NICER Analysis Workshop

May 2021

NICER

Neutron star Interior Composition ExploreR

NICER Calibration: Status/Update

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DTU

BROAD REACH

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NICER High Level Recommendations

- Use the 'nicerl2' processing tool for all data
  - Applies calibration and standard processing
- Consult on-line NICER documentation for analysis issues
  - Software guide overview
  - Analysis "threads" - procedures for common tasks
  - Analysis tips for specific known problems or issues you may encounter
  - Keep your CALDB up to date, and understand calibration limitations by reading calibration documents
- Send questions to the NICER helpdesk: https://heasarc.gsfc.nasa.gov/cgi-bin/Feedback

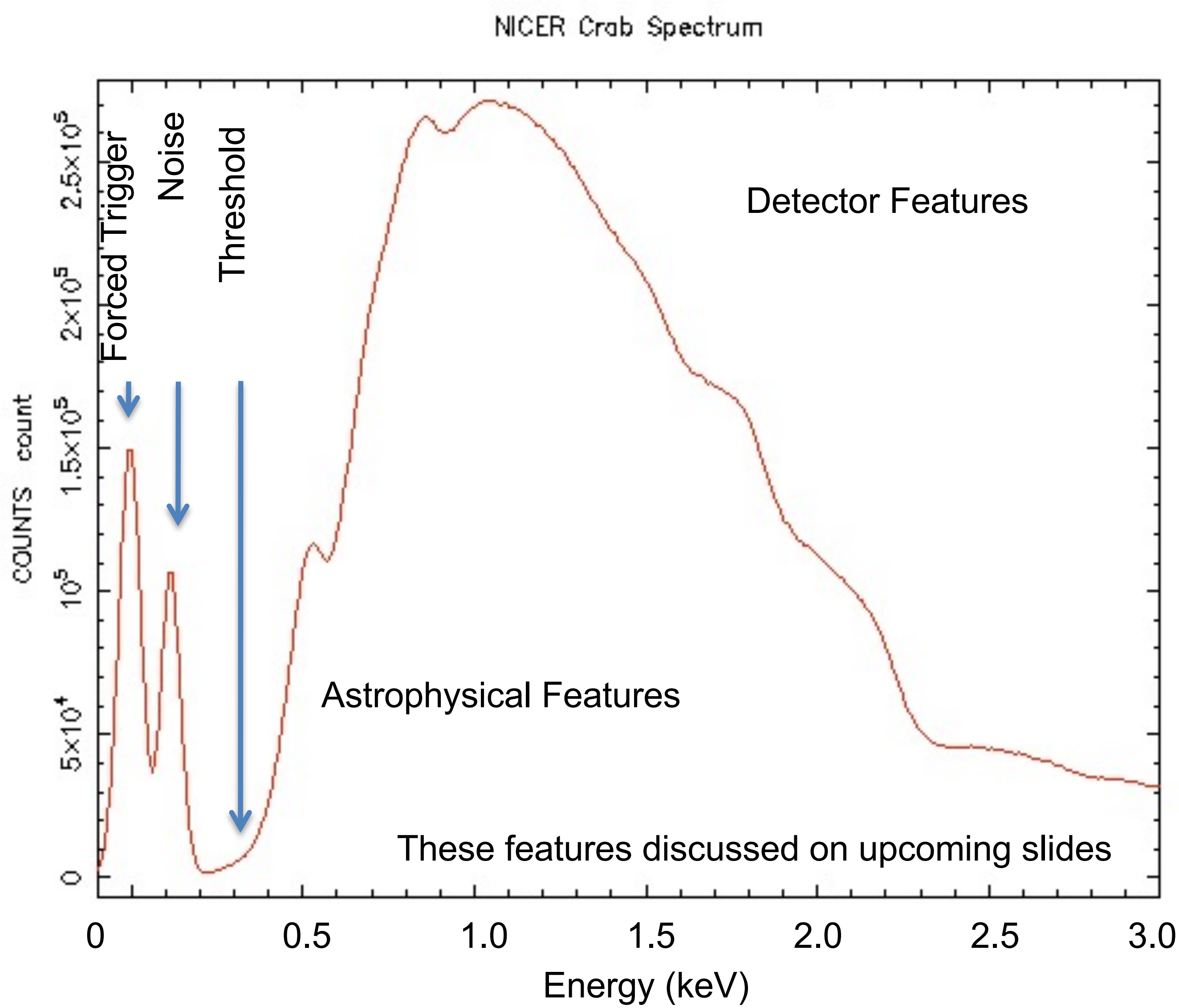
Data Processing Recommendations

- Use the 'nicerl2' processing task to process all NICER observations (part of standard HEASoft)
  - nicerl2 applies standard calibrations and screenings
    - Calibration: energy scale, timing offsets
    - Screenings: pointing, optical light, high background

When to Use nicerl2

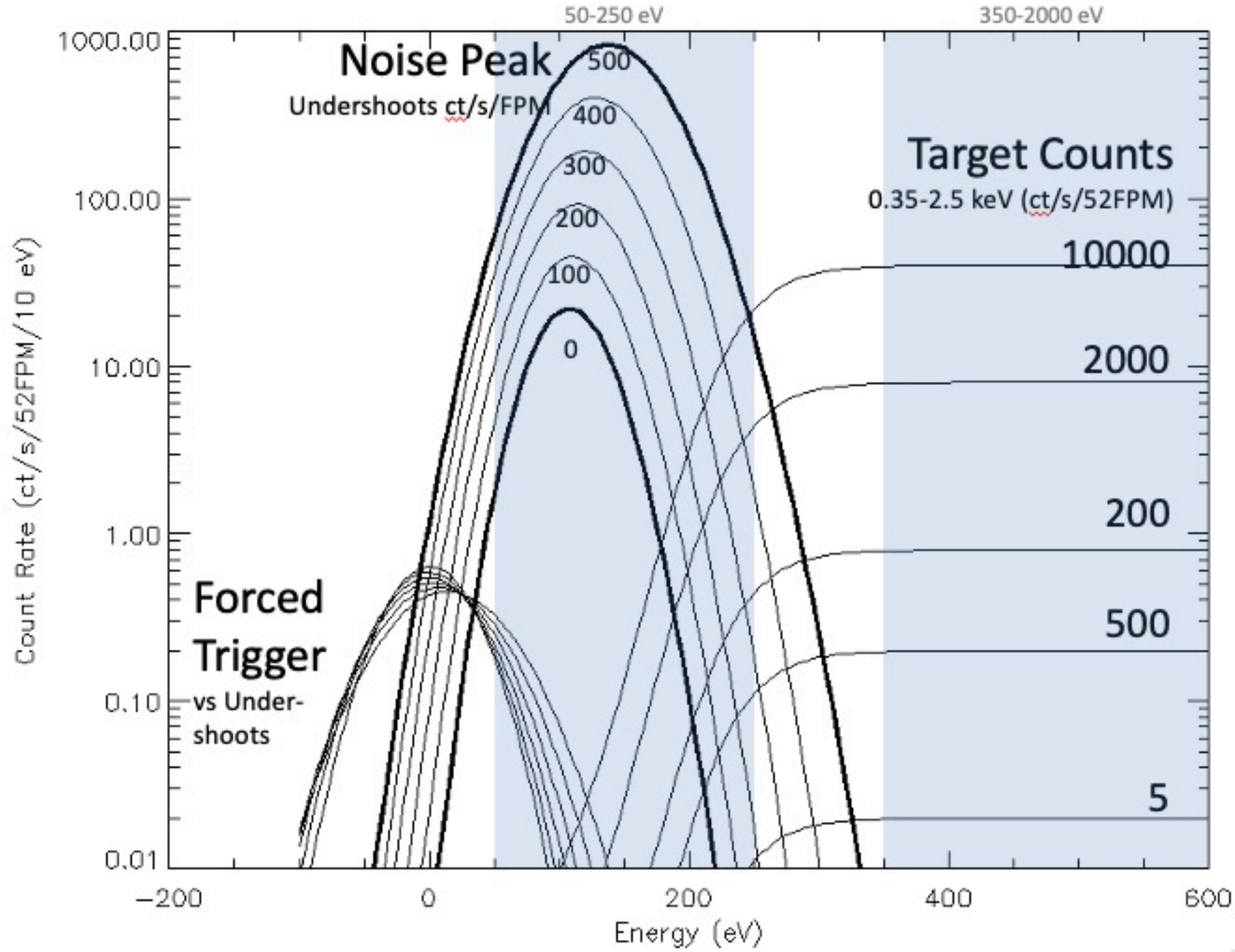
- Use nicerl2 even if you freshly download data from the archive
  - When new calibration becomes available, the NICER pipeline does not always reprocess old data, or apply it immediately to new data, so you need to do it yourself

"Typical" NICER Spectrum: Crab



NICER Detector Features

- These features are non-X-ray and non background
- Forced trigger
  - Const rate
  - 0 keV
- Noise peak
  - Varies w/ optical light
  - ~120 eV
- Trigger efficiency function
  - Cut-off of source counts
  - ~240 eV



NICER Array Average

NICER Calibration Status

- Energy scale
- Energy range
- Background
- Response (ARF & RMF)
- Published NICER calibration notes found here:
  https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/nicer/docs/nicer_caldb_docs.html
- Most recent calibration release
  xti20200722

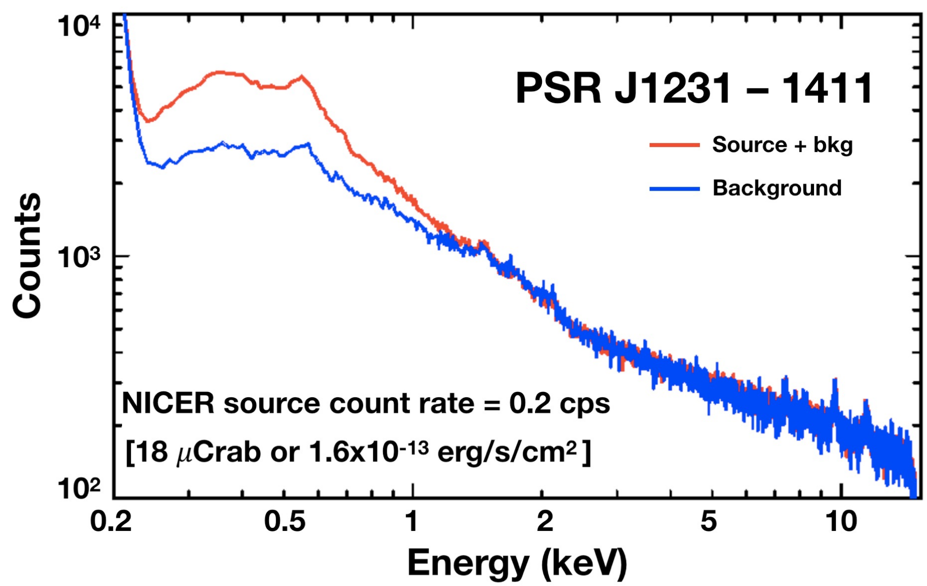
Energy Scale Calibration Status

- NICER energy scale (CALDB release xti20200722)
- After calibrations, all event files have “PI” column with common energy scale (“Pulse Invariant”)
  - **1 PI = 10 eV** (e.g. PI = 150 means E = 1.50 keV)
  - Accounts for temperature & optical loading (undershoots)
  - **Estimated error ~5 eV** (0-10 keV)
    - Assumes standard undershoot filtering of 0-200 ct/s/FPM

NICER Energy Range

- NICER response was calibrated against the Crab in **0.24-14 keV energy range** (see xti2020722 notes)
- At low end of range, large noise peak may interfere with spectrum, for undershoots > 100 ct/s/FPM
- At high end of range, quality of background subtraction will be dominant systematic error contributor

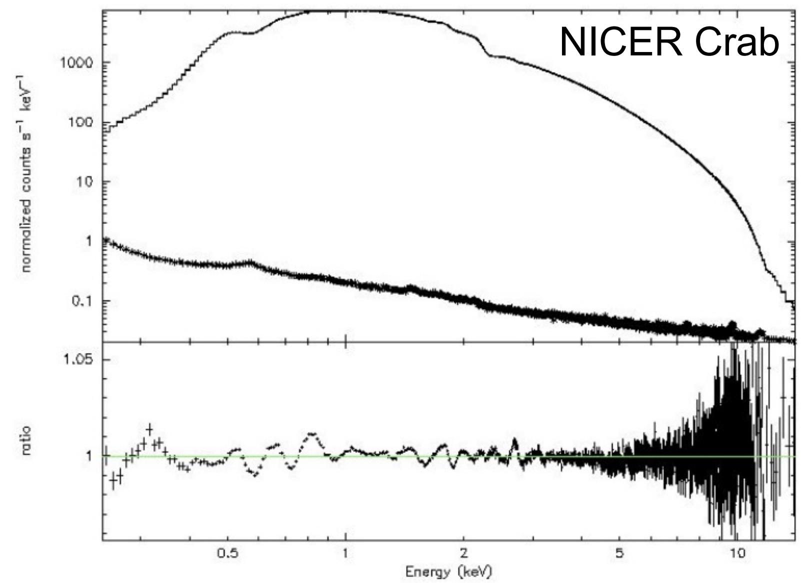
NICER Background Estimation



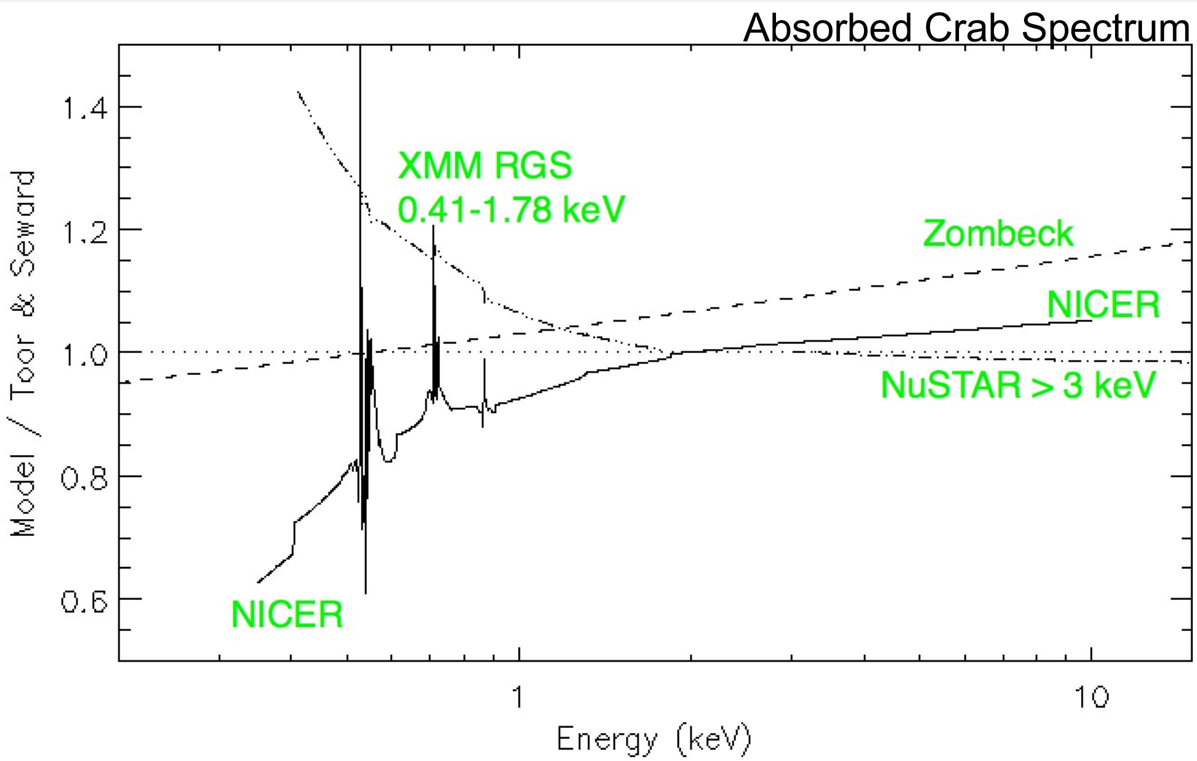
- NICER consists of **single-pixel detectors**
  - Background must be modeled
- Background models available from [Background Estimator Tools]page
- **“Space Weather” model** is based upon local space weather environment (nicer_bkg_estimator; Gendreau & Corcoran)
  - Scientist supplies filter file (.mkf) and spectrum, tool produces background spectrum and modified .mkf file with background rate estimates in various bands
- **“3C50” model** (nibackgen3C50; Remillard & Loewenstein; submitted for publication 2020)
  - Scientist supplies observation directory, tool produces source and background spectrum
- Both tools are based on array-averaged backgrounds (3C50 model will scale to actual number of detectors enabled)
  - Both tools may also require re-running nicerl2 with special settings, see their README documentation

NICER Effective Area (ARF)

- NICER response
  - NICER calibrated against Crab nebula as a “smooth” continuum
  - Systematic errors <1% (0.4-10 keV)
  - Total effective area and slope comparable to Madsen et al. 2017 NuSTAR
  - **For on-axis targets only**

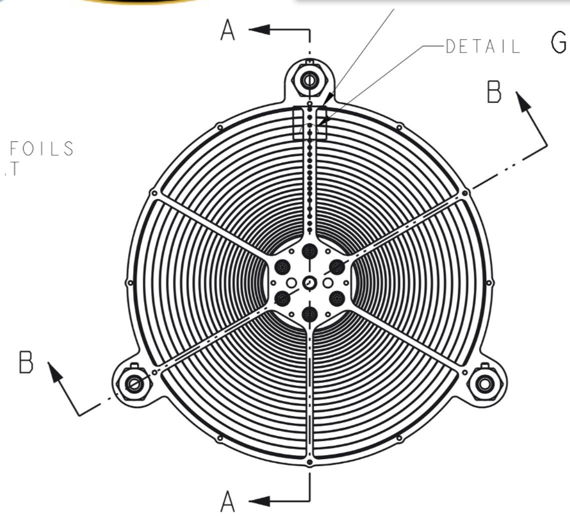


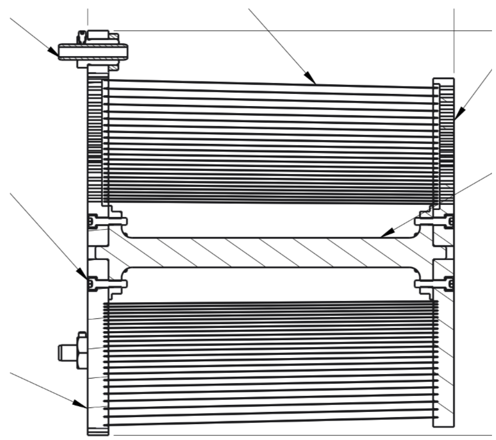
NICER ARF Performance: Crab

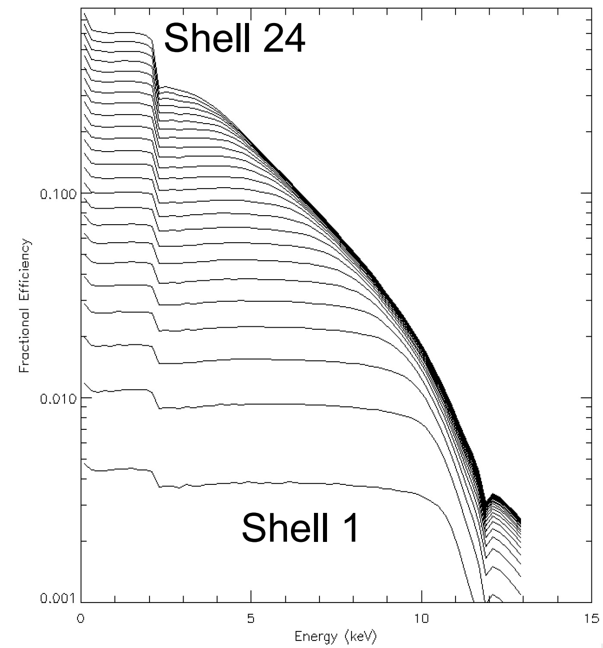


- Basis of comparison is Toor & Seward (1978) result, extended to lower energies
- Above ~1 keV, NICER is in the mix of other observatories
- Below 1 keV, very significant differences with XMM RGS (Kaastra et al. 2009)
  - These are primarily driven by minor differences in absorption and dust scattering which lead to large apparent differences in flux
- **Follow-up NuSTAR/NICER work (priv. comm.) suggests a slope error of ~0.03, and low energy response differences in the ~0.05e22 range**

How NICER ARF is Estimated



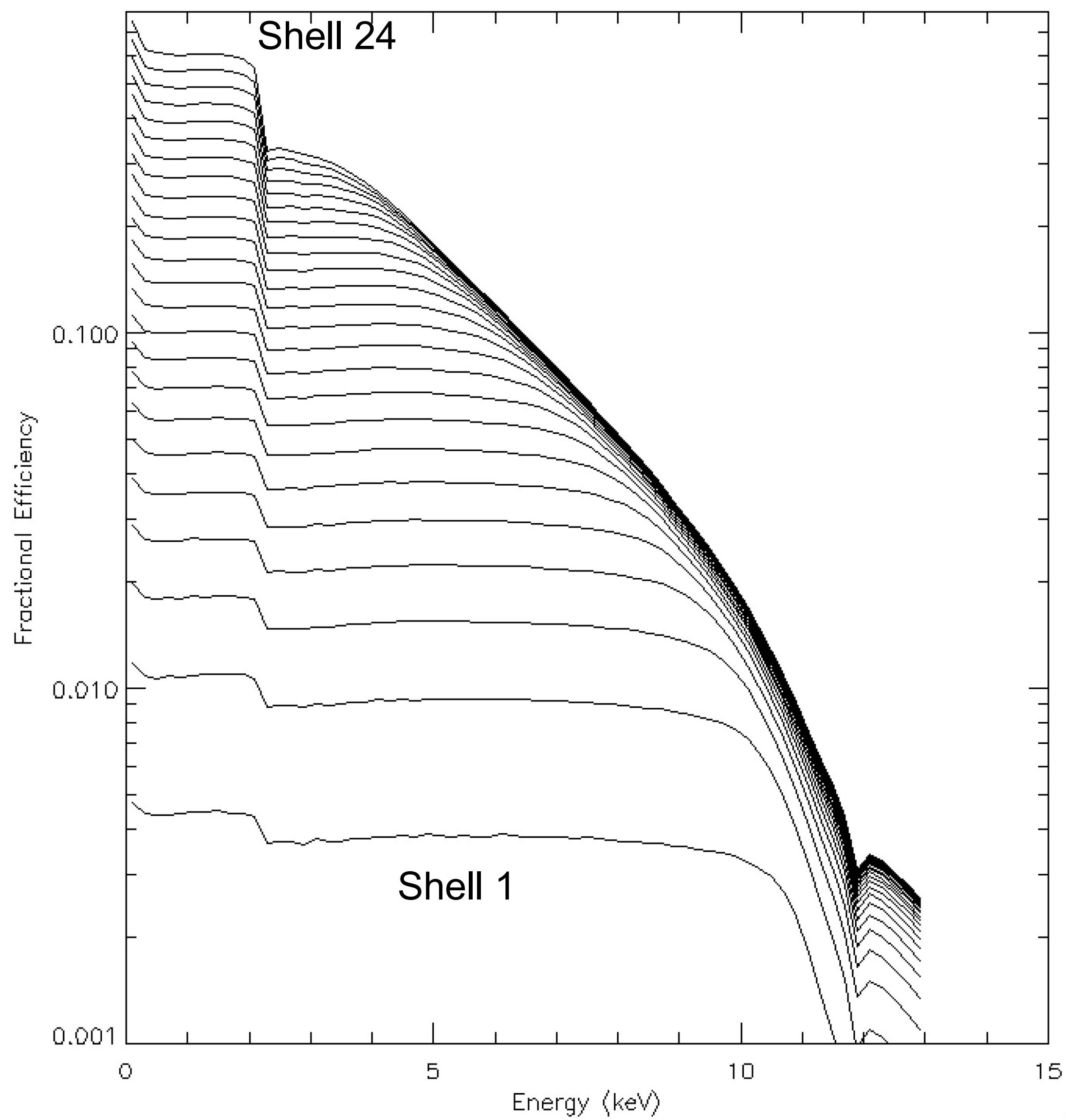




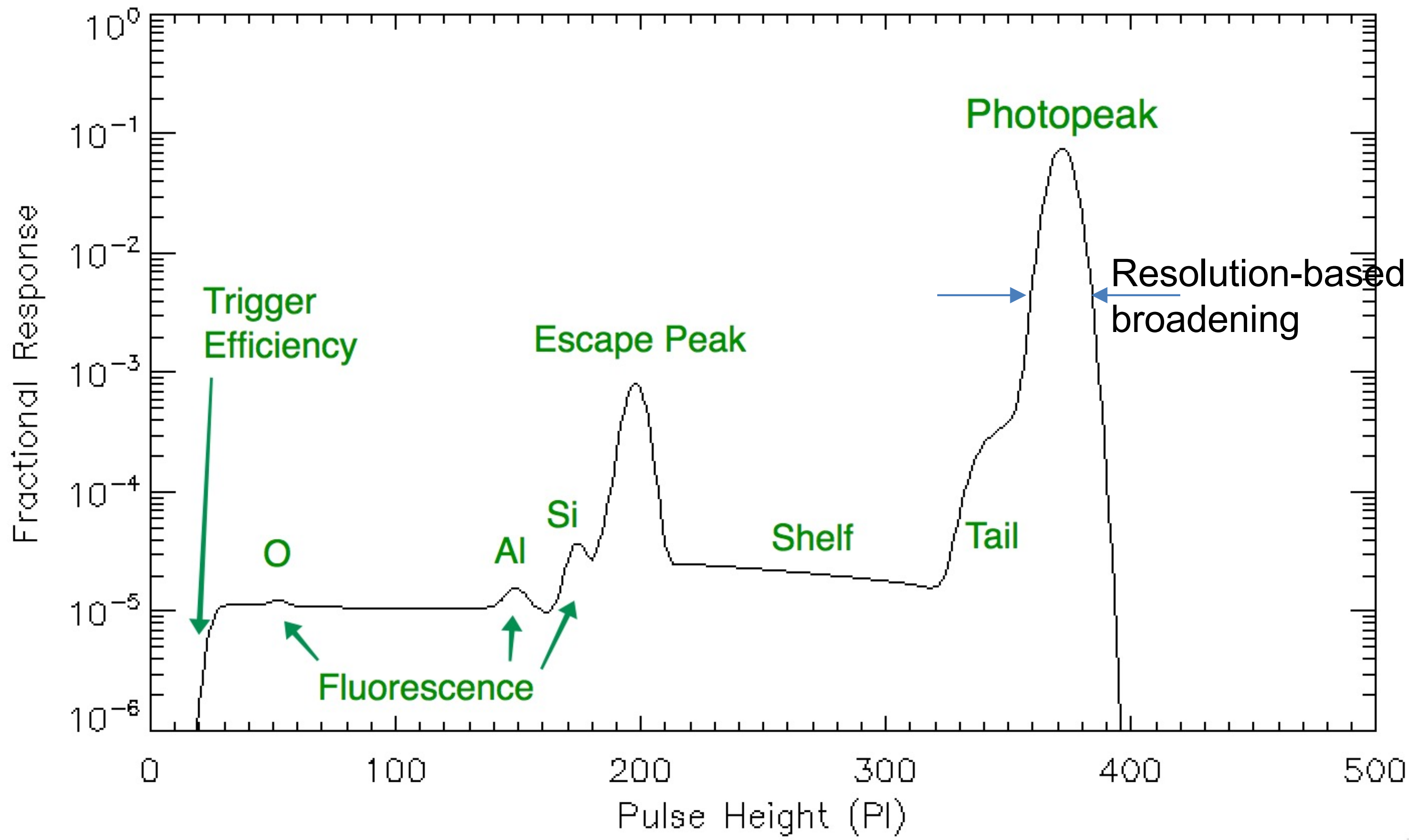
- X-ray ray-tracing program CONSIM
  - Physical structures and surfaces (24 shells)
  - X-ray reflectivity and scattering
  - Account for surface micro-roughness (2A – 12A)
- Throughput of each shell individually (vs Energy and roughness)
- Compared to calibration observations of Crab (see release notes)

Effective Area Rackup

- Per-shell effective area rack-and-stack for an idealized module
- Can see the effects of shell radius
  - Inner shells are more reflective at higher energies but lower geometric area
  - Outer shells have most effective area at soft energies
- Gold edges at 2.2 keV and 13.9 keV



NICER Redistribution (RMF)

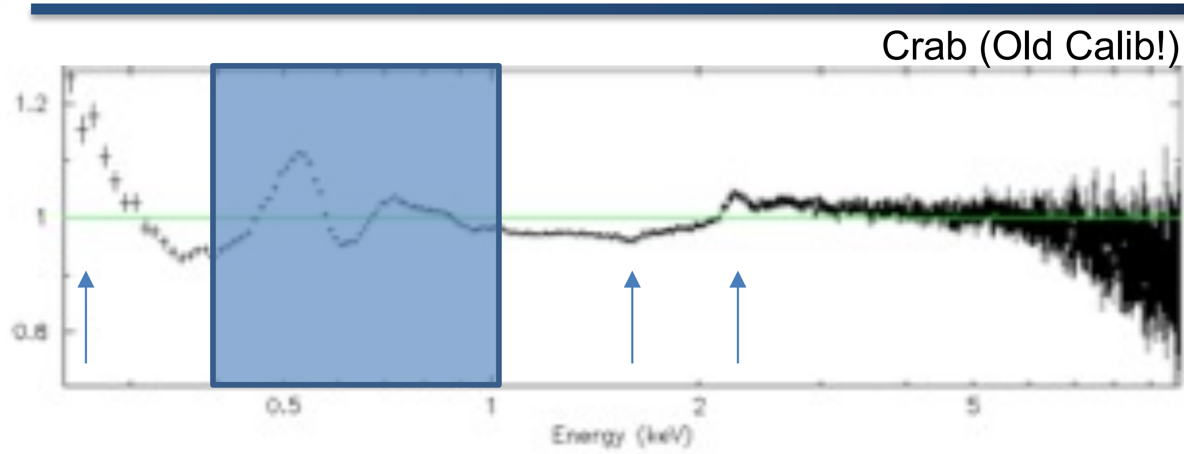


- Detector RMF published model (Scholze & Procop 2009)
  - Embodies detector and read-out physics
- Detector resolution based on ground calibration, typically 8-9 electron read noise
  - Assumes undershoots <100 ct/s (approx.)
- Trigger efficiency function fitted from on-orbit data

NICER Response Access

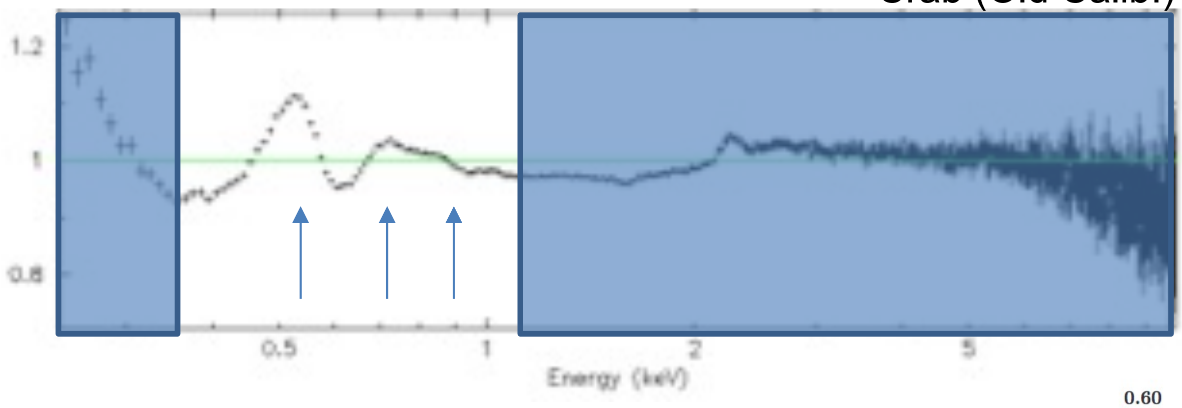
- Currently NICER responses are available as a separate download outside of CALDB
- A single ARF and RMF for each module, and simple tools to combine them for your observation
- Download information is here: https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/arf-rmf/
- Soon to be released: a response calculator which adjusts to conditions of a particular observation (see later slides)

Detector Features to Watch Out For

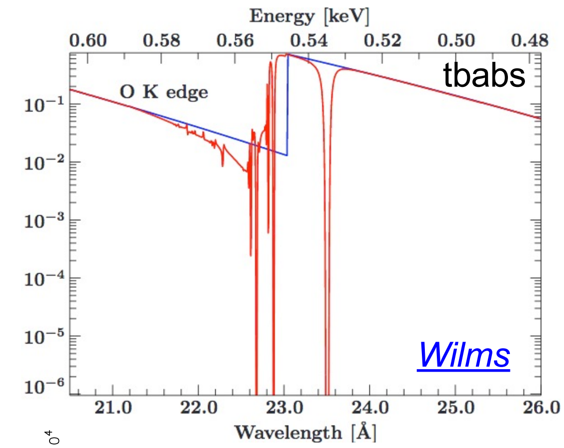


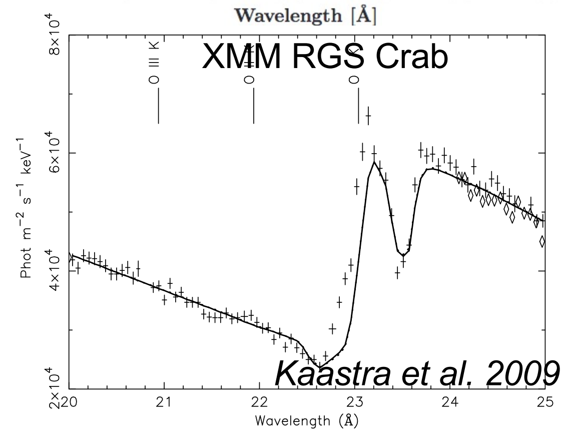
- ~2.2 keV – Gold M edge from XRC reflector gold coating (actually a complex from 2.1 – 4.5 keV)
- 1.84 keV – Silicon K edge (window & bulk detector)
- 1.56 keV – Aluminum K edge/fluorescence (detector window)
- ~0.25 keV – Trigger efficiency cut-off (varies by detector)
- ~0.15 keV – Noise peak (varies by detector & lighting)
- At high optical light levels response is broadened but this is not yet modeled
  - Noise peak may intrude into spectrum at low energies
  - Sharp lines may be degraded

Astrophysical Features to Watch Out For



- The interstellar medium is often modeled with neutral N_H models such as wabs, tbabs (Wilms et al.), etc.
- These models are general approximations to reality, especially with all parameters left at solar abundance
- Most common features:
  - Oxygen K edge (0.56 keV)
  - Iron L edge (0.71 keV)
  - Neon K edge (0.87 keV)
- If you see residuals in this energy range, consider using "tbfeo" or "tbvarabs" to allow abundances to vary; check literature for reported abundances
- Even so, actual edge profiles may not match "perfect" profiles tabulated in tbabs model (due to ionization, molecular compounds, or dust composition of ISM); see Crab to right
- Dust scattering halos – see bright target slide

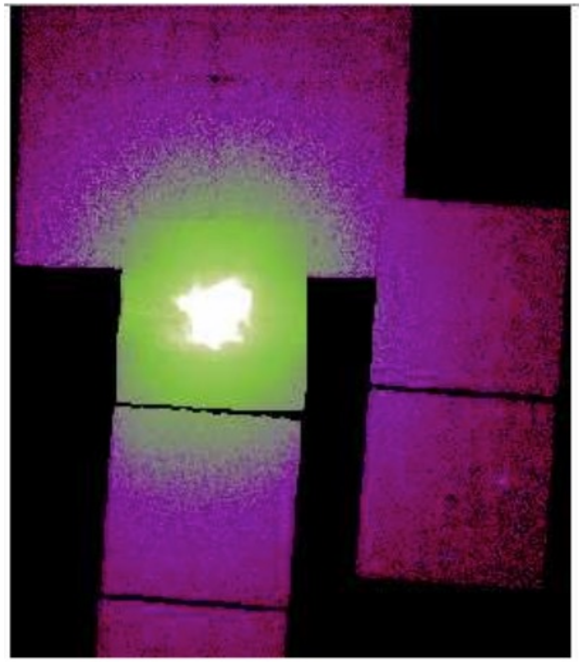




NICER Concerns: Bright Targets

- **Deadtime correction** affects all observations, but typically a few percent
  - Team is working on documentation and tools for deadtime corrections
- **Pile-up** is a concern only for the brightest targets (>>3.5 Crab); this is a difficult issue to model
- **Dust scattering halos** have significant effects
  - Energy dependent
  - Aperture size dependent
    - complicates comparing observatories with different apertures (NICER 360”, RXTE 1°, CCD imagers ~few arcsec)
  - Halo is time dependent if source varies
  - ‘xscat’ model in XSPEC recently updated by Randall Smith for larger radius apertures such as NICER. Use radius=180”

Crab Dust Halo (Chandra ACIS)

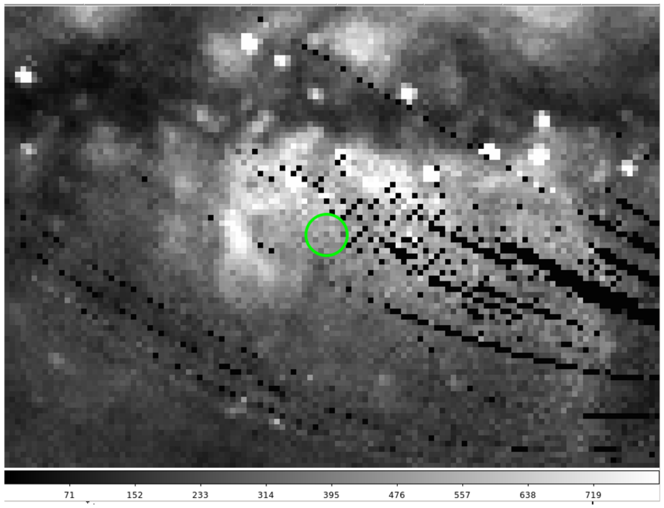


Seward et al. 2005

NICER Concerns: Faint Targets

- The primary concern for faint targets is proper background subtraction
  - May be worth trying both available models
- Some detectors are known to be noisier and may be worth excluding: "14" and "34"
- Working near the Galactic plane, beware of additional diffuse emission not in the background model (example of RX J1856)

ROSAT All-Sky Survey
RX J1856 Region



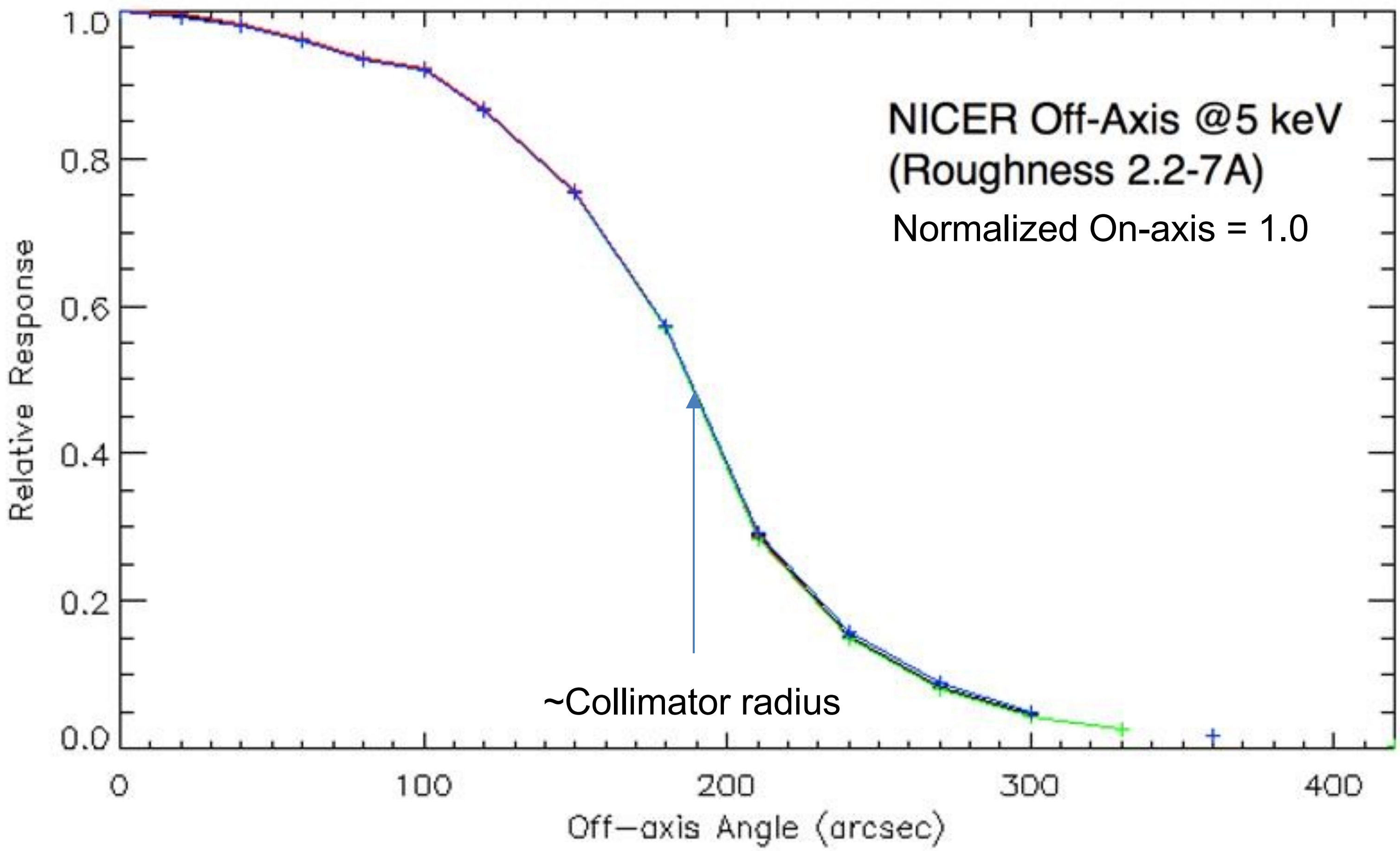
Statement of Problems for Current/Future Calibration Work

- Current NICER ARF is on-axis only
  - Calculator developed for different pointing scenarios (rasters, off-axis targets, spoiler sources, etc.)
  - Current per-shell ARF approach too difficult to maintain going forward: simplify
- Current dependence upon optical loading incomplete
  - Response matrix is at fixed (dark) resolution
    - Calculator developed to estimate response under conditions of actual observation
  - Energy scale tested in undershoot range 0-200 ct/s (dark to medium optical loading conditions)
    - Typically handles orbit night and >60 deg from sun
    - Need extension of gain scale to higher optical loading

Off-Axis Vignetting Performance

- How does vignetting behave? Versus
  - energy
  - reflector surface micro-roughness
  - shell
  - off-axis angle
  - optical tip/tilt
  - **Overwhelming number of dimensions!**
- How do we utilize this information in software?
- Solution: a vignetting lookup table
- Step through filter file 1 second at a time, use pointing information, calculate throughput for point source
  - Stretch goal: alternate surface brightness profiles

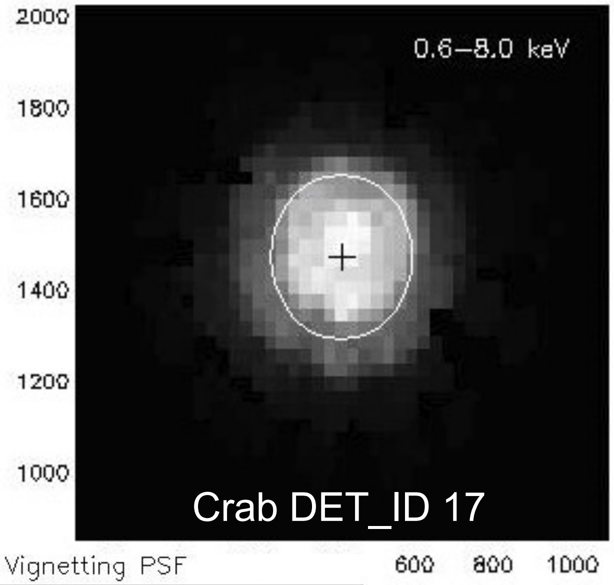
Initial Work: Azimuthal Symmetry

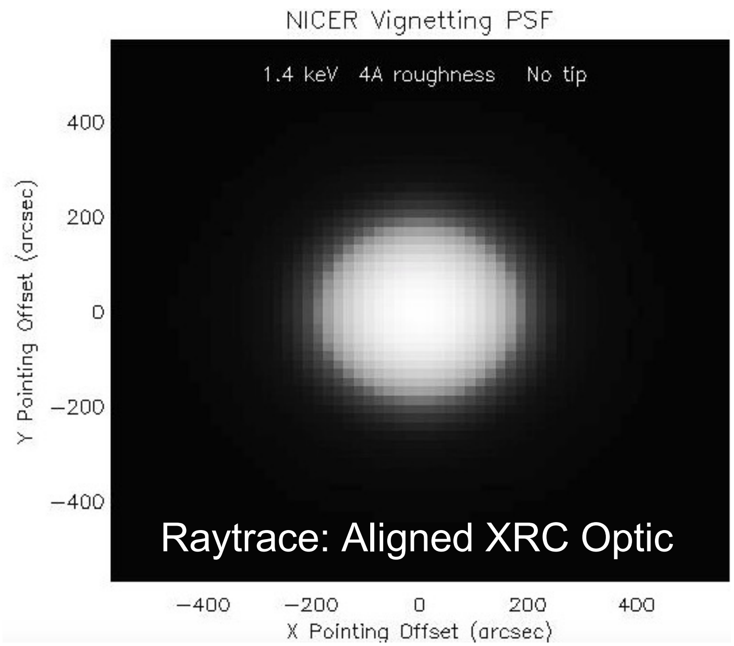


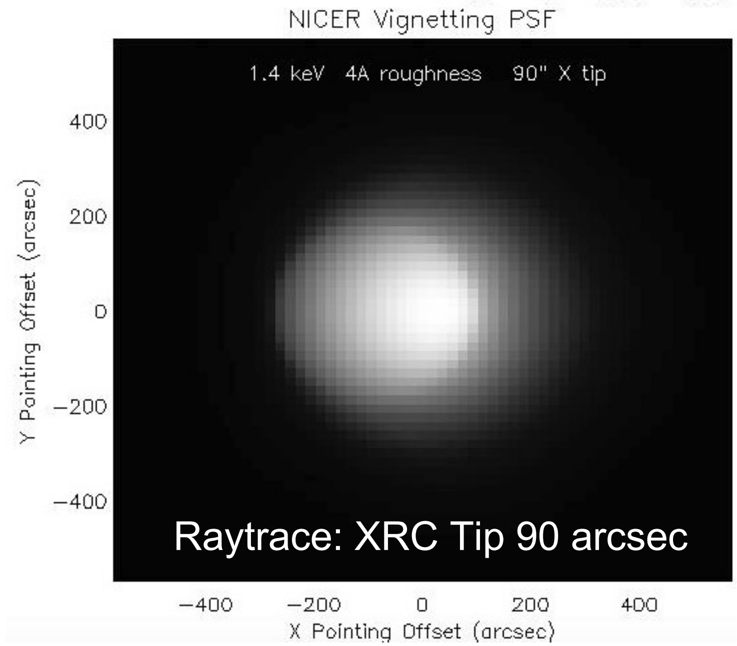
- This past Fall, our work started assuming azimuthal symmetry for vignetting profile
- Results: Very little change in throughput with roughness, vignetting shape dominated by geometry & collimator

Detailed Work: Full 2D Profile

- We now know vignetting profile is not symmetric
- Why? Some **XRC optics are tipped** by 0-90" from perfect alignment
- Module-to-module variations



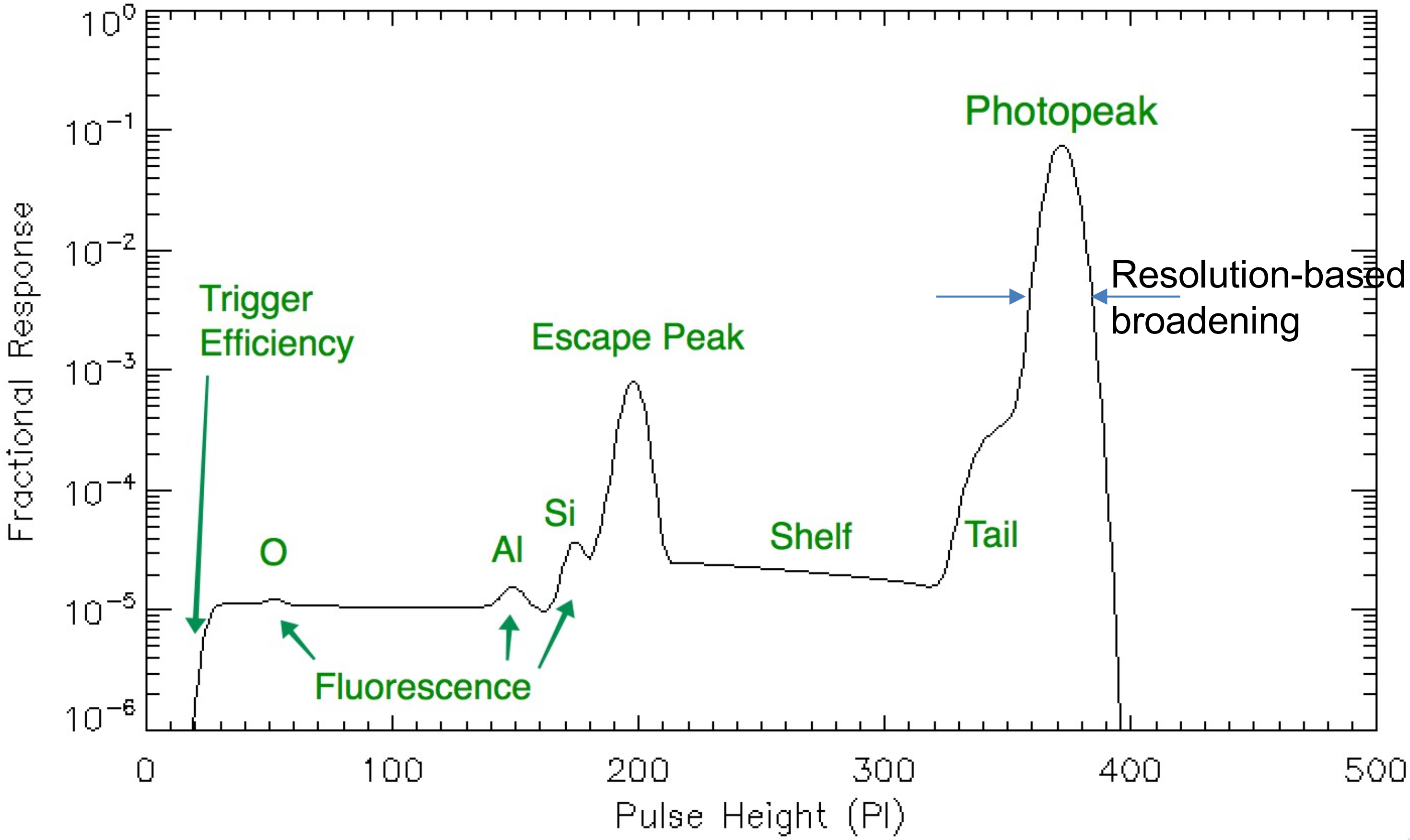




Additional Vignetting Details

- We now have a new ARF model that simplifies the number of dimensions (only two roughness values allowed)
- We have raytraced vignetting profiles
- Fitted vignetting profile to each module to derive
  - Best boresight
  - Tip angle
  - Azimuth of tip axis
- ARF calculator tool to use this data

New NICER RMF Calculator Tool



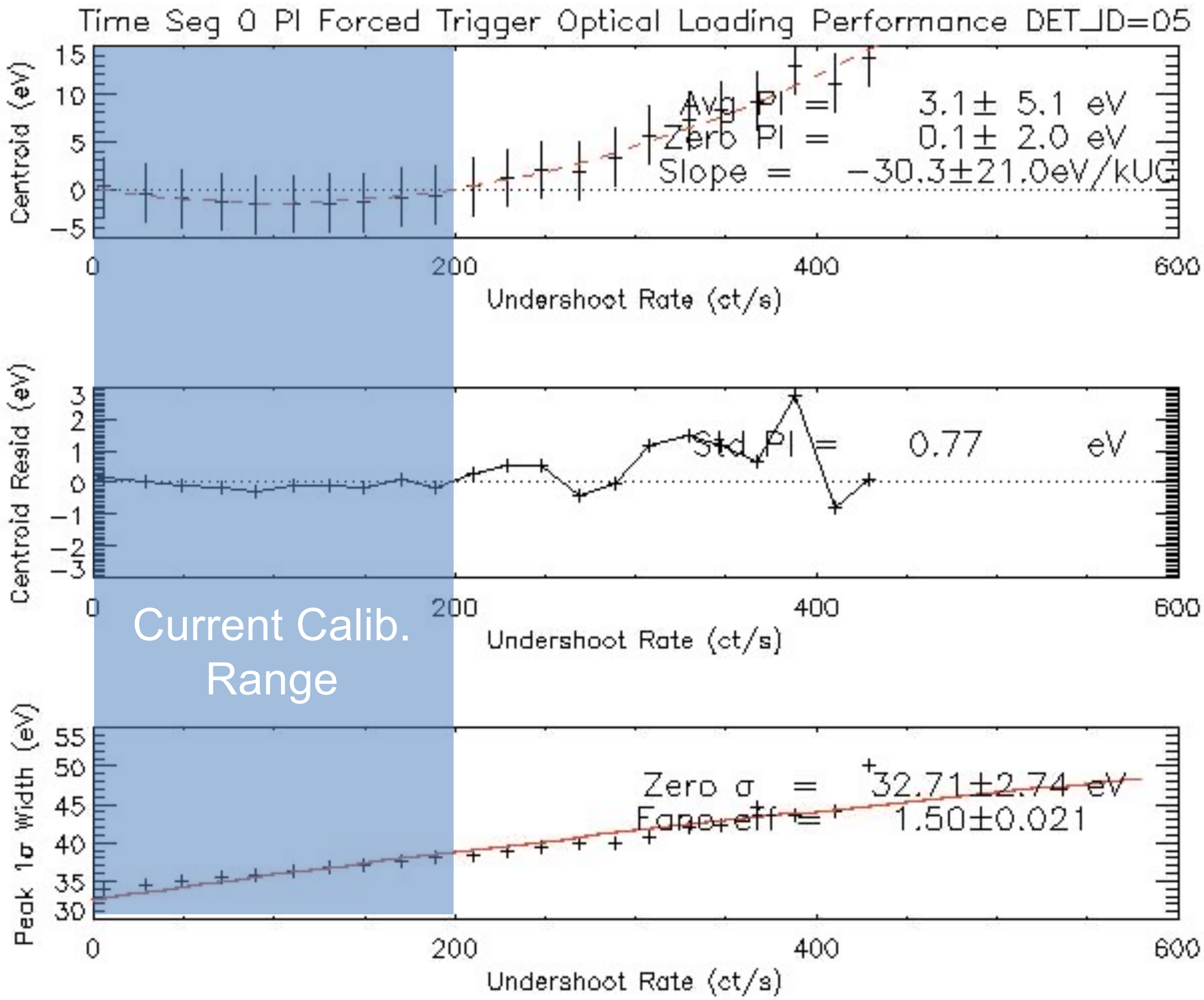
- Resolution and trigger efficiency will vary, depending upon optical loading conditions
- Calculator steps through filter file and estimates observation-dependent broadening

Extending to Higher Optical Loading

- Extend current range (0-200) to wider range (0-500 ct/s)
  - 0-200 ct/s: roughly >60 deg from sun
  - 0-500 ct/s: roughly >45 deg from sun
- New gain model (optmv12)
  - Complete (Next slide)
  - In current recommended undershoot range of 0-200 ct/s, change in energy scale <5 eV
  - Above 200 ct/s, change ~15-25 eV
- RMF calculator for custom per observation responses
  - Use known detector performance factors to estimate resolution-based broadening at each filter file time step

New Gain Model (optmv12)

- FT Centroid
  - Parabola
- Residual after parabola fit
- Resolution w/ Fano model



Improved behavior allows gain solution to undershoots of ~500 ct/s/FPM

Summary

- Current Released Calibration
  - Energy Range: 0.24-14 keV (undershoots 0-200)
  - Energy Scale: ~5 eV (undershoots 0-200)
  - Effective Area: ~1% (on-axis only)
  - RMF: not undershoot-dependent
- To-be-released Calibration
  - Energy Scale: undershoots 0-500
  - Effective Area: off-axis calculator
  - RMF: undershoot-dependent trigger efficiency

Beware Of

- Detector and astrophysical features
- Bright sources
  - Dust scattering halos can be significant
- Faint sources
  - Background subtraction is dominant systematic error