CIAO WORKSHOP BOLOGNA 2019 SEP 15

CHANDRA HIGH-RESOLUTION SPECTRA

VINAY KASHYAP (CXC/CFA)

OUTLINE

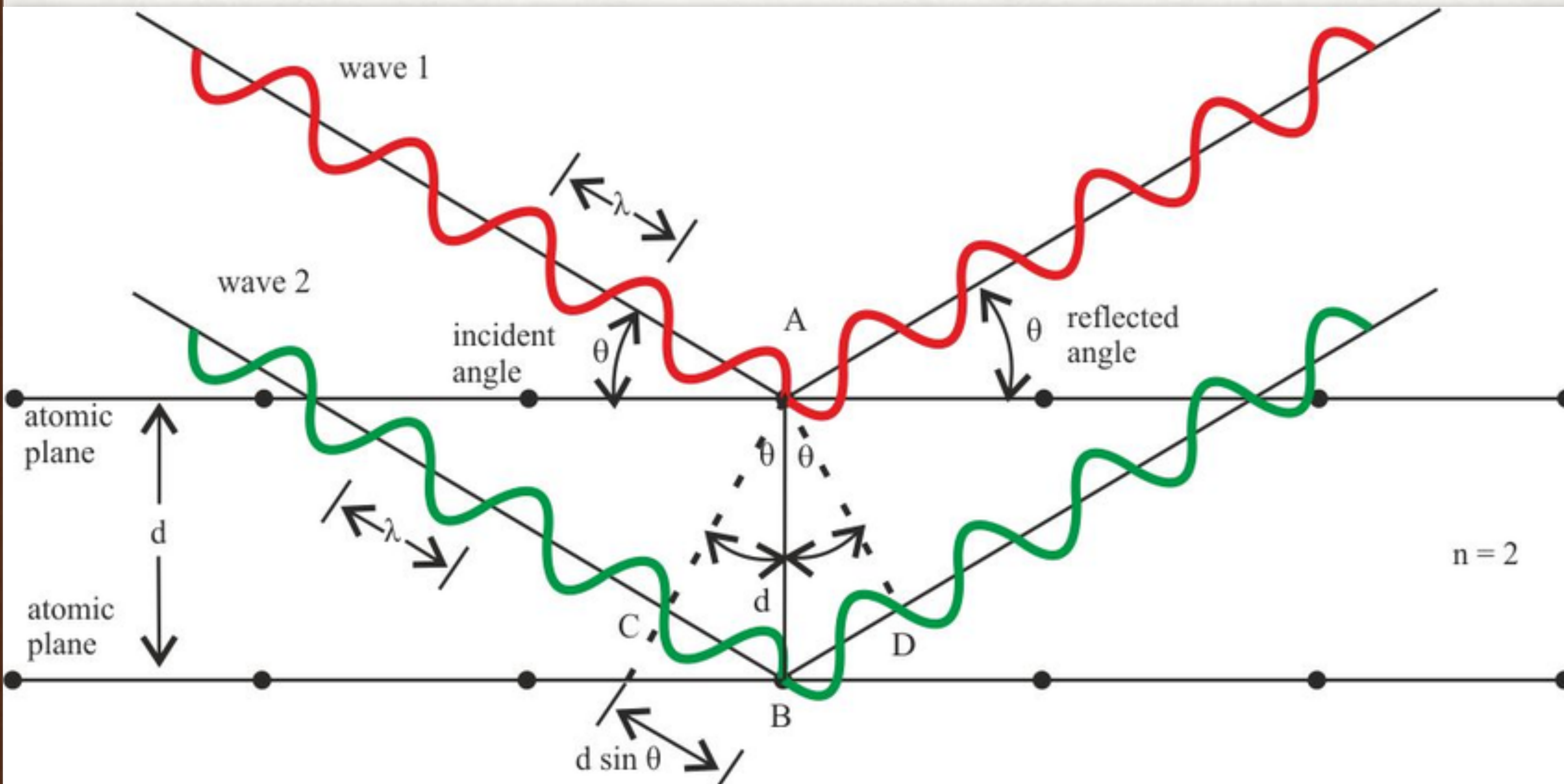
GOAL: EXTRACT AND ANALYZE CHANDRA GRATING SPECTRA

1. Theory
   - Braggs' Law, Rowland Circle, Orders
2. Hardware
   - [LETGS|HETGS]+[ACIS-S|HRC-[SI]]
3. Pipeline
   - tgdetect, tg_resolve_events, tg_create_mask, tgextract
4. Analysis

1. THEORY

BRAGGING ON THE X-WAVES

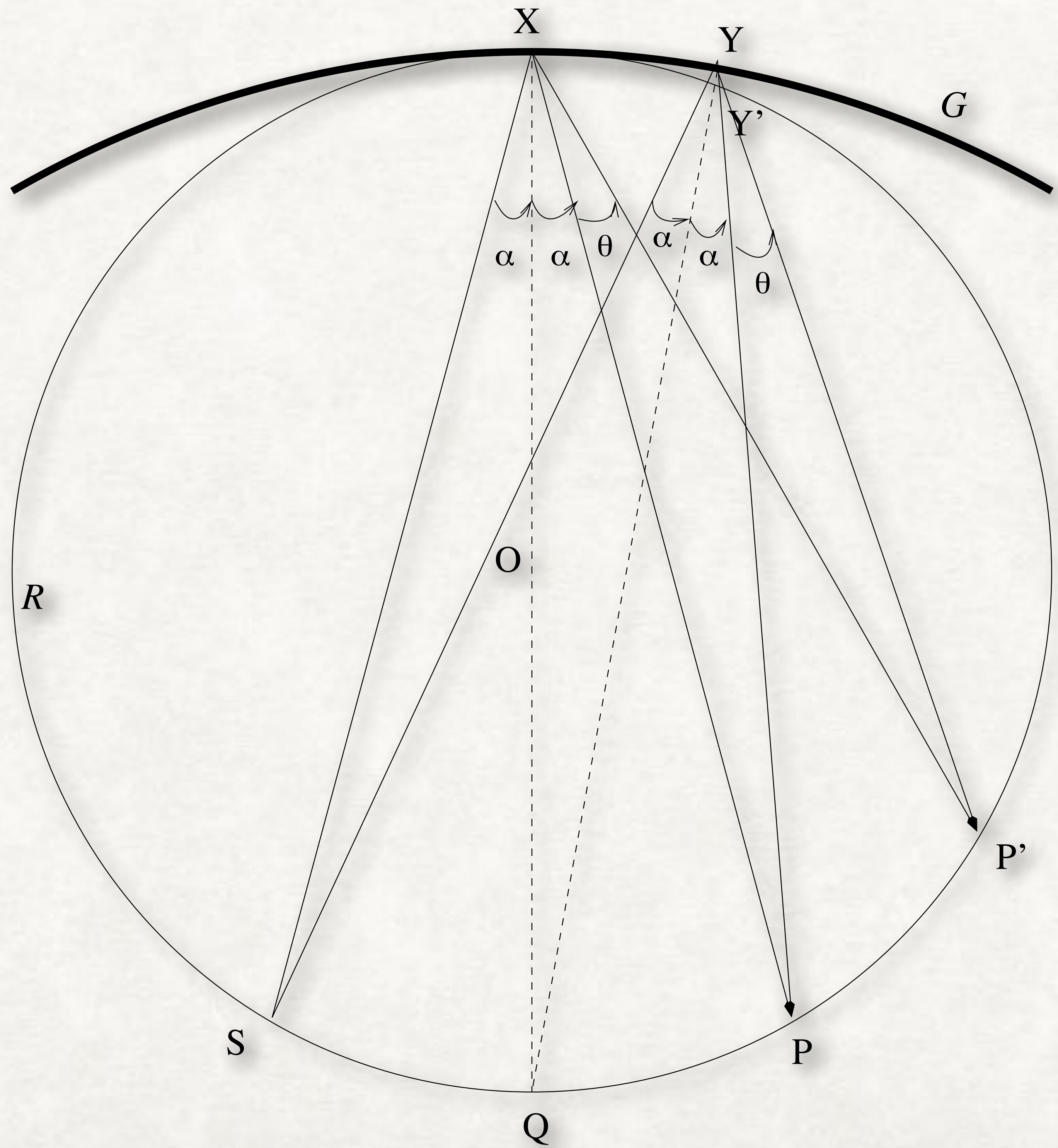
$$n\lambda = 2d \sin\theta$$



Naemi Waeselmann (researchgate)

1. THEORY

ROWLAND CIRCLE

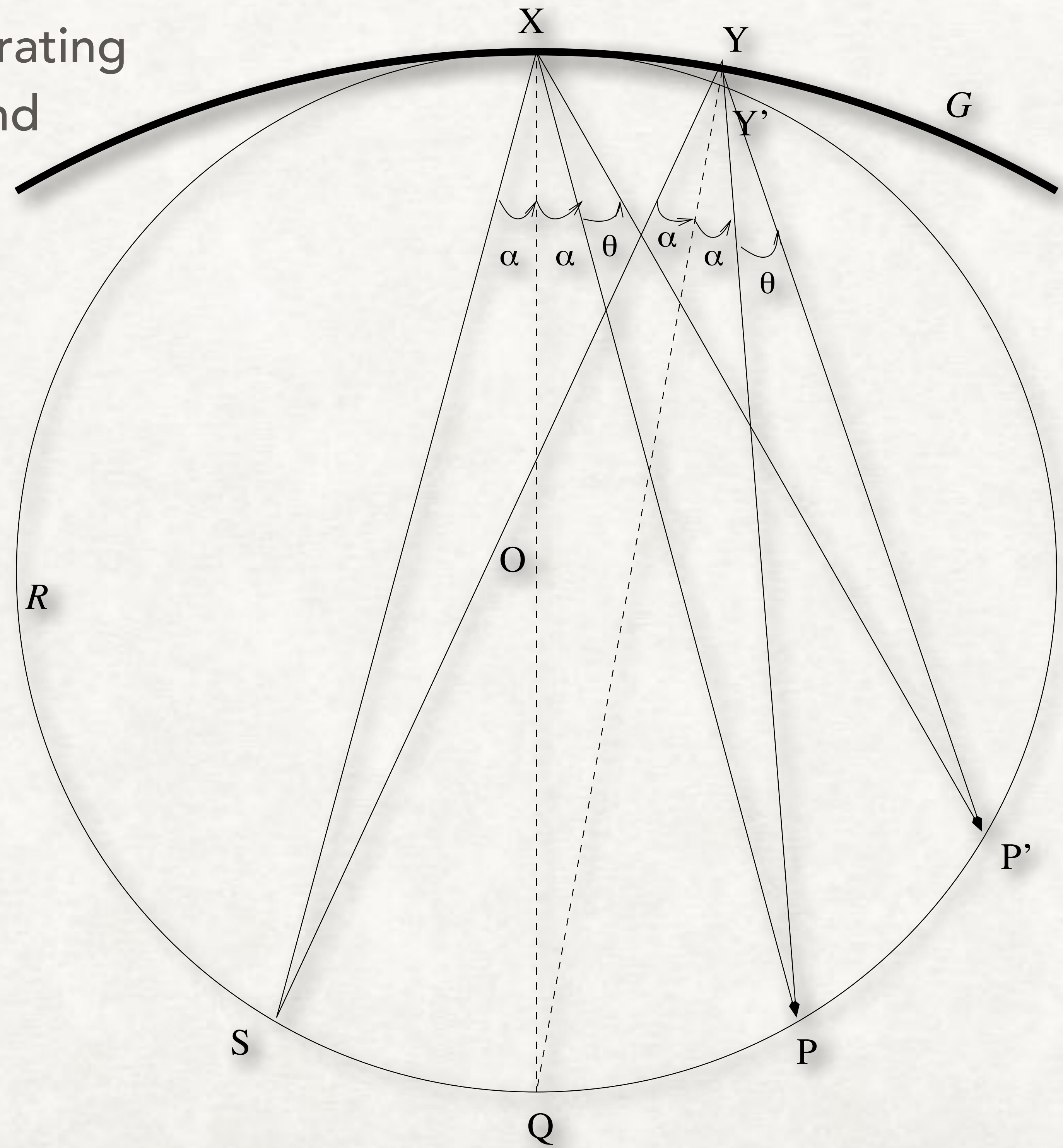


1. THEORY

ROWLAND CIRCLE

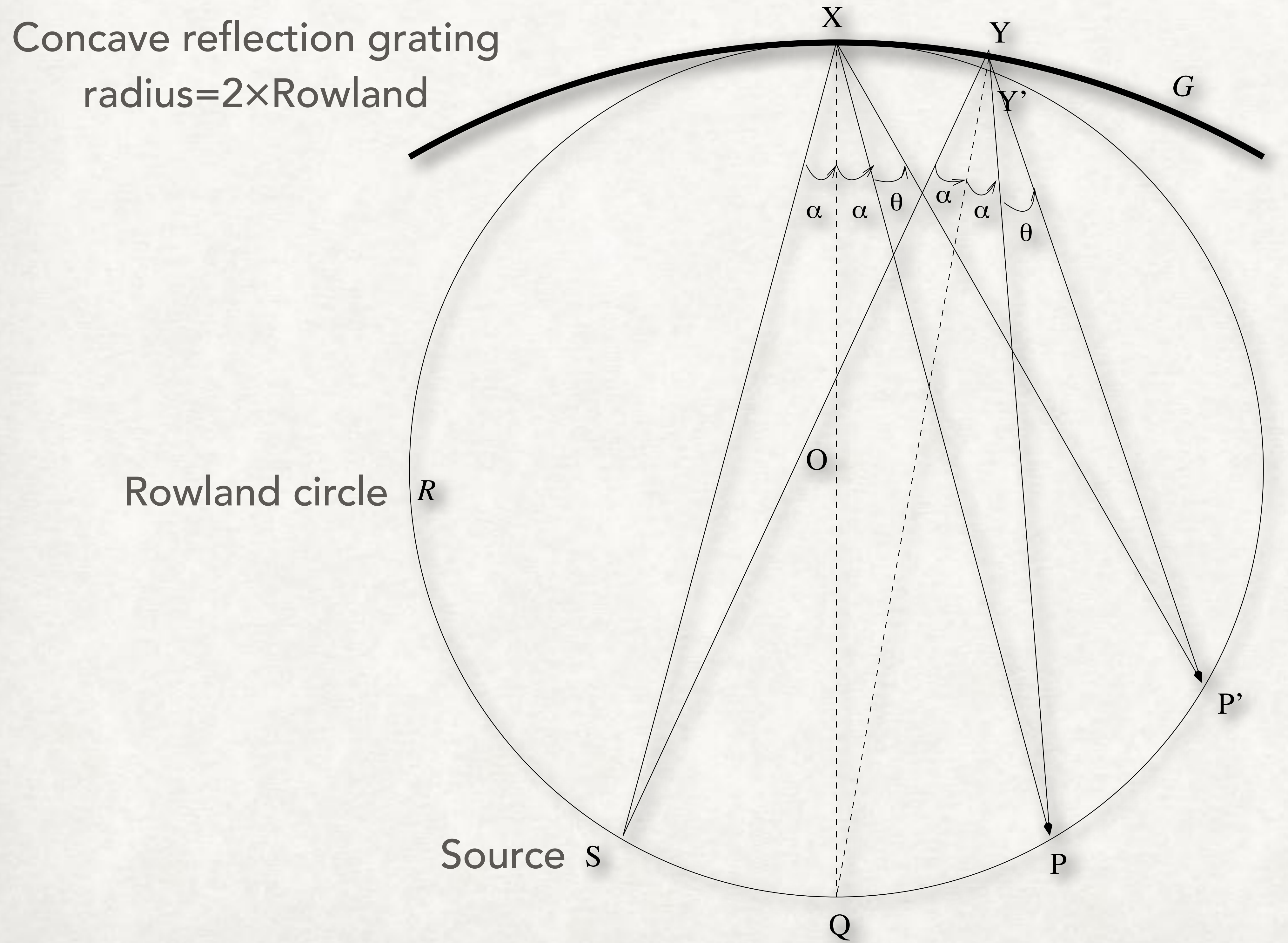
Concave reflection grating
radius=2×Rowland

Rowland circle



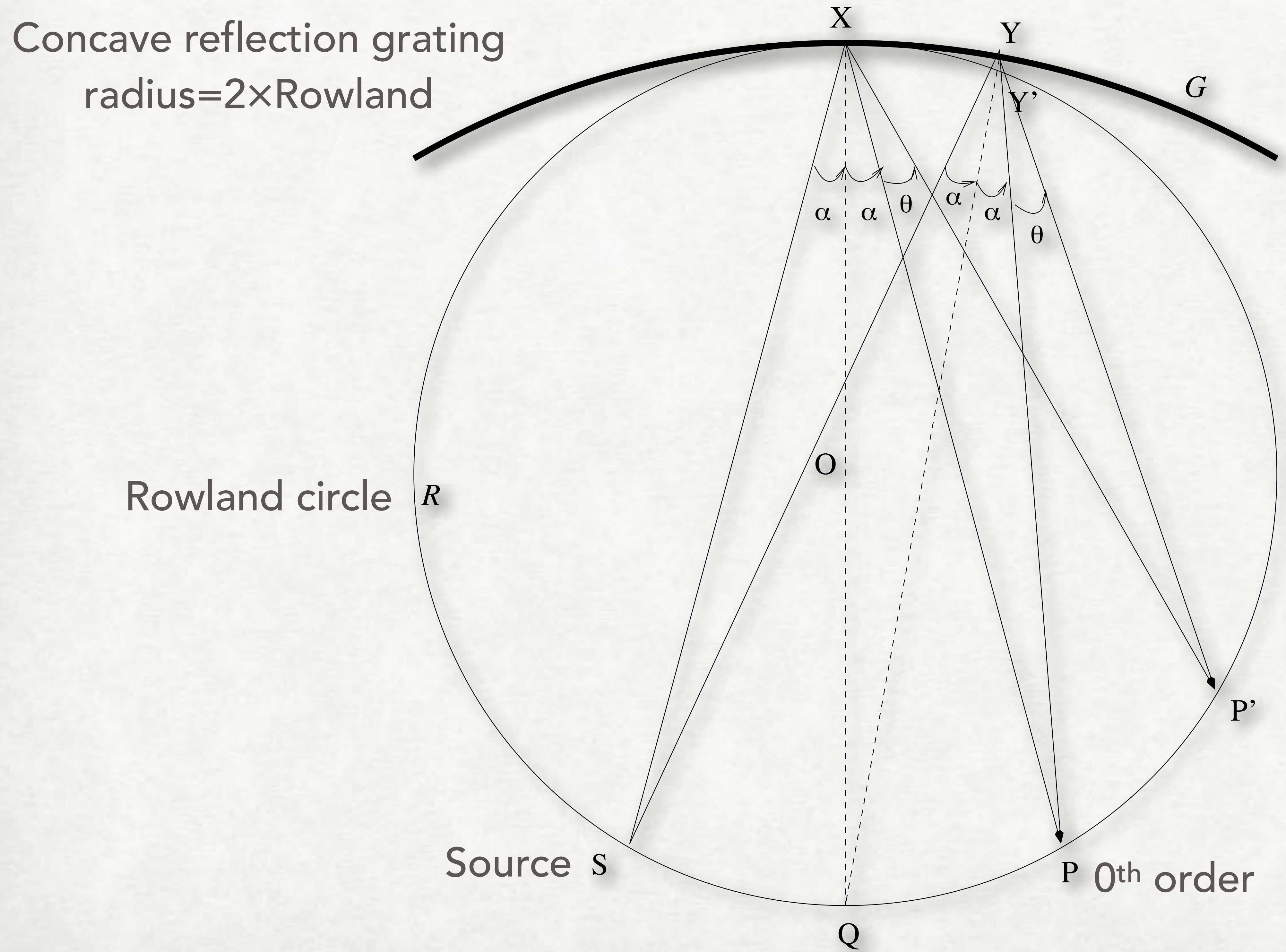
1. THEORY

ROWLAND CIRCLE



1. THEORY

ROWLAND CIRCLE



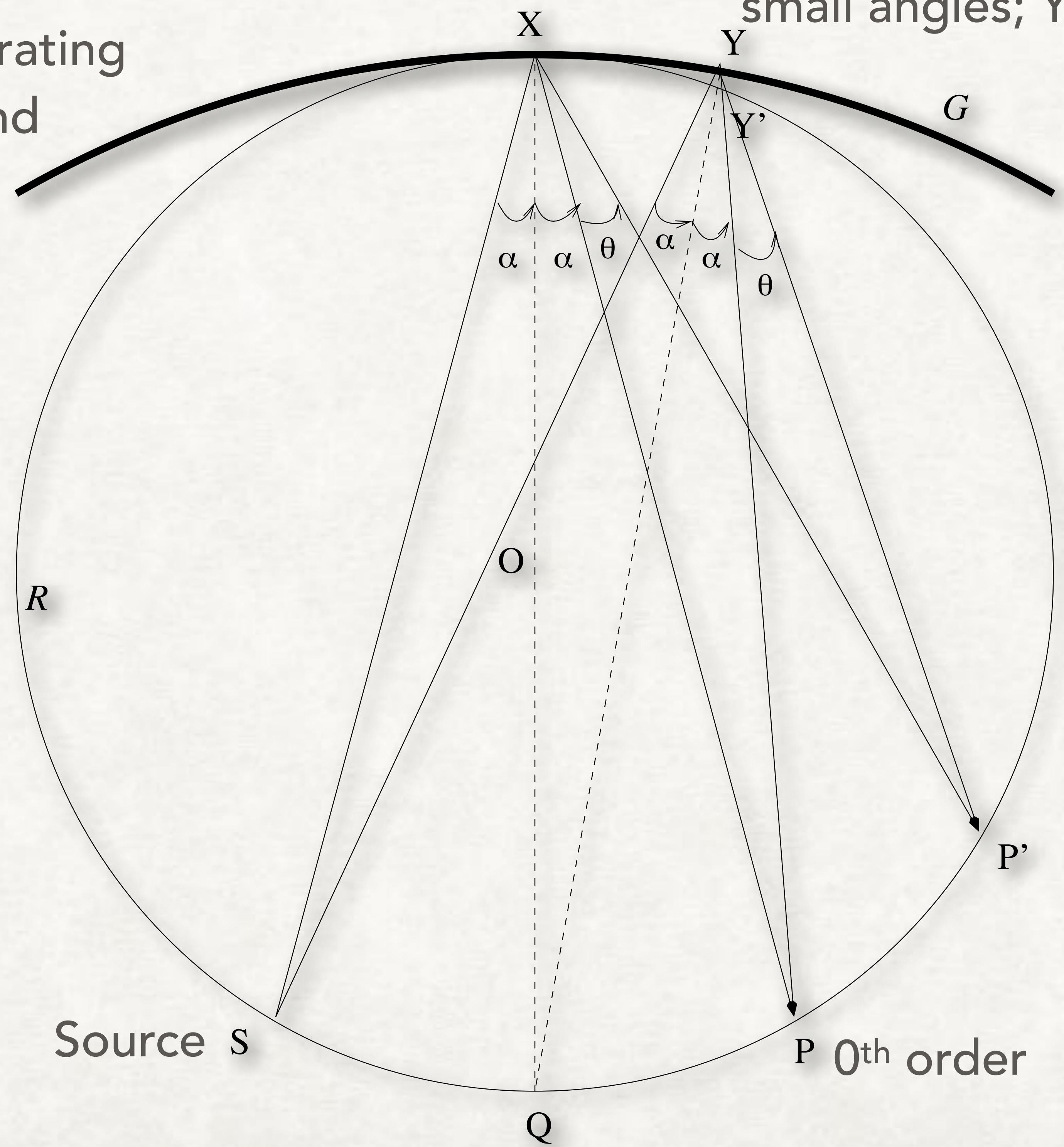
1. THEORY

ROWLAND CIRCLE

small angles; YY′ assumed negligible

Concave reflection grating
radius=2×Rowland

Rowland circle

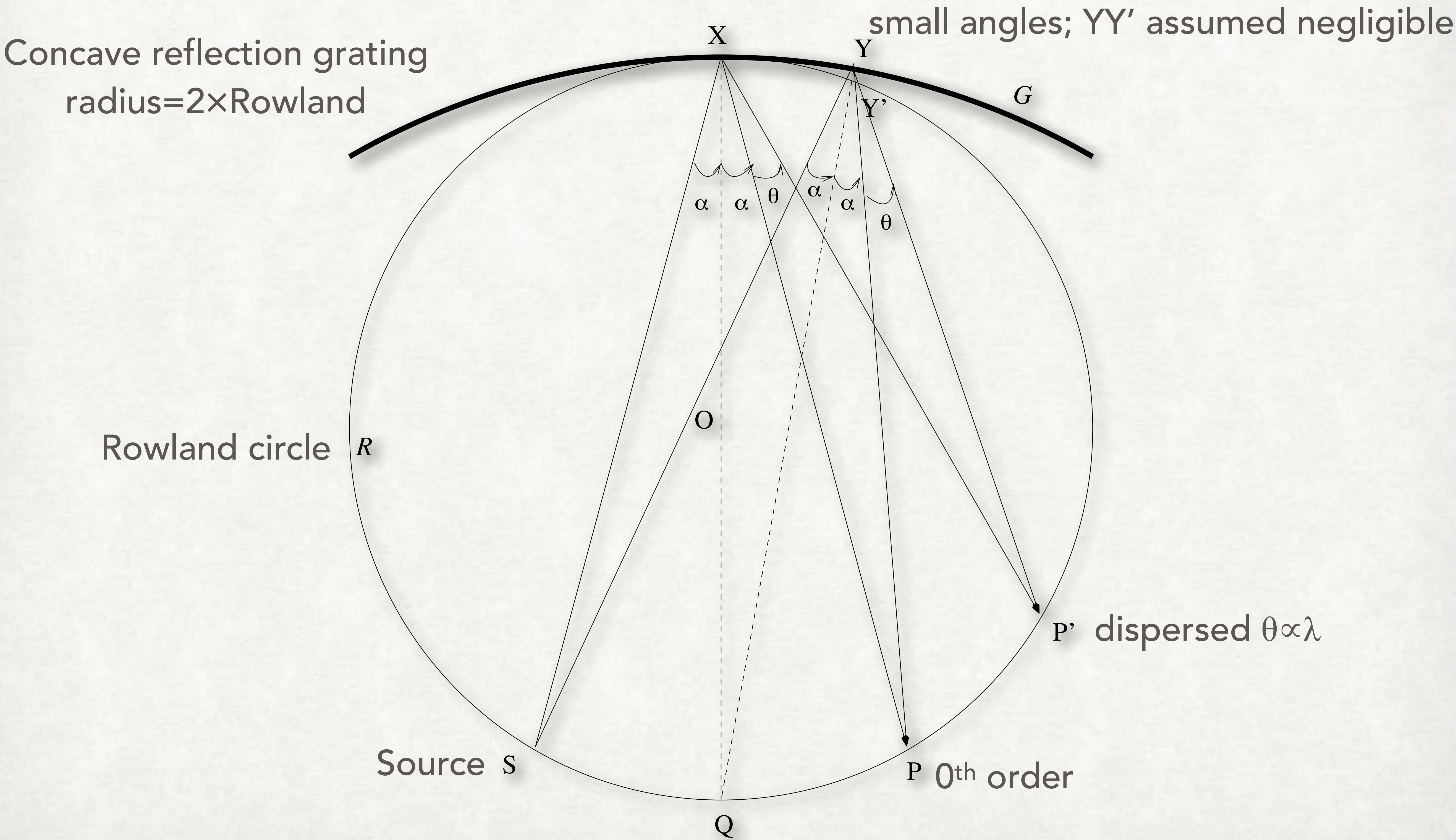


Source

0th order

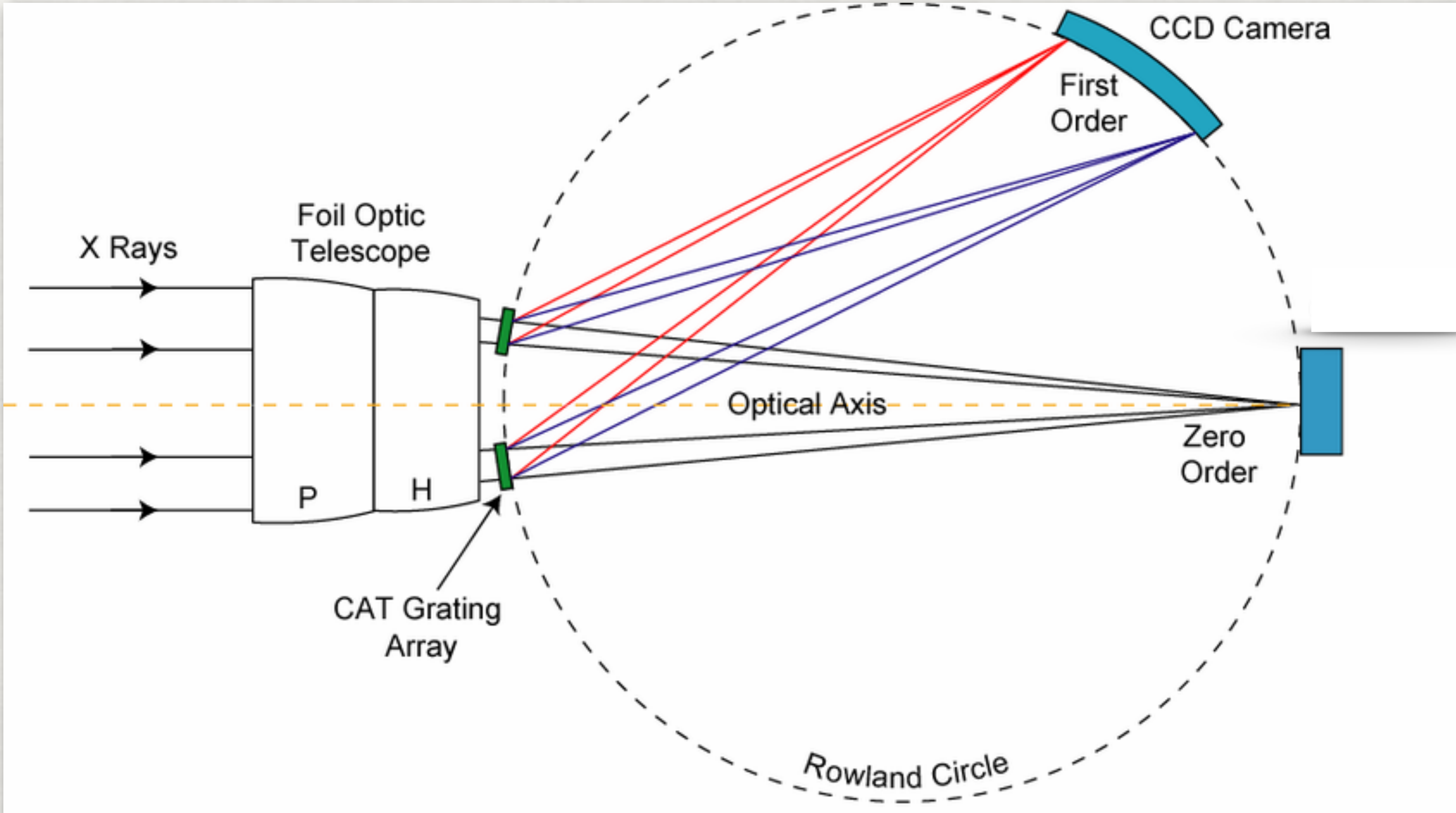
1. THEORY

ROWLAND CIRCLE



1. THEORY

TRANSMISSION GRATING GEOMETRY



Flanagan et al. 2007, Proc.SPIE 6688, 66880Y

1. THEORY

ORDERS AND DISPERSION RELATION

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- You can measure the distance of a photon from the zeroth order in the detector plane and translate that distance to $n\lambda$

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$$d \propto \delta\theta \propto \lambda$$

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- In the small angle approximation at which most gratings operate, distance along the detector,

  $d \propto \delta\theta \propto \lambda$

- Resolution is limited by the size of the 0th order image, with

  $\delta\lambda \propto PSF\text{-}width$

  Along the Rowland circle, this is fixed, so

  $\delta\lambda \approx constant \Rightarrow$ Resolution $\lambda/\delta\lambda\uparrow$ as $\lambda\uparrow$

2. HARDWARE

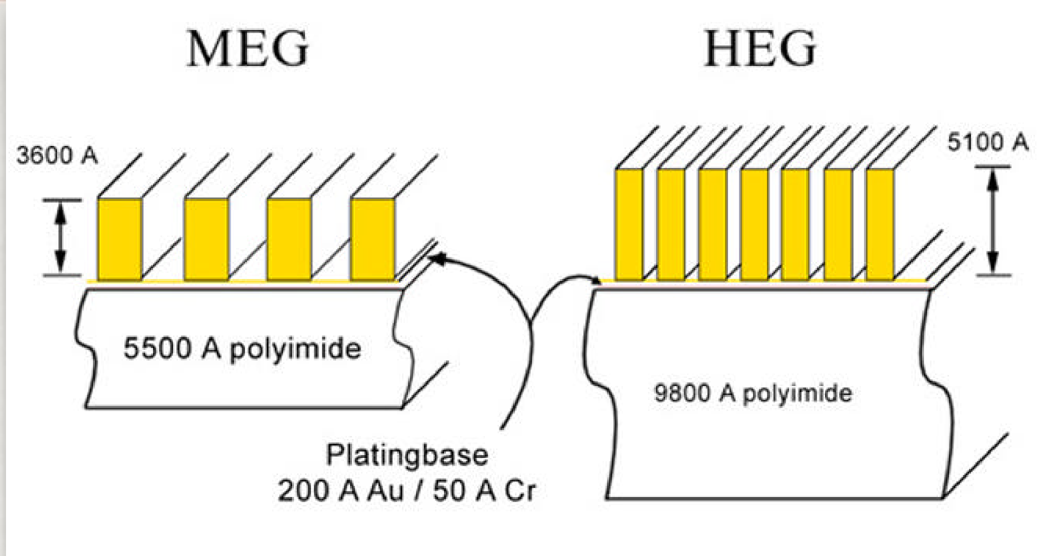
HETGS

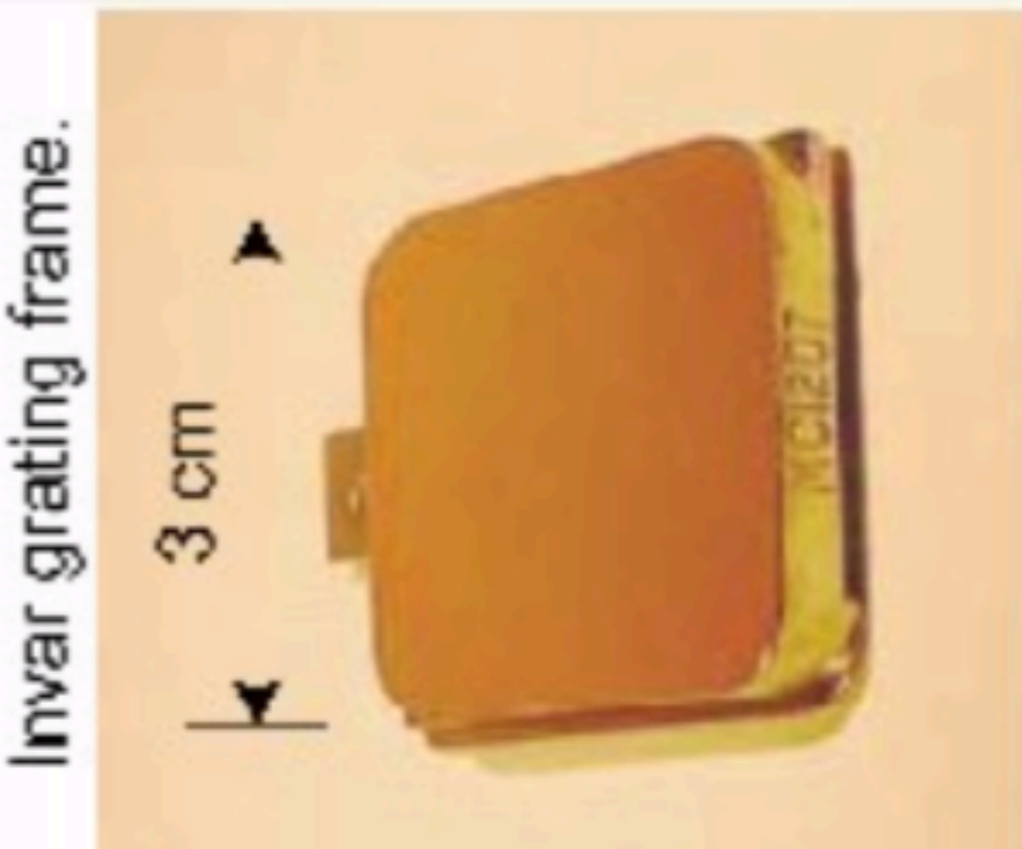
- High-Energy Transmission Grating Spectrometer
  - Two gratings in one: Medium Energy Grating (MEG) for outer mirror shells, and High Energy Grating (HEG) for inner shells
- The facets are tilted (+4.7° MEG, –5.2° HEG), leading to two arms which intersect at the 0^{th} order
- The MEG period is ≈2× HEG's, so wavelength coverage of MEG is double that of HEG, with half the resolution
- Primary detector is ACIS-S, optionally also HRC-I (but as yet unsupported)
- Chandra POG Chapter 8:

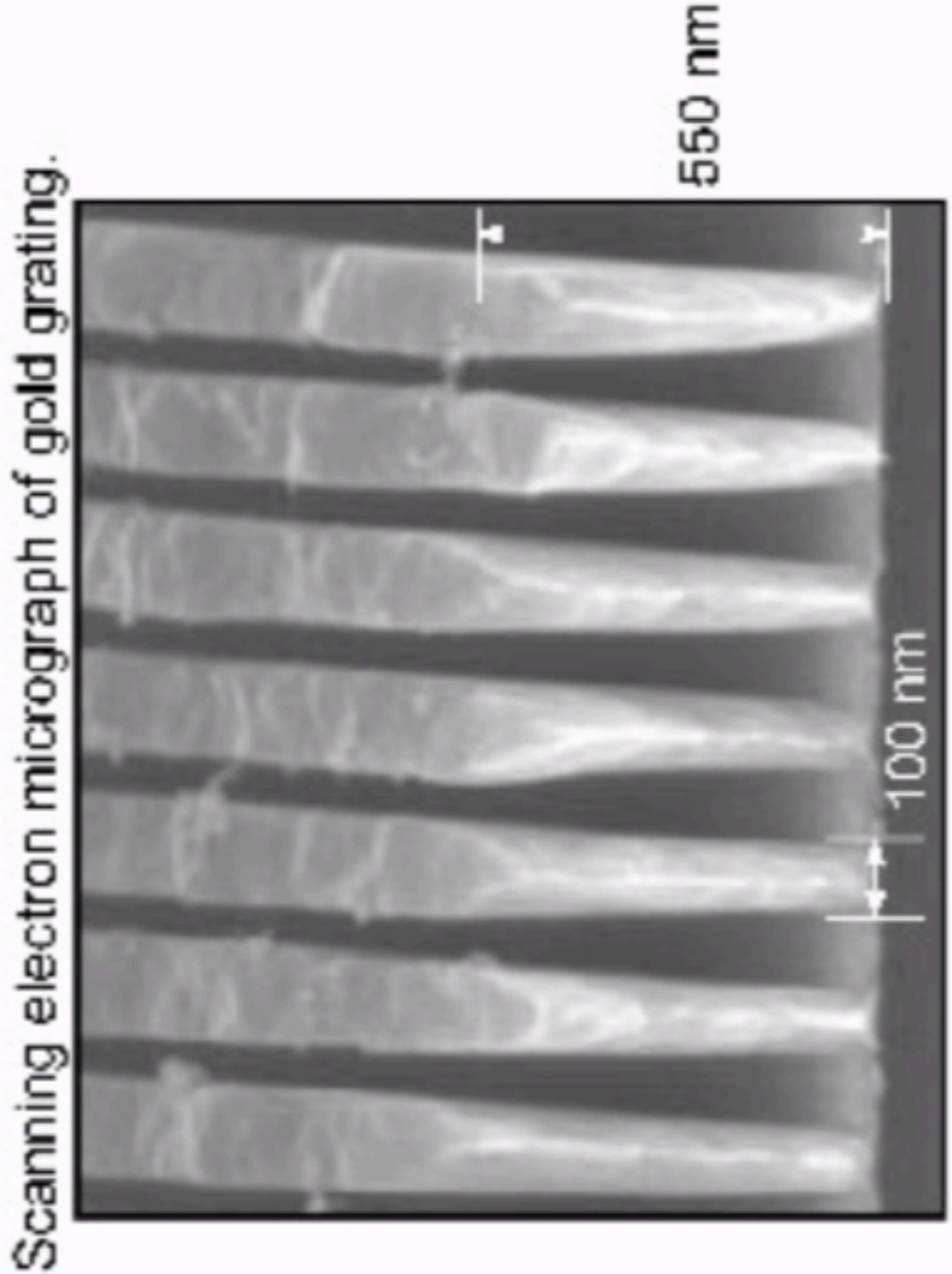
  http://cxc.harvard.edu/proposer/POG/html/chap8.html

HETG

https://space.mit.edu/HETG/hetg_info.html





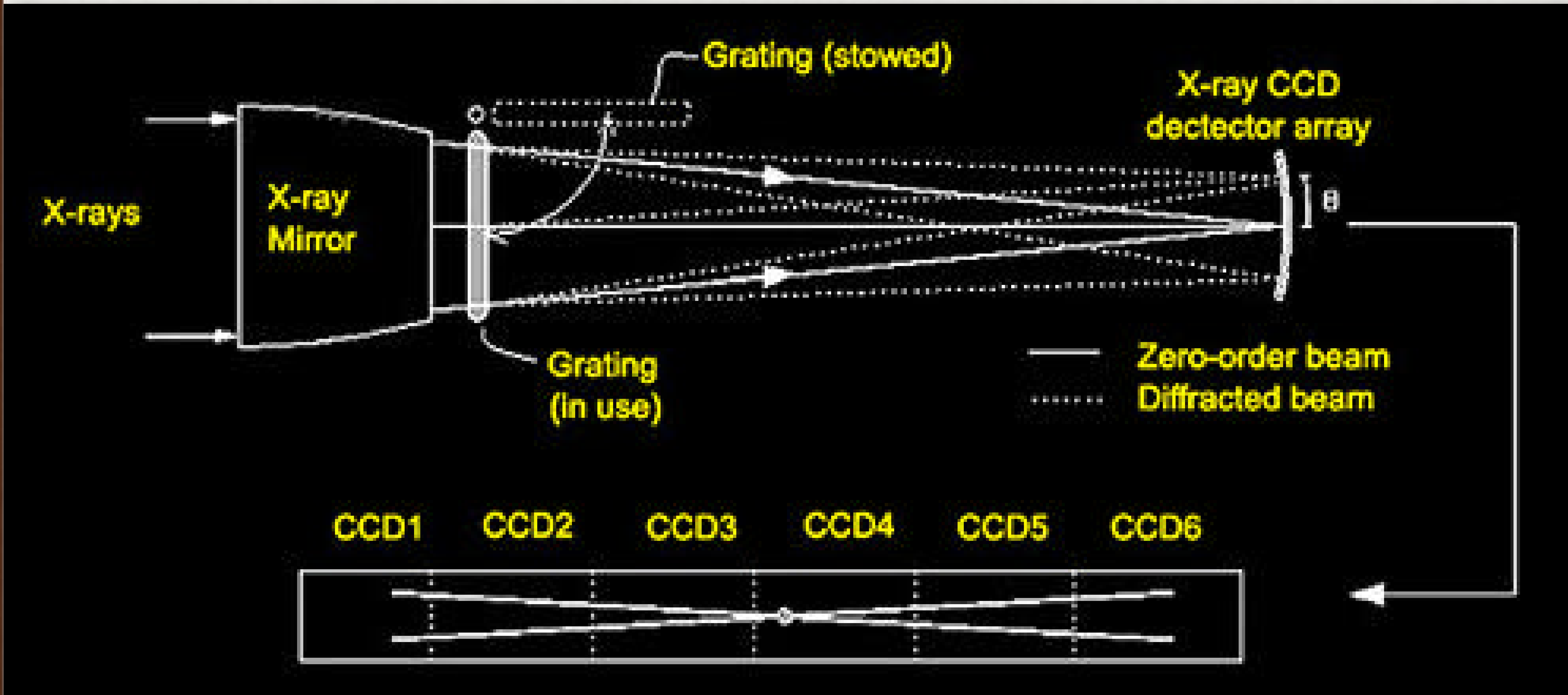


HETG facets and bars

https://space.mit.edu/HETG/hetg_info.html

(Mike Nowak)

HETGS schematic and footprint on ACIS-S



(chandra.harvard.edu)

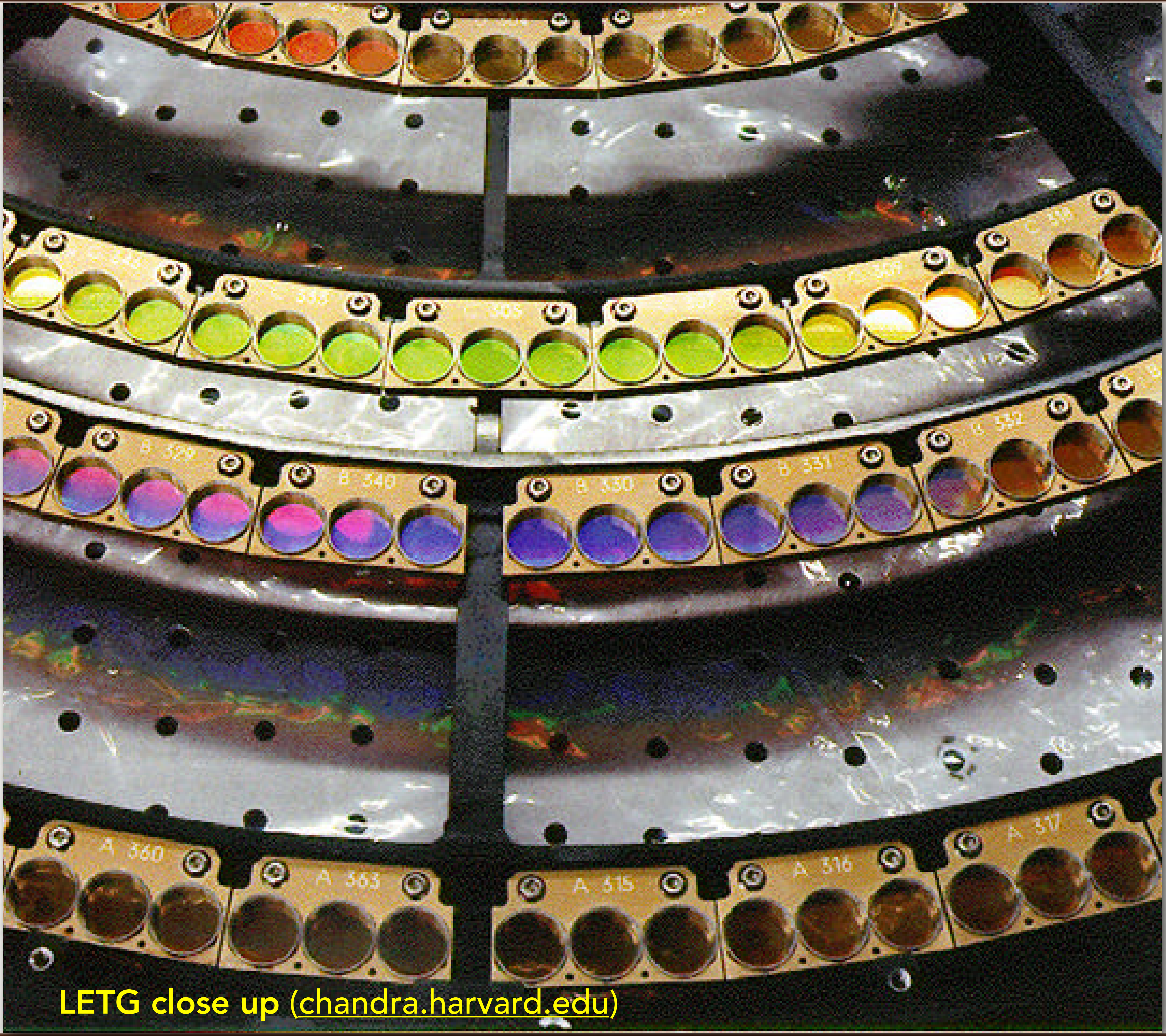
2. HARDWARE

LETGS

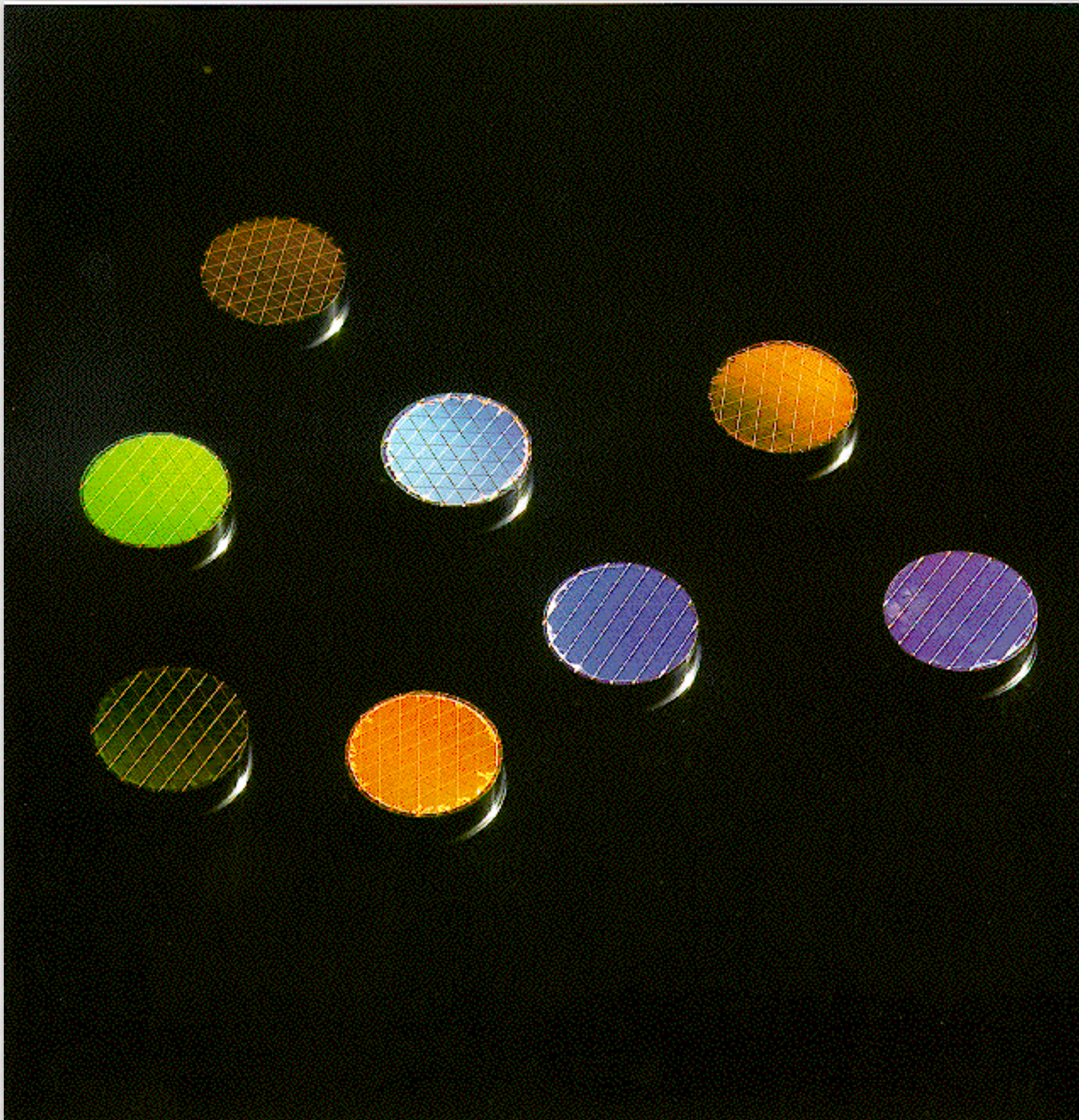
- Low-Energy Transmission Grating Spectrometer
- The Low Energy Grating (LEG) period is ≈2.5×MEG's, so resolution is lower, but wavelength coverage is larger
- Primary detector by usage is HRC-S, optionally also ACIS-S and HRC-I
- Chandra POG Chapter 9:

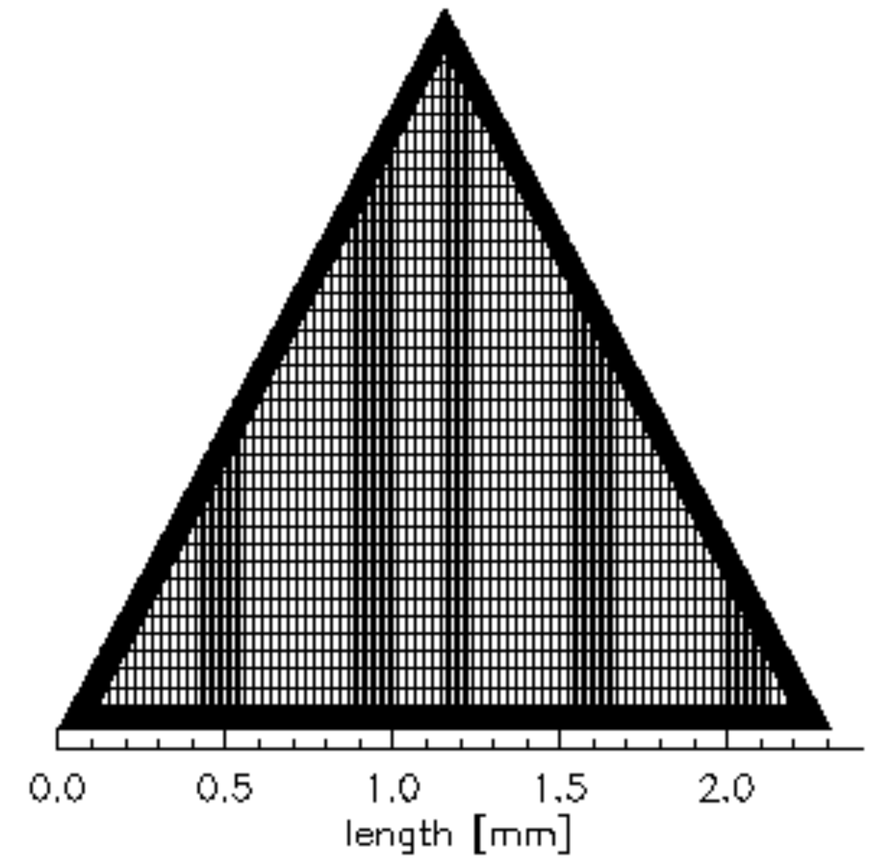
  http://cxc.harvard.edu/proposer/POG/html/chap9.html

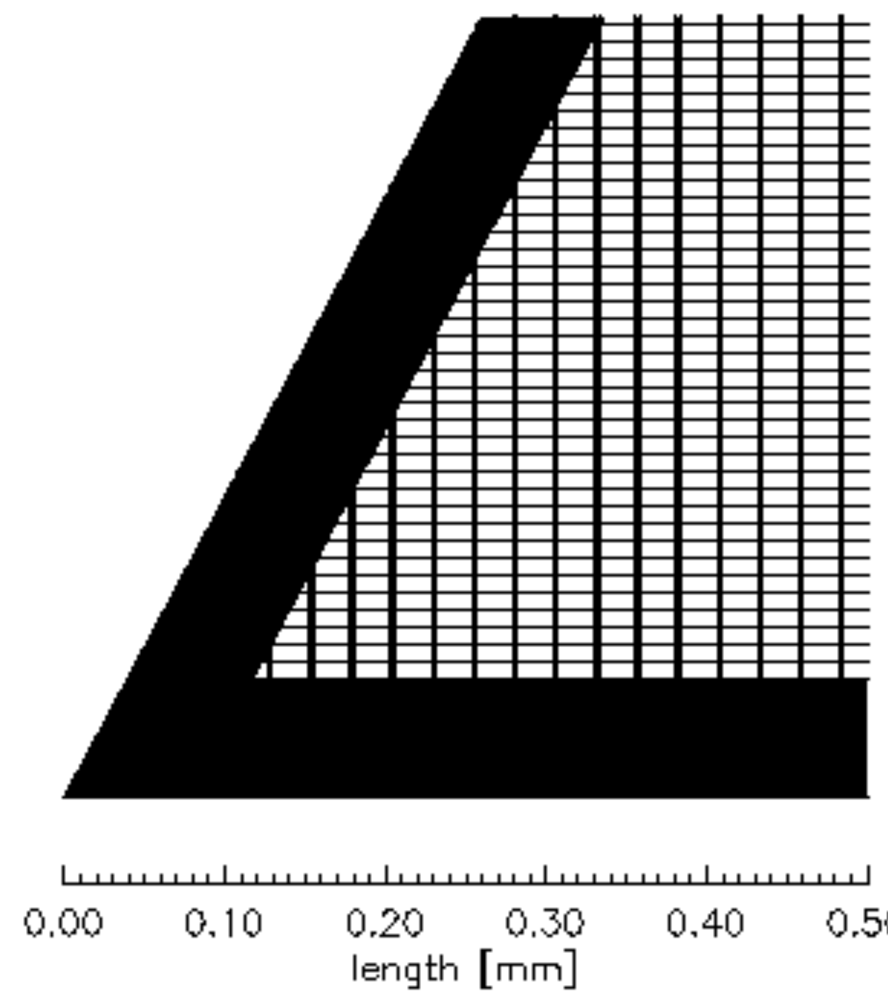
LETG being integrated into the optical bench (chandra.harvard.edu)



LETG close up (chandra.harvard.edu)





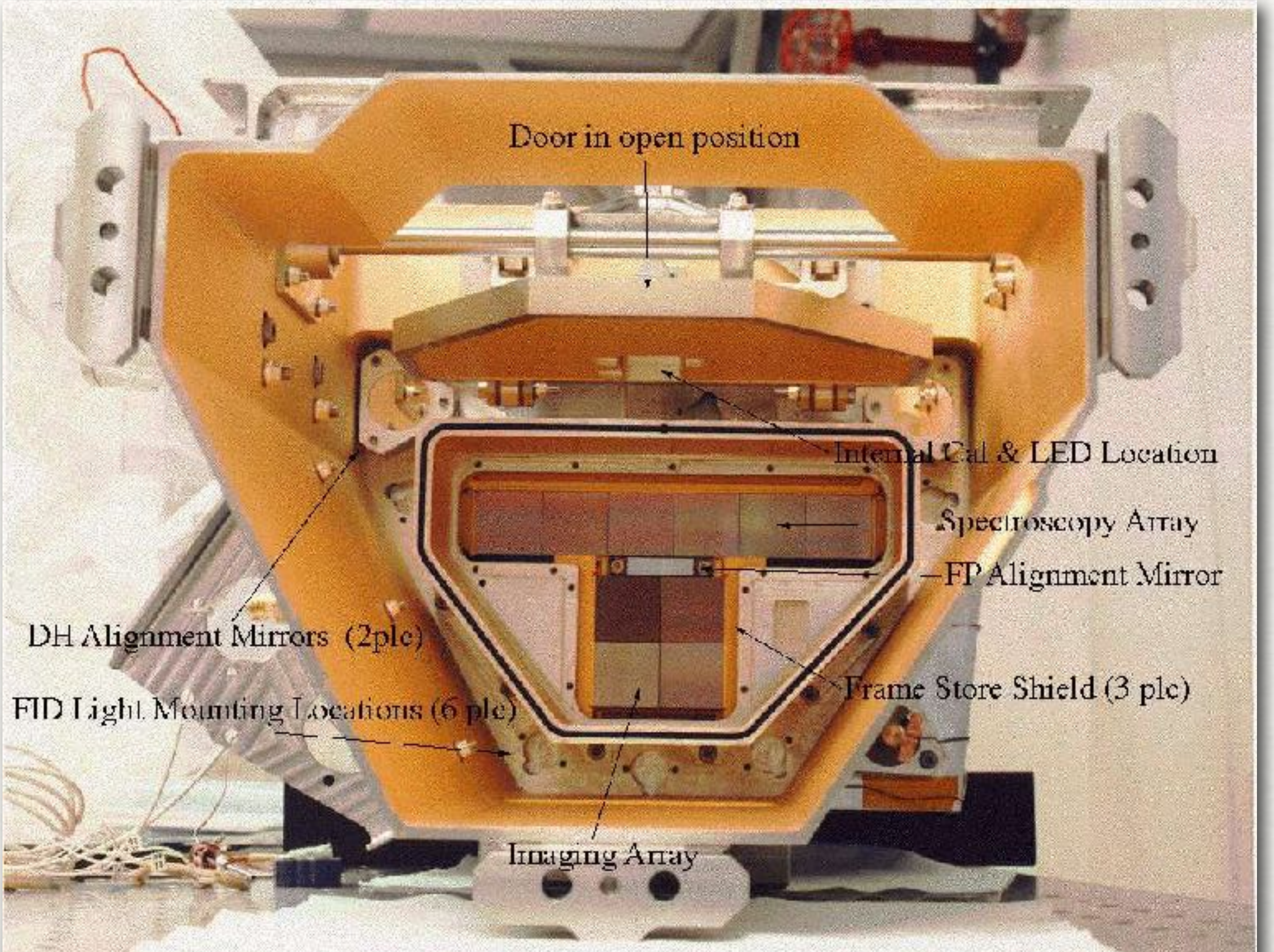


LETG gratings: wires, coarse, and fine support

https://www.sron.nl/experimenten-50-jaar-ruimteonderzoek-2820/i-letg

2. THE HARDWARE

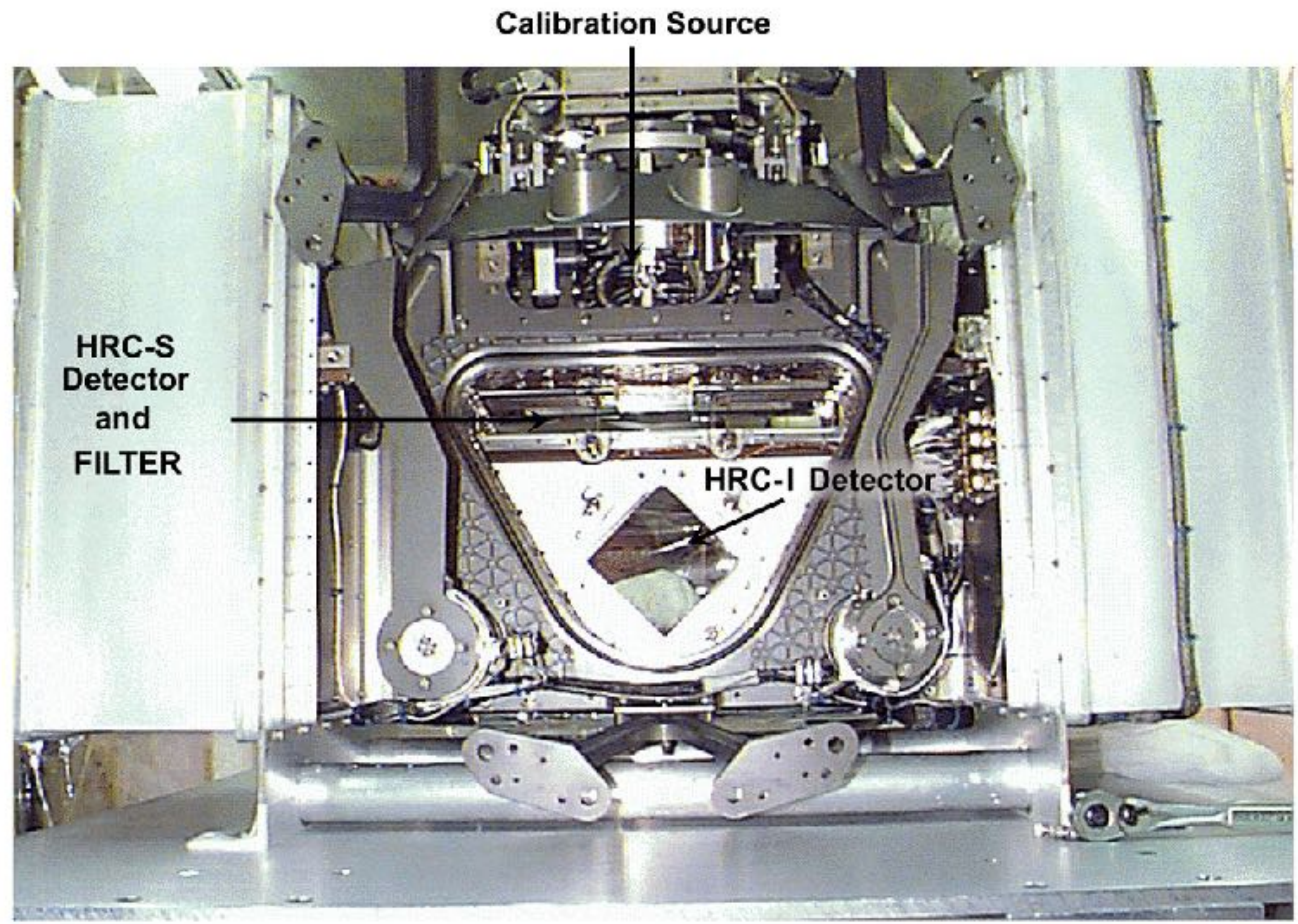
ACIS-S



ACIS focal plane array (chandra.harvard.edu)

2. THE HARDWARE

HRC-S & HRC-I

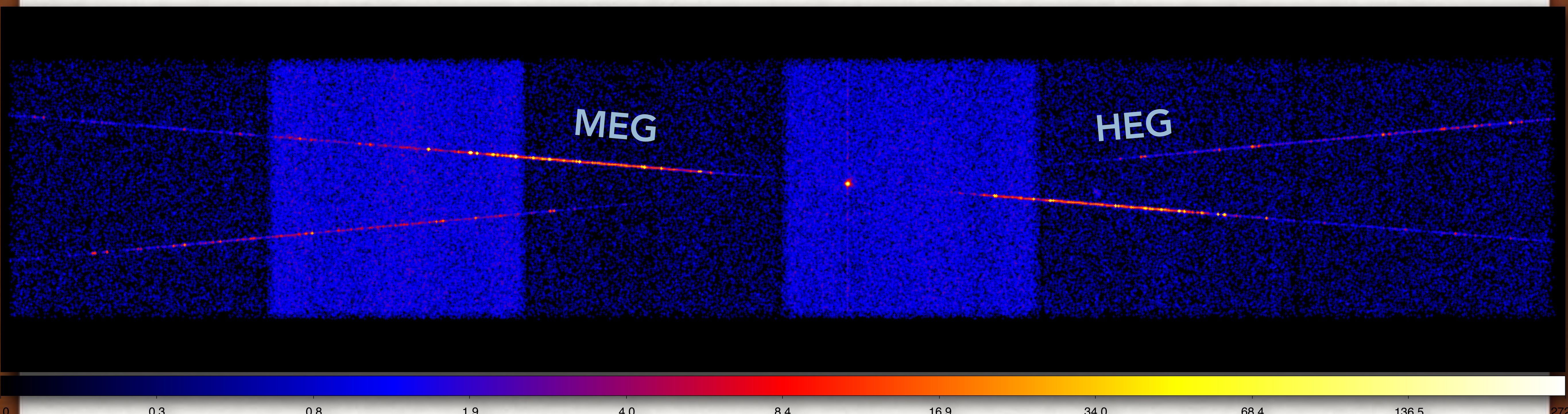


HRC focal plane array (chandra.harvard.edu)

Looking into the HRC Vacuum Housing

2. HARDWARE

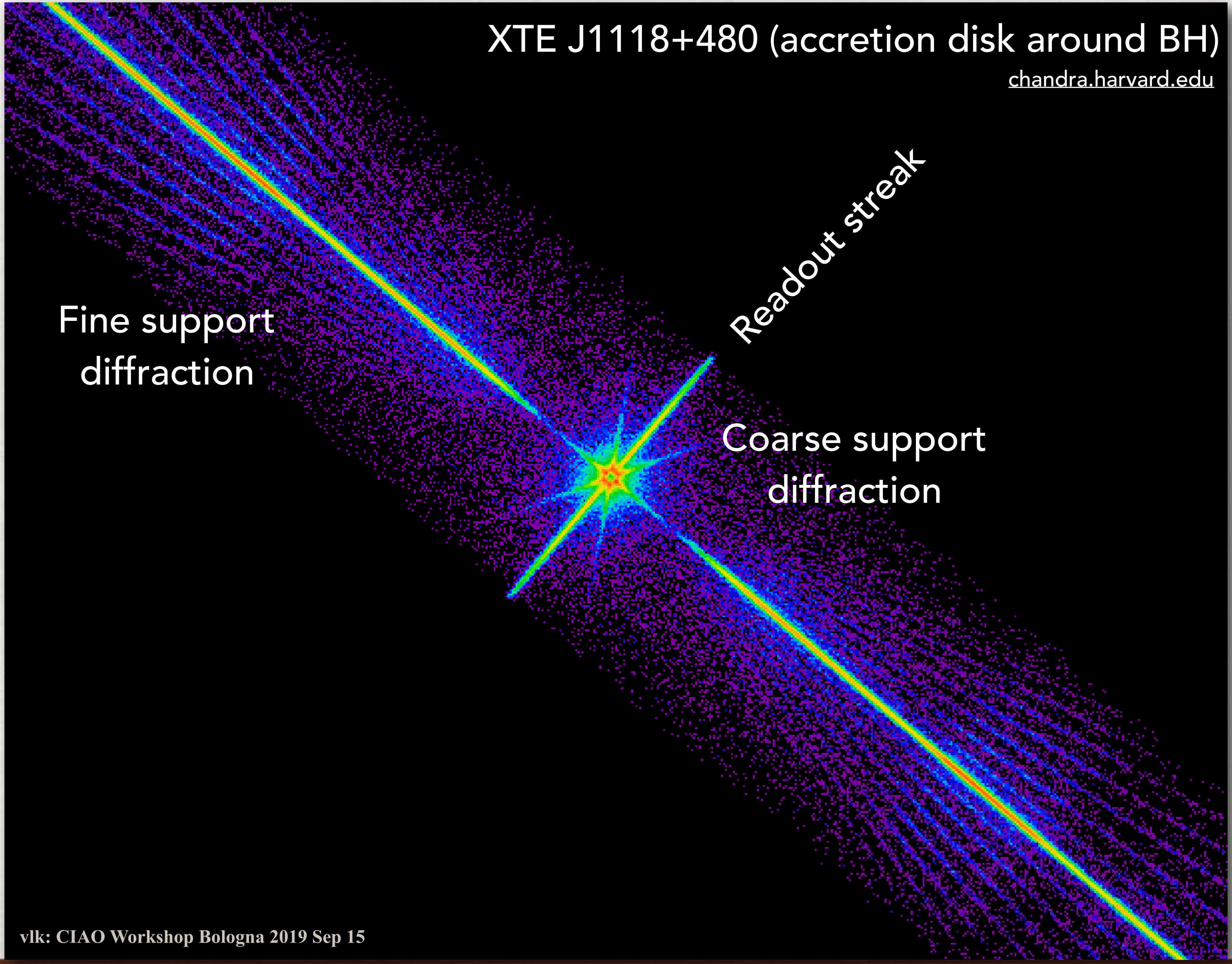
HETGS+ACIS-S



Capella ObsID 1235

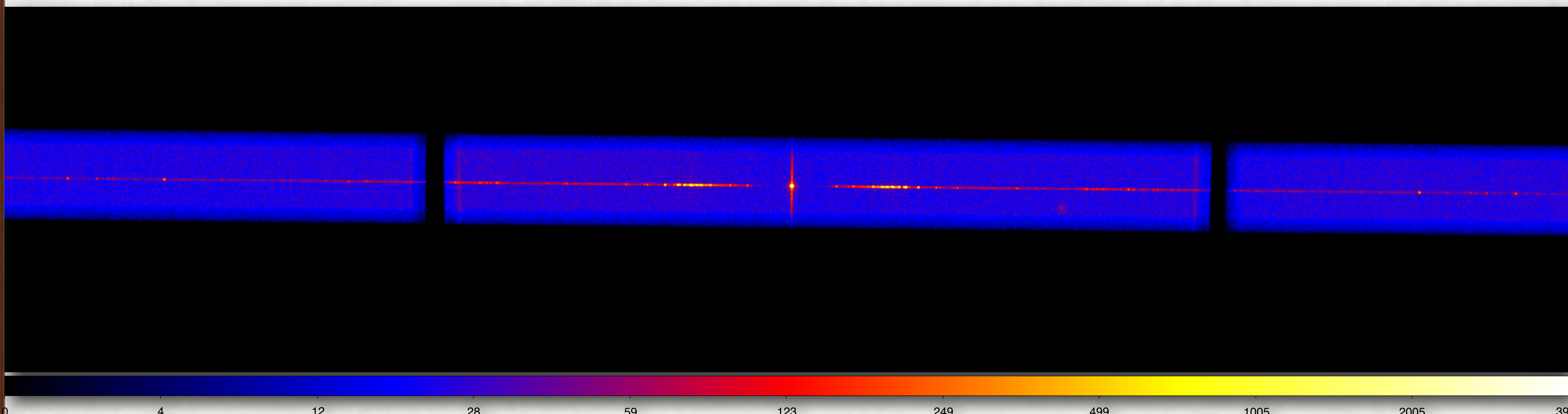
2. HARDWARE

LETGS+ACIS-S



2. HARDWARE

LETGS+HRC-S



Capella ObsID 1248

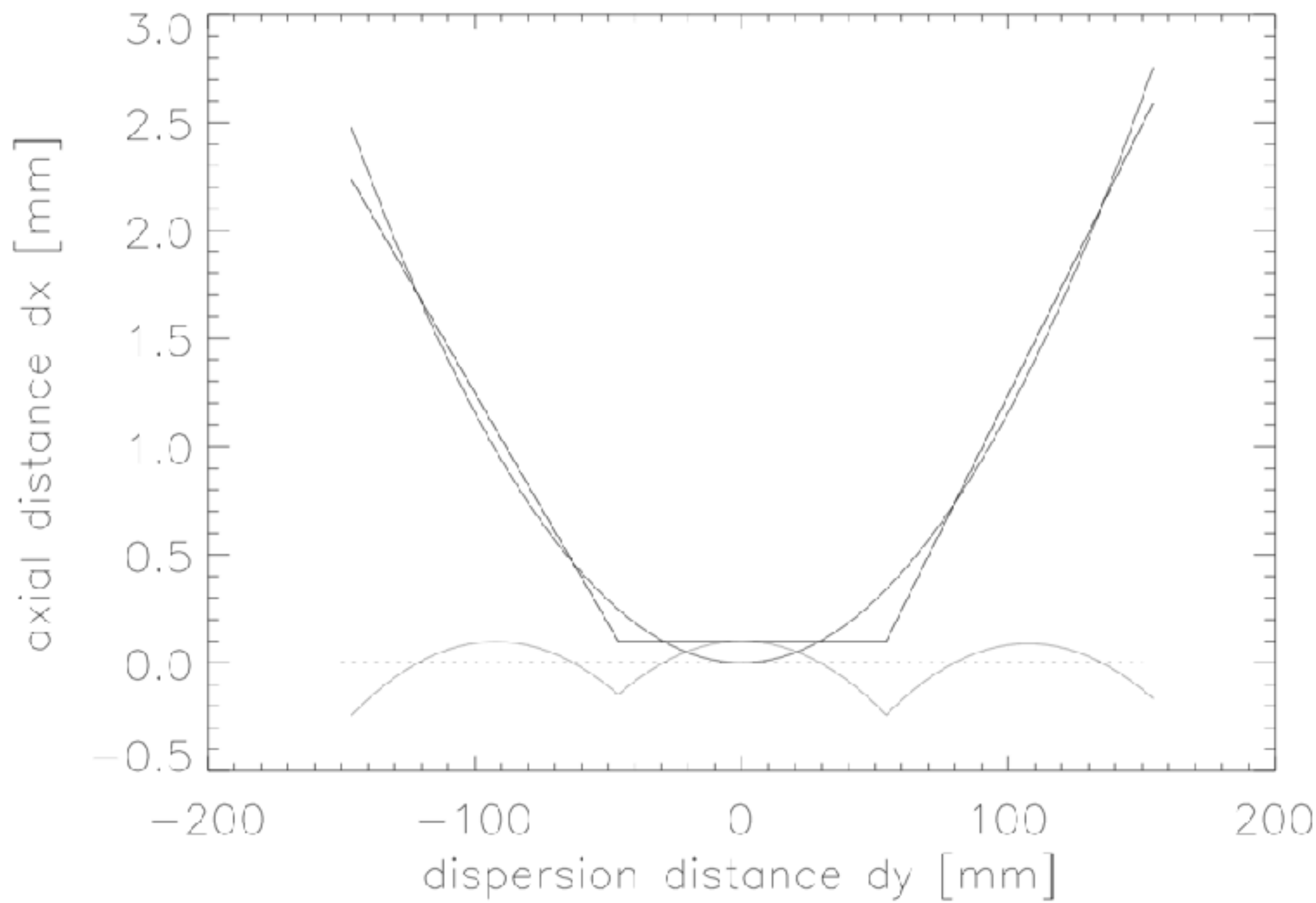
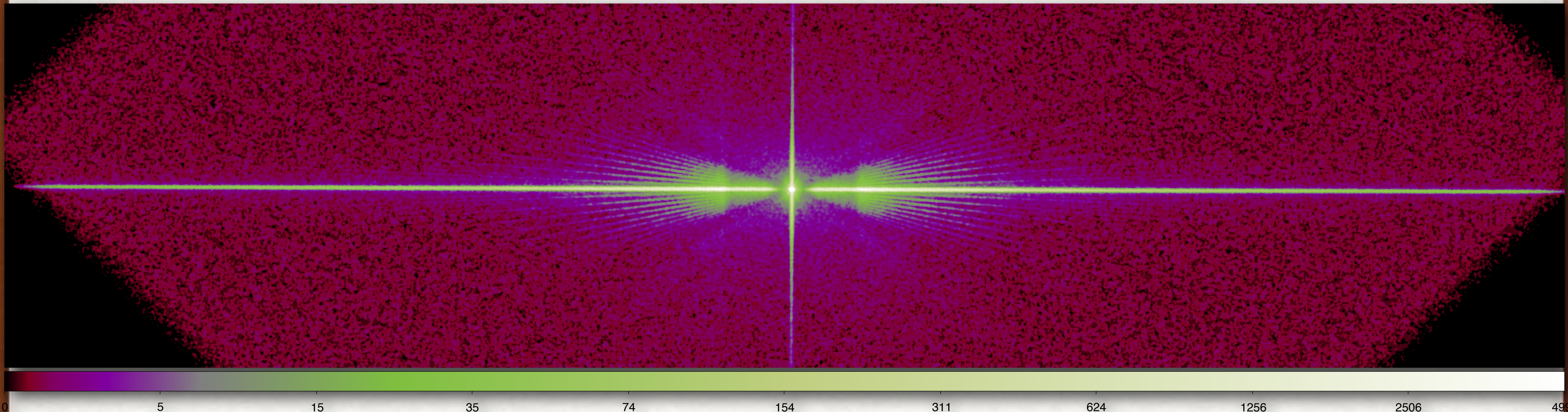


Figure 9.5: The front surfaces of the HRC-S detector segments and their relationship to the Rowland circle are shown schematically. The scalloped line beneath them is the difference between the detector surface and the Rowland circle.

(Jeremy Drake/Brad Wargelin)

2. HARDWARE

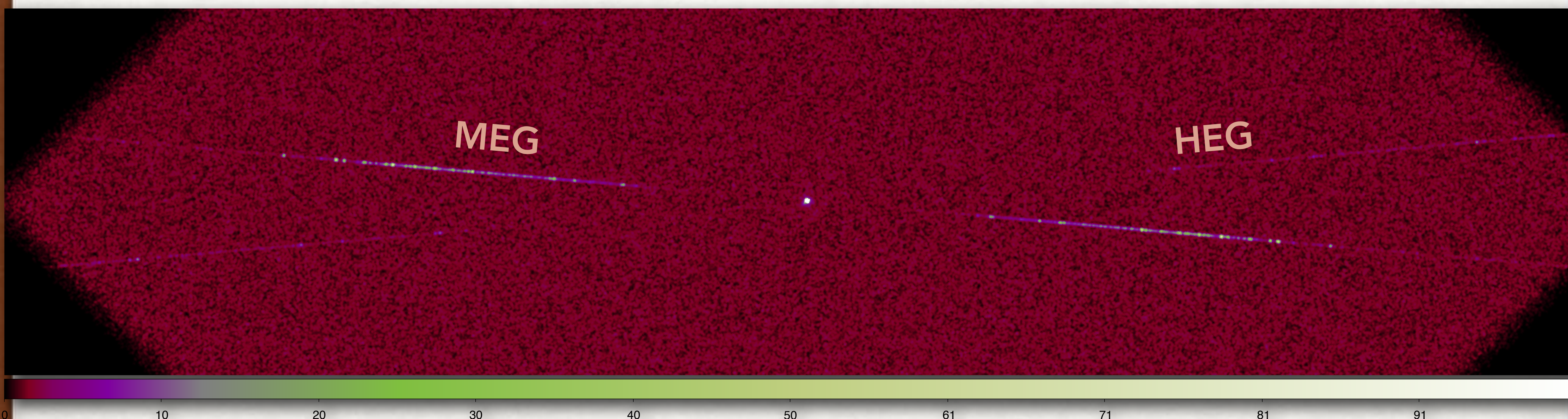
LETGS+HRC-I



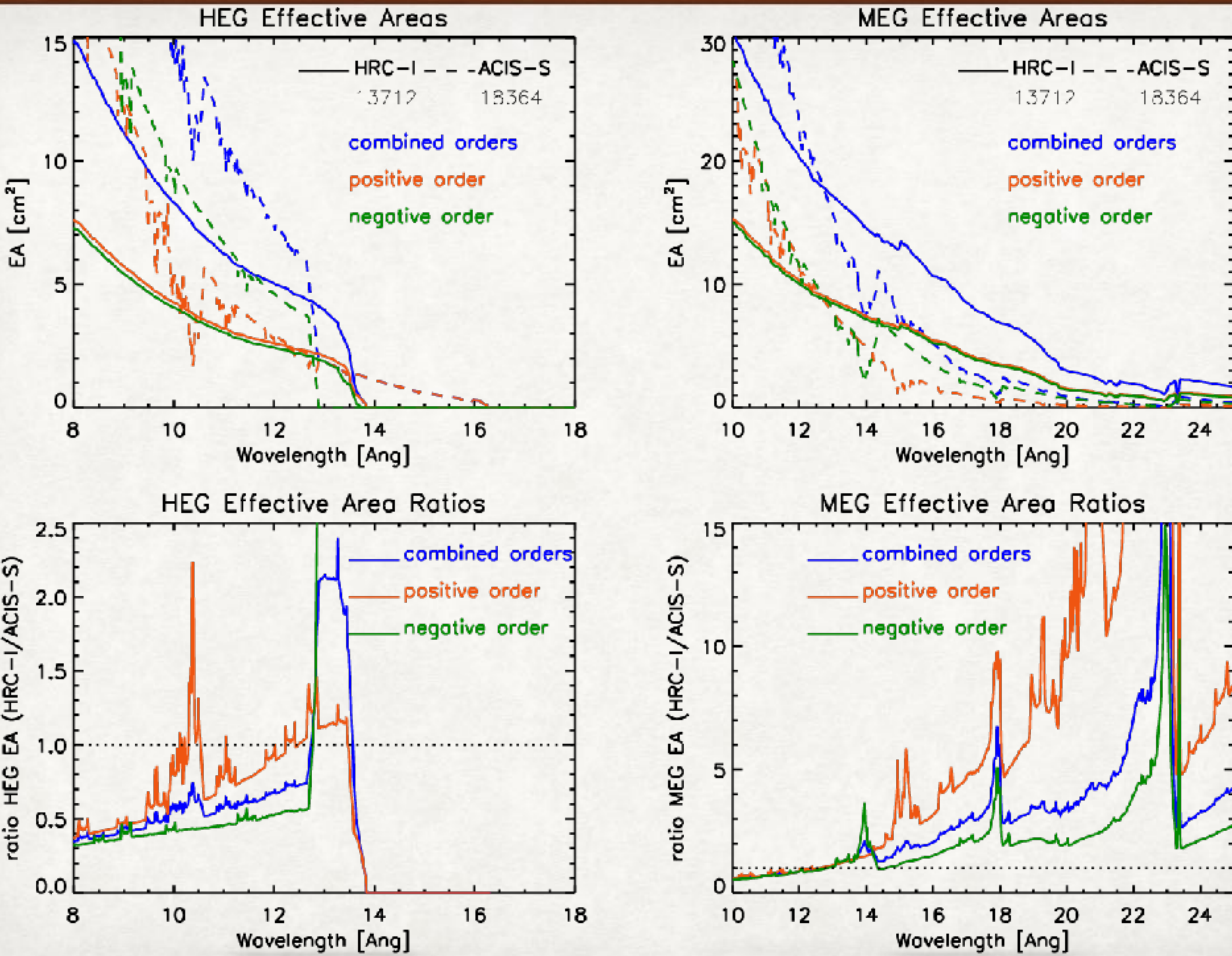
Cyg X-2 ObsID 87

2. HARDWARE

HETGS+HRC-I



Capella ObsID 19837



HEG Effective Areas
HRC-I - - -ACIS-S
13712 18364
combined orders
positive order
negative order
EA [cm^2]
Wavelength [Ang]
MEG Effective Areas
HRC-I - - -ACIS-S
13712 18364
combined orders
positive order
negative order
EA [cm^2]
Wavelength [Ang]
HEG Effective Area Ratios
combined orders
positive order
negative order
ratio HEG EA (HRC-I/ACIS-S)
Wavelength [Ang]
MEG Effective Area Ratios
combined orders
positive order
negative order
ratio MEG EA (HRC-I/ACIS-S)
Wavelength [Ang]

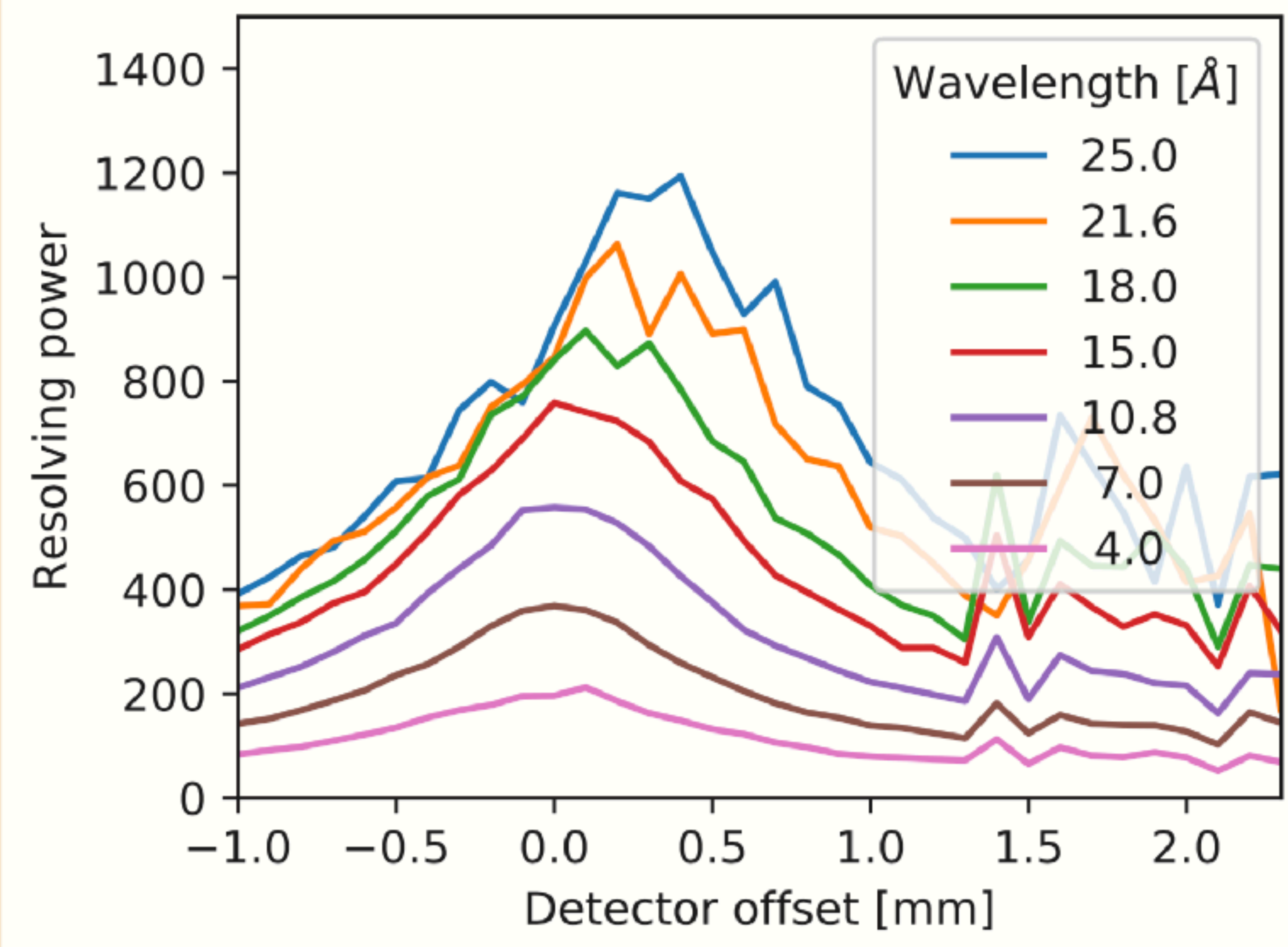


Figure 1: Expected spectral resolving power for HETG/HRC-I for different focus offsets based on MARX ray-trace simulations.

(Hans Moritz Günther)

3. SOFTWARE

EXTRACT DATA USING CIAO

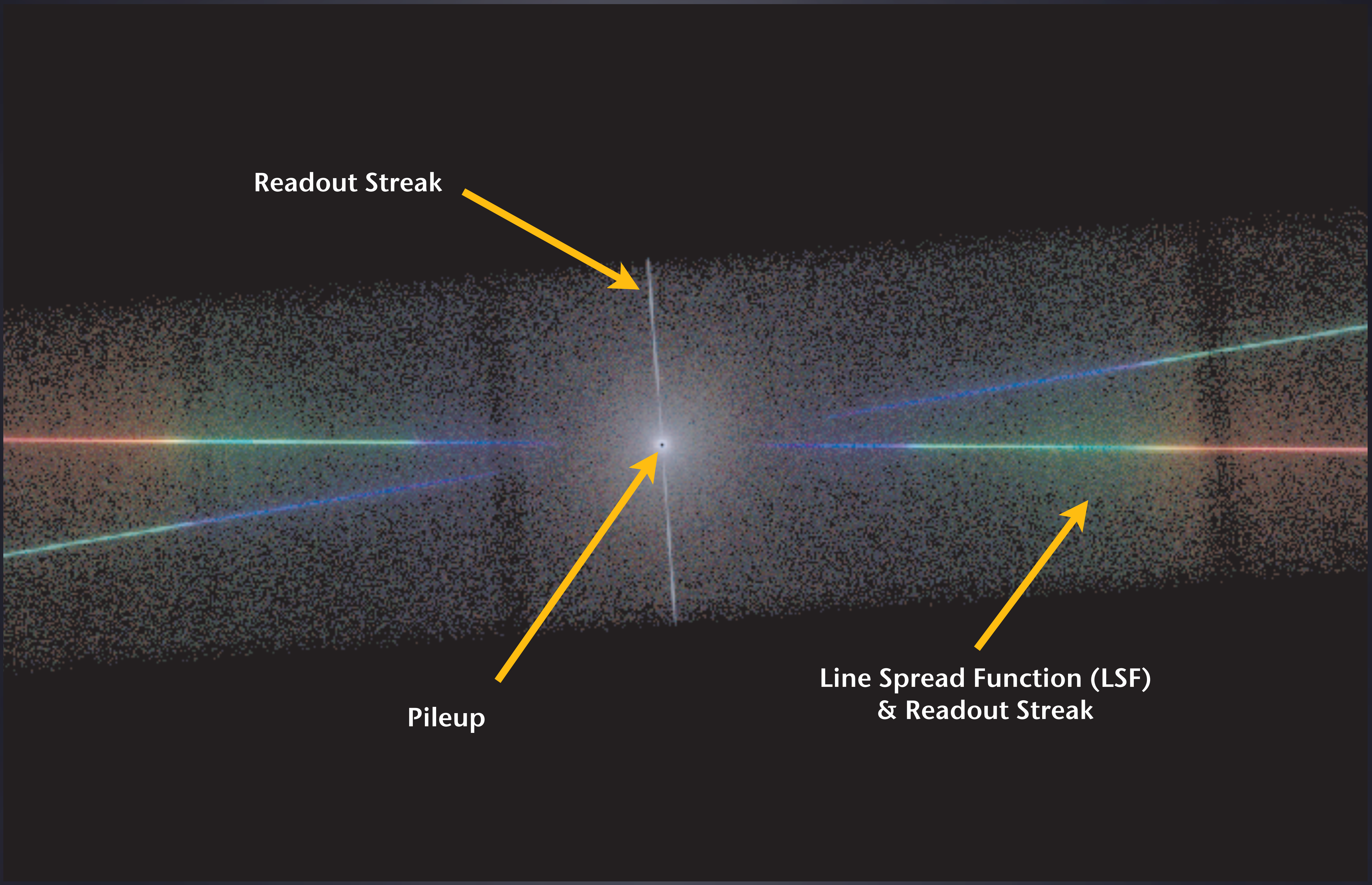
- Find the 0th order
- Fix the regions from which to extract dispersed spectra
- Assign wavelengths
- Extract into standard format files
- Create redistribution matrix (RMF) and ancillary response (ARF) files

3. SOFTWARE

WHERE IS THE SOURCE?

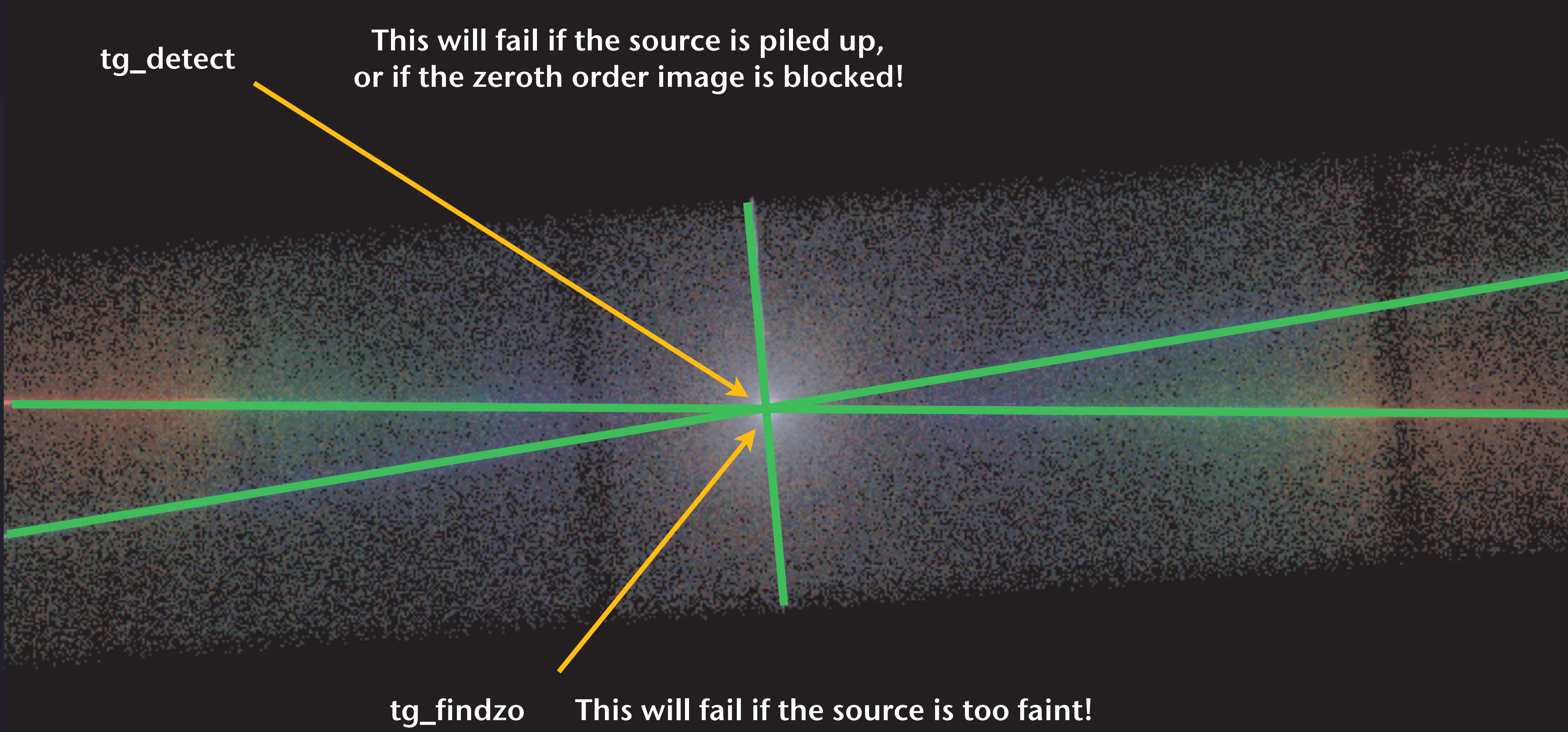
- Must first locate the 0th order
- Use tgdetect or tg_findzo, or tgdetect2 to automatically choose between them
- tgdetect: uses celldetect to find and centroid 0th order sources, works with either ACIS or HRC data
- tg_findzo: for ACIS, when 0th order is piled up, uses readout streaks and dispersion axis to pinpoint the intersection

Chandra HETG



(Mike Nowak)

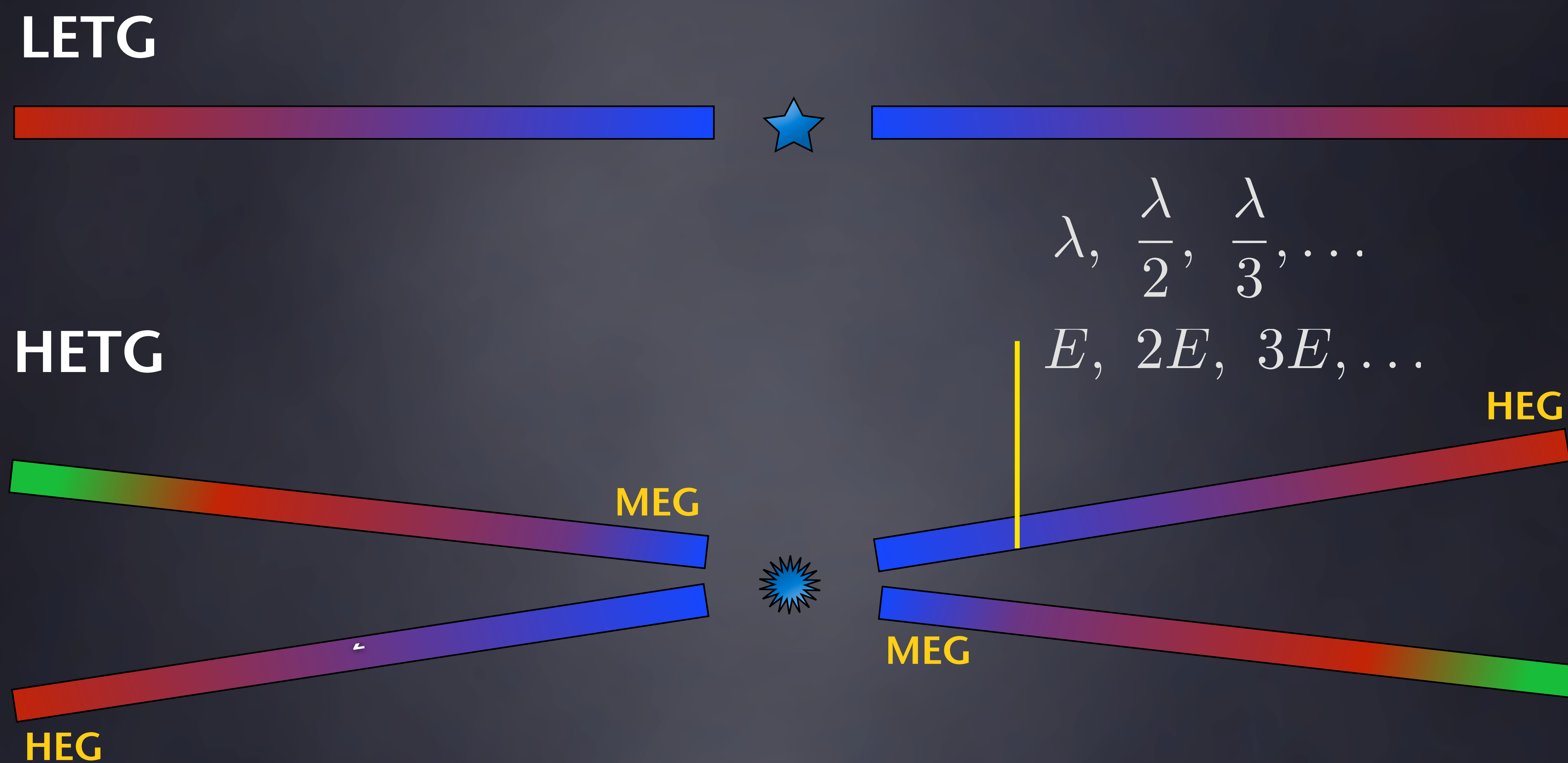
Where is my source?



Accuracy can be as good as 0.1 pixels

(Mike Nowak)

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



Greater Distance = Higher Resolution

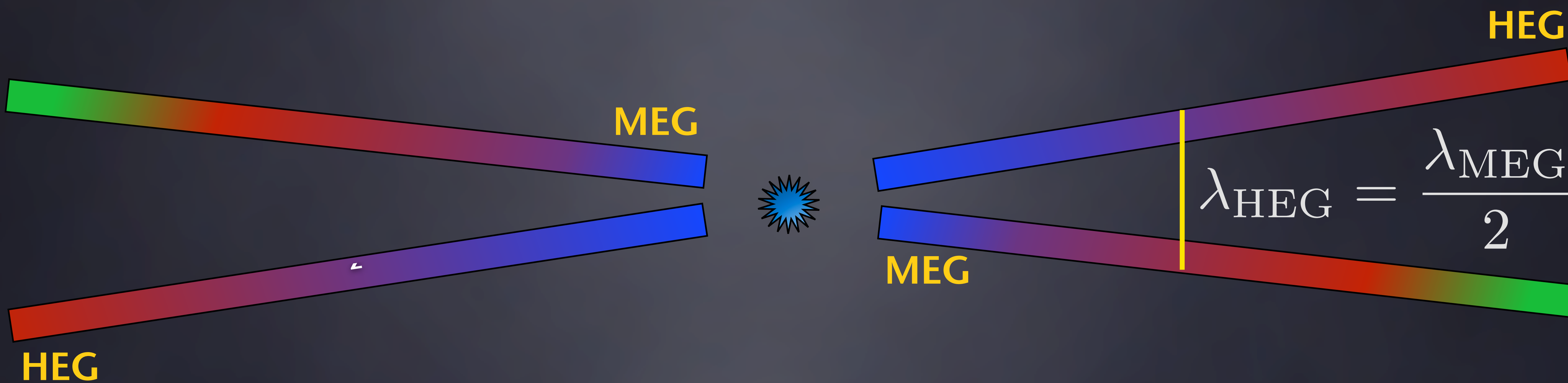
Resolution Limited by CCDs & Gratings Accuracy

(Mike Nowak)

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

LETG

HETG



Greater Distance = Higher Resolution

Resolution Limited by CCDs & Gratings Accuracy

(Mike Nowak)

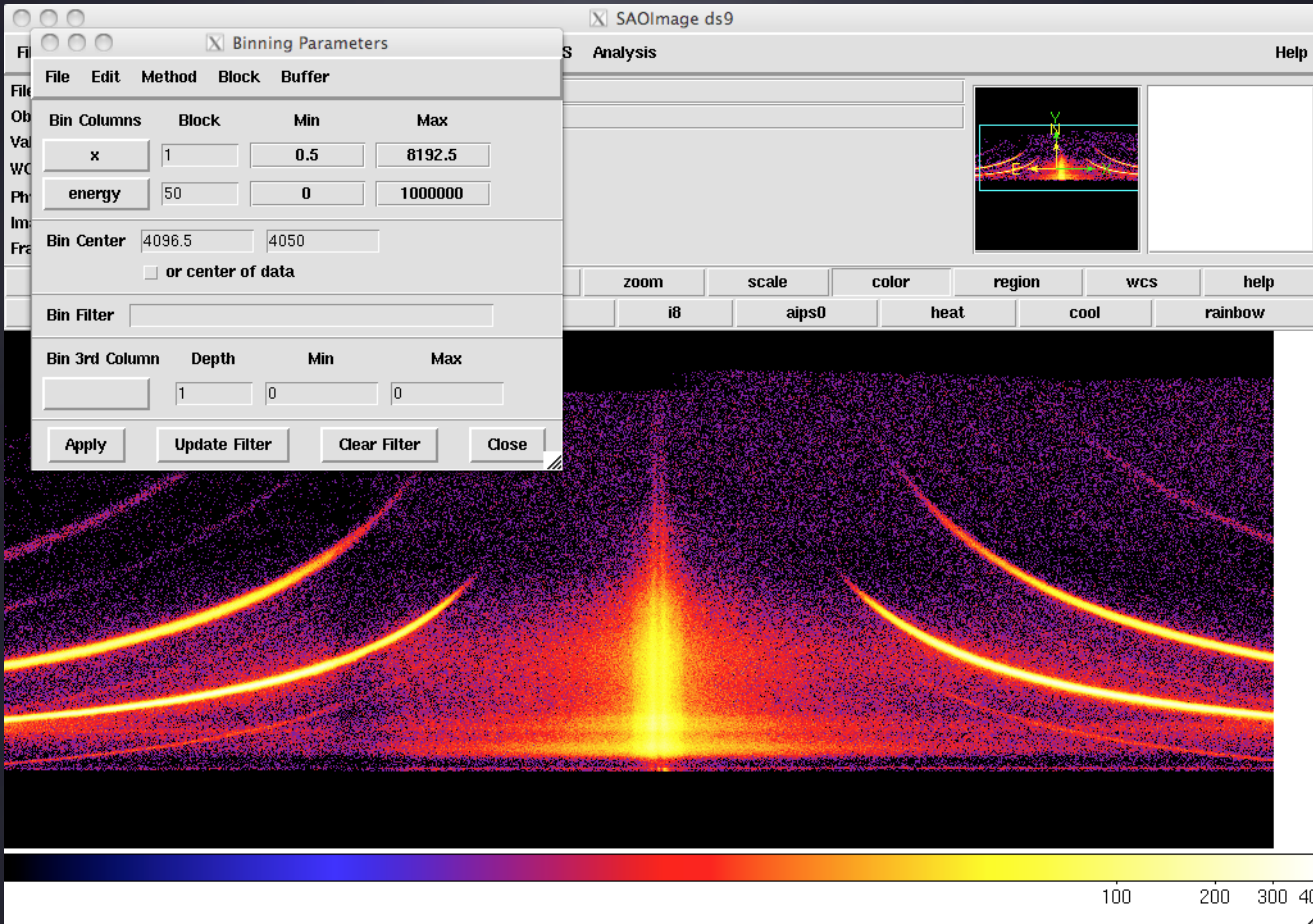
3. SOFTWARE

MAP TO WAVELENGTH

- OSIP (Order Sorting Integrated Probability) Tables for ACIS
- The ratio of CCD energy to inferred energy, $\mathcal{R}_0 = E_{CCD}/(mhc/\lambda)$ can be used to separate the orders
  - "Standard" — pre-calculated $\mathcal{R}_0$
  - "Flat" — set a fixed ratio for range of $\mathcal{R}_0$, e.g., 0.8-1.3
- You can't do this on the HRC because there is very little intrinsic energy resolution
  - Must construct grating RMFs using `mkgrmf` for several orders, and use this Sherpa thread to use them during fitting

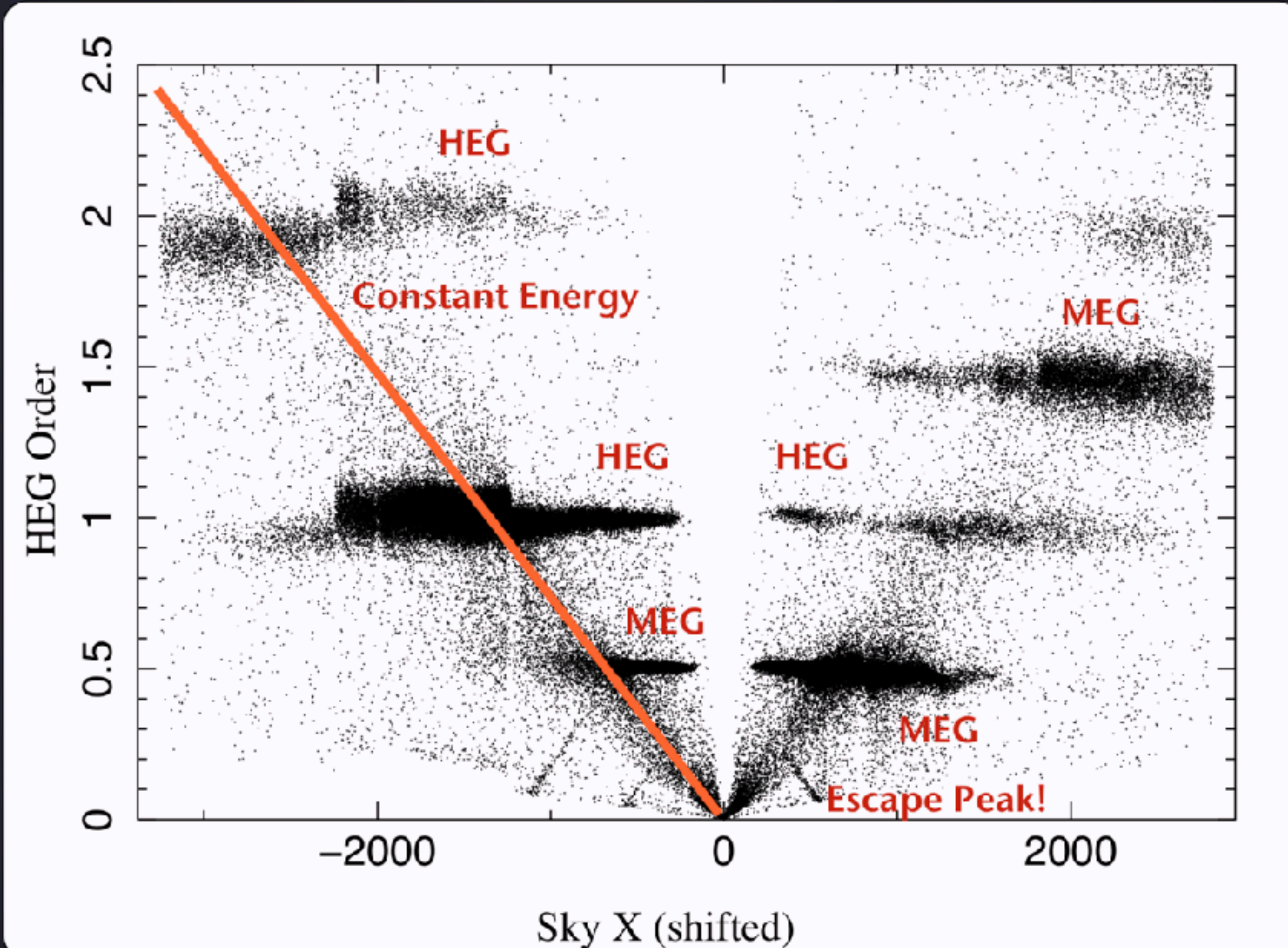
  http://cxc.harvard.edu/sherpa/threads/grating_hrcsletg/

unix%> ds9 acisf11044N002_evt2.fits.gz &



(Mike Nowak)

Order Sorting Plot



(Mike Nowak)

3. SOFTWARE

WATCH OUT: TIME FILTERING

- At this stage you have a Level 1.5 file, or the so-called `evt1a` file
- There is a bug in `dmcopy` where if you apply additional time filtering to this file, the `GTI` block gets corrupted and the `EXPOSURE` value in the header becomes incorrect
- To work around, do something like this:

```
cp -p evt1a old_evt1a
dmcopy old_evt1a"[time=@filter_spec]" evt1a clobber=yes
dmappend old_evt1a"[region][subspace -time]" evt1a
```

- NOT a problem if you run `chandra_repro`

(Mike Nowak/Kenny Glotfelty)

3. SOFTWARE

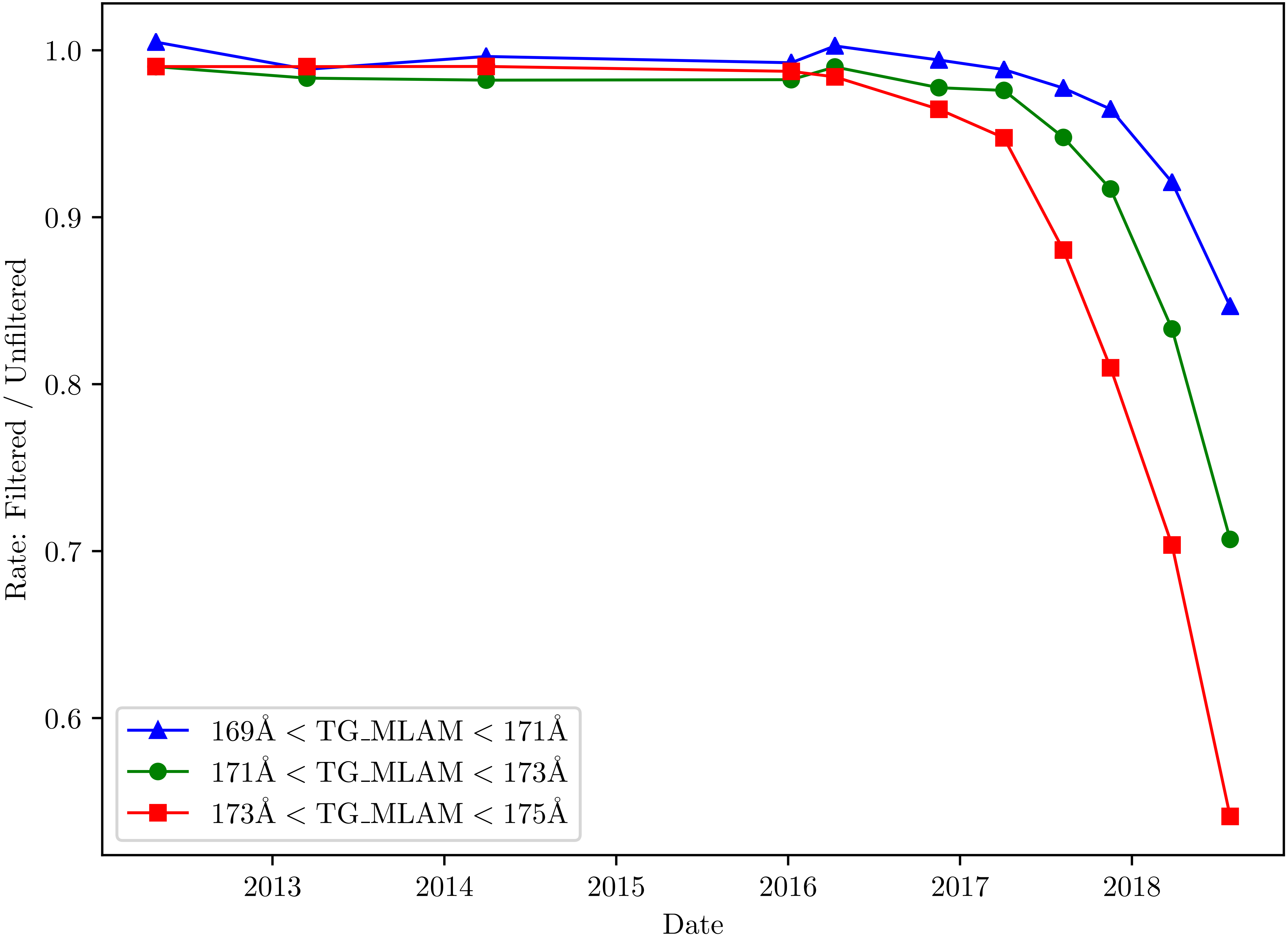
WATCH OUT: HRC-S BACKGROUND REDUCTION

- HRC-S does not have the intrinsic spectral resolution to do order sorting. This means that the background tends to be higher.
- There is a wavelength and PI based filter that can be applied to remove a large fraction of the particle background at minimal cost to the source counts,

  $CALDB/data/chandra/hrc/tgpimask2/letgD1999-07-22pireg_tgmap_N0001.fits

- HOWEVER: recently, because of the gain drop in the HRC, this filter is working less efficiently.
- If you are working with very soft sources $\lambda > 44$Å, it is better to not apply this filter.

(Brad Wargelin/Pete Ratzlaff)

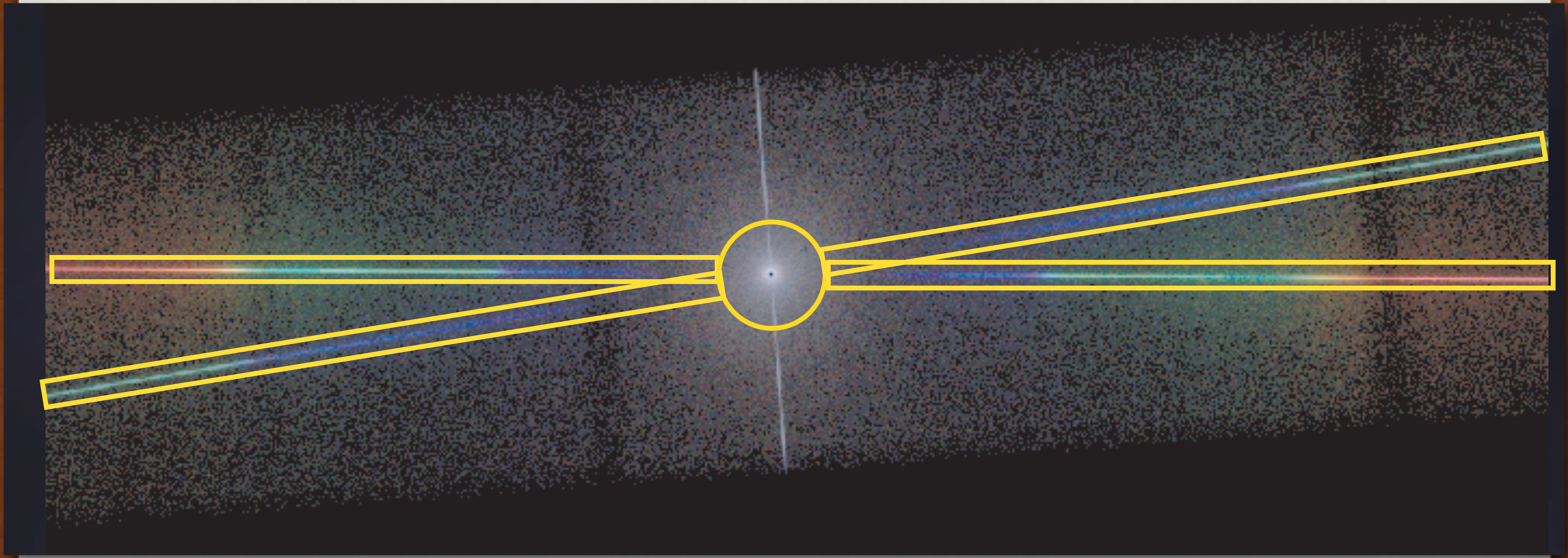


(Pete Ratzlaff)

3. SOFTWARE

TG_CREATE_MASK

- Picks out sky spatial region into which the photons are dispersed
- fraction of enclosed energy is put into RMF

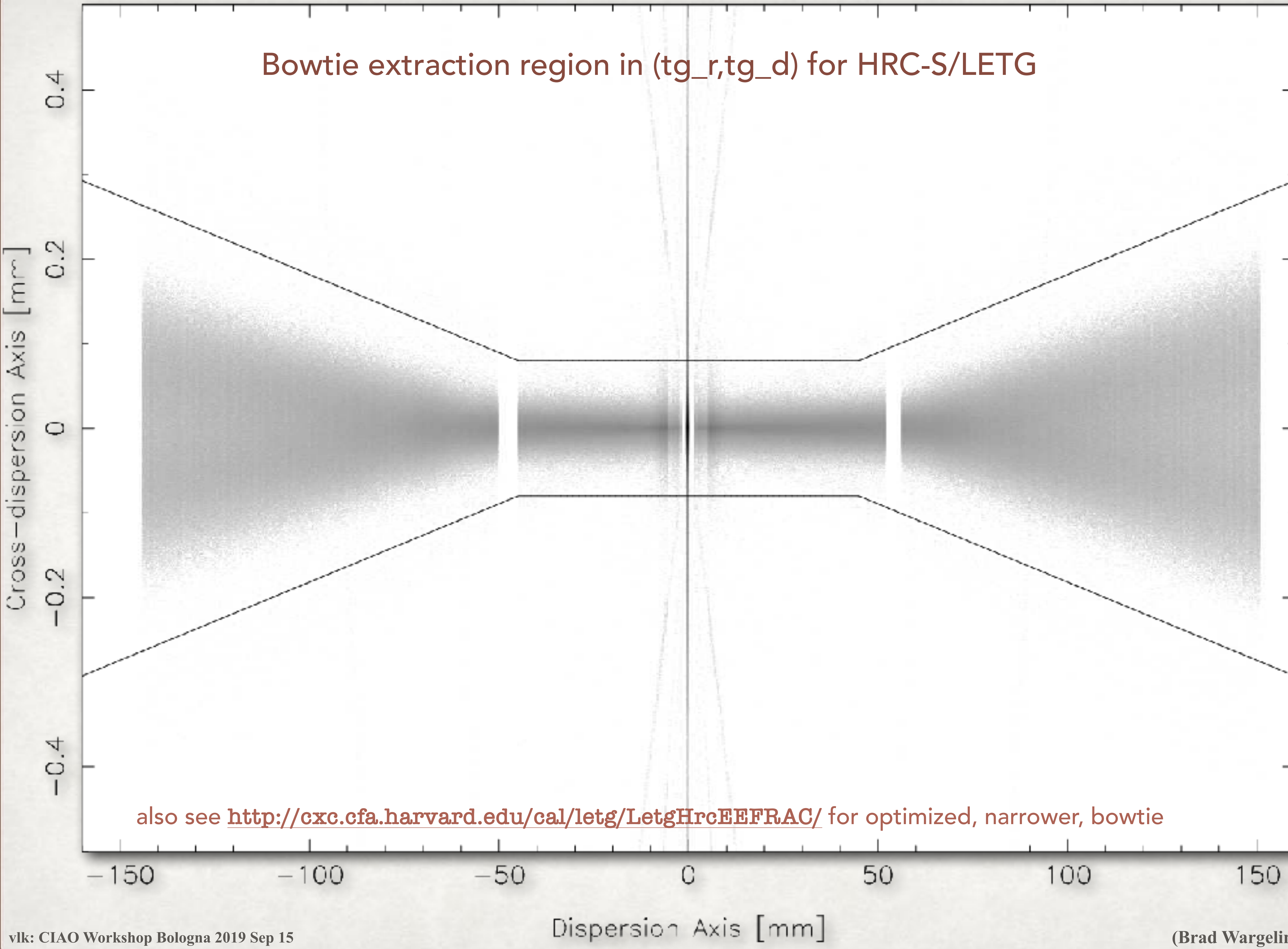


(Mike Nowak)

3. SOFTWARE

EXTRACT SPECTRA

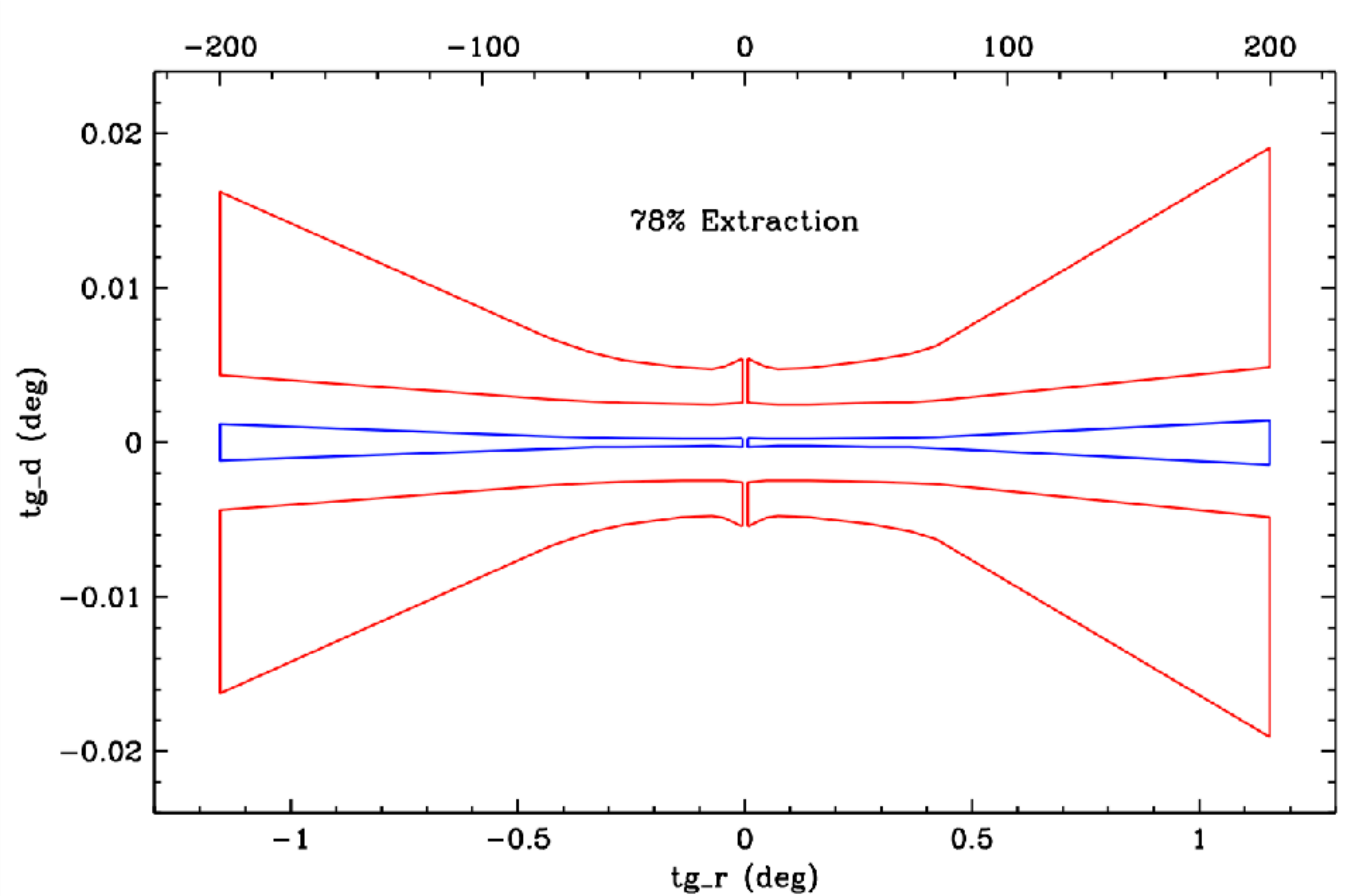
- `tgextract` to make pha2 files that can be read in and analyzed with Sherpa
  - Extraction efficiencies for adopted widths go into RMF, not ARF
- `mkgarf` to make effective area files, which includes detector spatial information (including QE uniformity, bad pixels, etc.), and the effect of dither
- `mkgrmf` to make RMFs
- XSPEC compatibility: `tgextract2` to make separate TypeI pha files, `tgsplit` to convert pha2 into pha, `tg_bkg` to create separate background files



(Brad Wargelin)

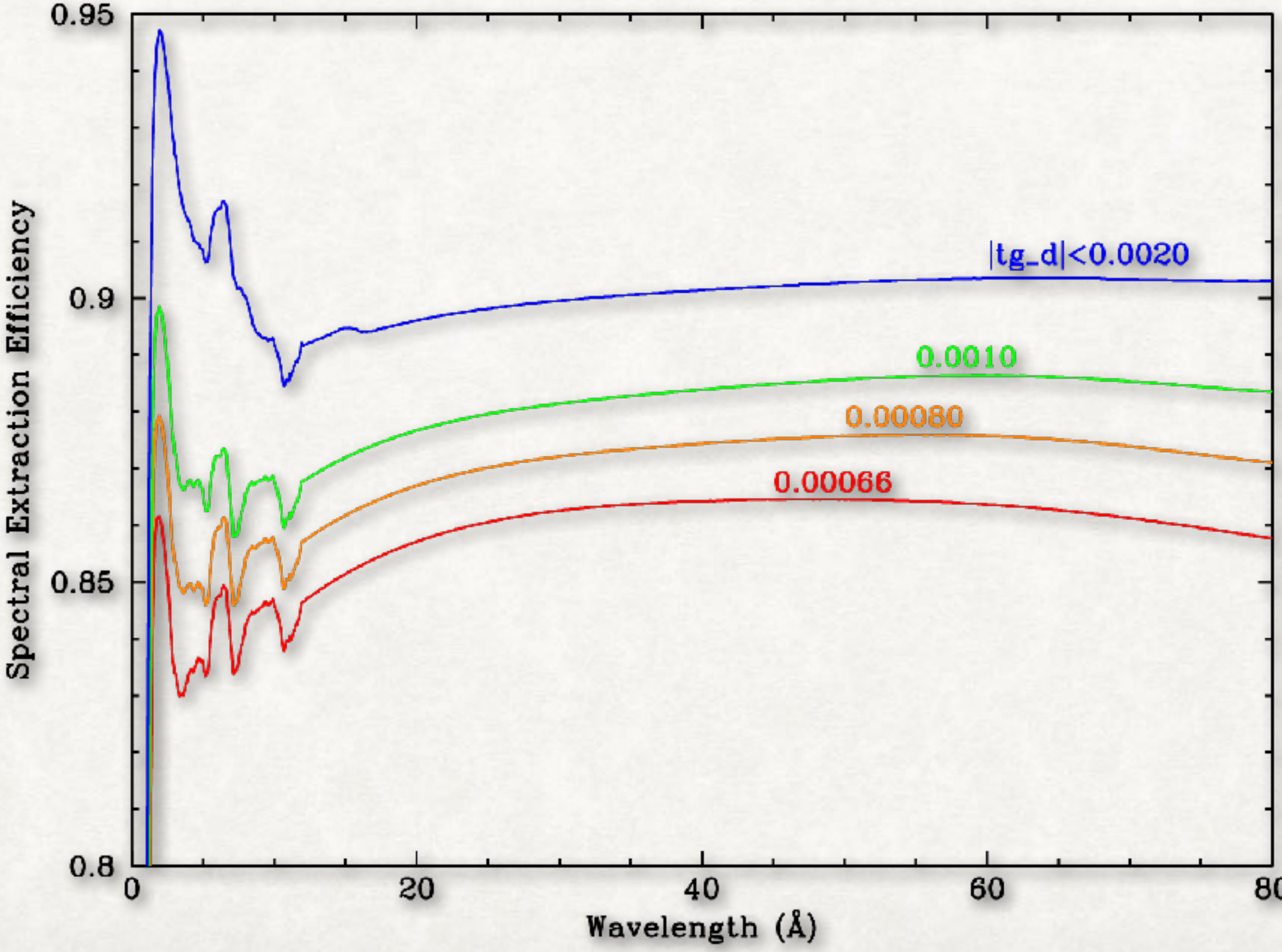
optimized, narrower bowtie

http://cxc.cfa.harvard.edu/cal/letg/LetgHrcEEFRAC/



(Brad Wargelin)

Extraction efficiencies for various half-widths [LETGS+ACIS-S]



(Brad Wargelin)

3. SOFTWARE

WATCH OUT: CONTINUOUS CLOCKING

- Image is collapsed into one dimension
- But MEG 2nd orders are suppressed, so HEG 1st order is always assumed
- Extraction width assumed to be 100%
- OSIP assumed flat (~0.8-1.3)
- For best results, put MEG –1 and HEG +1 off the chip

(Mike Nowak)

3. SOFTWARE

WATCH OUT: EXPOSURES

- Different chips can have different exposures
- event 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
- Be careful when making light curves!

(Mike Nowak)

3. SOFTWARE
VARIABLES

- Arrays of interest in evt1a/evt2
  - **tg_r, tg_mlam, tg_lam** — coordinates along dispersion axis
  - **tg_d** — coordinate along cross-dispersion axis
  - **tg_part, tg_m** — marker for grating type and order
- Arrays of interest in pha2
  - **tg_part, tg_m** — marker for grating type and order
  - **tg_srcid** — source identifier
  - **bin_lo, bin_hi** — wavelength grid
  - **counts** — counts from source area
  - **background_up, background_down** — counts from background areas (look for header keywords **BACKSCUP** and **BACKSCDN**)

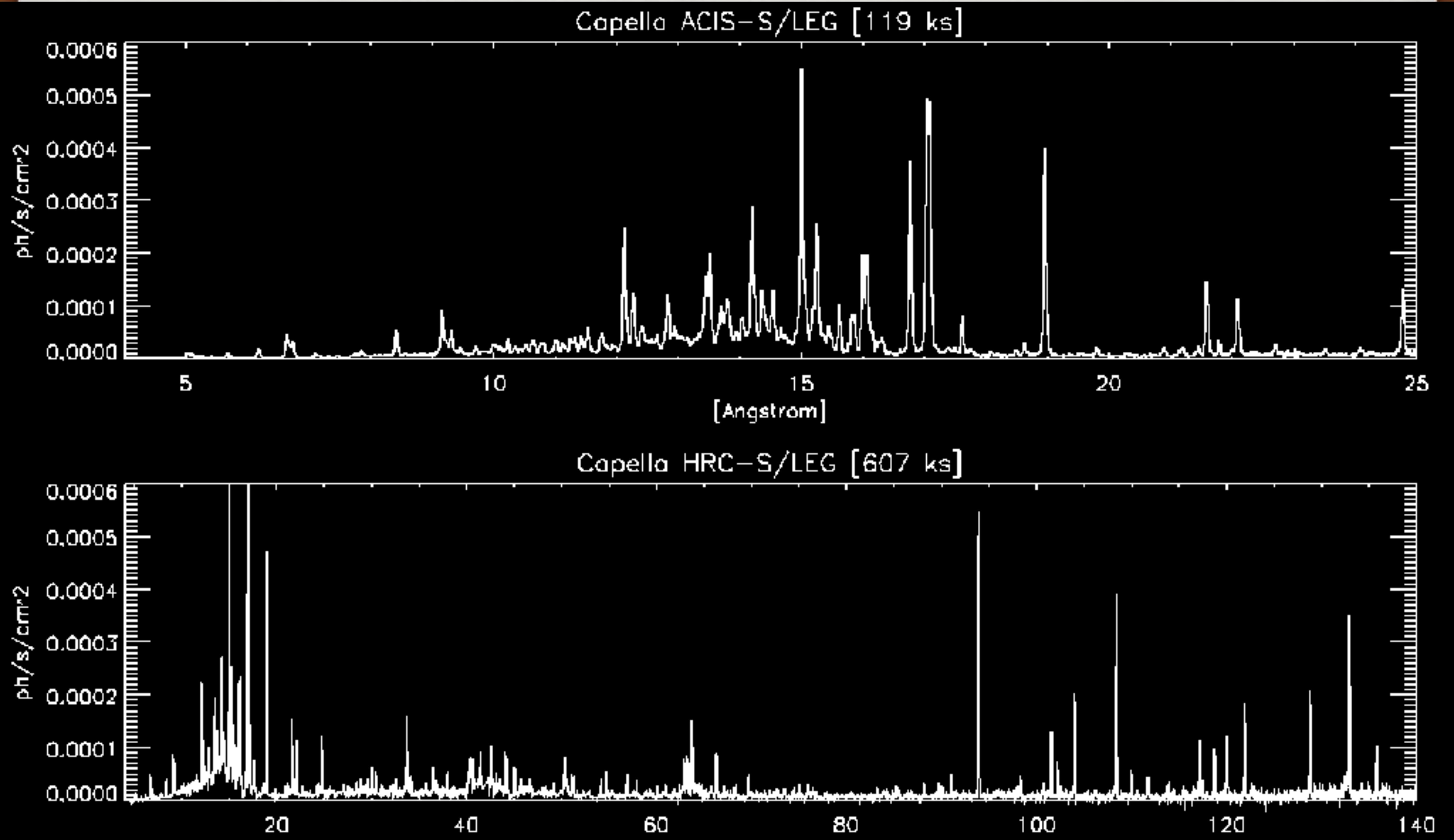
4. SOFTWARE

COMPLICATIONS

- No more global fits because most models are just not good enough
- pileup on ACIS, background in HRC can become important
- Chip and plate gaps, and mismatches between Rowland circle and detector plane require careful observation setups
- HETGS+HRC-I not yet supported in CIAO
- evolving calibration: contamination on ACIS, degap and gain drop on HRC

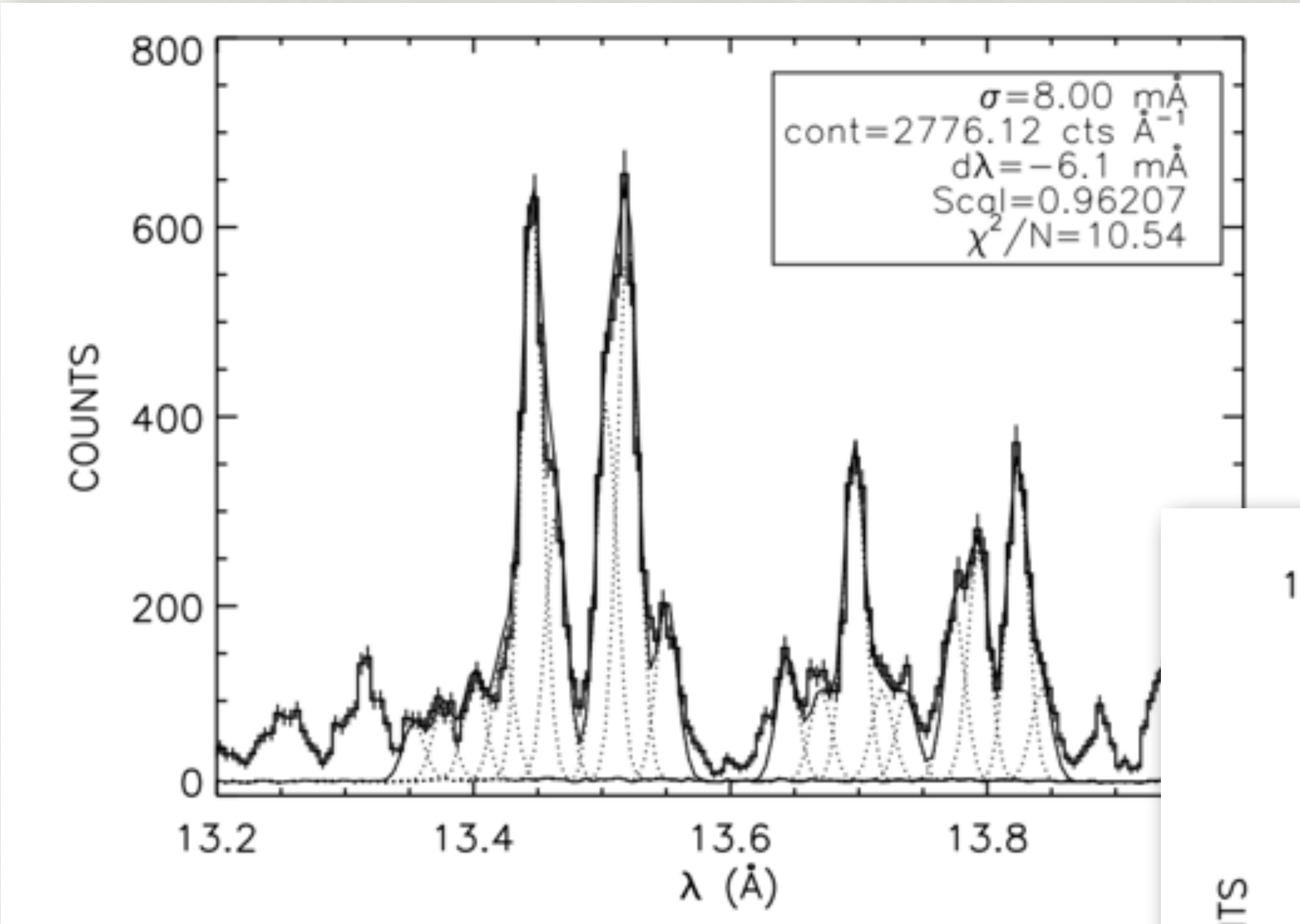
4. ANALYSIS

HIGH-RESOLUTION SPECTRA

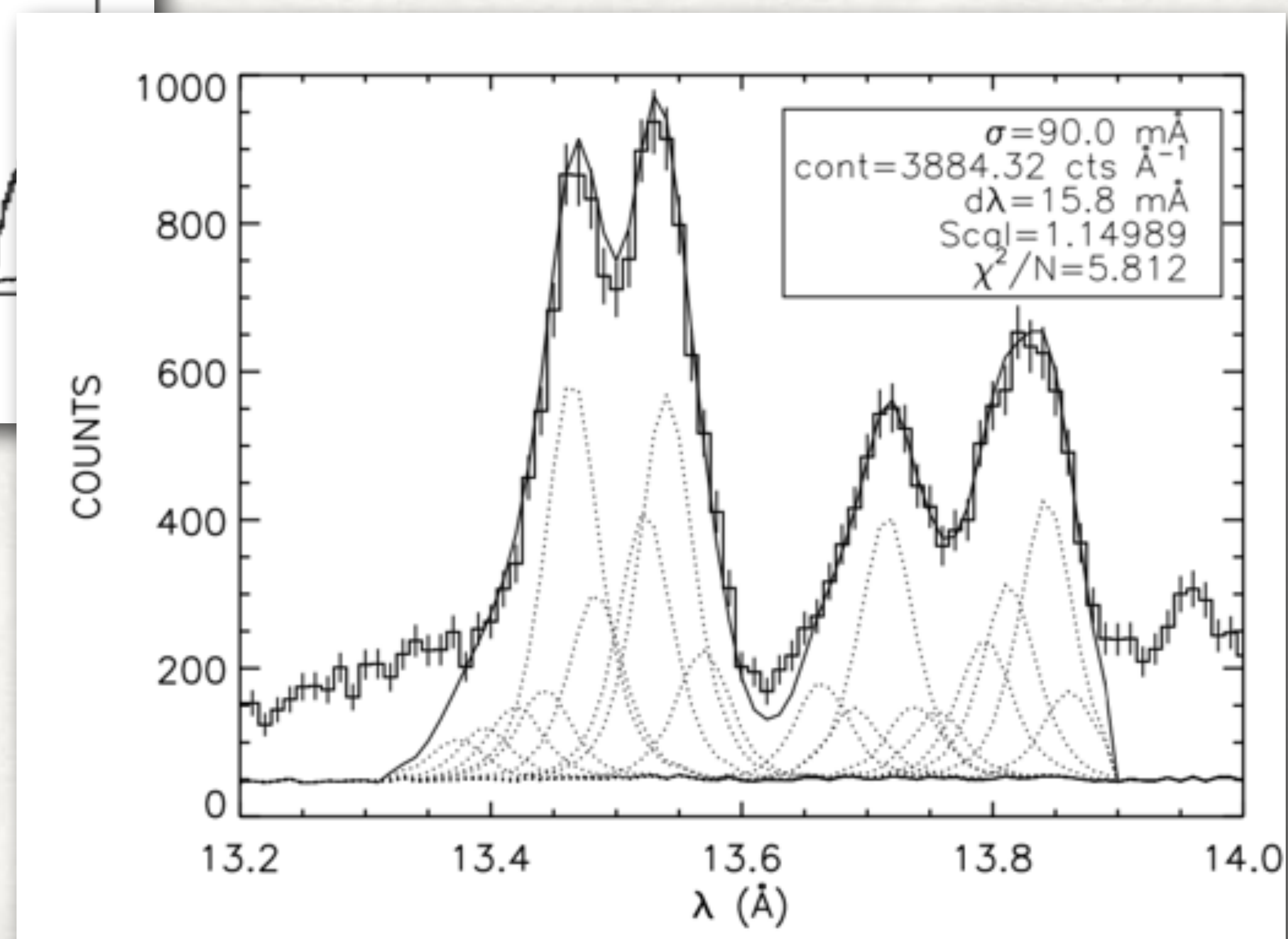


4. ANALYSIS

WHAT CAN YOU DO?



Ness et al. 2002, A&A, 394, 911



HEG model of density sensitive
Ne IX triplet (contaminated by Fe)
overlaid on
MEG (top) and LEG (right)

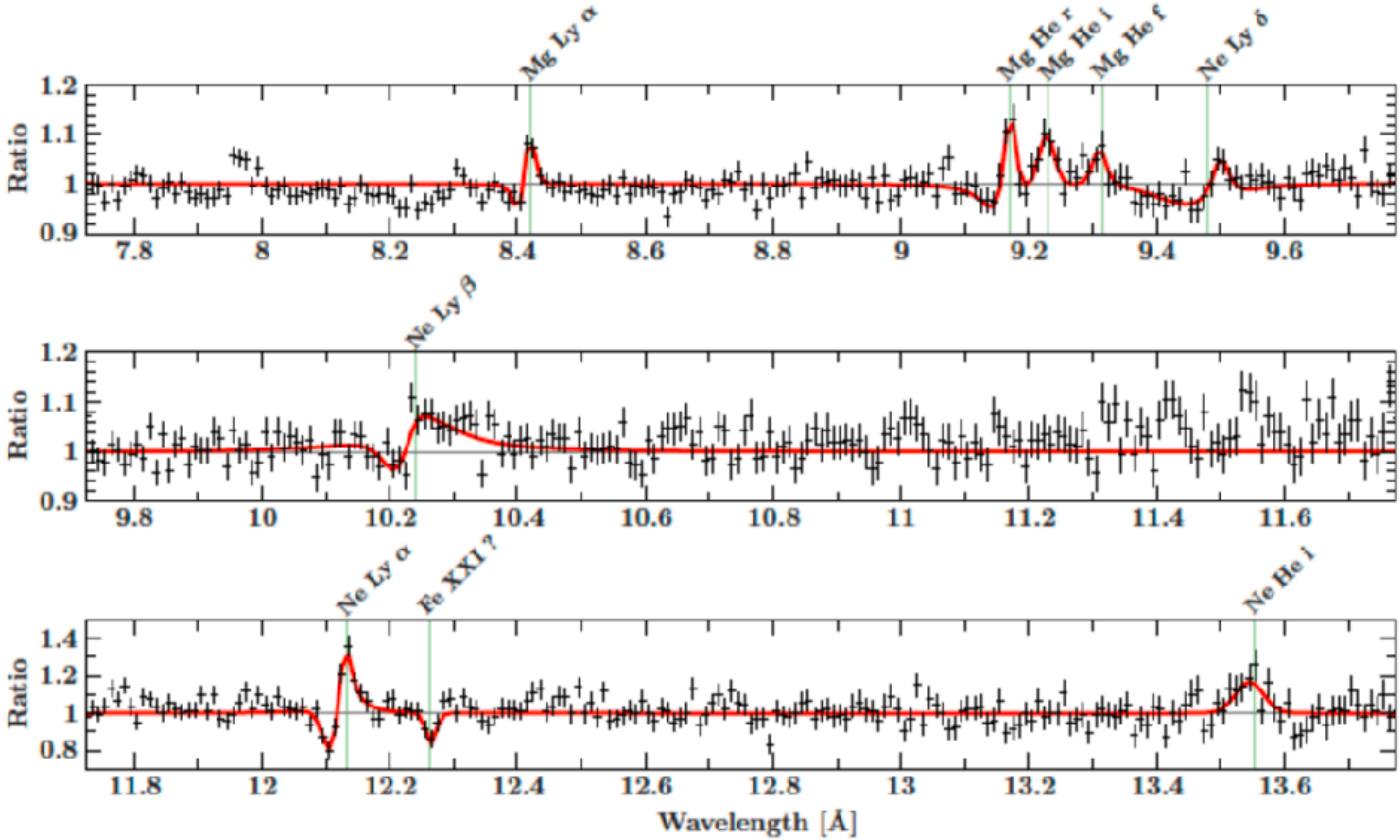
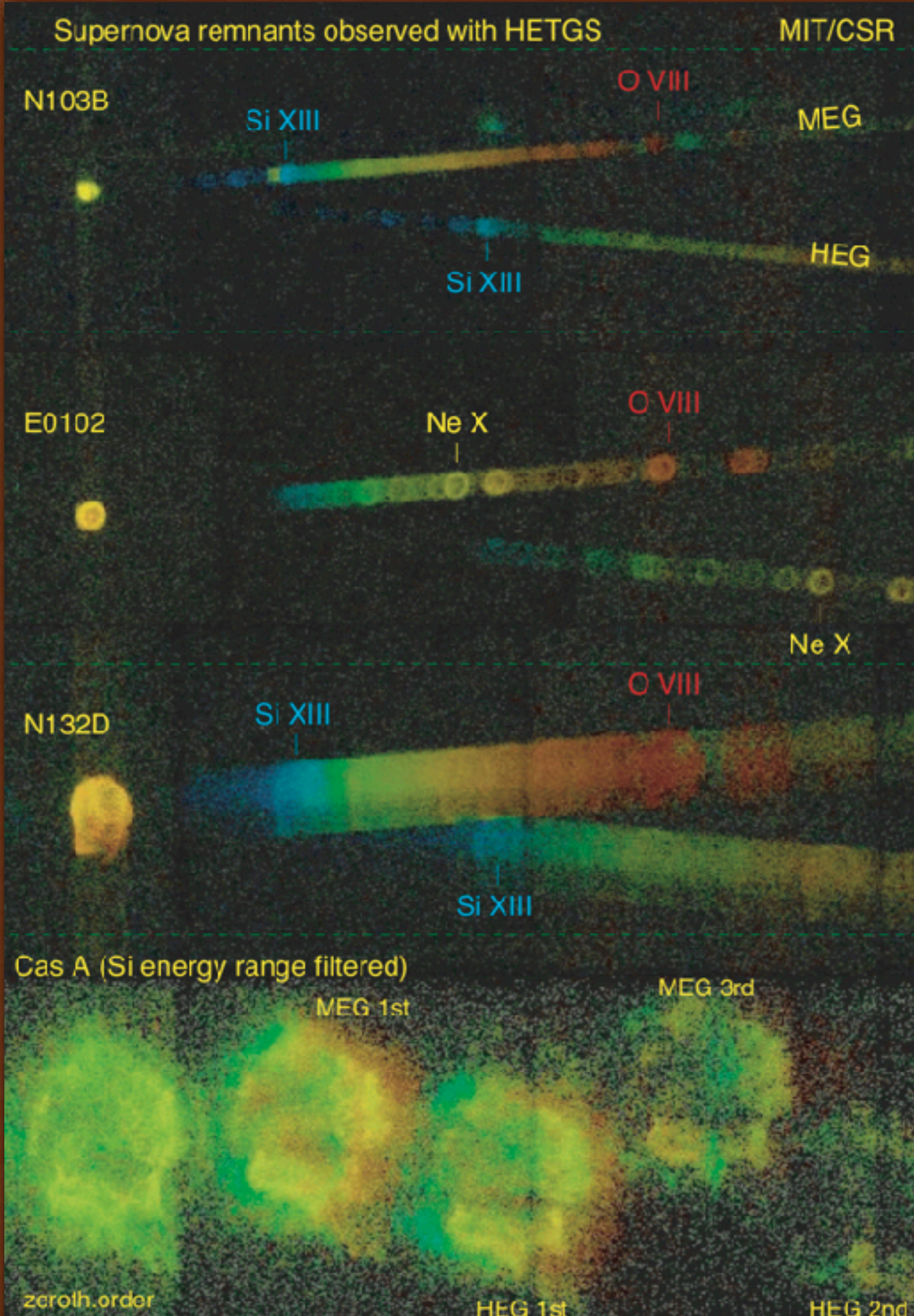
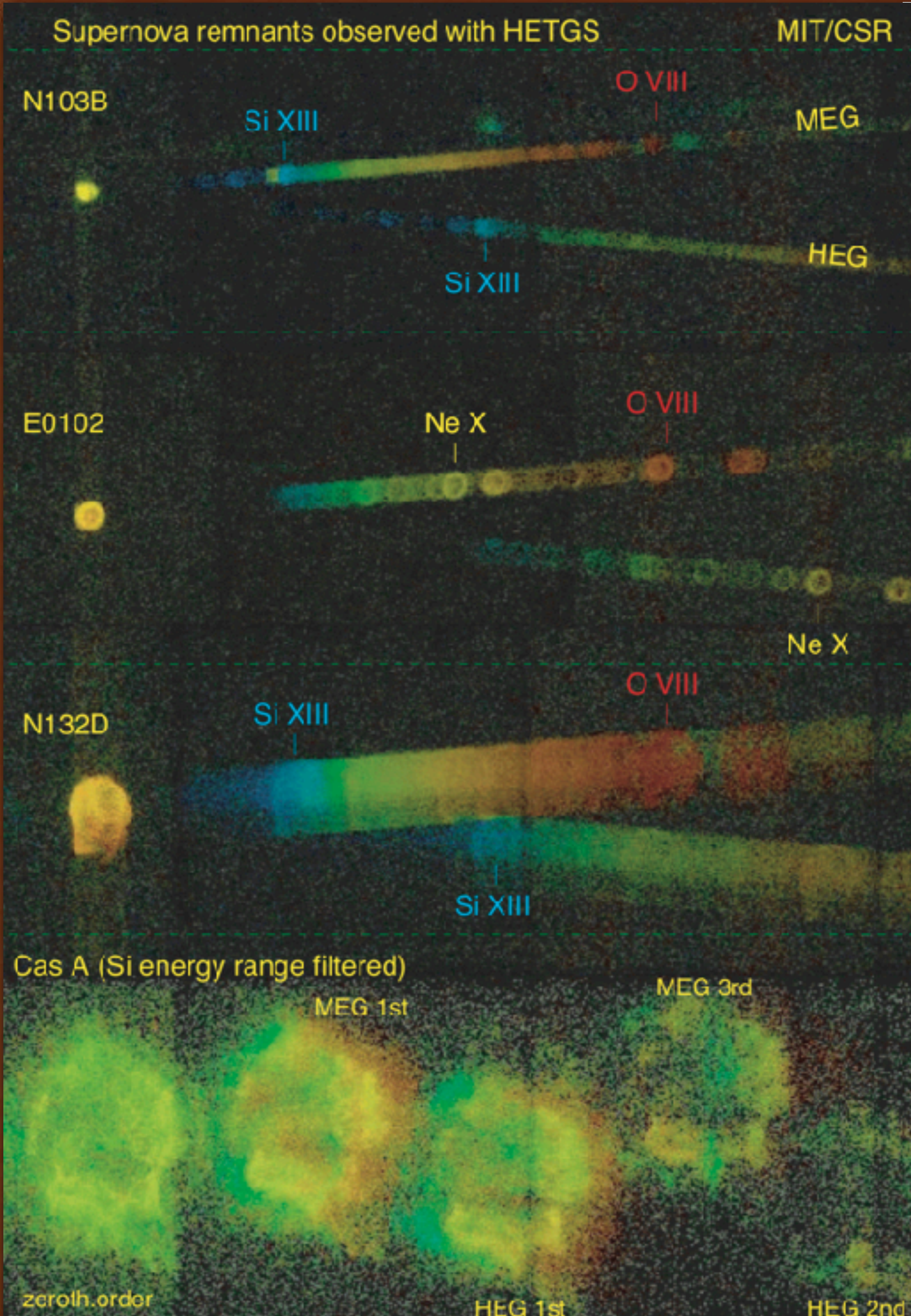


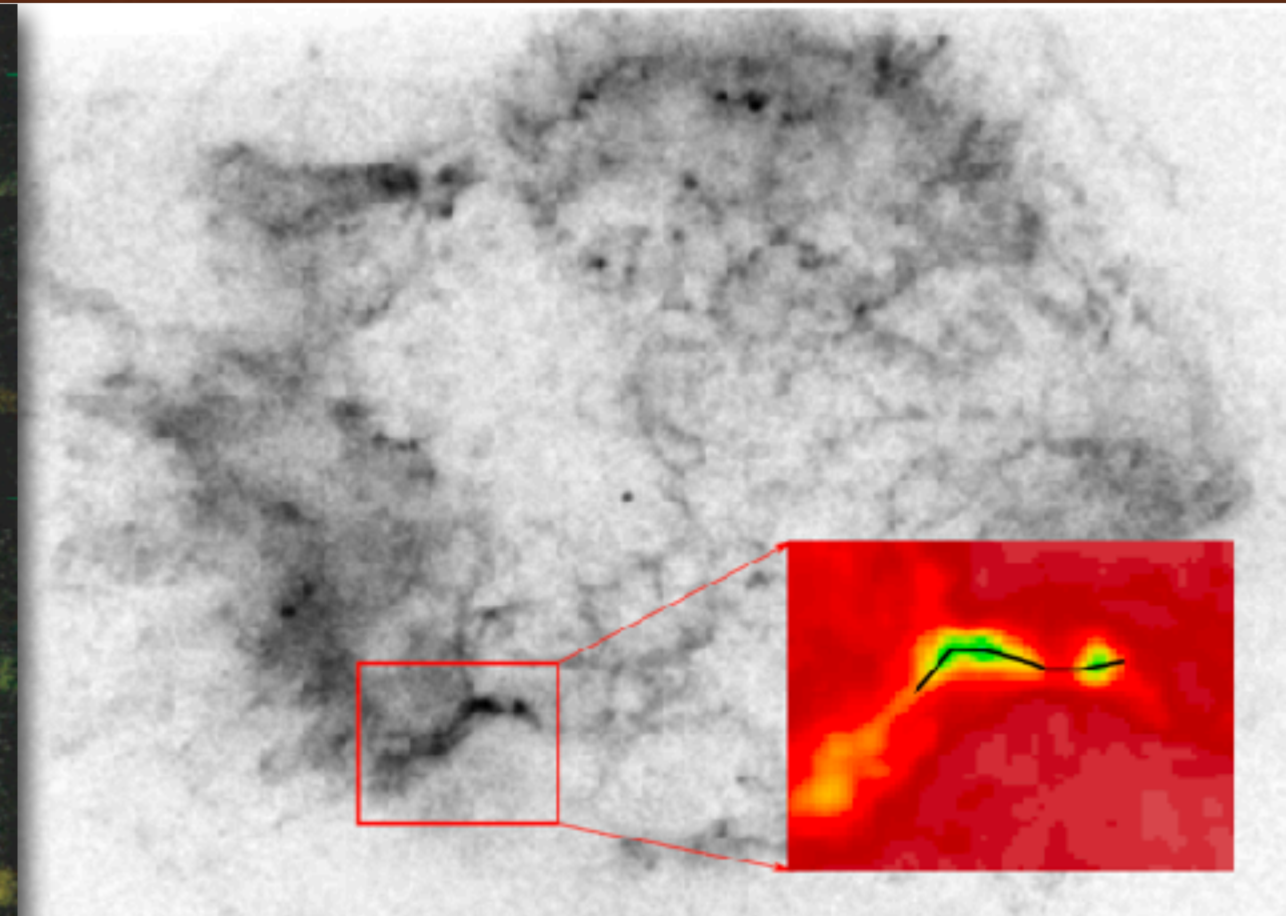
Figure 5: A portion of the HETGS spectrum of Cyg X-1 from ObsID 11044 (Miškovičová et al (2016, [11])). The data were divided by a model consisting of a power law absorbed by cold gas. Several lines show P Cygni profiles, such as Mg Lyα, Ne Lyα, and even Ne Lyβ. The observation is from inferior conjunction, where the disk wind is observed most clearly. Components of He-like Mg XI are readily discerned, providing density diagnostics.

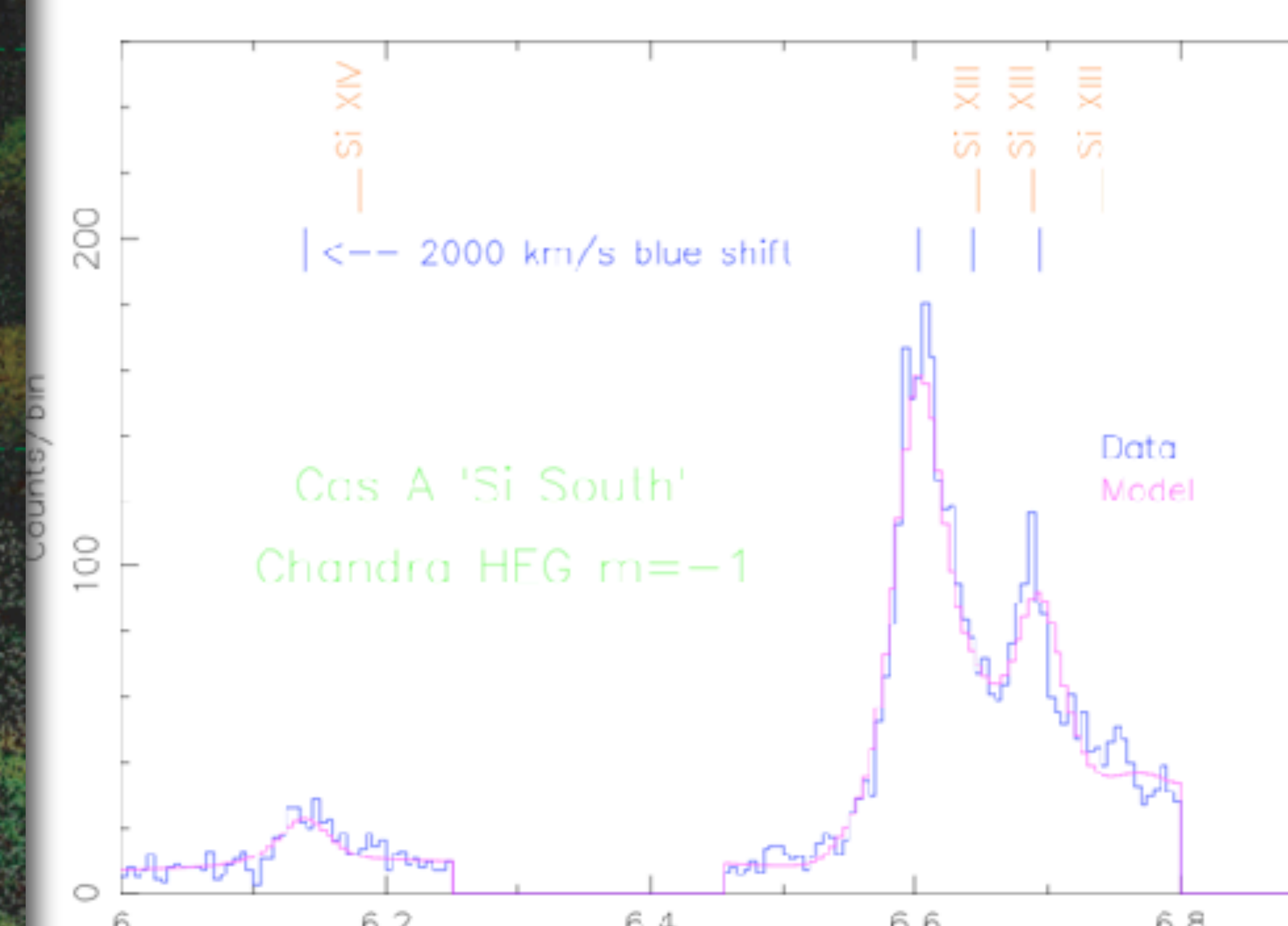
(Herman Marshall)



Dan Dewey
http://www.mssl.ucl.ac.uk/~gbr/rgs_workshop/papers/dewey_d.ps







Dan Dewey
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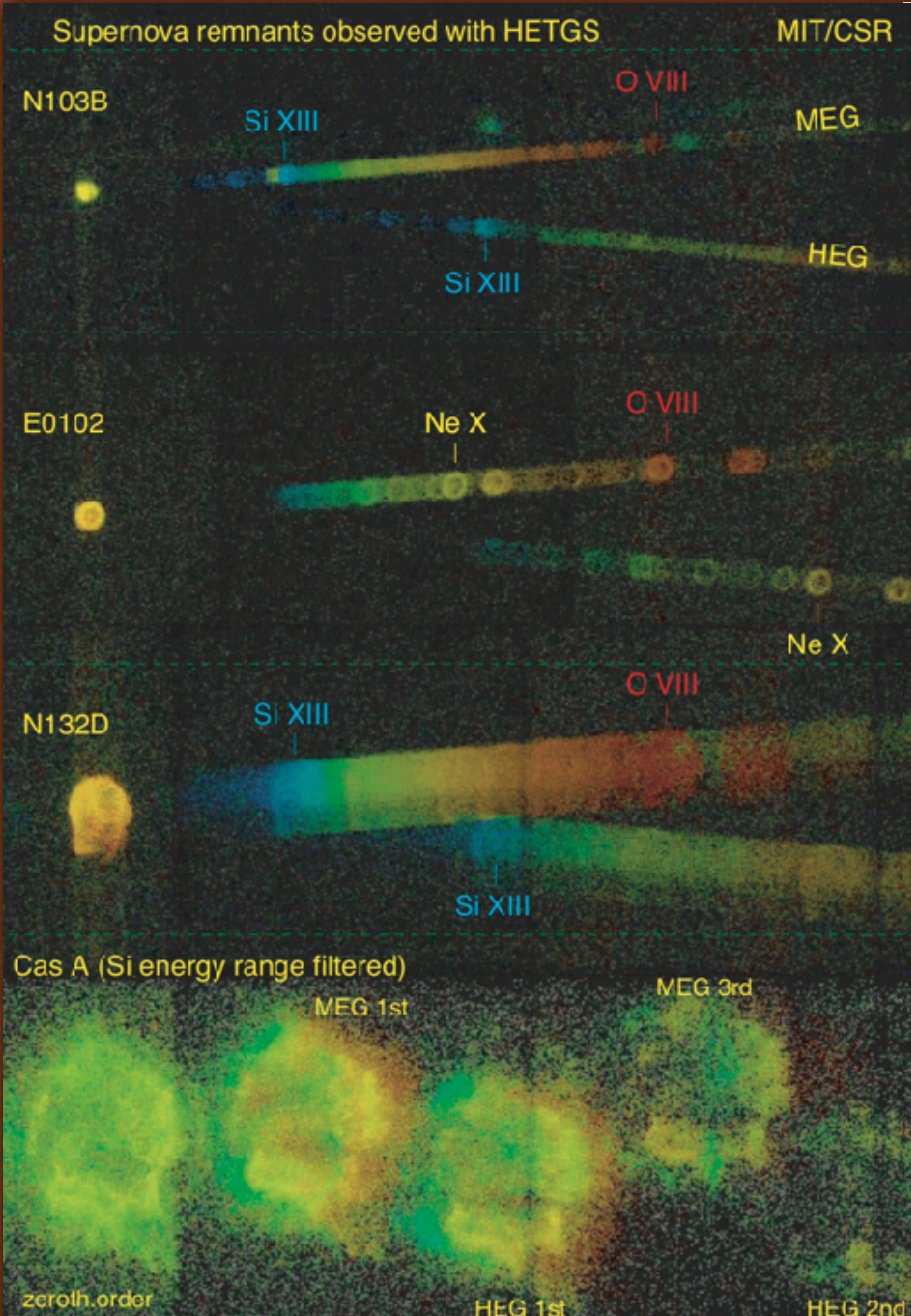

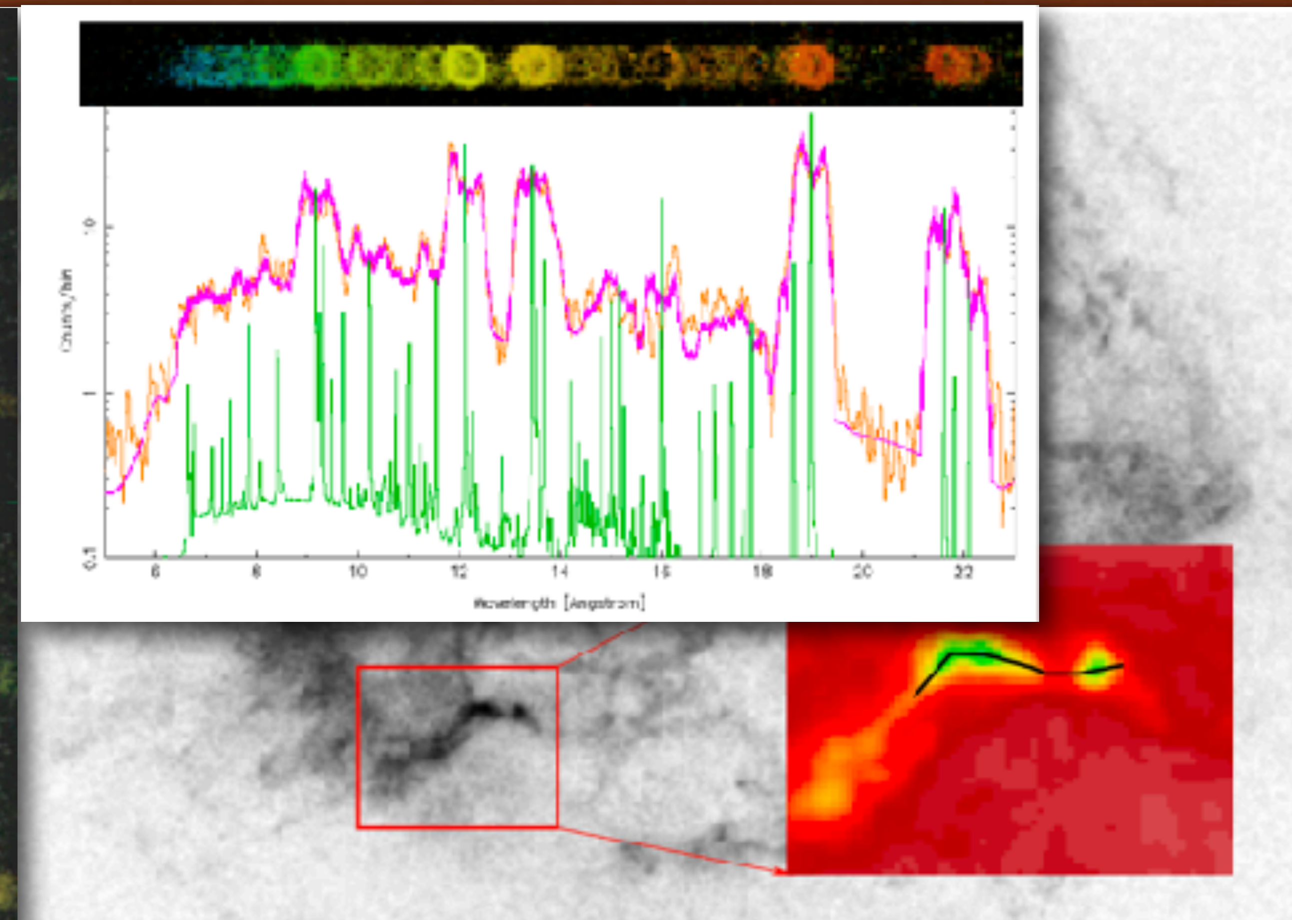

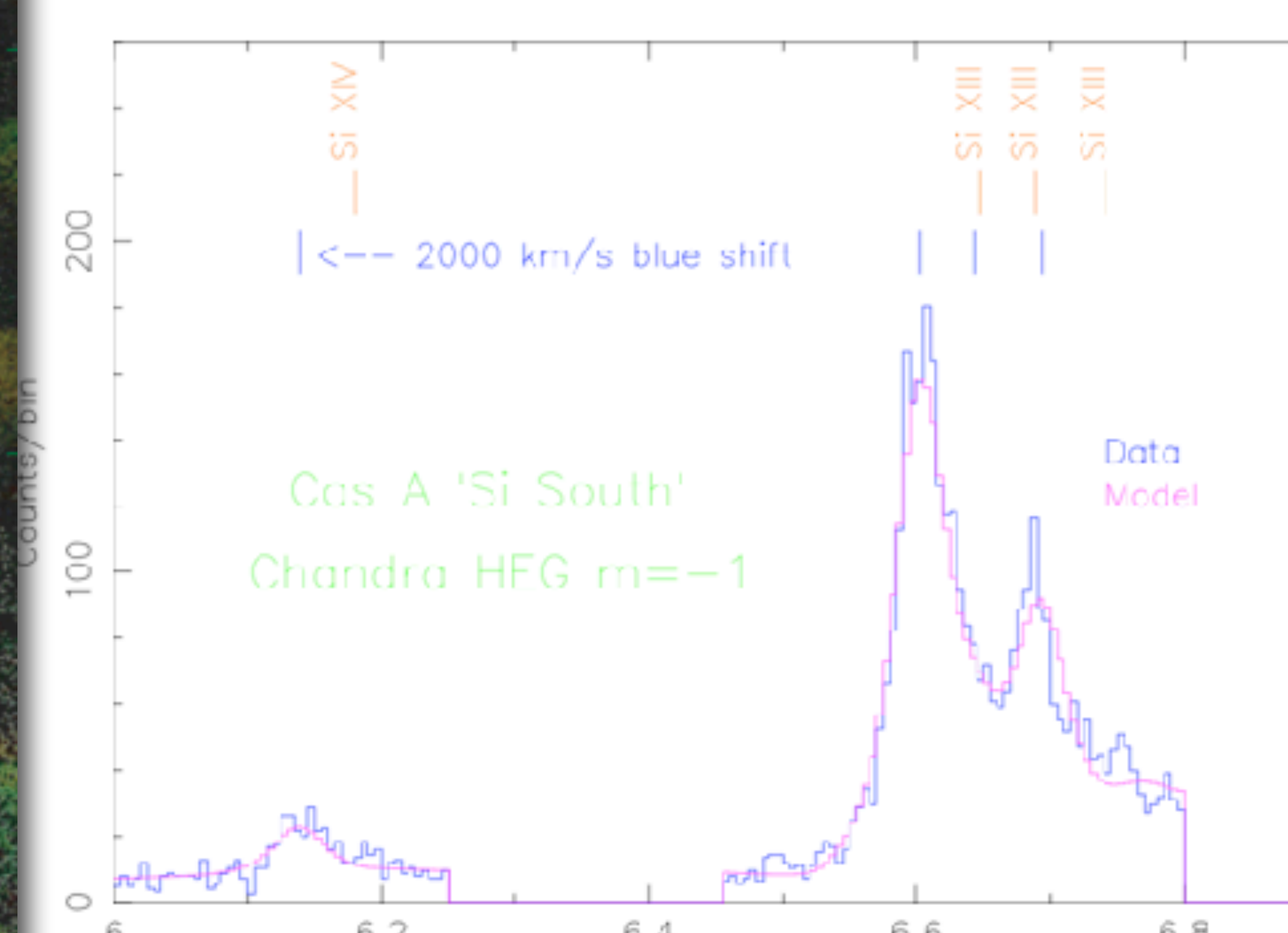

Dan Dewey
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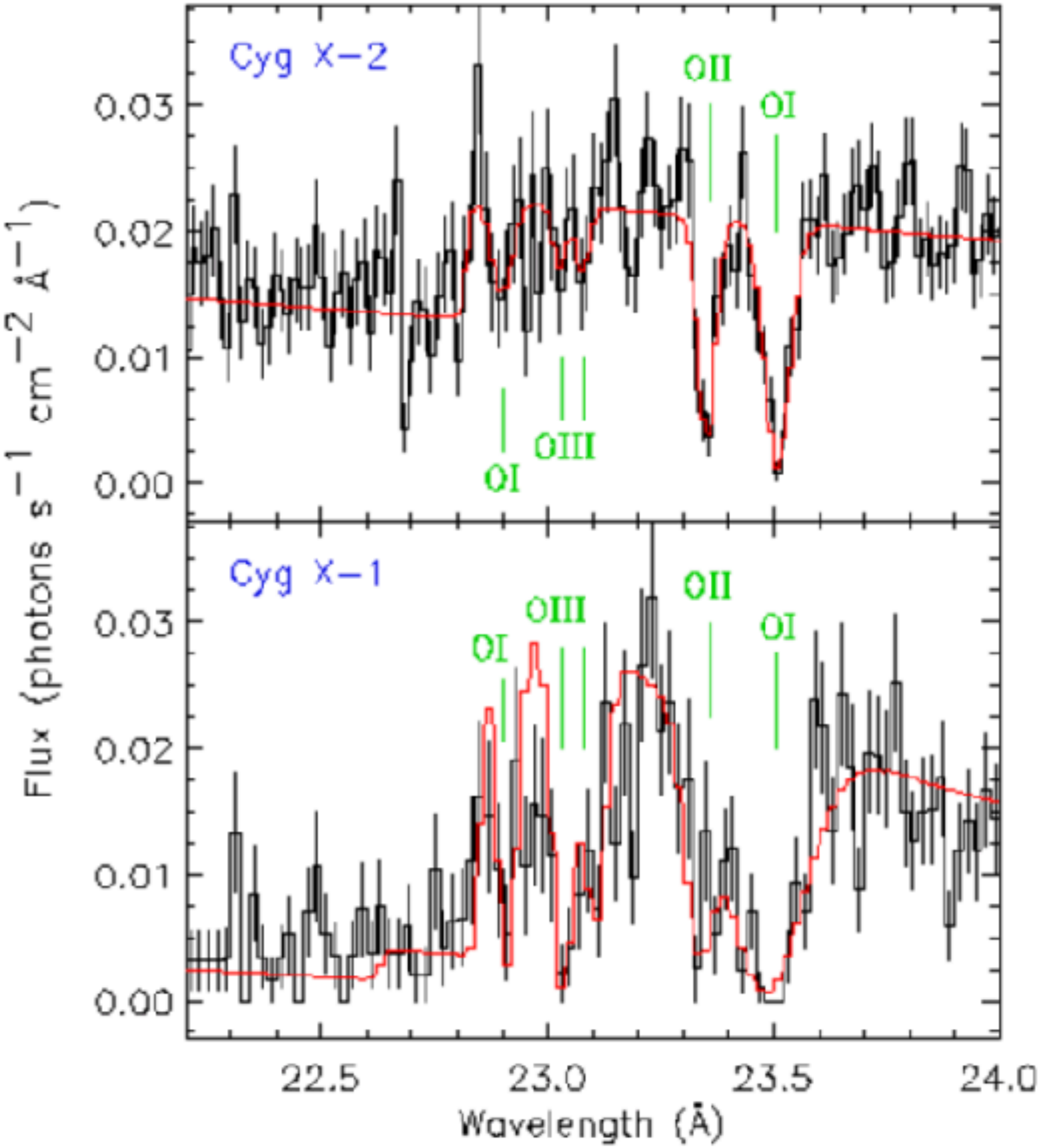

FIGURE 11: The bright continuum radiation from binary systems shows the imprint of the ISM along the line of sight. Absorption dips are seen in MEG spectra from neutral oxygen, O I, as well as singly and doubly ionized oxygen, O II and O III. For reference, the energy range shown is roughly 0.558 keV to 0.517 keV, left to right. From Juett, Schulz, and Chakrabarty (2004).

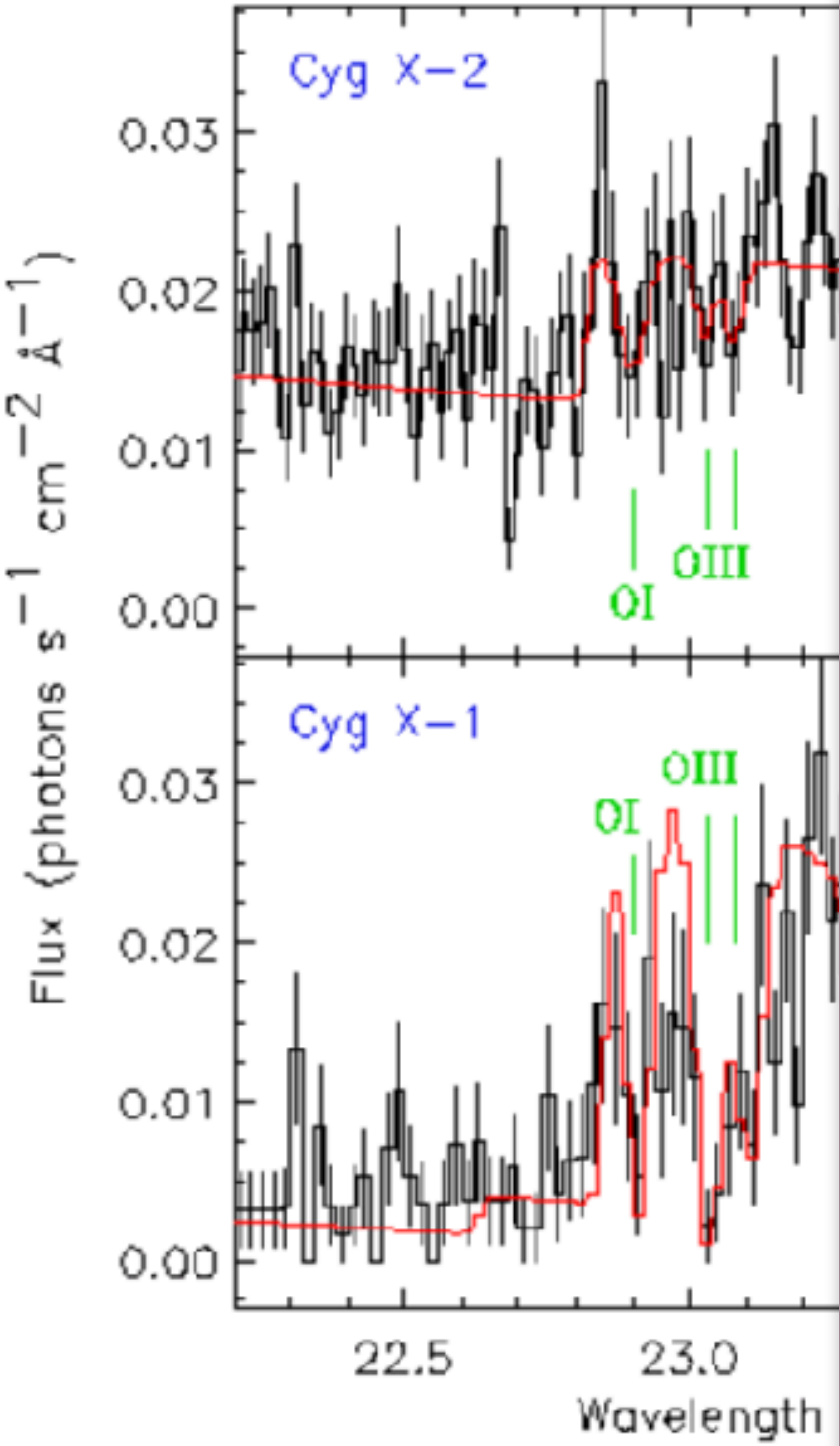

FIGURE 11: The bright continuum radia
shows the imprint of the ISM along the l
are seen in MEG spectra from neutral ox
and doubly ionized oxygen, O II and O I
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Juett, Schulz, and Chakrabarty (2004).

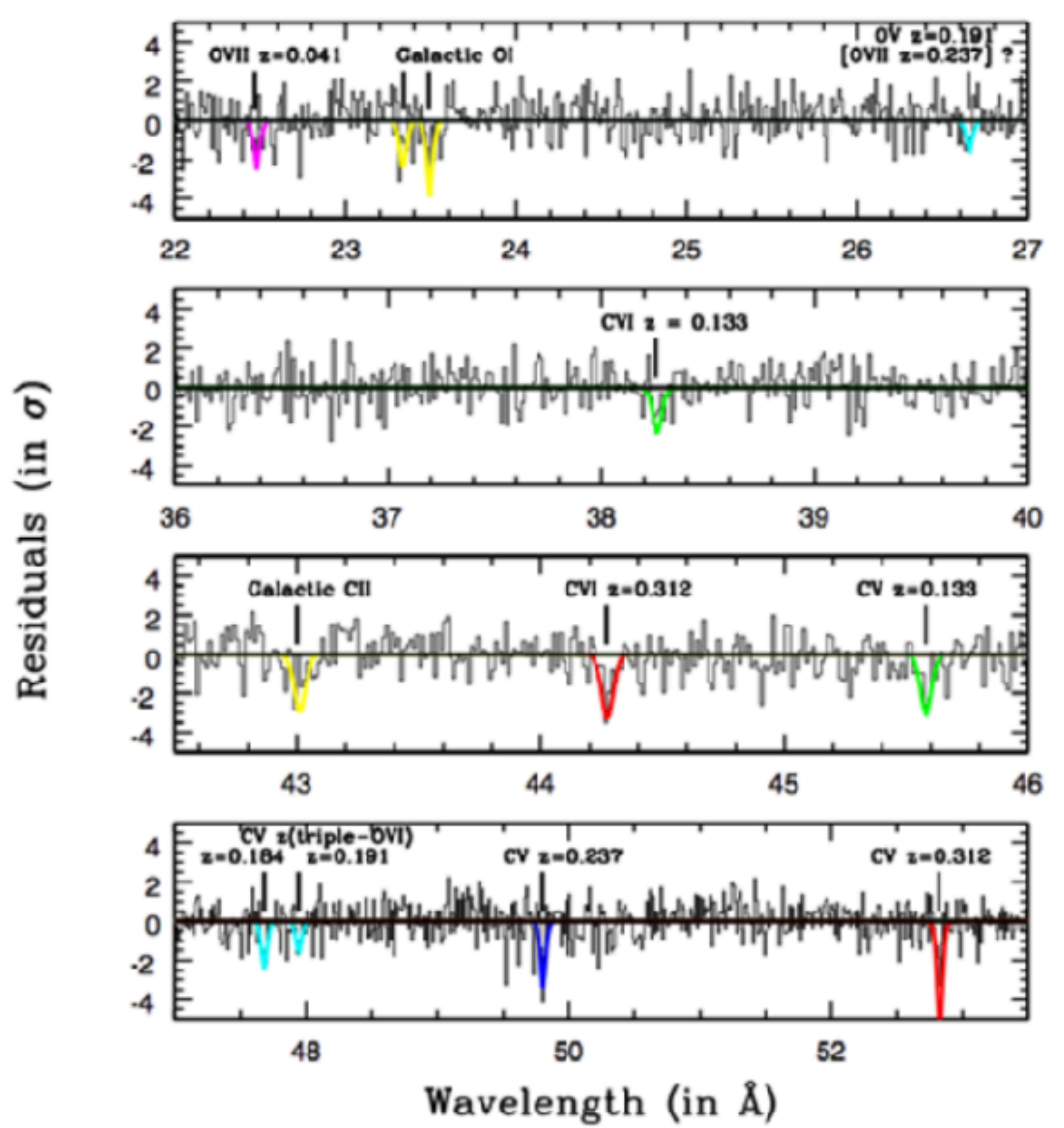

Fig. 2 — Residuals from a fit of the 500 ks LETG+HRC-S spectrum of the blazar 1ES 1553+113 to a continuum model. Galactic O I and C II are detected, as well as lines due to C V and C VI in different filaments of the WHIM. From Nicastro et al. (2013).

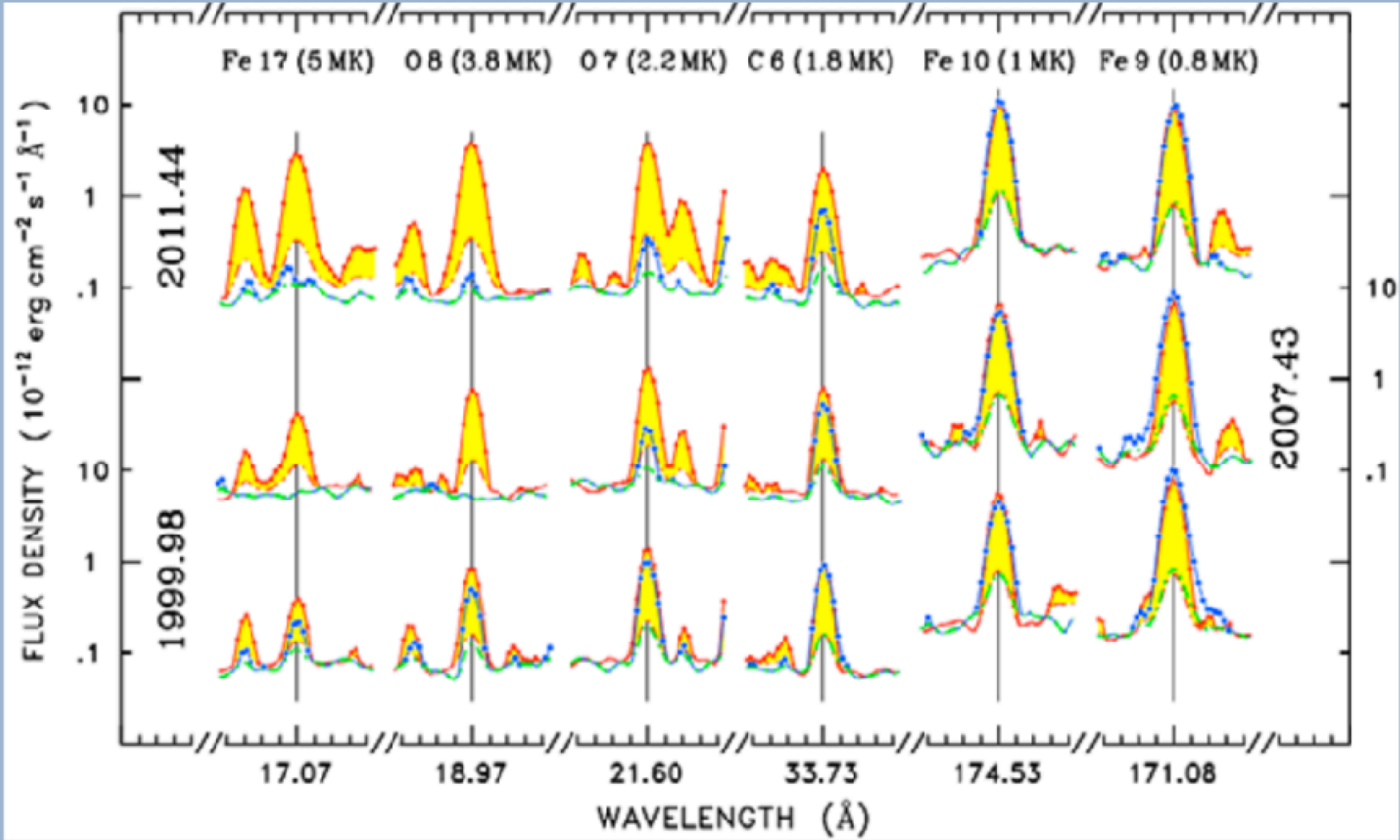

Fig. 3 — Spectra of selected lines from LETGS observations of α Cen A. The use of strong primary colors is designed to separate out behavior of the K star (shaded yellow and red dots) from that of the G star (blue dots). Delicate pastels indicate 1σ photometric errors for B in orange and A in green. Approximate line formation temperatures are listed. Note the dramatic differences between the two stars at the shortest wavelengths (< 20 Å) compared to the rather similar fluxes at the longest wavelengths (> 170 Å). From Ayres (2014).

4. ANALYSIS

RESOURCES

- Chandra Proposers' Observatory Guide
  - HETG (Chapter 8) **http://cxc.harvard.edu/proposer/POG/html/chap8.html**
  - LETG (Chapter 9) **http://cxc.harvard.edu/proposer/POG/html/chap9.html**
- Chandra Cal Pages
  - HETG — **https://space.mit.edu/CXC/calib/hetg_user.html**
  - LETG — **http://cxc.harvard.edu/cal/letg/detailed_info.html**
- CIAO Science Analysis Threads — **http://cxc.harvard.edu/ciao/threads/gspec.html**
- Sherpa Threads — **http://cxc.harvard.edu/sherpa/threads/fitting.html**
- D. Huenemoerder's Analysis Guide — **https://space.mit.edu/ASC/analysis/AGfCHRS/AGfCHRS.html**
- TGCAT — **http://tgcat.mit.edu**

(Mike Nowak)