Development of the detector simulation framework for the Wideband Hybrid X-ray Imager onboard FORCE

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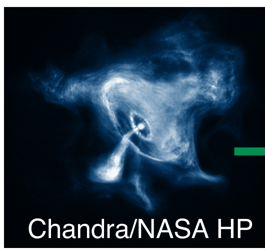
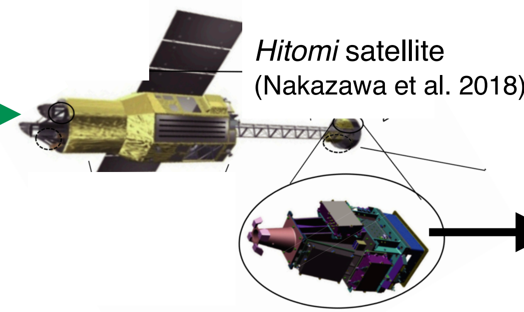
Detector response in **astrophysics**

Through observation of a celestial source,
We want to know photon spectrum --> derive physics
(emission process, temperature, etc.)
BUT we observe detector count spectrum

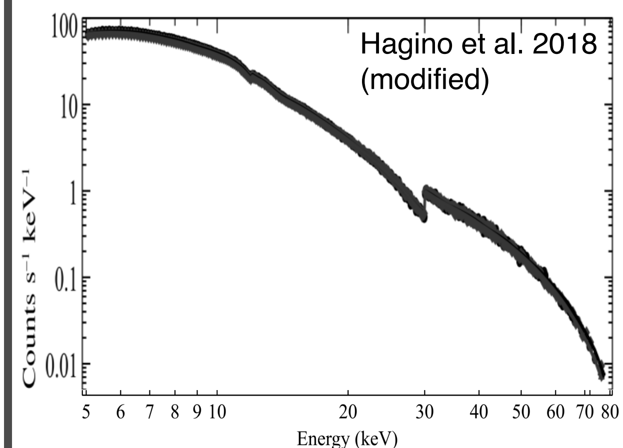


Pulsar wind nebula
Crab Nebula



Hitomi satellite
(Nakazawa et al. 2018)

Count spectrum



What we observe

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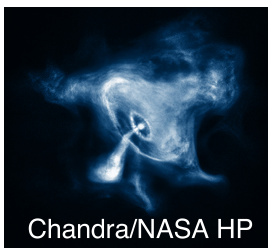

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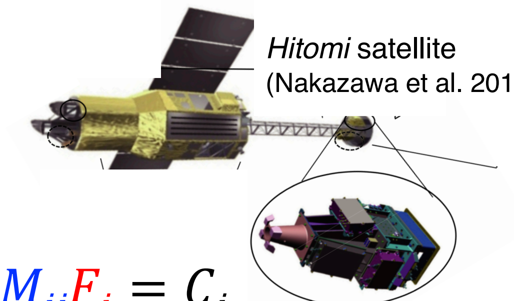
Detector response



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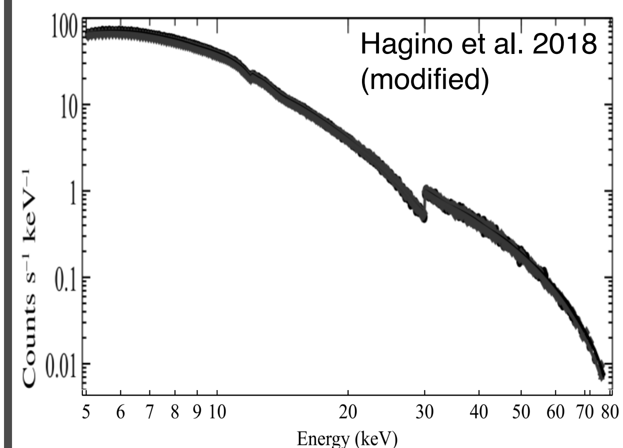
$$M_{ij}F_i = C_j$$

- C_j: Count spectrum
- F_i: Photon spectrum
- M_{ij}: Response matrix

Count spectrum



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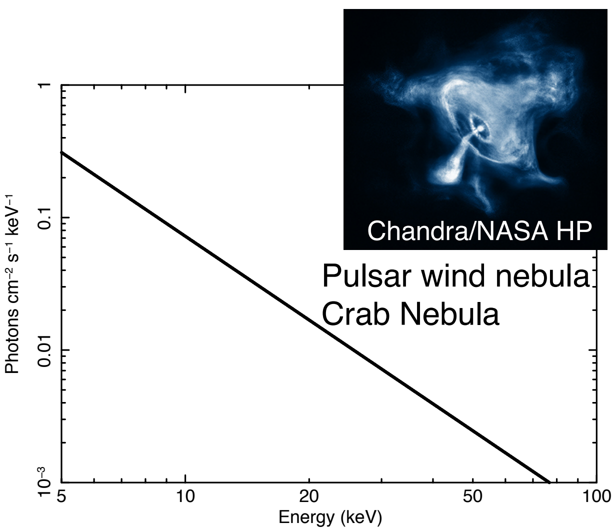
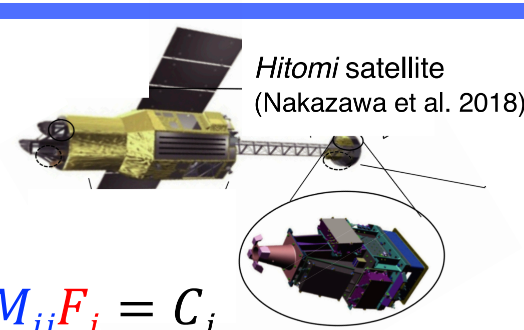
Photon spectrum



What we want to know

Detector response



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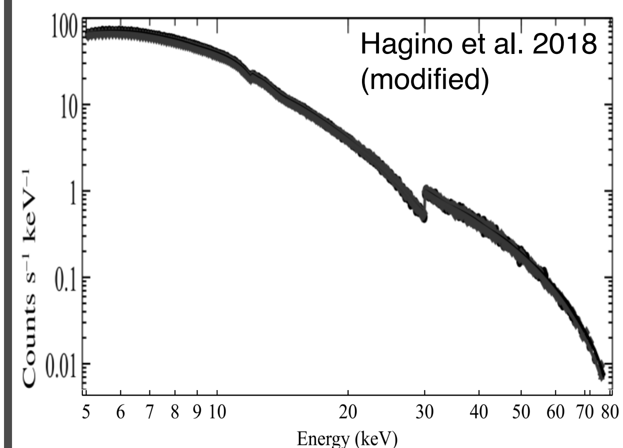


What we observe

Detector response essential in astrophysics.

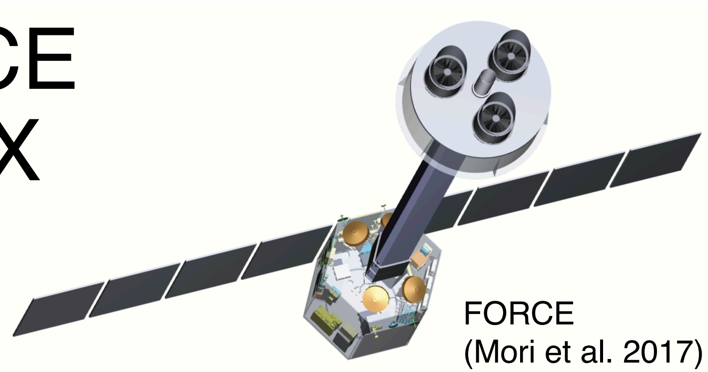
Response study for hard X-ray sensors

- In E > ~10 keV, physical processes complicated
  (absorption, scattering, secondary e-, fluorescence...)
  --> Monte-Carlo simulations on detector response study necessary
- Monte-Carlo (input photons + optics) & device (inside sensor) simulation
- Applied to hard X-ray detectors
  onboard *Suzaku* (2005–2015) and *Hitomi* (2016)

- Response study necessary for
  optimizing camera design & making science planning

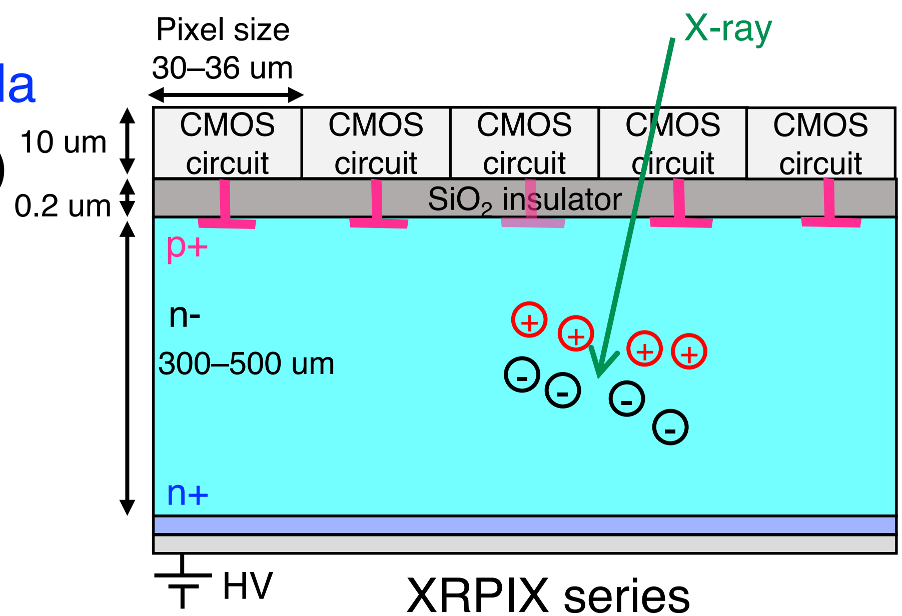
Future X-ray satellite FORCE and SOI pixel sensor XRPIX

- X-ray satellite FORCE (Mori et al. 2017)
  - Proposed Japan-US mission
  - Main science: finding hidden black holes
  - High angular resolution (< 15”) + wideband spectroscopy (1–80 keV)
  - Detector: SOI (Silicon-On-Insulator) pixel sensor “XRPIX” + CdTe



FORCE (Mori et al. 2017)

- XRPIX series
  - Posters by R. Kodama and A. Takeda
  - Pixel size < ~(2nd e- mean free path) + thick full-depleted sensitive layer
    --> Charge-share events significant
    (Charge-share evts. used as well to maximize statistics)
    --> Requires simulations including charge-share events correctly



XRPIX series

Our simulation framework

- Simulation flow

Comptonsoft

(Odaka et al. 2010)

Input photons
→ interactions (abs., scat., 2nd el., ...)
→ energy deposits in sensor
} **Geant4**

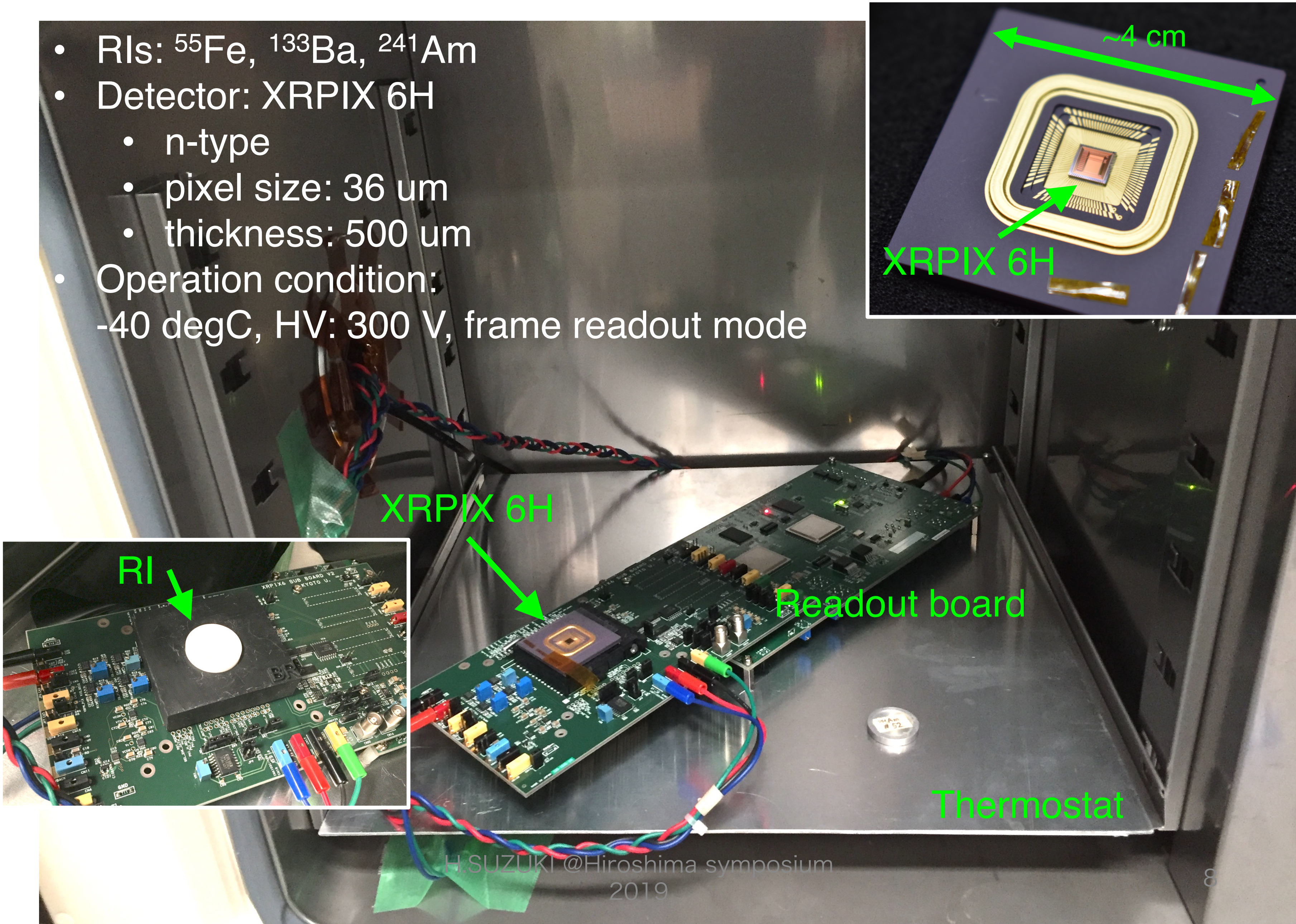
→ charge cloud behavior
(diffusion + E-field drag + charge loss)
→ collect charge clouds
} **Device simulation**

→ frame data
→ event extraction

- We determined sensor physical parameters to be inputted into simulations by comparing simulations to **laboratory measurements**
  - Readout noise
  - Charge collection efficiency (CCE) spatial distribution
  - Electric field structure
  - Coulomb replusion effect on charge sharing

Laboratory measurements

- RIs: ^{55}Fe, ^{133}Ba, ^{241}Am
- Detector: XRPIX 6H
  - n-type
  - pixel size: 36 um
  - thickness: 500 um
- Operation condition:
  -40 degC, HV: 300 V, frame readout mode

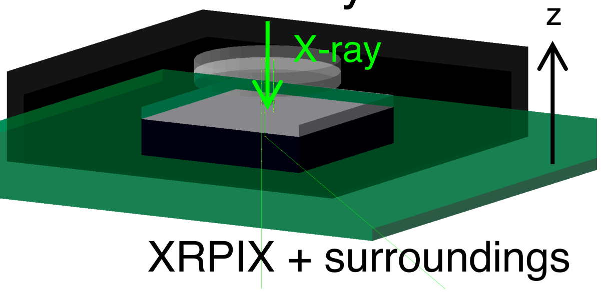


Determination of physical parameters

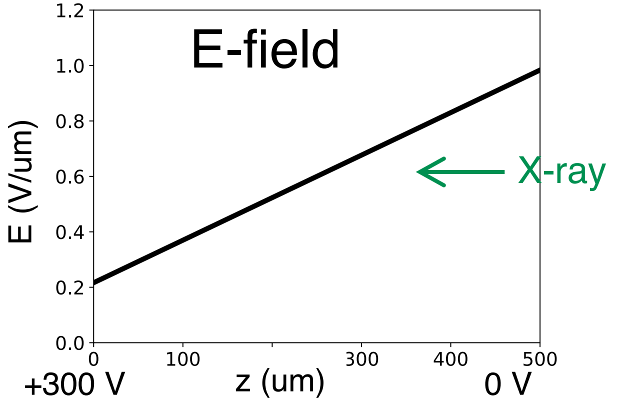
Simulation condition:

Readout noise: 0.16 keV, Coulomb repulsion factor: {1.0@5.9 keV, 1.0@30.9 keV}

Geometry

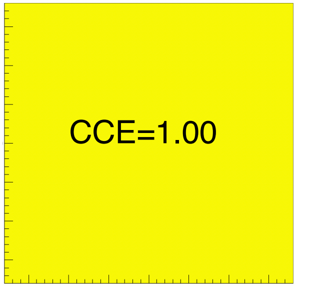


XRPIX + surroundings



Maximum at upper surface due to boundary of n- and p+

CCE distribution (inside one pixel)



Determination of physical parameters

Comparison of simulation to measurement

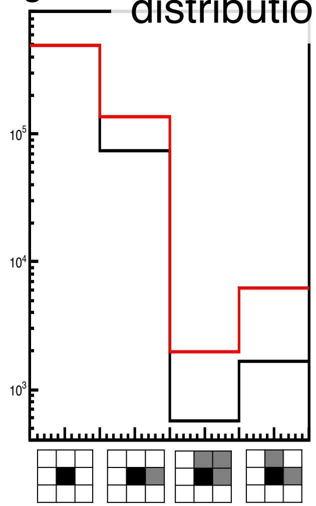
Before optimization @5.9 keV (^{55}Fe)

Simulation

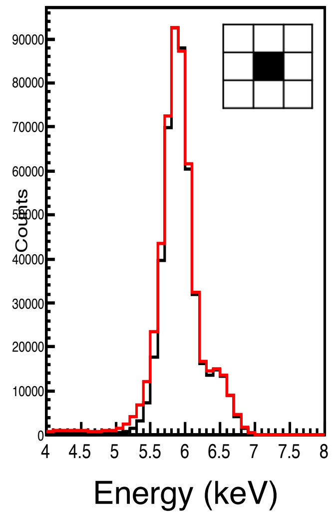
Measurement

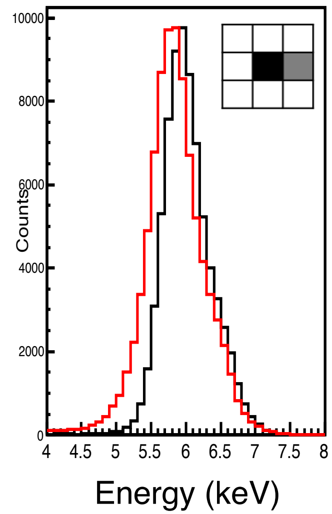
logY

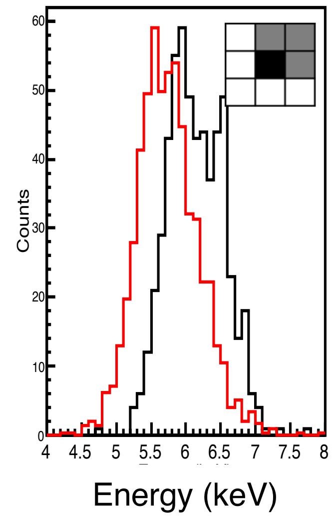
Event type distribution

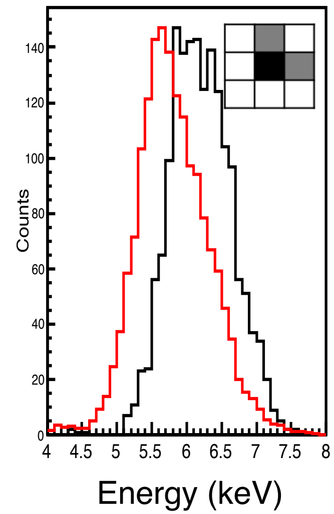


Spectrum of each event type









Simulations should have ...

- larger charge-share event fraction
- lower line centroids for charge-share events

Determination of physical parameters

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Before optimization @30.9 keV (^{133}Ba)

logY

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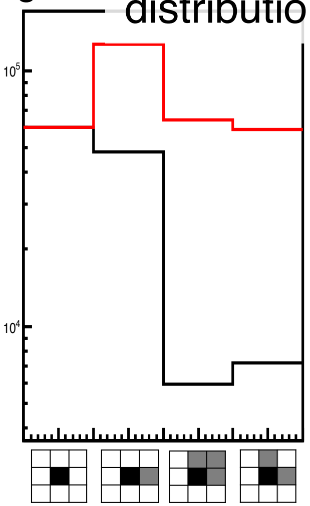

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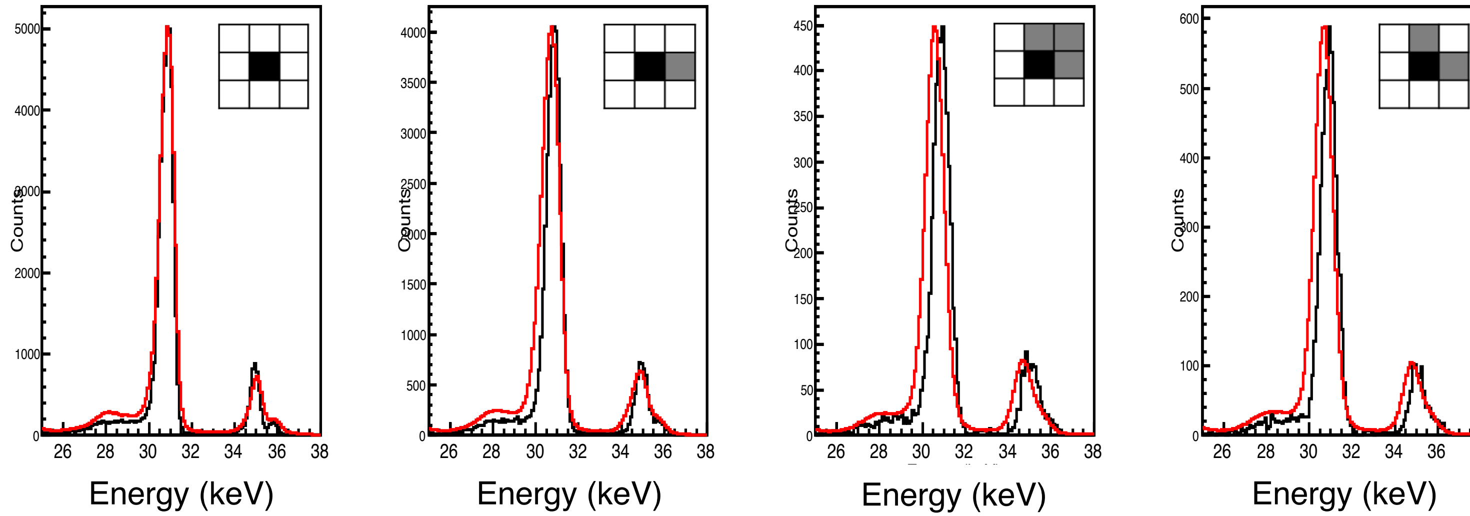
Simulation

Measurement



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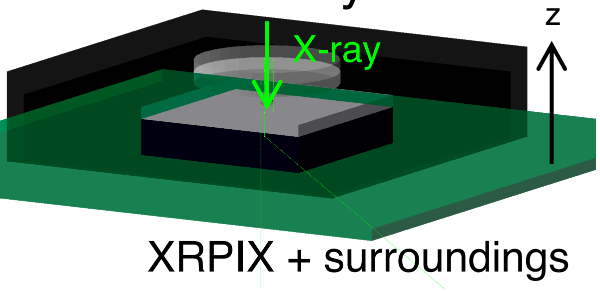
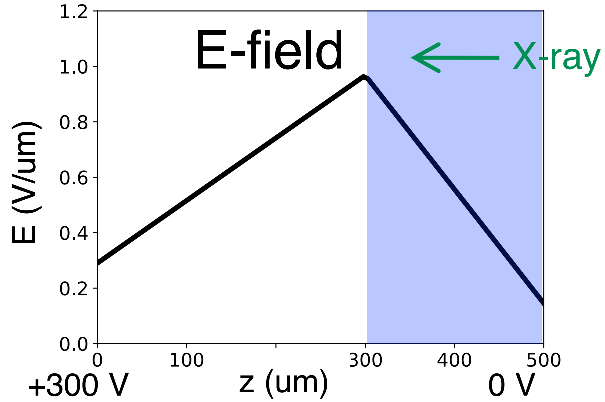
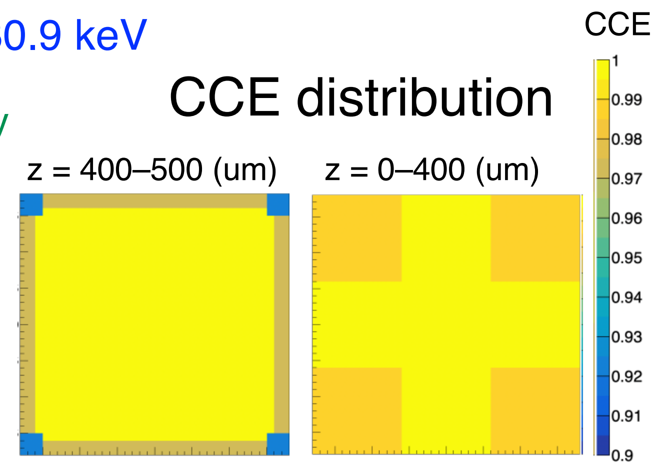


XRPIX + surroundings



CCE distribution



Make events more spread

Make line centroids lower

Physically,
contribution of pixel edges
where E-filed is weak

Determination of physical parameters

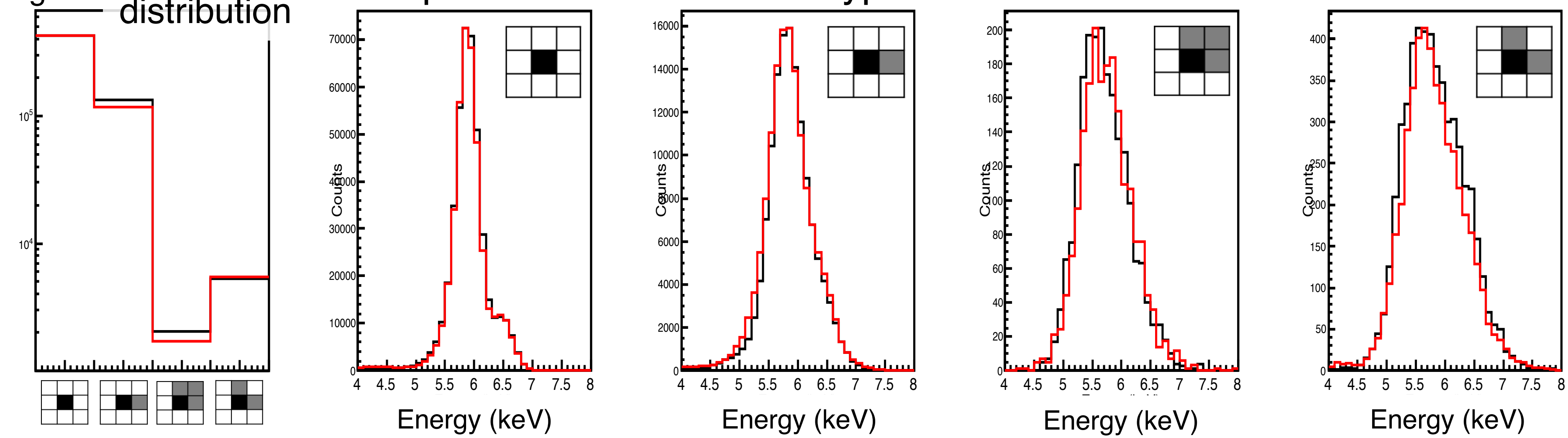
Comparison of simulation to measurement

After optimization @5.9 keV (^{55}Fe)

Simulation
Measurement

Event type distribution

Spectrum of each event type



Simulation explains the measurement

Determination of physical parameters

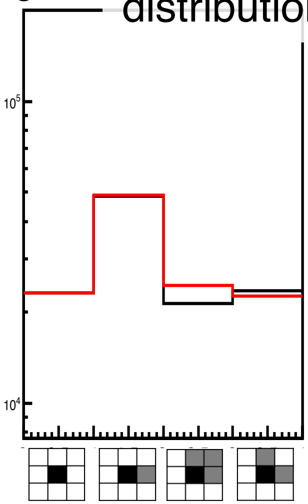
Comparison of simulation to measurement

After optimization @30.9 keV (^{133}Ba)

Simulation
Measurement

logY

Event type distribution



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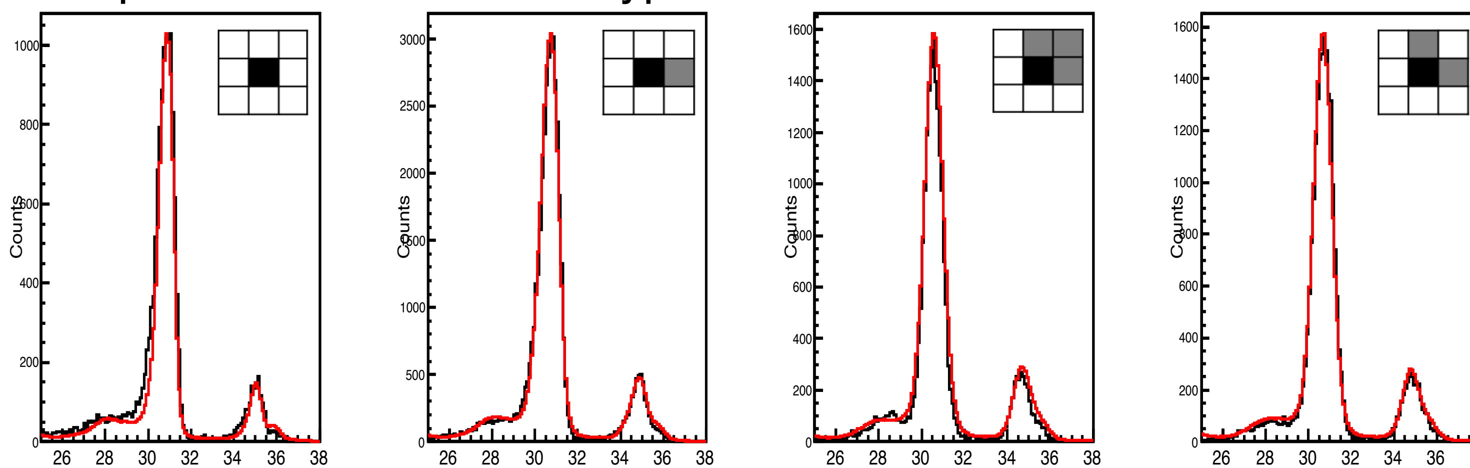
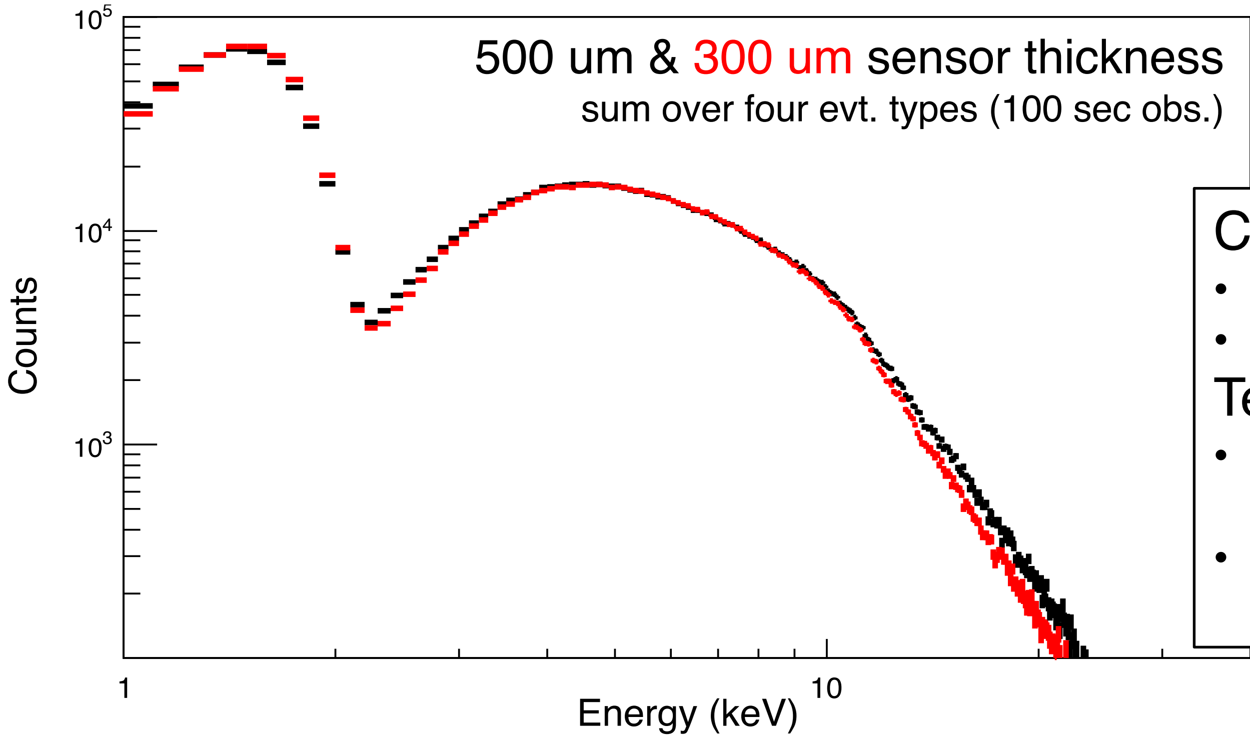
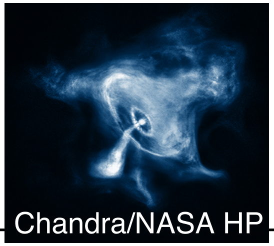


Simulation explains the measurement

Application to a celestial source simulation

- Simulation of a celestial source Crab Nebula with our framework





Crab Nebula

- Photon index = -2.1
- Flux = 2×10^{-8} erg s^{-1} cm^{-2}

Telescope

- Angular resolution = 15” (HPD)
- Effective area = 570 cm^2@10 keV

- Confirmed that our simulation framework works, and can be used for detector design (after further optimization of sensor parameters done)
- This simulation framework can also be...
  - used for particle background simulation.
  - applied to any semiconductor sensor.

Summary

- SOI pixel sensor XRPIX series will be used for the future X-ray satellite FORCE.
- Response study is necessary for optimizing camera design & making science planning
- We have developed the response simulation framework for XRPIX.
- By comparing simulation results to laboratory measurements, we determined the physical parameters of XRPIX 6H sensor.
- Applying to the celestial reference source Crab Nebula, we confirmed that our simulation framework works.
- This framework can be applied to any semiconductor sensor.

Backup

Analysis flow

- **Simulation**
  1. Run Monte-Carlo simulation
  2. Apply event selection with event threshold (x9 readout noise) & split threshold (x3 readout noise)
  3. Generate spectrum of each event type (single, double, ...)

- **Measurement**
  1. Run RI measurement
  2. Apply gain corrections to individual pixels @5.9, 17.8, 30.9 keV line emission
  3. Apply the same event selection as simulation
  4. Generate spectrum of each event type (single, double, ...)

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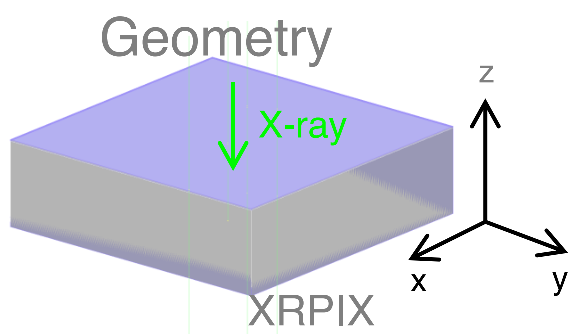
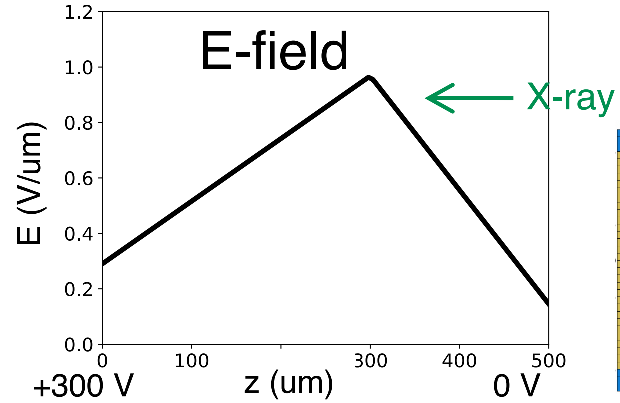
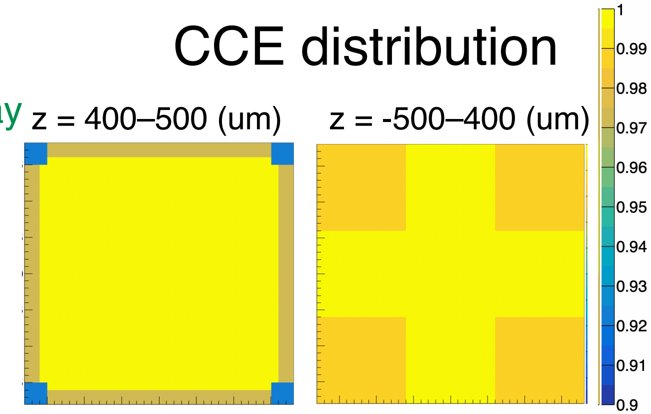




CCE distribution



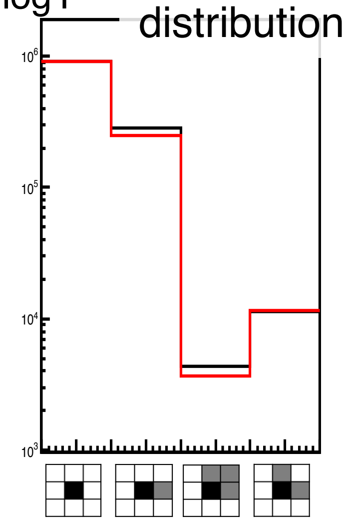
- **Comparison of simulation to measurement**

@5.9 keV (^{55}Fe)

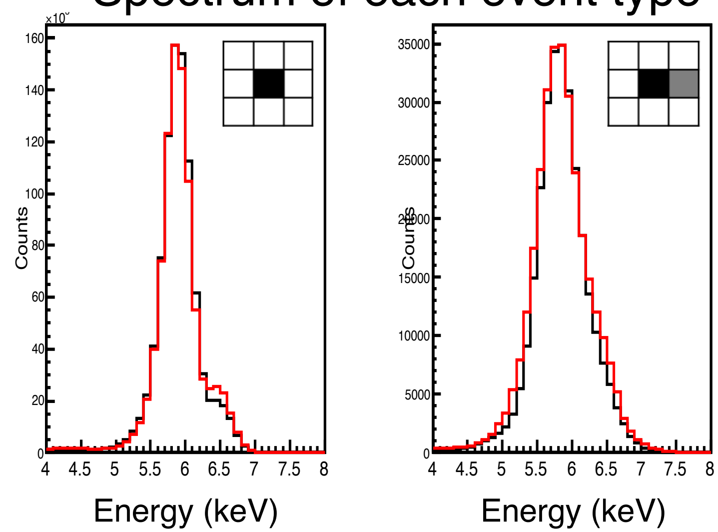
Simulation

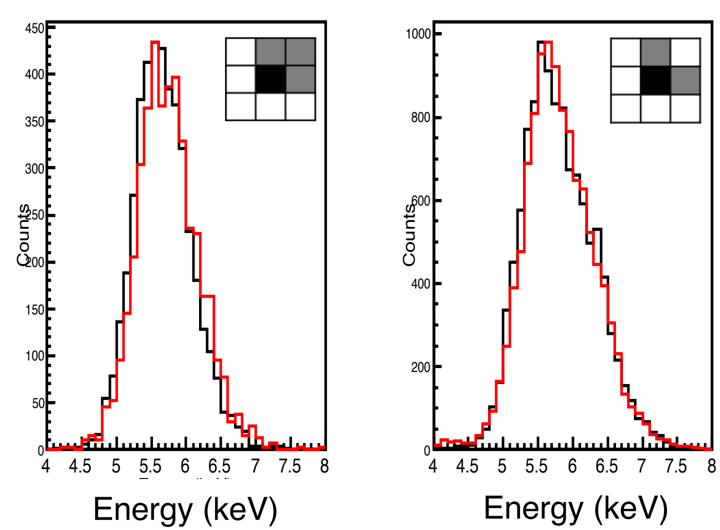
Measurement

Event type distribution



Spectrum of each event type





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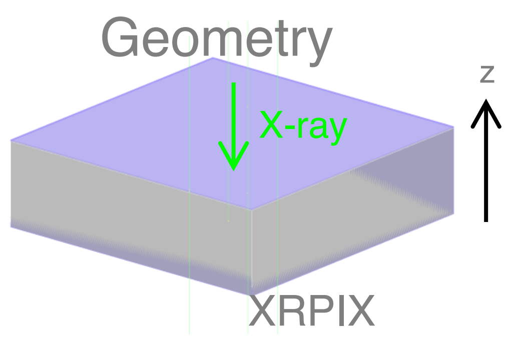
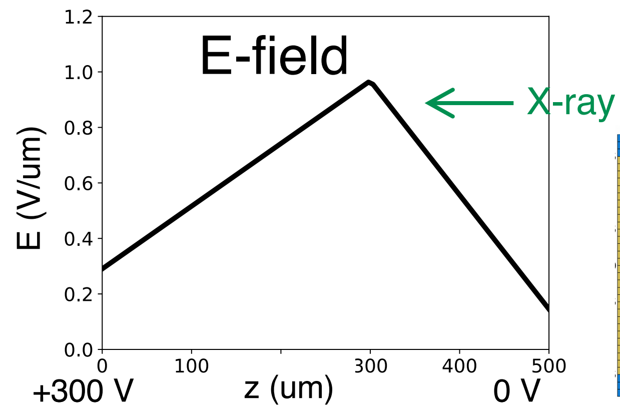
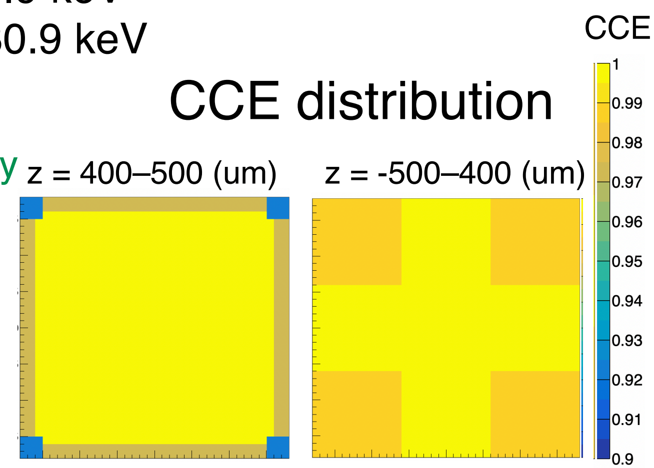
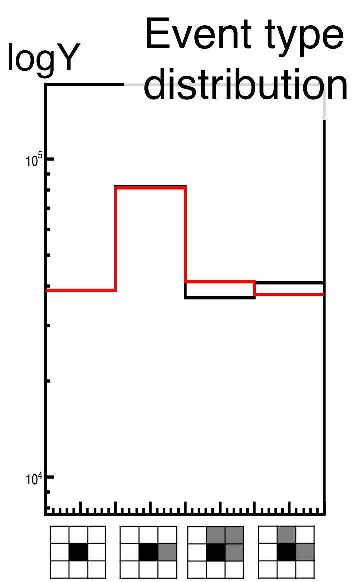


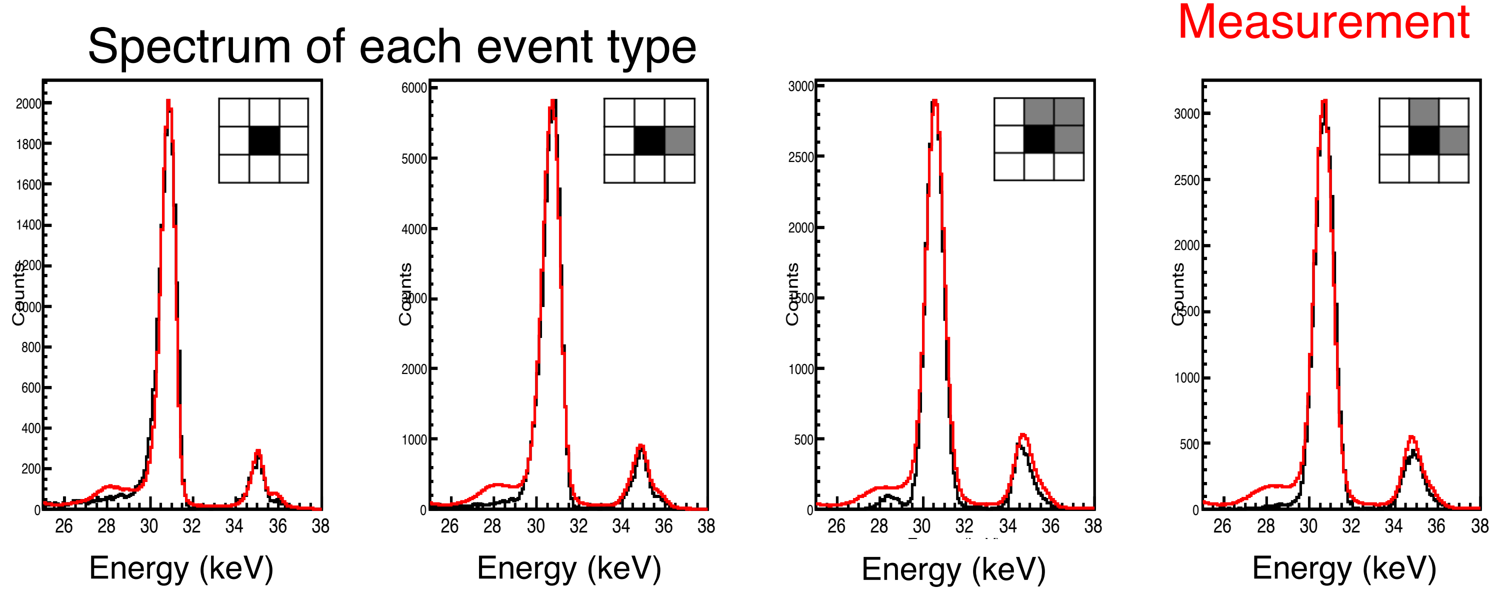




- **Comparison of simulation to measurement**

@30.9 keV (^{133}Ba)





FORCE (Mori et al. 2017)

Table 1. Instrument parameters

Angular resolution	<15″ (HPD)
Multi-layer Coating	Pt/C
Field of view at 30 keV	∼7′×7′ (50% response)
Effective Area at 30 keV	370 cm^2
Energy range	1–80 keV
Energy resolution at 6 keV	<300 eV (FWHM)
Background	comparable to Hitomi/HXI
Timing resolution	several × 10 μs
Working temperature	−20±1 °C

Theoretical calc. of Coulomb repulsion

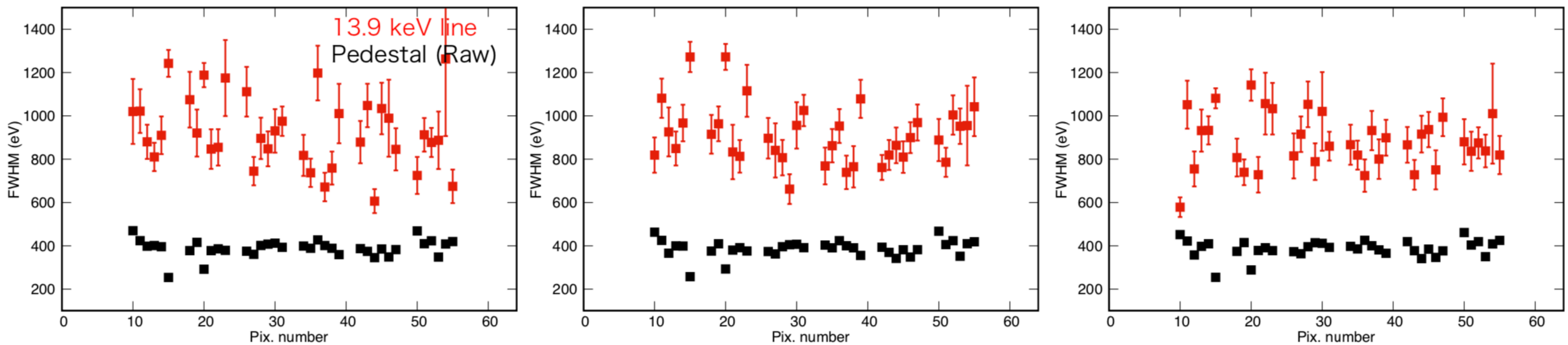
Since the effect of the photoelectron range was considered in the Geant4 Monte-Carlo simulation, we implemented charge spreading due to thermal diffusion and Coulomb repulsion. The width σ of Gaussians of charge spreading after the drift time was calculated by solving a differential equation derived by Benoit & Hamel (2009) [24],

$$\frac{\partial \sigma^2}{\partial t} = 2D + \frac{\mu_{\mathrm{p}} N e}{12\pi^{3/2}\varepsilon\sigma}, \tag{7}$$

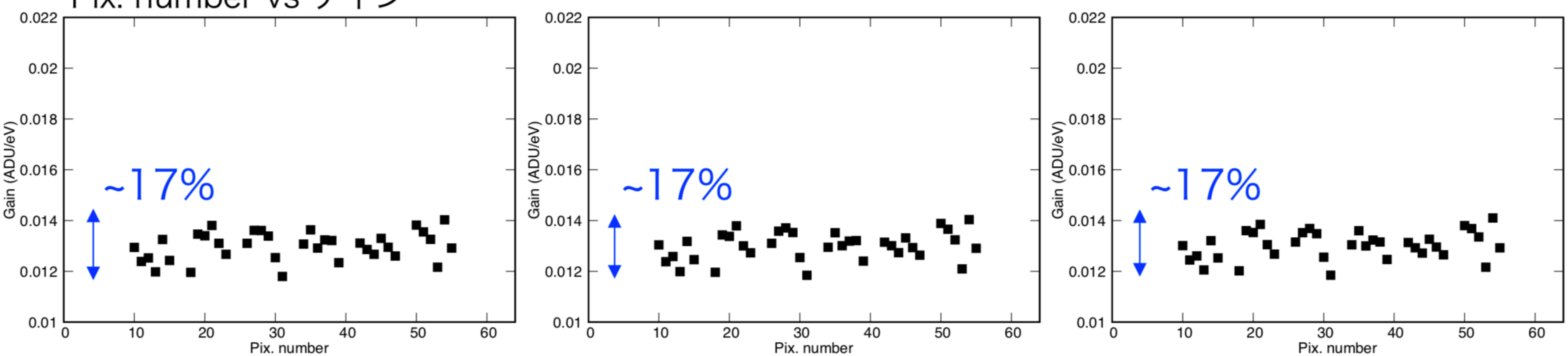
Gain fractuation of XRPIX

^{241}Am, 300V, -40 degC ^{241}Am, 350V, -40 degC ^{241}Am, 400V, -40 degC

Pix. number vs FWHM



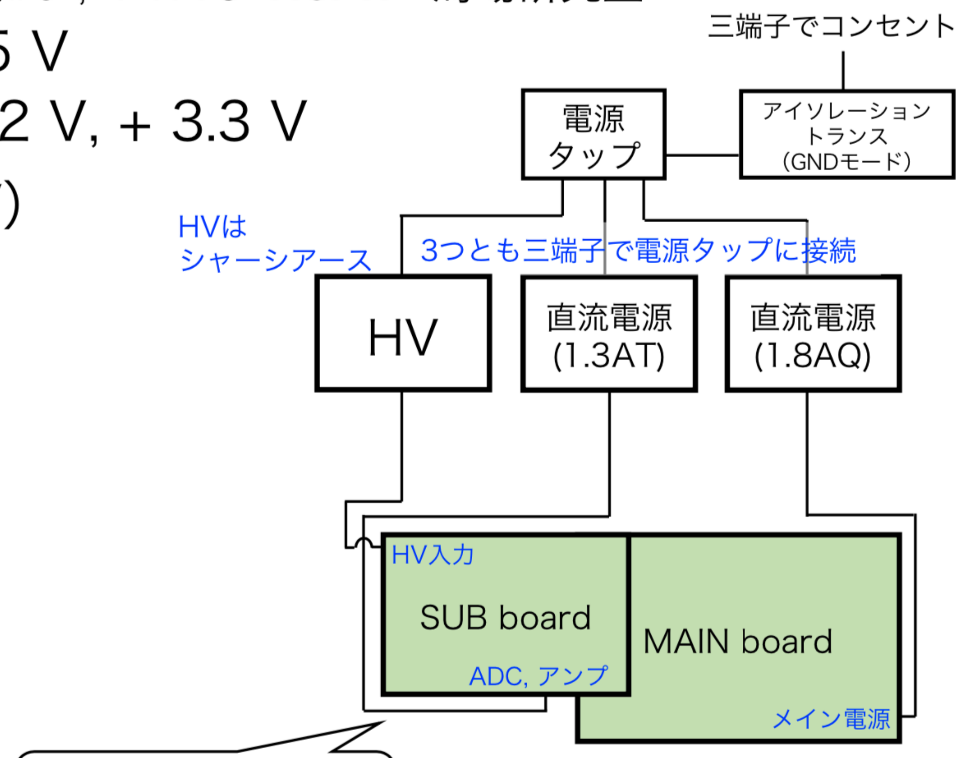
Pix. number vs ゲイン



Laboratory experiment environment

- 電源系:
  - 直流電源x2: PW18-**1.8AQ** "トラ電#5", PW18-**1.3AT** "馬場研究室"
    - 1.8AQ -> メインボード ± 5 V
    - 1.3AT -> アンプ, ADC ± 12 V, + 3.3 V
- HV: Keithley 2410（max 1100 V）
- 恒温槽: MC-711P（espec）
- 解析PC: 仮想マシンCentOS 6 in MacPro
- 使った線源: ^{241}Am, ^{137}Cs, ^{55}Fe

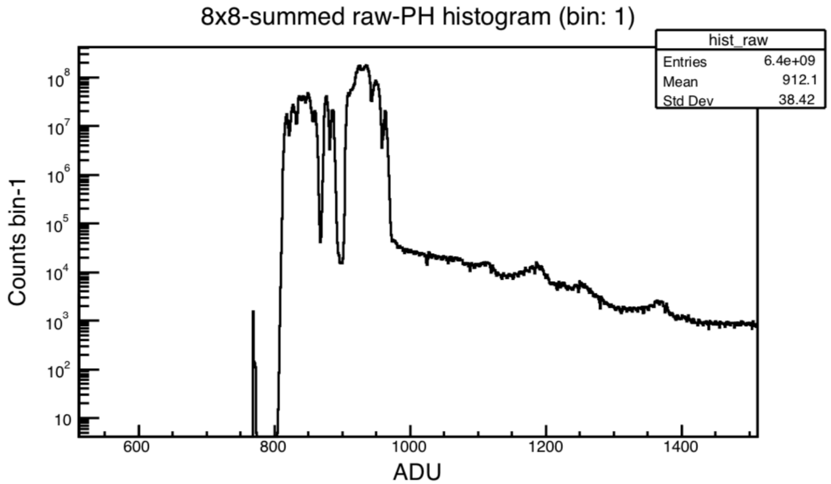
^{241}Am	^{137}Cs	^{55}Fe
#52	#50	#56
3.2 MBq	2.2 MBq	172 kBq

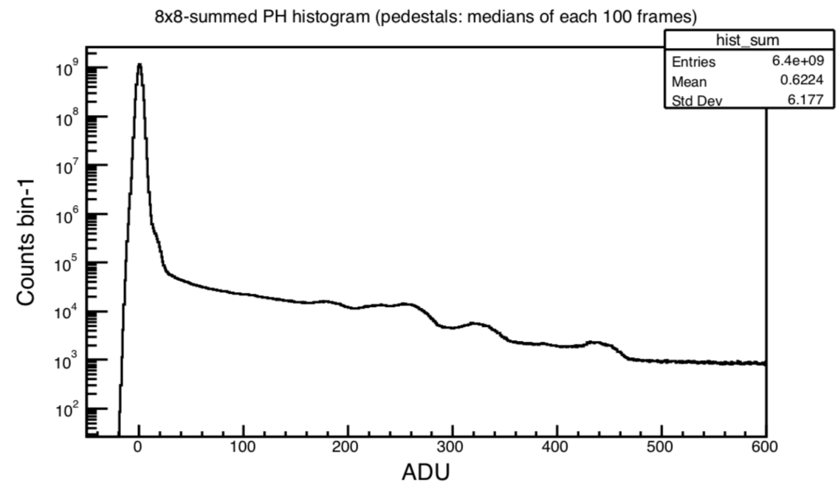


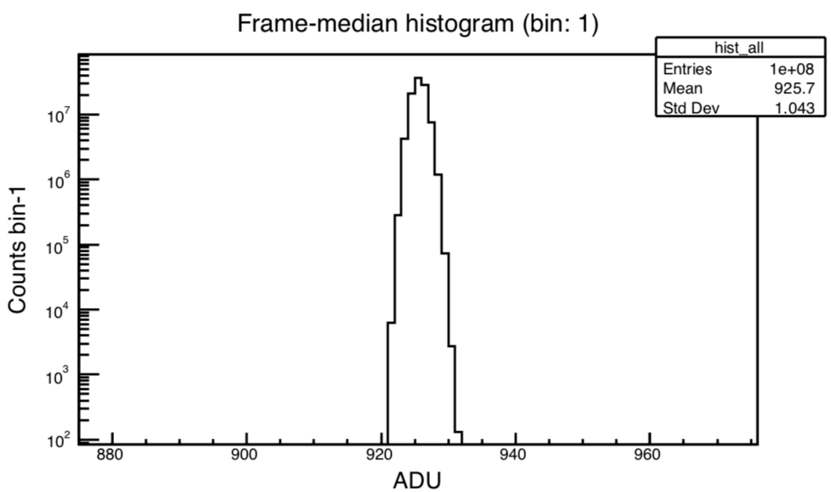
グラウンド線の配線図

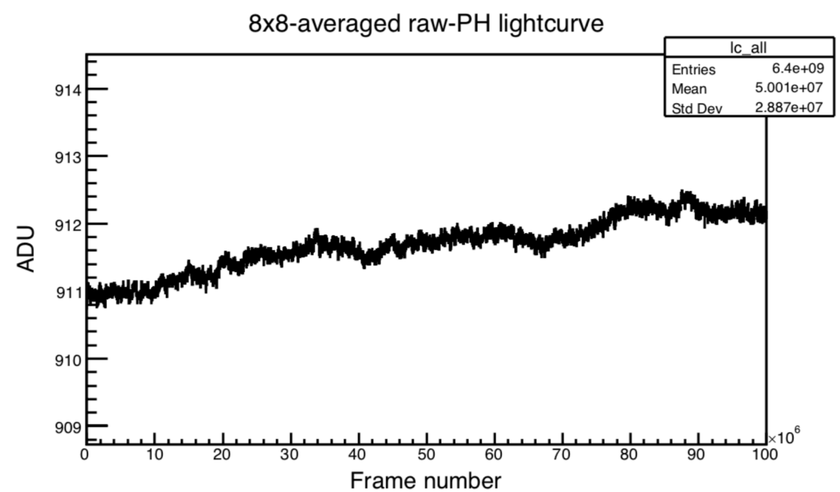
5

241Am, 40 degC, 300 V

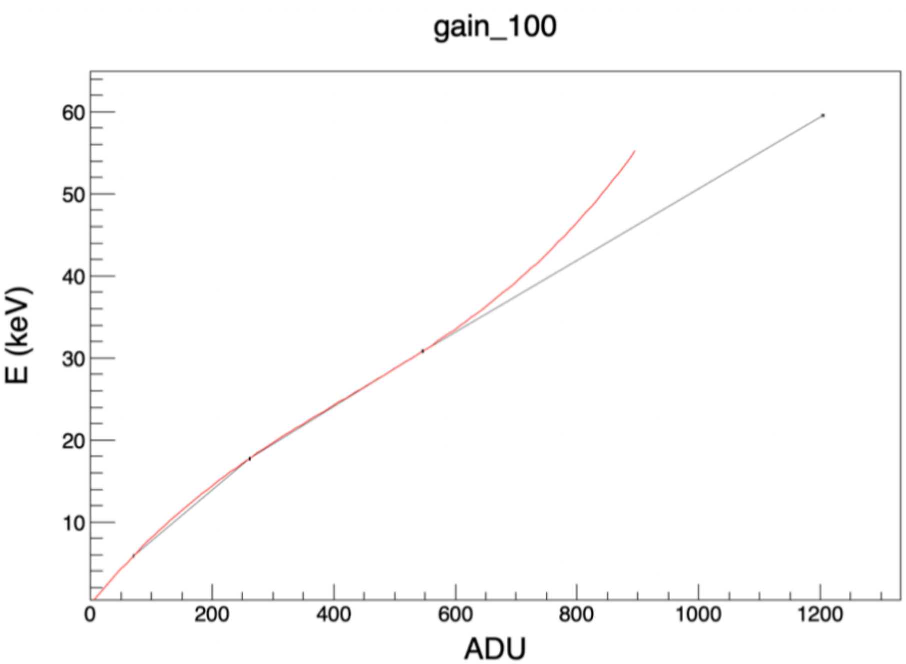


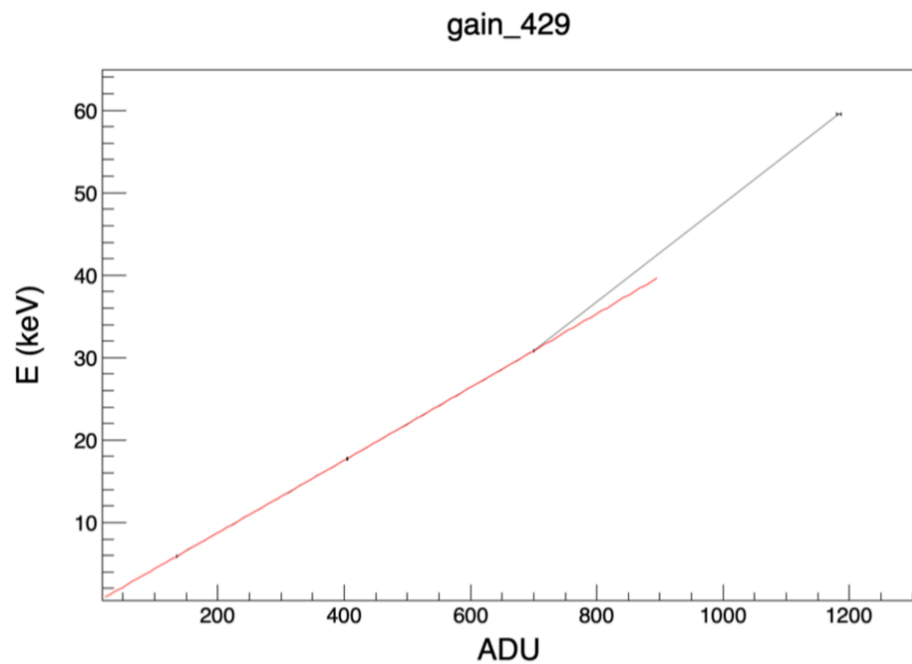




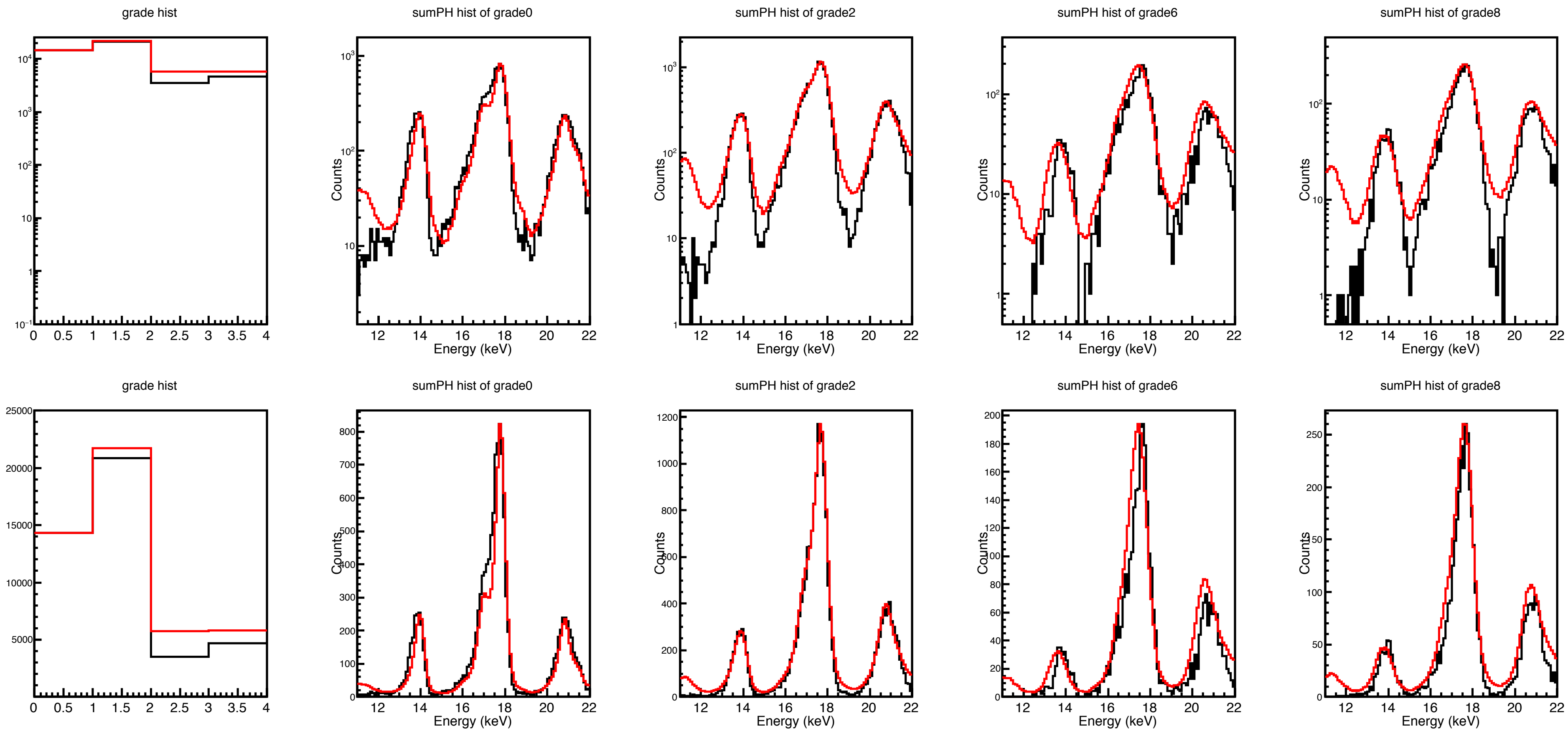


ex. of gain curves



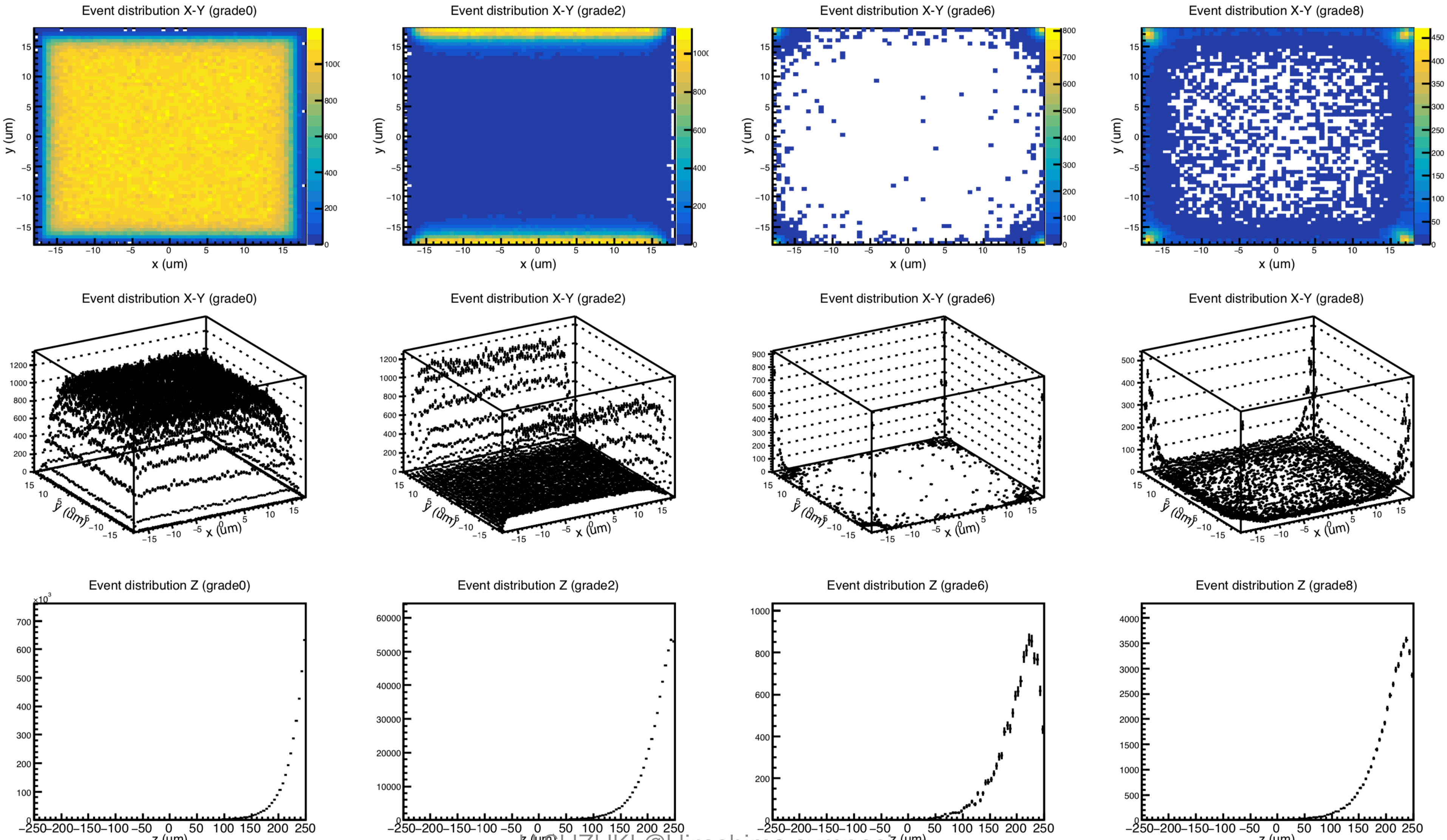


Comparison of sim./measure. for 241Am spectrum



event origin spatial distributions

gradeごとのイベント座標の空間分布　5.9 keV



event origin spatial distributions

gradeごとのイベント座標の空間分布　31 keV