IACHEC 2019

NICER

Neutron star Interior Composition ExploreR

NICER Calibration Overview and Details

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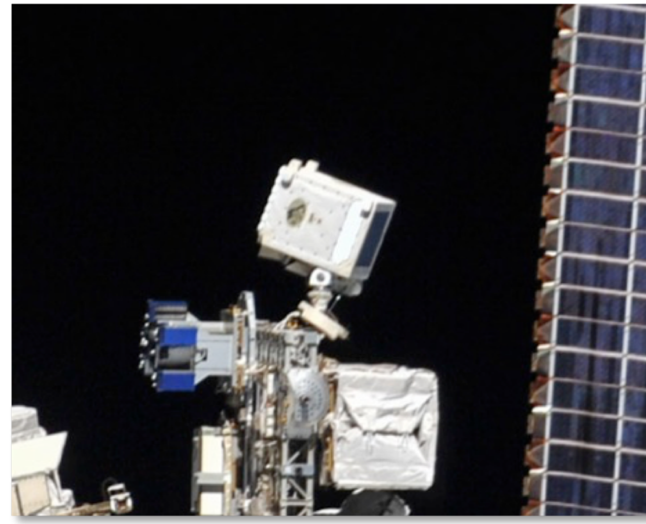
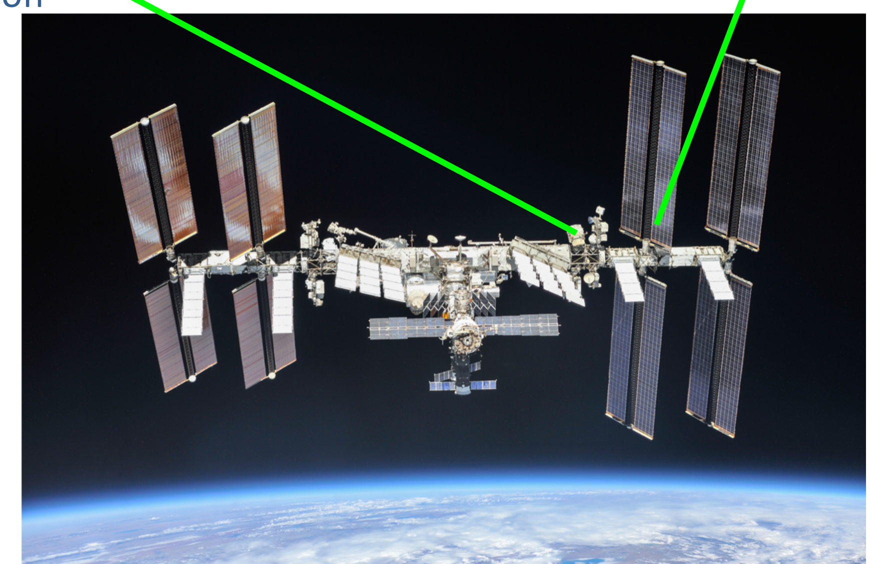
Backup

NICER: Astrophysics Mission of Opportunity on the International Space Station

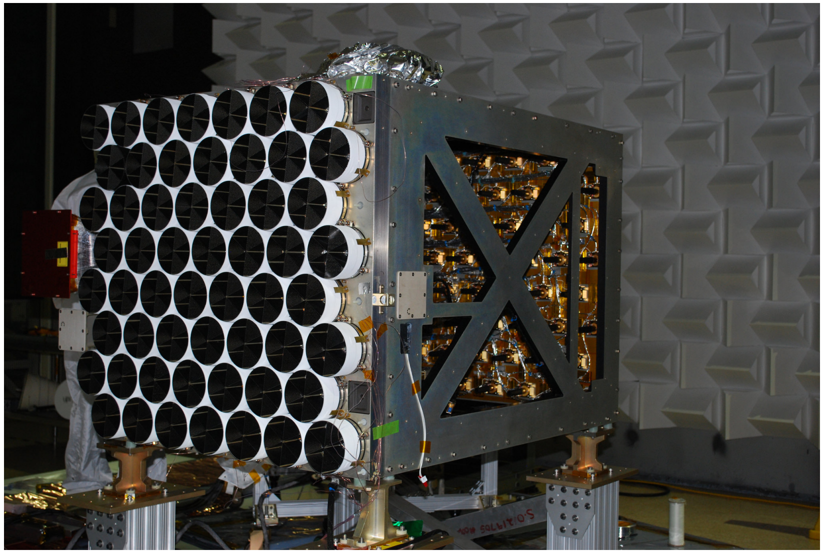
- PI: Keith Gendreau, NASA GSFC
- Science: Understanding ultra-dense matter via soft X-ray timing spectroscopy of neutron stars
- Platform: International Space Station ExPRESS Logistics Carrier external attached payload, with active pointing
- Launch: June 2017, SpaceX-11 resupply
- Duration: >= Sep 2019
- Instrument: X-ray (0.2–12 keV) “concentrator” optics and silicon-drift detectors; GPS position & absolute time tagging
- Enhancements:
  - Demonstration of pulsar-based navigation
  - Guest Observer program in Year 2+
- Status:
  - Public archive opened March 2018
  - GO Cycle 1 started March 2019
  - Awaiting Senior Review Results





NICER Layout

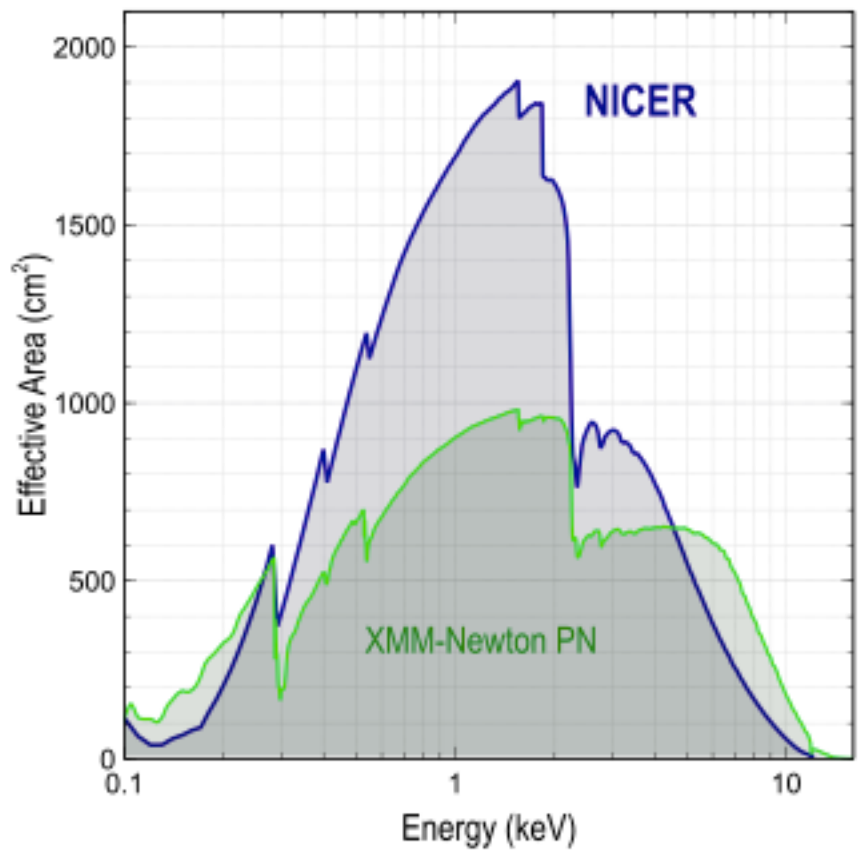
- NICER array consists of 56 co-aligned modules
  - Concentrator optic (XRCs)
  - X-ray silicon drift detectors (FPMs)
  - 4 modules are non-functional
    - broken before launch due to excessive testing per ISS requirements
- Each module must necessarily be calibrated separately to achieve full array calibration



Unique Capabilities, New Discovery Space

An unprecedented combination of sensitivity, timing, and energy resolution

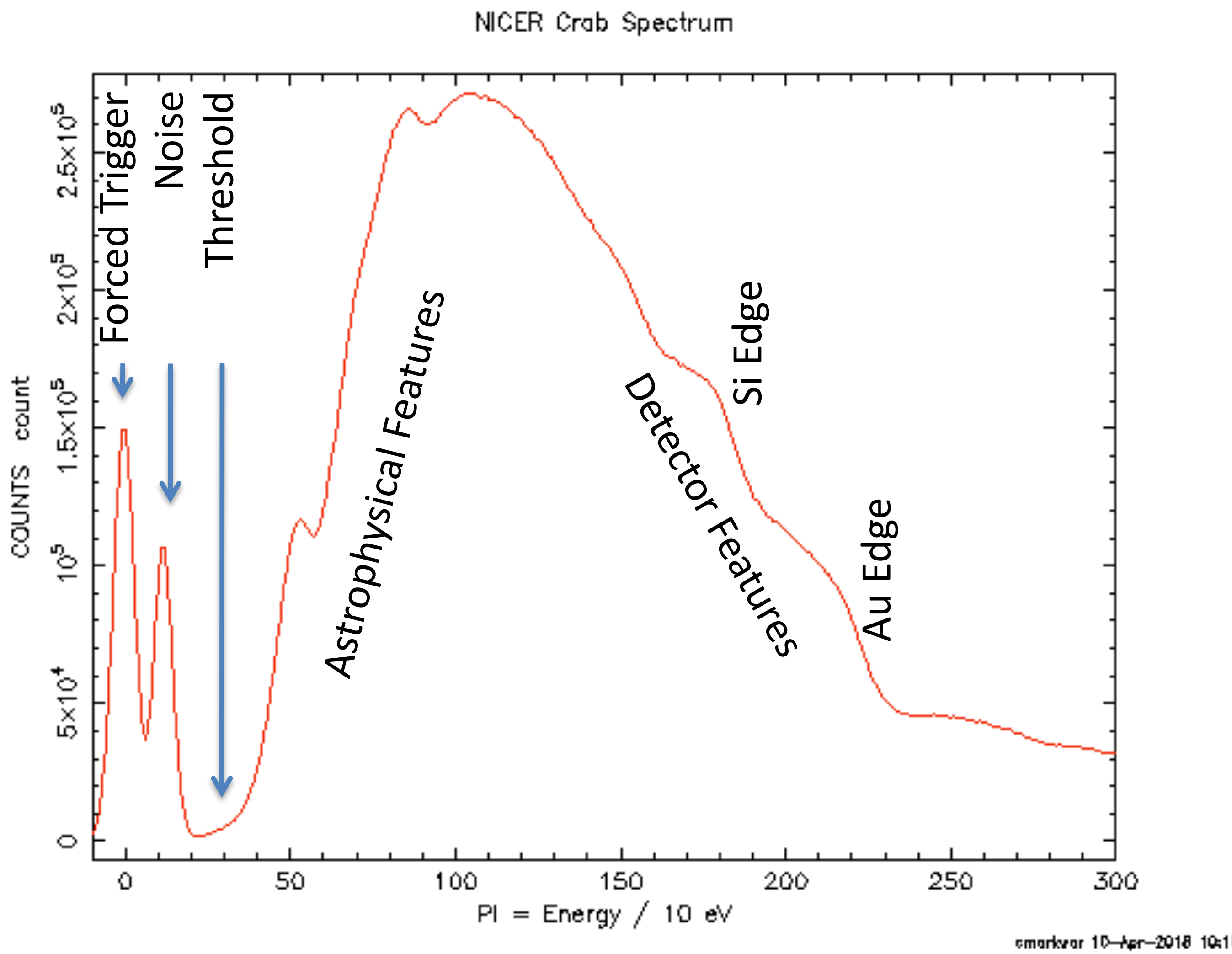
- Spectral band: 0.2–12 keV
  - Well matched to neutron star emissions
  - Overlaps RXTE, XMM-Newton, and other missions
- Energy resolution: < 150 eV @ 6 keV
  - 10x better than RXTE
- Timing resolution: 100 nsec RMS absolute
  - 50x better than RXTE
  - > 100x better than XMM-Newton
- Non-imaging FOV: 6 arcmin diameter
  - 10x finer than RXTE
- Sensitivity: 5.3 x 10^{-14} erg/s/cm^2 (5σ, Crab- like spectrum, 0.5–10 keV in 10 ksec)
  - 20x better than RXTE
  - 3x better than XMM-Newton's timing capability (PN clocked mode)



Calibration Effort Status

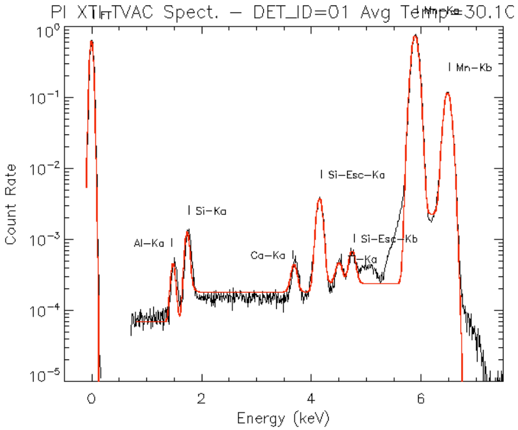
- Energy Scale – significant improvements since 2018
- Instrumental resolution: No additional changes this year
- ARF – major effort in 2018-2019
  - Relative module normalization
  - Mirror reflectivity parameters
  - Remaining issues
- Detector response
  - Resolution: ground and routine measurements
  - Redistribution: Scholze & Procop model
- Background
  - Two background modeling efforts are active now
- Timing
- Cross-calibration observations
- Module Alignment
- Contamination

"Typical" NICER Spectrum: Crab



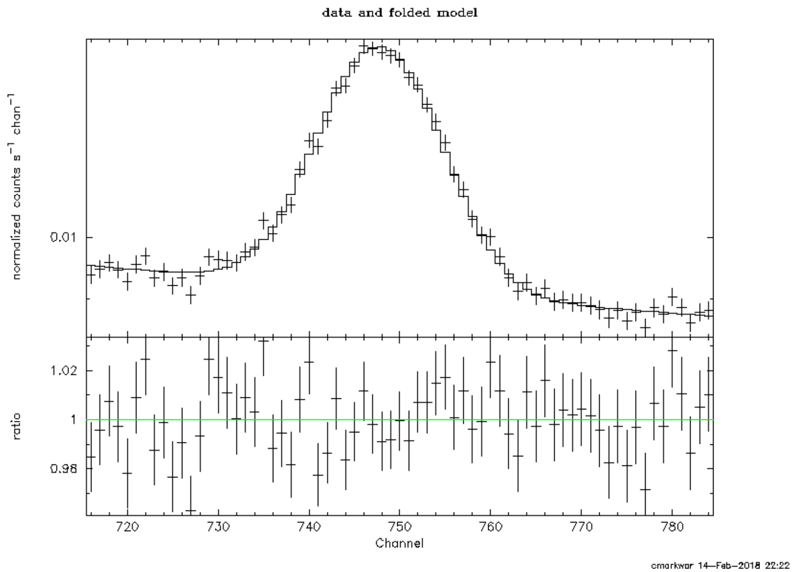
Gain Calibration Progress

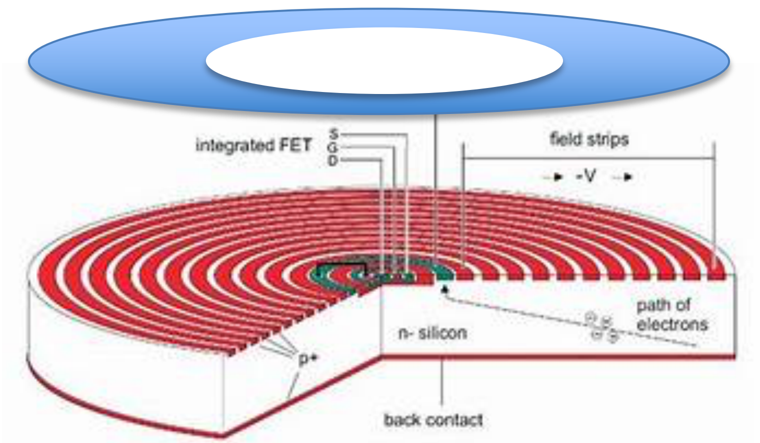
- Major progress since previous IACHEC meeting (new gain model "optmv7" in NICER CALDB)
- Ground calibration data was essentially discarded because of post-launch calibration shifts
- In-Flight Calibration
  - SAA radiation stimulated fluorescent lines
    - Si & Al fluorescent lines determined to be unreliable
    - Au L lines used but with low weighting: not always reliable
  - Astrophysical Targets
    - Vela X-1: 6.4 sharp line (heavily weighted)
    - E0102: O & Ne line complex < 1 keV
    - Crab
      - 2.2 keV Au mirror edge feature
      - Interstellar medium O absorption feature
      - 11.9 keV Au L absorption feature
- No evidence of long-term energy scale or resolution shifts
- Optical Light loading shifts gain but is corrected using HK data



In-Flight Gain Calibration: SAA

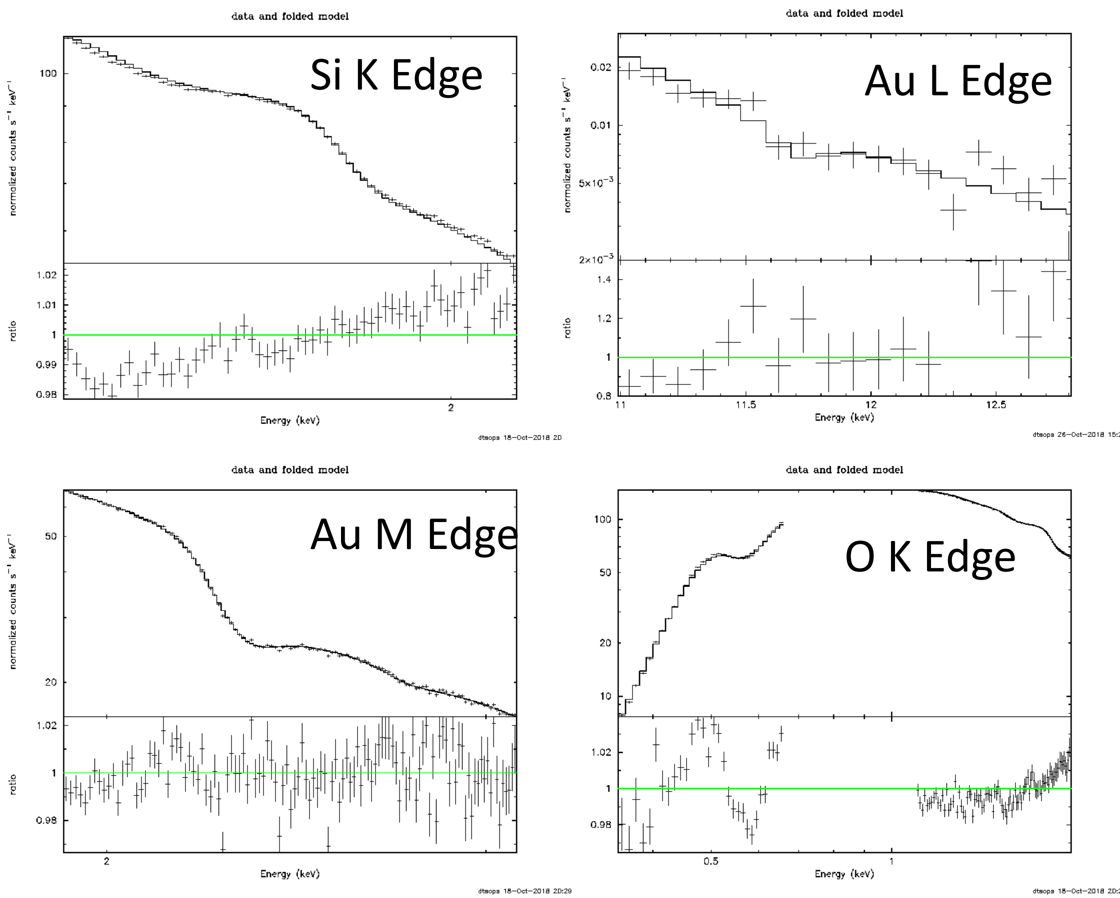
- During SAA passages, fluorescence lines present, due to materials near detector
- Al Ka 1.483 keV
  Si Ka 1.739 keV
  Ni Ka 7.478 keV
  Au La 9.715 keV
  Au Lb 11.442 keV
  Au Lg 13.330 keV
- These lines were determined to be **less reliable** because of additional charge cloud diffusion and charge losses
- Use data of astronomical sources for calibration.





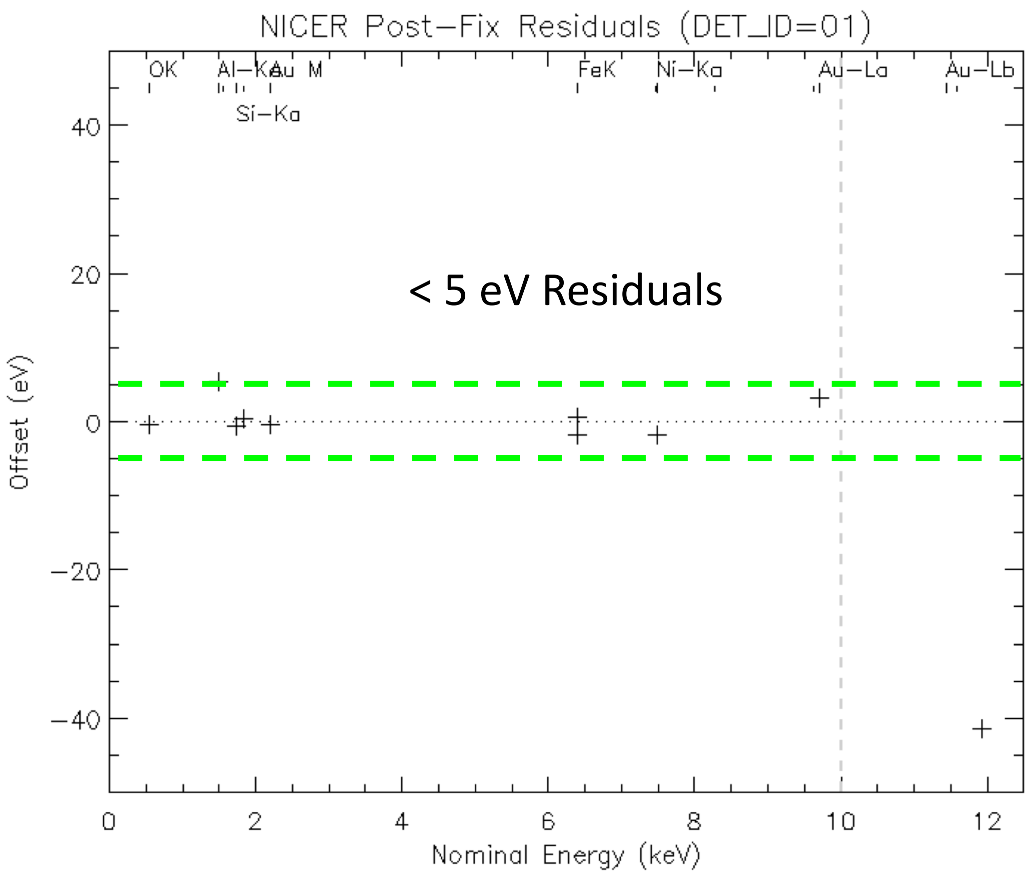
Crab Fits for Gain Scale

Highest weighting: Au M Edge & O K Edge

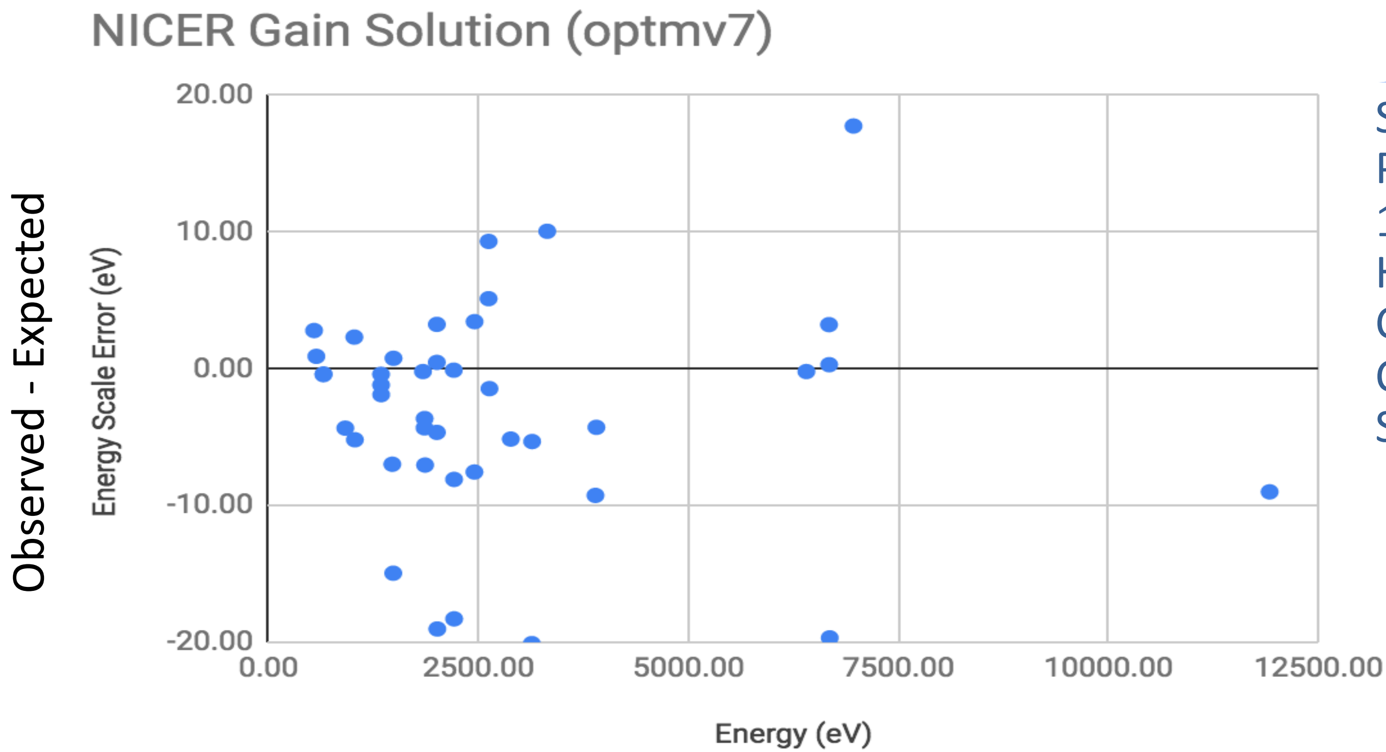


Per-Detector Gain Shift Fit

- Residuals for a single detector and measured calibration line positions



Full Array Gain Calibration: Astrophysical Targets



Samples: GX301-2, Perseus Cluster, WR 140, Eta Car, Cas A, HR 1099, Coma Cluster, E0102, N132, Cen X-3, Vela X-1, SAA, UX Ari, GT Mus

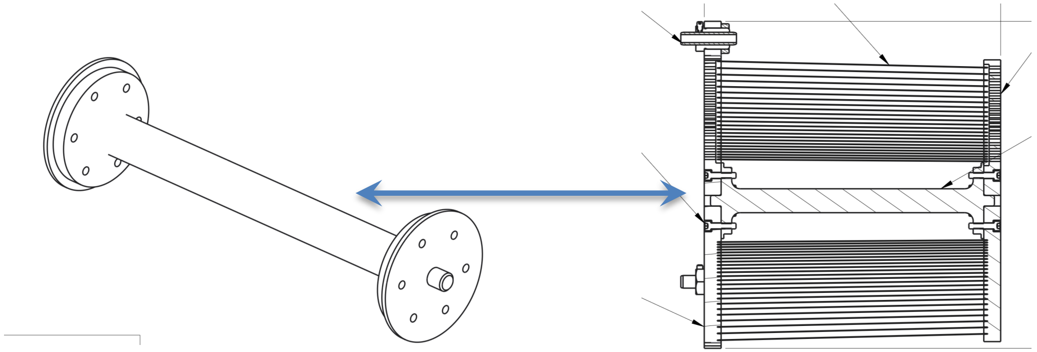
- Performance after 2018 Oct
  - **~5 eV (0.25 - 10 keV)**
  - **~20 eV (> 10 keV)**
- From the previous model, the gain shifts
  - **~30 eV below 6 keV**
  - **~200 eV below 12 keV**

Effective Area (ARF)

- Major effort this year to improve the ARF is still under way, not complete
- Current ARF
  - Based on “semi-analytical” code of Teruaki Enoto-san
  - This model does OK, but is limited by approximations it makes without ray-tracing
- Development efforts
  - CONSIM - ray tracing code (see next charts)

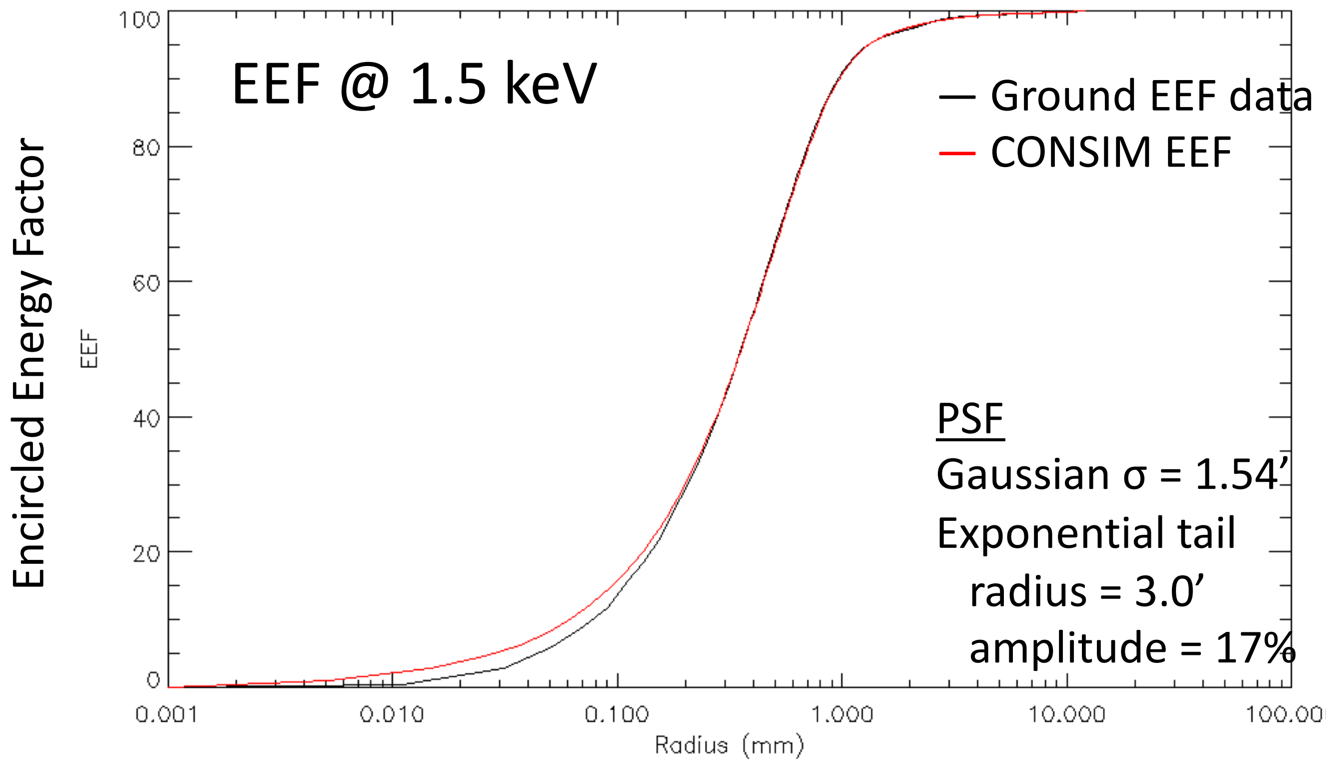
CONSIM: NICER X-ray Raytrace Code

- CONSIM (“CONcentrator SIMulator”) ray-tracing code for NICER geometry
  - Heritage of ASCARAY from the 1990s
  - Updated with newest gold reflectivity constants from Hitomi team
- NICER geometry has been brought up to date with best information
  - Inclusion of “dumbbell” is key change
- Improved X-ray scattering physics
  - Old physics in code was empirical and not based on real scattering physics
- Re-adjustment of “PSF” parameters based on new CONSIM and new scattering physics, to match ground-based lab PSF measurements



CONSIM Scattering / PSF Improvements

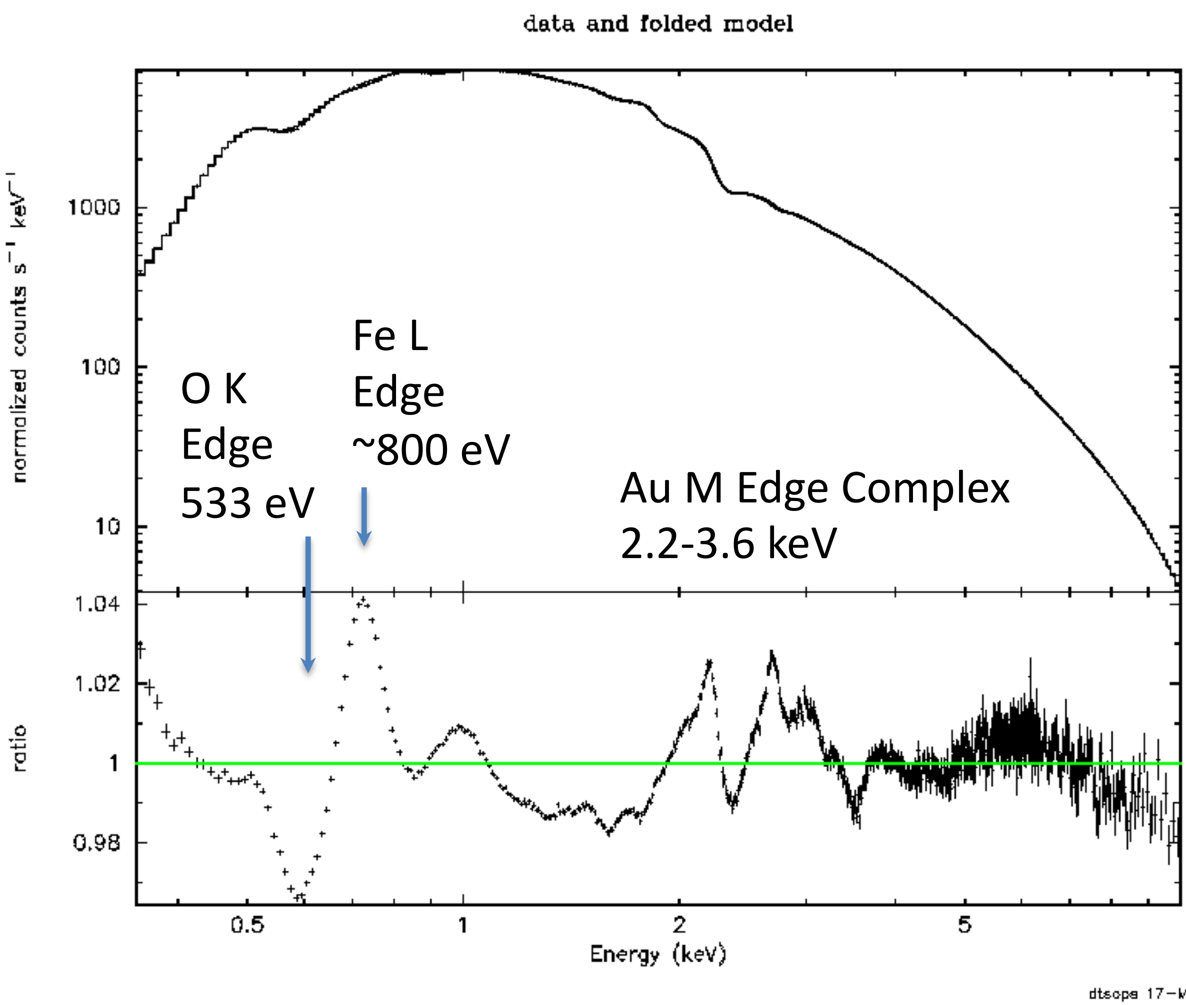
- Rayleigh-Rice X-ray scattering theory implemented properly in CONSIM, Au surface roughness 3.1 Å
  - PSF parameters matched to ground data



NICER ARF Performance: Crab

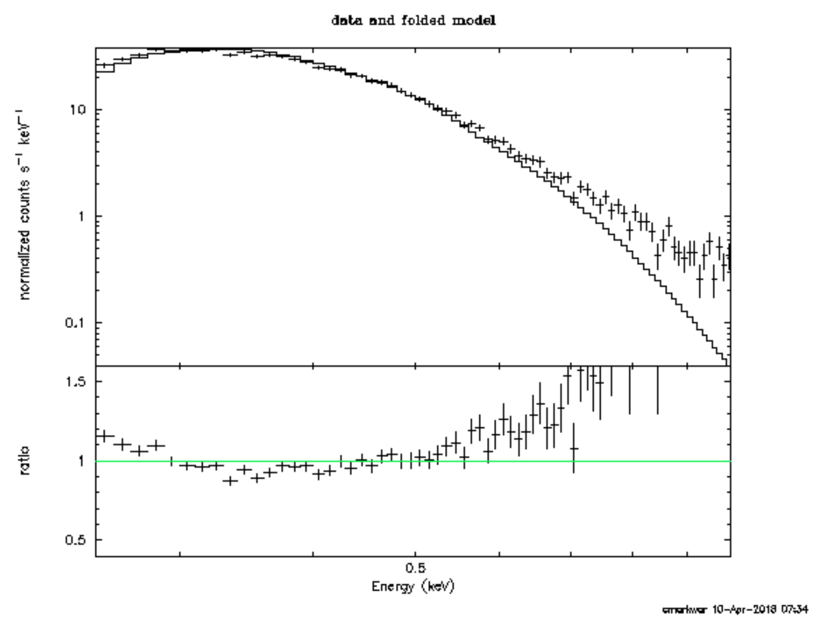
- $N_H = 0.38$ cm^{-2}
- $\Gamma = 2.11$
- F[3-50 keV] = 2.94 x 10^{-8} cgs
  - 13% low from Madsen+2017

- Residuals < 3%
- O K and Fe L edge residuals should be astrophysical (XMM grating; Kaastra+2009)
- Au M edge complex
  - Likely to be small gain errors ~5 eV and gold reflectivity differences

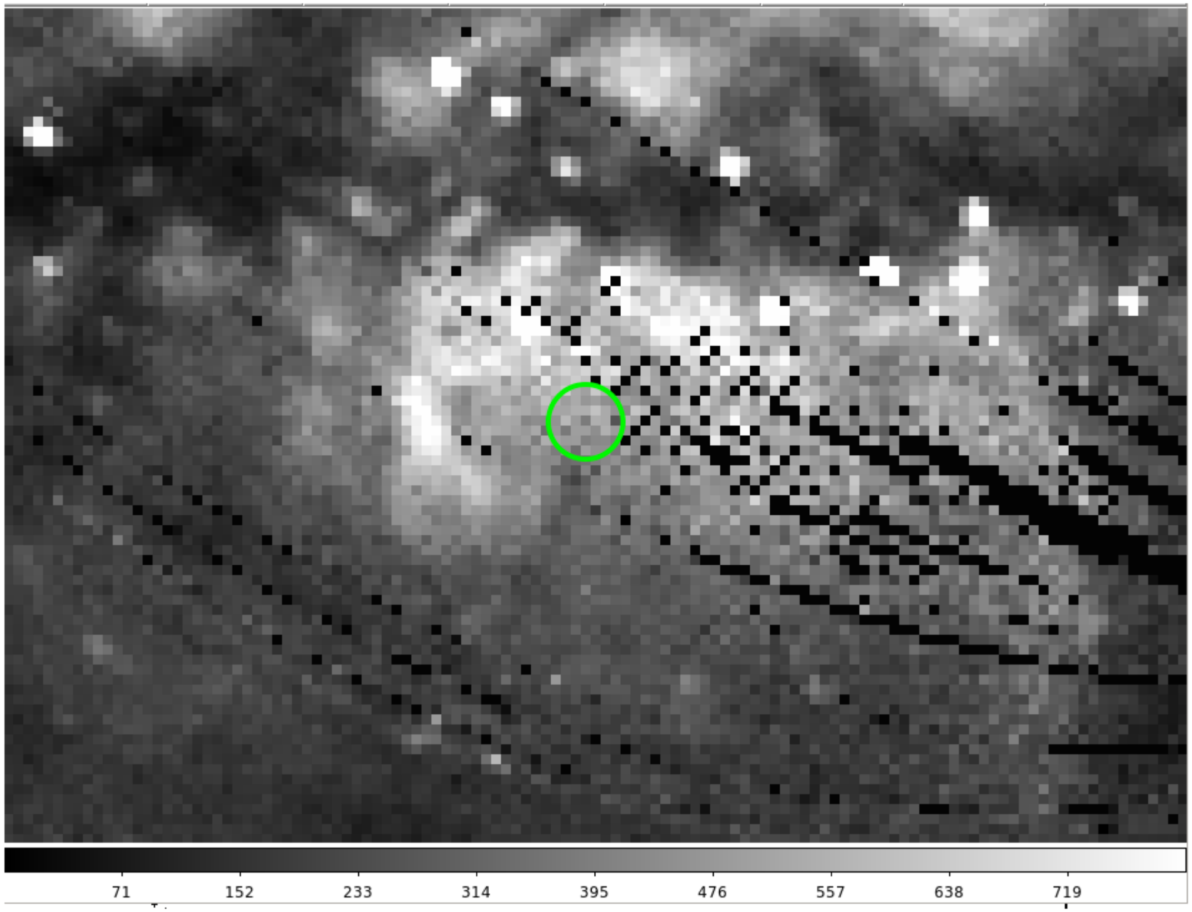


NICER ARF Performance: RX J1856.6-3754

- RX J1856.6-3754: isolated neutron star
  - soft spectrum (kT < 65 eV, low NH)
  - constant intensity (assumed)
- Claims of a hard tail (Yoneyama+2017, Suzaku XIS)
  - NICER sees it too, but …

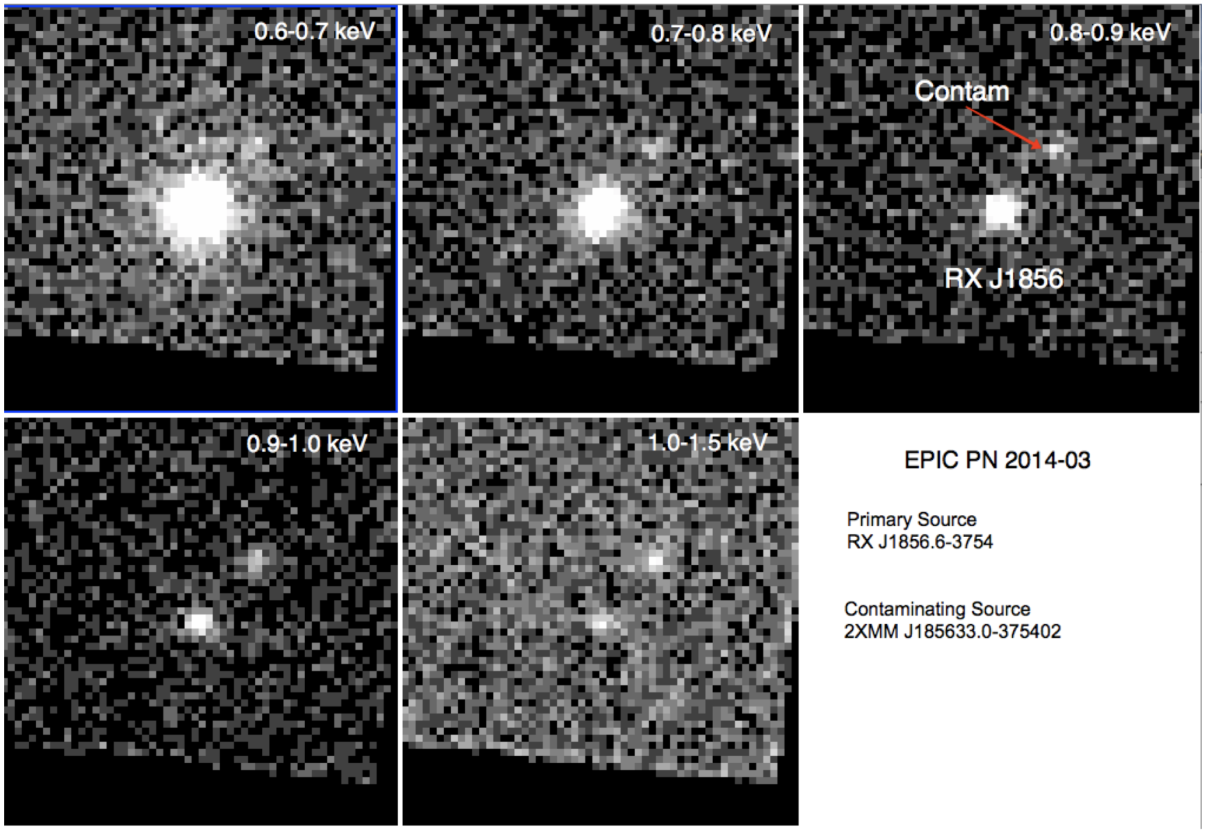


RX J1856 Diffuse Emission



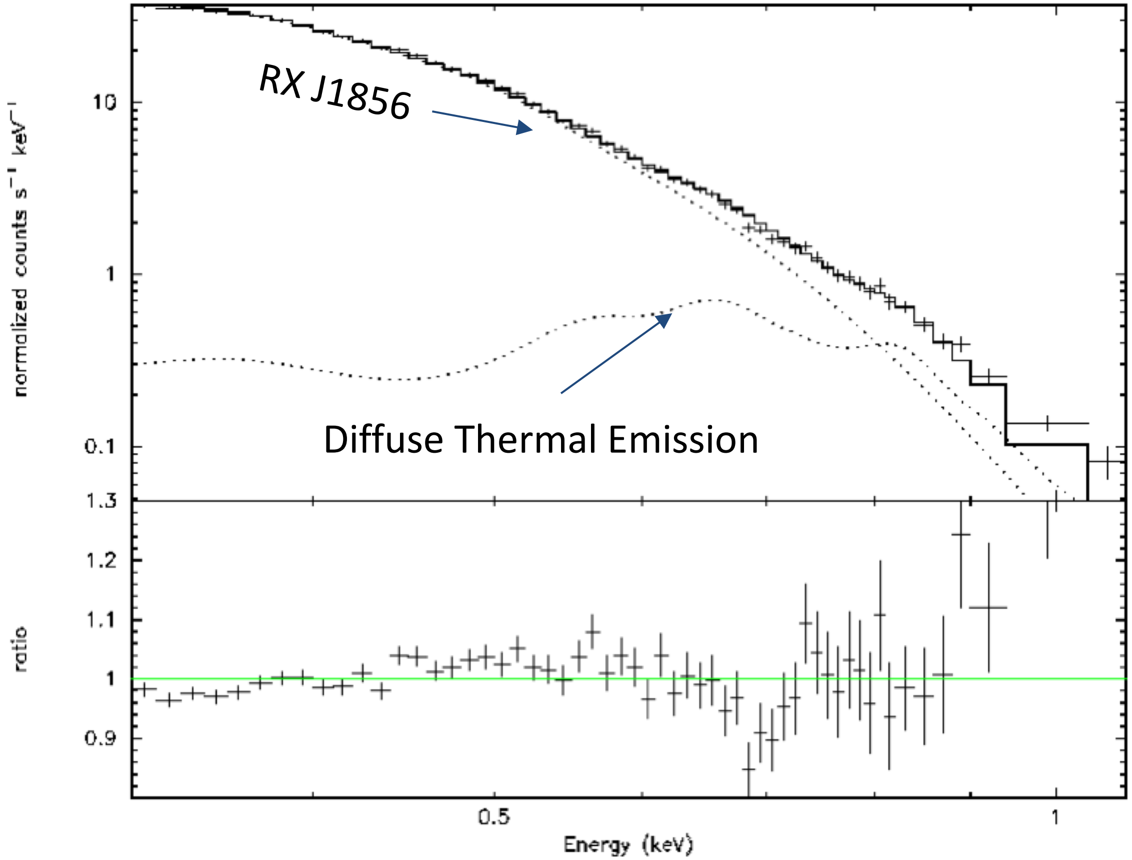
ROSAT All-Sky Survey ¾ keV ~ 500 ct/s/arcmin^2

RX J1856 Nearby Contaminator



Hard source 38” from RX J1856, spectrum consistent with kT=140 eV, highly variable on timescale of weeks-years; likely to be excess seen by Yoneyama et al 2017; far enough away to not contaminate XMM or Chandra spectra

RX J1856 NICER Spectrum



Spectral shape fixed at IACHEC values (NICER norm 93%), diffuse emission is consistent with ROSAT levels.

The norm difference will probably be fixed after including the effect of misalignments between modules in response.

NICER ARF Summary / Future work

- Significant effort in past year to improve ARF
- Instrumental residual artifacts < 2-3%
- NICER flux ~10% low compared to other observatories
- Future work - near term
  - team validation of current effort
  - summation of ARF using known per-module alignment offsets and relative norms
  - inclusion of new low energy threshold info (<350 eV)
- Far term
  - Response calculator using per-observation off-axis and resolution information

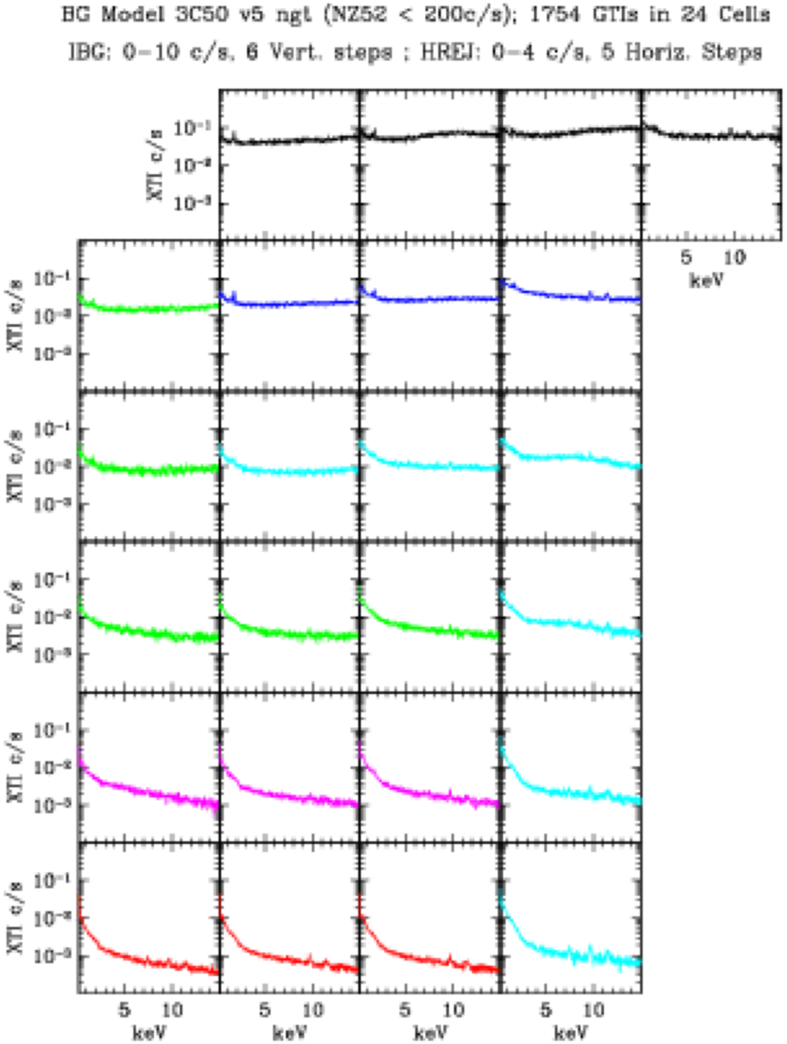
Background Modeling

- NICER is a non-imaging instrument
- Background modeling required to improve subtraction of background components
- To date, NICER has completed more than 1 Ms of background calibration observations in various orbital environments
  - different geomagnetic conditions
  - different solar activity levels
  - different day/night optical illumination
- NICER requires background proxy variable(s).

Event Driven Method

- 3C50 (current version: RGv5)
  - Developed by R. Remillard (MIT)
- Proxy variables are
  - "IBG" - 15-18 keV (outband) counts
  - "HREJ" - rejected counts based on pulse shape cut
  - Noise counts in low channels
- Library of spectra binned by these variables
- AWK scripts to assemble estimated background based on orbit conditions
- HEASoft-based script in development (M. Loewenstein)

3C50 Library of Background Spectra



Space Weather Method

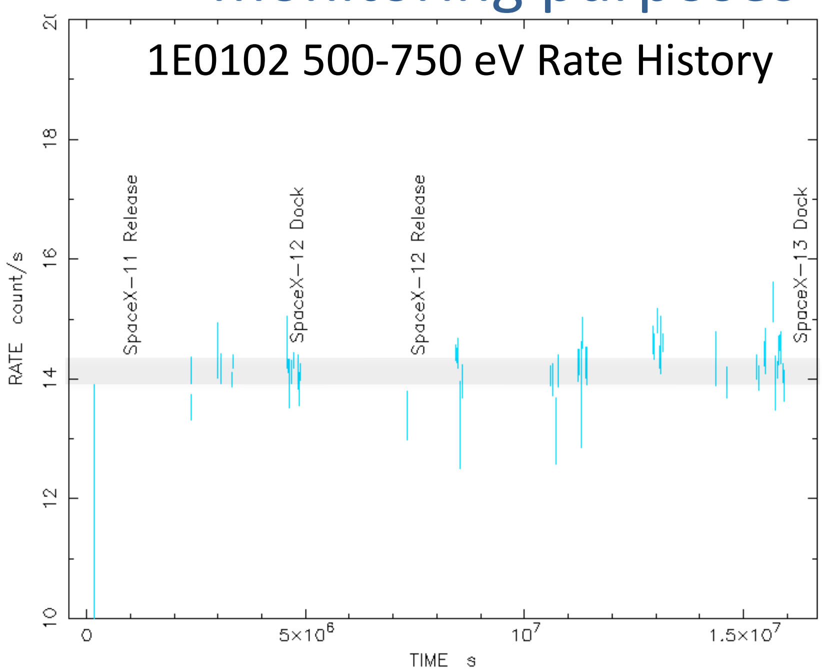
- Developed by K. Gendreau & M. Corcoran (GSFC)
- Proxy variables
  - COR - magnetic cut-off rigidity
  - Kp - solar activity level
  - Noise counts
- Library of spectra binned by these variables
- Developments
  - Currently, the tool is available for internal team only for testing
  - Soon, scripts and data files will be available for outside users to generate estimates

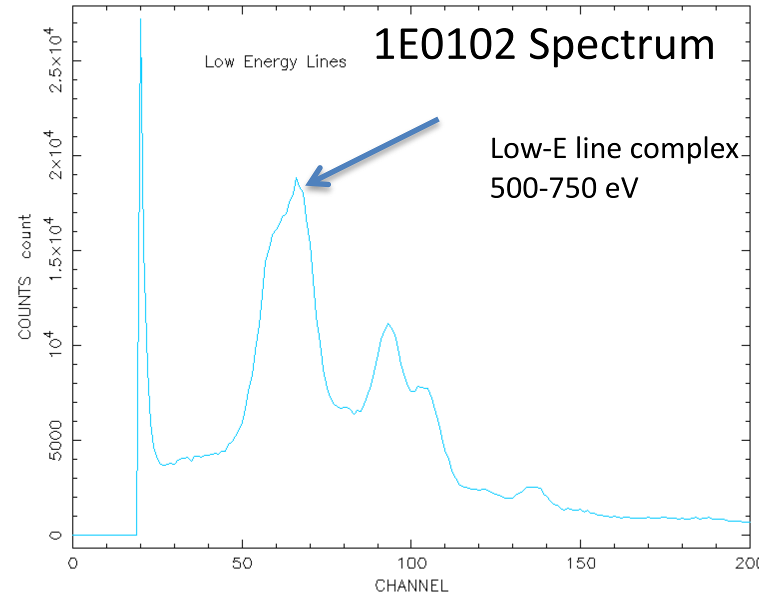
Background Modeling Summaries

- These models are capable of capturing background variations at the ~20% level
- Both of these methods are not perfect because of
  - imperfect interpolation - spectra are binned by proxy variable
  - imperfect proxy variables - may not always capture true nature of background environment
- Development effort will continue to improve these models

NICER Detects No Contamination

- NICER routinely observes 1E0102 supernova
  - Gain and contamination monitoring purposes





- Several events which potentially emit contamination
  - ISS solar panels (sealant outgassing)
  - ISS radiators (ammonia)
  - Ferry vehicles (propellant)
- We have measures of contamination on-board from SAGE III QCM
- **No evidence of response degradation due to contamination build-up on windows or detectors (at few percent level)**

NICER Calibration Summary

- Gain calibration: improved to <5 eV in 2018/2019
- ARF calibration
  - overall normalization appears low by about 10%
  - residual features improved to < 2% in 2018/2019
- Instrumental redistribution
  - ~140 eV FWHM (no change)
  - 200-300 eV threshold response curves (no change)
- Background modeling - new efforts 2018/2019
  - capable of capturing background variations at the ~10-20% level
- Detector window contamination - none seen
- Module co-alignment - ~20” (no change)
- Timing chain - 86 ns rms (no change)

Backup of Backup

NICER Calibration Activities

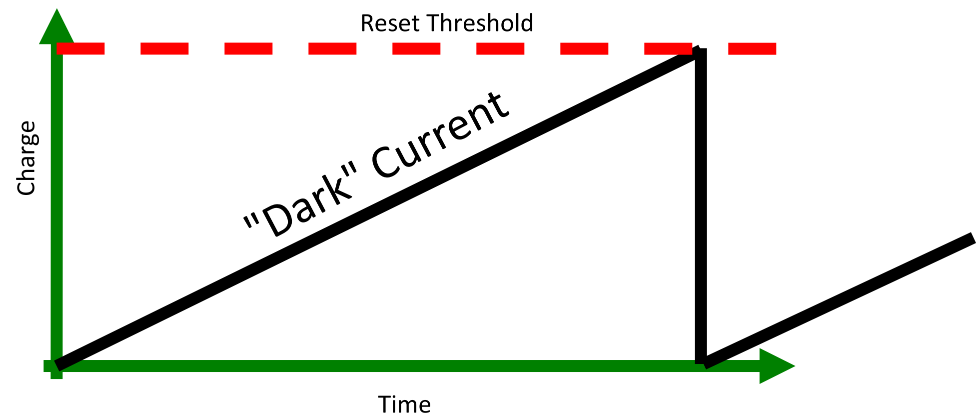
- NICER Focal Plane Modules Developed at MIT
  - Calibration activities: Bev LaMarr, Ron Remillard, Gregory Prigozhin, Jack Steiner
- NICER X-ray Concentrator optics developed at GSFC
  - Calibration activities: Okajima, Markwardt, Arzoumanian, Gendreau, Enoto
- NICER In-Flight Calibration Effort (GSFC leads)
  - Detector response: MIT
  - Mirror effective area: GSFC
  - Background: MIT & GSFC

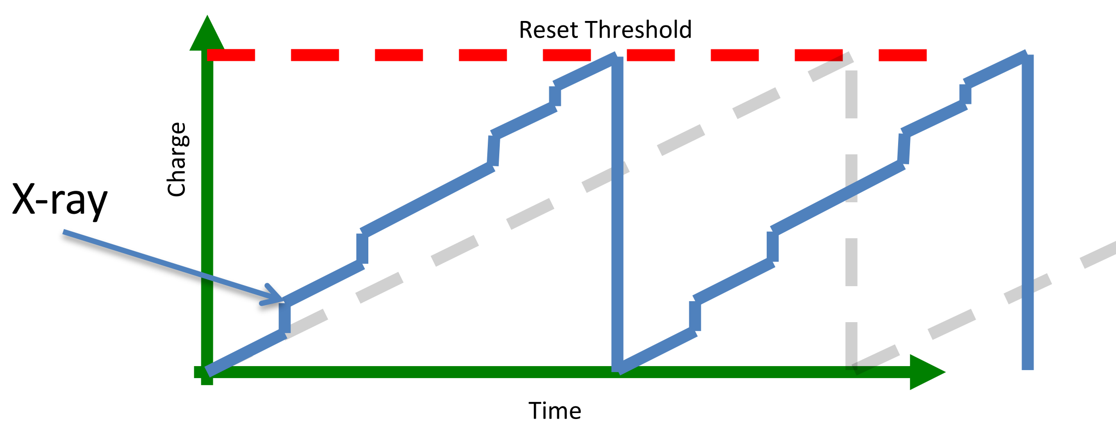
"Typical" NICER Spectrum: Crab

- ~0 eV - “Forced Trigger” - software readout of no-signal voltage
- 120-180 eV - Noise peak - noise events that survive threshold cut, but appear below threshold
- 200-300 eV - electronics LLD threshold transition
- 533 eV - O K edge (detector, windows)
- 1.83 keV - Si K detector edge
- 2.2 keV - Au M edge complex of concentrator optics

How NICER Detectors Work

- Amplified charge appears on capacitor and discharges after full capacity (Undershoot)
- Routine measurement of no-signal (Forced Trigger)





Two Shaping Circuits

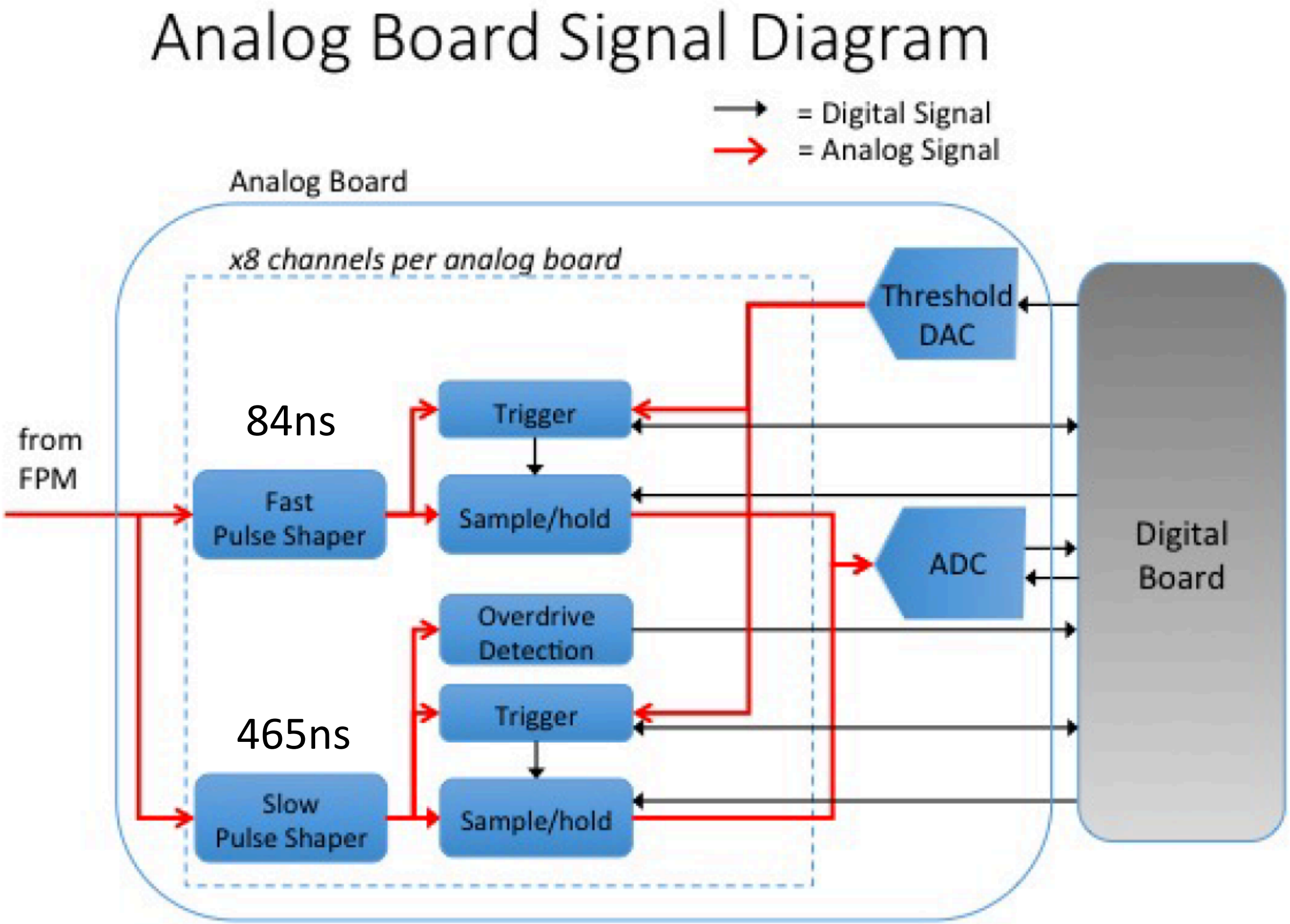
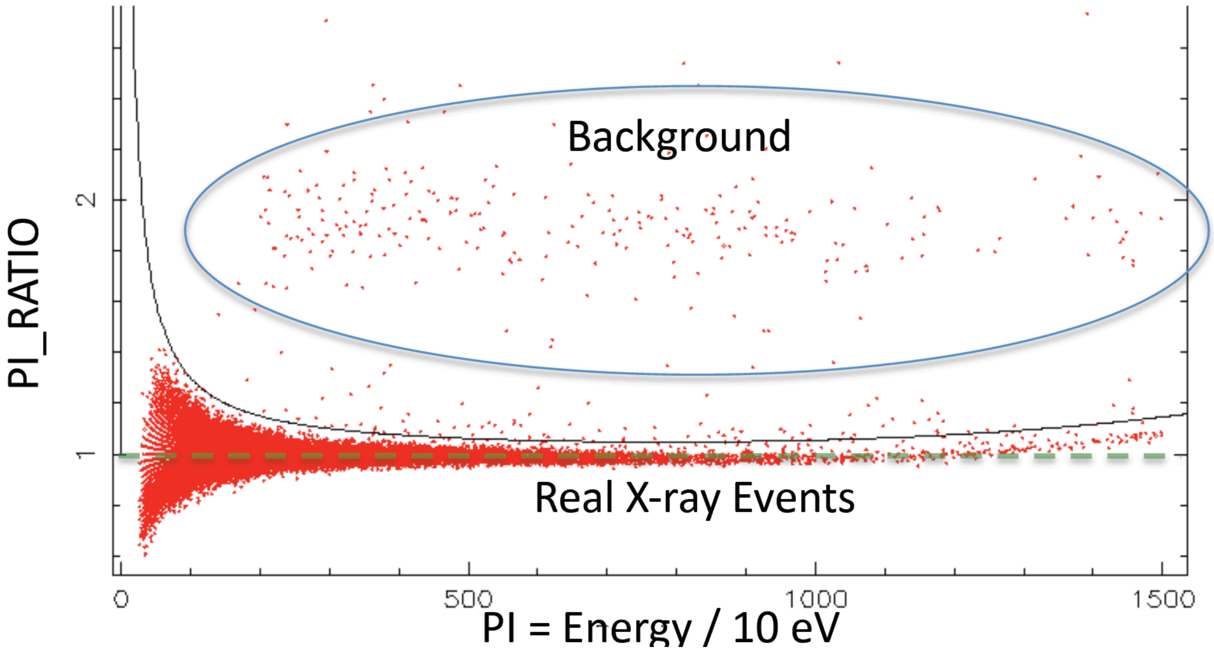


Figure 5. Analog board functional diagram.

Prigozhin+2016

PH PH-ratio relation



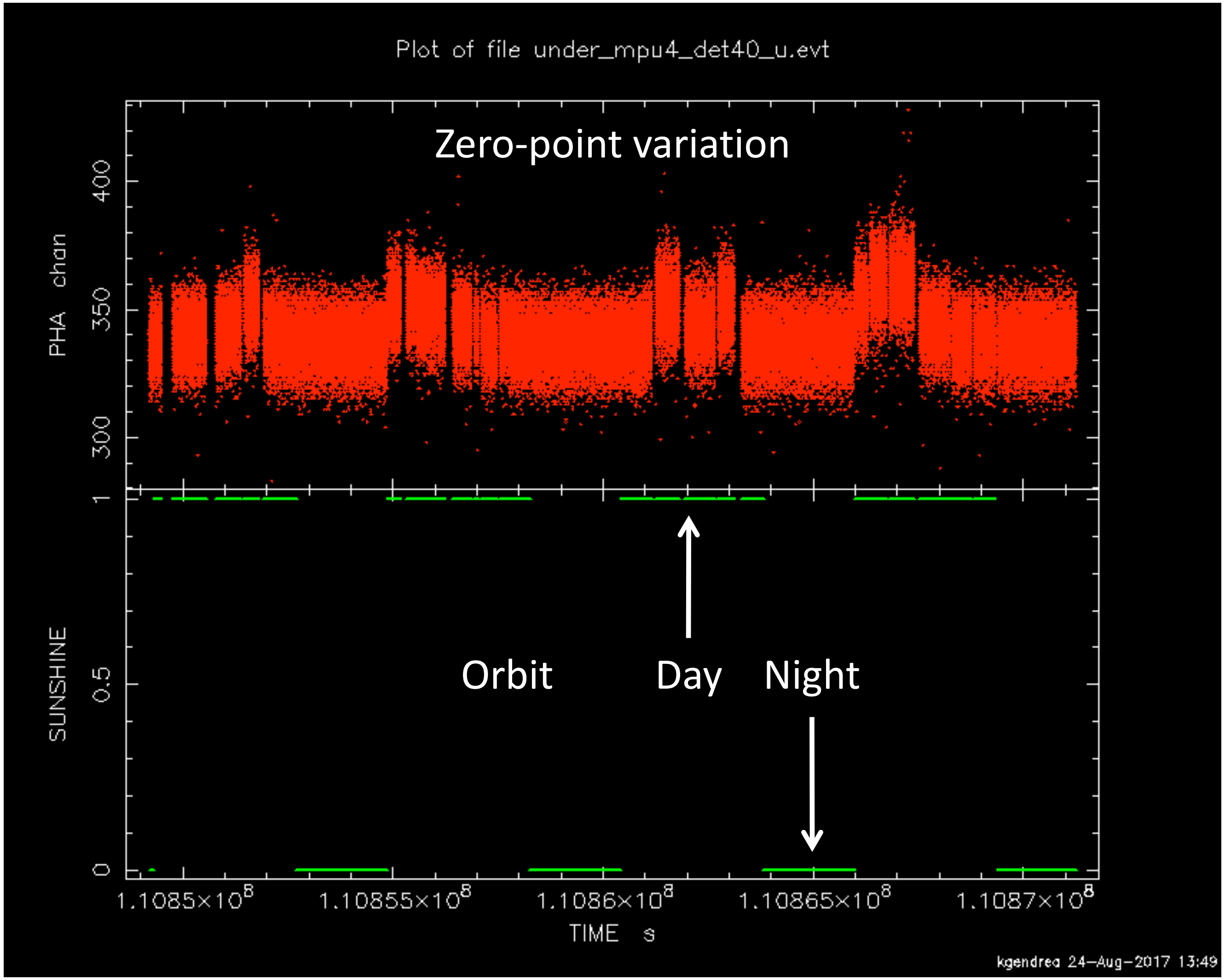
- Trumpet cut is designed to exclude background events that interact at outer edges of detectors
  - Relies on "ballistic deficit" effect which primary shows up in the fast channel
  - PI_ratio = PI/PI_FAST

Gain Calibration Caveats

- NICER detector gain calibration dependencies
  - Electronics gain parameters are temperature dependent
    - Dependence is measured in ground calibration (in CALDB)
    - Temperature is reported by electronics every 1 sec (in HK data)
  - Offset depends on optical light loading
    - We use “undershoot” as a proxy for optical light, and calibrate out zero-point shifts (in CALDB)
    - This also affects detector resolution and threshold, but this is not yet fully calibrated
  - No current evidence for major calibration shifts with time, although this is under study

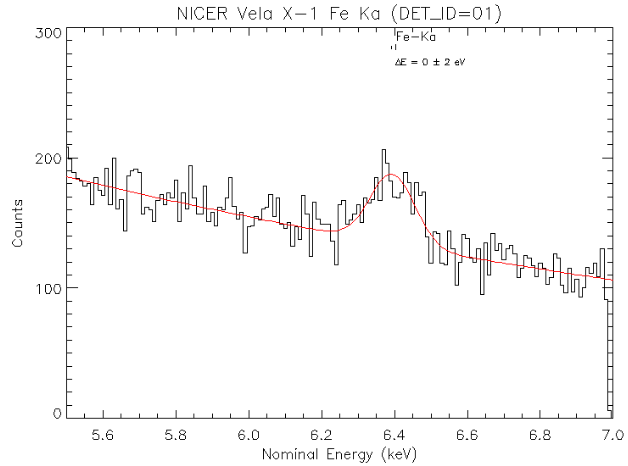
Gain Variation with Lighting Conditions

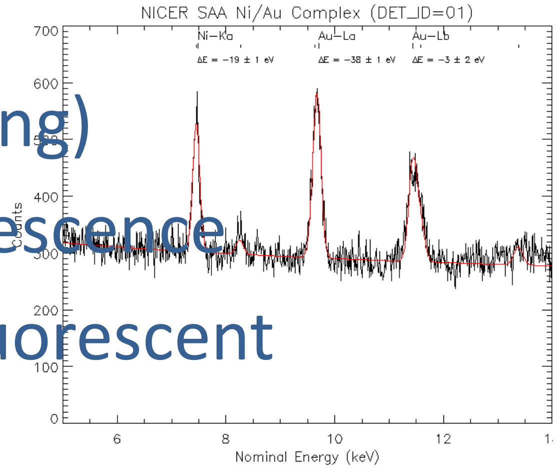
- Forced triggers provided zero-point of detectors.
- Zero-point clearly varies with day-night cycle

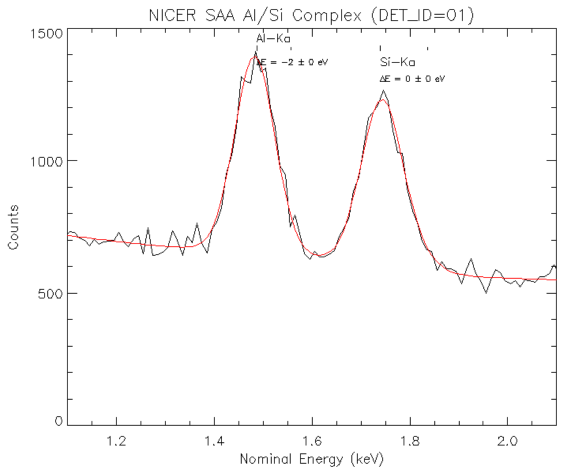


Vela X-1 and SAA Fits for Gain Scale

- Vela X-1
  - Fe K emission line
  - Highest weighting
  - Sharp and zero redshift based on Chandra grating measurement
- SAA (low weighting)
  - Si & Al K fluorescence
  - Au and Ni L fluorescent lines

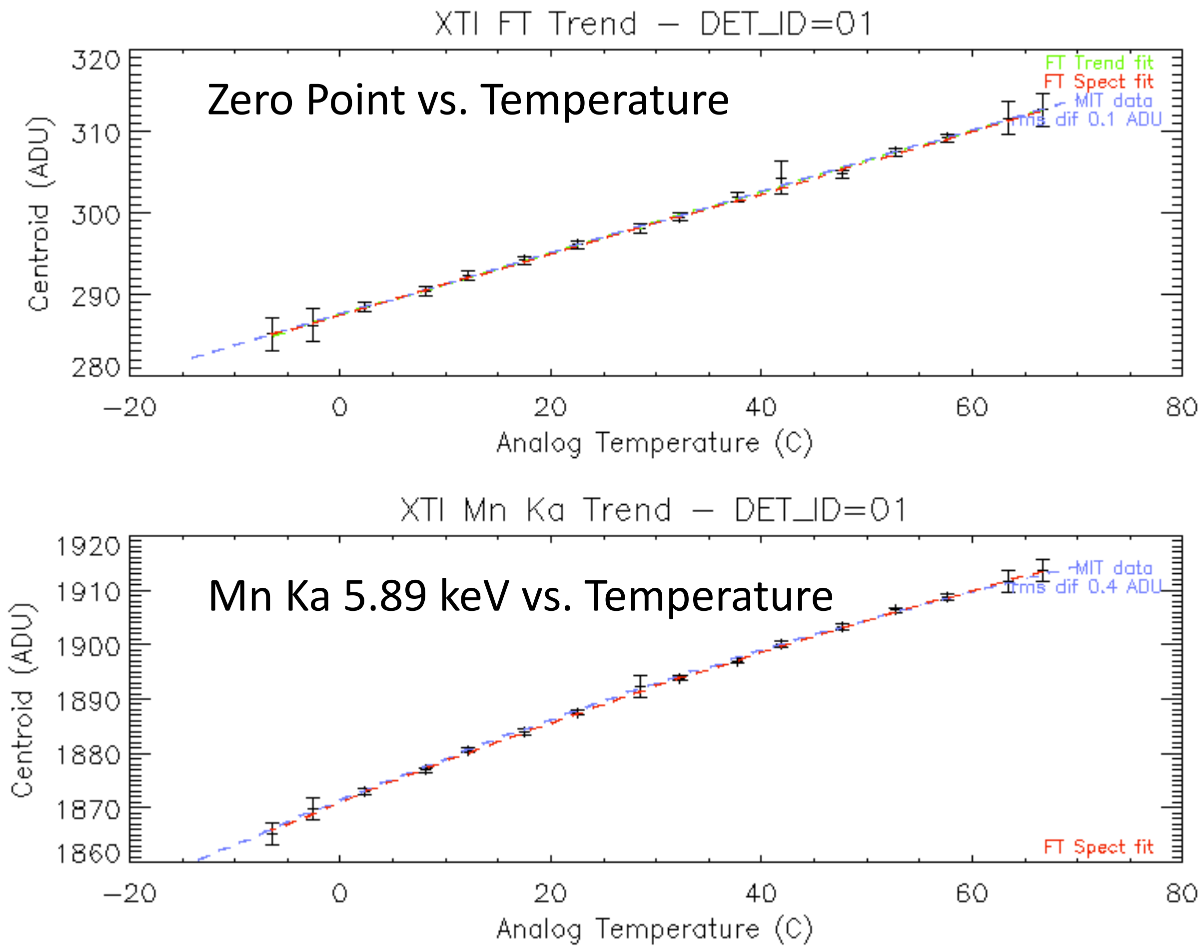






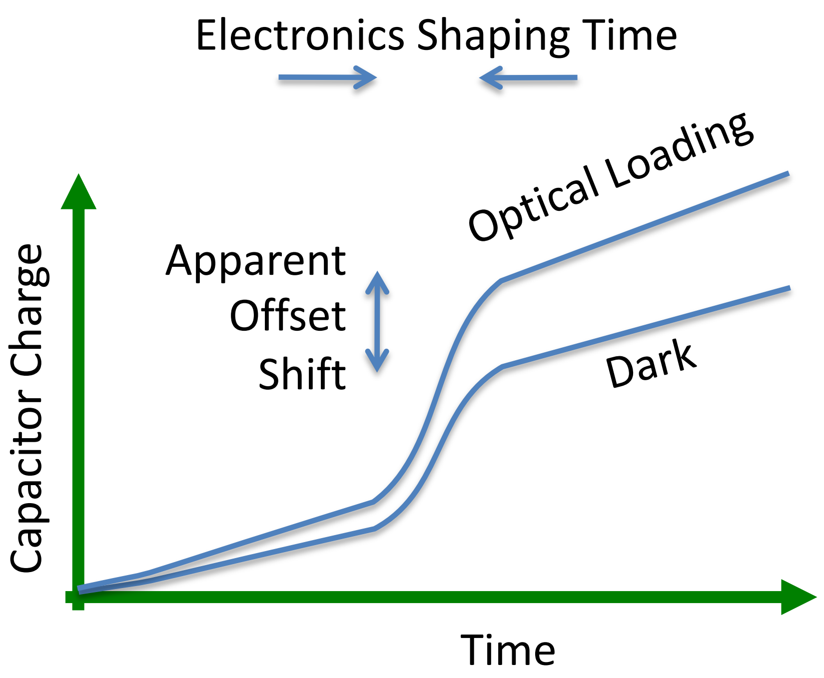
Ground Calibration: Measured Gain

- From ground calibration data, detailed knowledge of energy scale behavior versus temperature
  - Gain
  - Offset
- Detailed spectrum for each module

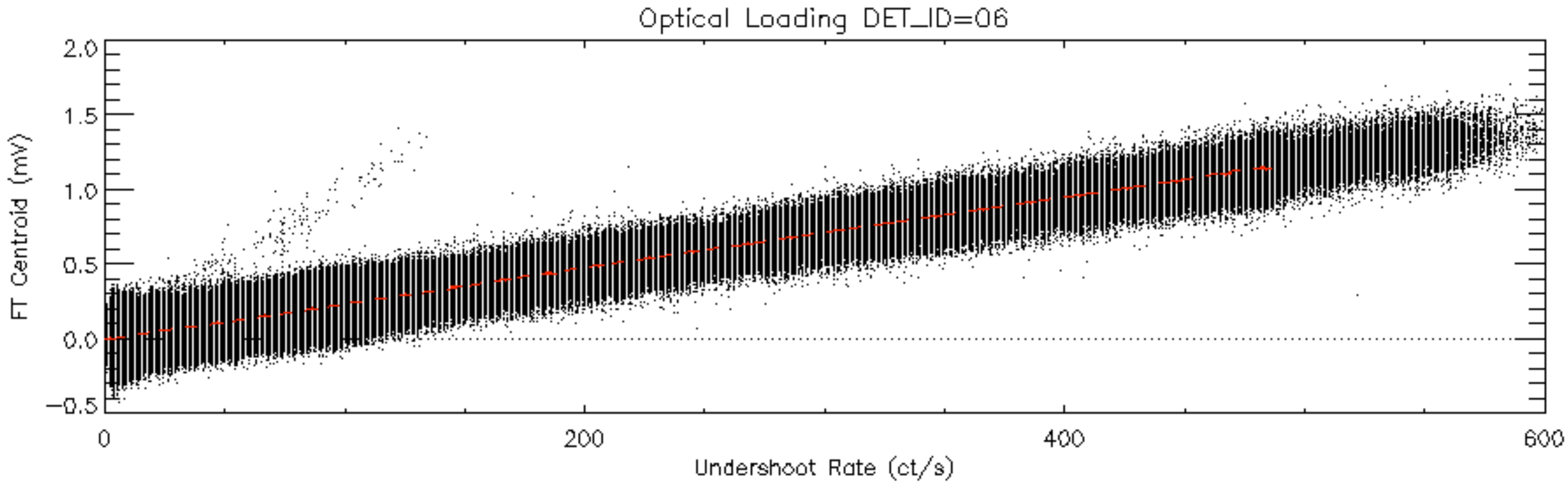


Effects of Optical Loading

- Optical light increases bias current
- Leads to an increased collected charge during electronics shaping time
- Apparent offset shift due to optical loading



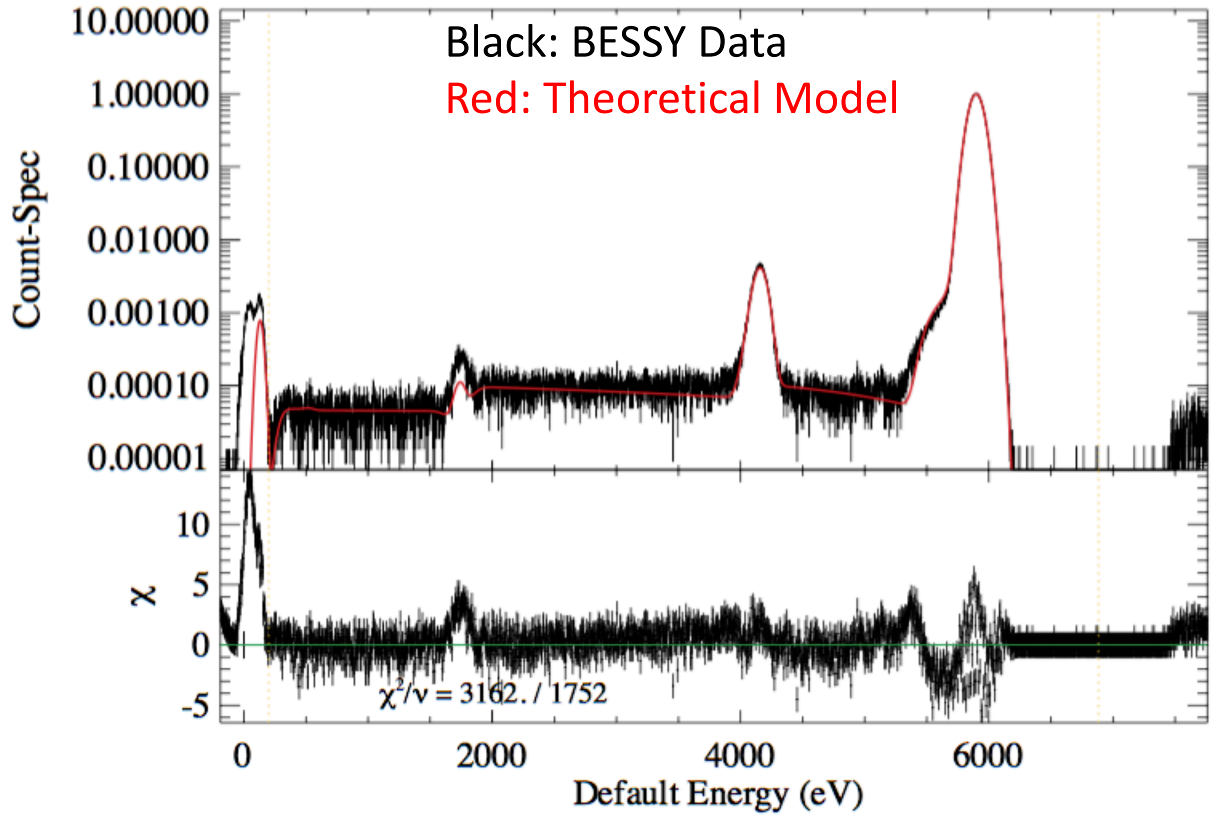
In-Flight Gain: Optical Loading



- Optical loading dominated by stray light from sun as well as International Space Station structures (solar panel glint, diffuse reflection from modules)

Resolution: Instrumental Resolution

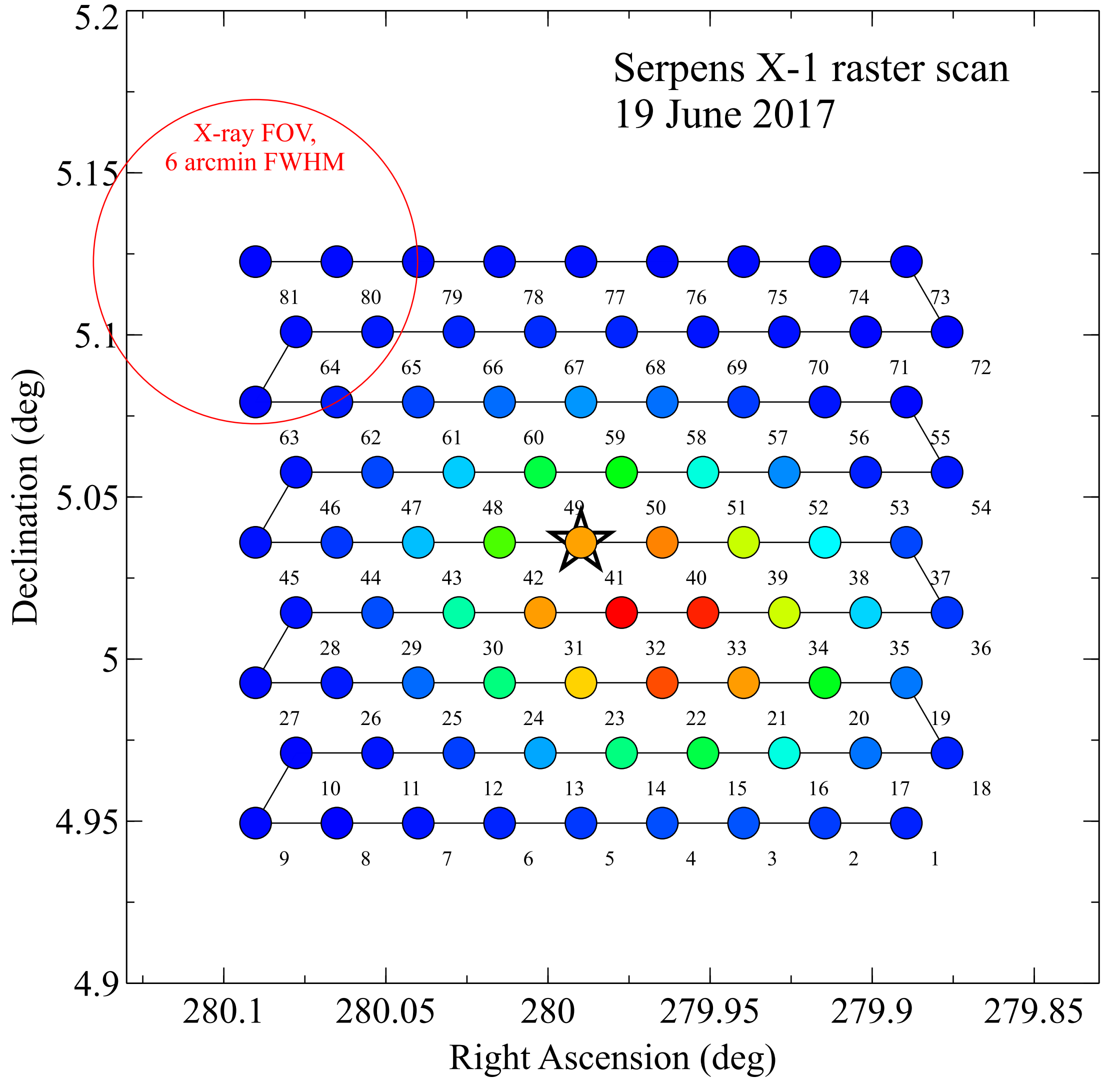
- BESSY synchrotron data allows detailed response modeling
- Model of Scholze & Procop (BESSY Collaborators)
- Model accounts for all instrumental features
- Measured read noise and detector resolution (Fano term)
- No additional changes this year



J. Steiner, G. Prigozhin (MIT), leads

Alignment — First Correction

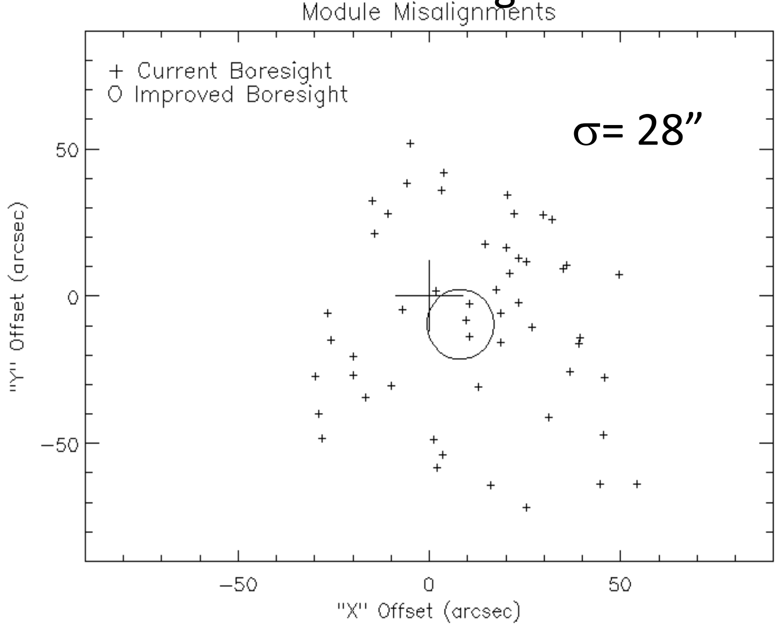
Initial correction good to ~3 arcmin…



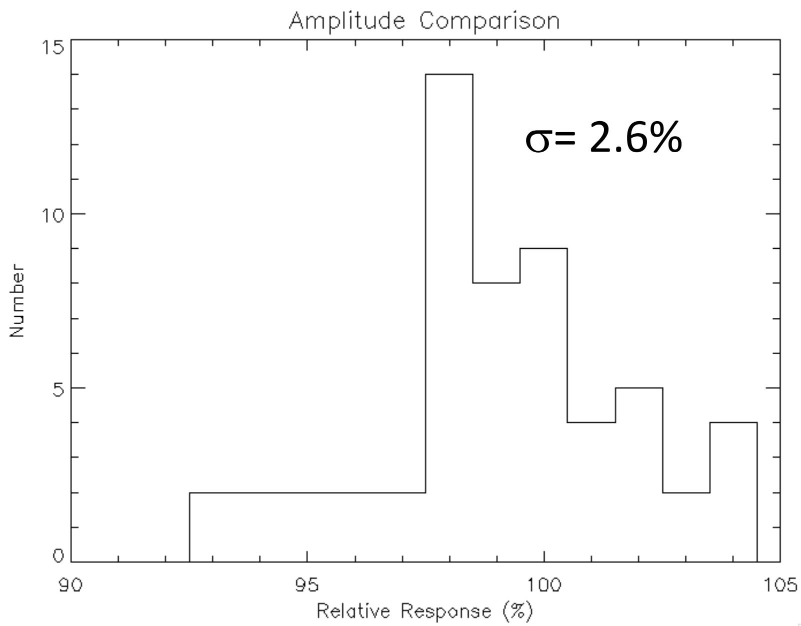
Module Misalignments & Area

- Individual modules well measured and provide input into ARF calculator

Vector Misalignment



Relative On-Axis Areas



- Module relative on-axis effective areas are within ~3% of nominal

Vignetting "PSF" Shape

- PSF shape compares well to pre-launch data
- FWHM ~338" ± 5"
- More detailed ray-tracing verifies and refines the shape of the PSF