

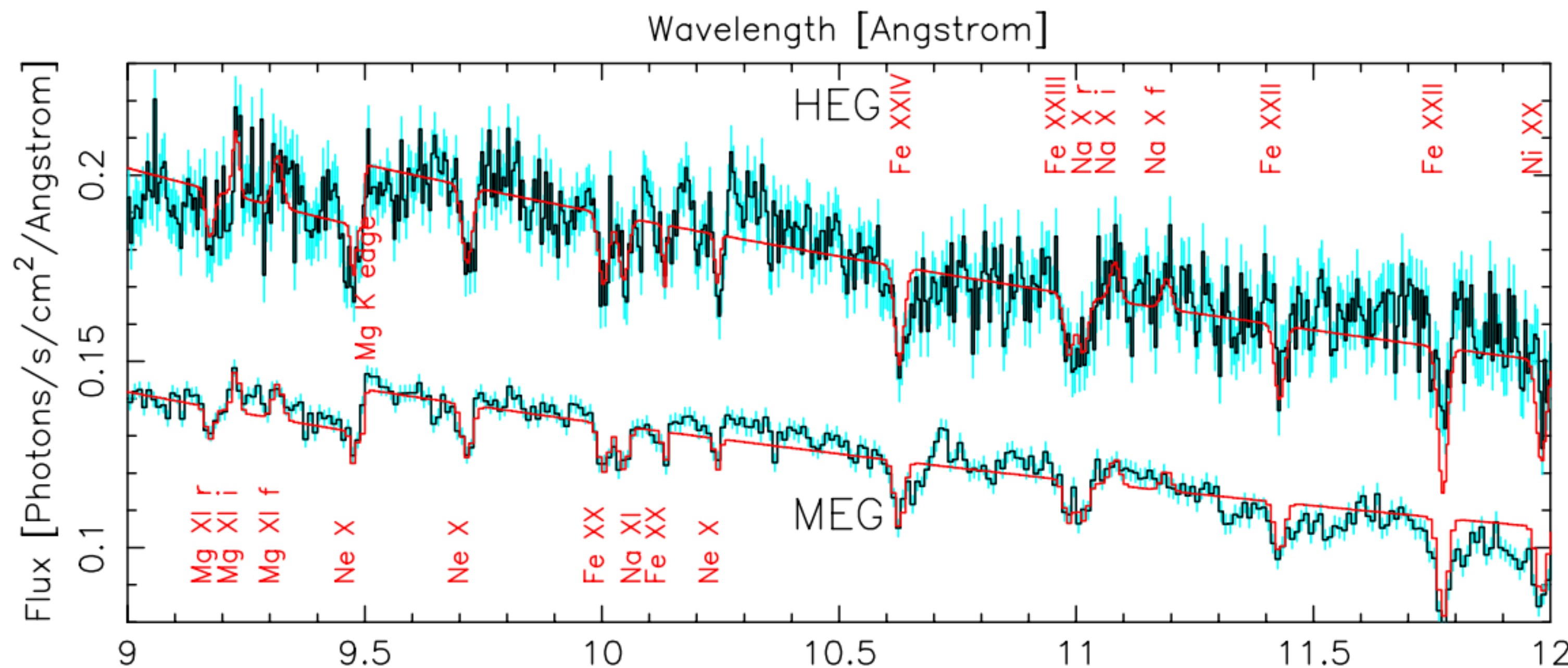
# Observing Bright Sources with Resolve

Edmund Hodges-Kluck  
for the XRISM Science Team

- Why do we want to observe bright sources with Resolve?
- Why are bright sources challenging?
- What is the best way to observe bright sources?
- What is the best way to analyze bright sources?
- Appendix: Cross-talk, off-axis PSF, and other detailed topics

# Why observe bright sources?

- Some transient and rapidly variable phenomena can only be studied in sources with high count rates (high S/N in a short interval)
- GO proposals can efficiently study phenomena like disk winds in bright sources



Cyg X-1  
2-10 keV  $F_x > 10^{-8}$  erg s<sup>-1</sup> cm<sup>-2</sup>

Miller+ 2002

# How Bright is "Bright"?

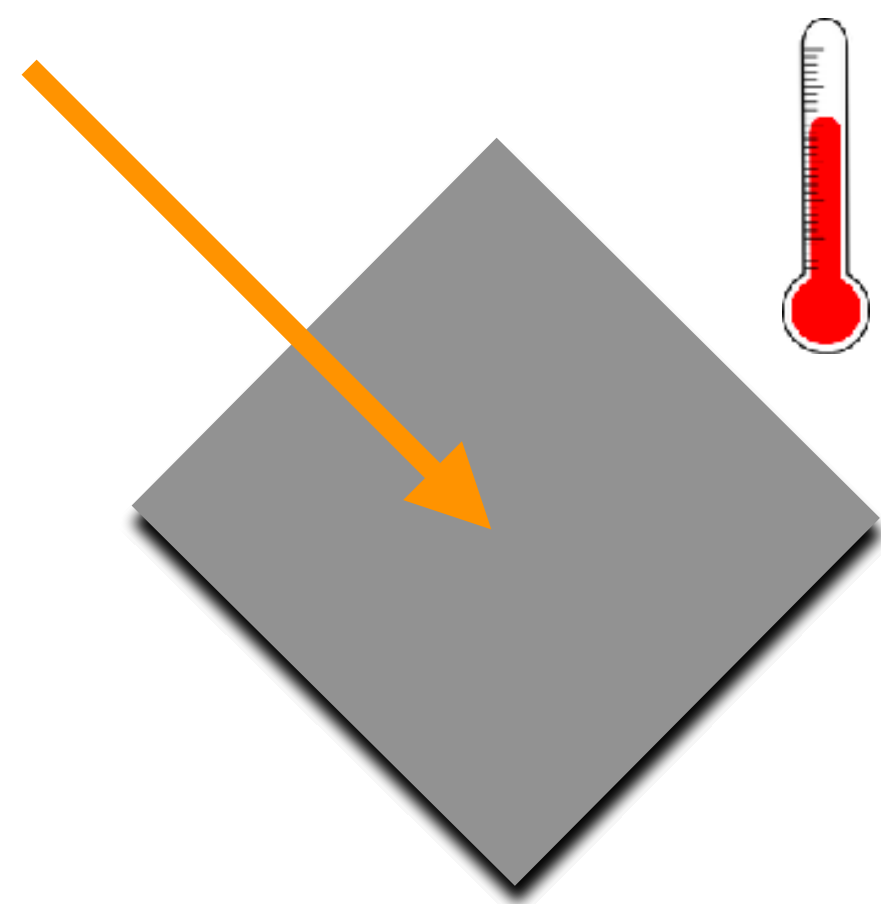
<b>Flux</b>	<b>Array Count Rate</b>	<b>Suboptimal H+Mp rate?</b>	<b>CPU Limit Effects?</b>	<b>xTalk Impact?</b>
<1 mCrab	<2	Check email or go to the bathroom		
10 mCrab	20	No	No	No
100 mCrab	200	Minor	Minor	No
1 Crab	2,000	Yes	Yes	Yes
10 Crab	20,000	Extreme	Extreme	High

# Bright Source Challenges

# Why are bright sources challenging?

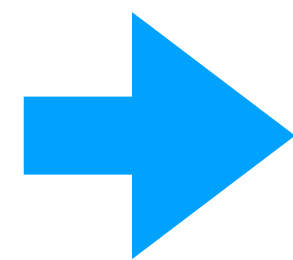
- The fraction of high resolution events is a function of count rate
- The onboard computer (pulse-shape processor; PSP) can only process so many events per unit time
- Electrical cross-talk (xTalk) can degrade event resolution
- There are subtle details – see Appendix for more information.

# From Detection to Measurement



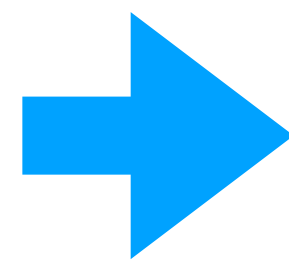
HgTe Detector

*X-ray strikes pixel*



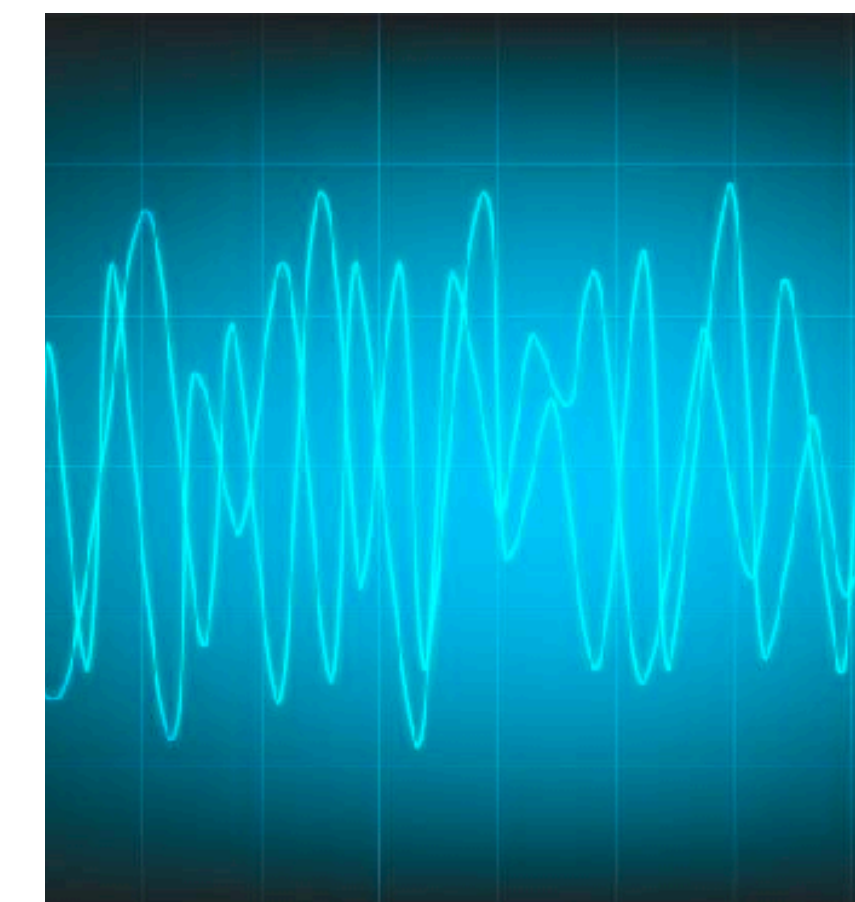
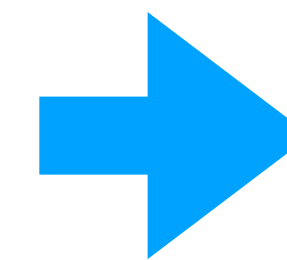
XBOX ADC

*Signal amplified,  
digitized*



PSP FPGA

*Event (pulse)  
triggered*

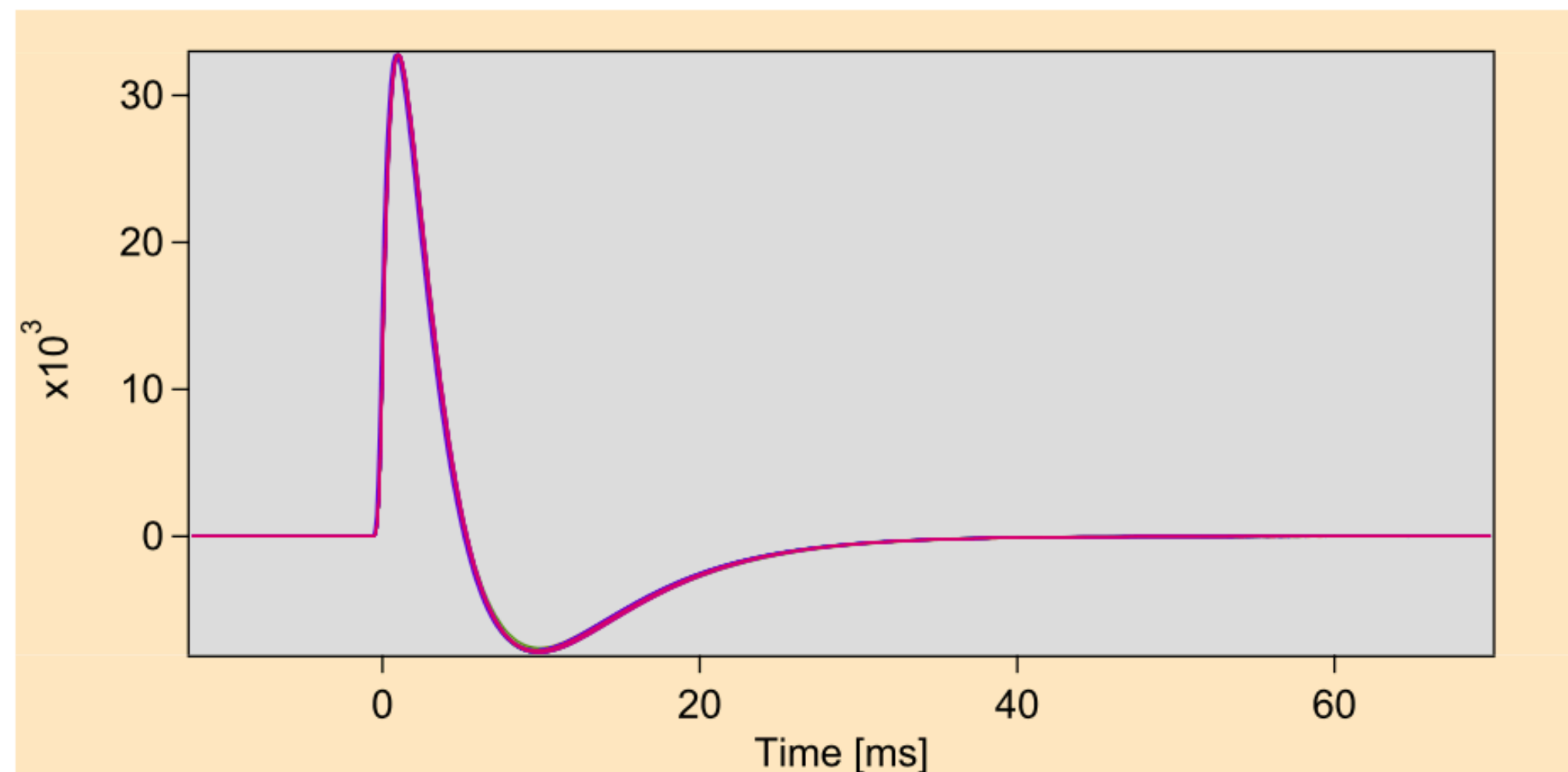


PSP CPU

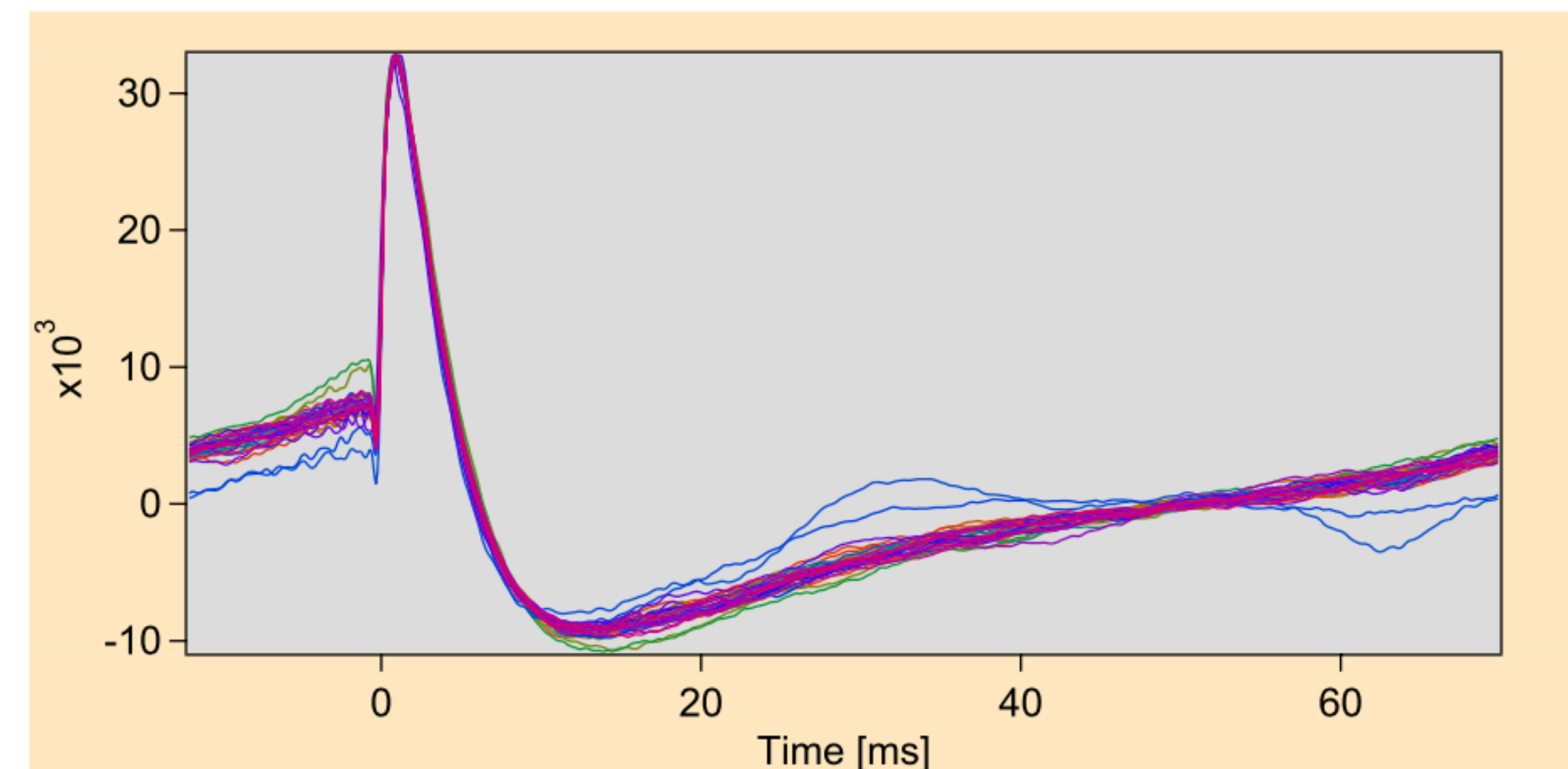
*Energy  
measured*

# How does XRISM measure energy?

- Incident photons produce a pulse with a characteristic shape in the detector electronics whose amplitude is proportional to the photon energy
- The pulse-shape processor cross-correlates a normalized pulse template with each pulse to measure the amplitude



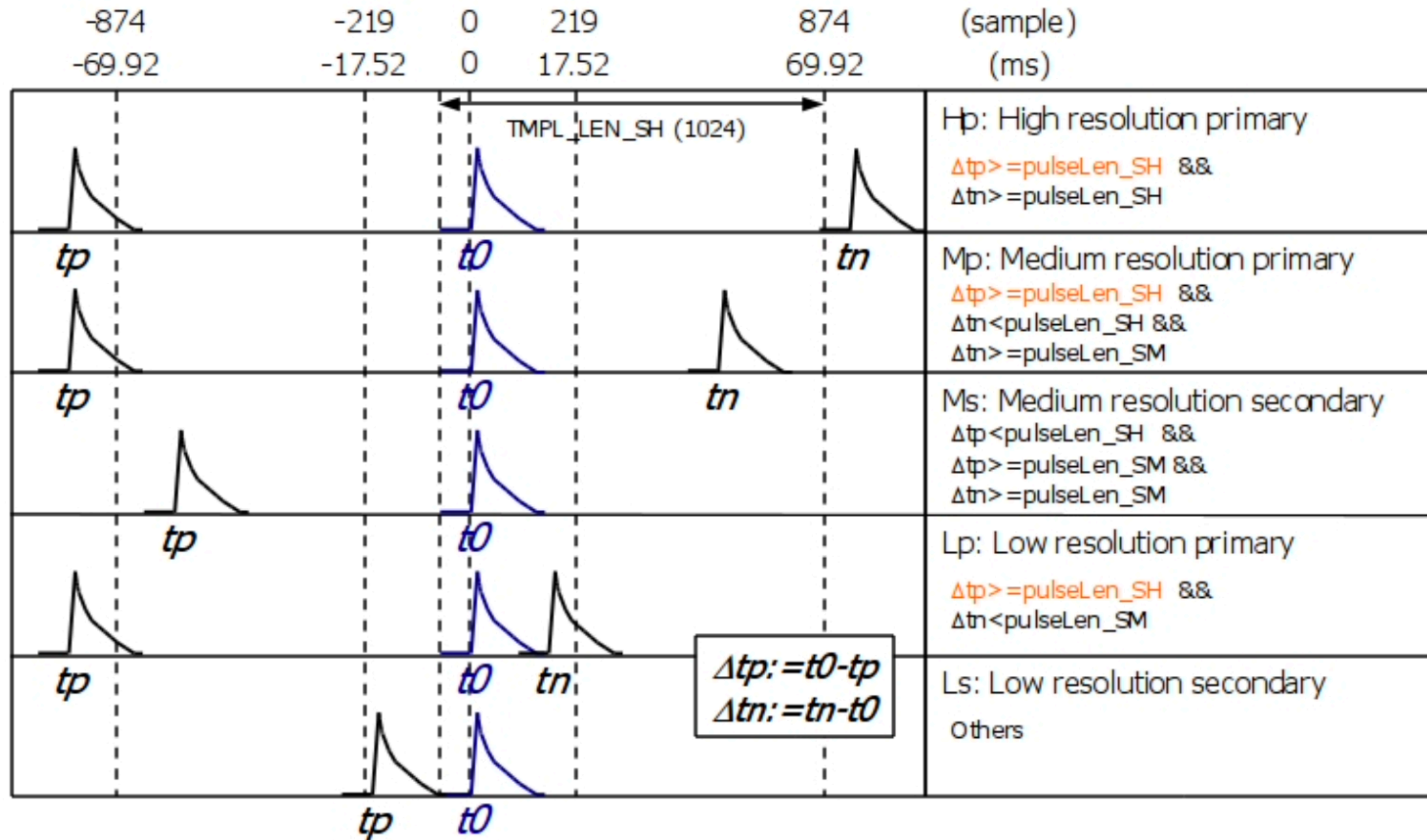
(a) Average profile  $S(t)$



(c) Filter template  $F(t)$



# XRISM Calorimeter Grades

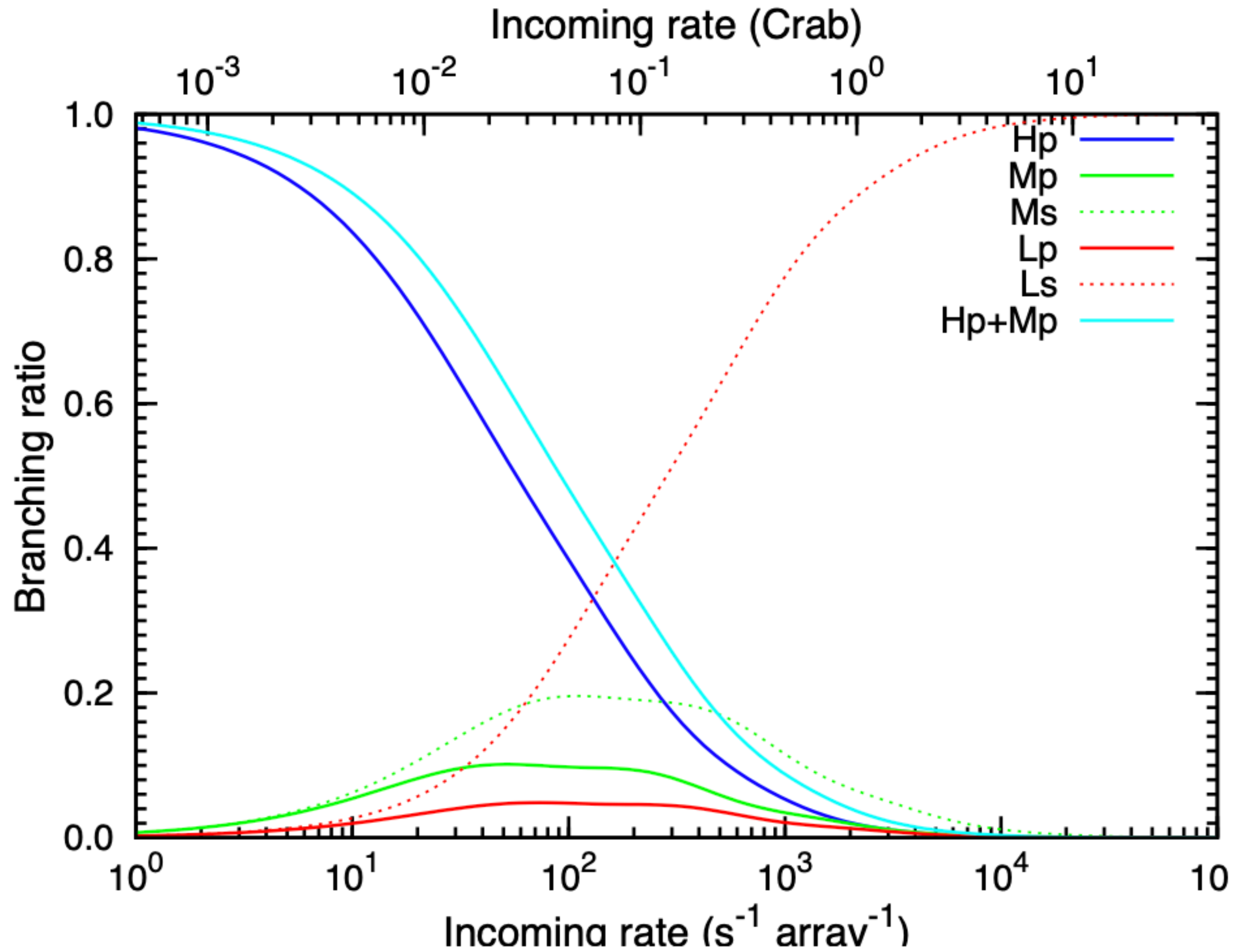


Photons separated by >81 ms

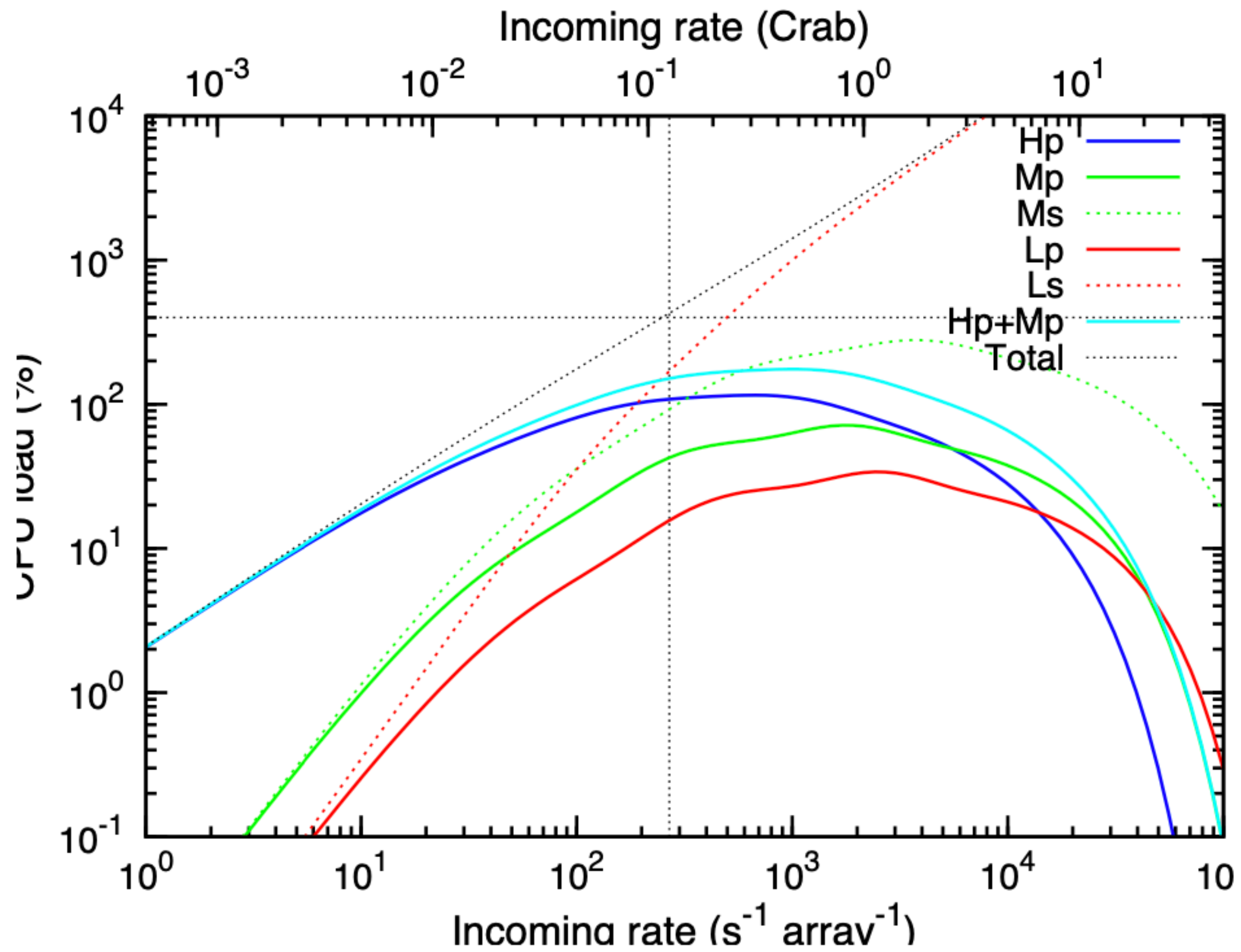
More than one photon in the 81 ms window

Photons arrive too close together, optimal filtering not performed

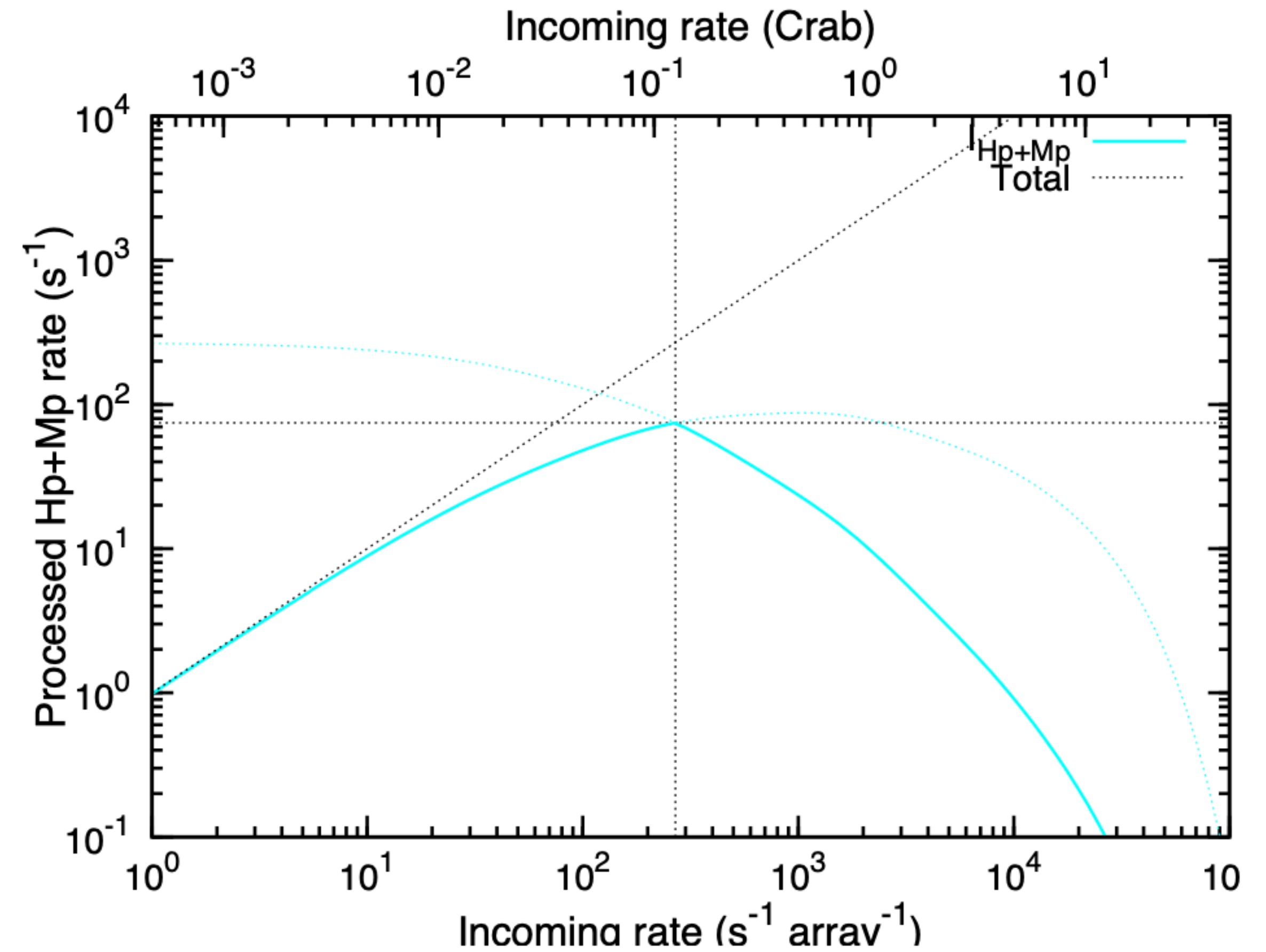
# Fraction of High-res Events



- Events are detected in an FPGA board and stored in a memory buffer while waiting to be processed
- The PSP computer ingests events (one CPU per quadrant) and performs the cross-correlation and recursive searches for secondary events
- If the buffer fills up before the events within are processed, it gets dumped (event loss) and starts filling up again
- Bright sources can clog the buffer with low-resolution events and lead to further loss of high-resolution events
- On average, CPUs saturate at  $\sim 200$  count/s/array ( $\sim 100$  mCrab), or 50 counts/s/quadrant, which produces 75 H+Mp ("calorimeter-grade") events/s



CPU Load from each event grade per total incident count rate

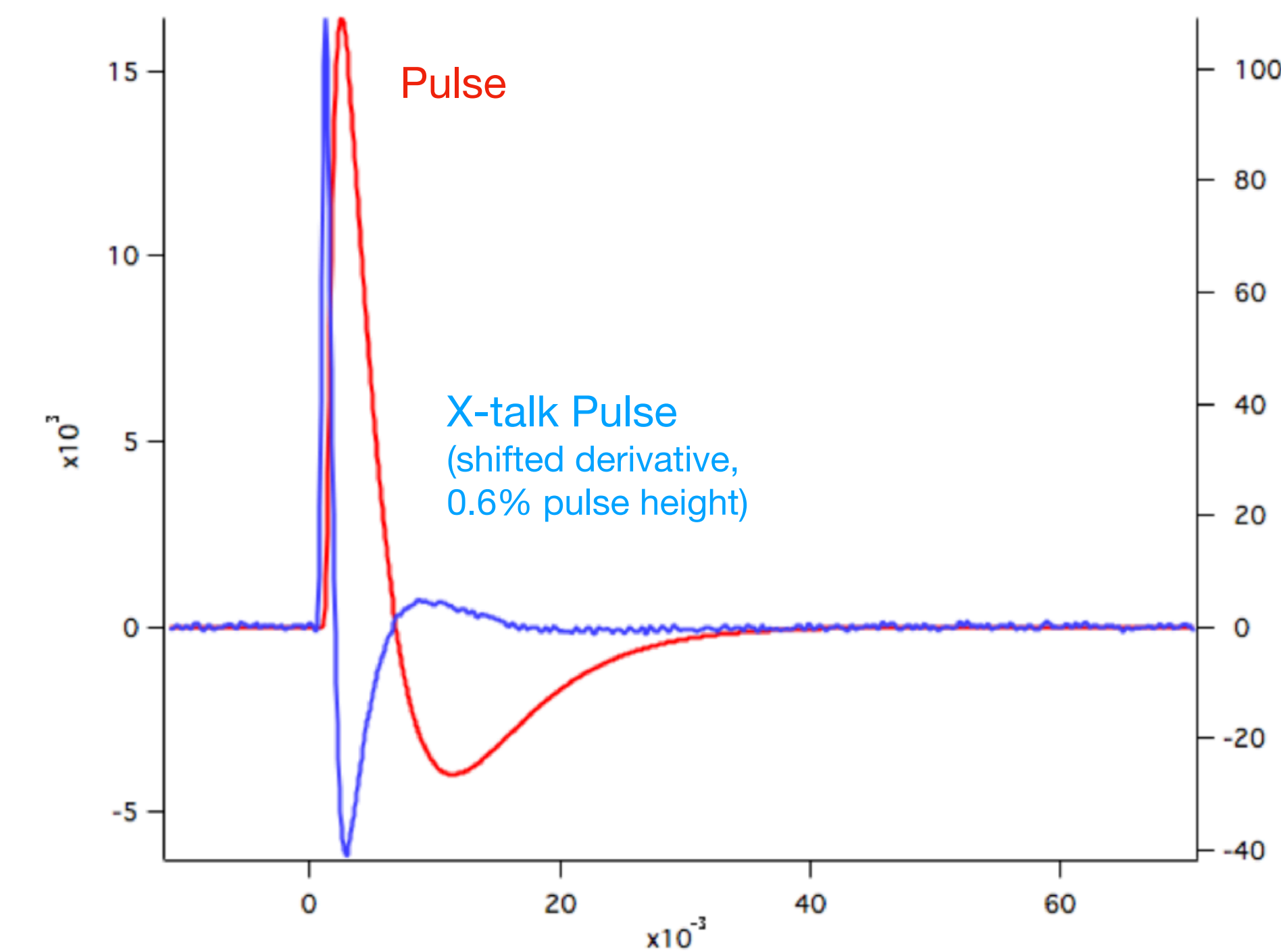


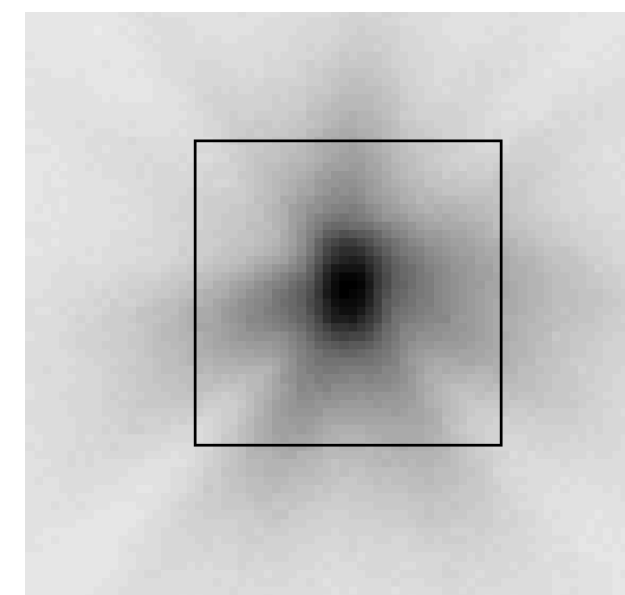
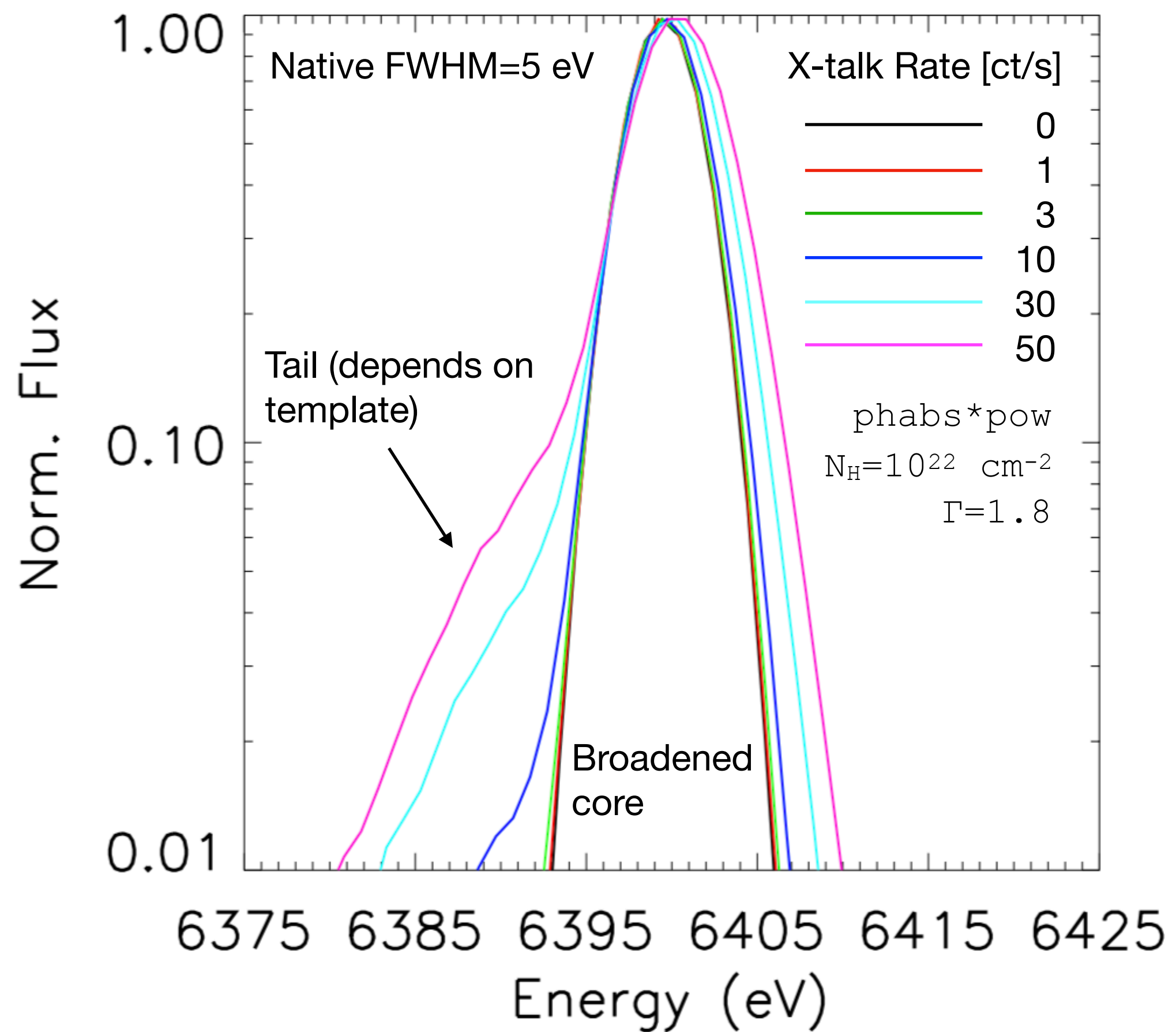
Maximum H+Mp event rate occurs at ~250 counts/s/array

- Signals in the wire from one pixel induce signals in neighboring wires with an amplitude proportional to the event energy
- xTalk signals are generally too weak to be detected as “events” but add noise that reduces the energy resolution of H+Mp events

30	32	34	26	24	23
29	31	33	25	22	21
27	28	35	18	20	19
1	2	0	17	10	9
3	4	7	15	13	11
5	6	8	16	14	

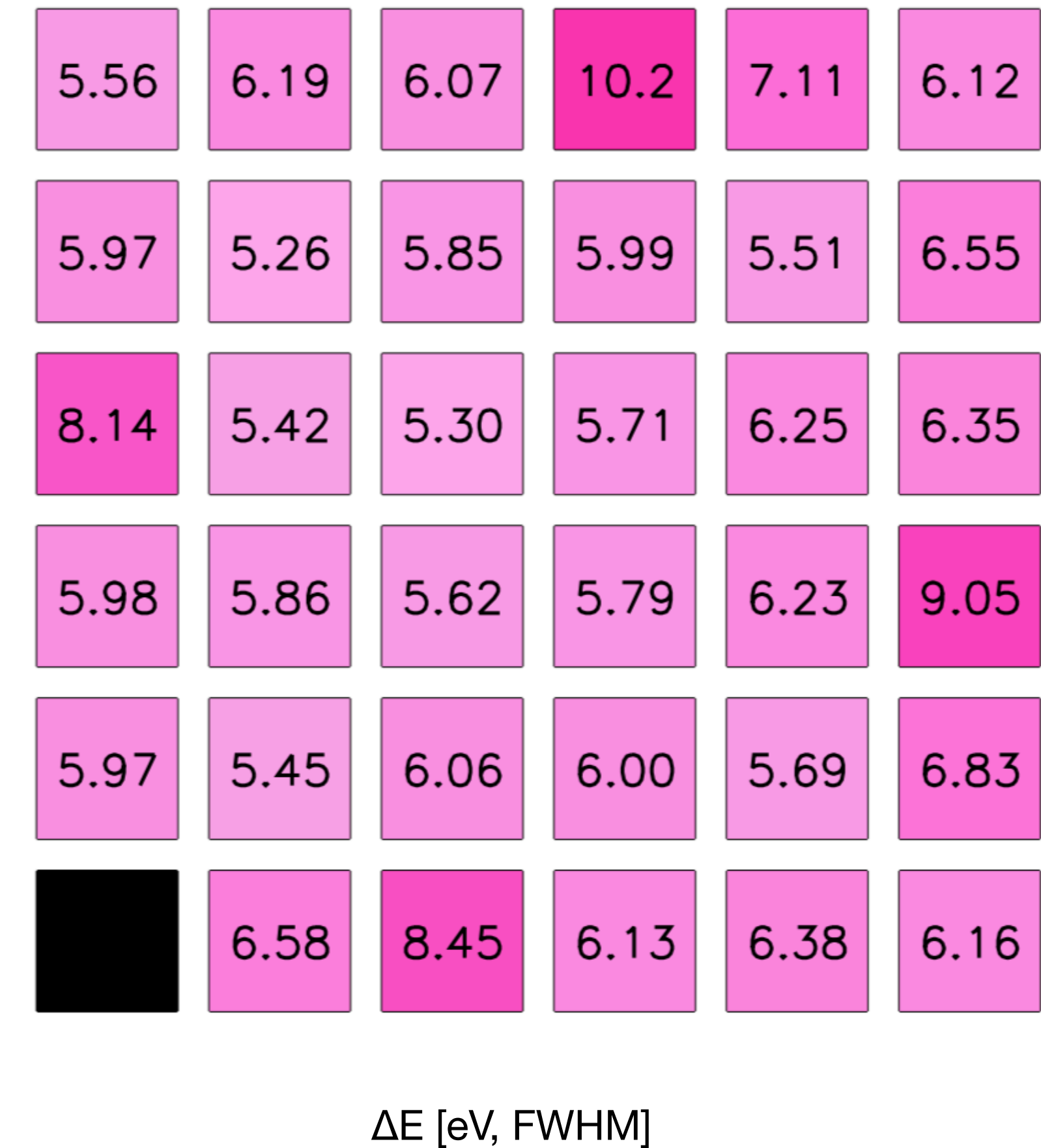
12





**phabs (pow+gauss)**

$N_H=1 \times 10^{21} \text{ cm}^{-2}$   
 $\Gamma=1.8$   
 $E_{\text{line}}=6.4 \text{ keV}$   
 $F_{\text{line}}=1 \times 10^{-9} \text{ erg/s}$   
 $F_x=2.4 \times 10^{-8} \text{ erg/s}$   
 [2-10 keV]  
 5 eV native FWHM  
 1 Crab



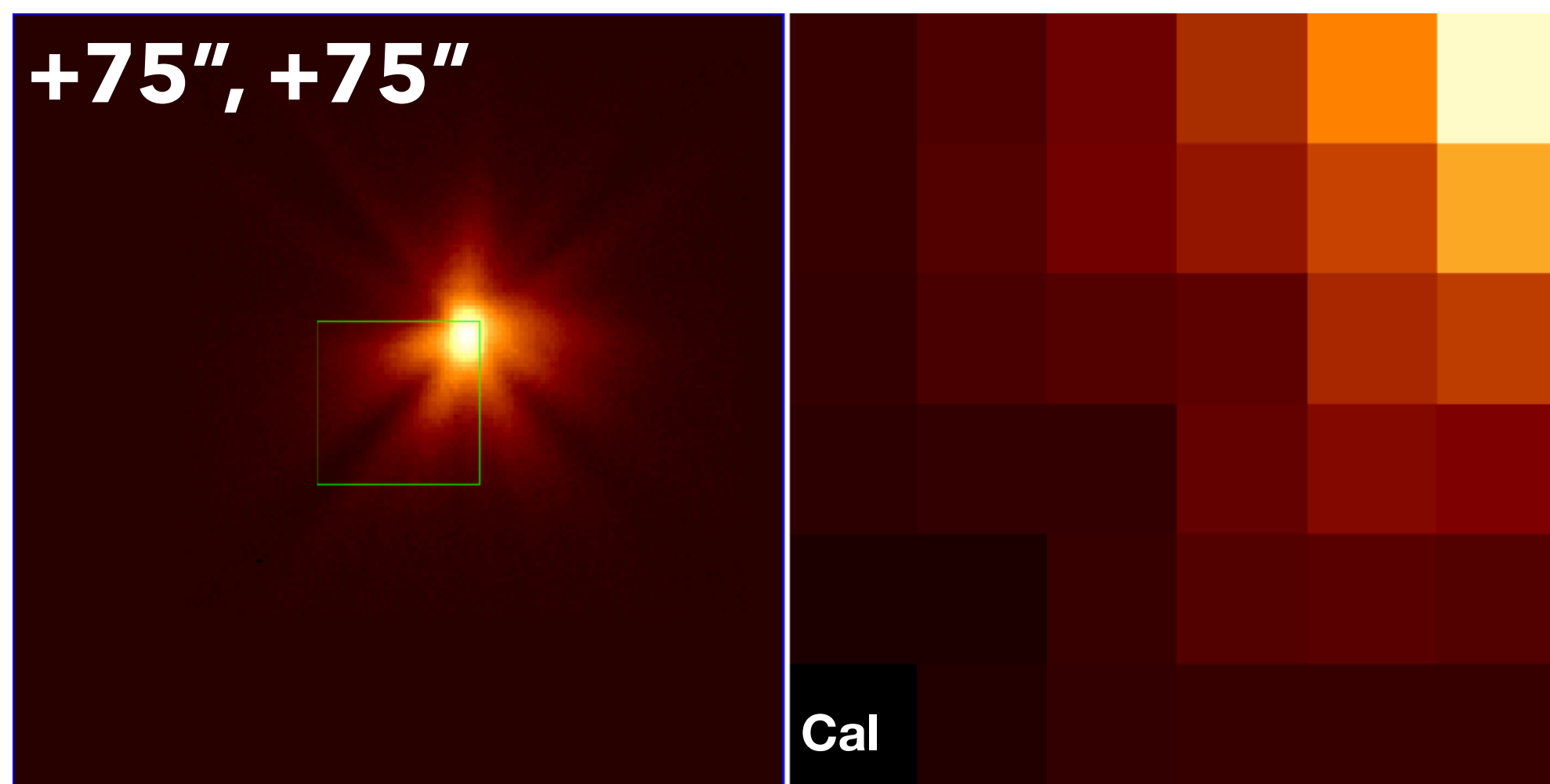
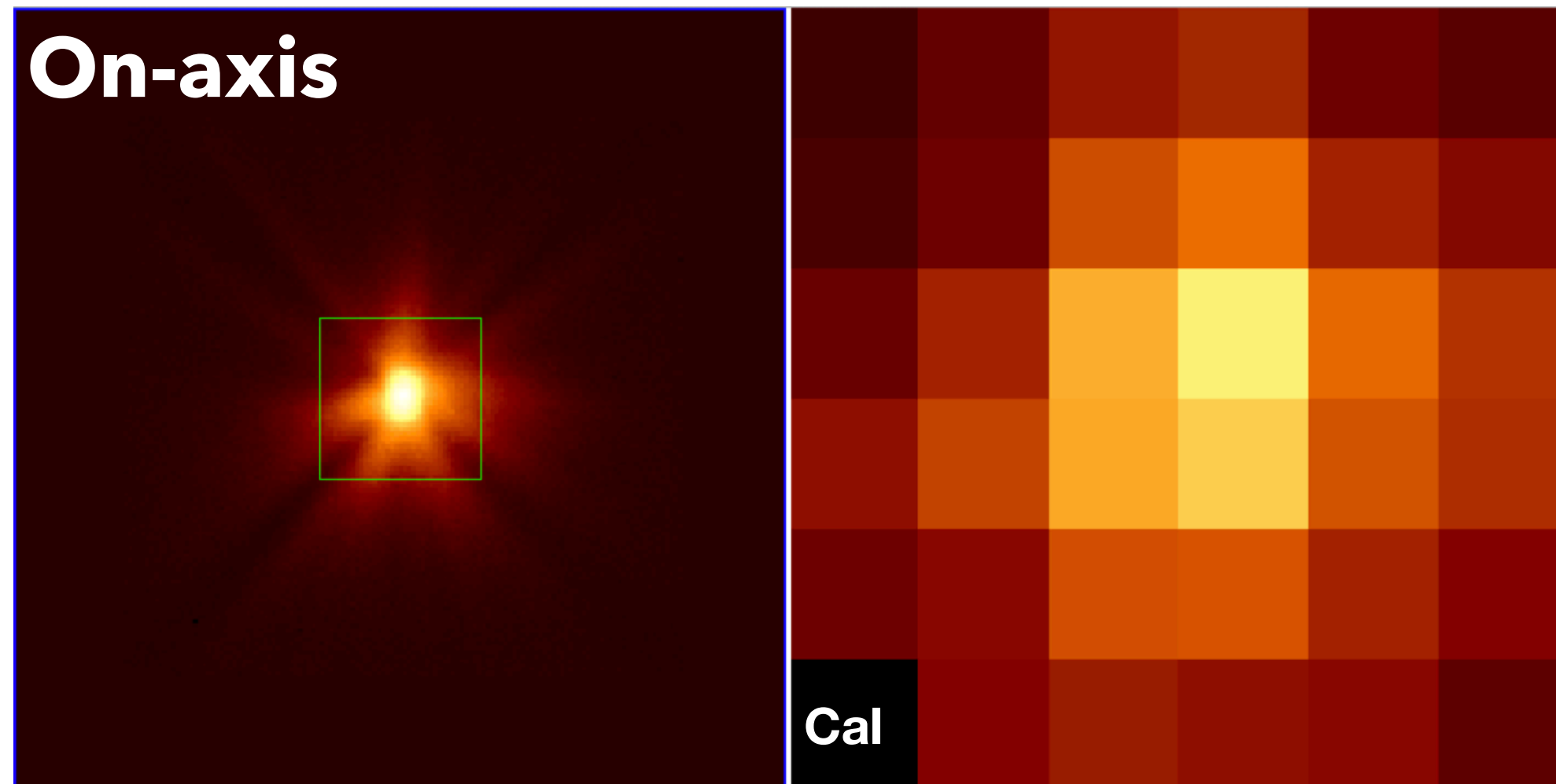
xTalk broadens lines *and* shifts centroids

Energy resolution in each pixel for an on-axis, 1 Crab source due to xTalk

# Observing Bright Sources

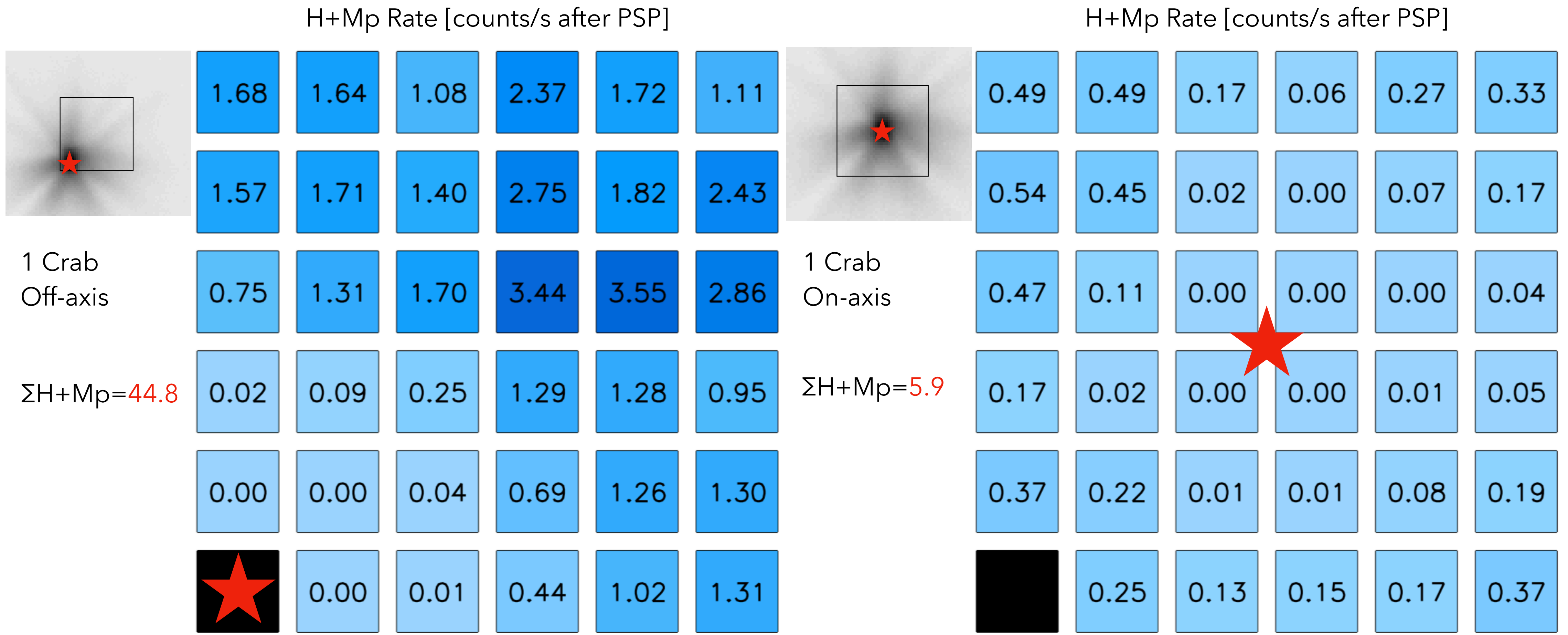
- Goal: Maximize H+Mp event rate
  - Off-axis pointing
  - Be25 filter, neutral density filter





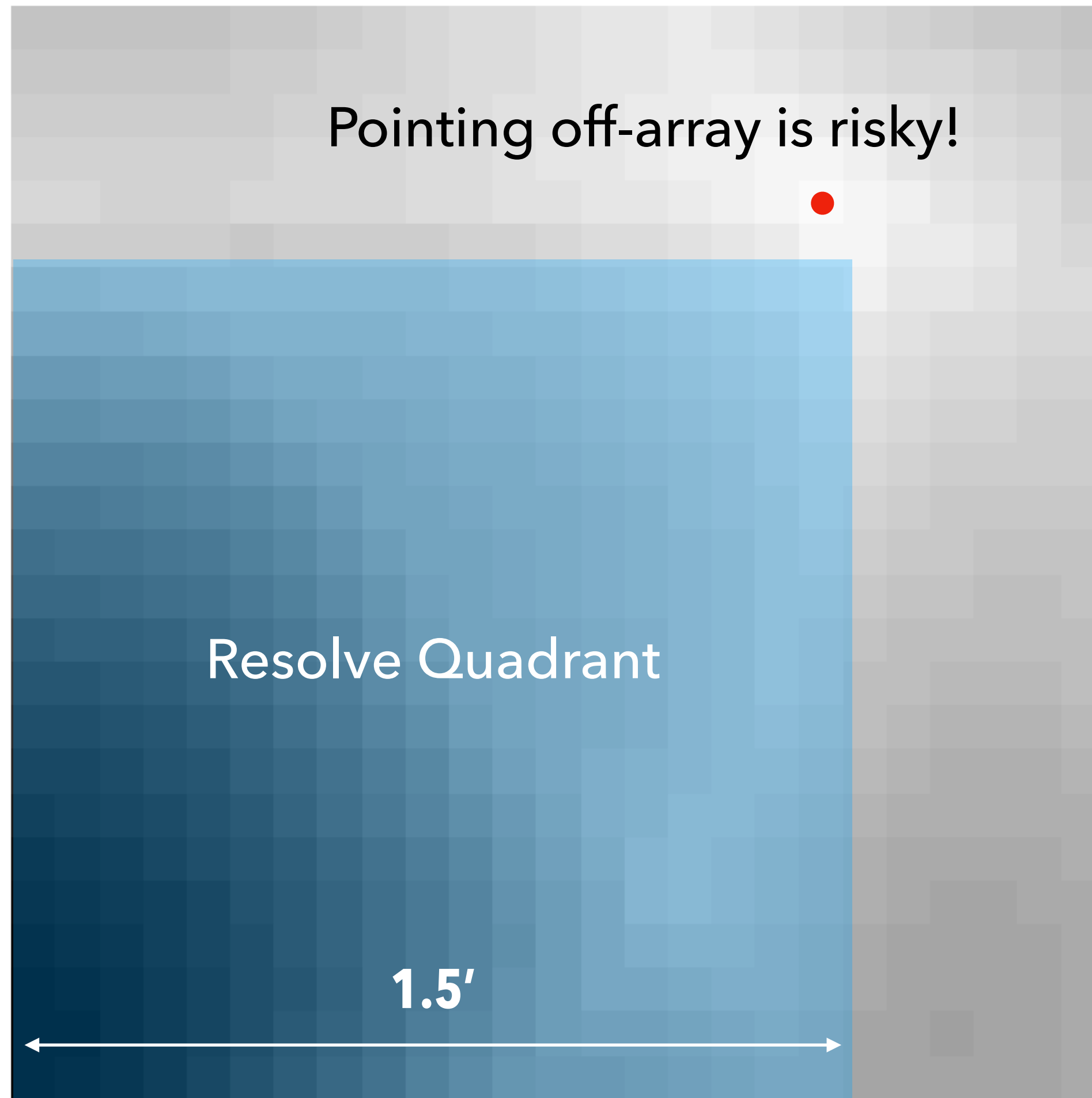
- Pointing next to a bright source causes most of its flux to miss the array
- Usually a bad thing (can't recover total flux as easily) but we're trying to reduce the incident count rate to  $<250$  counts/s
- "Sacrificing" one quadrant to low-resolution events can also maximize the H+Mp rate
- The best aim point must be decided once XRISM launches and the PSF shape is validated through the calibration campaign
- `heasim` already includes a way to estimate the H+Mp rate for an input spectrum and the PSP limit

# Observing Bright Sources



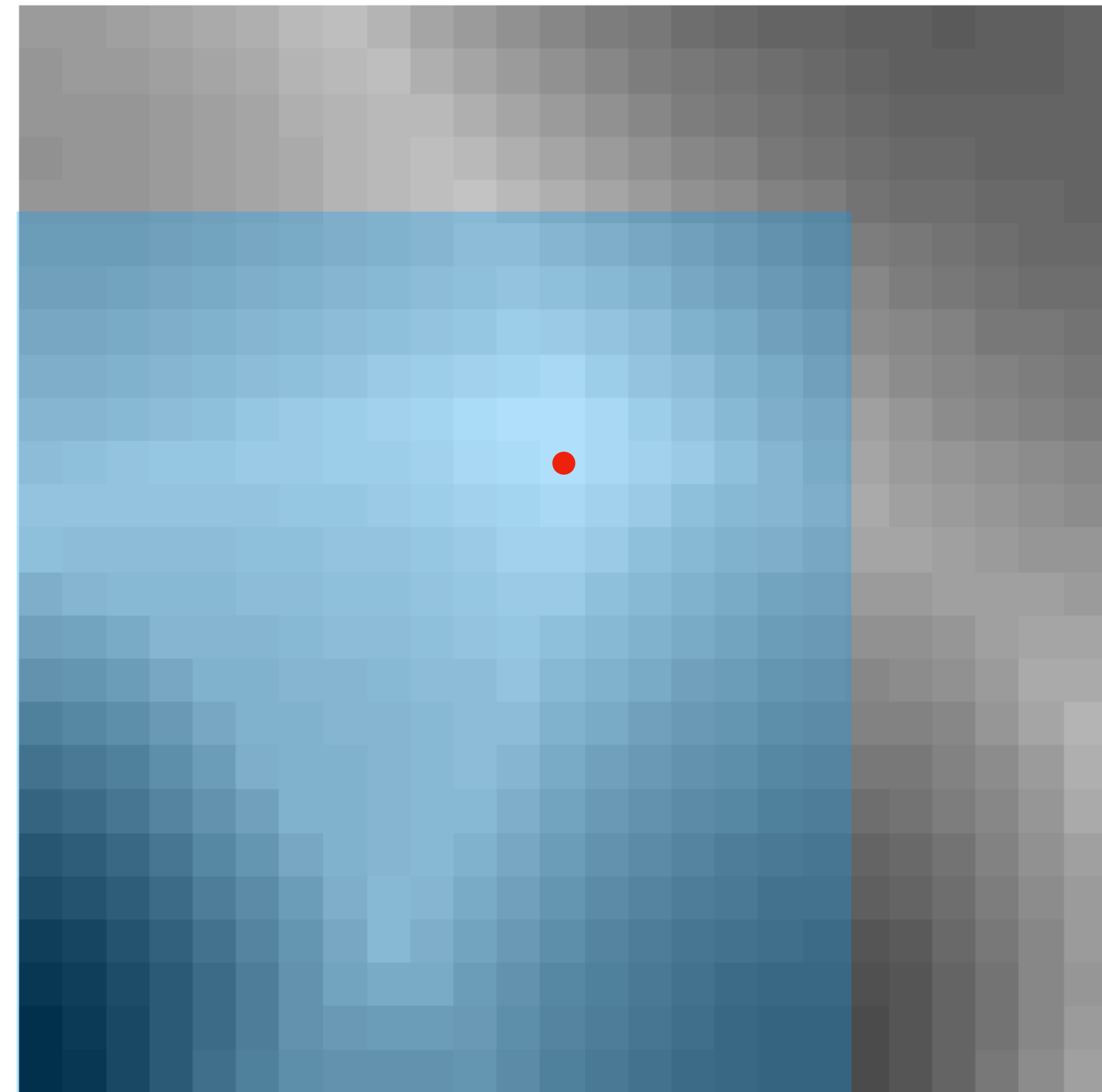
# Observing Bright Sources

H+Mp peak = 67.5 counts/s  
(+1.50, +1.67 arcmin)

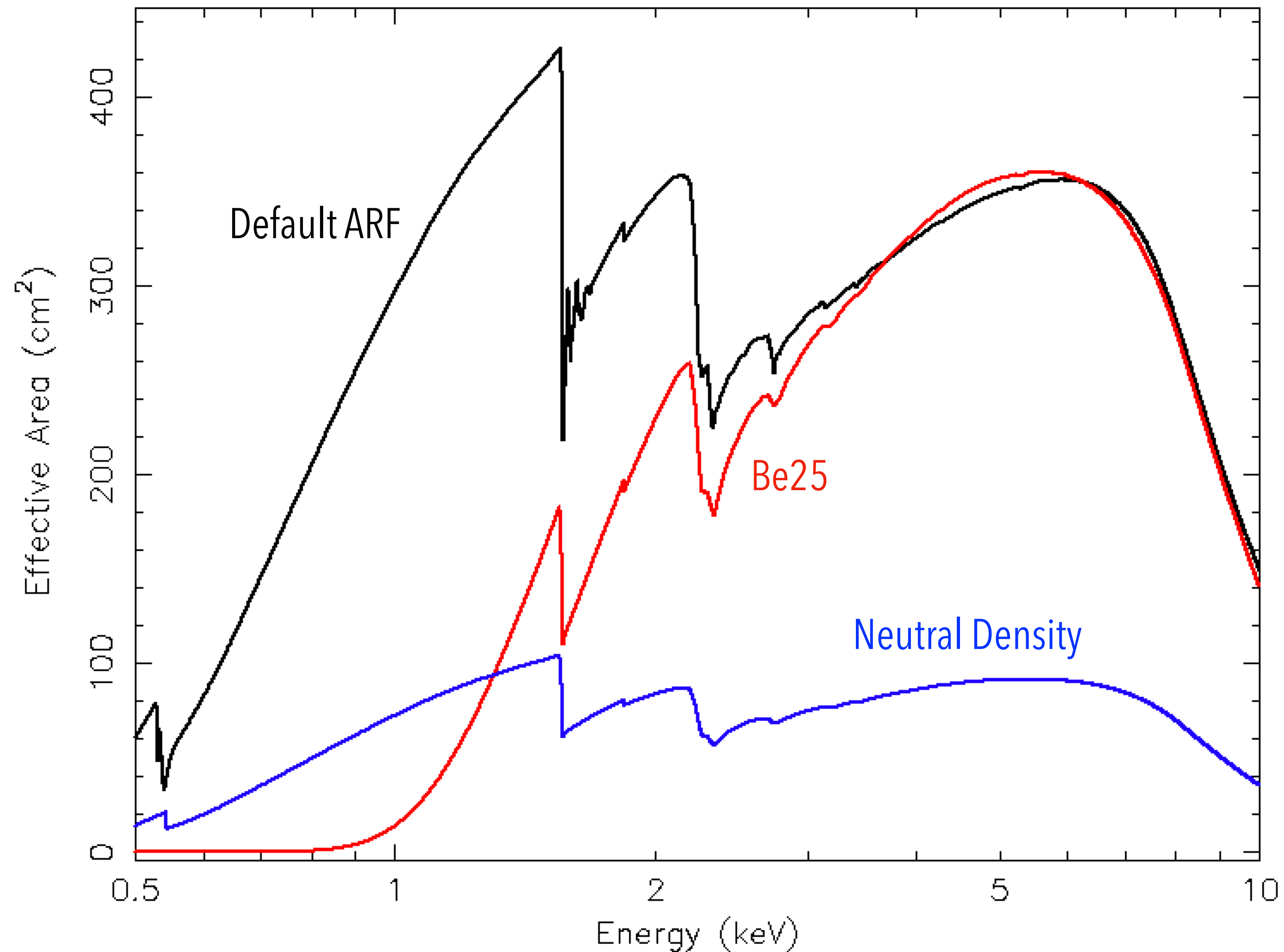


**2000** counts/s

H+Mp peak = 68.3 counts/s  
(+1.08, +1.25 arcmin)



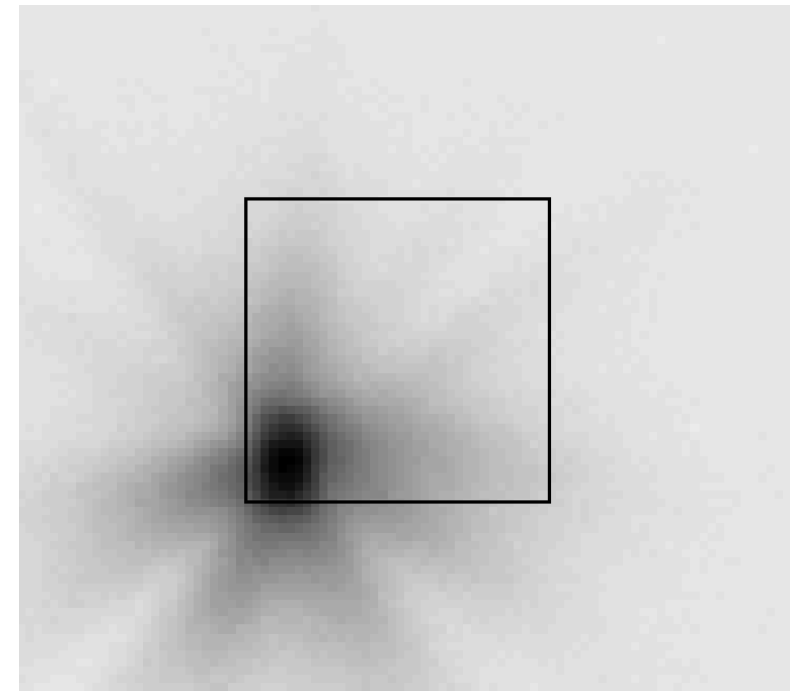
**1000** counts/s



- Power-law spectra typically have the largest photon flux at low energies. Be25 filter can remove most low-energy photons and preserves Fe K region
- Neutral density filter can be a good option if the source is extremely bright
- Off-axis pointing typically leads to a higher H+Mp rate than either

- Most science cases, focusing on lines/features, simply proceed normally and use only H+Mp events
- Select Clean Events
  - Iterate through each pixel and exclude time within  $\pm 10$  ms of an xTalk parent
  - Be wary of very fine velocity structure (compared to line-spread function)
  - In some cases, just extract a spectrum from selected pixels to minimize xTalk
- Estimate total flux from FPGA data if events are lost
  - Some of the XRISM PSF falls off Resolve anyway
  - The FPGA event-finder records the number of events it found without measuring energy; lost events have the same energy spectrum

# Analyzing Bright Source Data



**phabs (pow+gauss)**

$$N_H = 1 \times 10^{21} \text{ cm}^{-2}$$

$$\Gamma = 1.8$$

$$E_{\text{line}} = 6.4 \text{ keV}$$

$$F_{\text{line}} = 1 \times 10^{-9} \text{ erg/s}$$

$$F_X = 2.4 \times 10^{-8} \text{ erg/s} \text{ [2-10 keV]}$$

5 eV native FWHM

1 Crab

Incident Count Rate (raw)

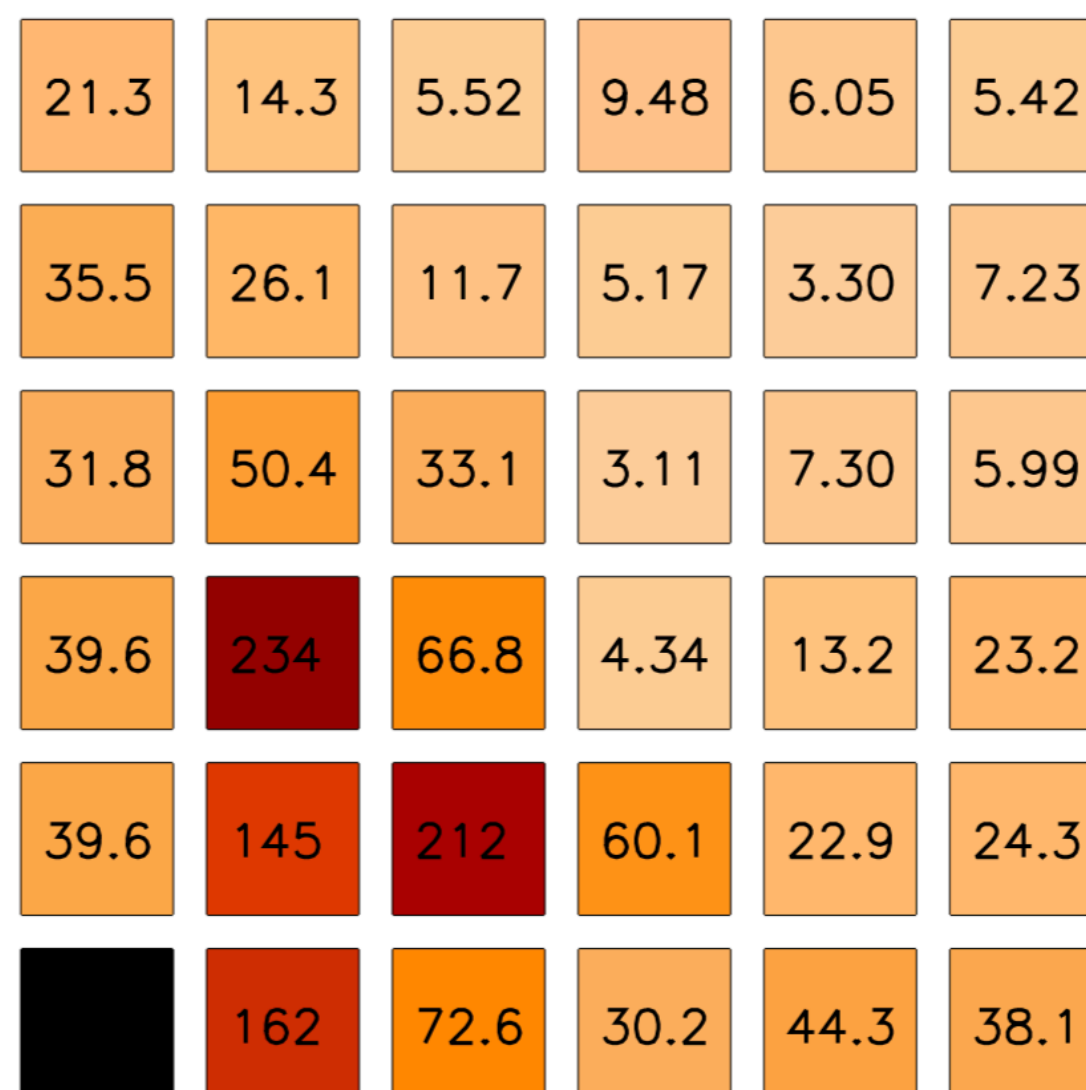


H+Mp rate (after PSP)

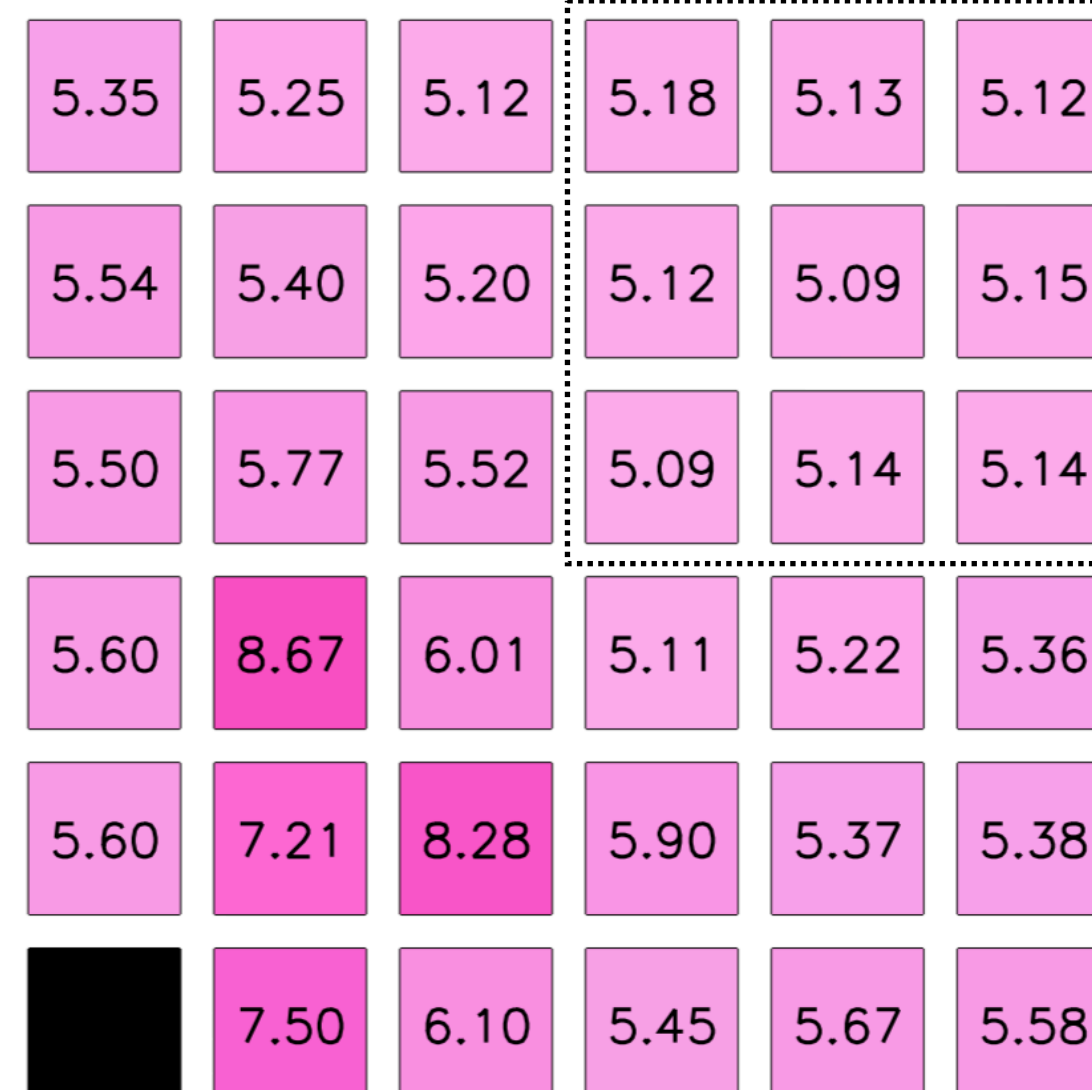


This quadrant has the highest rates per pixel...

X-talk Child Pulse Rate



$\Delta E$  [eV, FWHM]



.. and the least xTalk noise

- We hope and expect proposers to observe bright sources
- Above 100 mCrab, maximizing the high-resolution count rate requires creative observing strategies
- The optimal solution depends on the spectral shape as well as the flux
- Electrical cross-talk can degrade the energy resolution of each pixel in different ways. A combination of off-axis pointing and excluding the most affected pixels can keep this to a small fraction of the native resolution
- The proposers' guide will recommend strategies for different brightness levels but you may wish to optimize for a given source

# APPENDIX



# CPU Load

**Table 5.3:** Rate limits.

Data type	Description	Event rate (s <sup>-1</sup> ) (Crab)		Deadtime <sup>f</sup> (ms)
		4/4 <sup>a</sup>	2/4 <sup>b</sup>	
Pixel pulse	FPGA algorithm limit <sup>c</sup>	64285 (30.0)	64285 (30.0)	0.56
	<b>pxPulseEDB</b> overflow limit	3658 (1.7)	1829 (0.85)	—
	Branching ratio limit	1069	1069	
	PSP limit	269	135	See eqn. 5.8.
Pixel noise	FPGA algorithm limit <sup>d</sup>	220	220	—
	<b>pxNoiseEDB</b> overflow limit	4000	2000	—
Anti-co pulse	FPGA algorithm limit <sup>e</sup>	6250	6250	~0.5
	<b>acPulseEDB</b> overflow limit	915	915	—

<sup>a</sup> Full function case.

<sup>b</sup> Case for one of the two SpaceCard boards in both units is lost.

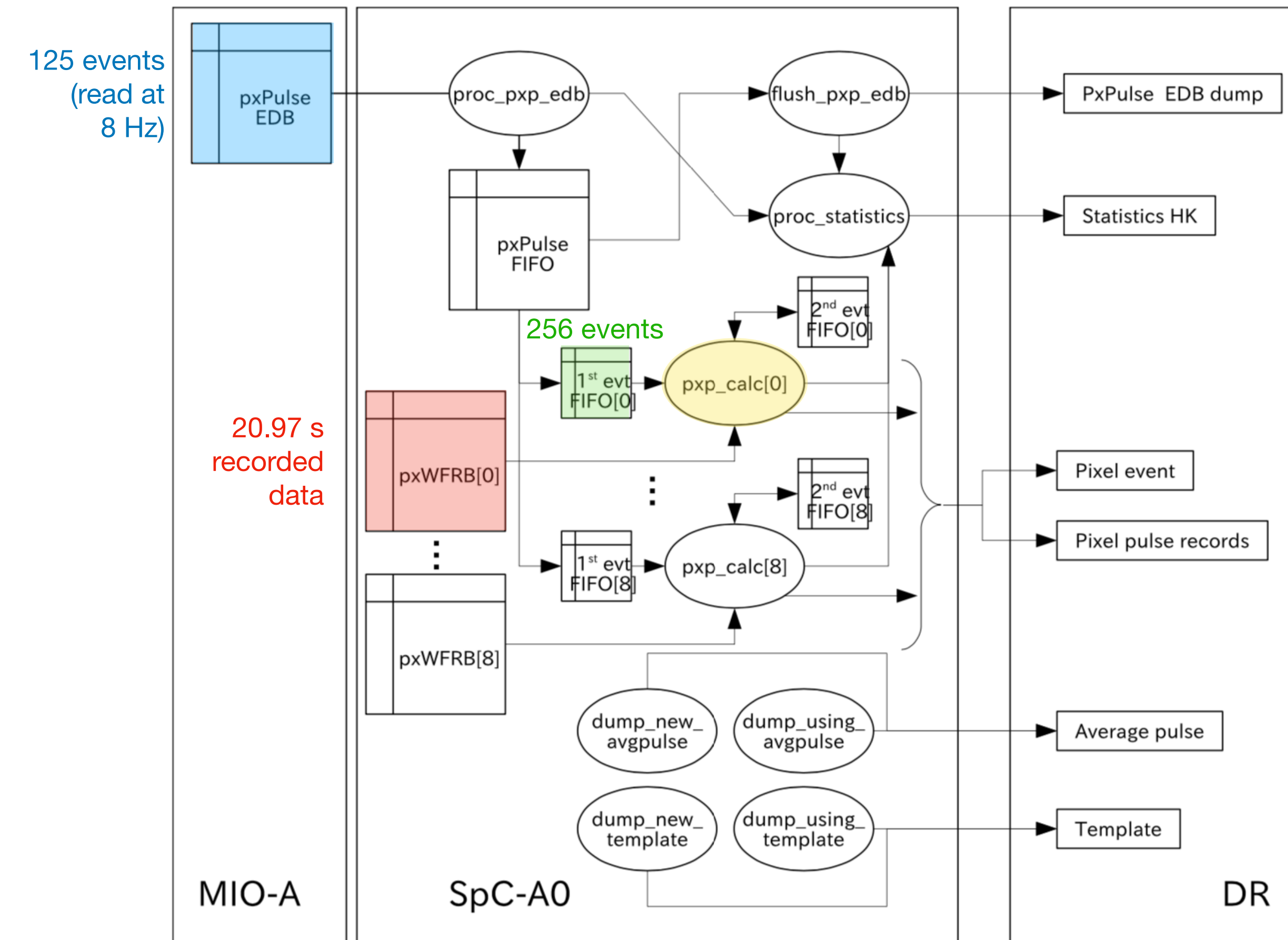
<sup>c</sup> A new event arrives immediately after the **PXP\_PEAKFIND** state of the previous event.

<sup>d</sup> Noise records arrive continuously.

<sup>e</sup> ADC sample values alternates below and above the threshold in the alternating samples.

<sup>f</sup> Dead time caused by an event.

# Event Processing Diagram



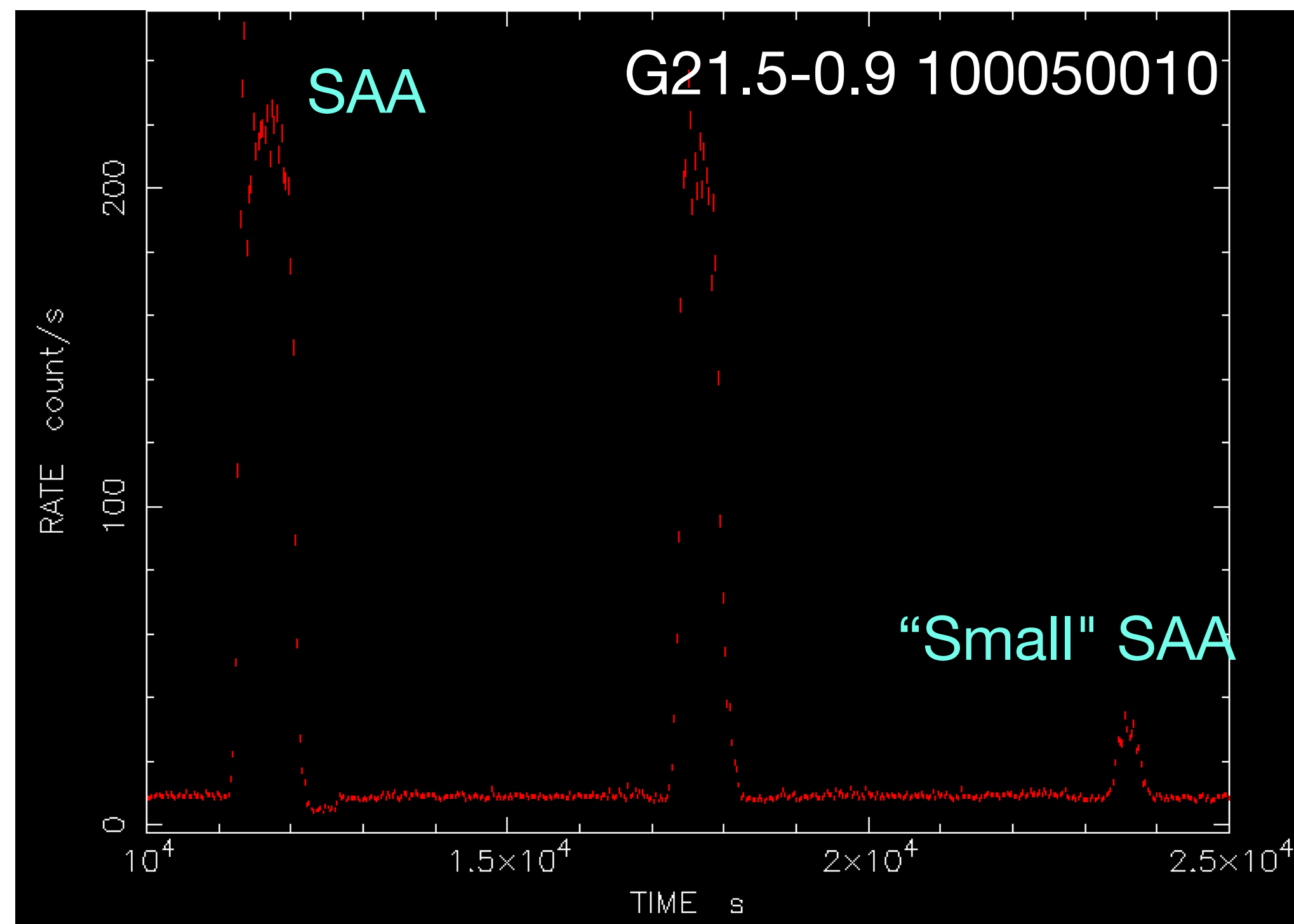
Event candidates detected in the MIO board are stored in an “event dual buffer” and read by the SpC board at 8 Hz. When events are read in (by `proc_pxp_edb`), they are distributed among pixels into FIFO buffers 1-9. The data stream is also copied over and stored in the `pxWFRB` waveform ring buffer for each pixel.

When an event is ready to be processed, the `pxp_calc` task runs the optimal filtering and other tasks. It reads in the event data, locates the event in the `WFRB` data stream, and processes it. This includes checking to see if it’s a real event, categorizing it as high, medium, or low-res, searching for secondaries, and measuring the energy.

The `pxp_calc` tasks are run simultaneously. They all have the same priority in the operating system for the SpaceCard CPU (TOPPERS). Within a priority level, if the CPU has spare capacity then it will begin running the next available process. Once a pixel has processed an event, that `pxp_calc` thread schedules itself at the back of the queue for its priority level. This is “round robin” scheduling.

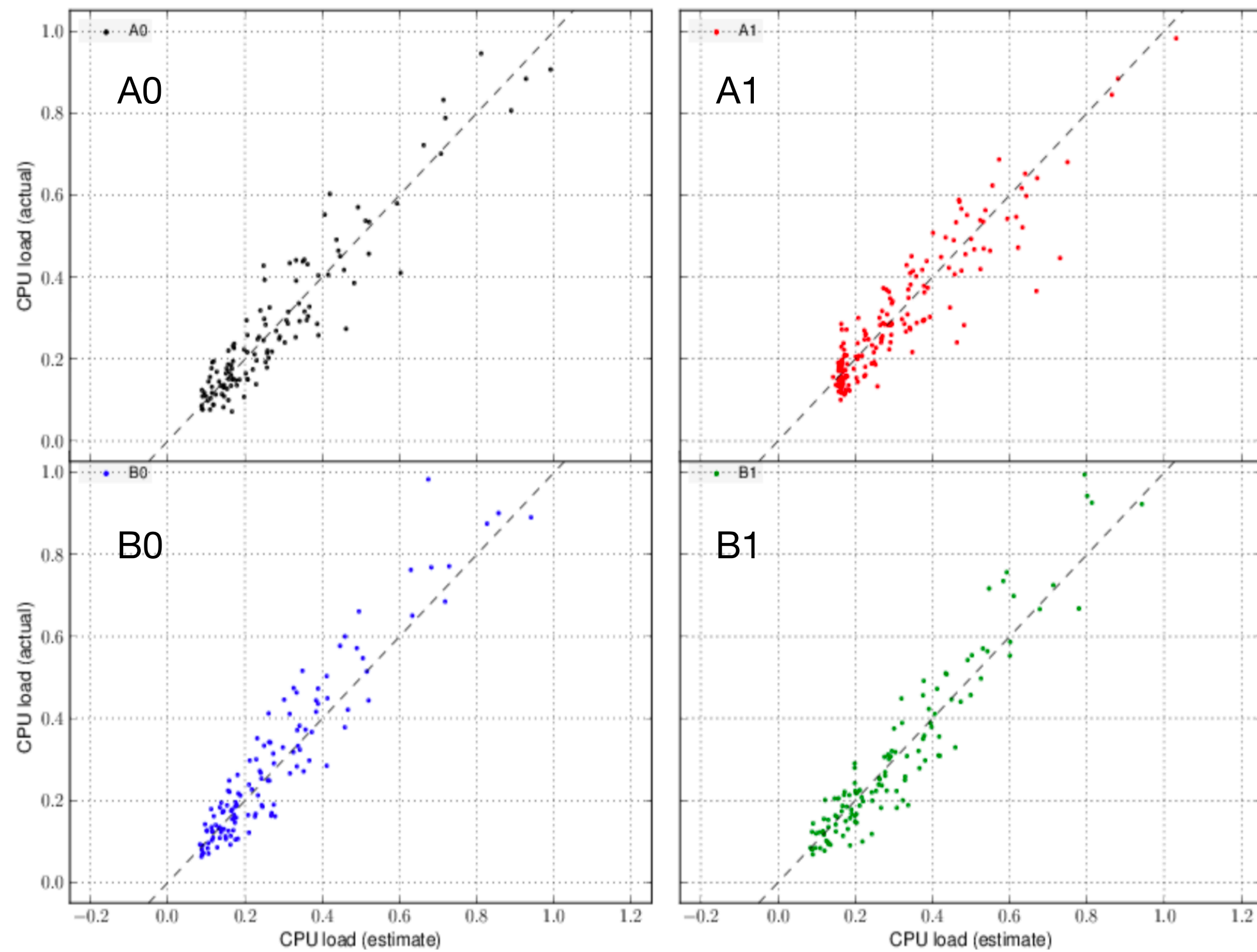
- Each pixel has a task to process events (`pxp_calc[i]`), an event log, and a data stream.
- If an event enters the buffer, `pxp_calc[i]` wakes up and processes it. Afterwards, `pxp_calc[i]` returns to sleep unless there is another event waiting.
- If there is an event waiting, `pxp_calc[i]` moves itself to the back of the line. The CPU scheduler activates the next task in line as it has capacity. This is 'round robin' scheduling. Multiple `pxp_calc` tasks can be active.
- Note that pixels may process different numbers of events. Hp events take longer to process than Lp events. If `pxp_calc[i]` finishes but no other tasks are 'done,' the CPU will select `pxp_calc[i]` next by default. This still favors H/M events.
- Events are lost on a per-pixel basis unless the FPGA event dual buffer overflows. **At low count rates, pixels may never lose events even at 100% CPU load.**
- Live time (per pixel) and H+M rate can be more accurately predicted if we know the CPU load per event.

$$\begin{aligned} (\text{CPU load}) = & a \sum_{\text{IPIX}} (\text{Hp count}) + b \sum_{\text{IPIX}} (\text{Mp} + \text{Ms count}) \\ & + c \sum_{\text{IPIX}} (\text{Lp} + \text{Ls count}) \\ & + d \sum_{\text{IPIX}} (\text{FPGA count}) + e, \end{aligned}$$



- Model Hitomi data at moderate/high count rate.
- CPU has 1000 ms to “spend.” Use average count rate to estimate CPU load per event. Assume each CPU is identical with the same base load.
- Secondary events are found recursively, but we measure the *average* time per event.
- Use periods when count rate exceeds baseline (to get many low-res events) but is not saturated (“small” SAA).

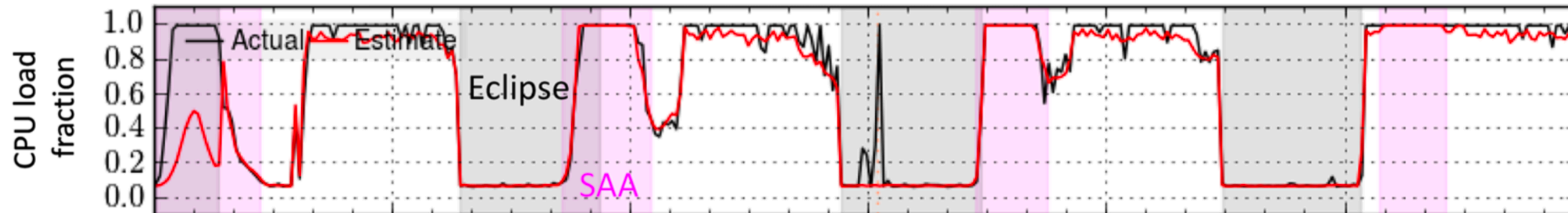
# CPU Load per Event

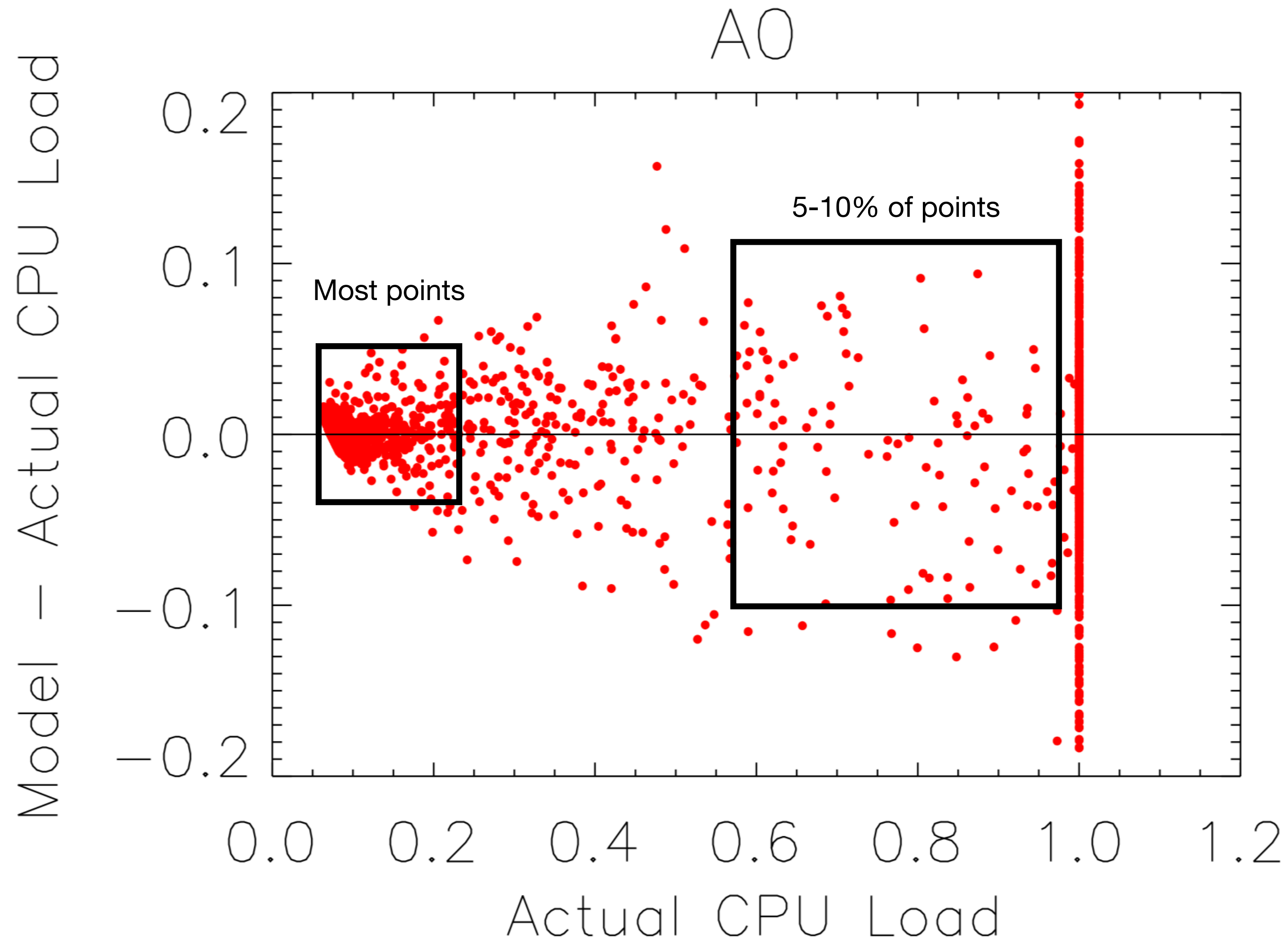


```
[[Fit Statistics]]
# function evals = 291
# data points = 542
# variables = 5
chi-square = 2.353
reduced chi-square = 0.004
Akaike info crit = -2933.281
Bayesian info crit = -2911.804
[[Variables]]
a: 0.01336677 (init= 0.03)
b: 0.01468106 (init= 0.03)
c: 0.00016663 (init= 0.001)
d: 0.00045255 (init= 0.001)
e: 0.06598735 (init= 0.08)
[[Correlations]] (unreported correlations are < 0.100)
```

Simple model reproduces Hitomi Crab data

SXS PSP-A0 events (PIXEL=00 - 08) 2016-03-25 12:00:00 – 17:58:56 UTC



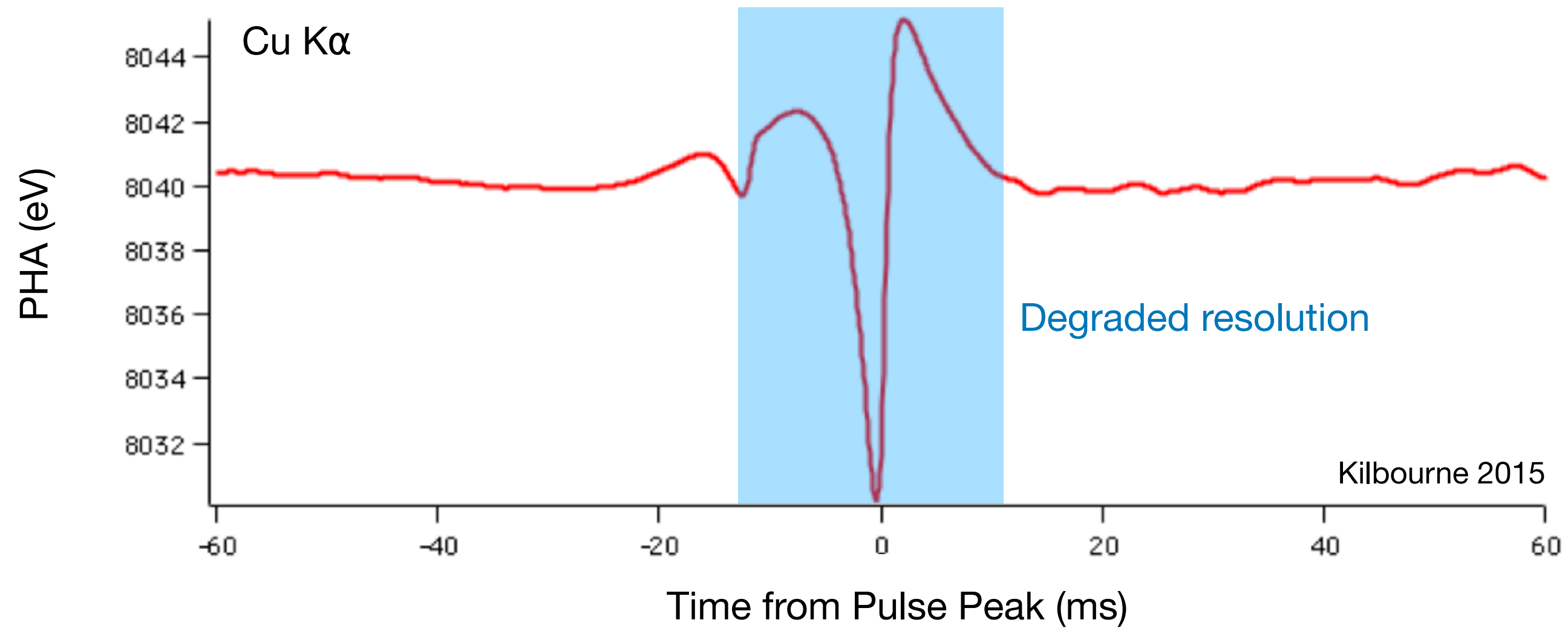


- The model is degenerate because there are few periods where Hitomi experienced a moderate count rate
- Data stream dominated by high-resolution and low-resolution events
- Better calibration this time around
- New model to be developed

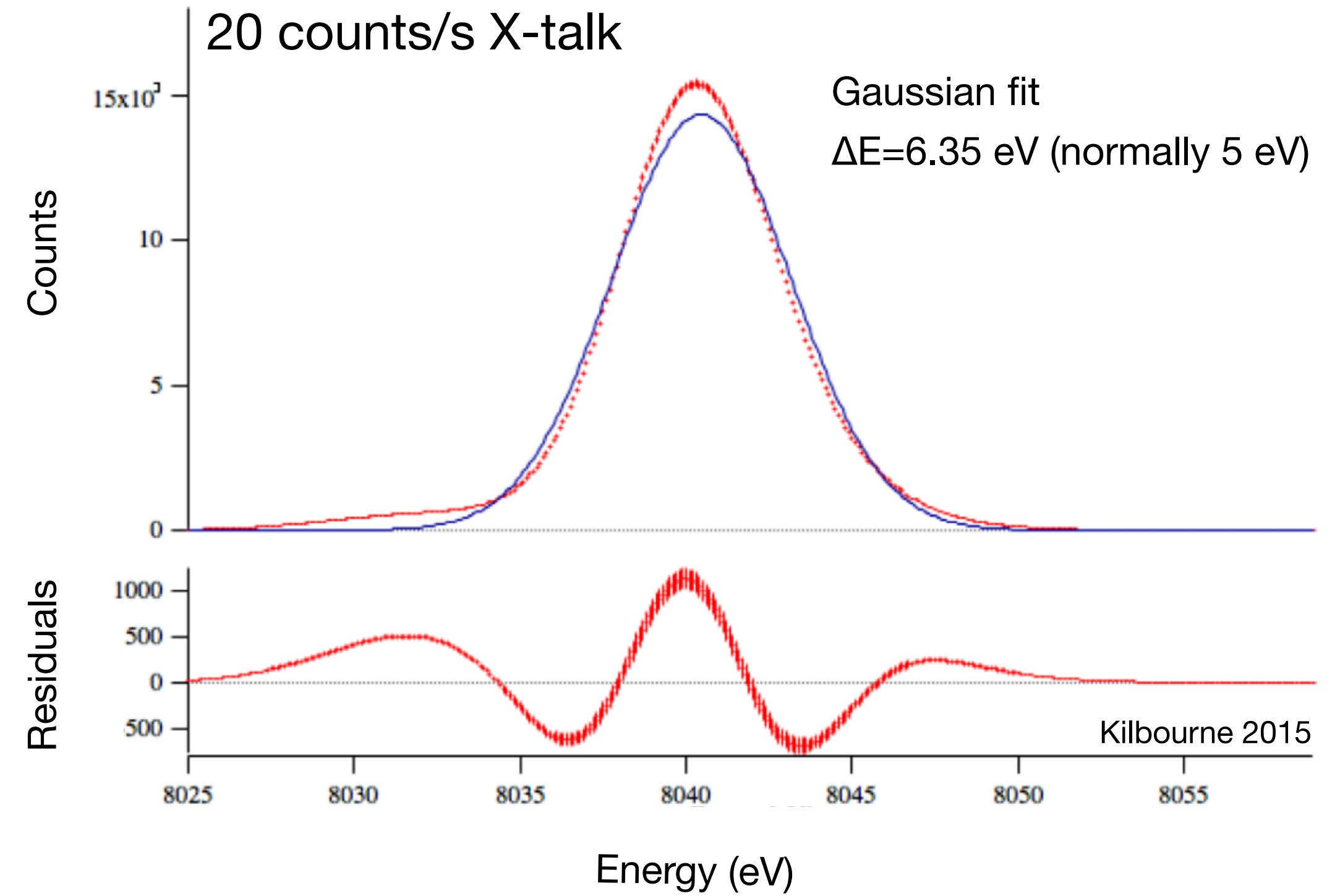
# Electrical Cross-Talk



Measured pulse energy as a function of X-talk arrival time



**Untriggered** X-talk can degrade energy resolution and perturb gain



### 5.2.2 Mathematical Background

Suppose that the power spectrum of noiseless signal and noise are  $S(\omega)$  and  $N(\omega)$ , respectively. An incoming data  $D(\omega)$  can be decomposed as

$$D(\omega) = HS(\omega) + N(\omega), \quad (5.1)$$

in which  $H$  is the pulse height of the signal. The best-fit value of  $H$  is determined so that the following  $\chi^2$  value is minimized.

$$\chi^2 \equiv \sum_{\omega} \frac{|D(\omega) - HS(\omega)|^2}{|N(\omega)|^2}. \quad (5.2)$$

$H$  is derived from  $\frac{\partial}{\partial H}\chi^2 = 0$  as

$$H = \frac{\sum_{\omega} \frac{D(\omega)S^*(\omega) + D^*(\omega)S(\omega)}{2|N(\omega)|^2}}{\sum_{\omega} \left| \frac{S(\omega)}{N(\omega)} \right|^2}. \quad (5.3)$$

The asterisk indicates the complex conjugate. By defining the filter template in the frequency domain as

$$F(\omega) \equiv \frac{S(\omega)}{|N(\omega)|^2} \frac{1}{\sum_{\omega} \left| \frac{S(\omega)}{N(\omega)} \right|^2}, \quad (5.4)$$

and converting into the time domain  $F(t)$ ,  $H$  is derived as

$$H = \sum_t D(t)F(t). \quad (5.5)$$

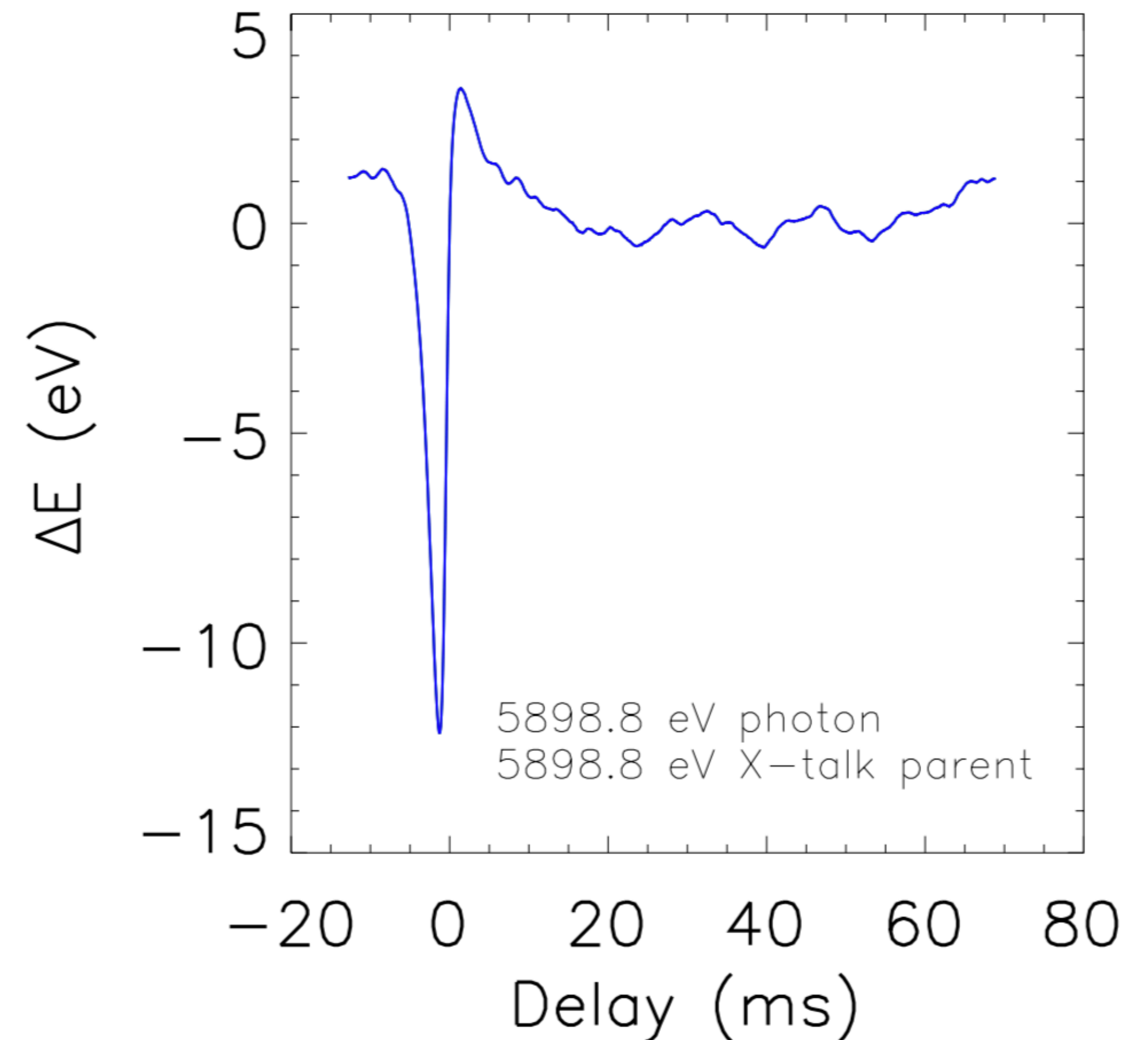
Let  $P(t)$  be the pulse profile for an event  
 $X(t)$  be the (shifted) X-talk child pulse profile  
 $\bar{P}(t)$  be the average pulse profile  
 $T(t)$  be the filter template for optimal filtering  
 $b$  be a normalization (144000 for 0.3 eV/channel)

Then  $P'(t) = P(t) + X(t)$  is the contaminated pulse

$$\text{PHA} = b \frac{\sum P'(t)T(t)}{\sum \bar{P}(t)T(t)} \text{ is the PHA}$$

$$\text{PHA} = \frac{b}{\sum \bar{P}(t)T(t)} \left[ \sum P(t)T(t) + \sum X(t)T(t) \right]$$

$$\Delta \text{PHA} = b \frac{\sum X(t)T(t)}{\sum \bar{P}(t)T(t)} \text{ is independent of } P(t)$$



$\Delta \text{PHA}$  for a 5.9 keV Mn Ka photon as a function of xTalk delay relative to measured photon

Define the energy resolution

\*X-talk broadening is not symmetric

$$\sigma = \sqrt{\sigma_{\text{RMF}}^2 + \sigma_{\text{XT}}^2}$$

5 eV                      X-talk

Illuminate the array with a spectrum, folded through the ARF

$$F_{\nu} \rightarrow \dot{N}_i(E) \quad \text{in pixel } i$$

Assume all X-talk is undetected and calculate average number of contaminating pulses per event for electrical neighbors.

$$\dot{N}_i(E) \rightarrow \lambda_{i-1}, \lambda_{i+1}$$

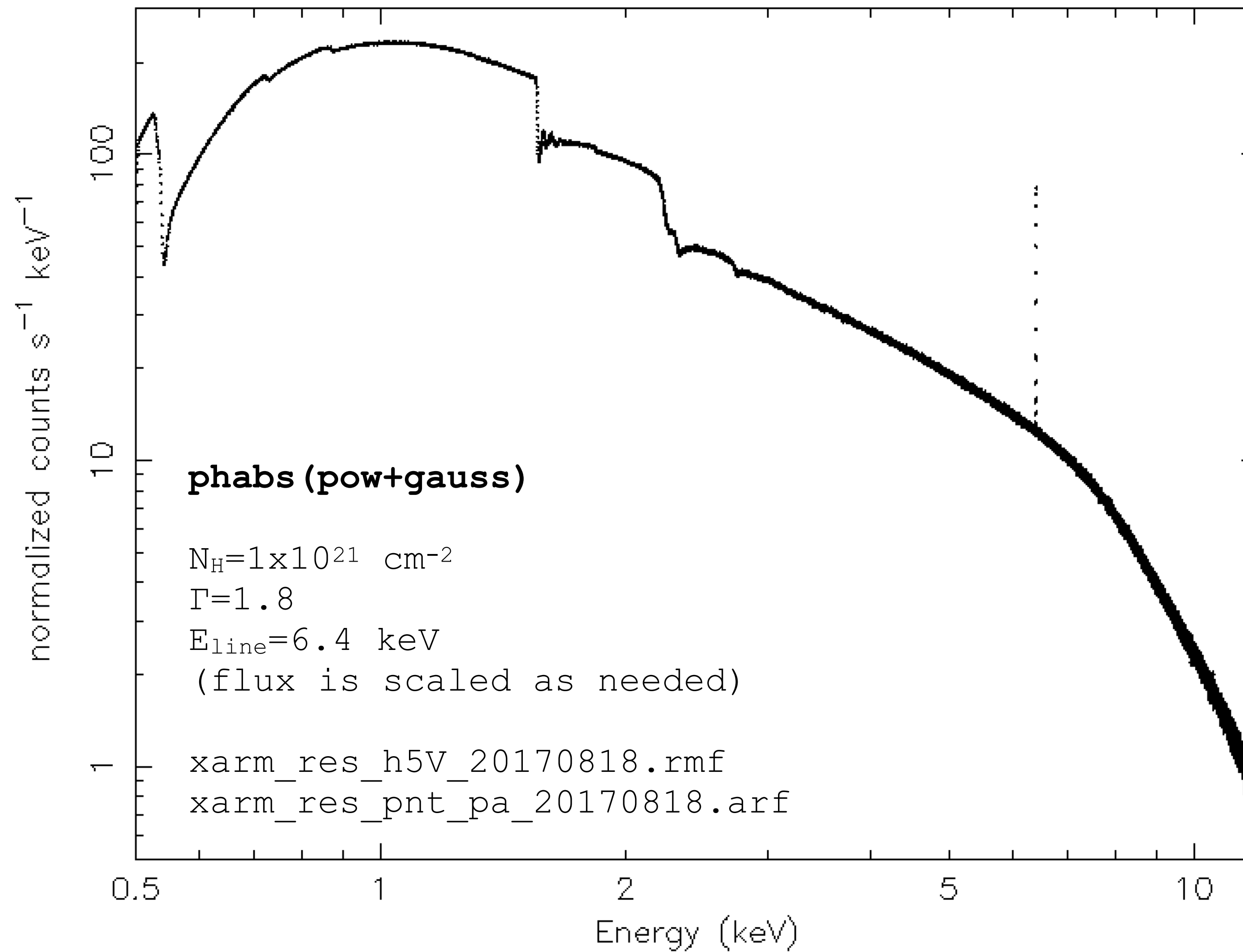
Use Poisson sampling and random arrival times for  $10^6$  simulated events to create PHA distribution with native 5 eV. Fit with a Gaussian to measure  $\sigma$  and solve for  $\sigma_{\text{XT}}$ .

$$F_{\nu}, \lambda_i \rightarrow \sigma_i$$

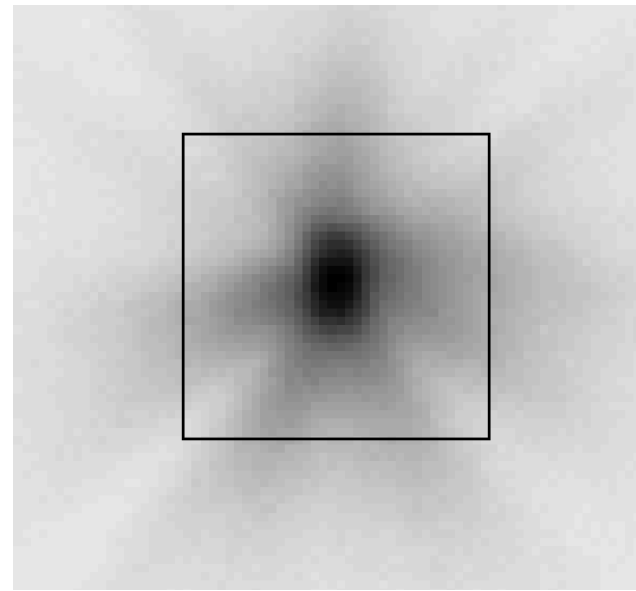
Since  $\sigma$  depends only on X-talk rate and spectrum, can calculate a single  $\sigma$  per pixel.

\* Caveats: Assume no removal of known X-talk contamination, no secondary searches, Hp templates only, used a single pulse, X-talk, average pulse, and filter template for just one pixel.

- Let's try it for an example spectrum



# On-axis Line Broadening

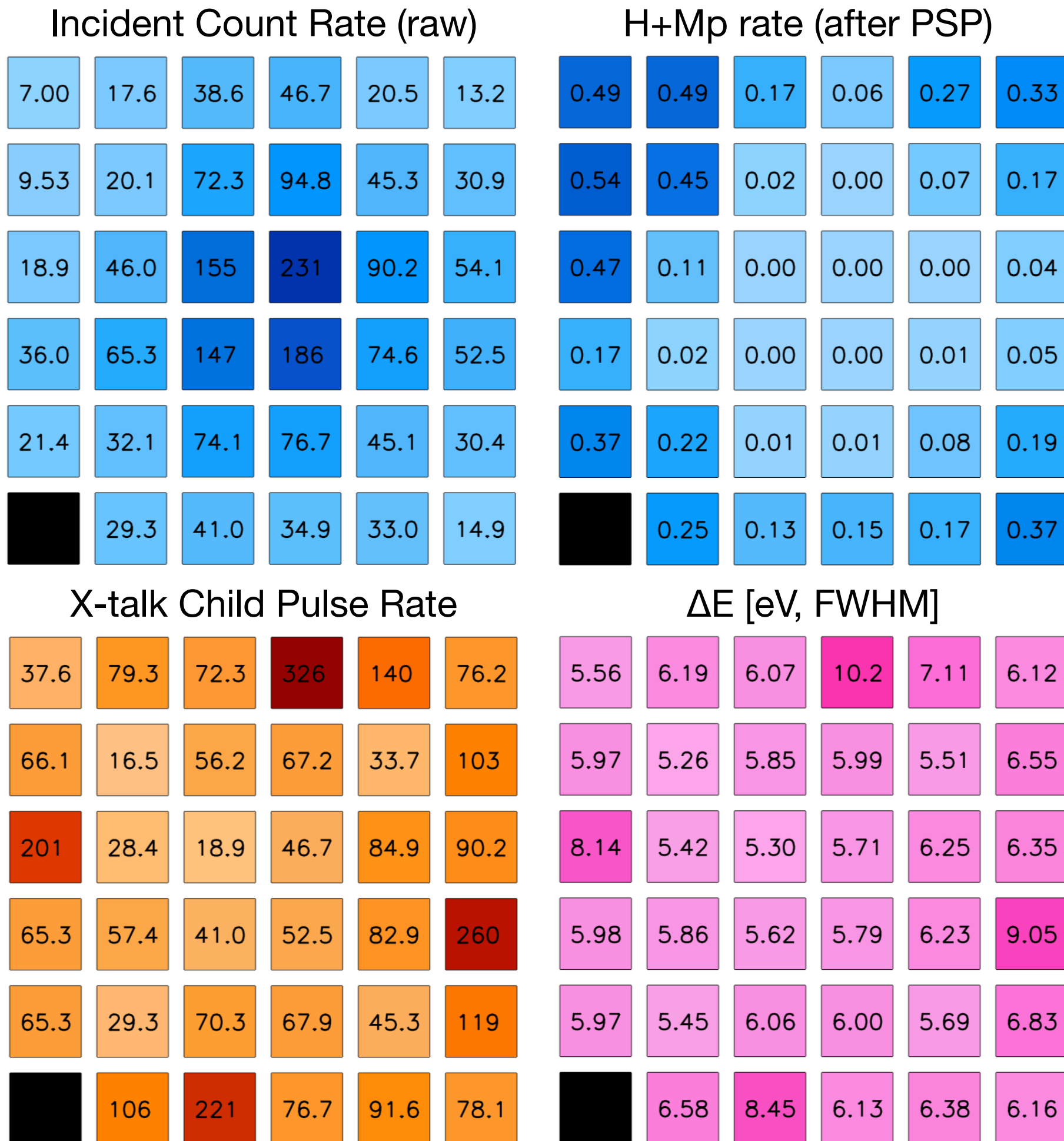


**phabs (pow+gauss)**

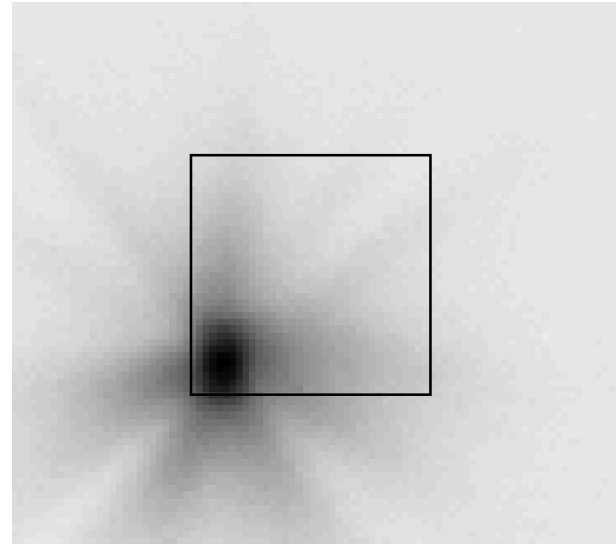
$N_H = 1 \times 10^{21} \text{ cm}^{-2}$   
 $\Gamma = 1.8$   
 $E_{\text{line}} = 6.4 \text{ keV}$   
 $F_{\text{line}} = 1 \times 10^{-9} \text{ erg/s}$   
 $F_X = 2.4 \times 10^{-8} \text{ erg/s}$   
 [2-10 keV]

5 eV native FWHM

1 Crab



# Off-axis Line Broadening

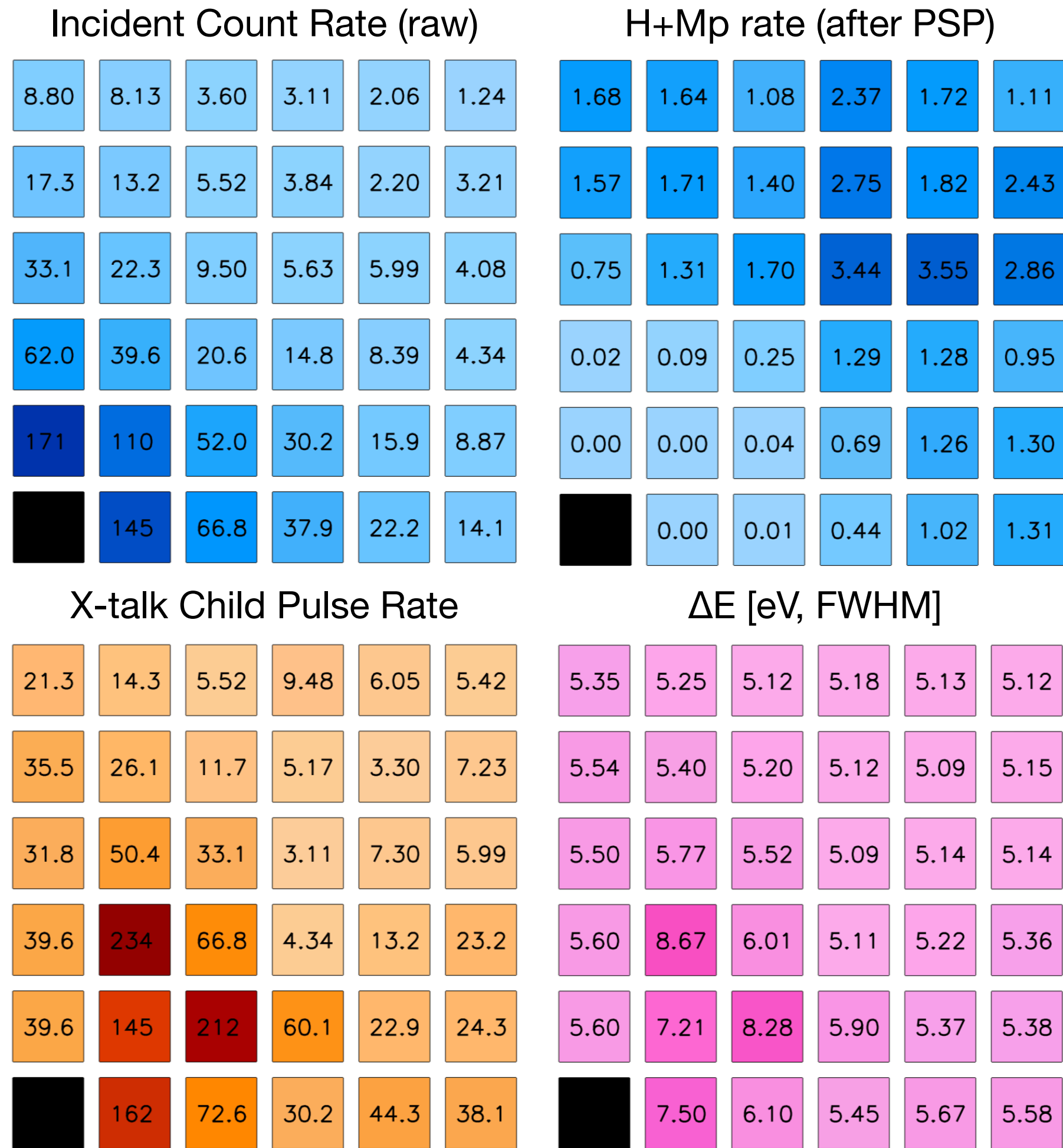


**phabs (pow+gauss)**

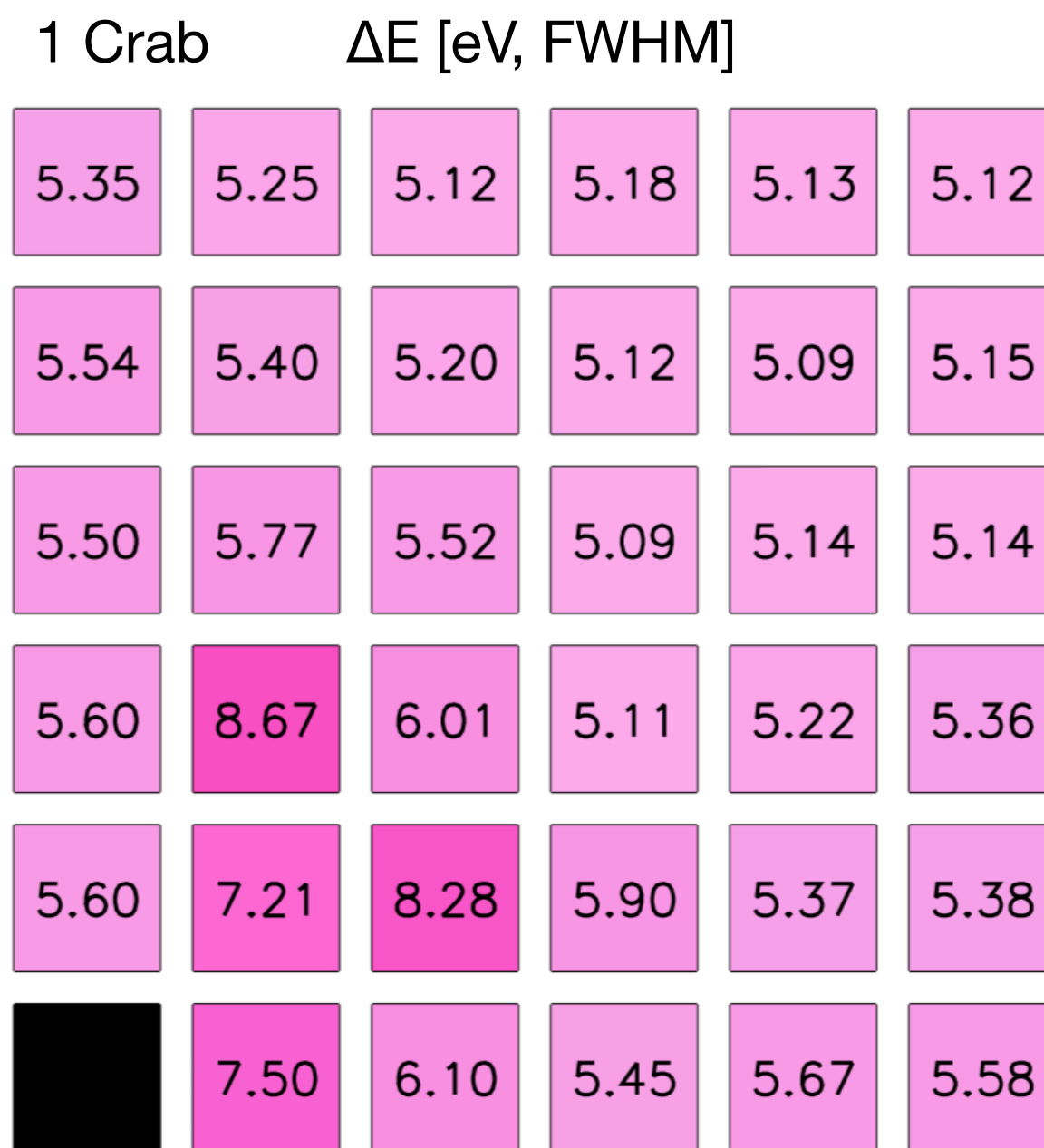
$N_H = 1 \times 10^{21} \text{ cm}^{-2}$   
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 [2-10 keV]

5 eV native FWHM

1 Crab

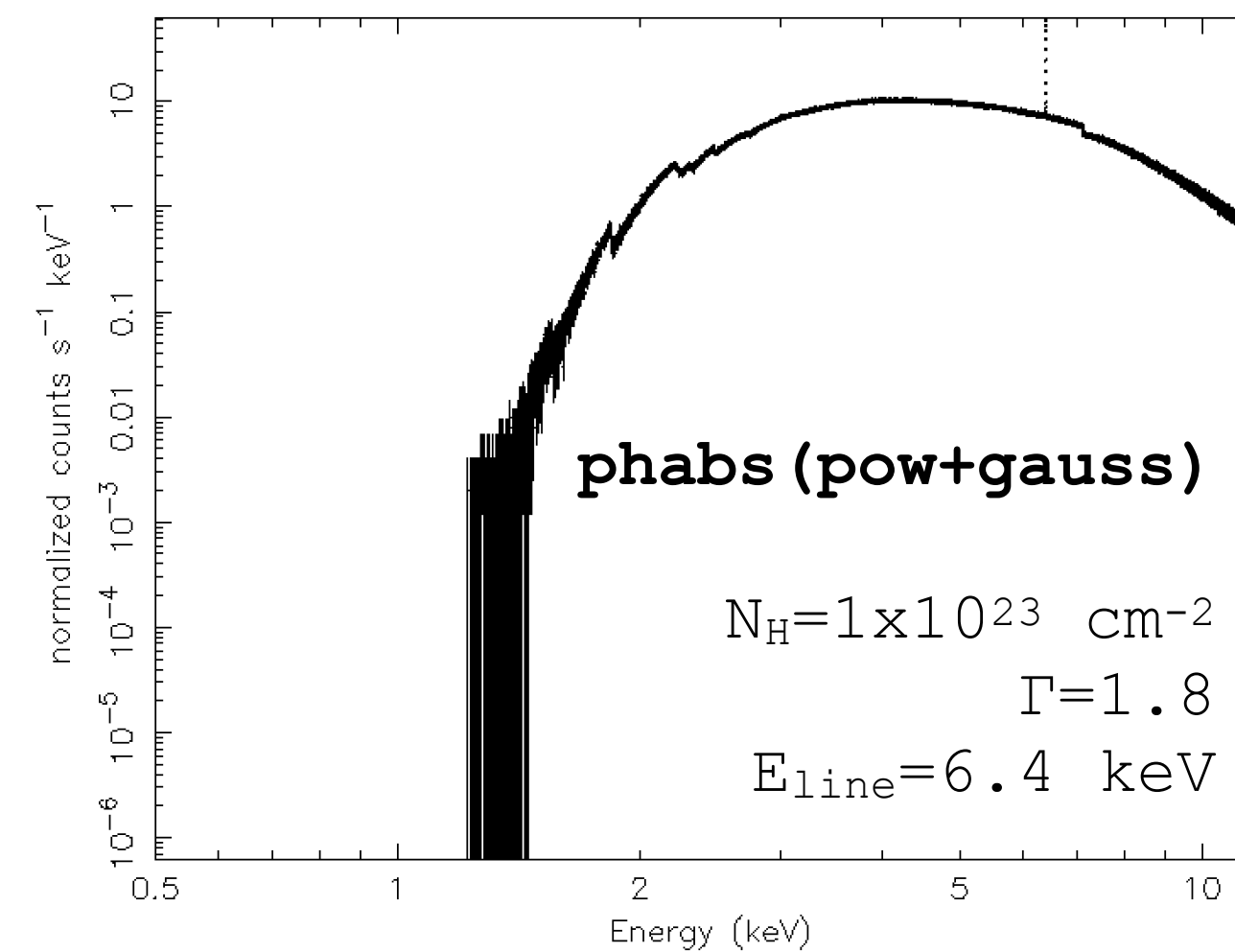
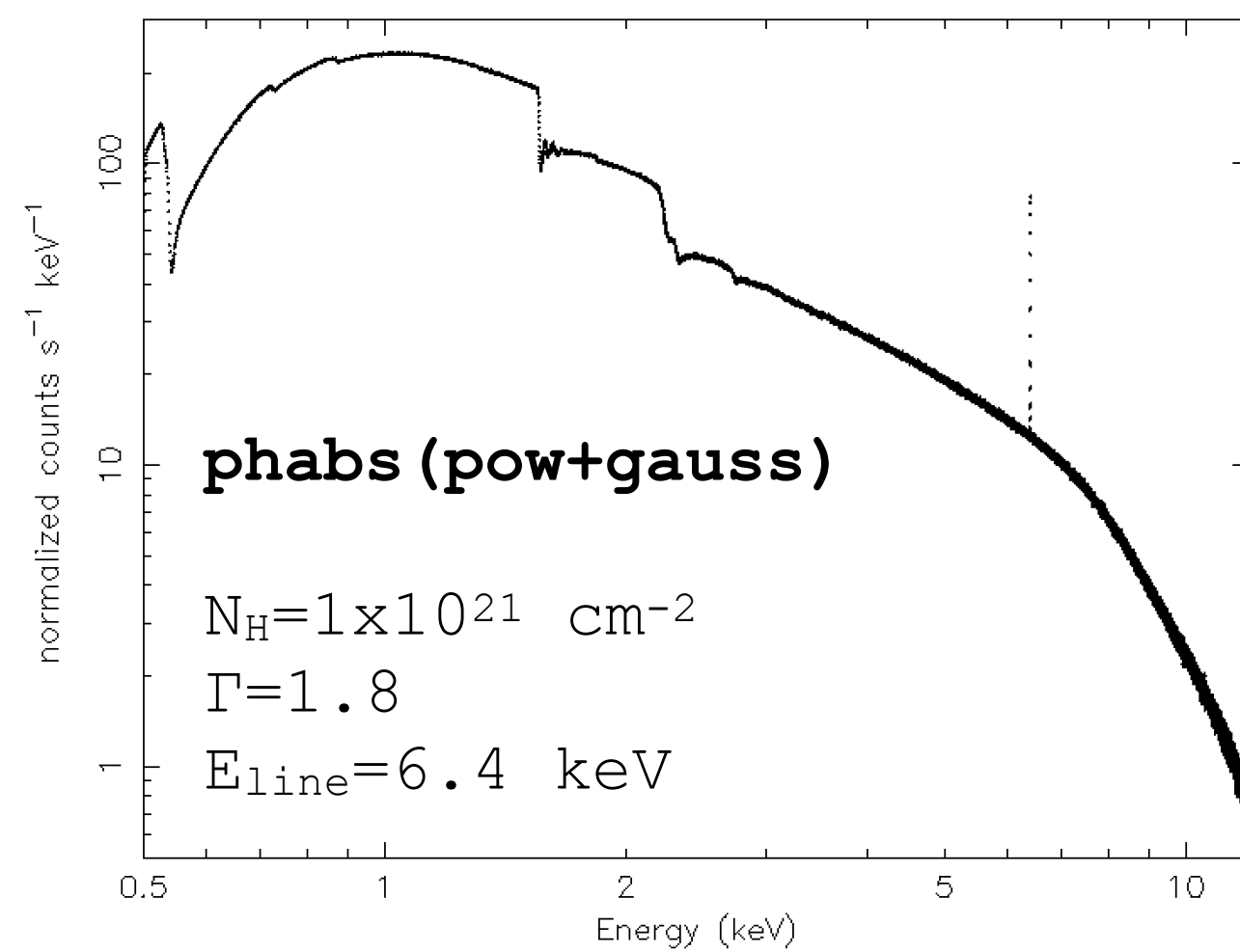


# Spectral Hardness



X-talk contamination is worse for a given photon flux with a harder spectrum.

The saving grace is that a harder spectrum will likely have a lower photon flux.

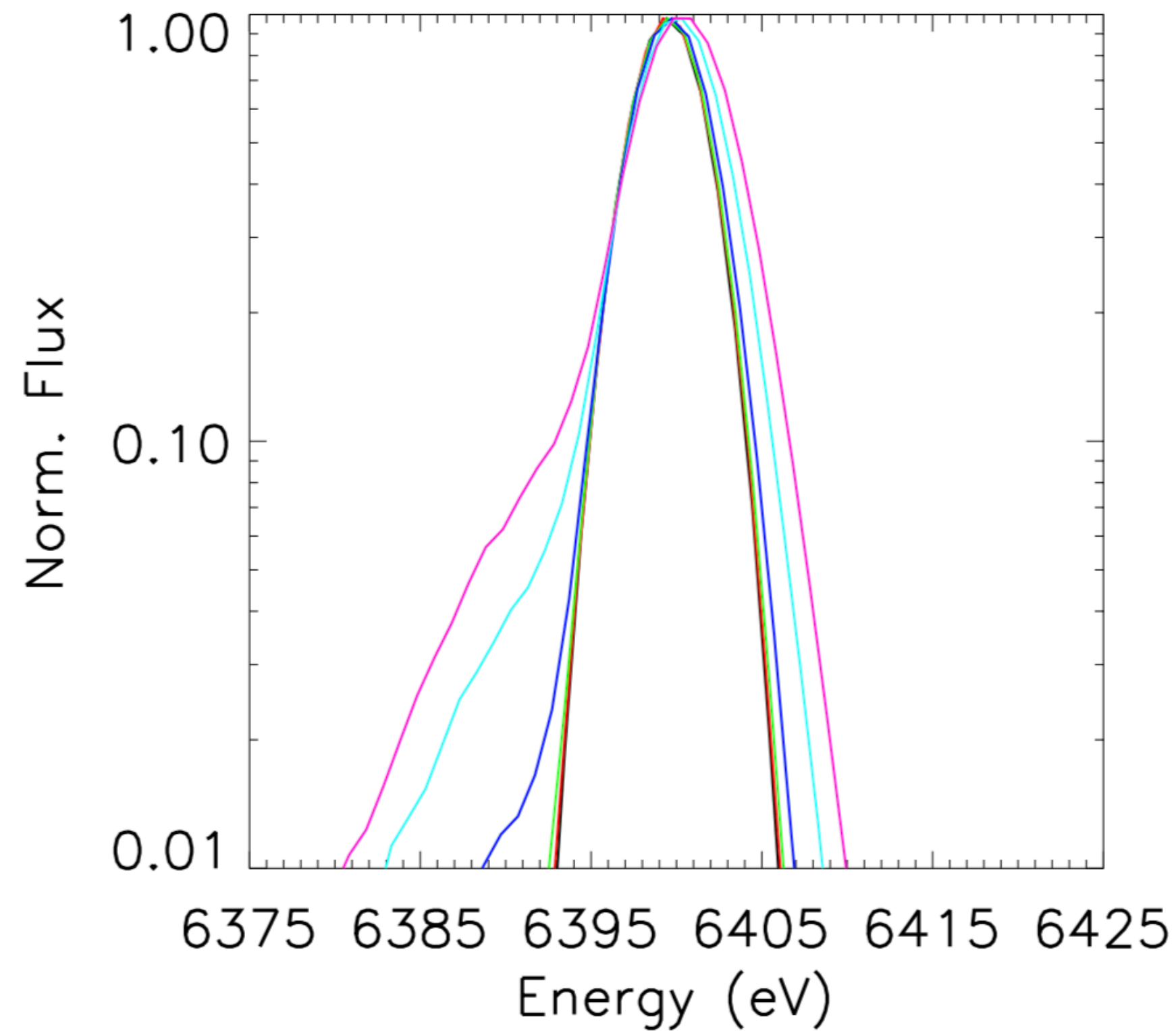




$\Delta E$  [eV, Centroid Shift]



1 Crab, off-axis source from above



The line profile is not strictly Gaussian, and fitting it with a Gaussian will lead to centroid shift errors that increase with X-talk rate.

Velocity Broadening:  $\sigma_{\text{XT}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{RMF}}^2} \in [0, 1.4] \text{ eV}$   
 0-65 km/s at Fe K $\alpha$

Centroiding:  $\Delta E \in [0, 1] \text{ eV}$   
 0-50 km/s at Fe K $\alpha$

Absorption Line Sensitivity:

$$N_c > S^2 \left( \frac{\Delta E}{W} \right)^2 \left( 1 + \frac{F_b}{F_c} \right) \rightarrow \left( \frac{5\text{eV}}{\Delta E} \right)^2 \approx 0.7 - 1$$

Continuum photons  $\uparrow$   $S/N$   $\uparrow$   $\uparrow$  Background/continuum  $\uparrow$  Fractional sensitivity  $\uparrow$   
 Equivalent width ( $\ll \Delta E$ )  $\uparrow$

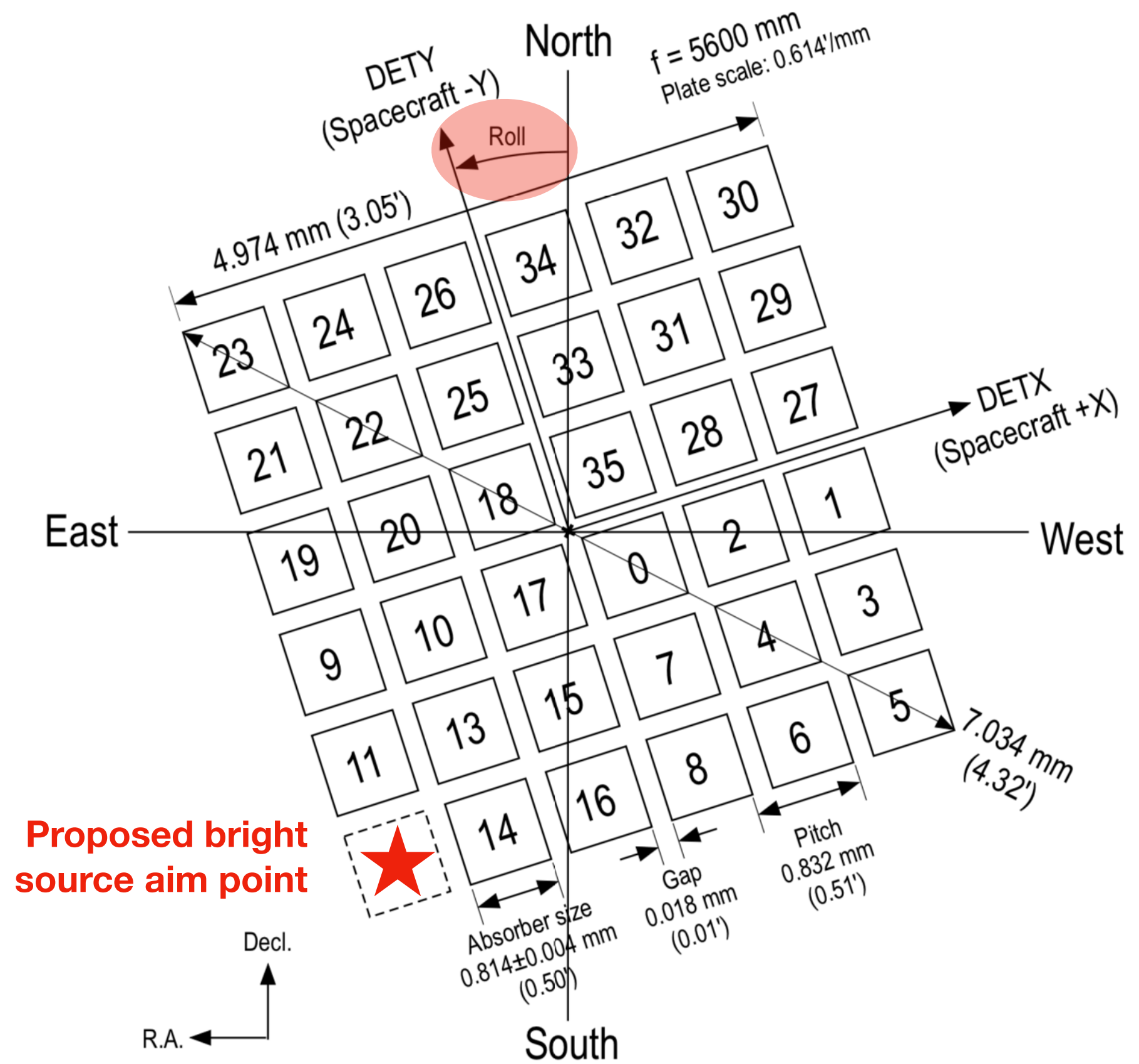
Ground testing with the MXS (Porter 2015, Kilbourne 2015) found FWHM~6.1 eV at an X-talk rate of 20 counts/s. We estimate FWHM<5.5 eV for the same rate. Why?

The MXS provides Cu and Cr K lines (8.4 and 5.4 keV), which are significantly more energetic than the average photon from a Crab-like spectrum.

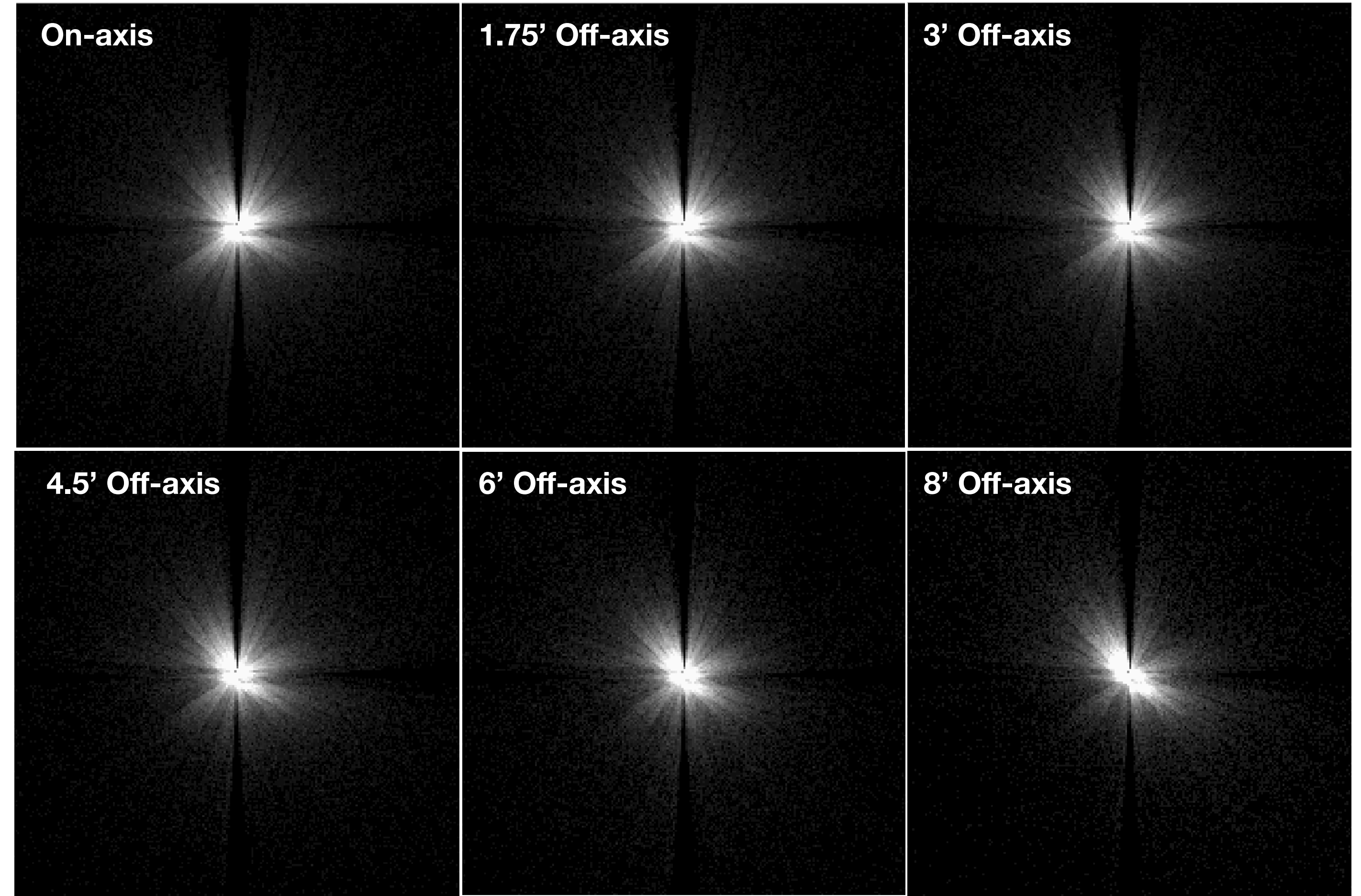
If we use the MXS spectrum, we recover a consistent result. However, note that the actual energy resolution depends quadratically on the event energy.

- Pointing jitter, source variability, or bursting could make xTalk behave unpredictably
- Jointly fitting data from most pixels may require iterative fitting to constrain xTalk and true velocity structure (which should not differ between pixels for a point source!)

PSF

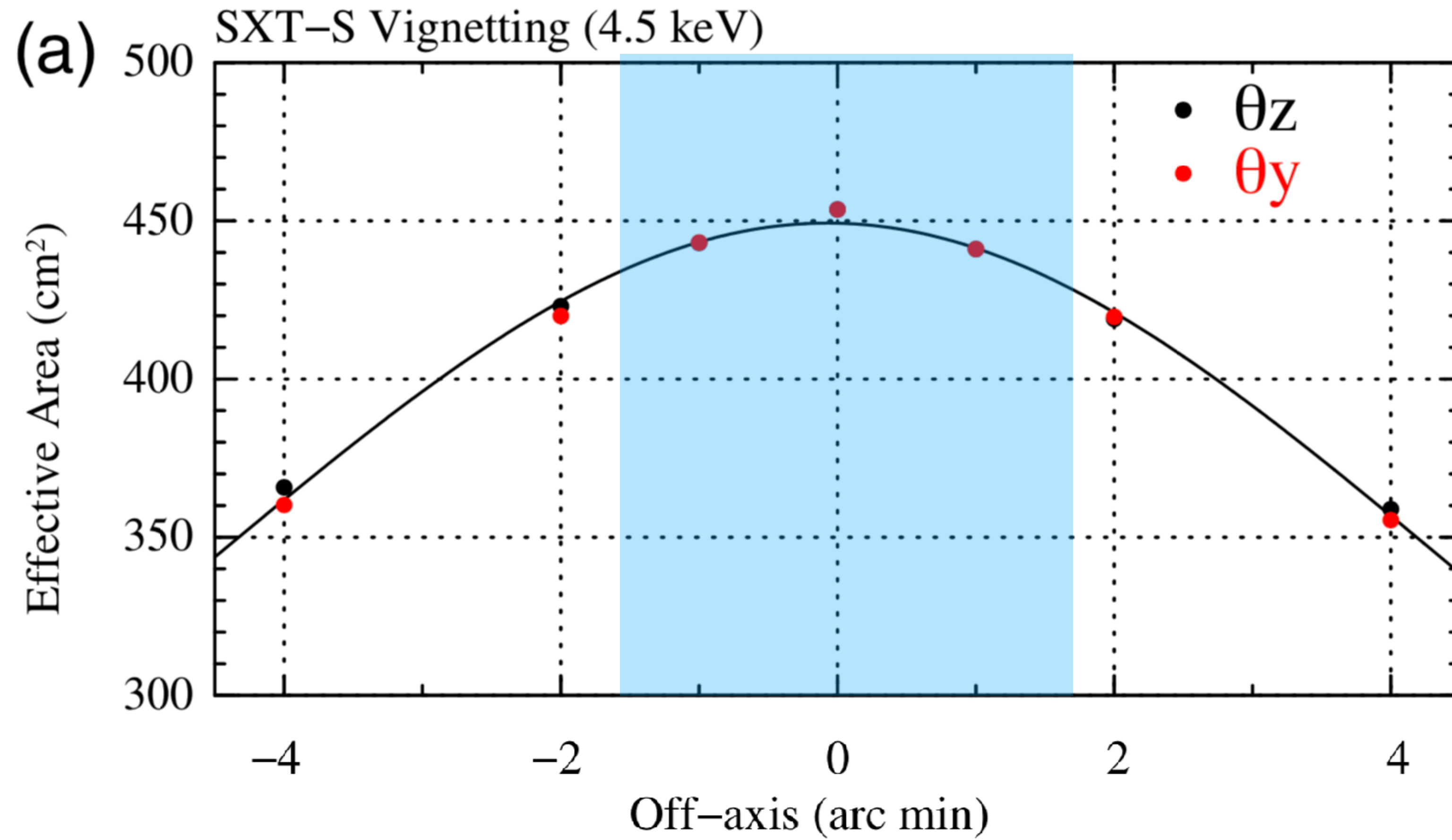


Look-up map of the SXS detector  
 (Pixel 12 is the cal pix and is not shown in this figure.)



PSF structure is similar with off-axis angle up to 8' off-axis... but it is highly structured, so we need to know to high fidelity where the counts in the wings will fall

- PSF was calibrated on the ground near a likely bright source aim point and at nearby angles
- PSF calibration data form inputs to the XRISM ray trace that accounts for all the elements in the optical path and should be used to create simulations (e.g., via `xrtraytrace`)
- The PSF calibration is expected to be validated on orbit, but the PSF will not be measured in detail unless the validation fails, as it will be somewhat degenerate with effective area



For off-axis pointing where the PSF core still falls on Resolve, vignetting is a much smaller factor than the off-detector flux.