X-Raying the evolution of SN 1987A

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  - use sharpened Chandra data and PSF
  - infer the intensity map that generates the data
  - compare across time, passband, and observatory

Chandra data

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- Chandra has been observing SN 1987A in the X-ray regime since 1999 on a semi-irregular biannual schedule
  - Thanks mainly to the Penn State group, starting with Burrows et al. 2000, through Frank et al. 2016
  - Basic picture: the blast wave from the SN is plowing through a circumstellar equatorial ring of clumpy material since c.1999 and is now pushing out past it into smoother material

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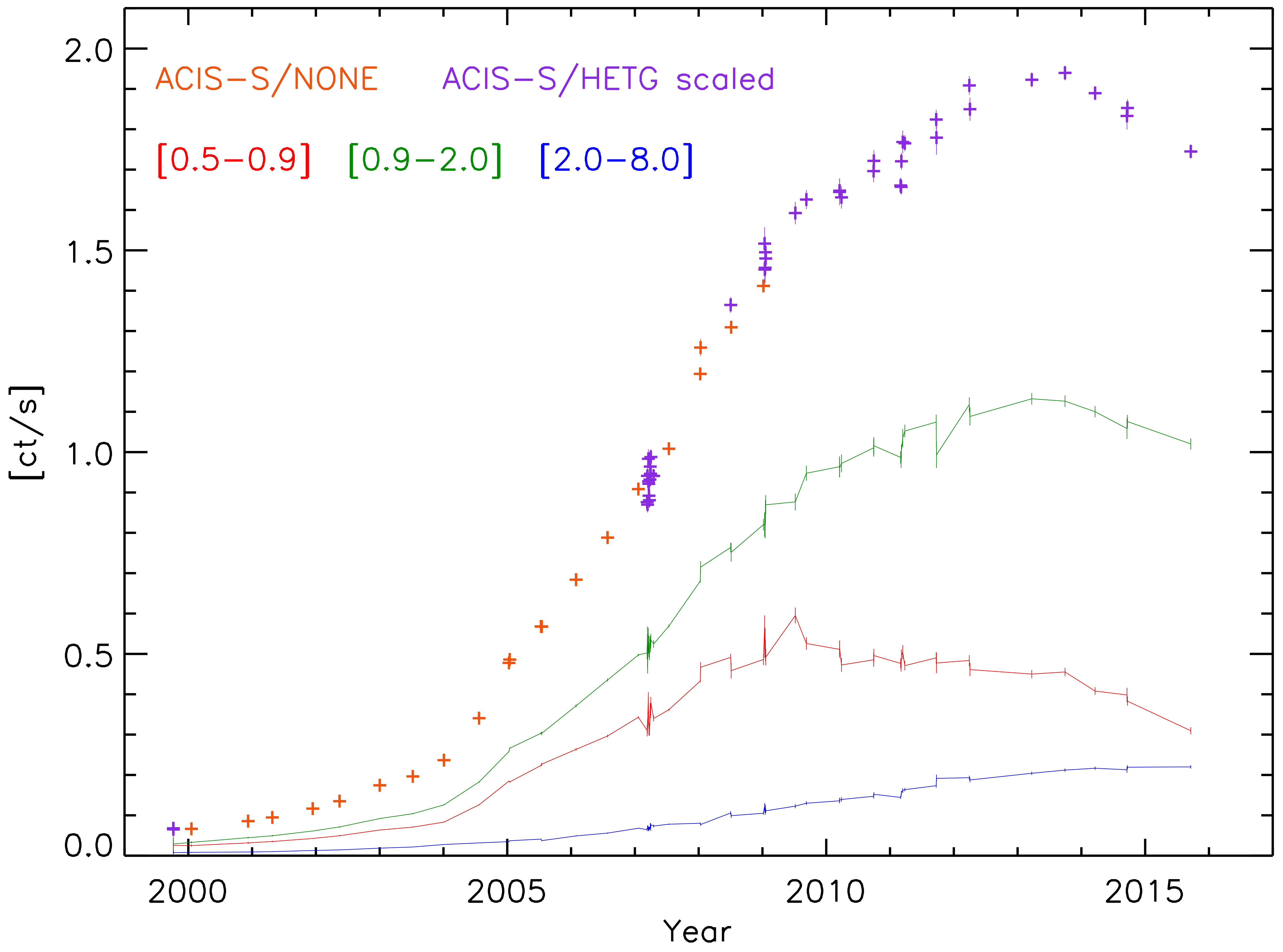
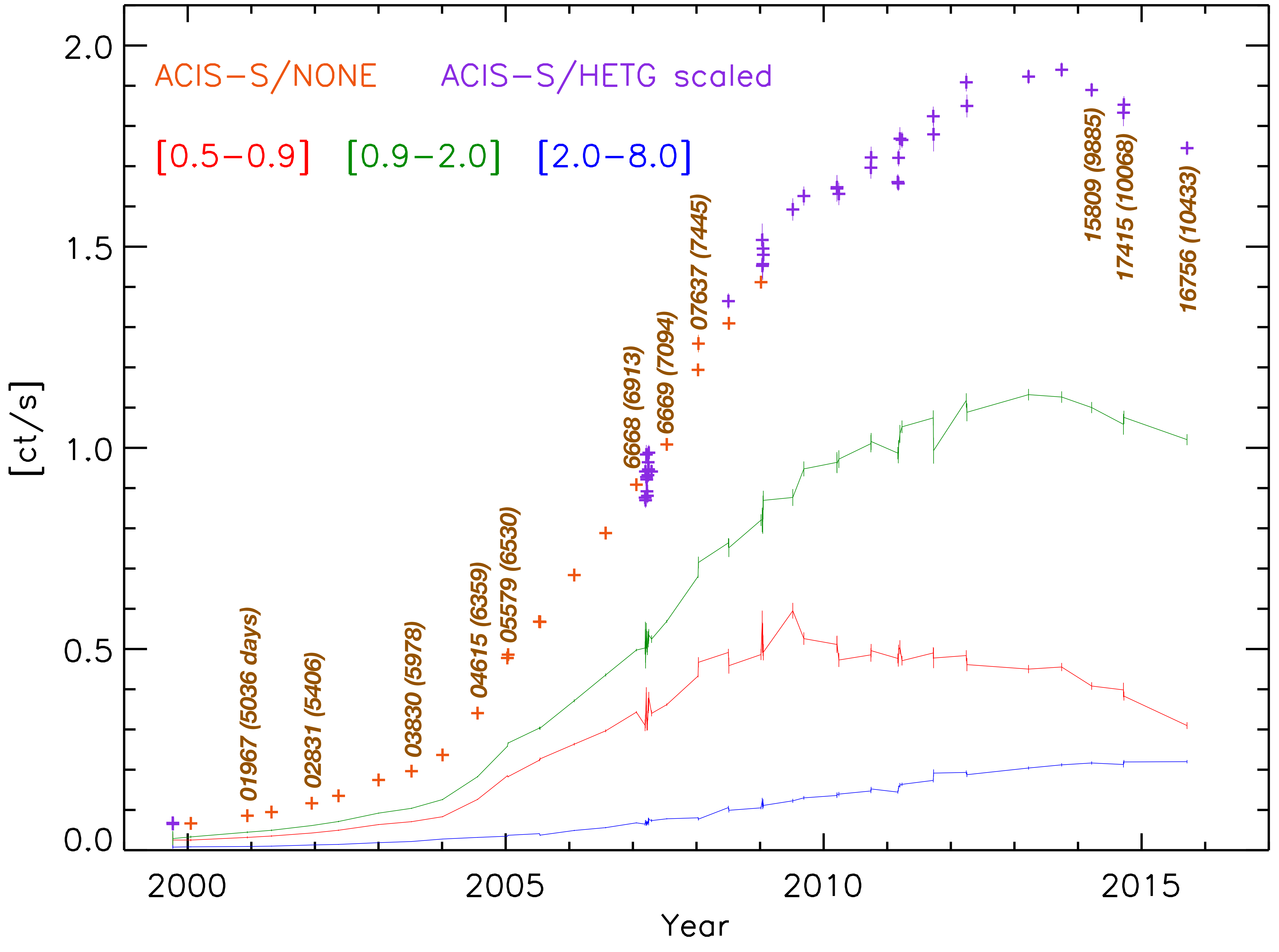
- The bare ACIS-S has accumulated 663 ksec of exposure, and the HETGS+ACIS-S combination has 1.45 Msec
- Observations with LETGS+ACIS-S and LETGS+HRC-S have also been made, but ignore here because the LETG introduces structure into the PSF that cannot be taken out yet

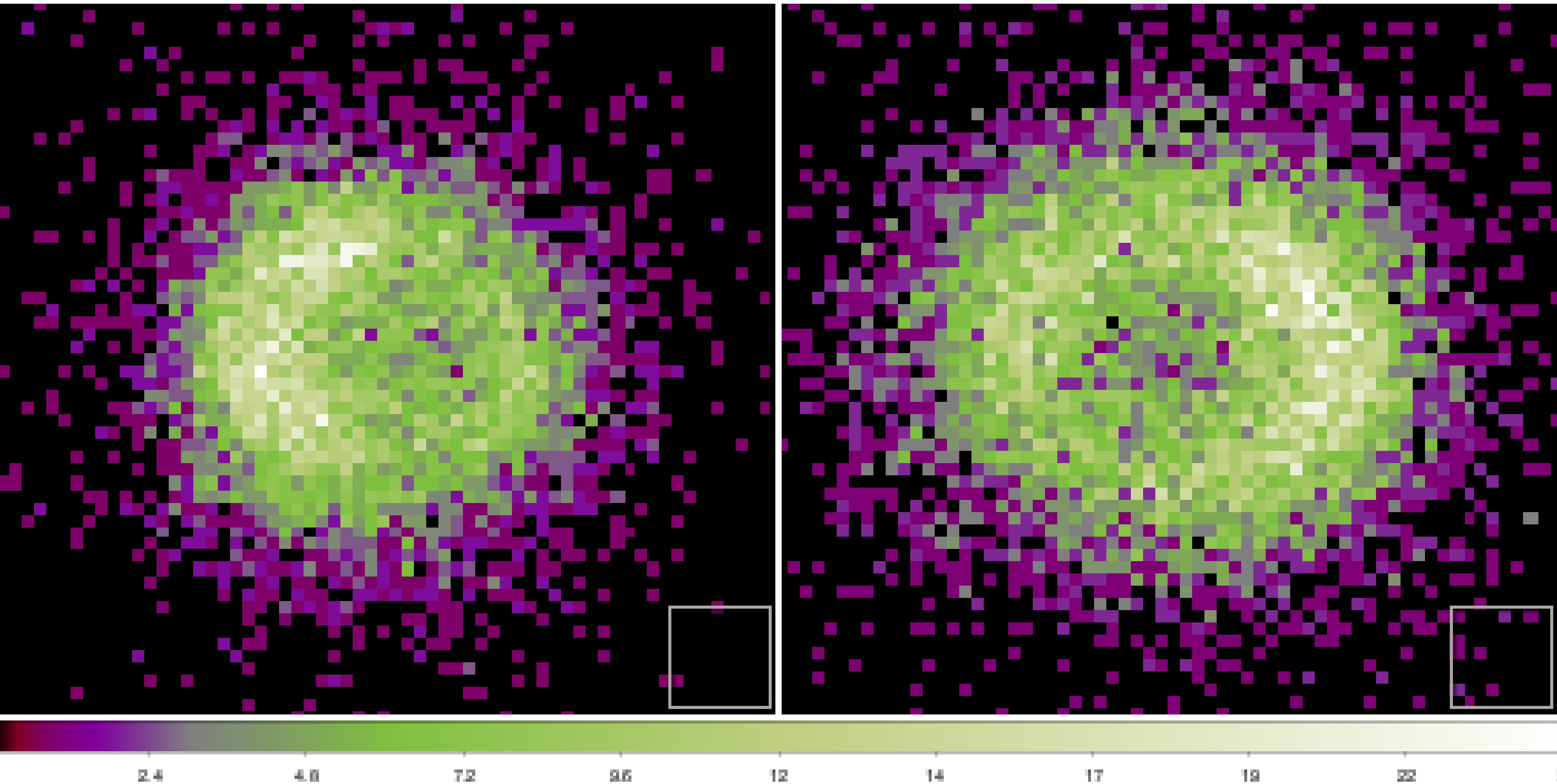


ACIS-S/NONE
ACIS-S/HETG scaled
[0.5-0.9]
[0.9-2.0]
[2.0-8.0]
[ct/s]
Year
0.0
0.5
1.0
1.5
2.0
2000
2005
2010
2015



ACIS-S/NONE
ACIS-S/HETG scaled
[0.5-0.9]
[0.9-2.0]
[2.0-8.0]
01967 (5036 days)
02831 (5406)
03830 (5978)
04615 (6359)
05579 (6530)
6668 (6913)
6669 (7094)
07637 (7445)
15809 (9885)
17415 (10068)
16756 (10433)
[ct/s]
Year
0.0
0.5
1.0
1.5
2.0
2000
2005
2010
2015

ObsID1967 : Dec 2000 : 98.8 ks   ObsID16756 : Sep 2015 : 66.6 ks



X-ray events binned at 1/8 ACIS pixel ≡ 0.0615″

Chandra PSF

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- Subpixel Event Repositioning (SER)
  - Chandra pixels are 0.492″, but because of telescope dither and charge bloom, events can be localized to higher resolutions
  - Energy dependent SER (EDSER) — Li et al. 2014, ApJ 610, 1204
  - BUT: no PSFs

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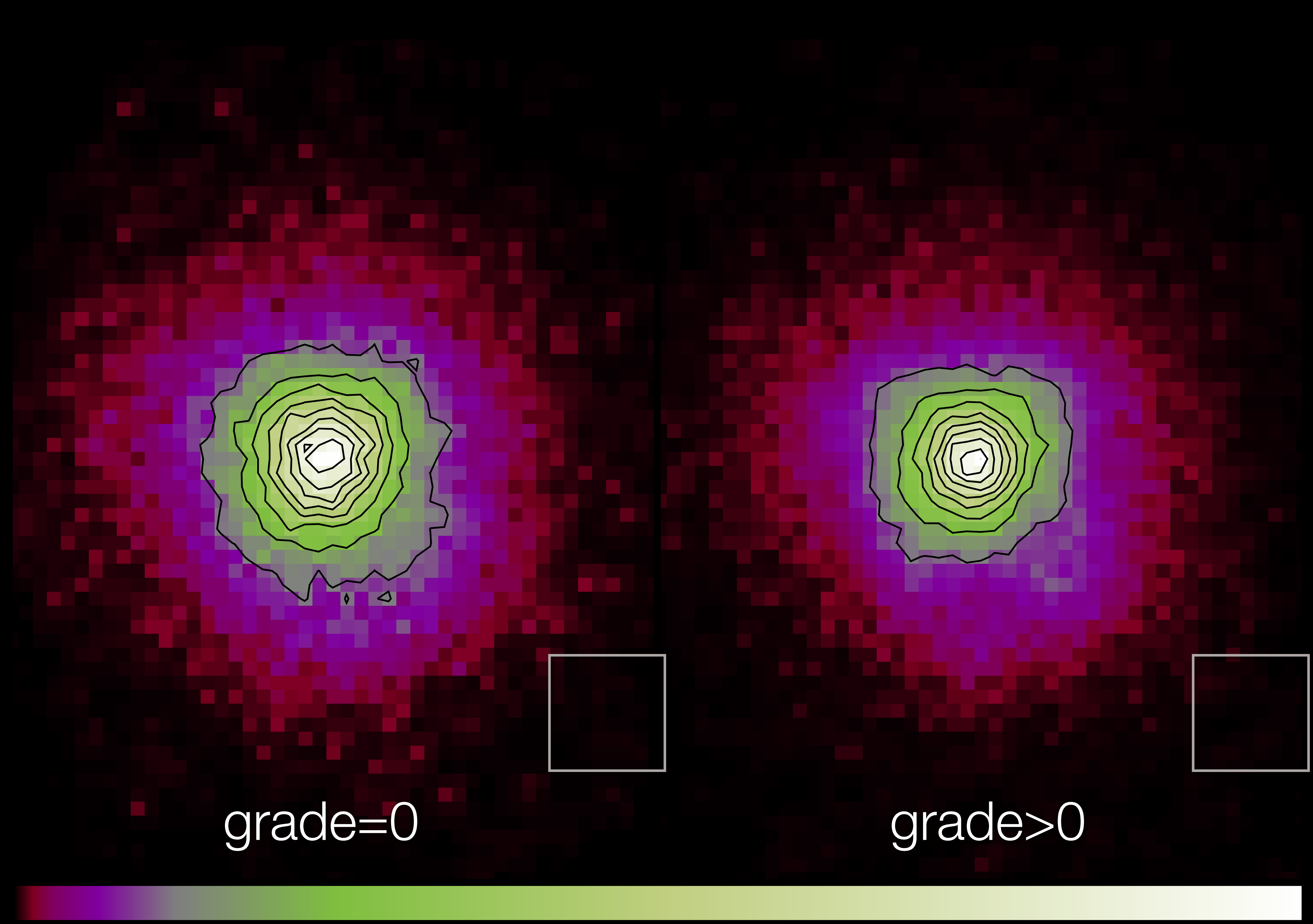
  - Energy dependent SER (EDSER) — Li et al. 2014, ApJ 610, 1204
  - BUT: no PSFs
- Empirical PSF
  - Collect all well-observed (>200 ct), on-axis (<1′), isolated (>6″), weak (<0.1 ct/s), point sources
  - deroll and stack them to get an empirical ACIS-S PSF made from 90 kct



Contours are at intervals of 0.1x. Color scale is in log.

LIRA

Low-counts Image Reconstruction and Analysis

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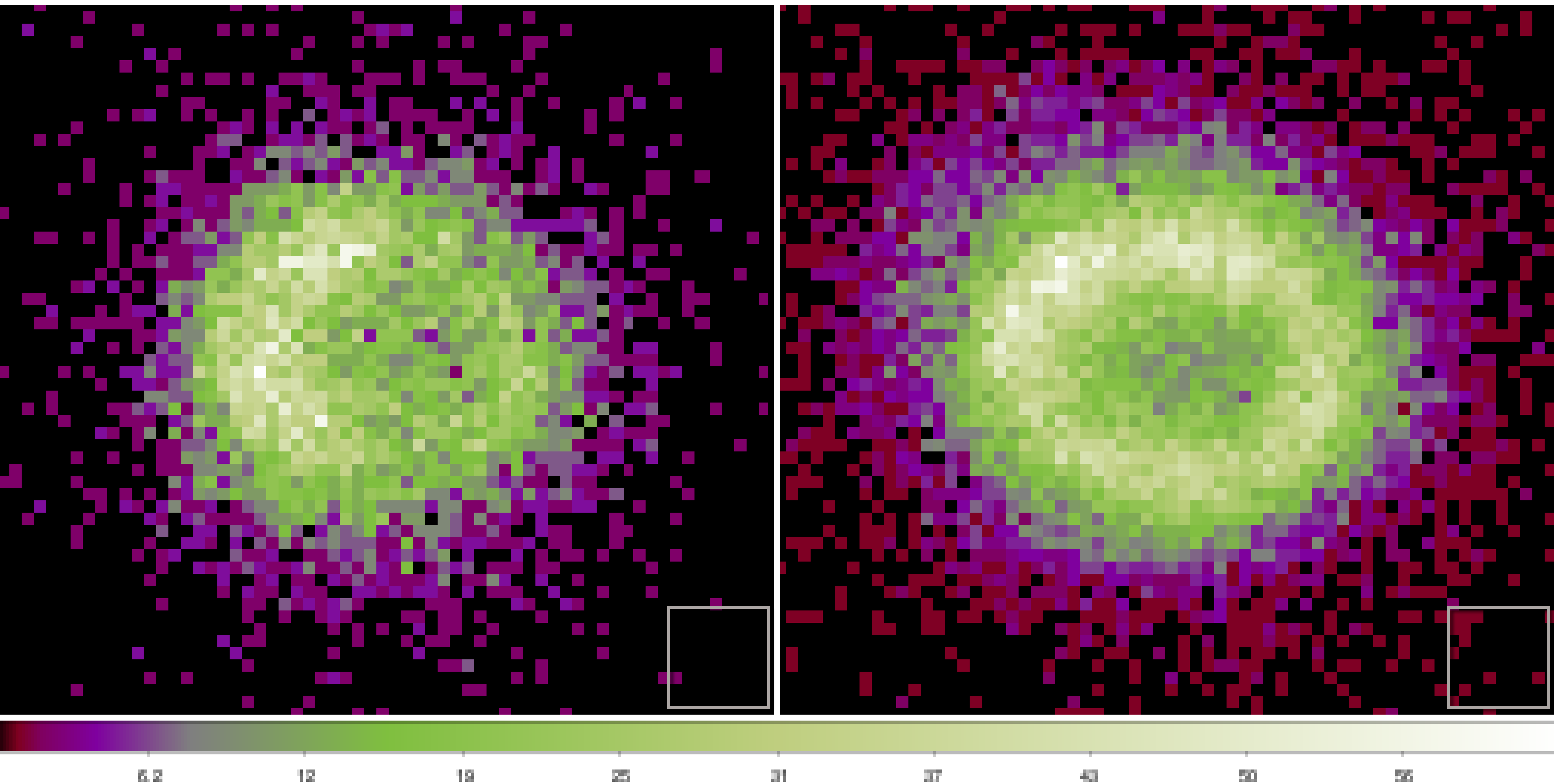
- Bayesian multi-scale counts image reconstruction
  - Given a baseline (background), estimates residual intensities via quadrantic allocations at different scales using MCMC
  - github.com/astrostat/LIRA
- Not just a deconvolution -- key output is uncertainty
  - Can compare differences between images of different passbands or at different epochs

ObsID1967 : Dec 2000 : 98.8 ks   ObsID7637 : Jul 2007 : 25.7 ks



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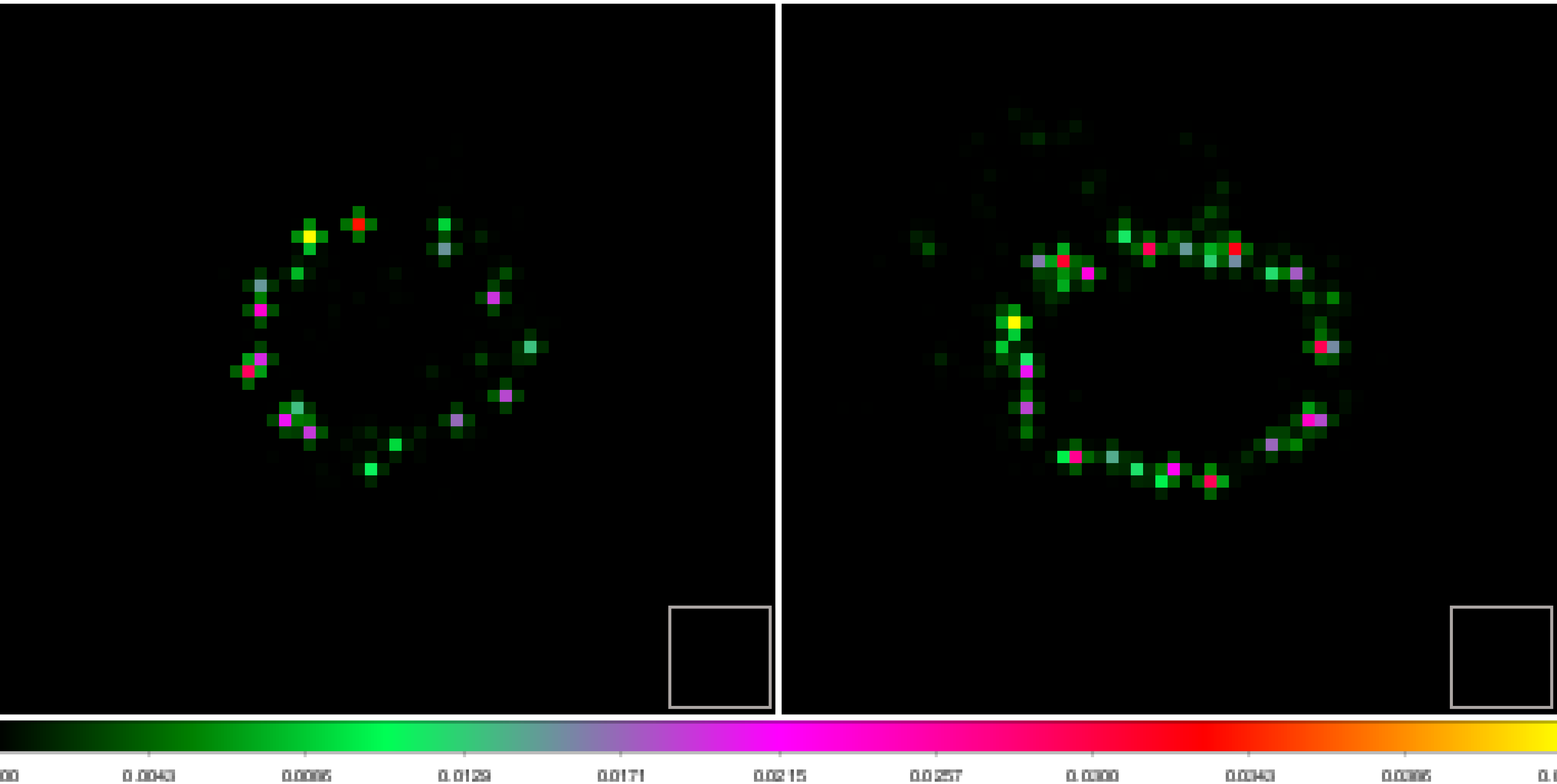


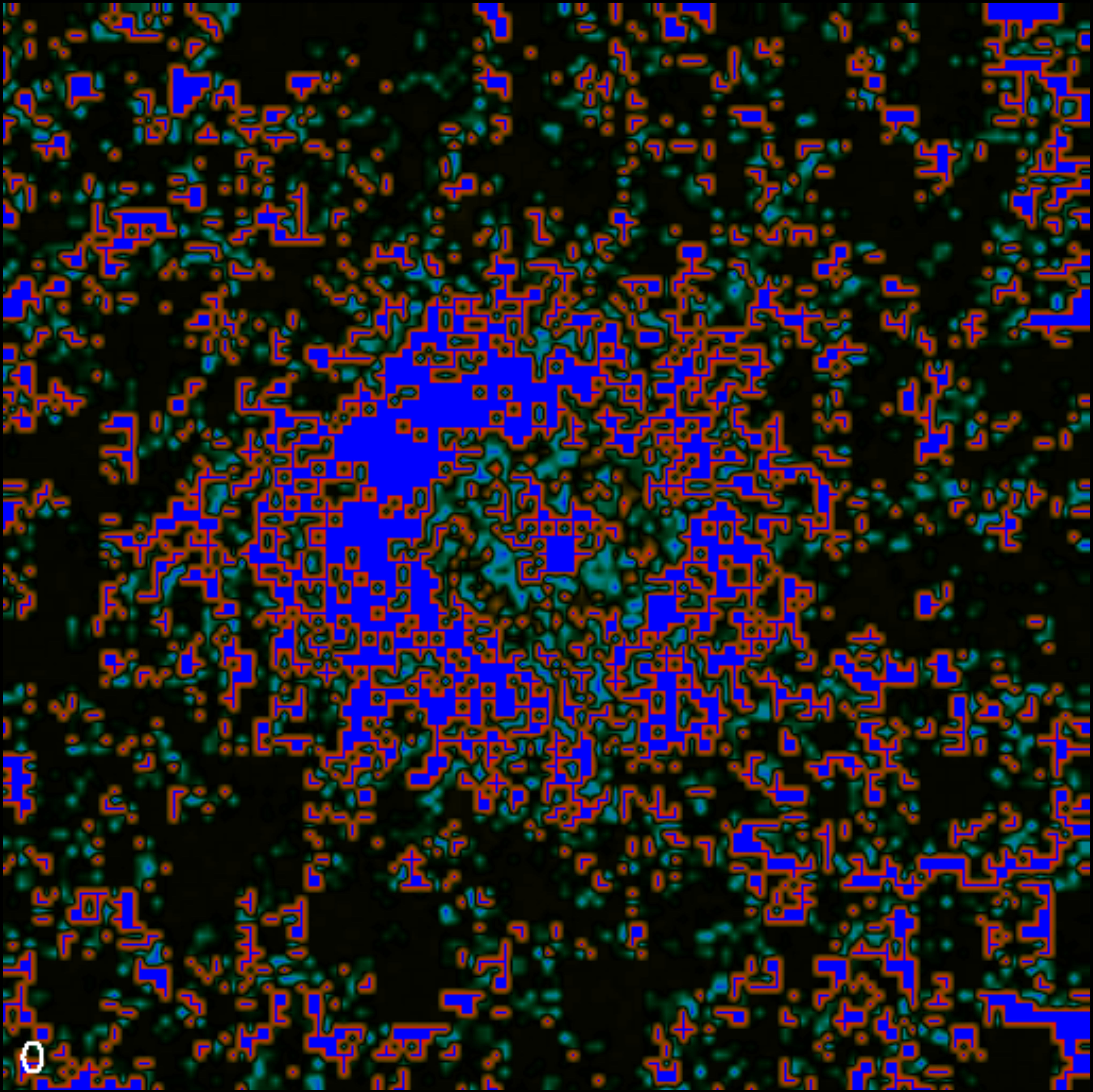
LIRA multi-scale component above flat background (averaged, smoothed, linear scale), at 1/8 ACIS pixel.

ObsID 1967

LIRA

iterations

difference
from mean:
red deficit
blue surplus



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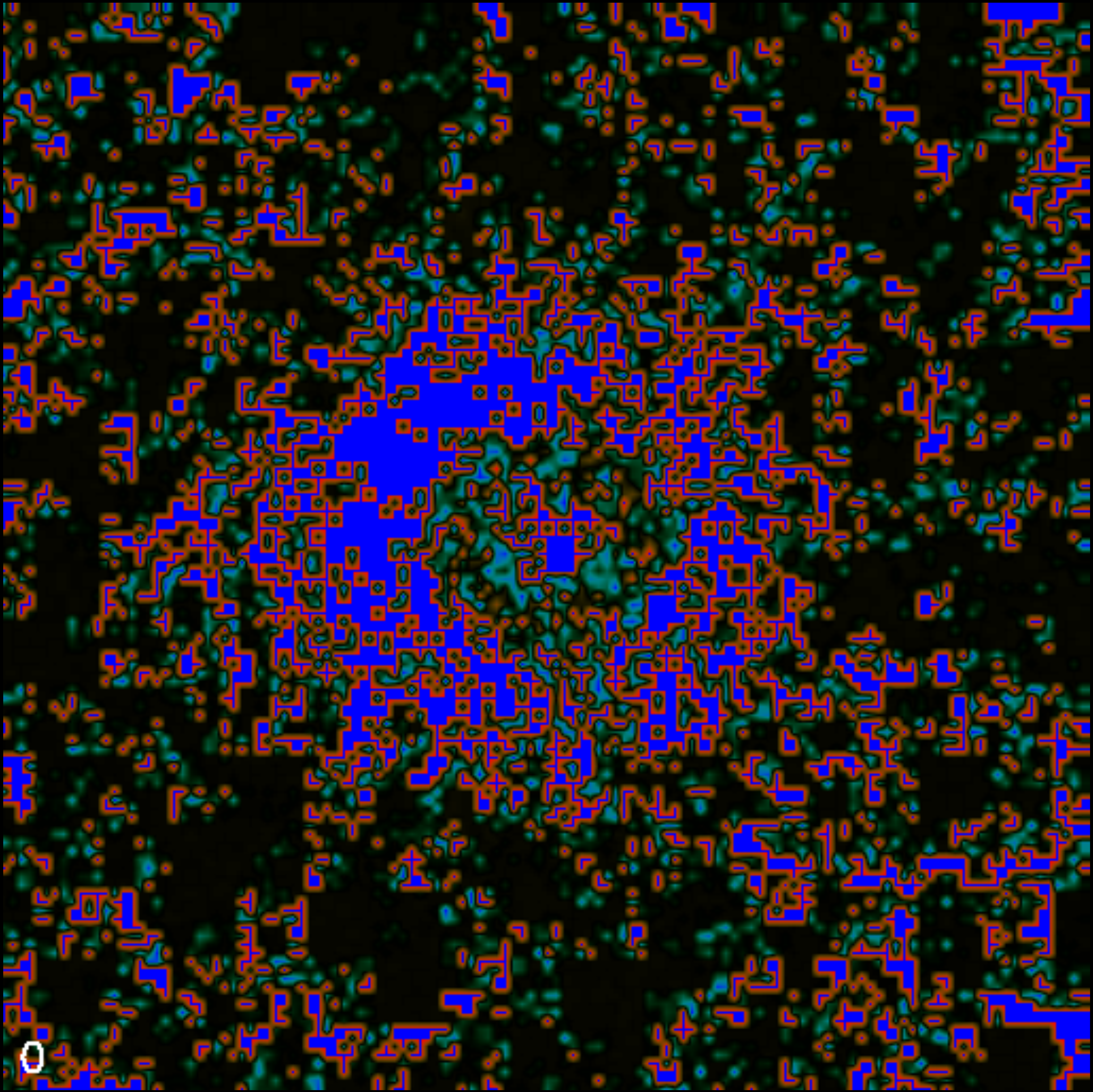
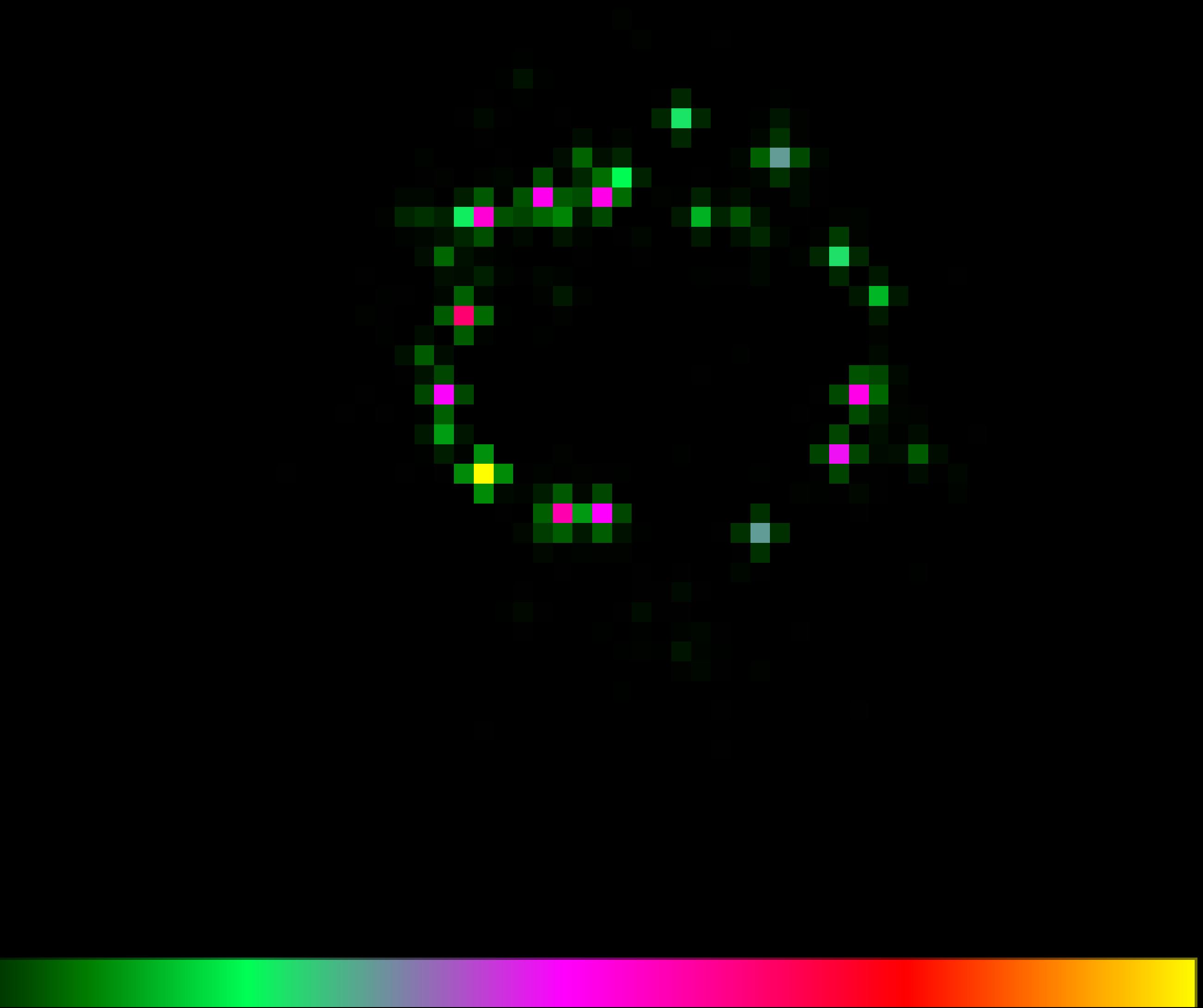
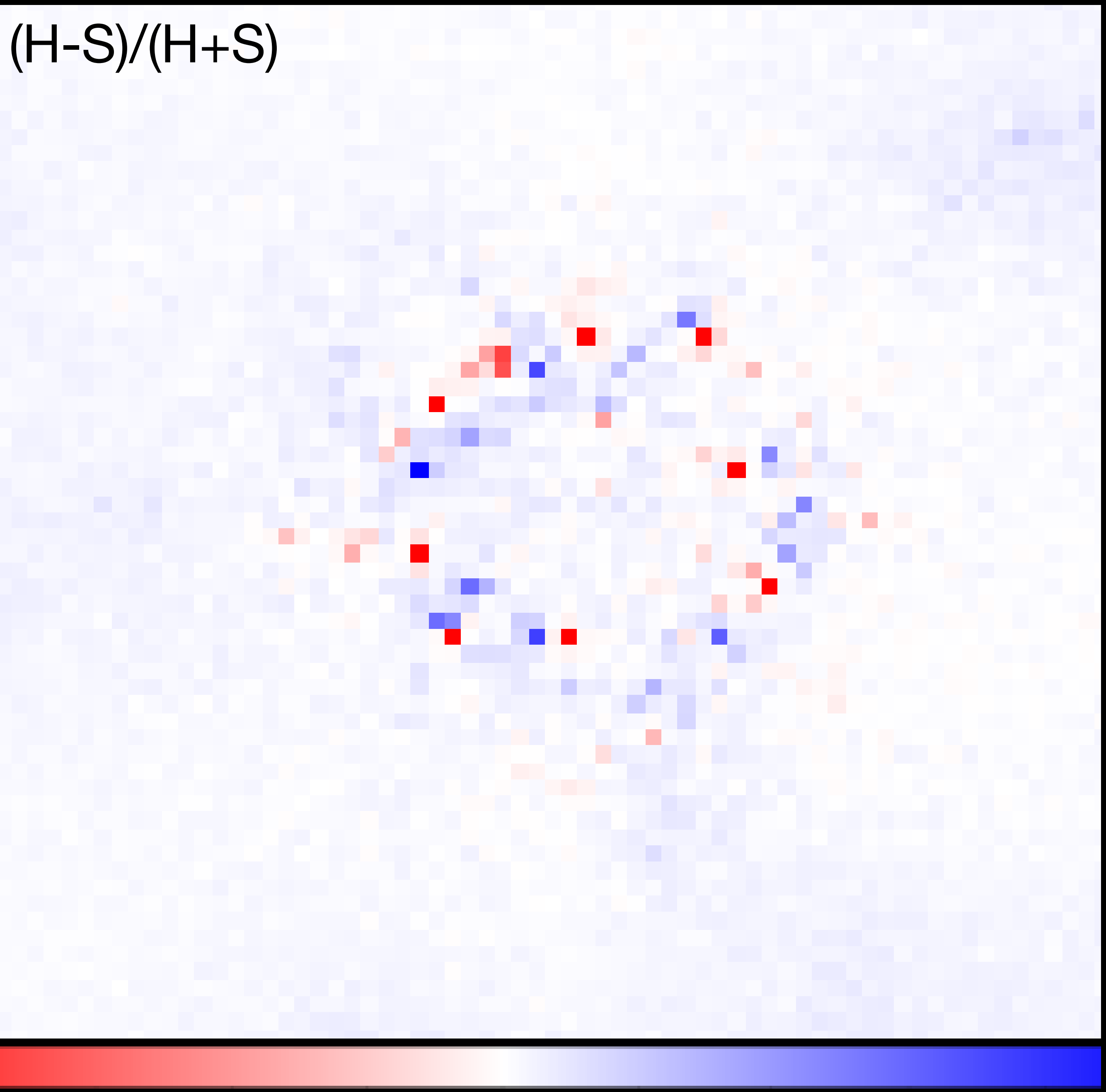





Fransson et al. 2015

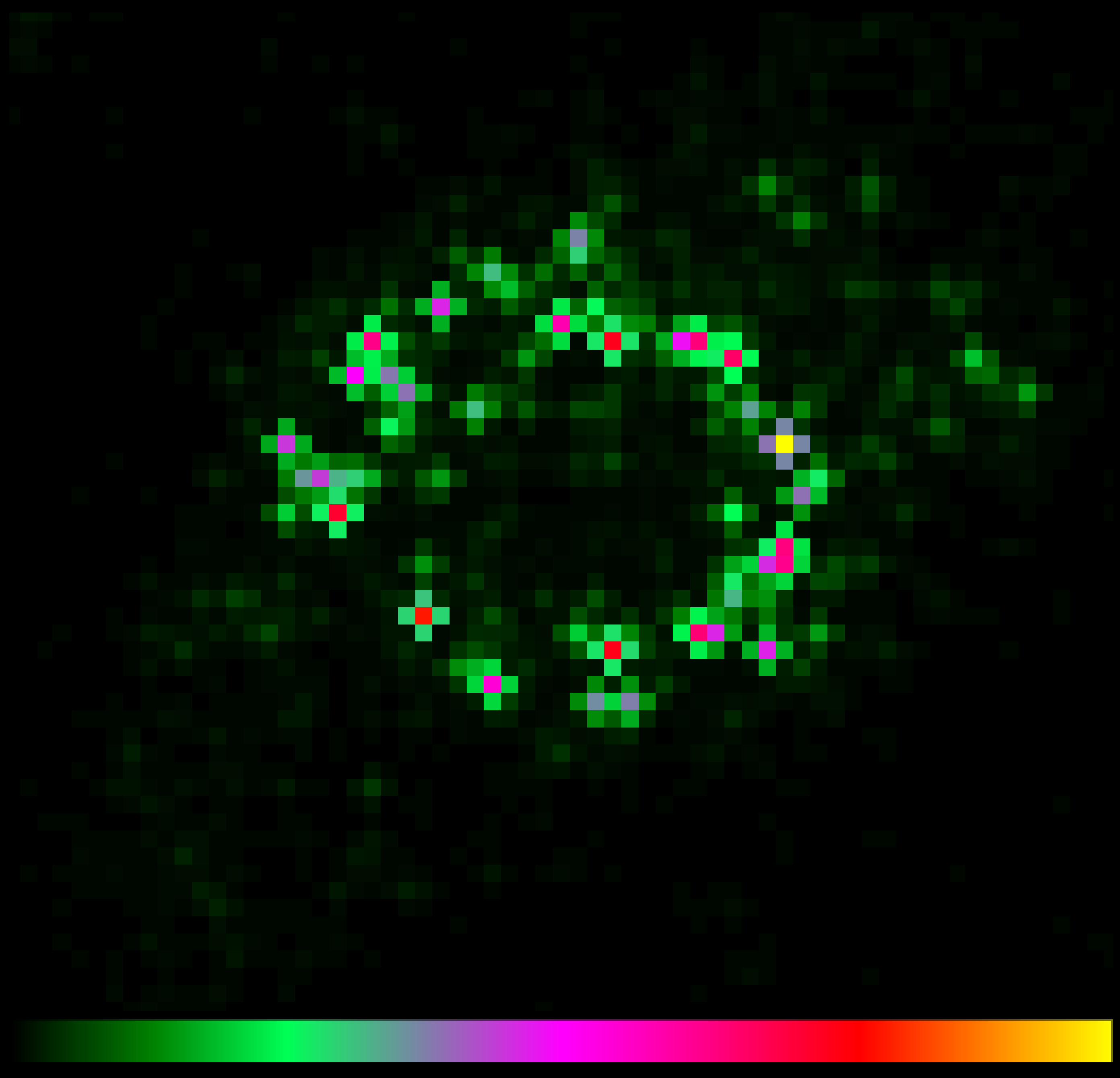
Dec 2001: Reconstructed X-ray (left) vs optical (right). LIRA output has been smoothed by a Gaussian to highlight structure. Most clumps in the optical have corresponding clumps in X-ray.



ObsID 2831

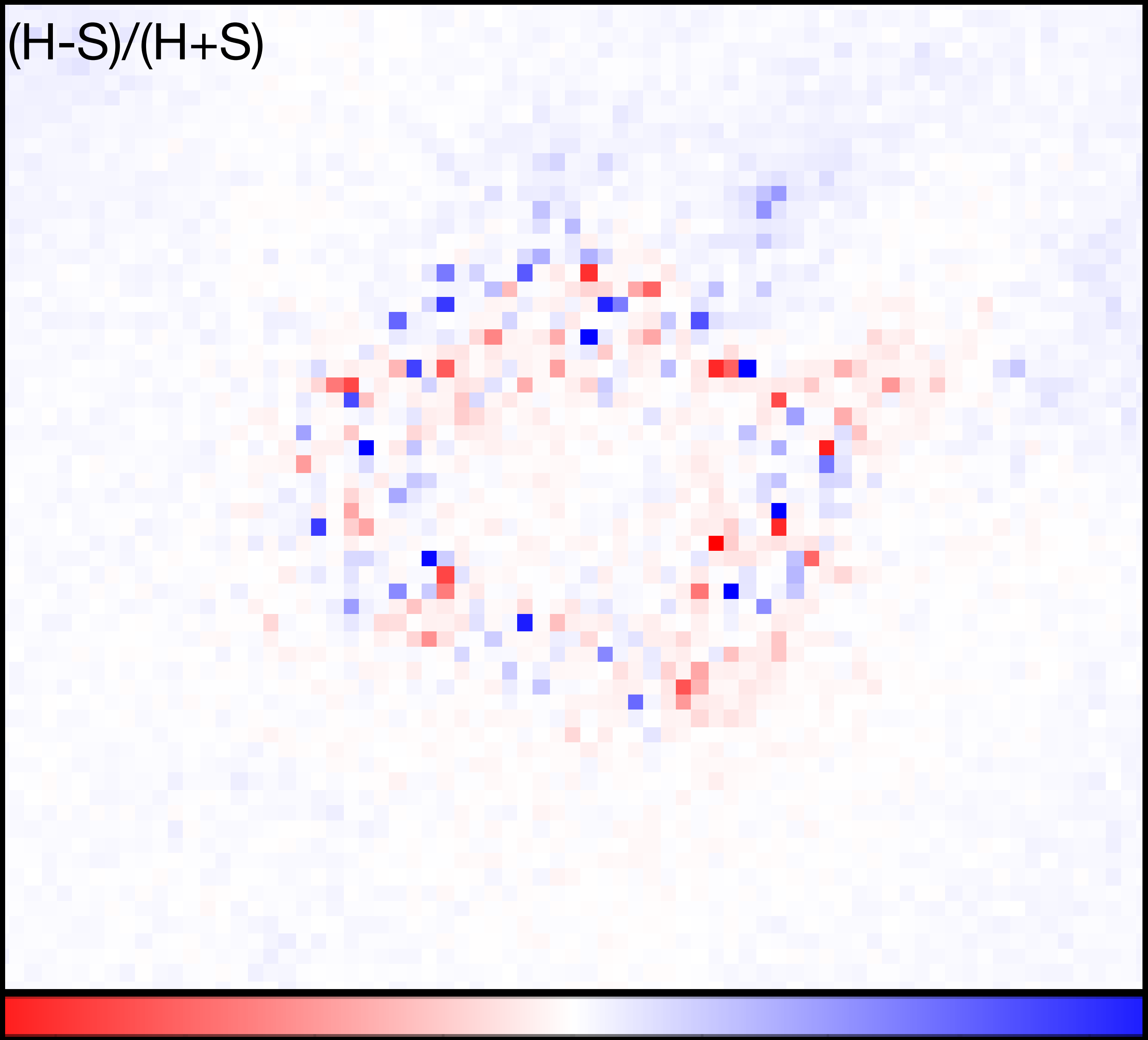
Fransson et al. 2015

Dec 2001: Reconstructed X-ray hardness (left) vs optical (right).



Fransson et al. 2015

Early 2014: Reconstructed X-ray from March (left; sqrt scale, smoothed) vs optical from June (right). Many common clumps, but many differences, especially at lower brightness.

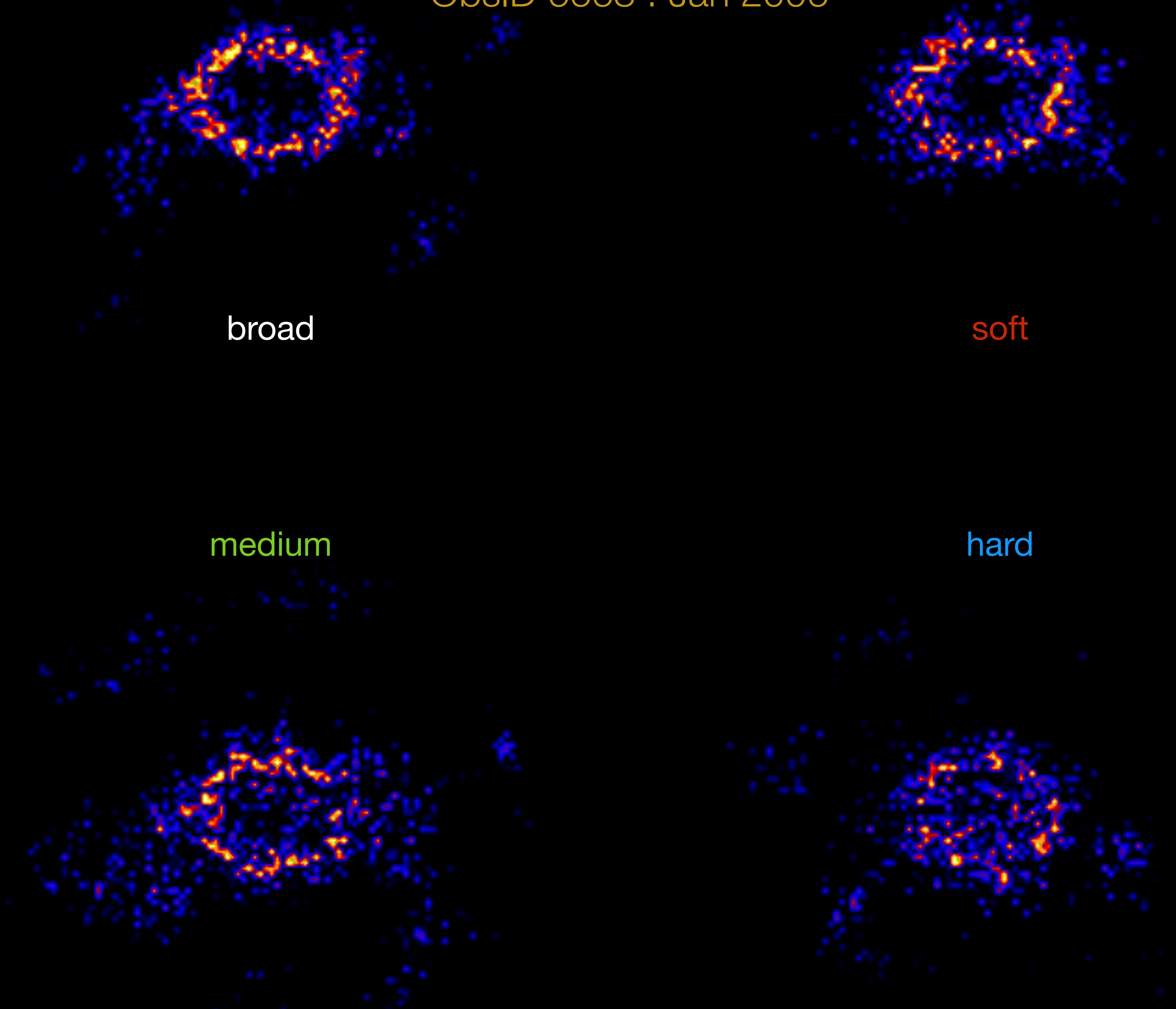


ObsID 15809

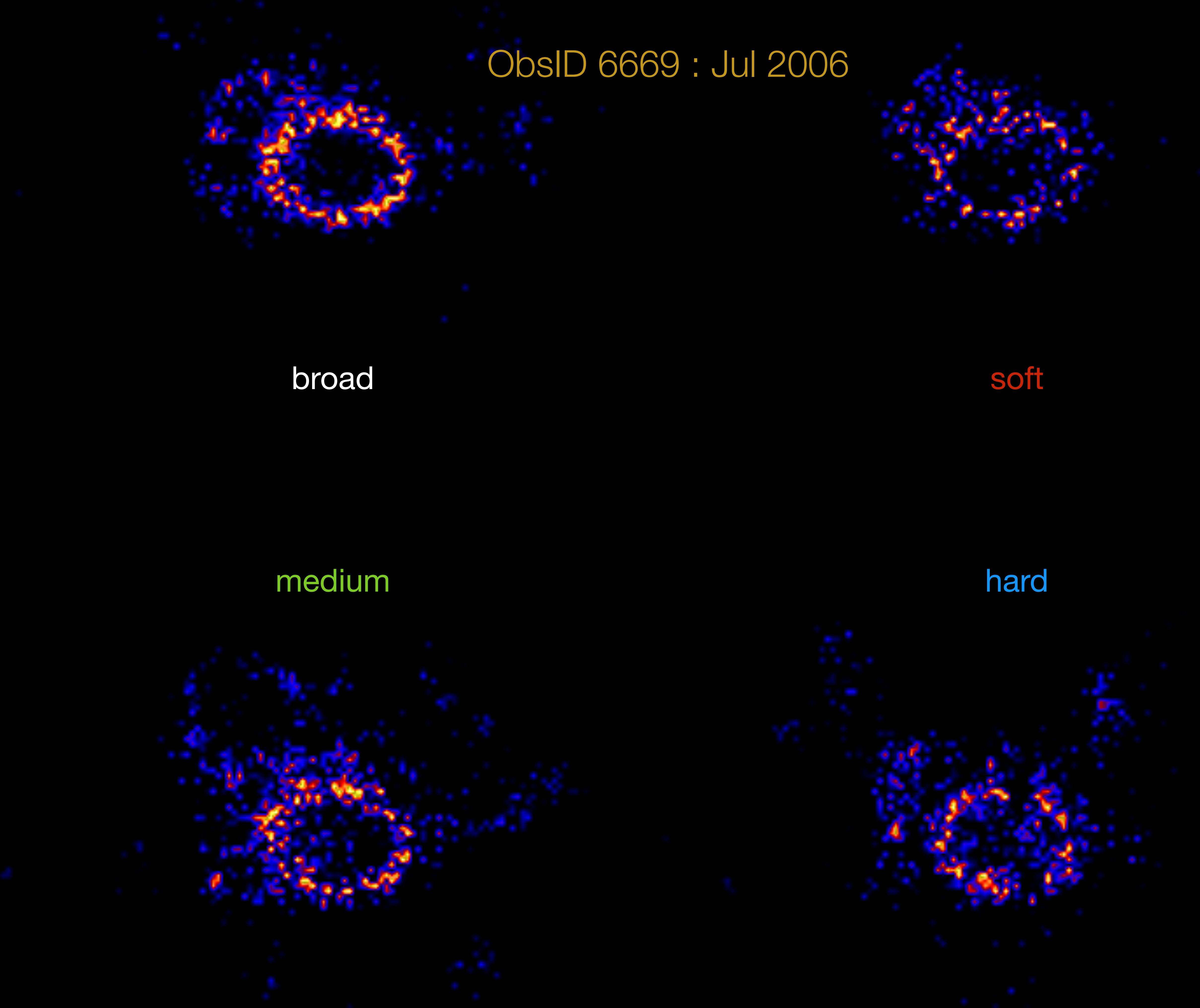

Fransson et al. 2015

Early 2014: Reconstructed X-ray hardness (left) vs optical (right).

ObsID 6668 : Jan 2006

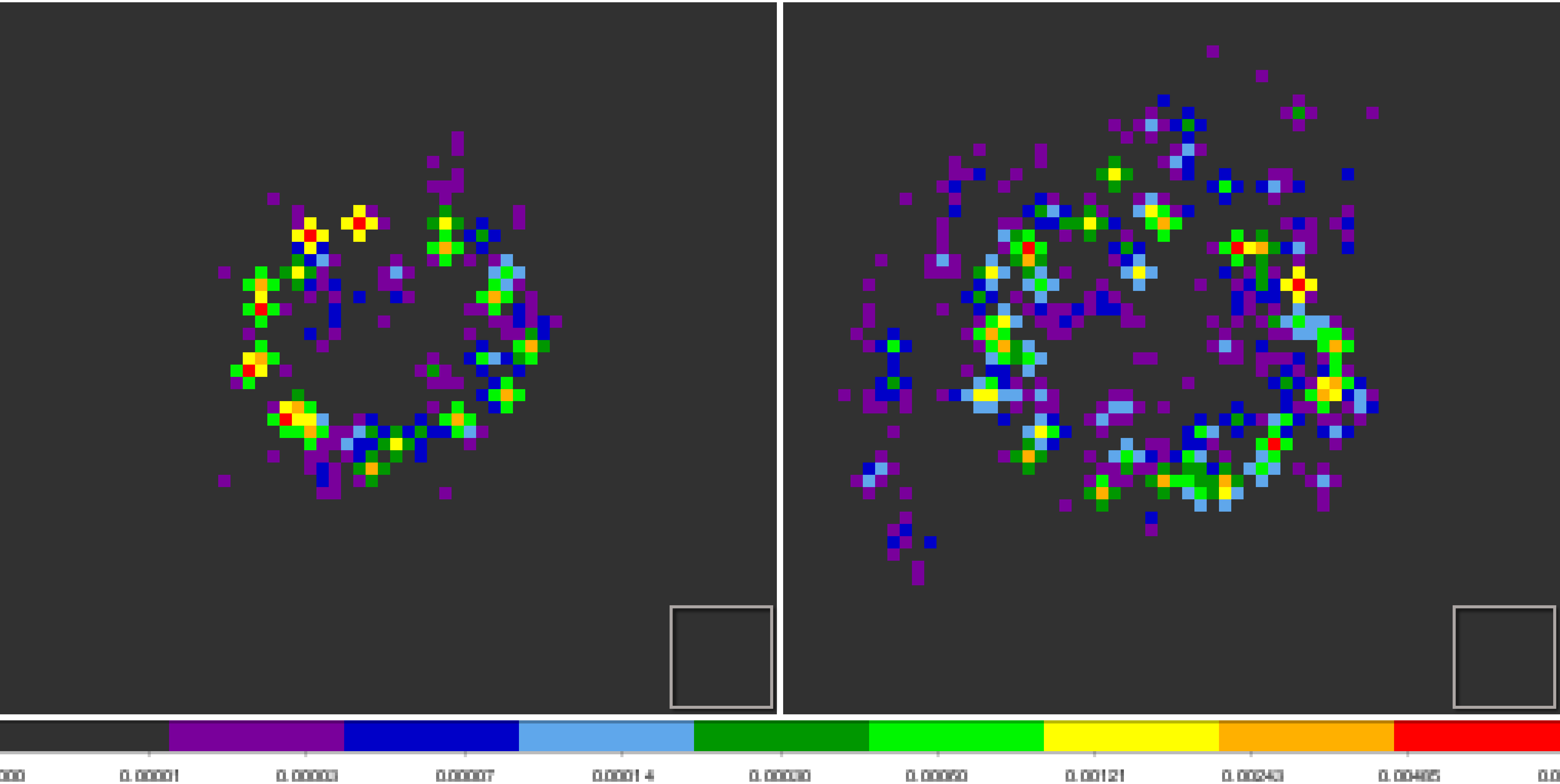


ObsID 6669 : Jul 2006



ObsID1967 : Dec 2000 : 98.8 ks

ObsID16756 : Sep 2015 : 66.6 ks



LIRA multi-scale component above flat background (log scale, averaged, smoothed), at 1/8 ACIS pixel.

Summary

- Sharpest X-ray maps so far, reconstructed at ~0.1 arcsec with best available PSF, best available reconstruction
- X-rays show clumpy spots as well as diffuse regions, varying on short timescales
- X-ray clumps could be offset from optical
- Clump spectra hardness highly variable
- Recent changes in morphology consistent with blast wave breaking out of clumpy inner shell, possibly making new hot spot sites
- Next:
  - Has the outer ring been detected?
  - Map the diffuse emission and tie to hydro