Low-flux Measurements with Cornell's LCLS Integrating Pixel Array Detector

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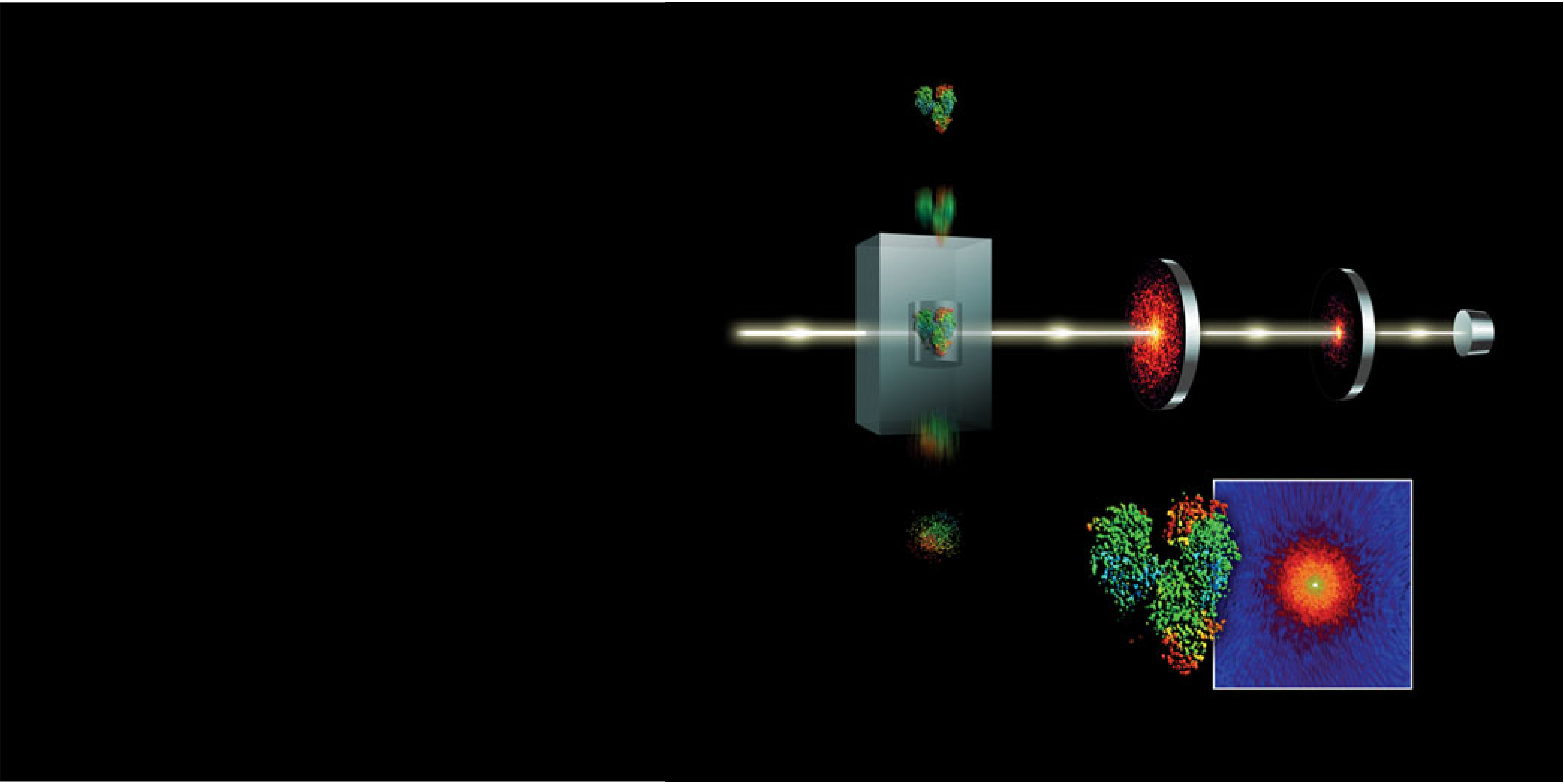
Outline

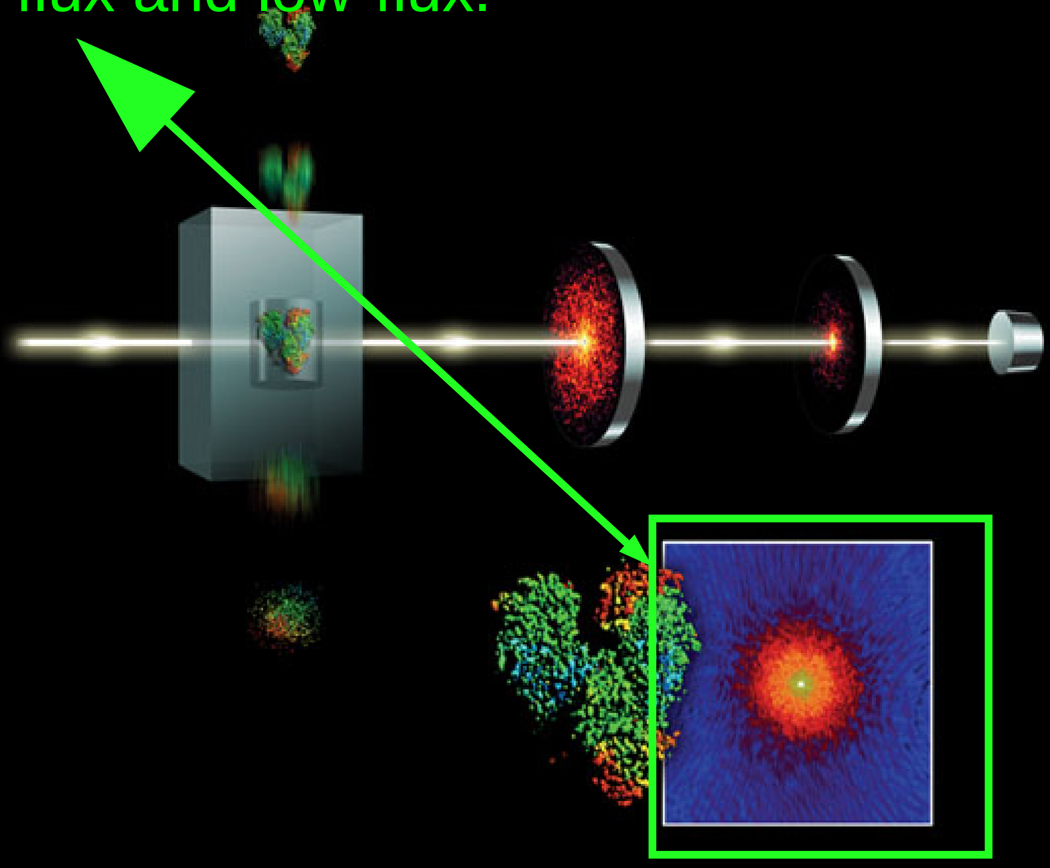
- Coherent x-ray imaging and detector need.
- Original specifications.
- Brief overview of PAD design.
- Single photon measurements.
- Thoughts on low flux measurement with integrating PAD.
- Measurements and data reduction with Cornell's single module detector.

CXI Instrument



CXI Instrument

- Combination of extremely high-flux and low-flux.



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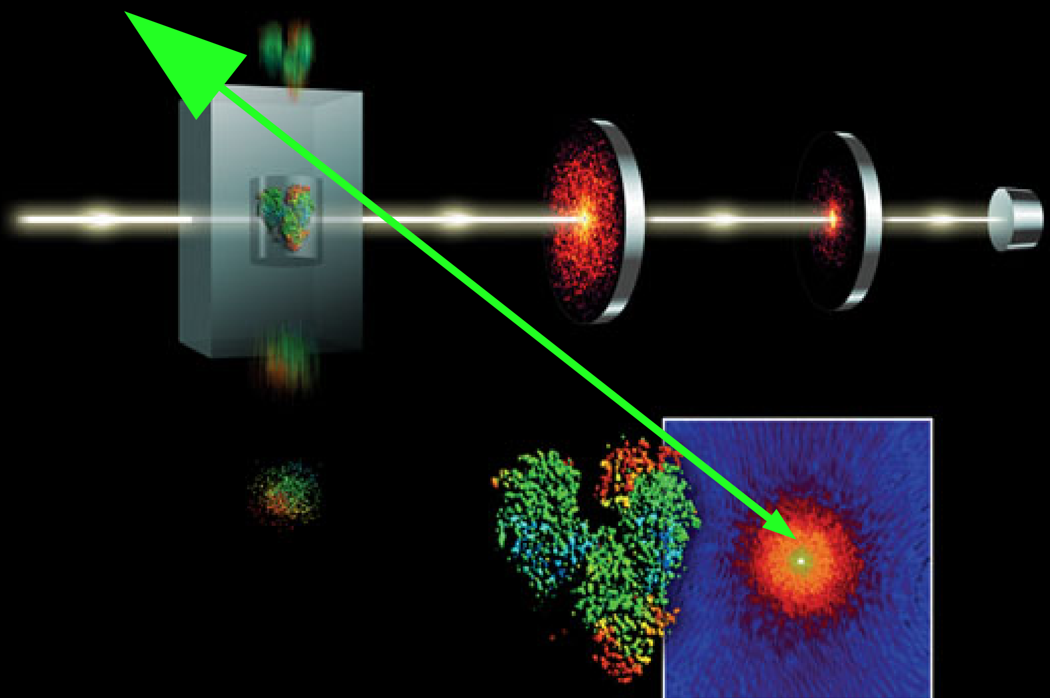
- Combination of extremely high-flux and low-flux.
- High-flux makes integrating detector necessary.



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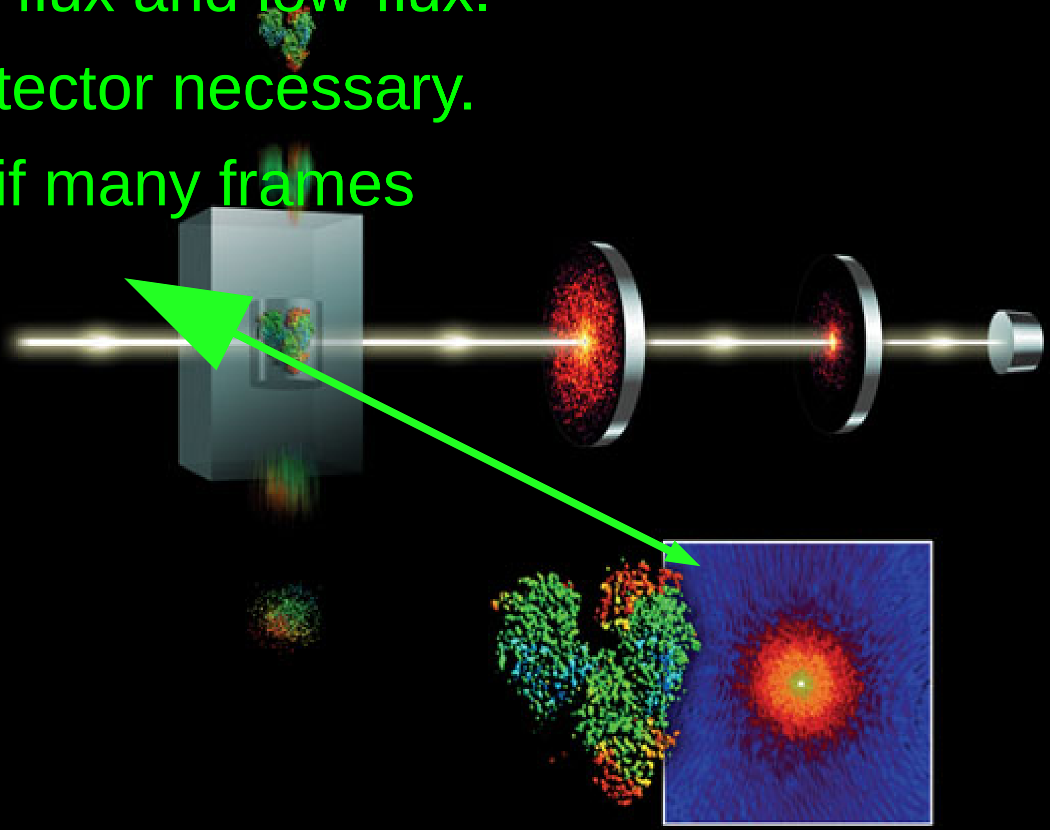

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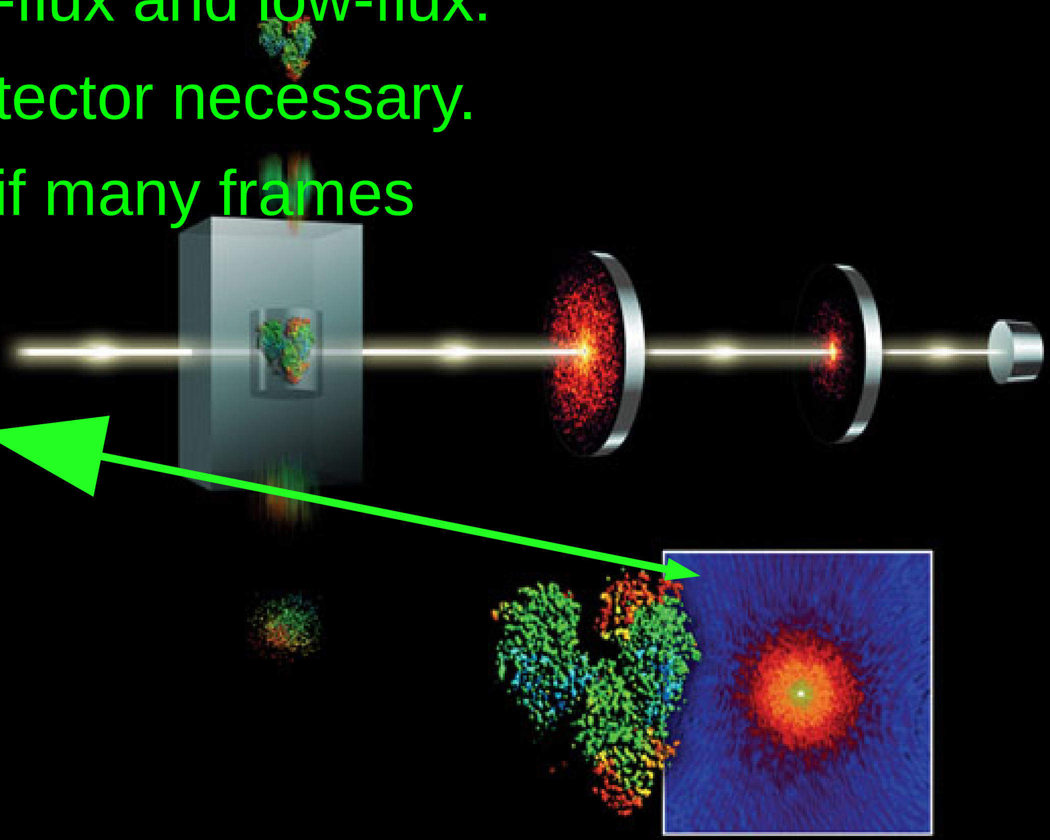

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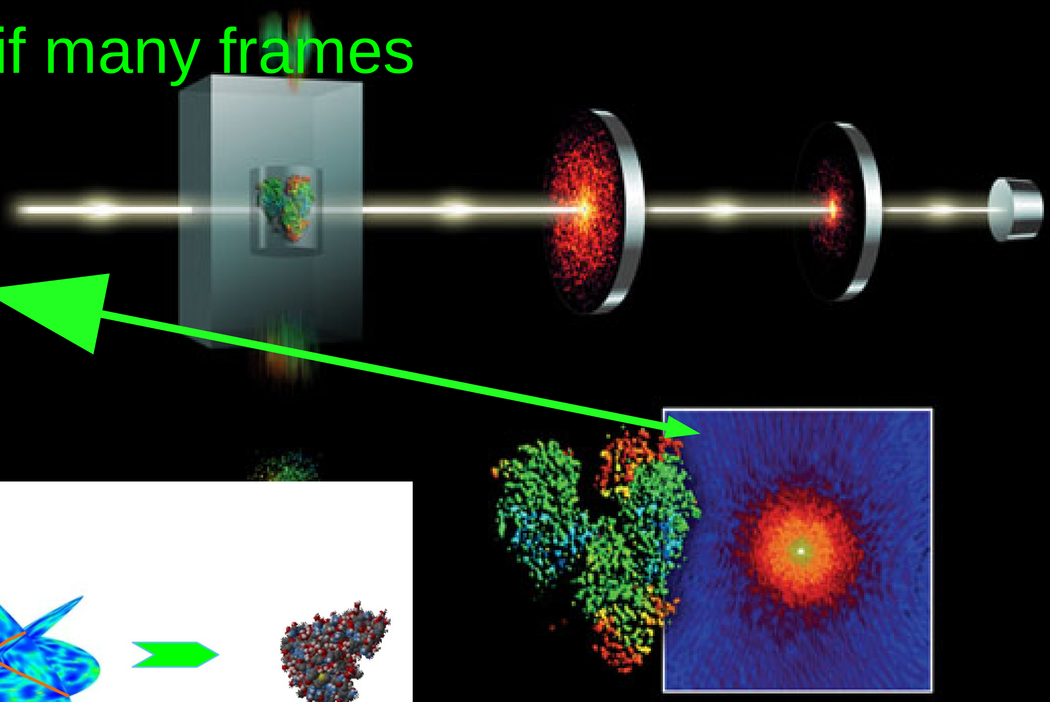

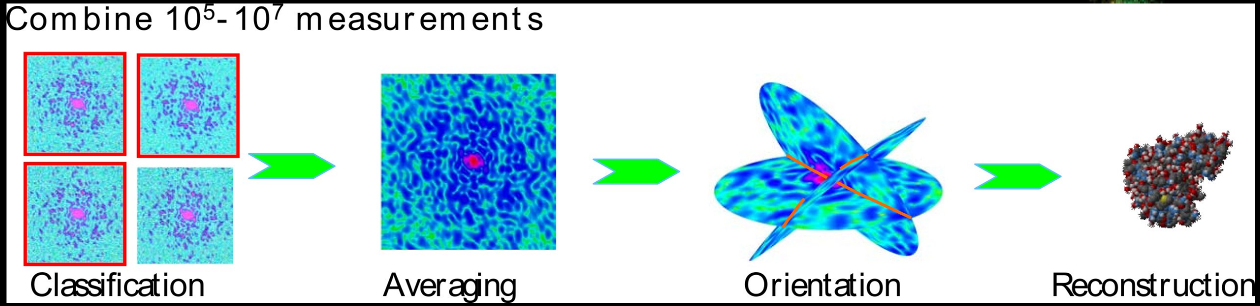

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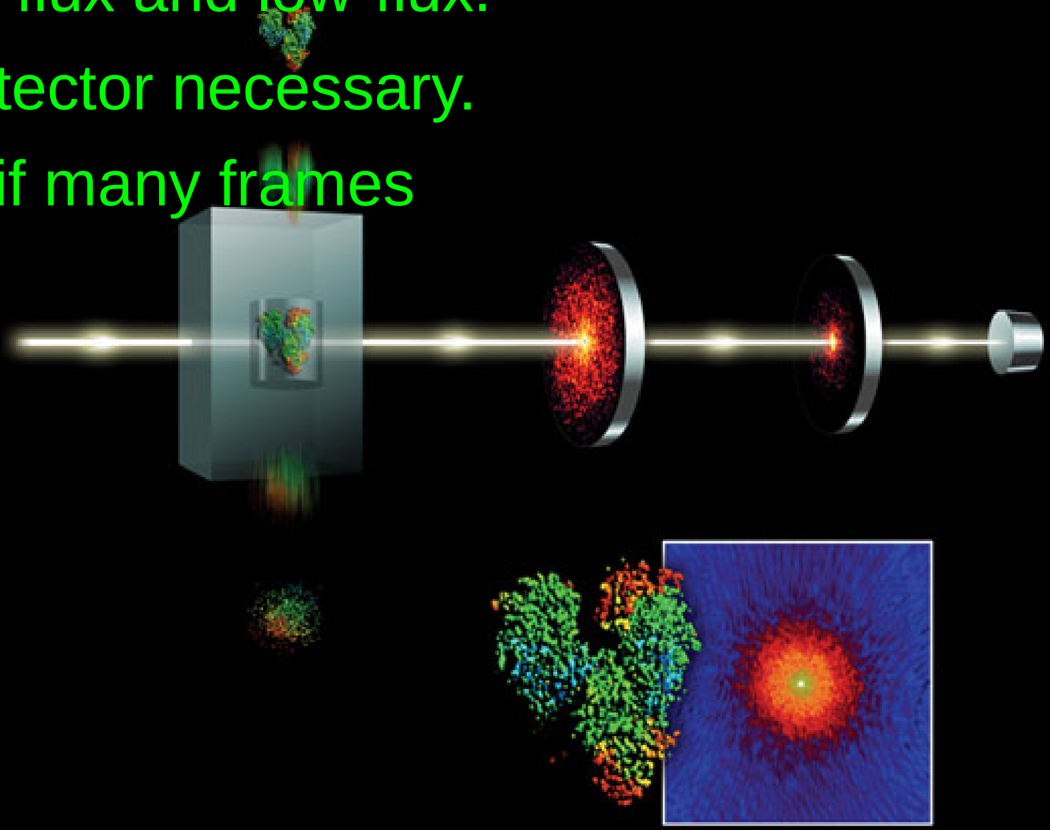


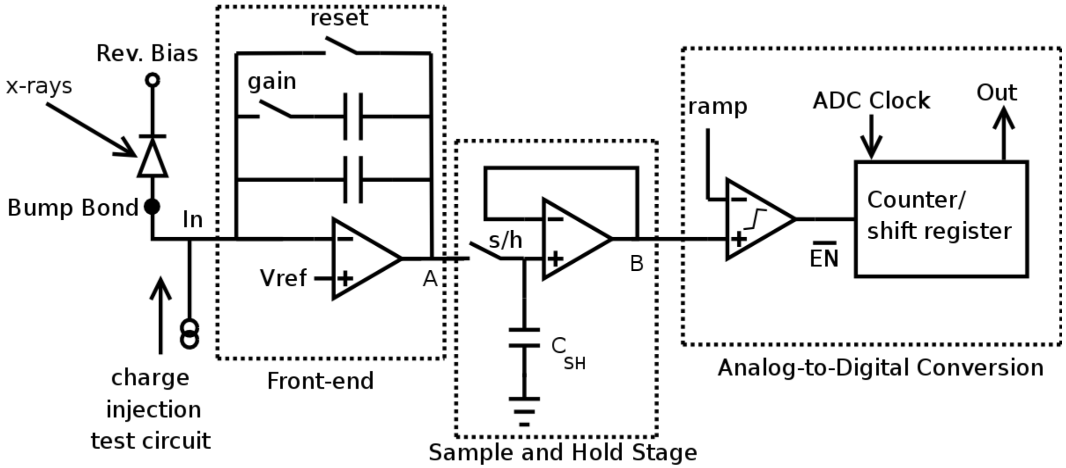
How do you deal with this when your detector noise is (say) 1/7 photon?

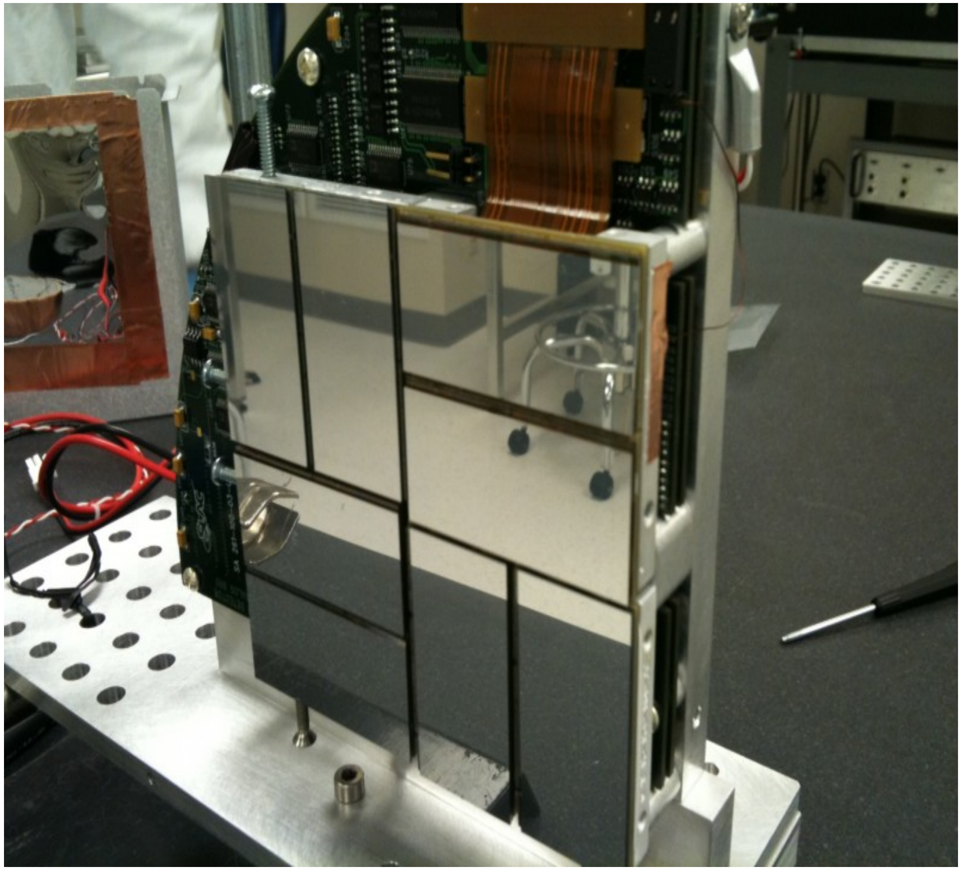
Originial Specs Given for Detector

Parameter	Requirement
Energy Range	4-8 keV
Well-depth/pixel	10^3
Readout frame rate	120 Hz
Signal/Noise	>3 for single 8 keV photon
DQE	> 90% at 8 keV
Pixel size	100-200 µm
Detector area	> 500x500 pixels

Cornell's LCLS PAD

- Basic pixel design.





Single ASIC: 192x185 pixels
ASIC: TSMC 0.25 micron.

1 quadrant of SLAC's detector based off Cornell's ASIC.

Picture from:
http://www.amaroq.com/ryan/2010/04/02/pictures-of-cxi-detector

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Detector area	> 500x500 pixels

~2500

7

110x110 um

1500x1500

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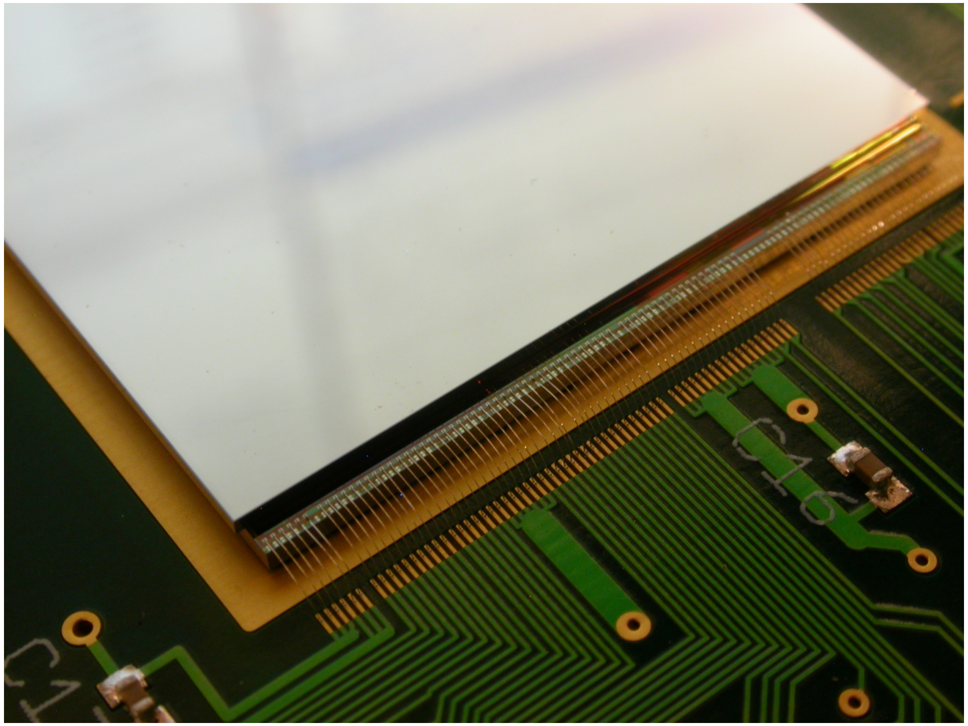
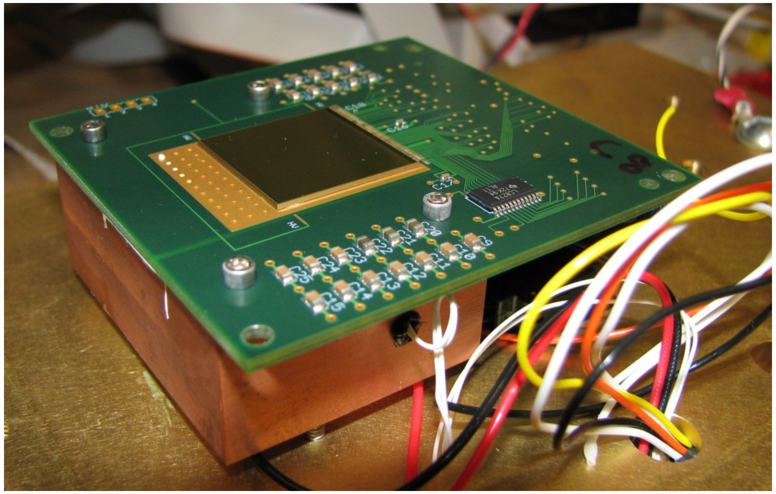
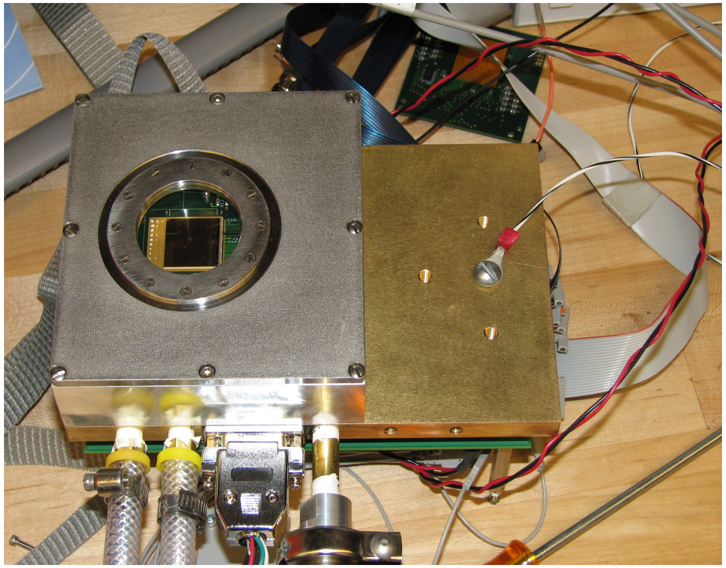
Single Module







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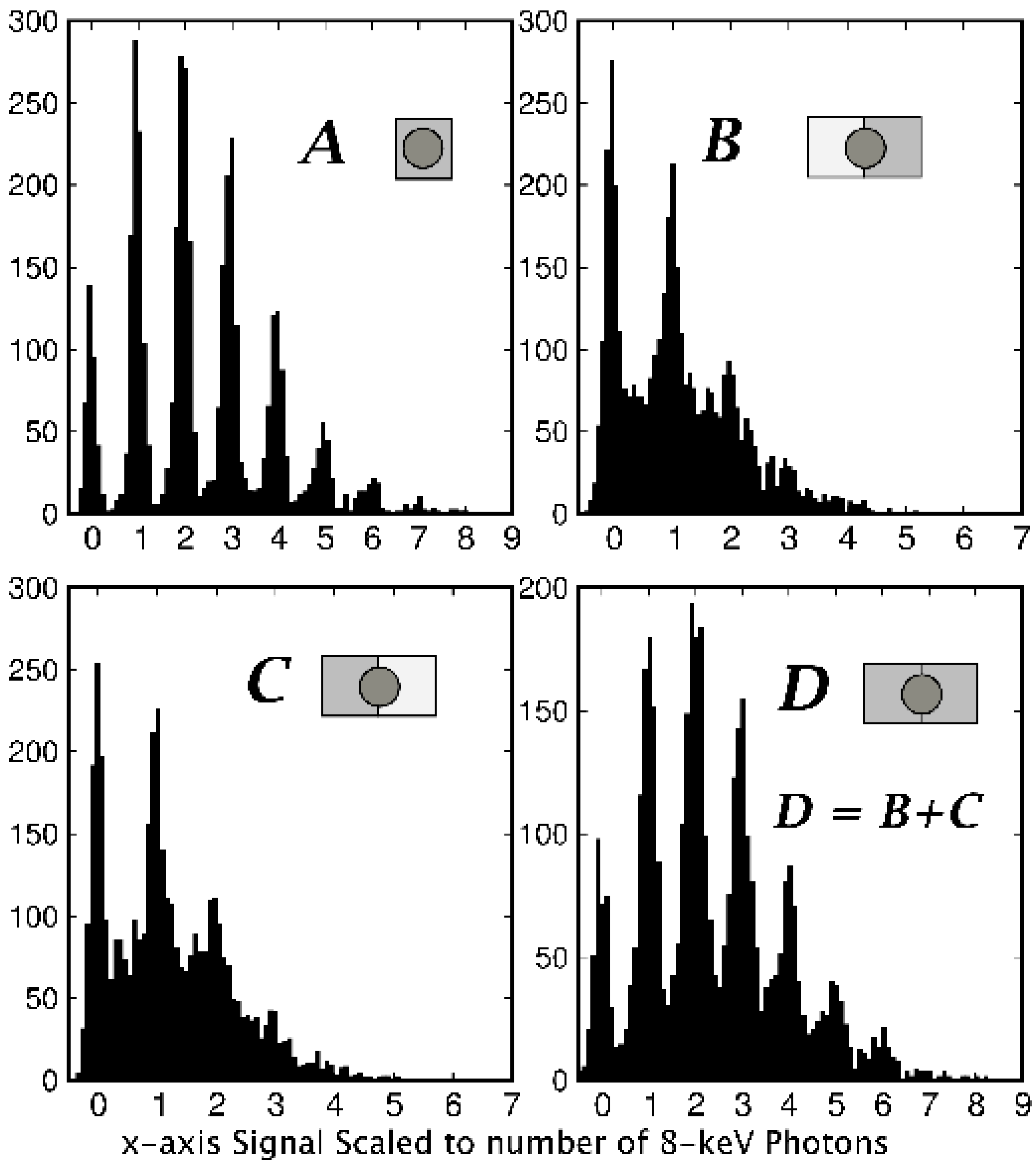
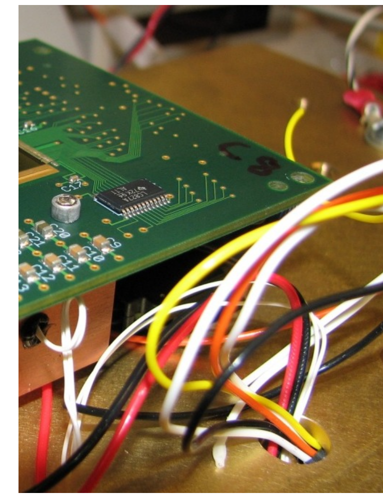
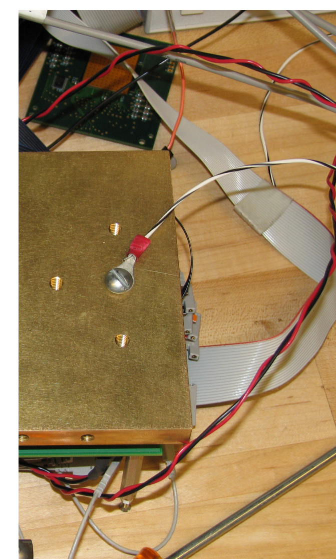
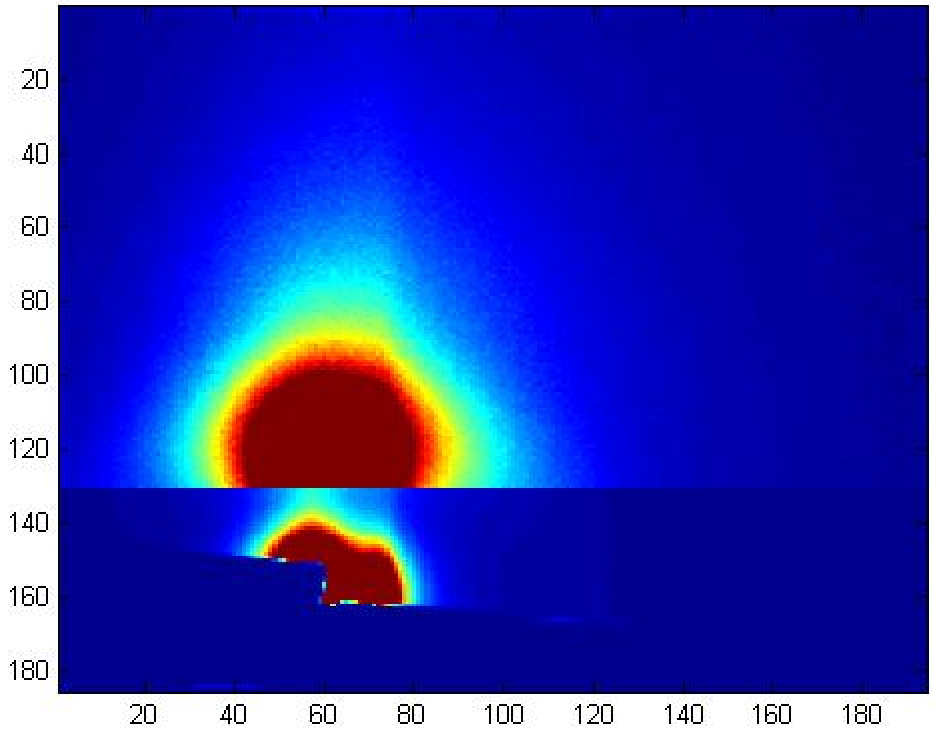
Single Module







Tested in Experiments



External movie

In-situ CNT forest growth.
Collaboration with
John Hart group,
University of Michigan.

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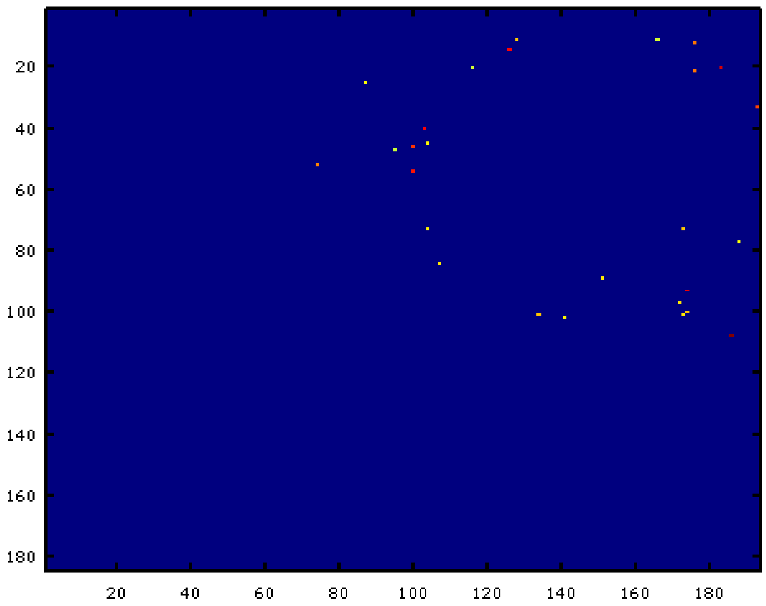
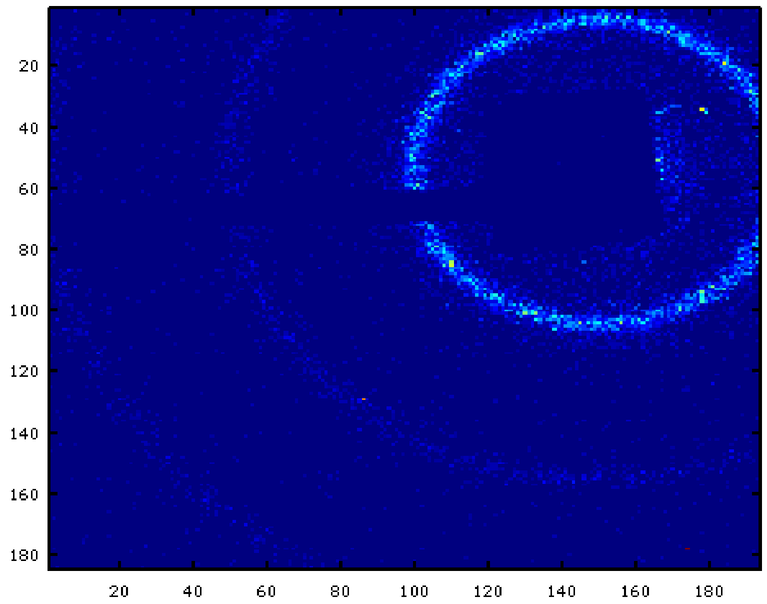
Adding Many Frames



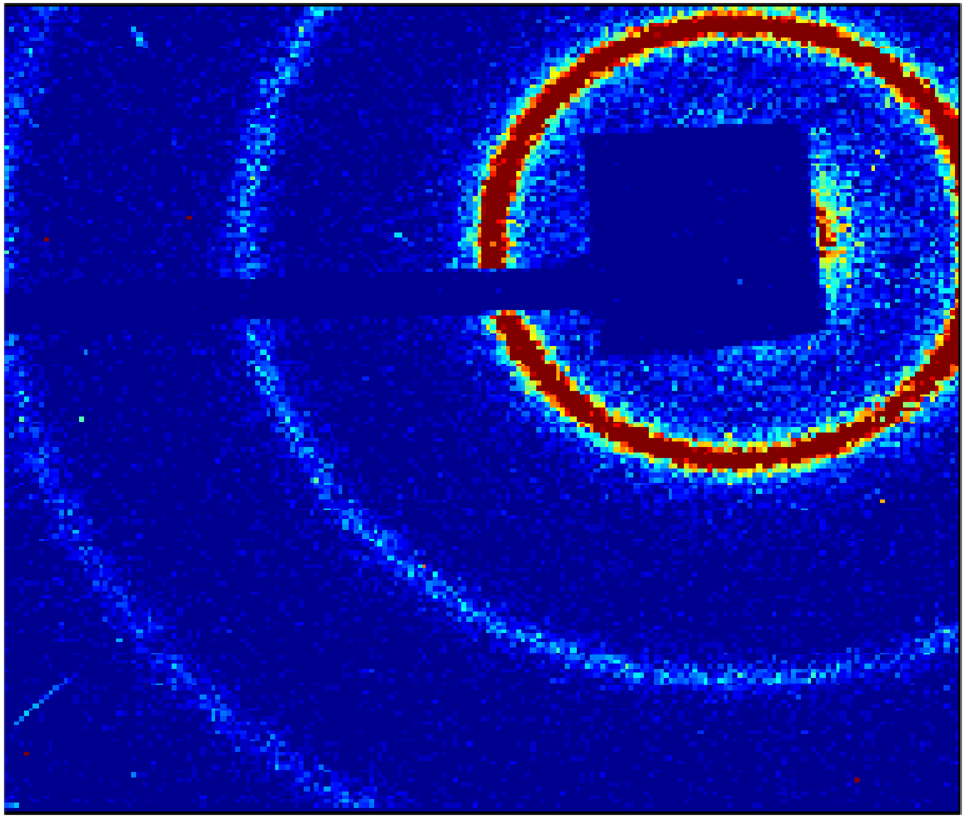


Single Frames

Added, thresholded frames
Up to ~350 frames

Have external movie.

Adding Many Frames



3000 frames, low flux data

Have video file.

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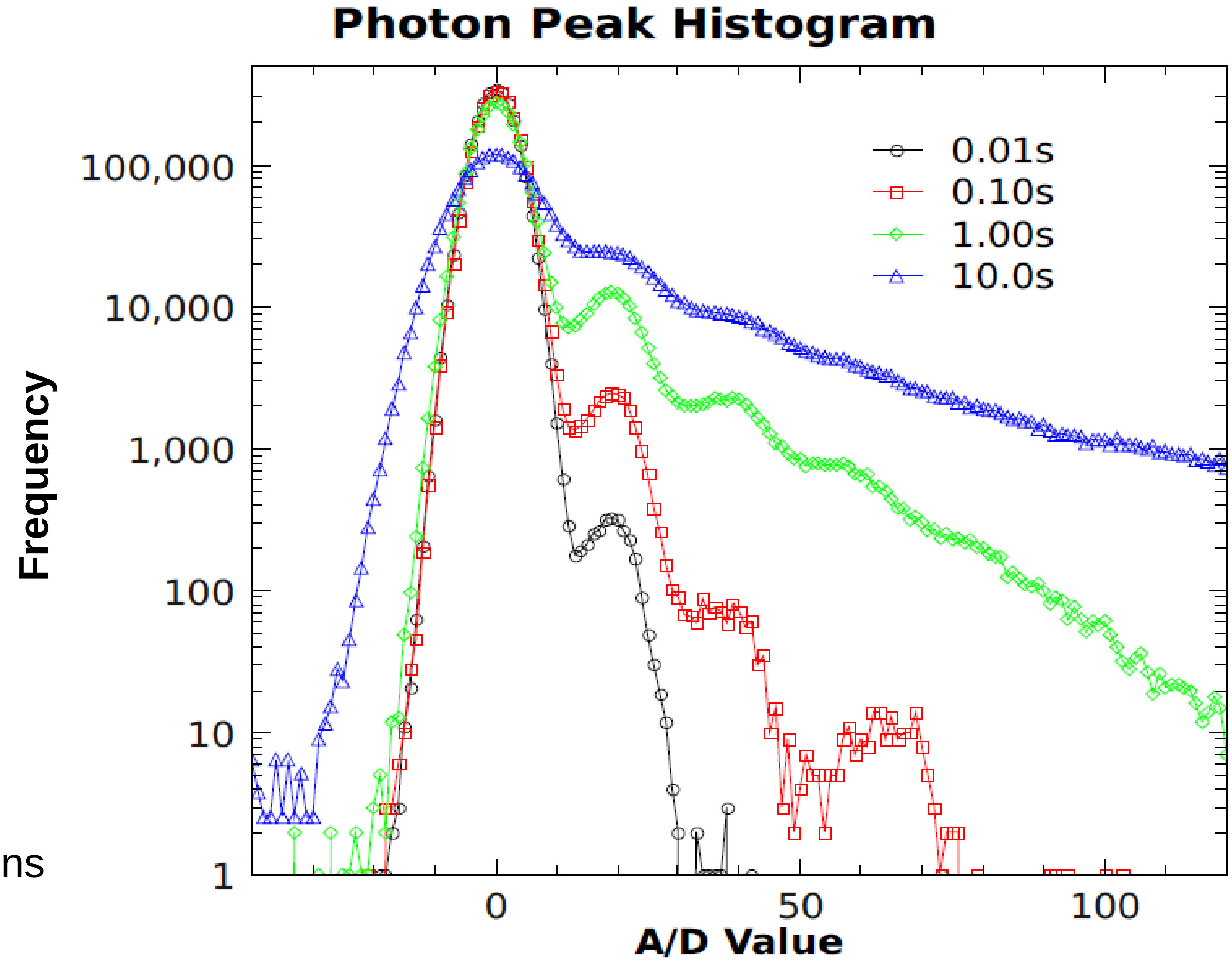
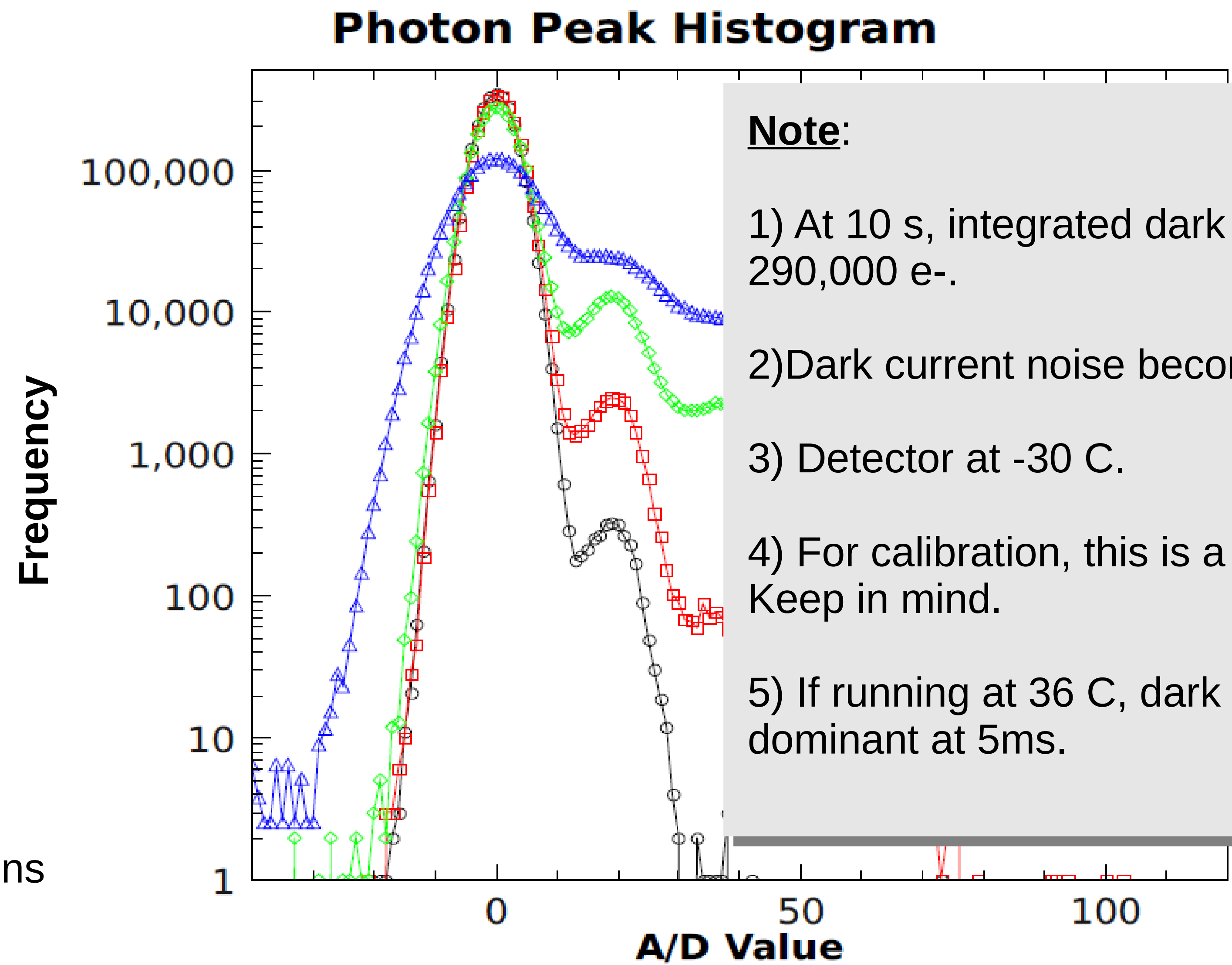
Whole Array Peak Histogram



8 keV photons

No gain correction applied.

Whole Array Peak Histogram



Note:

1) At 10 s, integrated dark current is 290,000 e-.

2)Dark current noise becomes dominant.

3) Detector at -30 C.

4) For calibration, this is a good thing to Keep in mind.

5) If running at 36 C, dark current noise dominant at 5ms.

8 keV photons

Adding many frames

- Basic problems
  - 1) How well do you know the background.

    Under best circumstances you have: $\sigma_{back} = \frac{\sigma_{pix}}{\sqrt{N_{back\ frames}}}$

  - So, if you want to have single photon sensitivity:

$$N_{Sigframes} * \sigma_{back} = \frac{N_{Sig\,frames}\,\sigma_{pix}}{\sqrt{N_{back\,frames}}} \ll 1$$

(hand wave) $N_{back\,frames} \gg \sigma_{pix}^{2} N_{sig\,frames}^{2}$

Adding many frames

- Basic problems

  1) How well do you know the background.

  - $N_{back\ frames} > \sigma^2_{pix} N^2_{sig\ frames}$ (very optimistic)
  - Are there any small scale drifts, frame to frame variations?

Adding many frames

- Basic problems

  1) How well do you know the background.

  - $N_{back\ frames} > \sigma_{pix}^{2} N_{sig\ frames}^{2}$ (at very least)
  - Are there any small scale drifts, frame to frame variations?
  - Errors in background add when adding frames.

Adding many frames

- Basic problems

  1) How well do you know the background.

  - $N_{back\ frames} > \sigma^2_{pix} N^2_{sig\ frames}$ (at very least)
  - Are there any small scale drifts, frame to frame variations?
  - Errors in background add when adding frames.
  - Applying a threshold allows you to avoid such stringent requirements.

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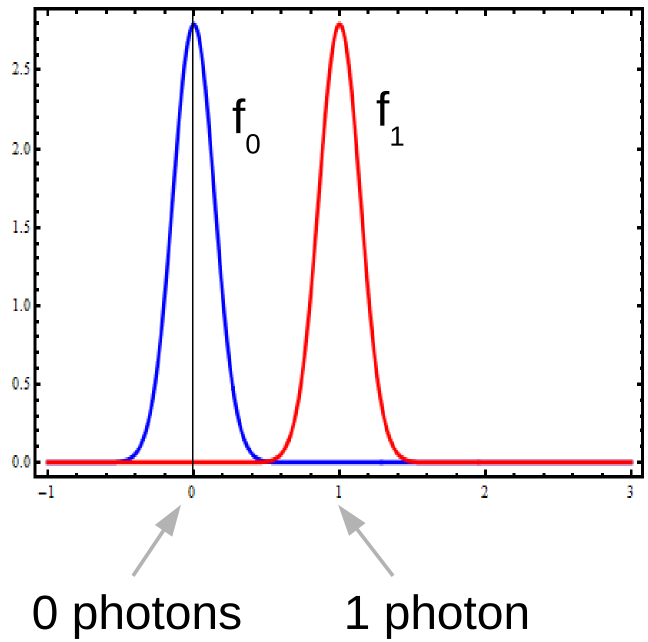
Thresholding



- Two distributions: 0 and 1 photons.
- If frequency (photon/pixel/frame) for 1 photon is A.
- Question – for some A, at what level does the threshold need f0 'noise' is low compared to f1 'signal'.

Neglecting charge sharing

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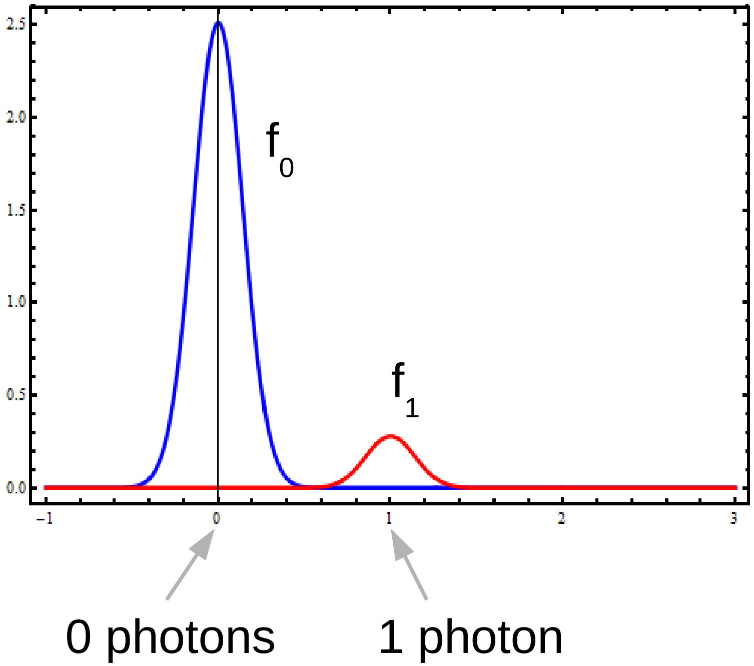
Thresholding



- Two distributions: 0 and 1 photons.
- If frequency (photon/pixel/frame) for 1 photon is A.
- <u>Question</u> – for an A, at what level does the threshold need f0 'noise' is low compared to f1 'signal'.

For half signal from each:

$$\int_{thr}^{\infty} f_0 = \int_{thr}^{\infty} f_1$$

Neglecting charge sharing

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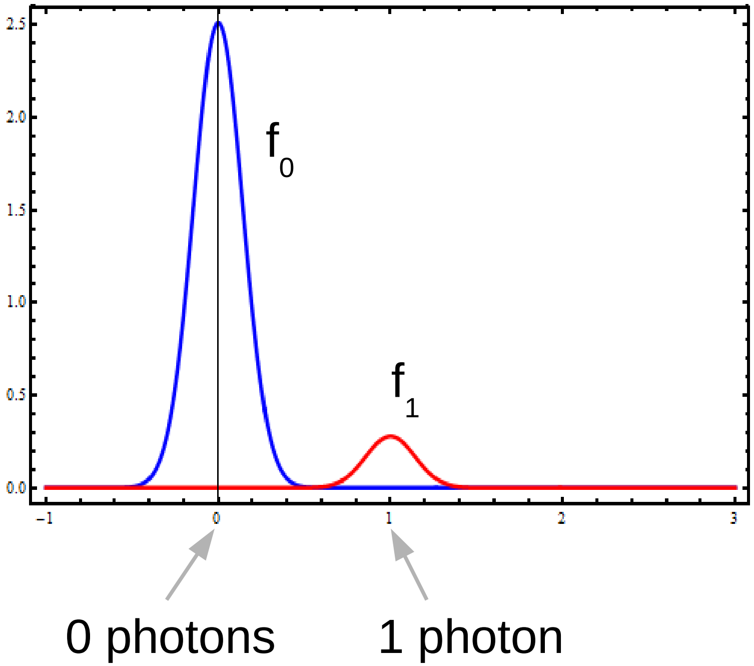
Thresholding



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- If frequency (photon/pixel/frame) for 1 photon is A.
- <u>Question</u> – for an A, at what level does the threshold need f_0 'noise' is low compared to f_1 'signal'.

For half signal from each:

$$\int_{thr}^{\infty} f_0 = \int_{thr}^{\infty} f_1$$

For A = 1/1000, and σ = 1/7 photon, at threshold of 0.44 photons, half the signal if from f_0

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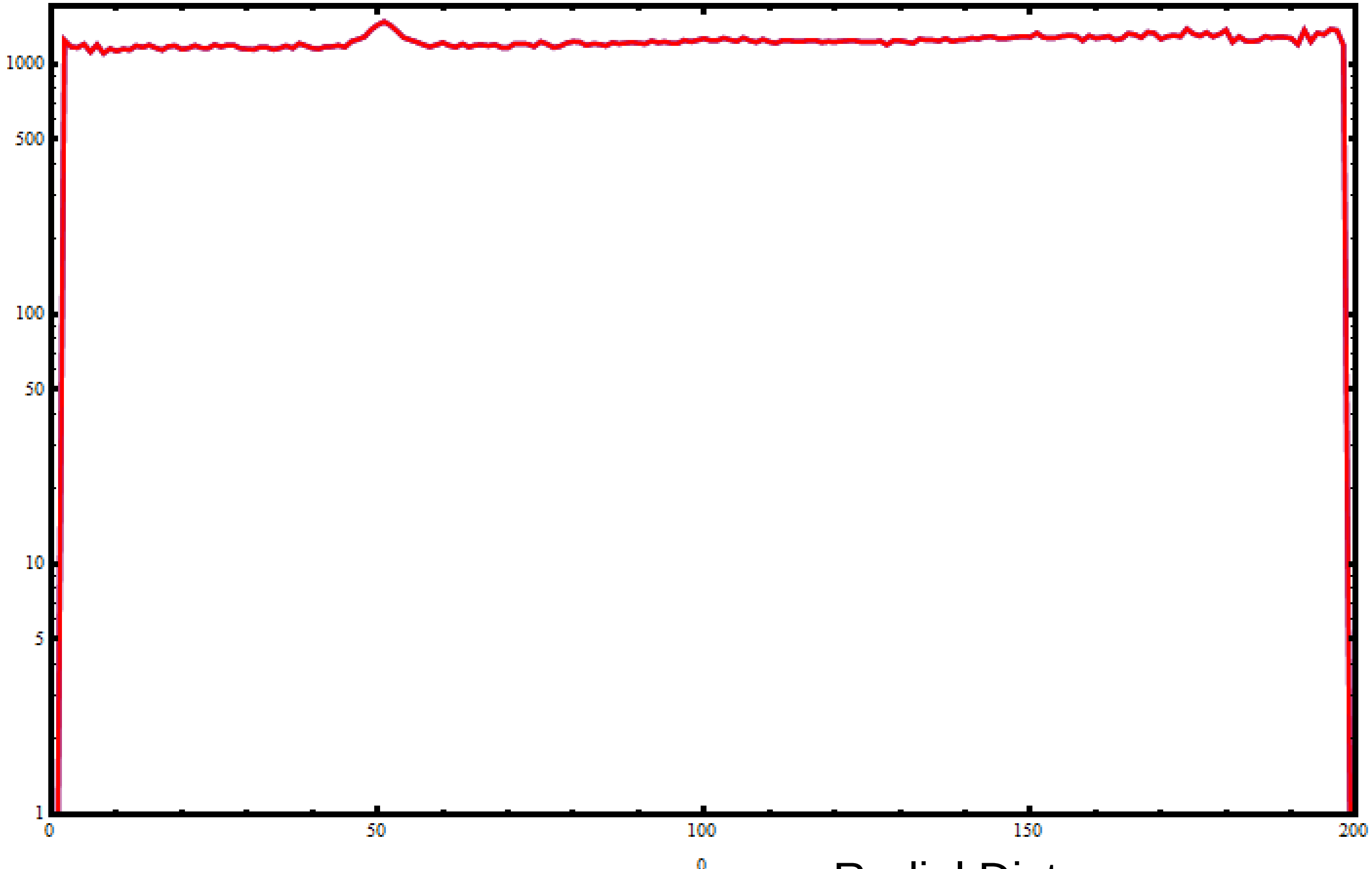
Neglecting charge sharing

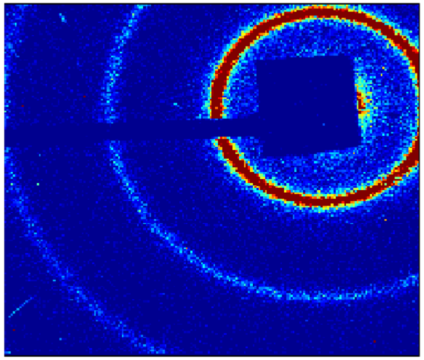
Varying Threshold



Radial Distance

~ 20 ADU/x-ray

1000 frame sum



(Azimuthal integration around detector)

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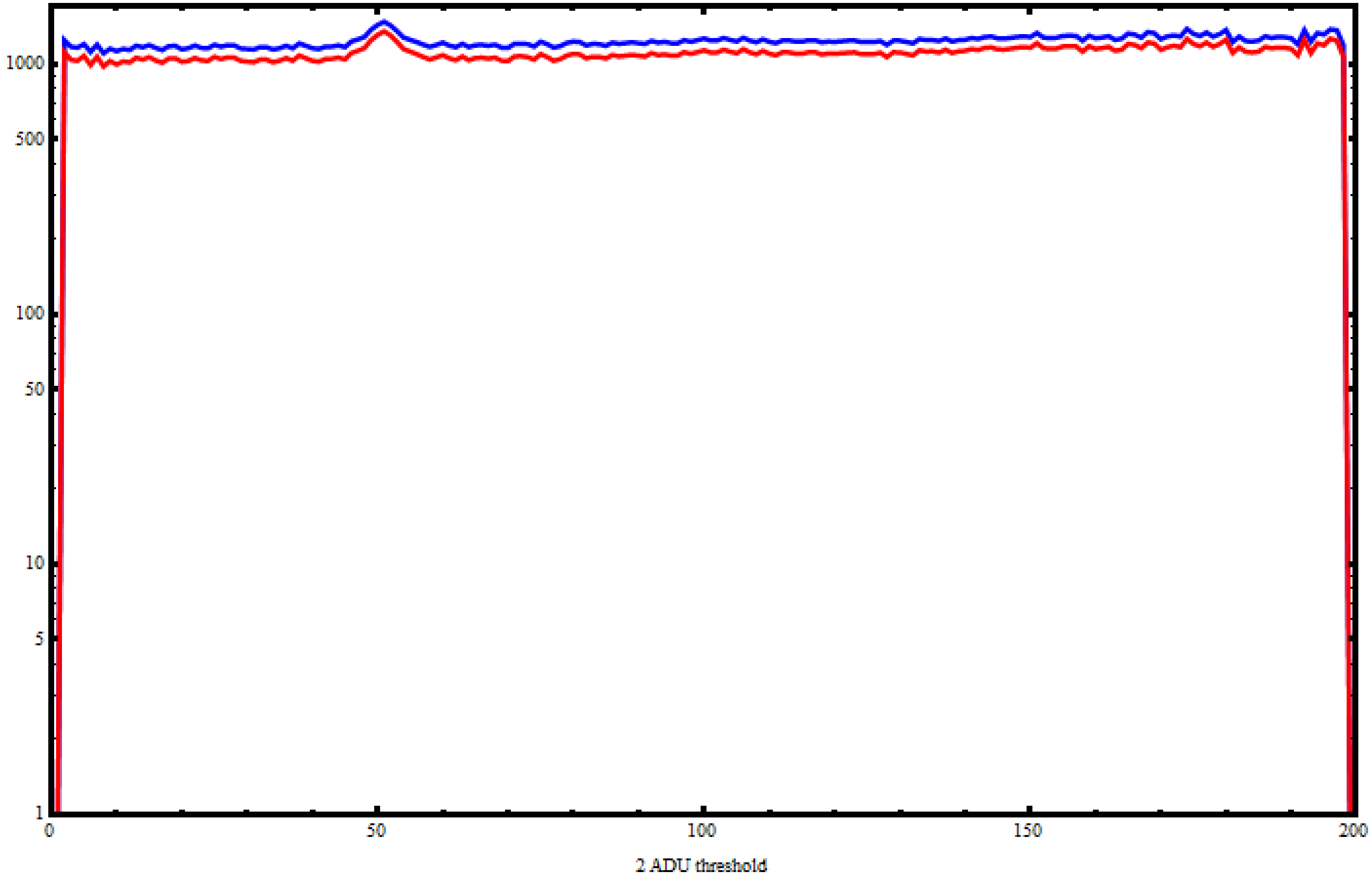
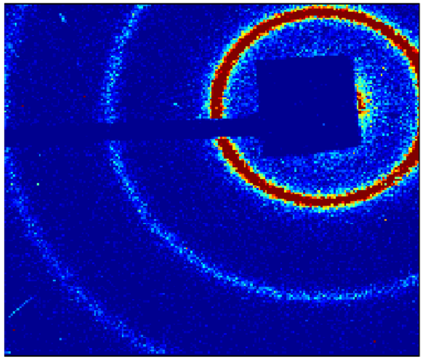
Varying Threshold





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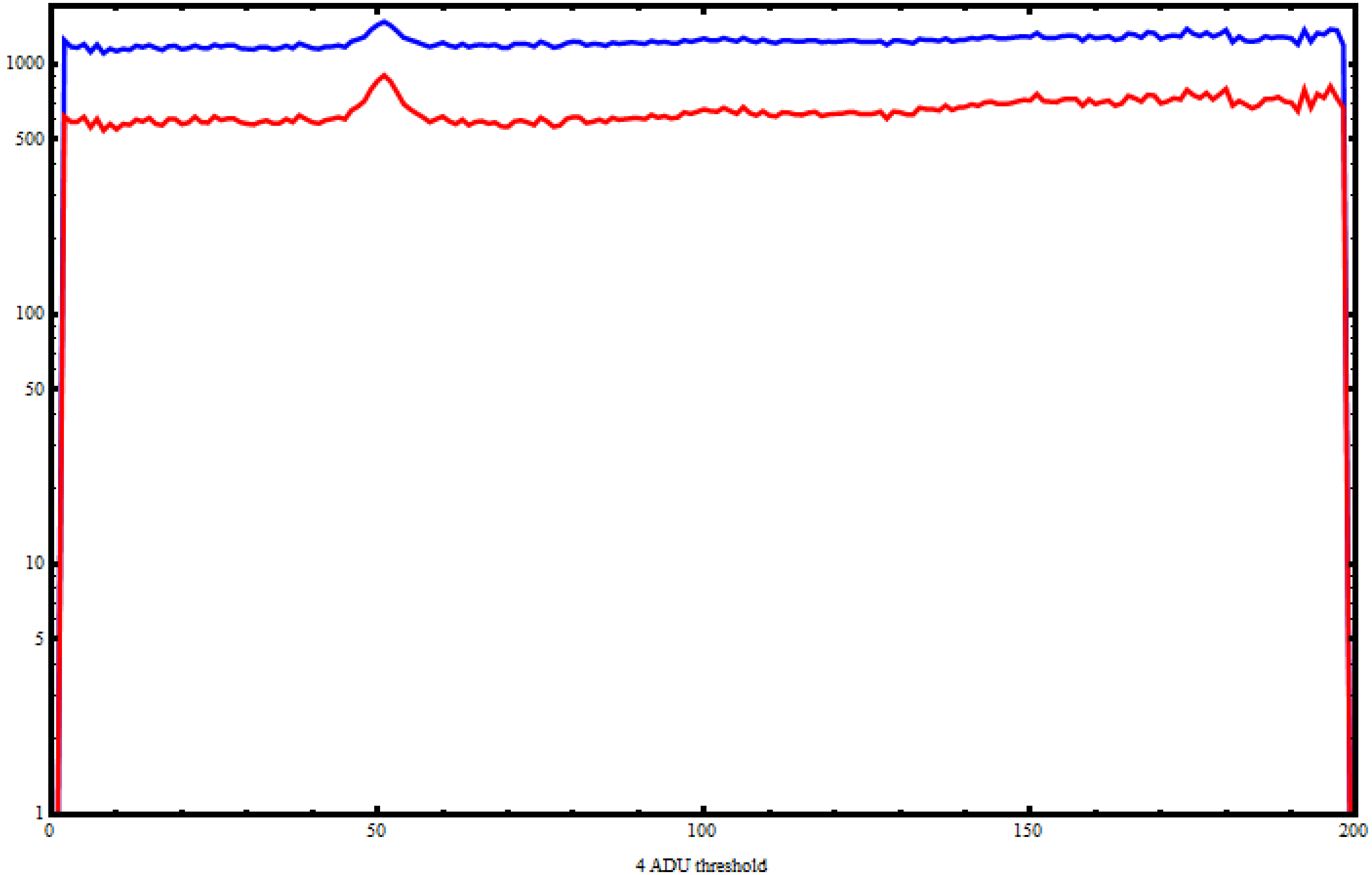

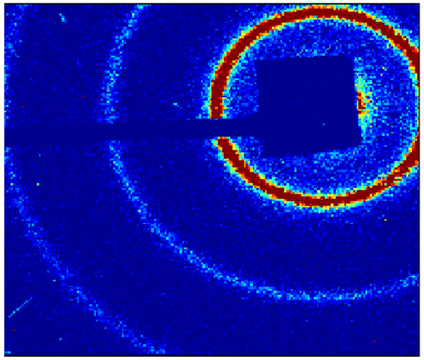

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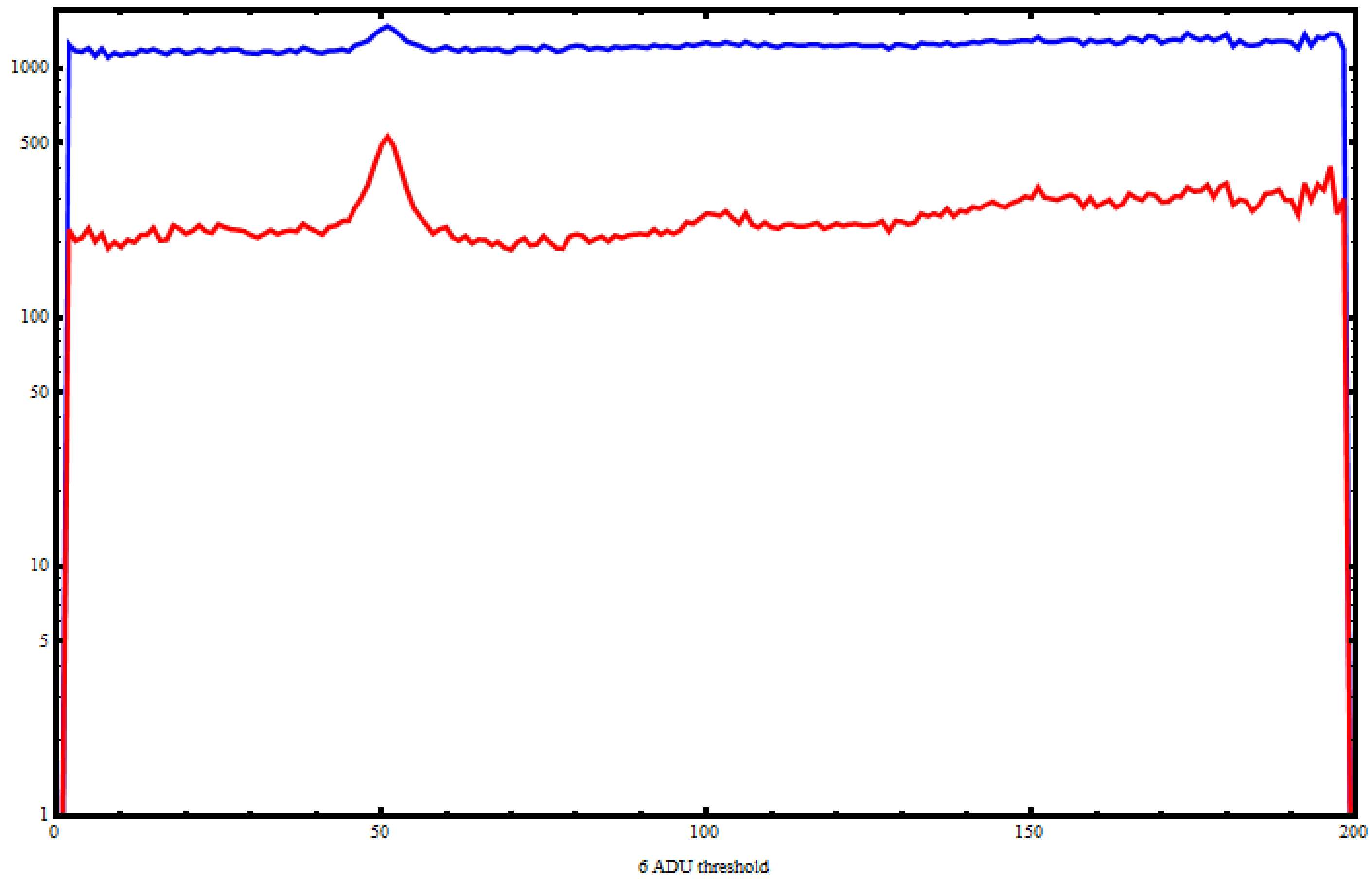

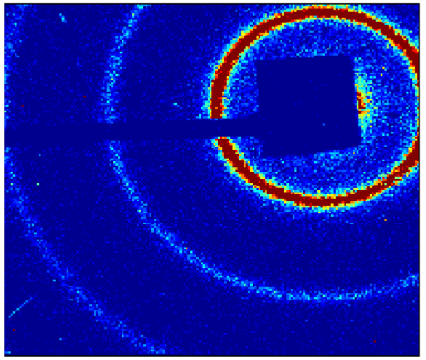

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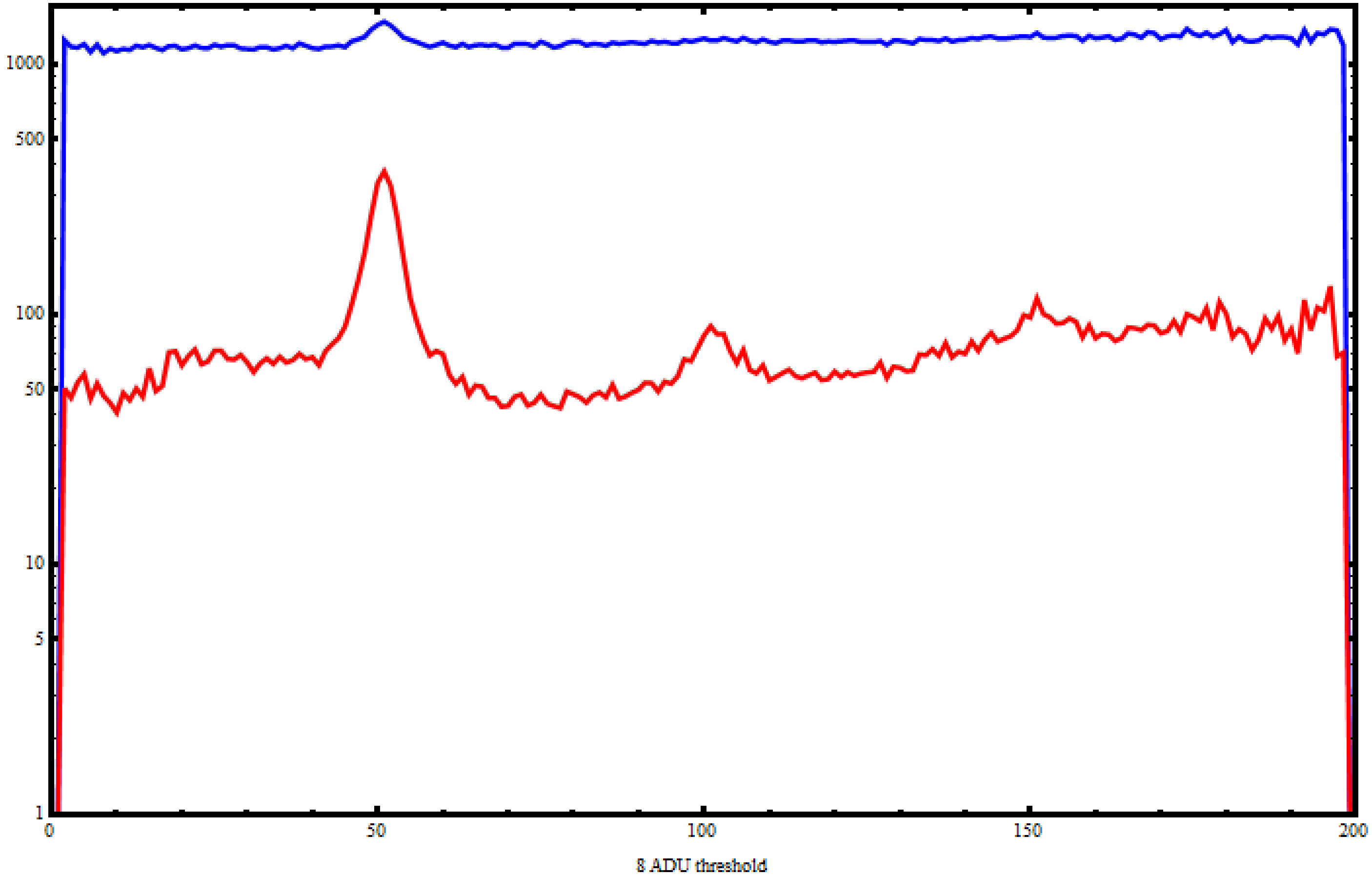

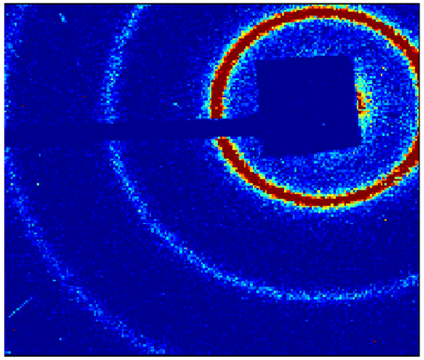

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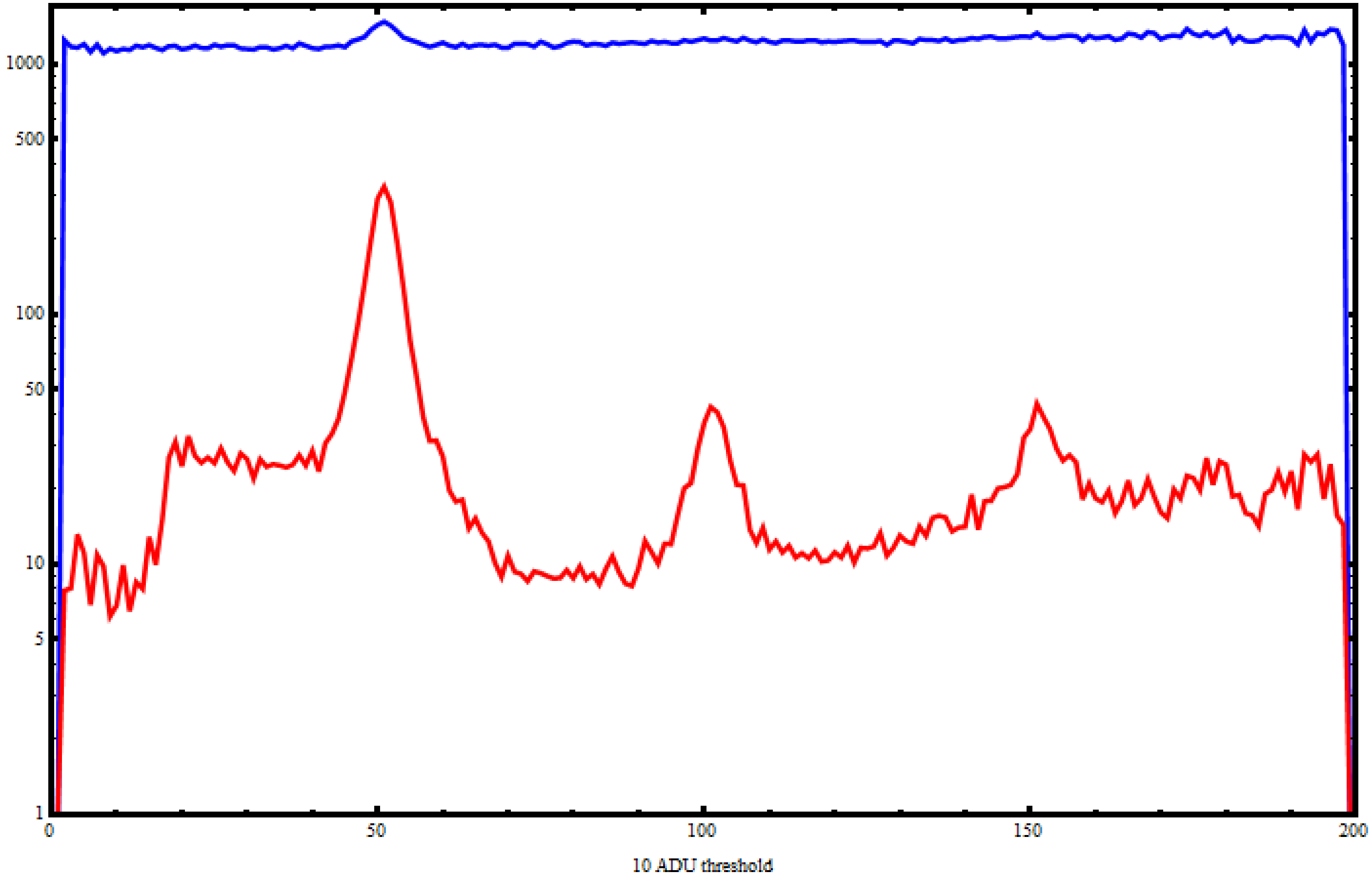

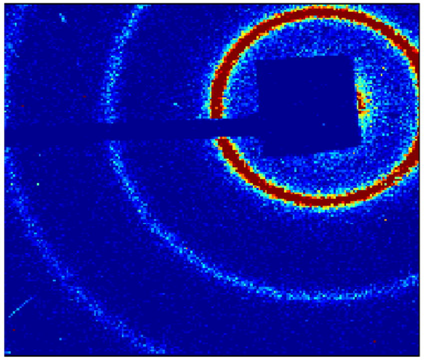

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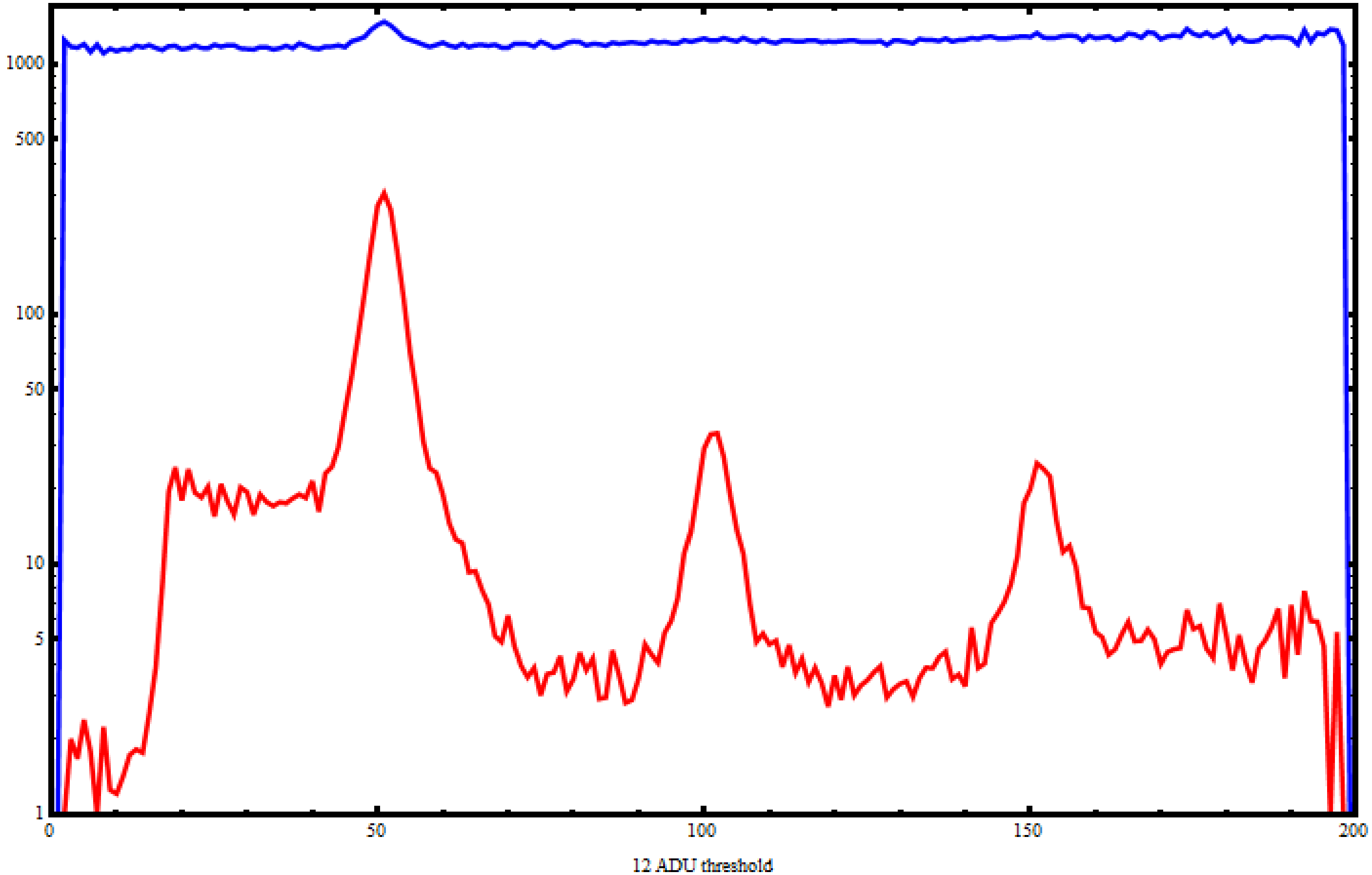
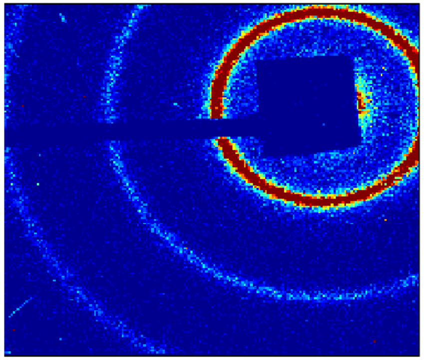
Varying Threshold





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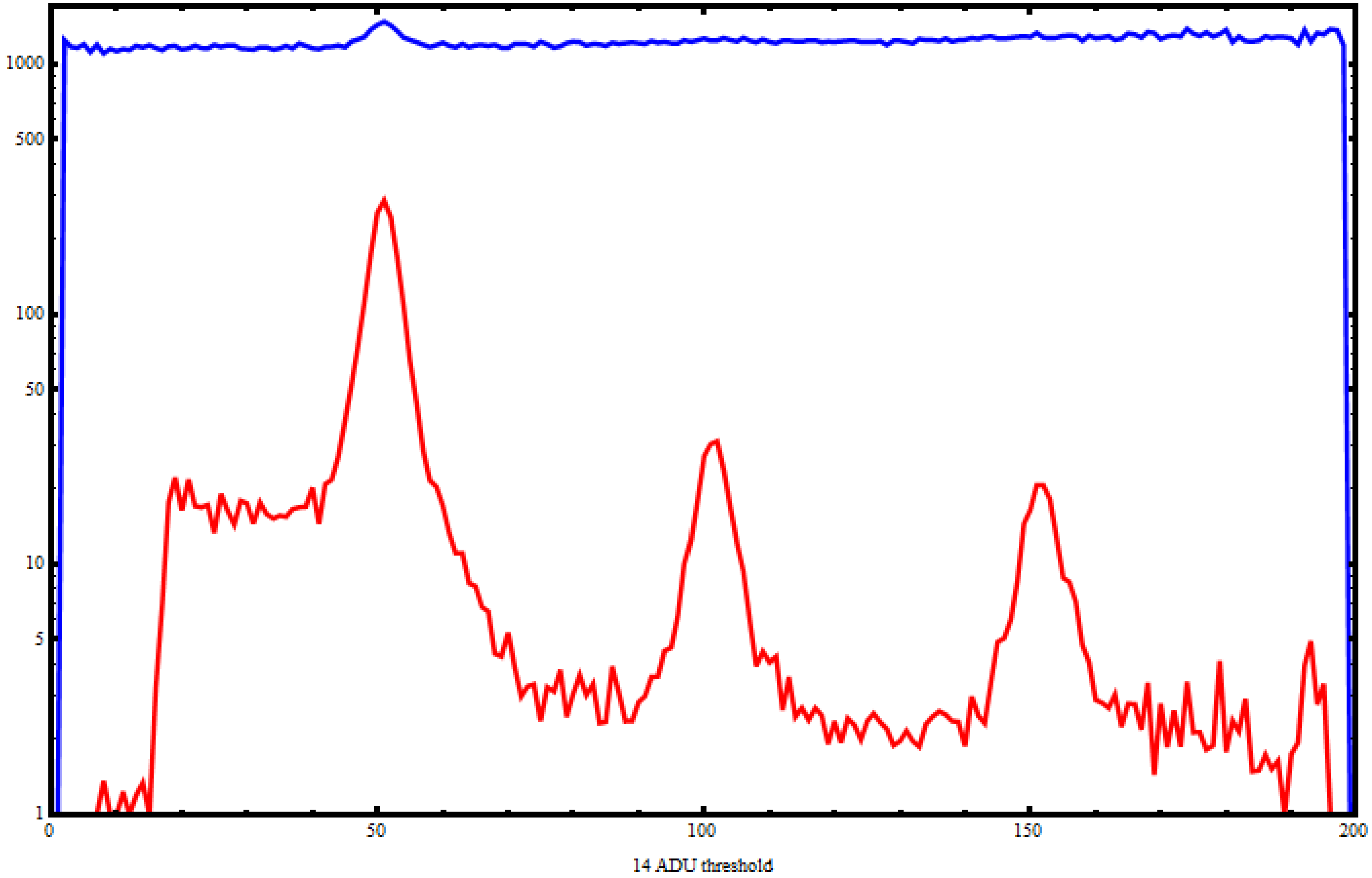

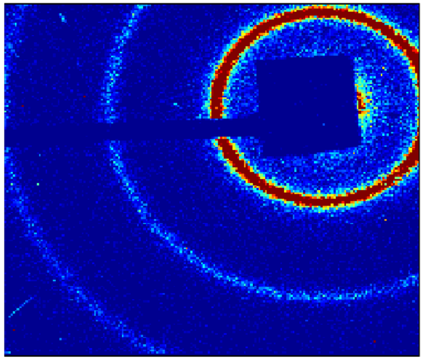

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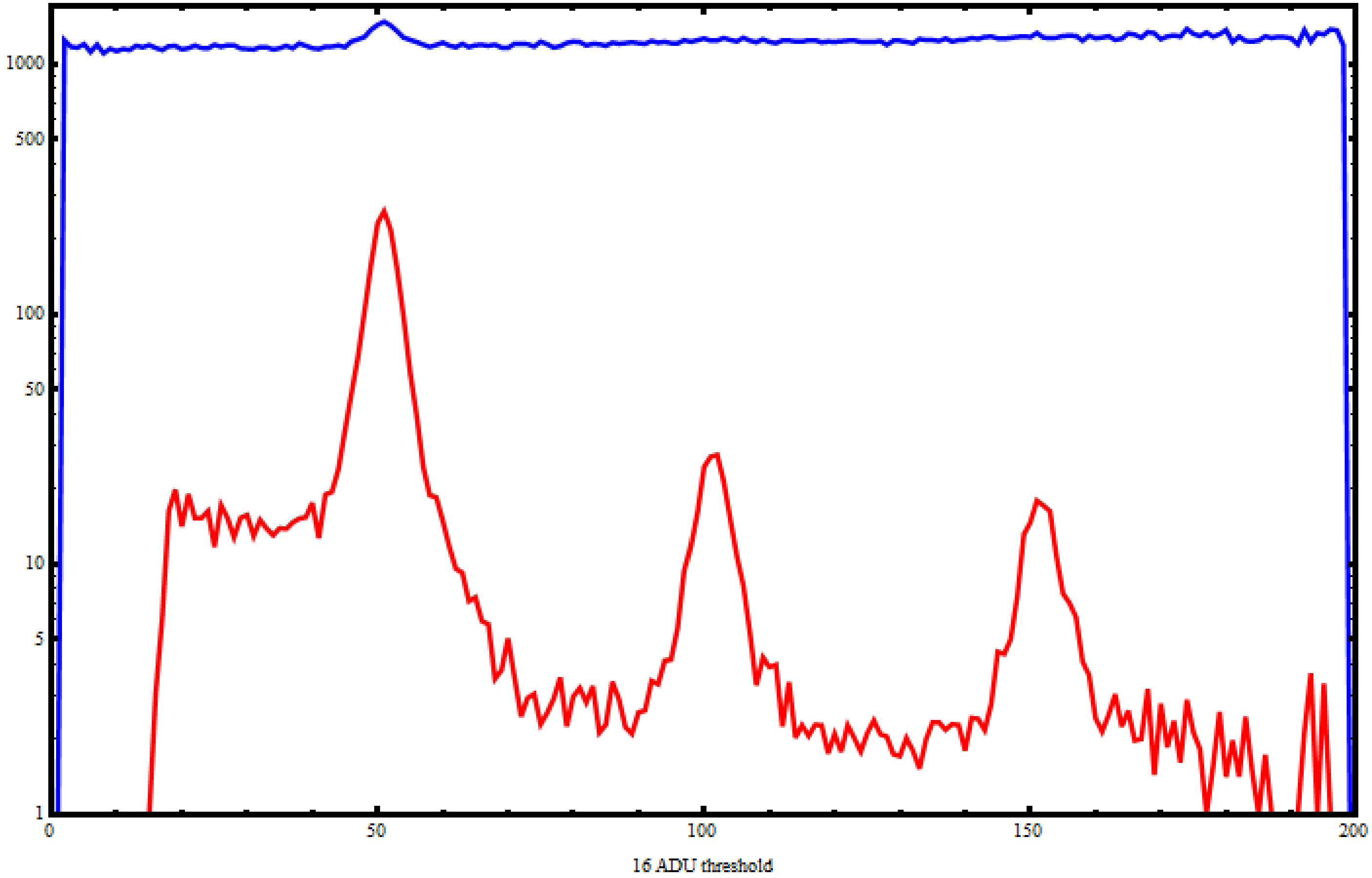

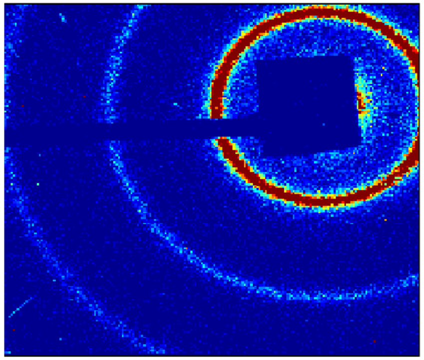

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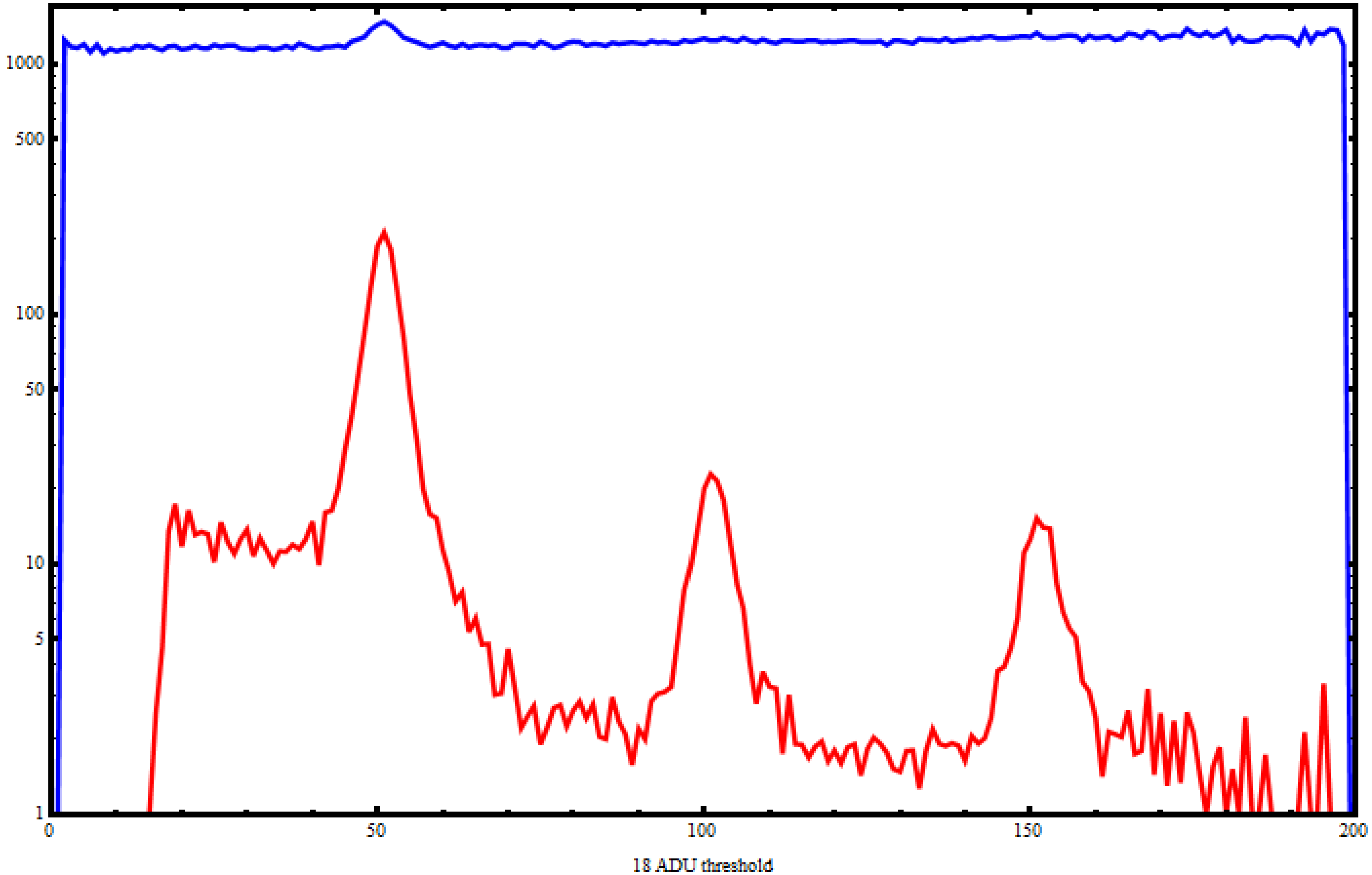

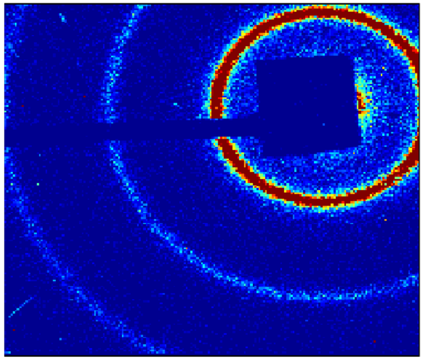

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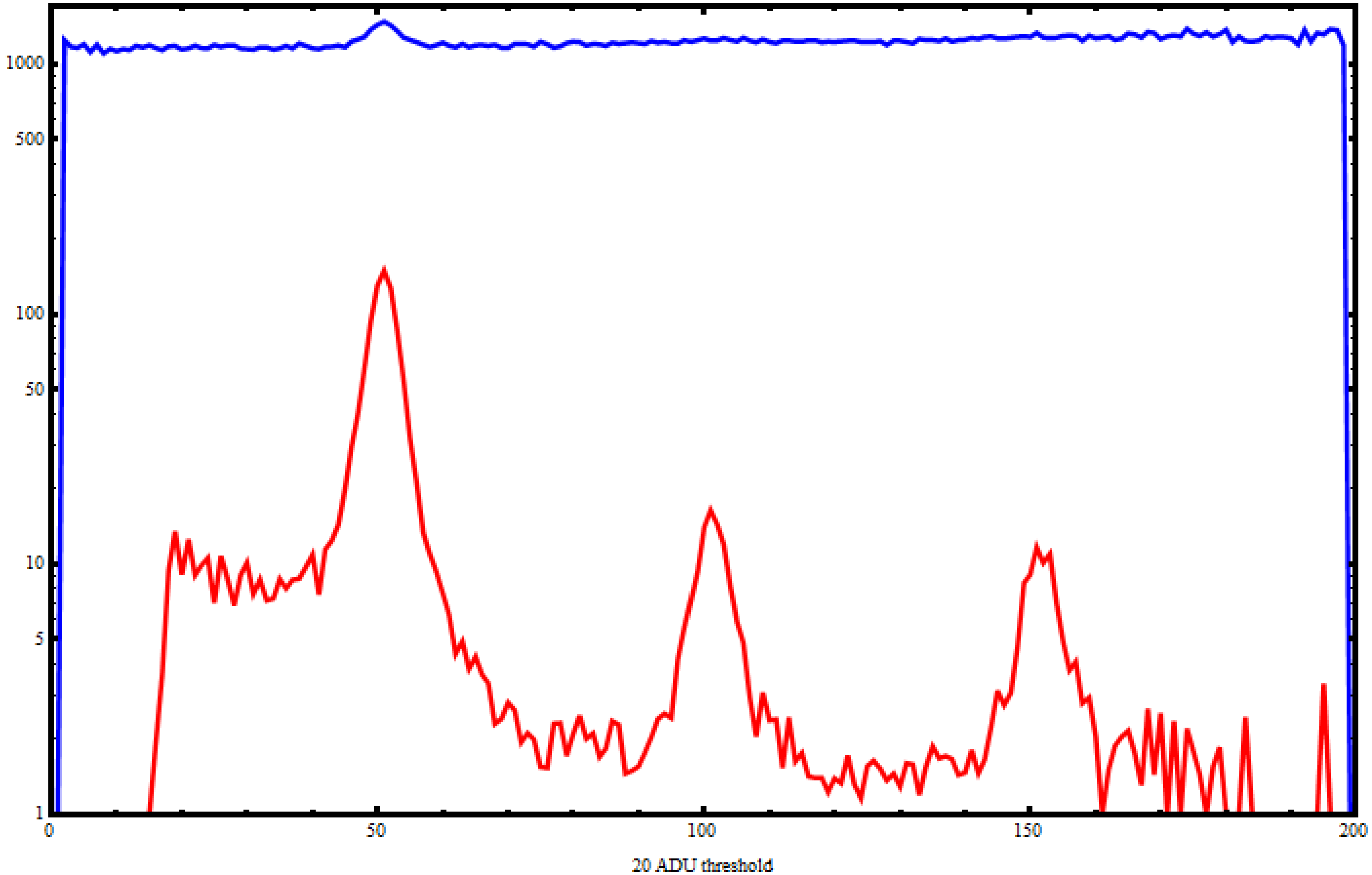

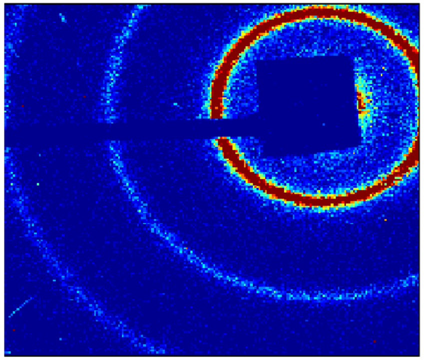

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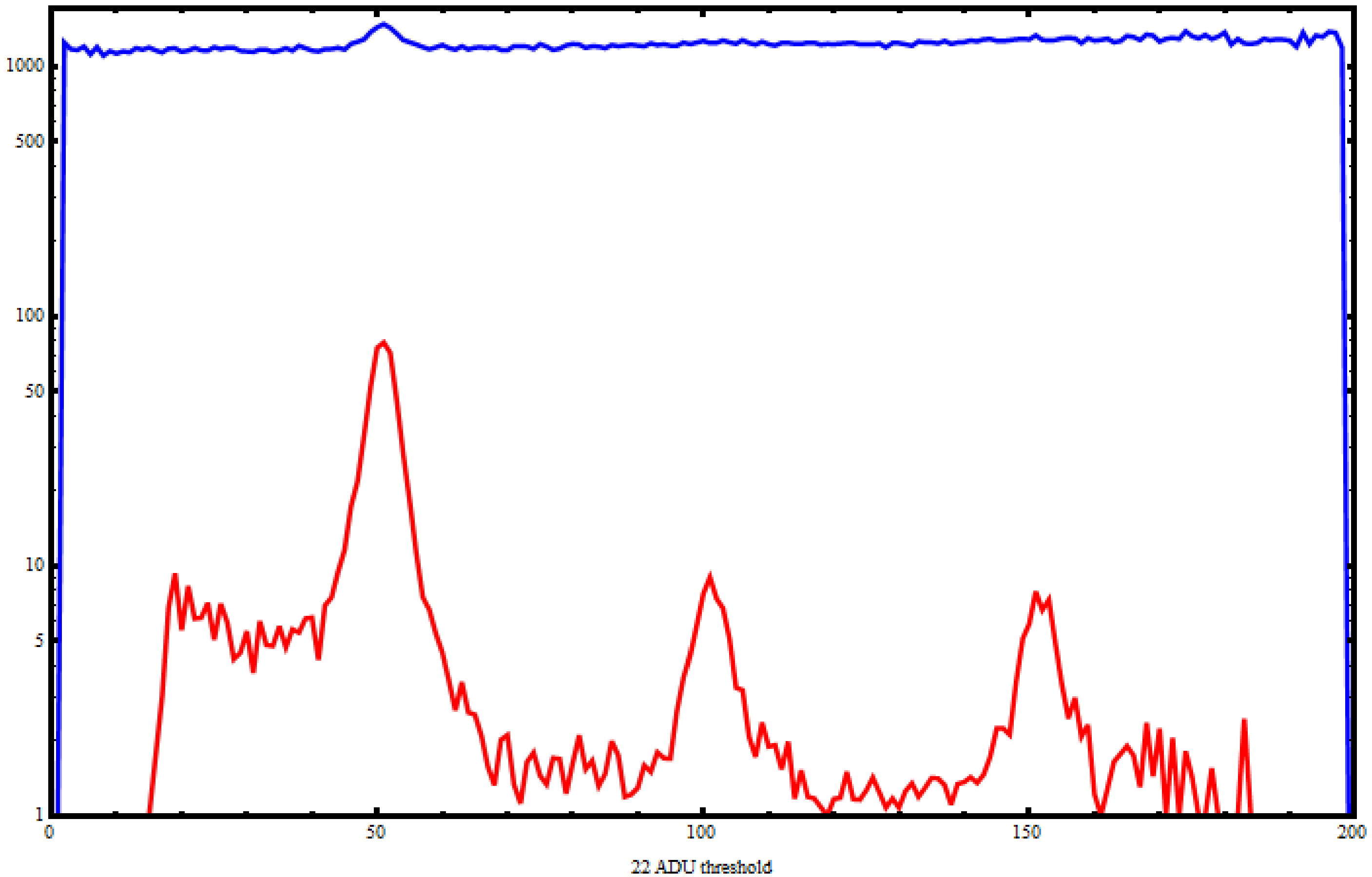

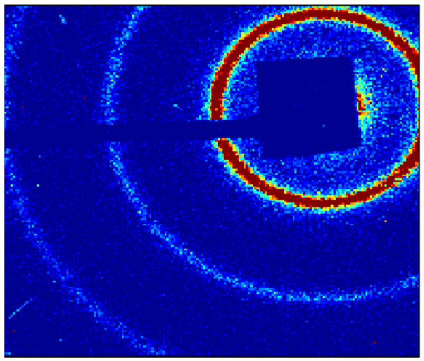

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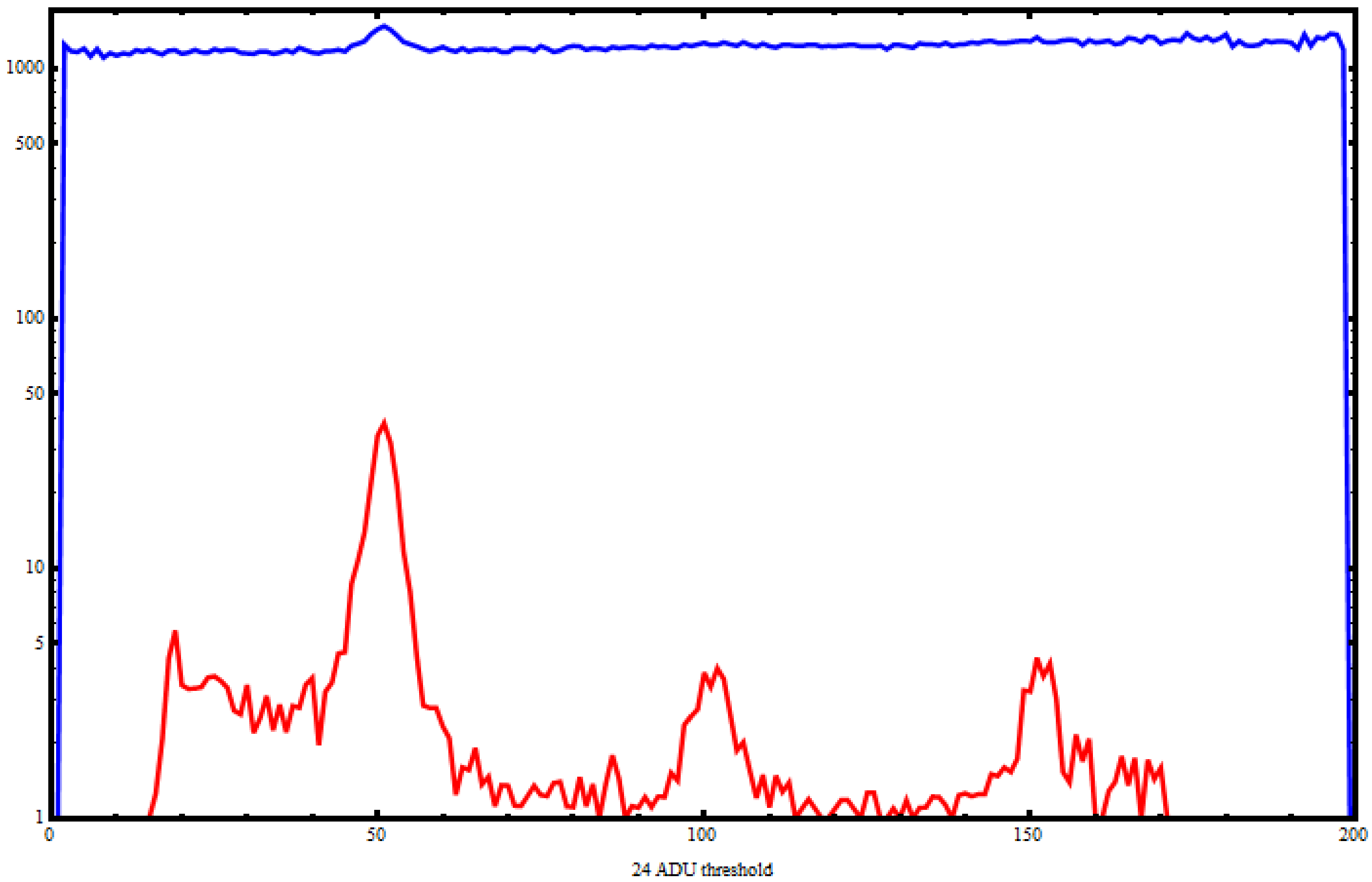

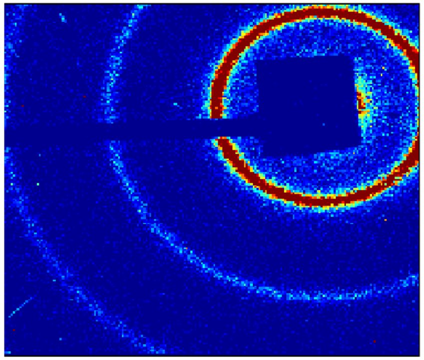

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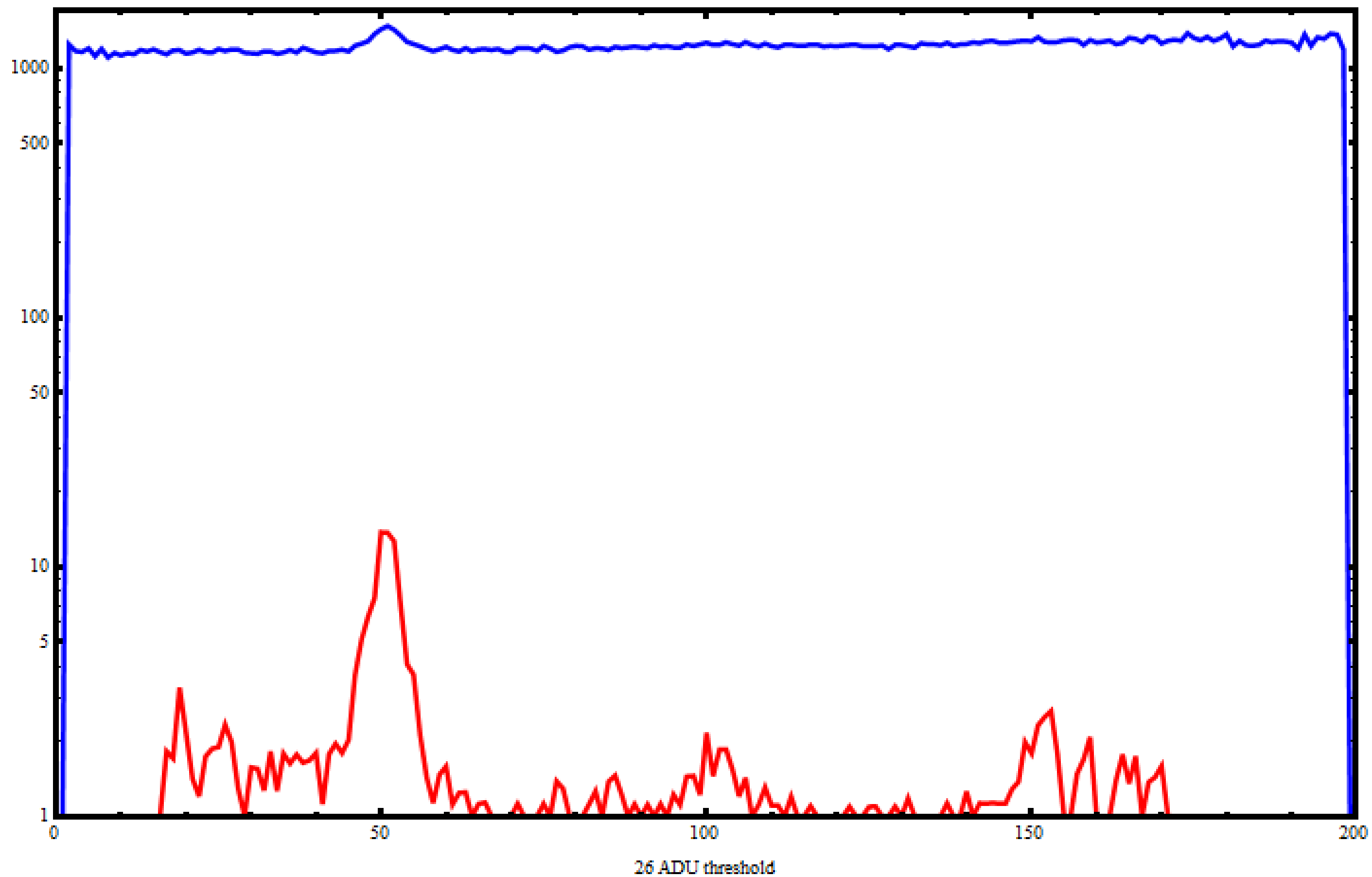

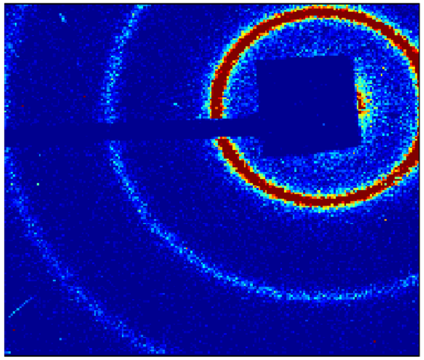

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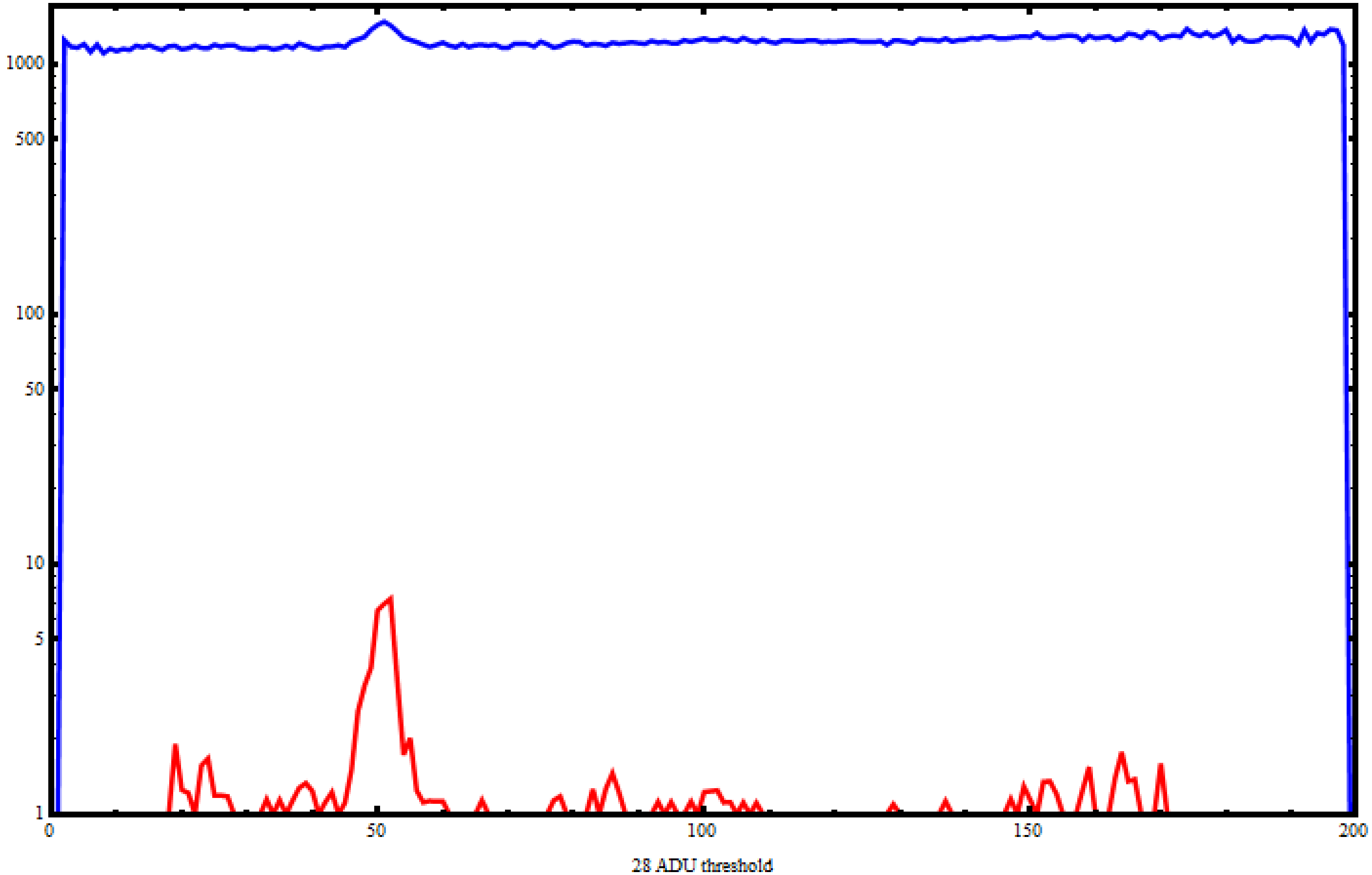

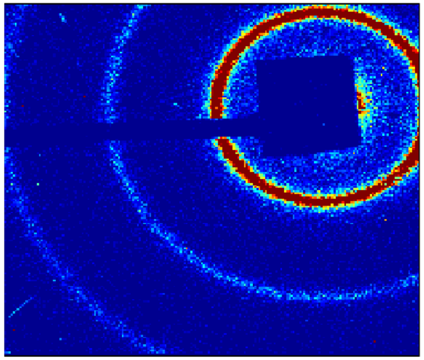

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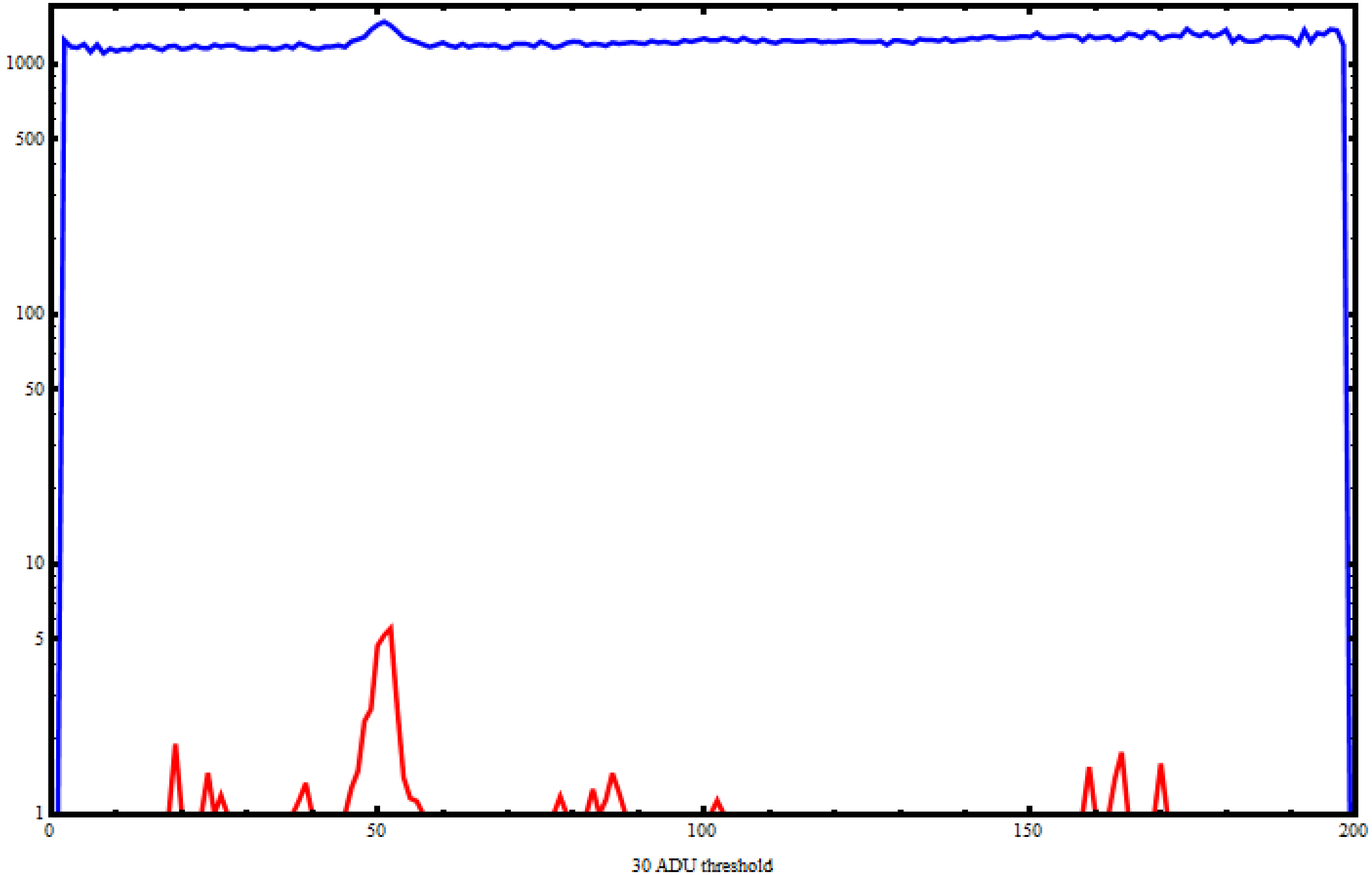

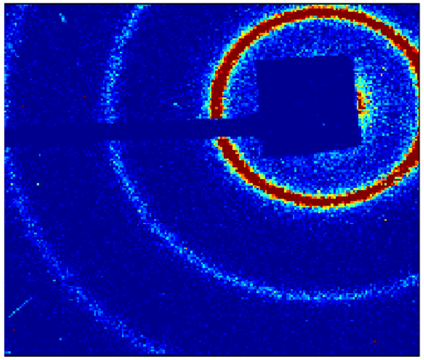

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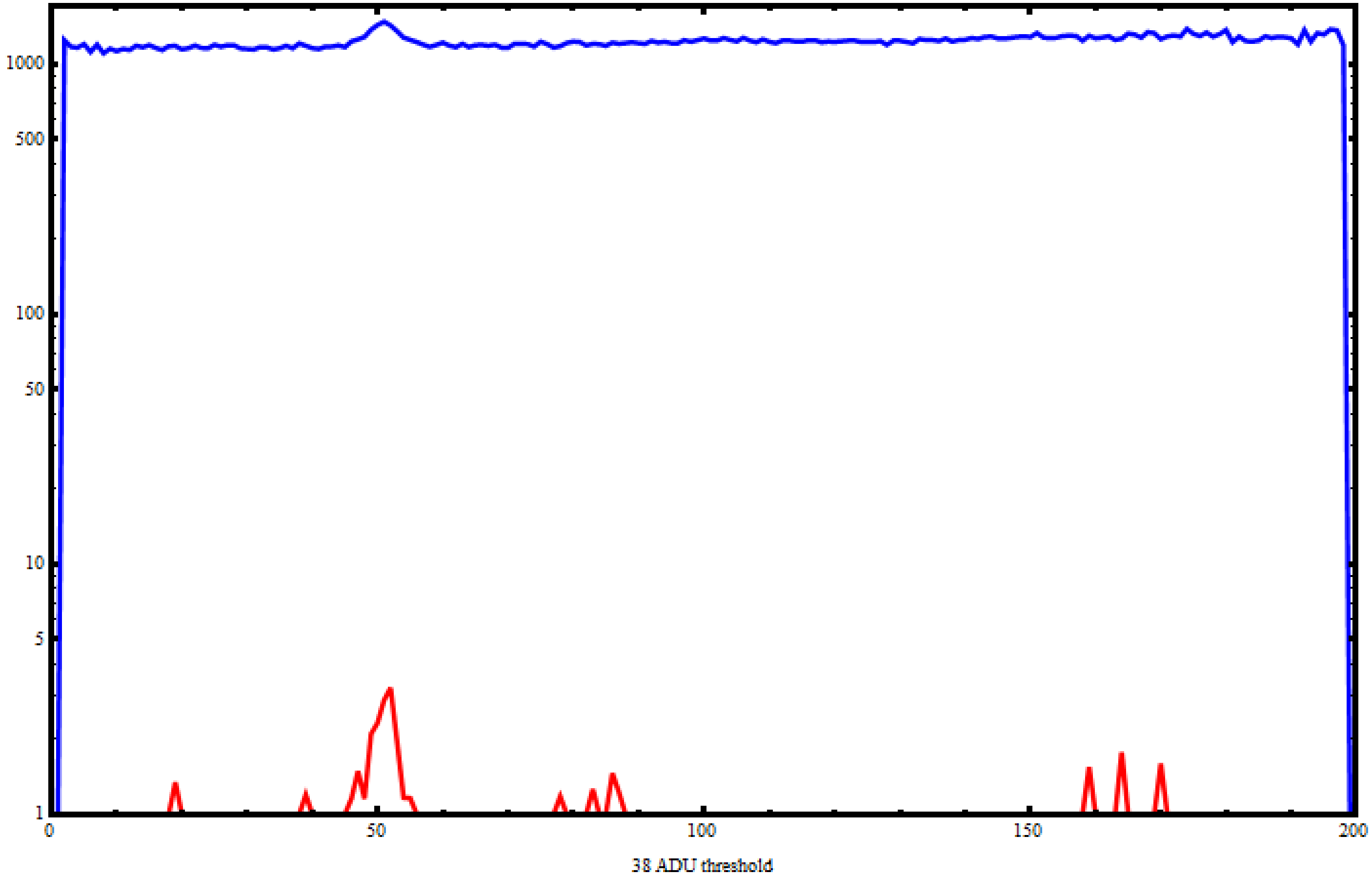
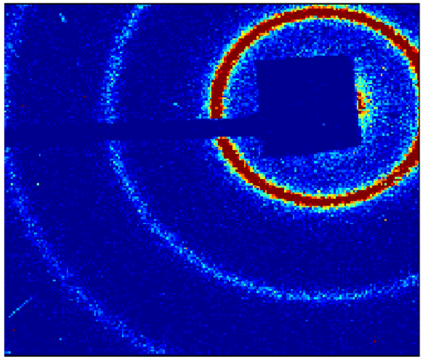
Varying Threshold





(Azimuthal integration around detector)

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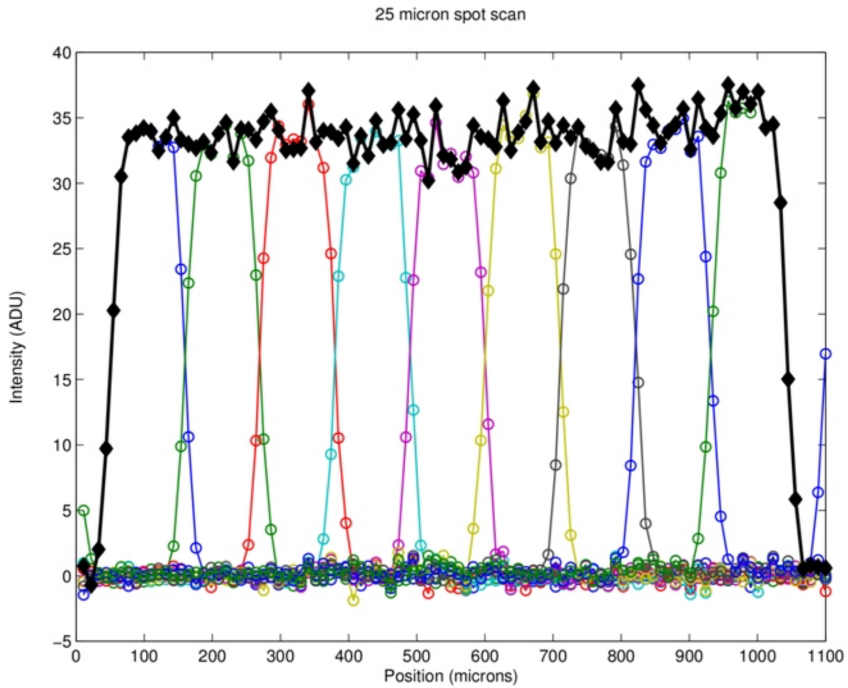
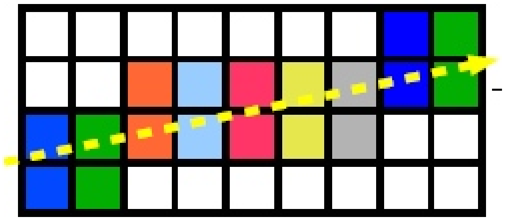
Charge Sharing

One Advantage of integrating detectors:

- Summed charge proportional to absorbed energy. Don't worry about assigning photons to pixels.
- But thresholds cause problems.
- In fact, we see this.





Lab of Atomic and Solid State Physics

Nearest Neighbors

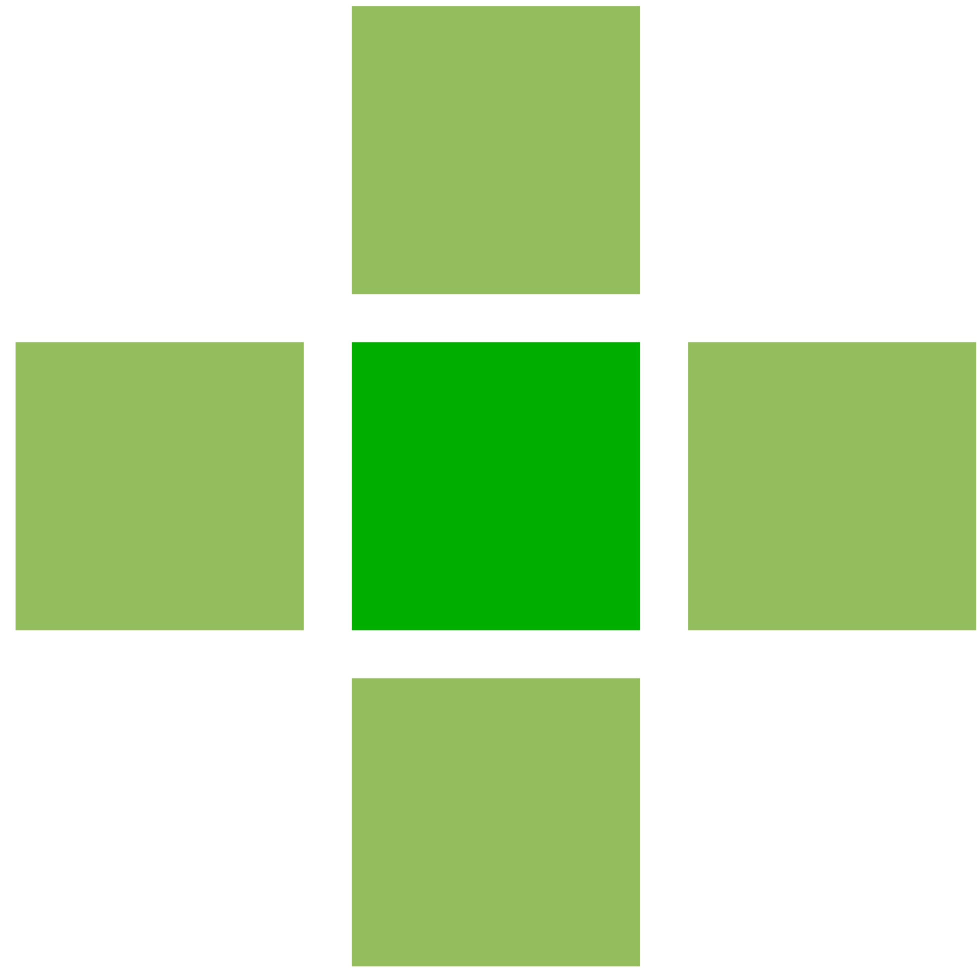
- Low flux data:

  Threshold ~ 0.6 photon

Signal reduction of 8% - just applied to central pixel.

But

Threshold allowing accumulation in nearest neighbors recovers 'most' Signal.



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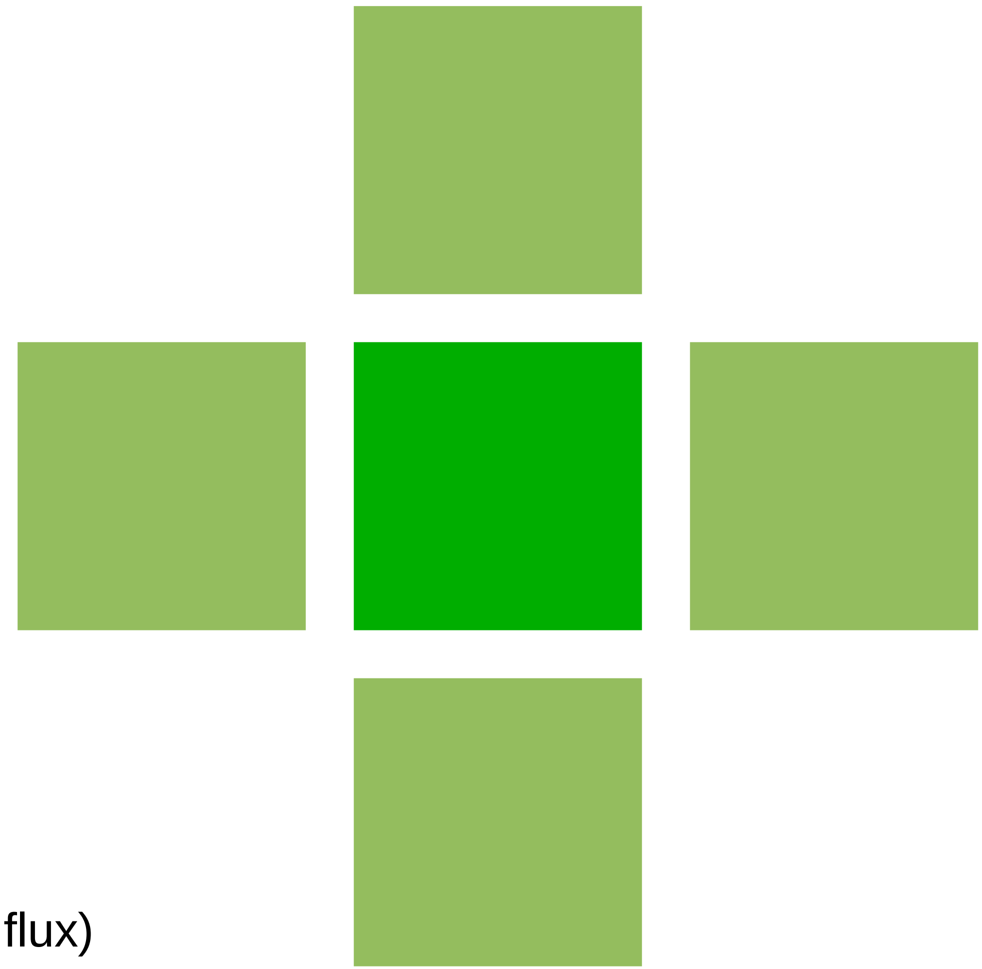
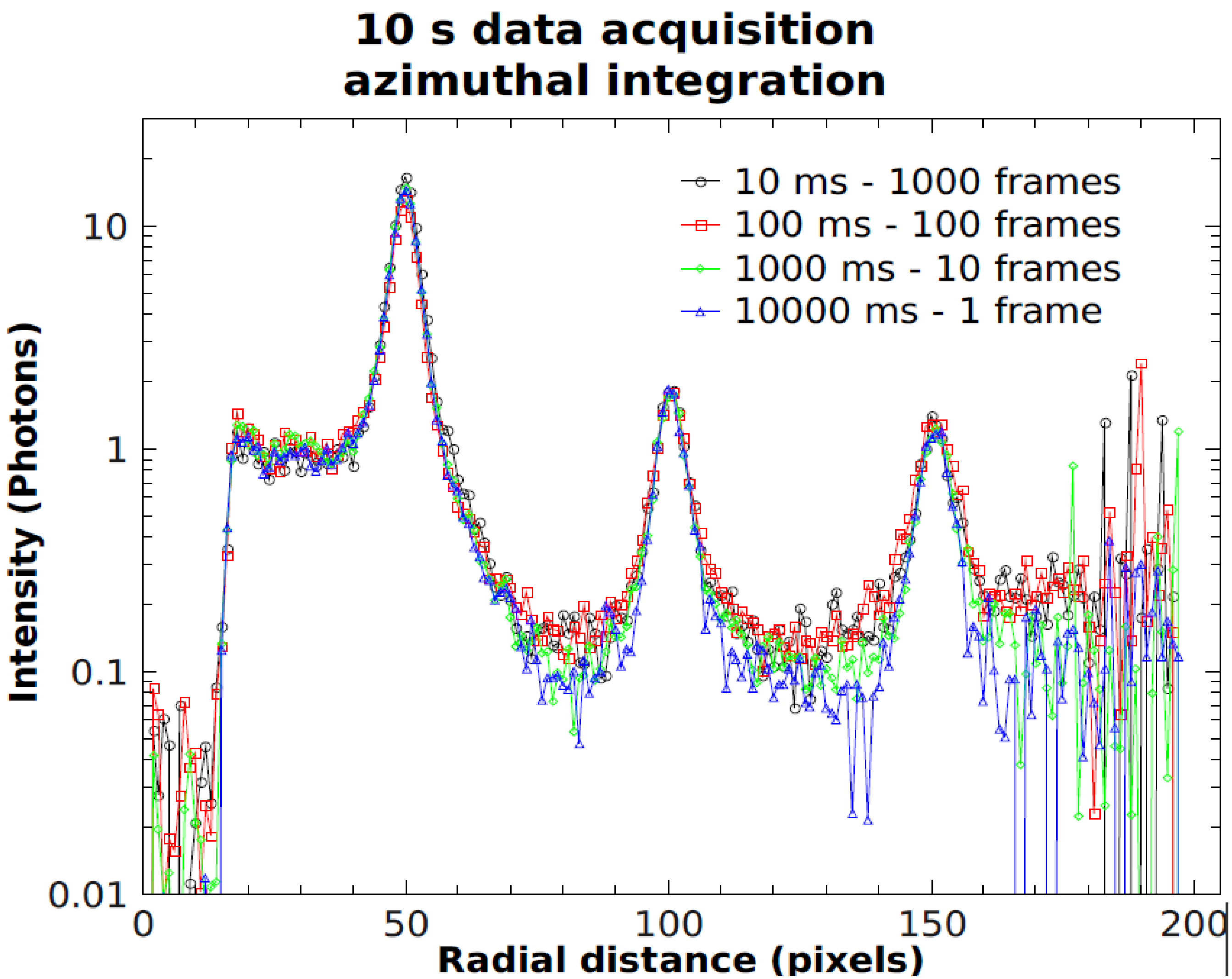


Method has problems (e.g. High-flux next to low flux)

Is this the 'real' Diffraction Pattern?



Threshold:
12 ADU for lowest flux

Nearest Neighbors

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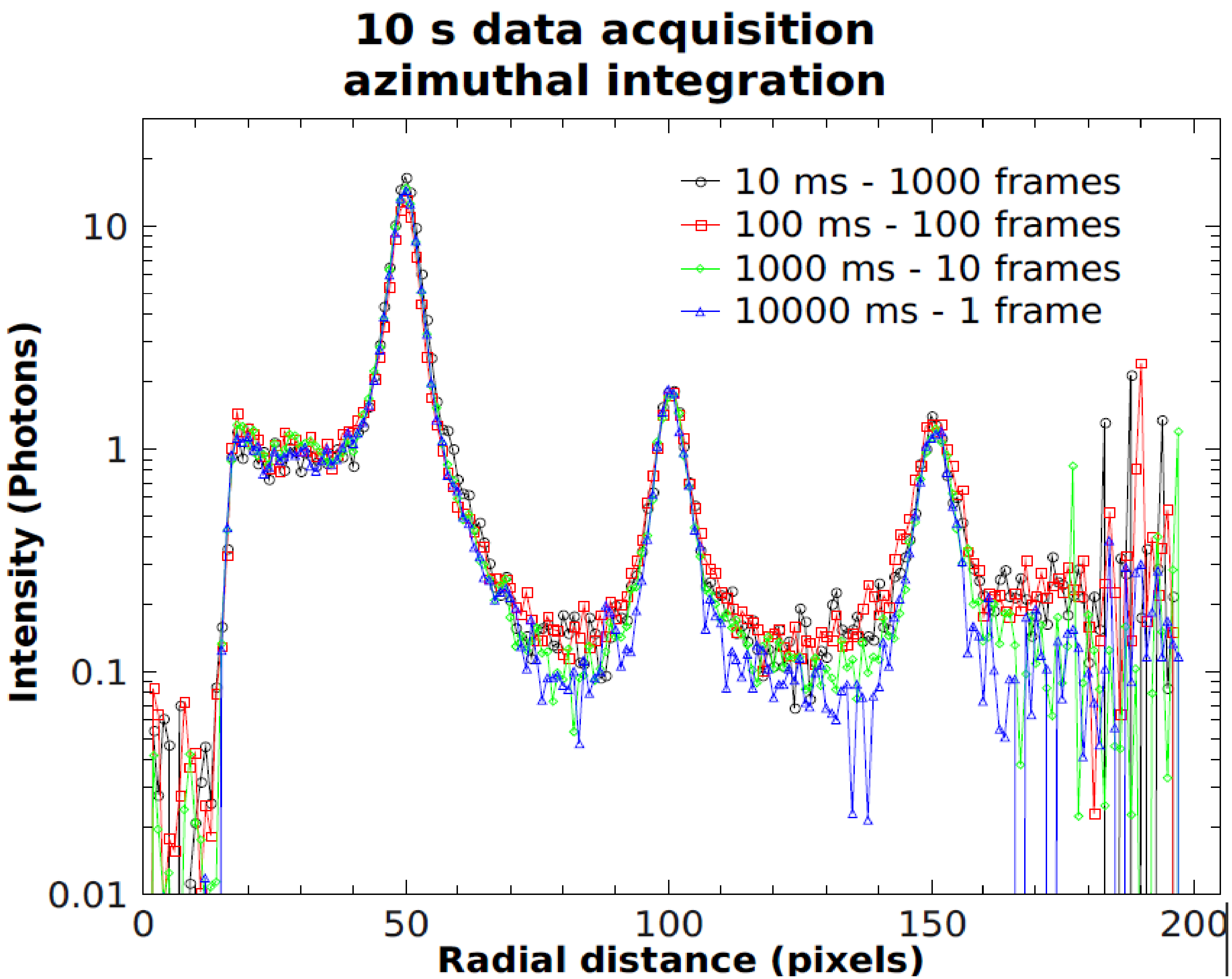
Is this the 'real' Diffraction Pattern?



Threshold:
12 ADU for lowest flux

Nearest Neighbors

Really good agreement
for widely varying fluxes.

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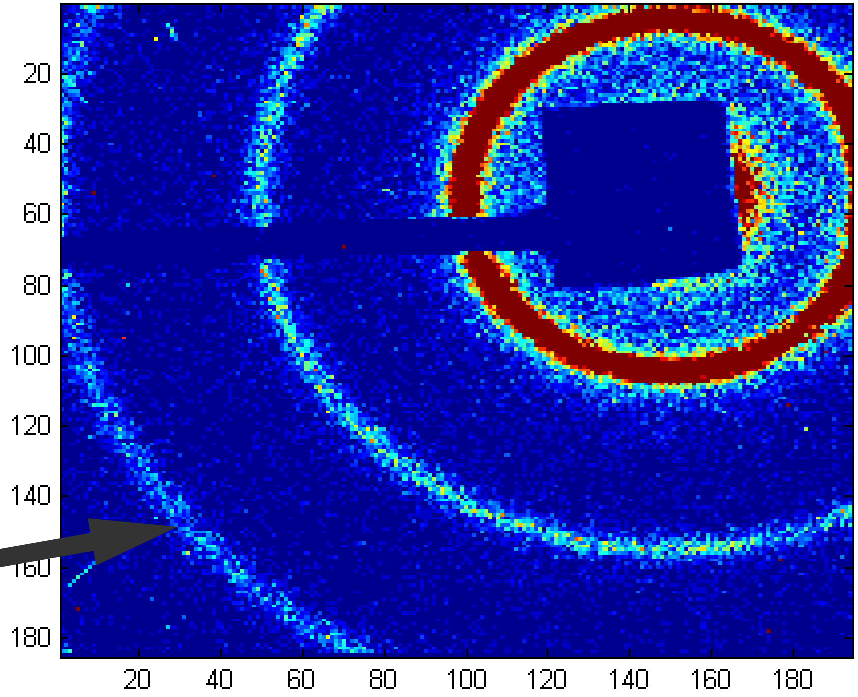
How Low?



This ring less than
10^{-3} photons/pixel/frame

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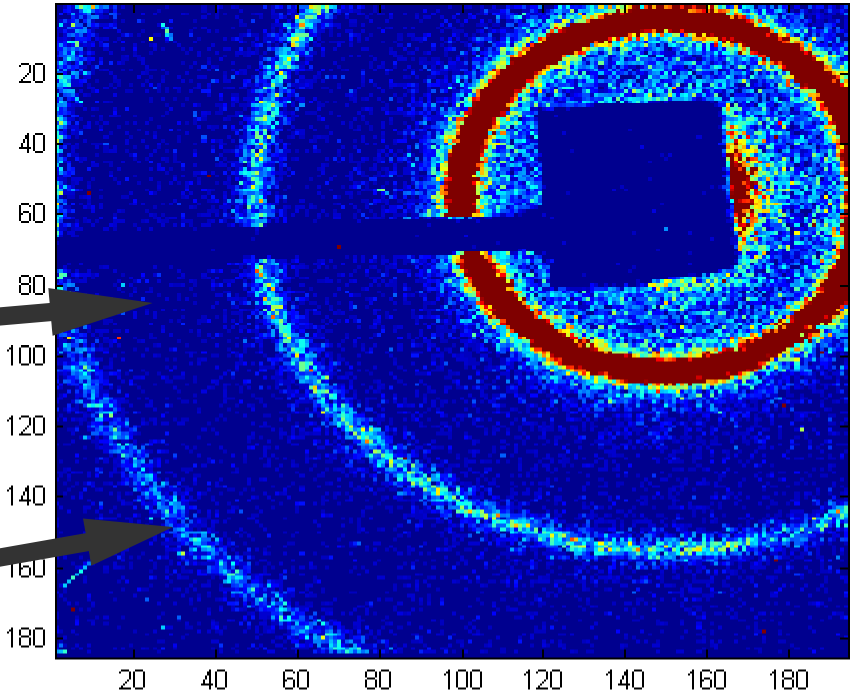
How Low?



More than an order of magnitude less

This ring less than
10^{-3} photons/pixel/frame

Some Important Points

- How you reduce the detector data to recover meaningful data is not always straight forward.
- Giving users mountains (TBs) without direction about how to look at it = frustration, duplicated effort.
- Full and diligent calibration of detectors is needed before users spend time taking data.

Conclusions

- For integrating detectors, thresholding (or something like it) is required for extremely low photon incidence.
- Cornell's pixel array detector (upon which the LCLS CXI detector is based) has demonstrated the capability of faithfully extracting diffractions patterns from extremely low flux (photons/pixel/frame).

Cornell University

SLAC today

Launch of Fourth LCLS Instrument Reveals Crisp, Fine Molecular Detail

The first set of user experiments with the Linac Coherent Light Source's newest instrument is under way, and about 40 researchers are working very long hours this week to decipher the structures of proteins involved in photosynthesis, parasitic disease and other important life processes.

The results won't be known for months, after extensive analysis of the data. But near the end of the second 12-hour shift on Tuesday morning, scientists gathered in front of a bank of computer monitors in the CXI control room were beaming and pointing at the screens, to a chorus of "oohs" and "ahhs."


The research team in the CXI control room. (Photo by Brad Plummer.)

"You see this protein, all these rings here?" Petra Fromme of Arizona State University asked me, pointing to a printed image of what looked like tiny, bright stars arranged in circular patterns against a dark sky. "What's really nice is that each spot is so very fine. The diffraction pattern is so much cleaner" than the ones obtained with traditional structural analysis. What that implies, at a preliminary glance, is that the team may have captured the structure of a photosynthetic protein complex in very fine, crisp detail, approaching atomic resolution.

The LCLS is the world's most powerful X-ray free electron laser. Its strobe-light pulses—120 of them per second—could burn through steel,