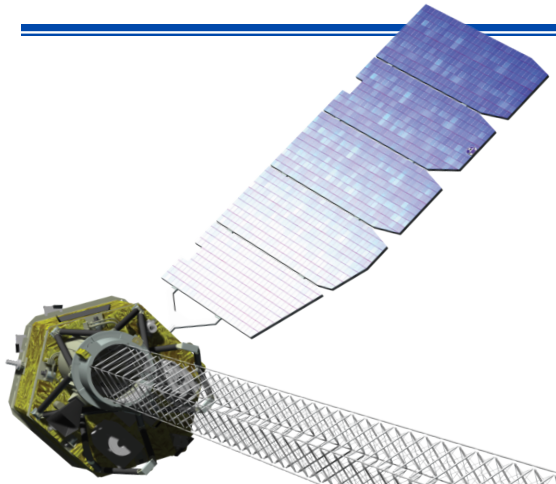
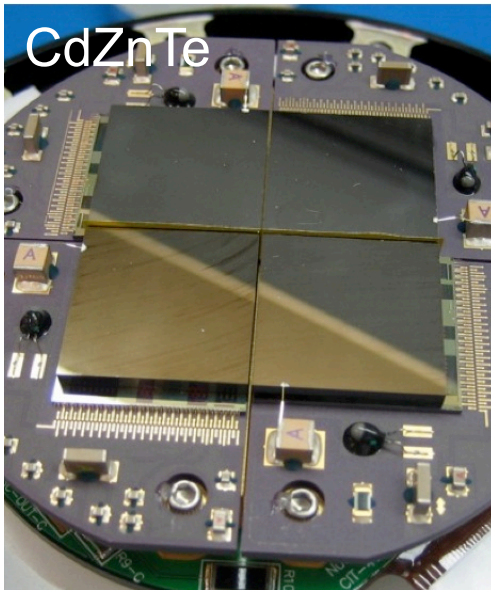
IACHEC meeting 2013
NuSTAR in-flight calibration

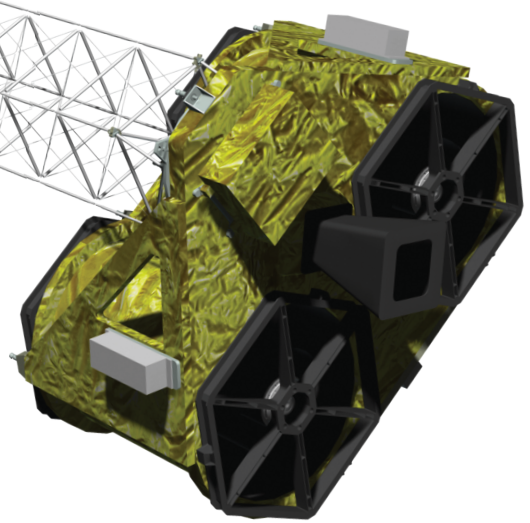
Kristin Kruse Madsen

caltech

NuSTAR





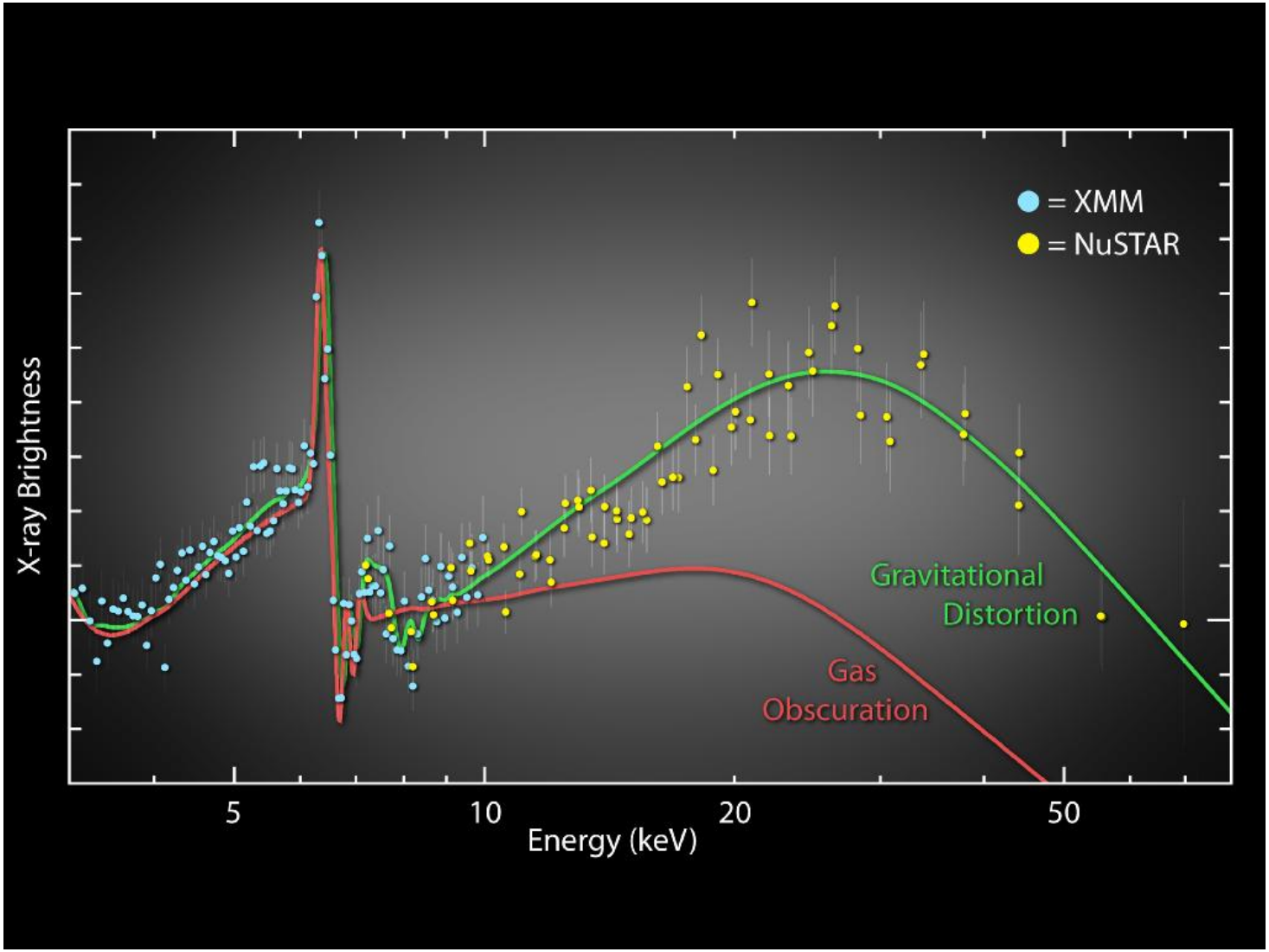


Energy range: 3 – 78.4 keV

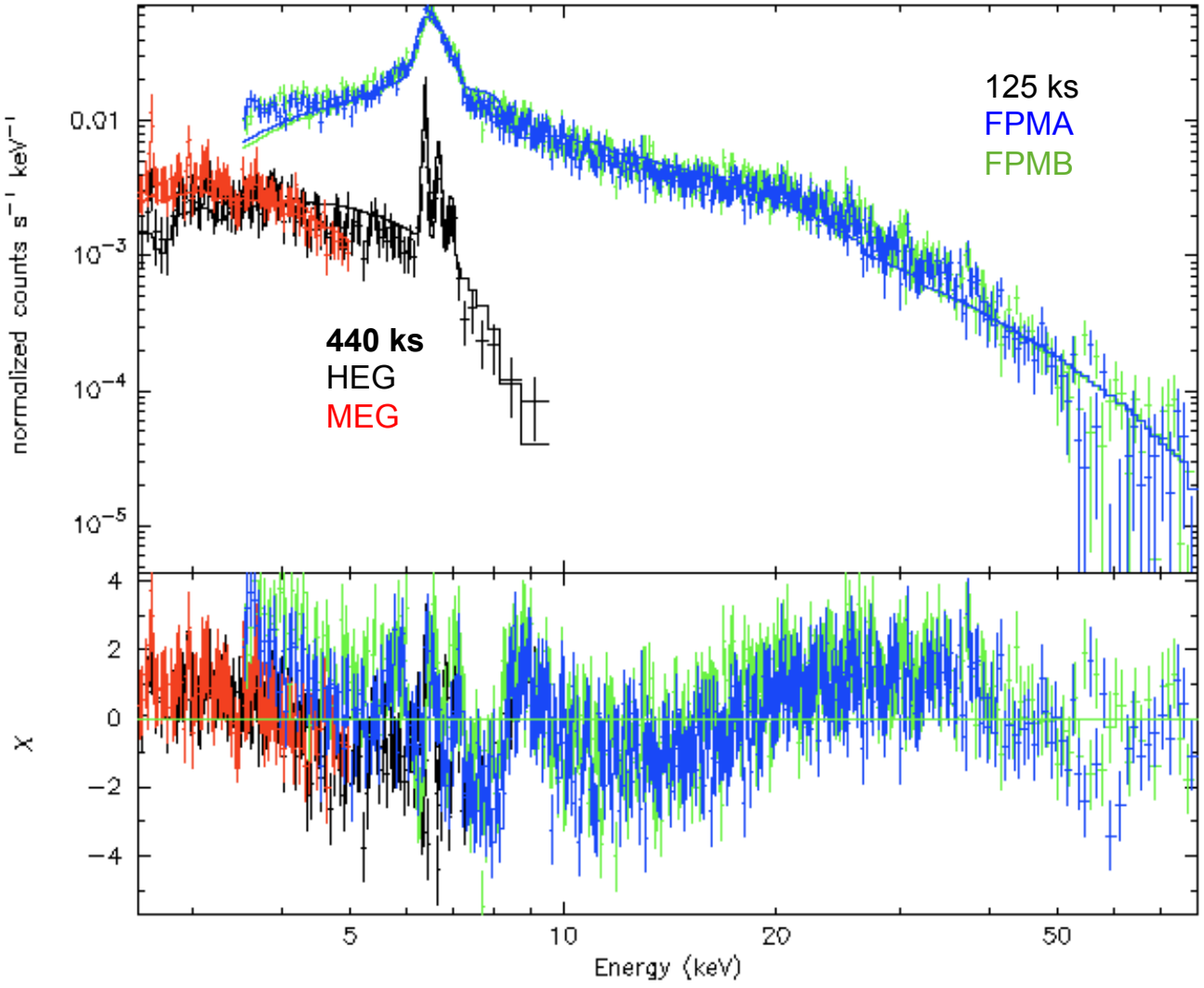
Outline

- NuSTAR data diorama part 1
- Detectors
  - RMF
- Optics
  - Physical motivated ray trace model
  - Intermission NuSTAR data diorama part 2
  - PSF
  - ARF
- Background
- Astrometry

NGC 1365

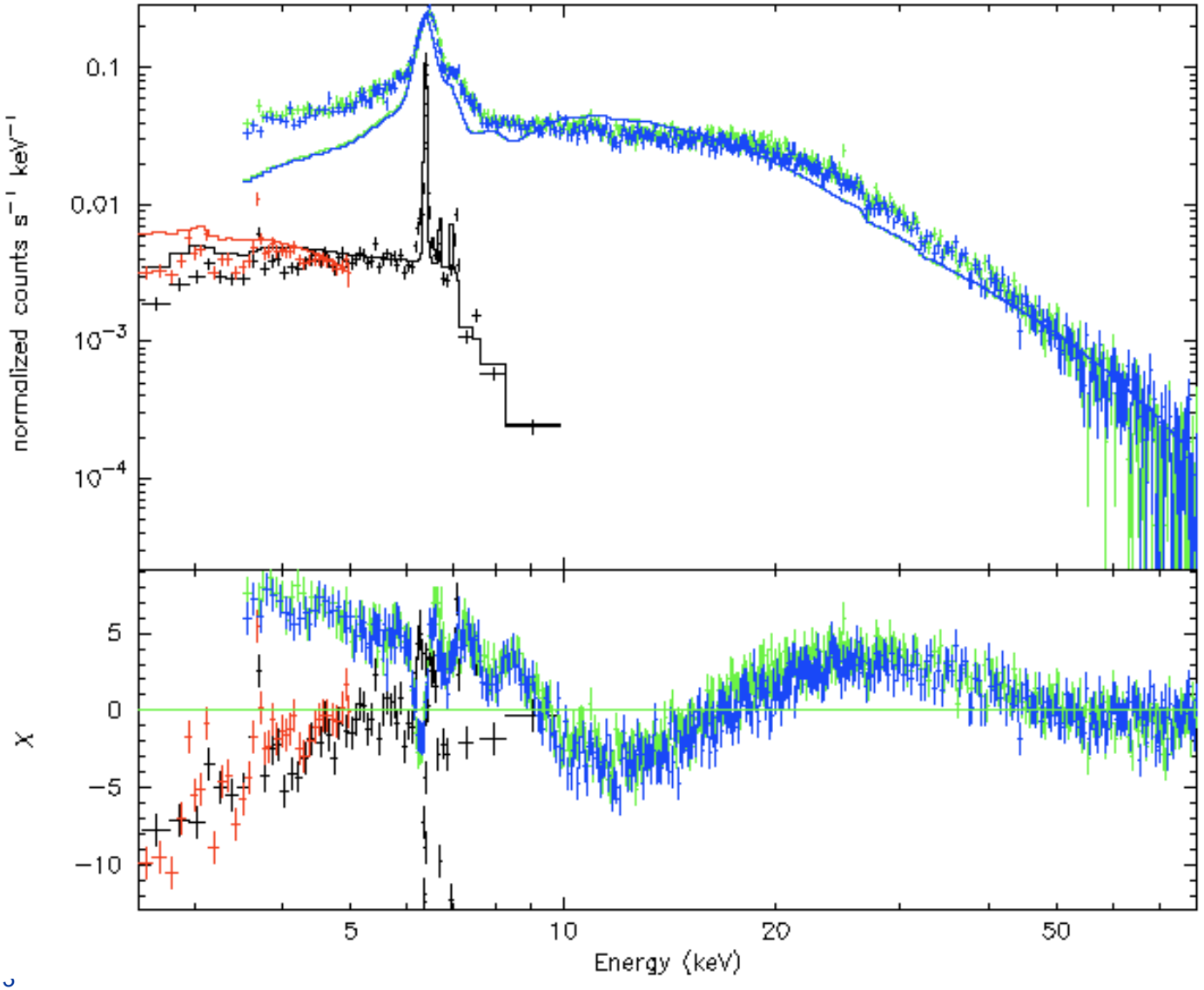

= XMM
= NuSTAR
X-ray Brightness
Gravitational Distortion
Gas Obscuration
5
10
20
50
Energy (keV)

NGC 1068

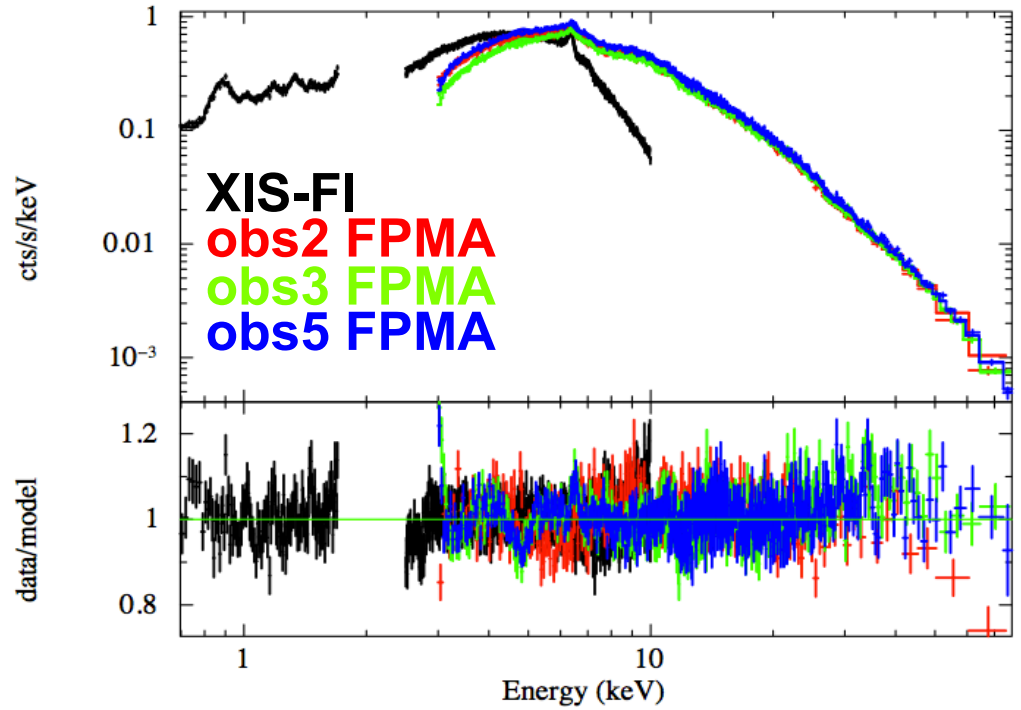


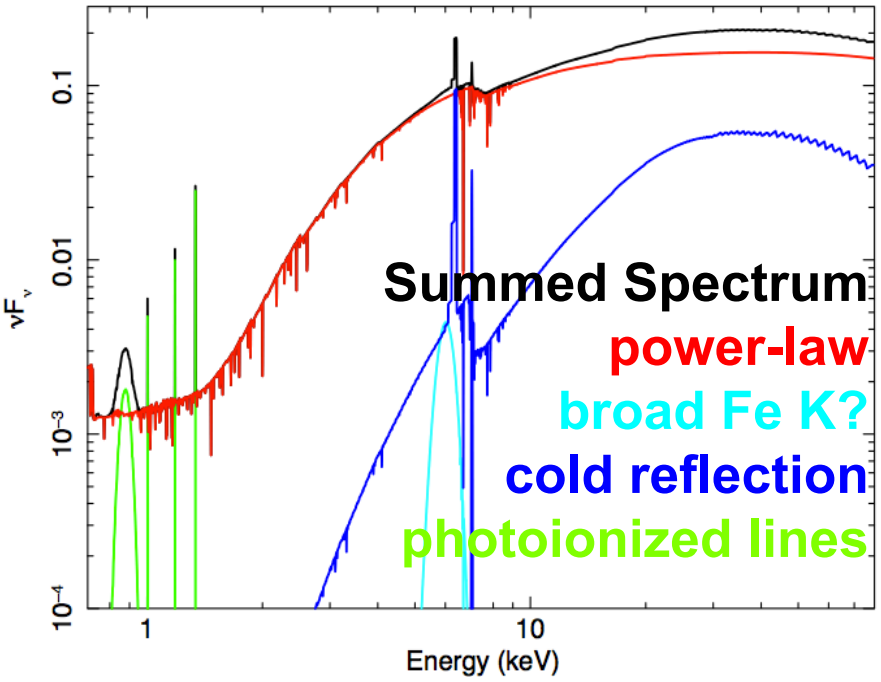
Model:
pexriv+zgauss

Circinus


normalized counts s^{-1} keV^{-1}
0.1
0.01
10^{-3}
10^{-4}
χ
5
0
−5
−10
5
10
20
50
Energy (keV)

NGC4151

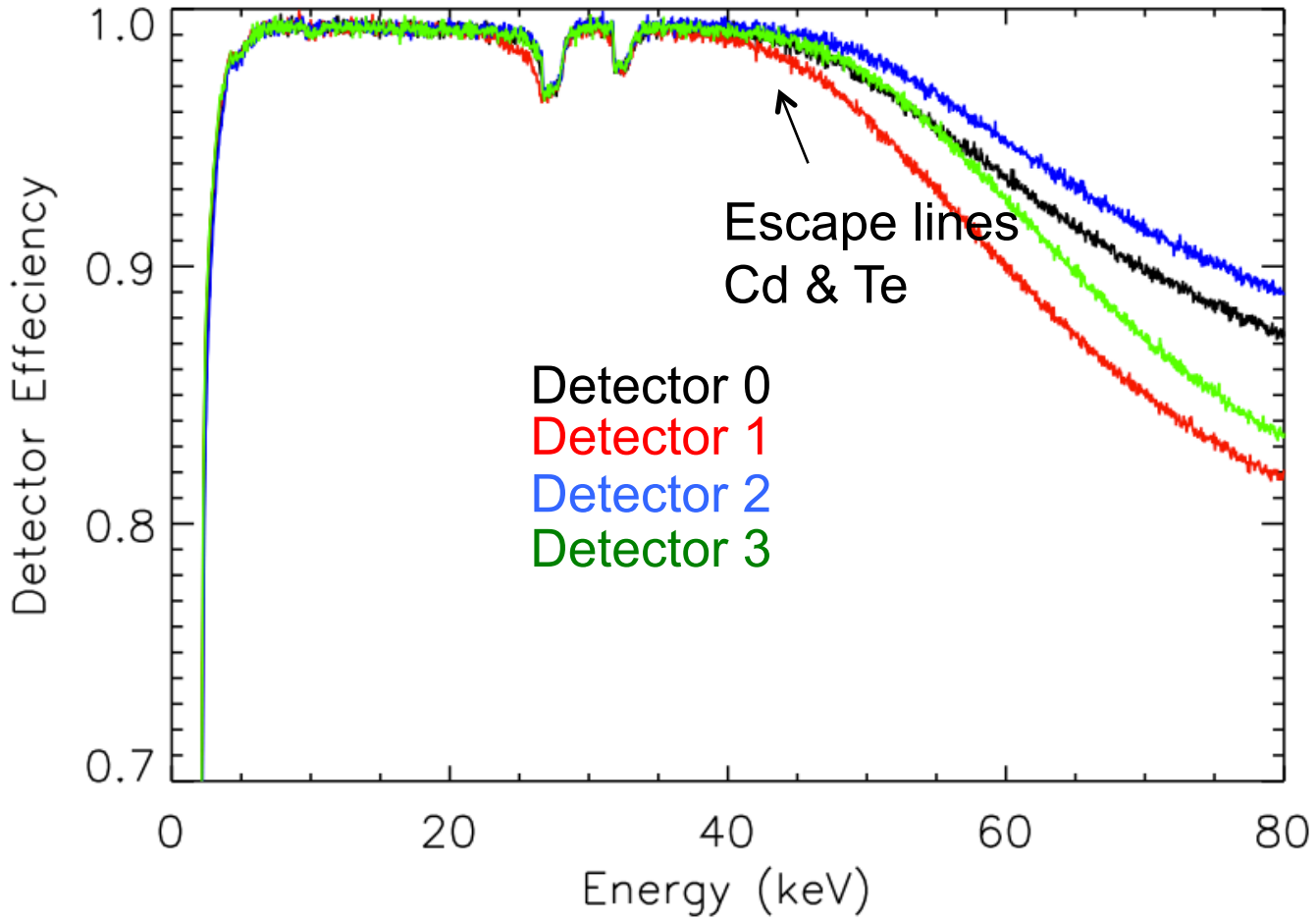


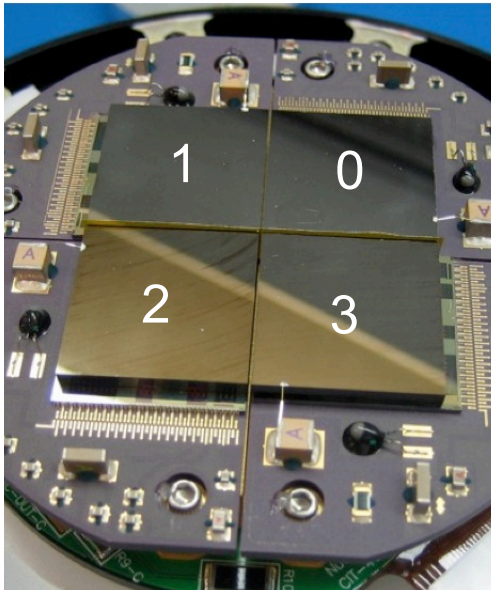


- One of the brightest Seyfert galaxies. Observed last November jointly with Suzaku (141 ks NuSTAR, about 150 ks Suzaku). Main goal: corona temperature

RMF

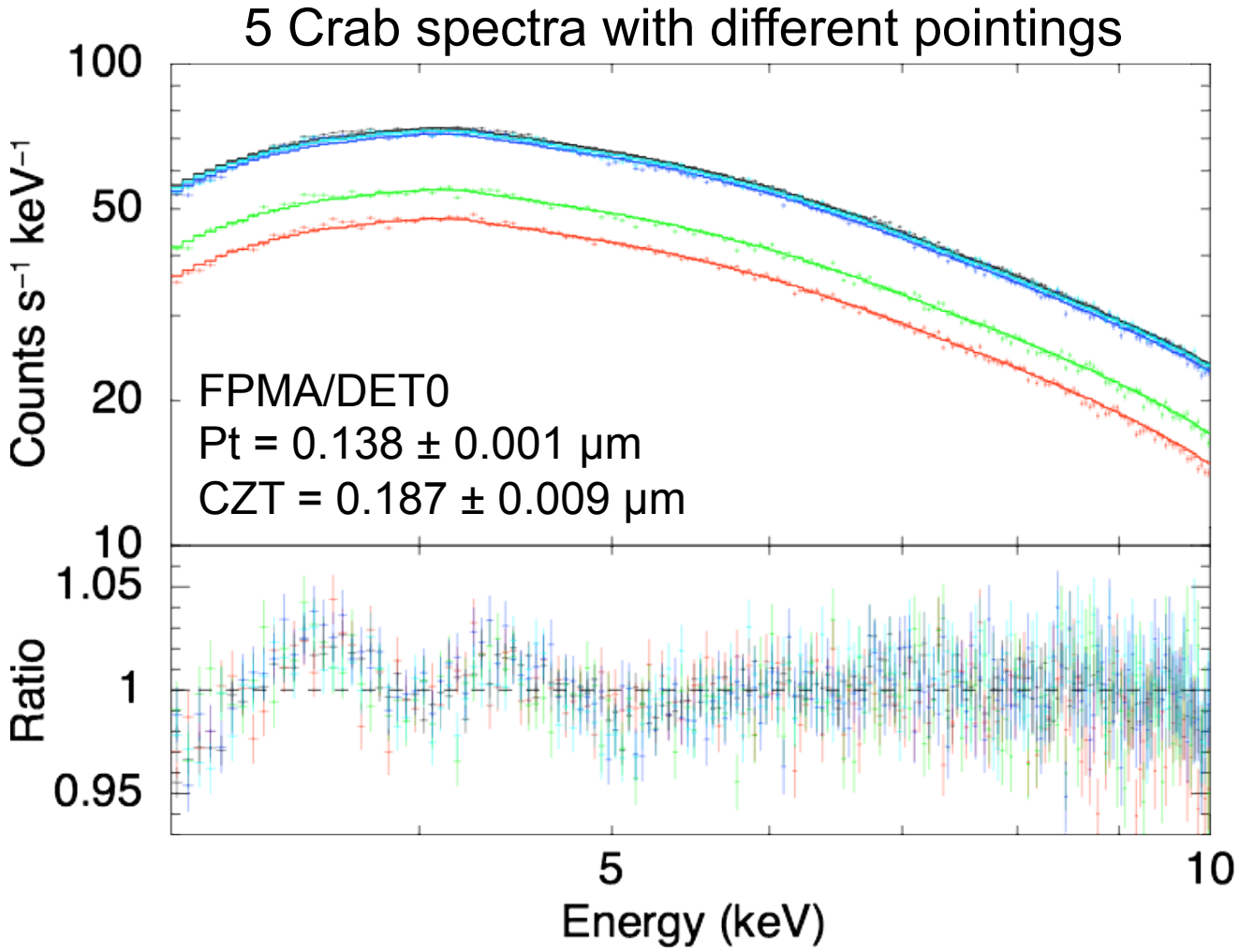
Detector Efficiency





Low-energy Detection Efficiency Drop

Credit: Takao Kitaguchi



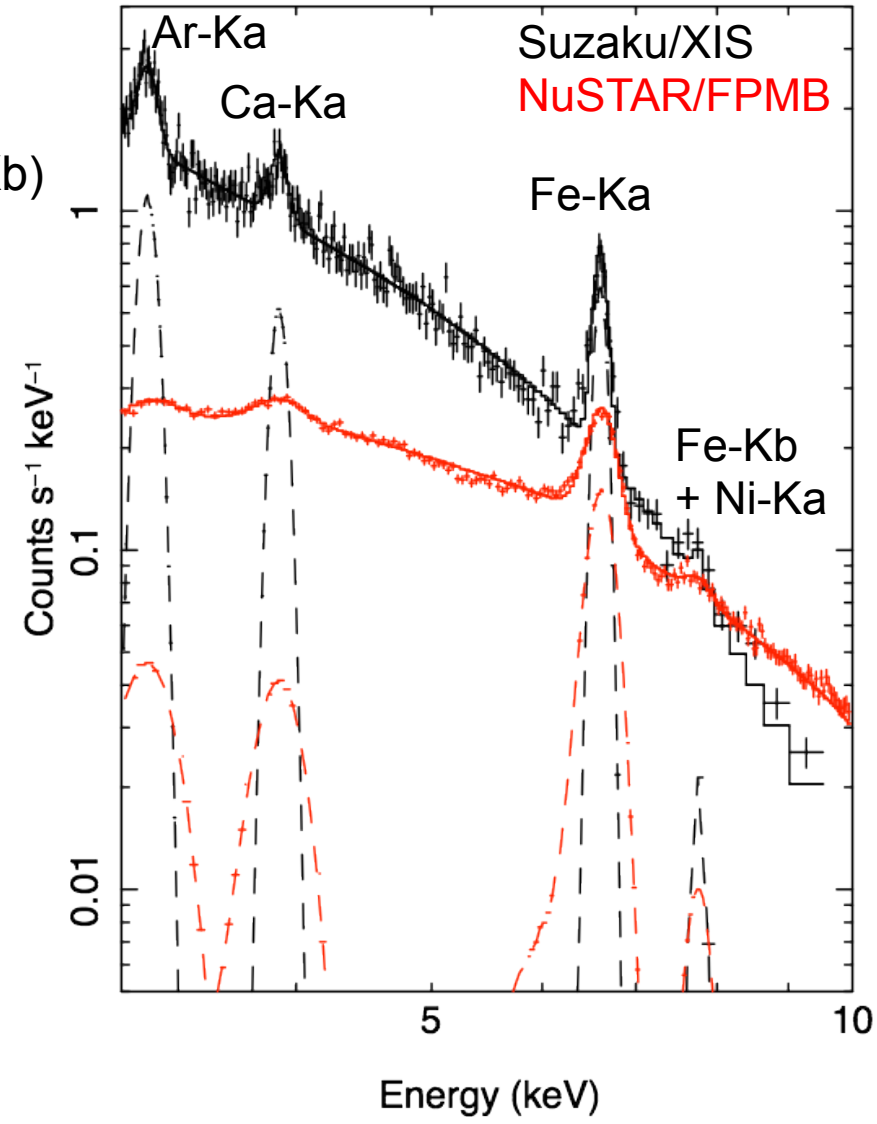
- <5% uncertainty produced by unknown residuals around 4 keV

Absolute Energy Scale Below 6 keV

Credit: Takao Kitaguchi

- W-SW knot region of Cas A
- Fitting model: PL + Bremss + 4 Gaussians (Ar-Ka, Ca-Ka, Fe-Ka, Fe-Kb +Ni-Ka)

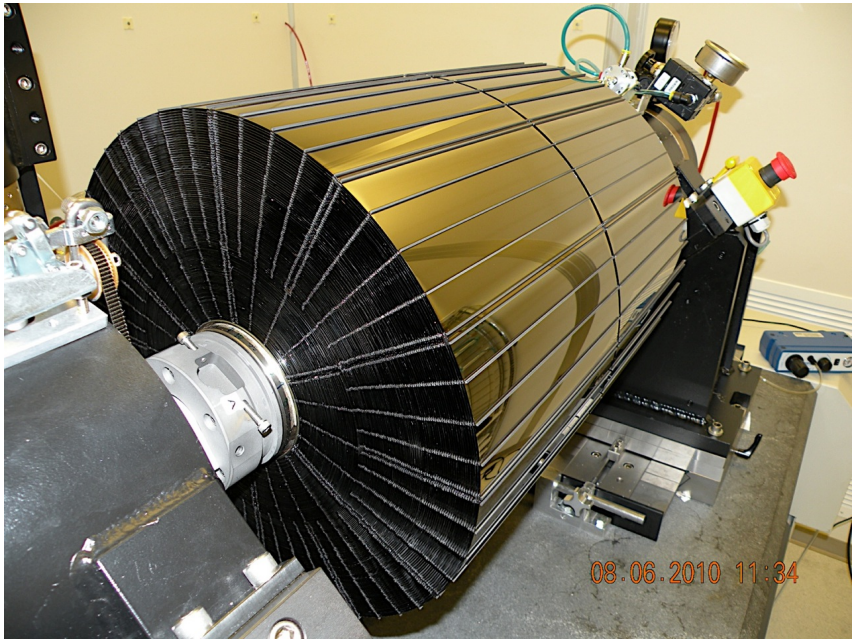
	Line Center Energy (keV)	
	Suzaku/XIS	NuSTAR
Ar-Ka	3.128 -0.004 +0.006	3.160 -0.040 +0.014
Ca-Ka	3.890 -0.008 +0.010	3.880 -0.006 +0.000
Fe-Ka	6.606 -0.006 +0.007	6.608 -0.008 +0.034
Fe-Kb + Ni-Ka	7.731 -0.095 +0.111	7.757 -0.037 +0.068



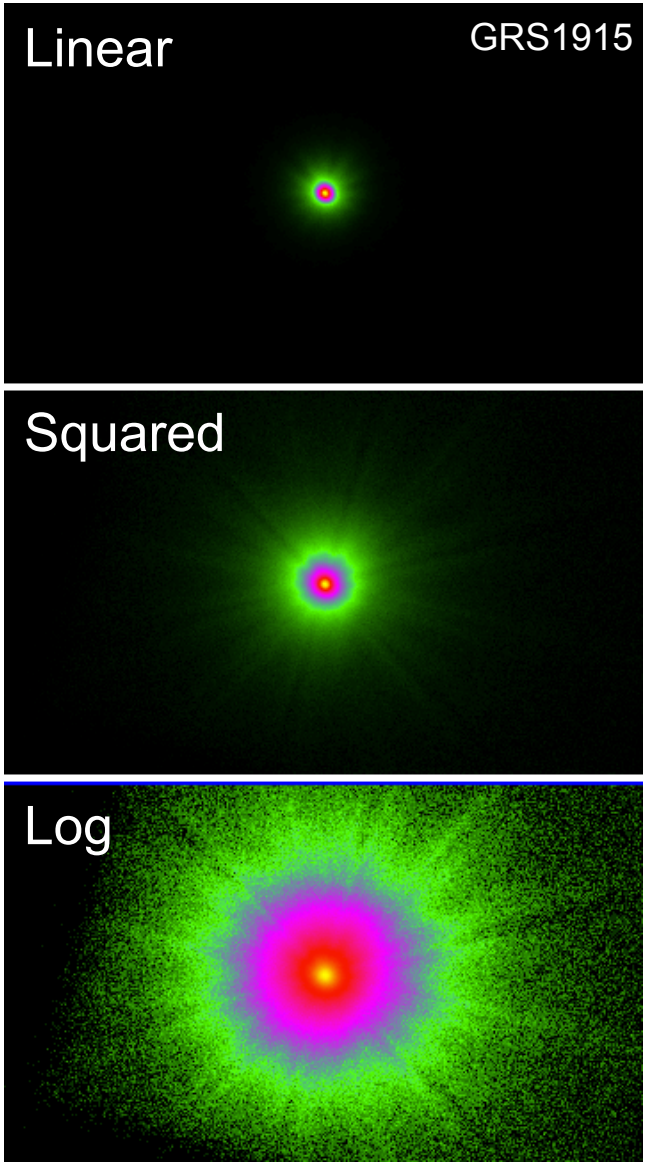
- Absolute energy scale accuracy is <50 eV

ARF

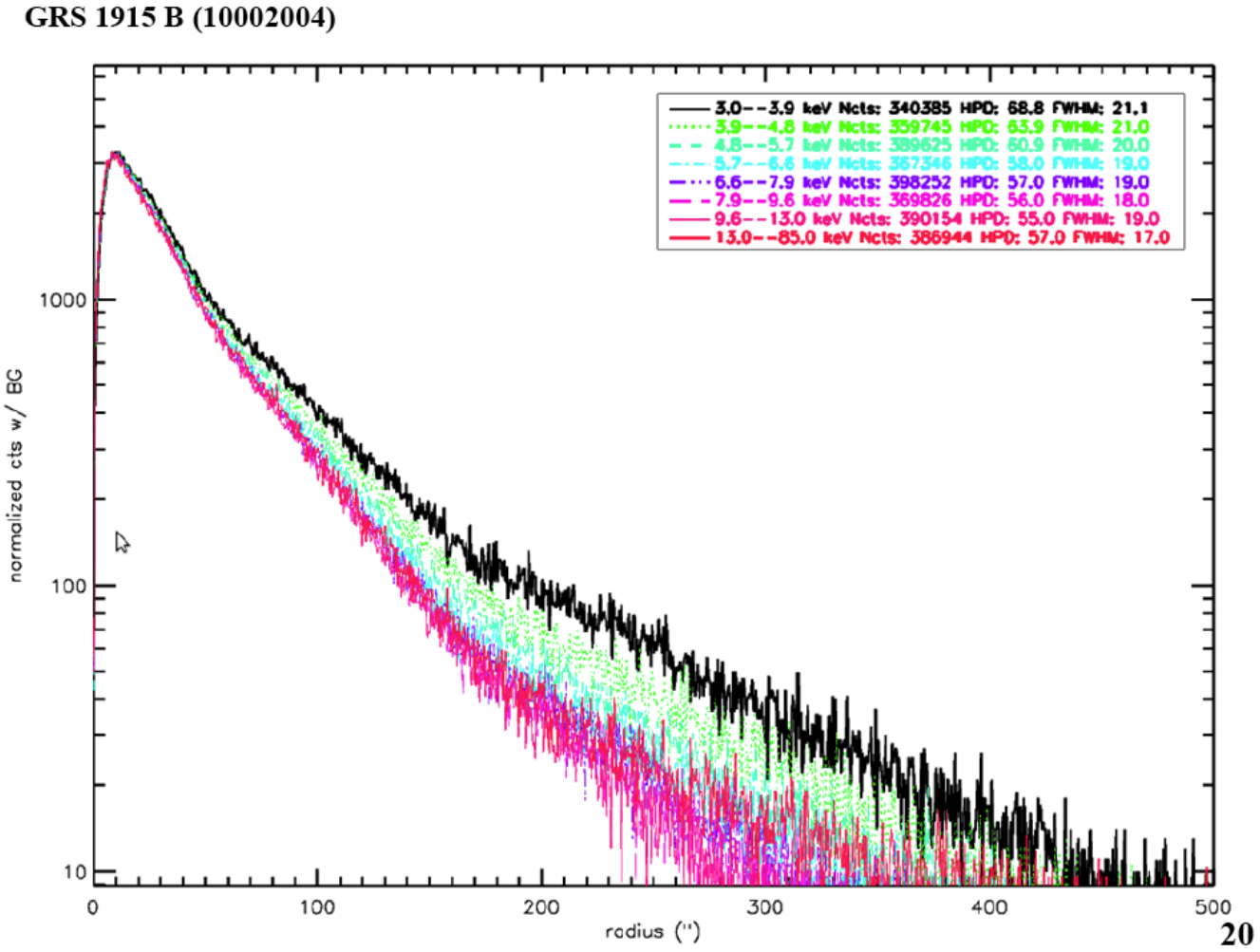
PSF



- Wolter-I conical approximation
- Focal length = 1015 cm
- 133 shells
- Multilayers (Pt/C, W/Si)



PSF

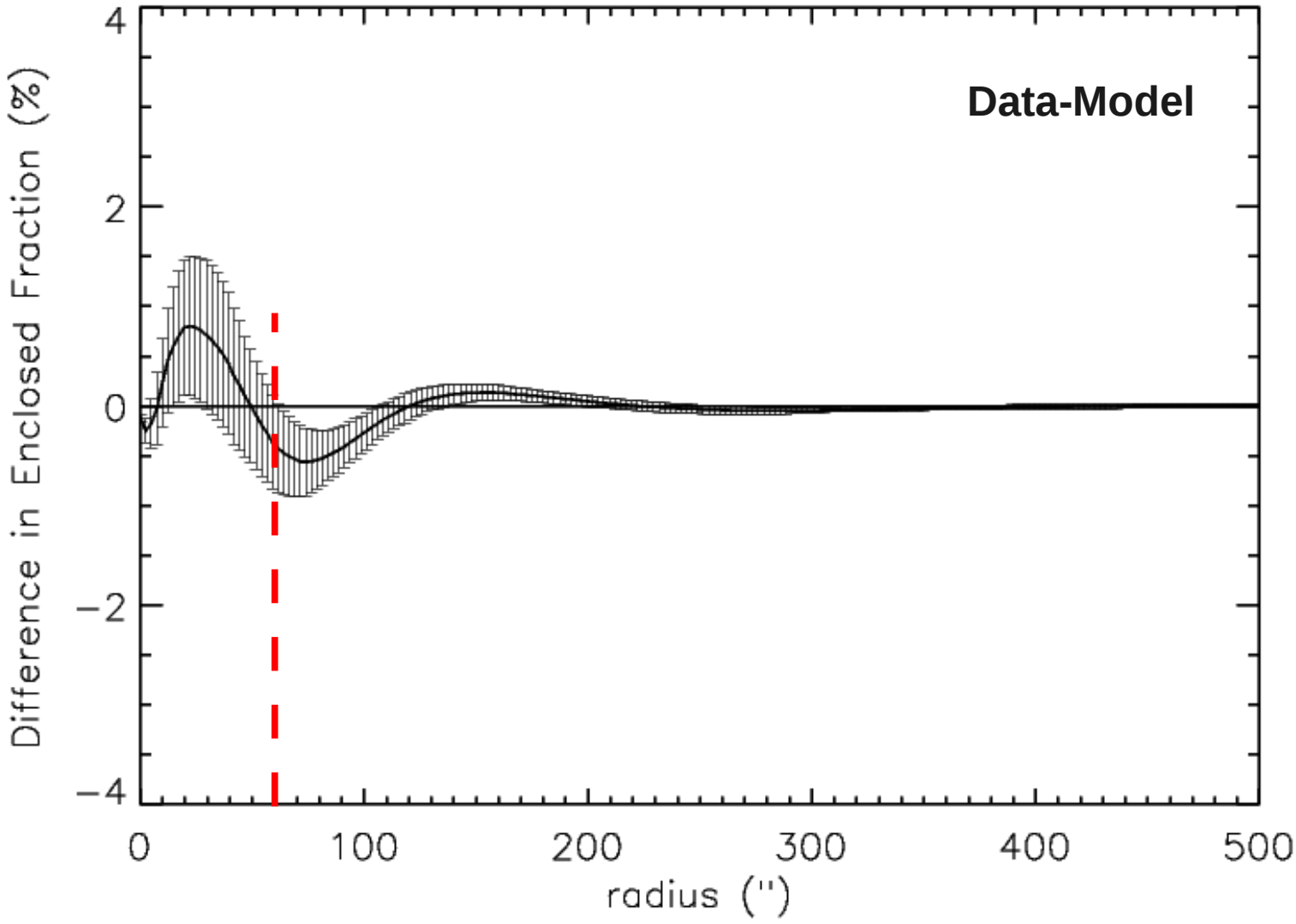


HPD = 59”/57”
FWHM = 18”

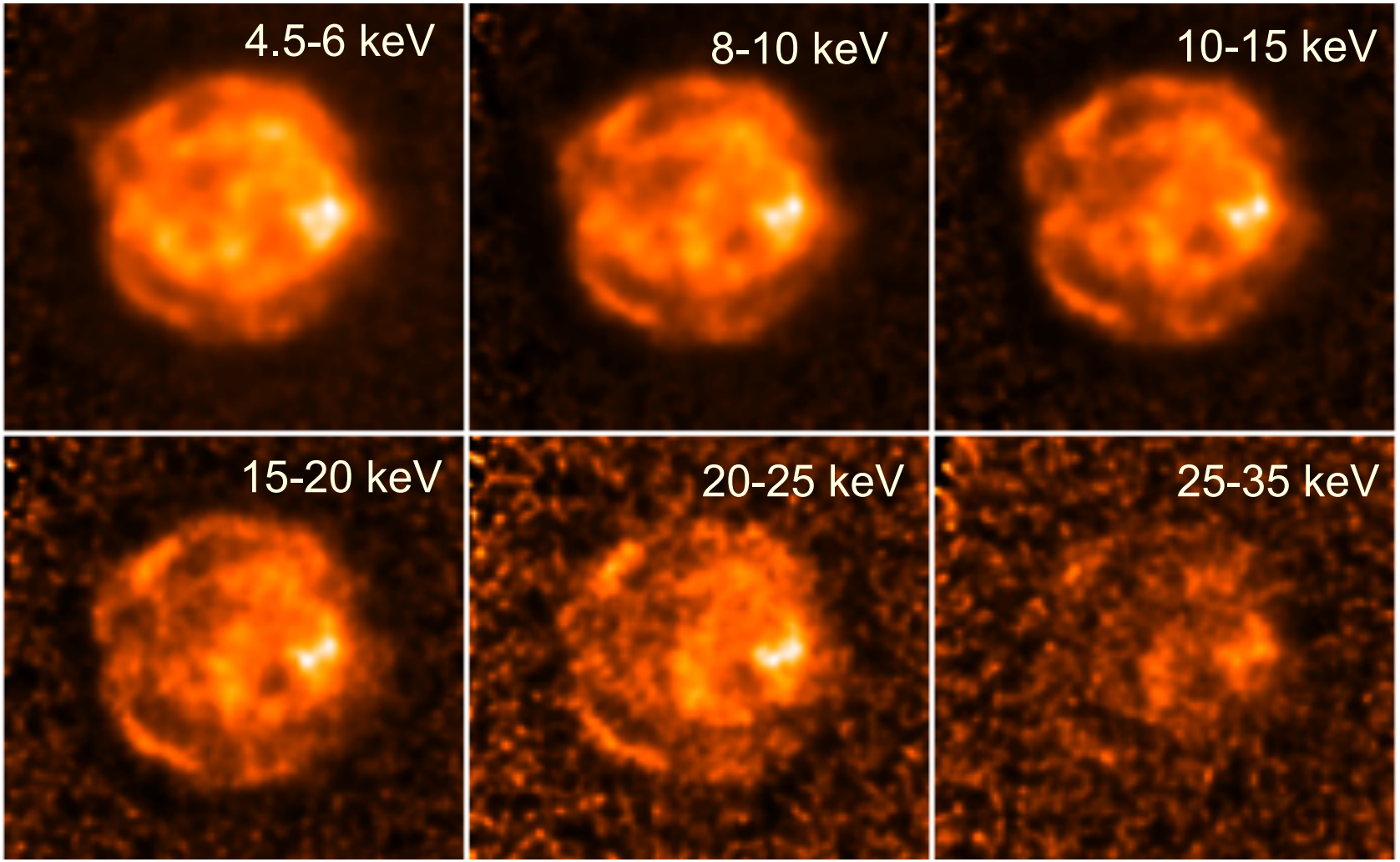
Used 7 bright sources to characterize the PSF

Her X-1
GRS1915
Cygnus X-1
Vela X-1
GS0834

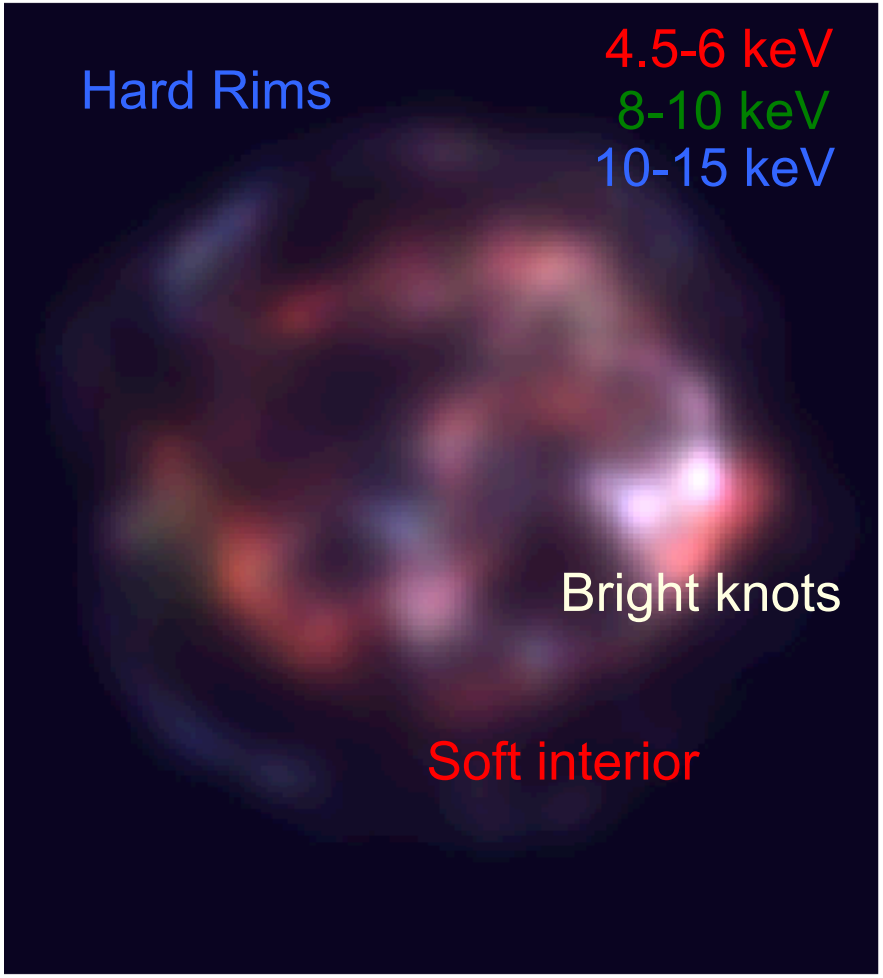
PSF Modeling

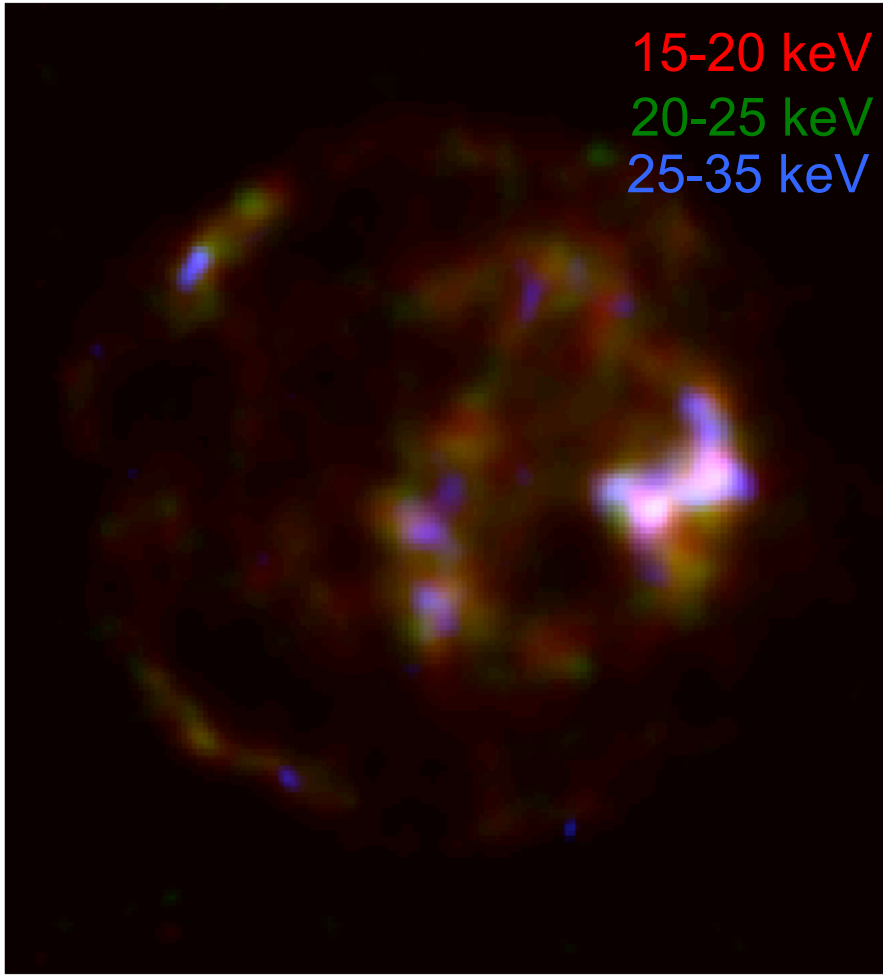


Cas A Imaging

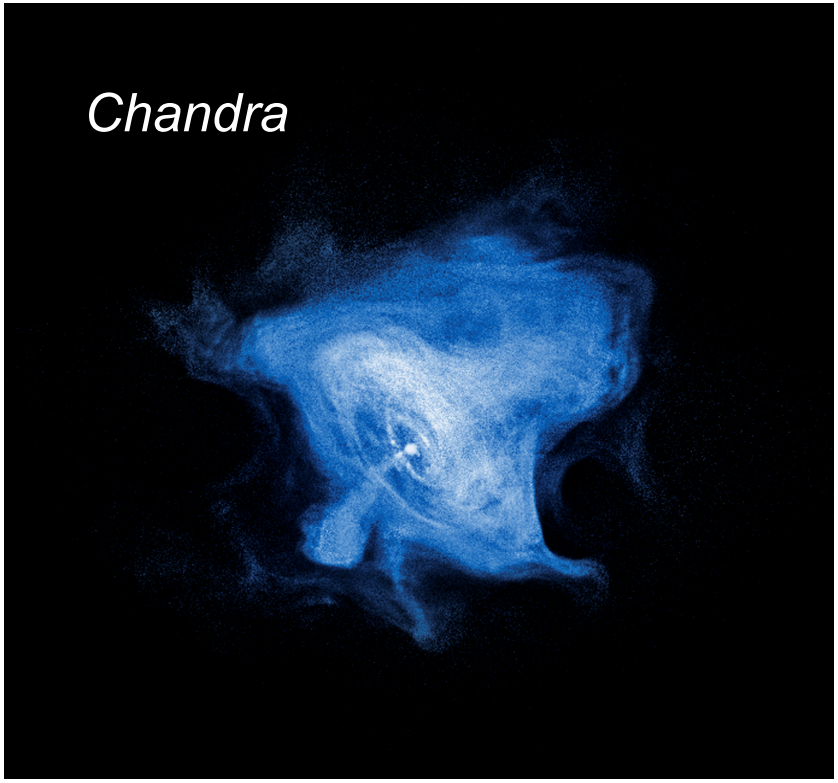


Cas A Imaging



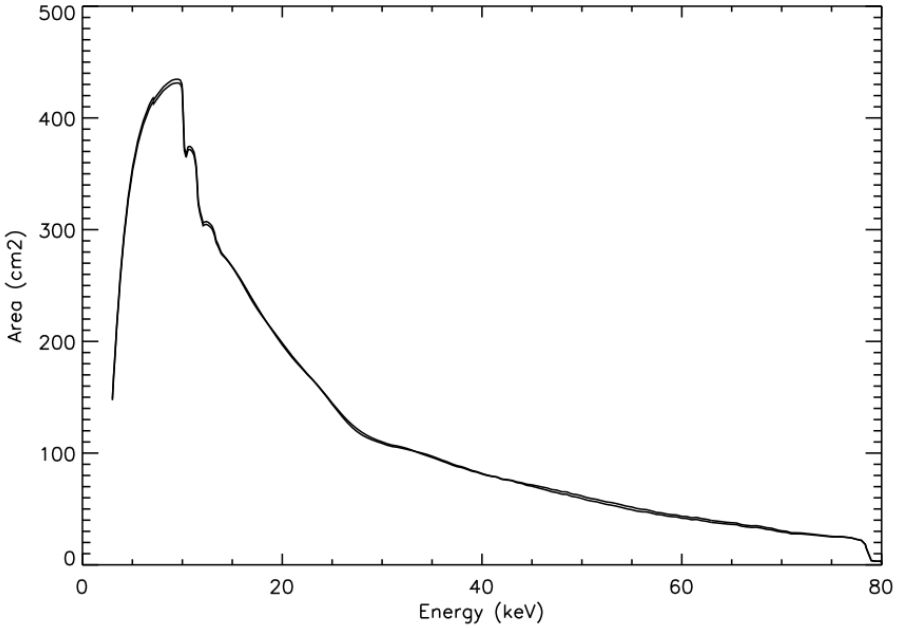


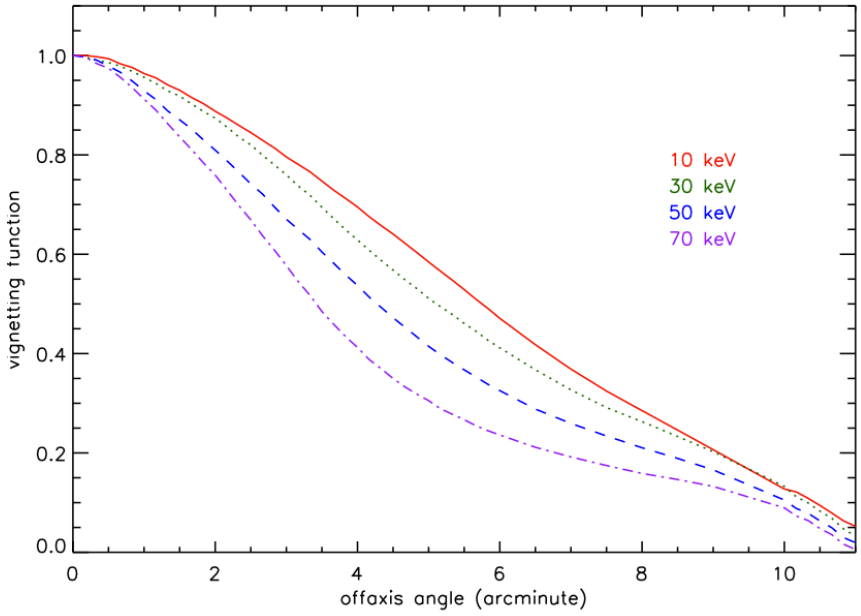
De-convolved Crab Image



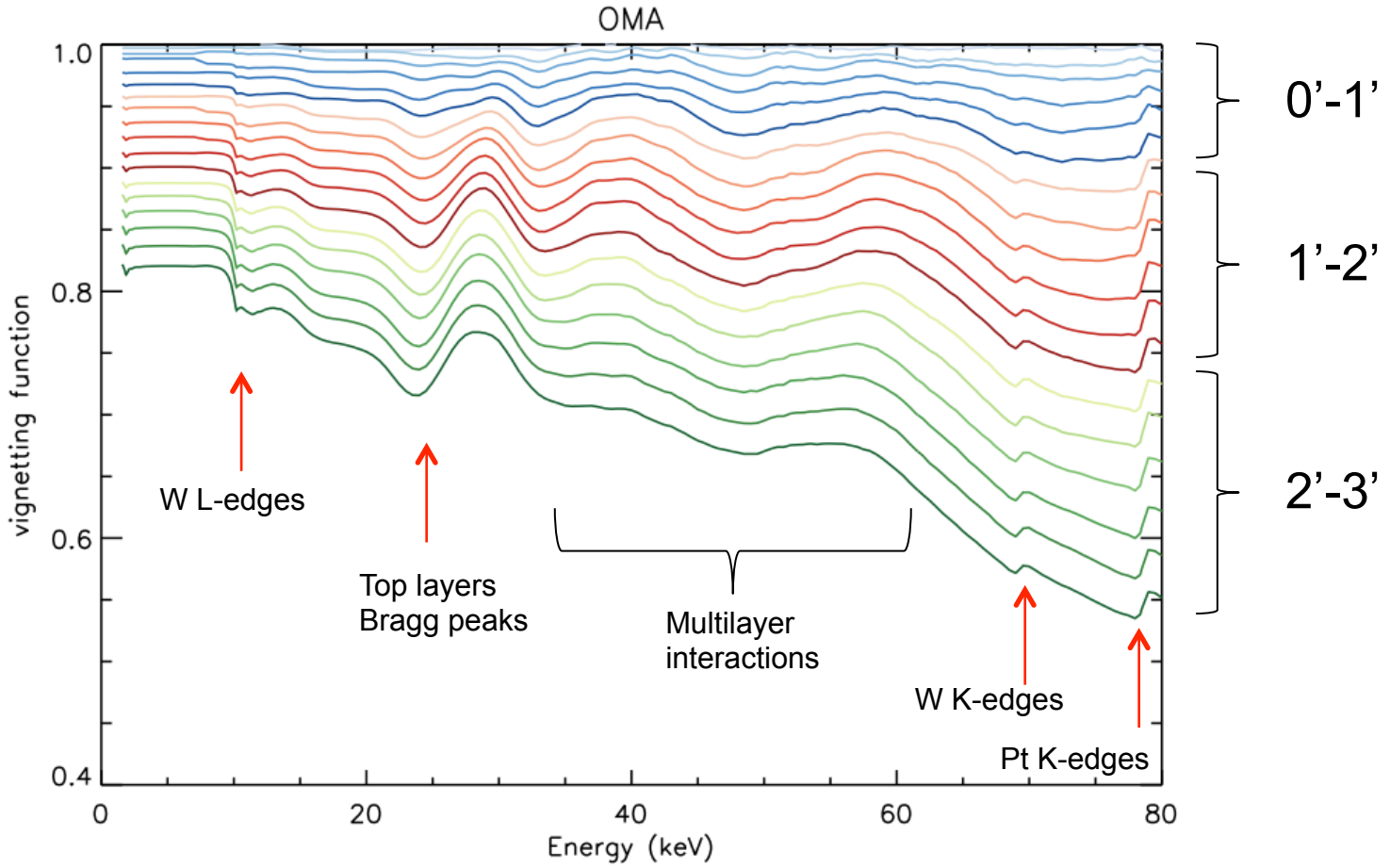
ARF

- Physically motivated Raytrace model. (Niels Jørgen Westergaard)
  - Geometrical model – obscuration, mirror slopes (LVDT).
  - Optical constants – LLNL effort.
  - Multilayer parameters (Pt/C, W/Si) – Fitting of witness samples and curved glass pieces, coupled with coating parameters.
  - Scattering mechanism – scattering model.

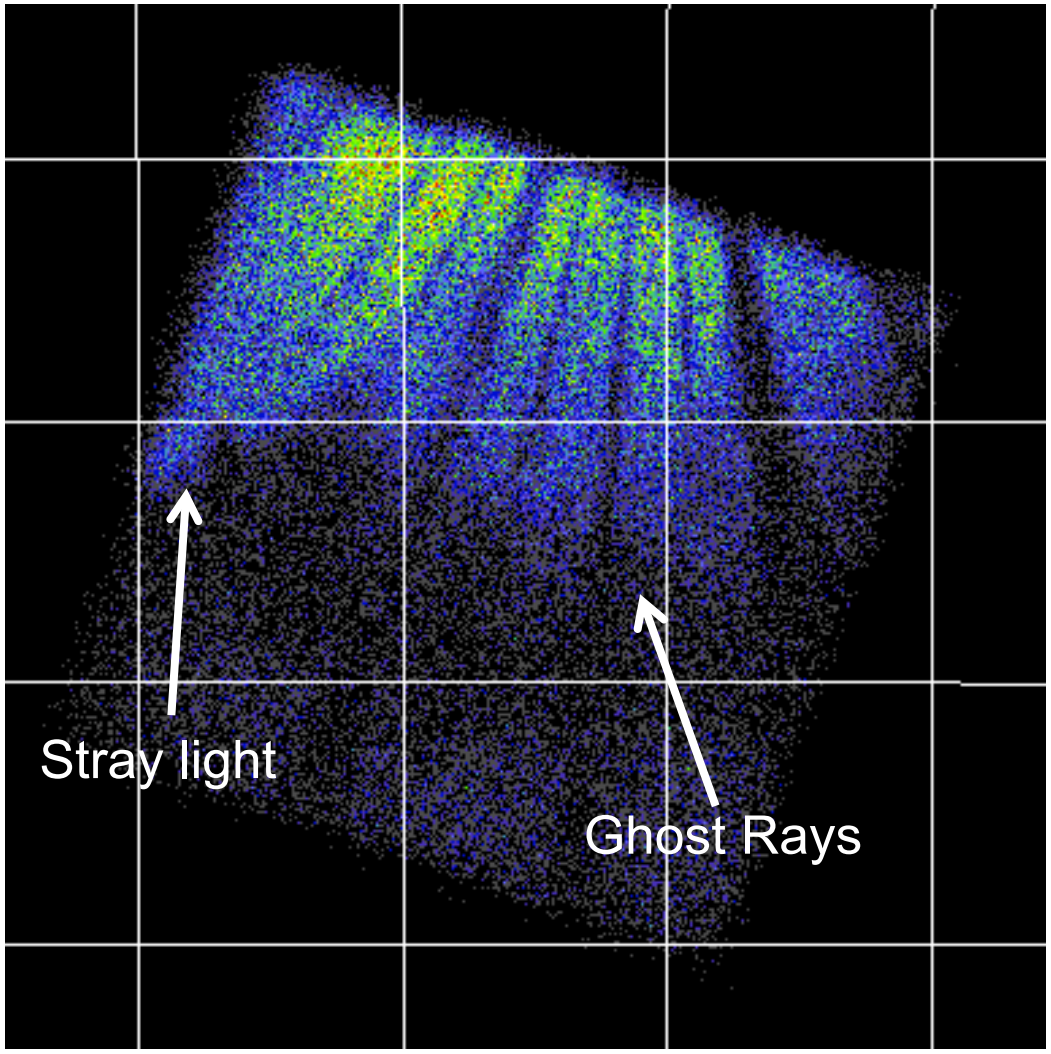




ARF: vignetting functions

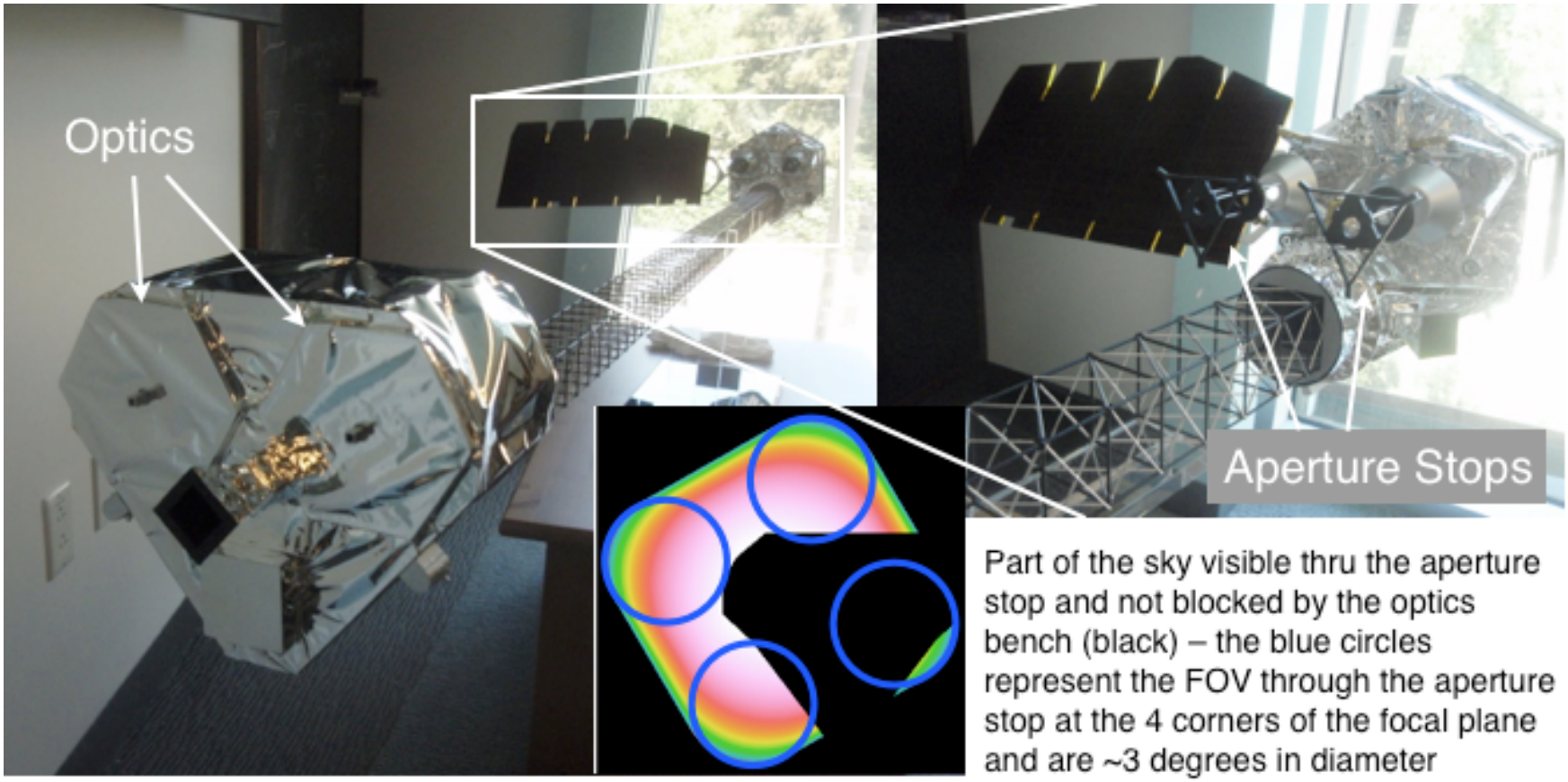


Stray light (zero bounce) and Ghost Rays (single bounce)



- Ghost rays come from sources between 3 and 40 arcmin offaxis.
- Stray light component comes from bright sources roughly between 3 and 6 degrees.

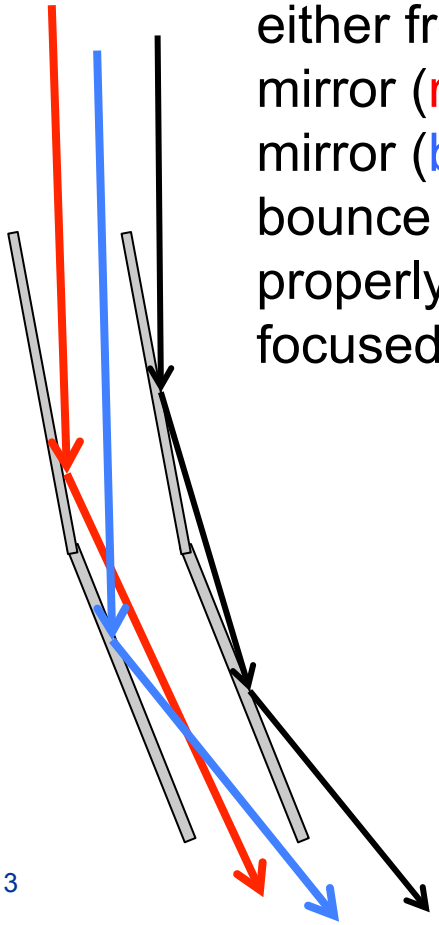
Stray light and Aperture Background

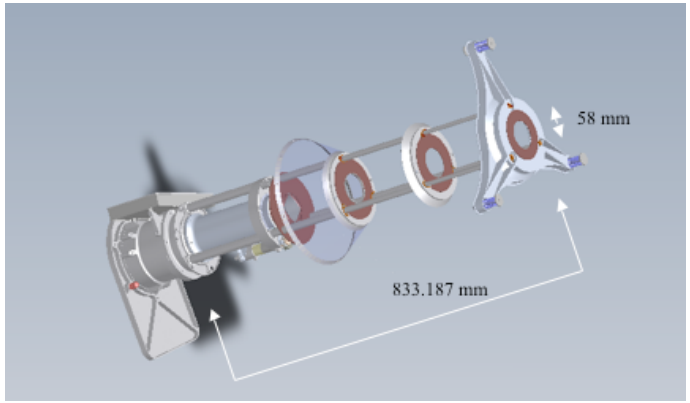


Part of the sky visible thru the aperture stop and not blocked by the optics bench (black) – the blue circles represent the FOV through the aperture stop at the 4 corners of the focal plane and are ~3 degrees in diameter

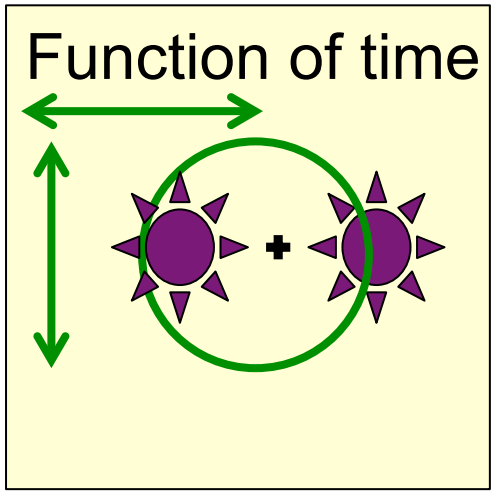
ARF corrections: Ghost Rays & Aperture Stop

- What are ghost rays?
  - Single bounce photons either from the upper mirror (red) or the lower mirror (blue). Double bounce photons are properly reflected and focused photons (black)



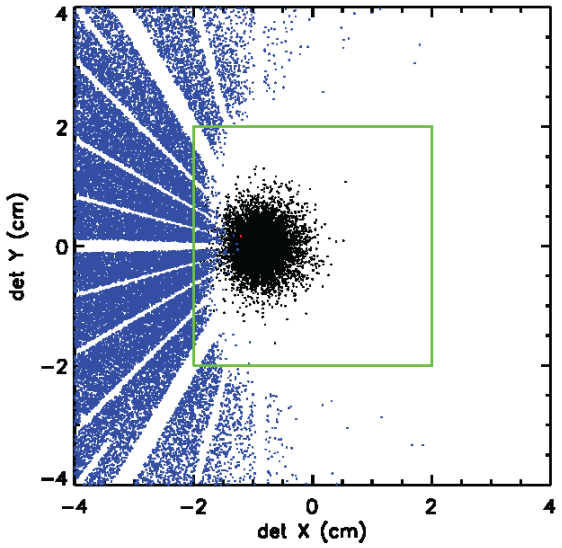


Azimuthal, Radial and time dependency

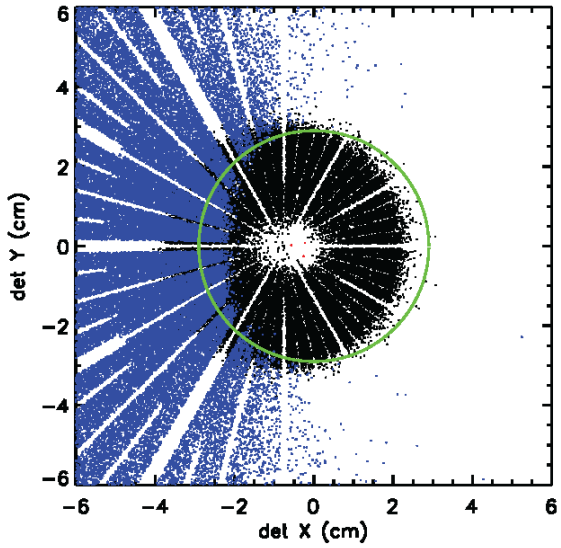


ARF corrections: Ghost Rays & Aperture Stop

Detector plane

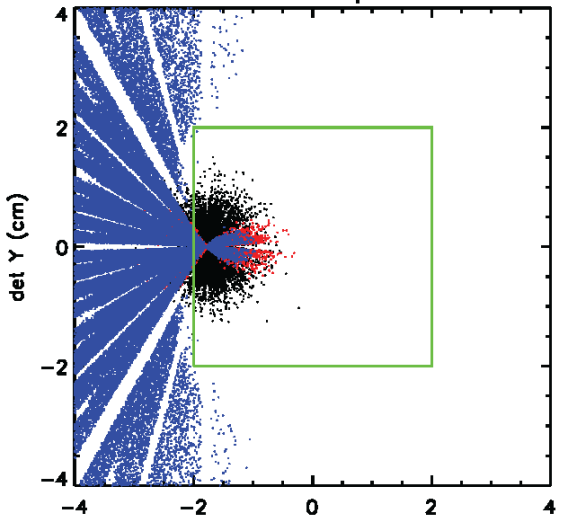


Aperture plane

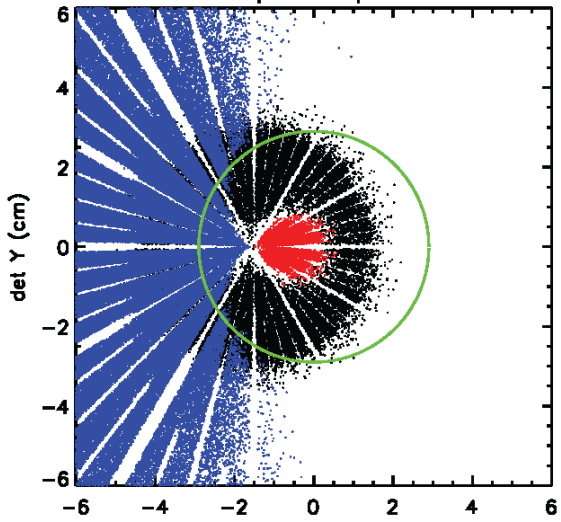


3 arcmin

At Detector plane

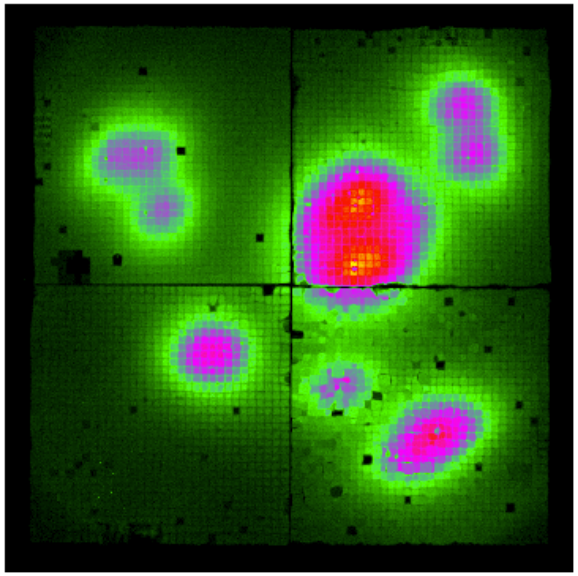


At Aperture plane



6 arcmin

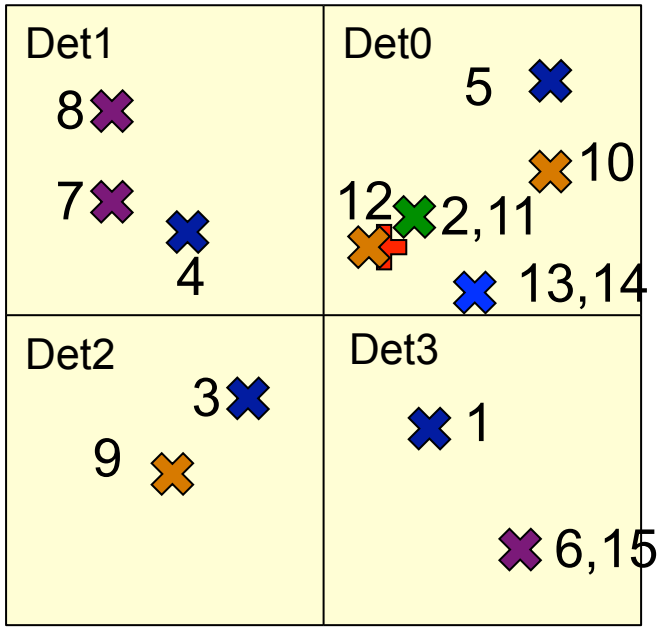
The Crab Calibration Data Set



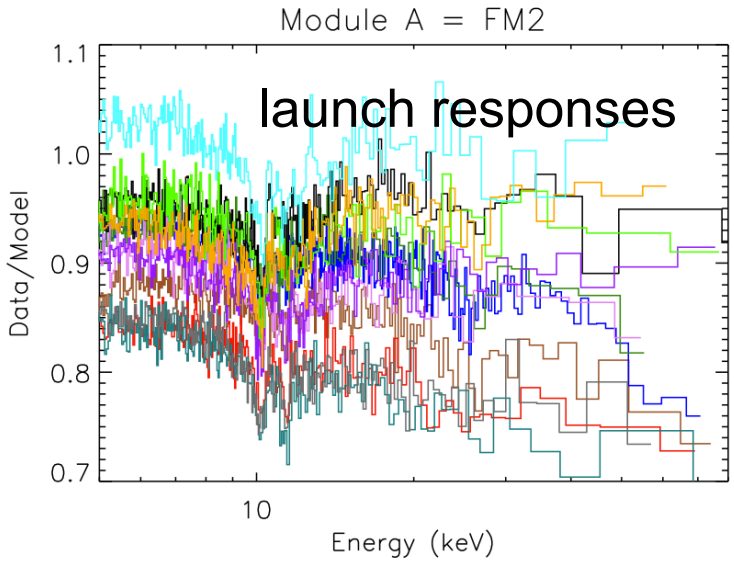
- Exposure times from 7ks (2 orbits) to 15ks (4 orbits)
- Off-axis angles range from 0.5 to 6 arcminutes.
- Minimum 2 pointings on each detector

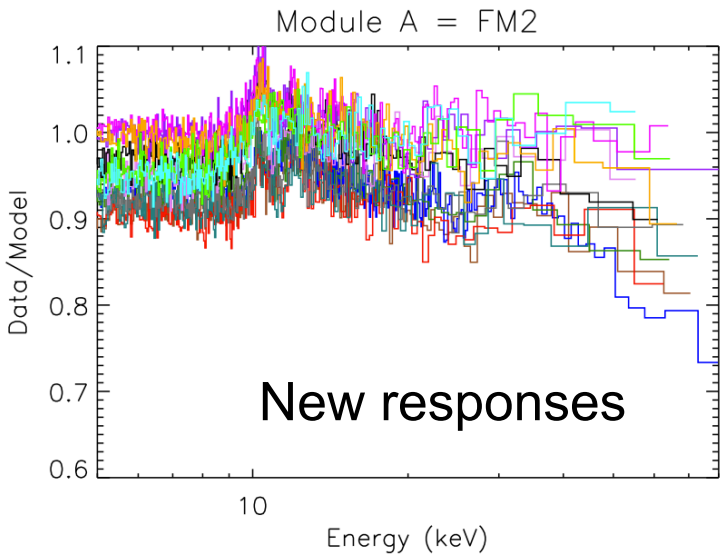
NuSTAR uses the Crab for:

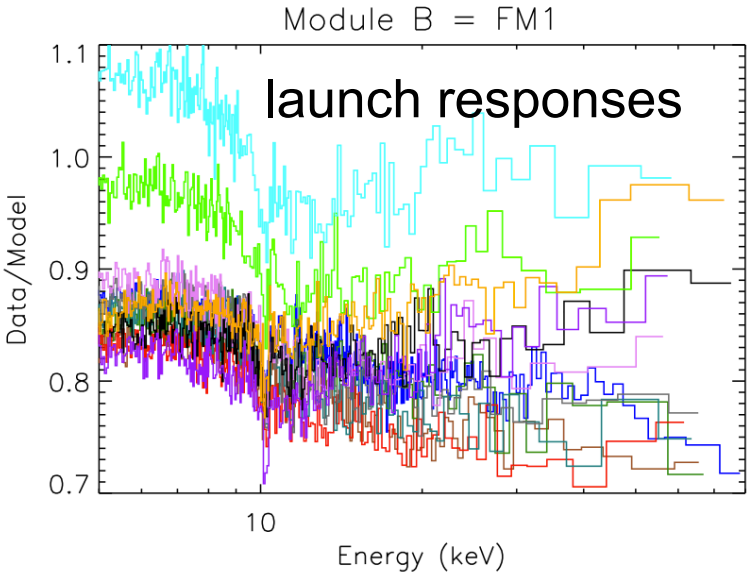
- Effective Area calibrator
- Internal normalization calibrator – detector to detector
- Optical Axis calibrator
- RMF calibrator
- (Timing calibrator)

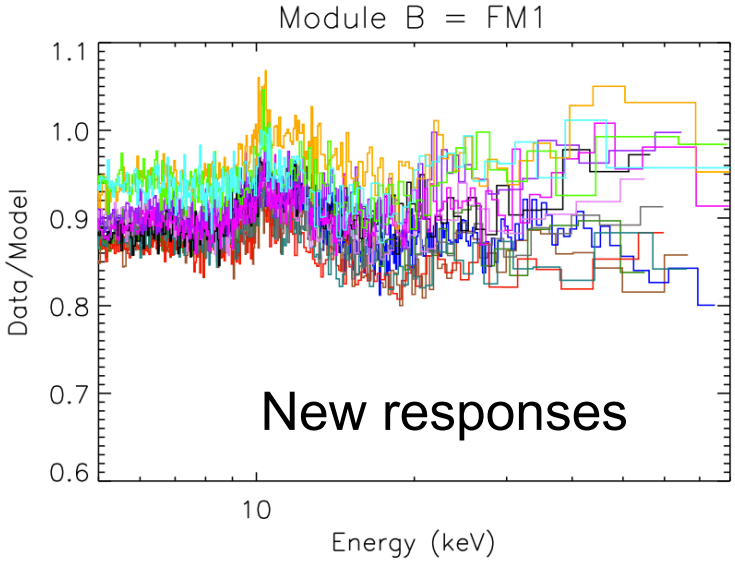


Progression since launch

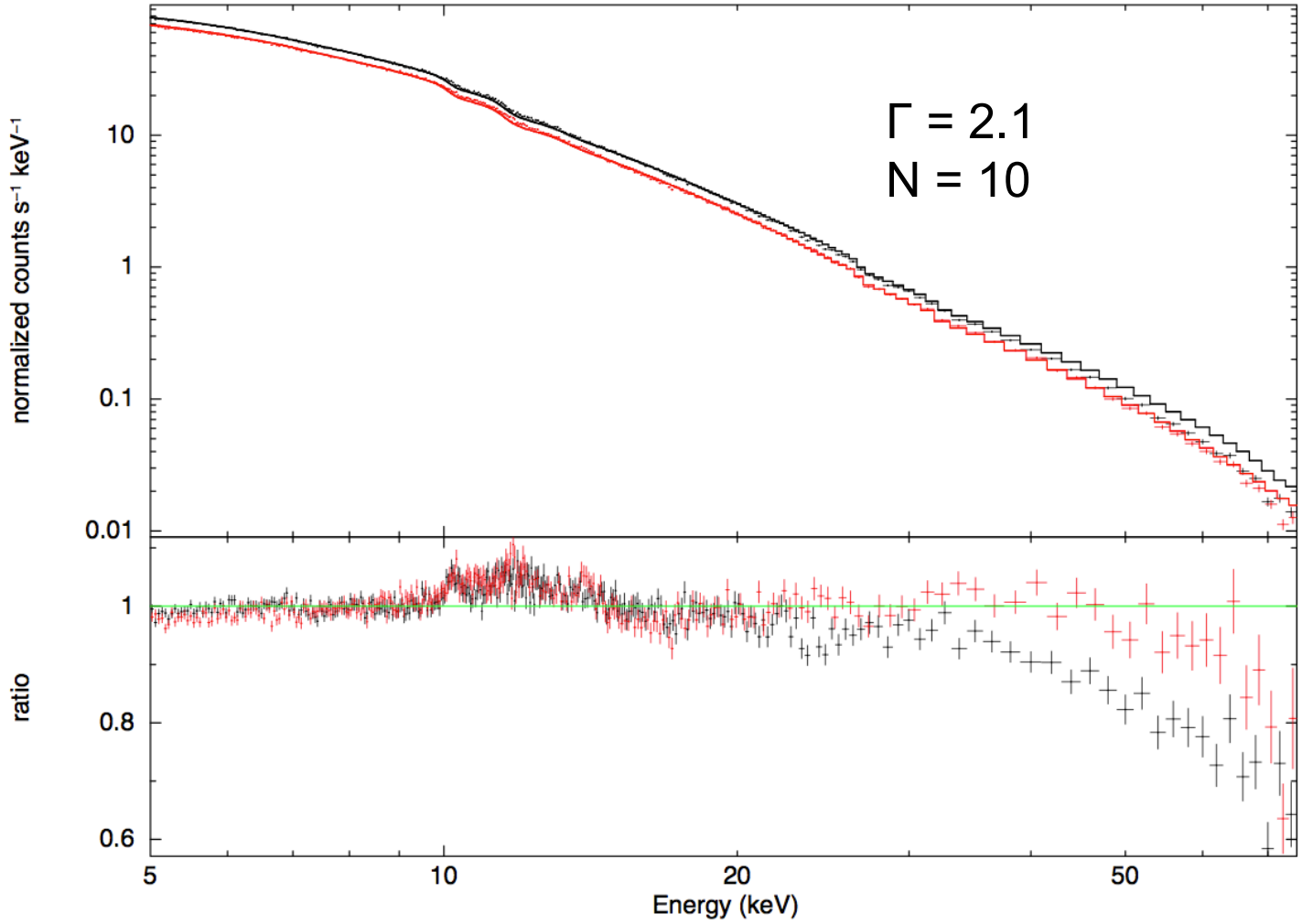








Crab

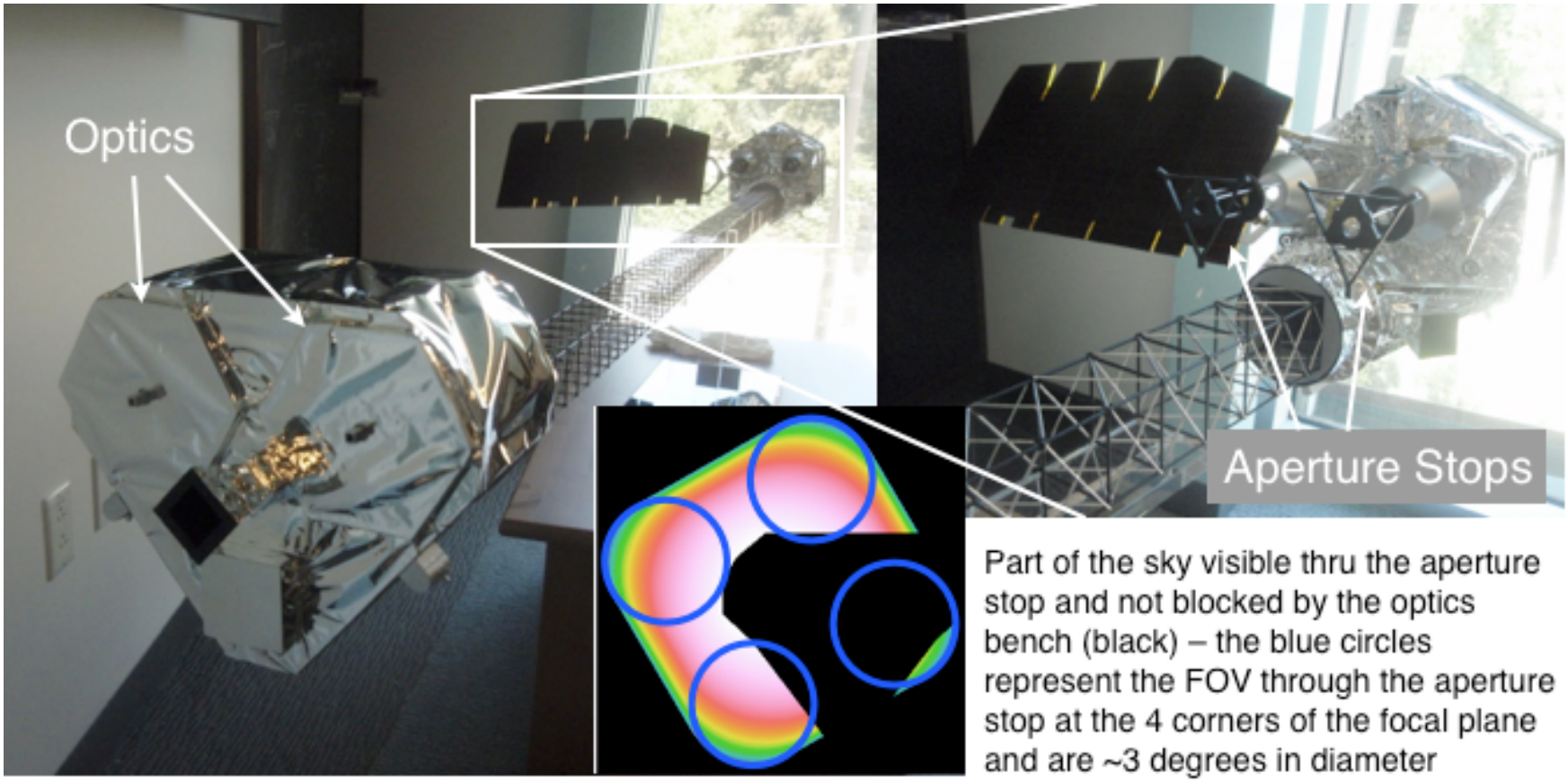

Γ = 2.1
N = 10
normalized counts s⁻¹ keV⁻¹
10
1
0.1
0.01
ratio
1
0.8
0.6
5
10
20
50
Energy (keV)

Calibration Path forward

- Model ARF
  - Optical constant improvements
  - Multilayer phase space search
- Crab corrected ARF
  - Robustness of method: test case 3C273, G21.5+0.9
  - Goal: Rectifying ARF and vignetting files with Crab corrected curves
  - Still need to decide on exact model parameter.

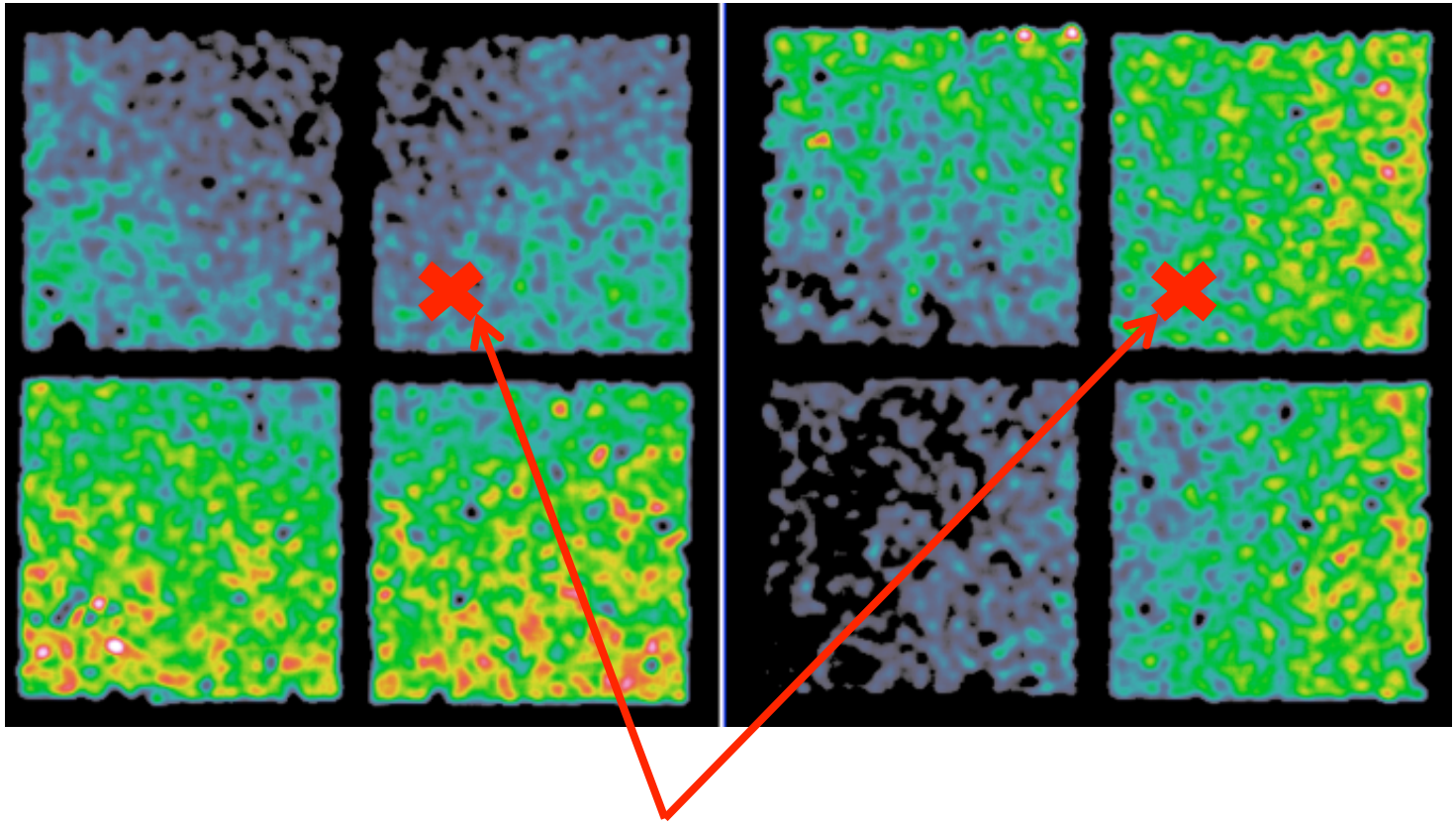
Background

Stray light and Aperture Background



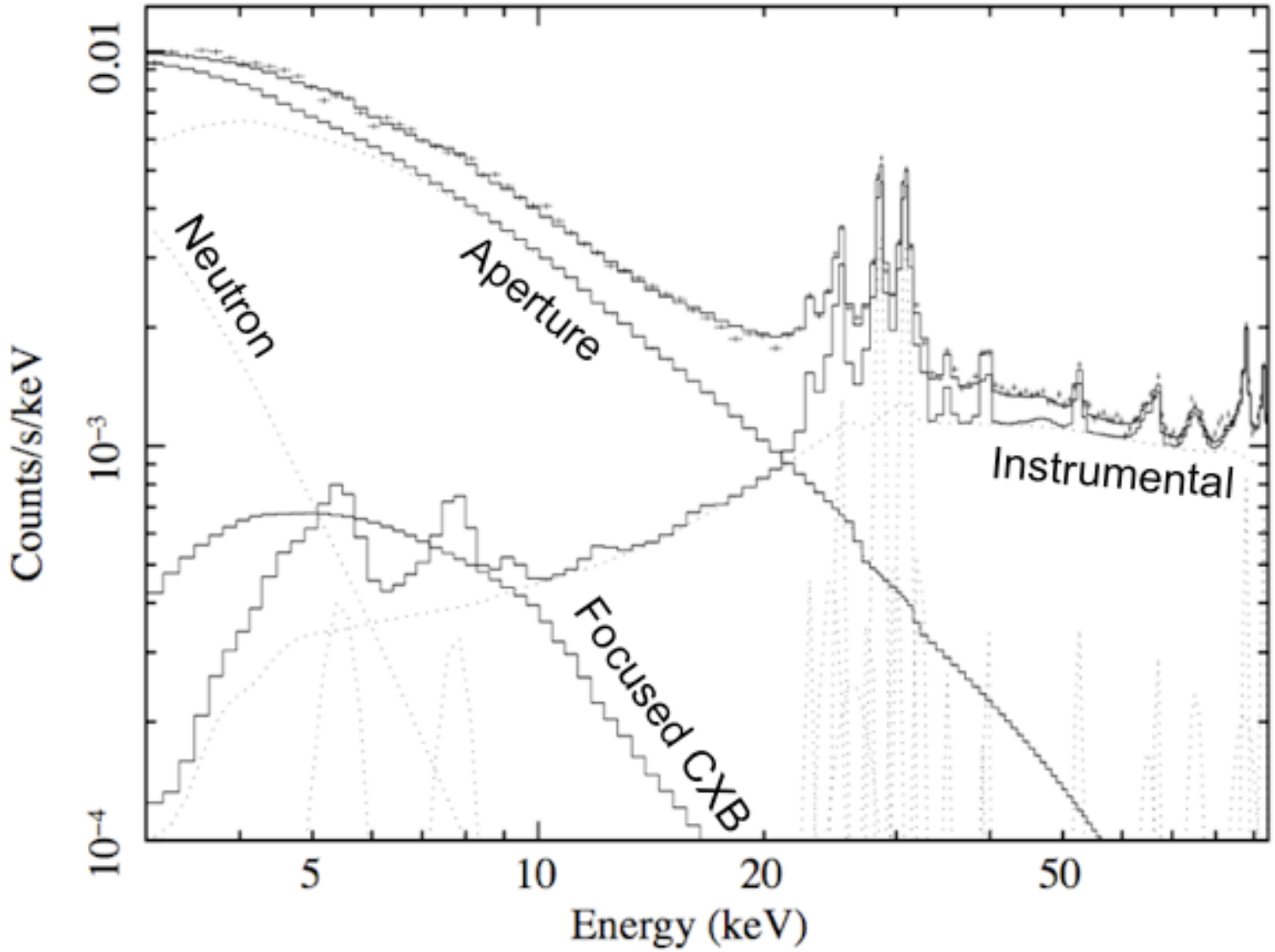
Part of the sky visible thru the aperture stop and not blocked by the optics bench (black) – the blue circles represent the FOV through the aperture stop at the 4 corners of the focal plane and are ~3 degrees in diameter

Cosmic X-ray Background (CXB)

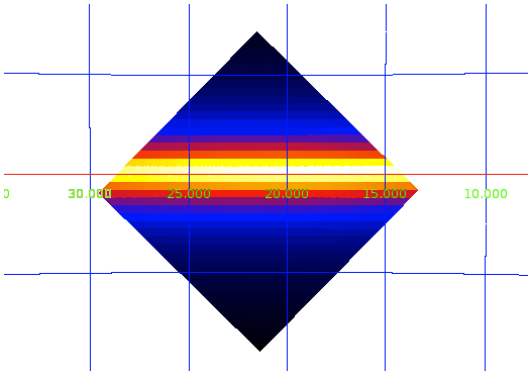


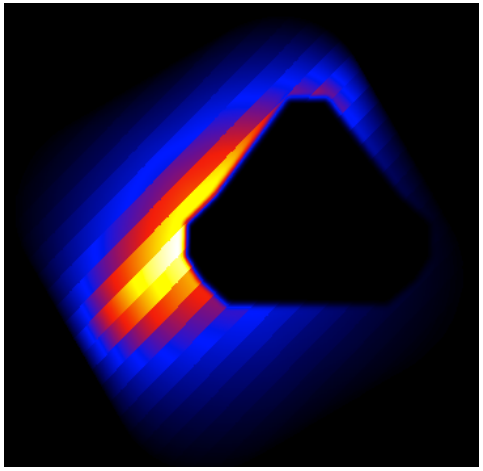
"Nominal" optical axis position

Spectral Model of CXB



Additional "aperture" flux component: Galactic X-ray Ridge Emission (GXRE)



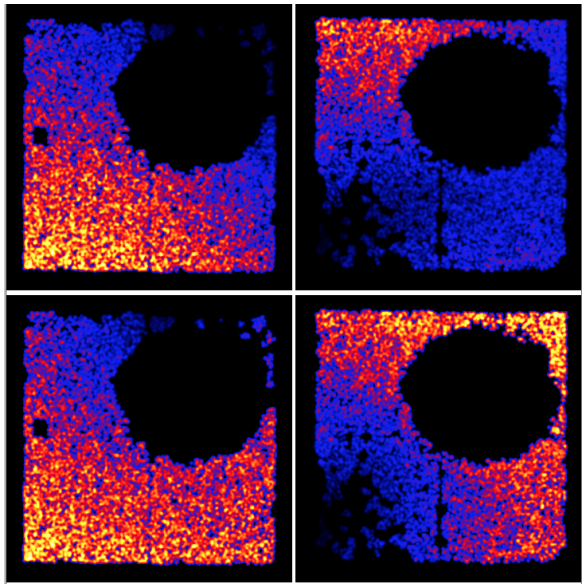


Spatial variation has a different shape based on the assumed spatial model of the GXRE.

Only important near galactic plane (<20 degrees latitude).

Top: Model of GXRE for G21.5

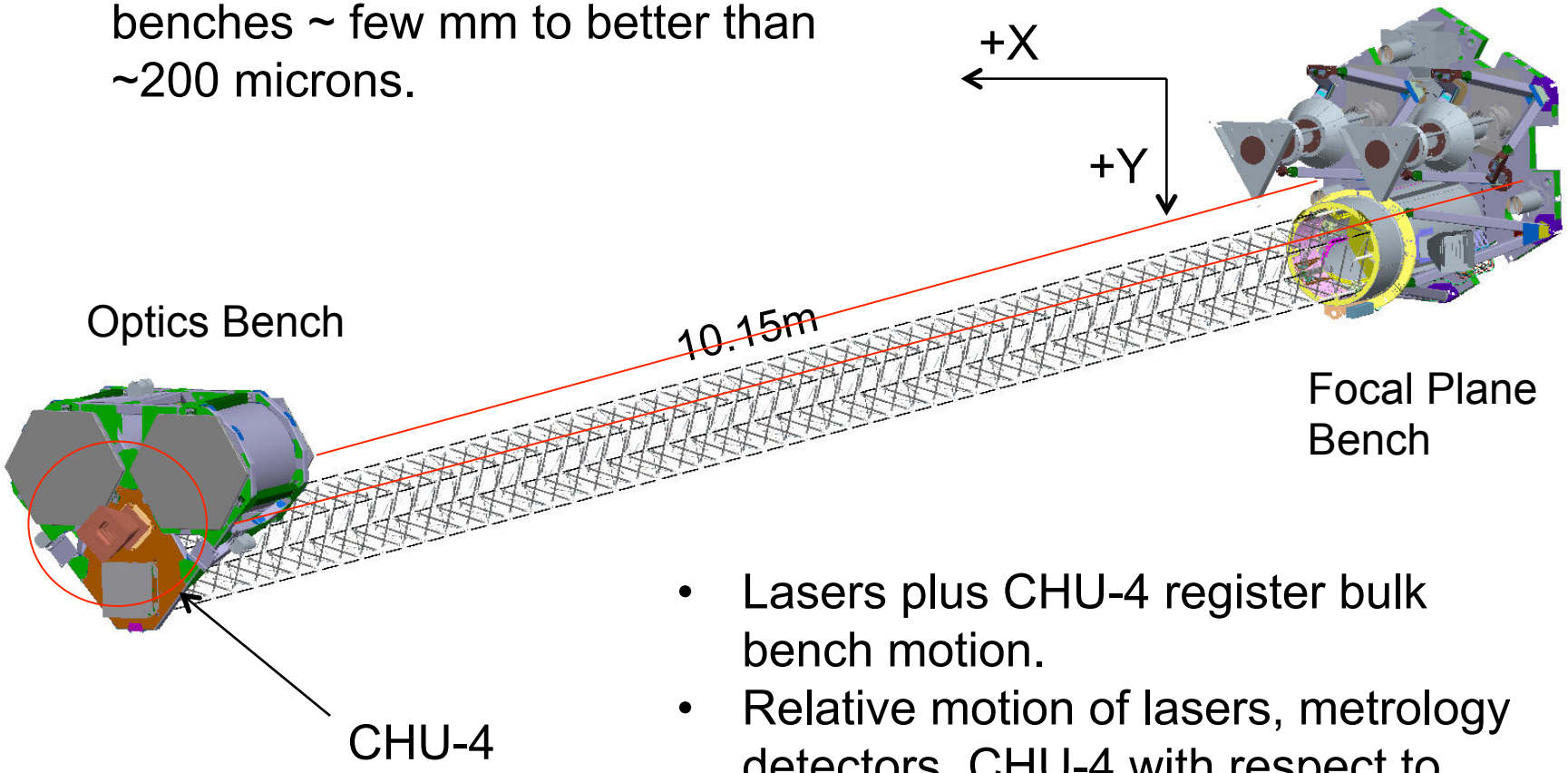
Bottom: Model of CXB for G21.5



Astrometry

Overview

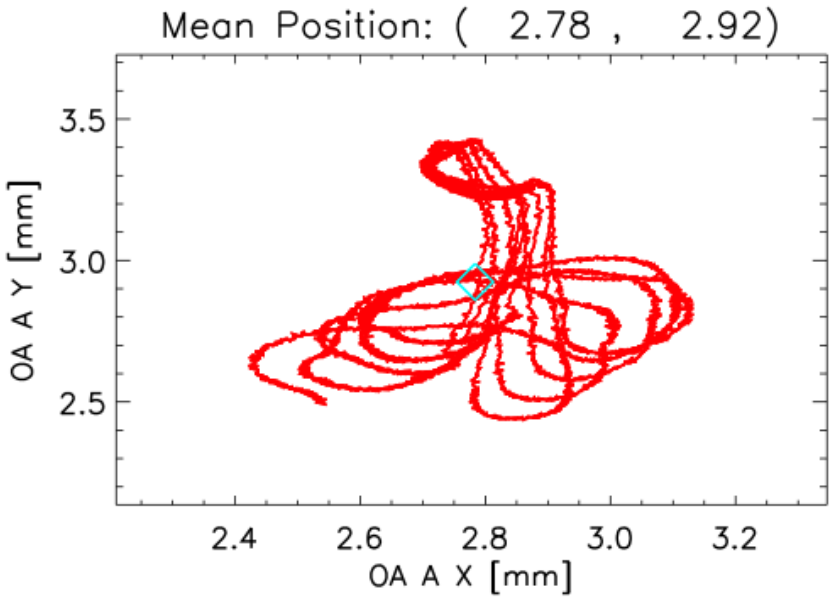
- Reconstruction challenge is to take out thermally driven motion of the benches ~ few mm to better than ~200 microns.

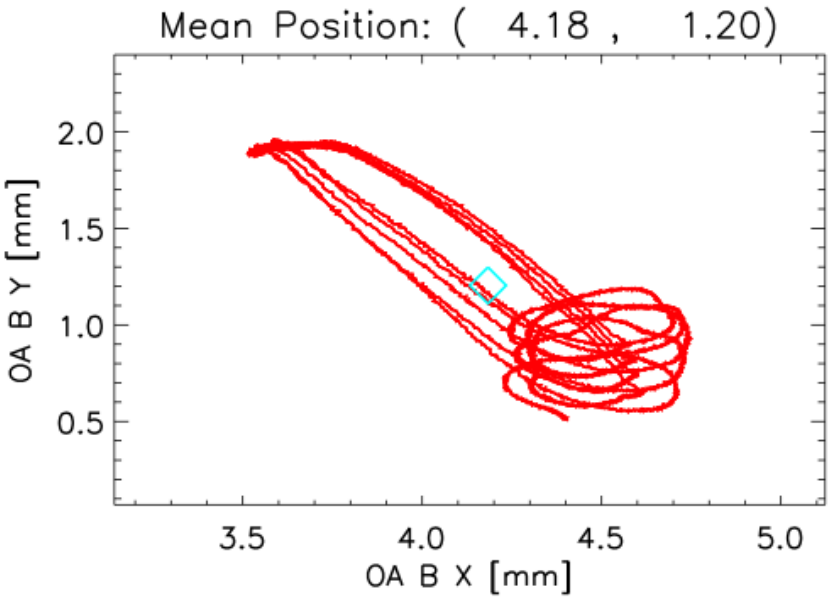


- Lasers plus CHU-4 register bulk bench motion.
- Relative motion of lasers, metrology detectors, CHU-4 with respect to bench is not measured.

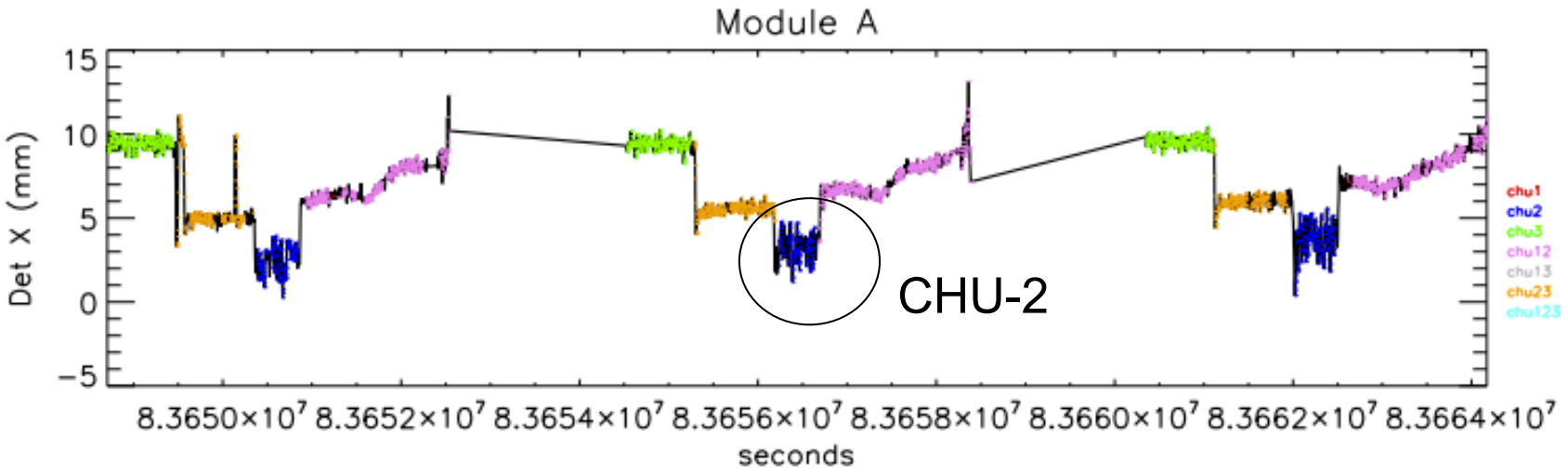
Registering the benches

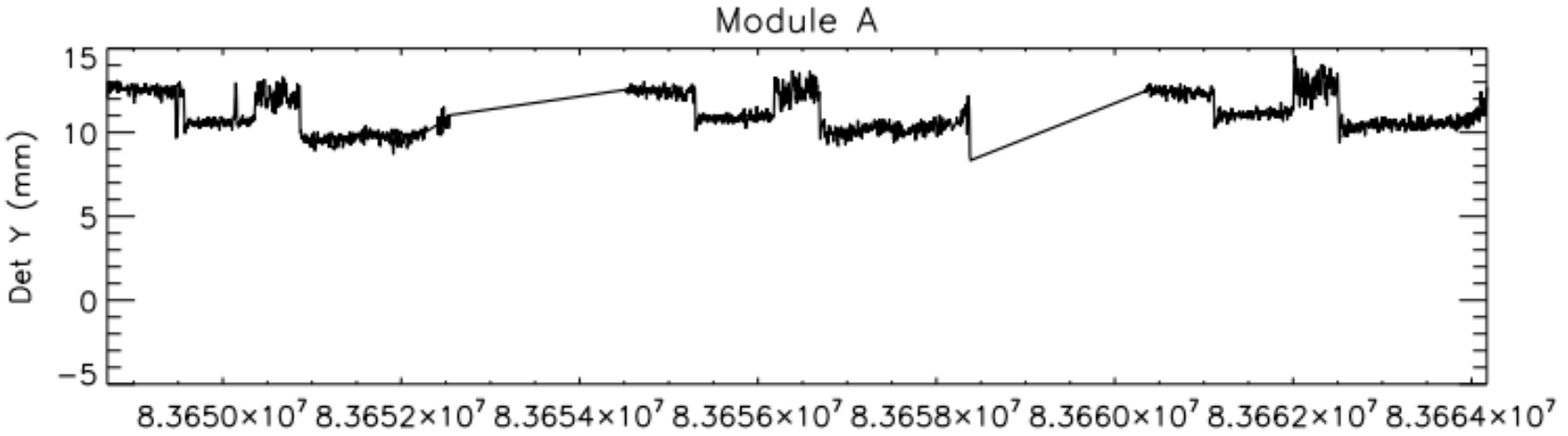
- Metrology traces typically range +/- 1 to 2 mm



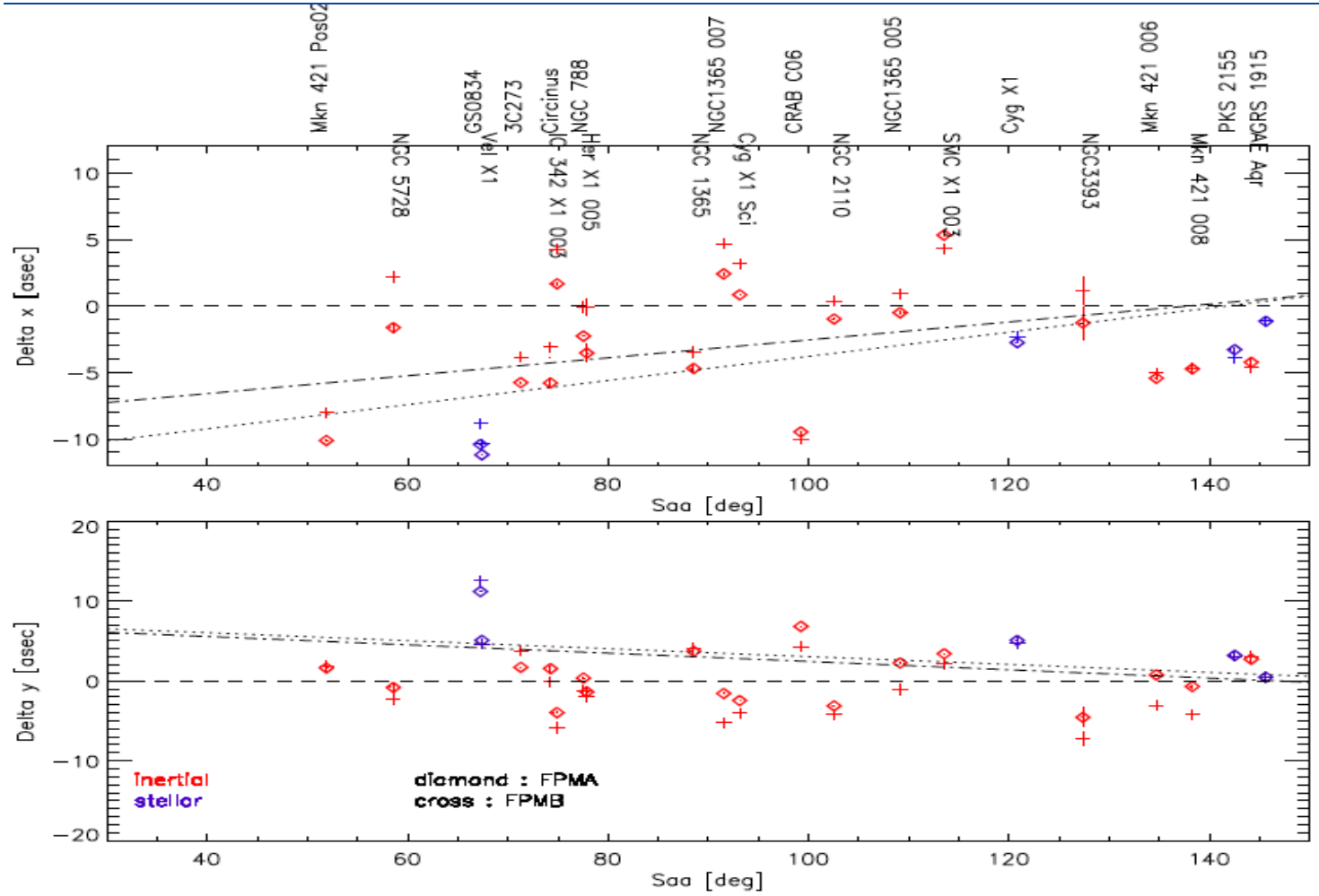


Pointing does not affect reconstruction but can influence PSF!



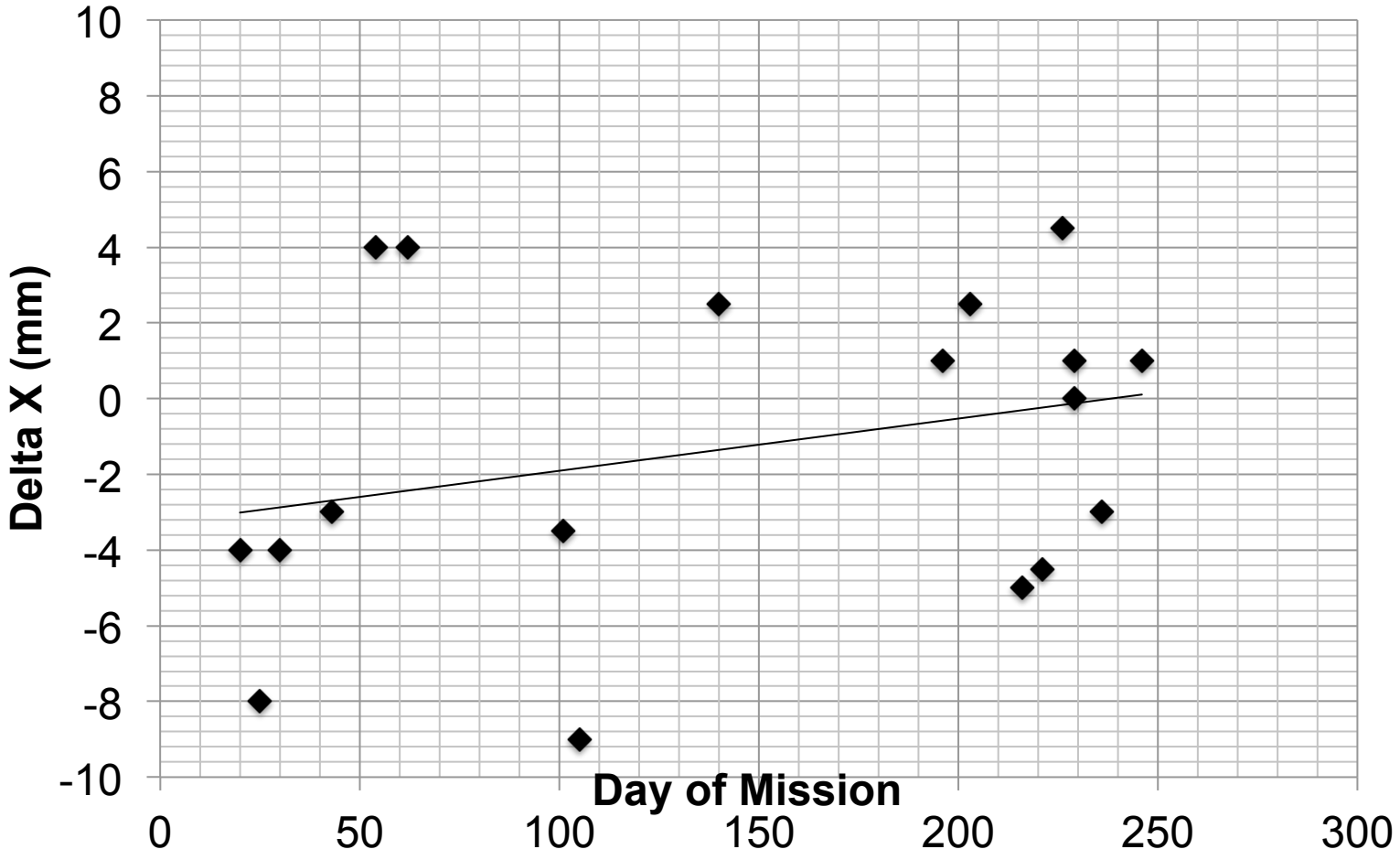


Absolute Astrometry: Sky X-Y

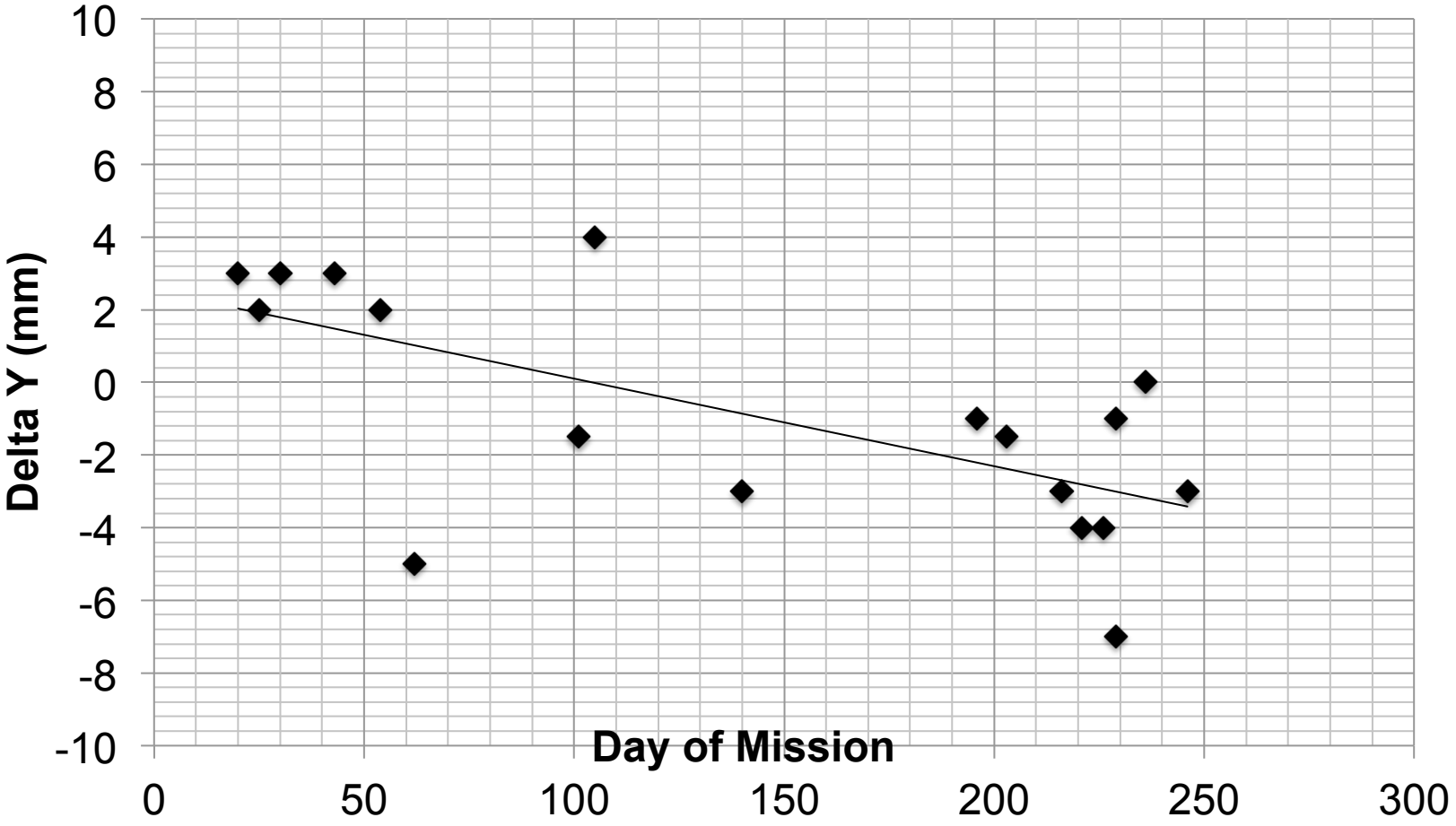


Absolute astrometry bounded by +/-7.5” in X, Y → 10” total with all points. Excluding 2 sources → 7” total

Delta X vs Day of Mission



Delta Y vs Day of Mission



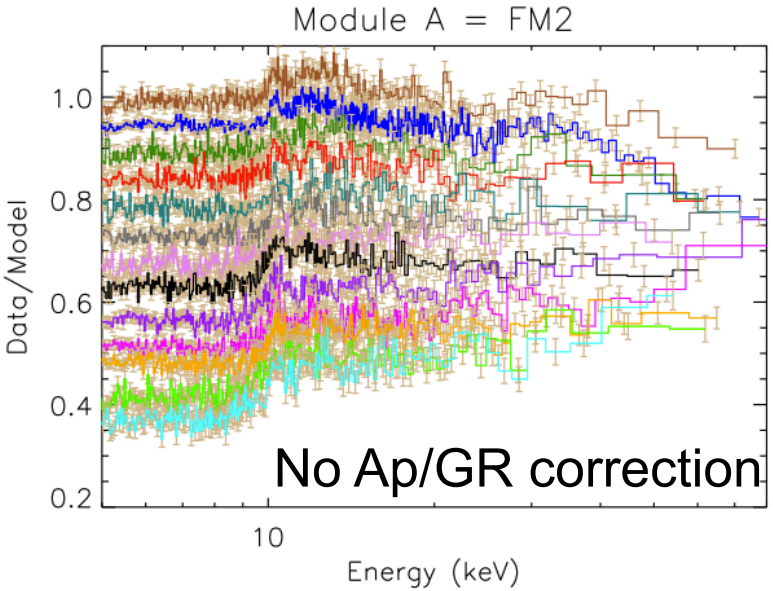
Summary

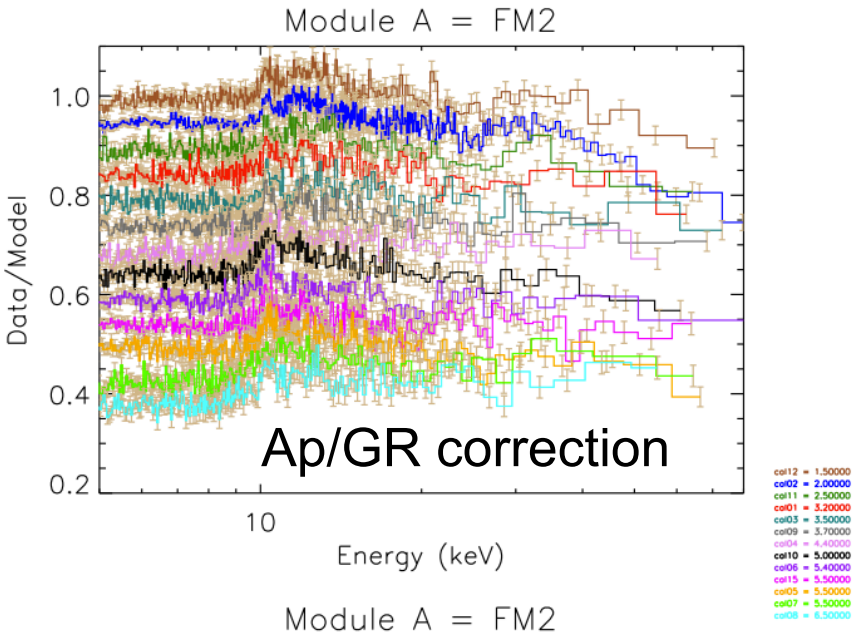
- Detectors
  - RMF
    - Good condition, ~5%
- Optics
  - ARF
    - 5 – 35 keV, ~5%
    - 35 – 40 keV, ~ 7-10%
    - 40 – 80 keV, ~ 30%
  - PSF
    - EEF, ~2%
- Background
  - Complex, but manageable
- Astrometry
  - +/- 10'' – Goal +/- 5''

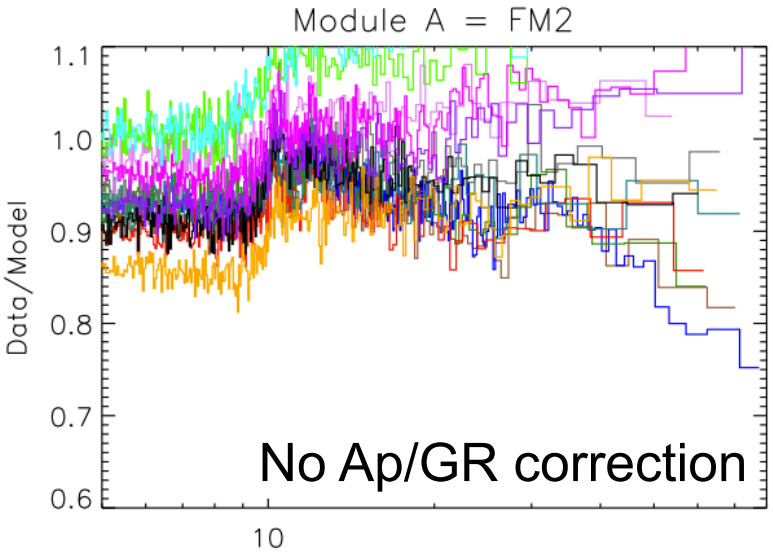
Any Questions?

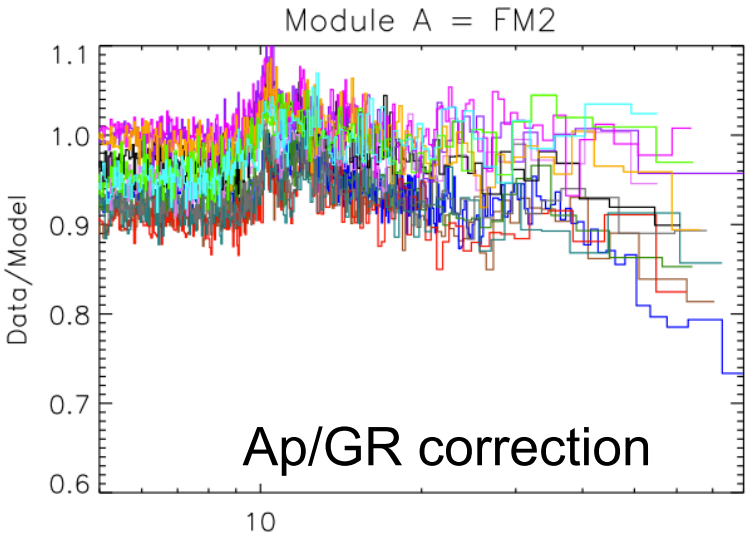
BACKUP slides

Module A Crab









Module B Crab