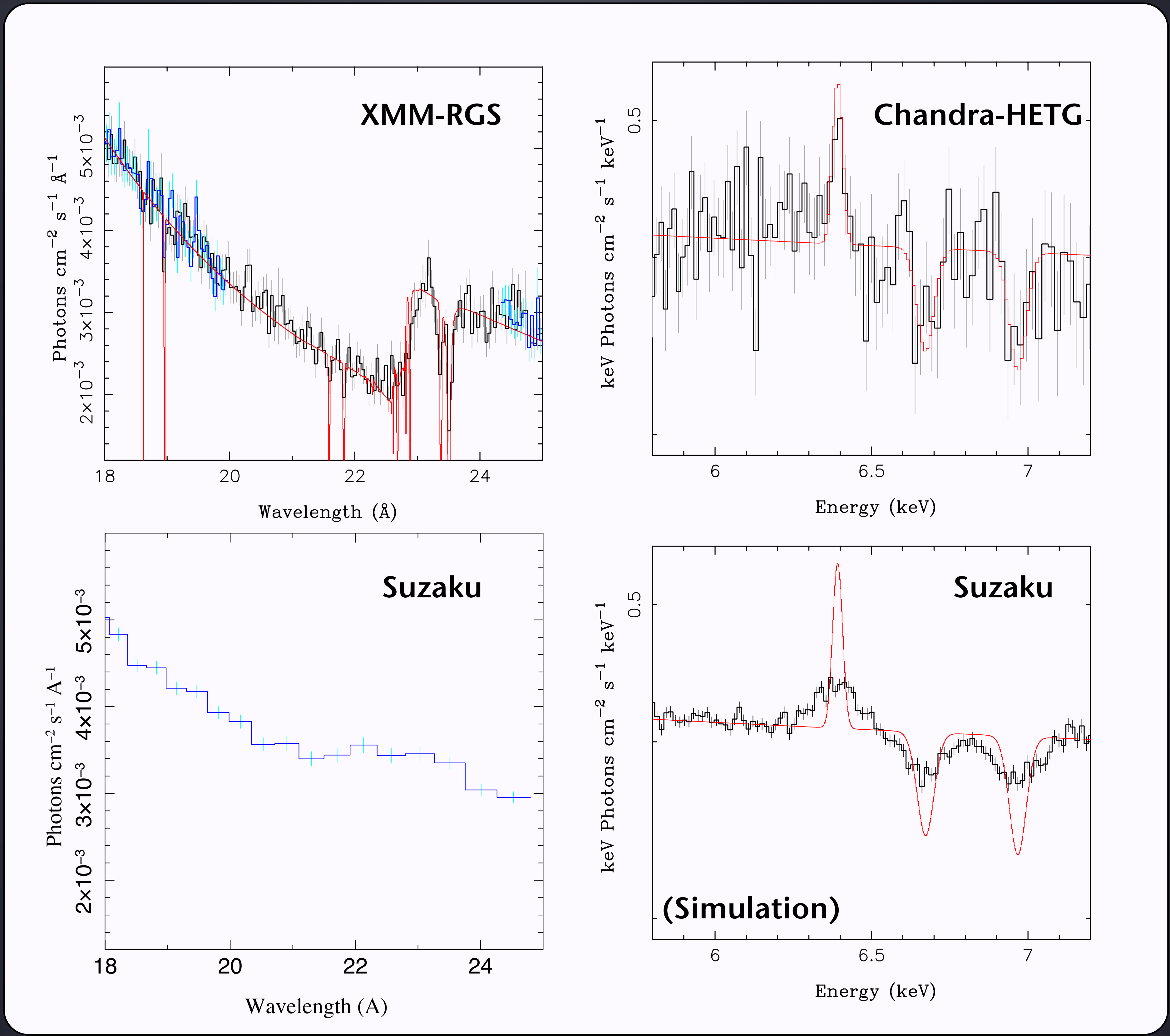
High Resolution X-ray Spectroscopy

Michael A. Nowak (MIT-Kavli Institute)

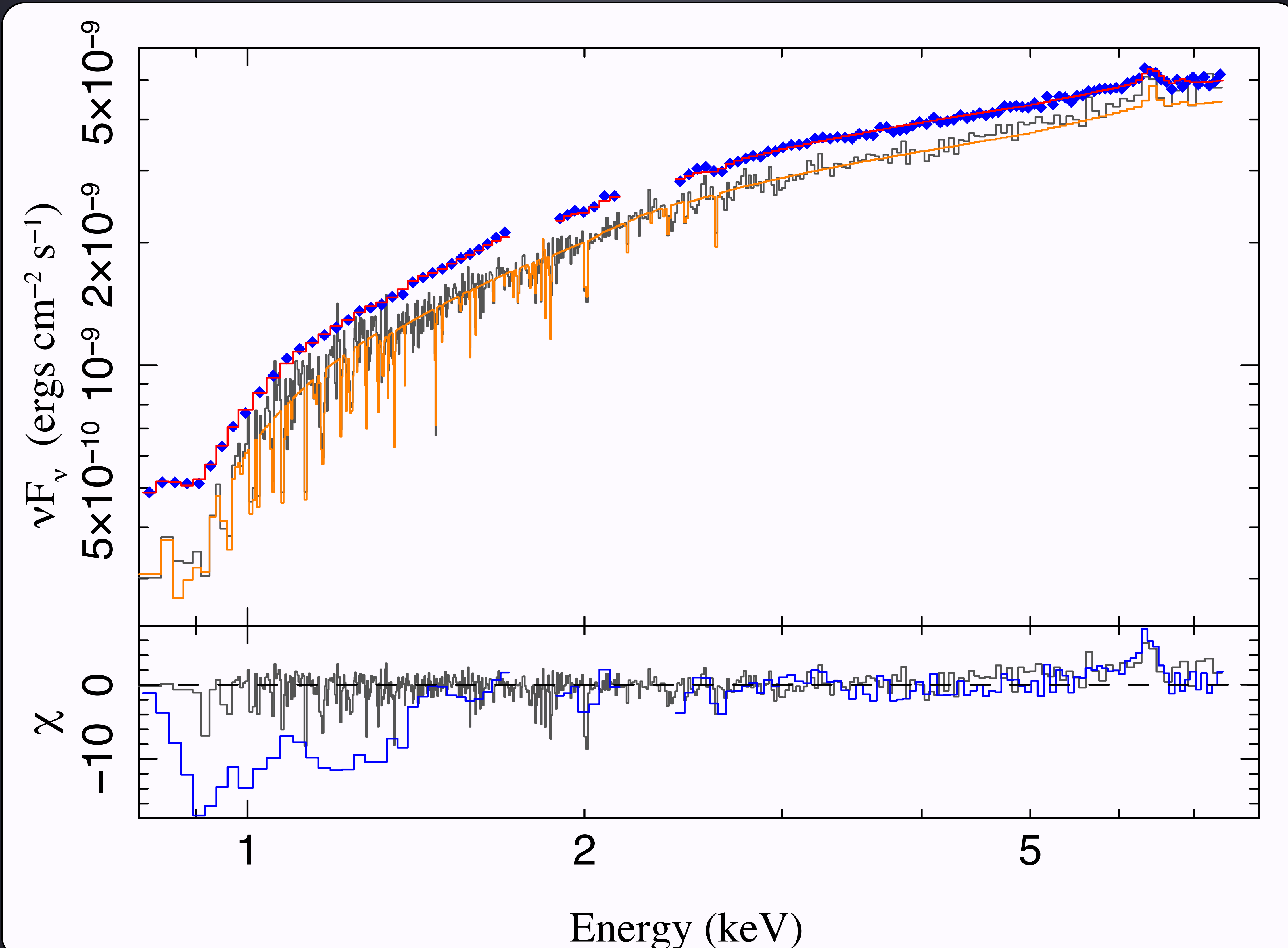
What Do We Mean by High Resolution?

- CCD Spectral Resolution (Suzaku):
  $E/\Delta E_{FWHM}$ ~18 @1 keV, ~46 @6.4 keV (scales as $E^{0.5}$)
- Gratings Spectral Resolution:
  $E/\Delta E_{FWHM}$ ~314 @1 keV (XMM-RGS)
  $E/\Delta E_{FWHM}$ ~1350 @1 keV, ~214 @6.4 keV (Chandra-HETG)
- Scales as E^{-1} (explanation coming up…)
- To date, X-ray High Resolution Means Gratings – Chandra-Low/High Energy Transmission Gratings & XMM-Reflection Gratings Spectrometer
- Near future, X-ray Calorimetry with Micro-X, XARM, ΔE_{FWHM} ~5–7 eV, $E/\Delta E_{FWHM}$ ~1000 @6.4 keV (scales as E)

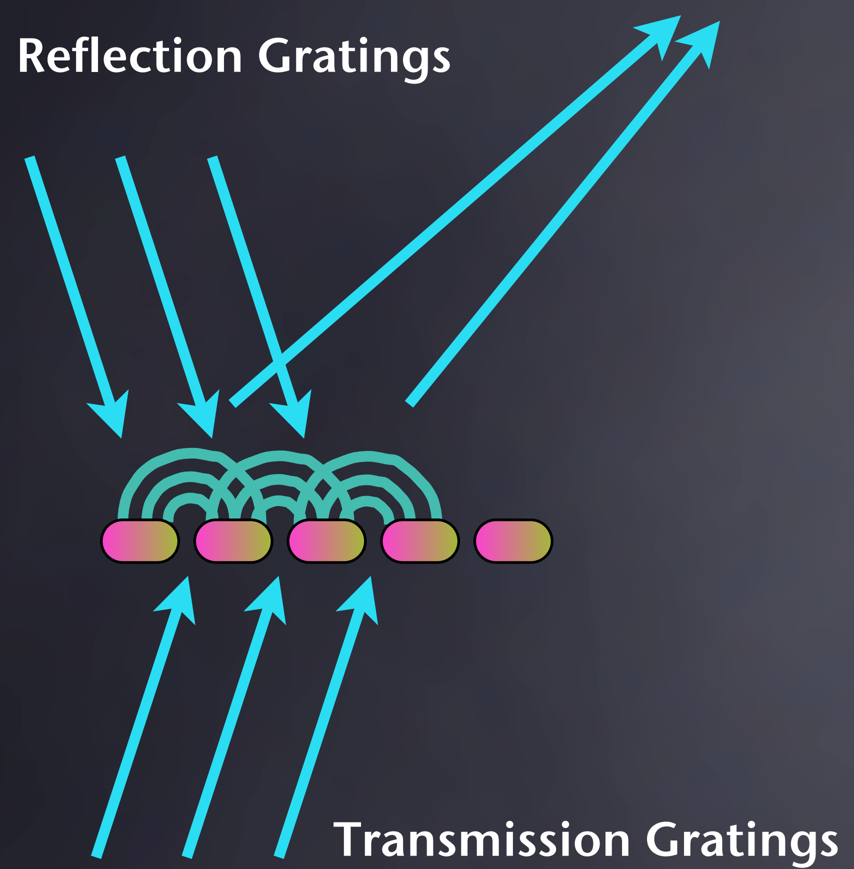
High/Low Res Comparison

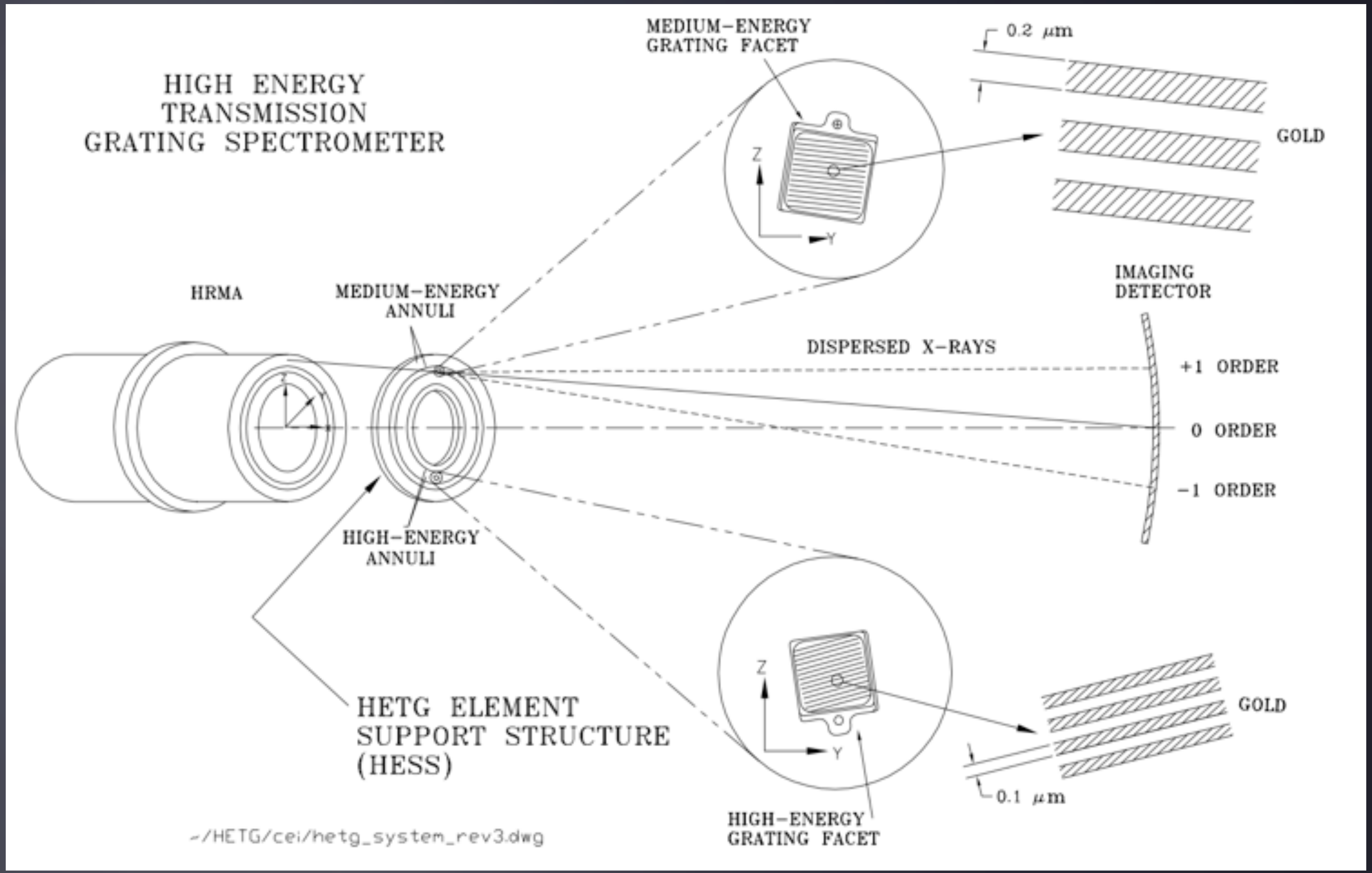


High/Low Res Comparison



Gratings

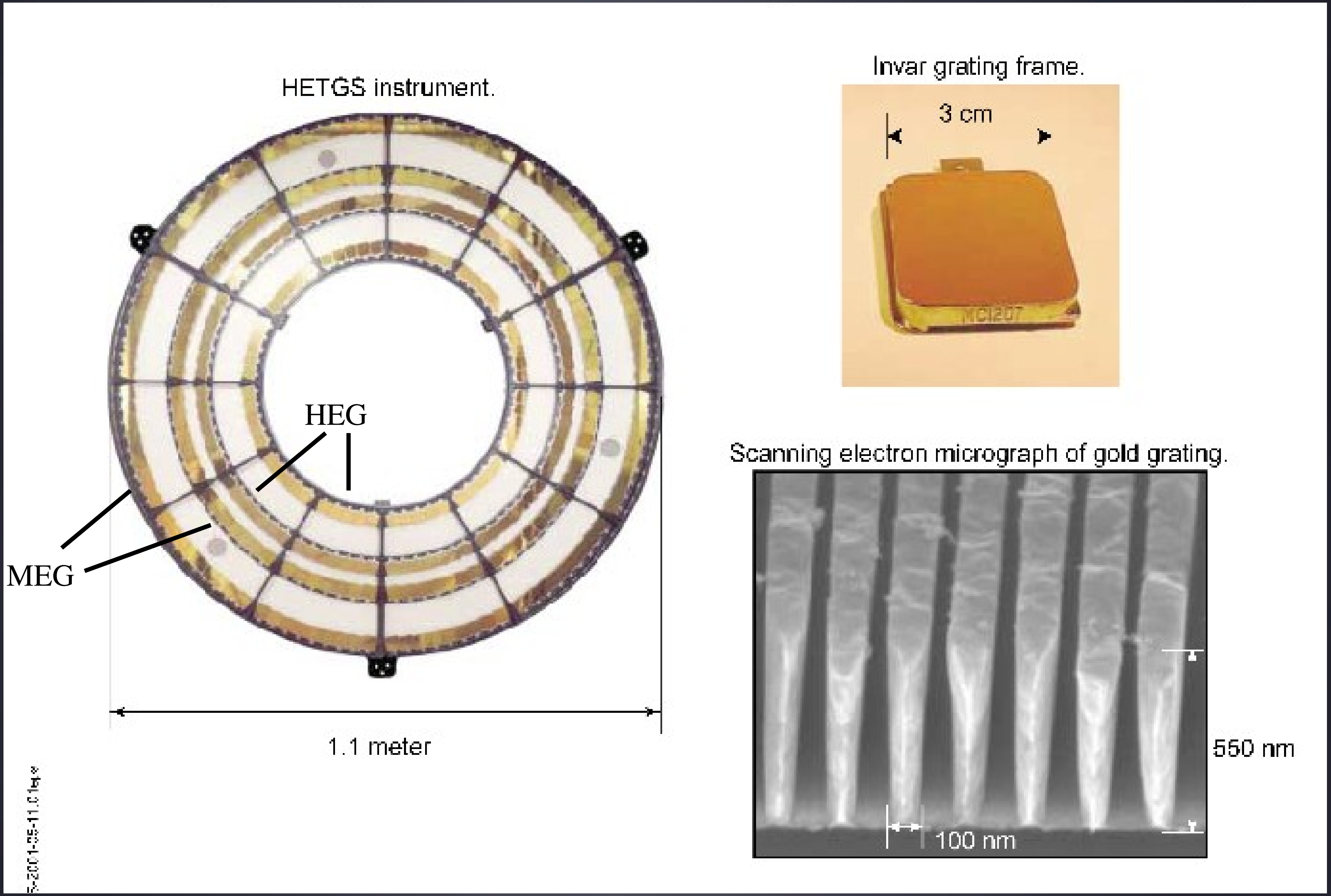




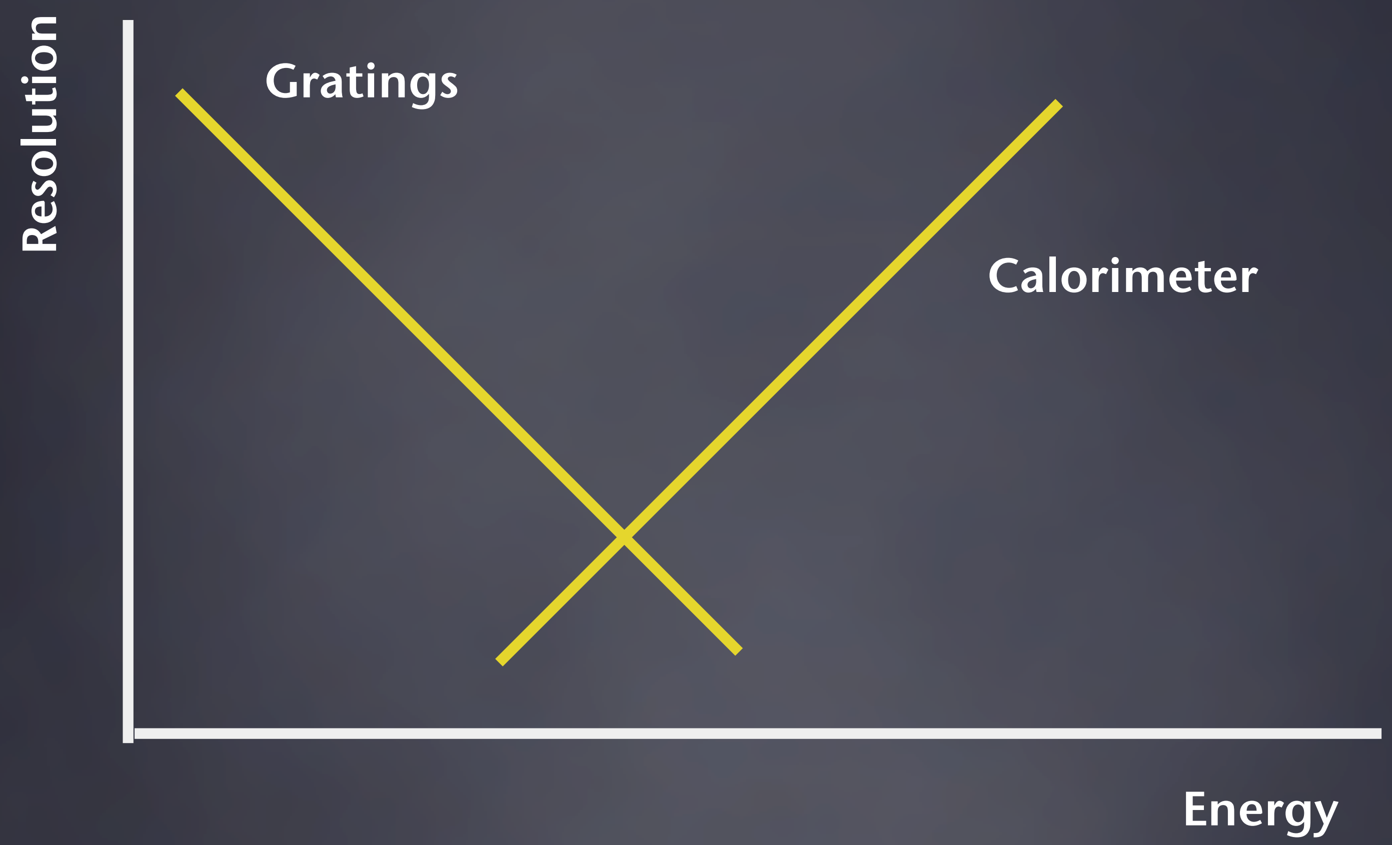
Gratings Equation:

$$\boxed{m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta}$$

Chandra-HETG



A Wistful Dream...

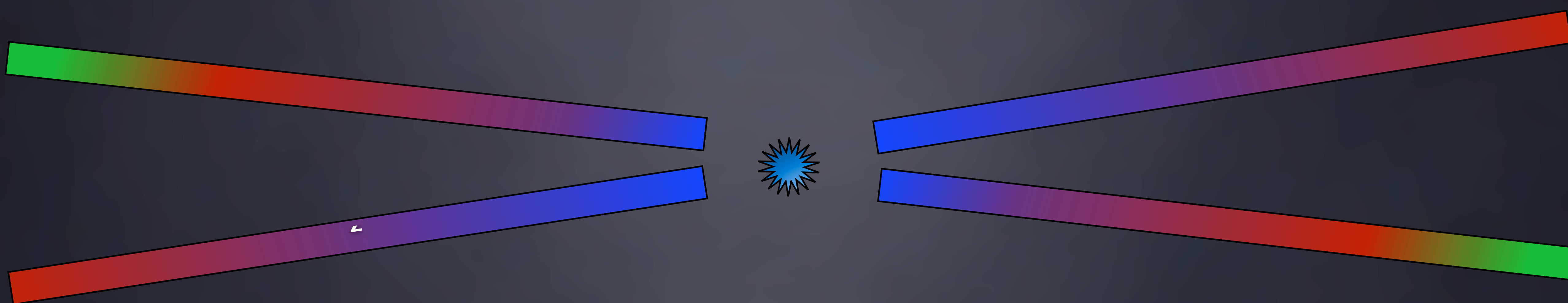


Lynx? (X-ray Surveyor)

$$m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta$$

LETG

HETG



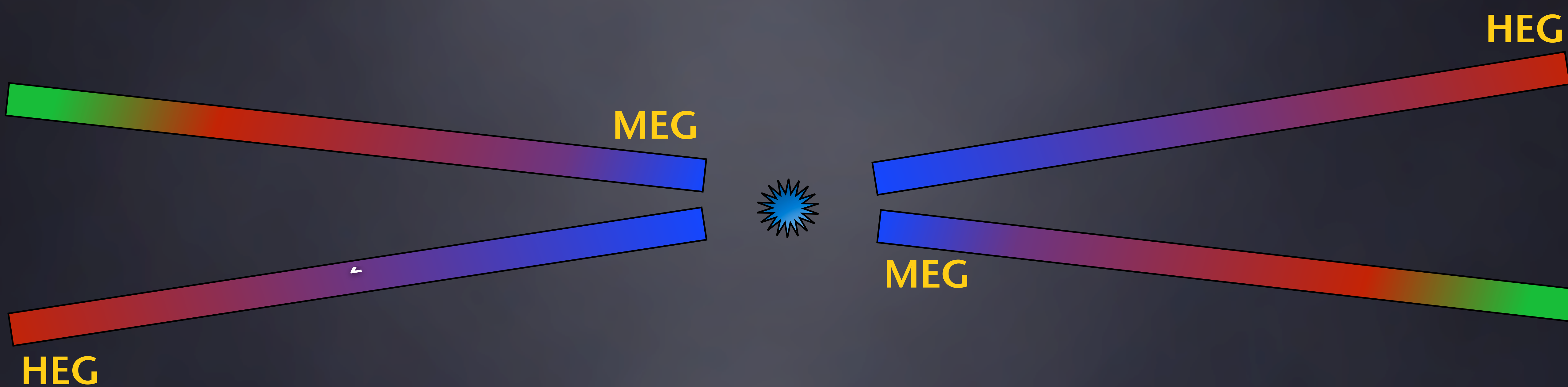
Greater Distance = Higher Resolution

Resolution Limited by CCDs & Gratings Accuracy

$$m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta$$

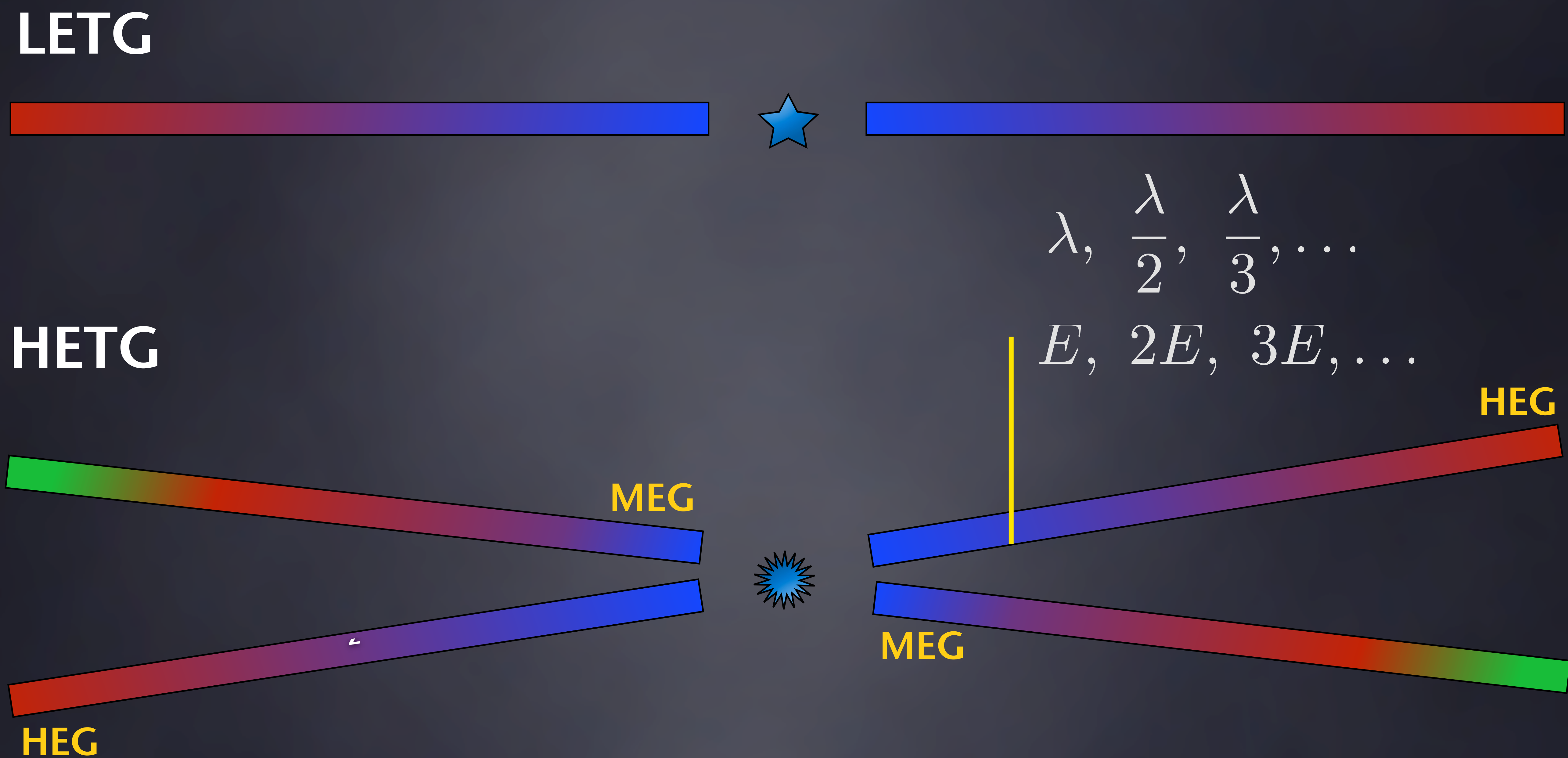
LETG

HETG



Greater Distance = Higher Resolution
Resolution Limited by CCDs & Gratings Accuracy

$$m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta$$



$$\lambda,\ \frac{\lambda}{2},\ \frac{\lambda}{3},\ldots$$

$$E,\ 2E,\ 3E,\ldots$$

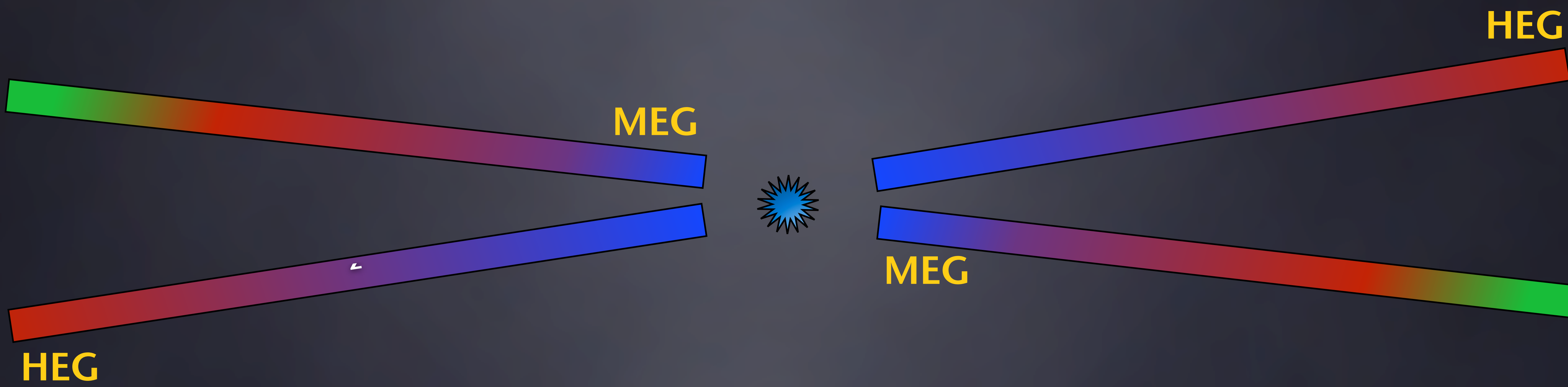
Greater Distance = Higher Resolution

Resolution Limited by CCDs & Gratings Accuracy

$$m\lambda = m\frac{hc}{E} = p\sin\beta \approx p\beta$$

LETG

HETG



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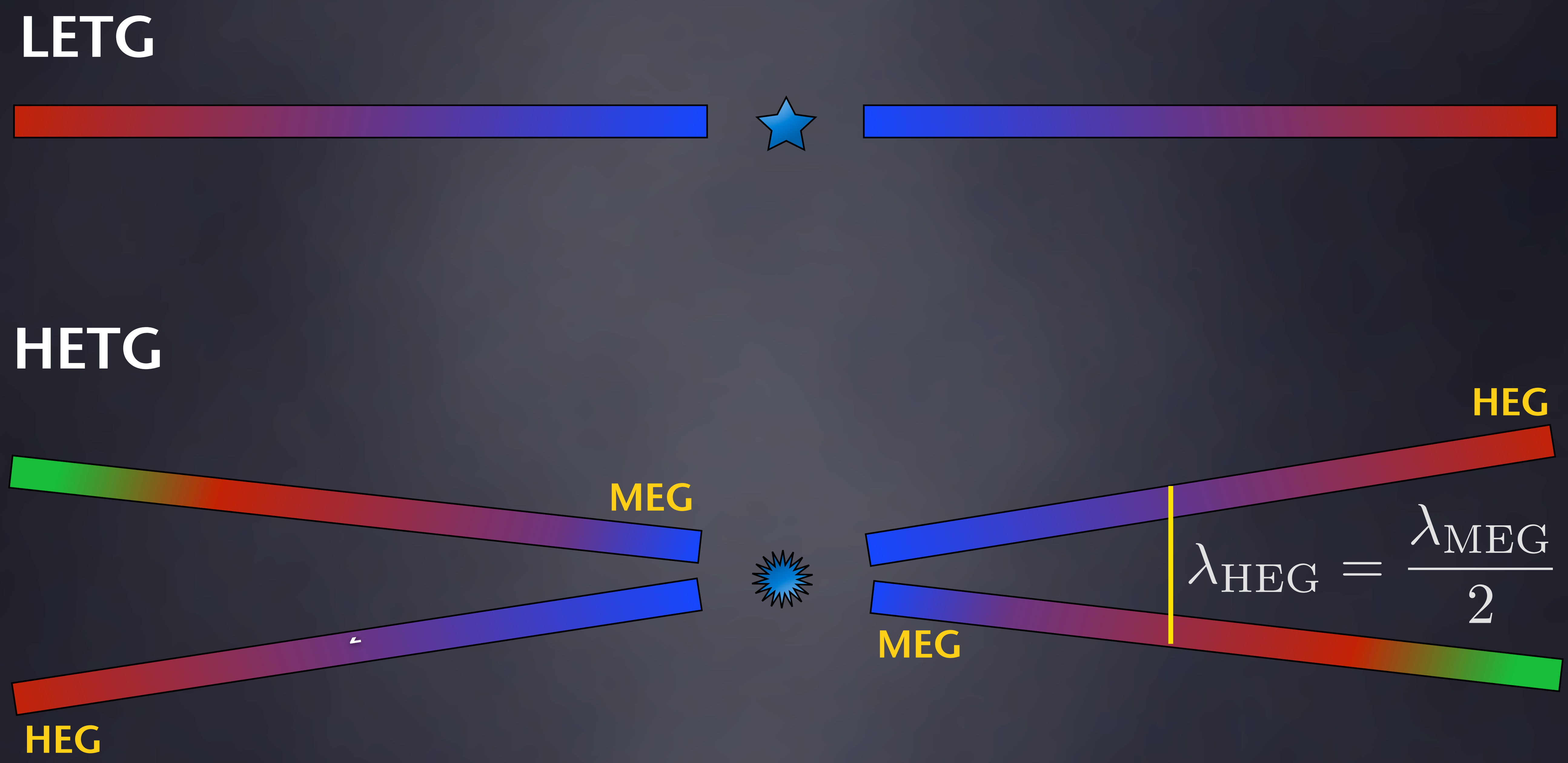
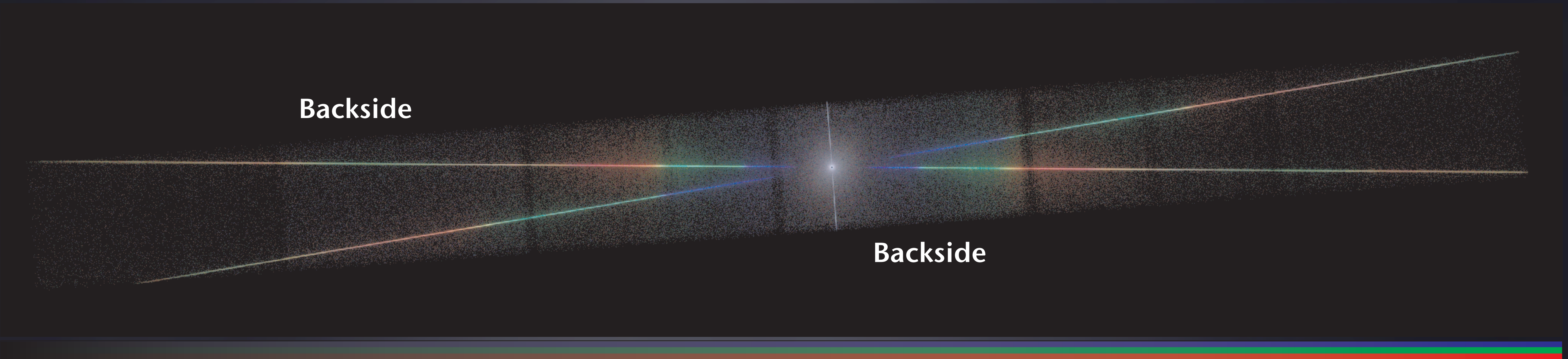


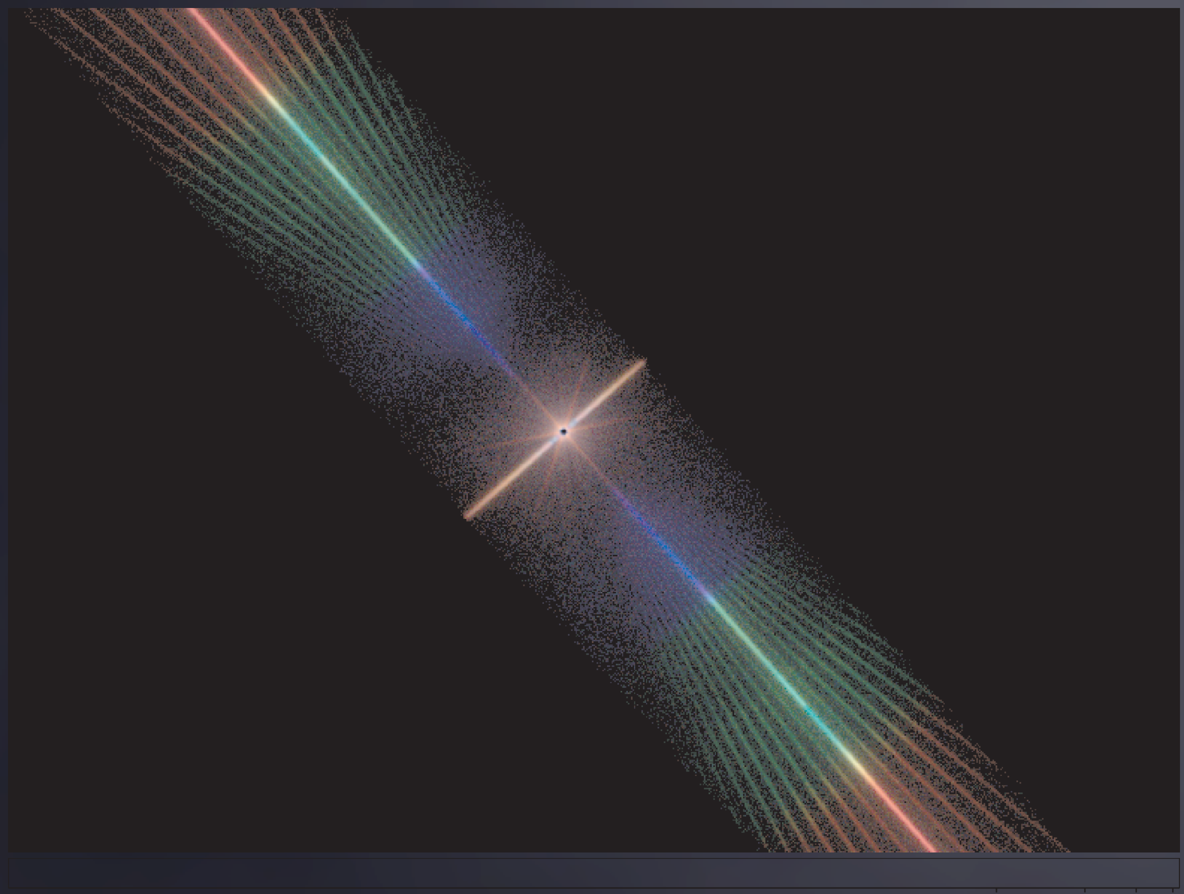
Greater Distance = Higher Resolution

Resolution Limited by CCDs & Gratings Accuracy

Chandra HETG

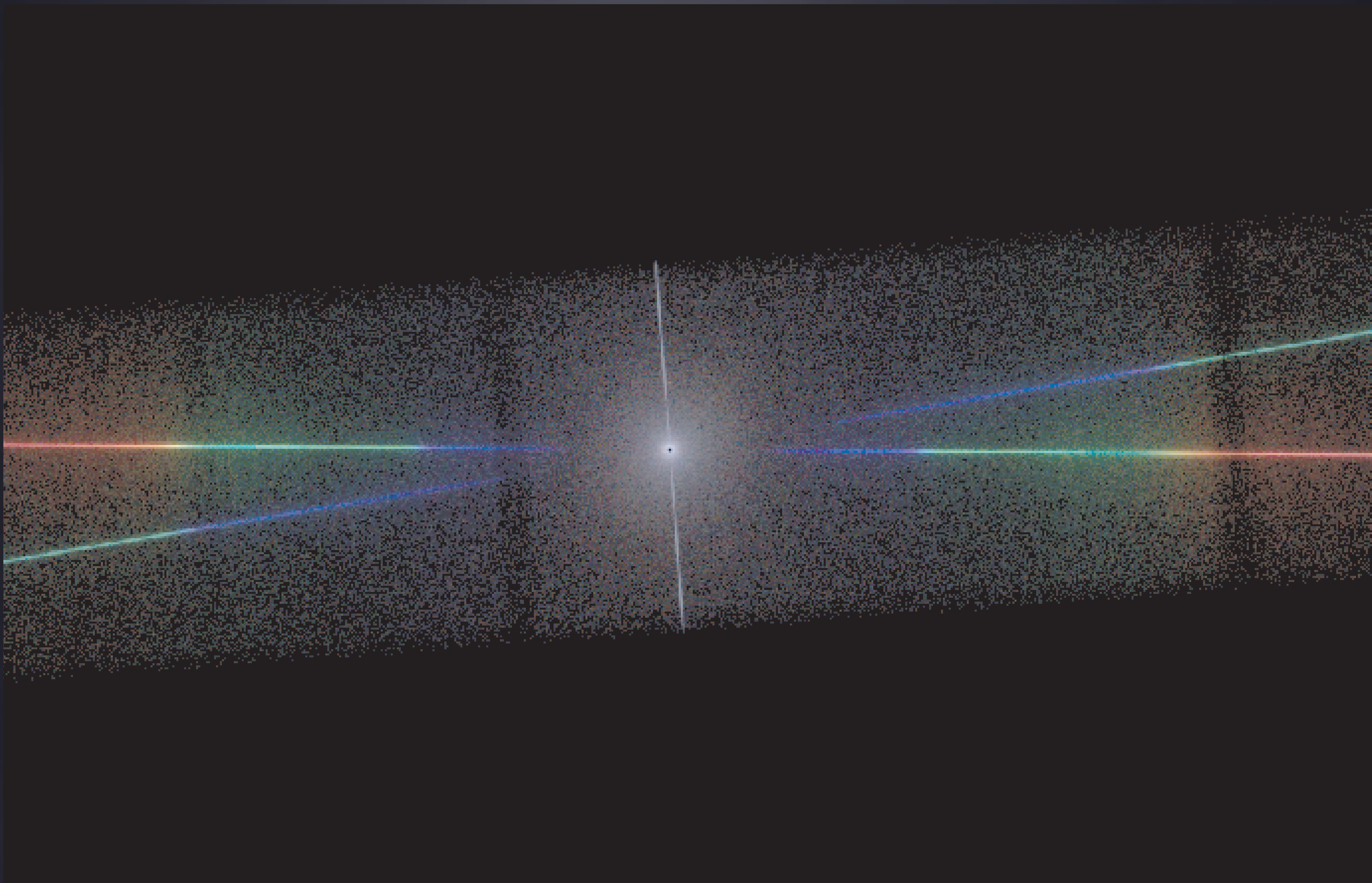


Chandra (ACIS) LETG

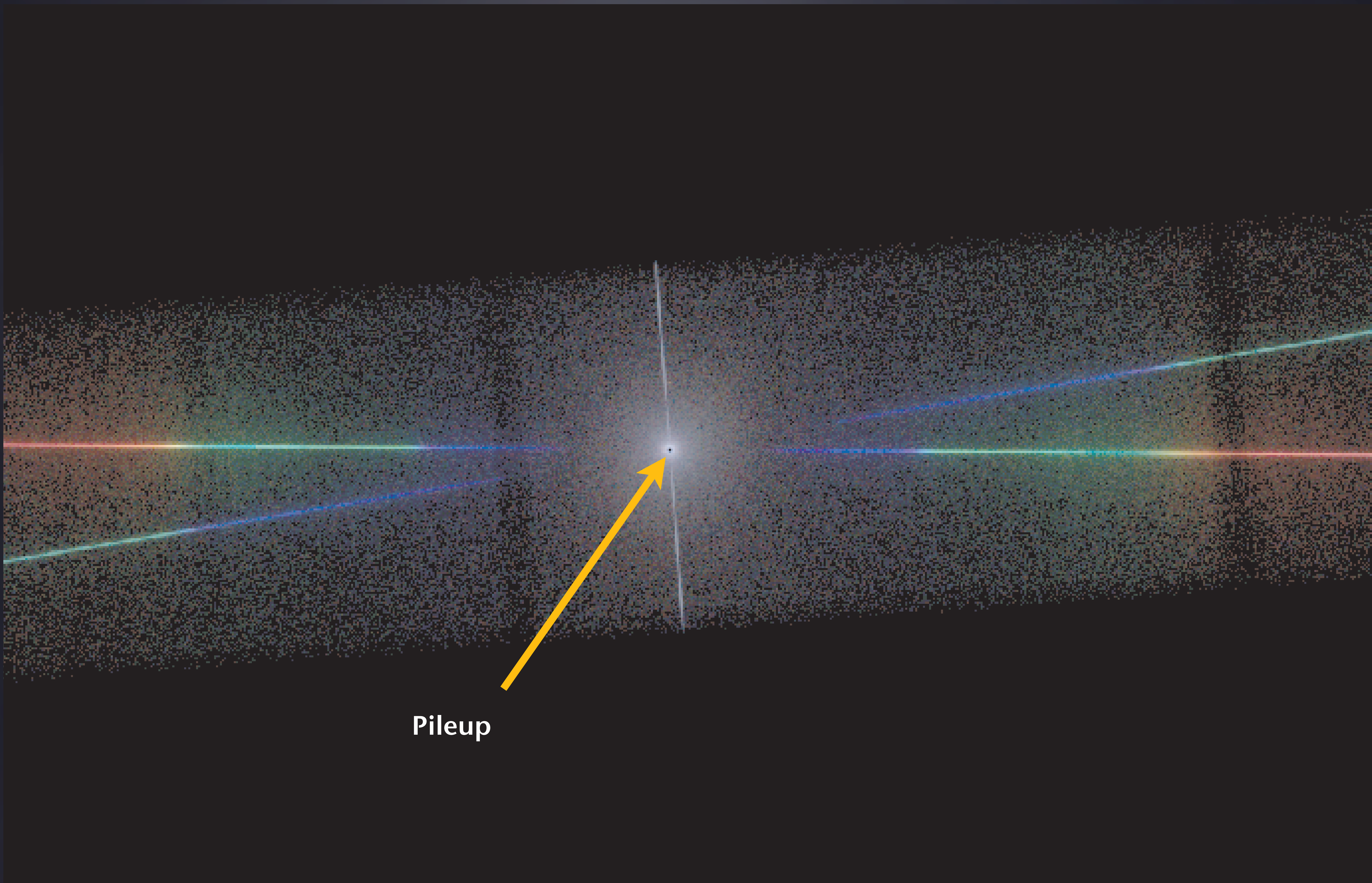


- 0^{th} order shows diffraction from coarse support structure
- "Whiskers" are diffraction from fine support structure

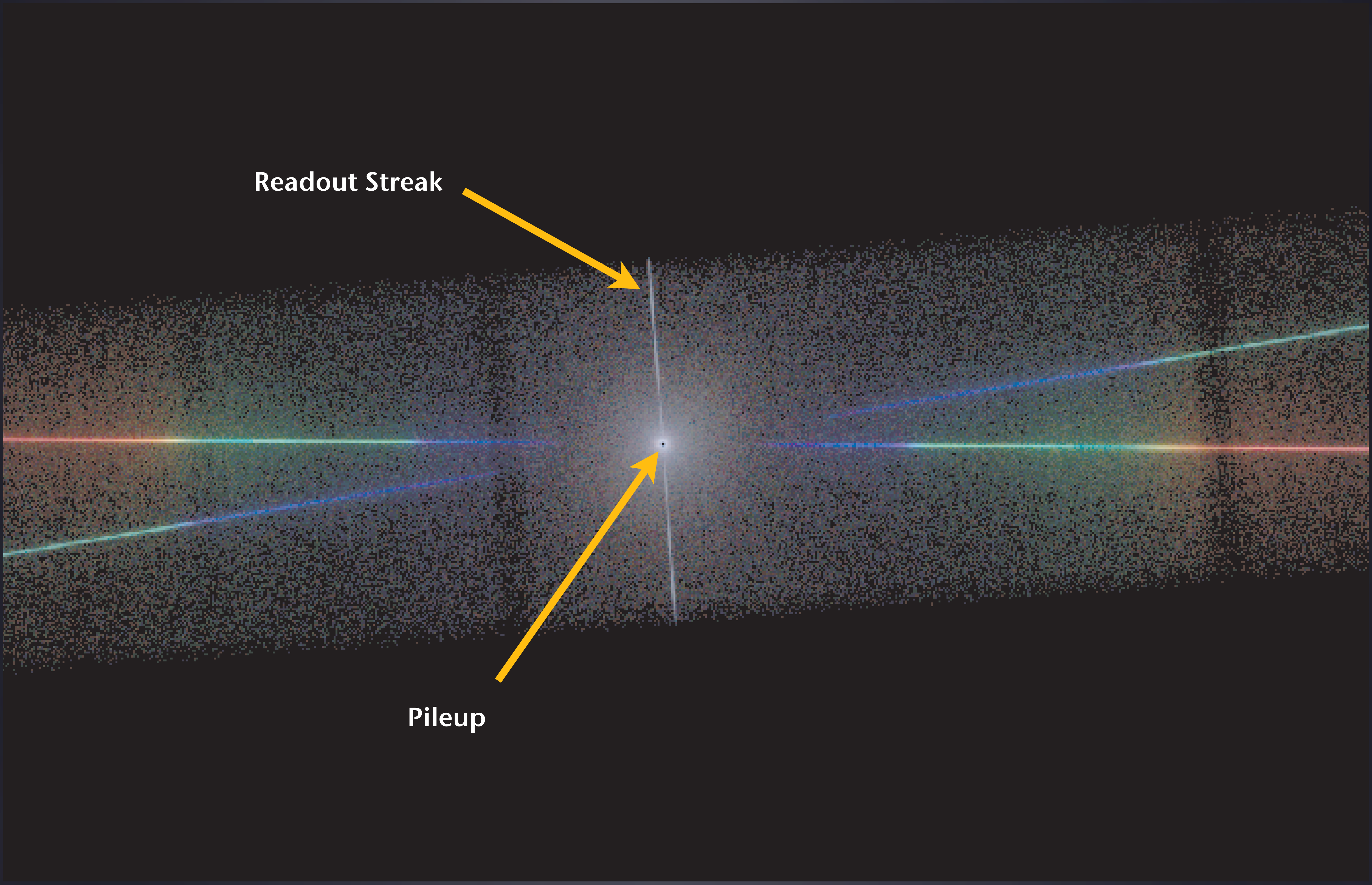
Chandra HETG



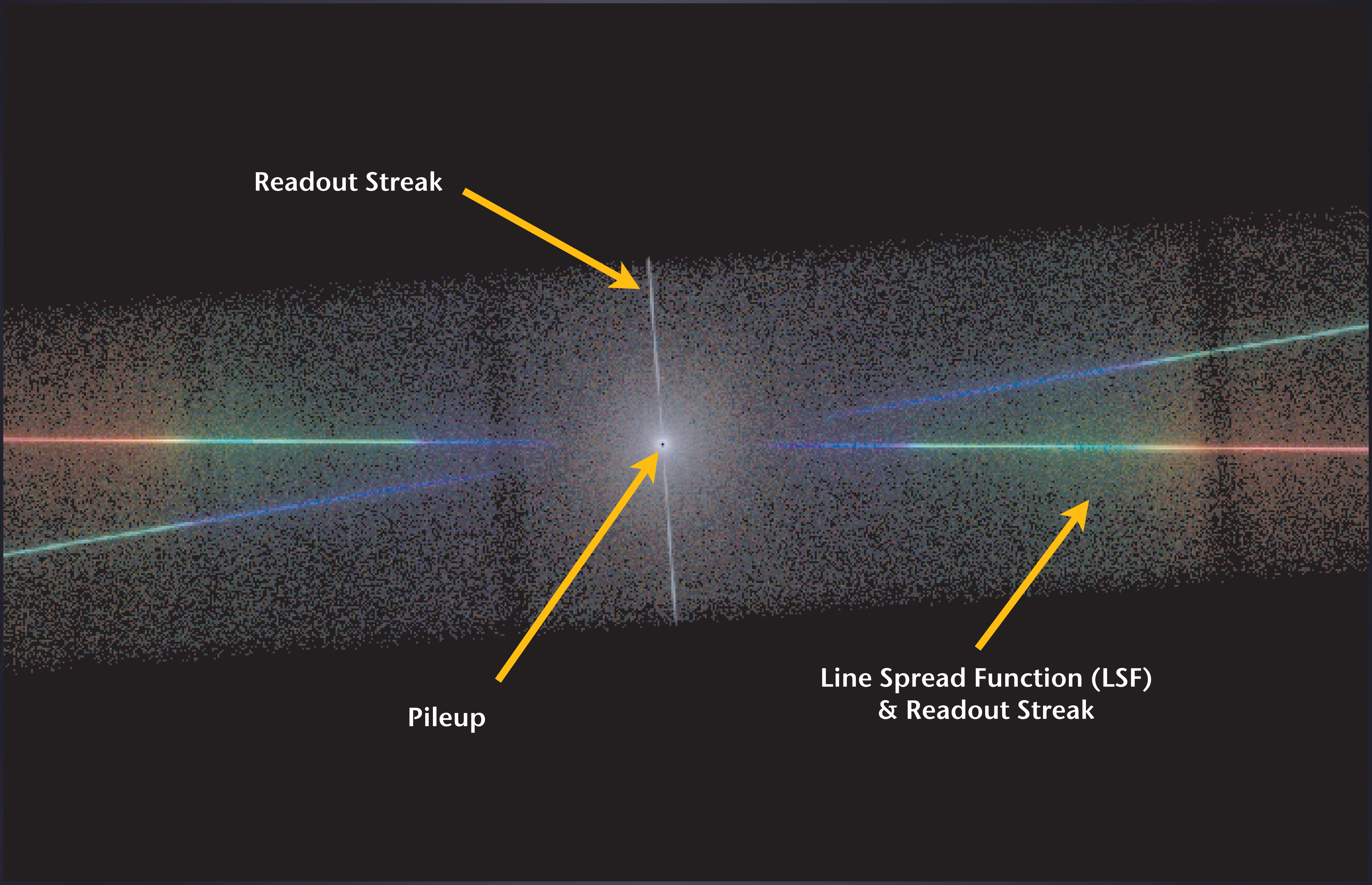
Chandra HETG



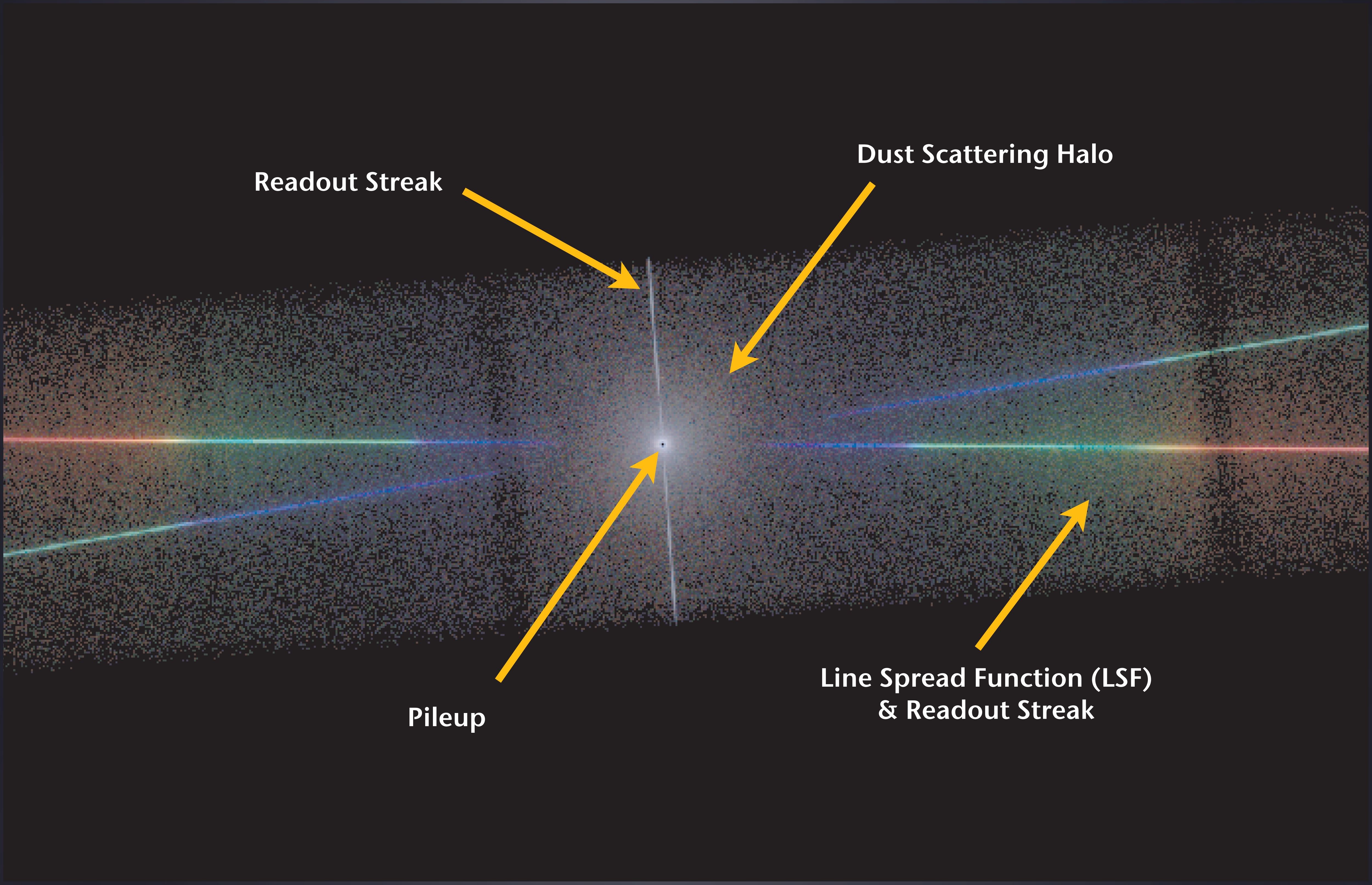
Chandra HETG



Chandra HETG



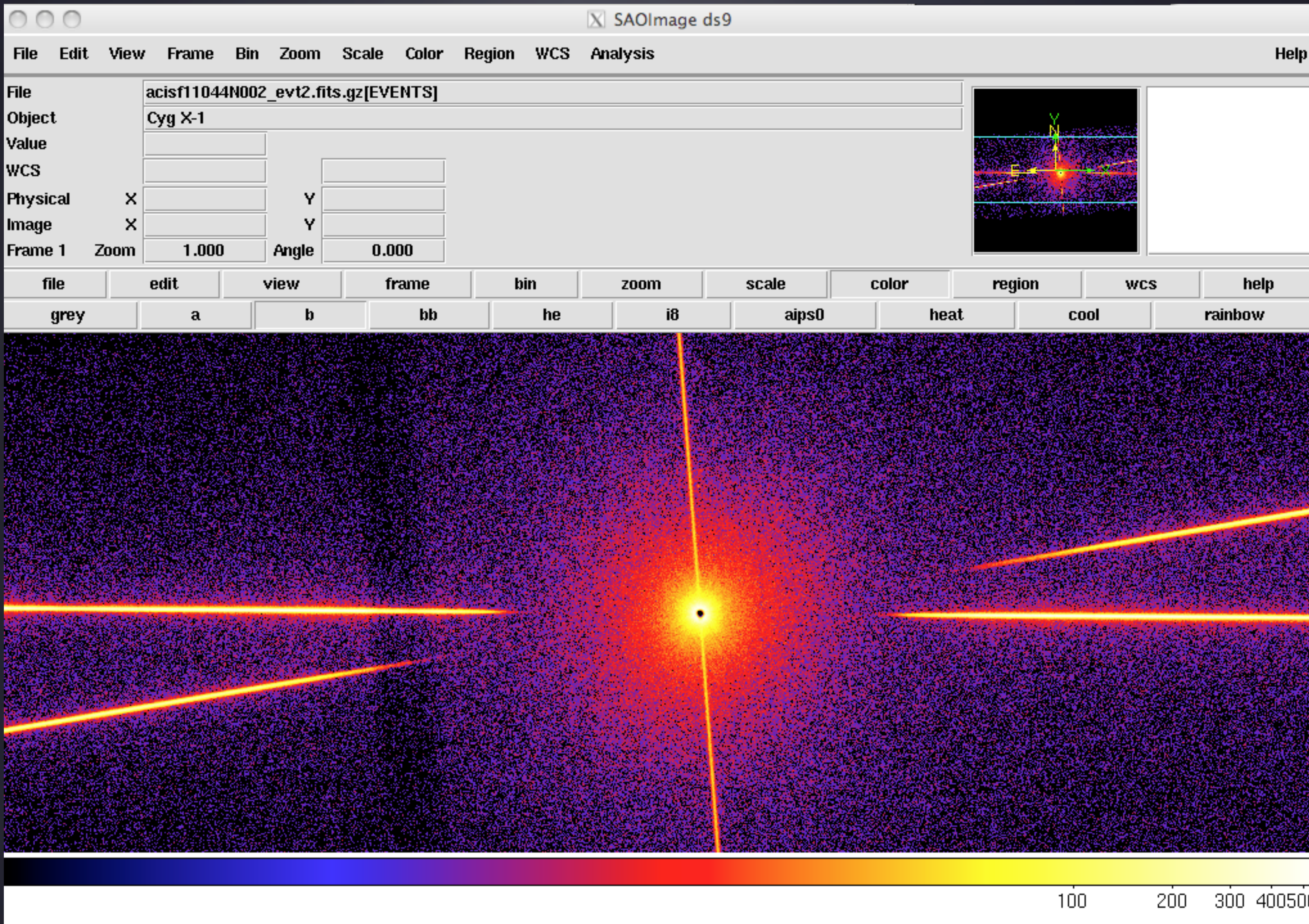
Chandra HETG



Order Sorting (aka Banana Plots)

- Multiple orders land on the same detector location
- CCD resolution is sufficient to separate these!
- Plotting E_{CCD} vs. $m\lambda$ should show "bananas"
- Or we can plot $m\lambda$ vs. $E_{CCD}\, m\lambda/hc$
- $E_{CCD}\, m\lambda/hc$ is the "order"

unix%> ds9 acisf11044N002_evt2.fits.gz &



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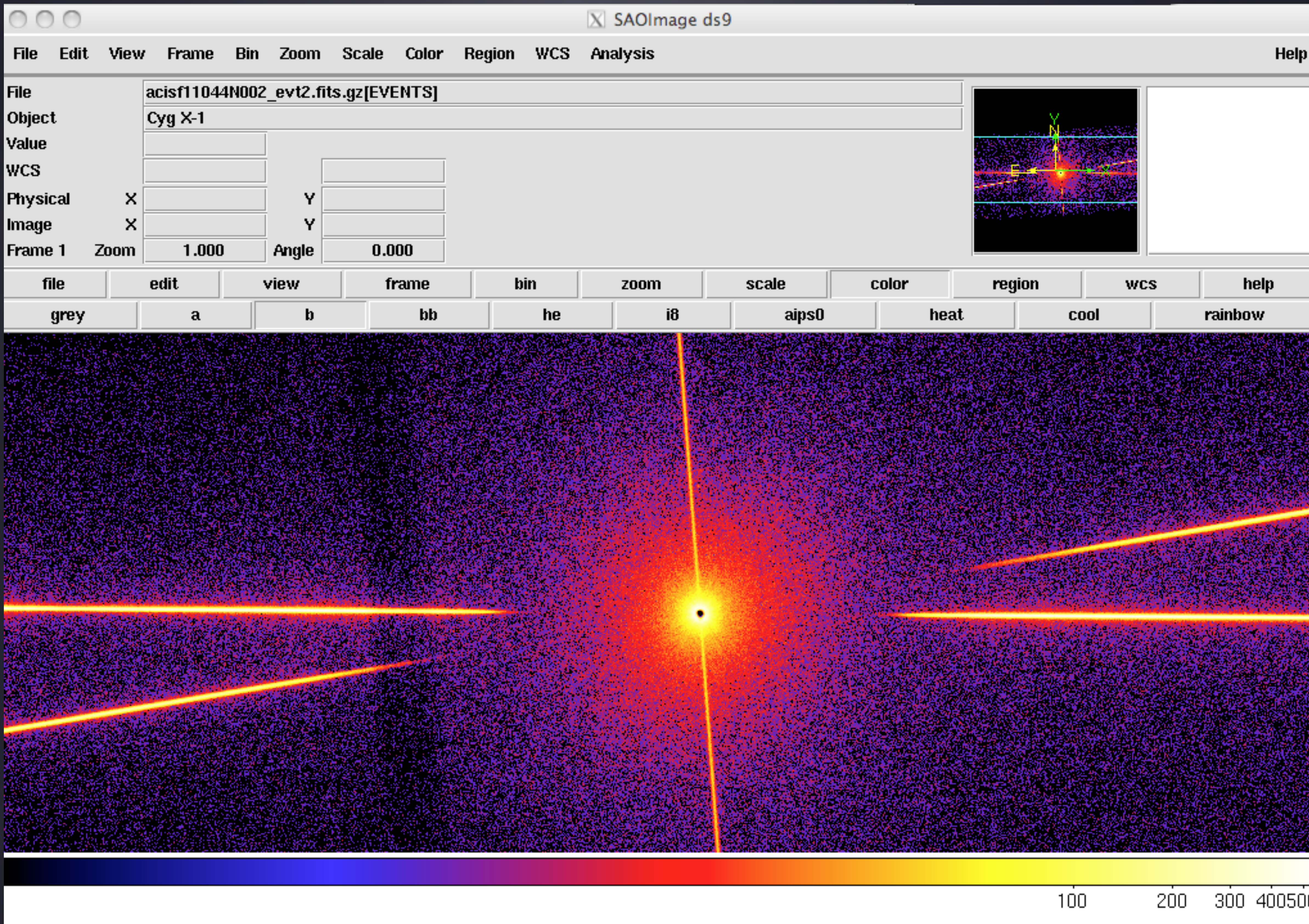

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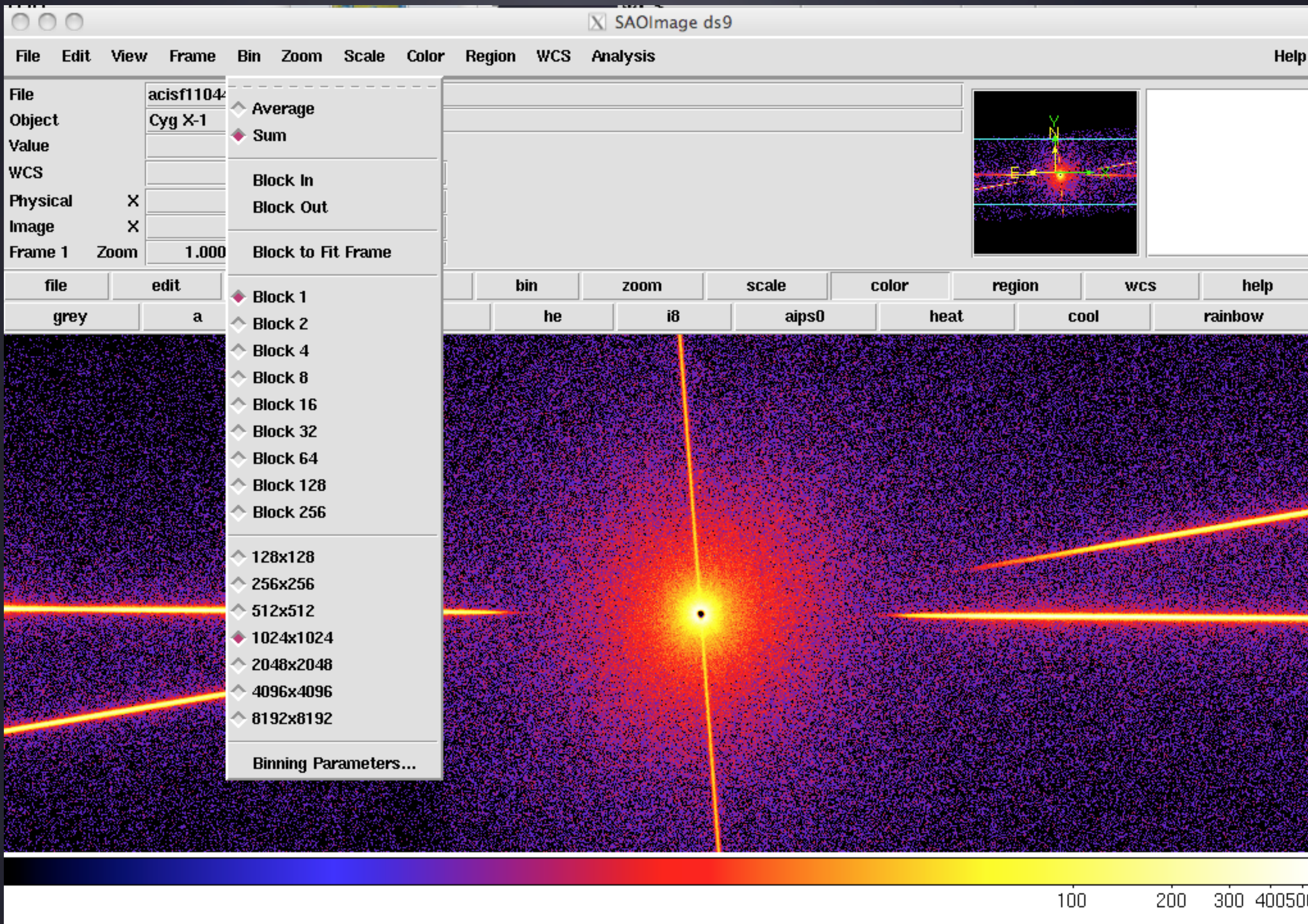

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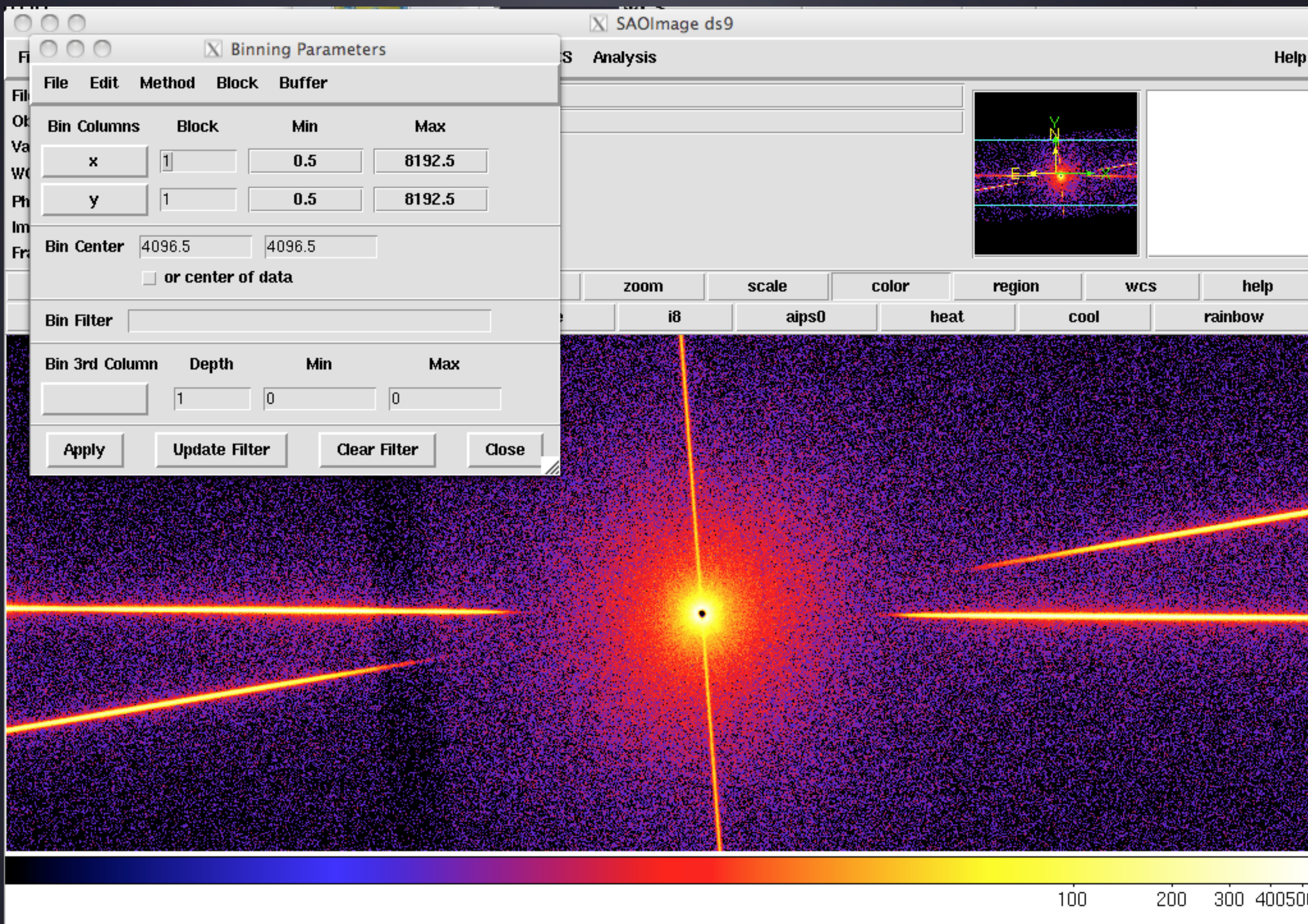

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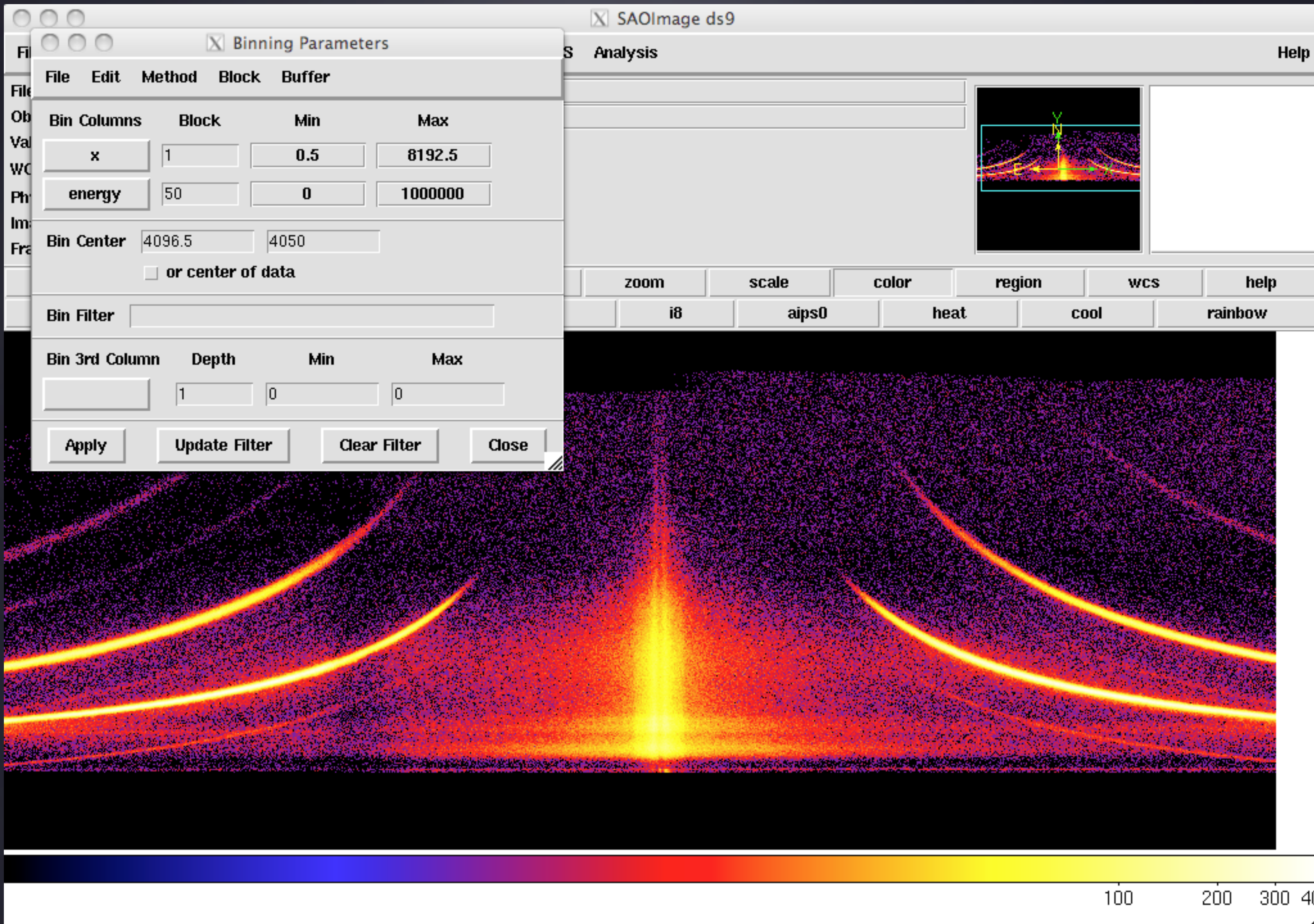
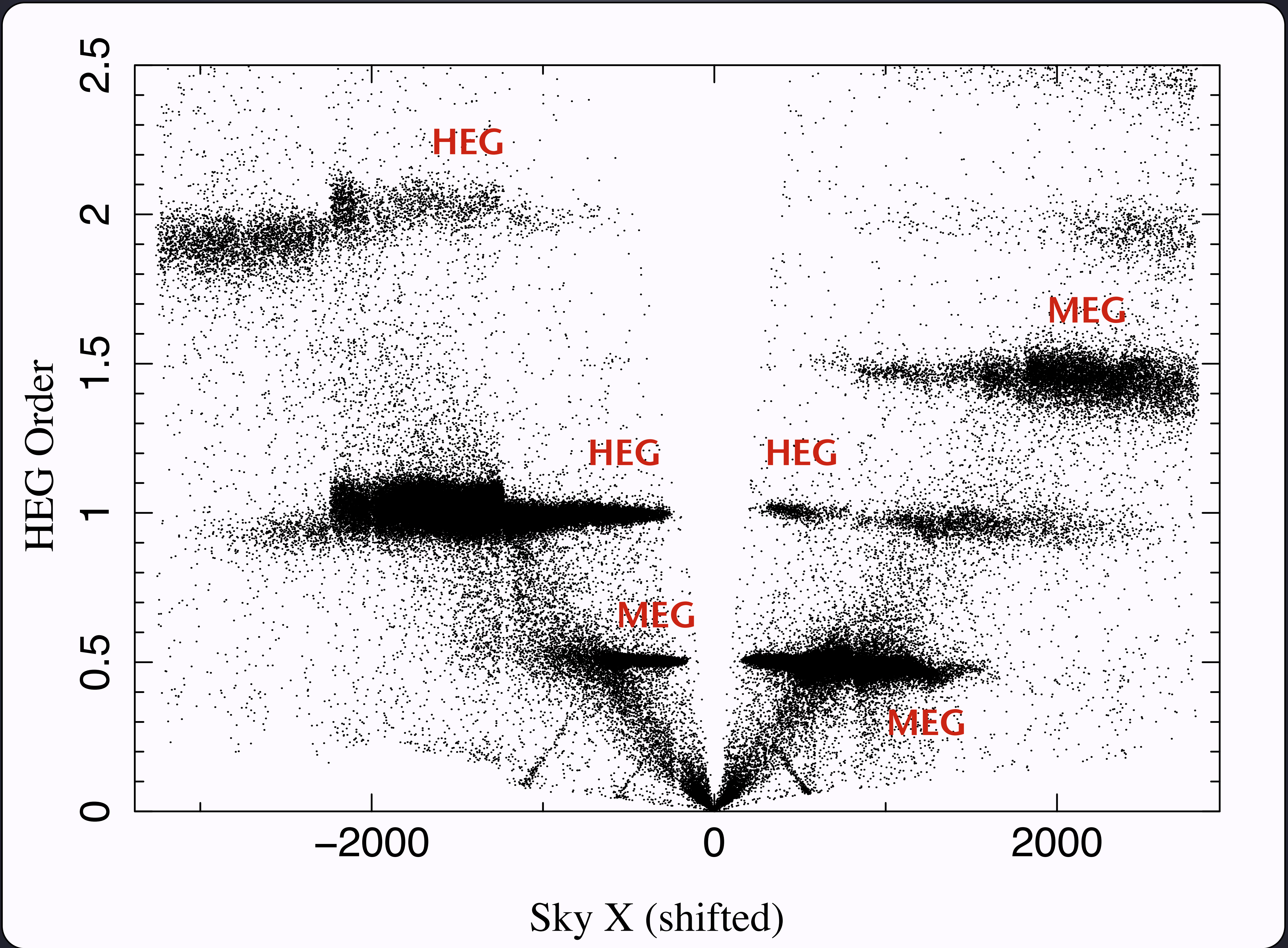
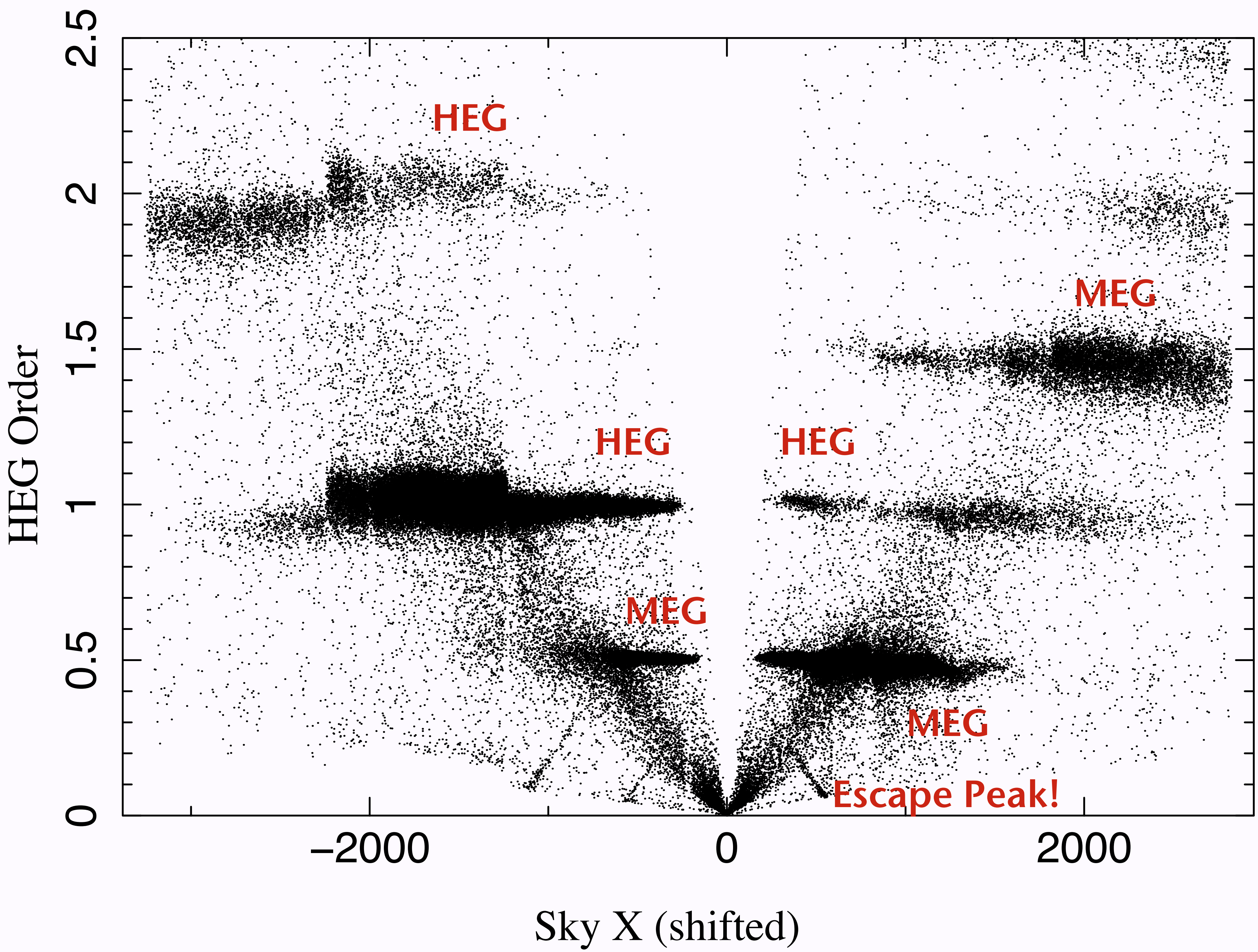


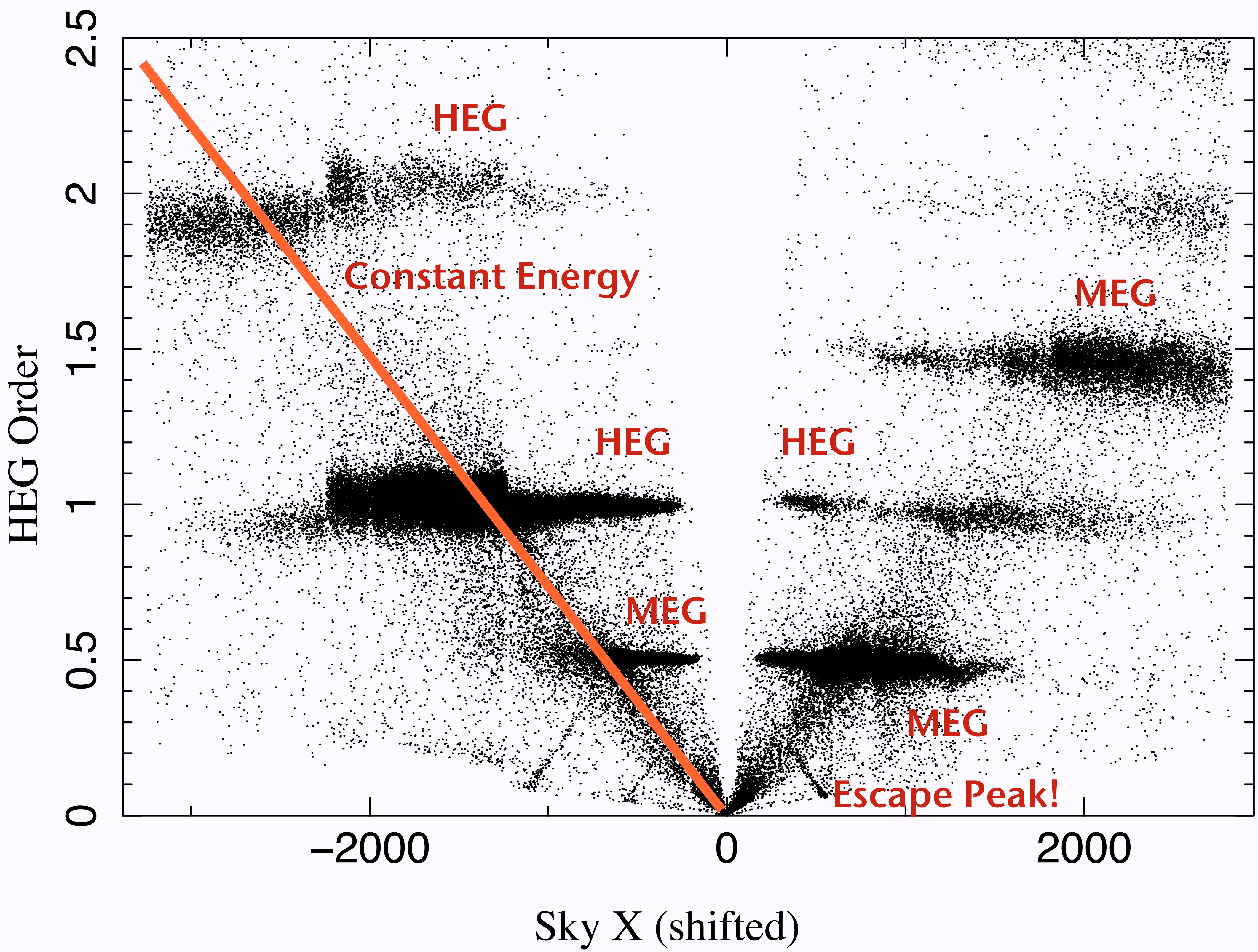
Order Sorting Plot



Order Sorting Plot



Order Sorting Plot



Data Extraction Tasks

- All these can be accomplished with CIAO tools
  - (Select time intervals, “clean” the data)
- Where is my source?
  - tg_detect – or – tg_findzo – or – “by hand”
- What regions should be assigned orders?
  - tg_create_mask
- Which events should be assigned to which orders?
  - tg_resolve_events
- What region (width) should I extract?
  - tg_extract
- Create Response (RMF and ARF files)
  - mkgrmf, asphist & mkgarf – or – fullgarf

Time Intervals & Data Cleaning

- “Event Files” come in three varieties:
  - Event0 – Only us at Chandra see this
  - Event1 – You get this. It has “bad pixels”, “streak events” (S4), etc.
  - Event2 – You also get this. Bad pixels & streaks removed. You can start here *if you aren’t choosing time intervals!*
- There is a bug within the gratings tools where you need to do time slices on the Event1 files.

Time Intervals & Data Cleaning

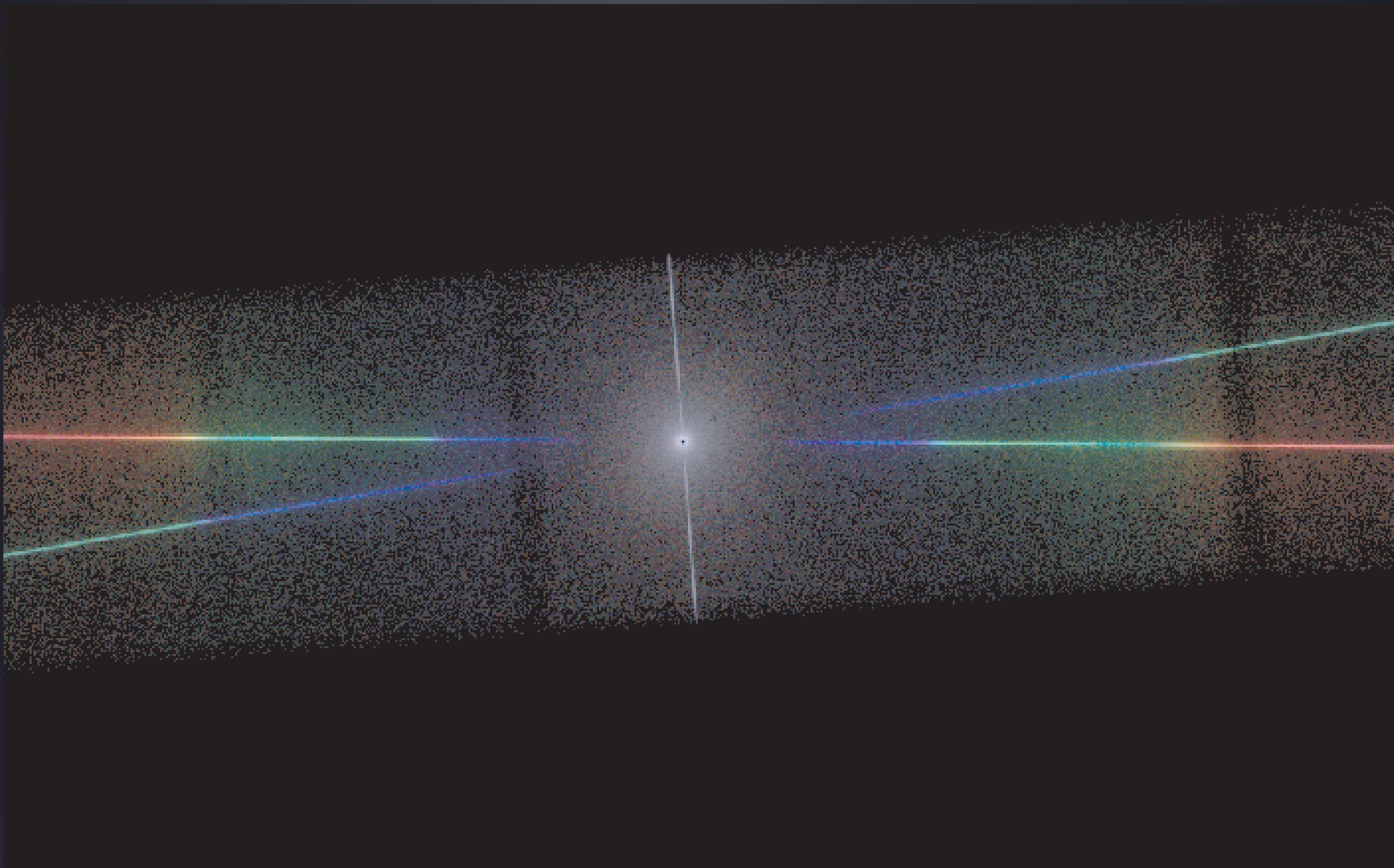
- You can do a time slice with dmcopy:

  dmcopy "evt1_file[stdevt][time=5.1096500e8:5.1098000e8]"

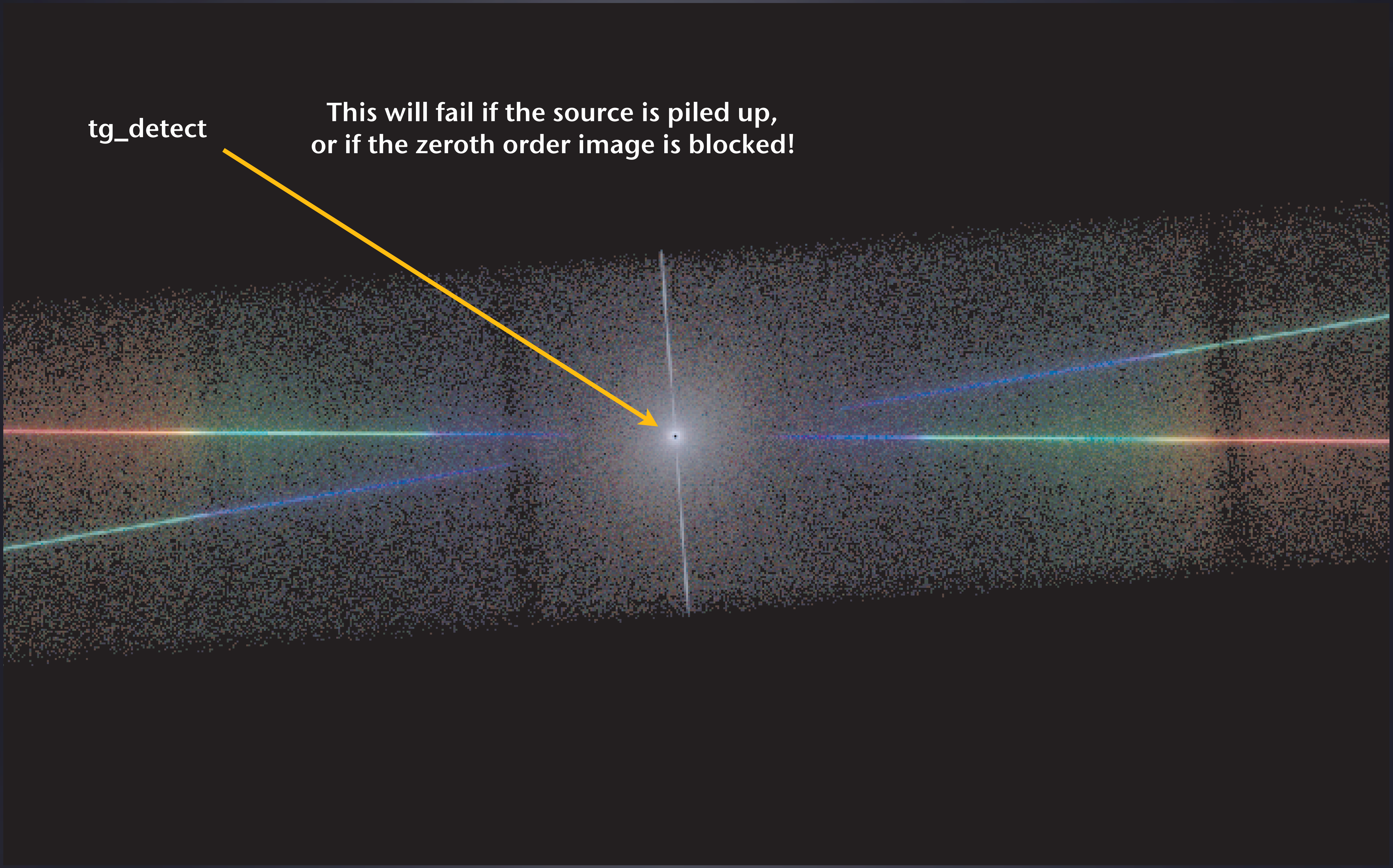
  evt1_new

- You can then run the chandra_repro script on this new file, and proceed from there
  - Removes bad pixels
  - Applies Good Time Intervals (GTI)
  - Removes "streaks" (S4 Chip)
  - Selects "Good Grades"

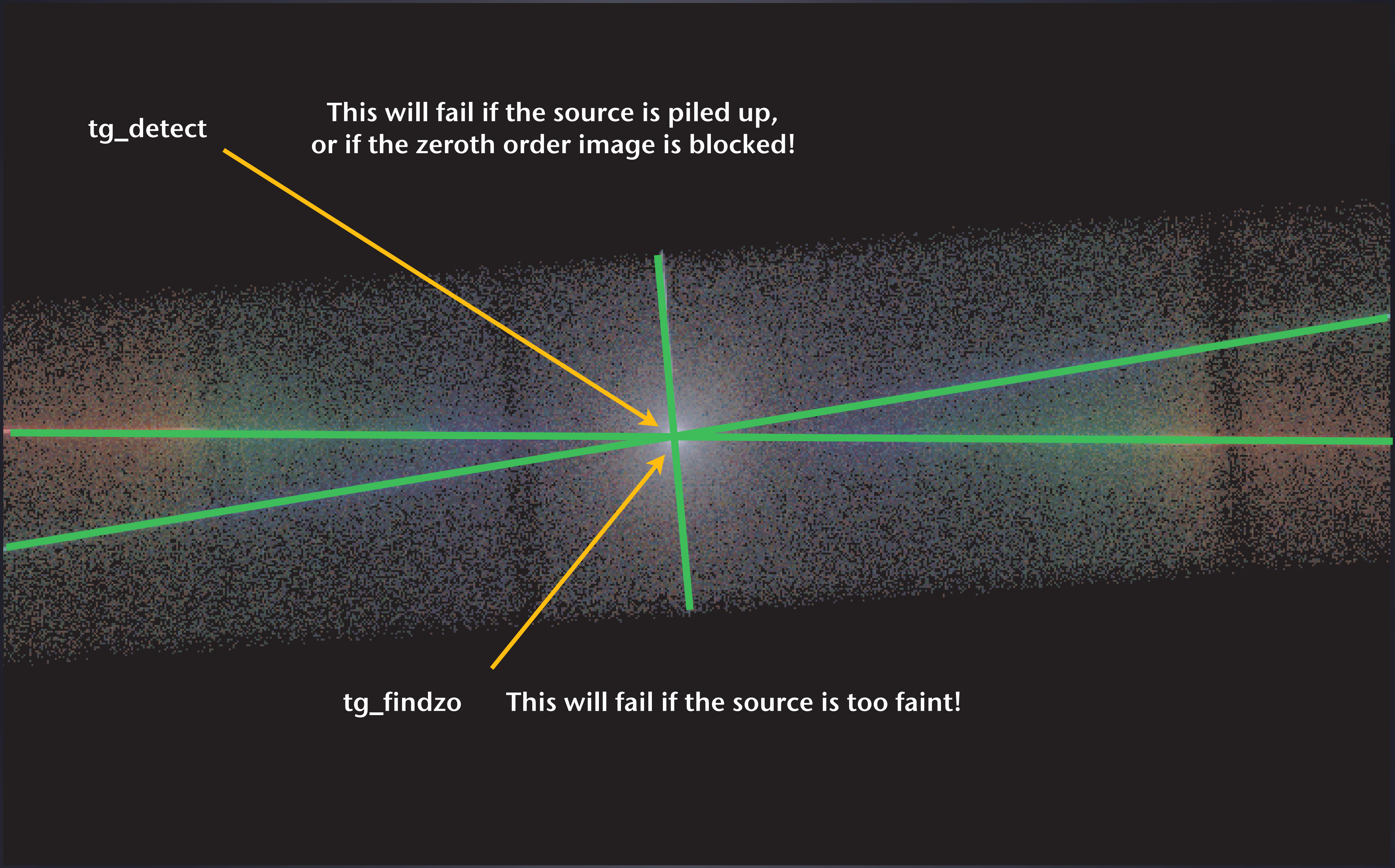
Where is my source?



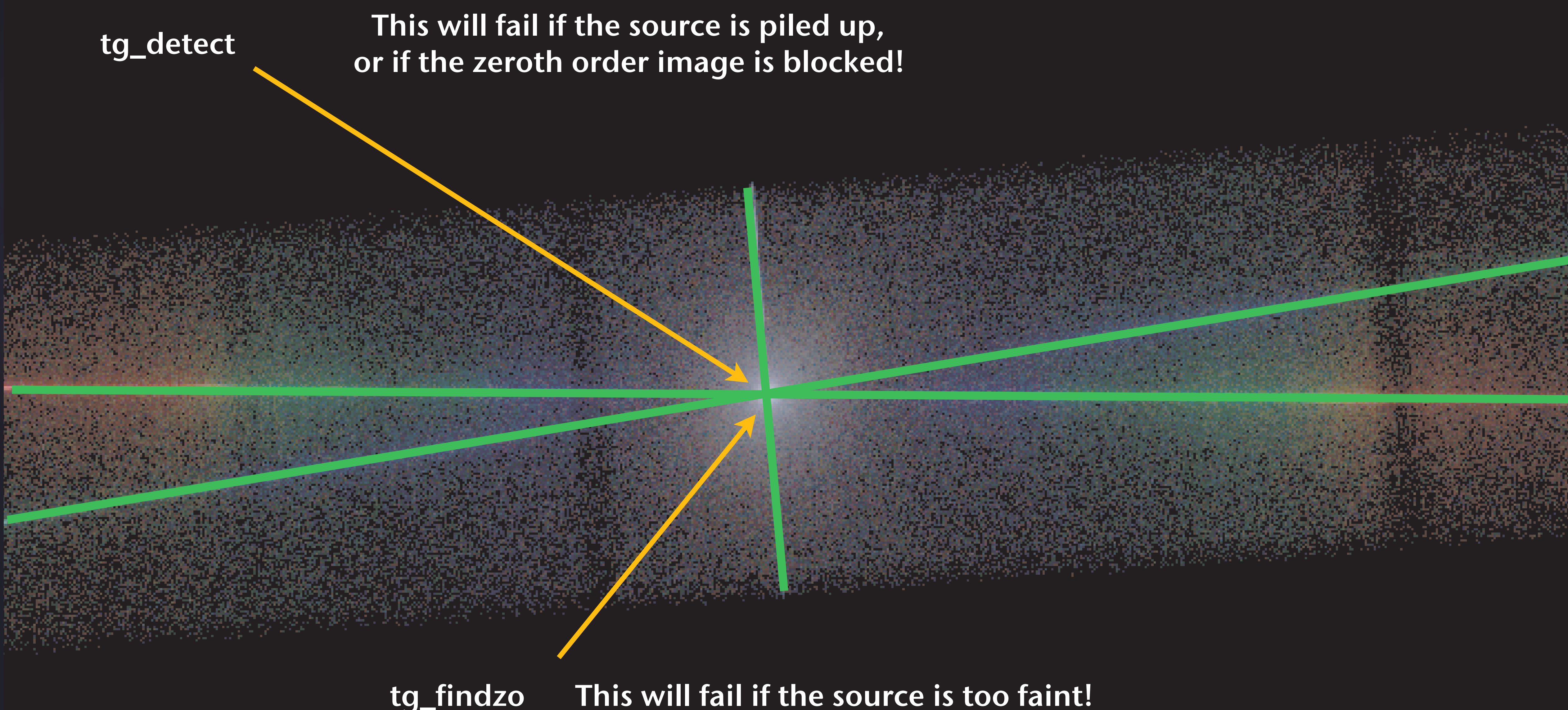
Where is my source?



Where is my source?



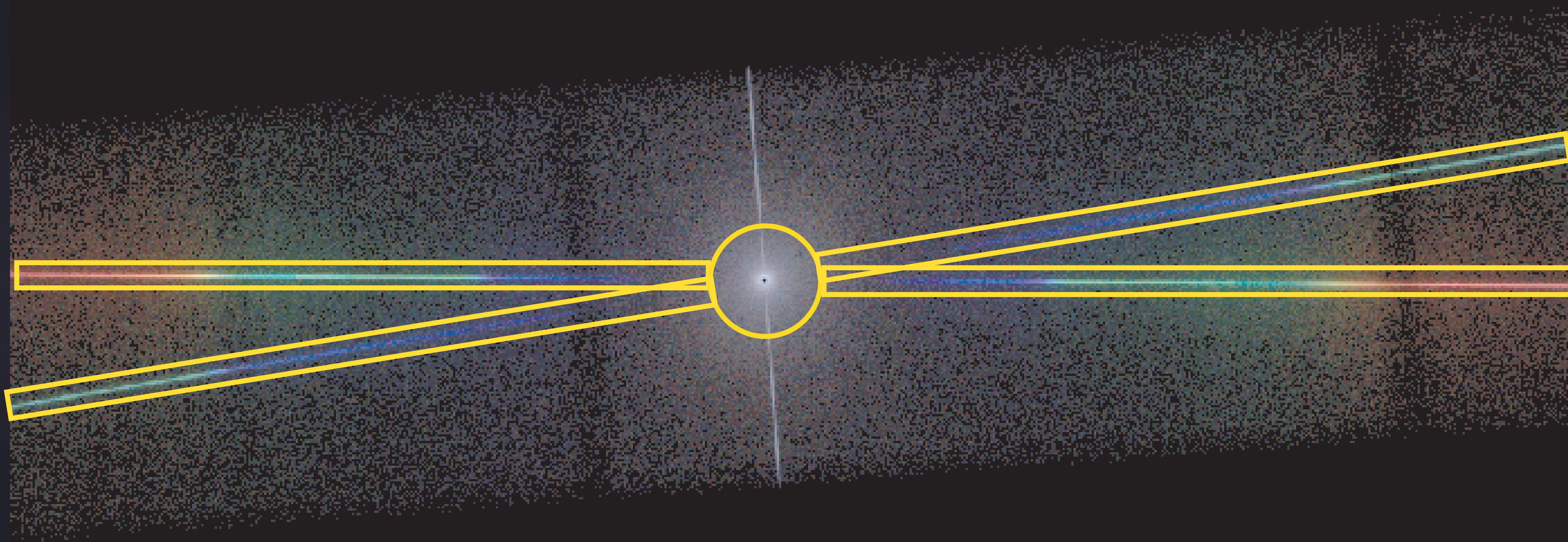
Where is my source?



Accuracy can be as good as 0.1 pixels

tg_create_mask

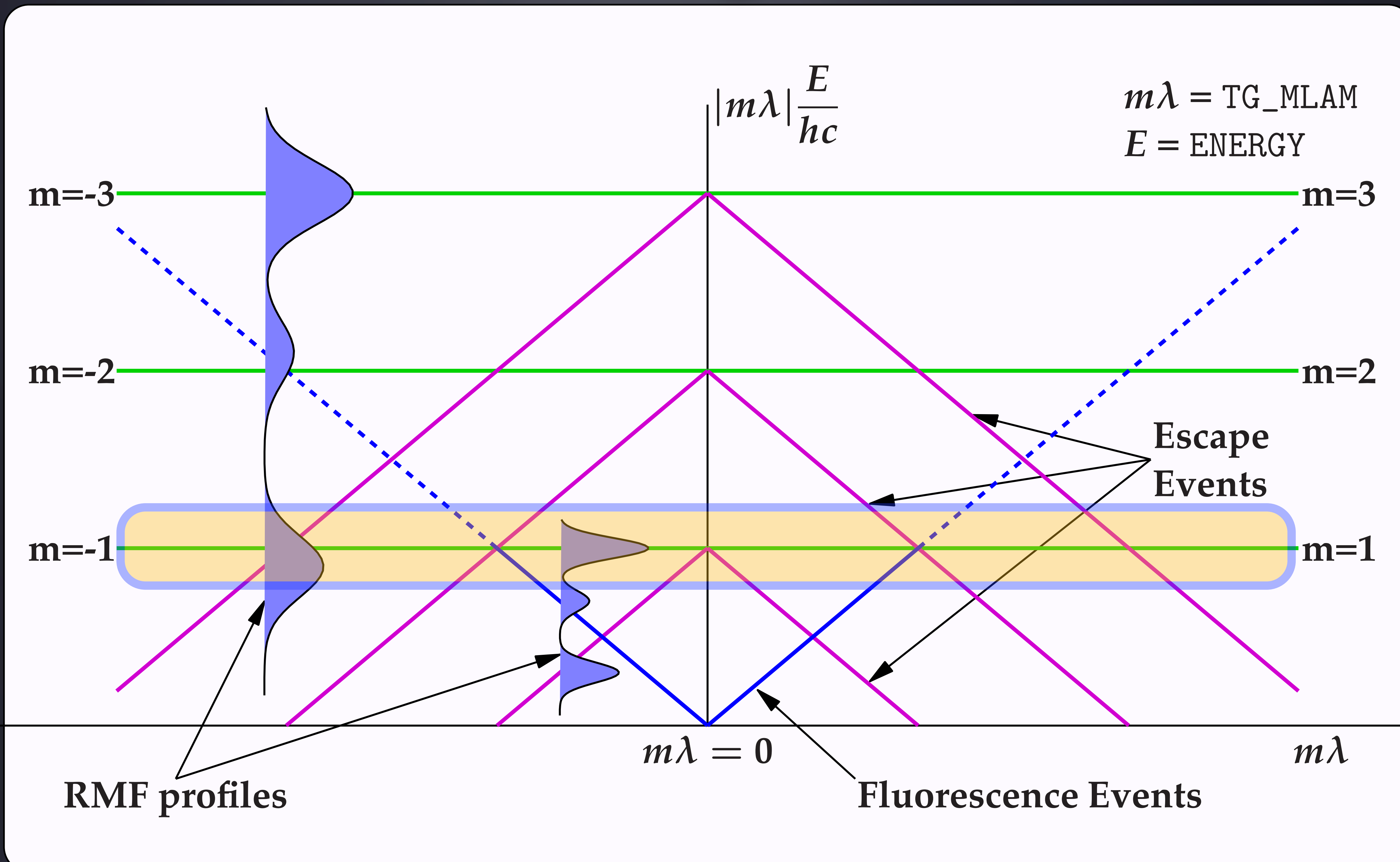
Hierarchy: 0^{th} Order > MEG > HEG



CIAO defaults are a bit too wide, so MEG "clips" HEG high energy for "Continuum" Sources

These are the *Potential* Gratings Events

“Resolving” Events



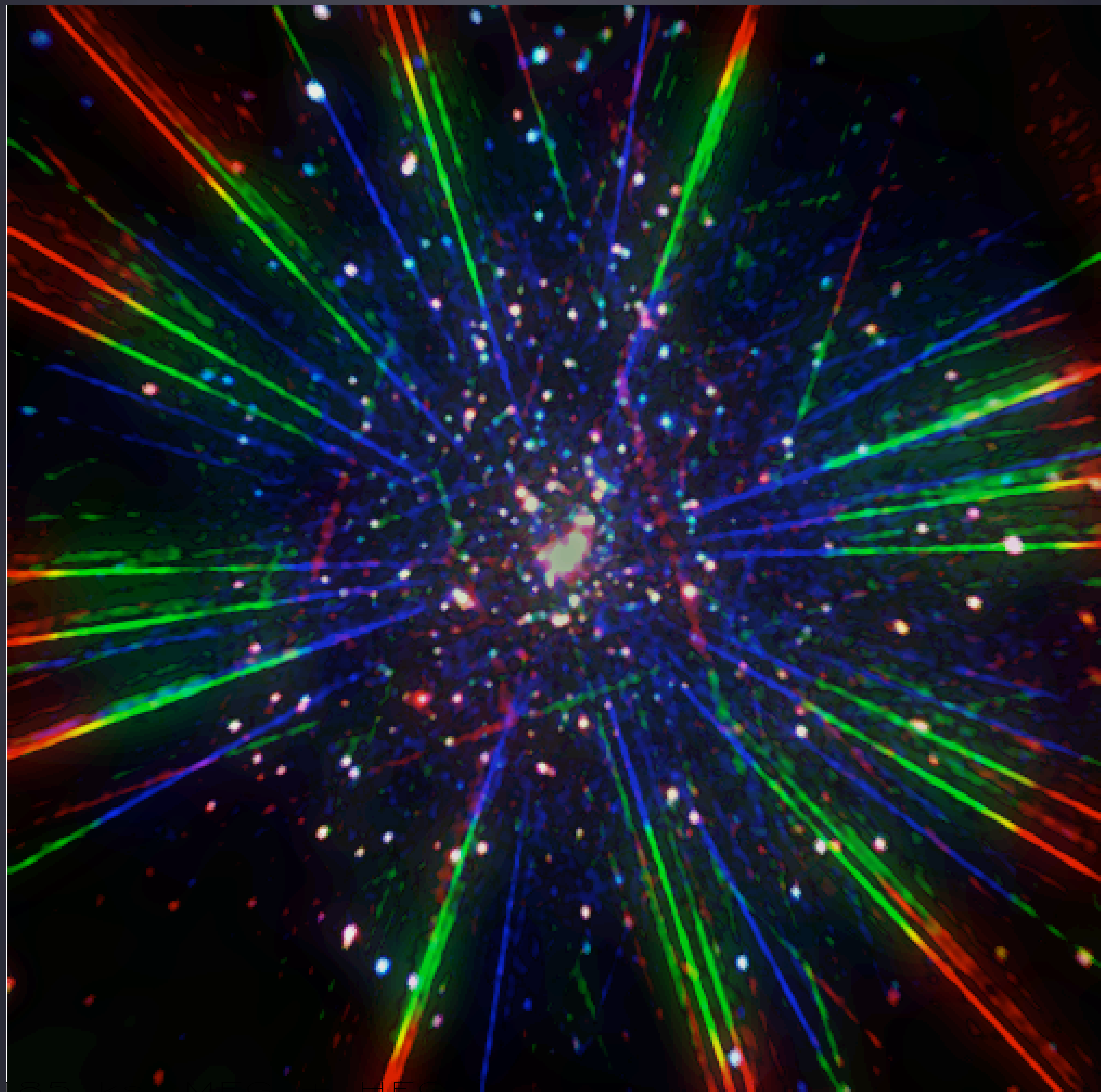
Fraction of RMF is the “Order Sorting Integrated Probability” (OSIP) and is Incorporated into ARF

Order Sorting

- For Chandra, there are two choices:
  - "Standard" (which varies with wavelength) with a pre-calculated OSIP
  - "Flat", with the user choosing a fixed ratio, e.g., $E_{CCD}\, m\lambda/hc = 0.8–1.3$ and OSIP assumed to be 1
  - Flat is usually the choice for "Continuous Clocking" mode
- To be a gratings photon, it has to be at the right place with the expected energy
  - Greatly reduces background!

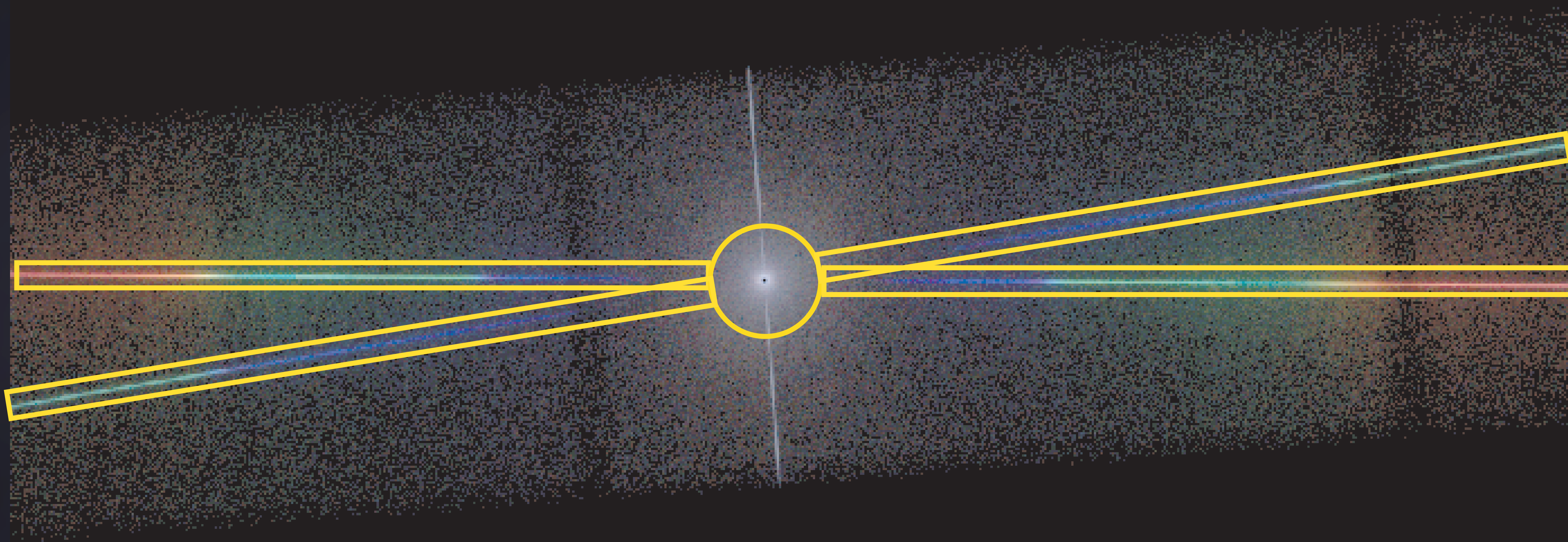
Orion Star Cluster

Orion Star Cluster



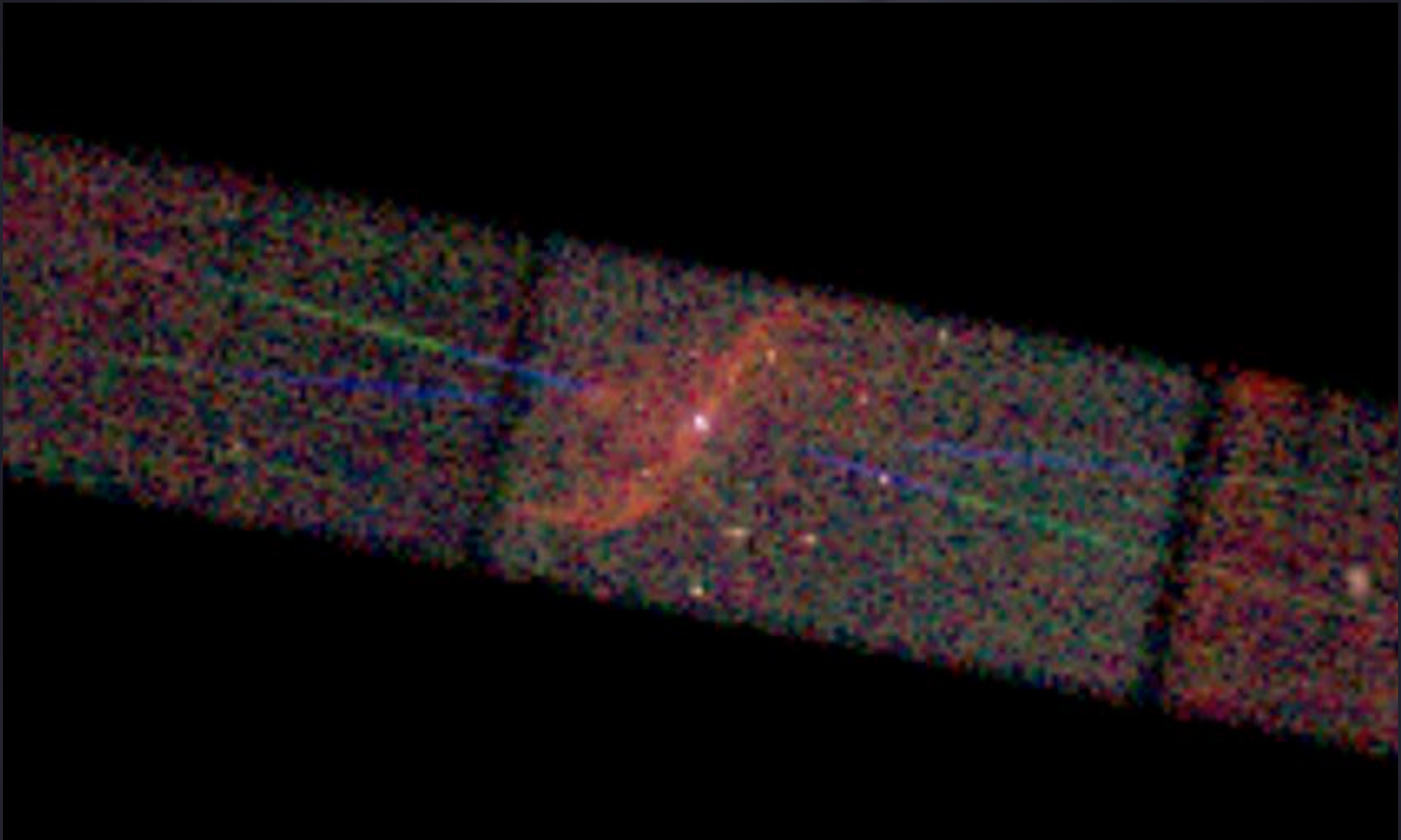
tg_extract_events

Isolated Source, Defaults are Fine



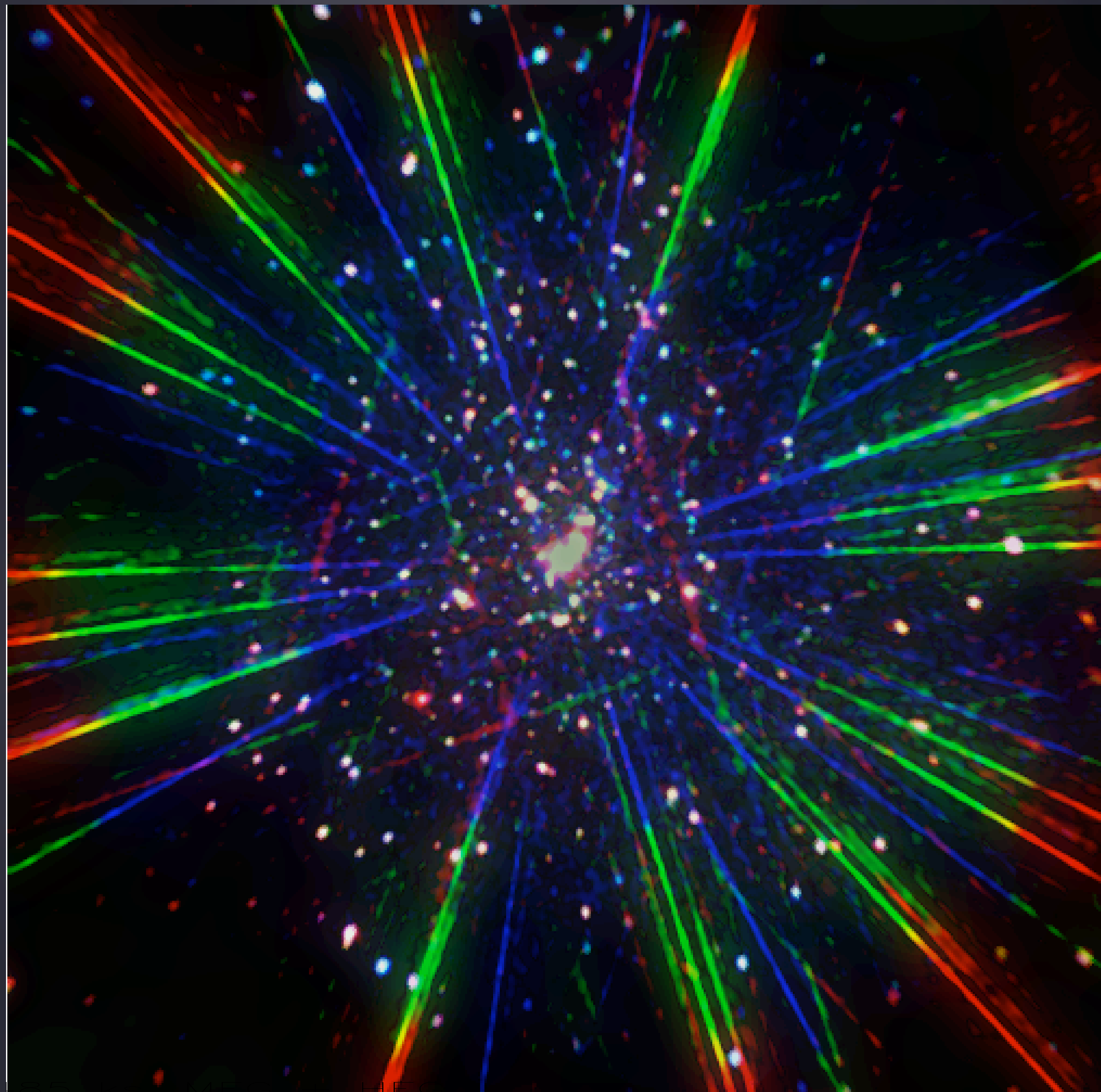
Fraction of LSF is Incorporated in RMF

Narrower is Sometimes Necessary



Orion Star Cluster

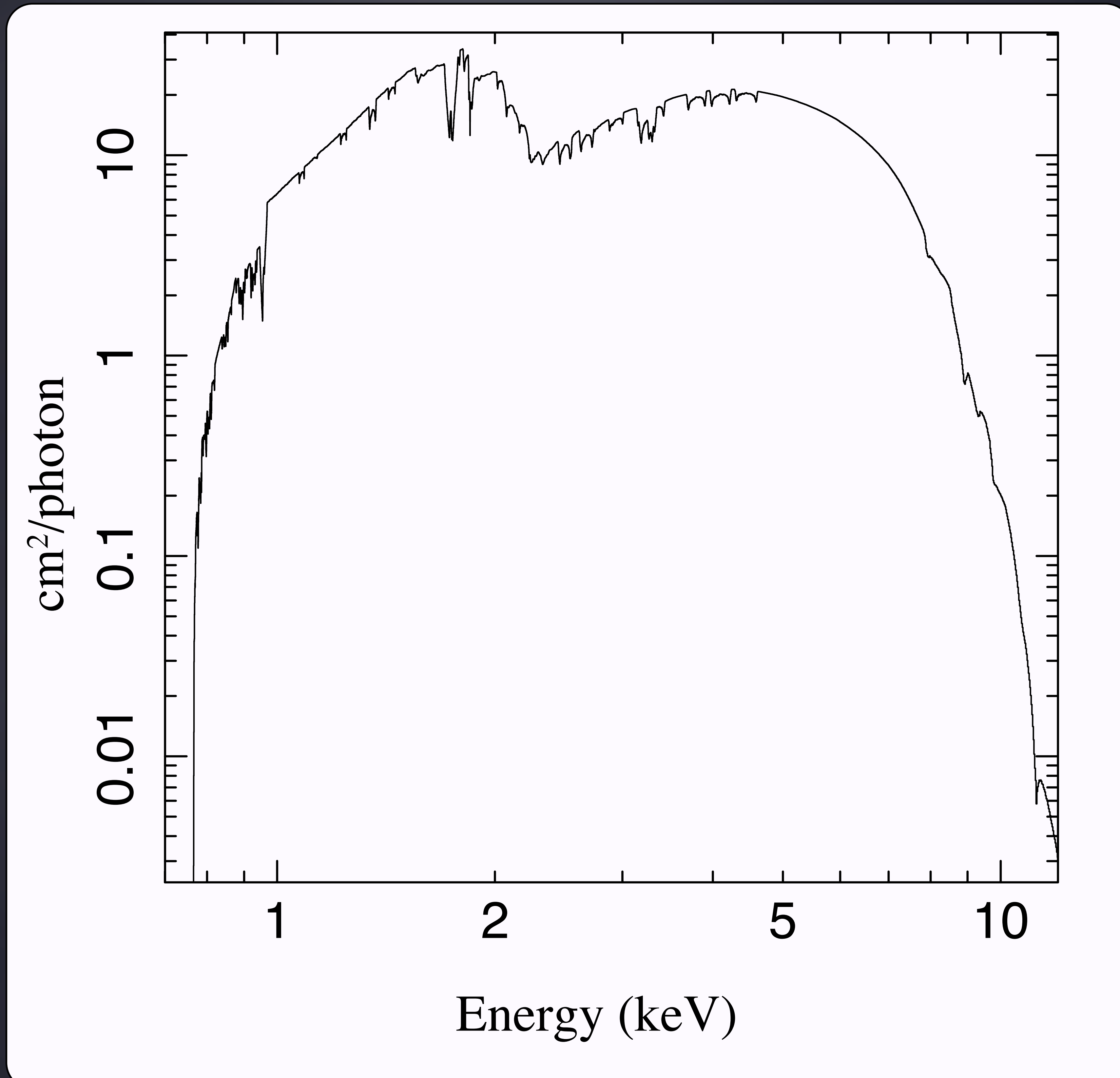
Orion Star Cluster



Response Matrices & ARF

- If you've extracted the standard width, the standard RMF is sufficient
- ARF (effective area file) has to incorporate spatial information about the detector. Not only chip gaps, but also bad pixels & columns
- There's also a "hidden" parameter – fractional exposure vs. wavelength
- Standard tools: mkgrmf, asphist & mkgarf, fullgarf

Sample Gratings ARF



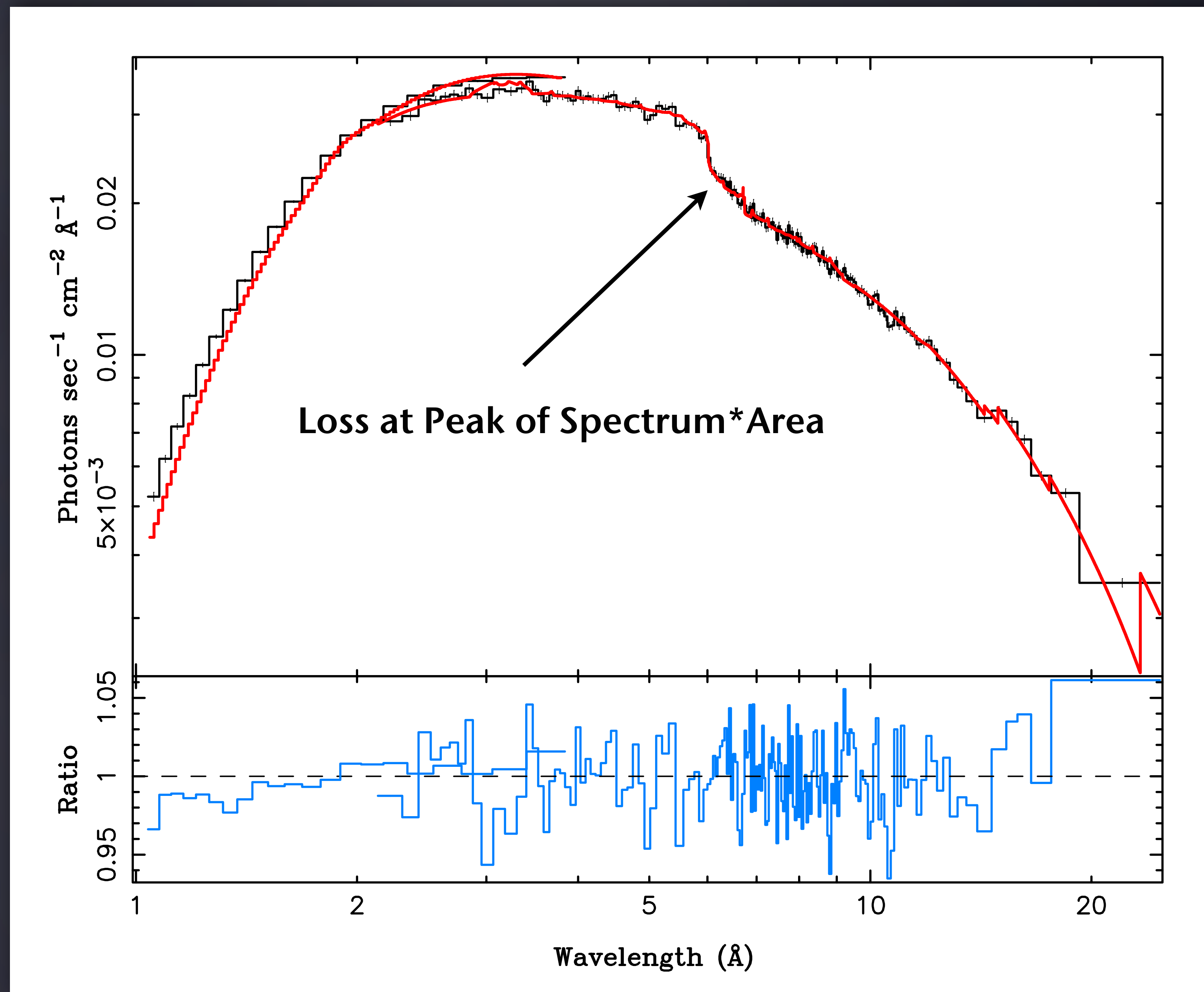
And Now Analysis Begins!

- You have extracted spectra and created response matrices/ effective area files
- Analyze in any standard program: ISIS, XSPEC, Sherpa, SPEX
- The standard is to extract 1^{st}, 2^{nd}, 3^{rd} (+/-) orders
  - Higher orders have less flux, and less accurate responses – difficult to use for continuum
  - Line dominated sources, good for separating blends of lines

Complex Cases

- Pileup – Less likely to happen, but it can ...
  - ISIS model (could write for Sherpa, not XSPEC[?])
- Continuous Clocking Mode (CC-mode)
- Sources with spatial structure
- Sources with spatial structure and CC-mode

Pileup in Gratings Spectrum



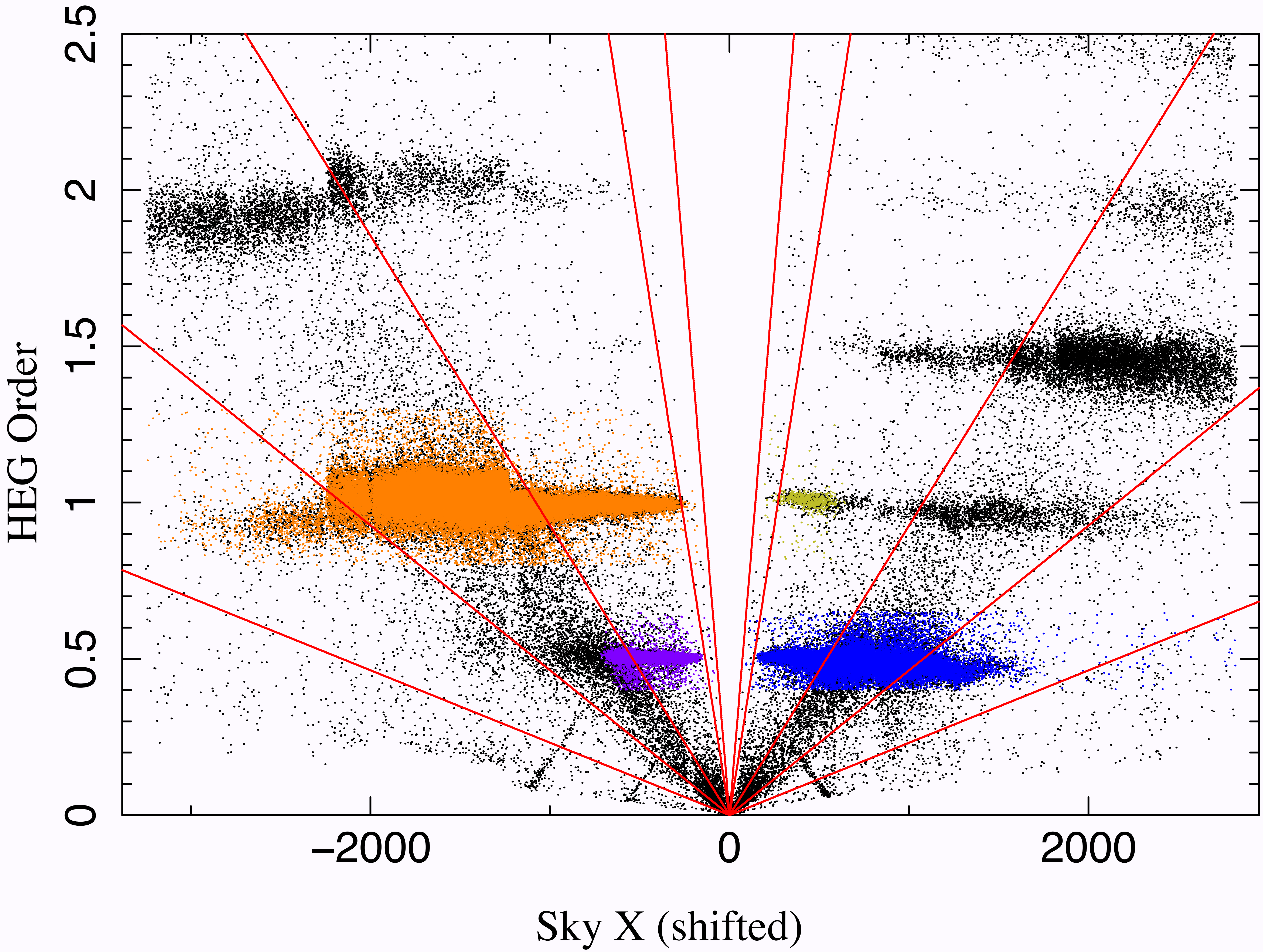
Most Significant in MEG (Higher Effective Area, Less Dispersion)

Continuous Clocking

- Image collapsed to one dimension
- But, MEG 2nd orders are suppressed, so HEG 1st order is always assumed
- Extraction width is assumed to be 100%, and OSIP is chosen to be flat (~0.8–1.3) and assumed 100%
- *No source is piled up in this mode – we've looked at Sco X-1! (The Chandra team was *not* happy!)*
- But, there are still issues at the few % level…
- We recommend putting MEG -1 and HEG+1 off the chips

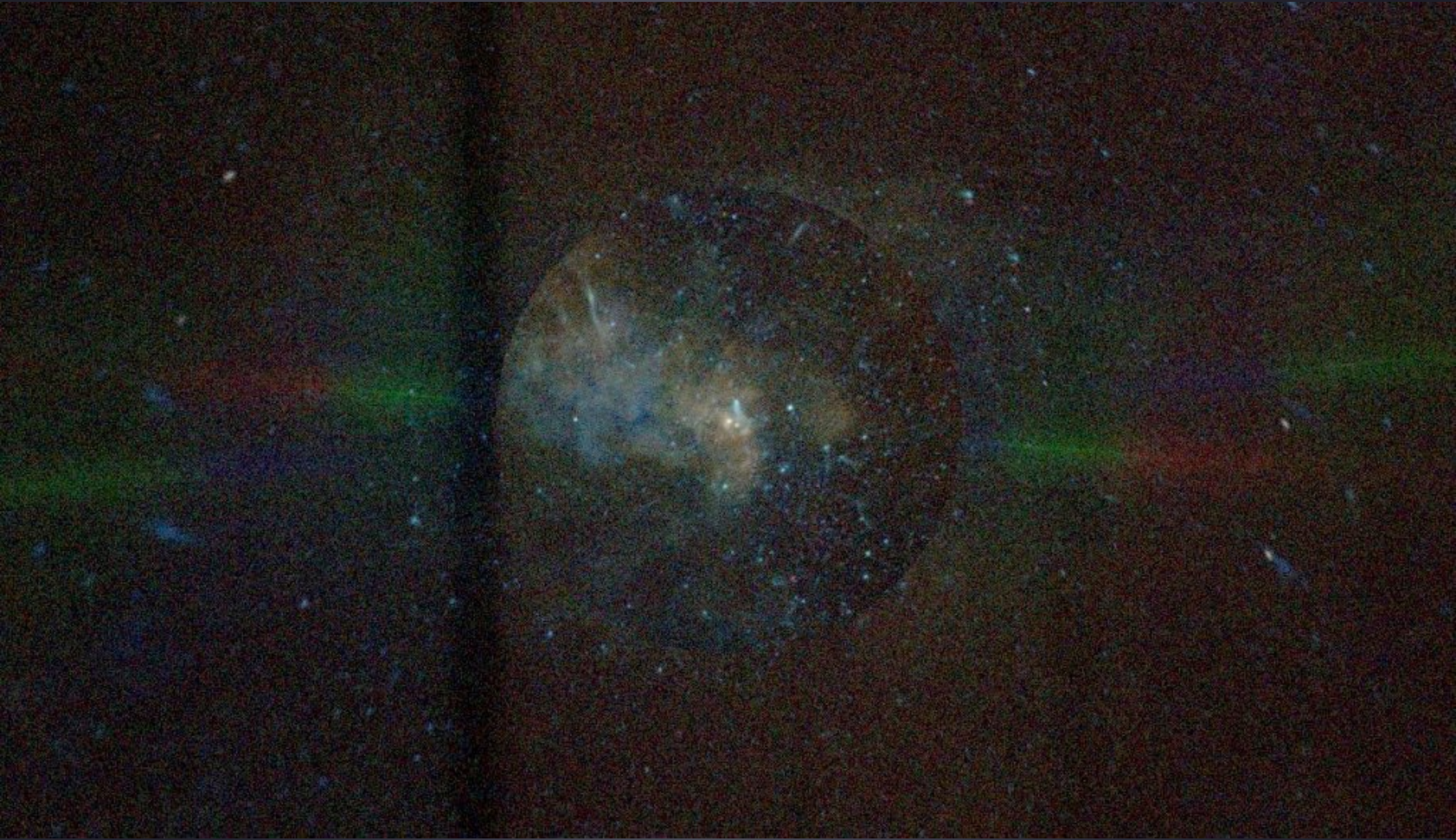
A Note About Exposures

- Different Chips Can Have Different Exposures
  - Especially True for Bright Sources with Data Loss
- Data files will have the mean exposure of all the chips
- Effective Area files will have the mean exposure of the chips associated with that detector
- None of these numbers may actually be the “true” exposure at a specific wavelength region
  - The issues are incorporated into the ARF
  - But might not be adequate when doing lightcurves



HEG Order
Sky X (shifted)
0
0.5
1
1.5
2
2.5
−2000
0
2000

Complex Case

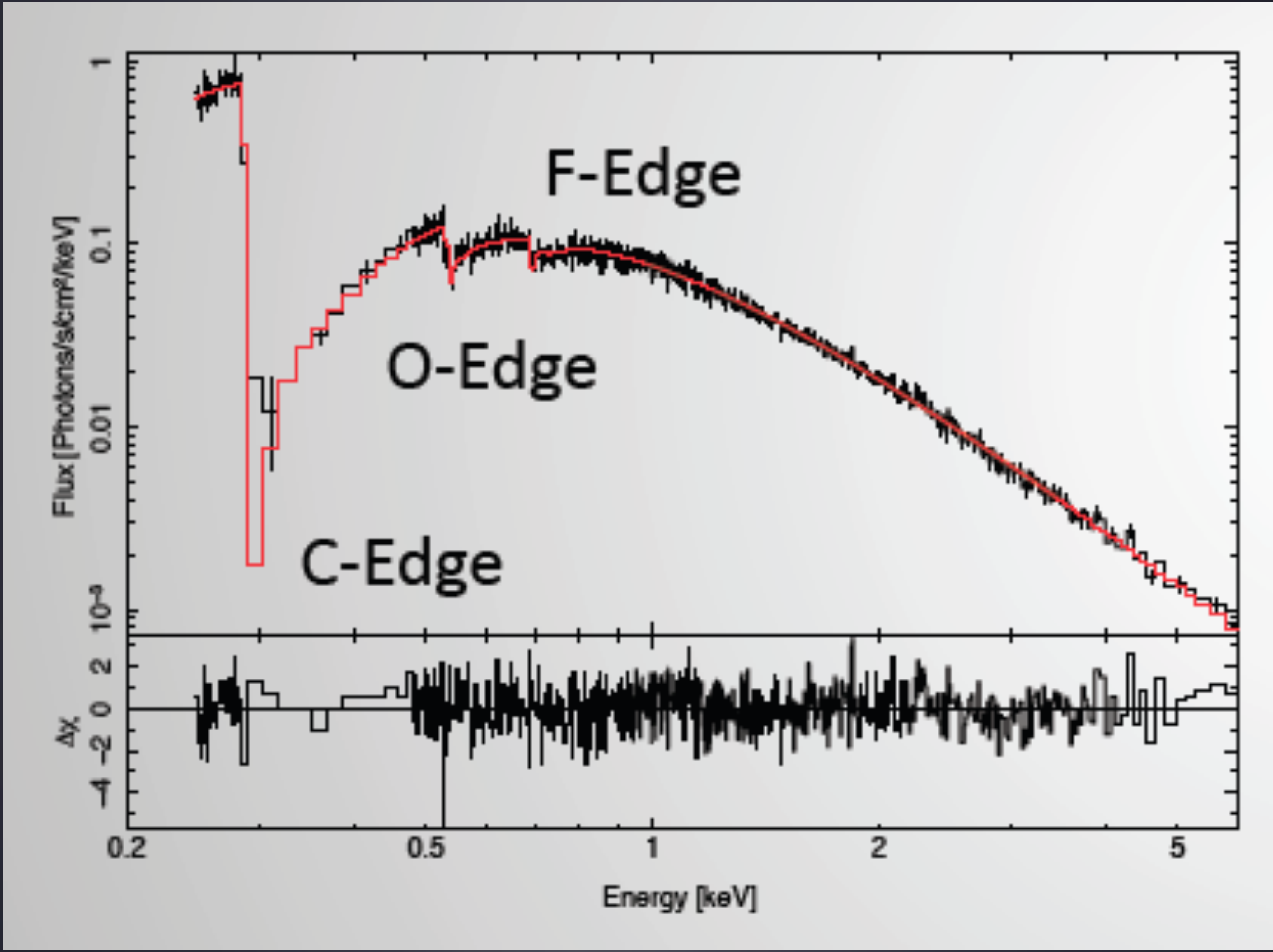


I'll get back to you on this one ...

Other Resources

- TGCat: www.tgcat.mit.edu
  - Spectral plots (counts & flux corrected), diagnostics, fluxes, variability plots
  - Standard data products – spectra & responses
  - Extraction scripts – all Chandra gratings modes

Science

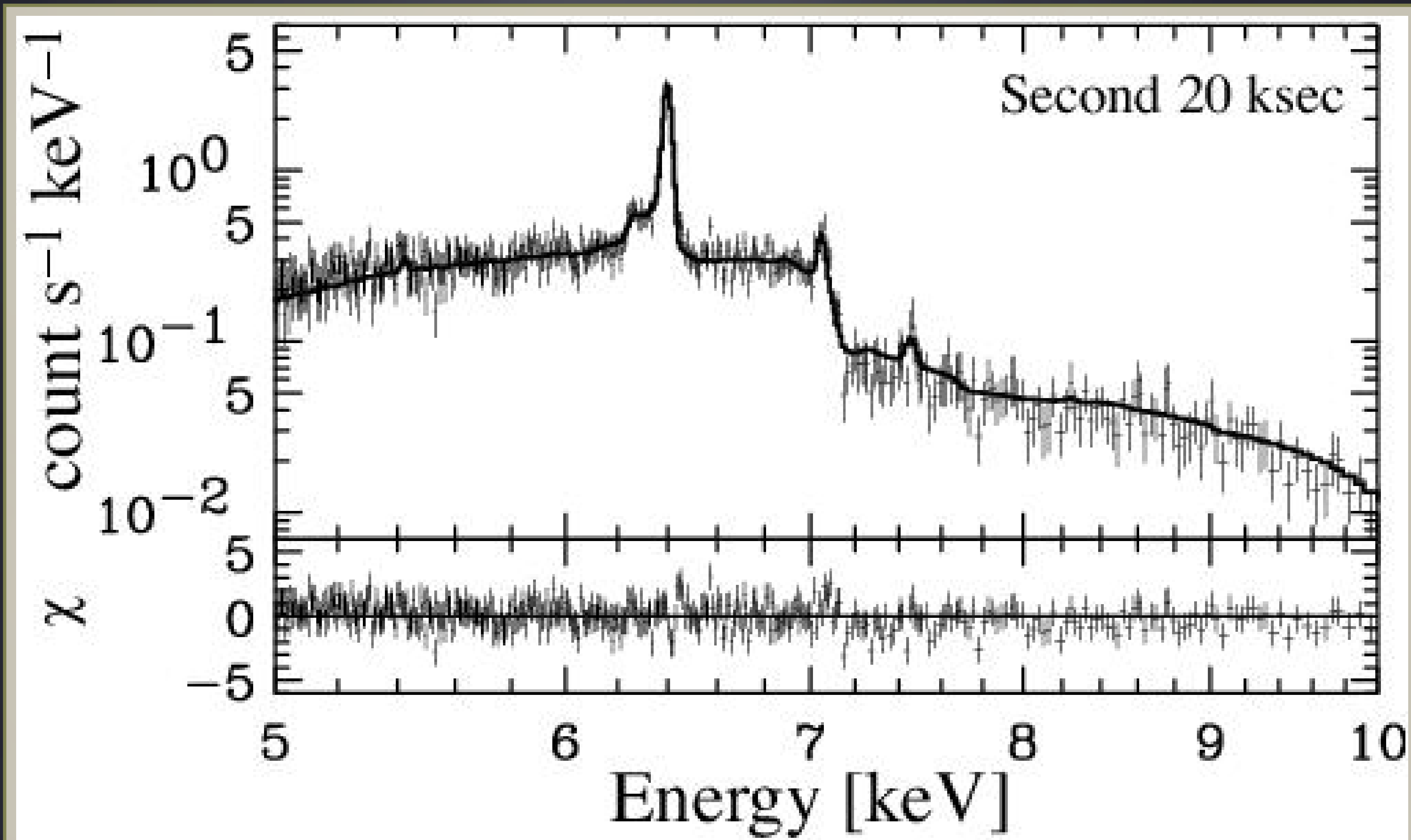


(H. Marshall)

Tracking Contaminant on Chandra-ACIS

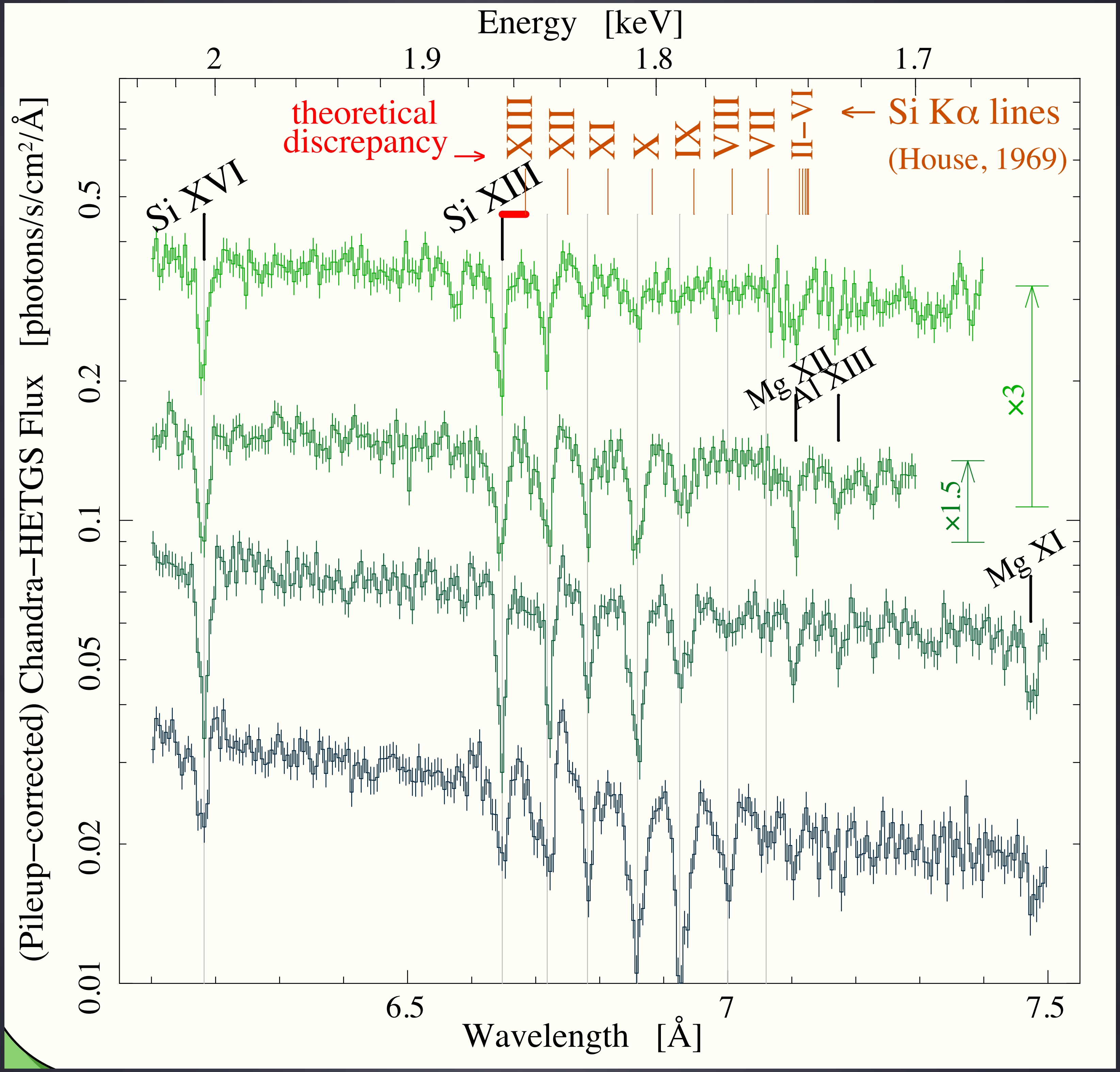
Science

GX 301-2



(Watanabe et al. 2004)

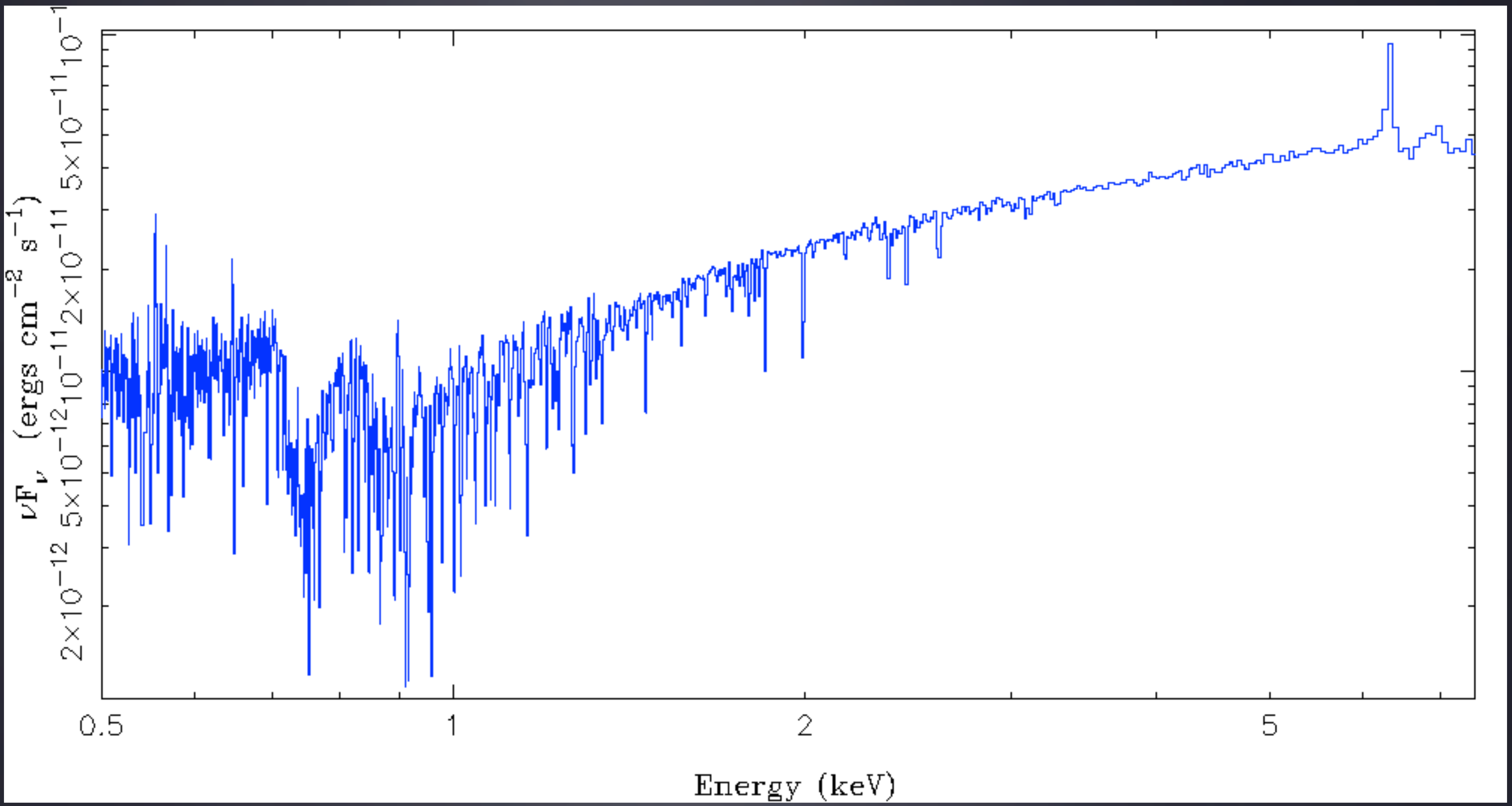
Science



Stellar Winds (Cyg X-1 HMXB Wind)

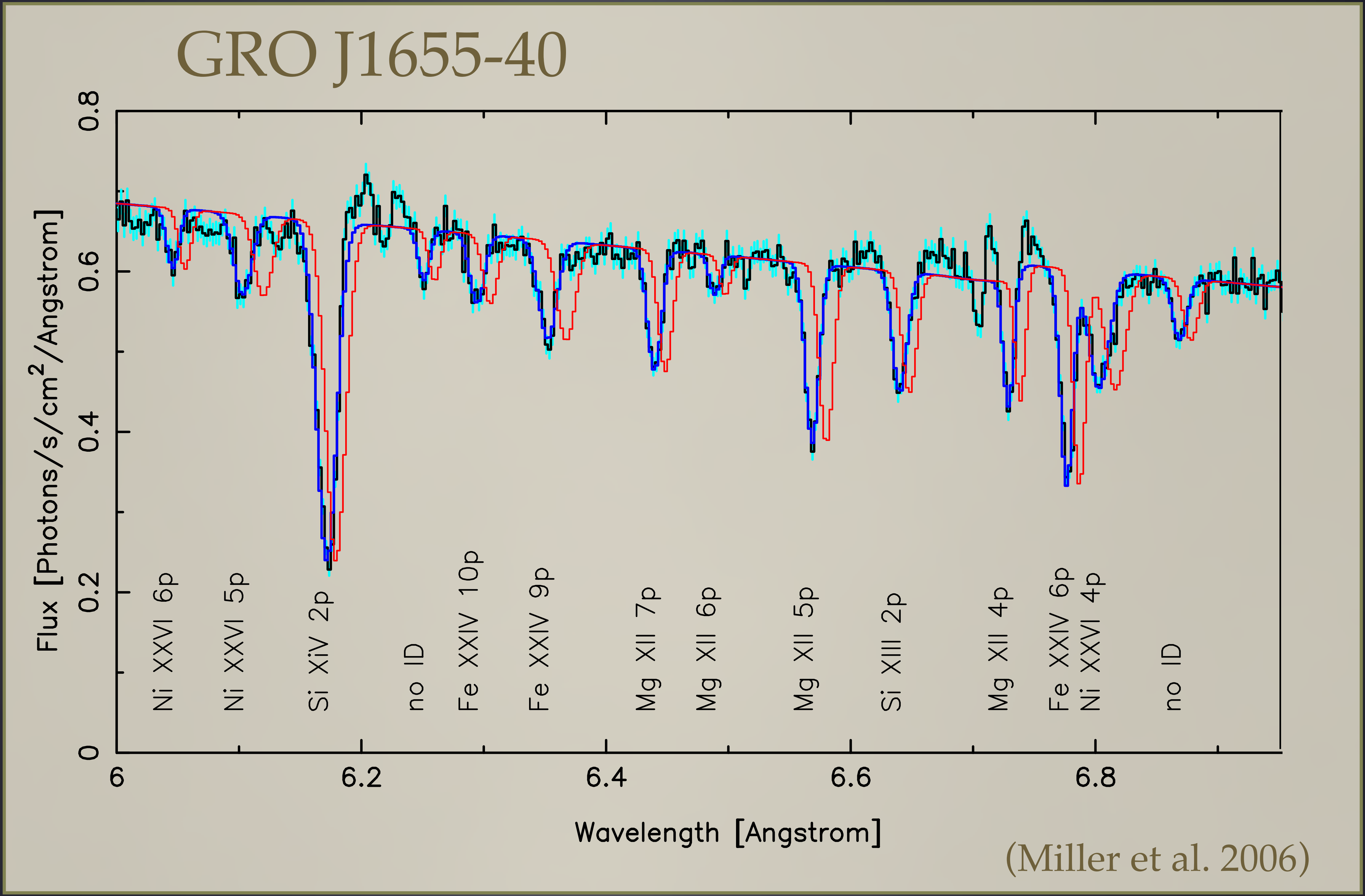
Science

NGC 3783 from the TGCat Catalog



AGN Warm Absorbers

Science



Magnetized Accretion Disk Winds