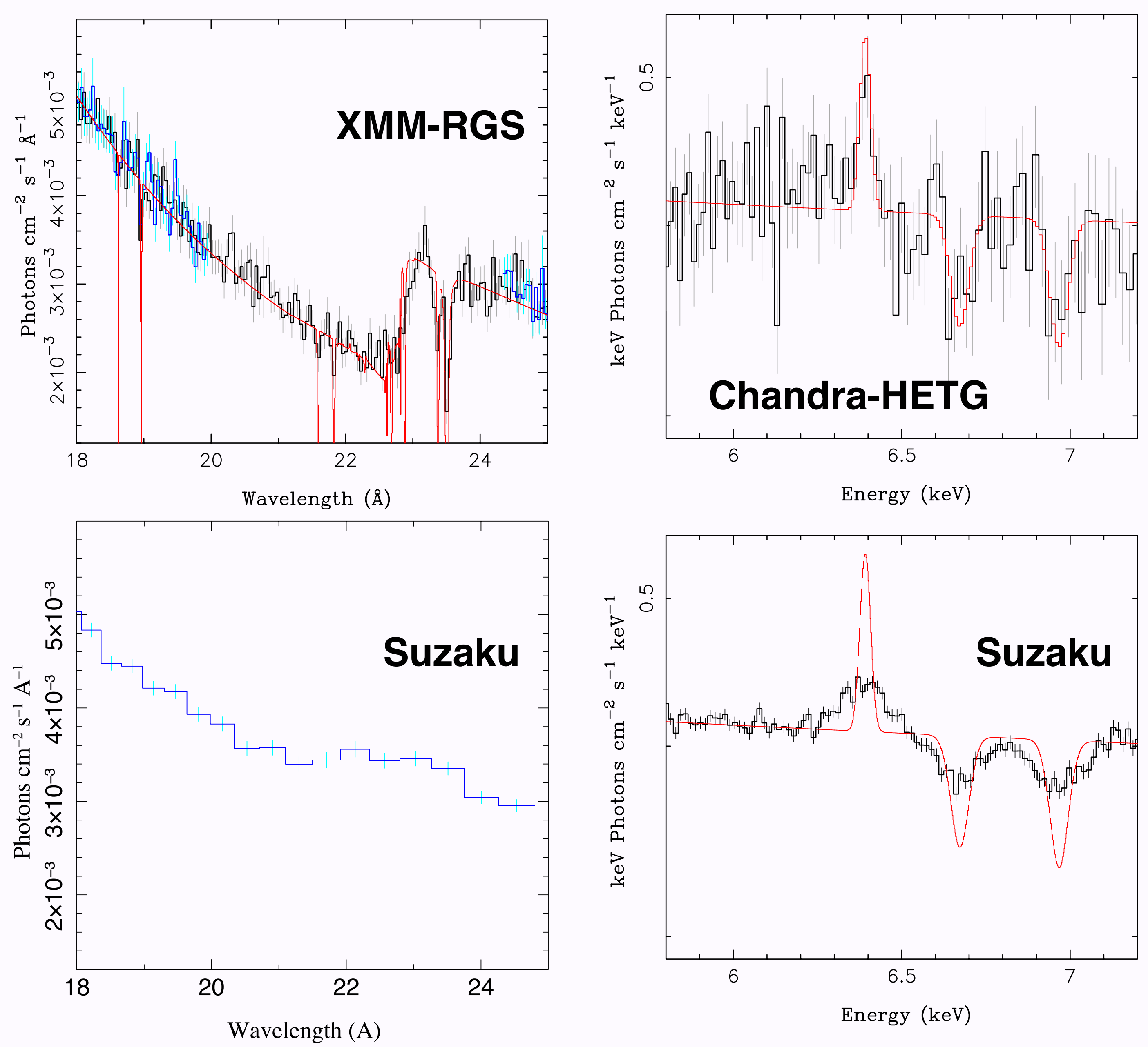
High Resolution X-ray Spectroscopy

Hans Moritz Günther (MIT)
with material from
Michael A. Nowak (Washington University St. Louis)

MIT KAVLI INSTITUTE

Resolution



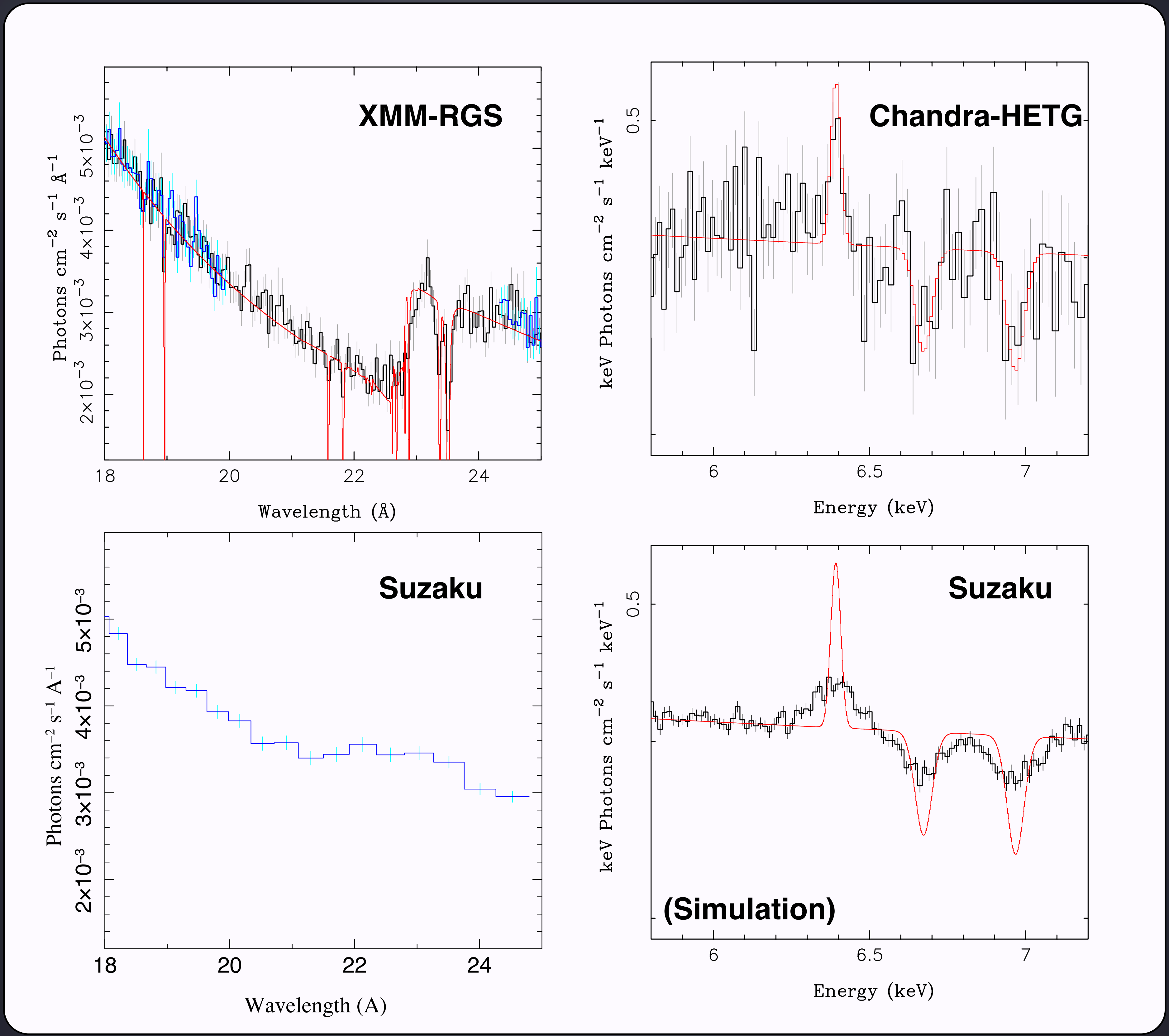
(Simulation)

$$R = \frac{\lambda}{\Delta\lambda} = \frac{E}{\Delta E}$$

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...)
- New: X-ray Calorimetry
  ΔE_{FWHM} ~5–7 eV, $E/\Delta E_{FWHM}$ ~1000 @6.4 keV (scales as E)

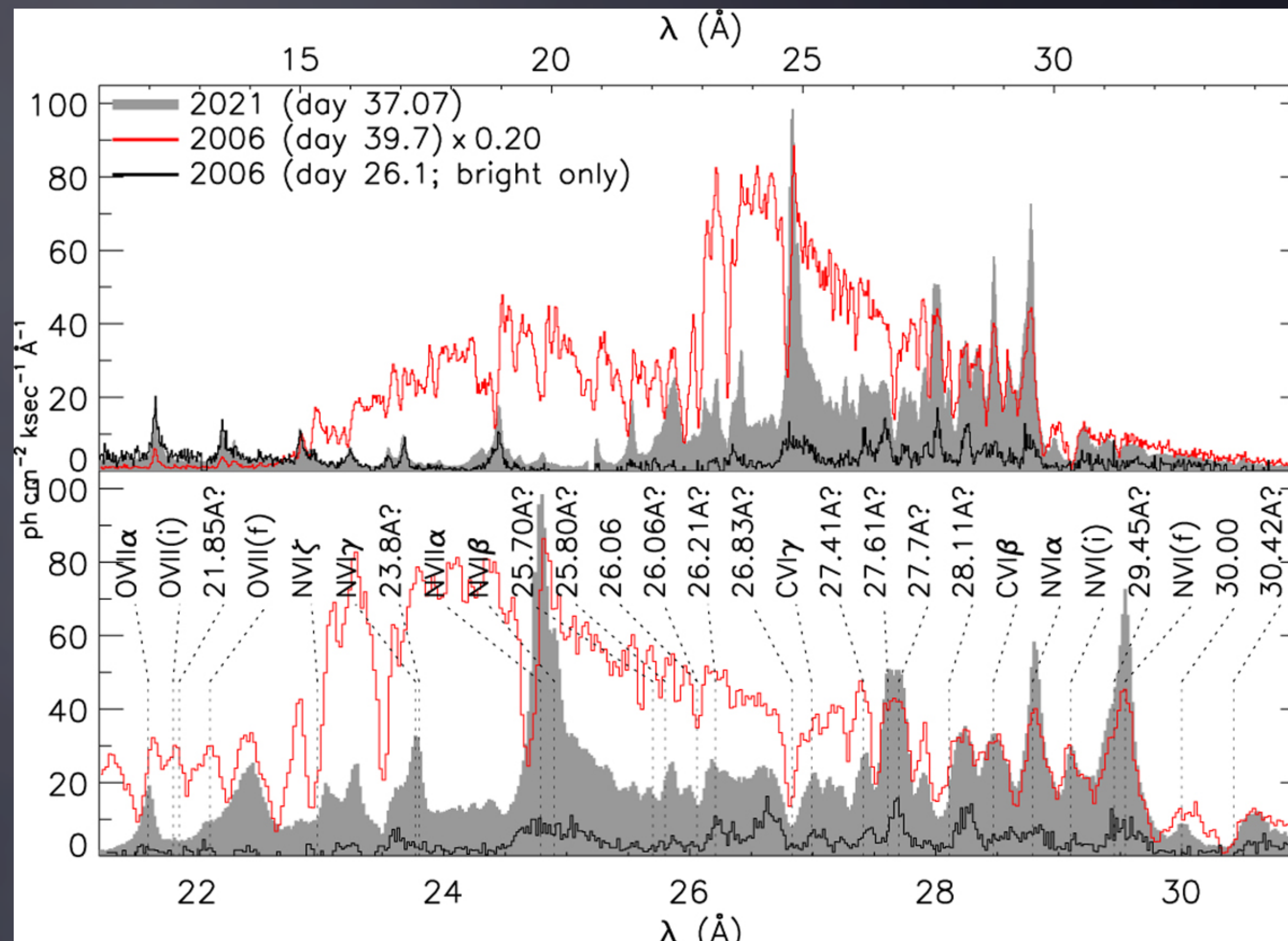
High/Low Res Comparison



Source:
4U 1957+11

Diagnostics in grating spectra

- Temperature
- Density
- Ionization
- Velocity shifts
- Line shapes
- Absorption lines
- …



RS Oph (recurrent nova)
Ness et al (2022)

Diagnostics in grating spectra

- Temperature
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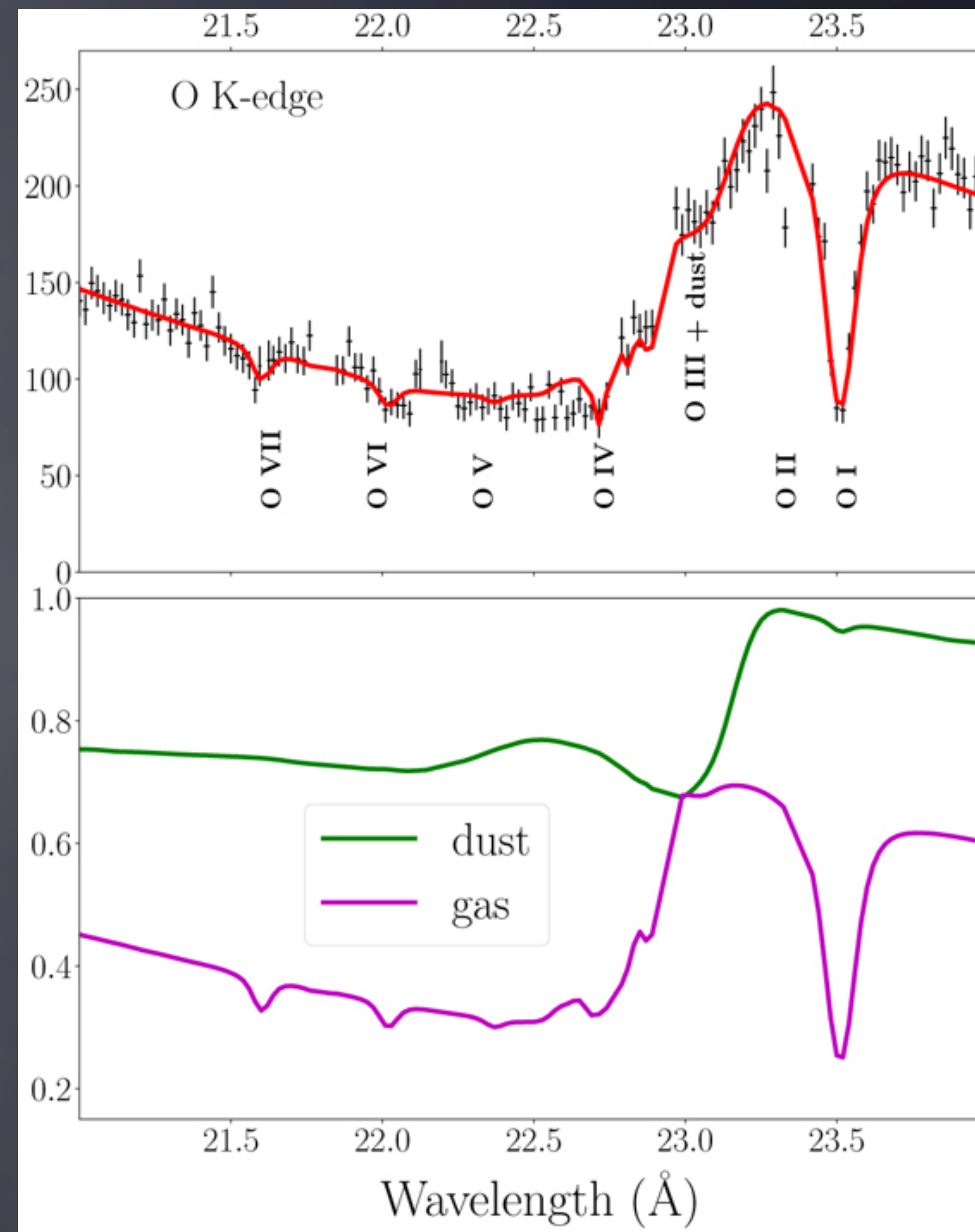
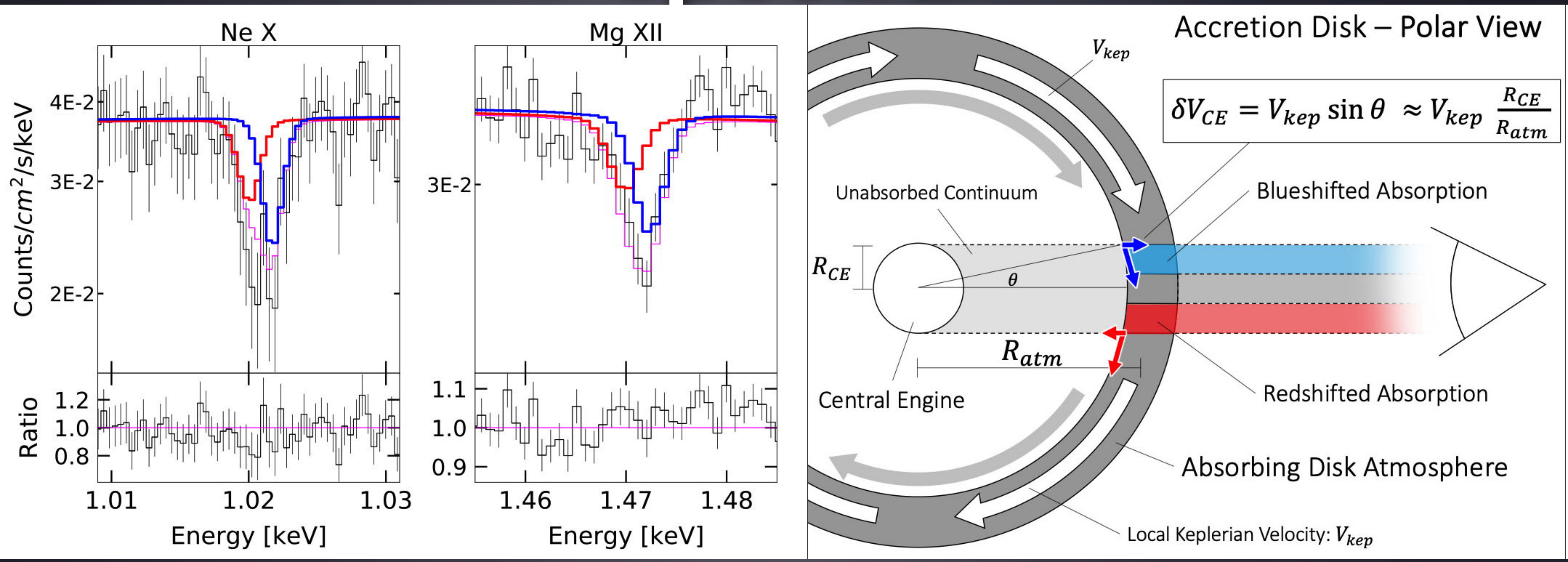
ISM gas and dust
Psaradaki et al (2023)



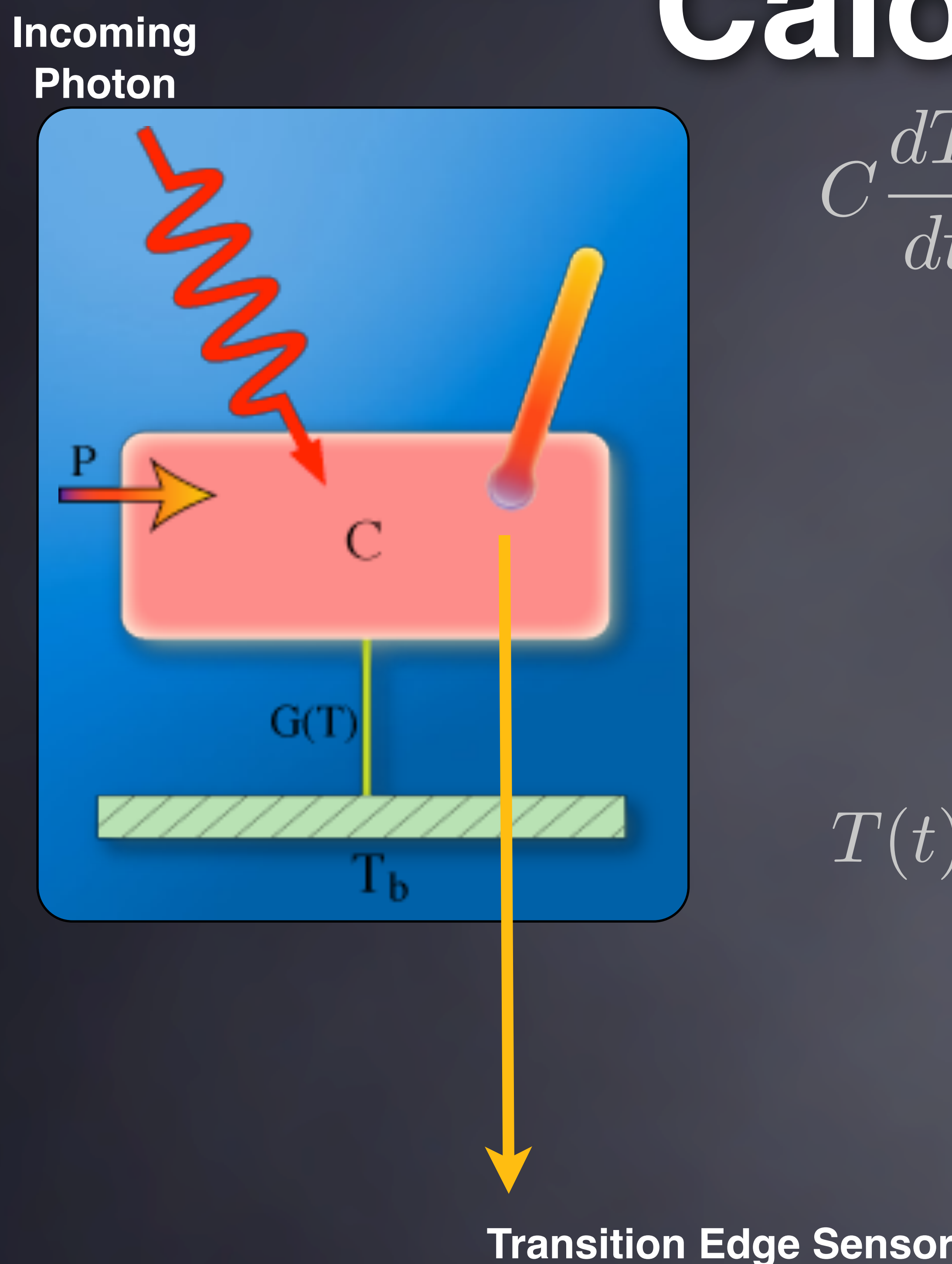
Diagnostics in grating spectra



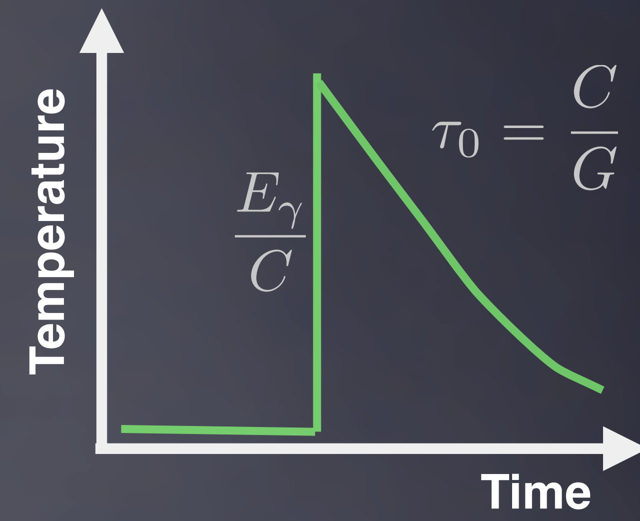
- **Absorption lines (here blue and red-shifted) allow constraining the size of neutron stars**

4U 1916-053 (an accretion neutron star)
Trueba et al (2022)

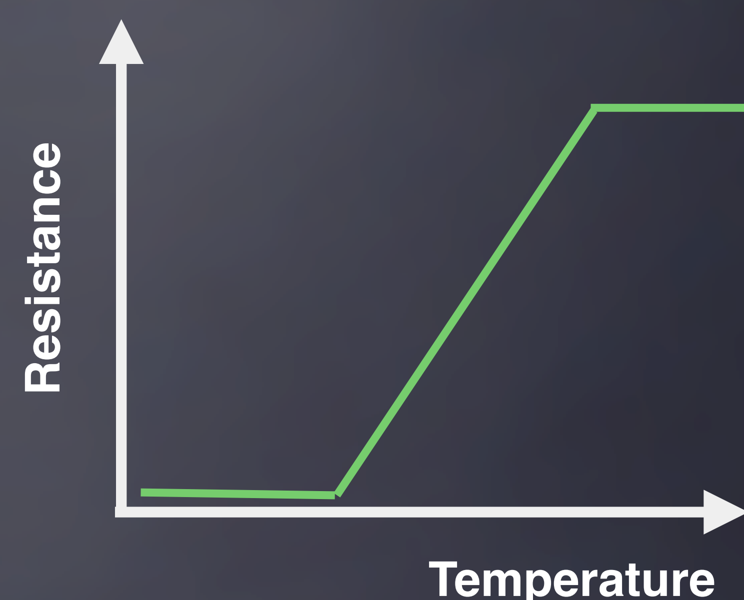
Calorimeter



$$C\frac{dT}{dt} = P - G(T - T_b) + E_\gamma \delta(t)$$



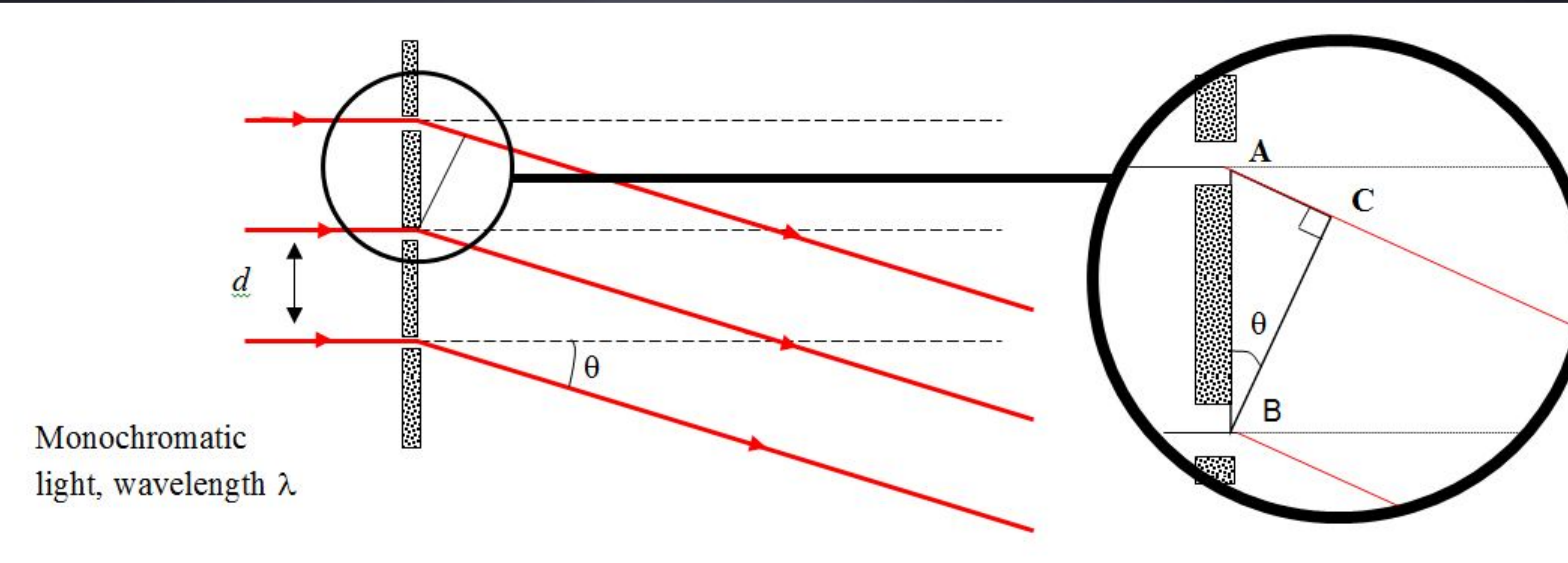
$$T(t) = \frac{E_\gamma}{C} exp(-t/\tau_0) + \left(\frac{P}{G} + T_b\right)$$



(See http://web.mit.edu/figueroagroup/ucal/ucal_basics/index.html)

Gratings

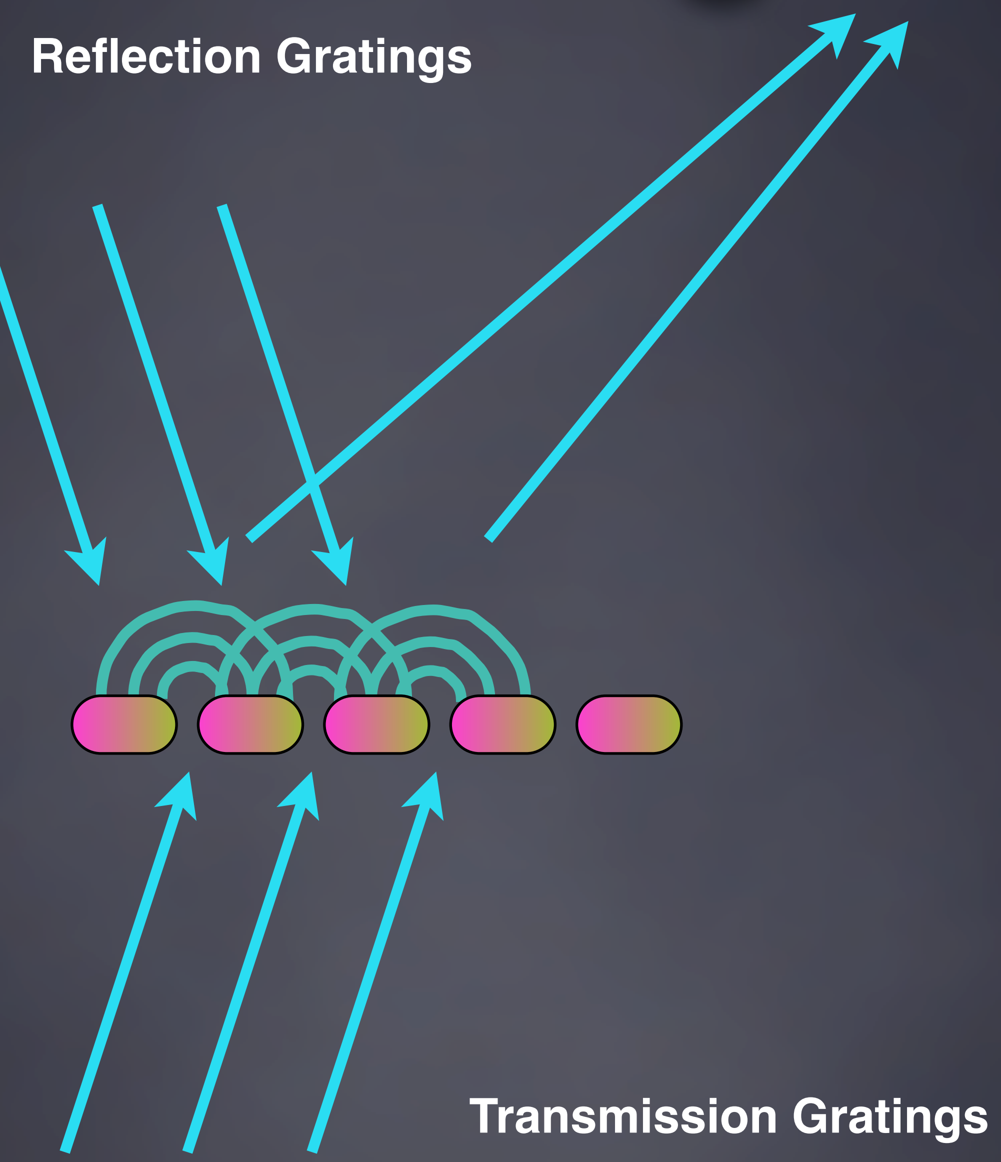
Figure taken from Antonine education website (which no longer exists)



Grating Equation:

$$n\lambda = n\frac{hc}{E} = d\sin\theta \approx d\theta$$

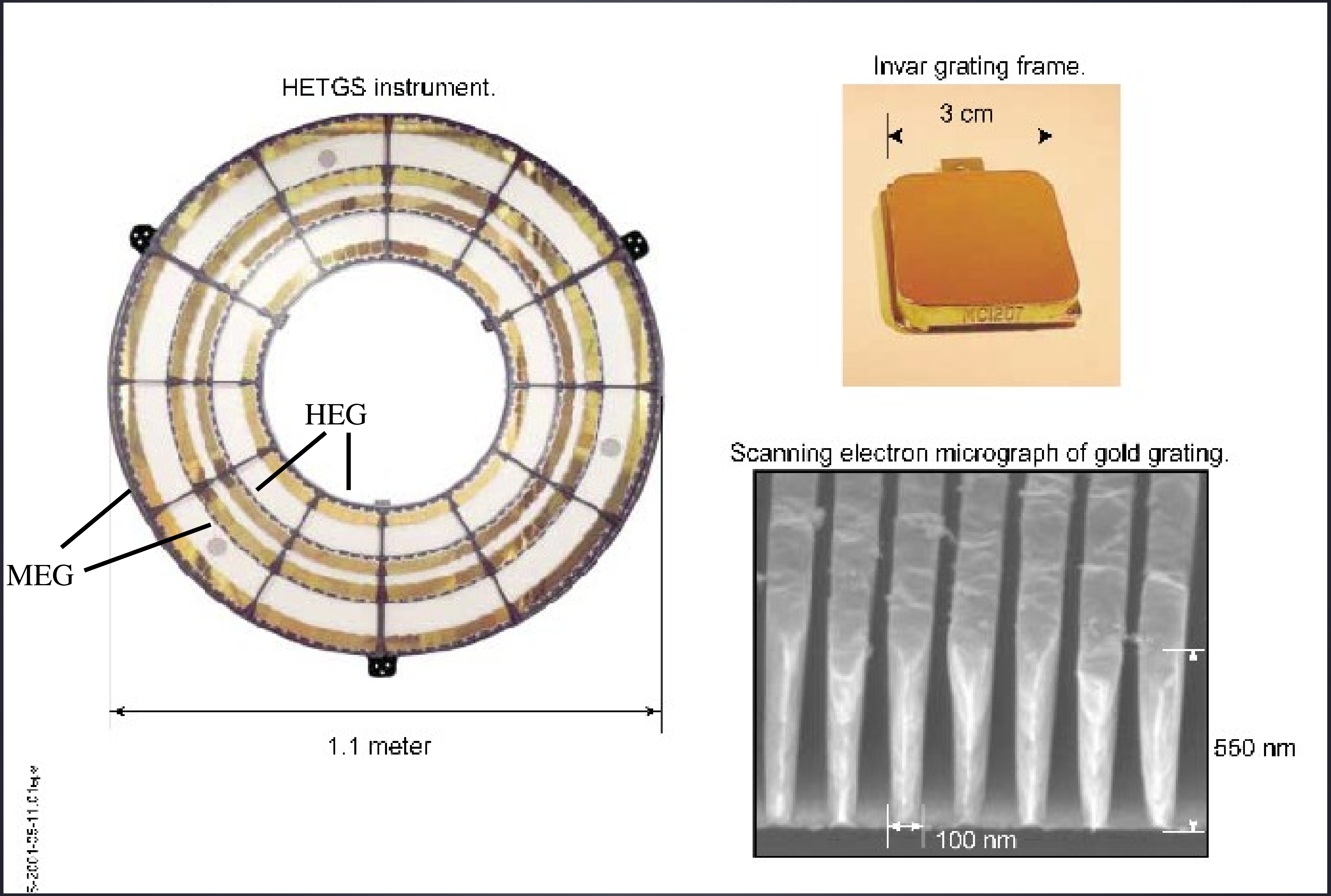
Gratings



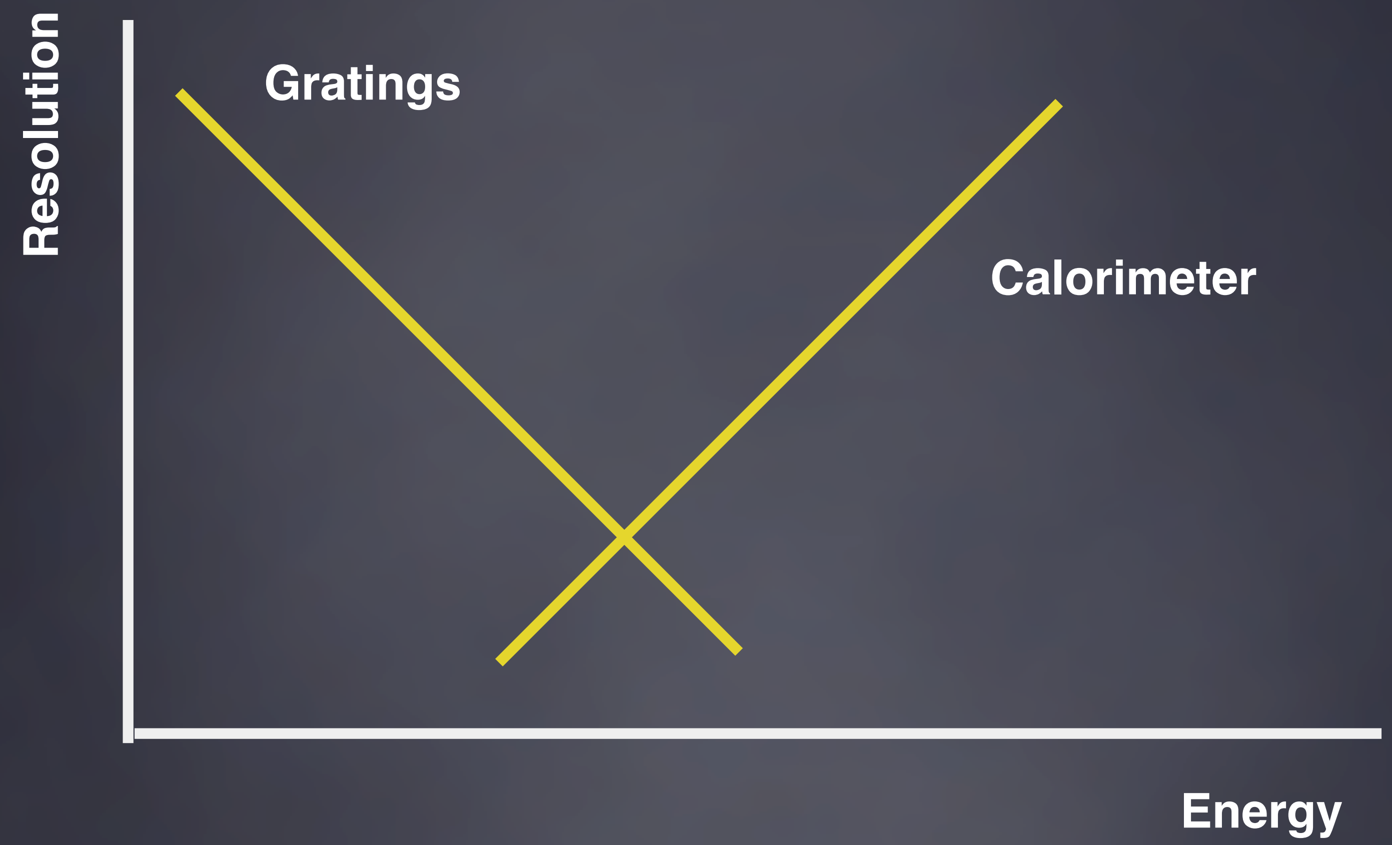
Grating Equation:

$$n\lambda = n\frac{hc}{E} = d\sin\theta \approx d\theta$$

Chandra-HETG

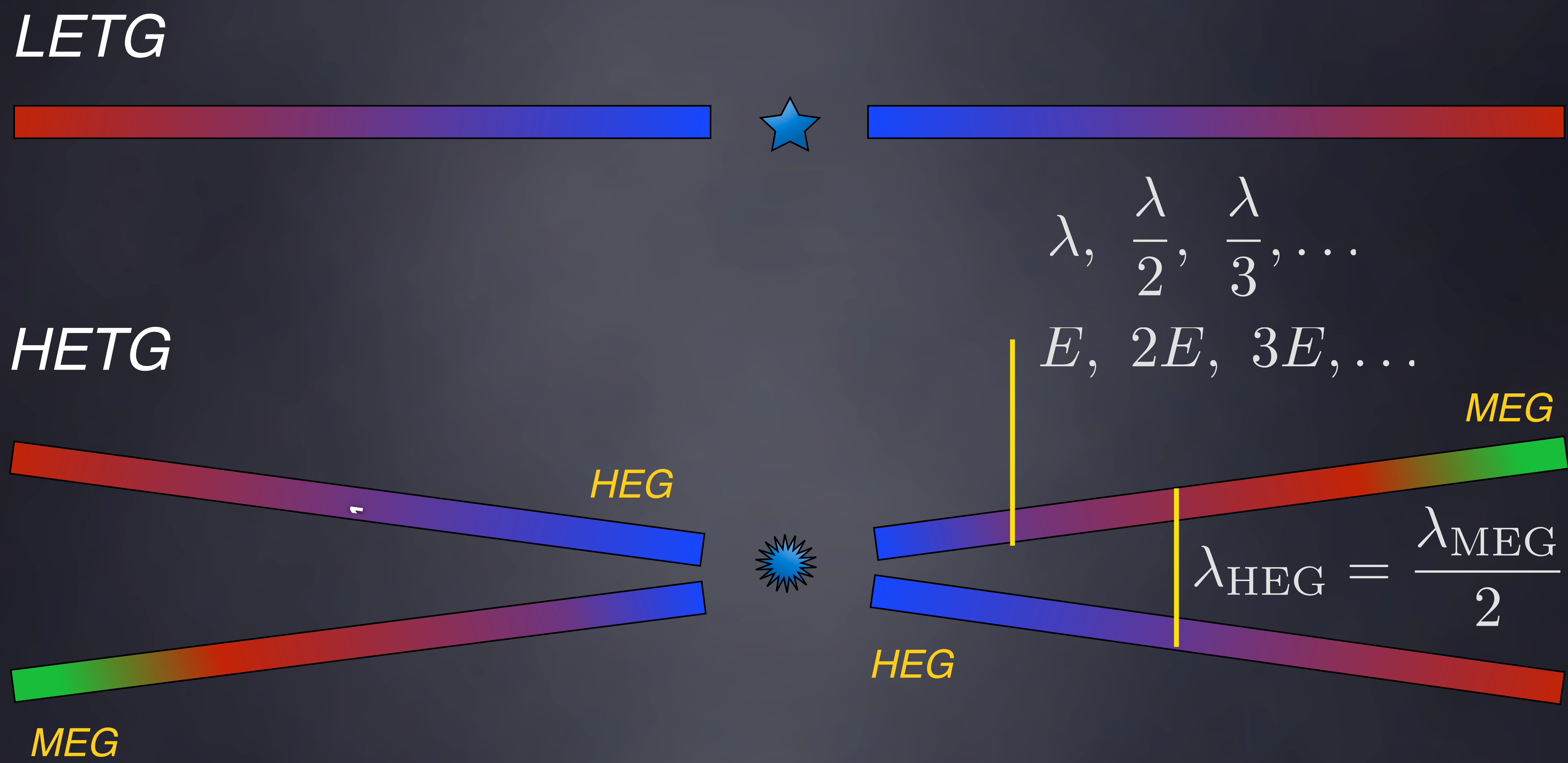


Gratings and Microcalorimeters…



If ever…

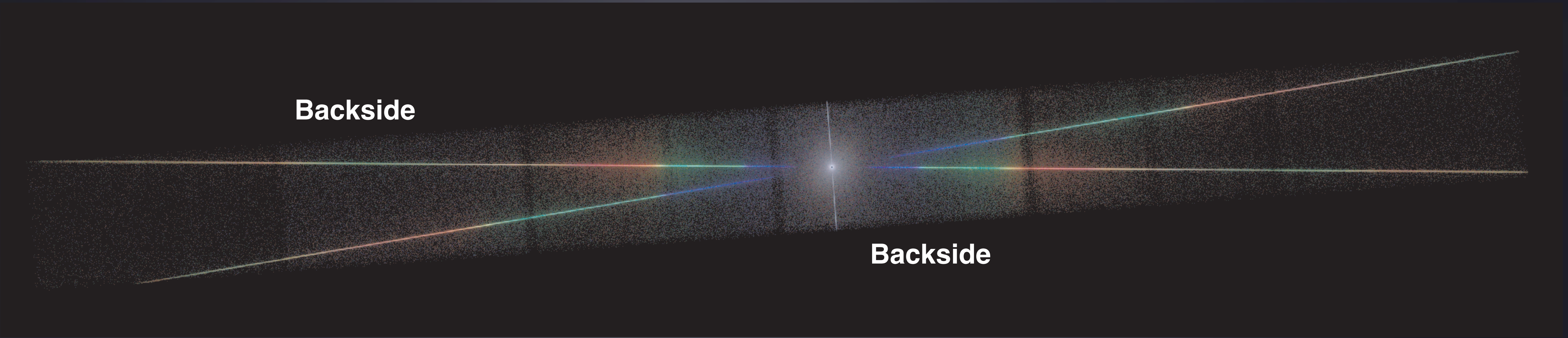
$$n\lambda = n\frac{hc}{E} = d\sin\theta \approx d\theta$$



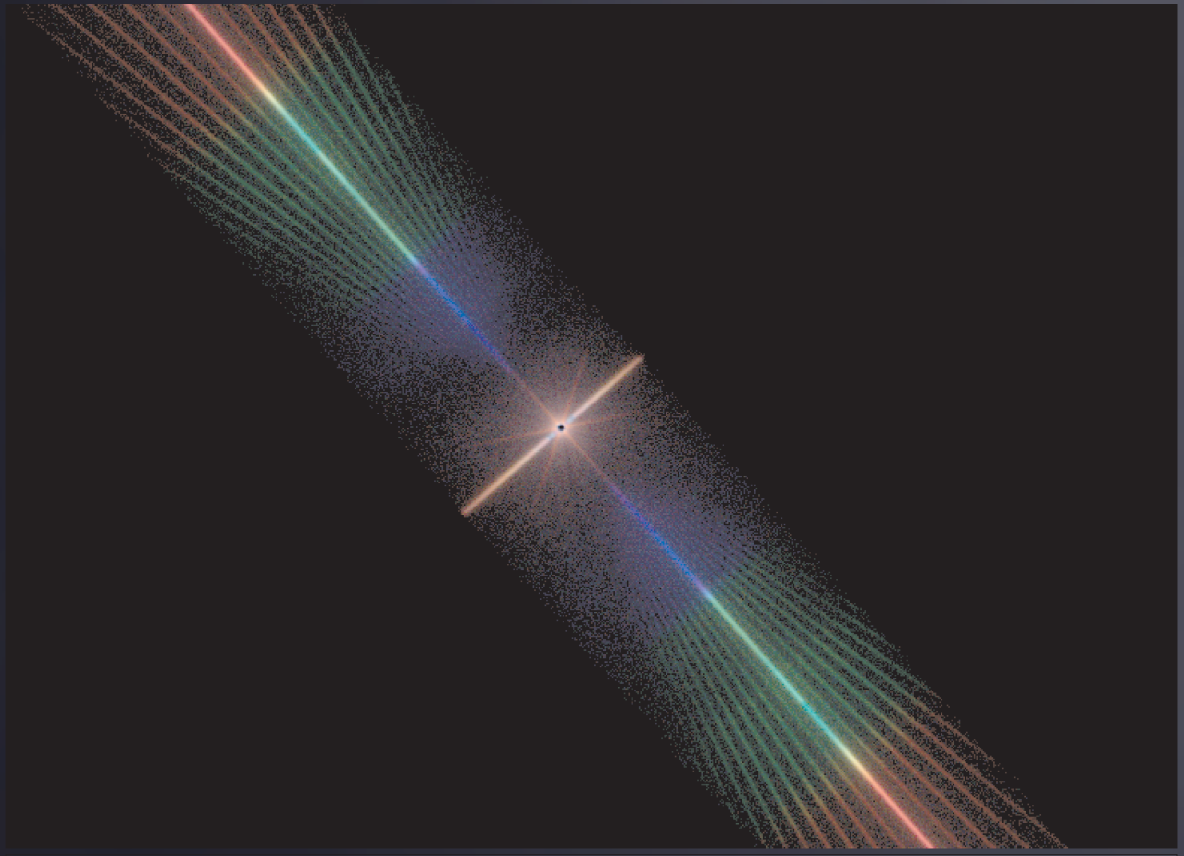
Greater Distance = Higher Resolution

Resolution Limited by CCDs & Gratings Accuracy

Chandra HETG

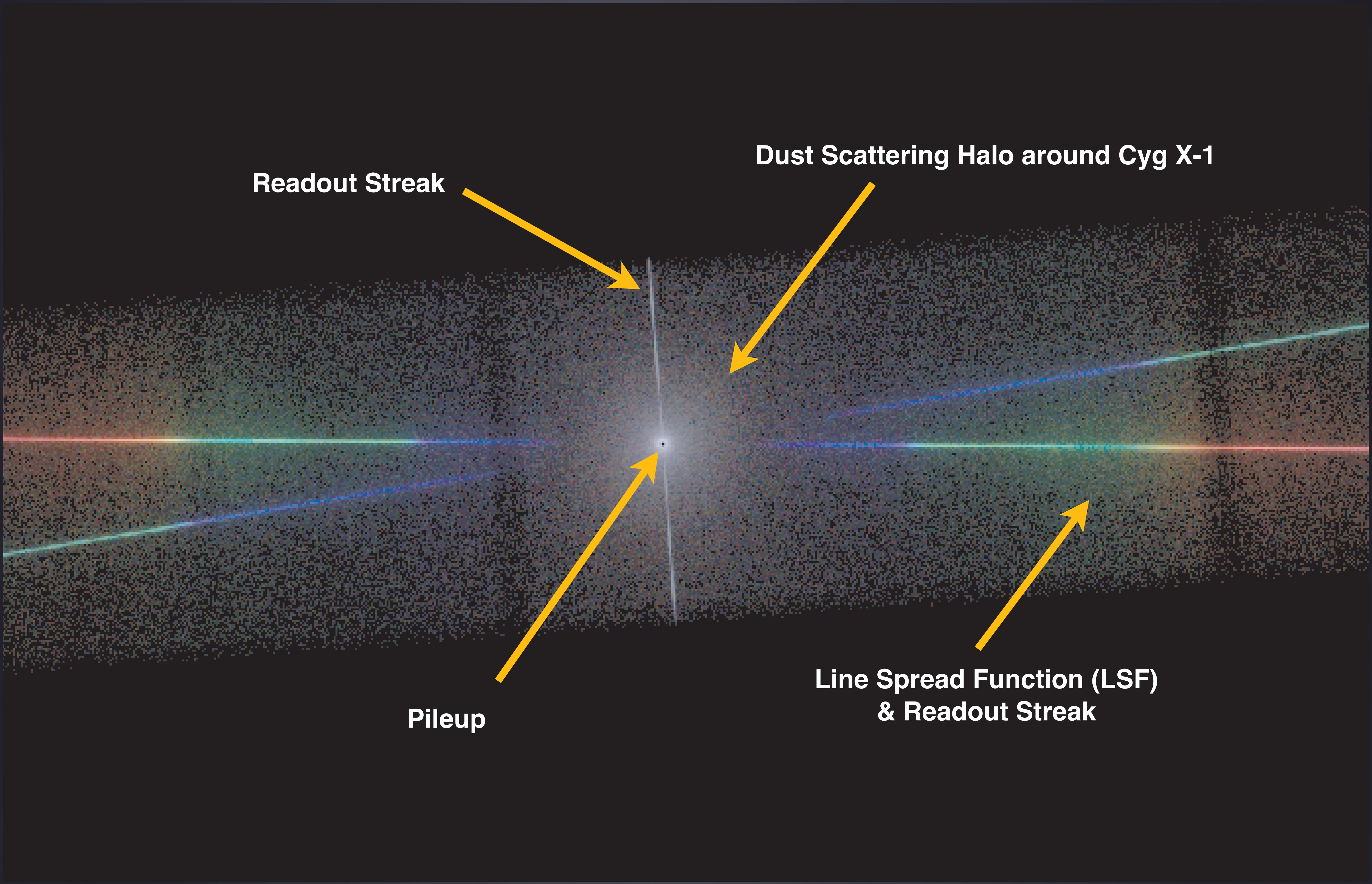


Chandra (ACIS) LETG



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

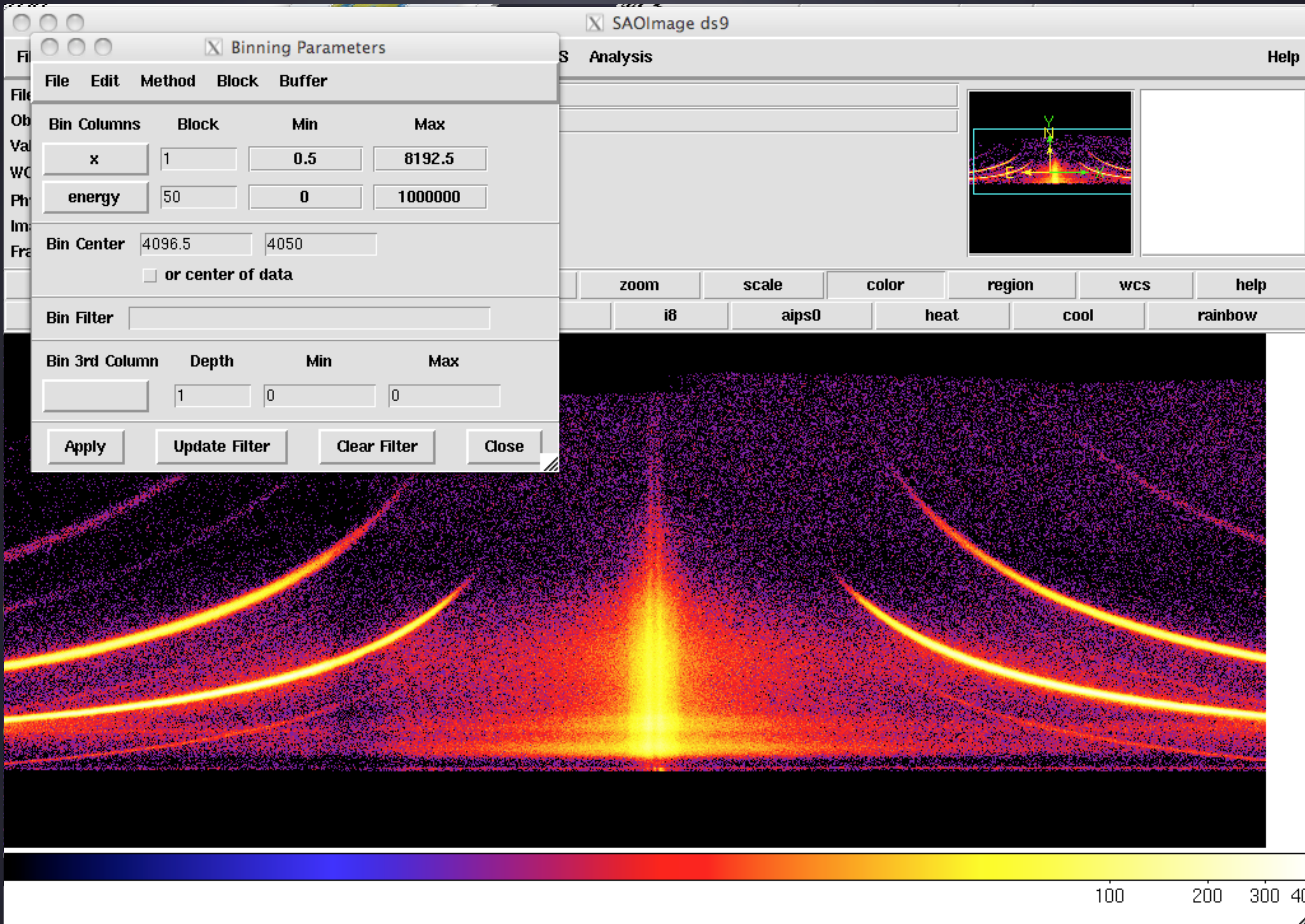
Chandra HETG



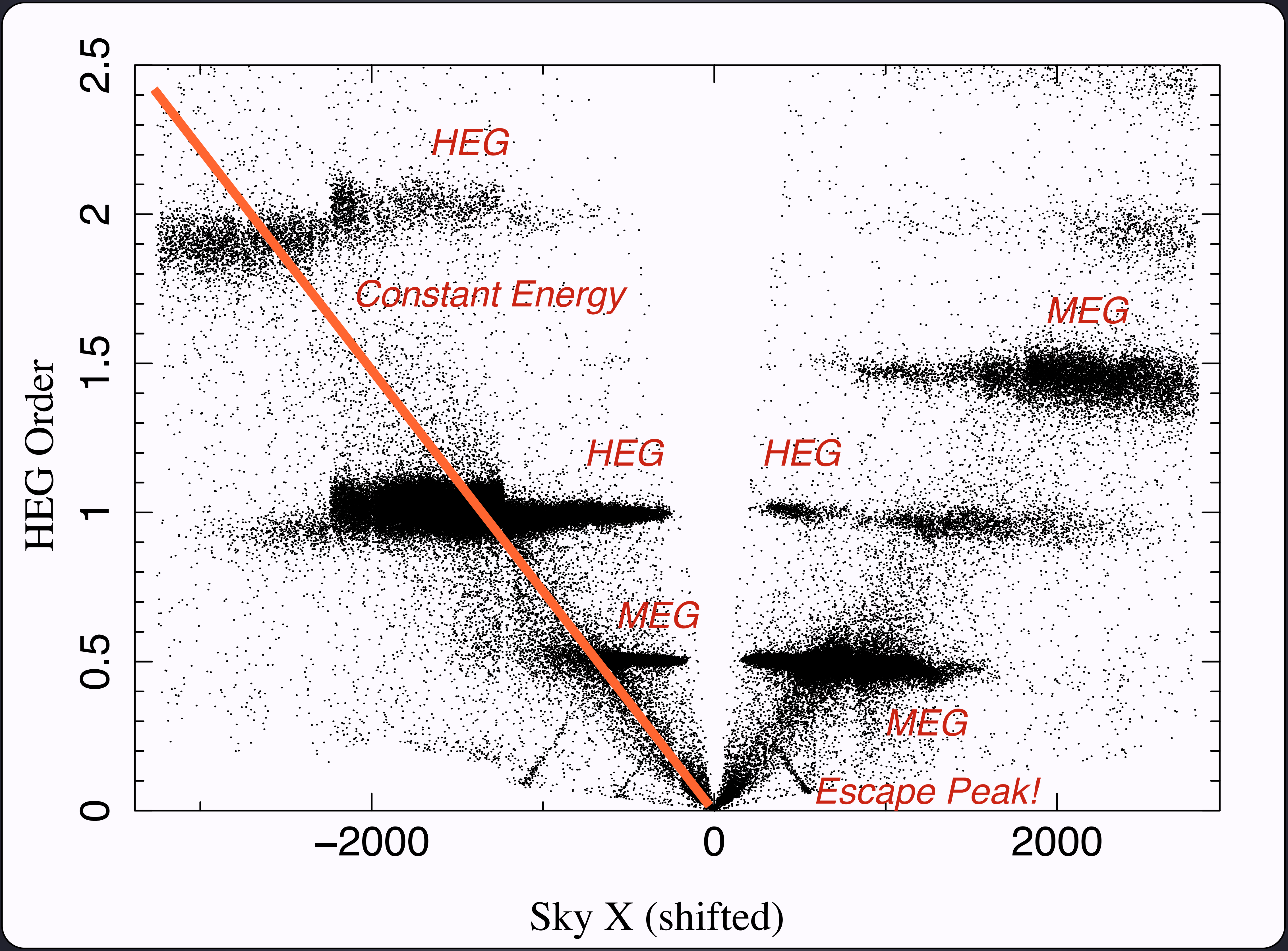
Order Sorting (aka Banana Plots)

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

unix%> ds9 acisf11044N002_evt2.fits.gz &



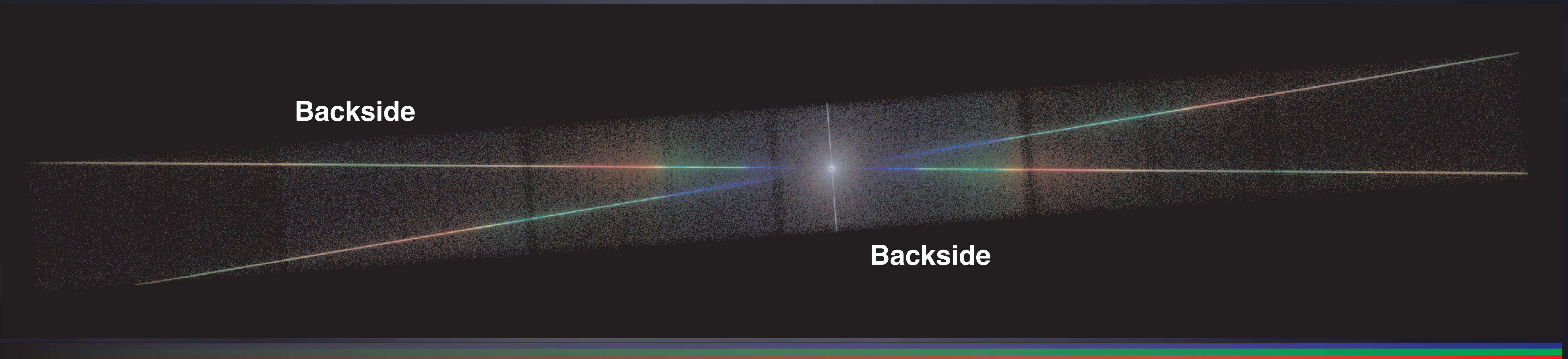
Order Sorting Plot



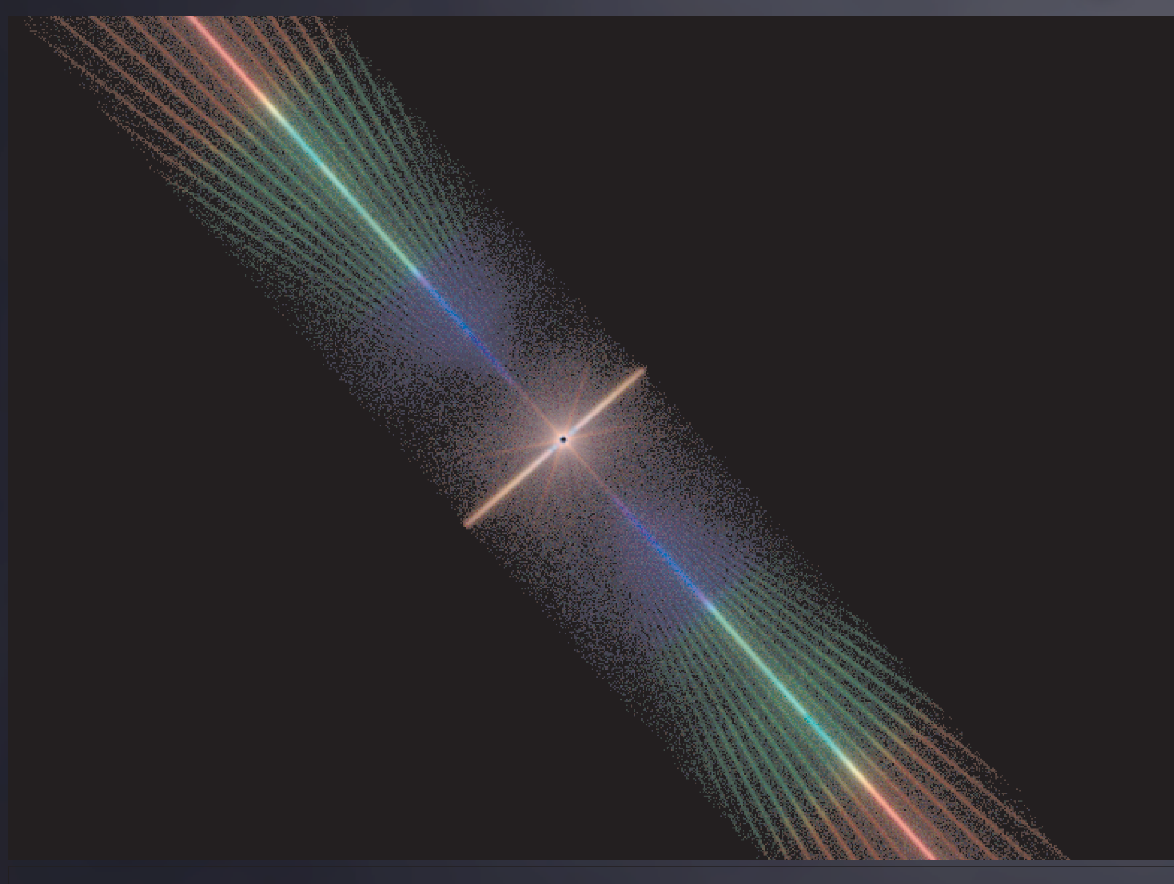
Data Extraction Tasks

- All these can be accomplished with CIAO tools
  - (Select time intervals, “clean” the data)
- Where is my source?
  - tg_detect2 – 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)
  - Mktgresp

Chandra HETG

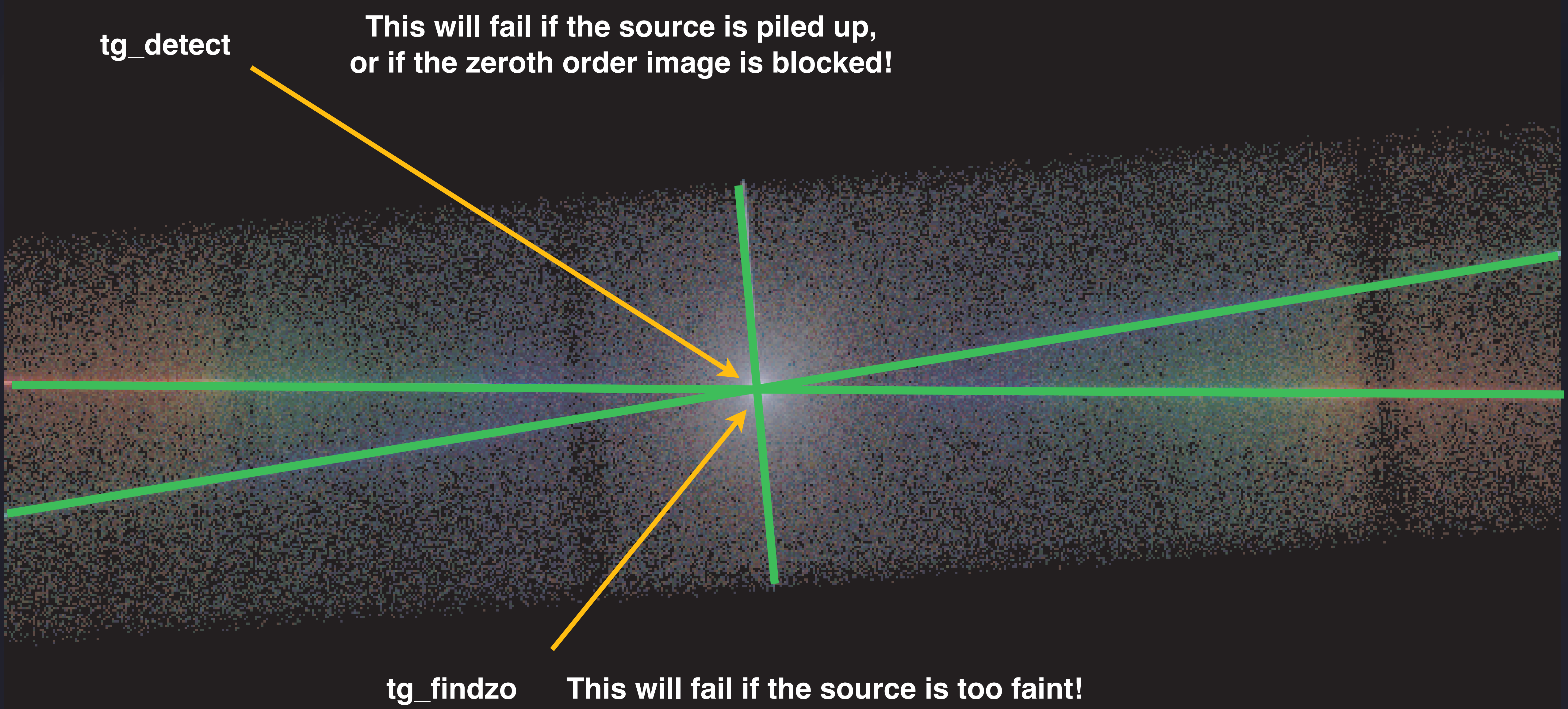


Chandra (ACIS) LETG



- 0th order shows diffraction from coarse support structure
- “Whiskers” are diffraction from fine support structure

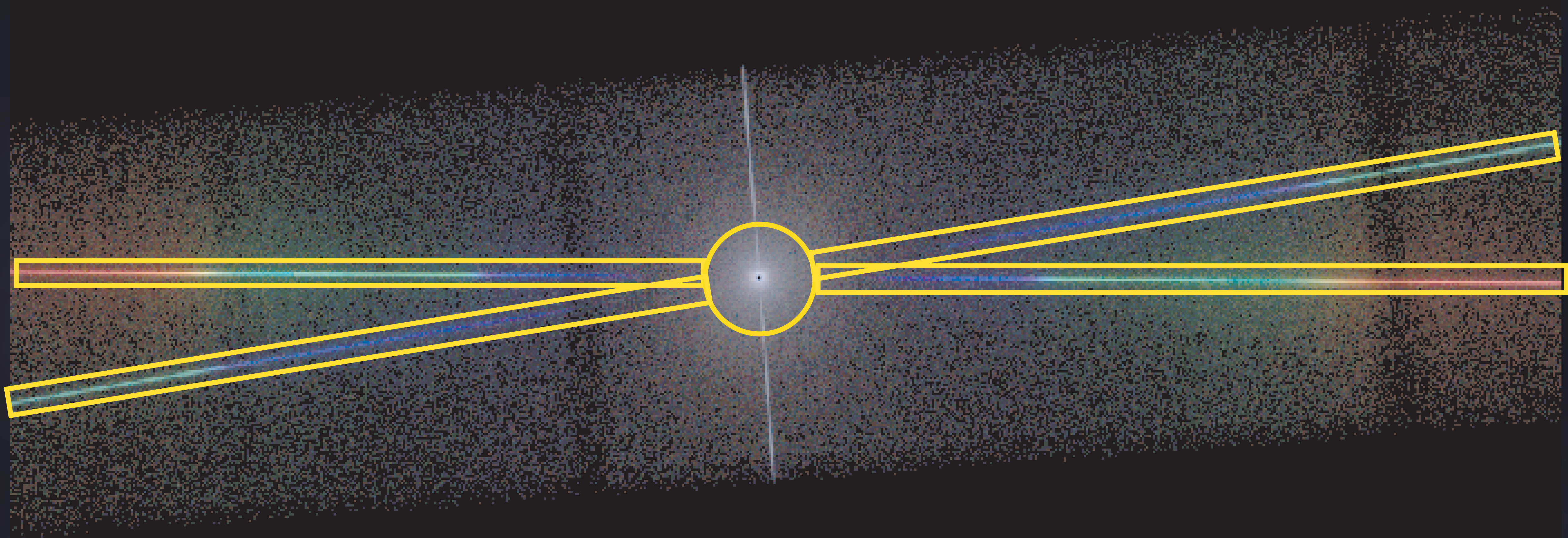
Where is my source?



Accuracy can be as good as 0.1 pixels

tg_create_mask

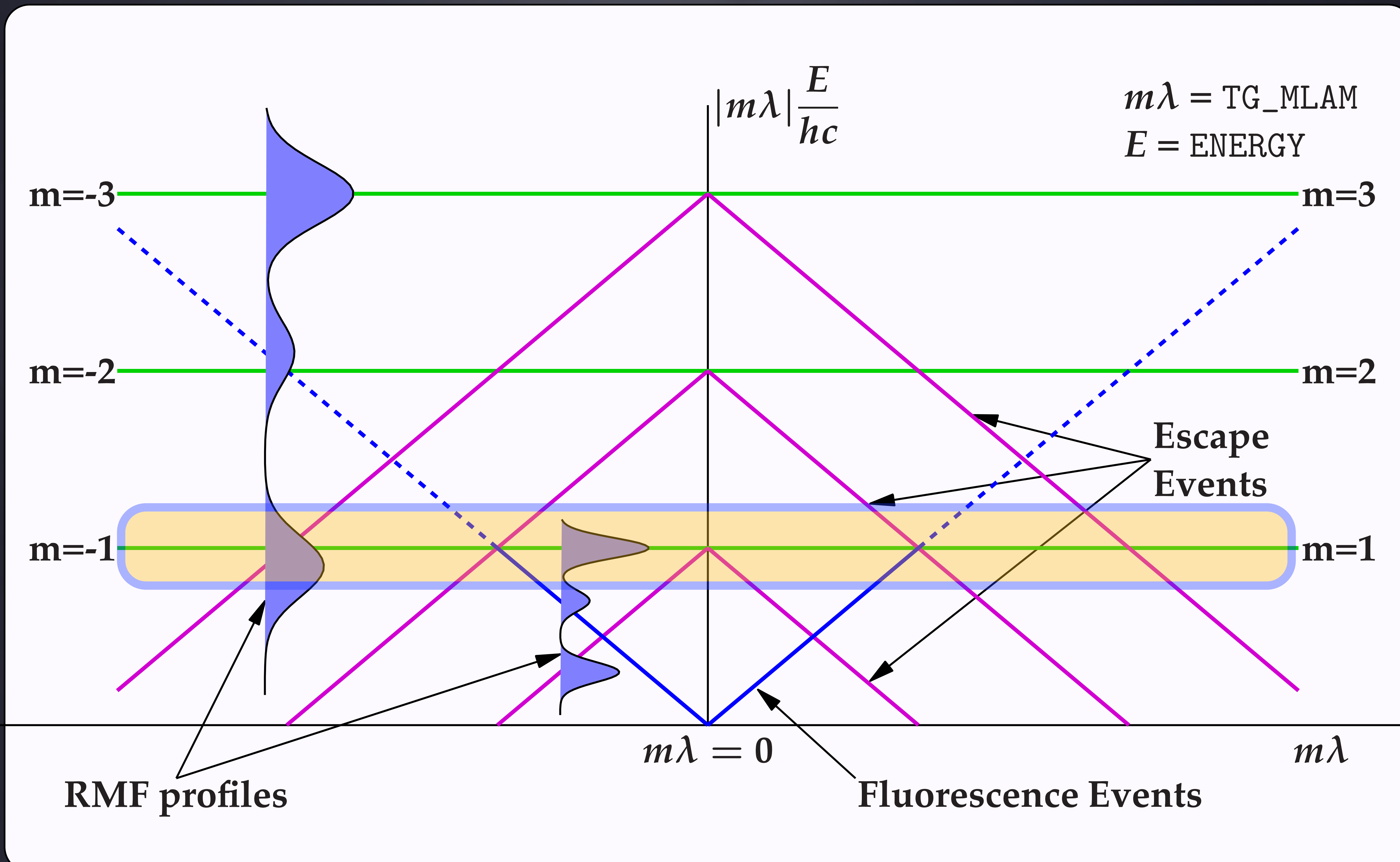
Hierarchy: 0th Order > MEG > HEG



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

These are the ***Potential*** *Gratings Events*

“Resolving” Events



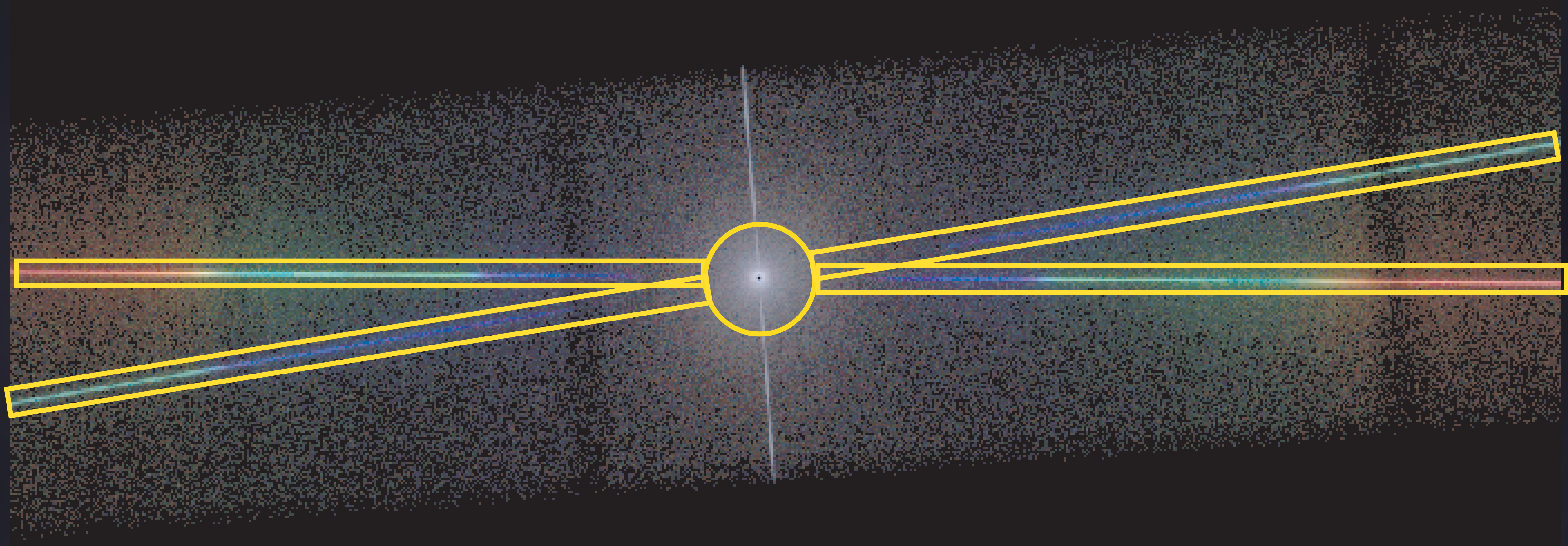
Fraction of RMF is the “Order Sorting Integrated Probability” (OSIP) and is Incorporated into ARF

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!**

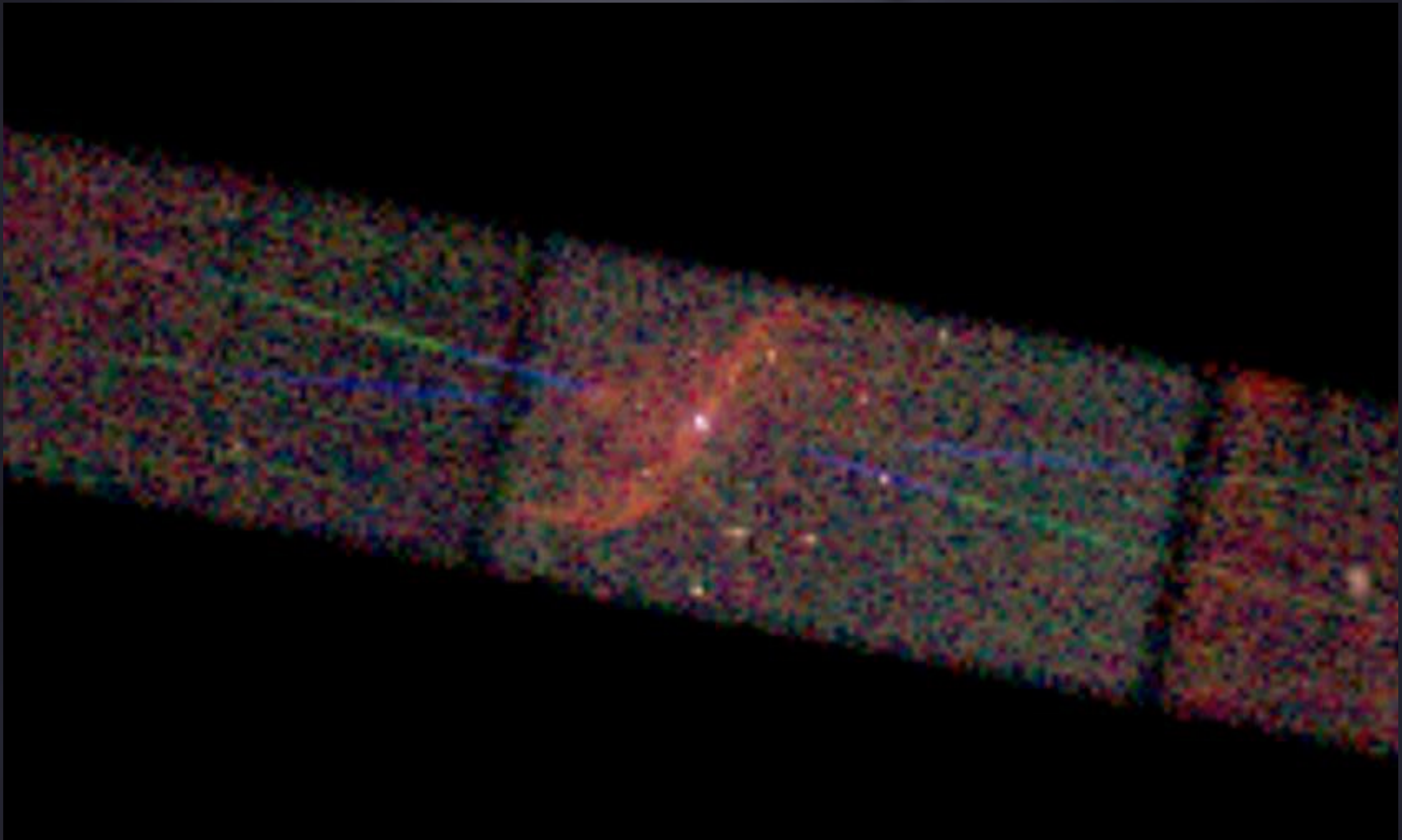
tg_extract_events

Isolated Source, Defaults are Fine

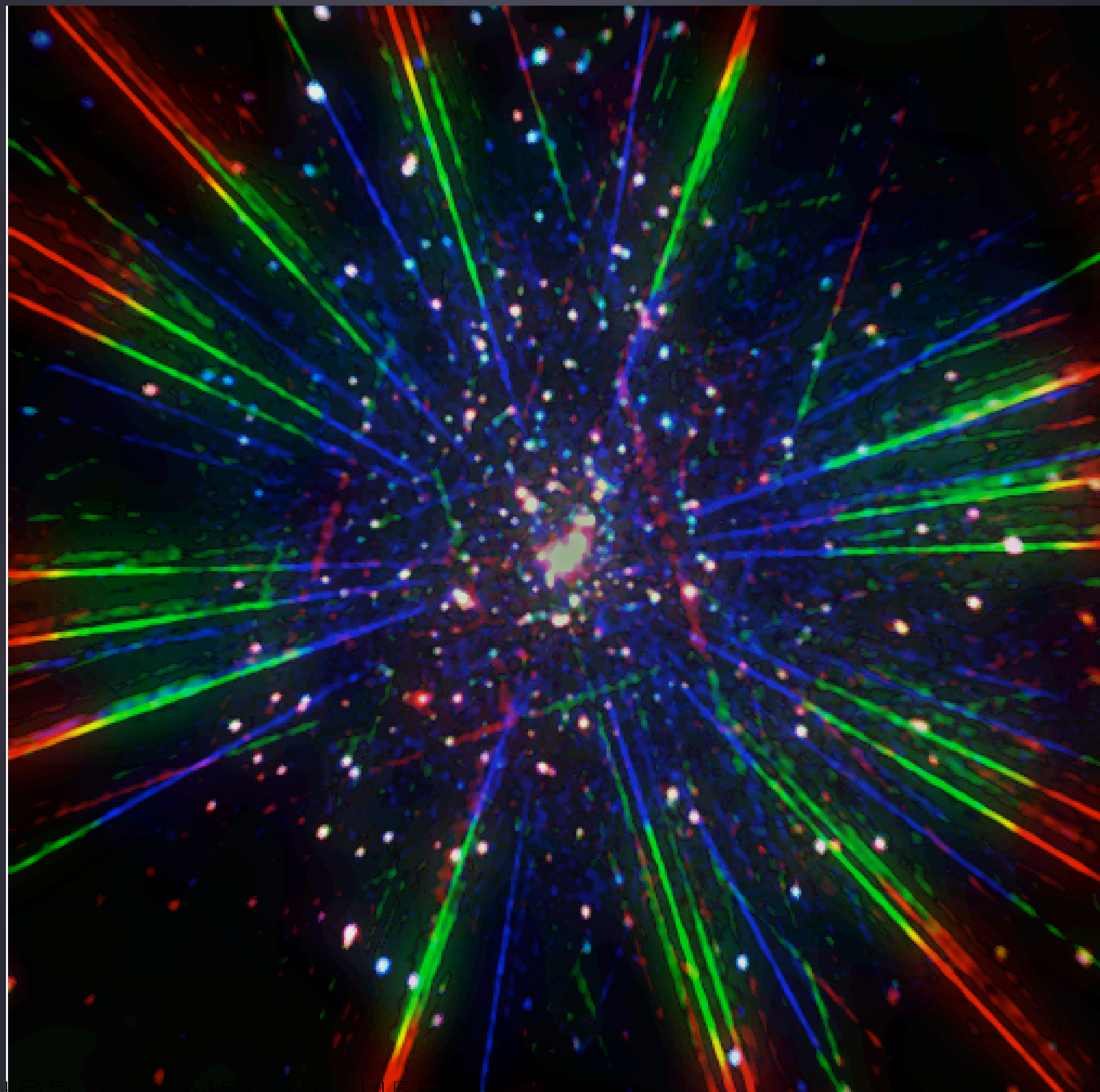


Fraction of LSF is Incorporated in RMF

Narrower is Sometimes Necessary



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*
- *Standard tool: mktgresp*

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 in bright sources*

Complex

- *Pileup – Less likely to happen, but it can ...*
  - *pile-up model for ISIS/Sherpa (XSPEC?)*
- *Continuous Clocking Mode (CC-mode)*
- *Sources with spatial structure*
- *Sources with spatial structure and CC-mode*

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”*

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*

An application: Accretion in young stars

- How do stars and planets form?
- How are stars and their disks connected?
- Measure accretion shock in grating spectra.

- Intro here, then I'll switch to a notebook with code.
- I'm currently working on this research project, so I don't have final answers.

Orion Nebula Cloud

Stars from in dense clouds of gas and dust.

Image: NASA, ESA, Hubble Space Telescope Orion Treasury Project Team, Massimo Robberto (STScI, ESA)

Phases of star formation

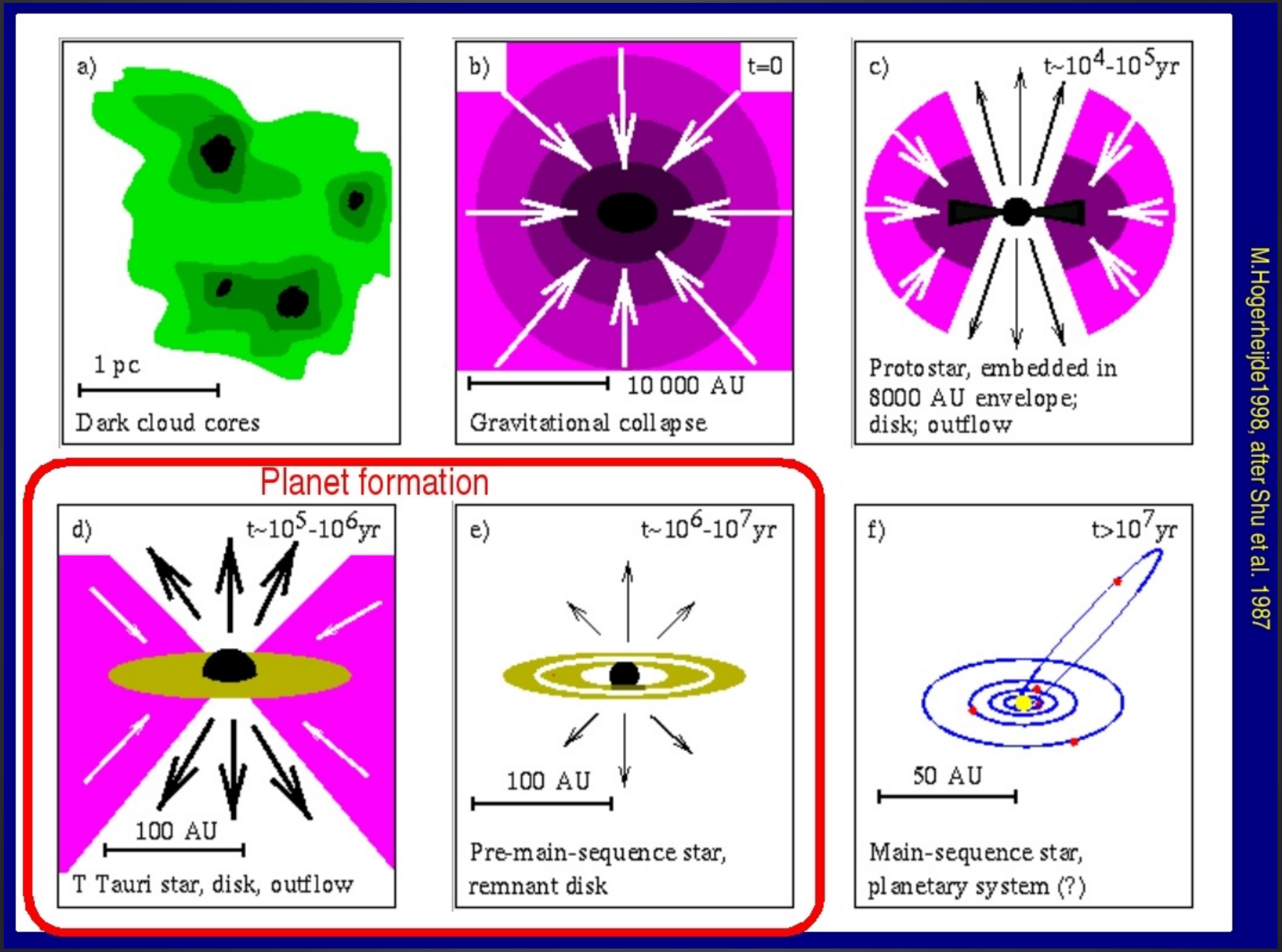
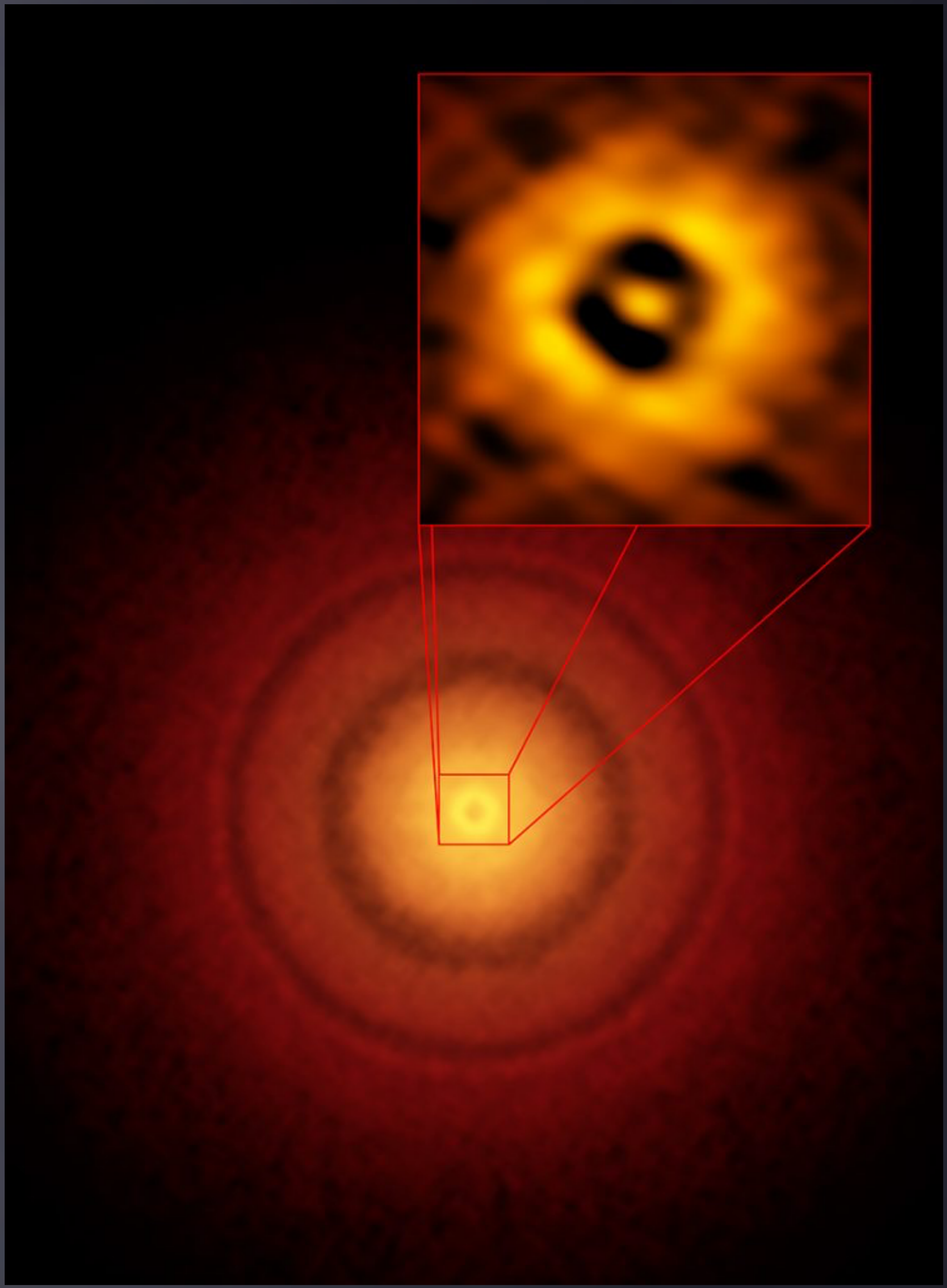


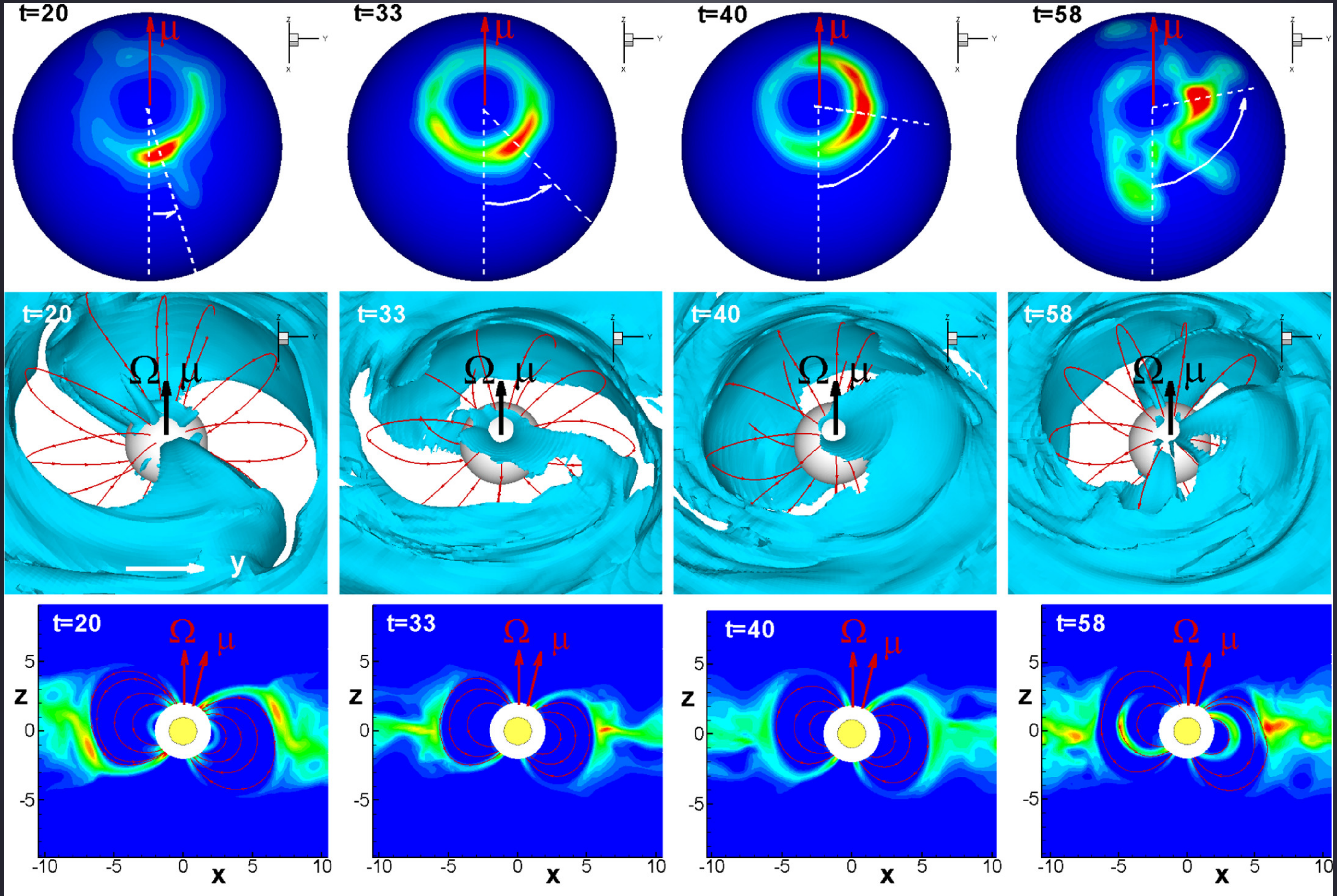
Image of a disk

- Young stars are surrounded by gas and dust disks.
- Planets from in these disks.
- Where does the mass go?

Credit: S. Andrews (Harvard-Smithsonian CfA),
ALMA (ESO/NAOJ/NRAO)

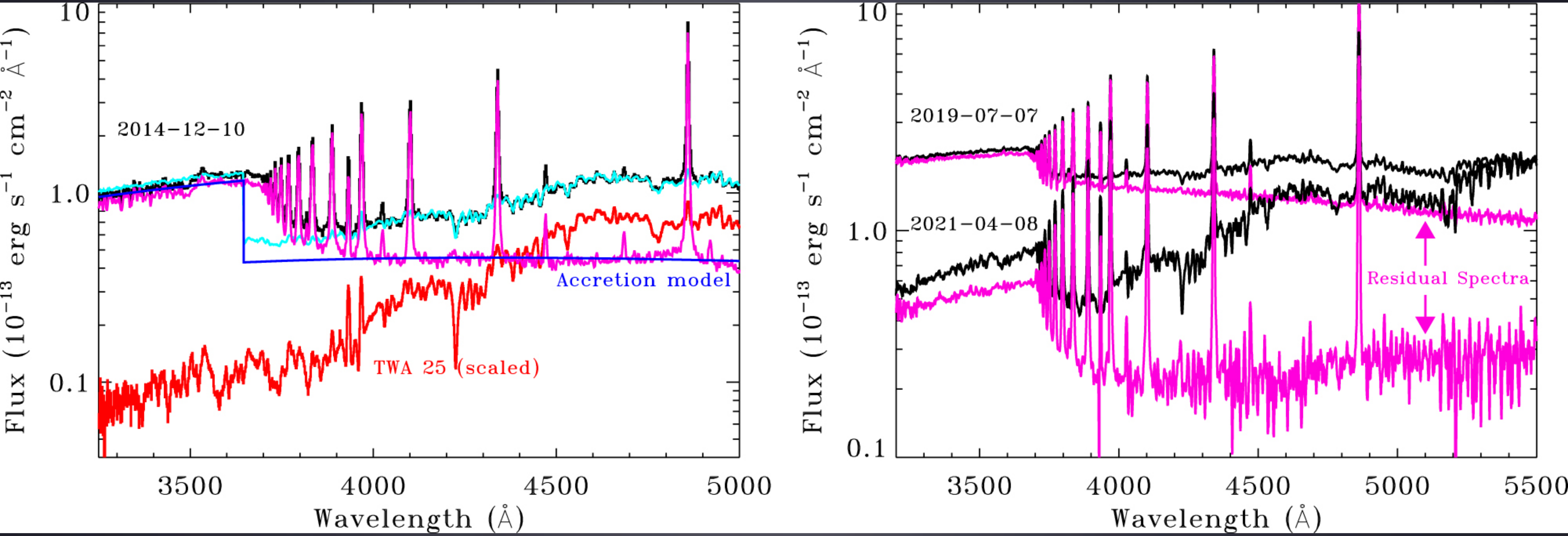


Simulations of accretion streams



Singh et al. (2024), ApJ

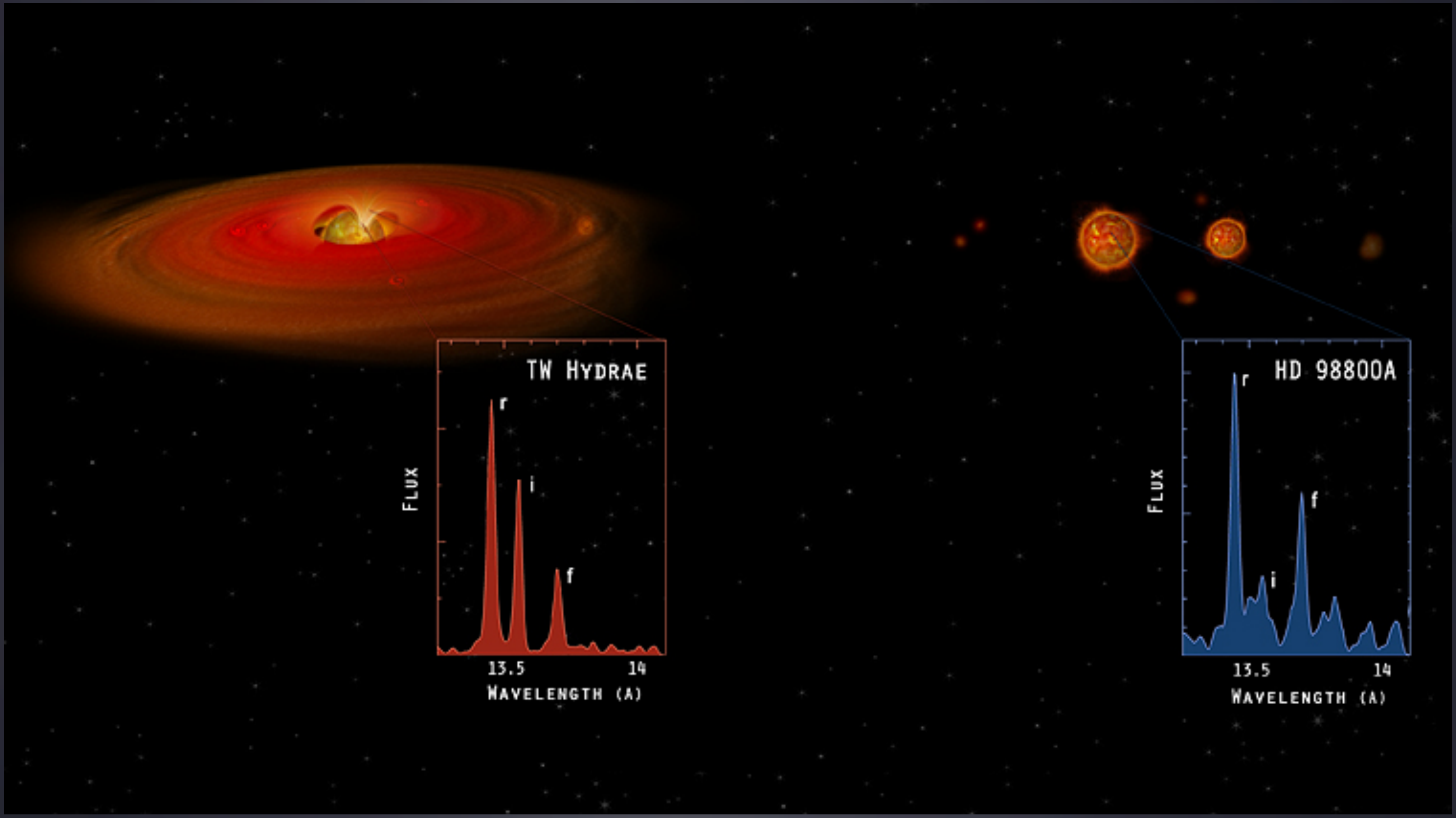
Spectral signatures of accretion



- Spectral template + continuum (veiling) + lines
- Energy conservation -> mass accretion rate

Herceg et al (2023), ApJ

Accretion changes the X-ray spectrum, too.



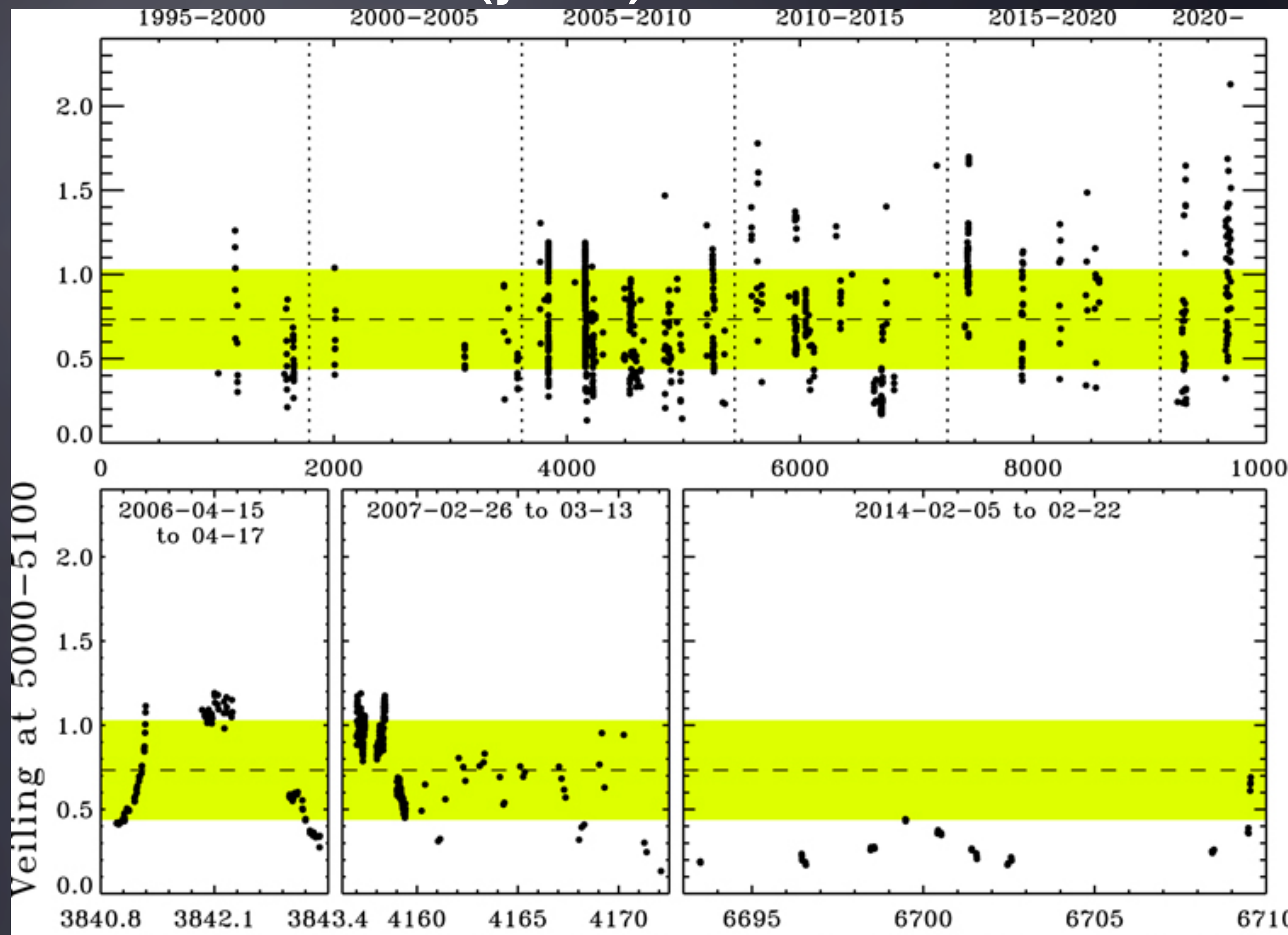
Credit: Spectra: NASA/CXC/RIT/J.Kastner et al.; Illustration: NASA/CXC/M.Weiss

Accretion changes with time

- A lot of fluctuation on short time scale
- But average stable for 25 years

Herceg et al (2023), ApJ

Time (years)



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