

Chandra's PSF: Use it Wisely

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Smithsonian Astrophysical Observatory

2019 Seattle CIAO Workshop

Outline

- 1 All you need to know
- 2 The Hardware
 - Wolter-I Optics
- 3 Focal Plane & Spectral Response
 - Energy Response
 - Focal Surface
- 4 PSF
 - 1D
 - 2D
 - Stability
- 5 Detector Effects
 - ACIS
 - HRC-I
- 6 Analysis Approaches
- 7 Resources

All you need to know (almost. . .)

- The best Astrophysical X-ray mirrors ever made
- 1'' resolution

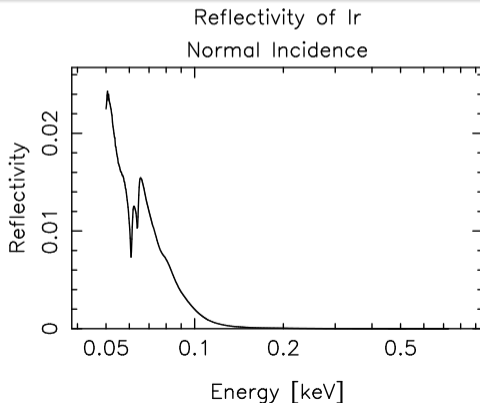
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Grazing vs. Normal Incidence Optics

X-ray optics are unlike most visible optics systems –

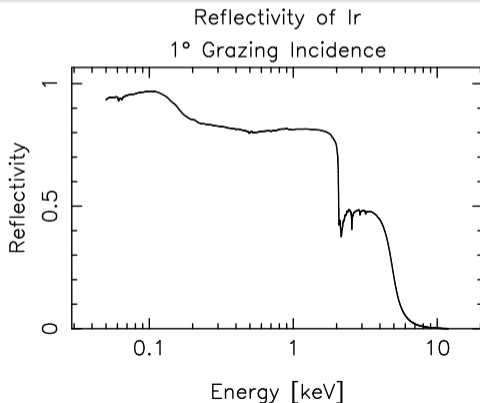
they are *grazing* incidence, not *normal* incidence



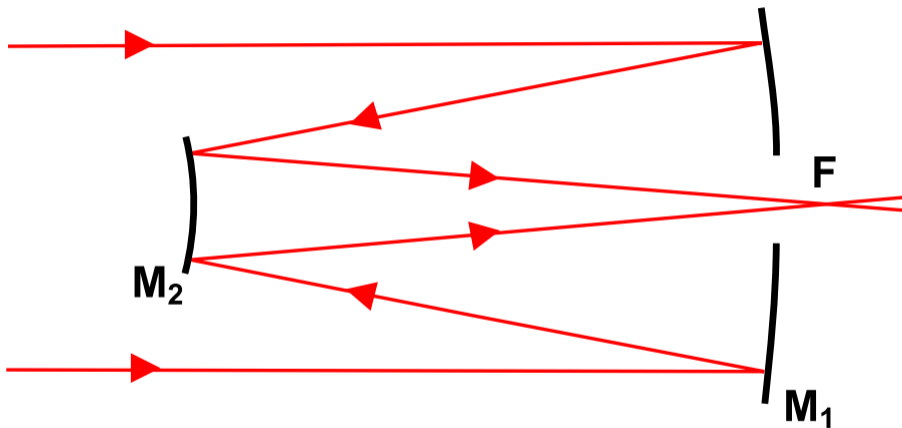
Grazing vs. Normal Incidence Optics

X-ray optics are unlike most visible optics systems –

they are *grazing* incidence, not *normal* incidence

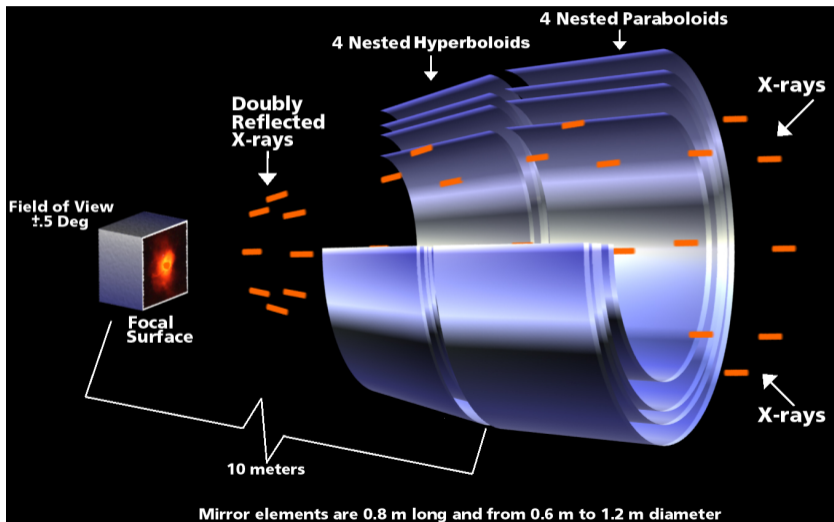


Normal Incidence

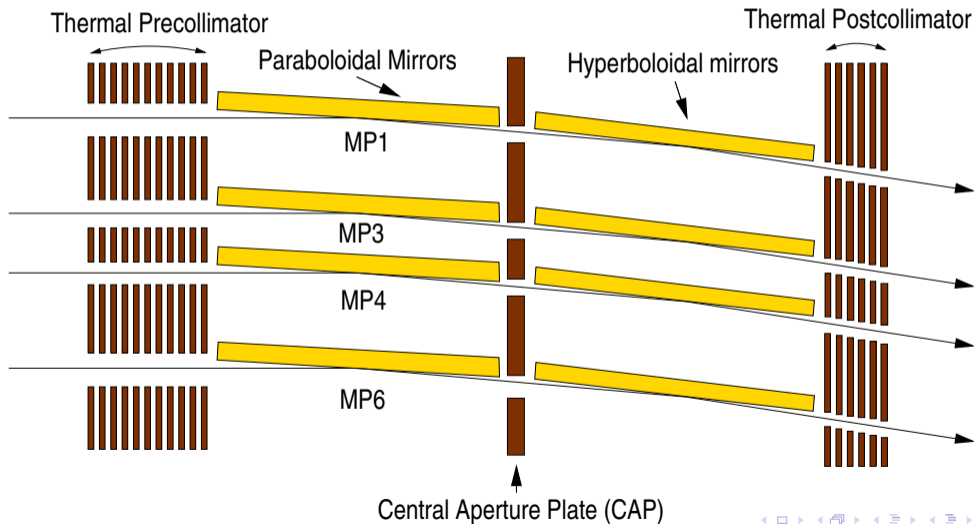


Ritchey-Chrétien

Grazing Incidence (Wolter-I)



Grazing Incidence, A schematic view



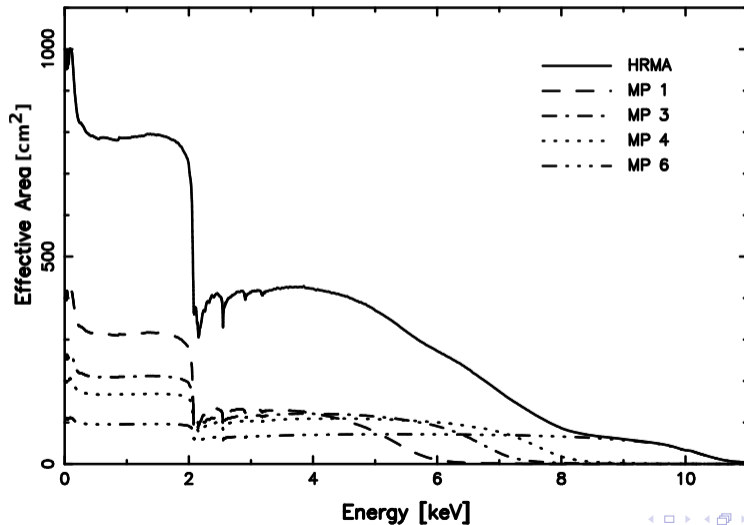
Peculiarities of Wolter-I Optics

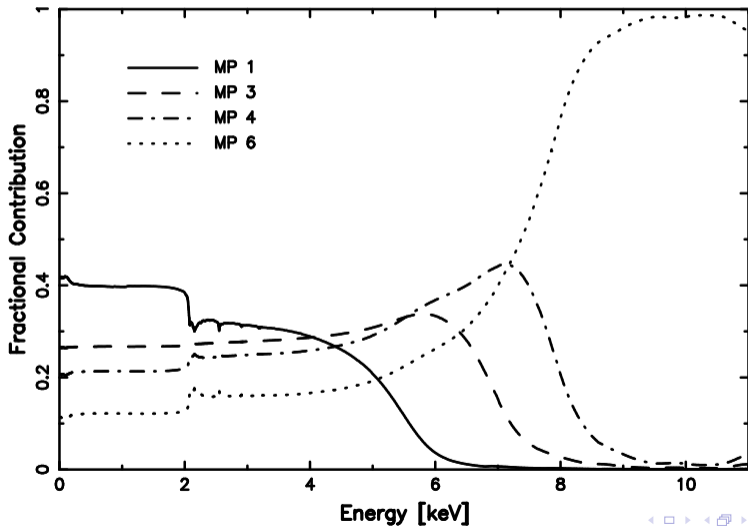
- The projected geometric area is small
- Optics are nested to increase the projected geometric area
- Grazing angles are different for each nested shell, so the energy response differs
- Focal *surface* is not a *plane*, but curved
- Each nested shell has a differently shaped focal surface.
- Good on-axis PSF, degrading off-axis

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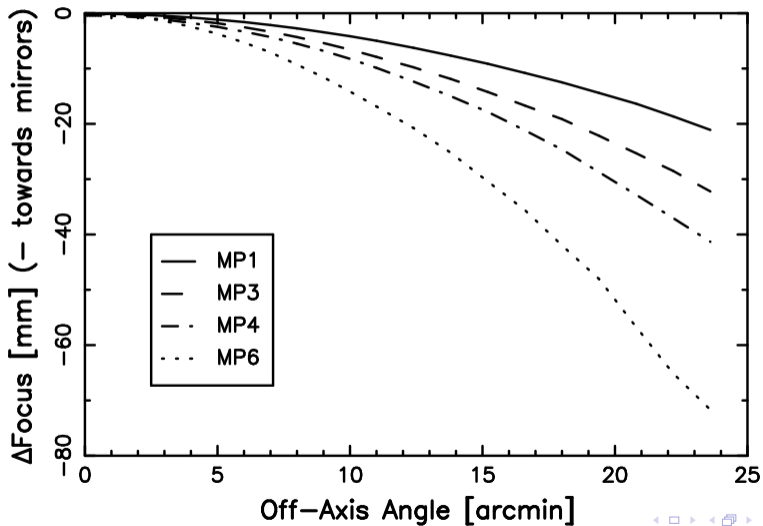
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Total Effective Area (A_{eff})

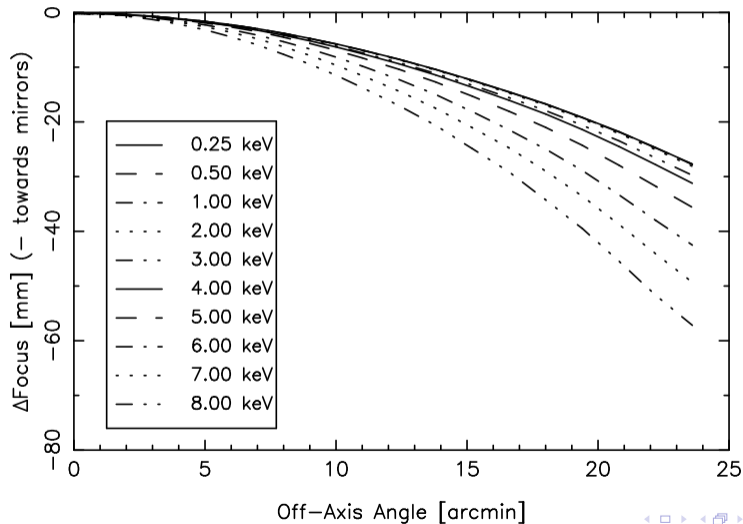


Fractional contributions of Shells to A_{eff} 

Geometric Focal Surfaces



Combined Energy Dependent Focal Surfaces

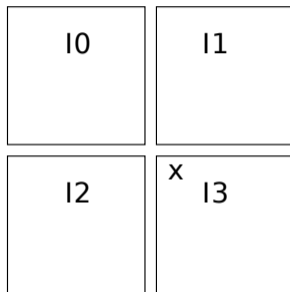


Focal Surface & Detectors

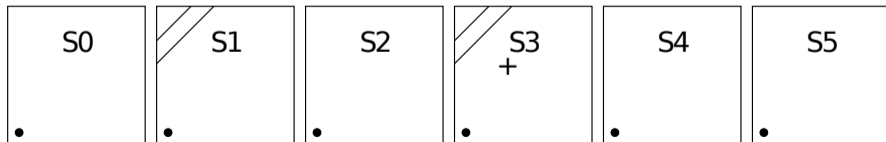
How do the imaging detectors interact with the focal surface?

- ... The ACIS-I chips are tilted to approximate the low-energy focal surface
- ... The ACIS-S array is curved to match the gratings' Rowland surface.
 - ... The S3 chip is fairly tangent to the focal surface on-axis
- ... HRC-I is tangent to the focal surface on-axis

ACIS Layout

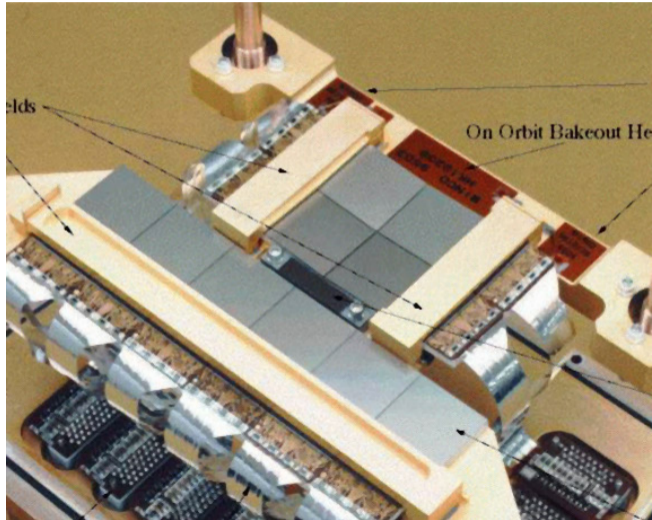


} ACIS-I

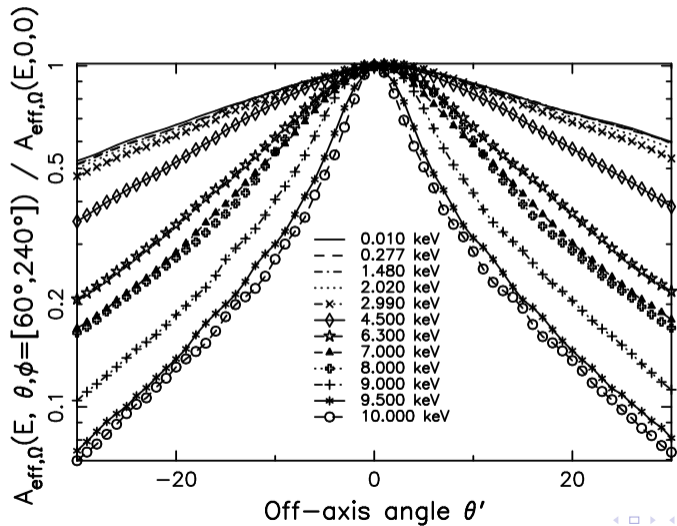


} ACIS-S

ACIS Layout



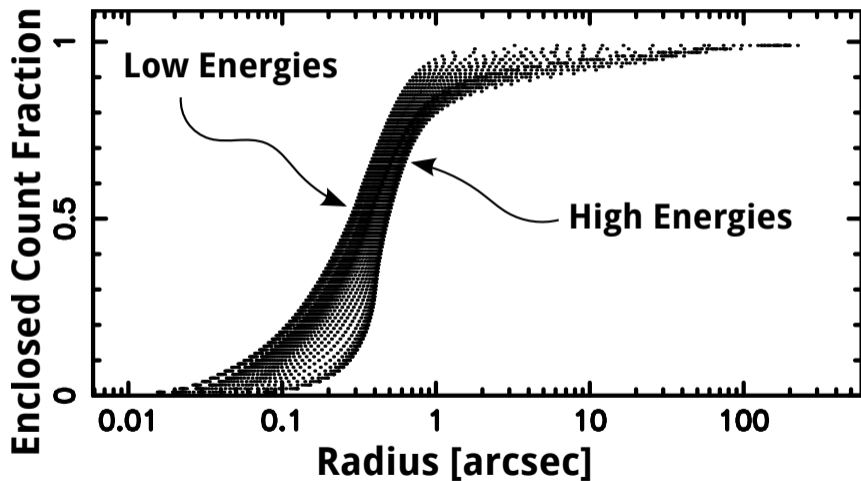
Vignetting



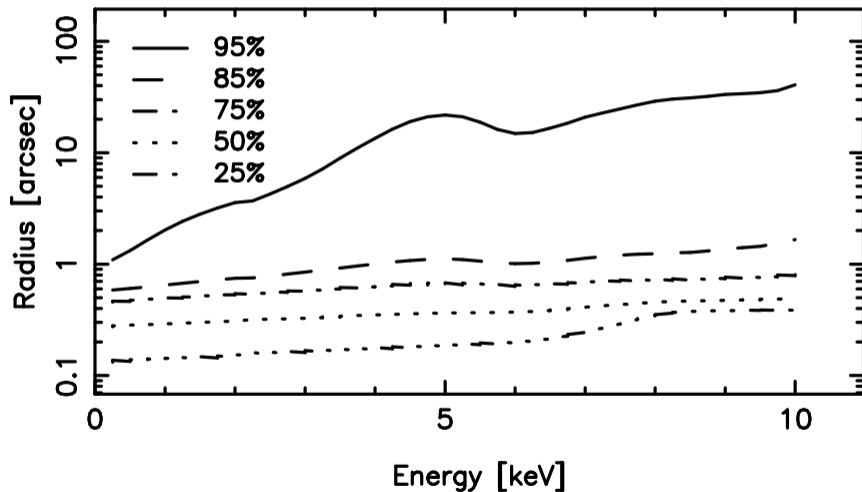
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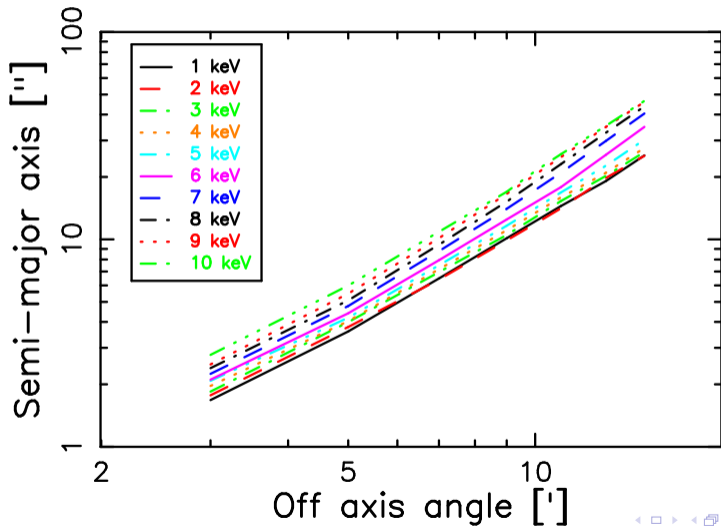
On-Axis Enclosed Counts Fraction (ECF)



On-Axis Enclosed Counts Fraction (ECF)

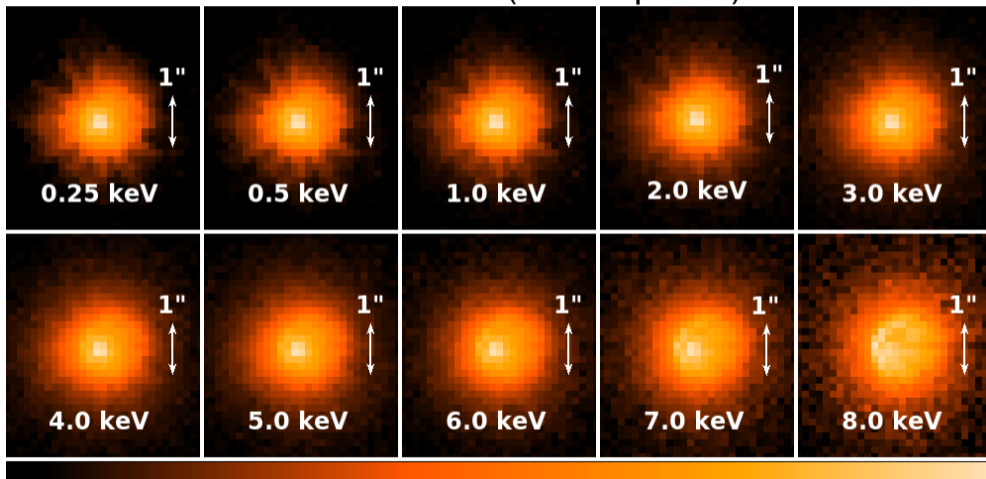


Off-Axis - 85% ECF

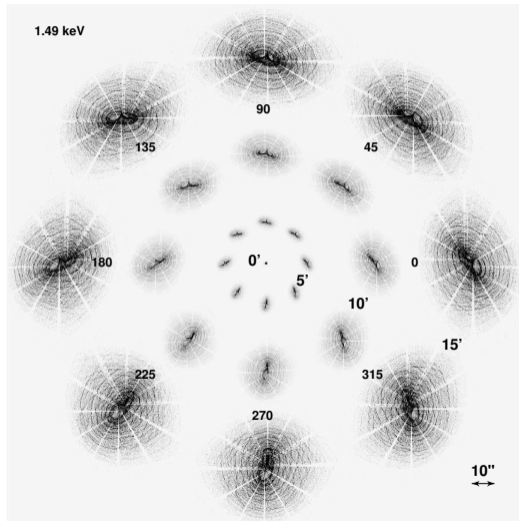


On-Axis

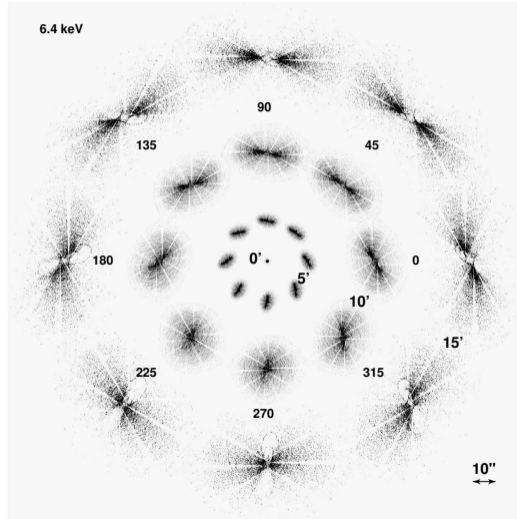
Ideal Detector (HRC-I pixels)



Off-Axis: 1.49 keV

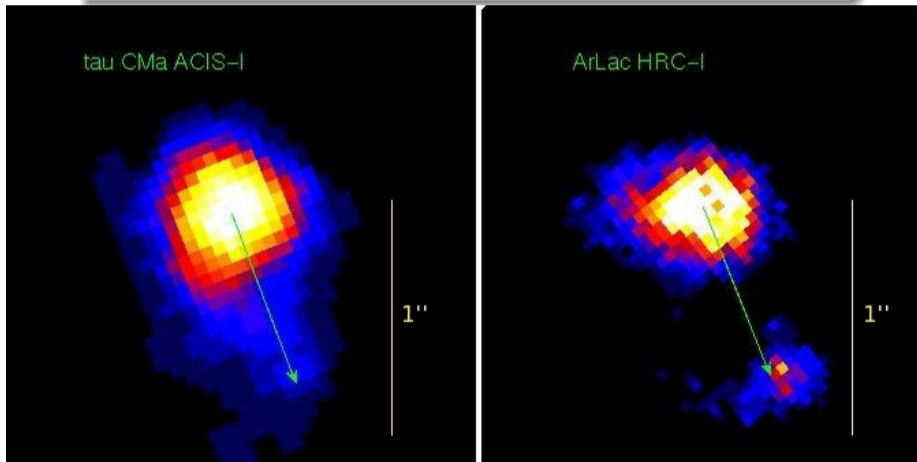


Off-Axis: 6.4 keV



Artifact

There is an anomalous “blob” $\sim 0.6''$ from the PSF Core.

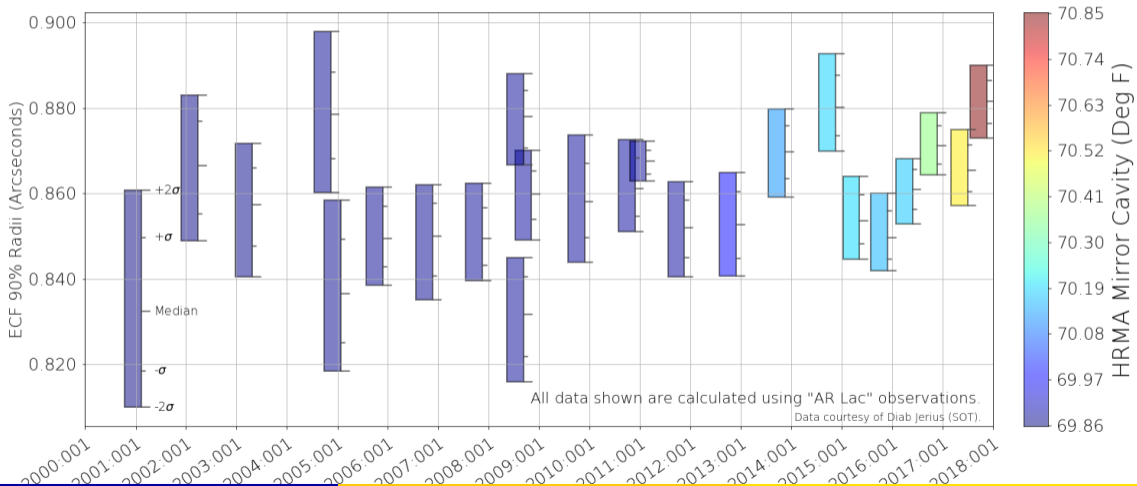


PSF Stability

- *Chandra* is aging, many of its subsystems have changed over time.
- The PSF has in general been quite stable.
- The PSF “artifact” *has* changed over time, but the recommended analysis removes it from the data.

PSF Size: 90% Enclosed Count Fraction Radius

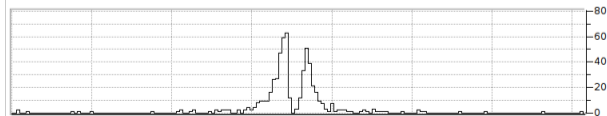
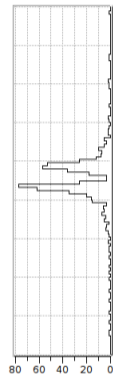
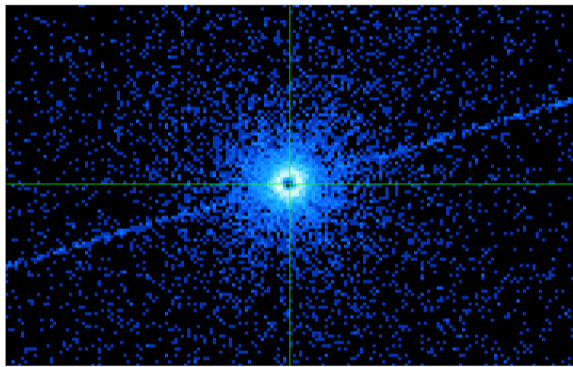
Impact of Time and Temperature on ECF 90% Radii



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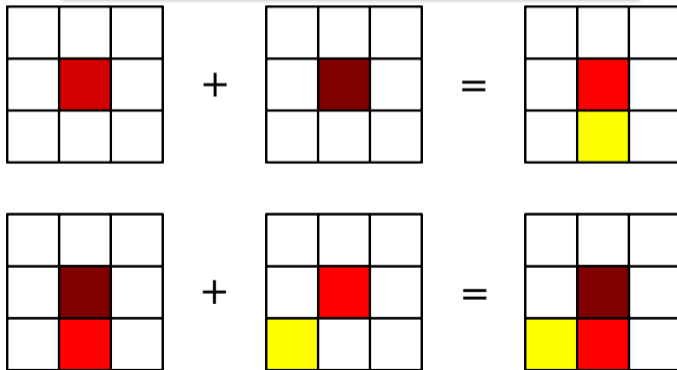
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Pileup (Mrk 421 OBSID 1714)



Pileup: Definition

Pileup occurs when 2 or more photons arrive in a 3×3 detect island in a single ACIS frame.



Pileup: Effects

Pileup results in:

- Spectral distortion
 - ... 2 photons \rightarrow 1 event with higher energy
- Grade distortion
 - ... merging charge clouds morph “good” events \rightarrow “bad” ones
 - ... loss of event

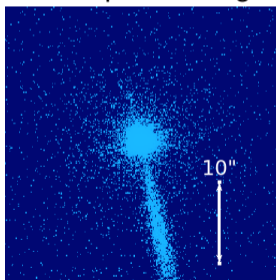
Pileup affects the PSF via:

- Loss of events in dense regions of PSF \rightarrow craters
- grade morphing, which confuses
Energy-Dependent Sub-pixel Event Reconstruction (EDSER)

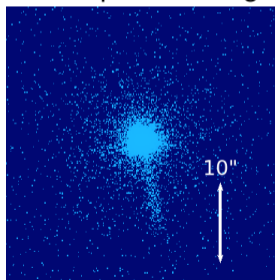
HRC-I: Ghosts

HRC-I artifacts (ghost “jets”) are *usually* filtered out of `evt2` files, but residues may remain for bright sources

evt1: pre-filtering



evt2: post-filtering

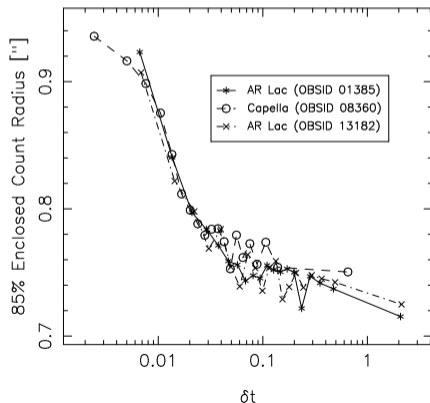


AR Lac (OBSID 13182)

HRC-I: Bright source PSF broadening

Some events have an additional blur component if they:

- occur less than ≈ 50 msec after their preceding event
- are physically proximate to the preceding event



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Overview

The *Chandra* PSF is

- ... marvelous
- ... complex
- ... marvelously complex

- It varies with energy and source off-axis and azimuthal position
- The detectors don't necessarily follow the focal surface
- The detectors aren't perfect
- The optics aren't perfect

Skepticism

To best use it:

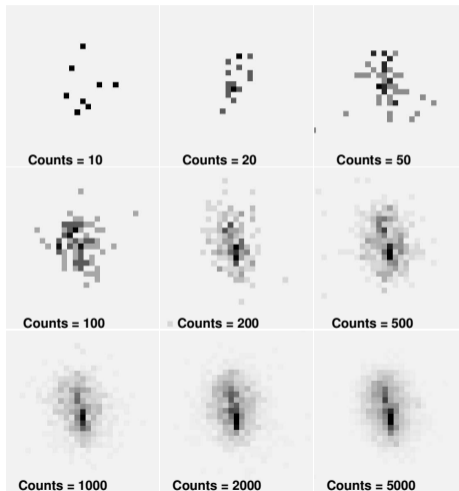
Be Skeptical

- Understand the vagaries of the PSF
- Understand how the detectors interact with it
- Be sure that structure is real.

Simulate, Simulate, Simulate

Example: Low-count confusion

Jet?
Multiple Sources?
No! Off-axis point source.



Simulation Tools

- MARX
 - ... a first-order model of the mirrors
 - ... models of the HRC and ACIS detectors
 - ... models of the HETG and LETG gratings
 - ... point and extended sources
 - ... can use as-observed telescope aspect
 - ... can use `SIMPUT MARX >= 5.3.1`
- SAOTrace
 - ... a detailed model of the mirrors
 - ... point and extended sources
 - ... can use as-observed telescope aspect

It relies on MARX or the CIAO `psf_project_ray` tool to model detectors.

Simulation Tools, con't

- ChaRT
 - ... web front-end to SAOTrace
 - ... can use as-observed telescope aspect
 - ... point sources only

Quantitative Analysis Techniques

- Monte-Carlo simulations of observations
 - ... sensitivity analysis of source parameters
 - ... explore systematics in system models
- 1D and 2D Source fits
 - ... CIAO provides `sherpa` fitting package

But...

- The models are not perfect
- Understand the limitations of the Optic and Detector models

How good are the models?

SAOTrace

- Backed by ground calibration
- 1D model good to $\sim 10''$
- Still working on PSF wings (beyond $\sim 10''$)
- 2D model qualitatively correct
- A_{eff} & Vignetting correct

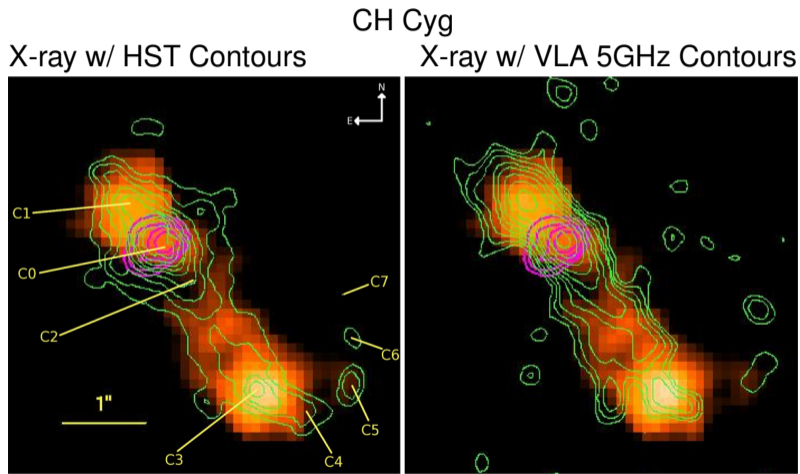
MARX Detectors

- Semi-empirical
- Not physics-based

Qualitative Analysis Techniques

- ACIS Sub-pixel Event Reconstruction (EDSER)
 - uses ACIS event grades to improve image resolution
 - on by default in standard products
 - not calibrated
 - use to identify interesting structure; use non-EDSER data for quantitative measurements
- Deconvolution
 - CIAO provides Lucy-Richardson via `arestore`.
 - use SAOTrace (or ChaRT) simulations
 - does not preserve flux; use to identify interesting structure; use non-EDSER data for quantitative measurements
 - Not everything you see is real.
- Adaptive Smoothing
 - CIAO provides `csmooth`, `dmimgadapt`.
 - does not preserve flux; use to identify interesting structure; use non-EDSER data for quantitative measurements
 - Not everything you see is real.

What's Possible



Karovska *et al.*, ApJ Letters, 710 132, 2010

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Resources

- PSF Central
http://cxc.harvard.edu/ciao/PSFs/psf_central.html
- Calibration web site
<http://cxc.harvard.edu/cal/>
- Calibration Workshop Presentations
<http://cxc.harvard.edu/ccr/>
- CIAO Imaging Threads and Guides
<http://cxc.harvard.edu/ciao/threads/imag.html>
- CXC Help Desk
<http://cxc.harvard.edu/helpdesk/>
- Others have done this before.
Check the literature, especially if you're trying something tricky
 - WebChaser
<http://cda.harvard.edu/chaser/>
 - *Chandra* Data Archive bibliography search
<http://cxc.harvard.edu/cgi-gen/cda/bibliography>