Calibration of *Chandra*'s Near On-axis Optical Performance

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Current Knowledge of the PSF

- *Chandra*'s PSF is a complicated function of source position, energy, and the focal plane detector.
- Calibration of the PSF on orbit is required.
- PSF core calibration is done in parastitic mode.
- Few true on-axis "pointings" (dither renders this somewhat meaningless, anyway).
- Few point-like astrophysical sources have "reasonable" flux above 2 keV
- The on-board science instruments have characteristics which interfere with optics' calibration:
  - HRC has no energy resolution.
  - HRC-I event position reconstruction introduces systematic offsets in recorded event positions
  - ACIS has large pixels ($\sim 0.5''$)
  - ACIS is easily piled up, so must use very faint sources, or use ACIS-S + transmission grating (HETG), introducing unknown distortions to the PSF.

Calibration with the HRC-I

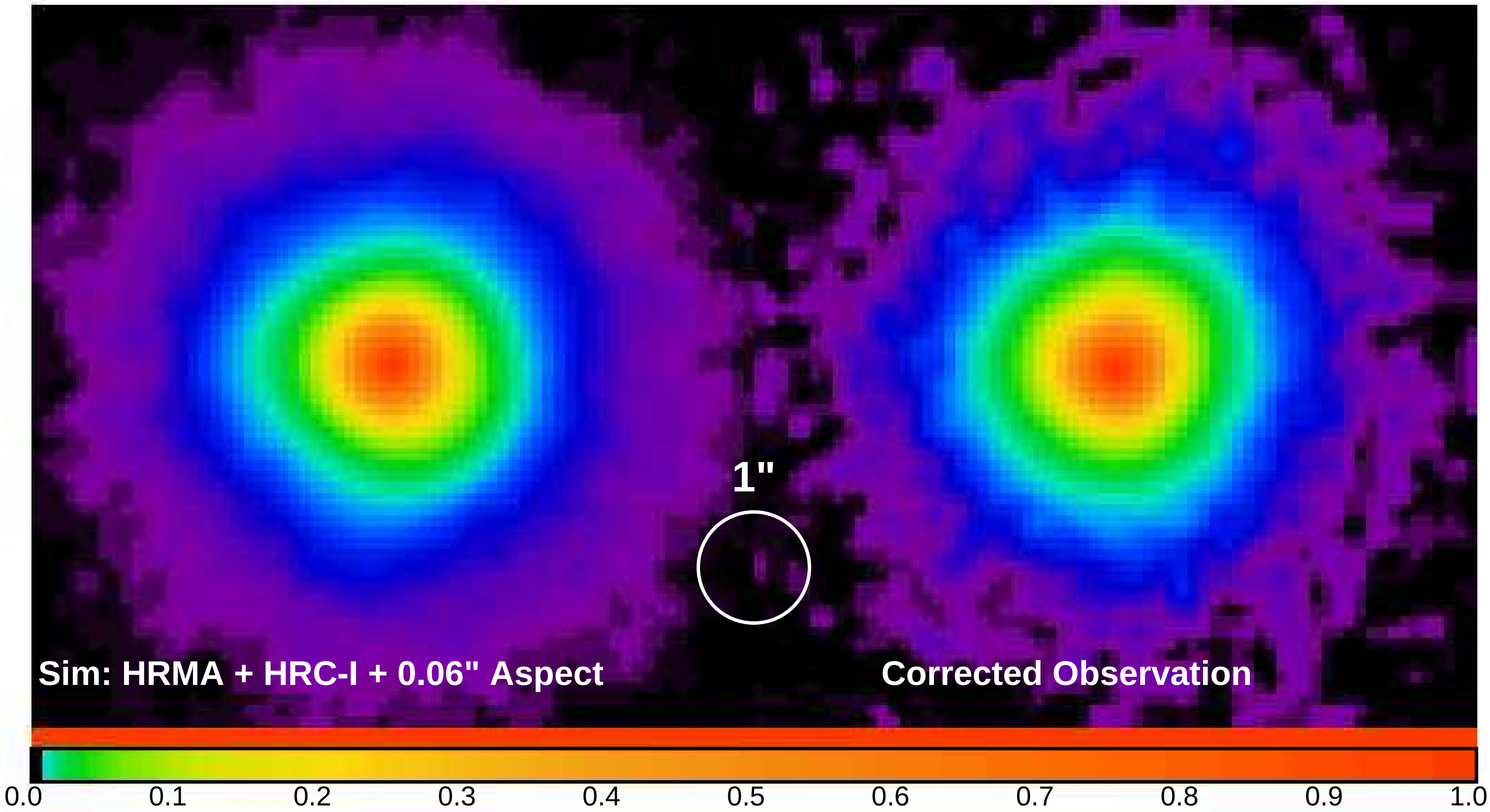
The best observation so far is a long (18.8 ksec) observation of AR Lacertae

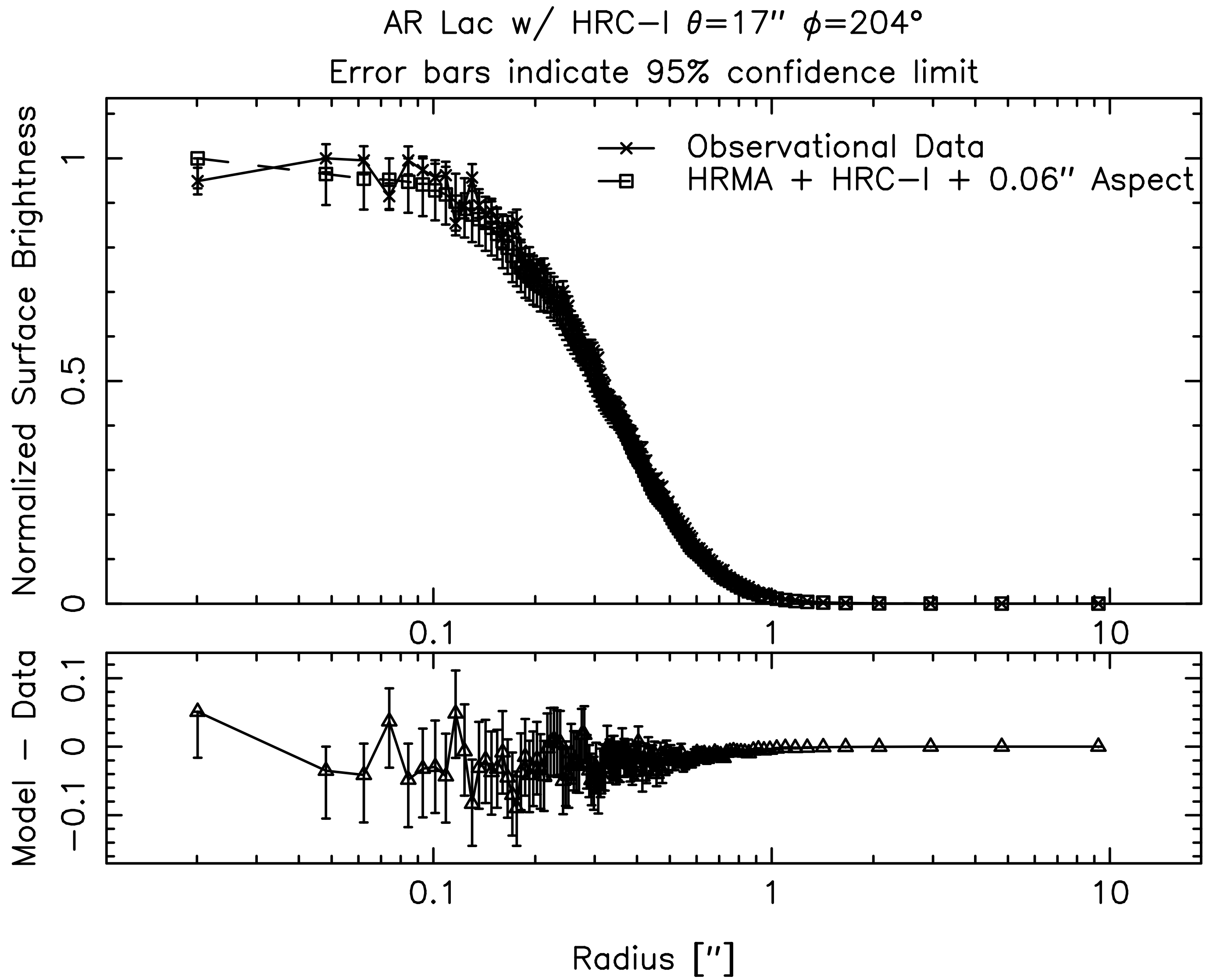
- ~ 124000 source events.
- apparently no extended X-Ray emission
- nominal pointing 17$''$ off-axis with HRC-I.
- soft source

But

- no energy resolution.
- HRC-I position reconstruction artifacts (function of event position relative to HRC-I tile). Telescope dither converts spatial artifacts to temporal artifacts, allowing one to use image centroid position to correct the event positions. (See CCW 2002, SPIE 2003, CCW 2003).

AR Lac w/ HRC-I: 17", 204deg az



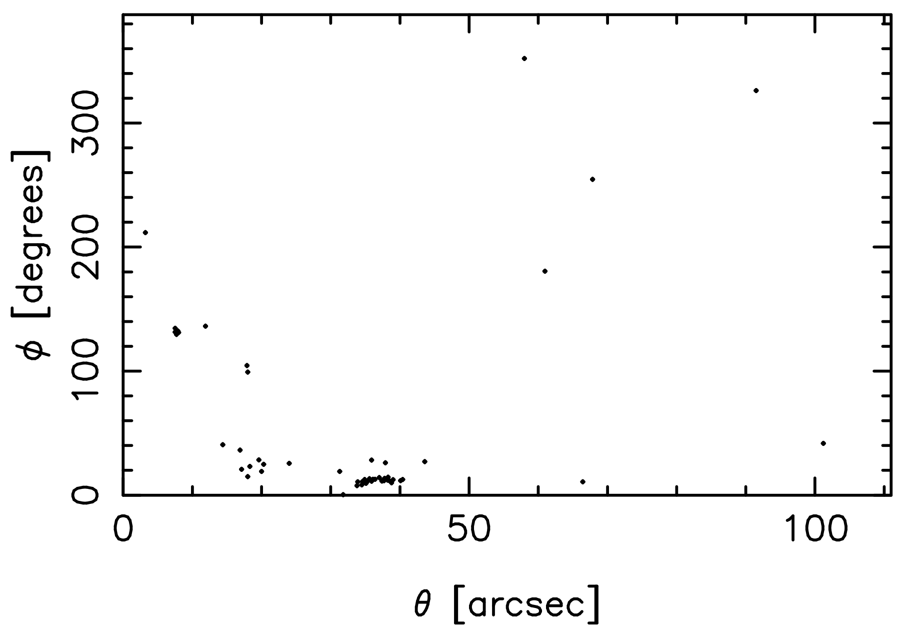

AR Lac w/ HRC−I θ=17″ ϕ=204°
Error bars indicate 95% confidence limit
Observational Data
HRMA + HRC−I + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
1
10
Model − Data
−0.1
0
0.1
0.1
1
10
Radius [″]

HRC-I PSF Conclusions

- SAOsac model fits "corrected" PSF well
- Correction can only be performed on known point sources with high flux.
- Current HRC-I models do not include this artifact, so forward folding is not yet possible.

Calibration with ACIS

- Due to pileup, limited to faint point sources.
- Of ~ 400 "pointed" observations of stars (normal, WD, BH) examined, 56 acceptable candidates.
- large spread in object positions:



ACIS Candidates:

Detector	Grating	No. Obs.
ACIS-I	NONE	7
ACIS-S	HETG	28
ACIS-S	NONE	21

Final selection:

Pointing	θ	ϕ	ACIS-S/HETG	ACIS-S
1	$35'' \pm 0.5$	$12^\circ \pm 1.4$	5	3
2	$7.7'' \pm 0.2$	$132^\circ \pm 1.5$	7	0

Data Reduction

To maximize the S/N, especially at higher energies, the observations in each group were coadded.

Coadding in sky coordinates normally causes distortions in the PSF due to resampled pixels because of different rolls.

We “re-pointed” the aspect data to indicate a nominal roll of 0°, so that the detector pixels would be minimally rotated when the aspect solution was applied.

Data Analysis

The events were split into energy bins appropriate to the spectra to obtain reasonable counts per bin:

Pointing	E_{min}	E_{max}	Counts
1	0.0	1.0	9884
1	1.0	2.0	11456
1	2.0	3.0	8843
1	3.0	5.0	17725
1	5.0	6.0	8231
1	6.0	9.0	12141
2	0.0	1.0	19966
2	1.0	2.0	13801
2	2.0	3.0	4475
2	3.0	5.0	4658
2	5.0	6.0	1861
2	6.0	9.0	3396

Background subtracted radial profiles were generated such that there were at least 400 counts per bin.

The ACIS Simulations

The observation was simulated with SAOsac.

Since the observed PSF is due only to the *detected* photons, not the *emitted* photons, no spectral analysis is required. We model a spectrum designed to exactly reproduce the observed one.

Currently, SAOsac models cannot directly simulate dither. (MARX can, but not with SAOsac rays). This severely complicates the analysis, as will be shown.

The detector and aspect contributions to the PSF were modeled by

① randomizing within an ACIS pixel to simulate the uncertain position of the event within a pixel

② randomizing within an ACIS pixel to simulate the effects of dither motion (definitely not correct).

③ Convolution with a Gaussian of $\sigma = 0.06''$ to simulate aspect pointing errors.

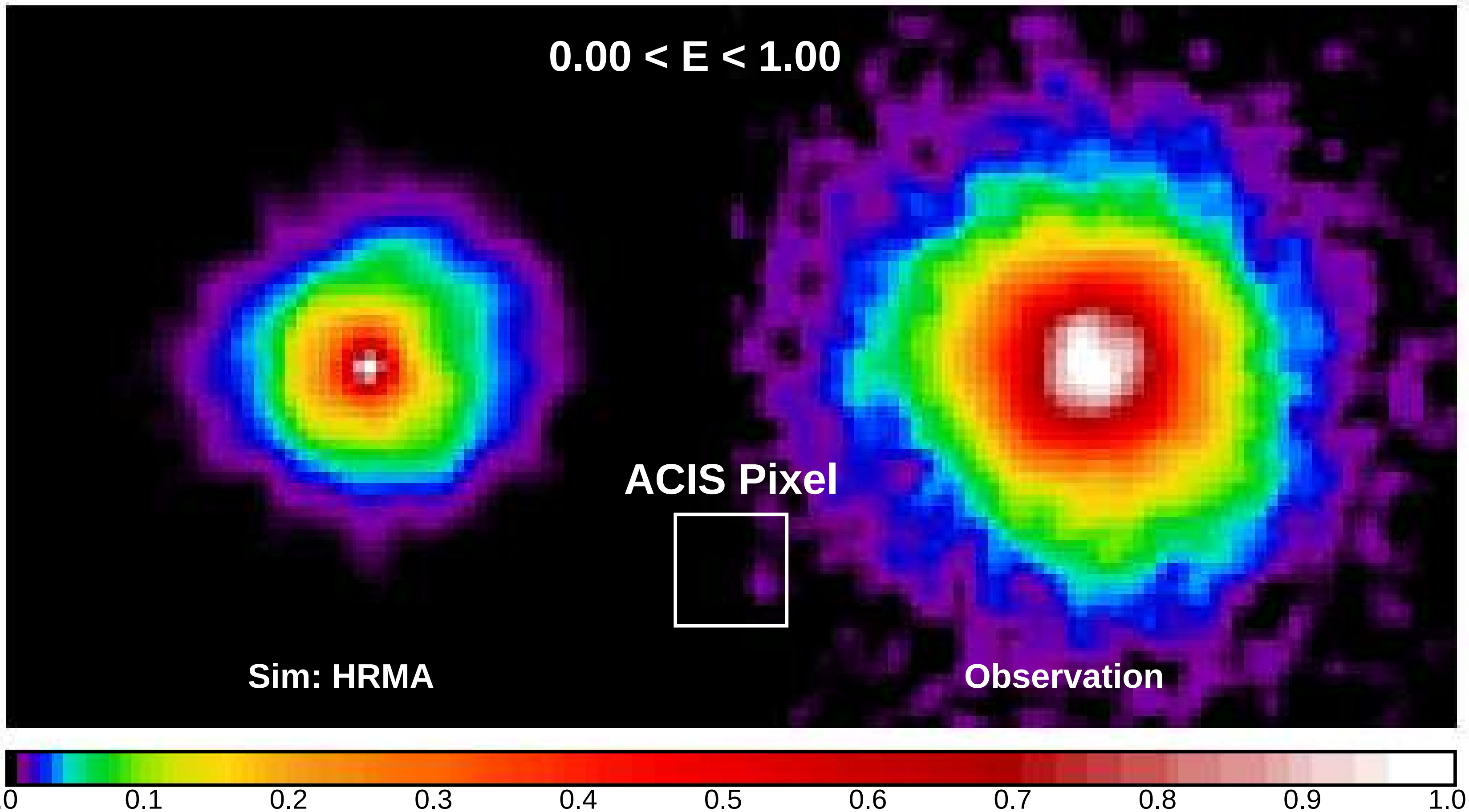
1000 simulations of the nominal pointing were performed.

Warnings!

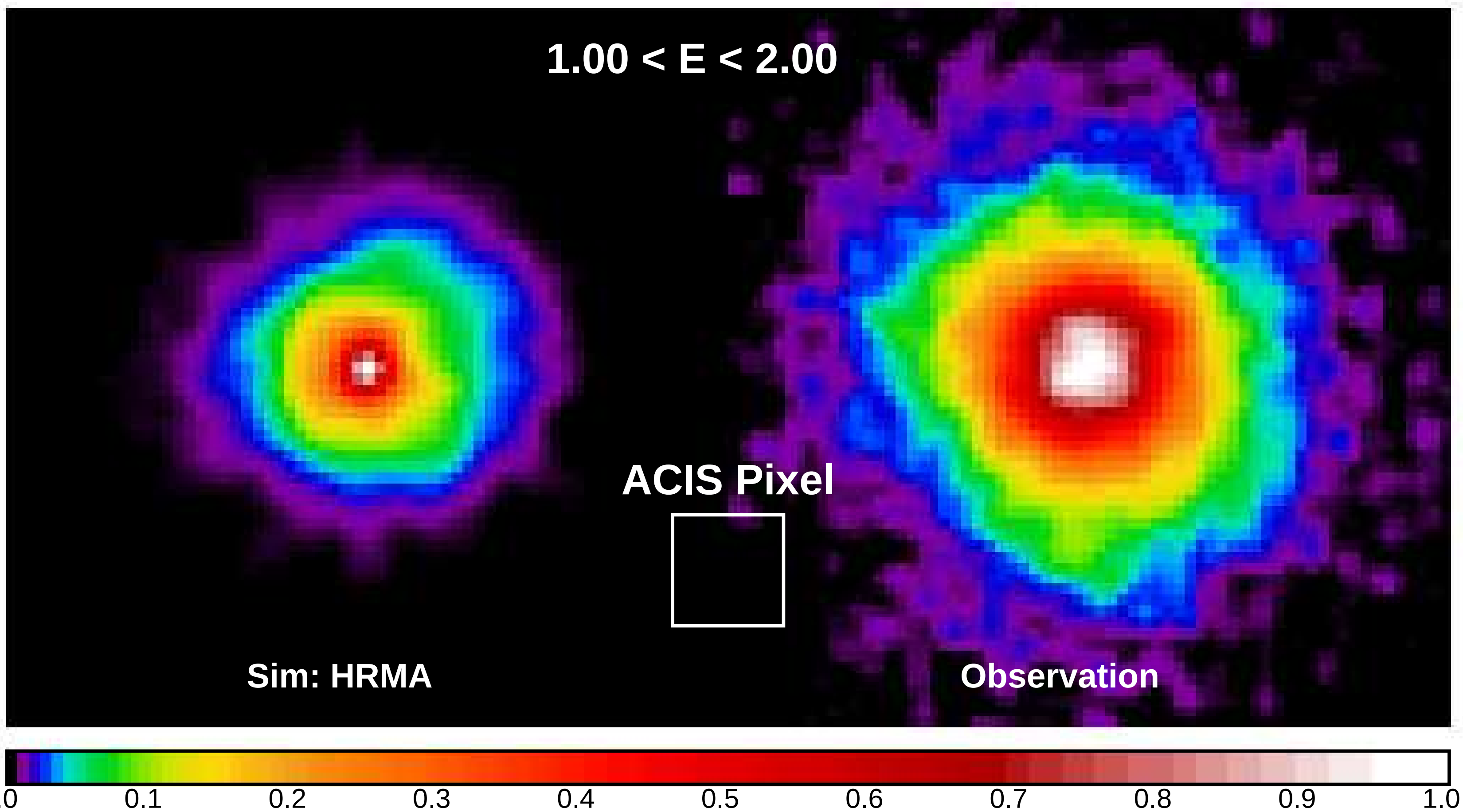
- The observation samples many off-axis positions due to dither. This has *not* (yet) been introduced into the model.
- Background was *not* simulated.
- The simulations treat blurring of the PSF due to the dithered sampling of pixels as a random process. I no longer believe that this is adequate.
- The images are binned at 0.1 ACIS pixels and Gaussian smoothed with $\sigma = 0.1$ ACIS pixels. Why so small? Because there's some indication (as may be shown) that gross structure on the $0.5''$ scale is resolvable.
- Much of the data are derived from **zero order HETG images**.

Don't believe everything that you see.

Merged off-axis ACIS Data: 7.7", 132deg az



Merged off-axis ACIS Data: 7.7", 132deg az



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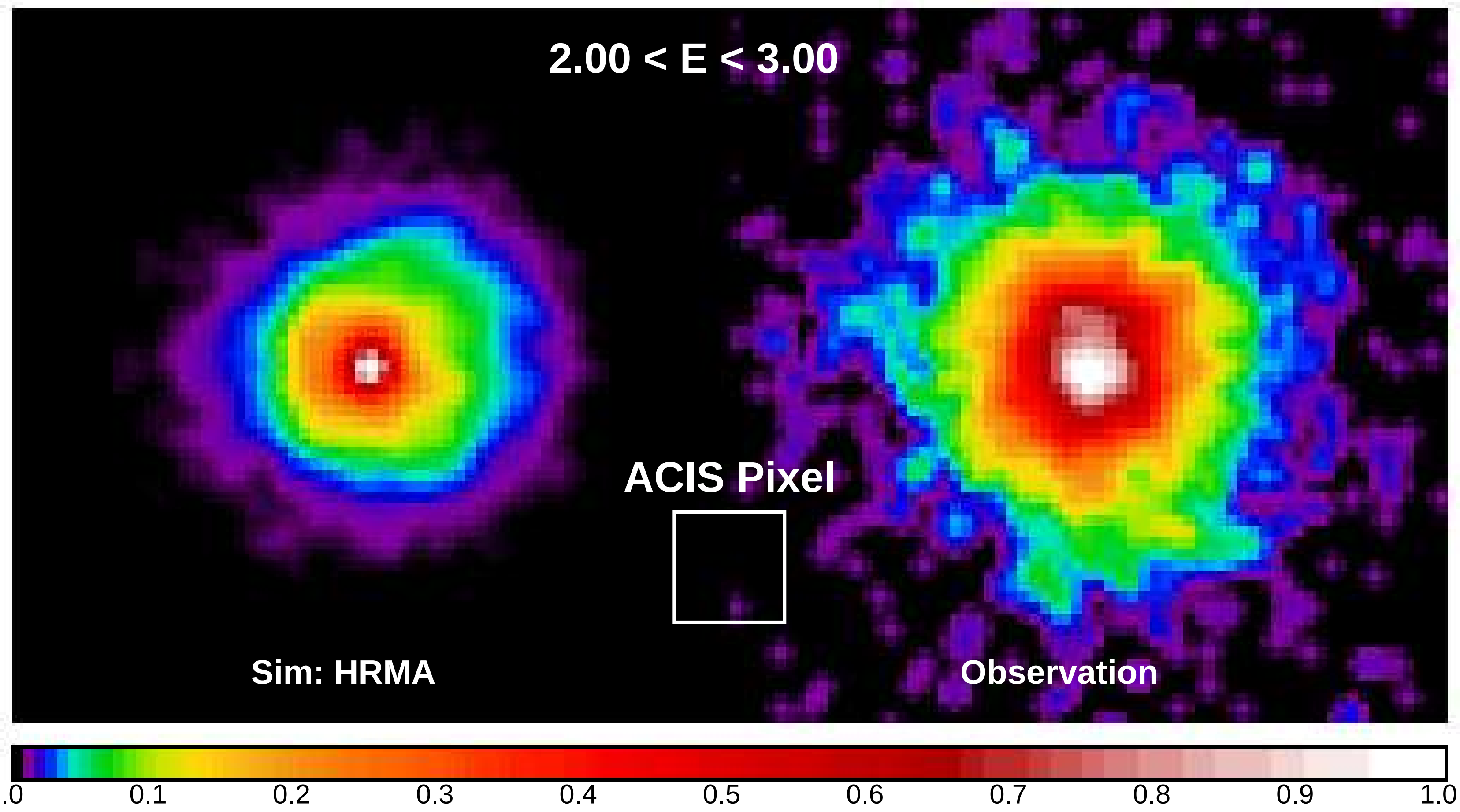
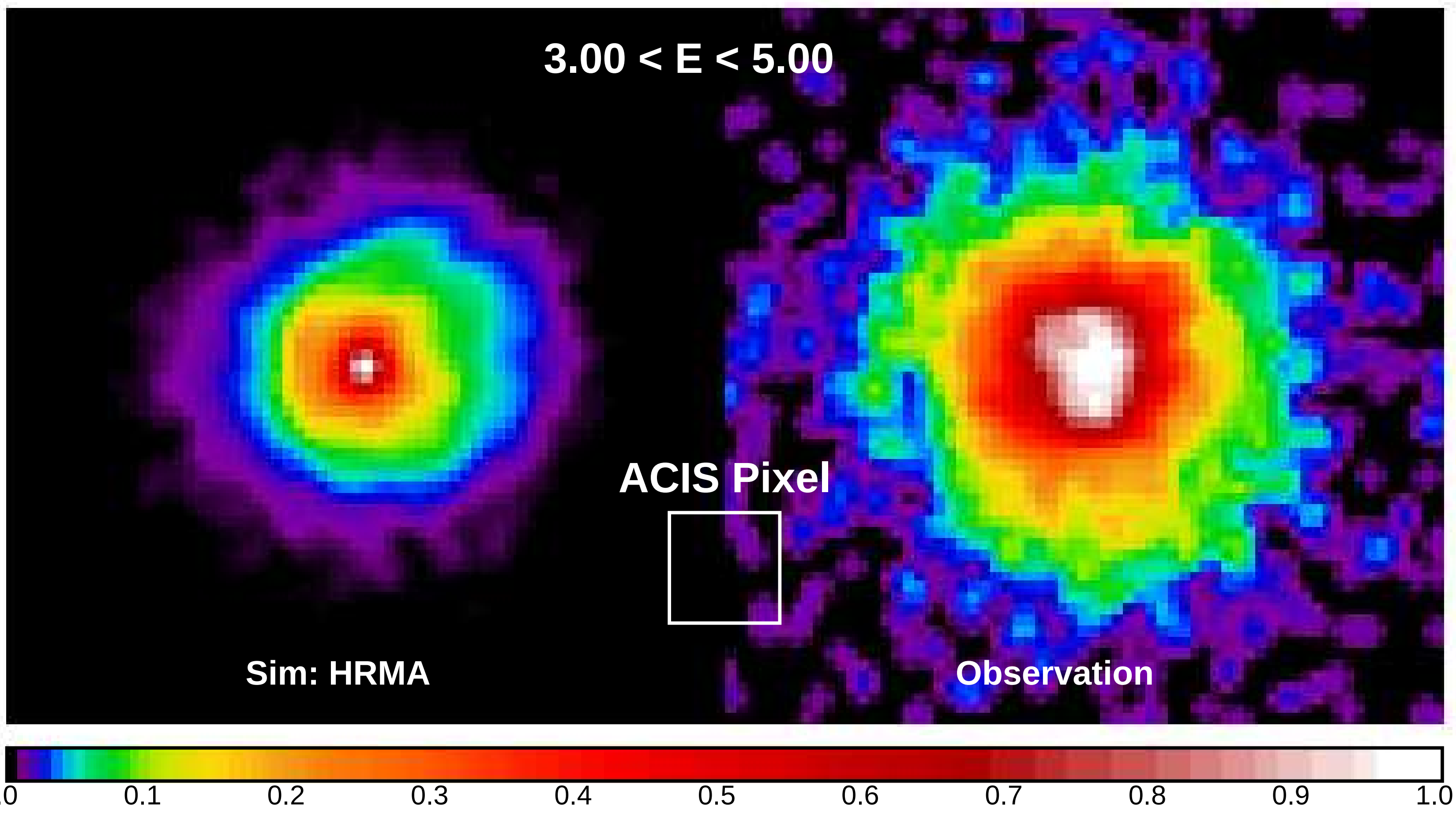
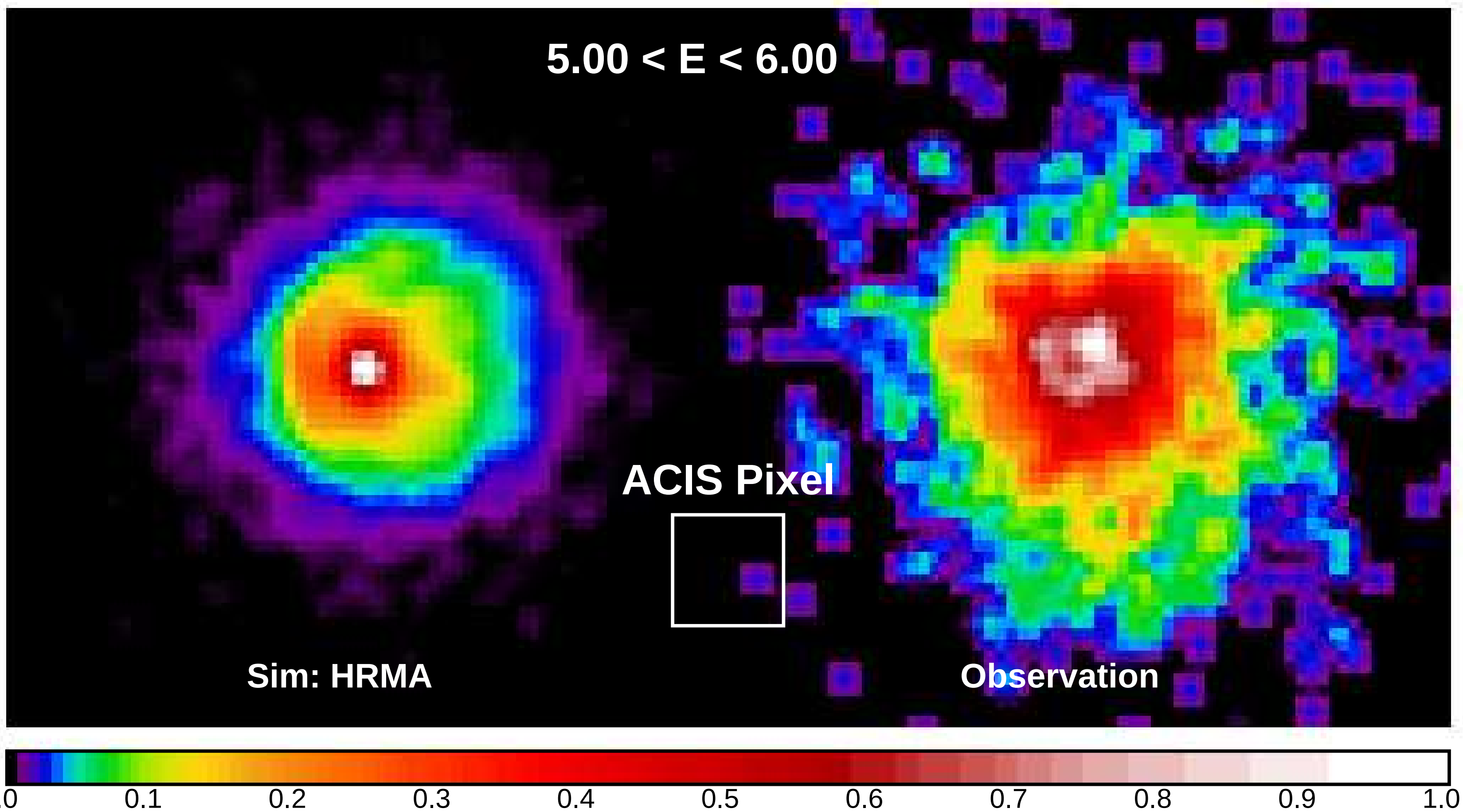


Merged off-axis ACIS Data: 7.7", 132deg az



Merged off-axis ACIS Data: 7.7", 132deg az



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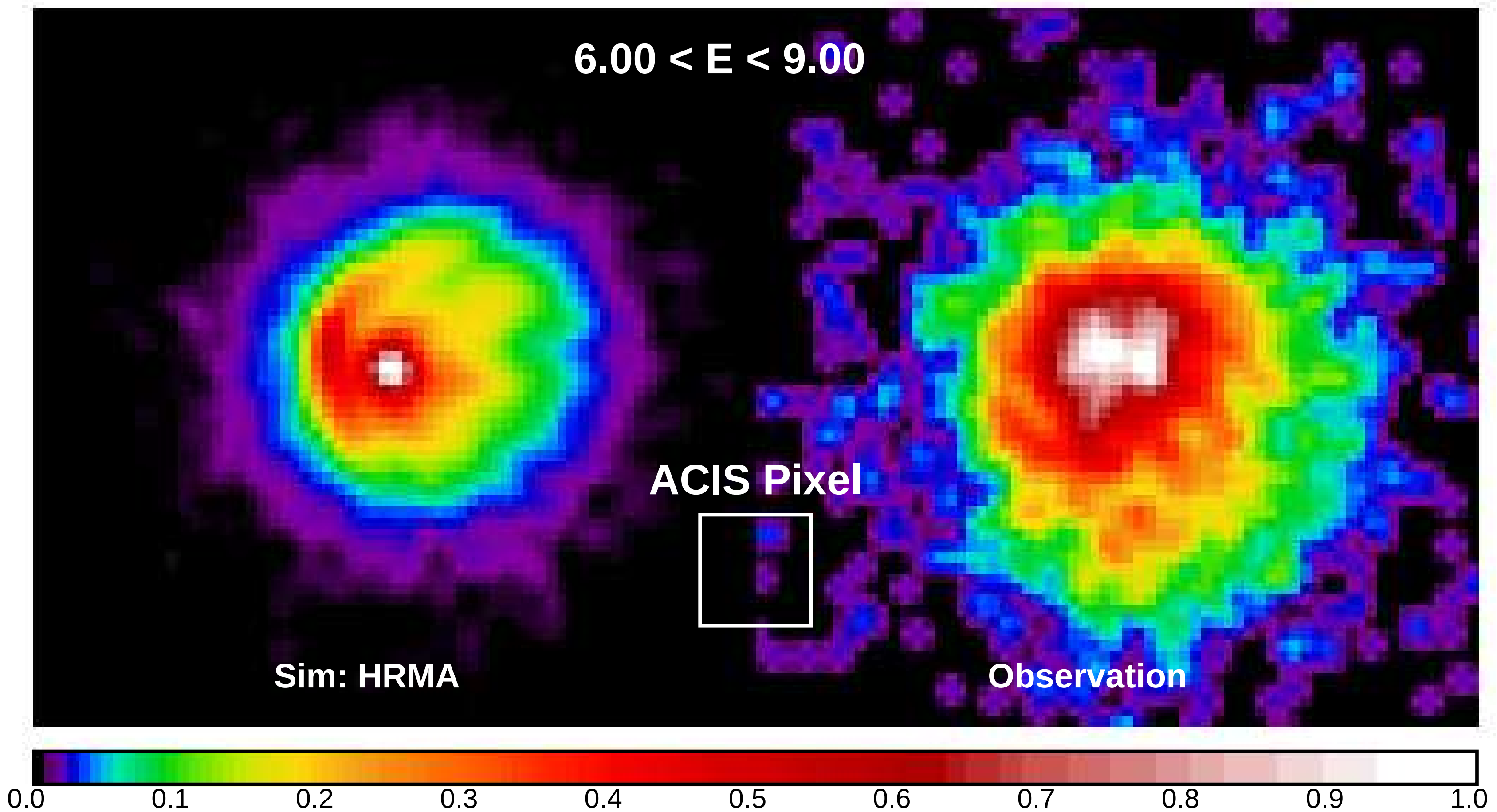

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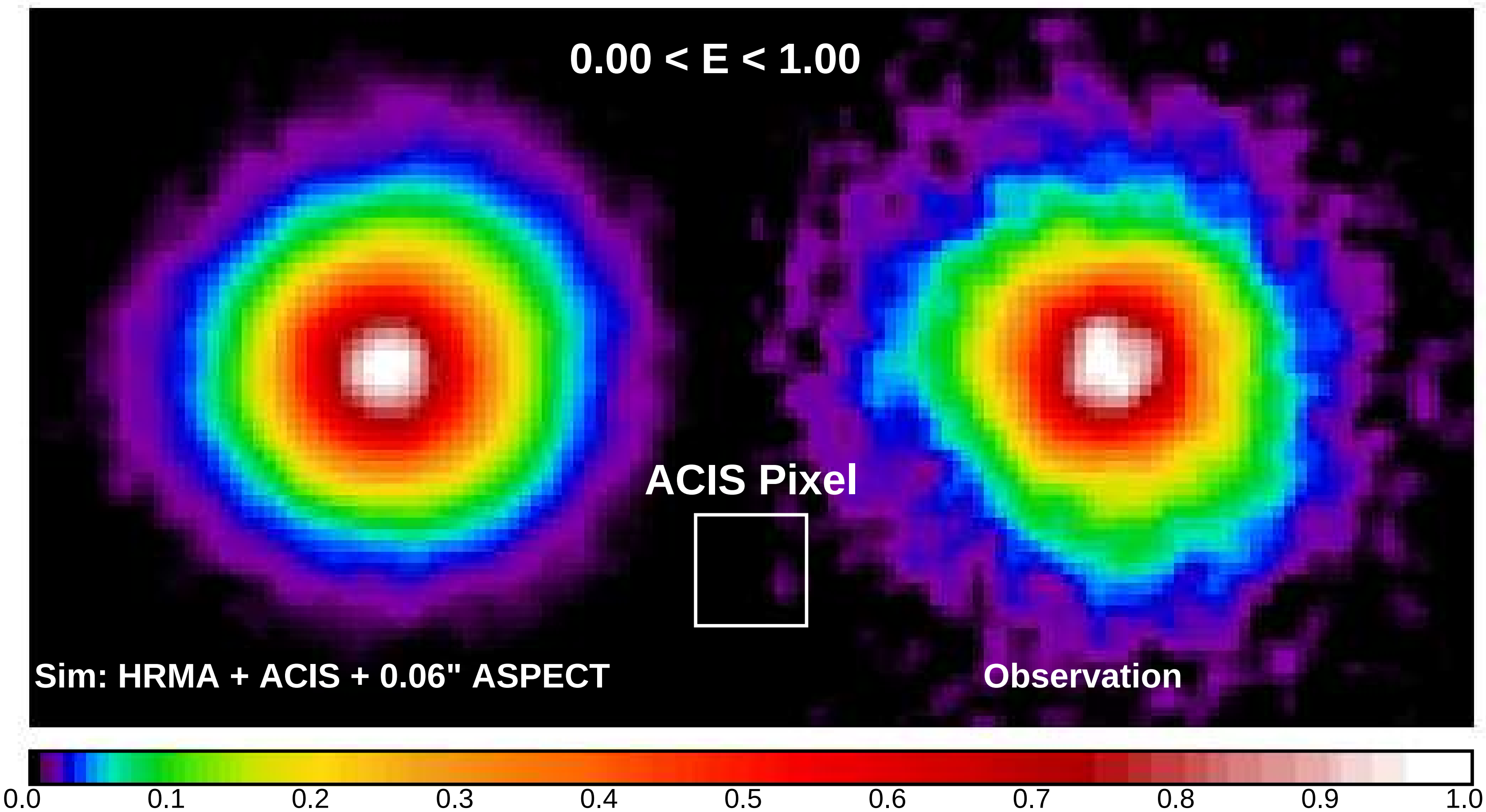

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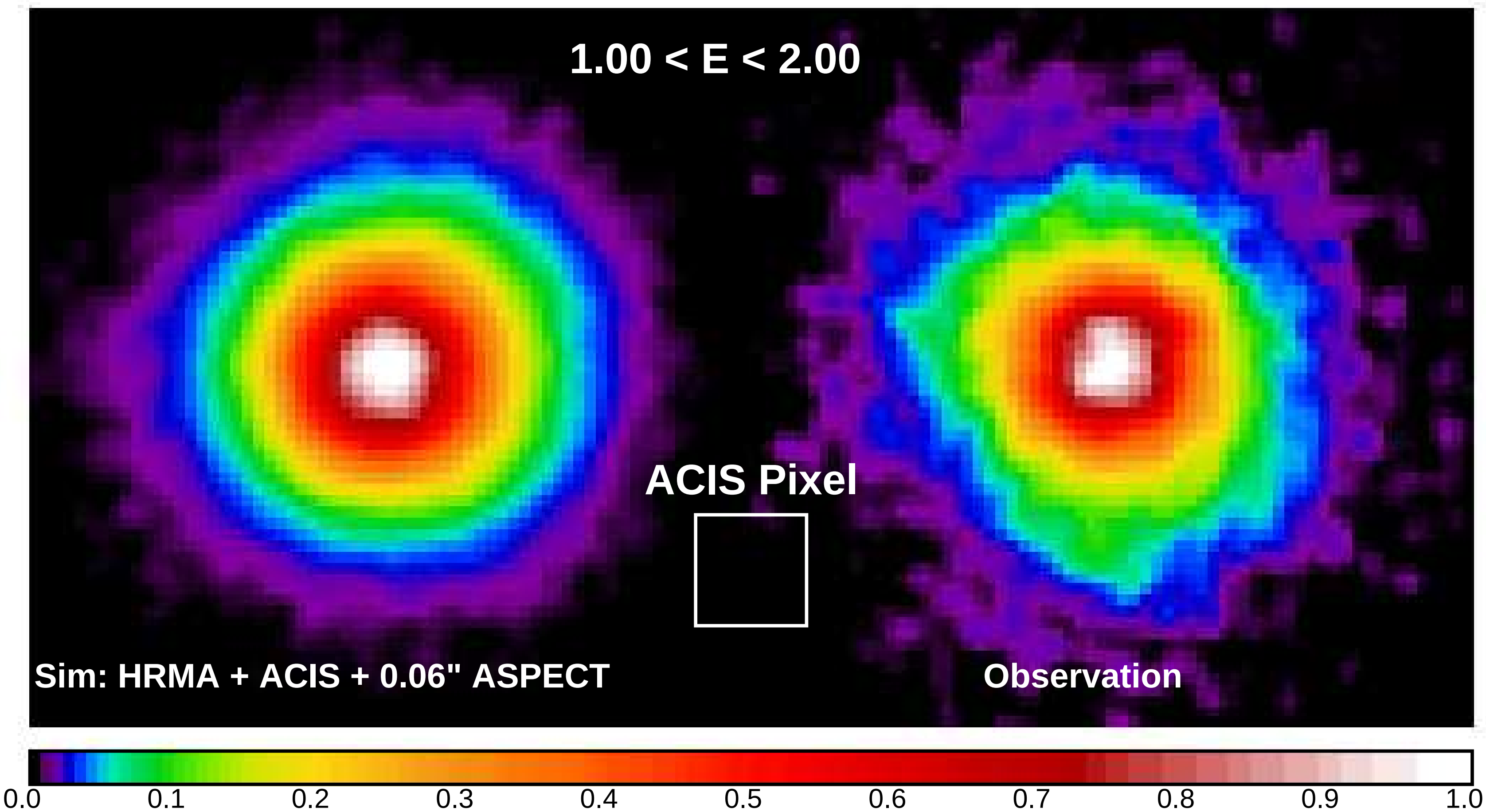

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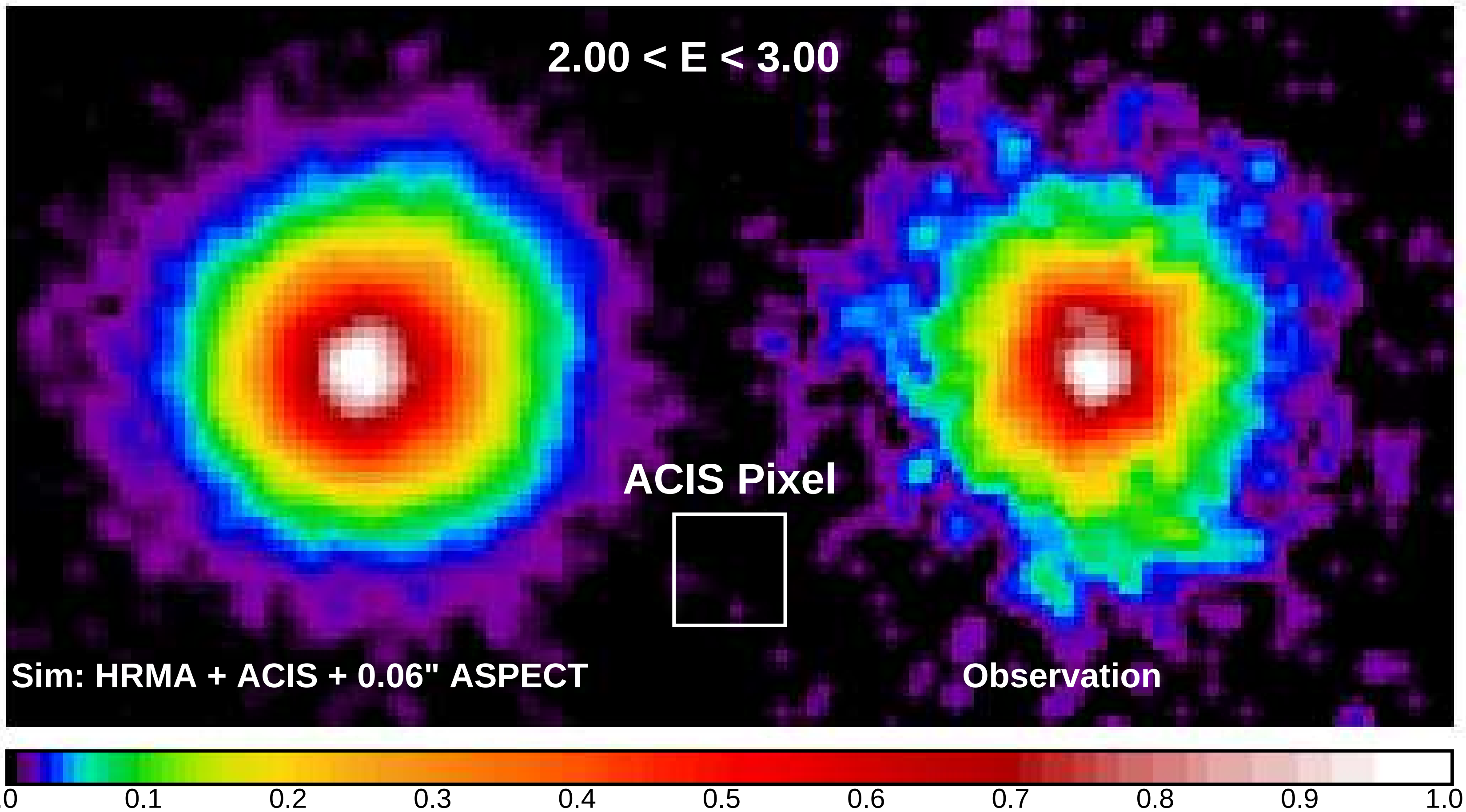

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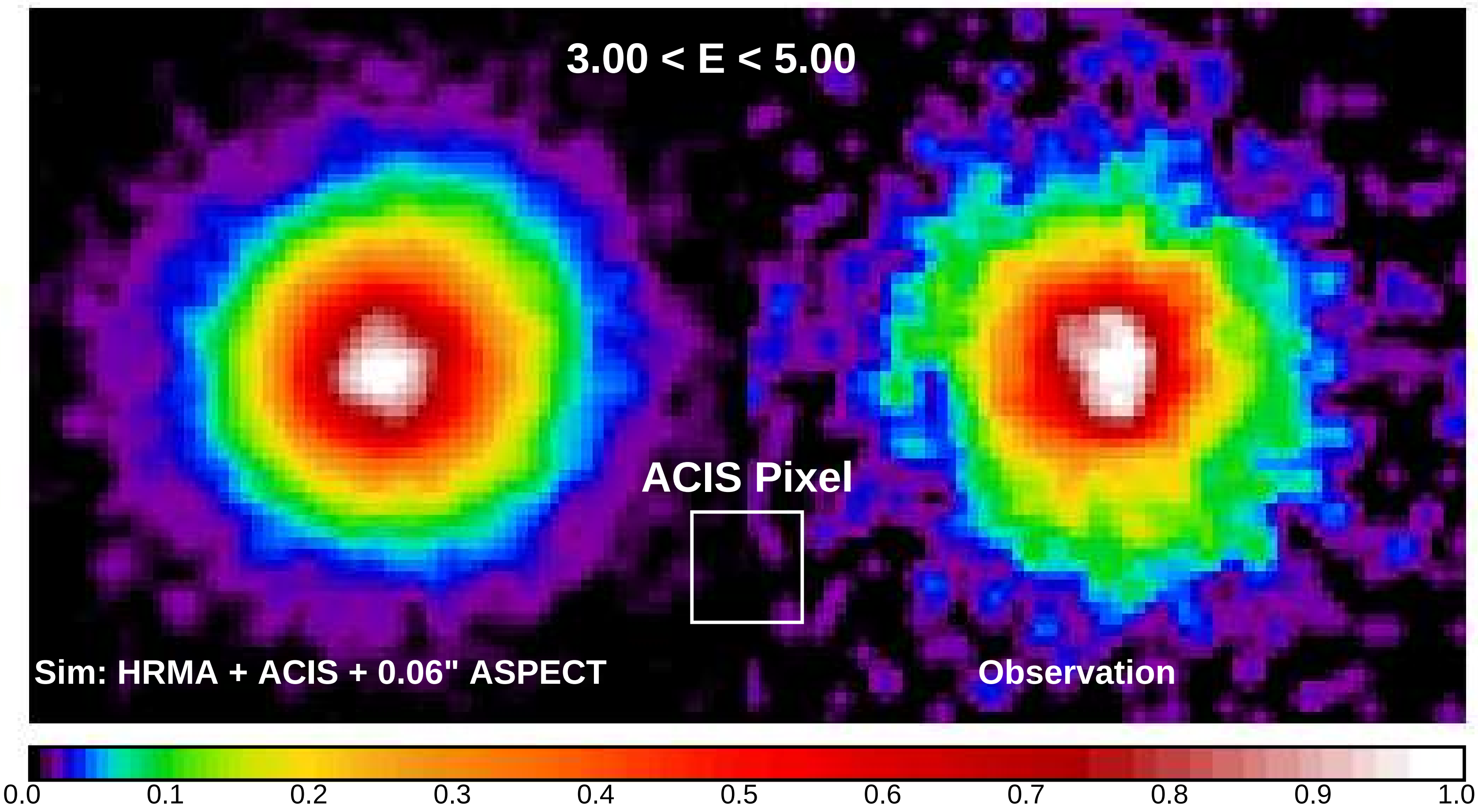

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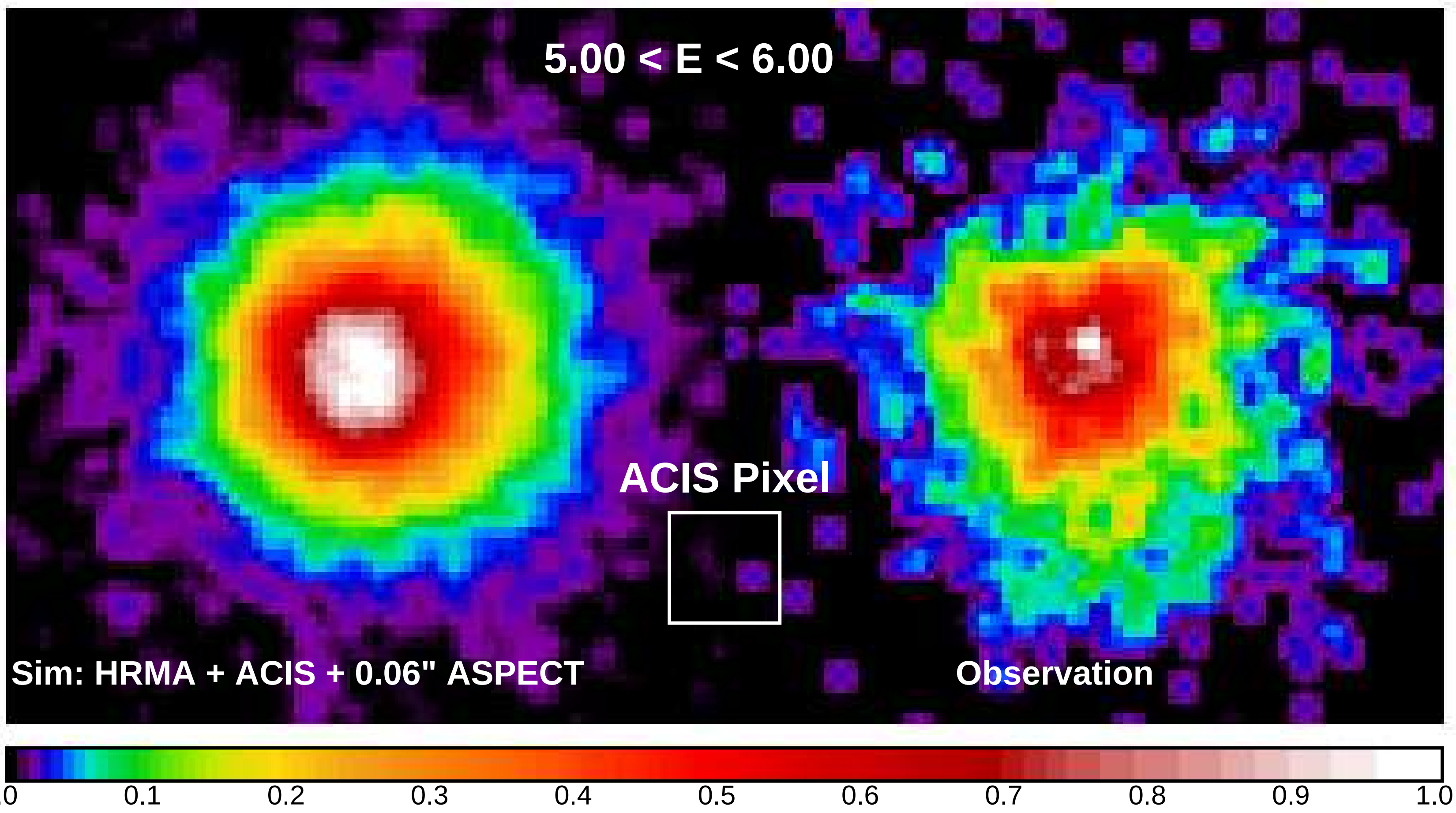

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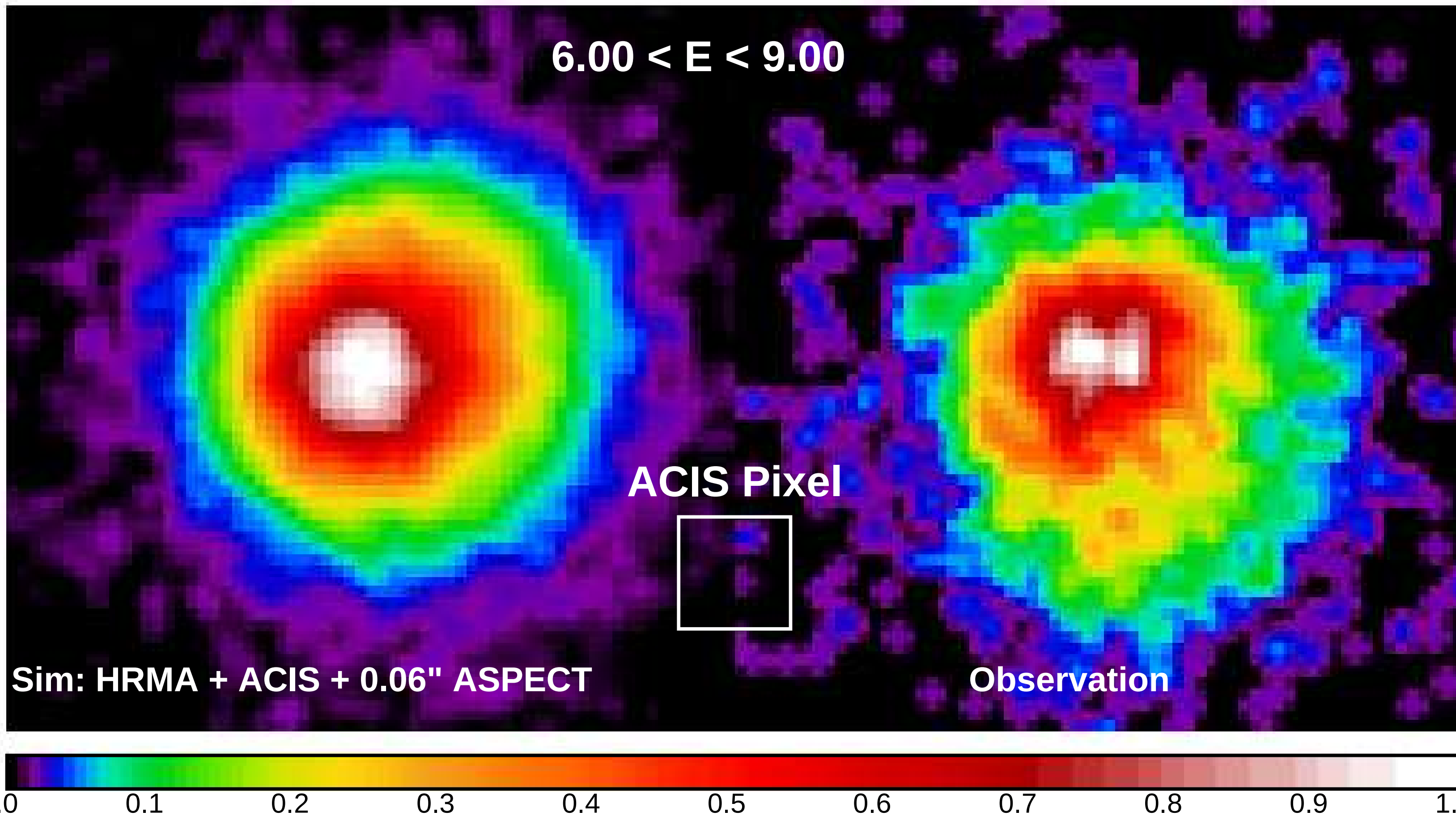
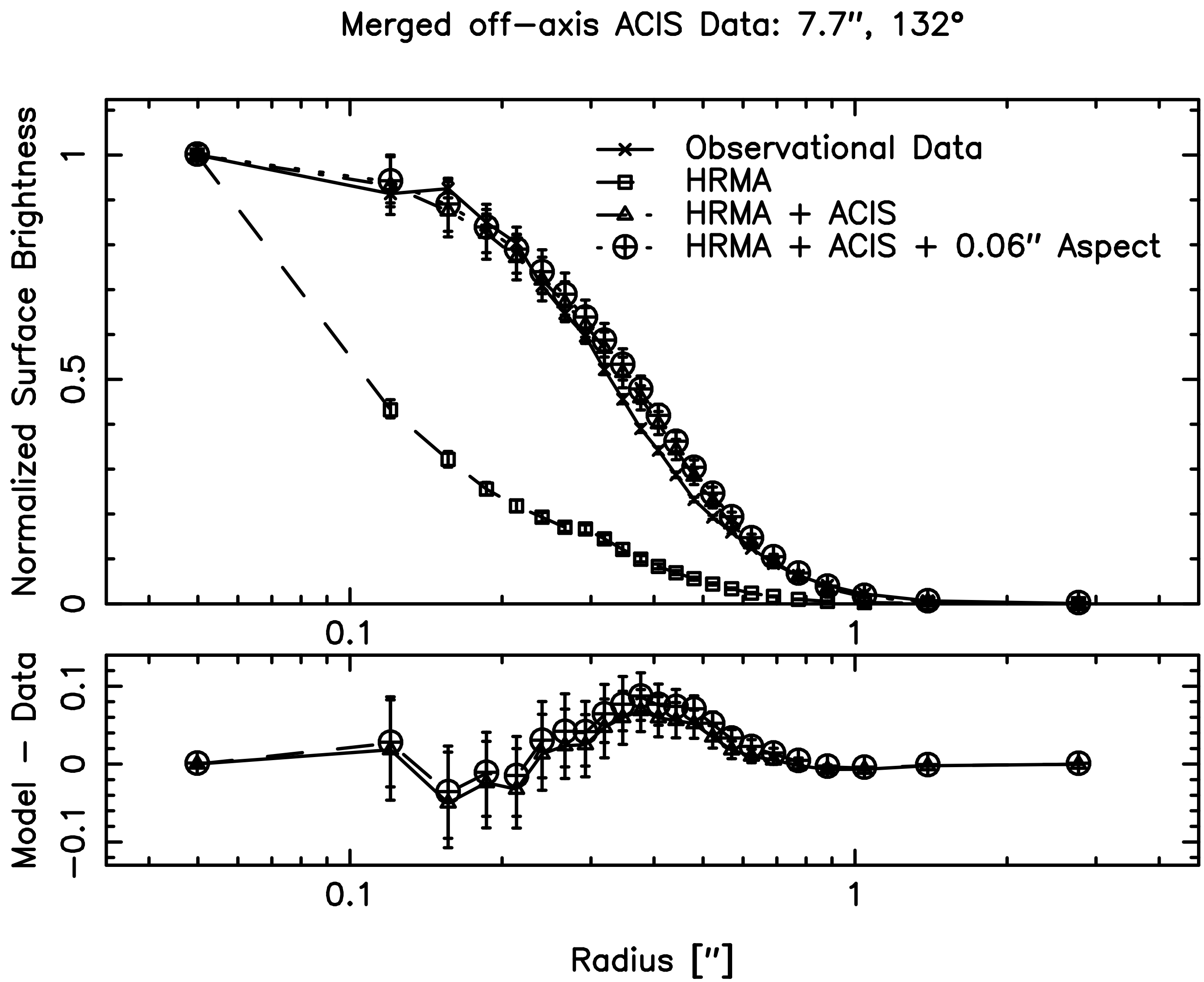
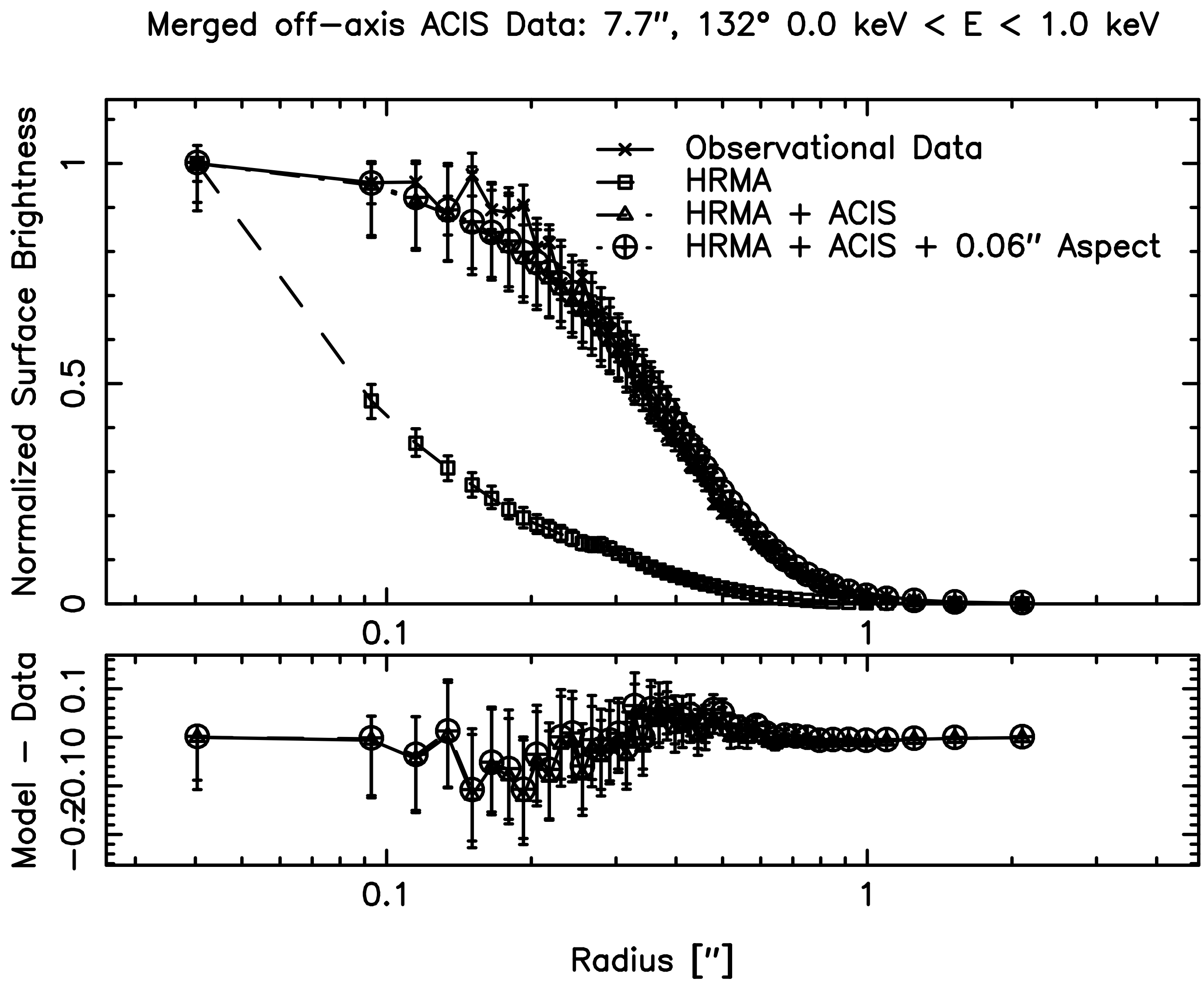
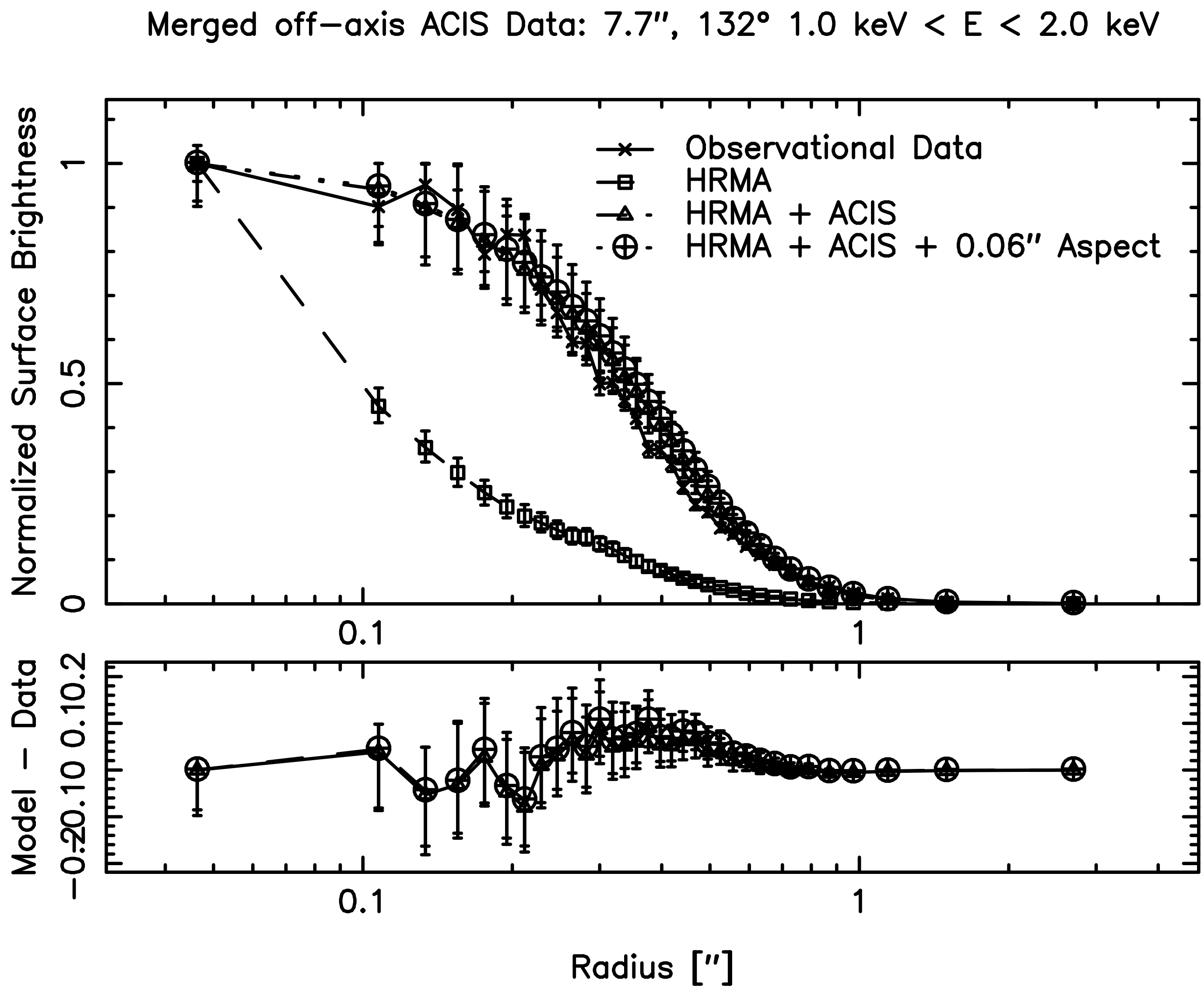


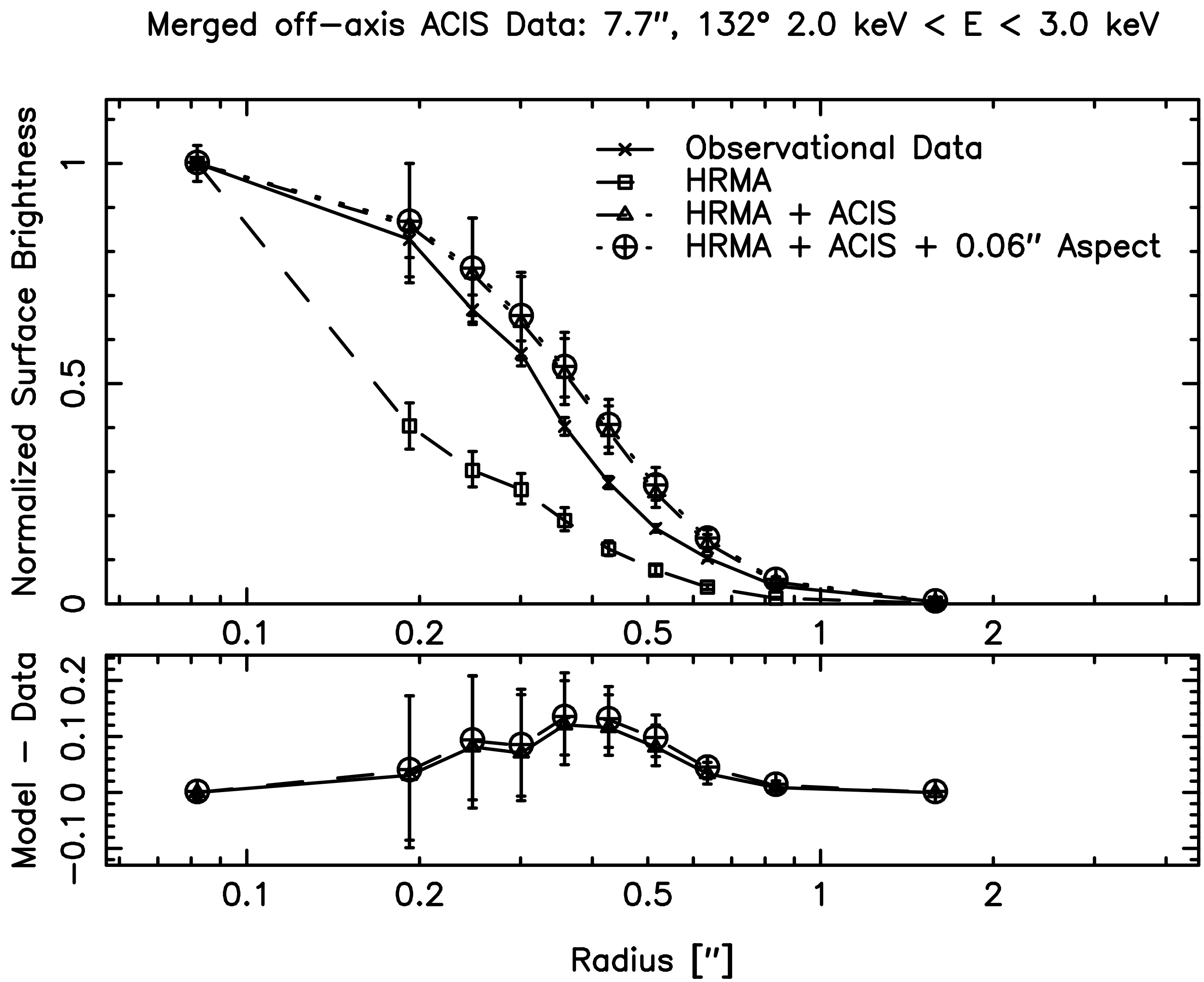


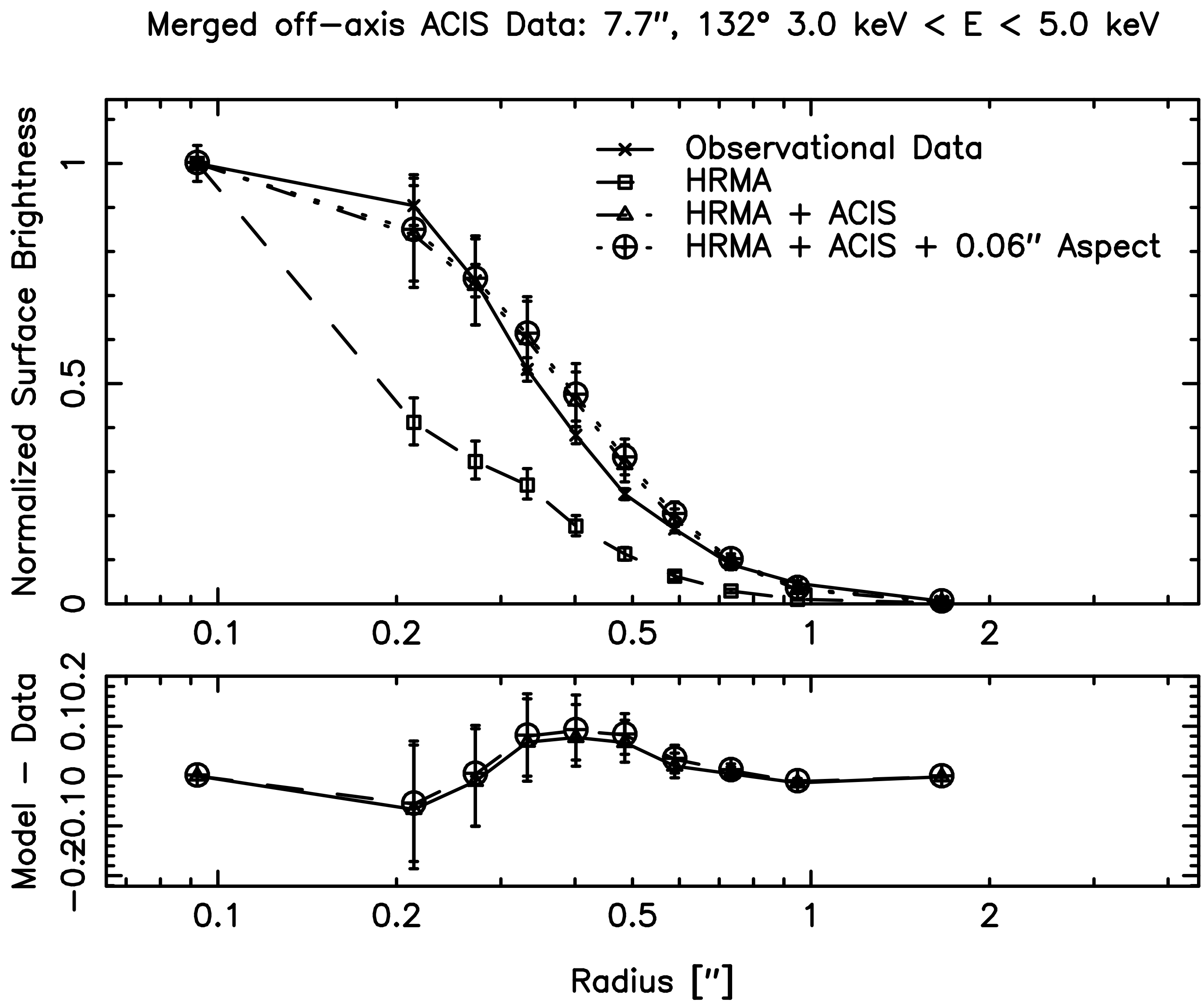
Merged off-axis ACIS Data: 7.7″, 132°
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
1
0.5
0
0.1
1
Model – Data
0.1
0
–0.1
0.1
1
Radius [″]

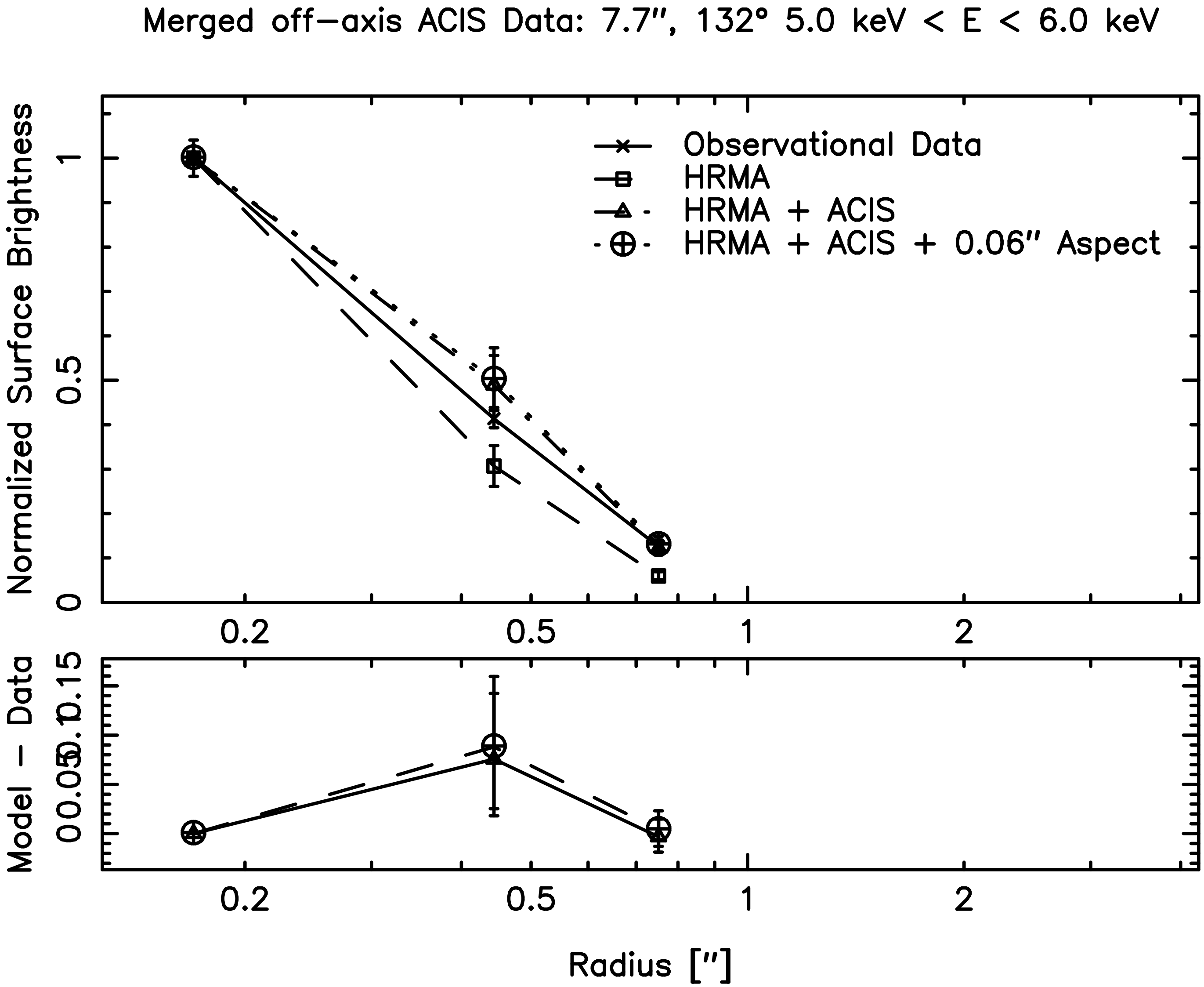


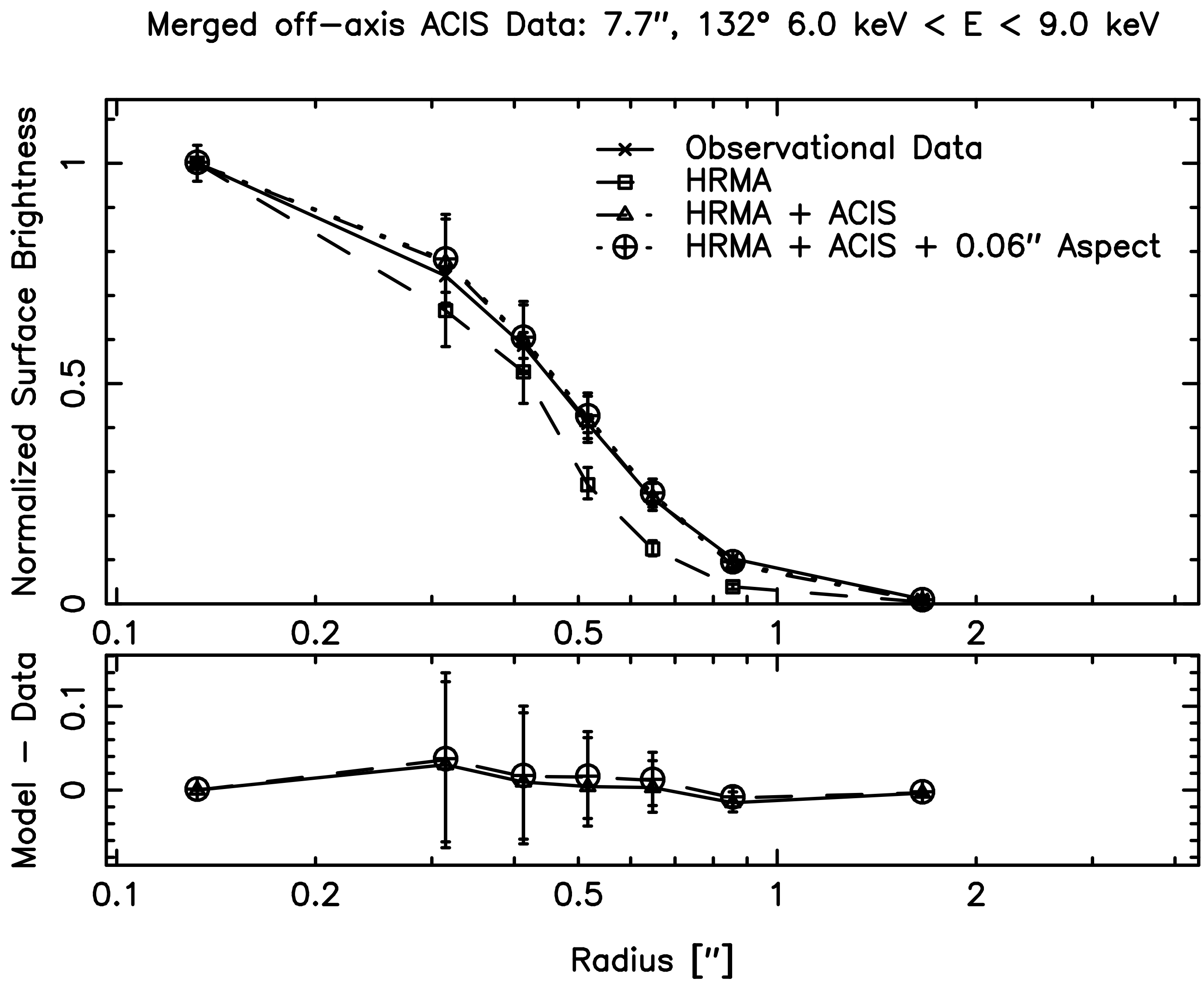
Merged off−axis ACIS Data: 7.7″, 132° 0.0 keV < E < 1.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
1
Model − Data
−0.2
−0.1
0
0.1
0.1
1
Radius [″]


Merged off-axis ACIS Data: 7.7", 132° 1.0 keV < E < 2.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06" Aspect
Normalized Surface Brightness
0
0.5
1
0.1
1
Model − Data
−0.2
−0.1
0
0.1
0.2
0.1
1
Radius ["]


Merged off−axis ACIS Data: 7.7″, 132° 2.0 keV < E < 3.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
0.2
0.5
1
2
Model − Data
−0.1 0 0.1 0.2
0.1
0.2
0.5
1
2
Radius [″]

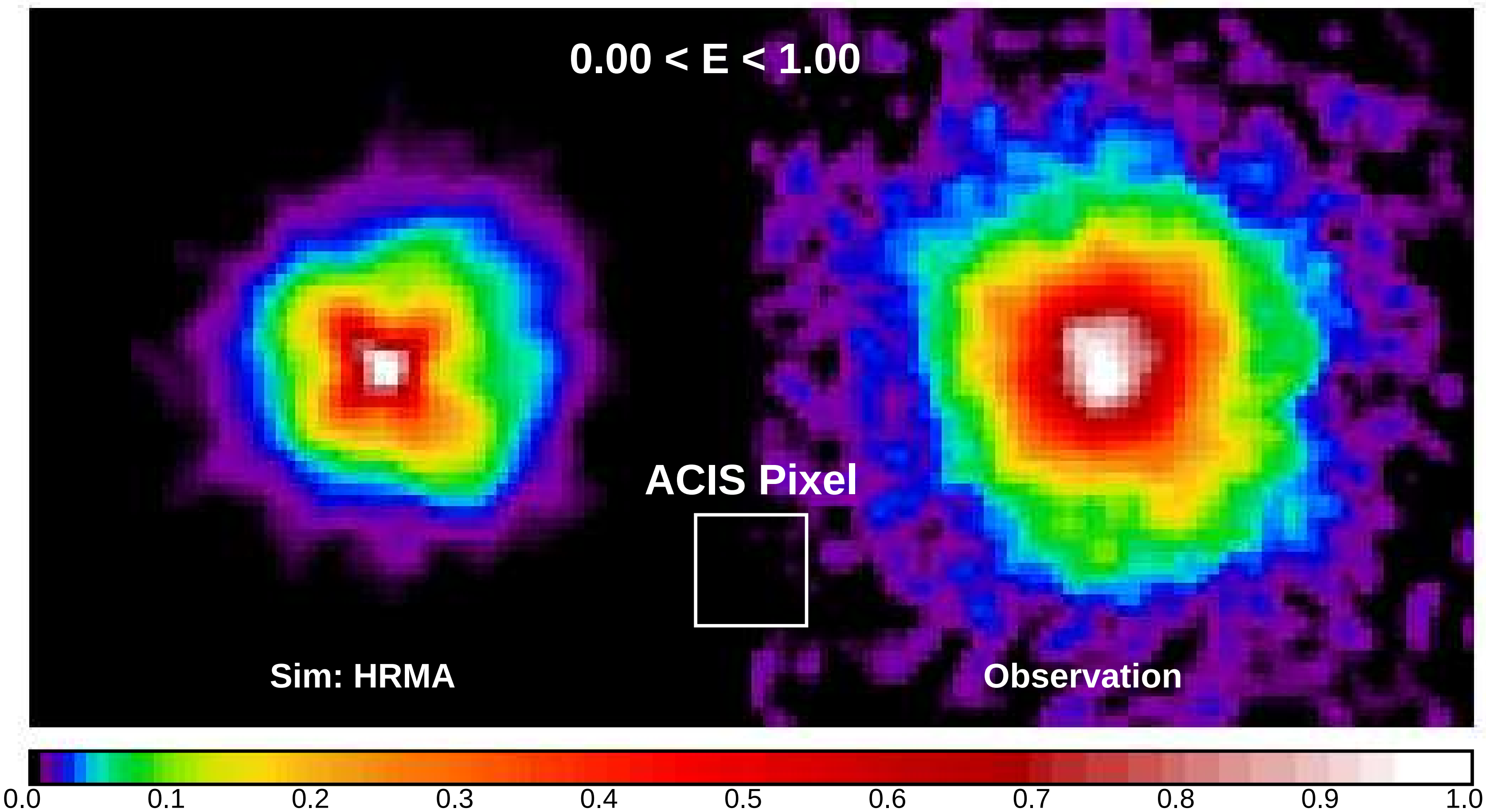

Merged off−axis ACIS Data: 7.7″, 132° 3.0 keV < E < 5.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
0.2
0.5
1
2
Model − Data
−0.2
−0.1
0
0.1
0.2
Radius [″]


Merged off−axis ACIS Data: 7.7″, 132° 5.0 keV < E < 6.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.2
0.5
1
2
Model − Data
0
0.05
0.1
0.15
0.2
0.5
1
2
Radius [″]

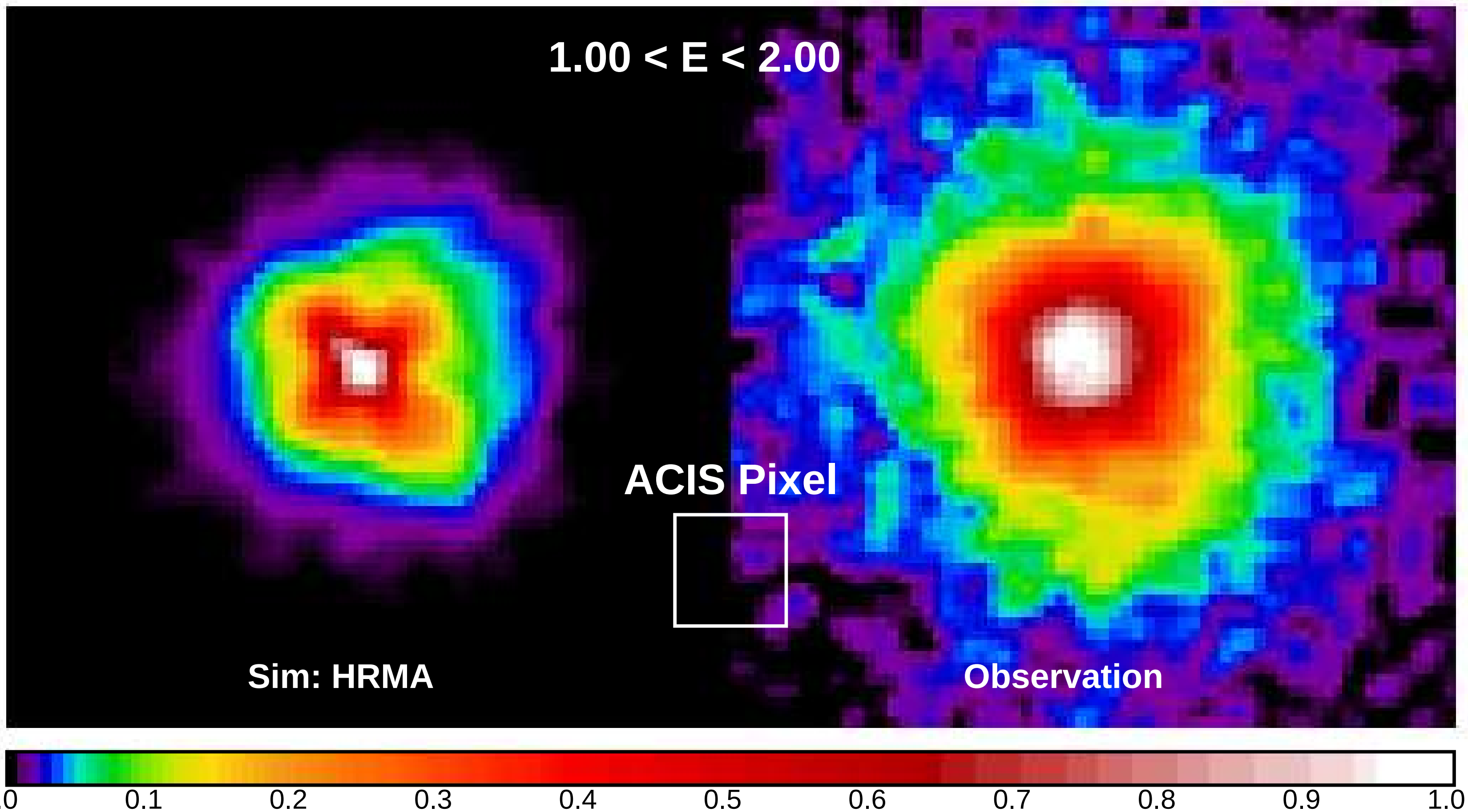


Merged off–axis ACIS Data: 7.7″, 132° 6.0 keV < E < 9.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
0.2
0.5
1
2
Model – Data
0
0.1
0.1
0.2
0.5
1
2
Radius [″]

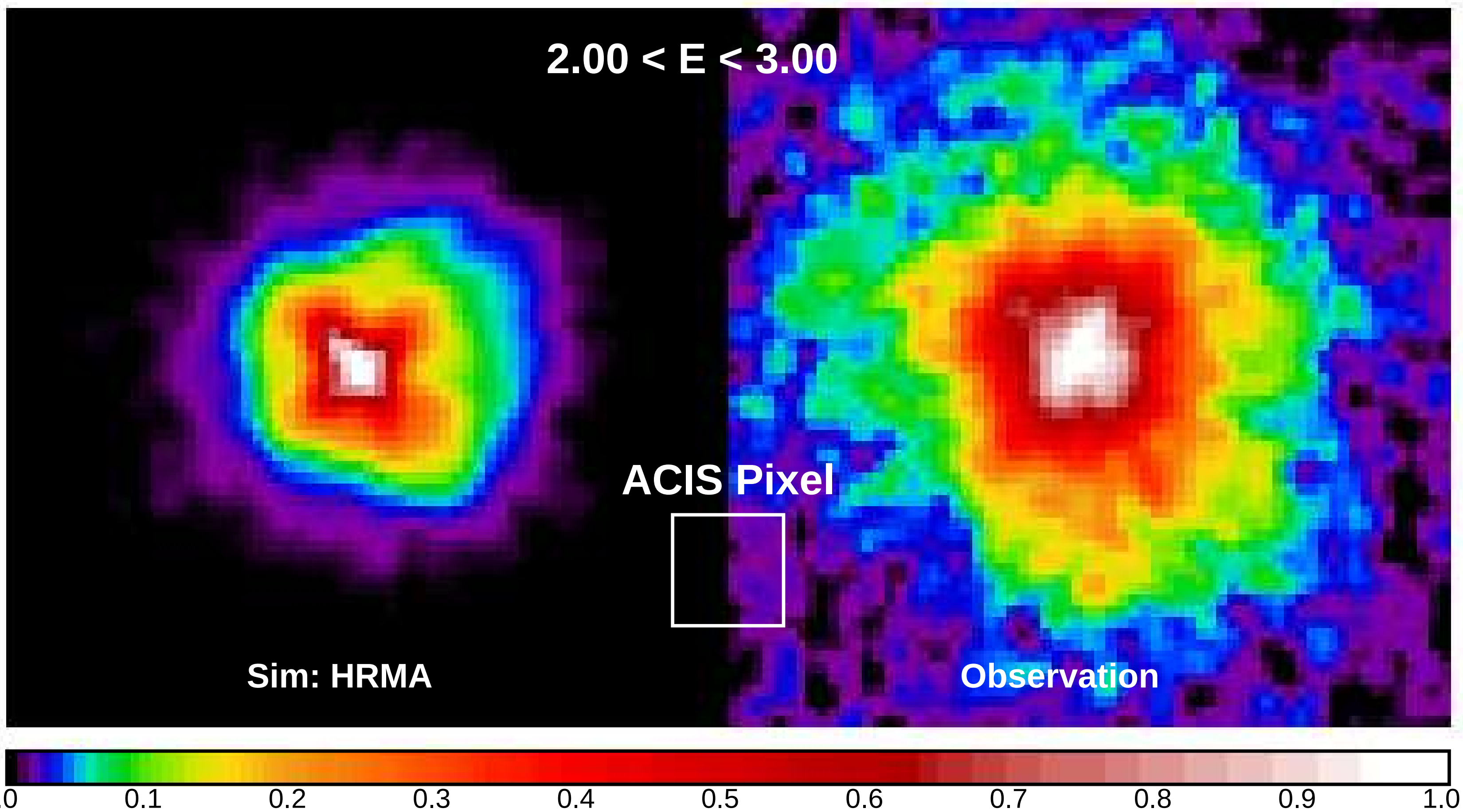
Merged off-axis ACIS Data: 35", 12deg az



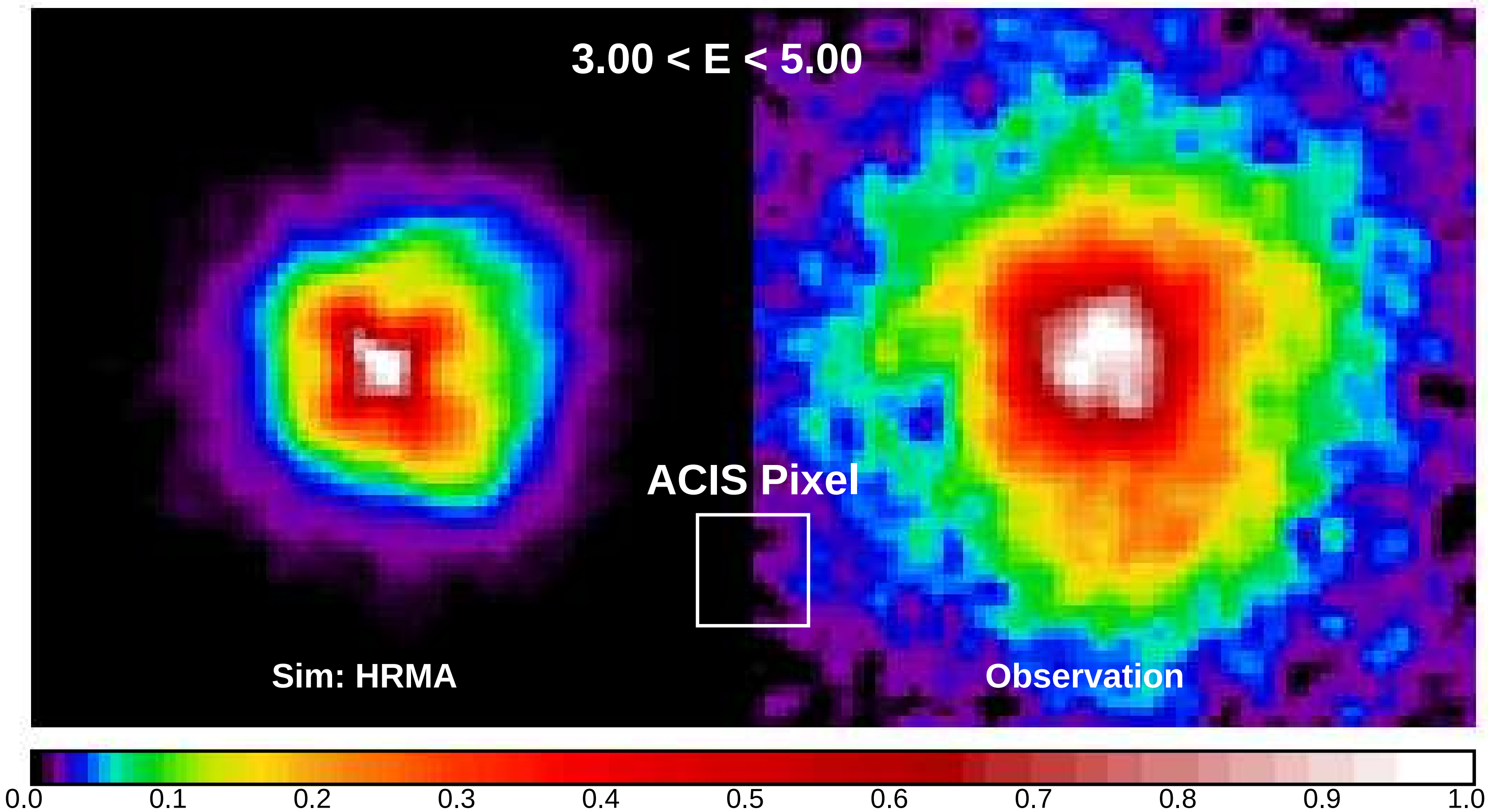
Merged off-axis ACIS Data: 35", 12deg az



Merged off-axis ACIS Data: 35", 12deg az



Merged off-axis ACIS Data: 35", 12deg az



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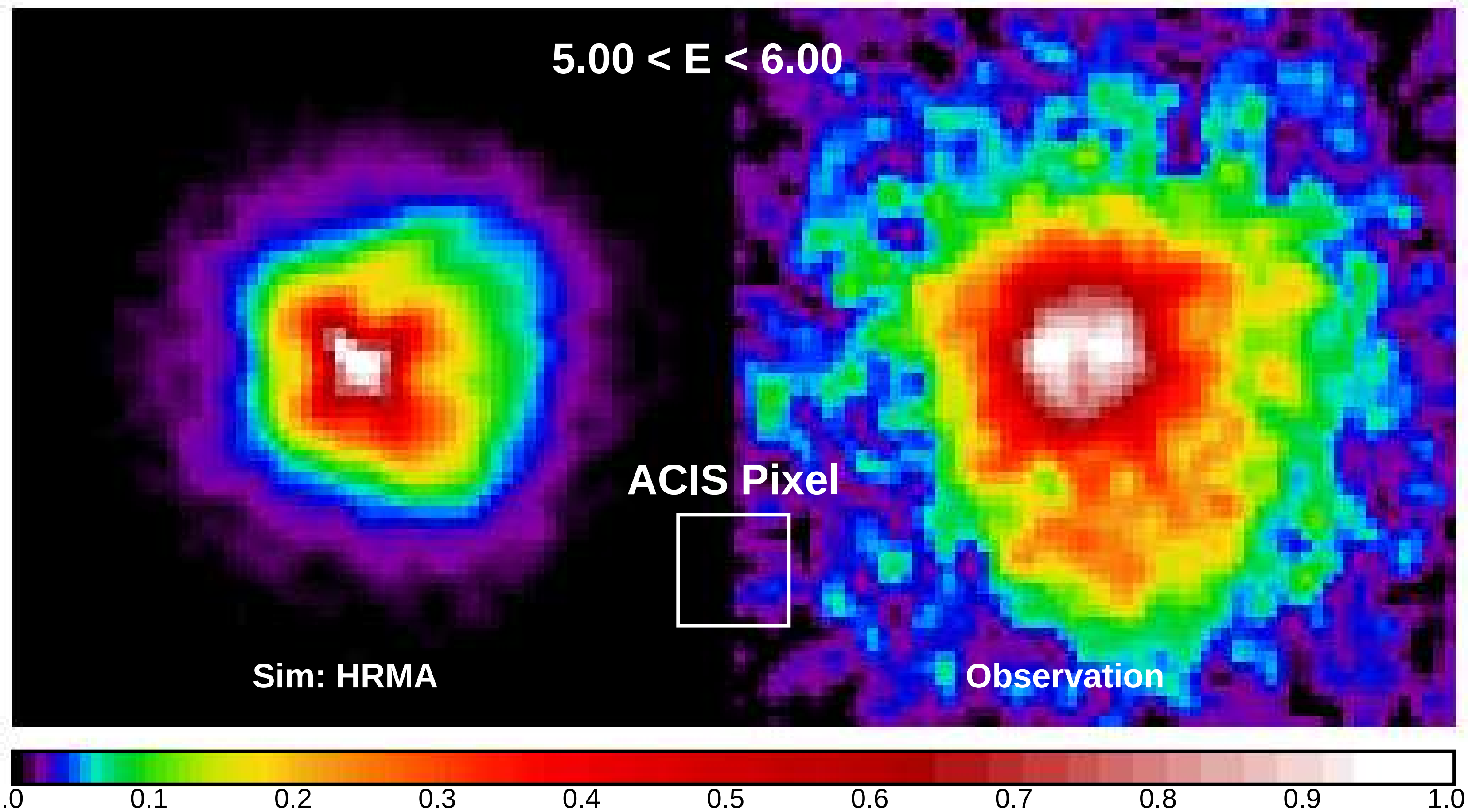
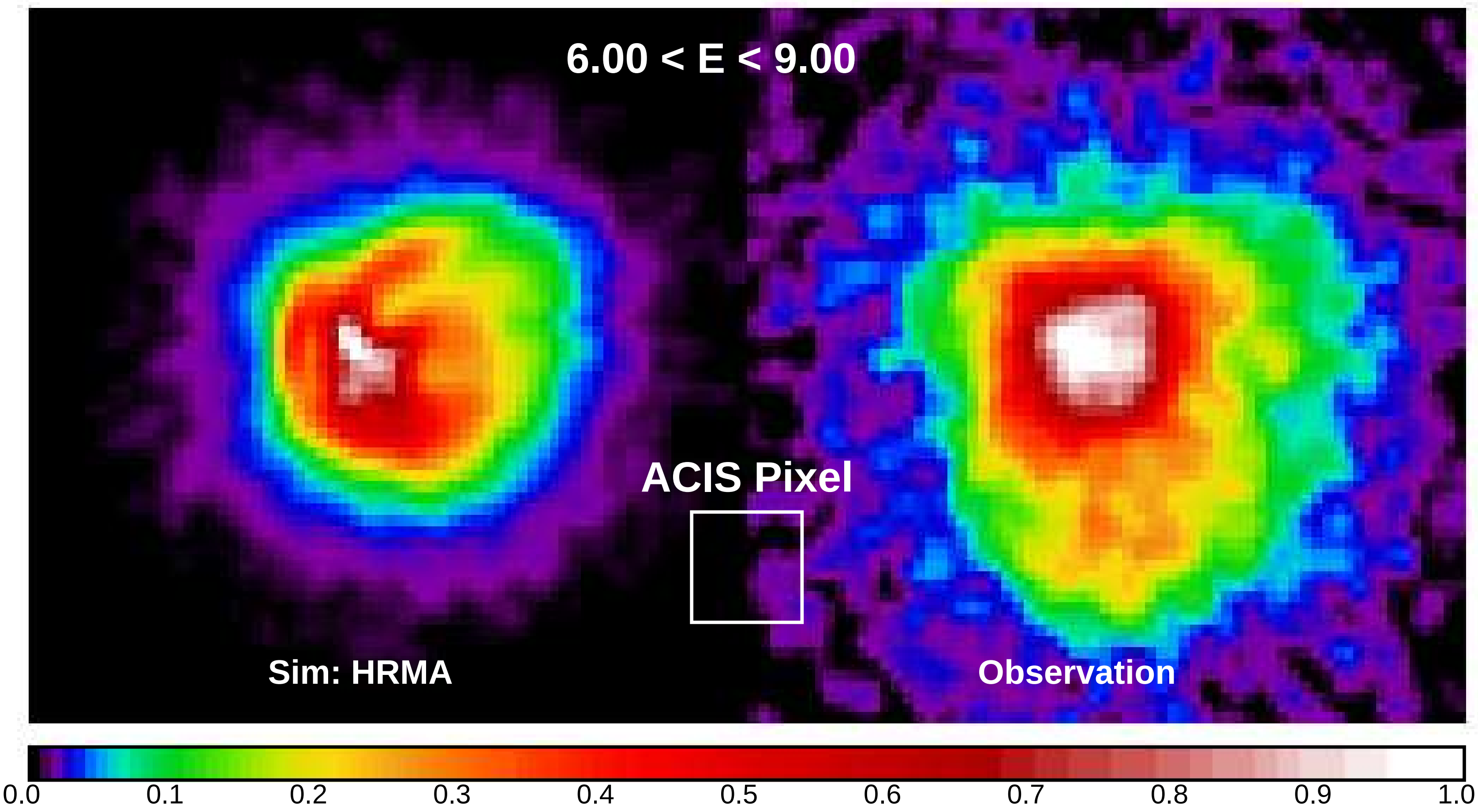
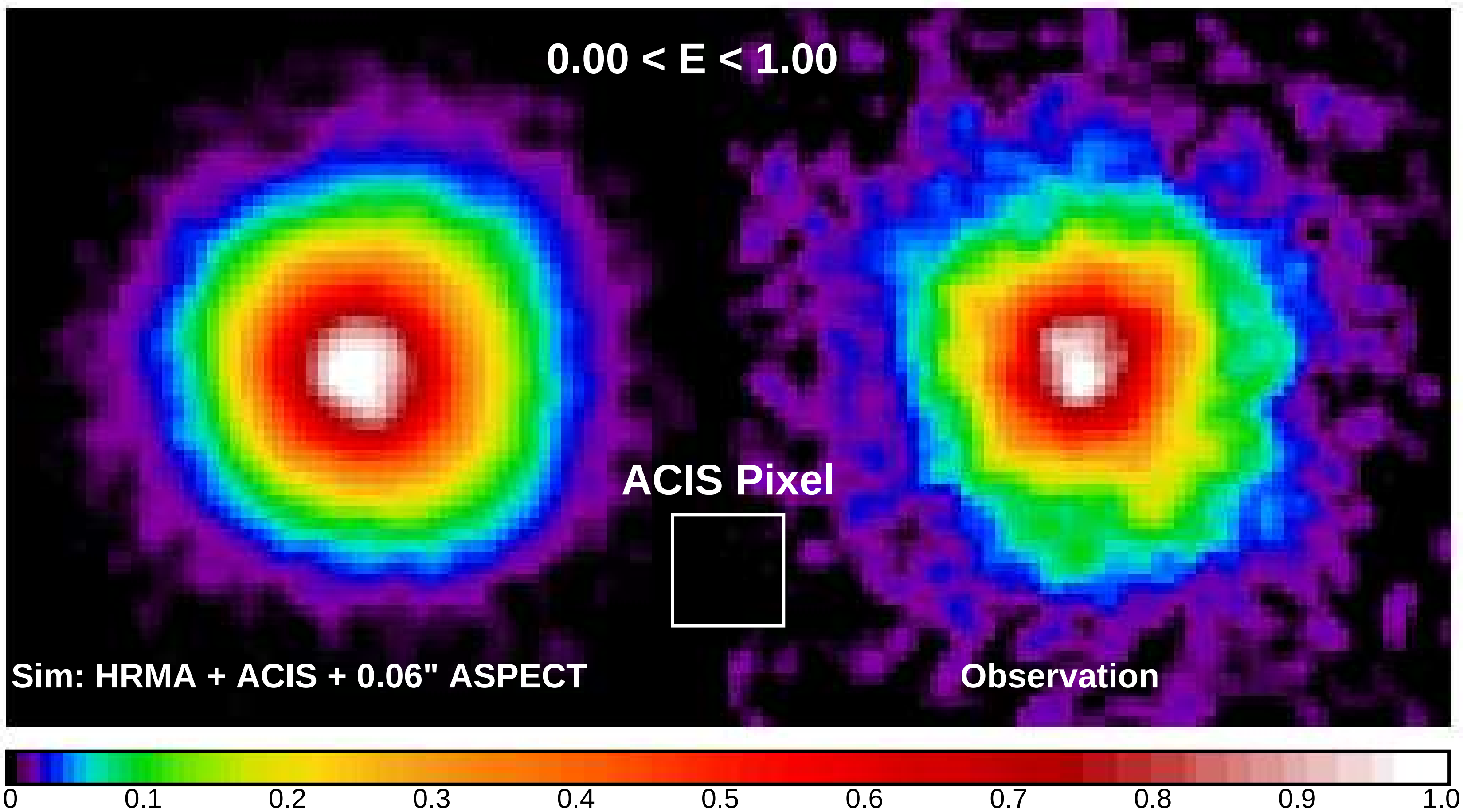


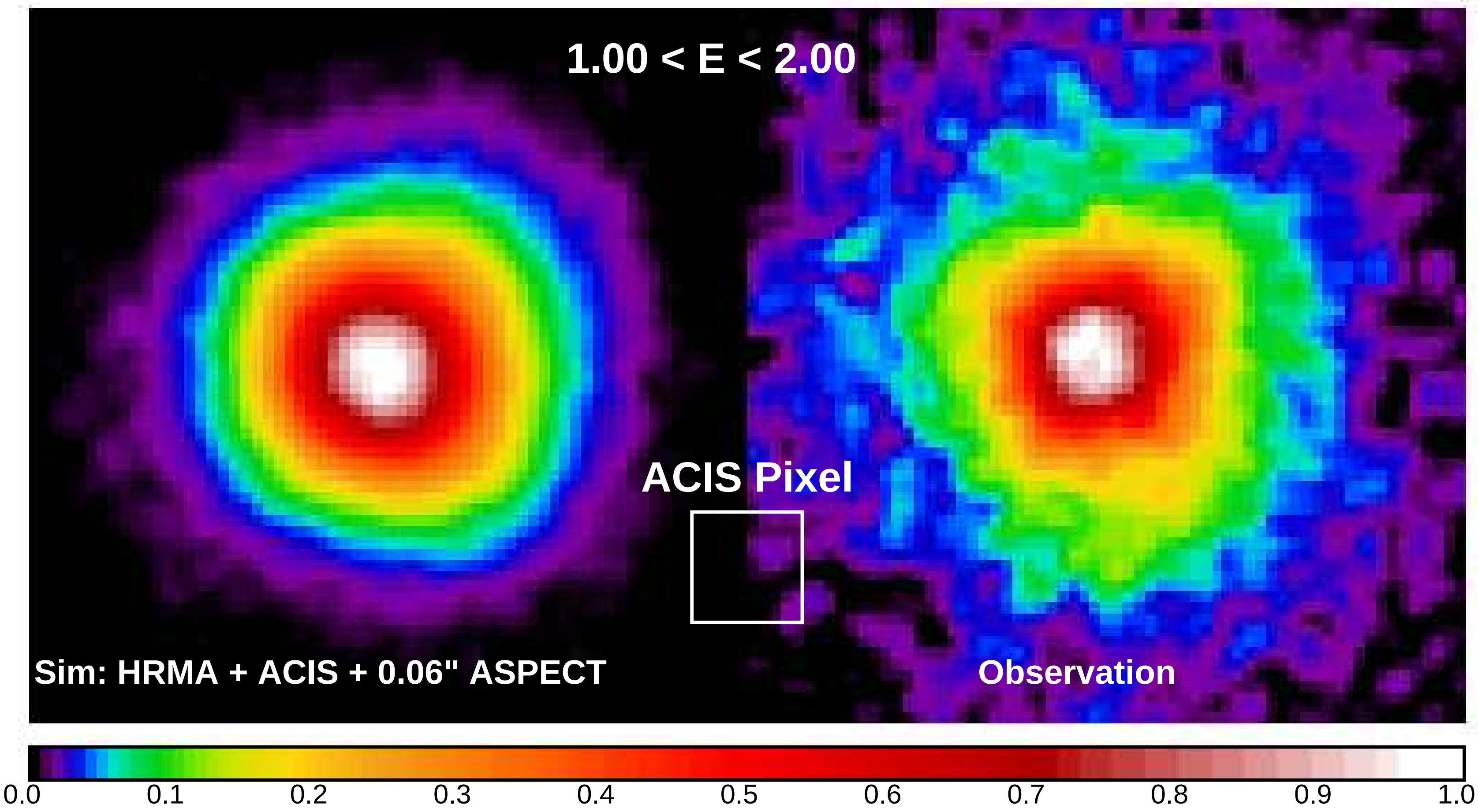
Merged off-axis ACIS Data: 35", 12deg az



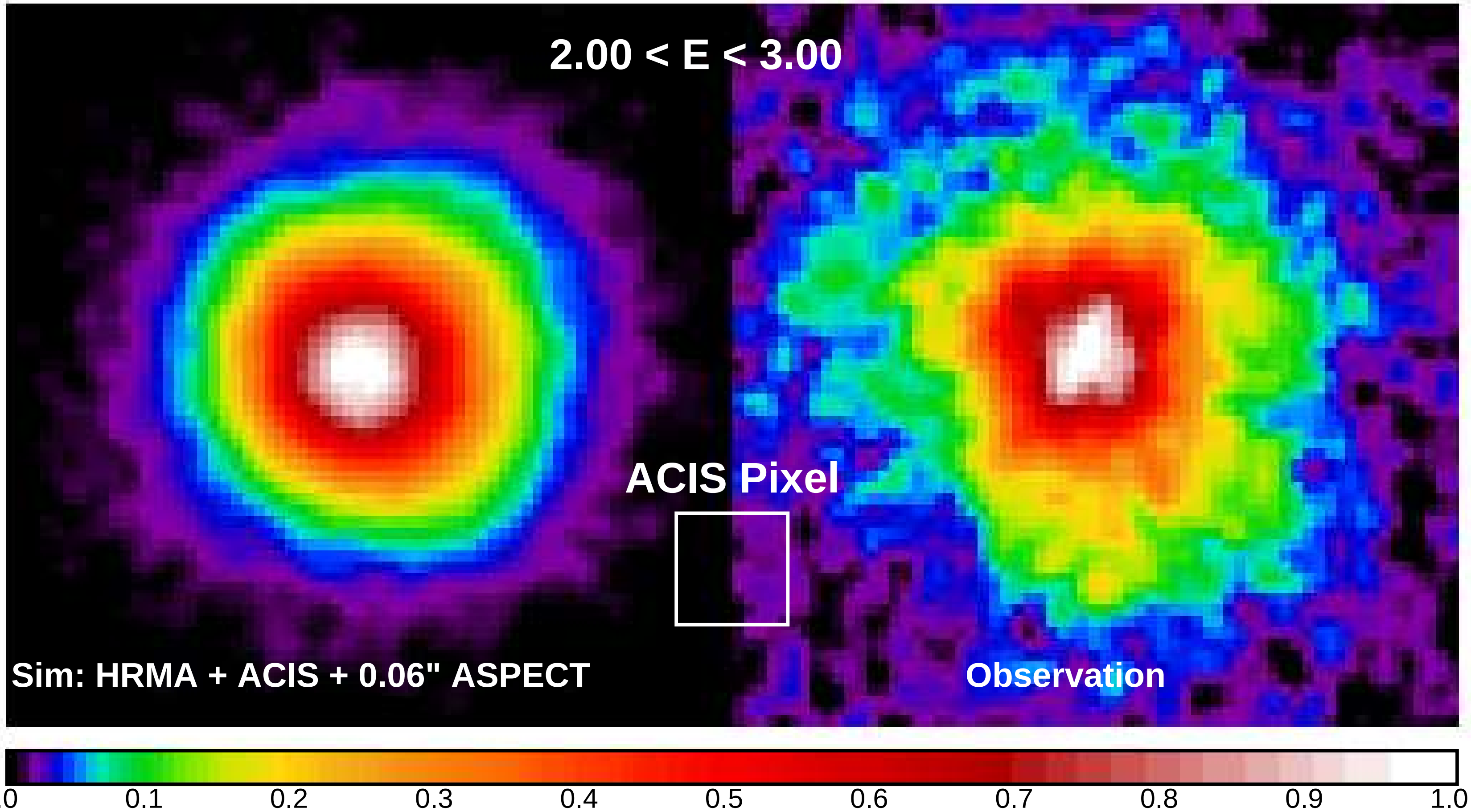
Merged off-axis ACIS Data: 35", 12deg az



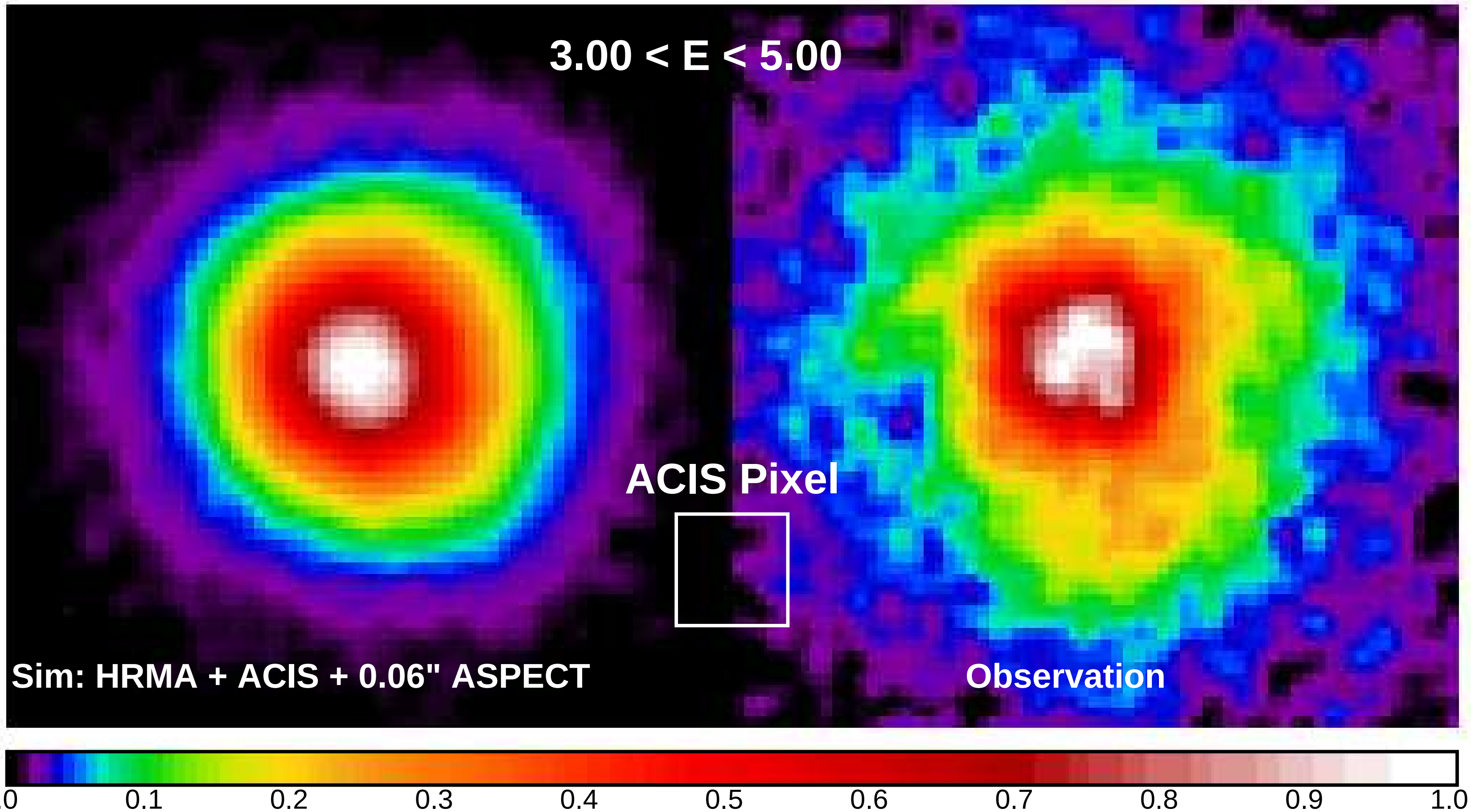
Merged off-axis ACIS Data: 35", 12deg az



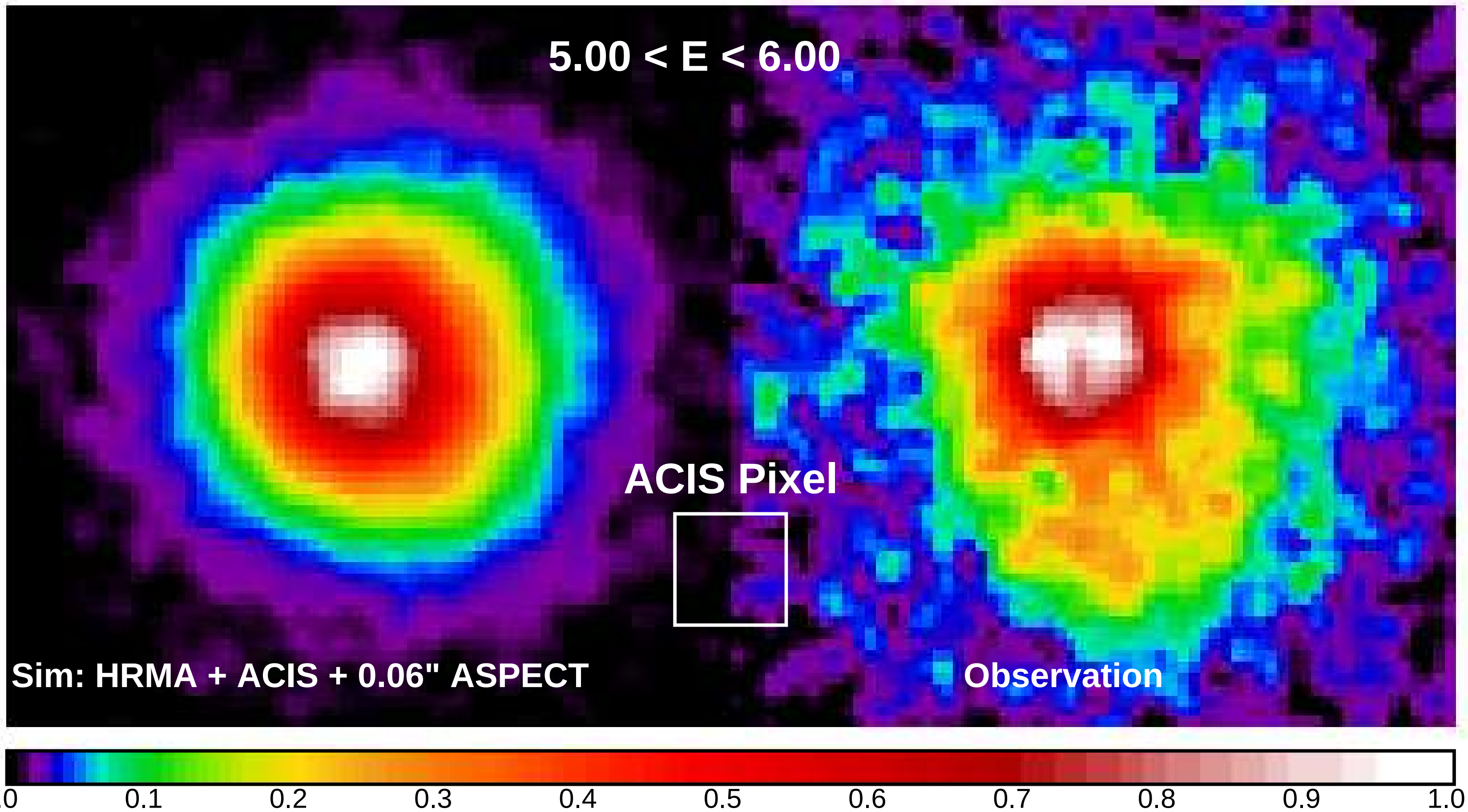
Merged off-axis ACIS Data: 35", 12deg az



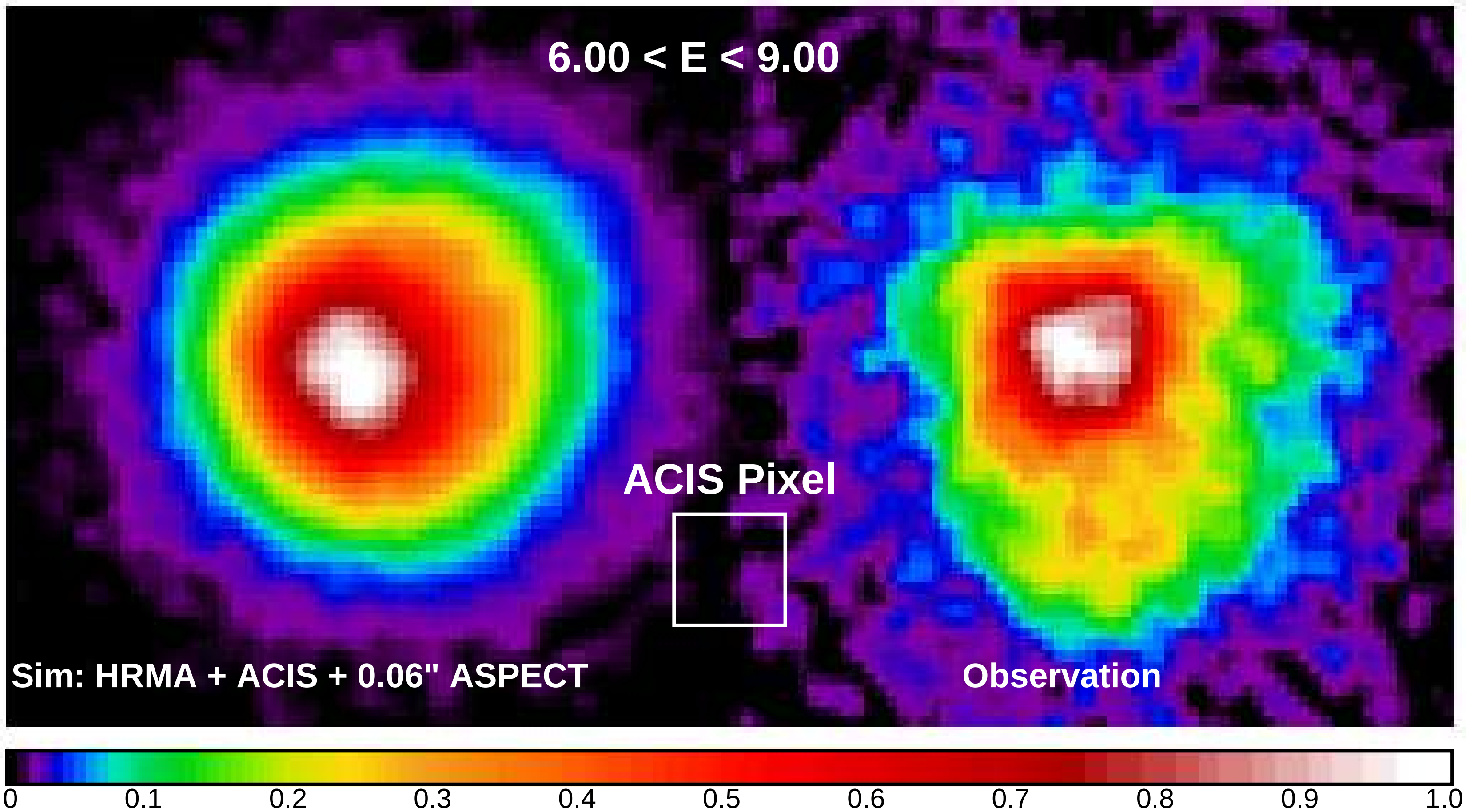
Merged off-axis ACIS Data: 35", 12deg az

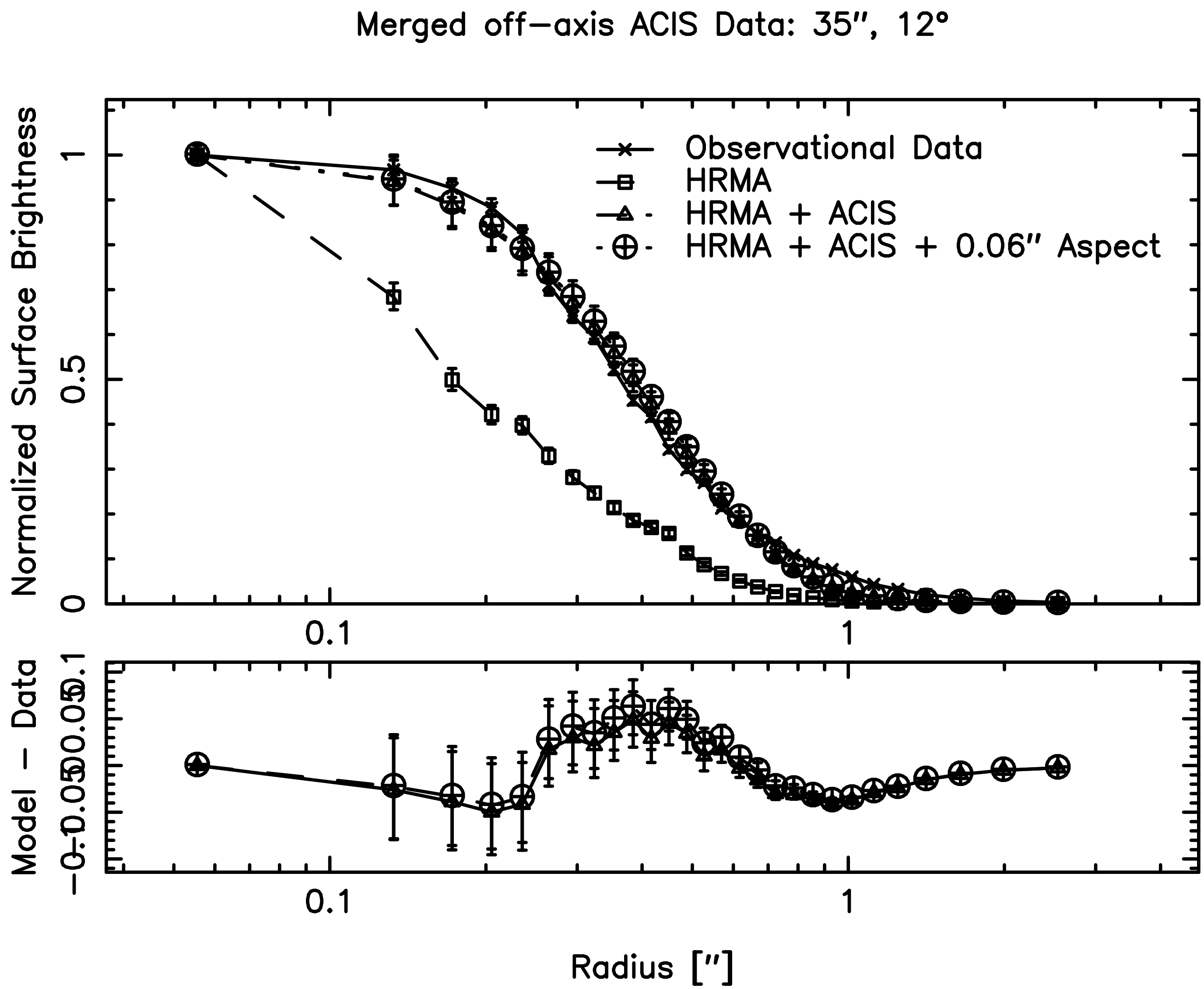


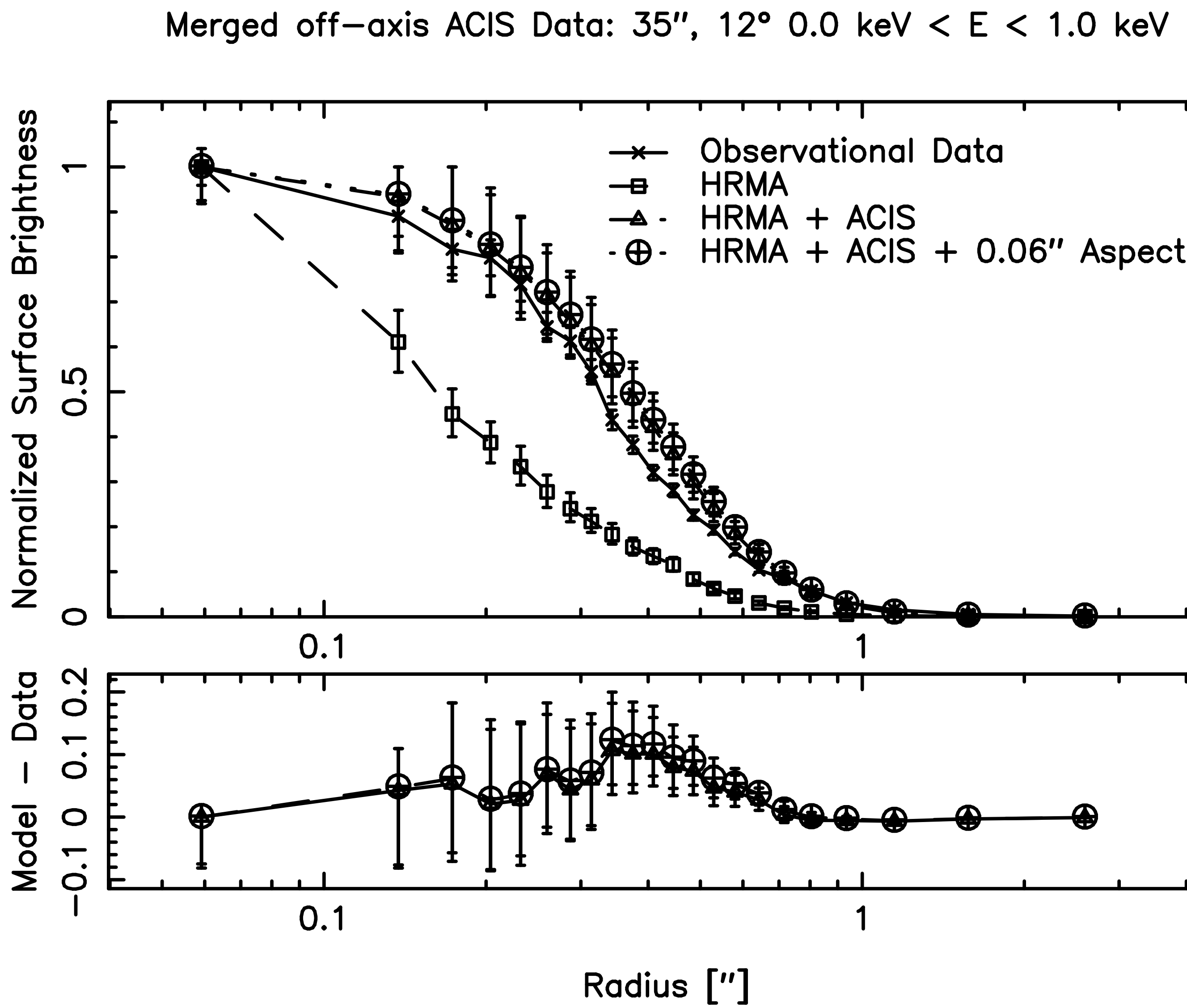
Merged off-axis ACIS Data: 35", 12deg az

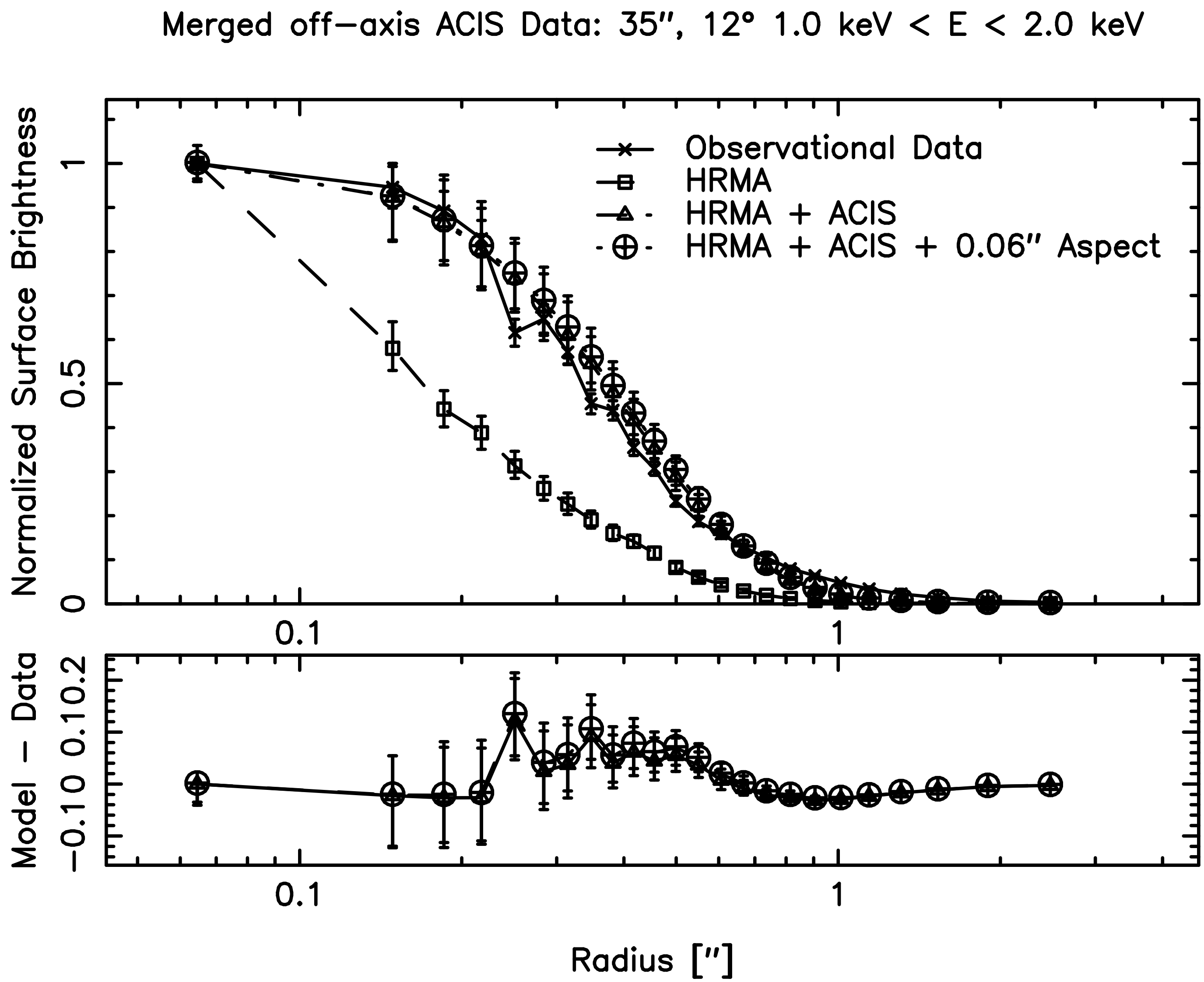


Merged off-axis ACIS Data: 35", 12deg az

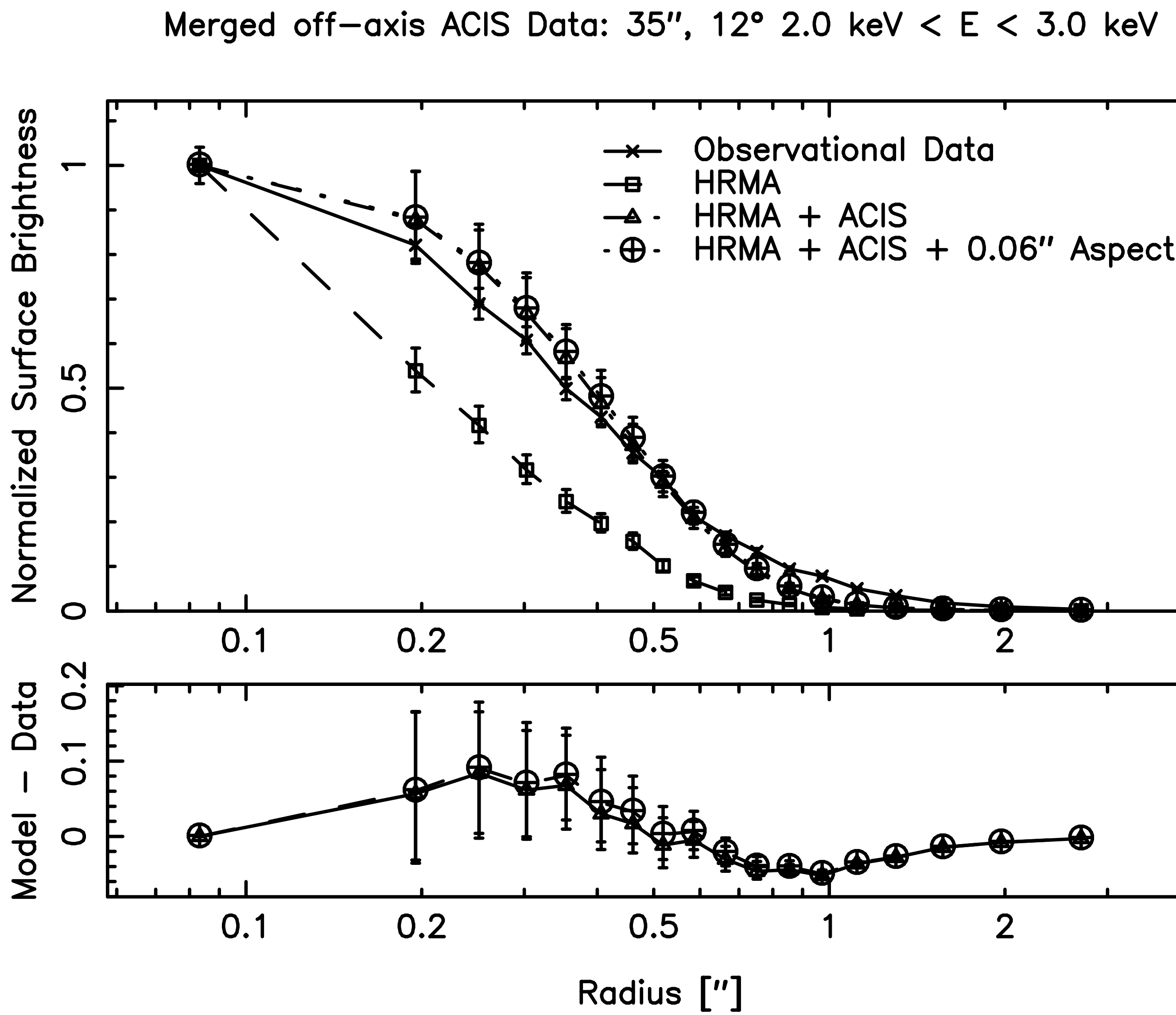


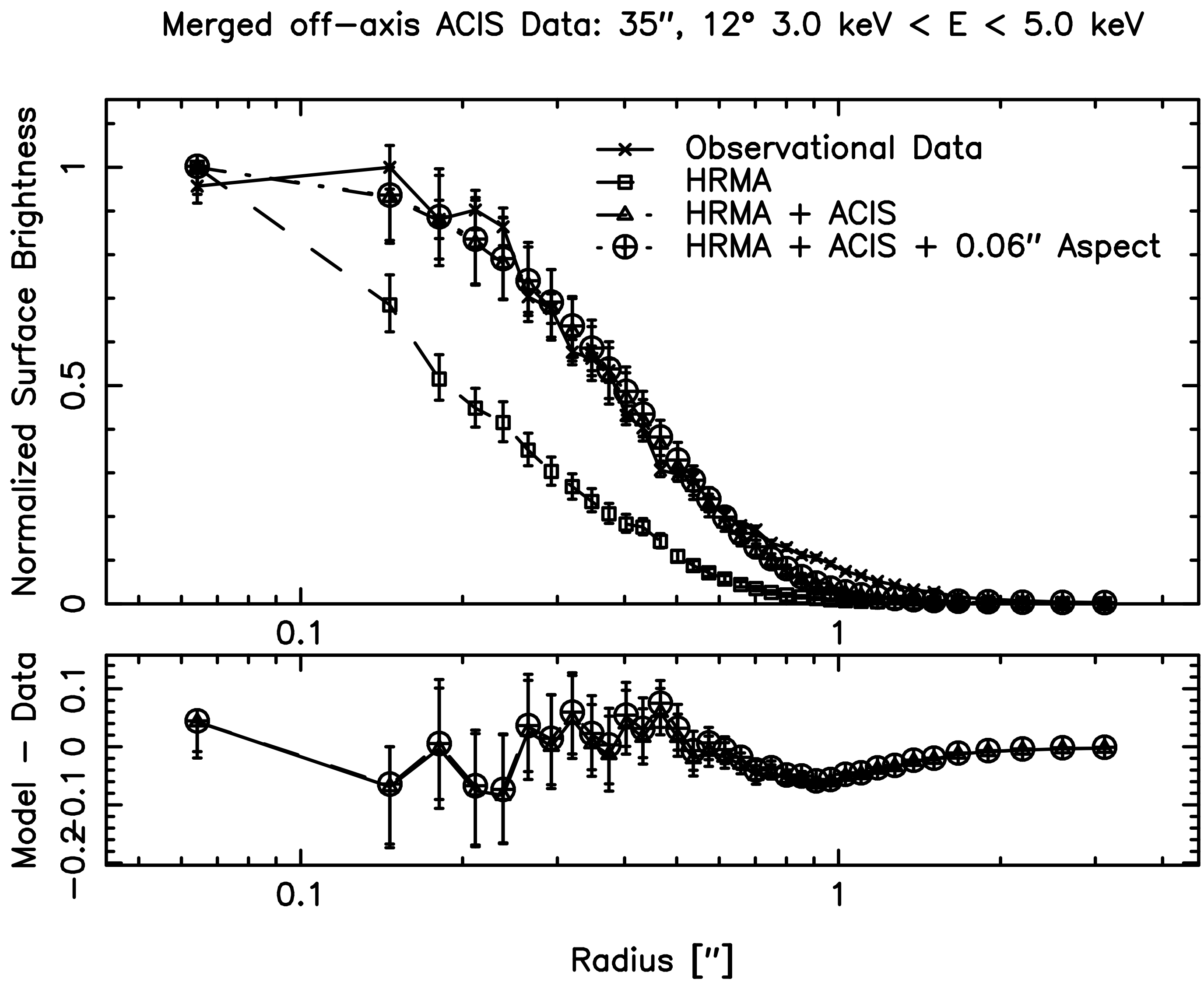

Merged off-axis ACIS Data: 35″, 12°
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
1
0.5
0
0.1
1
Model – Data
0.1
1
Radius [″]


Merged off−axis ACIS Data: 35″, 12° 0.0 keV < E < 1.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
1
Model − Data
−0.1 0.0 0.1 0.2
0.1
1
Radius [″]

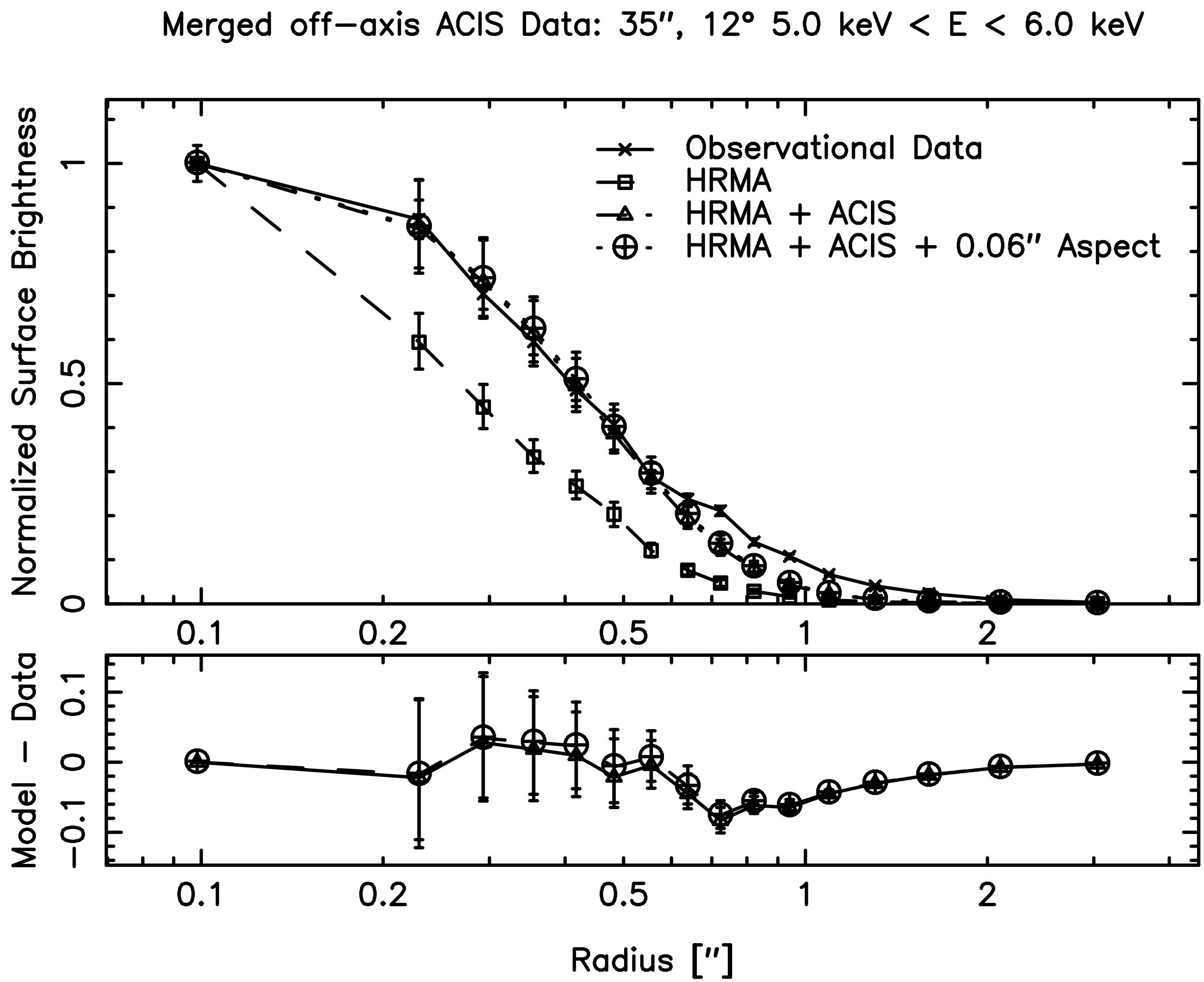


Merged off–axis ACIS Data: 35″, 12° 1.0 keV < E < 2.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
1
0.5
0
0.1
1
Model – Data
−0.1 0 0.1 0.2
0.1
1
Radius [″]

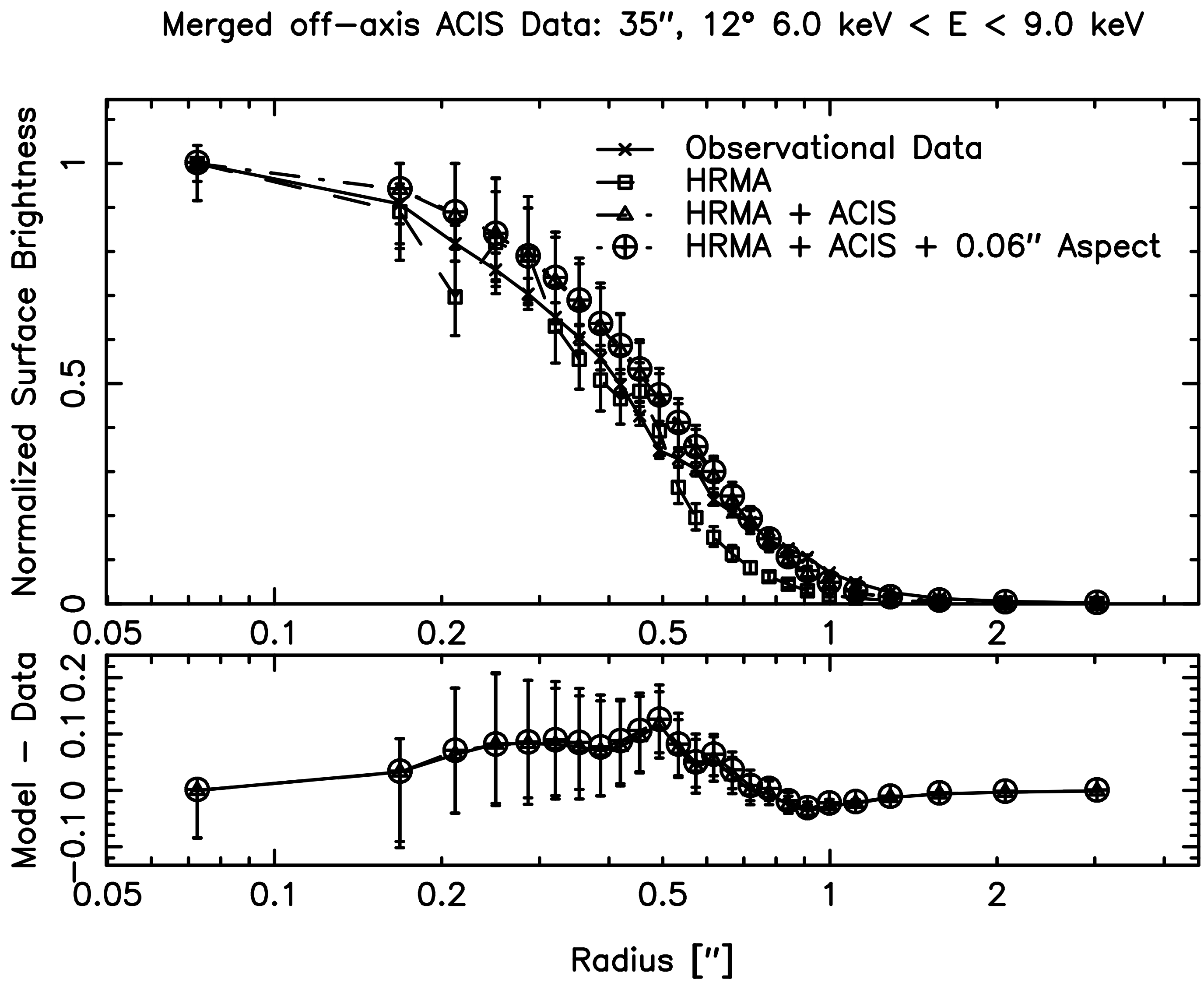

Merged off−axis ACIS Data: 35″, 12° 2.0 keV < E < 3.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
Model − Data
Radius [″]
0
0.5
1
0.1
0.2
0.5
1
2
0.1
0.2
0.5
1
2
0
0.1
0.2



Merged off–axis ACIS Data: 35″, 12° 3.0 keV < E < 5.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
1
Model − Data
−0.2
−0.1
0.0
0.1
0.1
1
Radius [″]



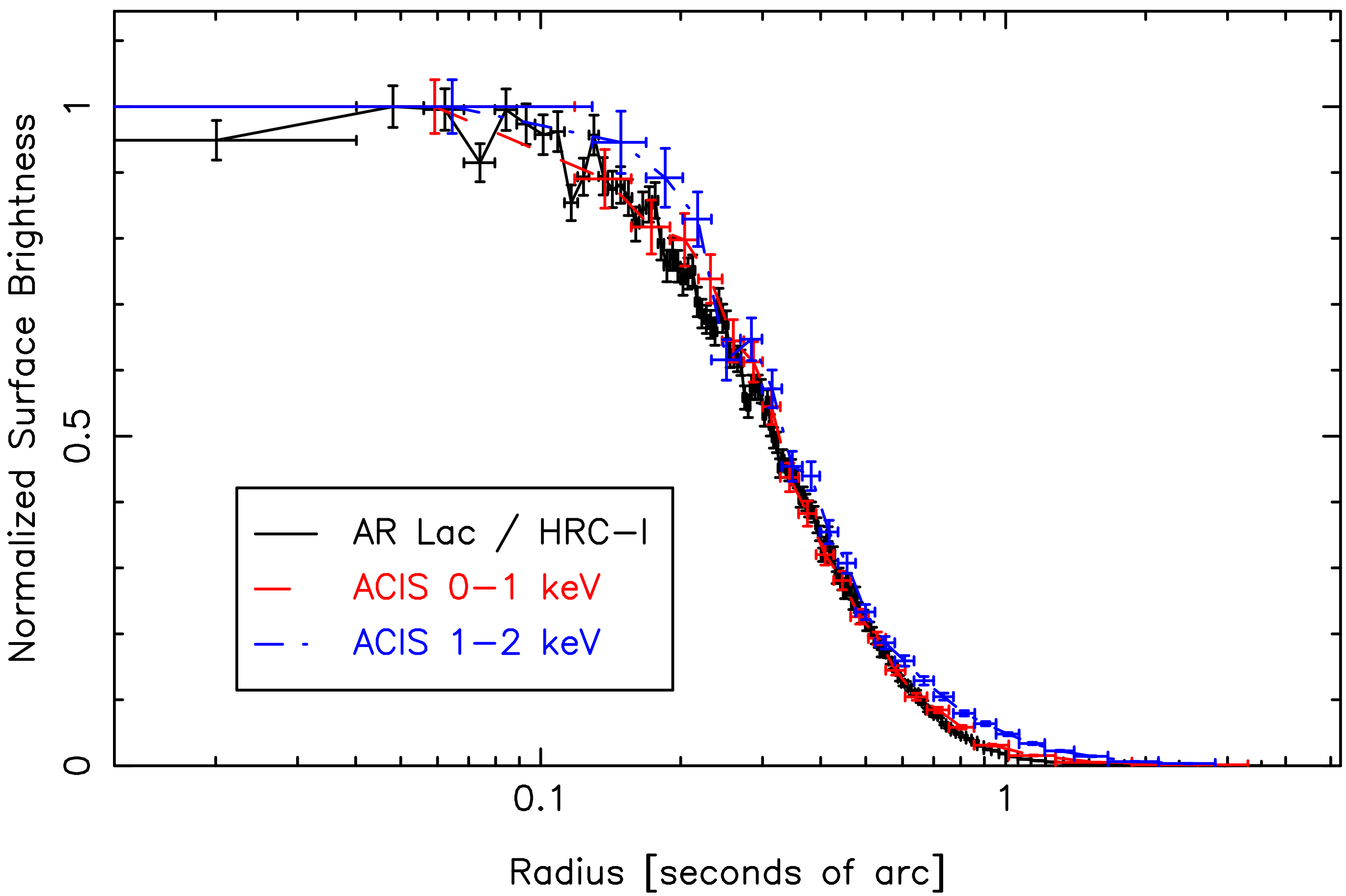
Merged off−axis ACIS Data: 35″, 12° 5.0 keV < E < 6.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
0
0.5
1
0.1
0.2
0.5
1
2
Model − Data
−0.1
0
0.1
0.1
0.2
0.5
1
2
Radius [″]


Merged off−axis ACIS Data: 35″, 12° 6.0 keV < E < 9.0 keV
Observational Data
HRMA
HRMA + ACIS
HRMA + ACIS + 0.06″ Aspect
Normalized Surface Brightness
Model − Data
Radius [″]

Conclusions drawn from the ACIS Comparisons

- The ACIS + Dither model does worse at predicting the on-orbit performance than does the HRC + Dither model
  - There is unexpected structure at mid- to high- energies in the observations.
  - The effects of dither are much more complex than was thought at the time these simulations were designed. We need to handle dither much more realistically.
- There are indications that the misalignments in the models may be rotated from what's in the actual hardware.
- **Without a better model of how the telescope acquires data, the SAOsac HRMA + Spacecraft model cannot adequately reproduce ACIS observations.** HRC-I observations (if properly corrected) are another story.
- **The sample of candidate target sources is too small to perform a full calibration**. There are only *2* objects with good high energy flux.
- The effect of the HETG zero order on the PSF are not known.

HRC-I vs ACIS-S3



HRC-I vs ACIS-S3