Development of a new analysis framework for pile-up data of X-ray CCDs based on Monte-Carlo simulation

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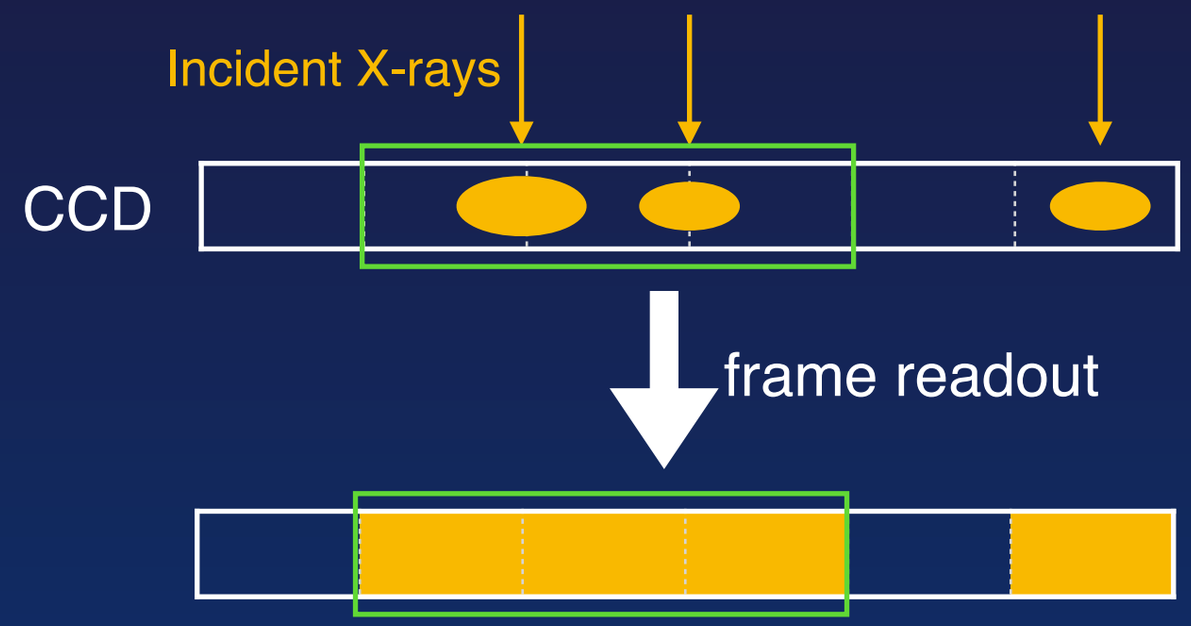
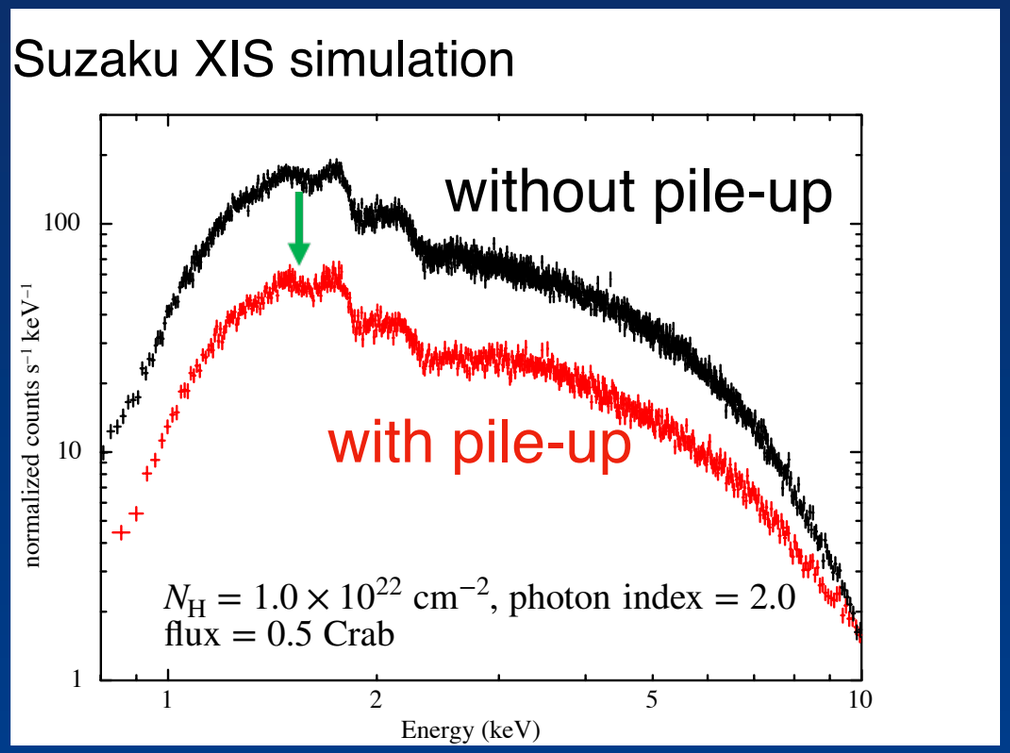
Photon pile-up in X-ray CCDs

pile-up:
Due to a high event rate, some multiple incident photons could be incorrectly detected and processed as a single photon event.



Two incident events are merged and incorrectly processed as one event.

The effects of pile-up on spectrum



The linearity of spectral response would be distorted by photon pile-up.

Instead, we face observational biases such as

- hardening of spectral index
- decrease in counts or flux

Science backgrounds and goals

❖ Background: XRISM project

- Will be launched within ~1 year.
- CCD (Xtend-SXI) onboard.
  → Even for ~1 mCrab source (and full window mode), pile-up affects spectral analysis.
- For observations of most moderate- or high-flux sources, it is necessary to construct a spectral analysis method which is compatible with pile-up.

❖ Goal: Construction of a new spectral analysis method for pile-up affected data observed by XRISM.

This work consists of two steps:

① Development of a new spectral analysis method for pile-up affected data
→ Utilizing Suzaku XIS pile-up data

② Tuning the framework for the application to XRISM CCD.

In this talk, I focus on the first step. The second step is now under development by Dr.Yoneyama (JAXA).

Monte Carlo simulation as an approach to CCD pile-up

❖ **What is difficult about solving pile-up problems?**

- The linear detector response is distorted to a complicated non-linear form.
- The pile-up effects strongly depend on energy of each photon, as event-shape distribution much depends on incident photon energy.
- The pile-up effects also depends on the location of incident photons because of non-uniform PSF.
- Therefore, pile-up does not allow any simplified assumption such as
  - ☑ event-shape distribution is independent of photon energy.
  - ☑ photon count rate is same at any place on the detector.

  Some previous researches derived analytical solutions based on such simplified assumptions (Ballet 99, Davis 01), but they do not reflect real pile-up phenomena.

❖ **An effective approach is Monte Carlo simulation.**

- The simulation does not discard any parameters regarding CCD observation.
- The simulation just reproduces all the steps in an observation, that is physical processes and data reduction processes.
- We utilized Geant4 for physical simulation, and ComptonSoft (Odaka+10) for manipulating the whole pile-up simulation.

Outline of pile-up simulator

The simulator aims to reproduce the following two processes of CCDs separately:

(a) Physical processes

(b) Data reduction processes (frame readout)

Reconstruction of spectrum

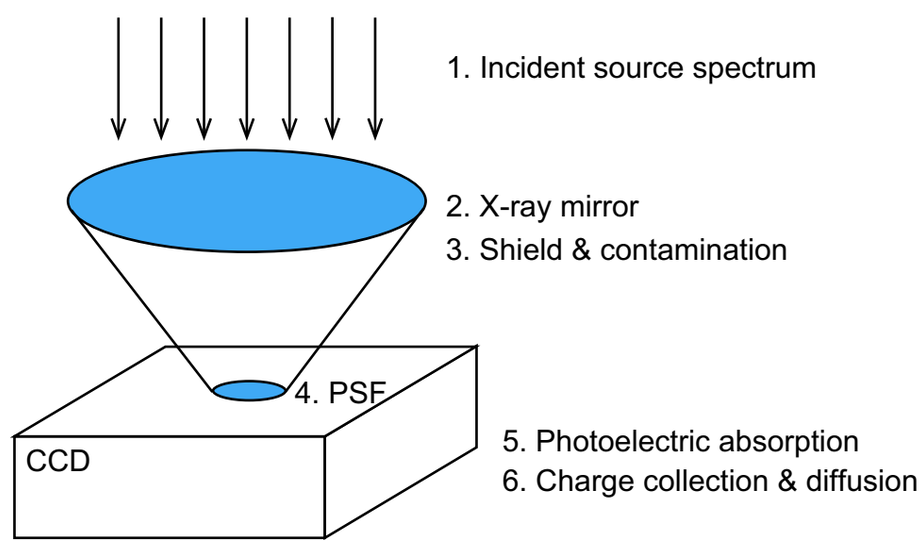
$S(E)$ —— (a) ——→ $C(h)$ —— (b) ——→ $C'(h)$

Incident spectrum

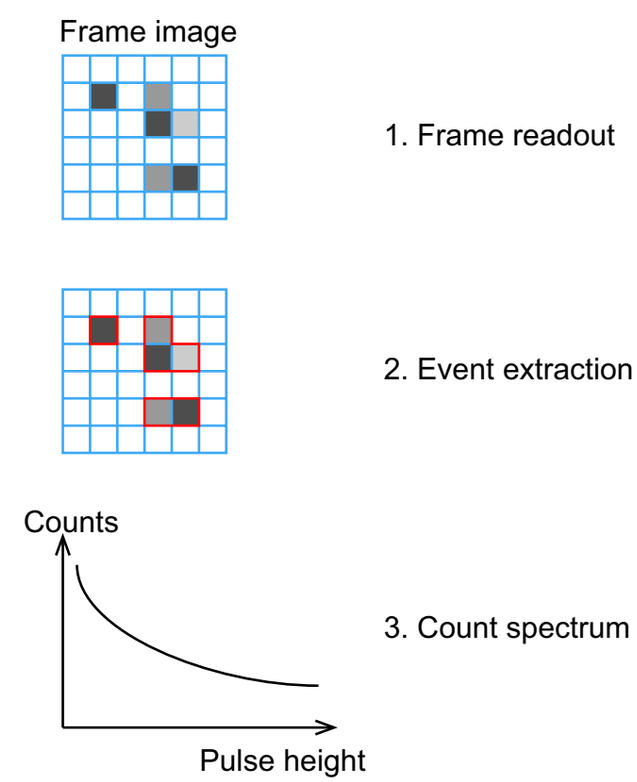
Detector spectrum (without pile-up)

Detector spectrum (with pile-up)

(a) Physical processes



(b) Data reduction



Schematic view of this work

- Reproduction of detector response (without pile-up)

$$S(E) \xrightarrow{\text{physical processes}} C(h) \xrightarrow{\text{frame readout}} C'(h)$$

- Simulation of pile-up effects

$$S(E) \xrightarrow{\text{physical processes}} C(h) \xrightarrow{\text{frame readout}} C'(h)$$

- Application to pile-up affected data

$$S(E) \xrightarrow{\text{physical processes}} C(h) \xrightarrow{\text{frame readout}} C'(h)$$

Reproduction of Suzaku XIS response by simulation

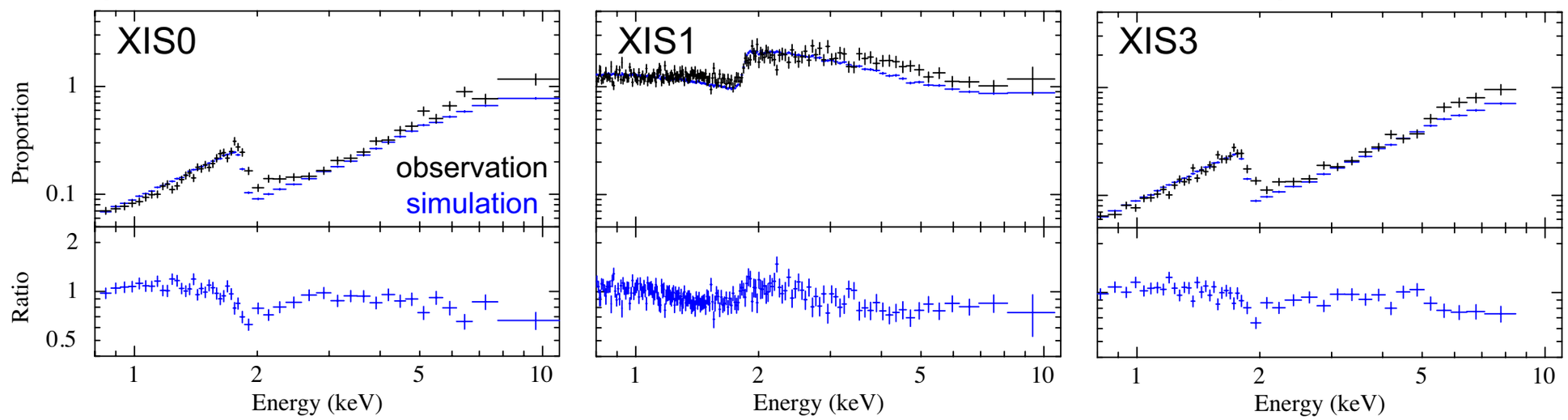
$$S(E) \xrightarrow{\boxed{\text{physical processes}}} C(h) \xrightarrow{\text{frame readout}} C'(h)$$

In order to reproduce detector responses of real detectors, we regulated simulation parameters so that the simulation agrees with observed data properties.

In specific, we did parameter tunings for

- thickness of dead layer and depletion layer, which affect quantum efficiency.
- E-field structure in depletion layer, which affects event-shape distribution.

Energy dependence of event-shape distribution (double/single)



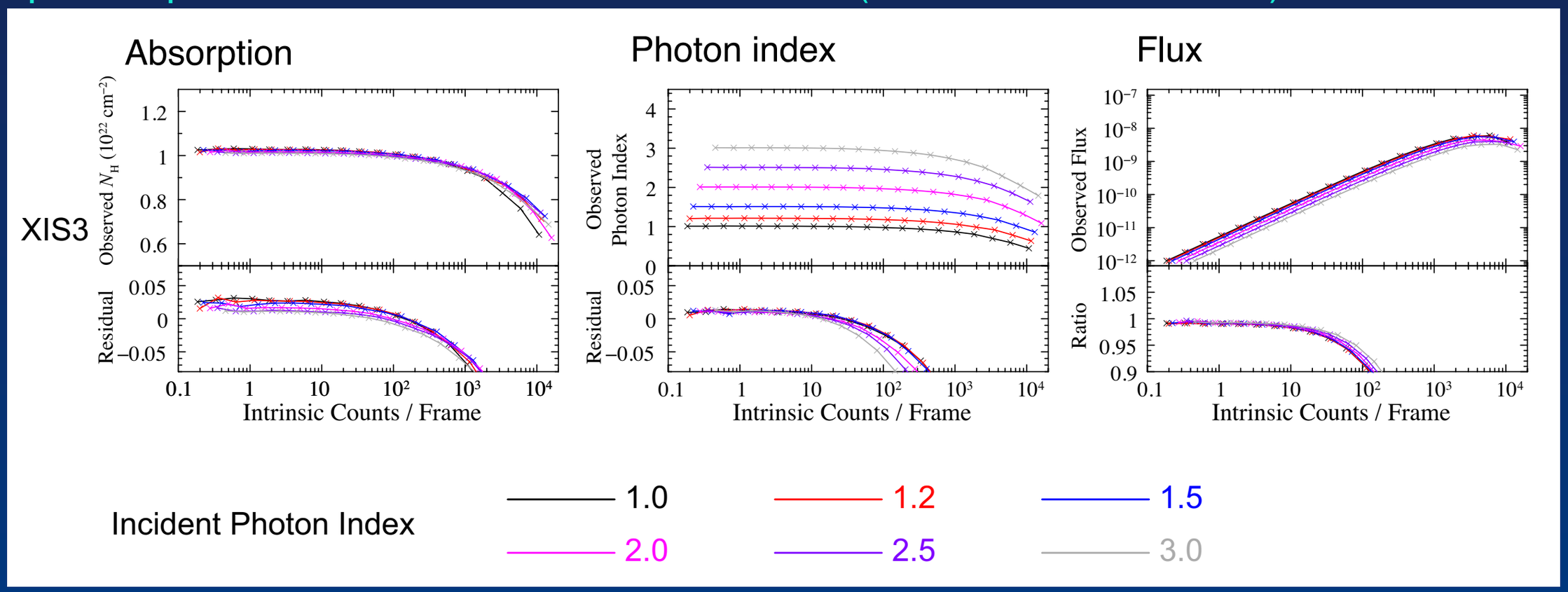
The simulator successfully reproduced detector responses of Suzaku XIS by tuning some important simulation parameters.

Simulation of pile-up effects

$$S(E) \xrightarrow{\text{physical processes}} C(h) \xrightarrow{\text{frame readout}} C'(h)$$

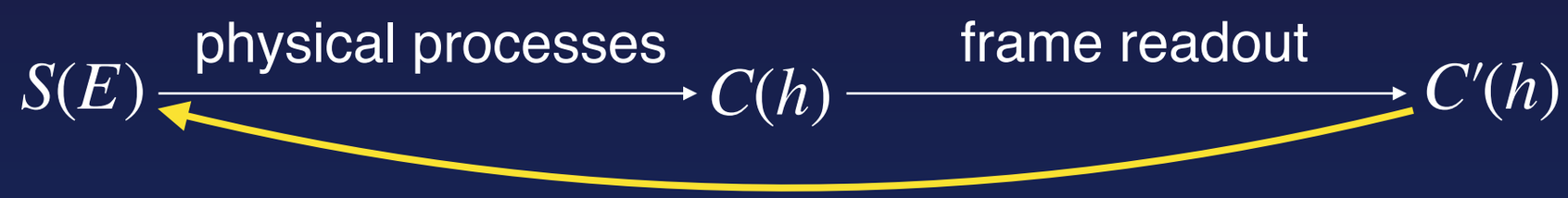
Assuming an absorbed power-law incident spectrum, we investigated the pile-up effects on spectral parameters, which are changed from the original values.

Spectral parameters variations vs source flux (intrinsic counts/frame)



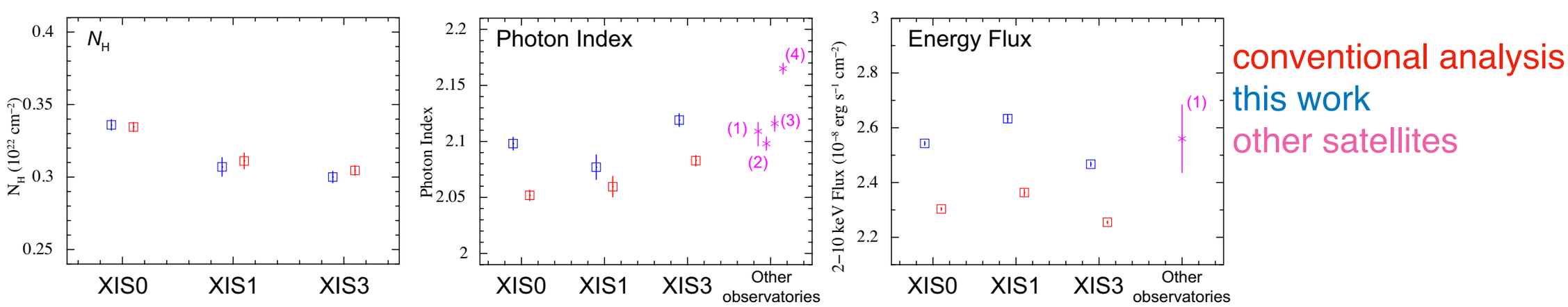
Main pile-up effects, such as spectral hardening and flux decrease, can be evaluated quantitatively.

Application to pile-up affected data



- For each set of parameters, the simulator calculates pile-up affected detector spectrum. Then we search for the best-fit parameter sets by evaluating χ^2 between the simulation result and observation data.
- The above method costs a lot of calculation time, so we developed “data sampling algorithm” that greatly reduces the amount of simulation. (For details, see our paper)

Crab Nebula observation data by Suzaku XIS



The pile-up effects, such as spectral hardening and flux decrease, are corrected by the simulation-based method.
Our framework succeeded in performing spectral analysis for pile-up affected observation data.

Summary and future work

❖ Summary

- We developed a new simulation-based method for pile-up affected data observed by CCDs. The framework is especially useful for observations of high-flux sources.
- Monte Carlo simulation is our approach. We developed a simulation-based framework which reproduces all the processes in observations by CCDs, such as physical processes and data reduction processes.
- Utilizing our simulation-based framework, we performed
  - reproduction of detector response
  - simulation of pile-up effects
  - application to pile-up affected data

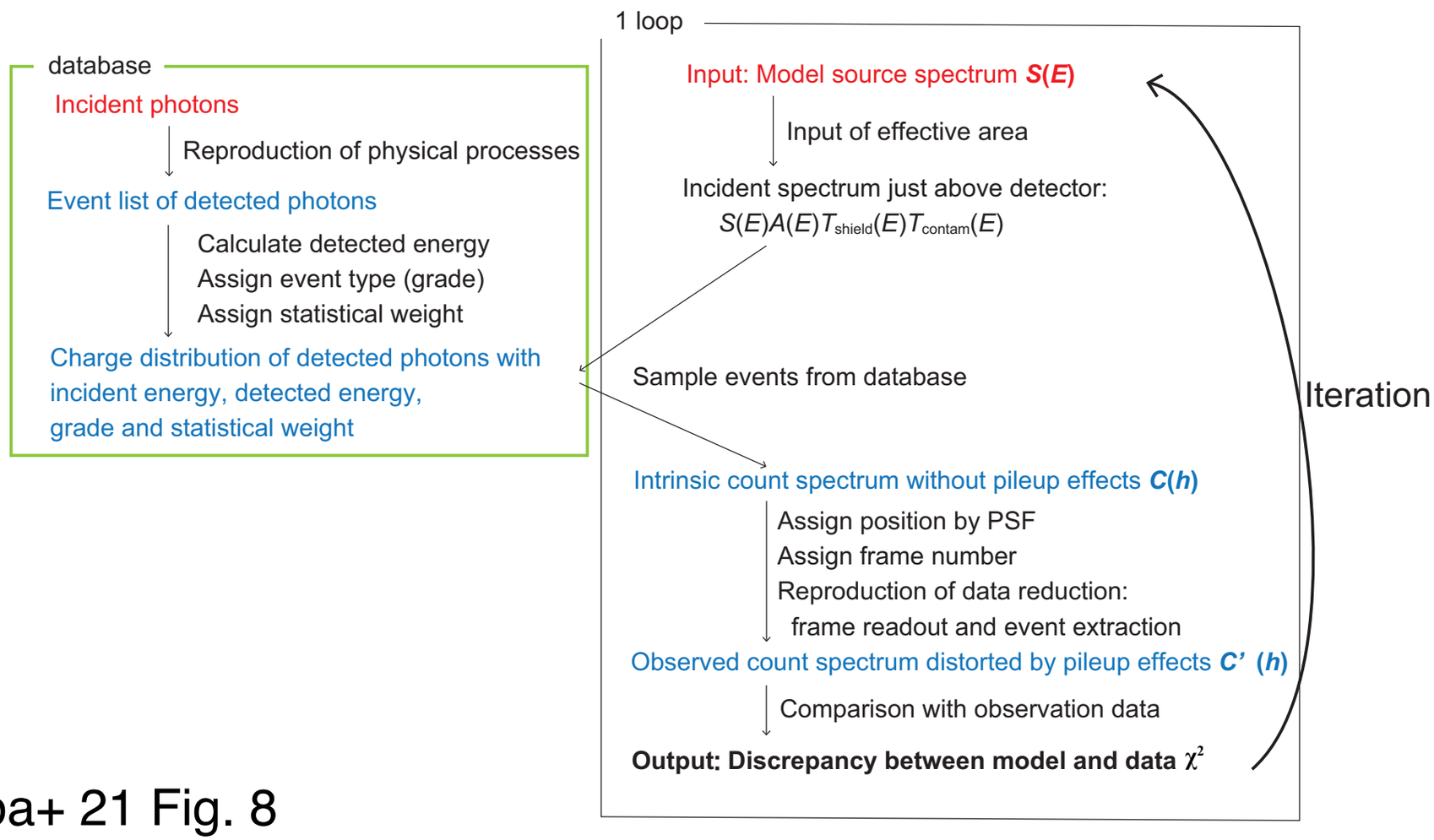
  All of these results show that our framework is an effective tool to deal with pile-up affected observation data of X-ray CCDs.

❖ Future works: application to XRISM CCD

- We are developing a similar simulation framework for XRISM Xtend-SXI. As reference data, we utilize data of ground calibration experiments.
- We will calculate pile-up effects using the new framework until the launch of XRISM.

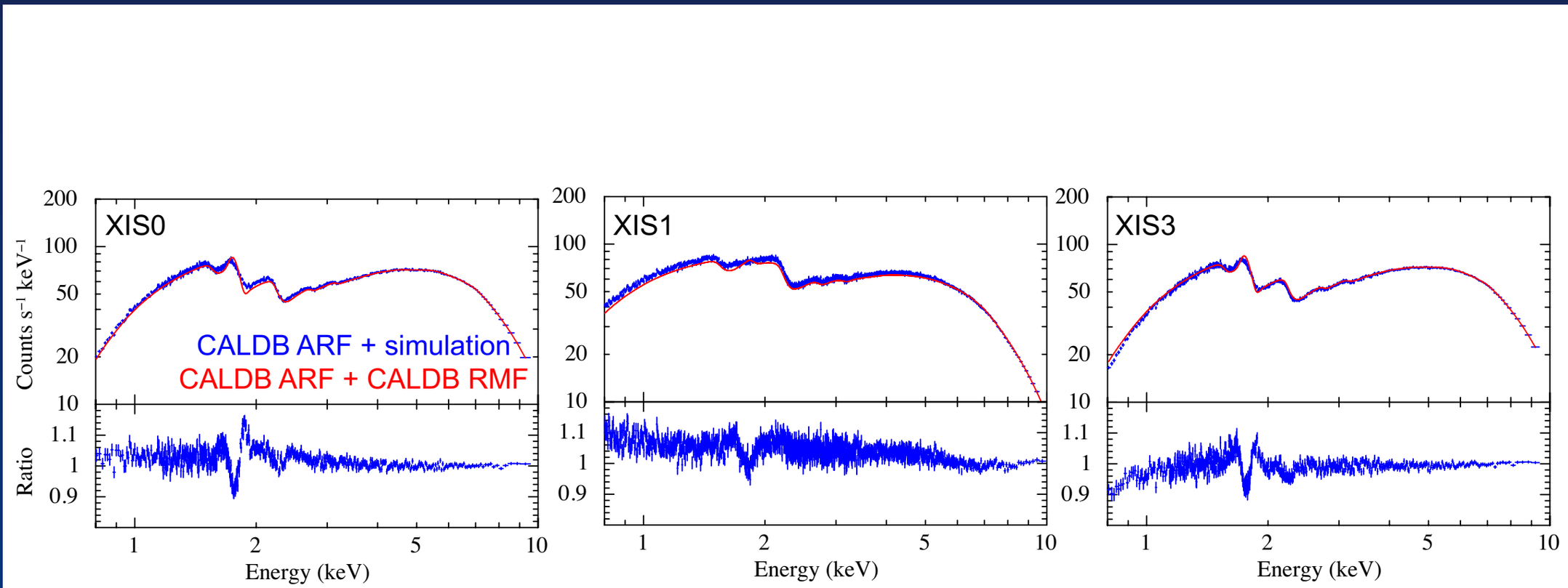
Back up

Data sampling algorithm

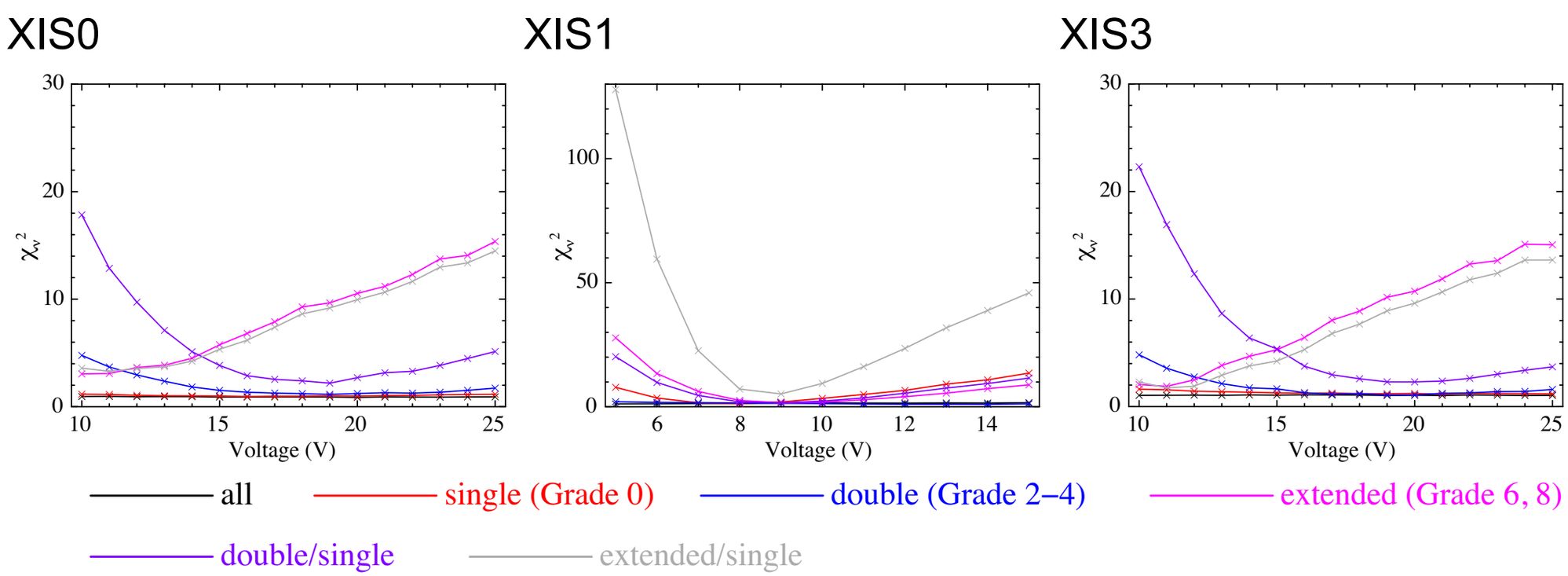


Tamba+ 21 Fig. 8

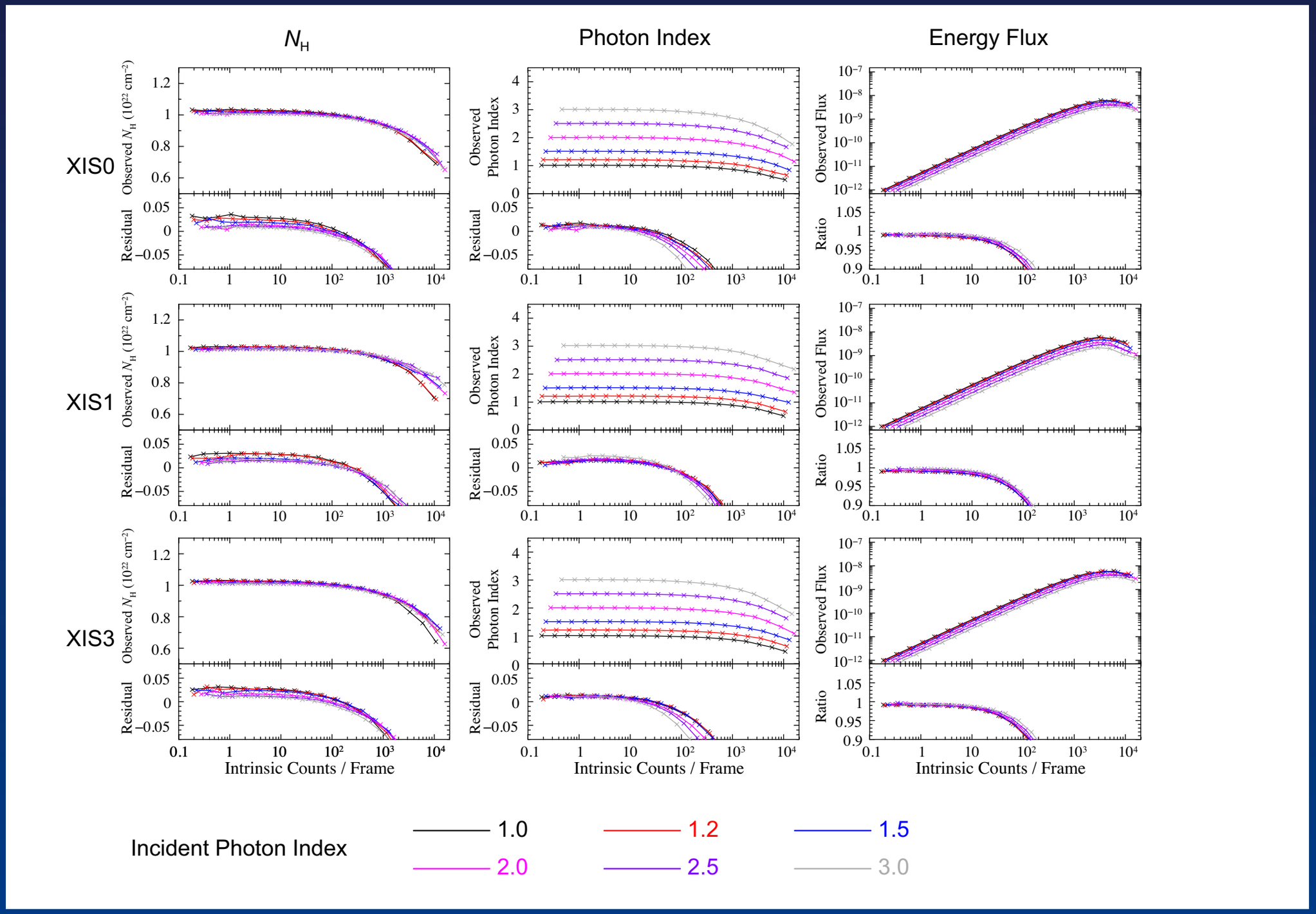
Comparison of simulation and detector response



Parameter tuning: voltage



Pile-up effects



Spectral fitting: Crab Nebula