The *Nu*clear *S*pectroscopic *T*elescope *AR*ray (or *NuSTAR*)

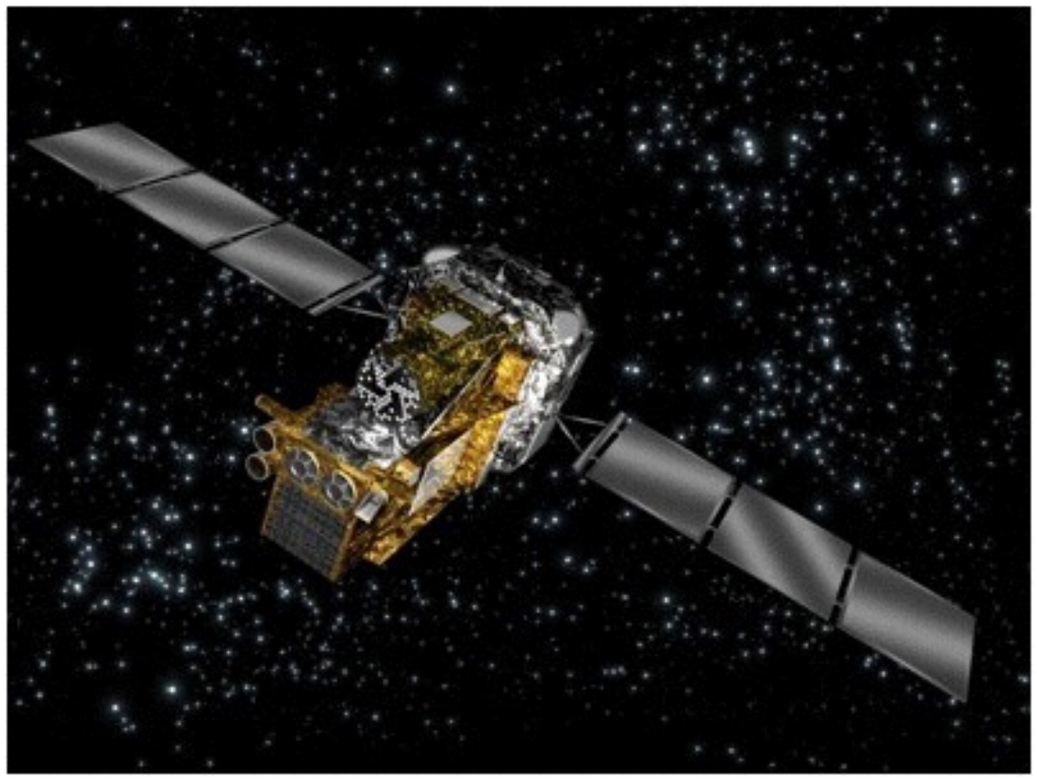
How it works and what to be aware or wary of

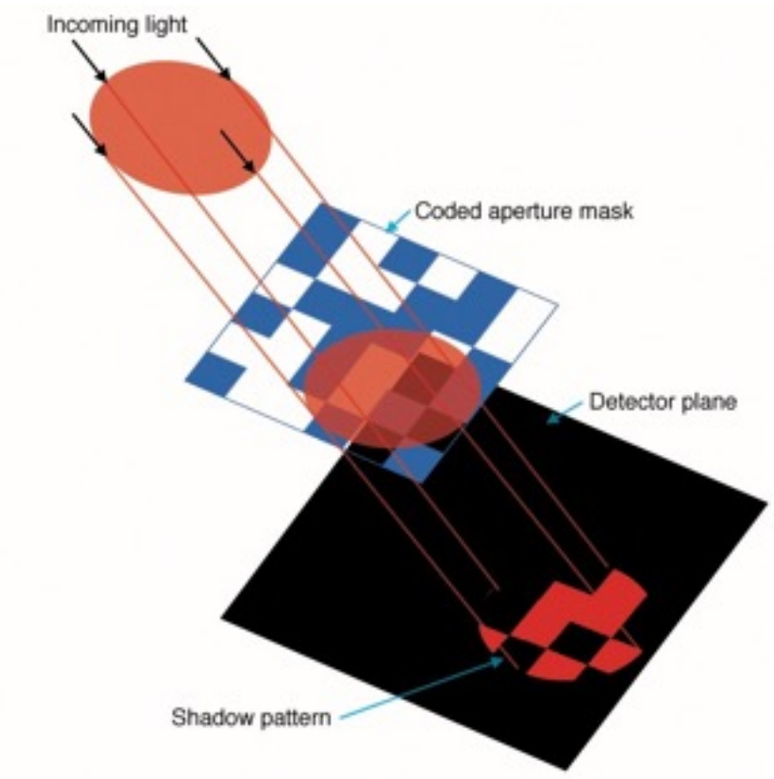
Daniel R. Wik

NuSTAR

NASA

INTEGRAL, Swift BAT

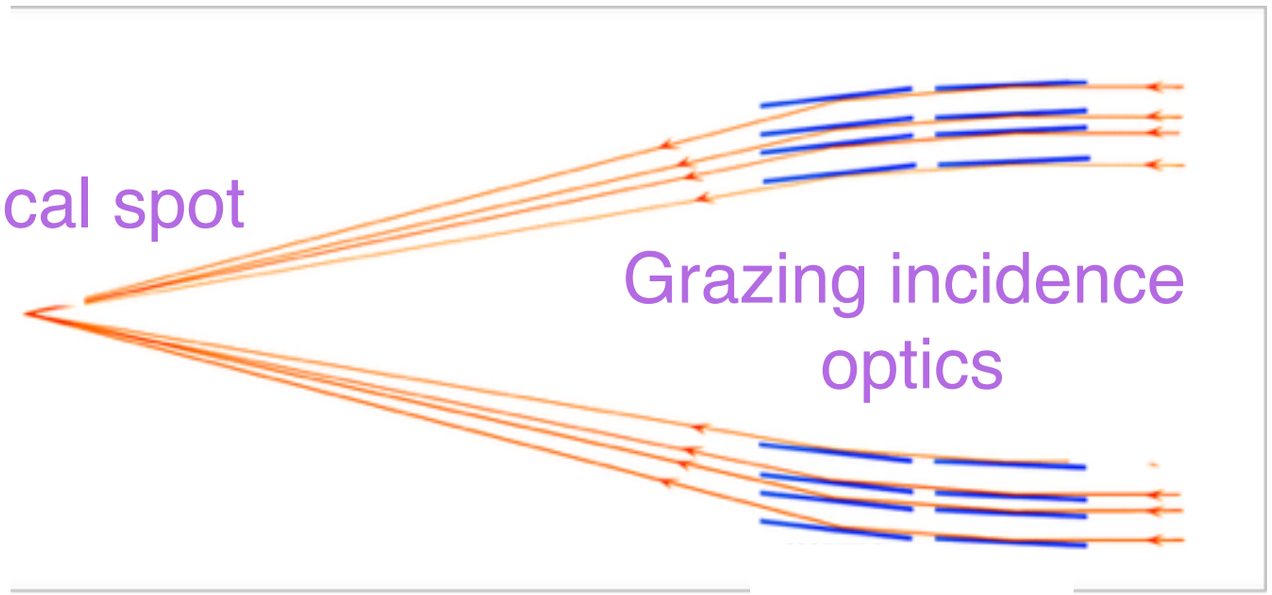




NuSTAR

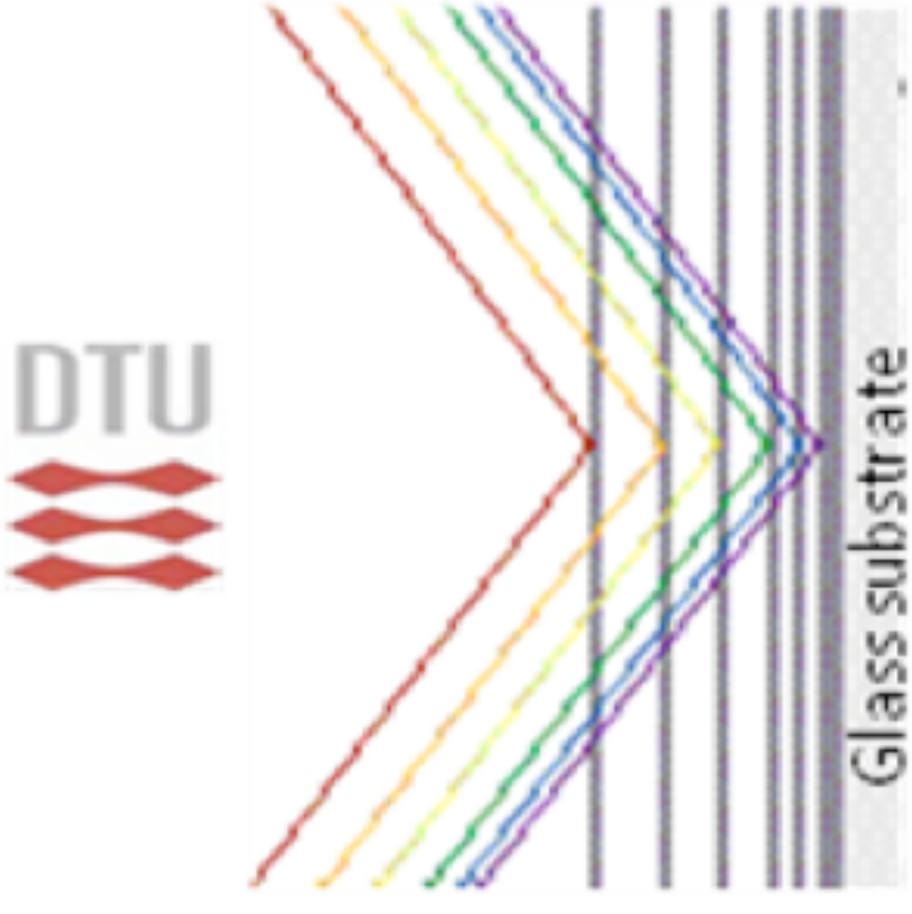
Focal spot

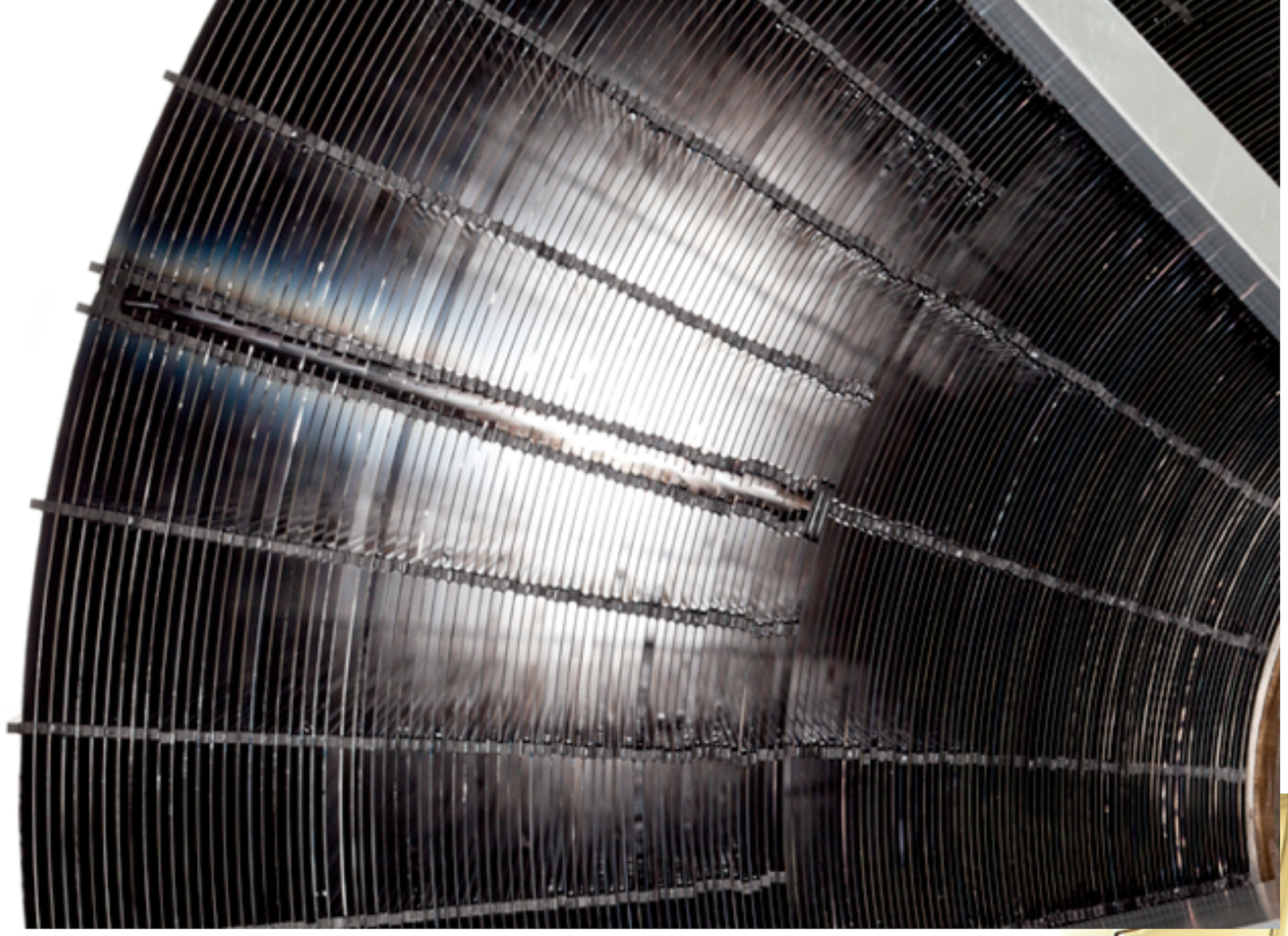
Grazing incidence optics



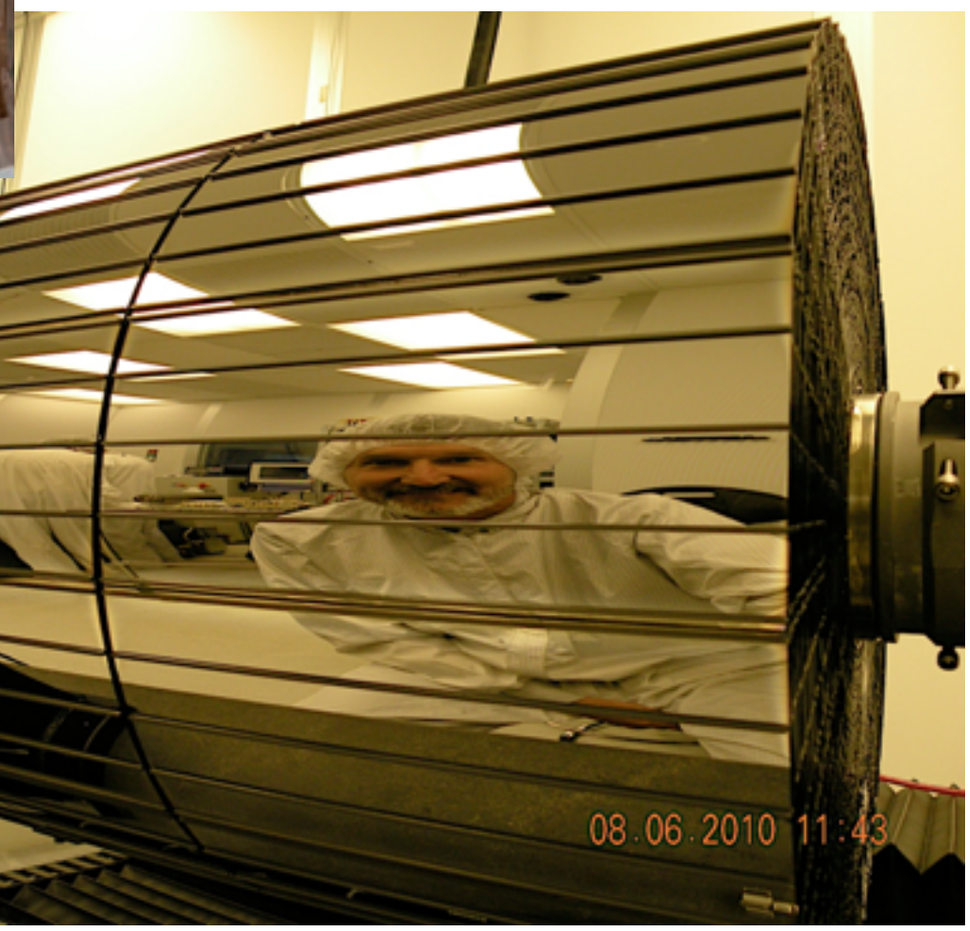
Mirror glass is slumped
in an oven at Goddard

The glass is then shipped (via FedEx, no insurance) to Denmark where they receive multilayer Pt/C coatings





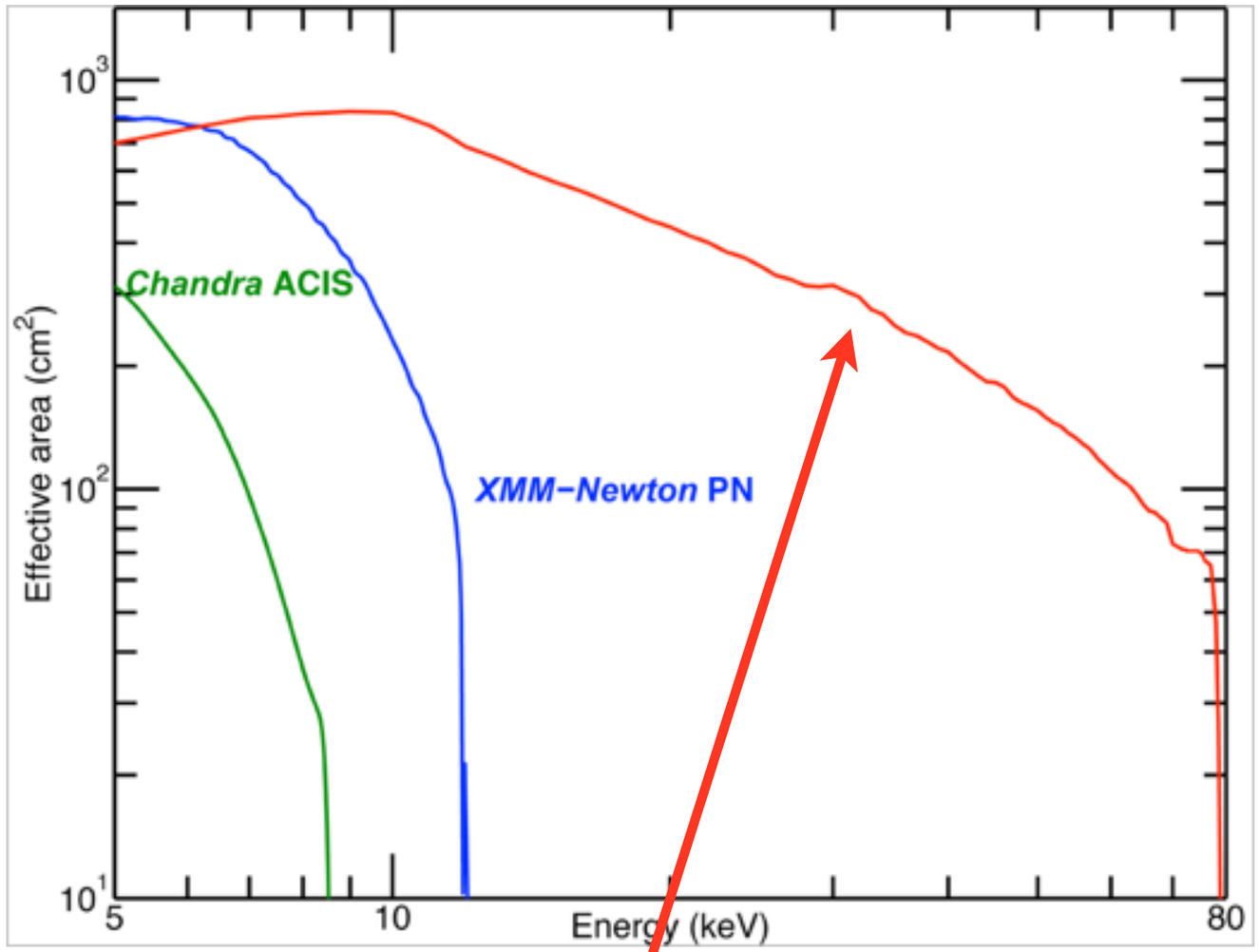
They are then shipped to NYC and glued together to create 133 nested shell mirror modules. (Chandra has 4)




Mirror Module Assembly
Detector Room
Optics Room
X-RAY ON
Columbia Nevis Lab

Collecting Area

NuSTAR two-telescope total collecting area



Unprecedented! But equivalent to an 8” diameter normal incidence mirror

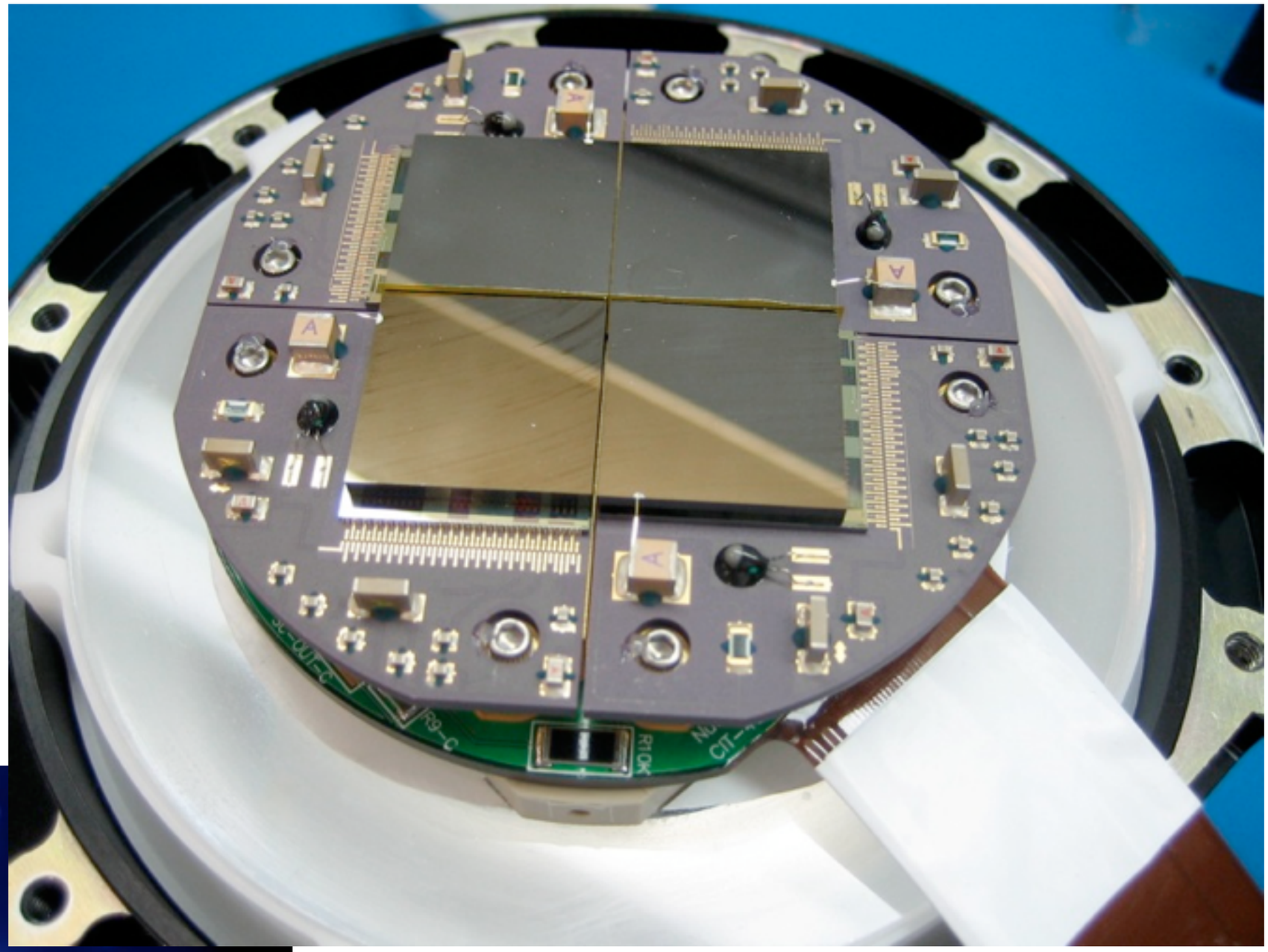
Sensitivity comparison

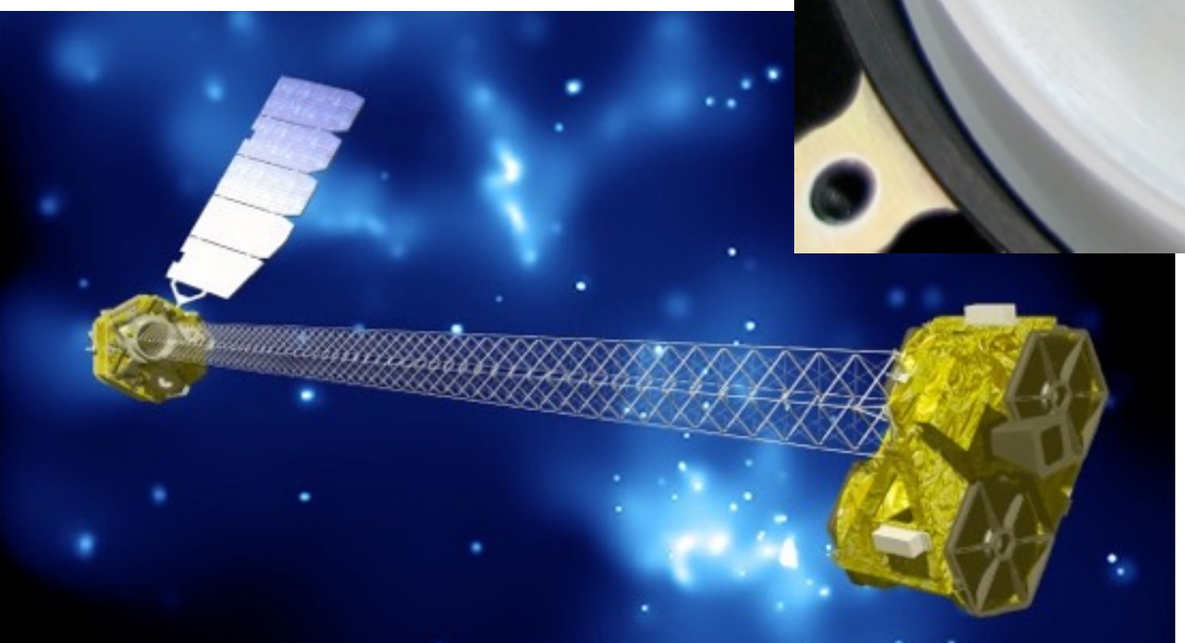
Satellite (instrument)	Sensitivity
INTEGRAL (ISGRI)	~0.5 mCrab (20-100 keV) with >Ms exposures
Swift (BAT)	~0.8 mCrab (15-150 keV) with >Ms exposures
NuSTAR	~0.8 μCrab (10-40 keV) in 1 Ms

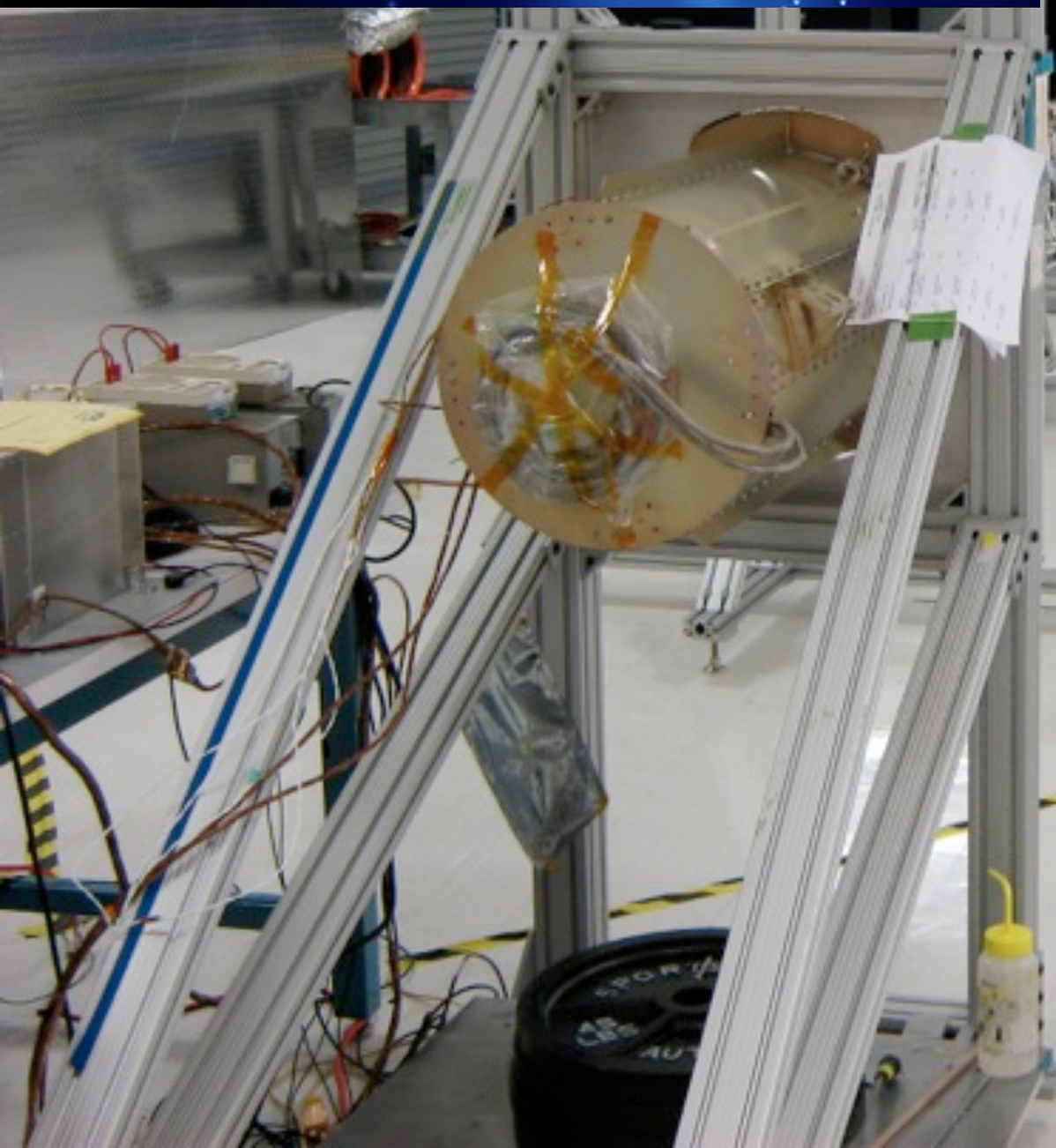
Imaging

HPD	58”
FWHM	18”
Localization	2” (1-sigma)

CdZnTe Crystal Detector developed at Caltech

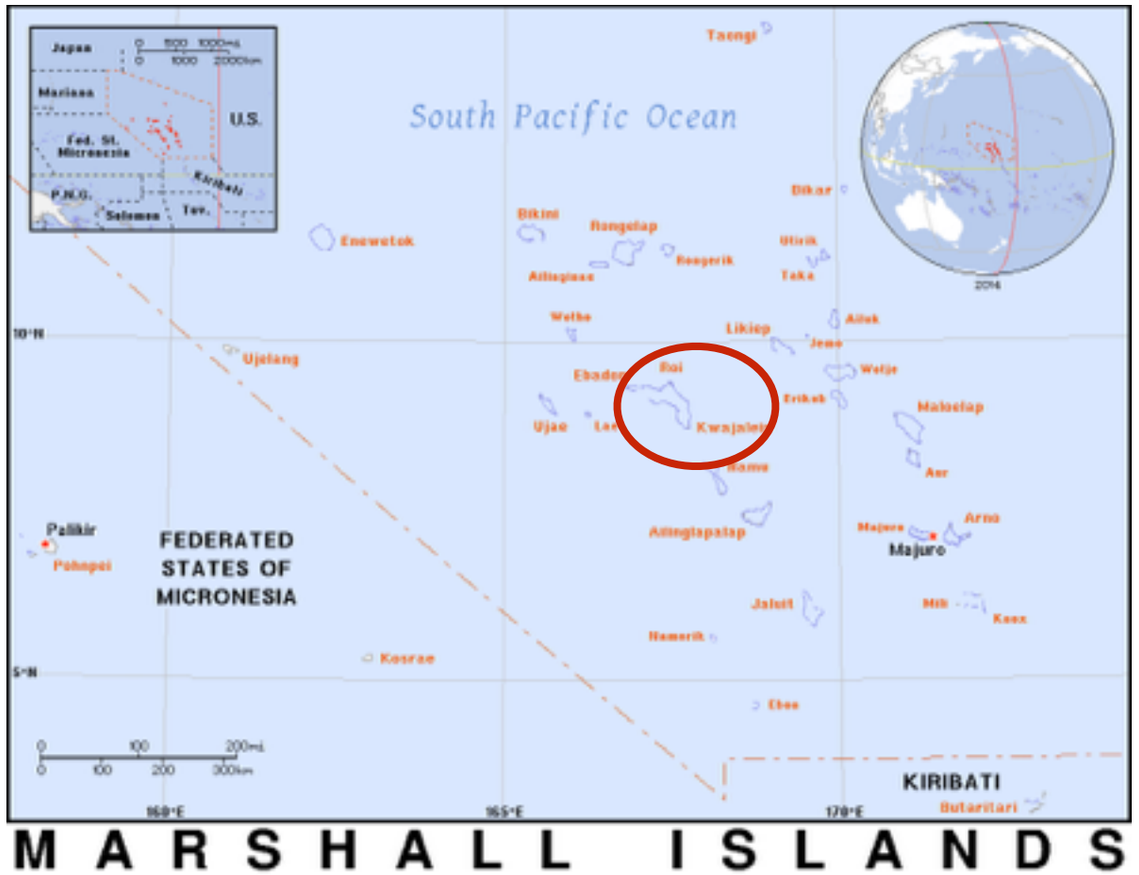




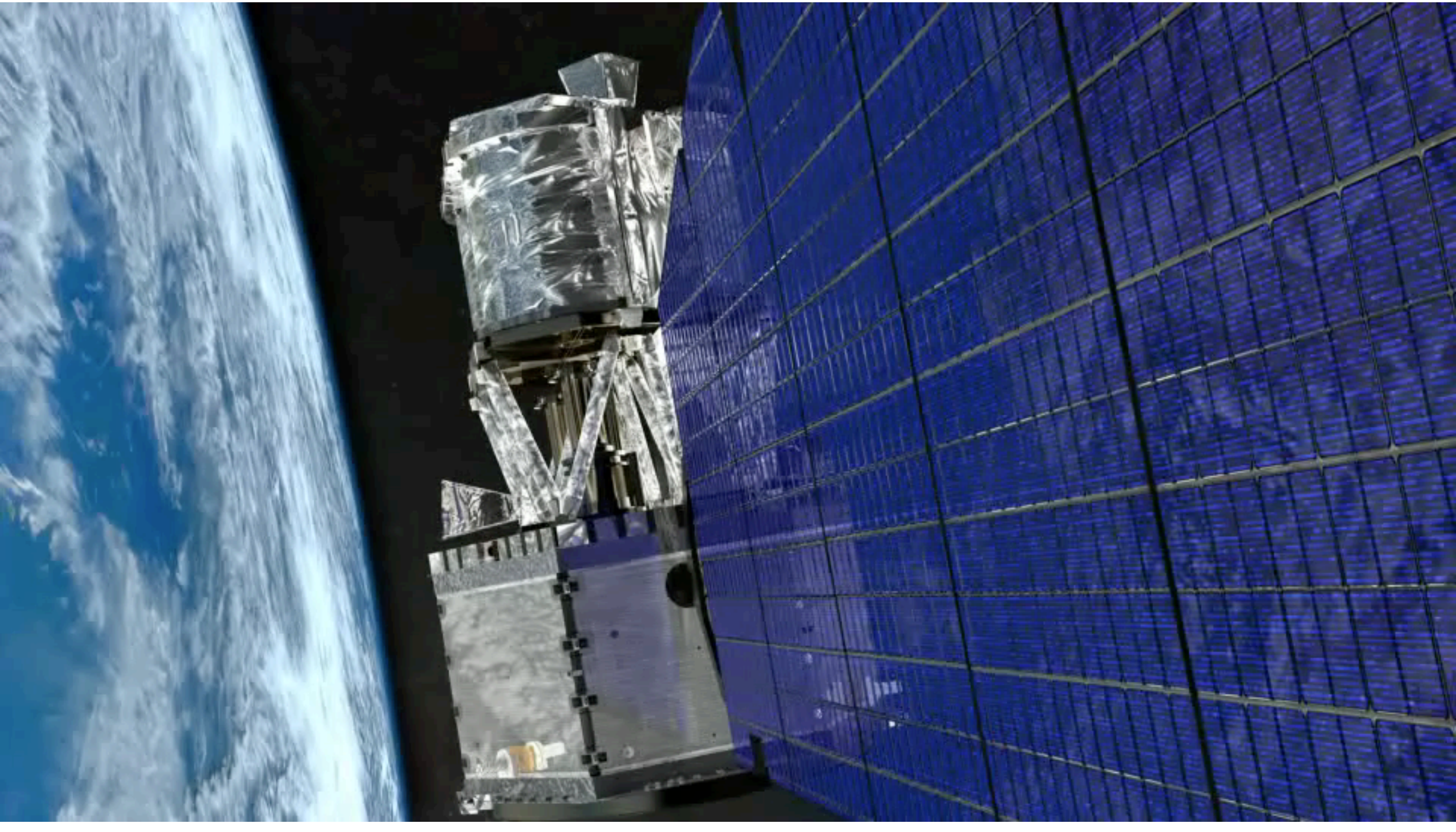



FLAMMABLE


CAUTION
CAUTION


Japan
Mariana
U.S.
Fed. St. Micronesia
P.N.G.
Kiribati
Solomon
Tuv.
South Pacific Ocean
Tasngi
Bikar
Bikini
Rongelap
Utirik
Enewetok
Rongerik
Taka
Ailinginae
Wotho
Likiep
Ailuk
Jemo
Ujelang
Ebadon
Ujae
Kwajalein
Wotje
Erikub
Maloelap
Aur
Namu
Ailinglapalap
Majuro
Arno
Jaluit
Mili
Knox
Kosrae
Ebon
Palikir
Pohnpei
FEDERATED STATES OF MICRONESIA
KIRIBATI
Butaritari
10°N
5°N
160°E
165°E
170°E
MARSHALL ISLANDS

Fake Movie of the Deployment of the Mast



What you need to know

- TWO very similar telescopes, meaning everything has to be done TWICE (not all routines need to be run twice, but they do)

- NuSTAR “data” are in the form of event lists: an event is a trigger of detector pixel(s) that registers an intensity
    - Pixel location/pattern tells you WHERE
    - Trigger event time tells you WHEN
    - Intensity or “pulse interval (PI)” tells you the ENERGY

- An event may be an X-ray photon (either focused by the mirrors or some form of stray light) or particle induced (cosmic ray or electron strike or irradiation of surrounding structures)

- Events you care about are referred to as “source”, and those you don’t are referred to as “background,” typically defined as inside or outside a “region”

- Usual Goals:
    - Extract an IMAGE in a given energy band
    - Extract a spectrum of a given region
    - Extract a light curve of a given region

- Complications:
    - Point sources are “blurry,” so photons arrive over a larger area following the Point Spread Function (PSF)
    - The telescope structure flexes during an orbit, so the optical axis moves in the detector plane
    - Energy resolution is also blurry, so a spectral line at some energy is convolved by a Gaussian

cd 30002032002/event_cl

fv nu30002032002A01_cl.evt &

fv: Summary of nu30002032002A01_cl.evt in /Users/dwik/Work/nustar/science/caldata/30002032_...

File Edit Tools Help

Index	Extension	Type	Dimension	View
0	Primary	Image	0	Header / Image / Table
1	EVENTS	Binary	14 cols X 21784 rows	Header / Hist / Plot / All / Select
2	GTI	Binary	2 cols X 135 rows	Header / Hist / Plot / All / Select
3	BADPIX	Binary	5 cols X 5 rows	Header / Hist / Plot / All / Select
4	BADPIX	Binary	5 cols X 31 rows	Header / Hist / Plot / All / Select
5	BADPIX	Binary	5 cols X 20 rows	Header / Hist / Plot / All / Select
6	BADPIX	Binary	5 cols X 23 rows	Header / Hist / Plot / All / Select

GTI

fv: Binary Table of nu30002032002A01_cl....

File Edit Tools Help

Select	START	STOP
	1D	1D
All	s	s
Invert	Modify	Modify
1	8.228296524999E+07	8.228296602499E+07
2	8.228296700000E+07	8.228296702499E+07
3	8.228296899998E+07	8.228490700000E+07
4	8.228615900000E+07	8.228733102499E+07
5	8.228733124999E+07	8.228733142499E+07
6	8.228733200000E+07	8.228733202499E+07
7	8.228733249999E+07	8.228733262501E+07
8	8.228733375000E+07	8.228733502499E+07
9	8.228733524999E+07	8.228733542499E+07
10	8.228733600000E+07	8.228733602499E+07
11	8.228733649999E+07	8.228733662501E+07
12	8.228733749999E+07	8.228733762501E+07
13	8.228733949999E+07	8.228733962501E+07

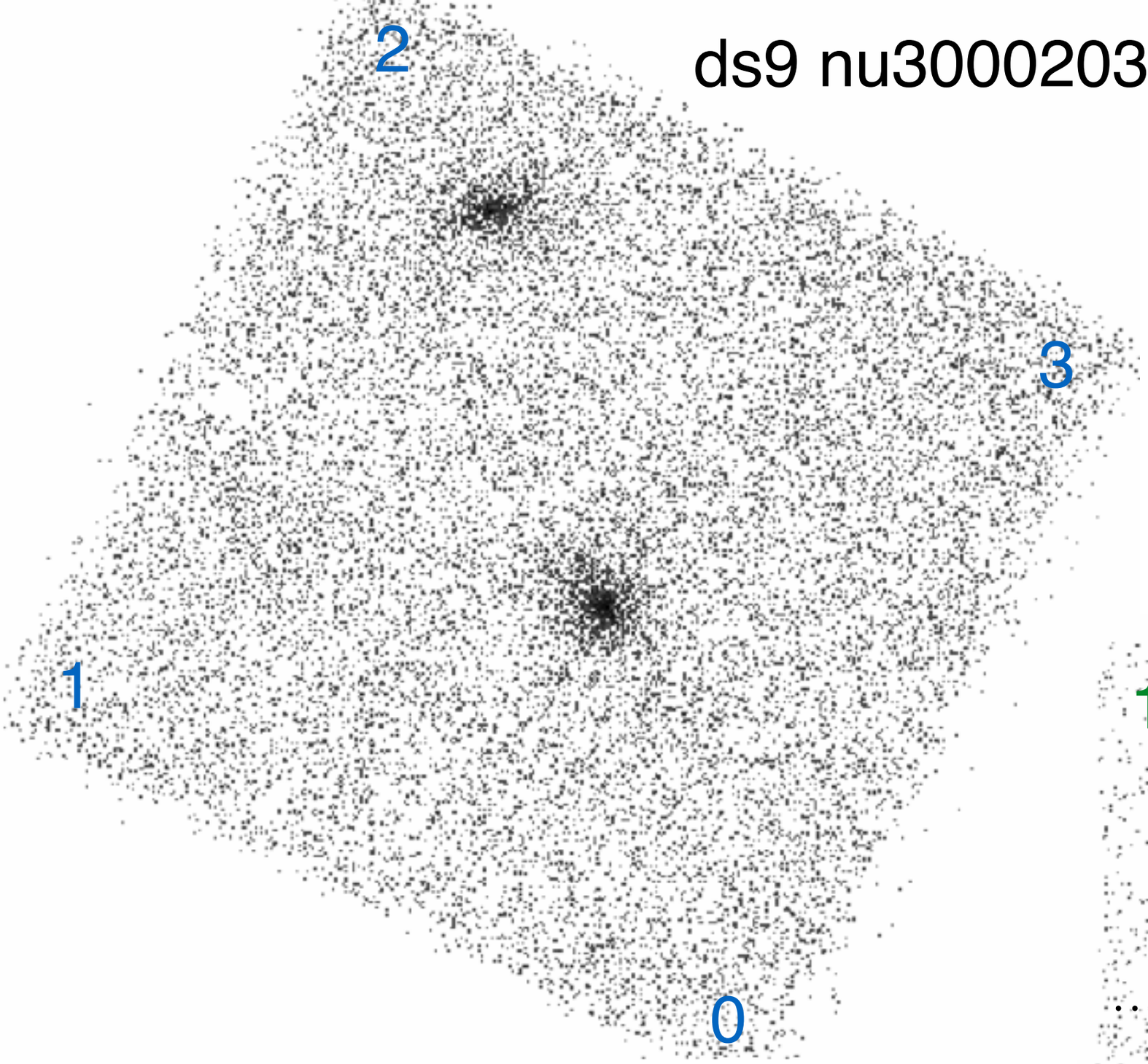
EVENTS

fv: Binary Table of nu30002032002A01_cl.evt[1] in /Users/dwik/Work/nustar/science/caldata/30002032_IC342_X1/30002032002/event_cl/

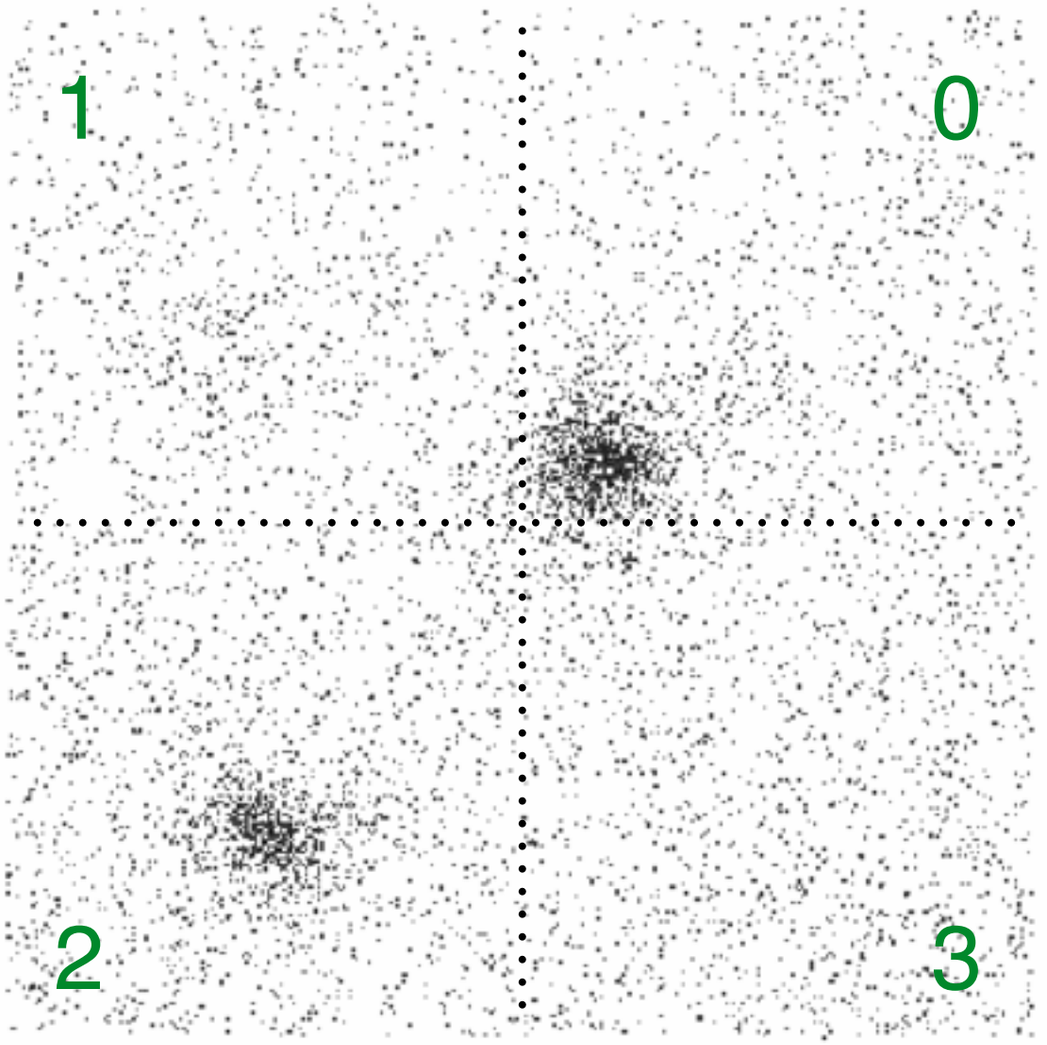
File Edit Tools Help

Select	TIME	DET_ID	RAWX	RAWY	STATUS	GRADE	SURRPI	PI	DET1X	DET1Y	DET2X	DET2Y	X	Y
	1D	1B	1B	1B	16X	1I	1J	1J	1I	1I	1I	1I	1I	1I
All	s	NA	NA	NA				short	pixel	pixel	pixel	pixel	pixel	pixel
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	8.228296599726E+07	2	12	1	0	2	-27	732	170	115	302	202	523	586
2	8.228296927090E+07	3	24	15	0	0	-323	3078	306	100	437	186	649	541
3	8.228297148495E+07	3	3	12	0	0	-33	1670	203	118	335	204	548	571
4	8.228297231221E+07	2	16	25	0	0	-35	83	53	98	185	186	422	654
5	8.228297243070E+07	3	13	1	0	2	7	3727	255	173	388	259	570	498
6	8.228297284029E+07	2	18	11	0	2	1	138	123	86	255	173	490	634
7	8.228297308898E+07	0	4	2	0	0	-32	36	197	204	330	291	504	495
8	8.228297316857E+07	3	24	10	0	23	-100	1214	NULL	NULL	NULL	NULL	NULL	NULL
9	8.228297427765E+07	2	4	27	0	5	-108	3683	45	157	178	244	388	605
10	8.228297478858E+07	3	11	31	0	0	-331	2586	240	18	371	104	622	644

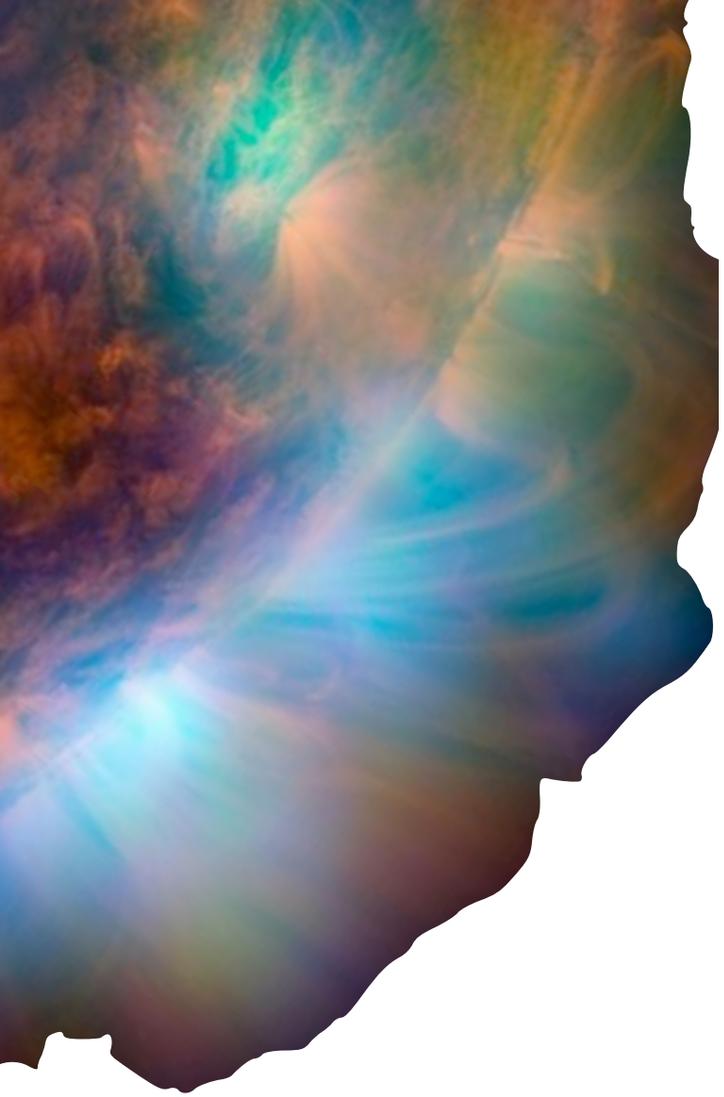
ds9 nu30002032002A01_cl.evt &

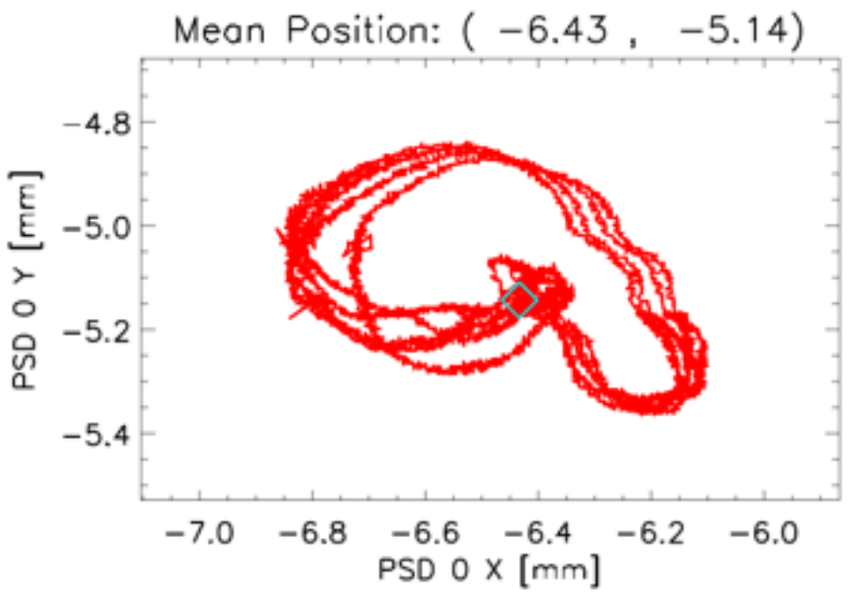


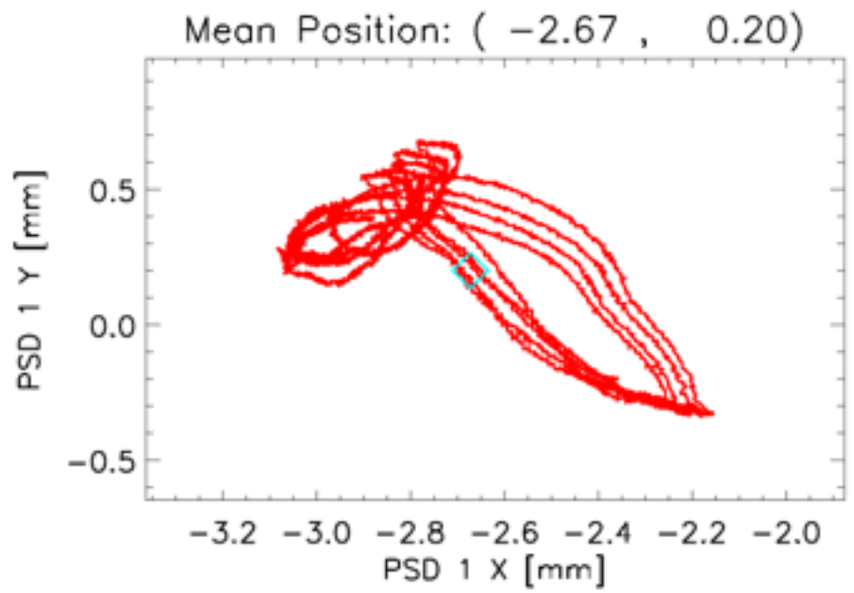
- 4 detectors
- 32x32 RAW pixels each
- probabilistically sub-binned by ~5x

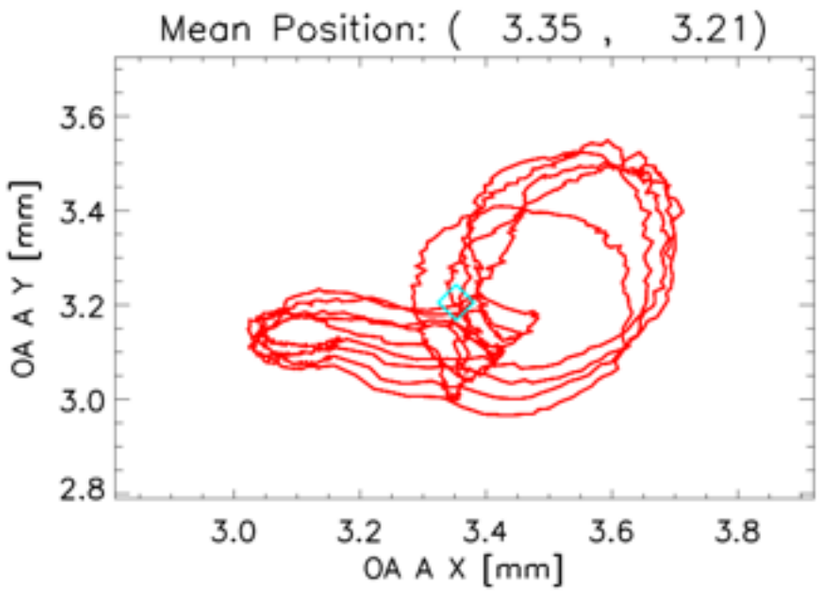


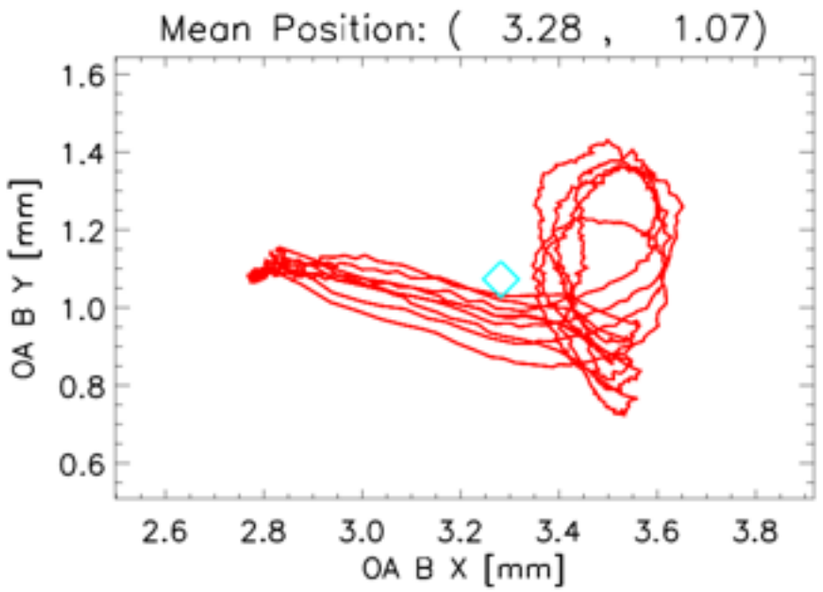
Same, but in DET1X/Y coords

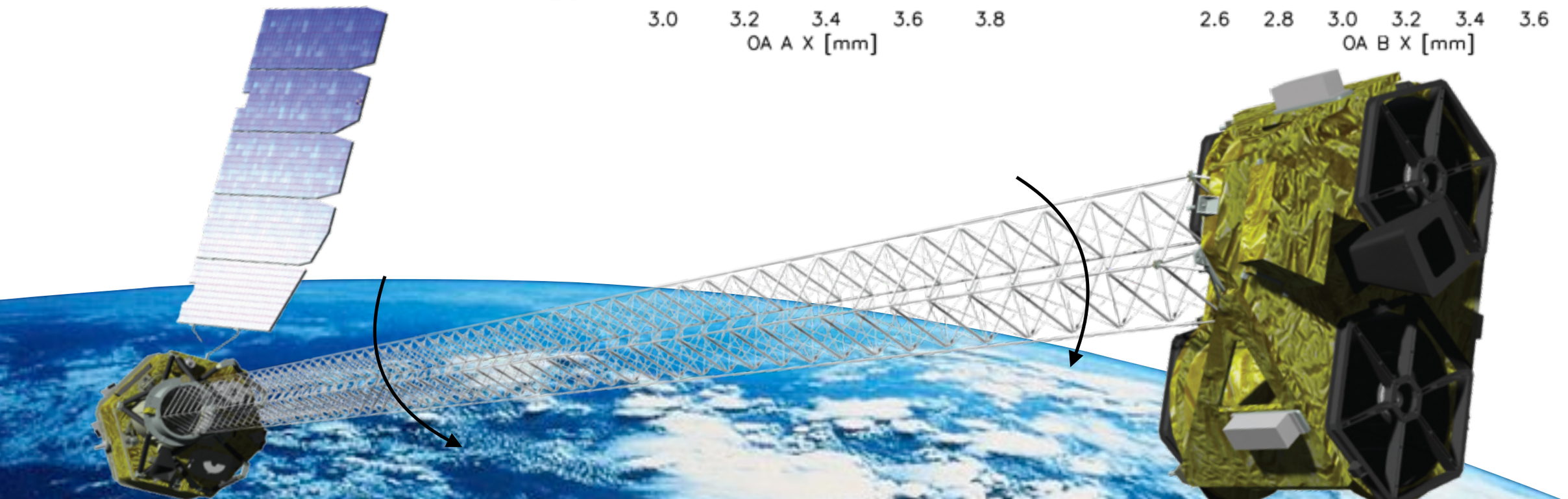



Mean Position: (−6.43 , −5.14)
PSD 0 Y [mm]
−4.8
−5.0
−5.2
−5.4
−7.0 −6.8 −6.6 −6.4 −6.2 −6.0
PSD 0 X [mm]

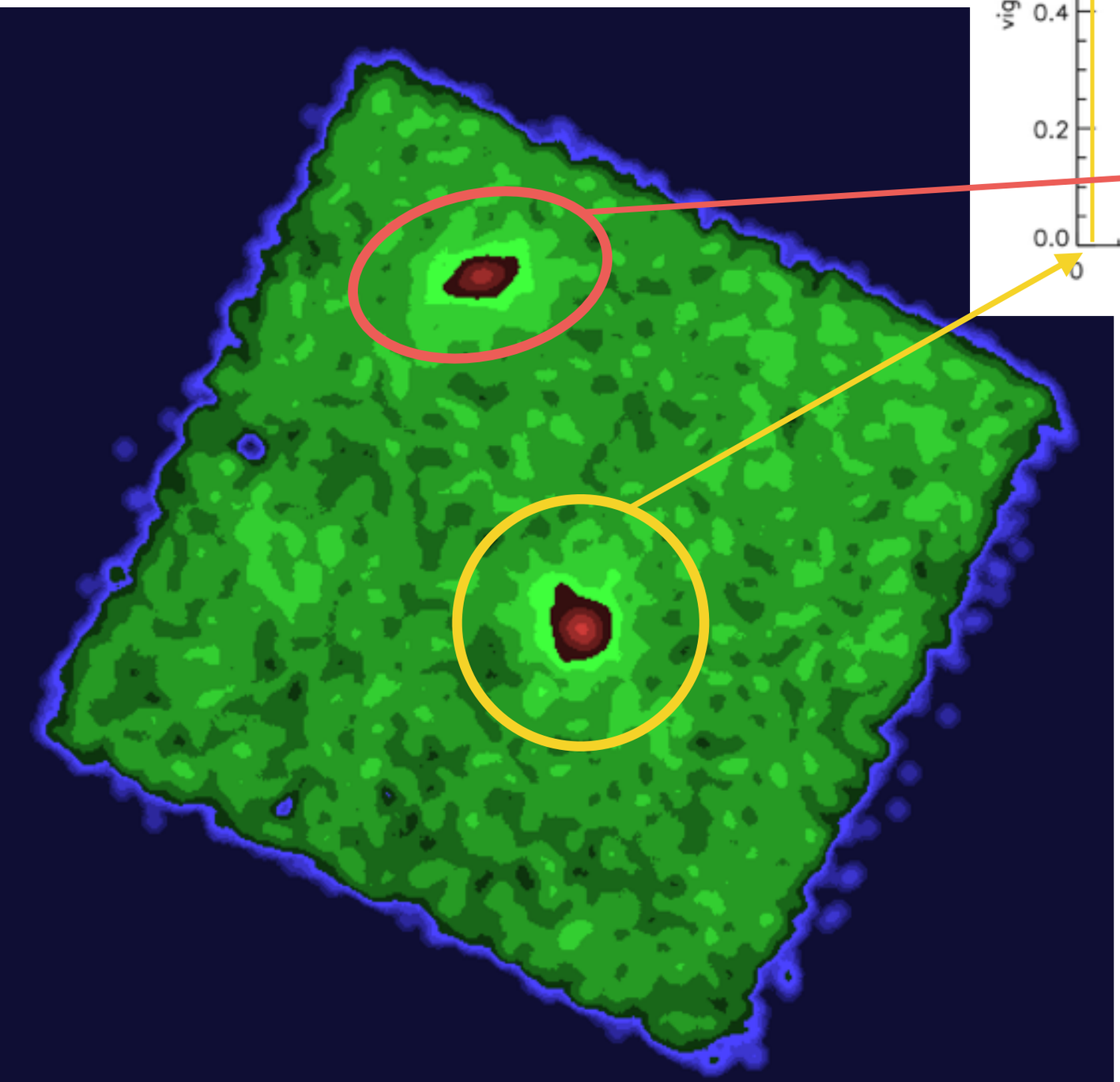

Mean Position: (−2.67 , 0.20)
PSD 1 Y [mm]
0.5
0.0
−0.5
−3.2 −3.0 −2.8 −2.6 −2.4 −2.2 −2.0
PSD 1 X [mm]

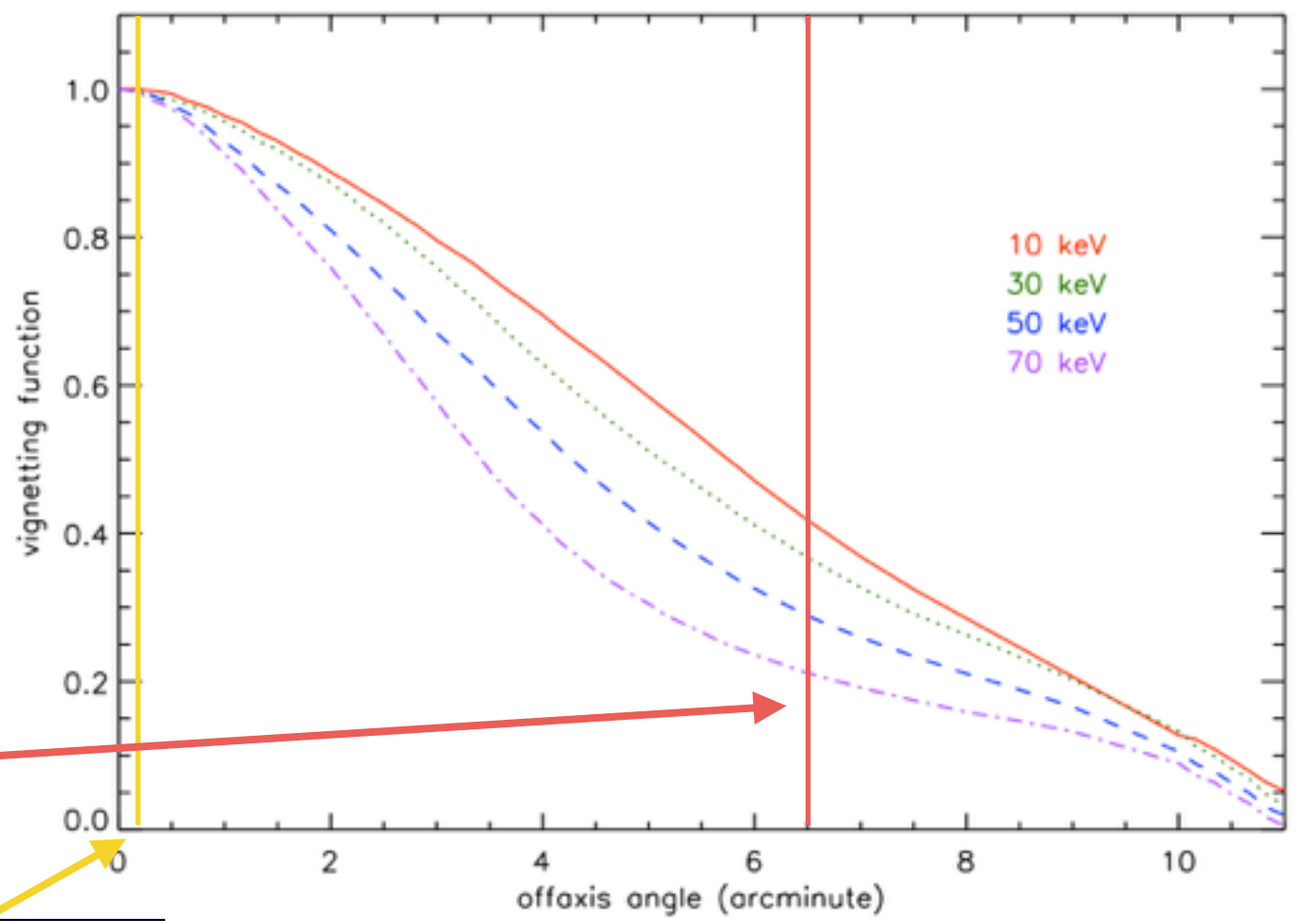

Mean Position: (3.35 , 3.21)
OA A Y [mm]
3.6
3.4
3.2
3.0
2.8
3.0 3.2 3.4 3.6 3.8
OA A X [mm]

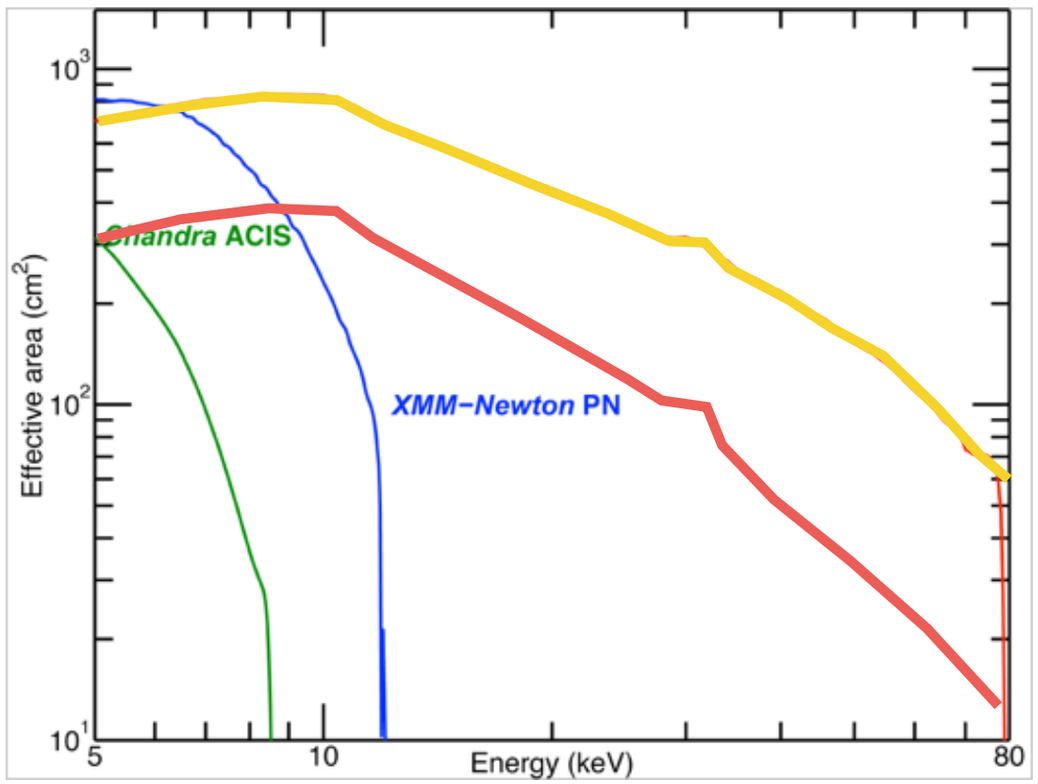

Mean Position: (3.28 , 1.07)
OA B Y [mm]
1.6
1.4
1.2
1.0
0.8
0.6
2.6 2.8 3.0 3.2 3.4 3.6 3.8
OA B X [mm]



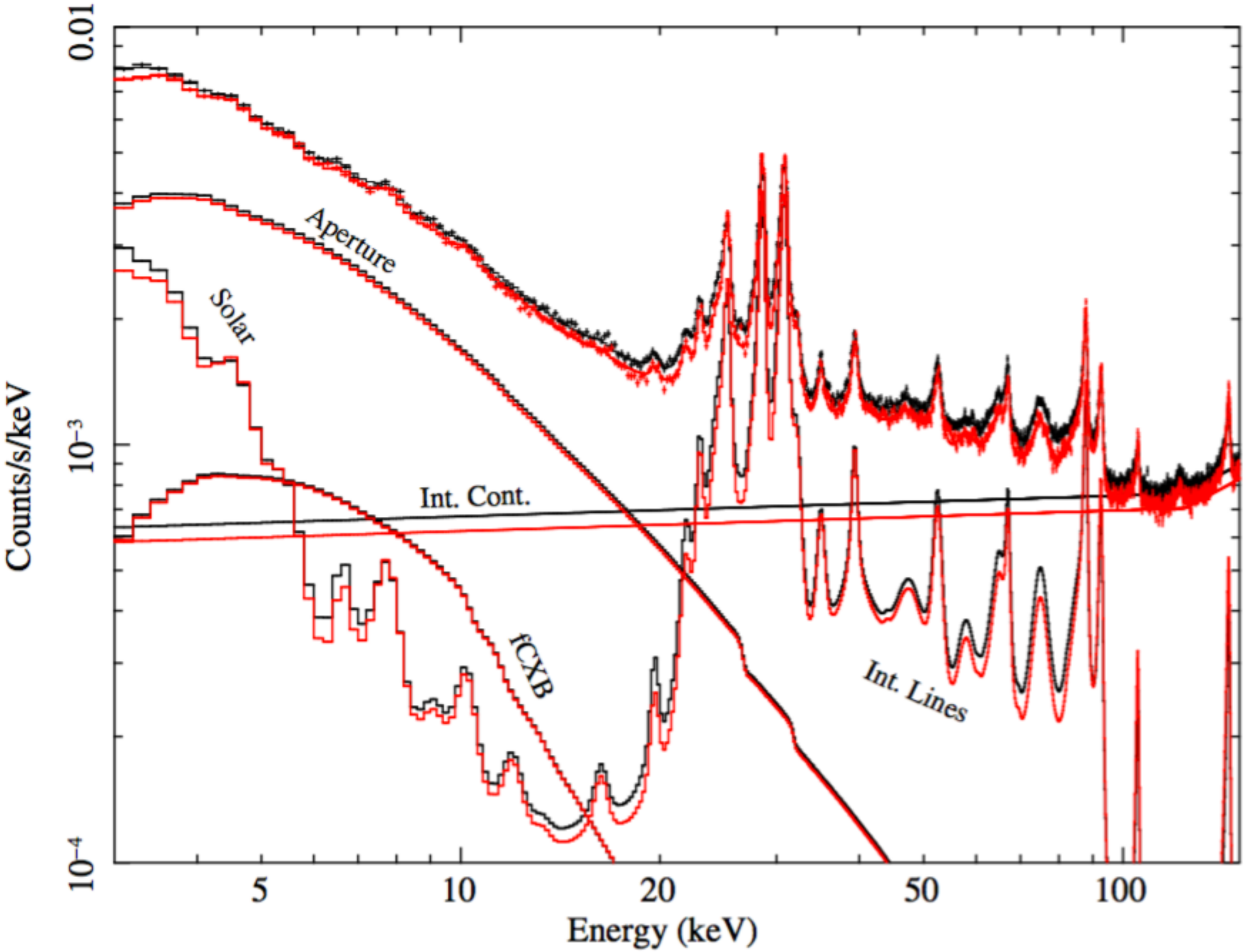
PSF shape distorts off-axis (squishes mostly)



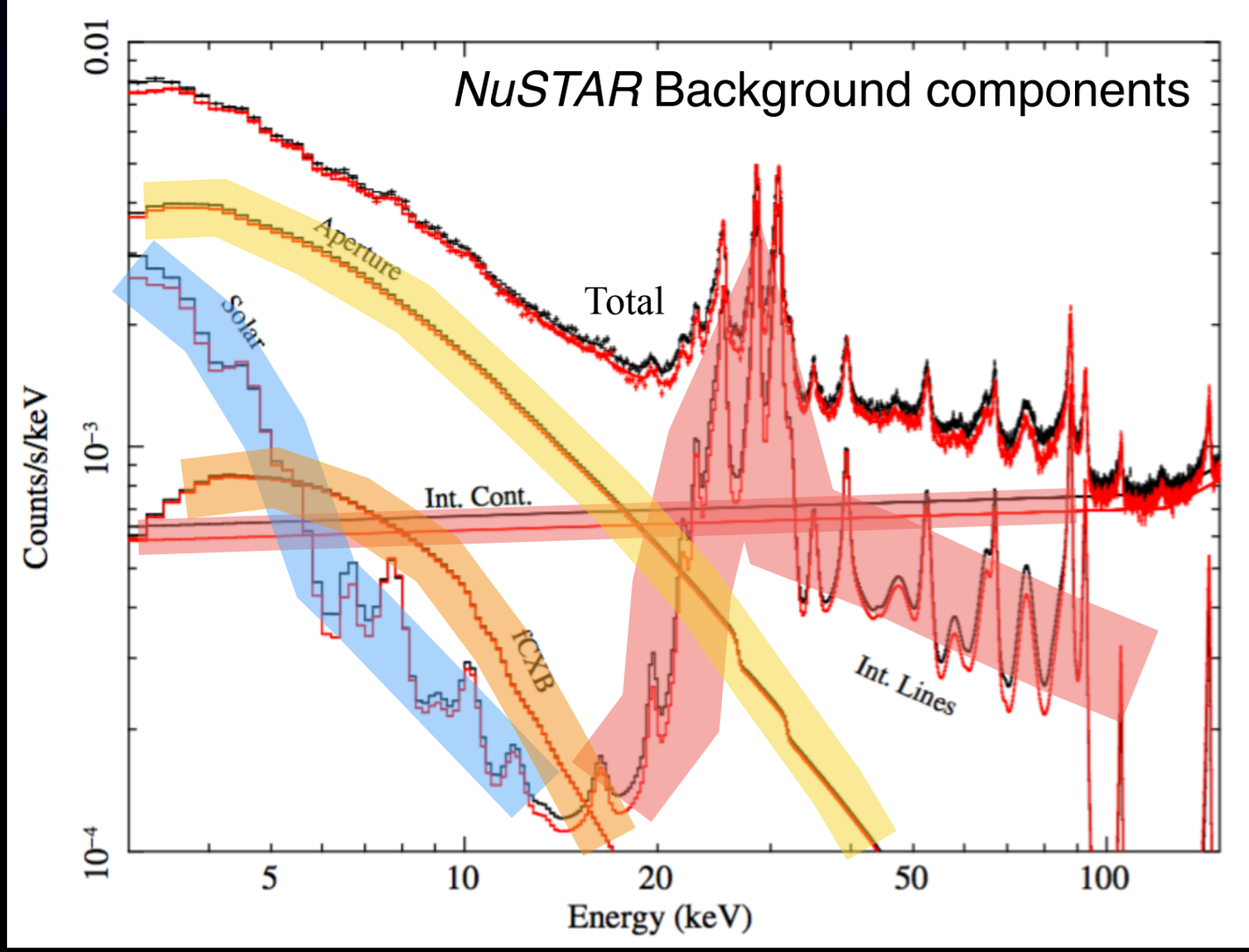




Collecting area drops too



from Wik et al. 2014



Solar

Cosmic Ray

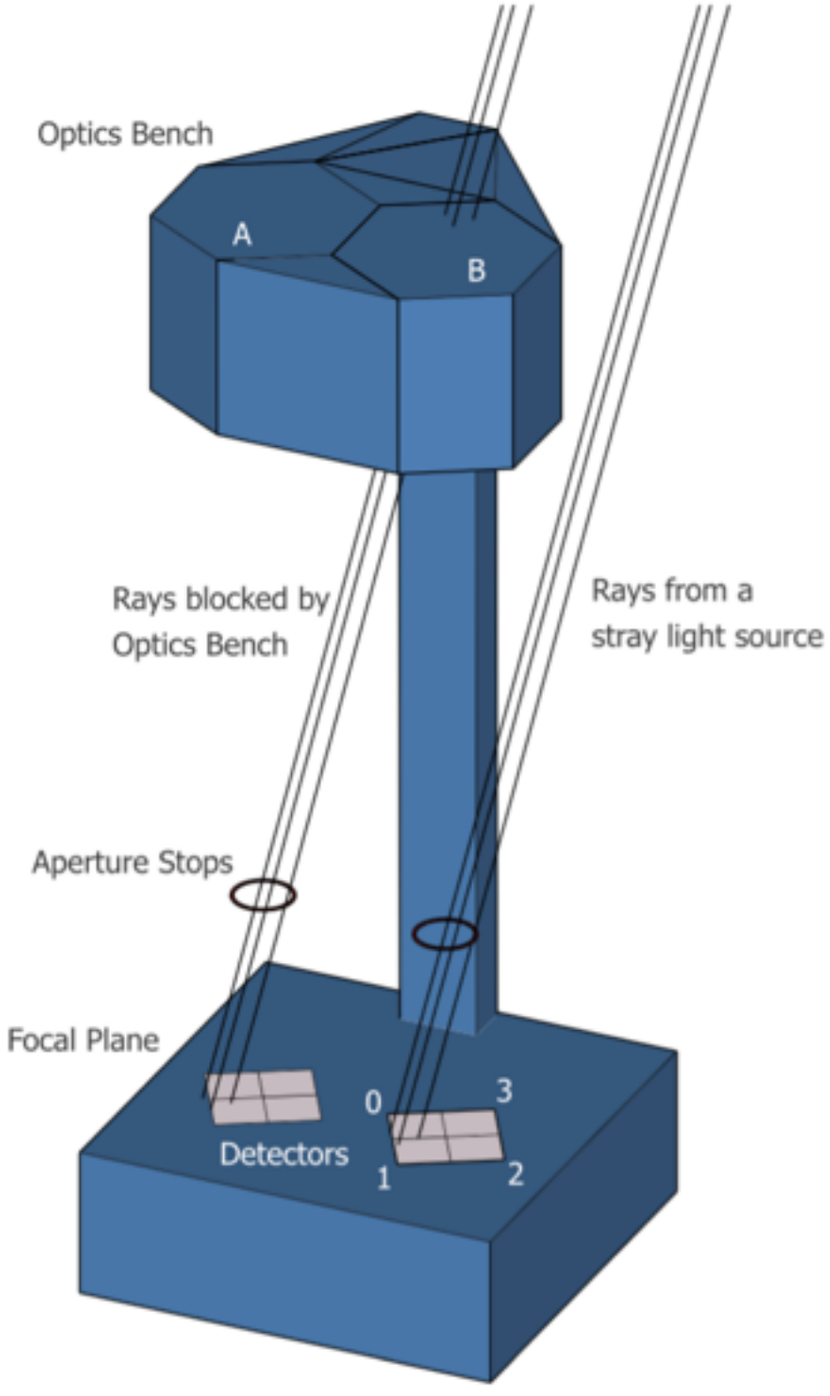
Internal Lines & Continuum

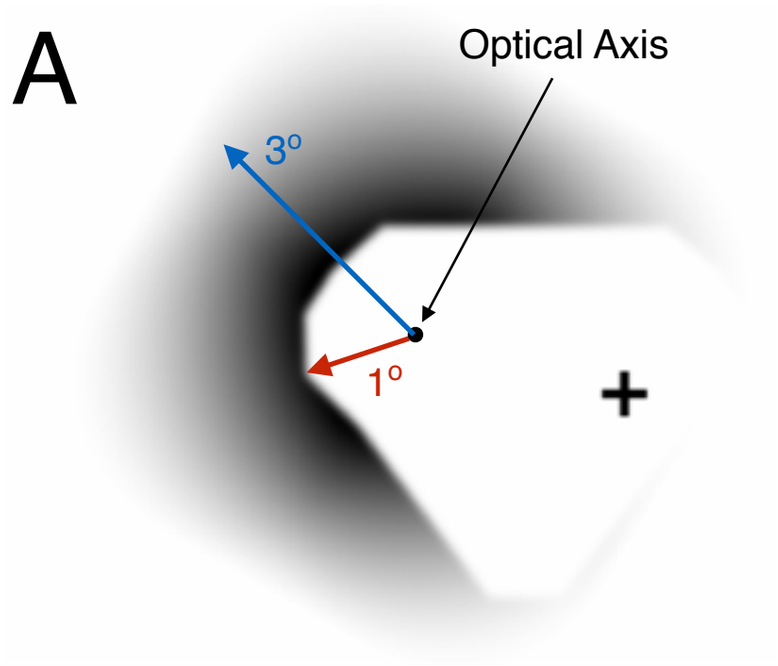
Earth Albedo

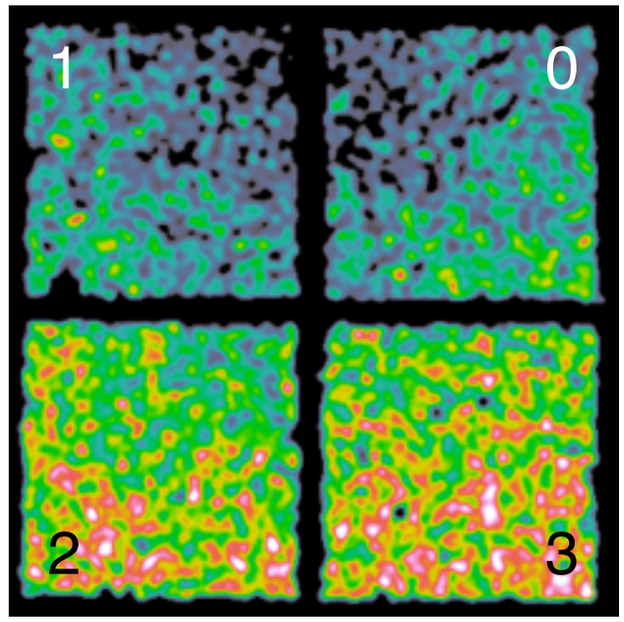
Aperture (aCXB)

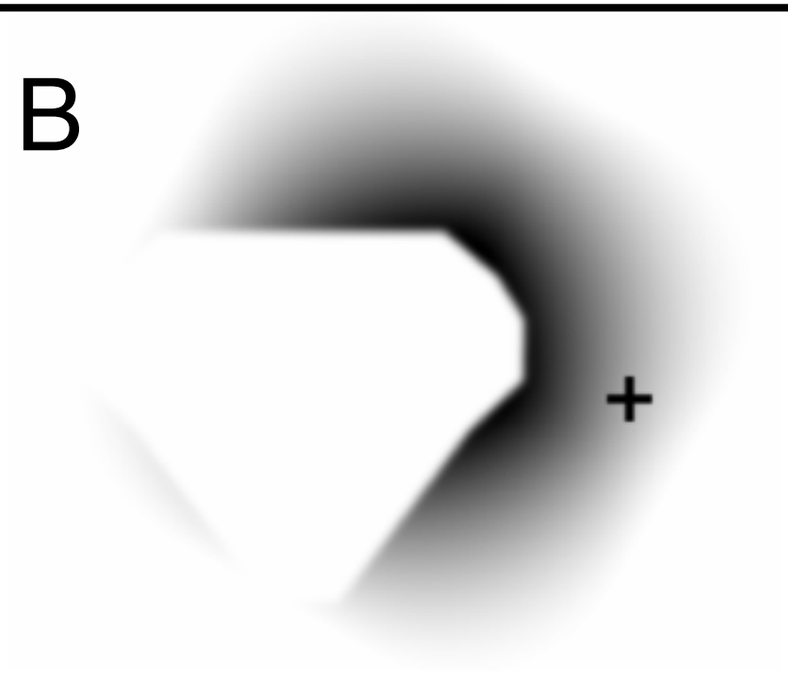
focussed (fCXB)

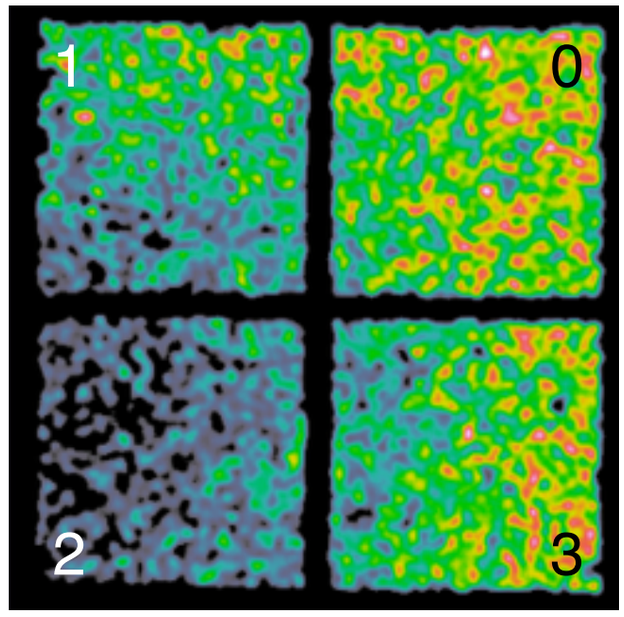
From 3-20 keV, background is dominated by stray light from a large area of (blank) sky —> Cosmic X-ray Background





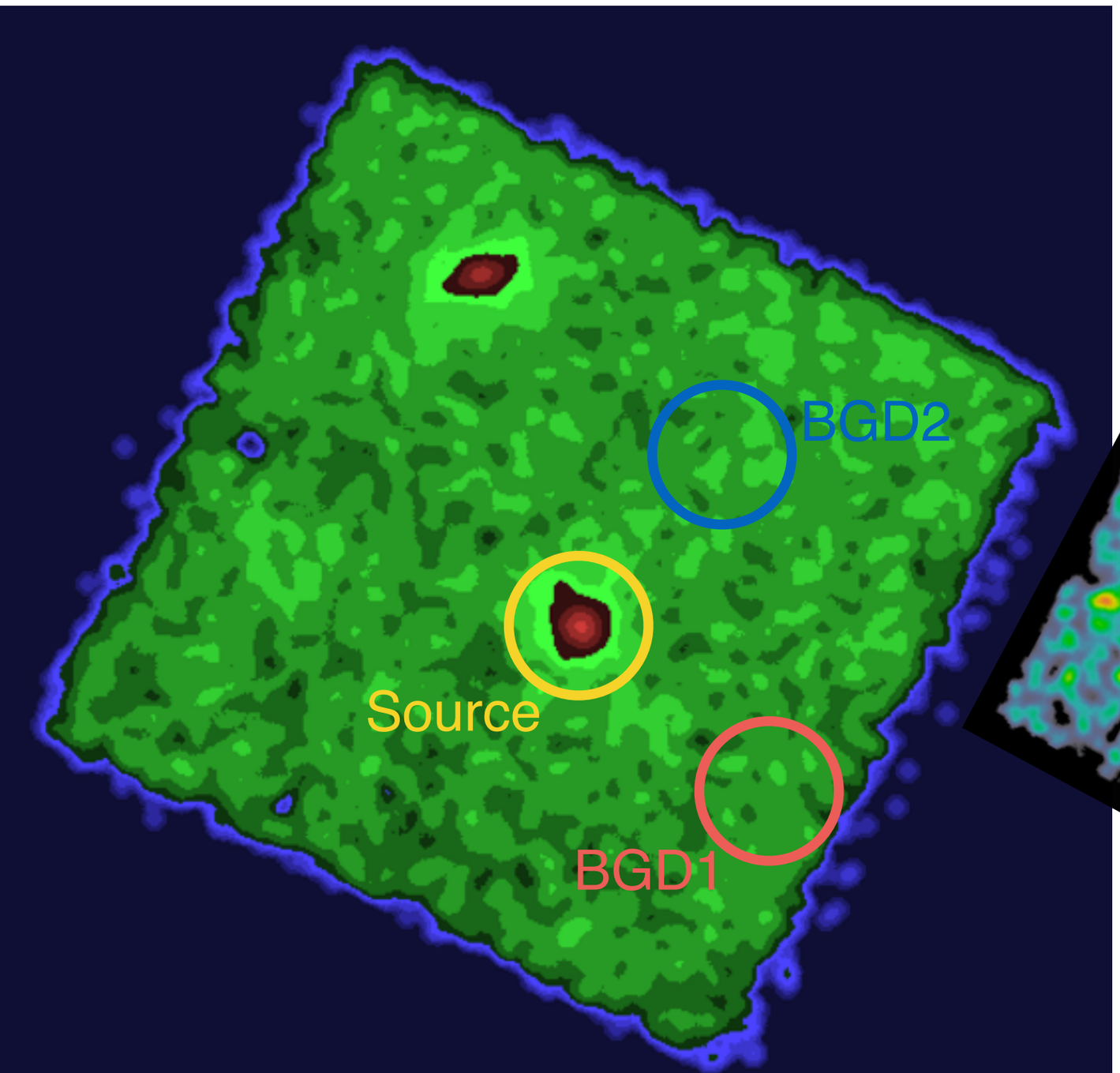


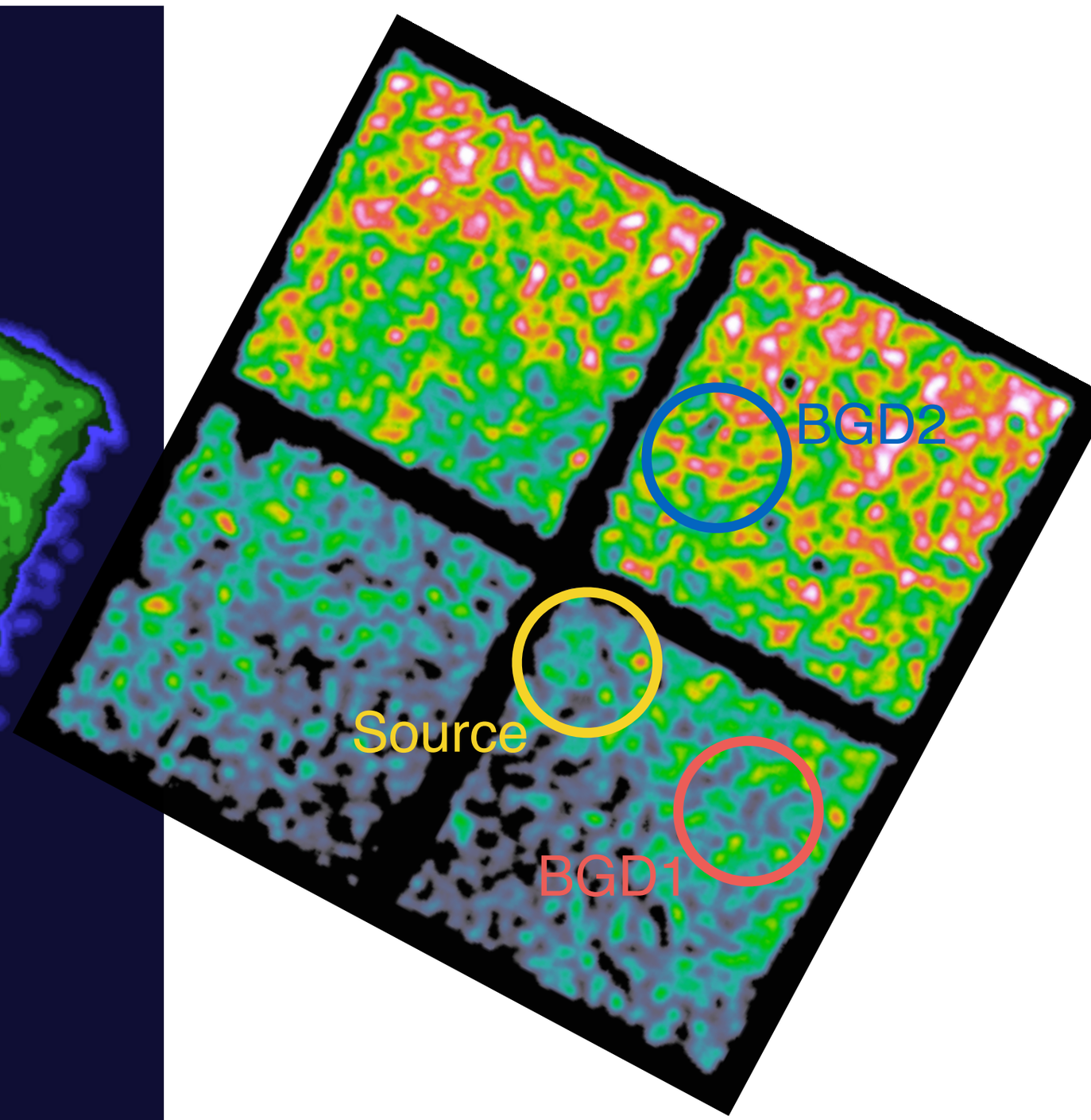




Background

Need to be careful where you place a background region.
Better yet, model the background with
nuskybgd: Wik et al. 2014, ApJ, 792, 48



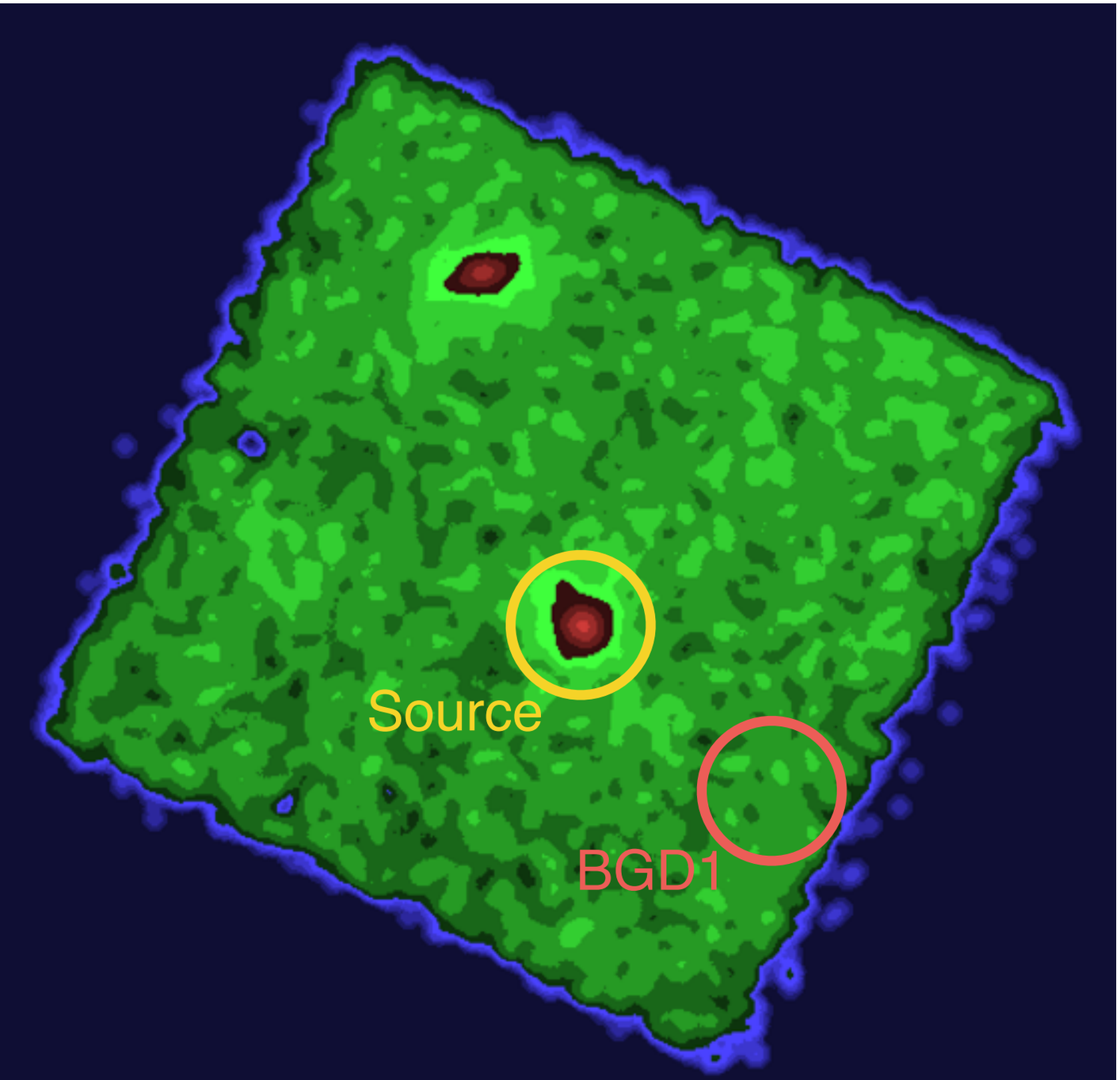


Extracting and fitting a spectrum

- Typical procedure is to “forward-model” data instead of correcting the data for instrumental effects
    - Leave data (PHA) in original form (counts per energy bin, counts per E bin per second), but subtract background (BGD or BKG)
    - Start with a physical model for incoming X-rays (F[E]—>photons/cm^2/s/keV)
        - Multiply model by effective area as a function of E (auxiliary response function, ARF)
        - Convolve model with detector energy resolution and quantum efficiency (redistribution matrix function, RMF)
    - Modify model parameters until model matches the data
- The nustardas software `nuproducts` can extract these files for a given region, assuming the source is point-like and located at the center of the region

What does the software do?

(makes files that allow fitting in XSpec)



- PHA/BGD: Searches the event file for all events within the source and background regions, saves them to separate FITS files
- ARF
  - Computes the fraction of time the source is at different off-axis angles, constructs an effective area $A_{eff}(E)$
  - Computes the average PSF shape and corrects for the fraction of photons that fall outside the region
- RMF
  - Computes the fraction of events coming from each detector
  - Computes a weighted average of the single detector RMFs

- 4096 energy channels (PIs), 40 eV wide, 1.6 keV to ~160 keV (but no collecting area above 79 keV)
    - E (keV) = PI * 0.04 + 1.6 keV
- PSF is NOT Gaussian, but has a King profile (larger wings)
    - Full Width at Half Maximum (FWHM) ~18”
    - Half Power Diameter (HPD) ~1’

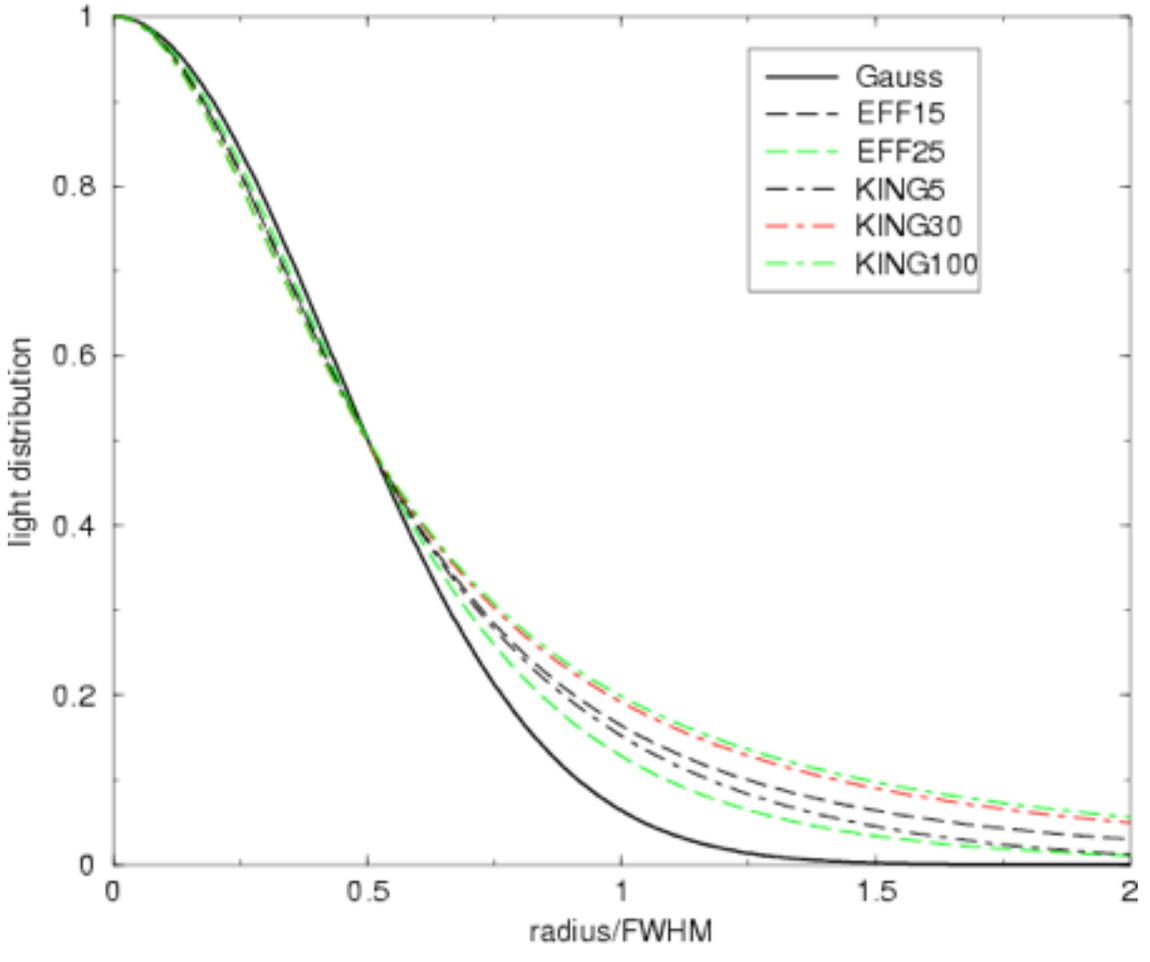
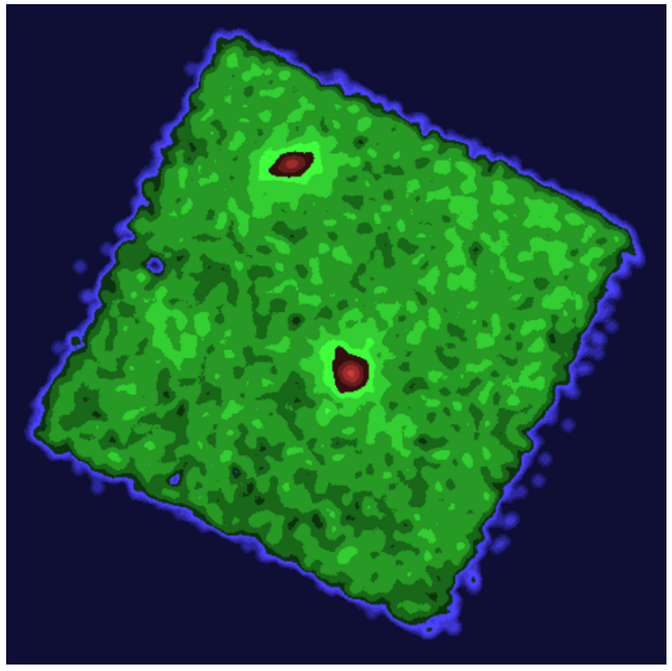
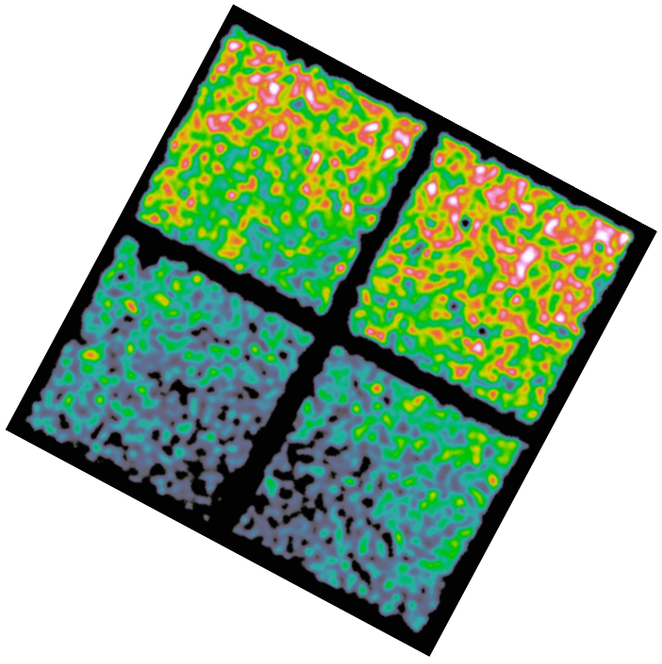


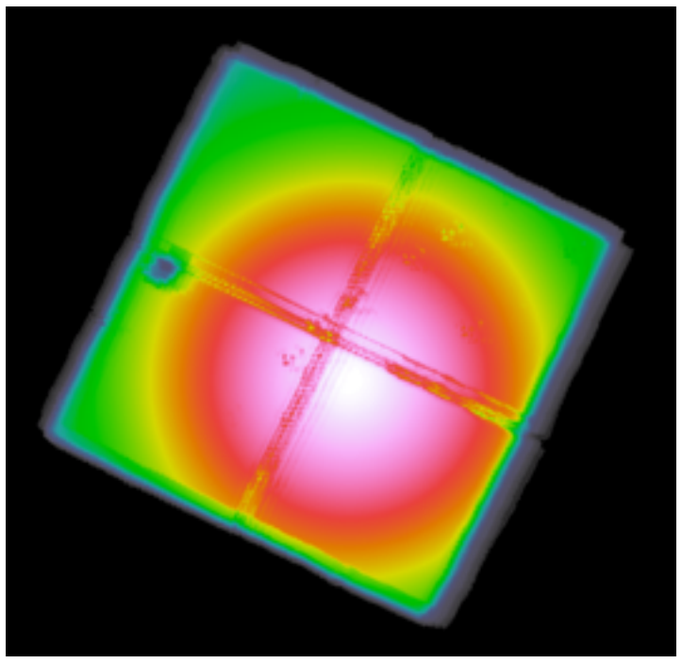
Image Analysis

- Extract an image in some energy band (select correct PI channels)
- Create a background image (`nuskybgd`)
- Create an exposure map (`nuproducts`) at the average energy <E> of *source counts* of interest
    - Exposure map reduces exposure time at each pixel according to the vignetting of A_{eff} (<E>)
    - For point sources, you want to use the central value
- Make a rate image: (data-bgd) / exp
    - fine for display, but not so useful for science

$$\left(\quad - \quad \right)$$







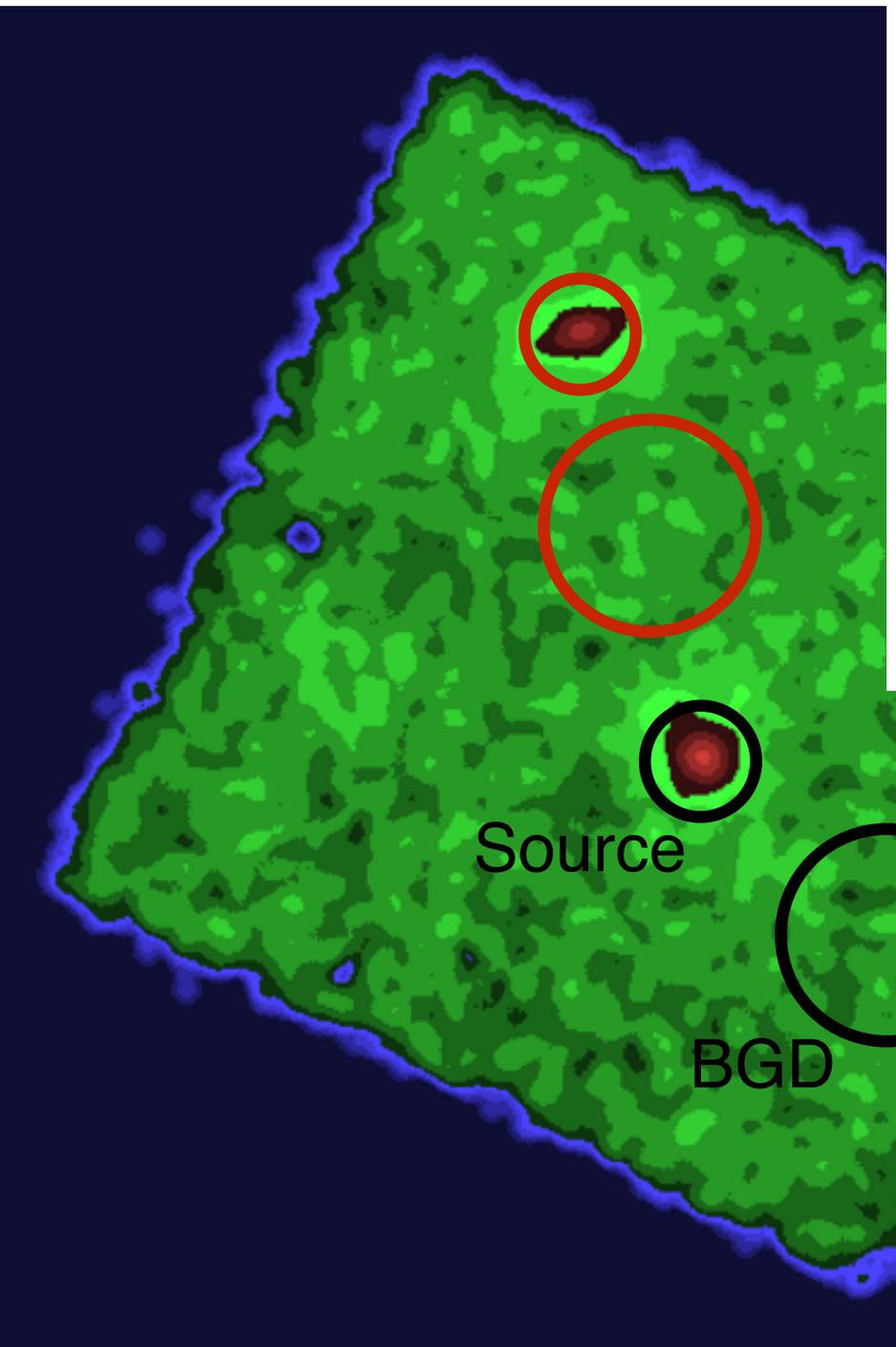
- In practice for point sources, better to work on each image individually to get a RATE
    - Get counts within an aperture (your region)
    - Correct for source counts that fall outside of the region based on the PSF at that position
    - Subtract the expected number of background counts inside that region
    - Divide by the exposure time at that position

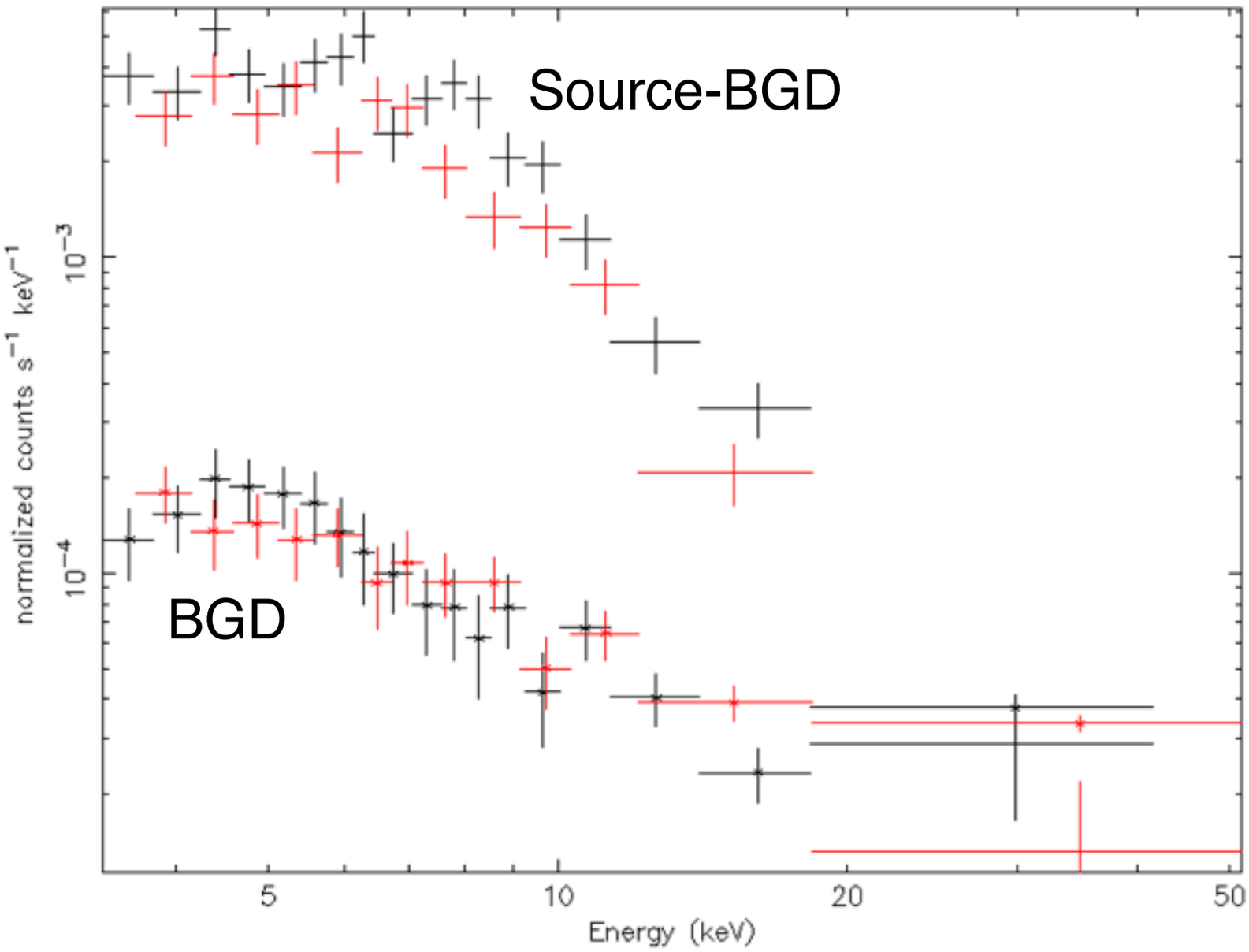
Tools to Use

- `XSpec`: distributed with `HEASoft`, good if old-school spectral fitting package

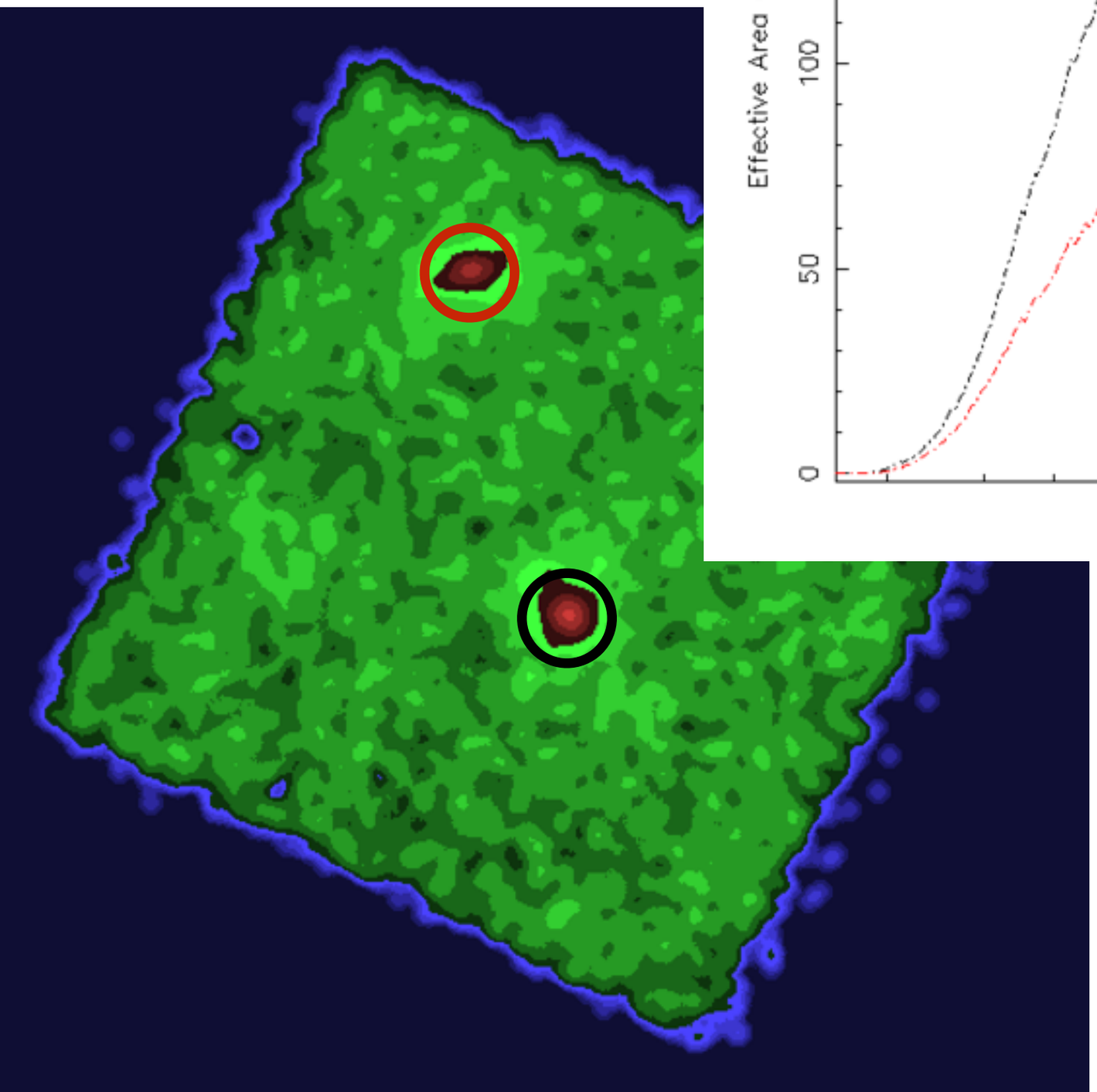
- Background: `nuskybgd`, publicly available on github (ask me for correct distribution, will need some help to get started most likely)

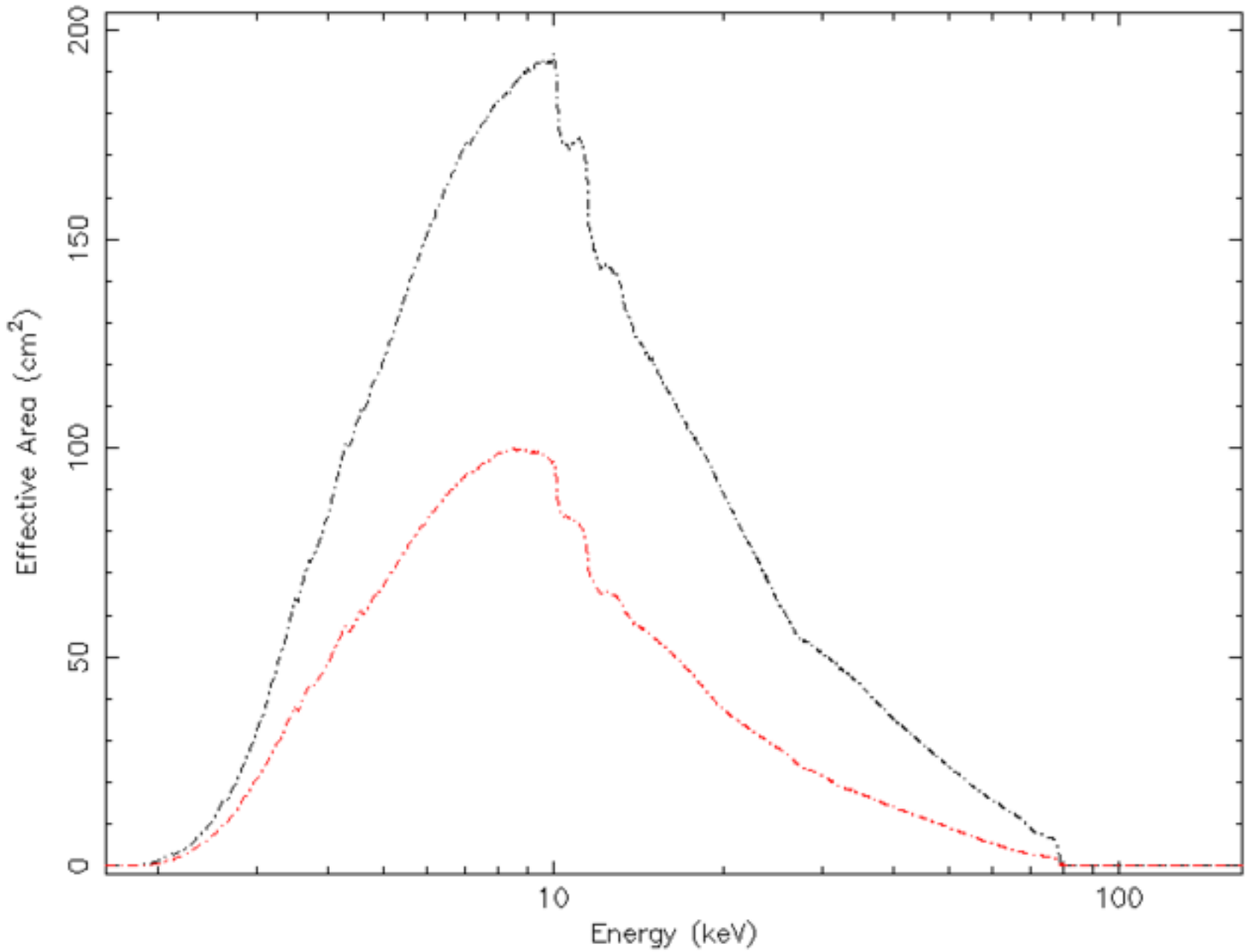
- Image fitting: `nuskycube`, privately available on my computer, still in beta for non-me users

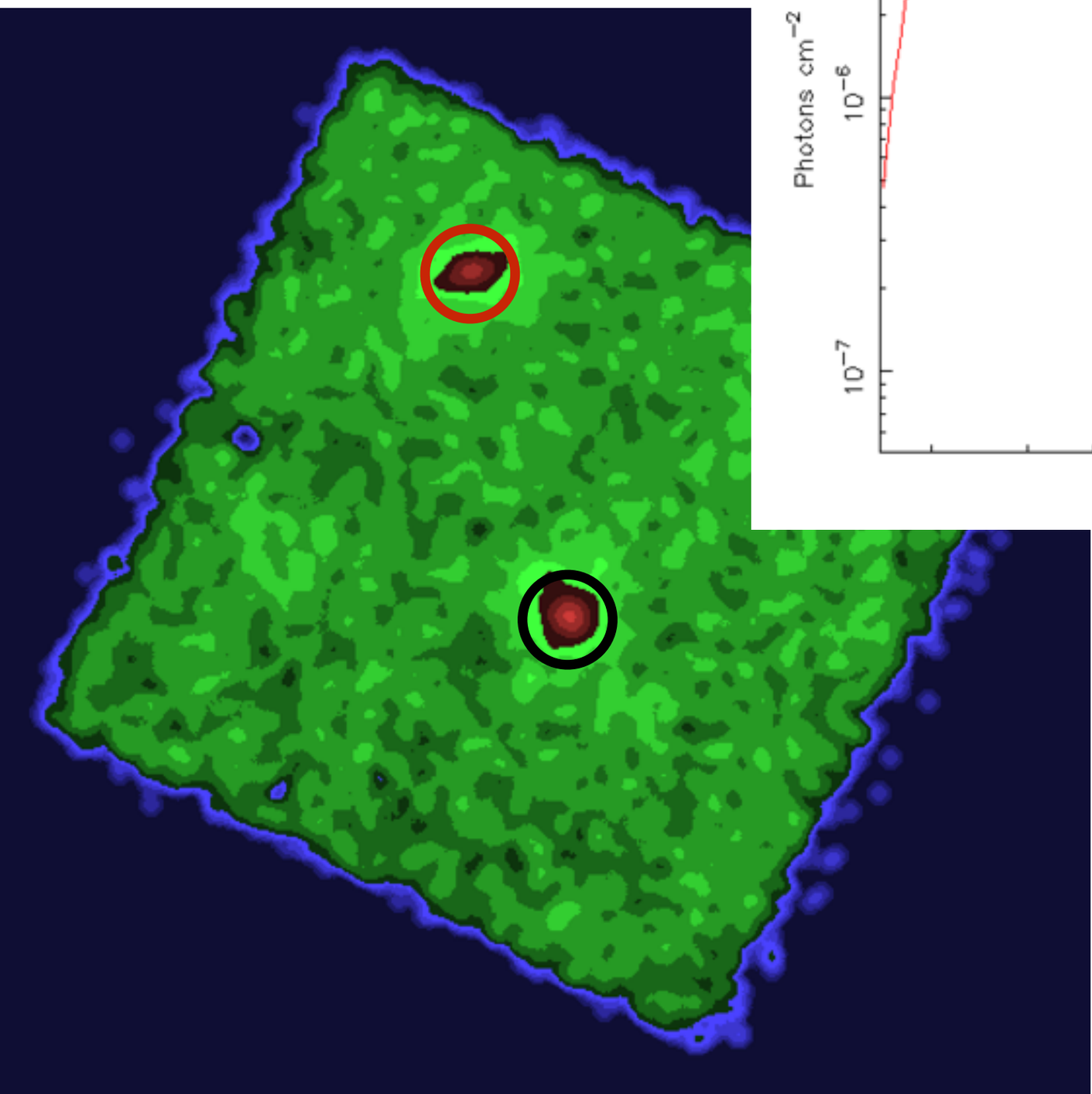


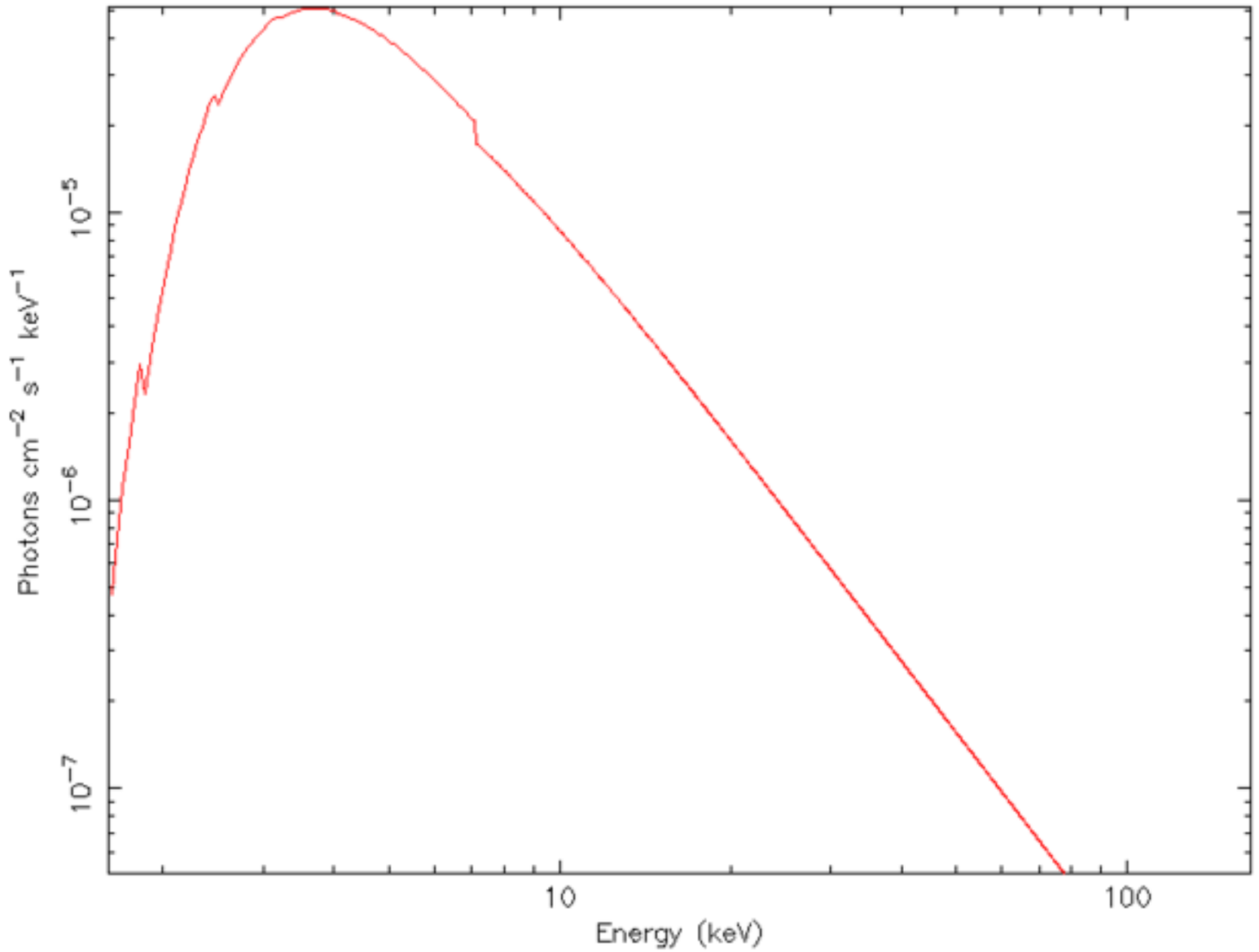



```
prompt> xspec
XSPEC12> data src1A_sr_g30.pha
XSPEC12> response src1A_sr.rmf
XSPEC12> arf src1A_sr.arf
XSPEC12> data 2 src2A_sr_g30.pha
XSPEC12> response 2 src2A_sr.rmf
XSPEC12> arf 2 src2A_sr.arf
XSPEC12> ignore **:***-3.,79.-**
XSPEC12> setplot energy
XSPEC12> setplot background
XSPEC12> cpd /xs
XSPEC12> plot ldata
```

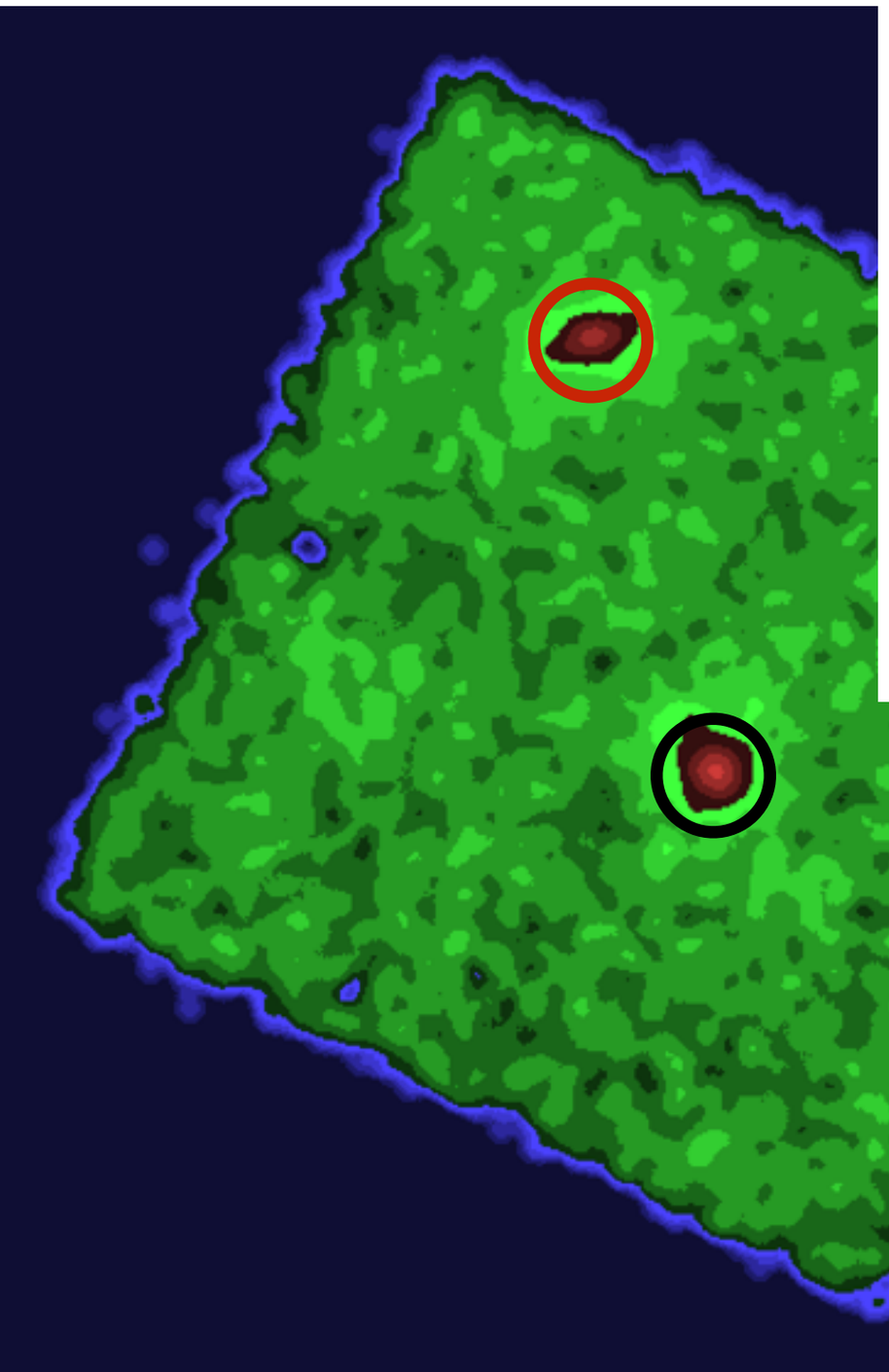


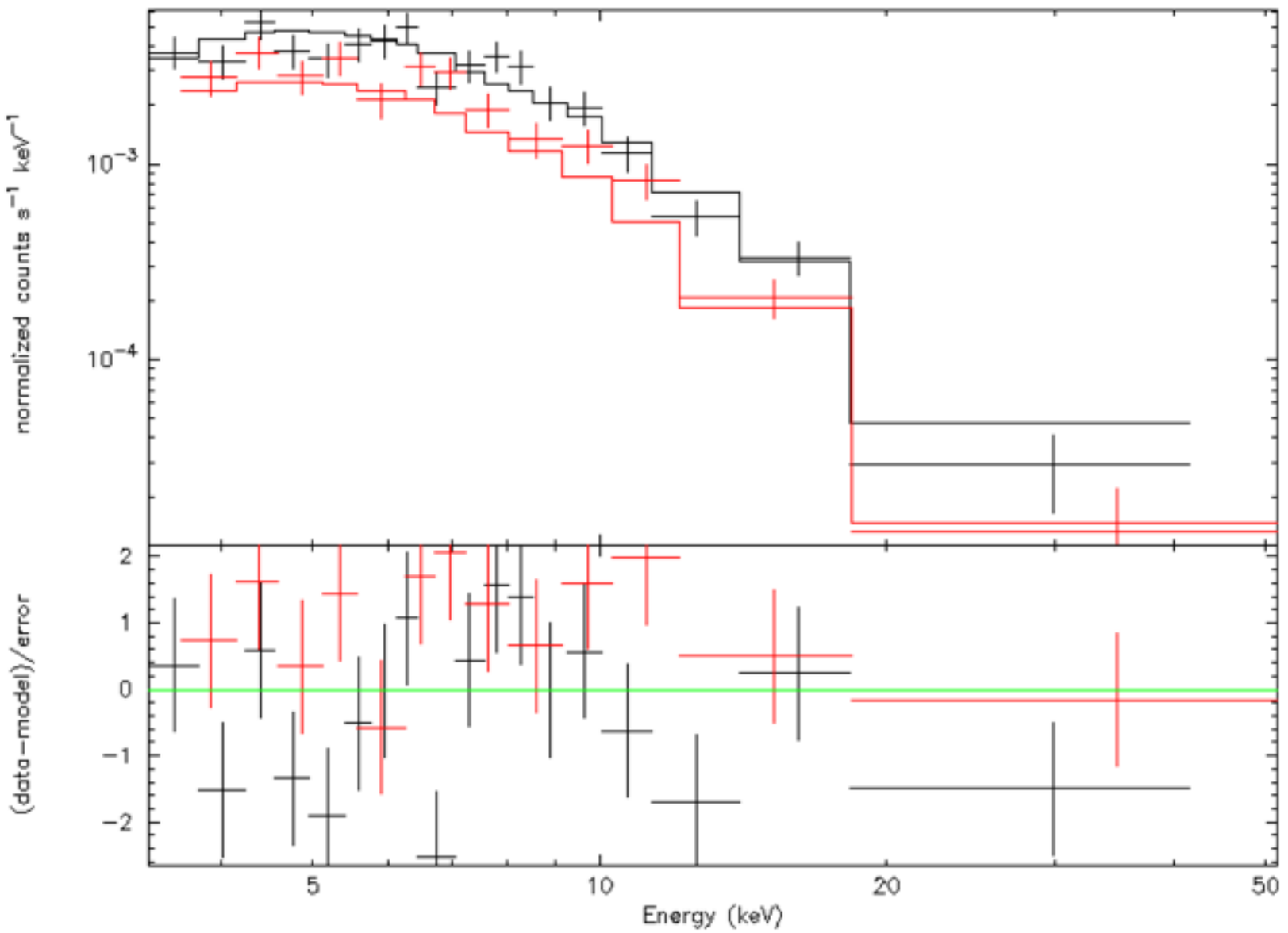

200
150
100
50
0
Effective Area (cm^2)
10
100
Energy (keV)






```
XSPEC12> model phabs*powerlaw & 1. & 2. & 1.
XSPEC12> renorm
XSPEC12> fit
XSPEC12> plot model
```





XSPEC12> plot ldata delchi