Chandra's PSF: Use it Wisely

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Smithsonian Astrophysical Observatory

2017 Pune CIAO Workshop

Outline

All you need to know (almost. . .)

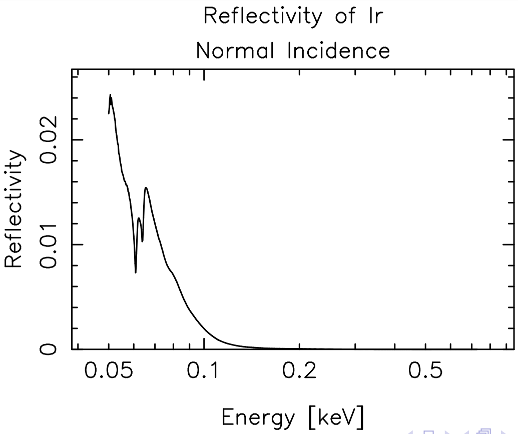
- The best Astrophysical X-ray mirrors ever made
- $1''$ resolution

Outline

Grazing *vs.* Normal Incidence Optics

X-ray optics are unlike most visible optics systems –

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



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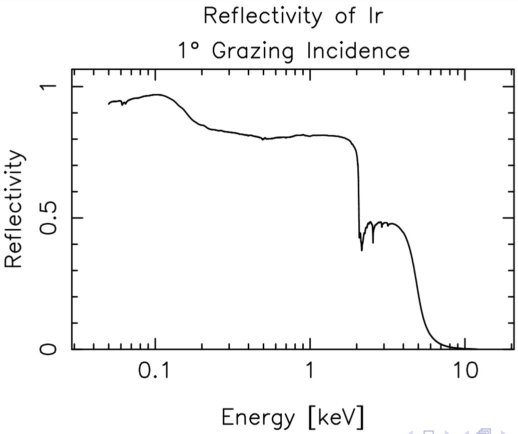
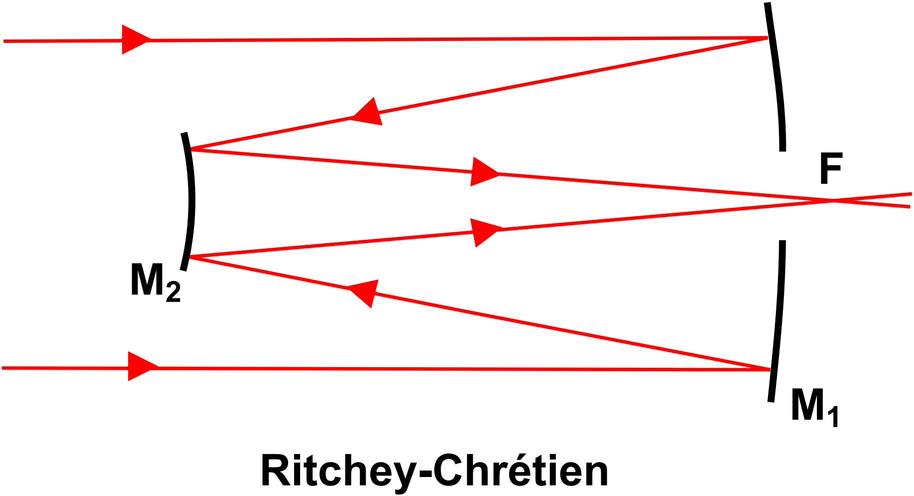
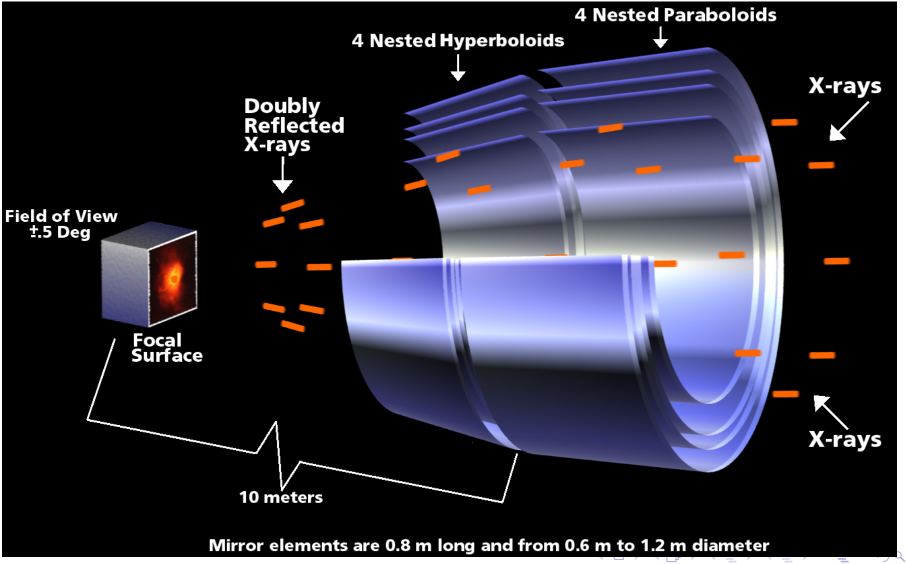


Normal Incidence

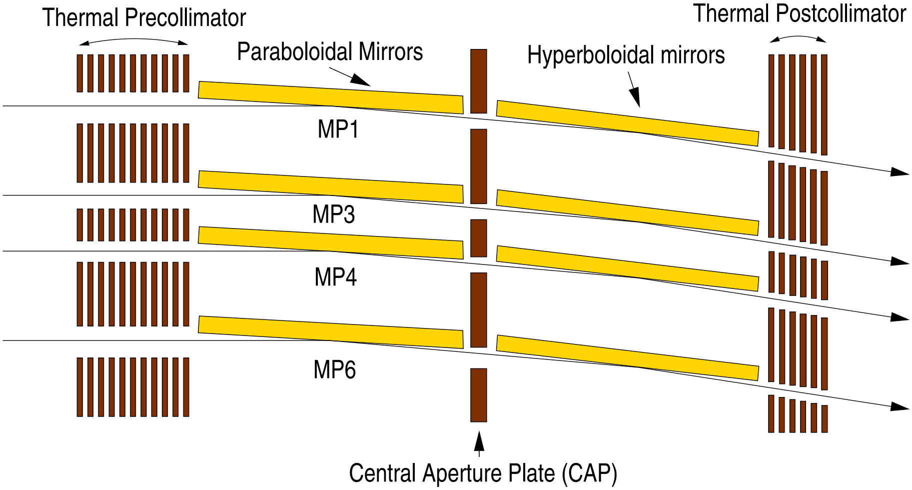


http://commons.wikimedia.org/wiki/File:Diagram_Reflector_RitcheyChretien.svg

Grazing Incidence (Wolter–I)



Grazing Incidence, A schematic view

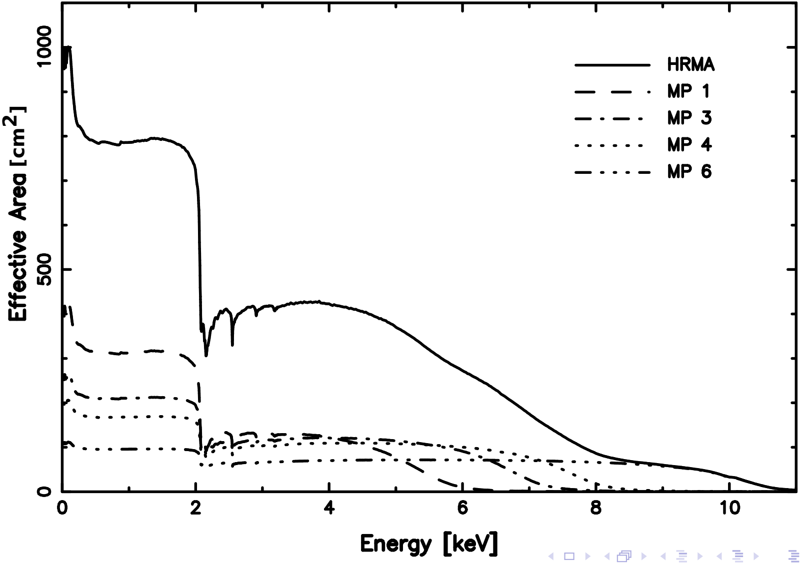


Peculiarities of Wolter–I Optics

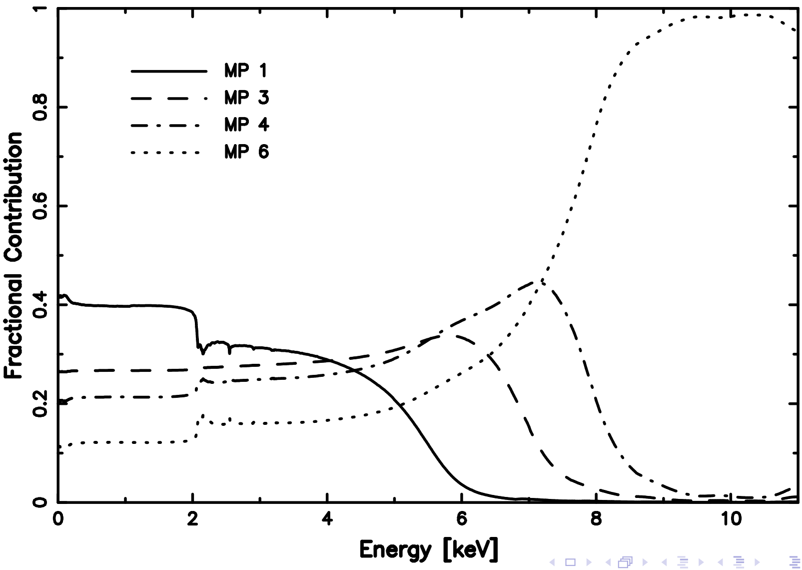
- The projected geometric area is small
- Optics are nested to increase the projected geometric area
- Grazing angles are different for each nested shell, so the energy response differs
- Focal *surface* is not a *plane*, but curved
- Each nested shell has a differently shaped focal surface.
- Good on-axis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

Outline

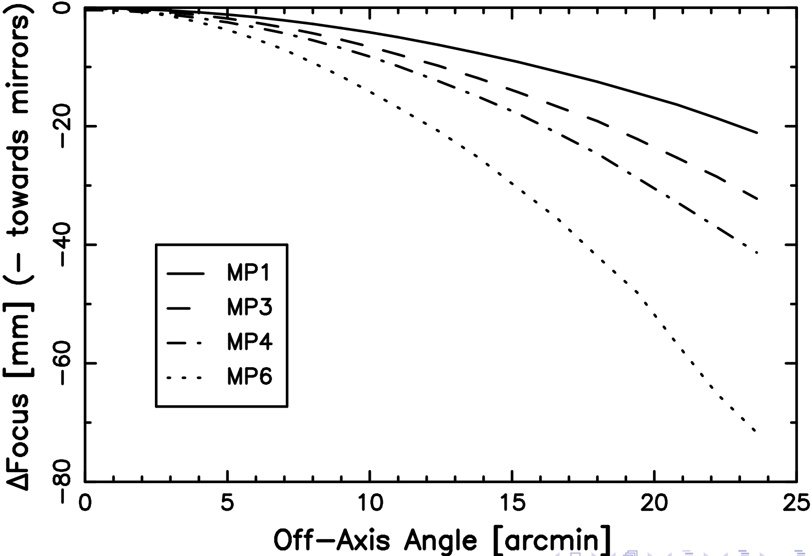
Total Effective Area (A_{eff})



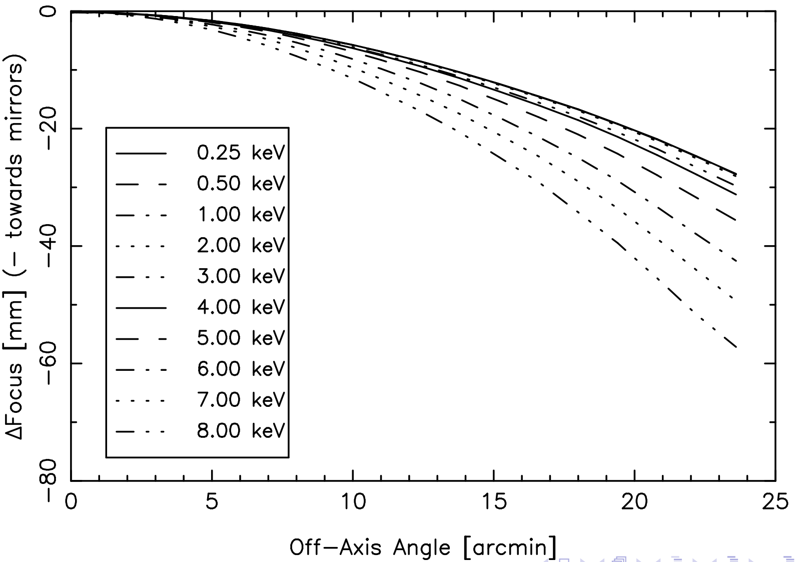
Fractional contributions of Shells to A_{eff}



Geometric Focal Surfaces



Combined Energy Dependent Focal Surfaces

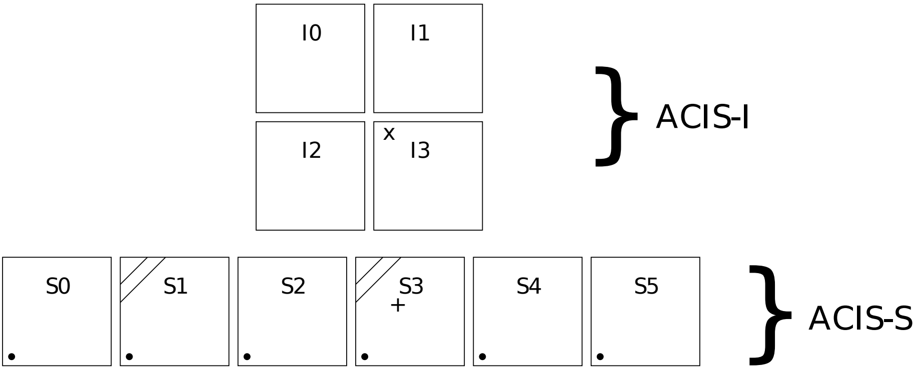


Focal Surface & Detectors

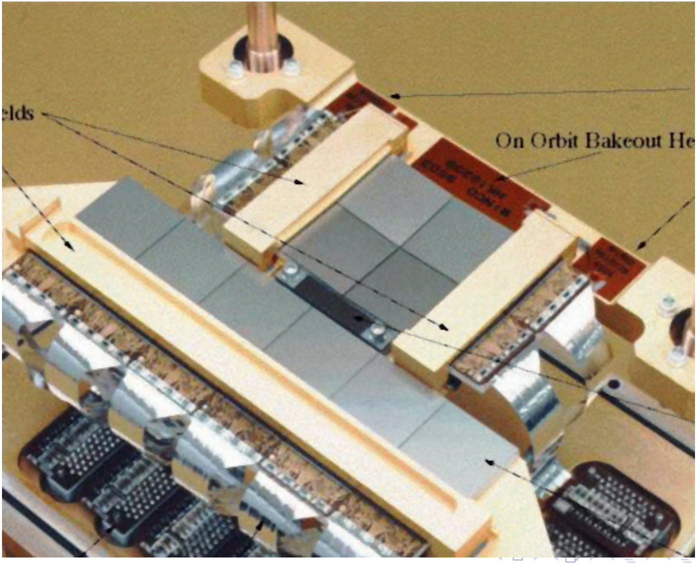
How do the imaging detectors interact with the focal surface?

- ... 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

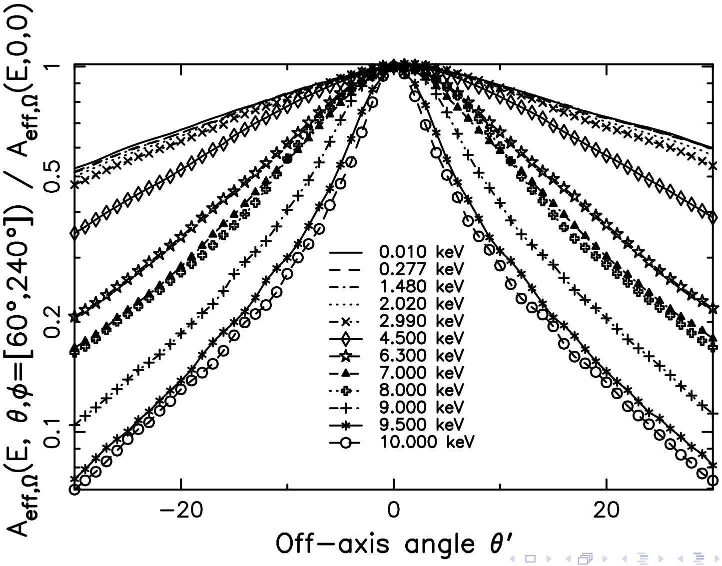
ACIS Layout



ACIS Layout



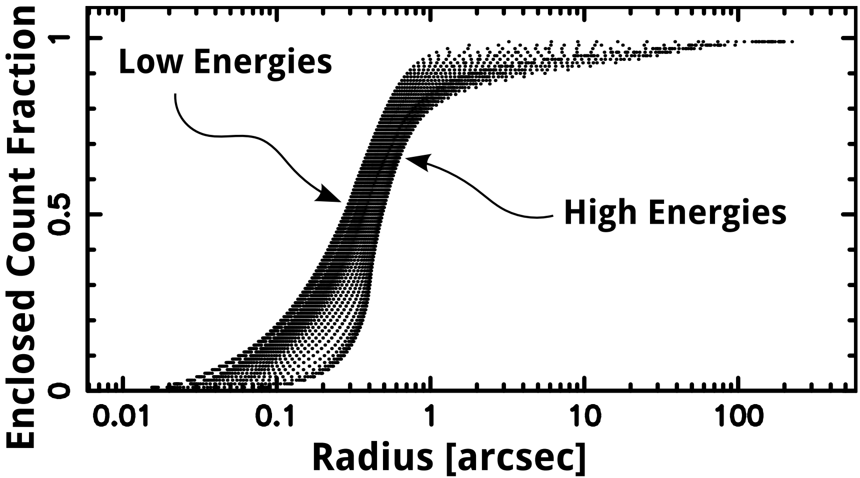
Vignetting



$A_{eff,\Omega}(E, \theta, \phi=[60°,240°]) / A_{eff,\Omega}(E,0,0)$
0.1
0.2
0.5
1
−20
0
20
Off−axis angle θ'
0.010 keV
0.277 keV
1.480 keV
2.020 keV
2.990 keV
4.500 keV
6.300 keV
7.000 keV
8.000 keV
9.000 keV
9.500 keV
10.000 keV

Outline

On-Axis Enclosed Counts Fraction (ECF)



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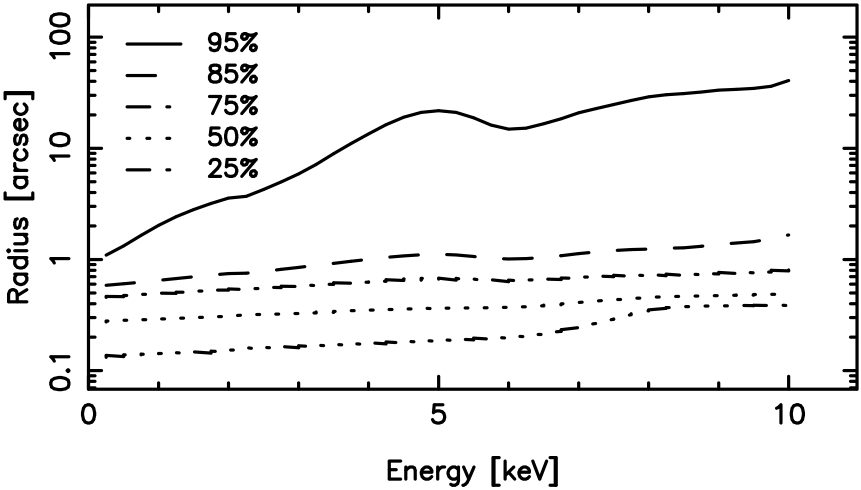
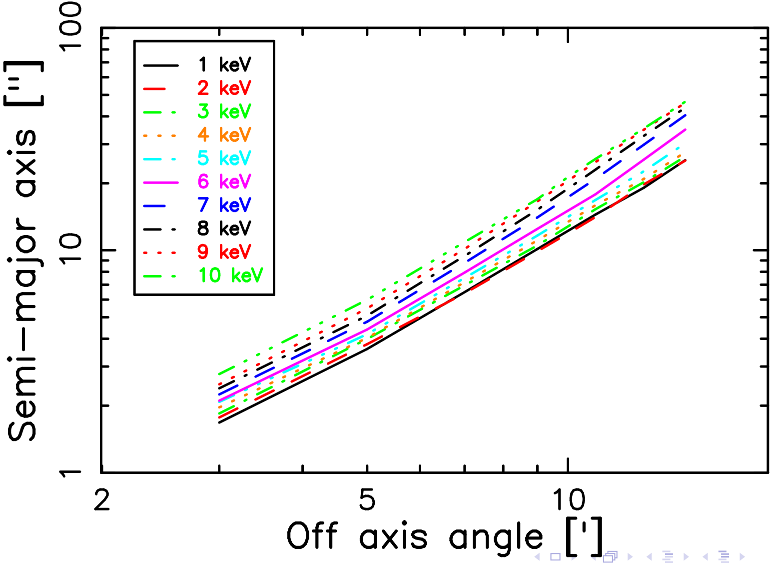
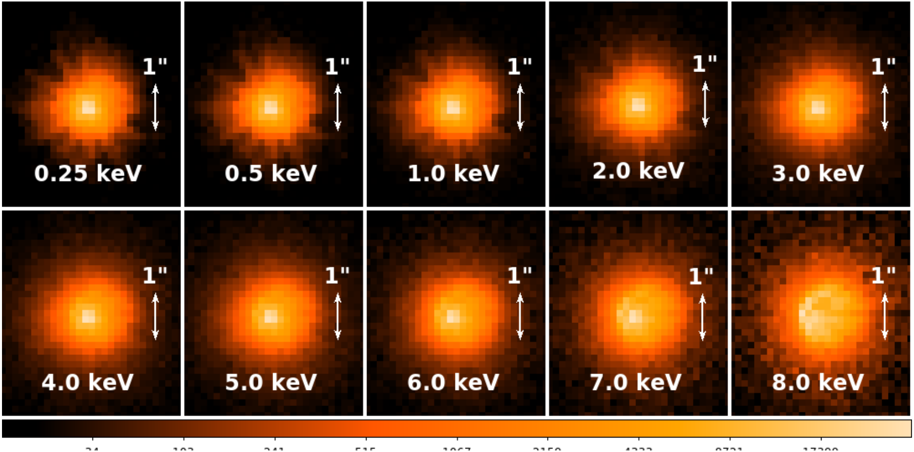


Off-Axis - 85% ECF

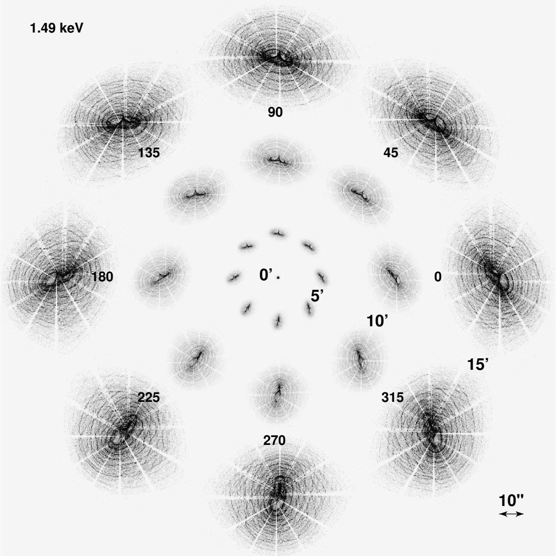


On-Axis

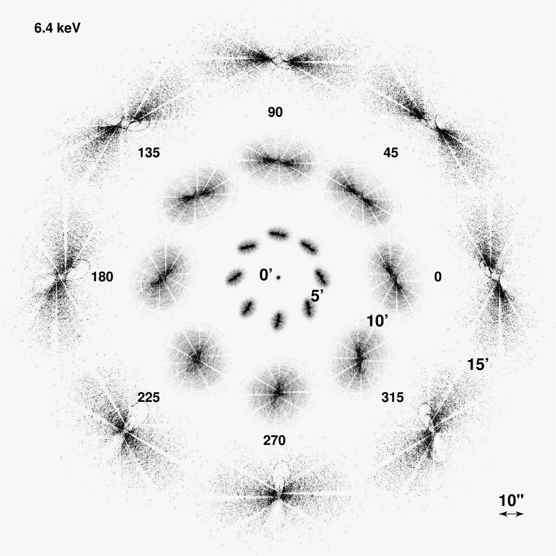
Ideal Detector (HRC-I pixels)



Off-Axis: 1.49 keV

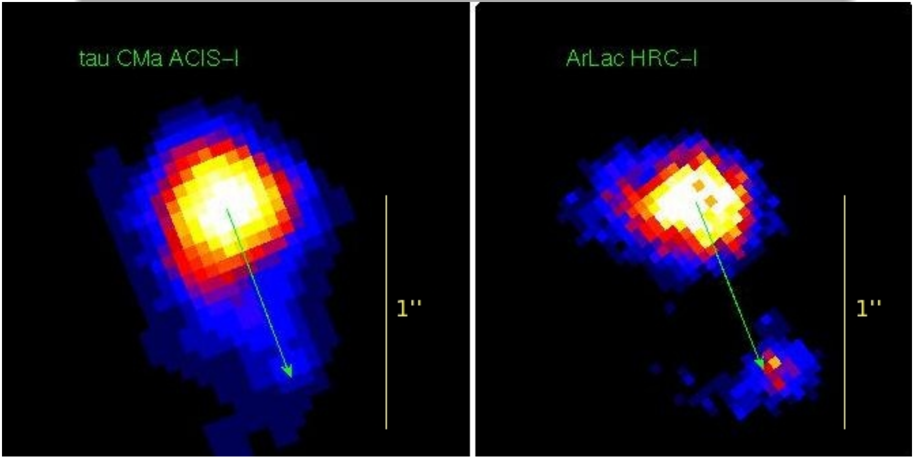


Off-Axis: 6.4 keV



Artifact

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

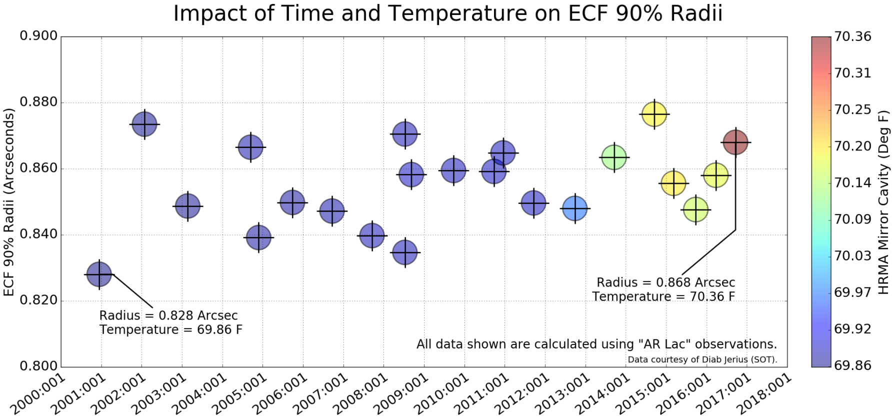


http://cxc.harvard.edu/ciao/caveats/psf_artifact.html

PSF Stability

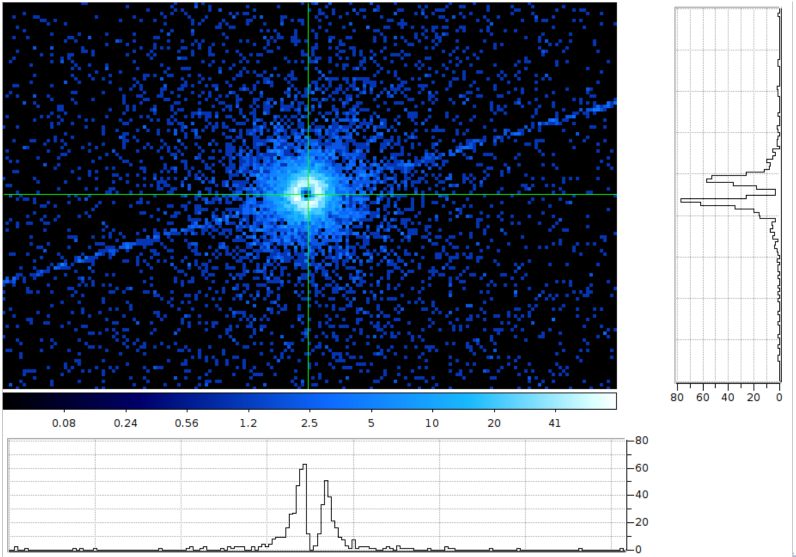
- *Chandra* is aging, many of its subsystems have changed over time.
- The PSF has in general been quite stable.
- The PSF "artifact" *has* changed over time, but the recommended analysis removes it from the data.

PSF Size: 90% Enclosed Count Fraction Radius



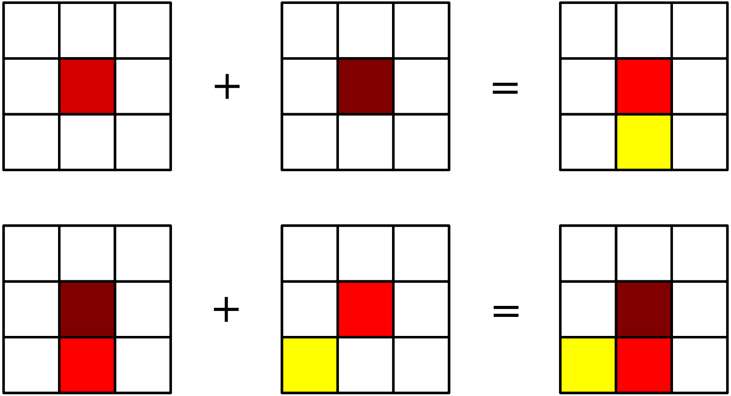
Outline

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 → 1 event with higher energy
- Grade distortion
  ... merging charge clouds morph “good” events → “bad” ones
  ... loss of event

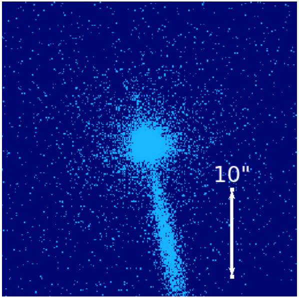
Pileup affects the PSF via:

- Loss of events in dense regions of PSF → craters
- grade morphing, which confuses
  Energy-**D**ependent **S**ub-pixel **E**vent **R**econstruction (EDSER)

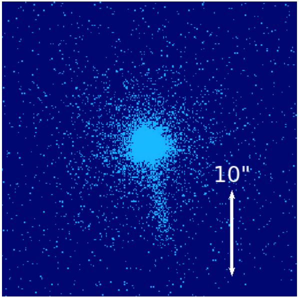
HRC-I: Ghosts

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

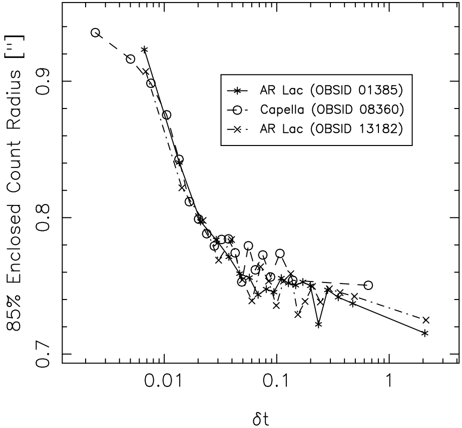


AR Lac (OBSID 13182)

HRC-I: Bright source PSF broadening

Some events have an additional blur component if they:

- occur less than $\approx$ 50 msec after their preceding event
- are physically proximate to the preceding event



Outline

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:

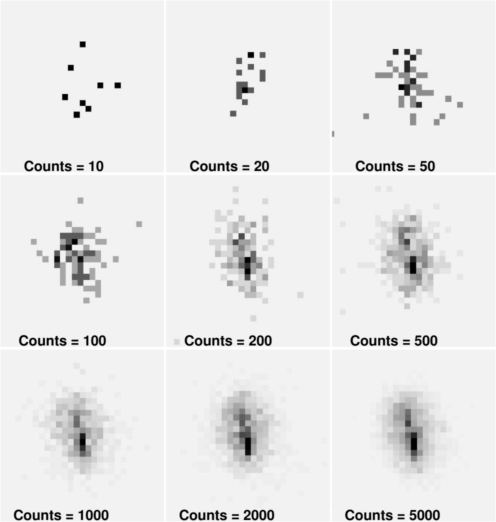
Be Skeptical

- 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-emperical
- Not physics-based

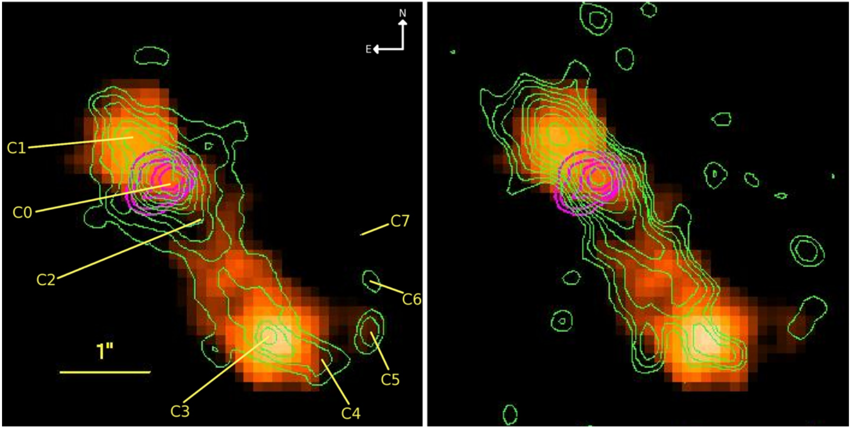
Qualitative Analysis Techniques

- 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

CH Cyg

X-ray w/ HST Contours X-ray w/ VLA 5GHz Contours



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

Outline

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`