Calibration of the Chandra PSF Wings

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2003 October 27

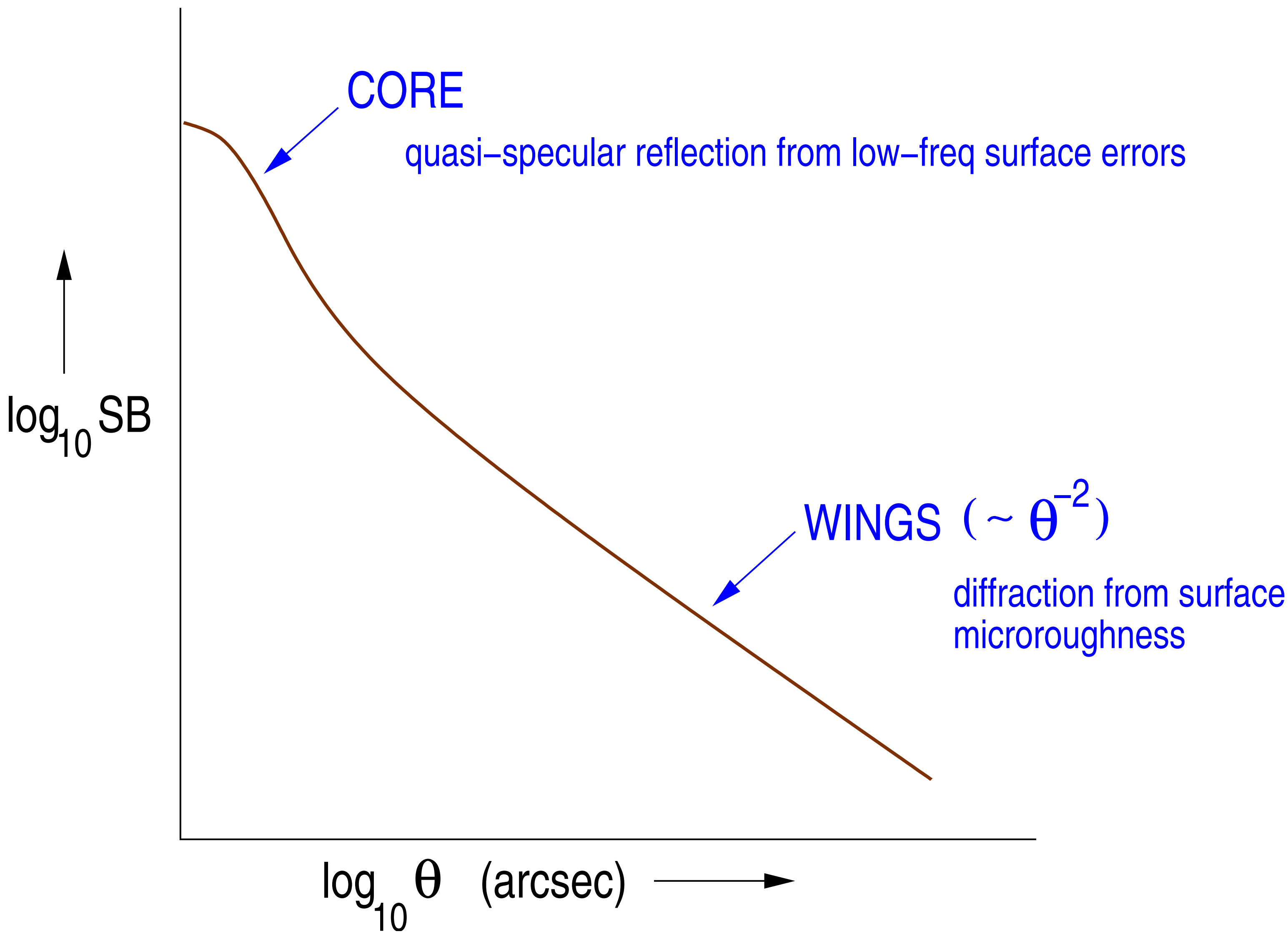
HRMA On-Axis PSF

- core
  - sub-arcsecond imaging
  - quasi-specular reflection from low spatial frequency surface errors
- wings
  - faint diffuse halo extending to large angles
  - diffract off surface microroughness
  - energy-dependent
  - azimuthally averaged profile is approximately powerlaw ($\theta^{-\gamma}$) with $\gamma \sim 2$

Detailed knowledge of this scattering halo as a function of energy and radius is needed for interpretation of observations with faint structure adjacent to bright sources. For example:

- X-ray scattering halos from cosmic dust along the line of sight
- extraction of faint sources adjacent to bright sources
- detecting faint structure (*e.g.*, cosmic ray precursors) ahead of shocks in supernova remnants

Schematic of the PSF



The HRMA PSF

The aim:

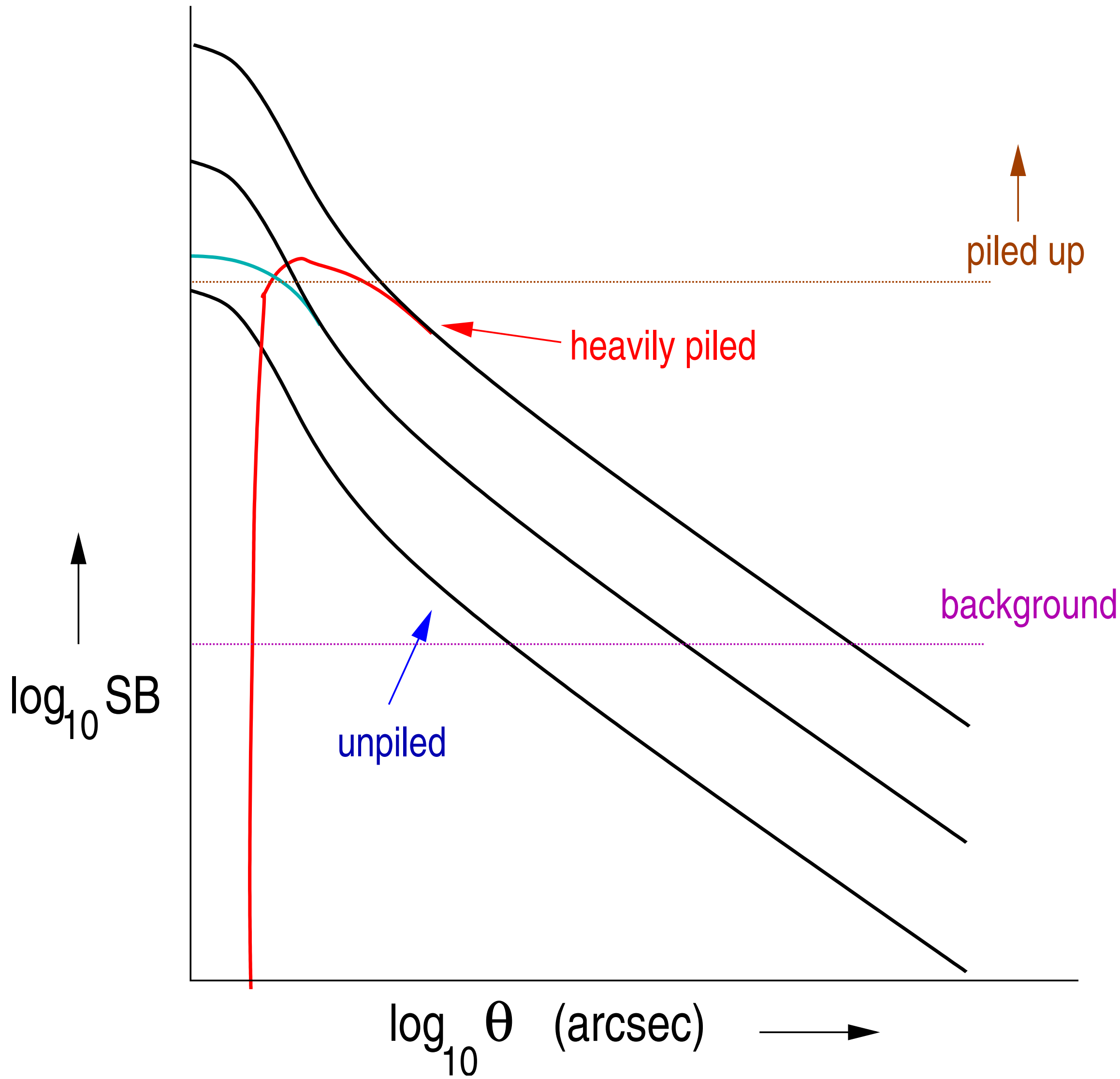
full on-axis PSF radial profile: core ⇔ near wings ⇔ far wings
spatial/spectral problem: want PSF as function of energy.

The *Chandra* PSF core is very narrow, the wings very faint ⇒ huge dynamical range

Detector limitations:

- HRC: limited energy resolution; high background
- ACIS: limited dynamical range (pileup, count rate limits); background
  - PSF core: need low count rate
    - long integration times needed
    - lose wings in background
  - PSF wings
    - high count rate needed to get above background
    - core heavily piled up

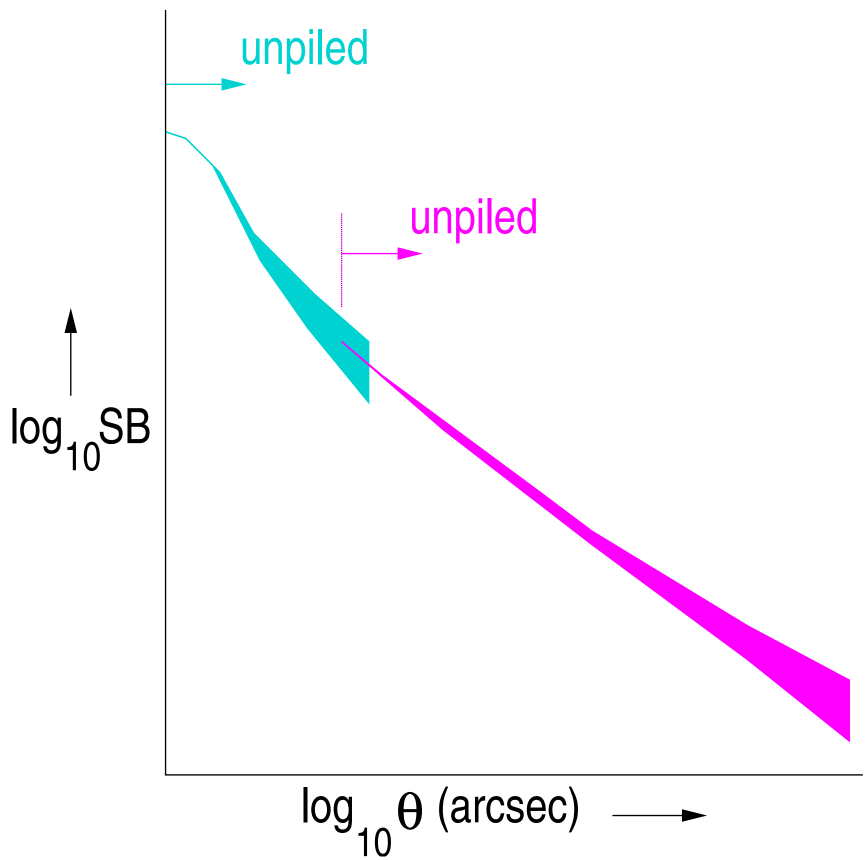
Limitations: ACIS pileup and background



The HRMA PSF

One approach: combine observations with different count rates (and pileup).

- overlap unpiled portions of profiles
- profiles steeply decreasing radially outward ⇒ statistics worse outward



Conservative principle: avoid building astrophysics into the calibration, *e.g.*:

- intervening cosmic dust column ⇒ dust scattering halo.
  - increases with N_H column.
  - most important at lower energies: total scattered power scales roughly as E^{-2}; at fixed angle, very roughly as E^{-1}
- diffuse structure, *e.g.* galaxy or cluster emission (AGN), or PWN (pulsars)
- companion objects

⇒ match deep PSF wings observation with fainter sources (probe the near wings and the core)

Data Sets

	ObsID	Object	Exposure	Frame Time	θ	$N_H(\text{ cm}^{-2})$
Far wings	3662	Her X-1 (high state)	50 ks	3.1 s	$45''$	1.8×10^{20}
Core	2749	Her X-1 zero order	50 ks	3.2 s	$8''$	1.8×10^{20}

- Her X-1 obsid 3662: Main High state; high count rate and good statistics for far wings; reasonable energy resolution, but inner wings heavily piled up.
- Her X-1 obsid 2749: low state; grating zero order data. ~ 9000 cts (0.5–8 keV; within $10''$) ⇒ limited statistics.

ACIS Pileup

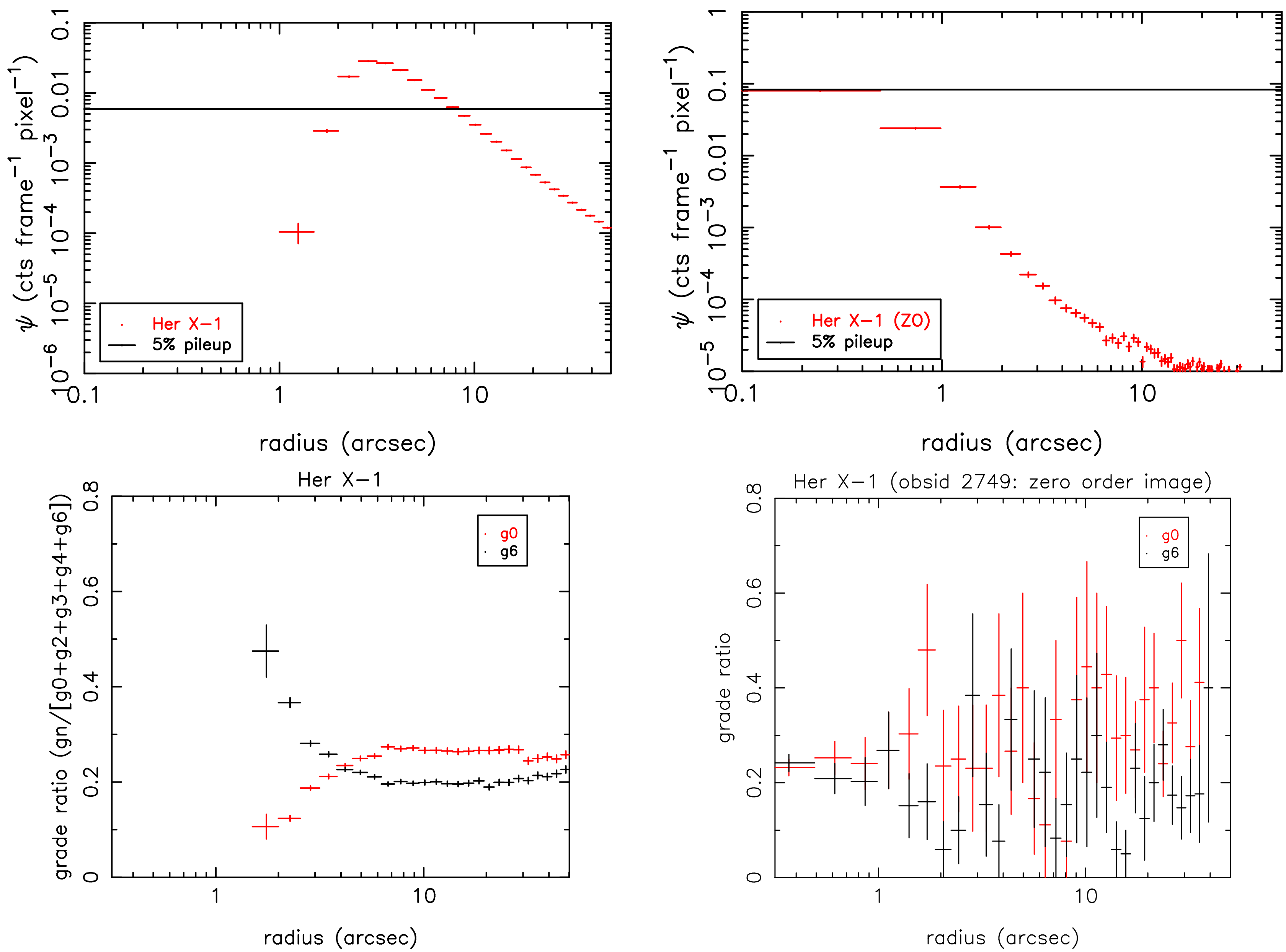
Complications:

- Energy error: event energies too large; spectral distortion
- Grade morphing and loss:
  - grade 0 events → worse grades, (*e.g.* grade 0 → grade 6)
  - grade 0 fraction decreases, grade 6 fraction increases
  - good grades → bad grades; events lost entirely.

    reduction of QE!

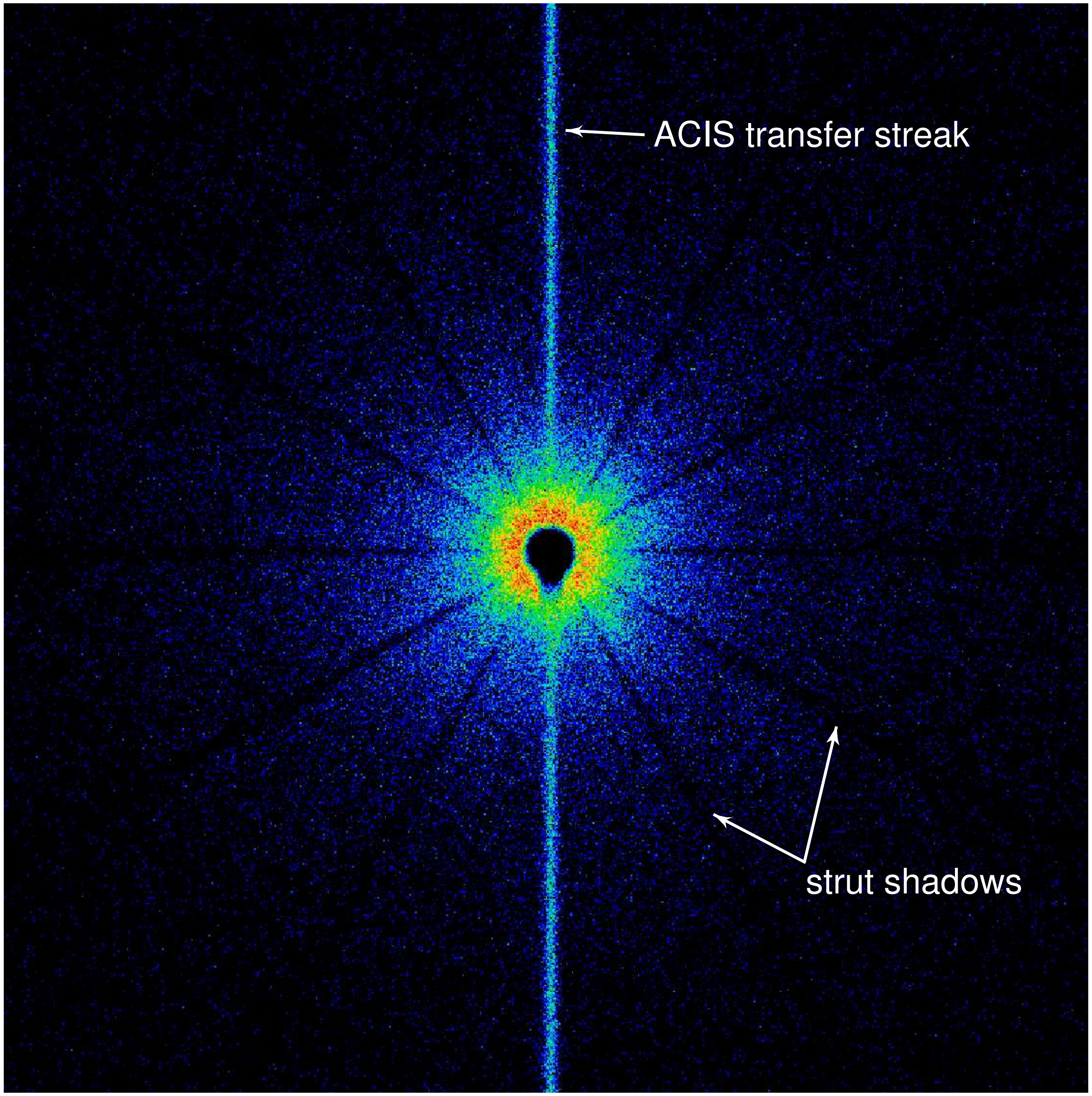
Estimating pileup:

- estimate based on count rate (Poisson statistics); assume uniform photon distribution (wings), or photons within a single pixel (core).
- grade morphing: use profile of grade 6 and grade 0 as fractions of *ASCA* good grades (0,2,3,4,6). Pileup is indicated by increasing g6 fraction and decreasing g0 fraction.


ψ (cts frame⁻¹ pixel⁻¹)
radius (arcsec)
Her X−1
5% pileup
Her X−1 (ZO)
Her X−1
grade ratio (gn/[g0+g2+g3+g4+g6])
g0
g6
Her X−1 (obsid 2749: zero order image)
grade ratio

Her X-1 Observation (obsid 3662; derolled)

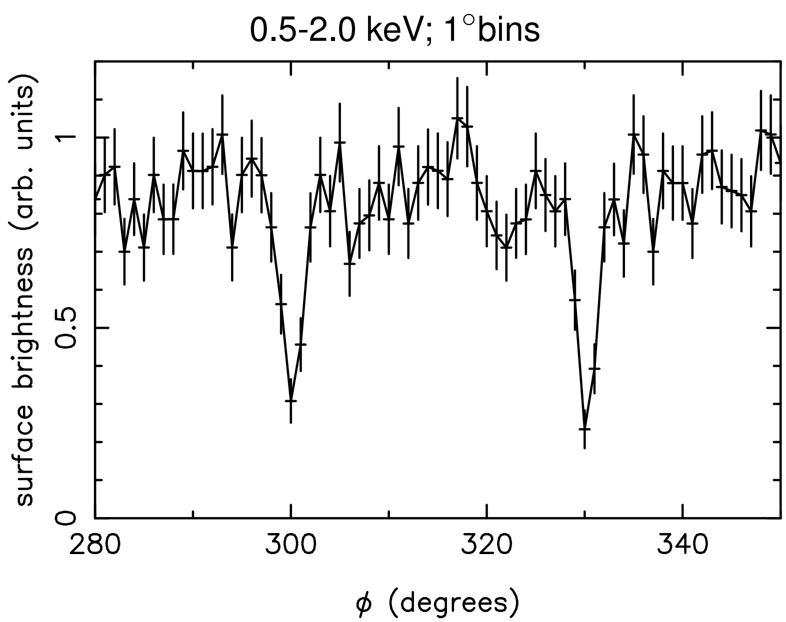
(Frame store is toward the top)



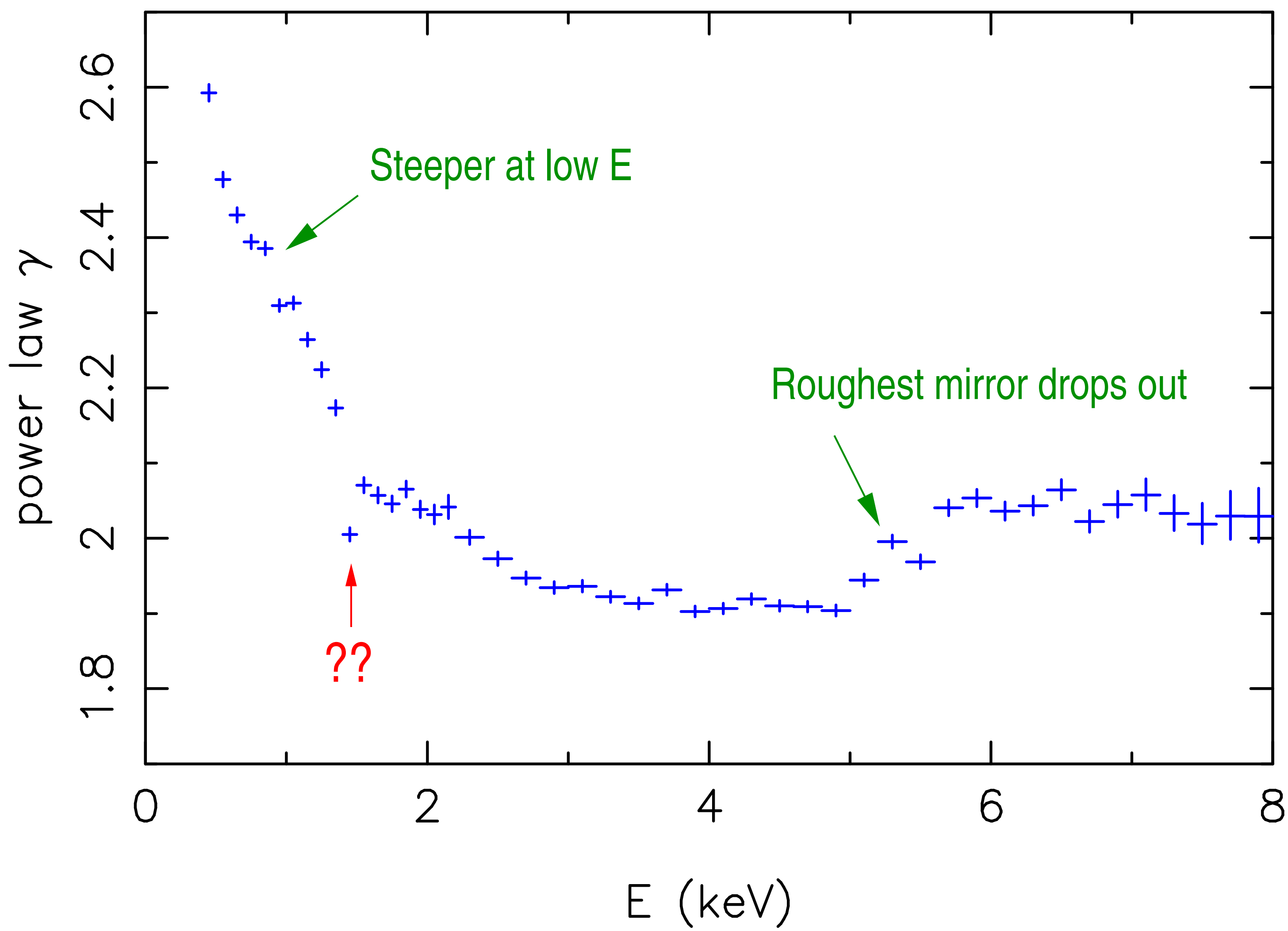
Strut Shadows

The lines at $\sim 30^\circ$ intervals are shadows cast by the mirror support struts. Implications:

- halo: predominantly mirror scattering (in-plane), not a diffuse astrophysical halo
- strut shadows: surface brightness lower by a factor of $\gtrsim 3.5$ $\Rightarrow$ strict limit on any contribution from a cosmic dust scattering halo



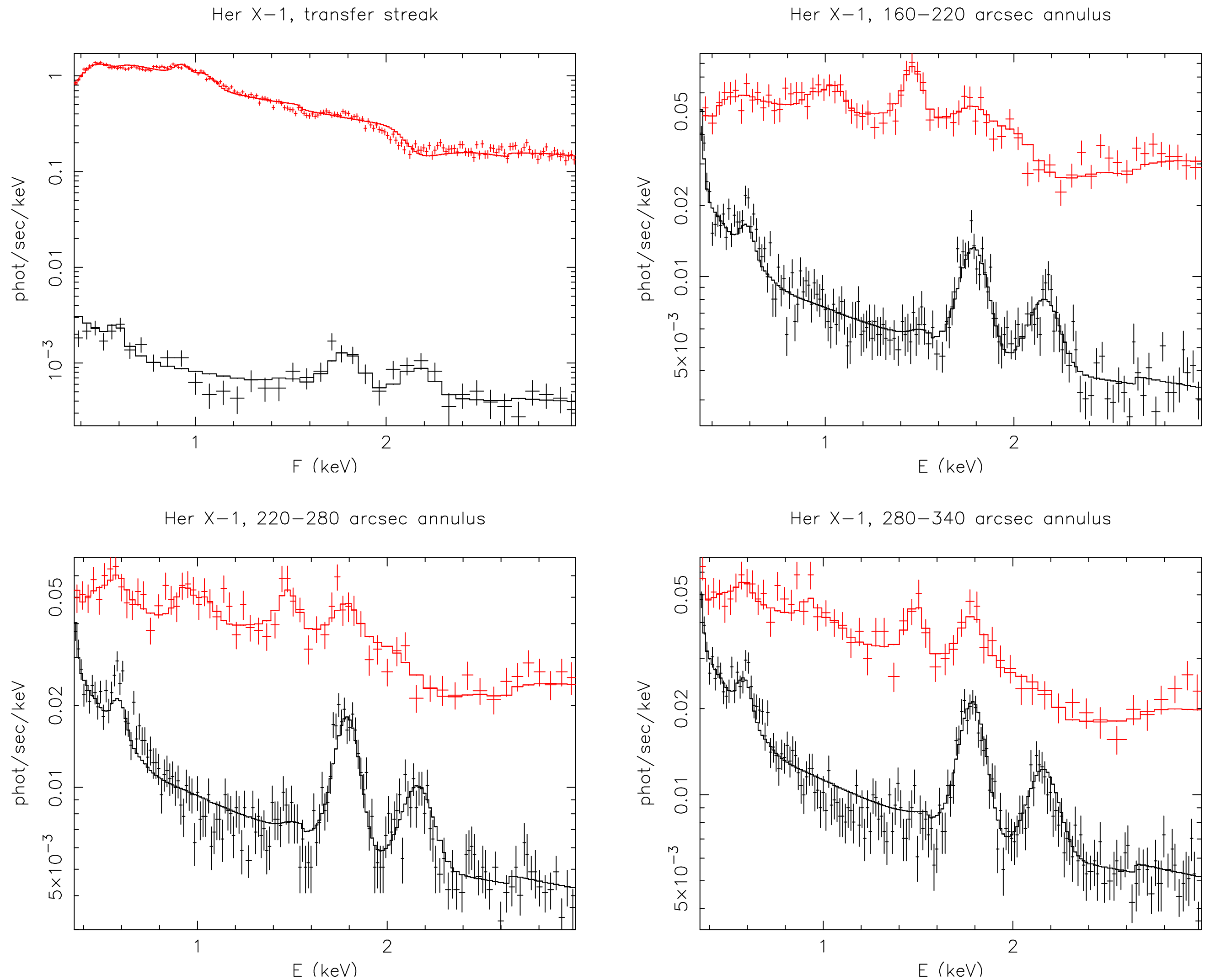
Powerlaw Index (Her X-1 obsid 3662)



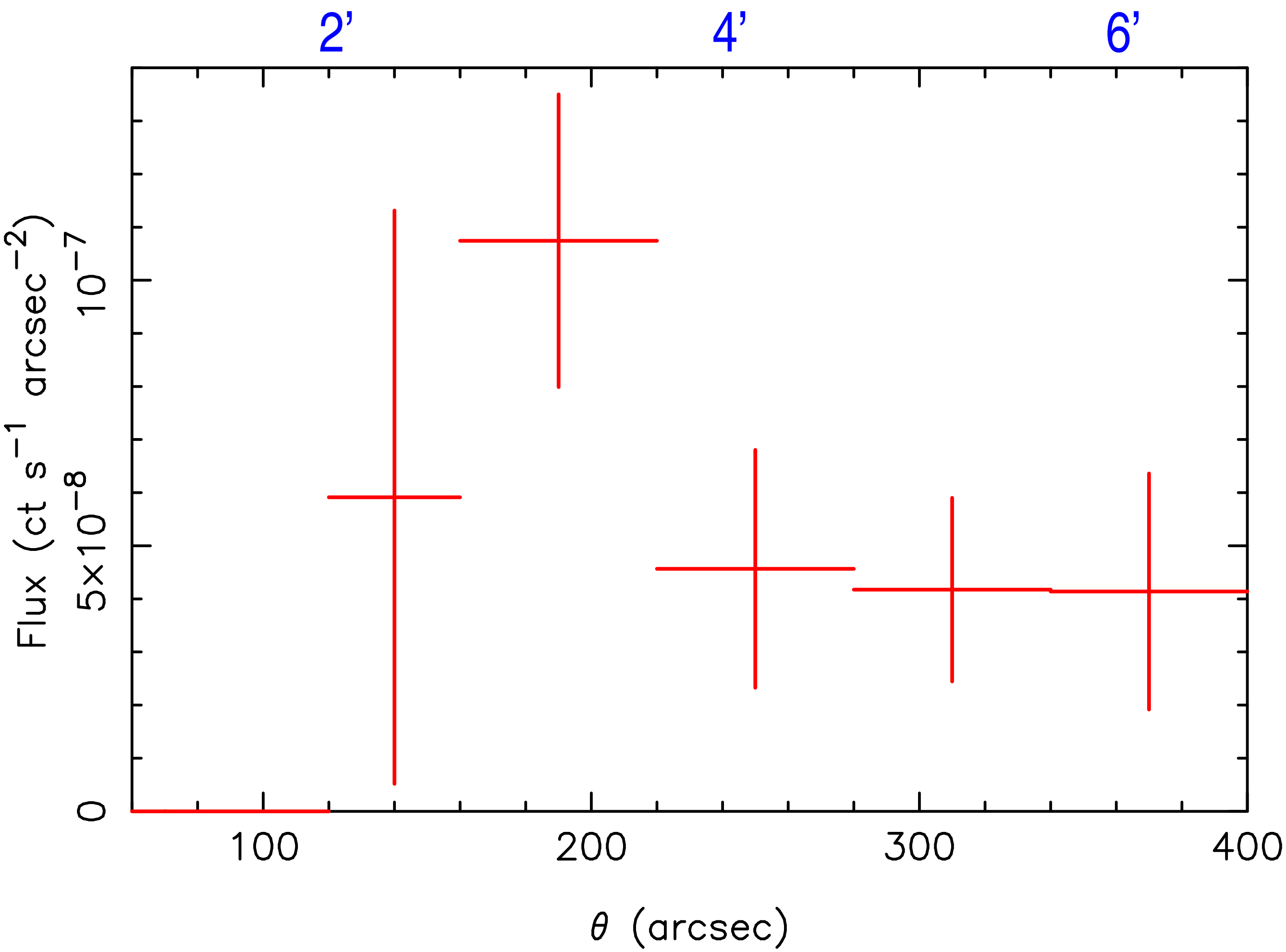
Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background

Anomalous Diffuse (Al Kα?) Feature

source=red background=black



Anomalous Diffuse Al Kα Artifact



To avoid the Al line artifact in the Her X-1 high state observation, the 1.4-1.6 keV band was interpolated from adjacent bands.

Profile Fit and Normalization

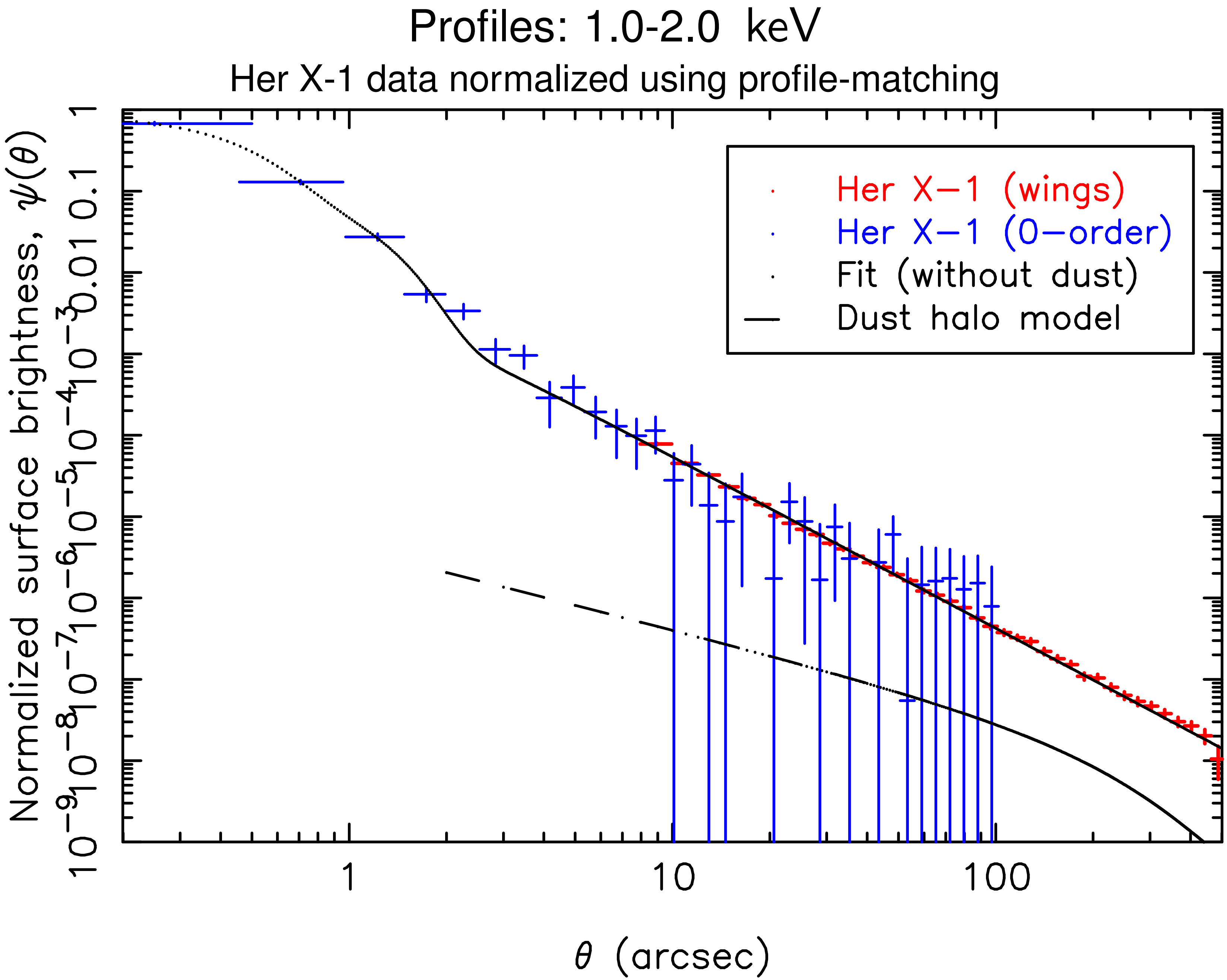
- simultaneously fit radial surface brightness profiles for Her X-1 obsids 3662 (“wings” observation) & 2749 (grating zero-order)
- use 1 keV bins; sum Her X-1 (obsid 3662) narrow energy slices to get 1 keV wide bins.
- Fit: $\psi(\theta) + \text{constant background}$ where

$$\psi(\theta) = A_\beta \Big/ \left[1 + (\theta/1'')^2\right]^{\gamma/2} + \text{gaussian}(\text{FWHM} \sim 1'') + \text{gaussian}(\text{FWHM} \sim 2-5'')$$

- Resulting model profile (and datasets) are normalized:

$$\psi_{norm}(\theta) = \psi(\theta) \Big/ \left[2\pi \int_0^{\theta_{max}} d\theta\, \theta\, \psi(\theta)\right]$$

- **NOTE: The fit procedure forces obsid 3662 and 2749 to match at overlap. 3662 and 2749 profiles are rescaled to match at the overlap.**


Profiles: 1.0-2.0 keV
Her X-1 data normalized using profile-matching
Normalized surface brightness, $\psi(\theta)$
θ (arcsec)
1
10
100
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Her X−1 (wings)
Her X−1 (0−order)
Fit (without dust)
Dust halo model

Comparison to AR Lac (HRC-I)

AR Lac (obsid 1385)

- HRC-I observation early in the mission; no gratings
- $17''$ off-axis;
- exposure time 18.8 ksec; 124000 source cts.
- data “corrected” to remove a blur from residual errors in the HRC event position reconstruction (Jerius *et al.* 2003, SPIE 5165-43)
- soft source; appropriate comparison is low-energy ACIS profile

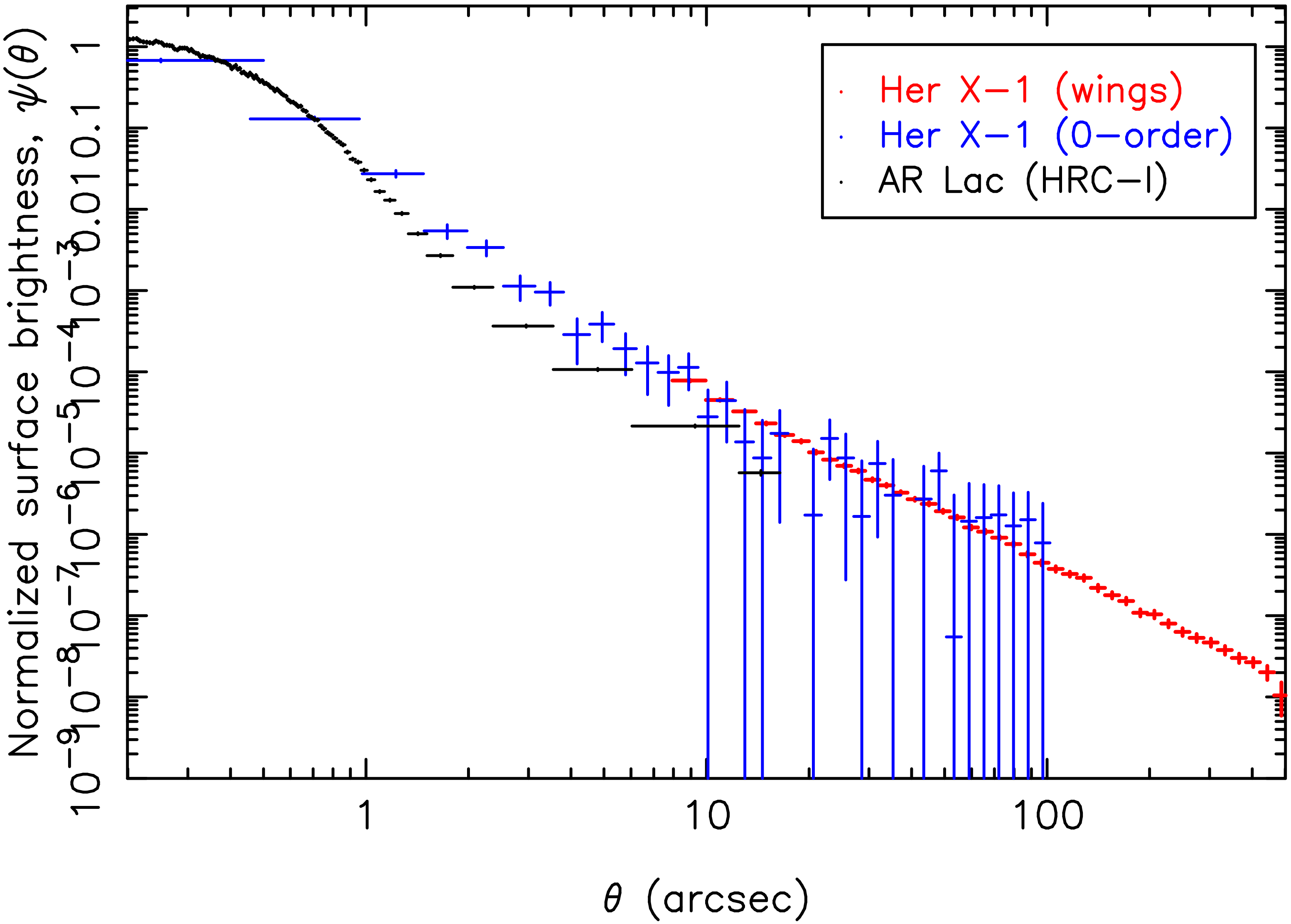
Compare the low energy 1.0–2.0 keV ACIS observations to the HRC-I AR Lac data.

- normalization:
  - AR Lac: by area-weighted sum out to 15″
  - Her X-1: by area-weighted integral of fit out to 300″

- AR Lac HRC-I profile systematically below Her X-1 profile for $\theta \gtrsim 1''$!

Comparison to AR Lac (HRC-I)

Her X-1 data normalized using profile-matching



Alternative Her X-1 Normalizations

- Her X-1 obsid 2749 (grating zero-order): normalize by source spectrum integrated over 10$''$ radius region
- Her X-1 obsid 3662 ("wings" observation): normalize using transfer streak spectrum

⇒ relative offset between "core" dataset and "wings" dataset!

- better agreement of wings data with AR Lac HRC-I data
  - detector artifact? ACIS or HRC?
  - low-level grating artifact in zero-order data?

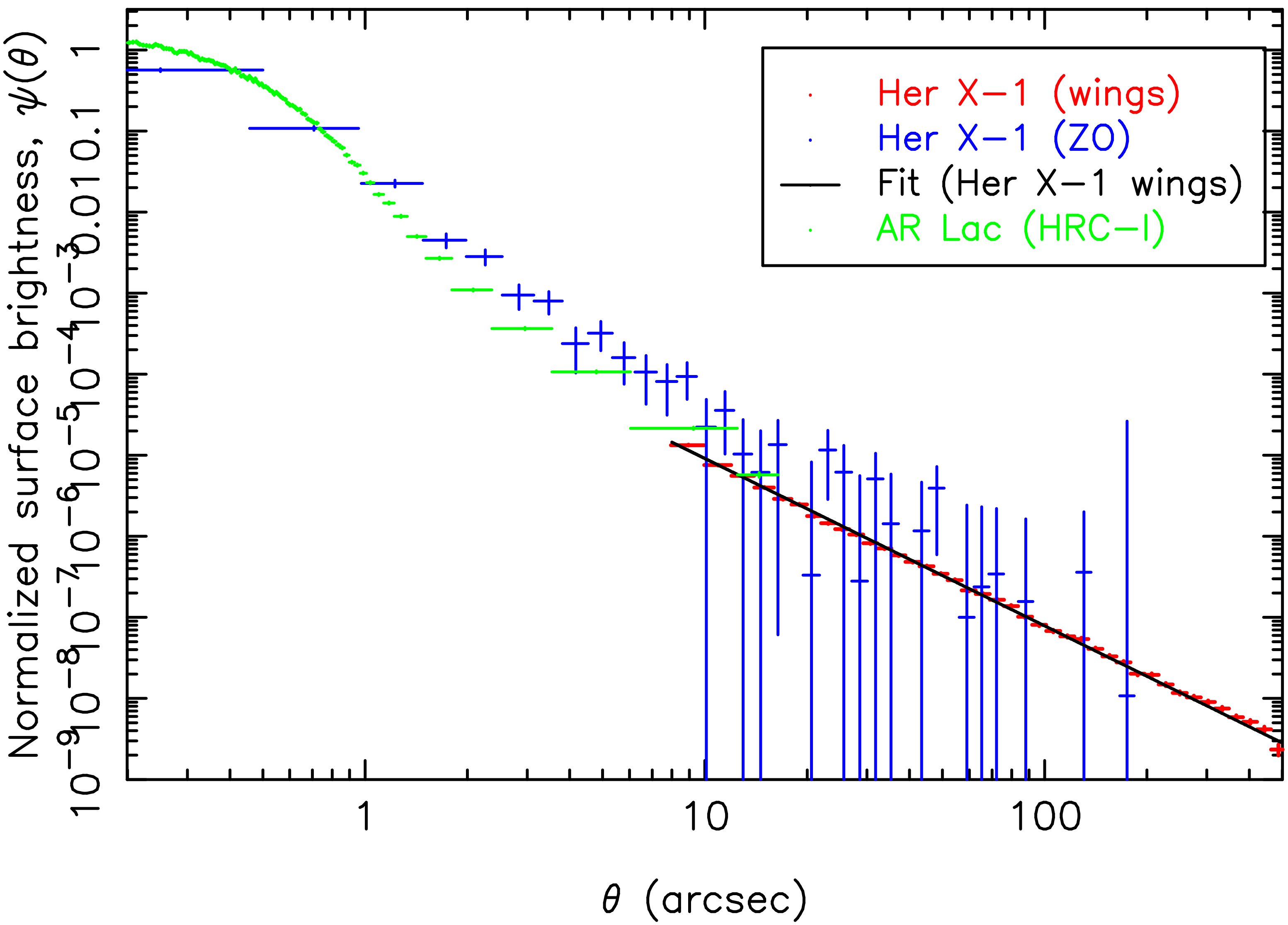
Tentative conclusion:

- normalization of wings dataset by transfer-streak is currently probably more reliable than profile-matching with zero-order grating data.
- However: the response during frame transfer is relatively uncalibrated.
  - slope of the gain curve differs by at least a few percent.
  - effective QE uncertain.

⇒ Consider powerlaw fits to wings data (obsid 3662) normalized by the ACIS transfer streak.

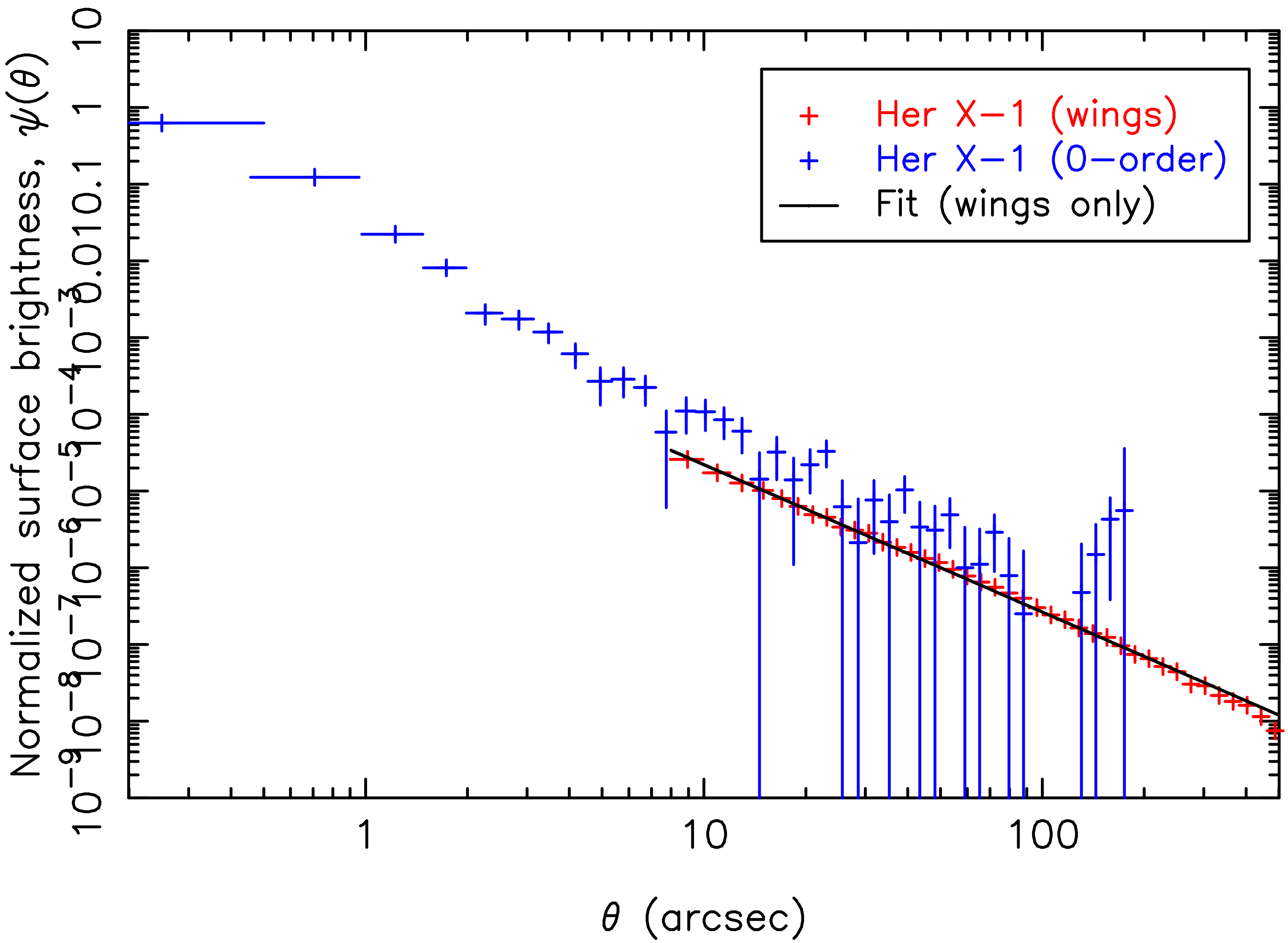
Profiles: 1.0-2.0 keV

Her X-1 wings data normalized using transfer streak



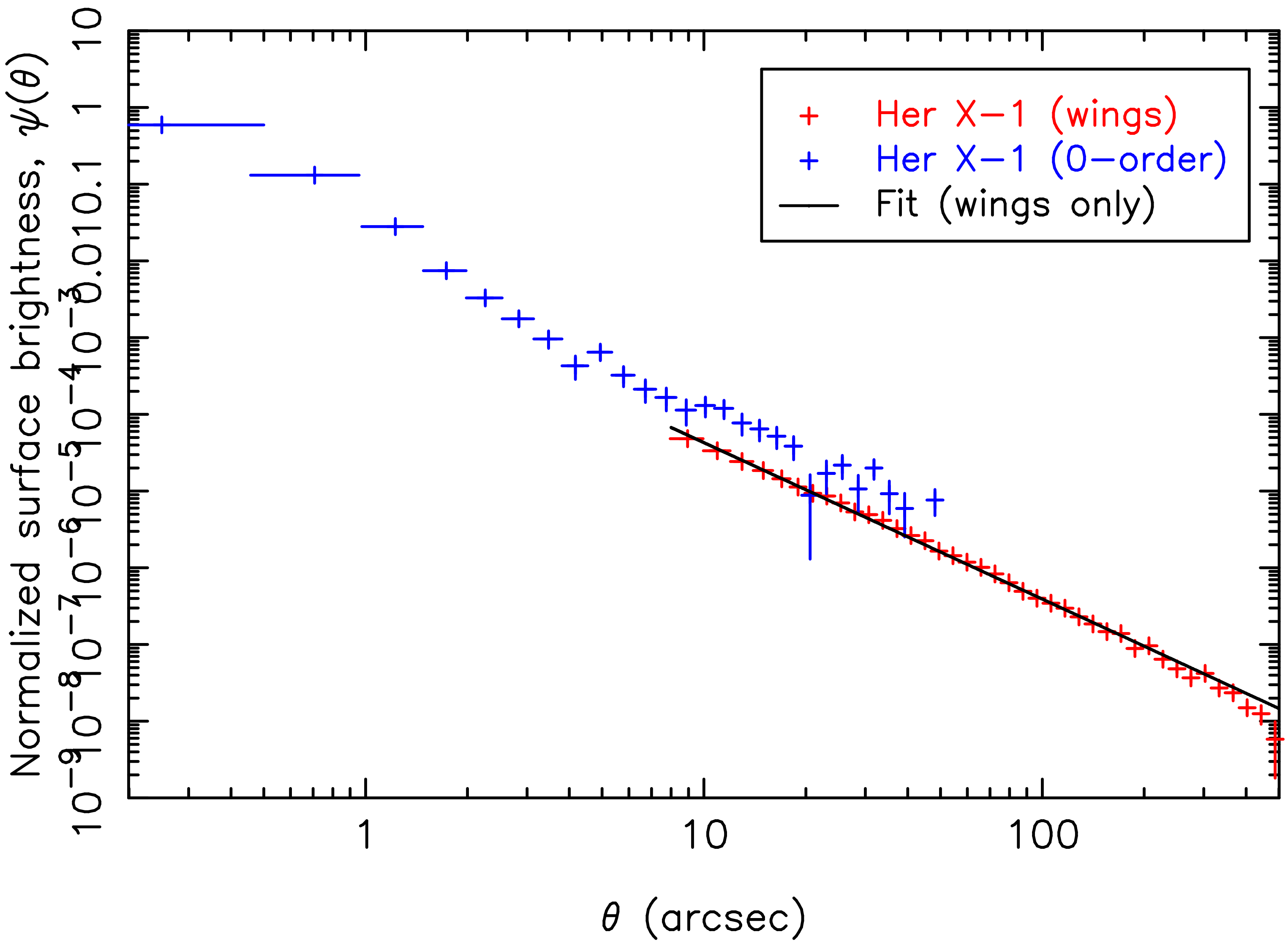
Profiles: 3.0-4.0 keV

Her X-1 wings data normalized using transfer streak

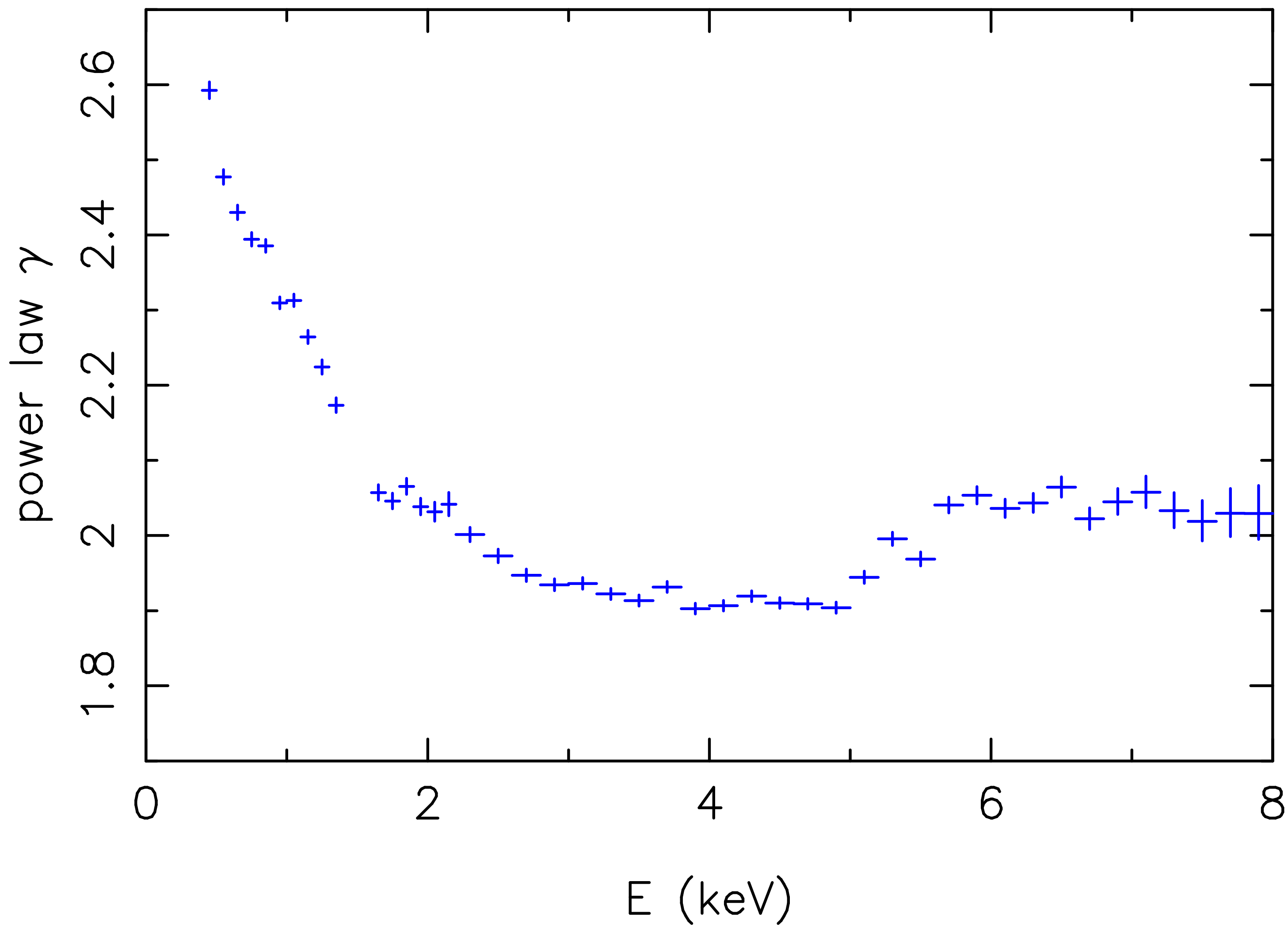


Profiles: 6.0-7.0 keV

Her X-1 wings data normalized using transfer streak

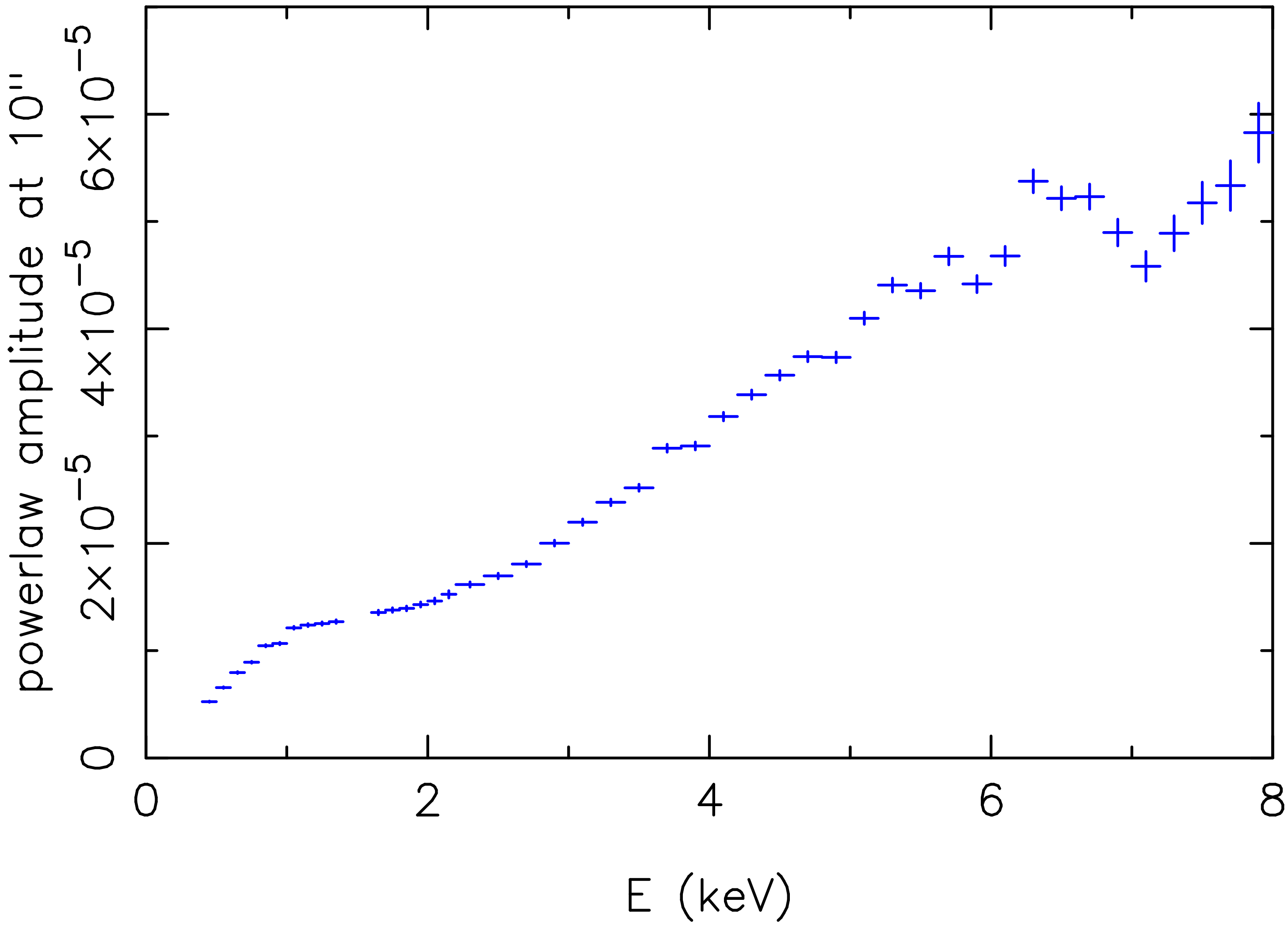


Powerlaw Index; Her X-1 wings



Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background (1.4-1.5 keV and 1.5-1.6 keV fits not included.)

Powerlaw Normalization (at 10″); Her X-1 wings



Simultaneous fit to obsid 3662 (powerlaw+background) and blank sky background
(1.4-1.5 keV and 1.5-1.6 keV fits not included.)

Summary

- Significant progress toward understanding the on-axis PSF at large angles;
  - PSF Shape is well constrained for $10'' \lesssim \theta \lesssim 6'$, and for $1\ \text{keV} \lesssim E \lesssim 8\ \text{keV}$.
  - Profiles unreliable below 1 keV (low energy QE uncertainties)
  - Wings shape fit reasonably well by a powerlaw out to $\sim 6'$. Residuals indicate slight steepening of the profile outward
  - differences between HRC-I and ACIS-S grating zero order data $\Rightarrow$ transfer-streak normalization likely better than profile-matching with available non-piled data (grating zero-order datasets)
  - normalization may be uncertain at level of a factor of ~ 1.25 or 1.5 (in addition to statistical errors); systematic errors:
    - transfer streak gain error
    - transfer streak effective QE
- Difference in near wings profile between HRC-I (AR Lac) and ACIS/grating zero-order not yet understood. ACIS or HRC artifact? Grating artifact?
- Reasonably detailed investigation of the angular (ϕ) distribution of the wings can also be pursued.