiroshima University)

Takafumi Kawano, Ikumi Edahiro, Hiroyuki Shirakawa, Norie Ohashi, Chiho Okada, Sho Habata, Jun'ichiro Katsuta, Yasuyuki Tanaka,Hiromitsu Takahashi, Tsunefumi Mizuno, Yasushi Fukazawa (Hiroshima U.), Hiroaki Murakami, Shogo Kobayashi, Katsuma Miyake, Ko Ono, Yuuichi Kato, Yoshihiro Furuta, Yuki Murota, Kazufumi Okuda, Yuuki Wada, Kazuhiro Nakazawa, Kazuo Makishima (Univ. of Tokyo), Taketo Mimura, Jun Kataoka (Waseda U.), Yuto Ichinohe, Yusuke Uchida, Miho Katsuragawa, Hiroki Yoneda, Goro Sato, Rie Sato, Madoka Kawaharada, Atsushi Harayama, Hirokazu Odaka, Katsuhiro Hayashi, Masayuki Ohta, Shin Watanabe, Motohide Kokubun, Tadayuki Takahashi (ISAS/JAXA), Shin'ichiro Takeda (OIST), Masaomi Kinoshita, Kazutaka Yamaoka, Hiroyasu Tajima (Nagoya U./STEL),Yoichi Yatsu (TITech), Hideki Uchiyama (Shizuoka U.), Shin'ya Saito (Rikkyo U.), Takayuki Yuasa (RIKEN), and the ASTRO-H HXI/SGD team

The ASTRO-H Mission



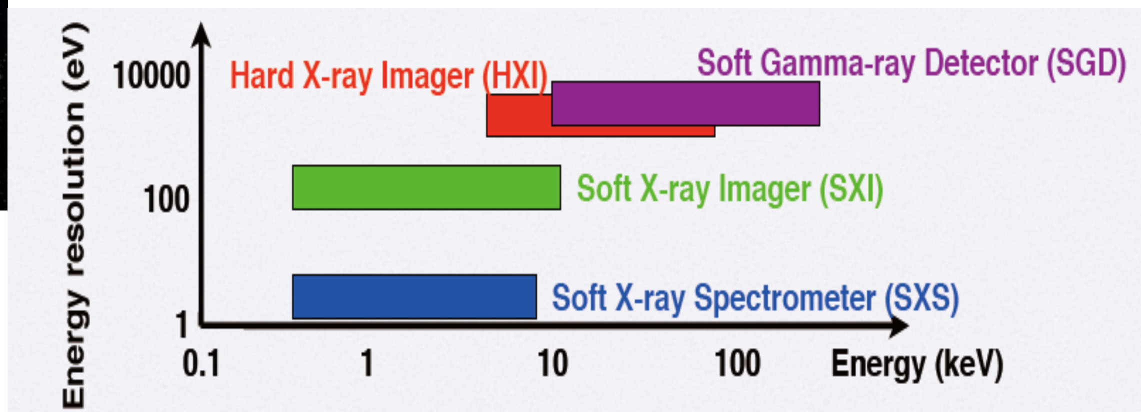
ASTRO-H is Japanese 6th series of X-ray observatory. It is scheduled to be launched in the end of JFY 2015 with an H-II A rocket.

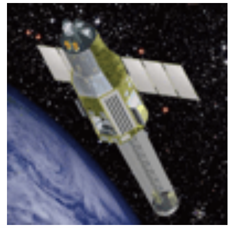


Total length : 14 m
Weight : 2.7 t
Largest scale satellite for Japan

Scientific instruments

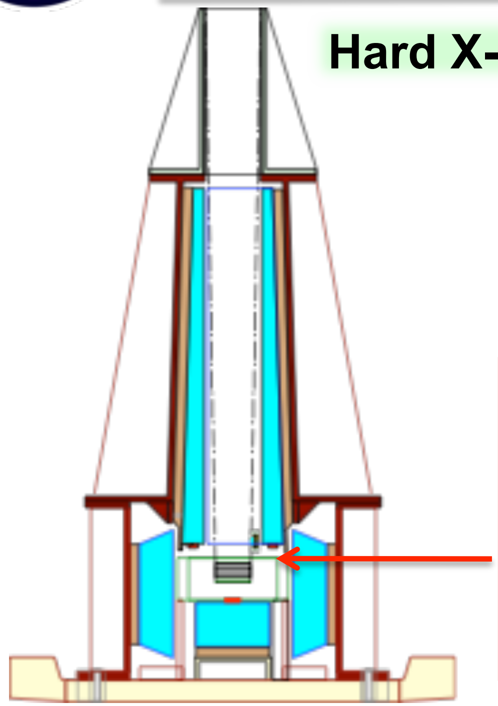
- ❖Soft X-ray Spectrometer (SXS)
  Soft X-ray telescope + X-ray calolimetor
- ❖Soft X-ray Imager (SXI)
  Soft X-ray telescope + CCD
- ❖Hard X-ray Imager (HXI)
  Hard X-ray telescope + hard X-ray imager
- ❖Soft Gamma-ray Detector (SGD)
  Narrow field-of-view Compton camera



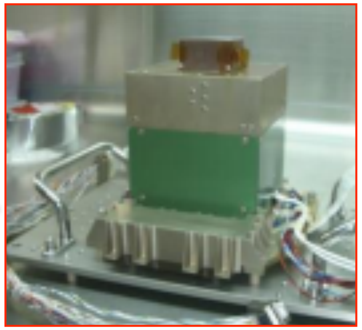


BGO Active Shields for HXI/SGD

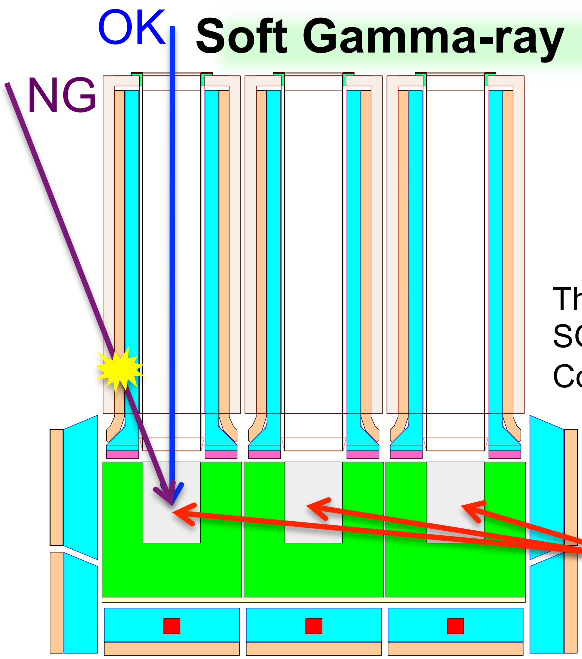
Hard X-ray Imager (HXI)



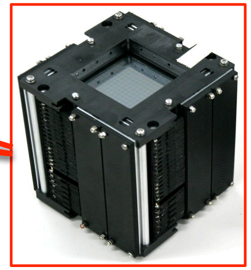
The main detector of
HXI (HXI-camera)
See Hagino-san's talk



Soft Gamma-ray Detector (SGD)



The main detector of
SGD (Multi-layer Si-CdTe
Compton Camera)

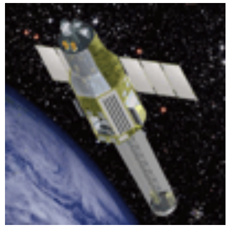


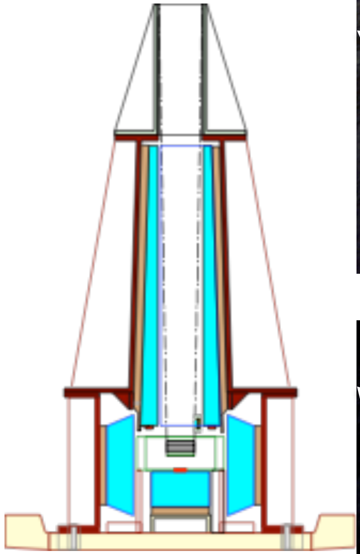
The most sensitive observation in high energy band

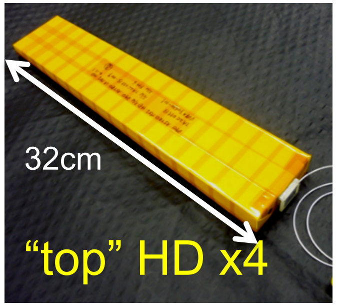
- 5-80 keV : Hard X-ray Imager (HXI)
- 50-600 keV : Soft Gamma-ray Detector (SGD)

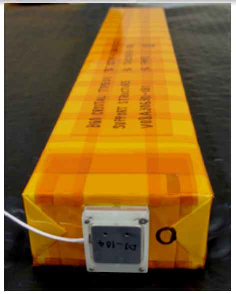
Reducing background is one of important issue
Large/thick $Bi_4Ge_3O_{12}$ crystal scintillators surround the main detectors of HXI/SGD ➔ BGO active shields

BGO Active Shields for HXI/SGD

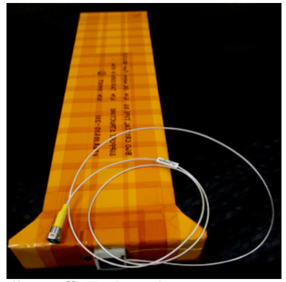




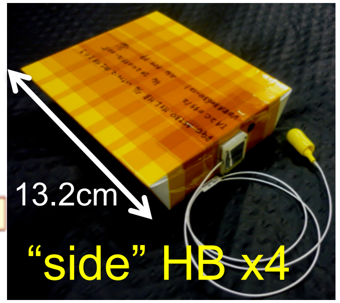


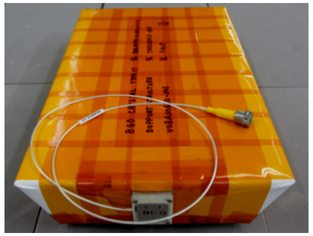


“top” D1 x6

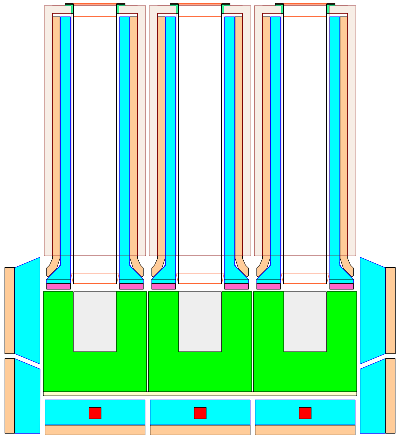


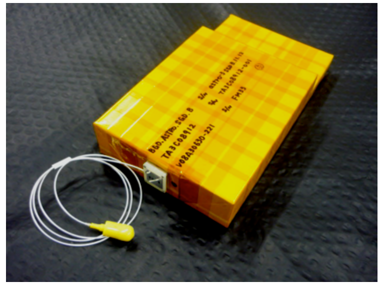
“top” D2 x6



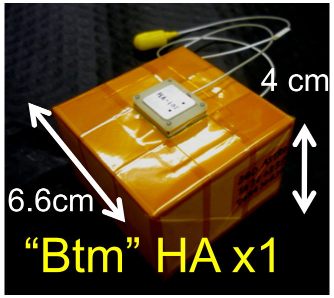


“side” C1 x2

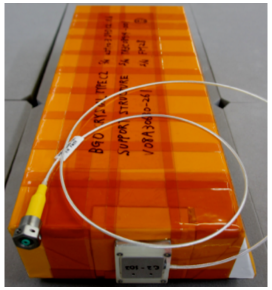




“side” B x6

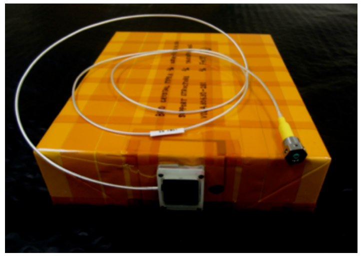


HXI: 9BGOs
w/ 3types



“side” C2 x2

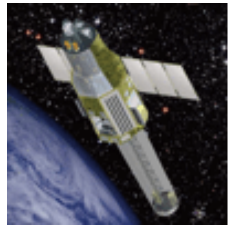
SGD: 25 BGOs
w/ 6 types



“Btm” Ax3

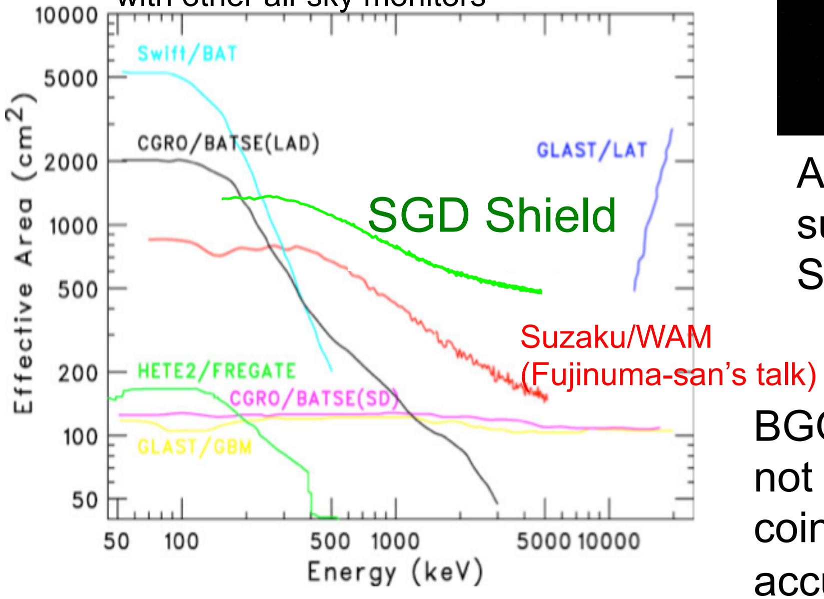
There are various complicated shape of BGO crystals
Readout each crystal independently by avalanche photo-diode

SGD shield as the all-sky monitor

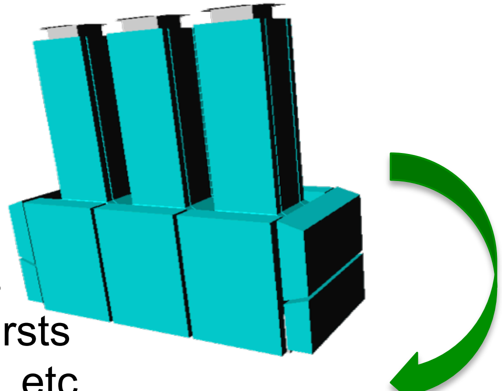


Large geometrical area + high photon stopping power of high-z material
➔ BGO shield detectors can acts not only active shield but also powerful all-sky monitor for transient astronomical phenomena up to MeV energy band

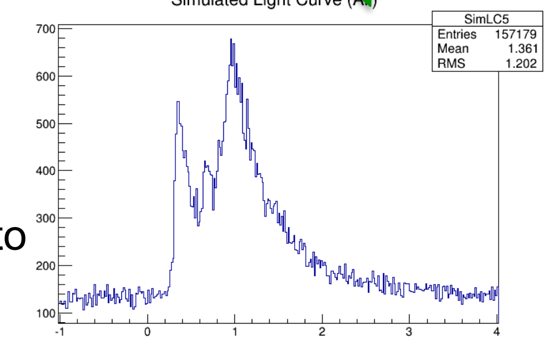
Comparison of Effective area of SGD shield with other all-sky monitors



Astronomical transients such as Gamma-ray bursts Soft Gamma Repeater ..etc

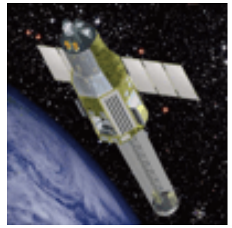


BGO shield take the data not only to generate anti-coincidence signal but also to accumulate science data

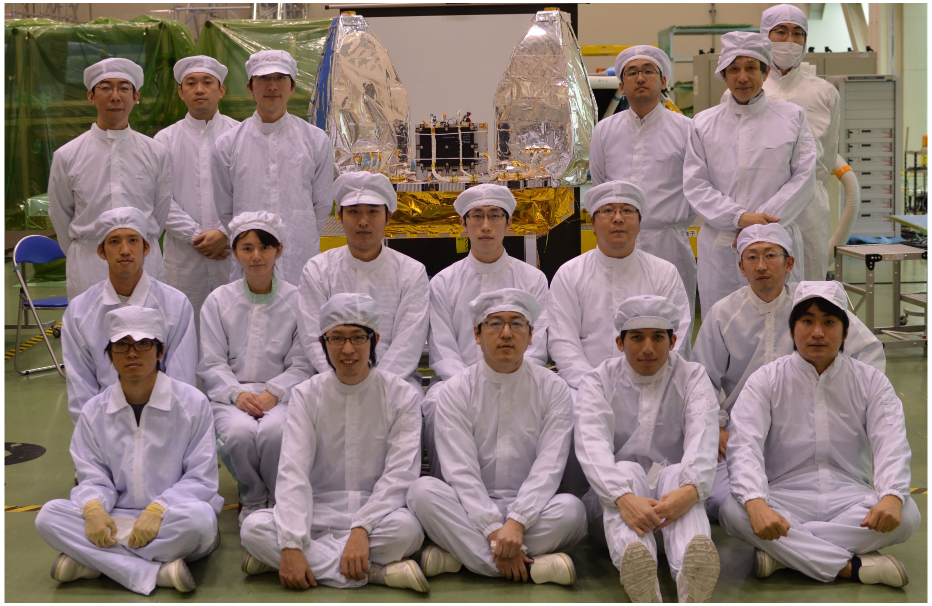


Gamma-ray response as the all-sky monitor is also important for SGD

Current status of HXI/SGD

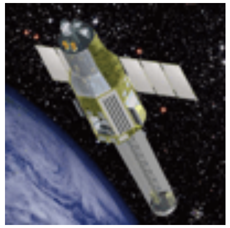


- ❖Fabrication of flight model has been completed. (~Dec. 2014)
- ❖Ground calibration tests in operating temperature have been performed. (~Feb. 2015)
- ❖HXI/SGD are installed on the satellite and satellite thermal-vacuum test has been passed. (~Jun. 2015)
- ❖Vibration/acoustic test is ongoing before moving to the launch site (Tanegashima)



Now, fabrication/verification phase is almost finished, and we have to construct gamma-ray response of detectors considering the results obtained in the ground calibration tests.

Gamma-ray response with Monte-Carlo approach



There are many large, thick and various types of shape of BGO crystals
➔ multiple Compton scattering in complicate detector shape

Geant4-based Monte-Carlo approach is useful to calculate the gamma-ray response of BGO active shields

Gamma-ray response specific to the BGO active shield should be implemented
- Light correction efficiency depending on the photon interaction position.
- Temperature dependency of BGO light yield and APD gain.
- trigger efficiency around threshold due to noise jitter.

We have to develop the framework of the simulator and verify it using various calibration results.

Framework of simulator

"ComptonSoft" framework (Odaka+10)

Monte-Carlo simulation by Geant4

(edep, x, y, z, detid) for each hit

3D Light correction Map (x1,y1,z1,cor1 x2,y2,z2,cor2…) → Correction of light yield depending on hit position

(Light yield, detid)

Energy resolution for each unit/energy → Gaussian randomization

(Convolved Light yield, detid)

Calibration gain curve for each temperature → Energy to pulse-height conversion

(PHA, detid)

- Trigger threshold
- Probability function of trigger efficiency

→ Anti-coincidence trigger generation

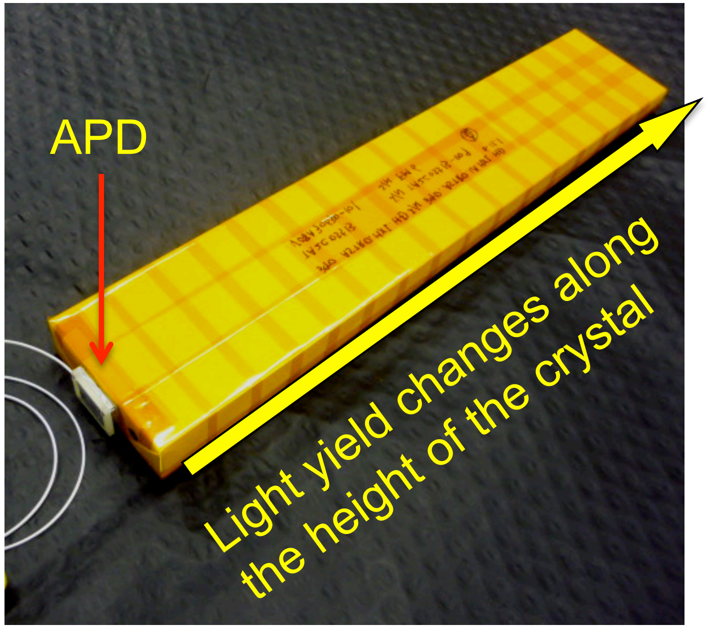
(PHA, detid, anti-coincidence flag)

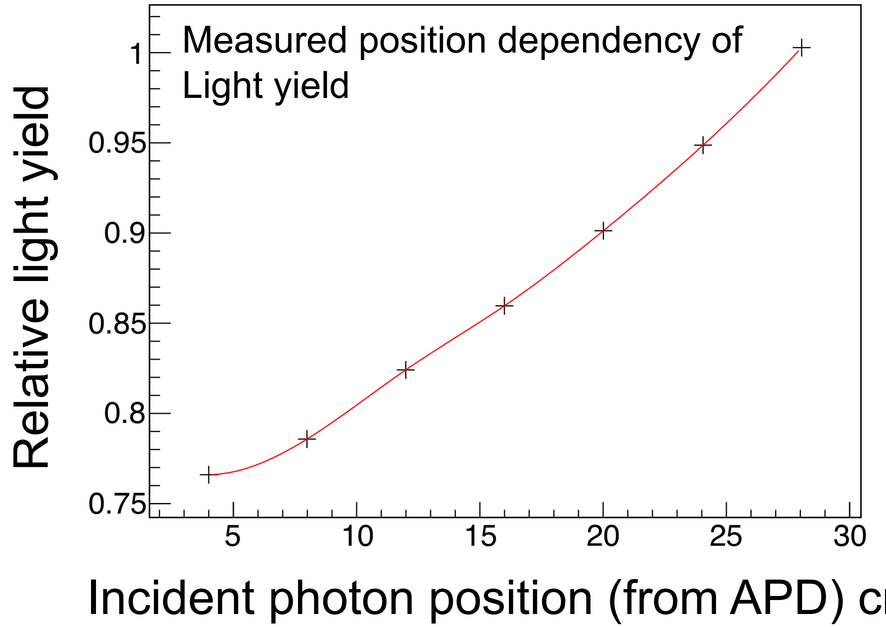
Event file

(blue box): input parameter files based on calibrations

Input parameter
(1) light yield correction map

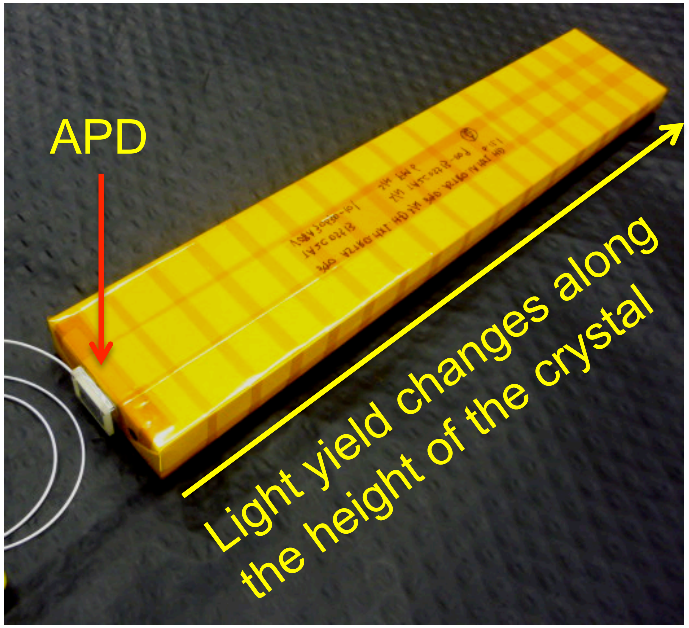
- Due to its trapezoidal structure, the light yield of "top" part of HXI BGO crystal shows strong position dependency.
- Although, lay-tracing of scintillation lights can reproduce a tendency of this property, we apply a simple empirical measured function to the input of the simulator.

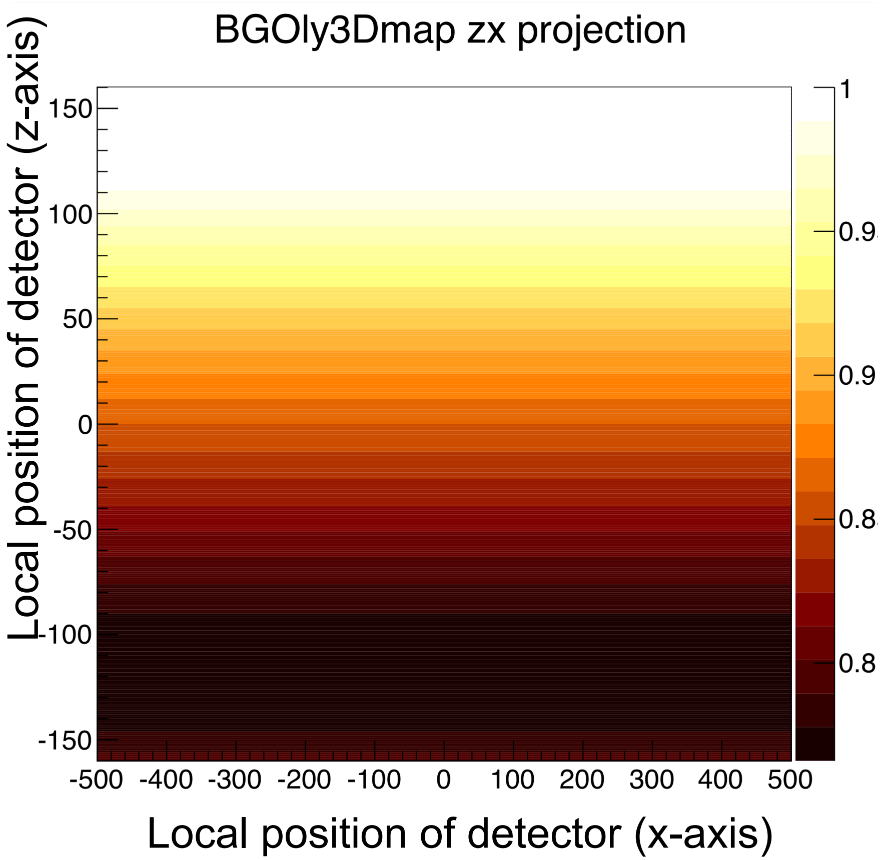




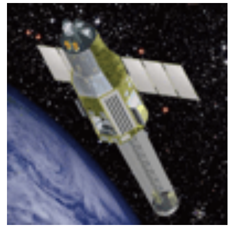
Input parameter
(1) light yield correction map

- Due to its trapezoidal structure, the light yield of “top” part of HXI BGO crystal shows strong position dependency.
- Although, lay-tracing of scintillation lights can reproduce a tendency of this property, we apply a simple empirical measured function to the input of the simulator.



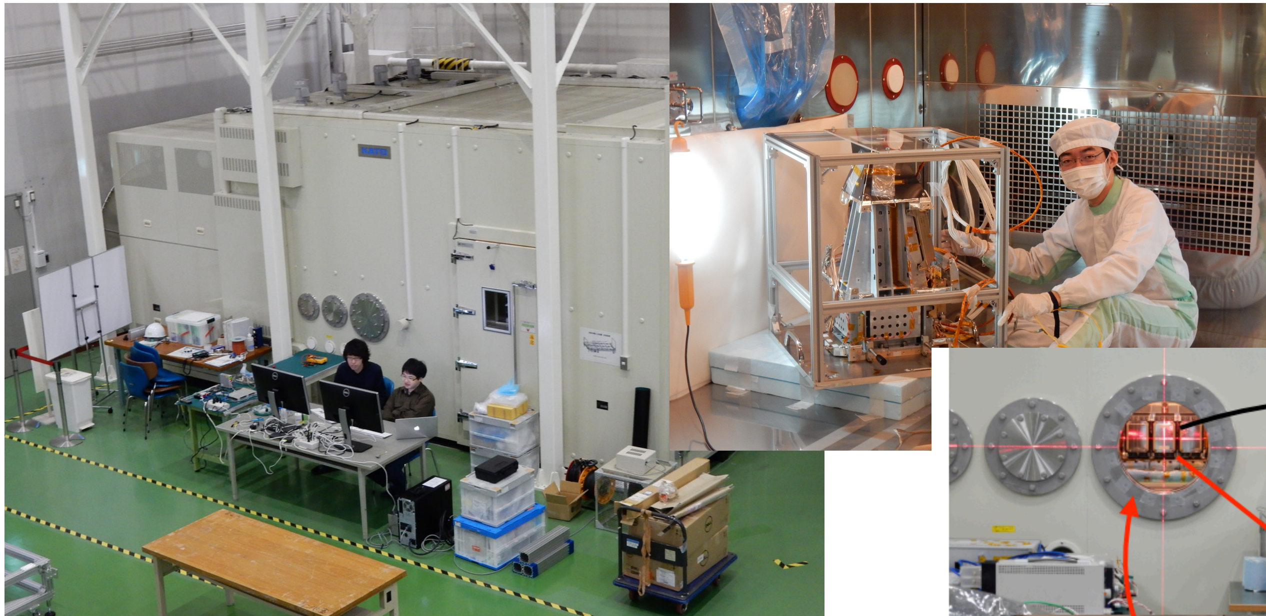


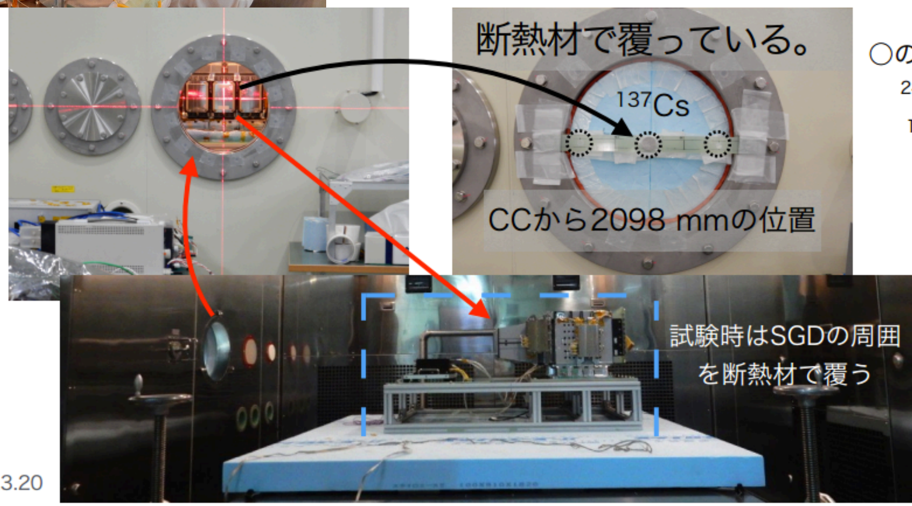
Input to the simulator as the 3-Dimensinal map as the same framework to semiconductor simulation in ComptonSoft but only has height (z)-axis dependency.



Input parameter
(2) Energy resolution, Gain curve, and Energy threshold

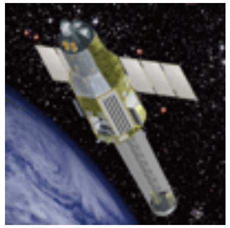
- These parameters are measured in the ground calibration test in the operational temperature (~-20℃), using flight model of HXI/SGD sensors
- Various kinds of radioisotopes (^{57}Co, ^{137}Cs, ^{22}Na) were irradiated, and obtain photo-peak channel and its energy resolution.
- Background data is used to determine the energy threshold.



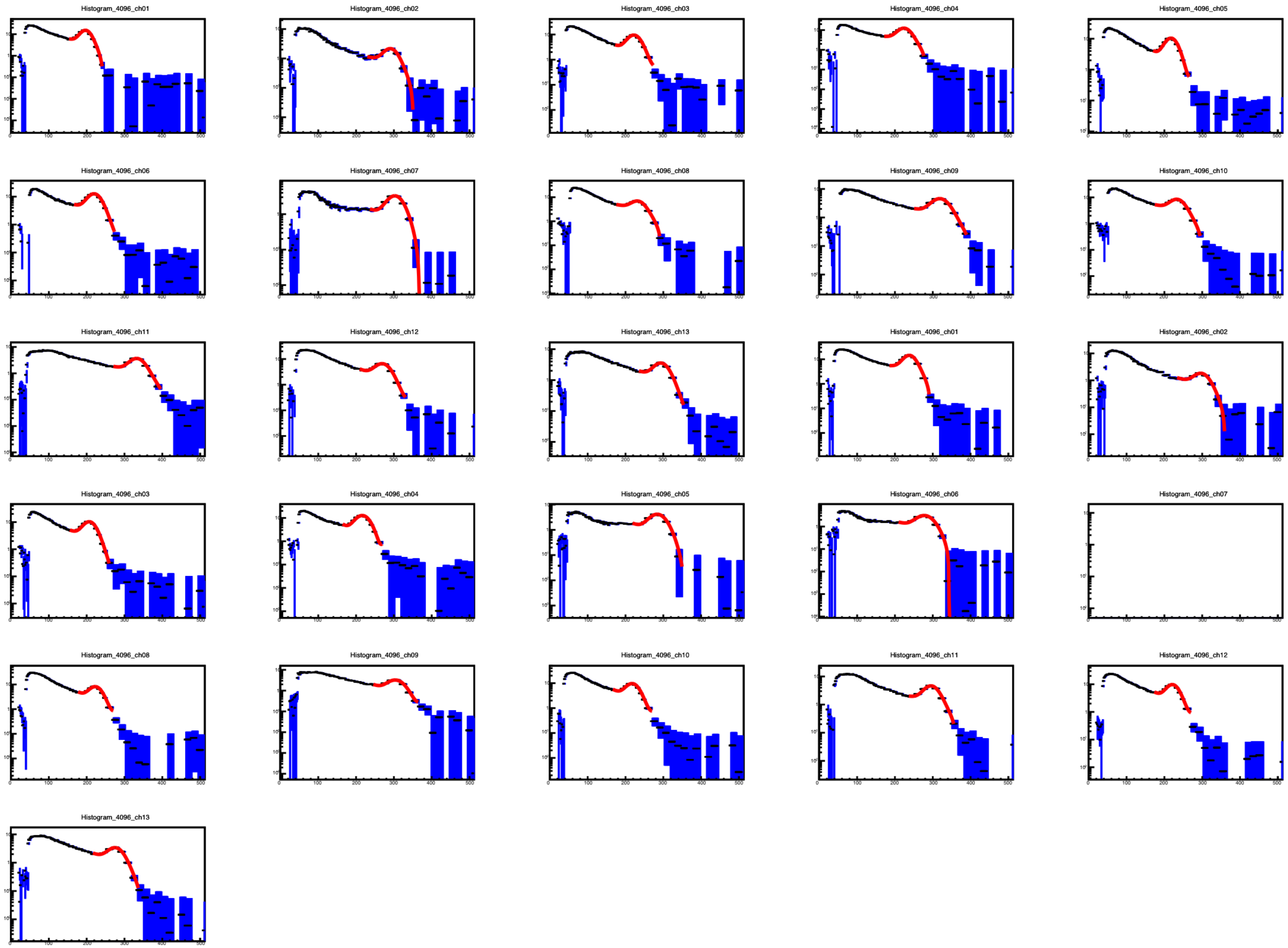


Calibration test at large thermal chamber in ISAS Bld.C (Sep.2014~Feb.2015) ~2w for each sensor

Input parameter
(2) Energy resolution and gain curve

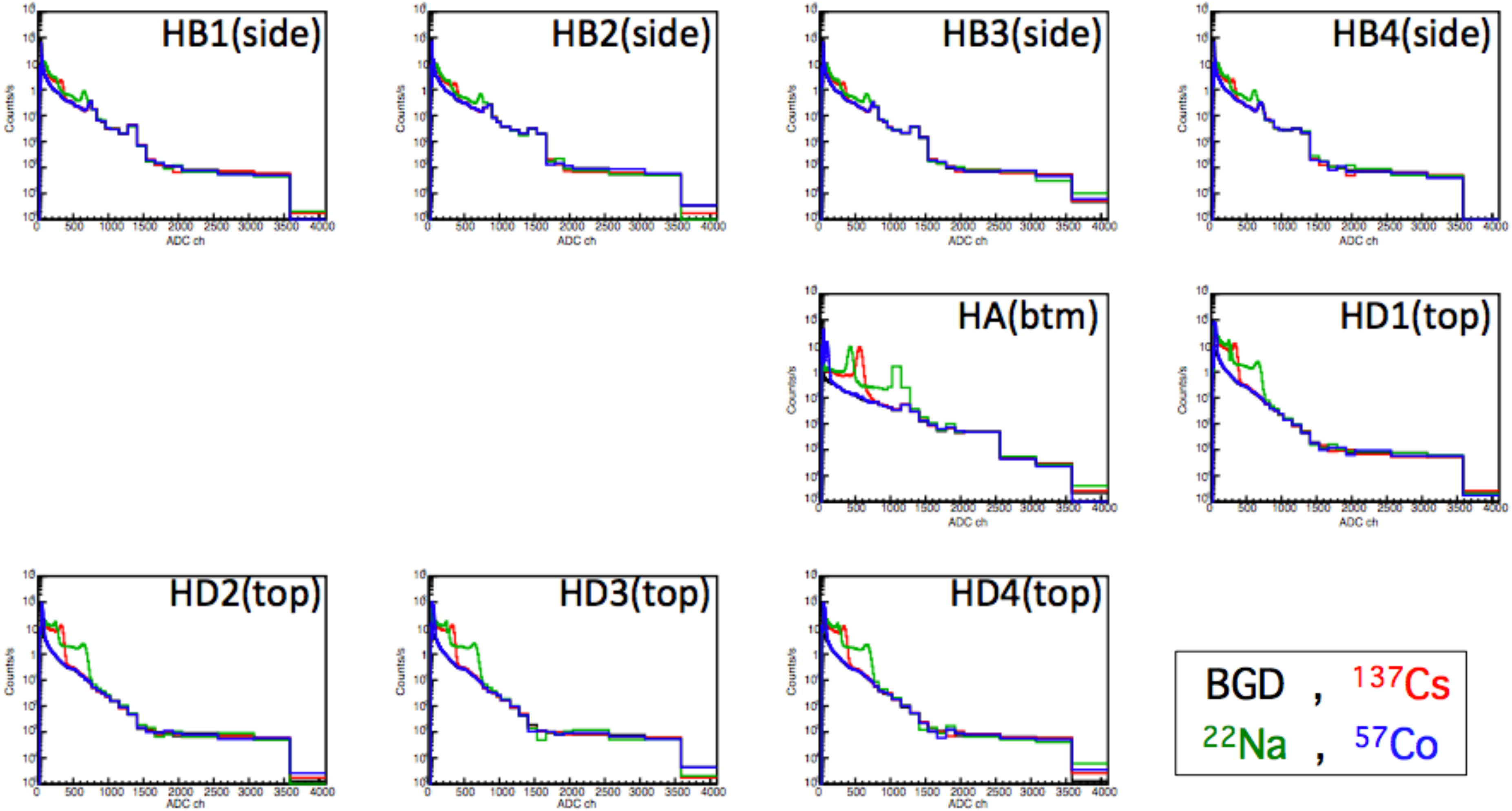


Example of ^{137}Cs 662 keV spectra of SGD (25 BGO units)
(Background-subtracted)

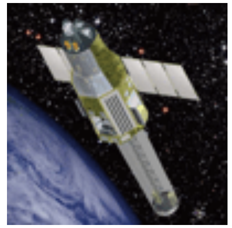


Input parameter
(2) Energy resolution and gain curve

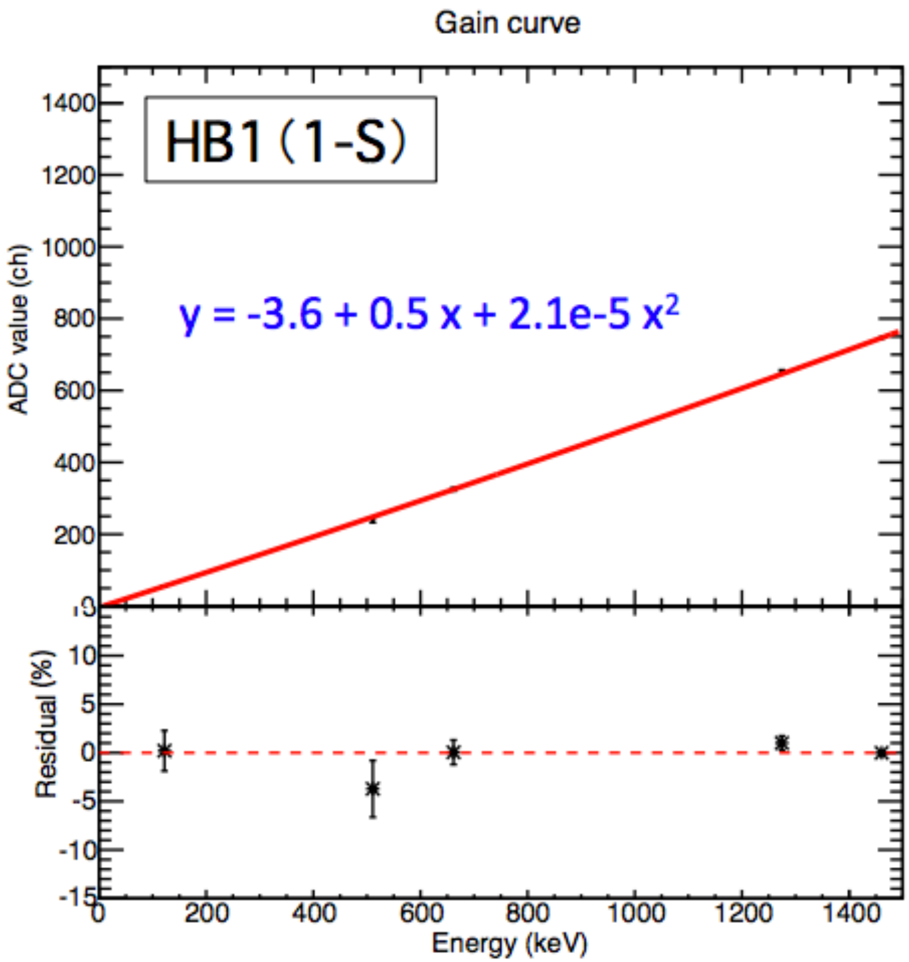
Example of various RI spectra of HXI (9 BGO units)
(Background-included)

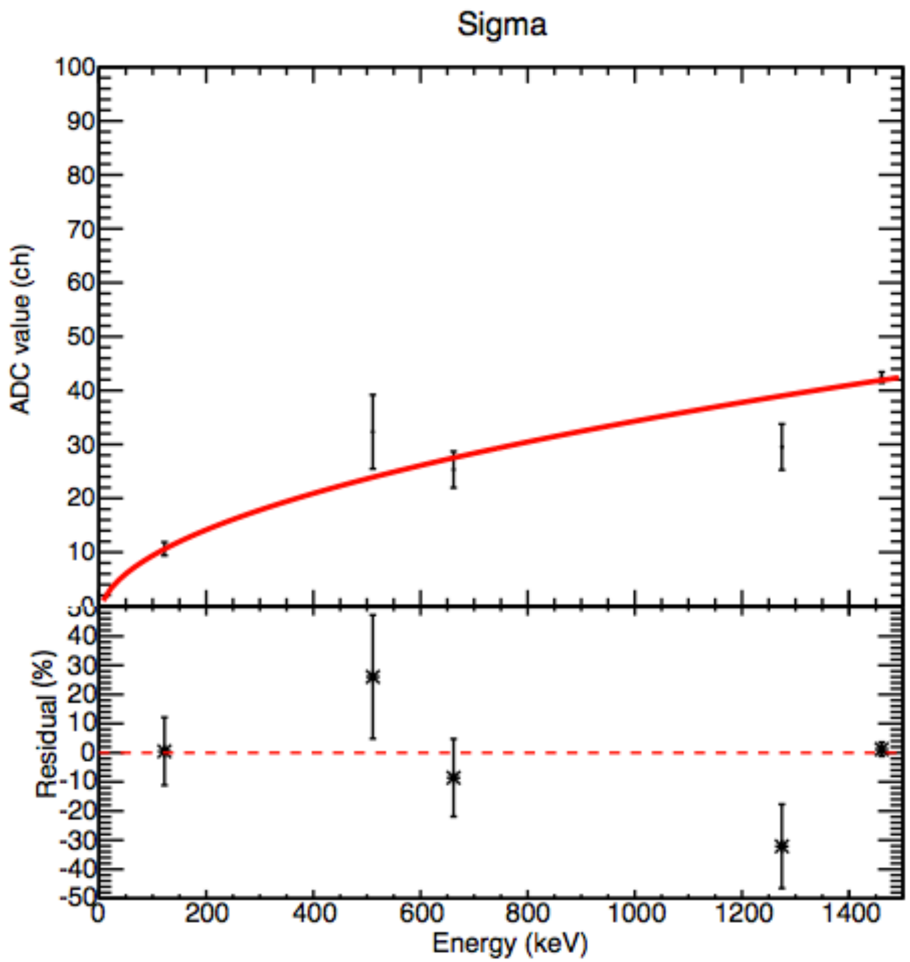


Input parameter
(2) Energy resolution and gain curve



Example of various resulting gain curve and energy resolution for a unit of HXI

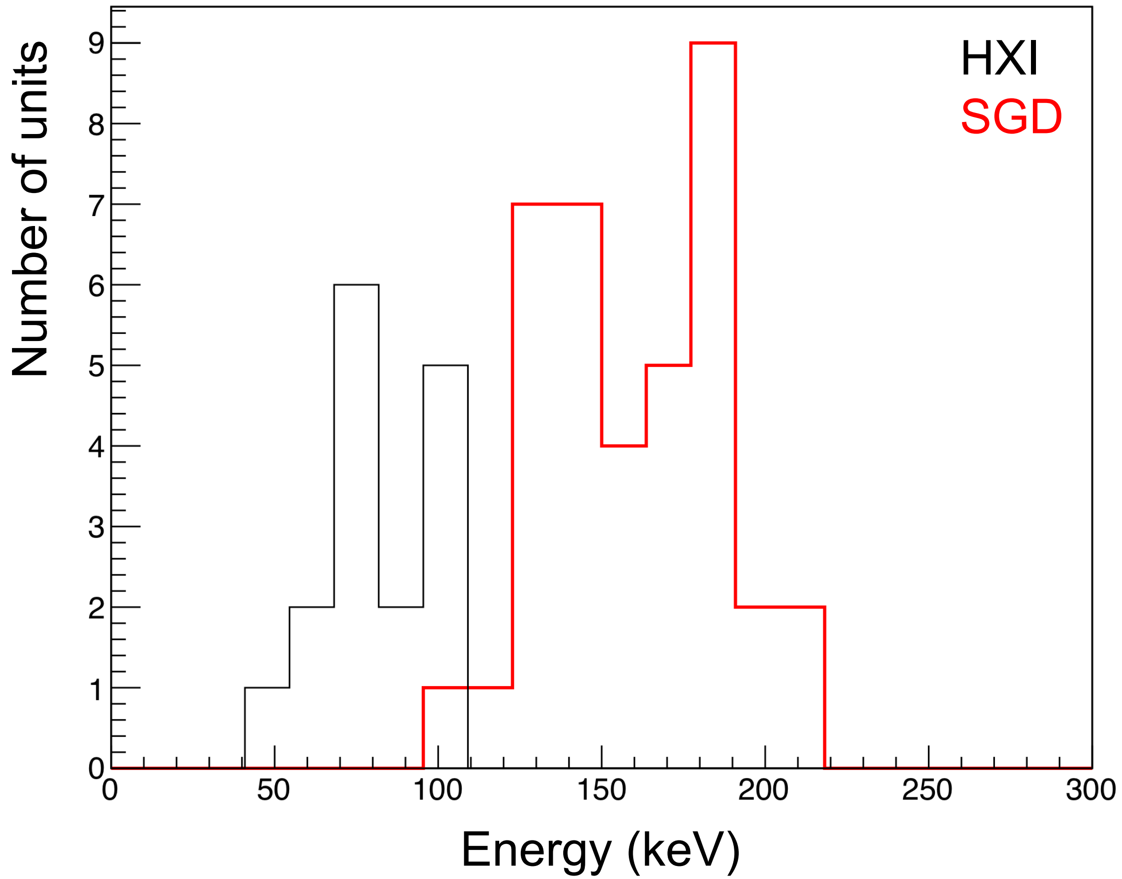




Such gain curve and energy resolution are obtained for all BGO units of HXI/SGD

Input parameter
(2) Energy threshold

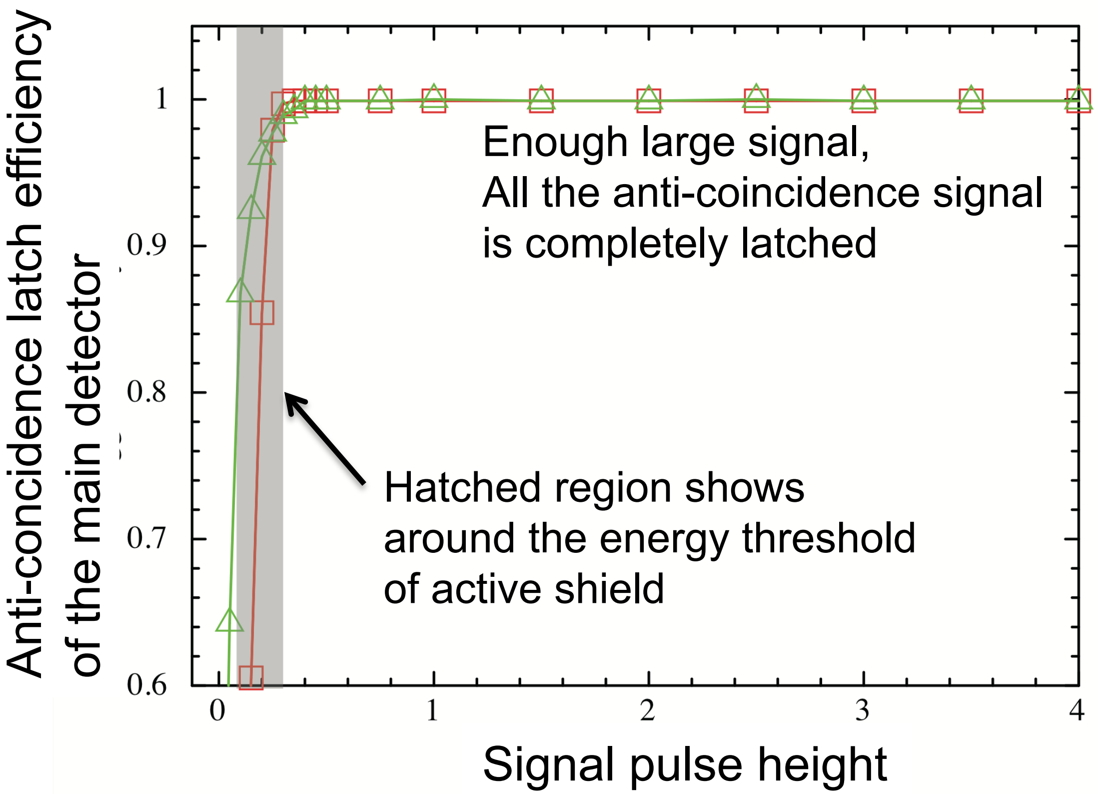
Using background measurement data, we can evaluate the energy threshold for all BGO units of HXI and SGD



These threshold value are also implemented to the simulator

Input parameter
(3) trigger efficiency around threshold

- Trigger generation timing could be changed for the low-pulse height around the threshold due to noise "jitter".
- The anti-coincidence latch efficiency of the main detector decreases at a certain rate in such low-level signals.
- We have to consider this effect to reproduce the background rejection function more accurately.

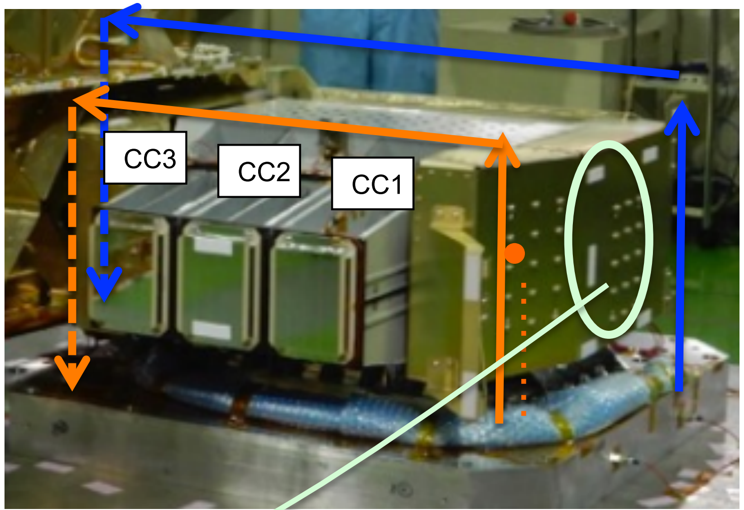


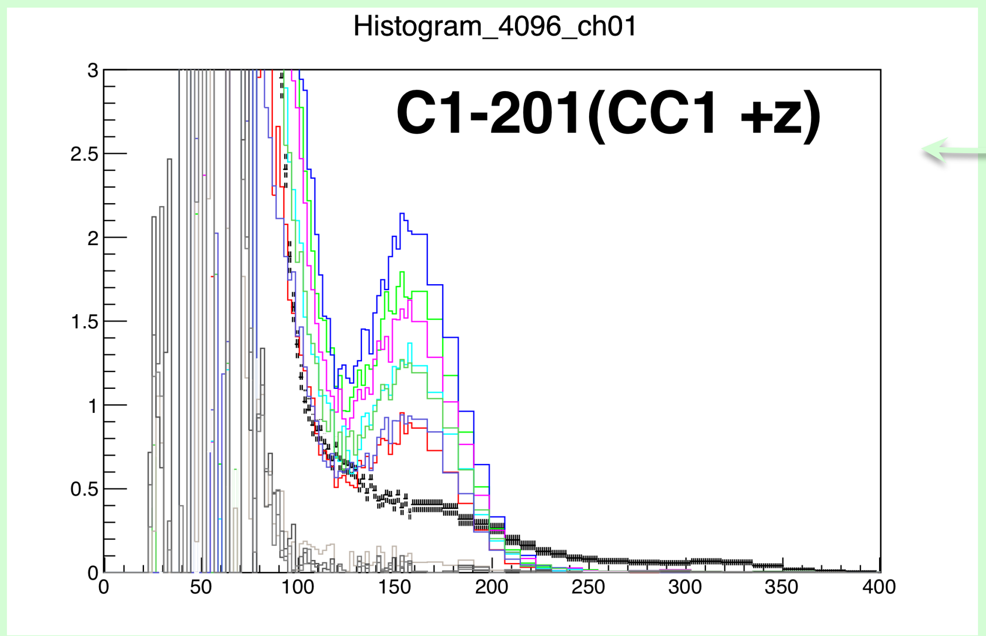
We implement this effect as the probability function in the trigger generation module.

Angular response

SGD shield can be used as the all-sky monitor
Gamma-ray response depending on the incident photon direction should be reproduced by our simulator

Measurement has been performed by irradiation of ^{22}Na at room temperature
(we can only see 1275 keV photo-peak)



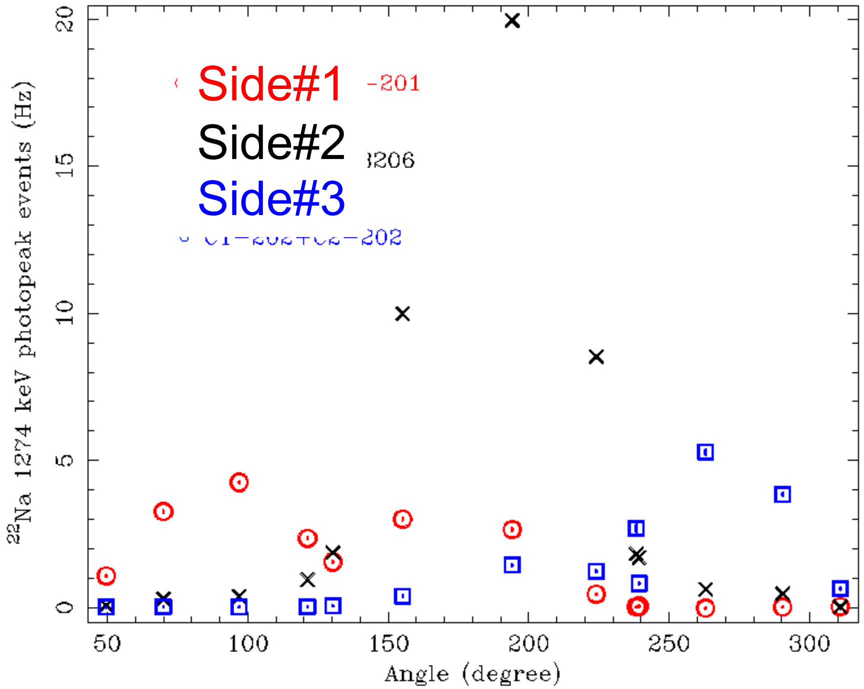


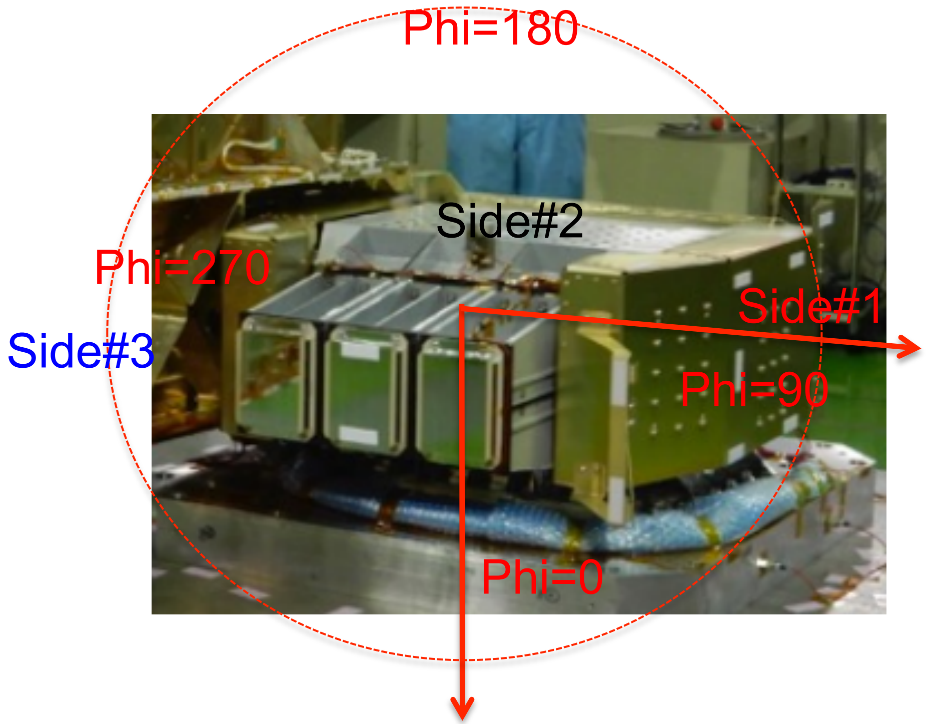
Move ^{22}Na RI source to various positions (15degree/step)

1275 keV photo-peak area count at each RI position is measured

Angular response

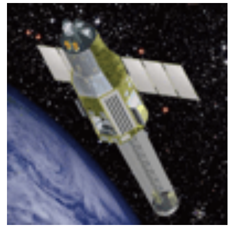
RI position and ^{22}Na photopeak area

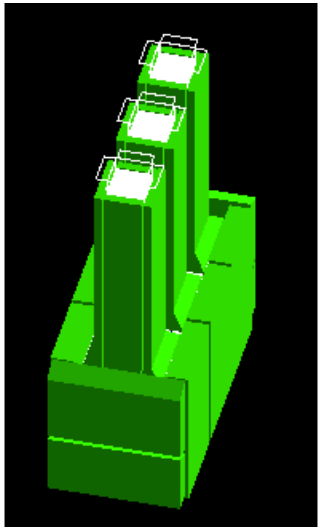


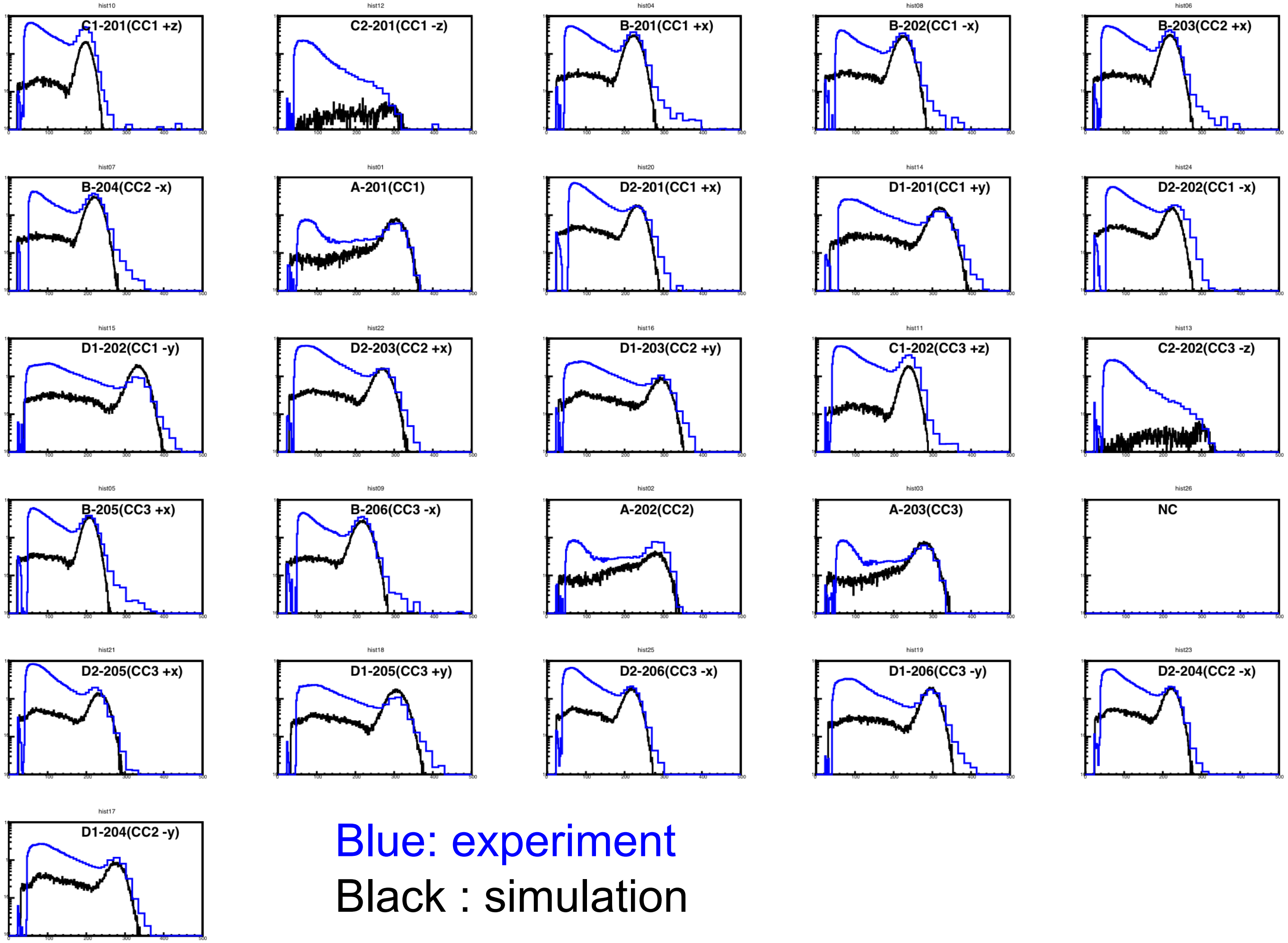


- We can see simple angular response for almost incident position
- But there are some unexpected count increases (phi=150, phi=200).
- These angular response is also checked by our simulator

Verification of the simulator (simple case: SGD)



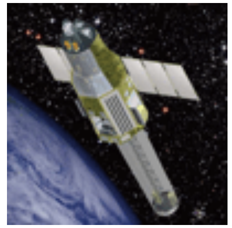


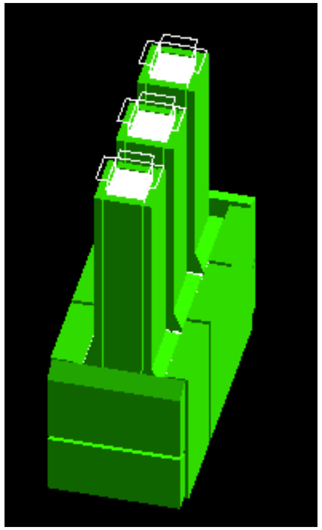


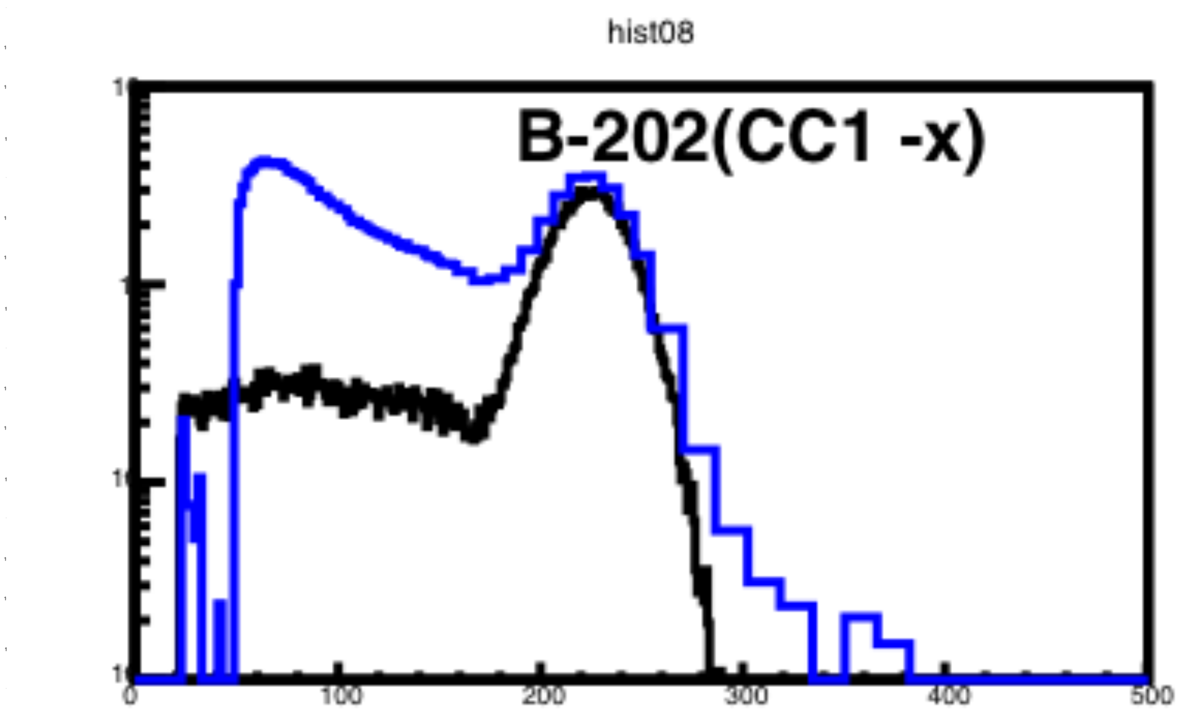
Blue: experiment
Black : simulation

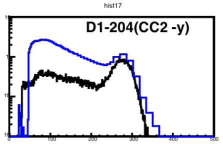
Simulation spectra well reproduce gain and energy resolution, but Compton scattering component is not enough obviously. Surrounding structures also should be included to verify our simulator.

Verification of the simulator (simple case: SGD)





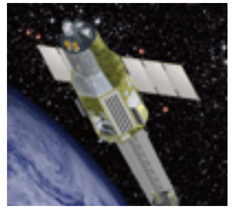


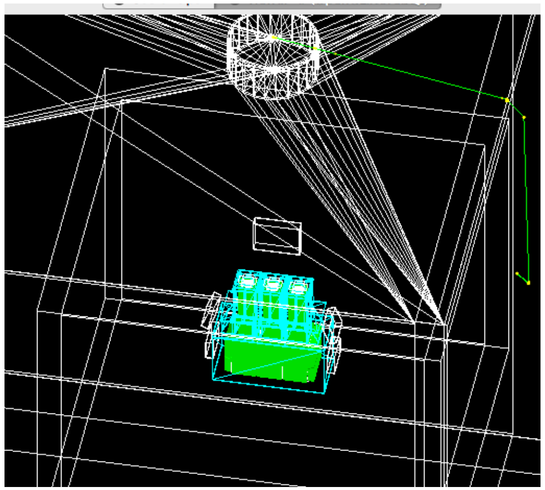


Blue: experiment
Black : simulation

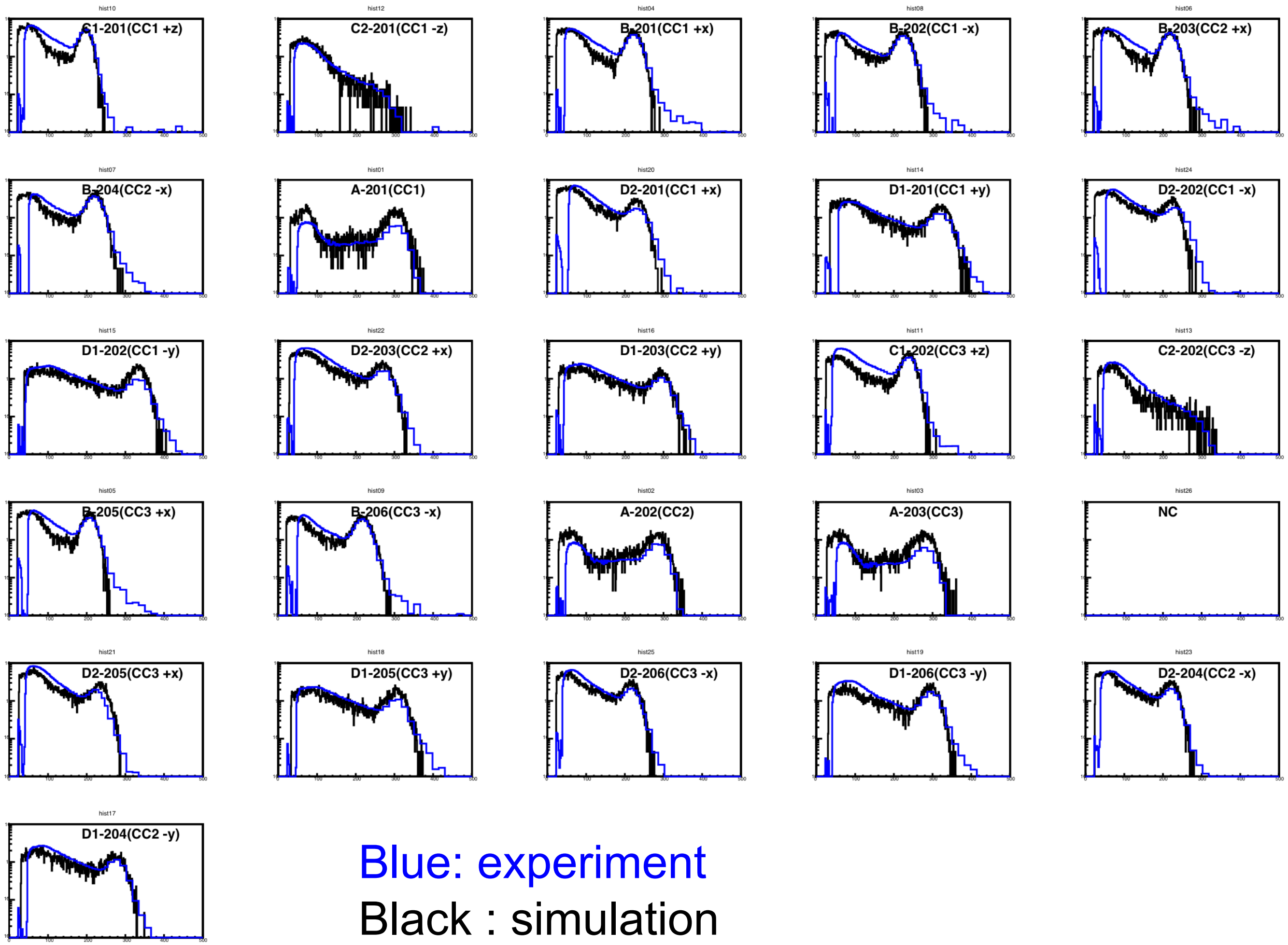
Simulation spectra well reproduce gain and energy resolution, but Compton scattering component is not enough obviously. Surrounding structures also should be included to verify our simulator.

Verification of the simulator (simple case: SGD)





Experimental room,
Thermal Chamber,
Housing structure ..etc
Added to the geometry

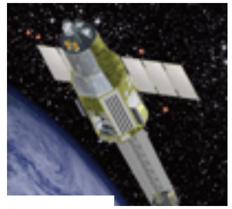


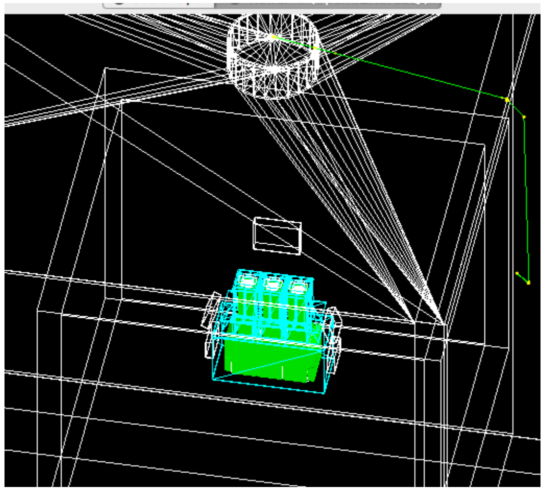
Blue: experiment
Black : simulation

We have successfully reproduce the experimental spectra including Compton scattering component.

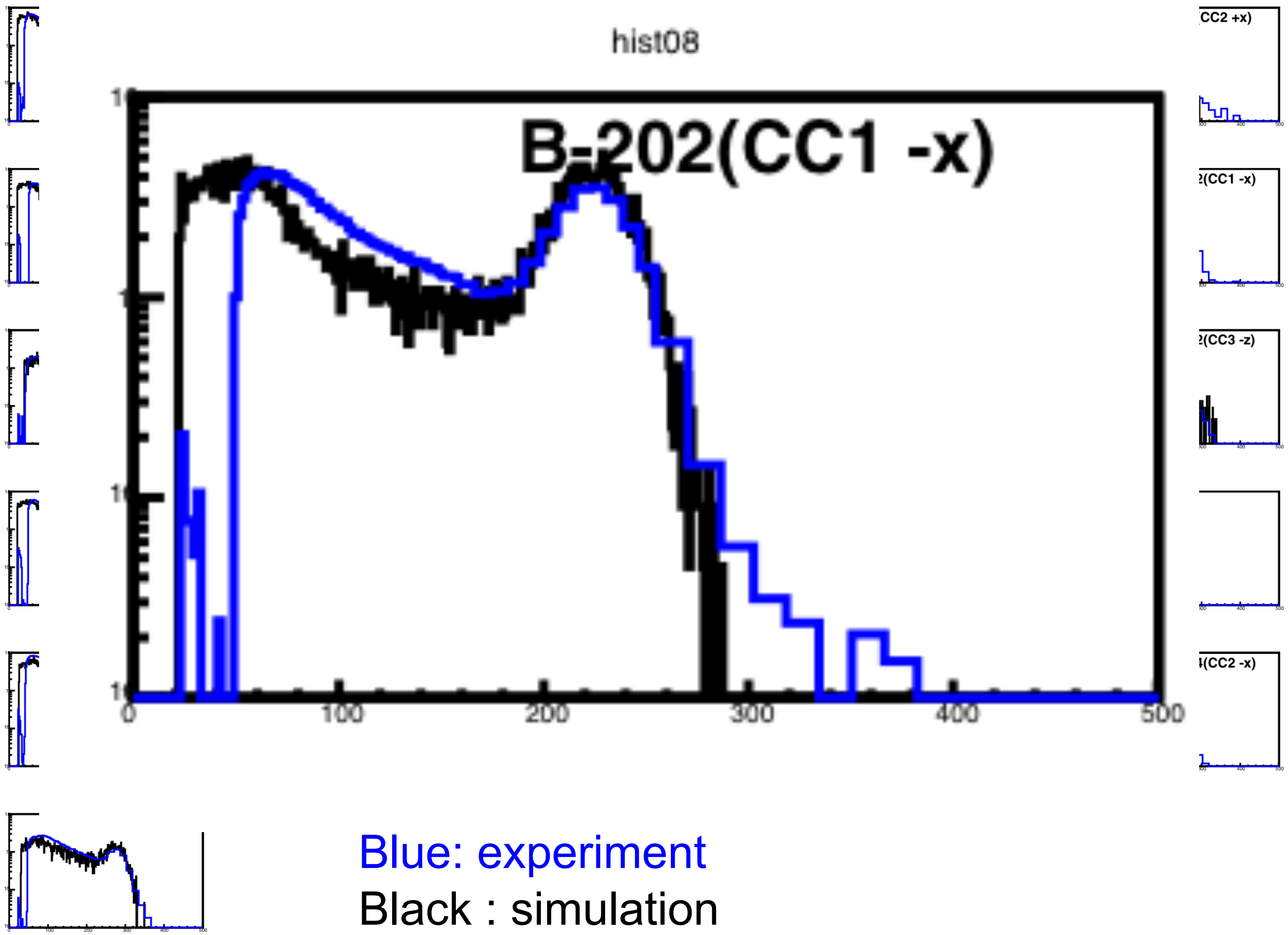
➔ our simulator works well for the simple case

Verification of the simulator (simple case: SGD)





Experimental room,
Thermal Chamber,
Housing structure ..etc
Added to the geometry

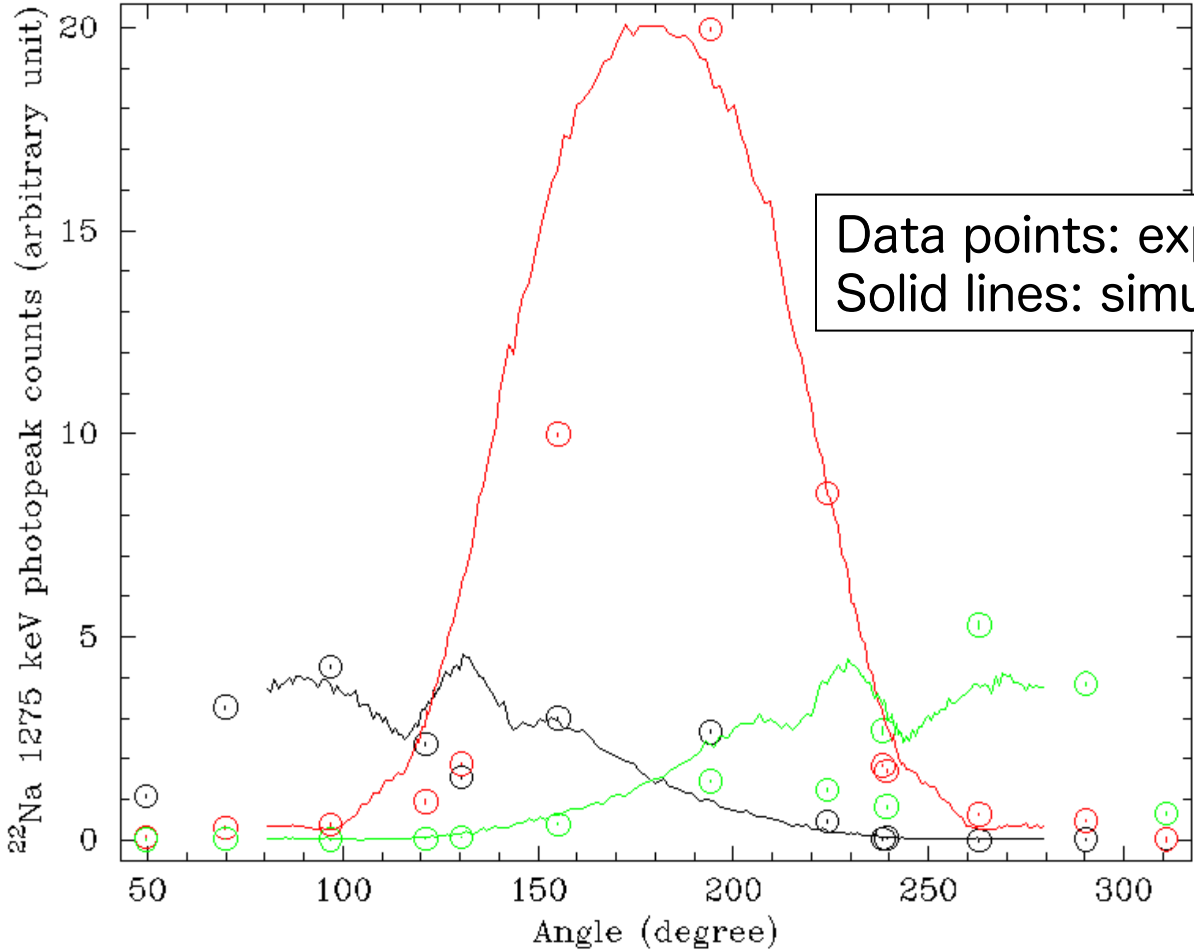


Blue: experiment
Black : simulation

We have successfully reproduce the experimental spectra including Compton scattering component.

➔ confirm that our simulator works well for the simple case

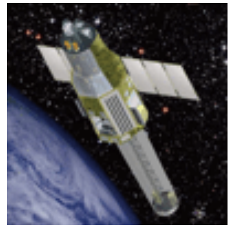
Verification of the simulator (angular response: SGD)

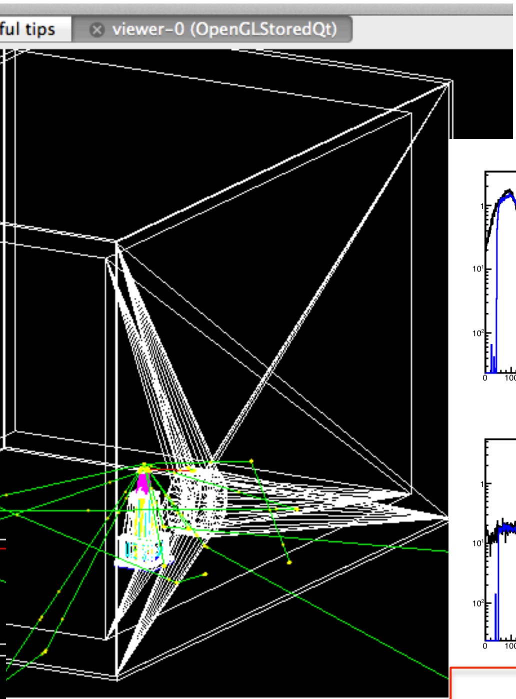


Data points: experiment
Solid lines: simulation

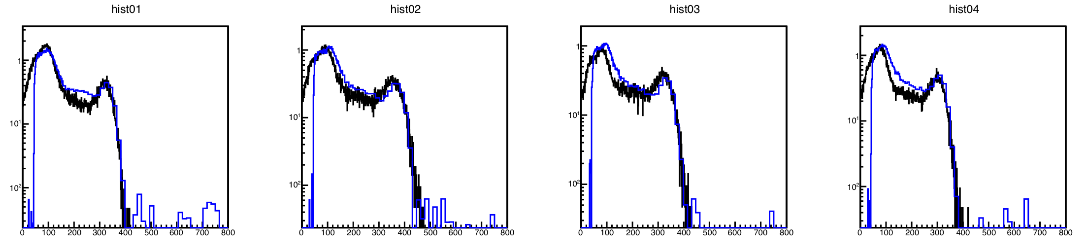
Overall structure including unexpected increase of counts around Phi=150, and phi=200 degree can be reproduced.
Fine tuning of the geometry may be required for further comparison.

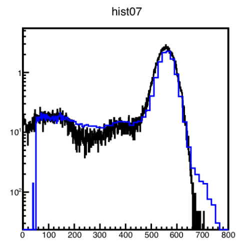
Verification of the simulator (light yield correction: HXI)





HXI "top" part of crystals has strong position dependence of light yield.

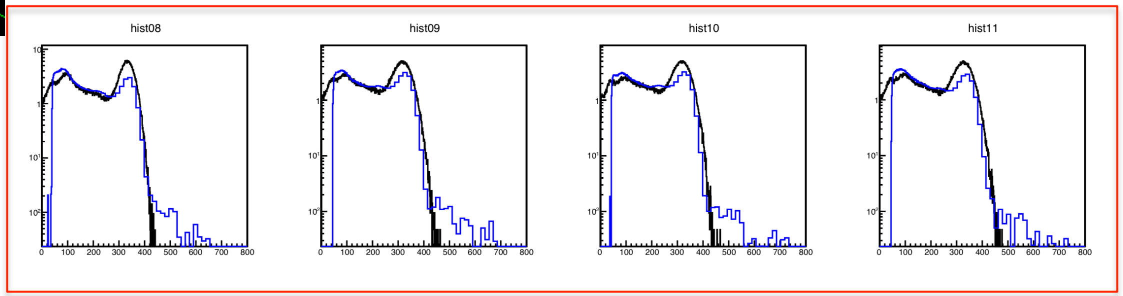




Blue: experiment

Black : simulation

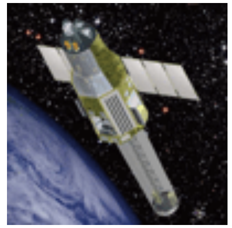
The "top" part of BGO crystals (w/o L.Y. correction)

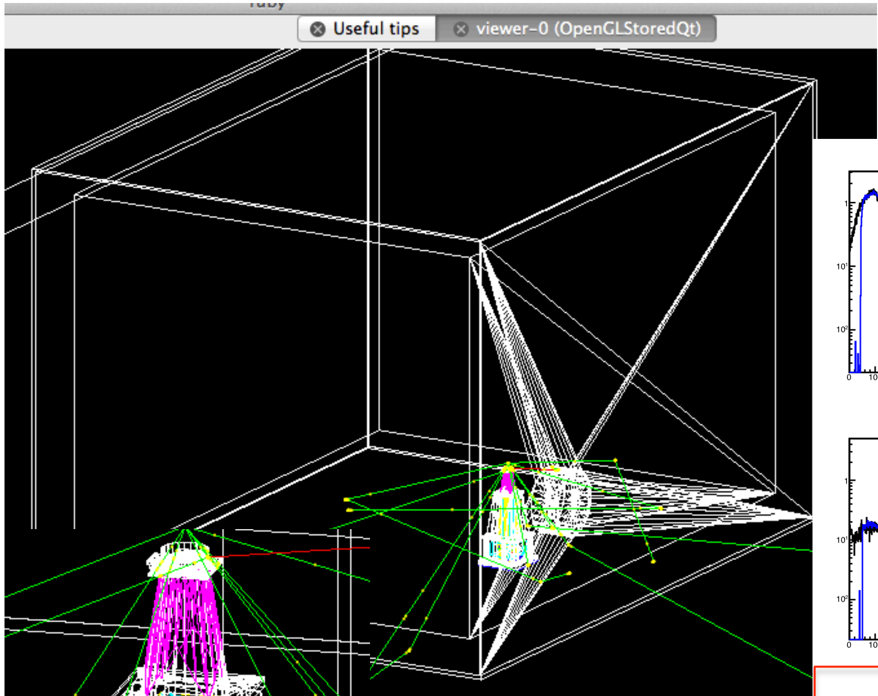


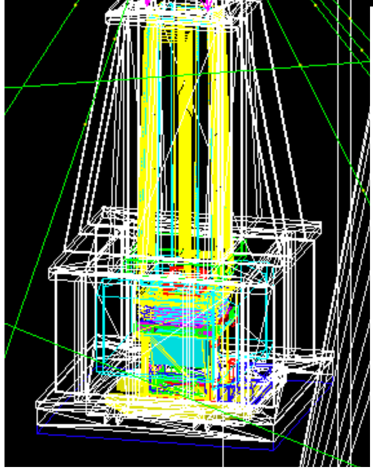
Add Exp. Room and Thermal chamber like SGD case

Again, our simulator works well for other than "top" part of crystals. For top crystals, "tail"-like structure can not be reproduced…

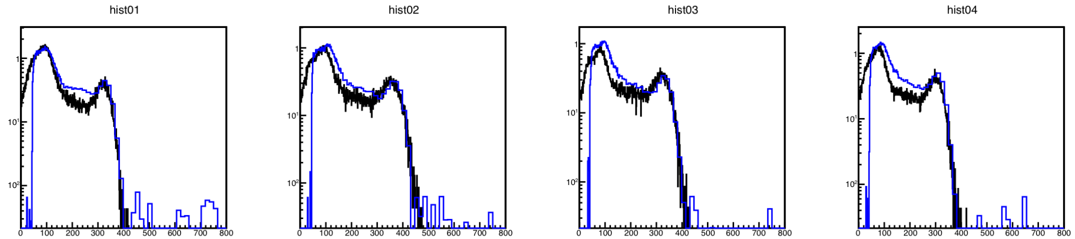
Verification of the simulator (light yield correction: HXI)

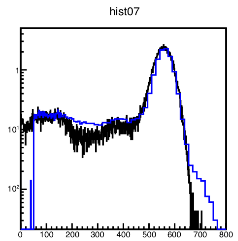






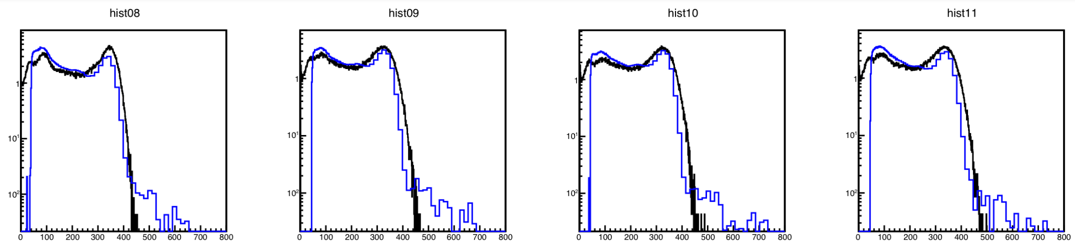
HXI “top” part of crystals has strong position dependence of light yield.





Blue: experiment
Black : simulation

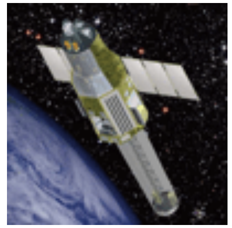
The “top” part of BGO crystals (w L.Y. correction)



Add Exp. Room and Thermal chamber like SGD case

With L.Y. correction model, “tail”-like structure is also reproduced. However, fine tuning of parameter is still needed…

Conclusion



❖We have developed Monte-Calro simulator for BGO active shield of HXI/SGD onboard ASTRO-H satellite

❖By implementing various parameters based on ground calibrations, our simulator reproduces experimental data well.

❖Fine-tuning and/or verification with component model is still needed for light yield correction for HXI

❖Remaining framework (energy threshold/trigger generation) will be implemented soon, and background simulation for the main detector is also verified.

❖For SGD, performance as the all-sky monitor is now under verification using this simulator.