A Multiwavelength View of the HST Frontier Cluster MACS J0416.1-2403

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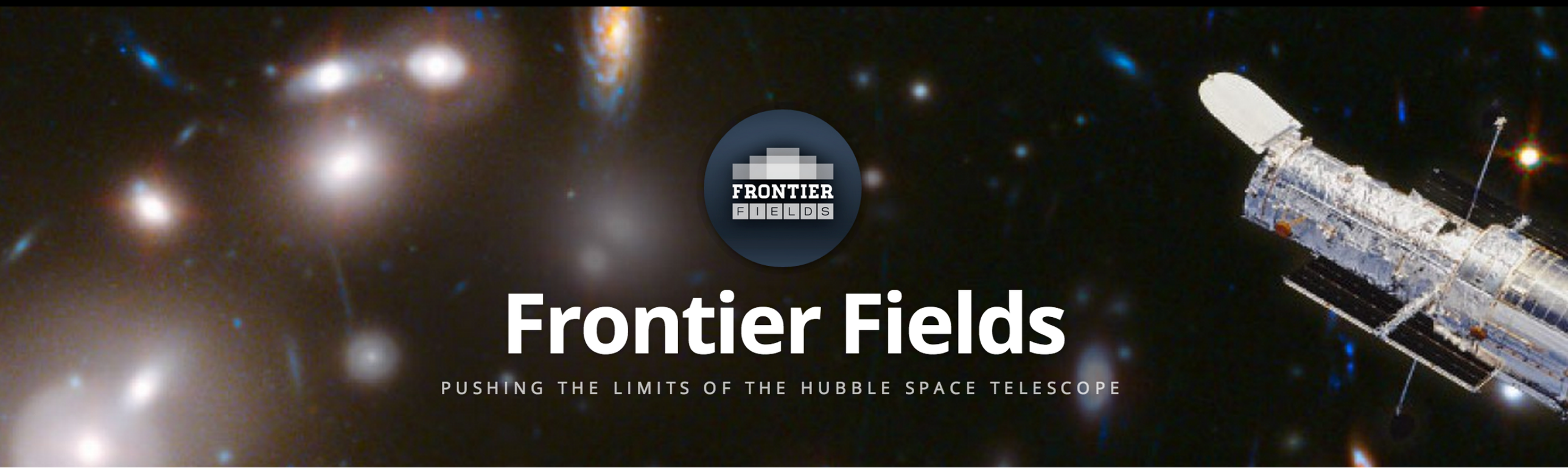
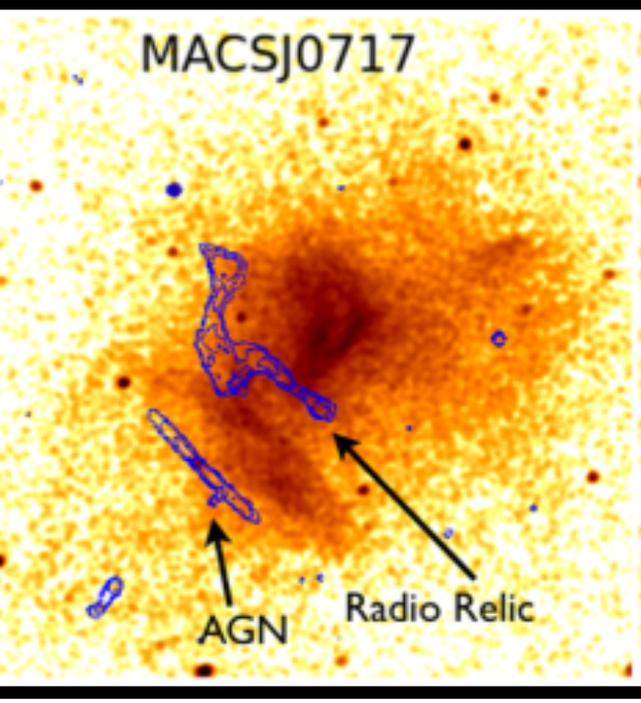
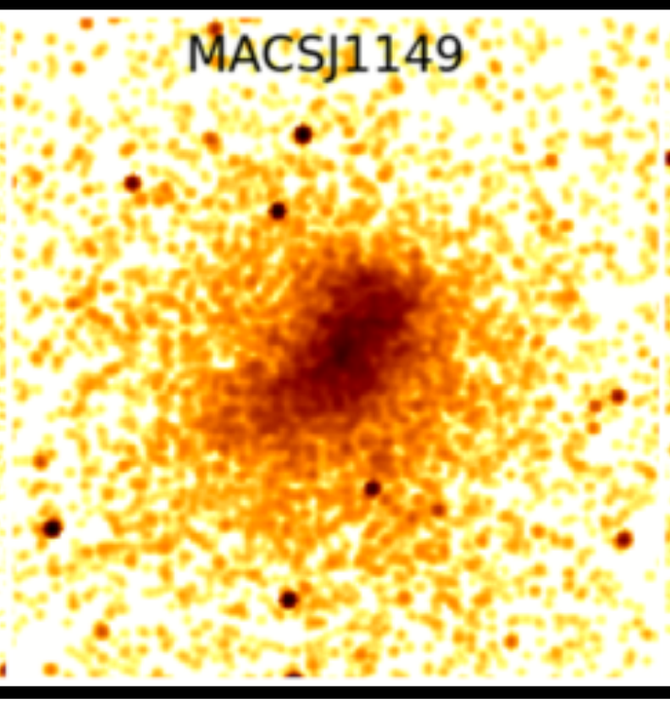
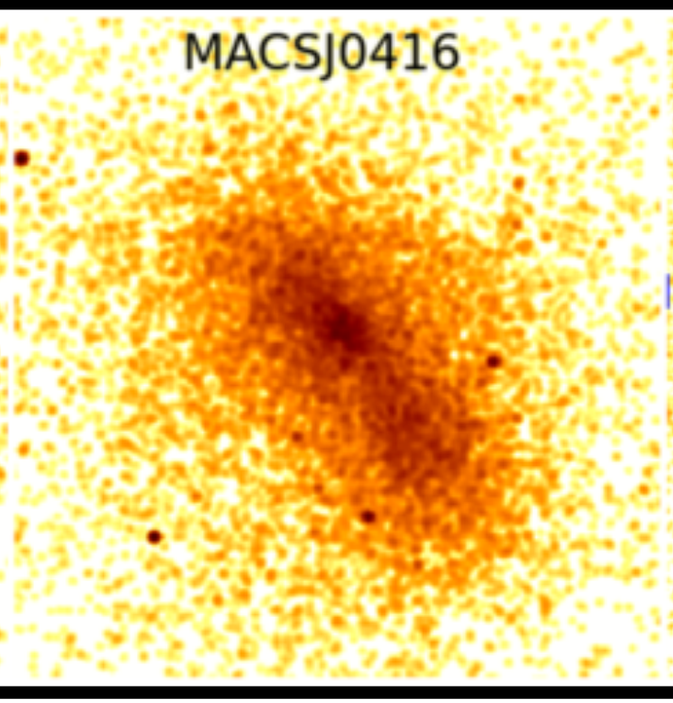
Hubble's Bucket List

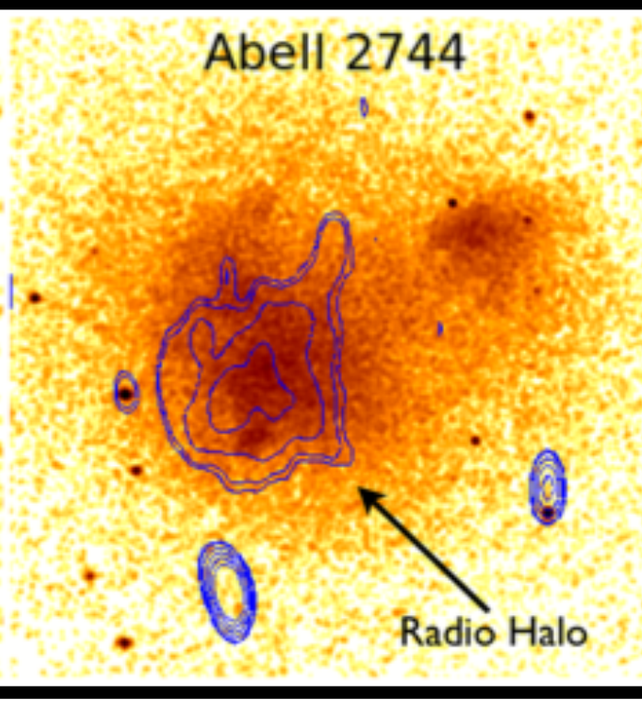


Hubble's Bucket List









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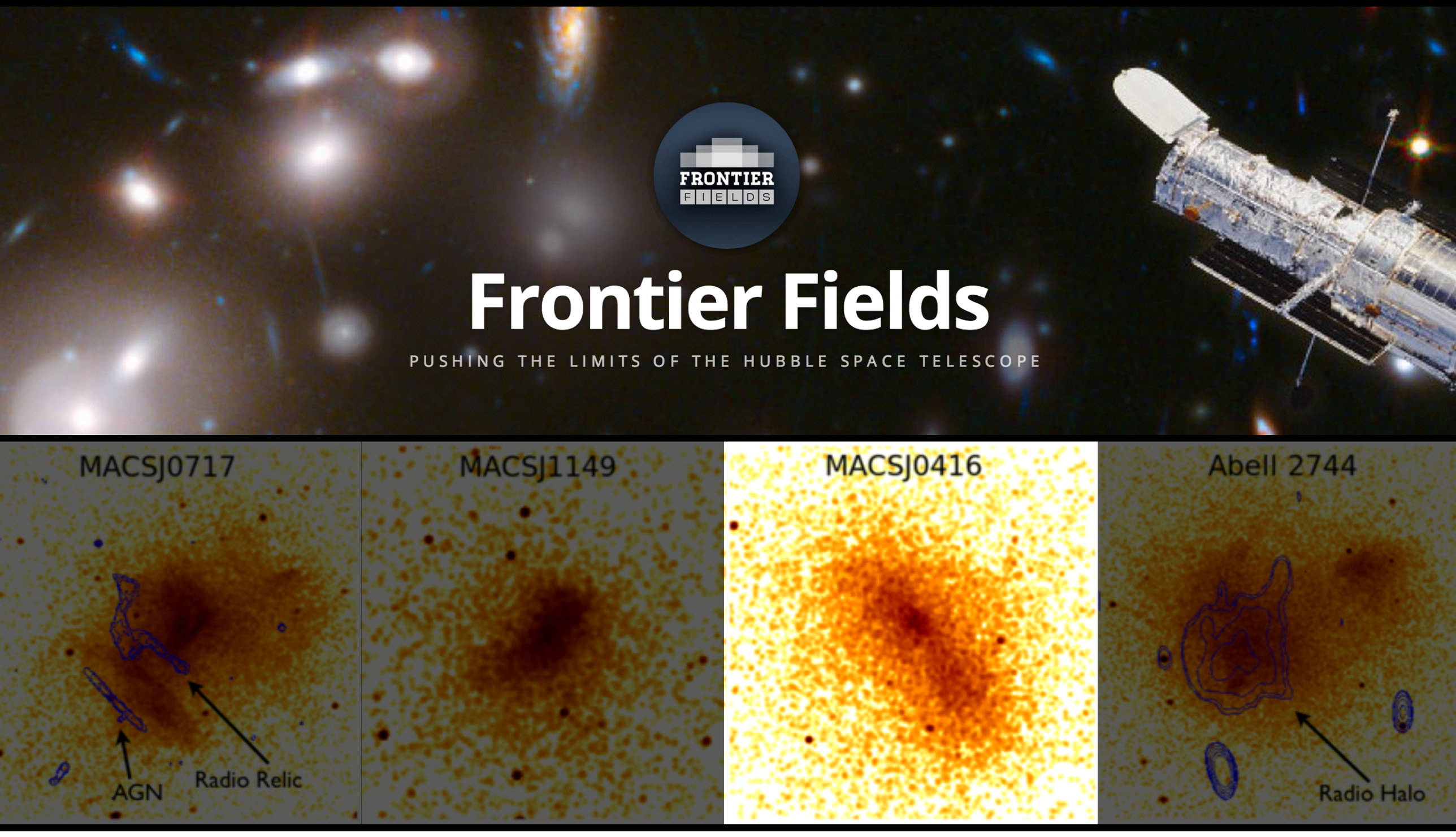


≈ 200 kpc

Total mass within a radius of 950 kpc:

~1e15 $M_\odot$

C1

C2

S2

M ~ 1e13 $M_\odot$

S1

M ~ 4e13 $M_\odot$

Jauzac et al. (2014)

SCENARIO 1

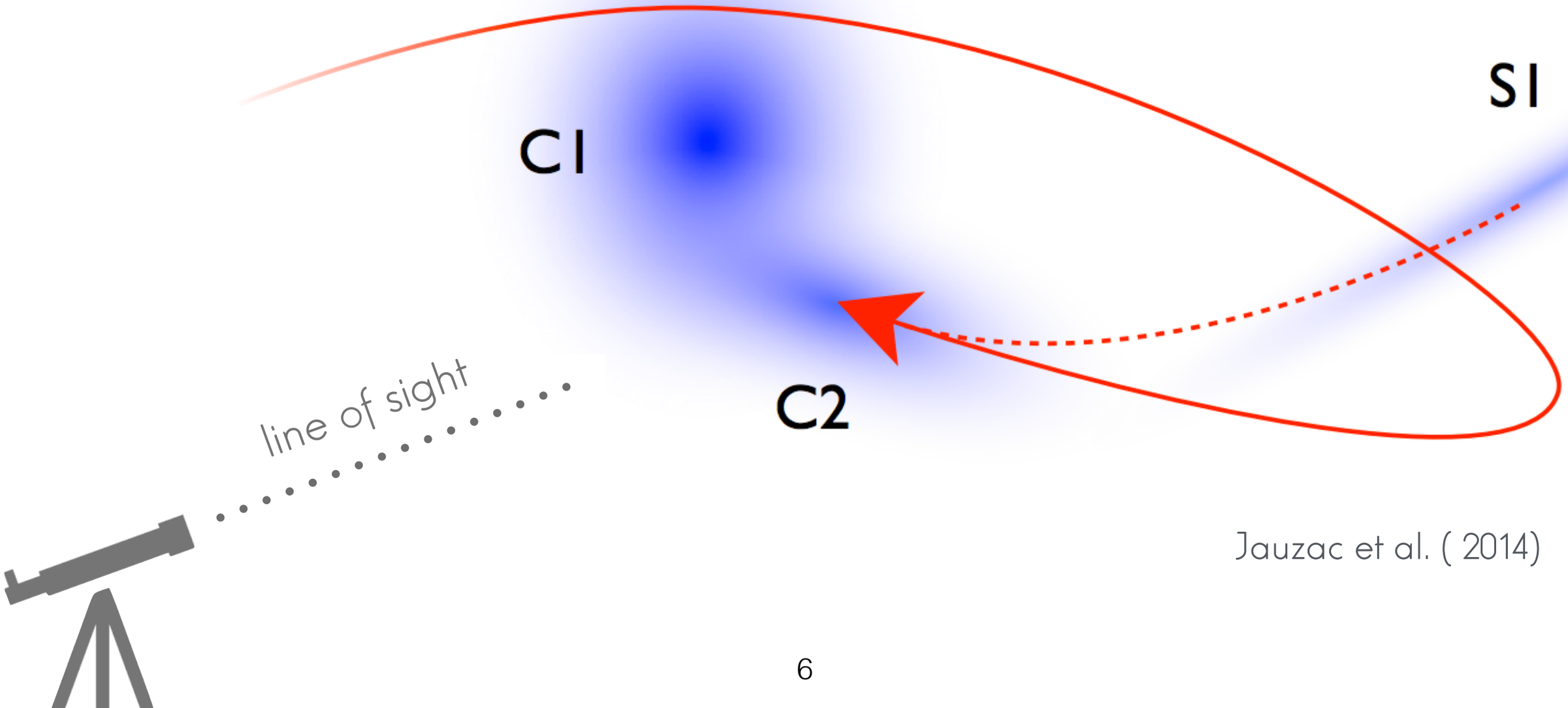
A pre-merger system:

C2 approaches C1 for the first time.

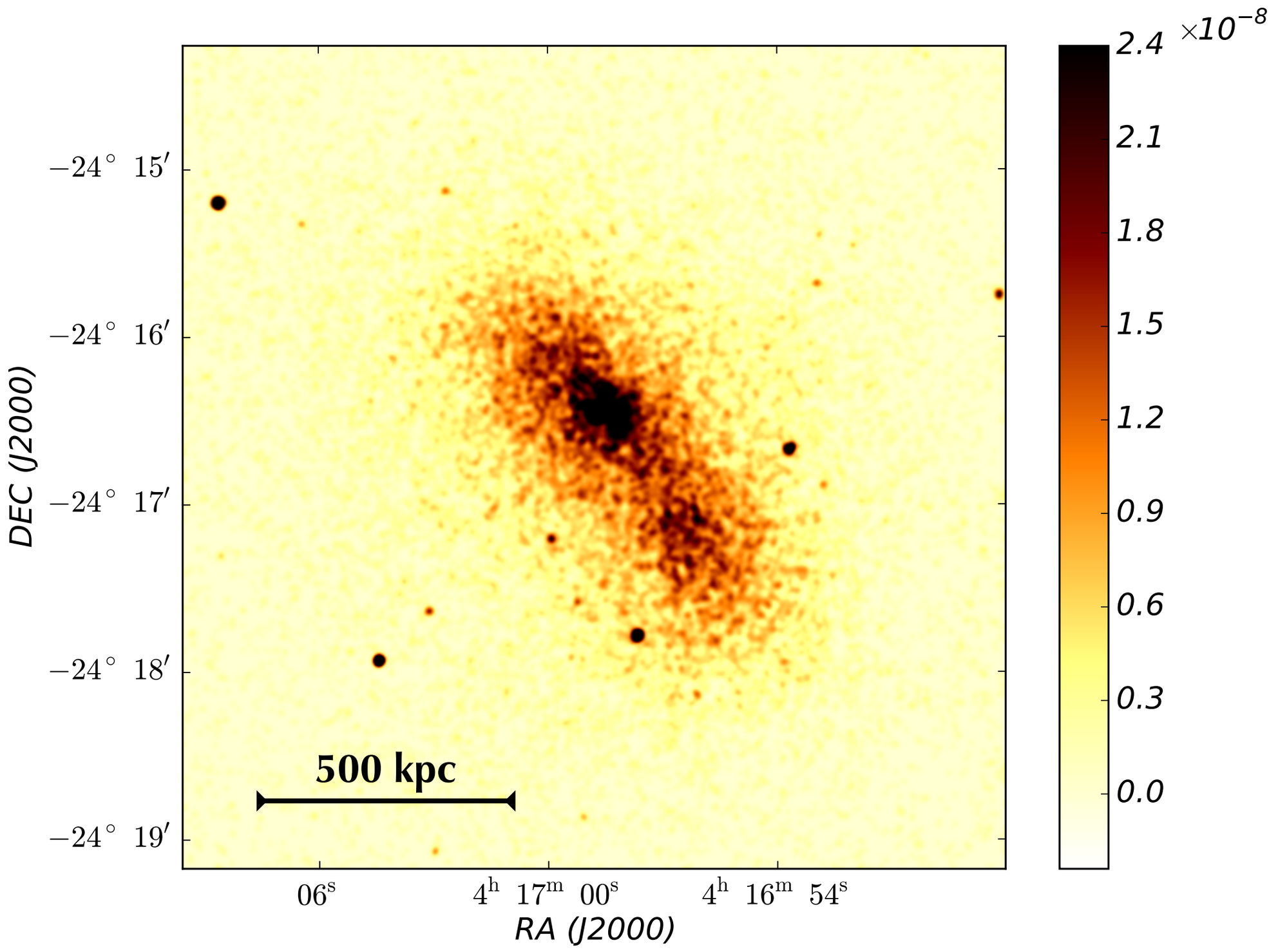
SCENARIO 2

A post-merger system:

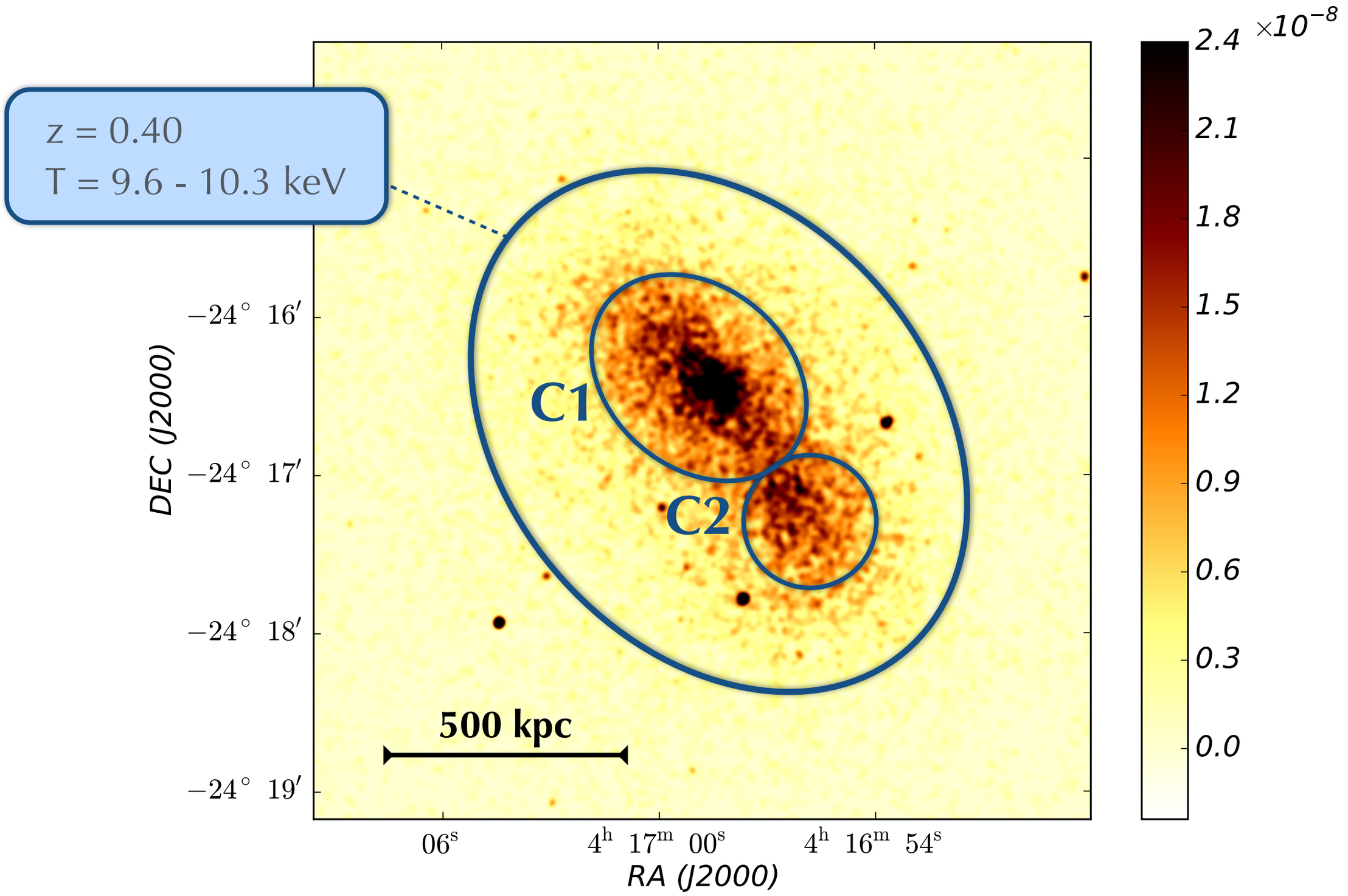
C2 approaches C1 for the second time.



Jauzac et al. (2014)

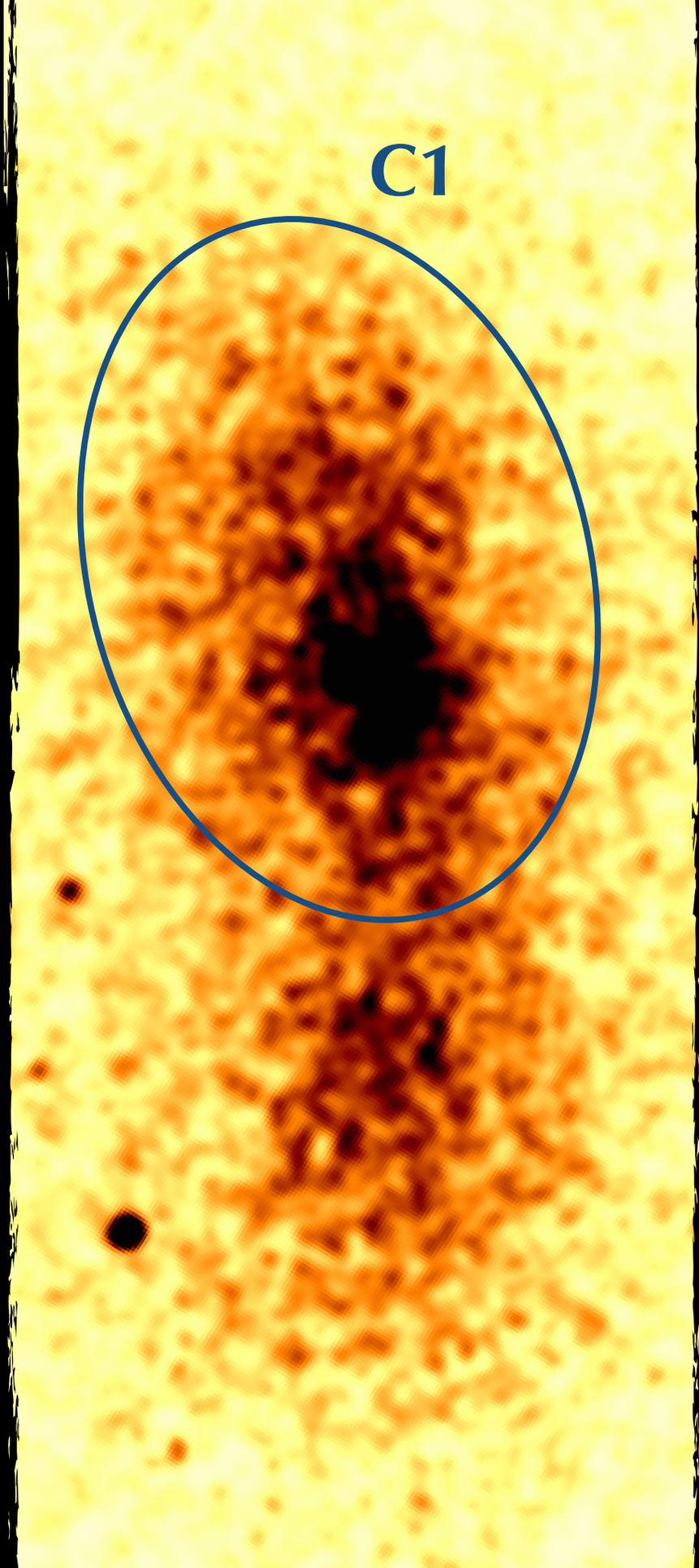


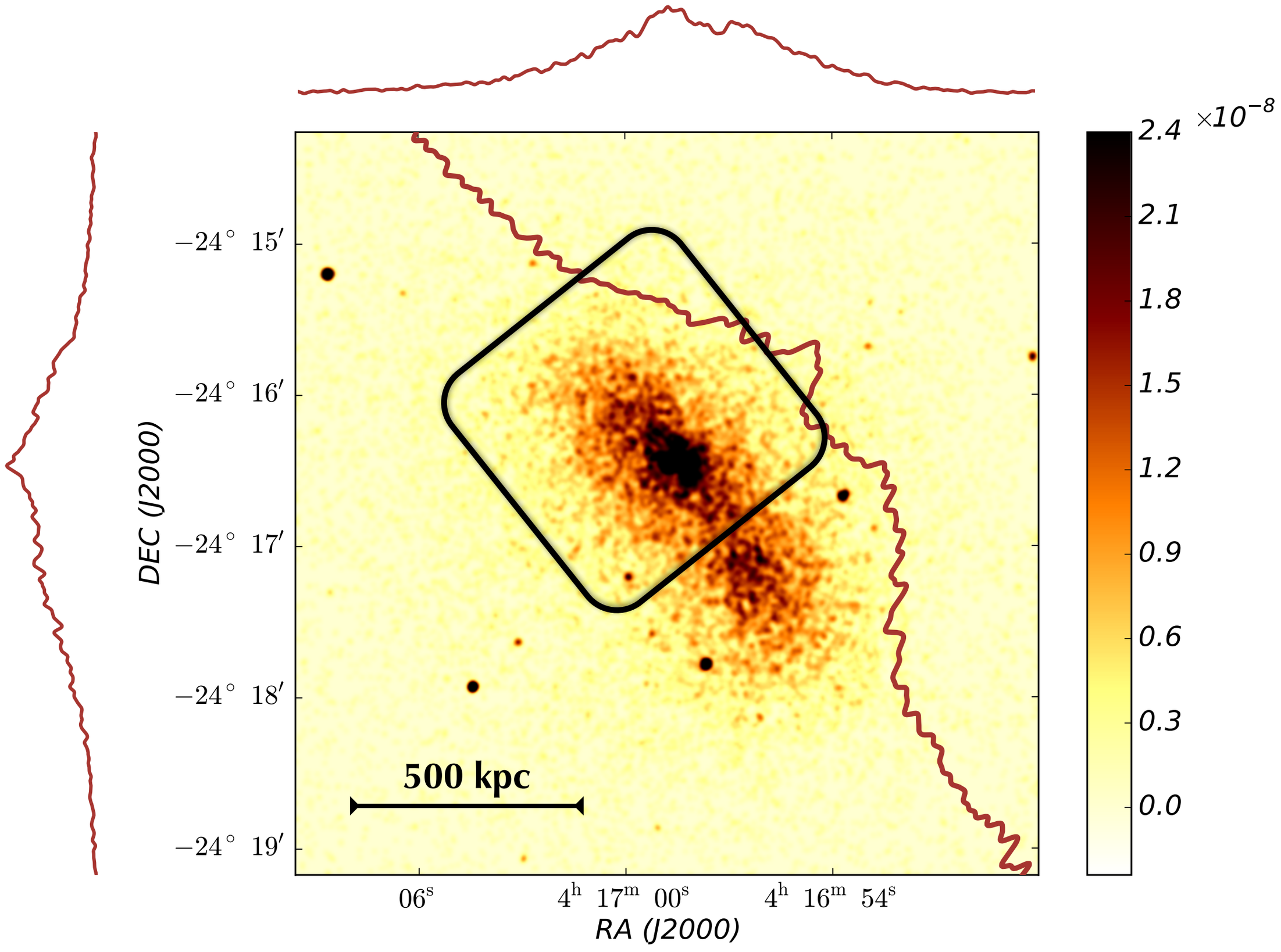
0.5 - 3 keV Chandra surface brightness map, based on 180 ks of data (PIs: Murray, Jones).



0.5 - 3 keV Chandra surface brightness map, based on 180 ks of data (PIs: Murray, Jones).

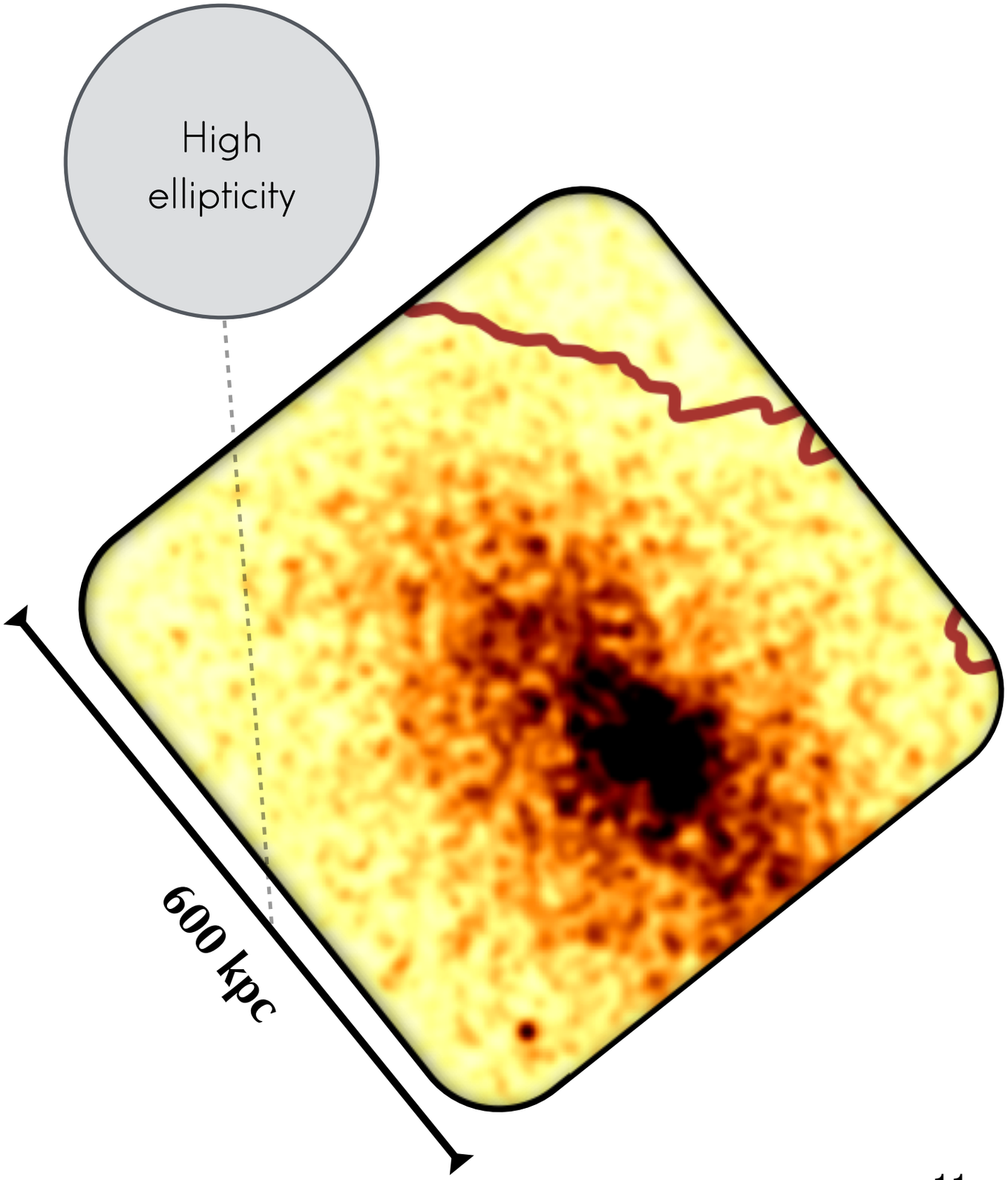
Is C1 a cool core?



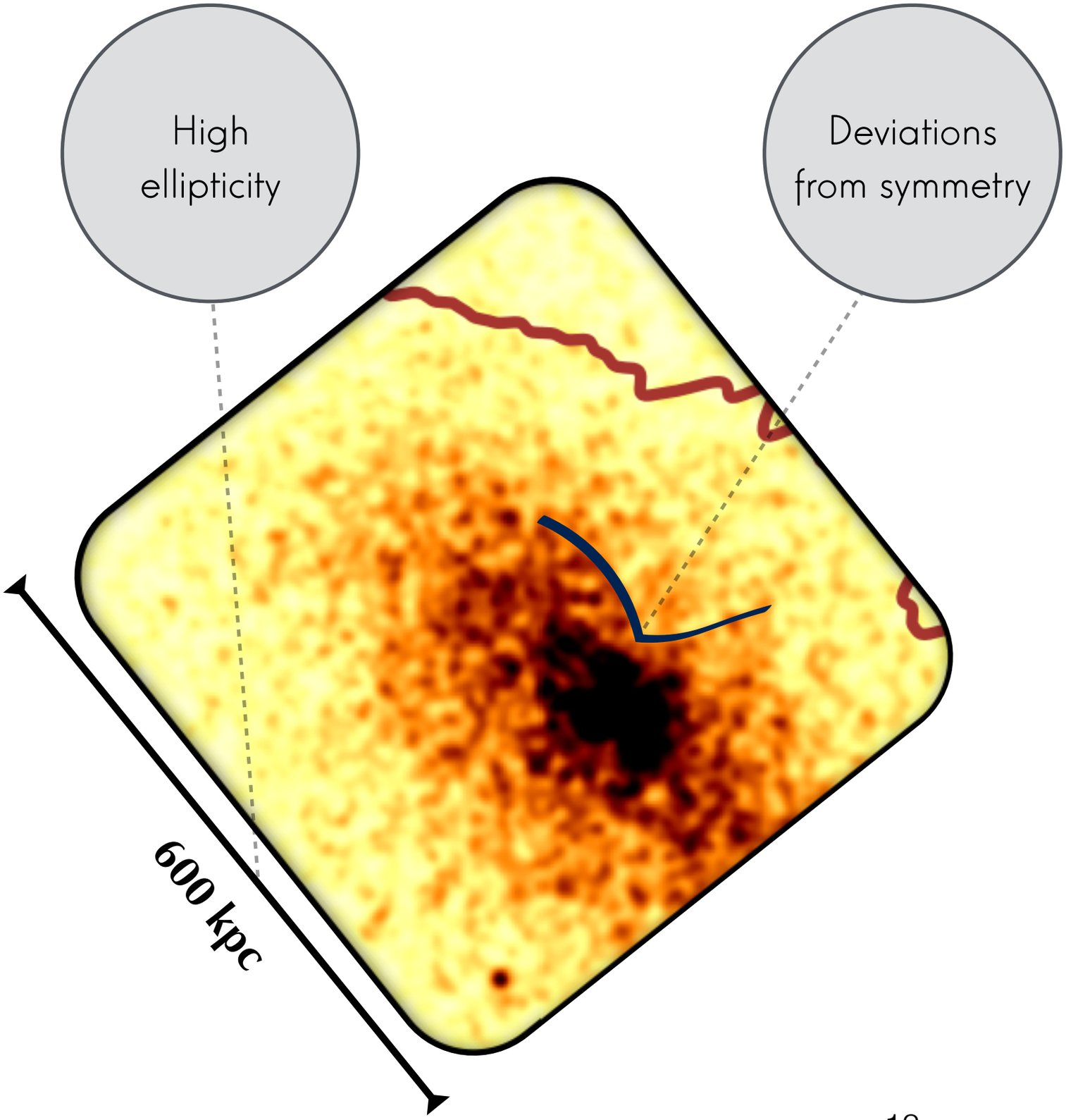


0.5 - 3 keV Chandra surface brightness map, based on 180 ks of data (PIs: Murray, Jones).

Peaked central brightness BUT...



Peaked central brightness BUT...

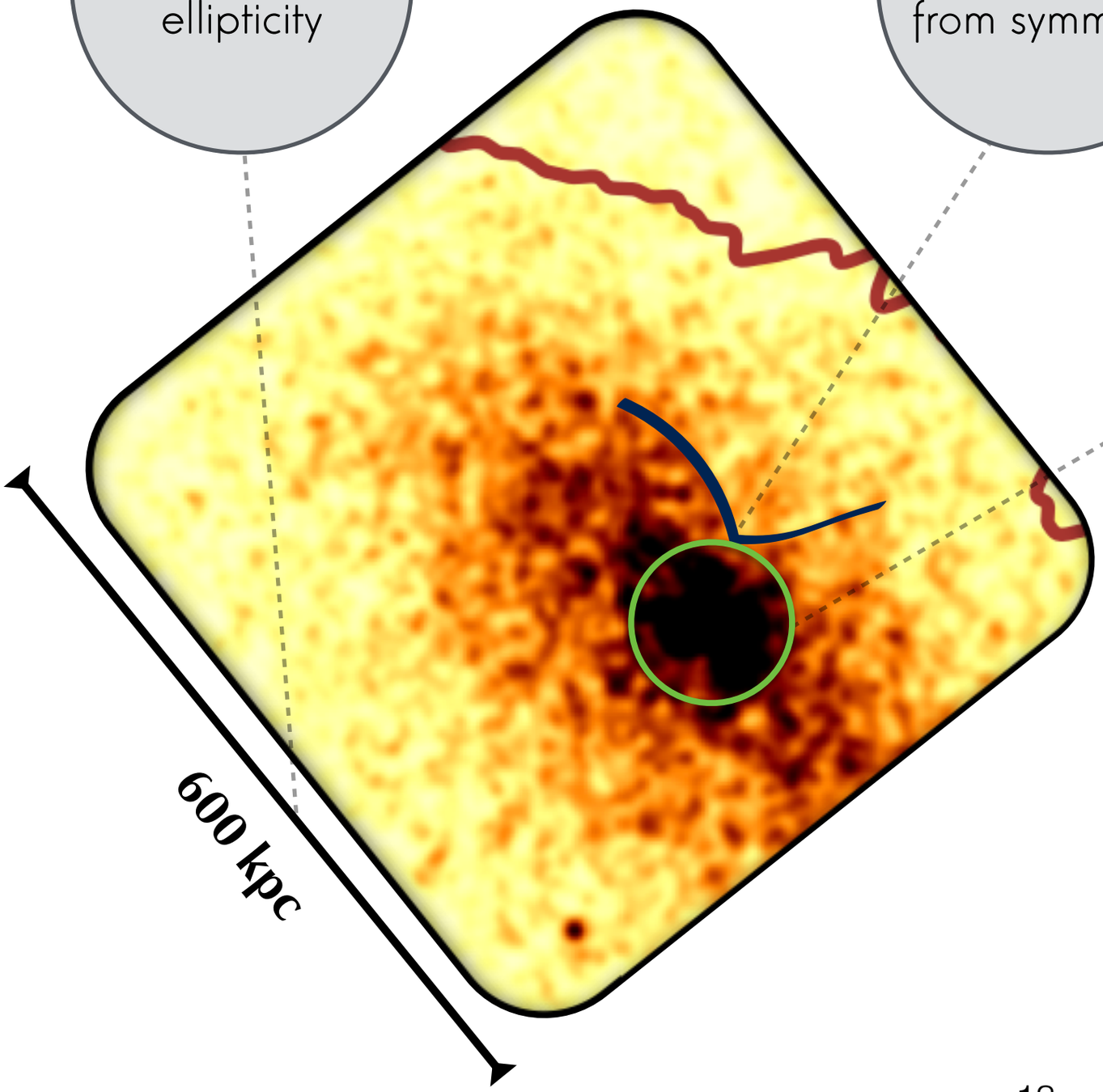


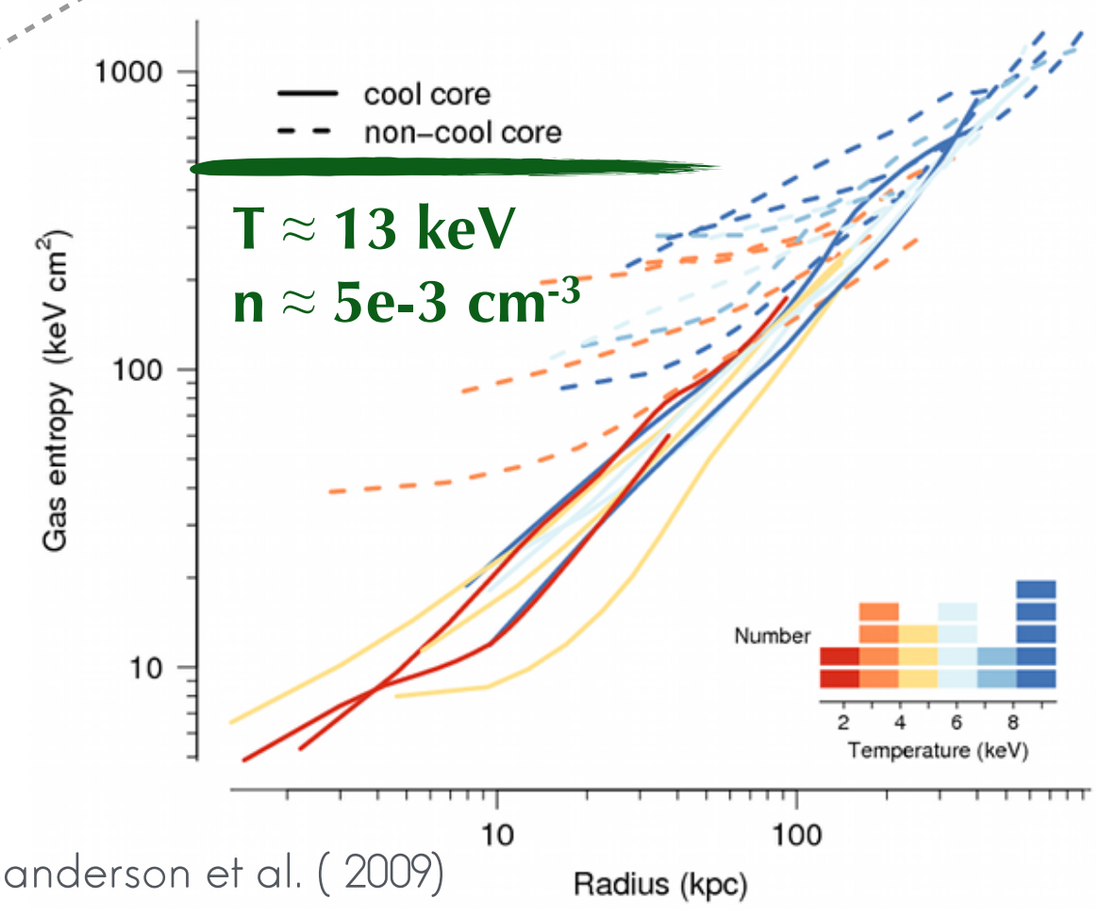
Peaked central brightness BUT...

High ellipticity

Deviations from symmetry

Hot, high-entropy core





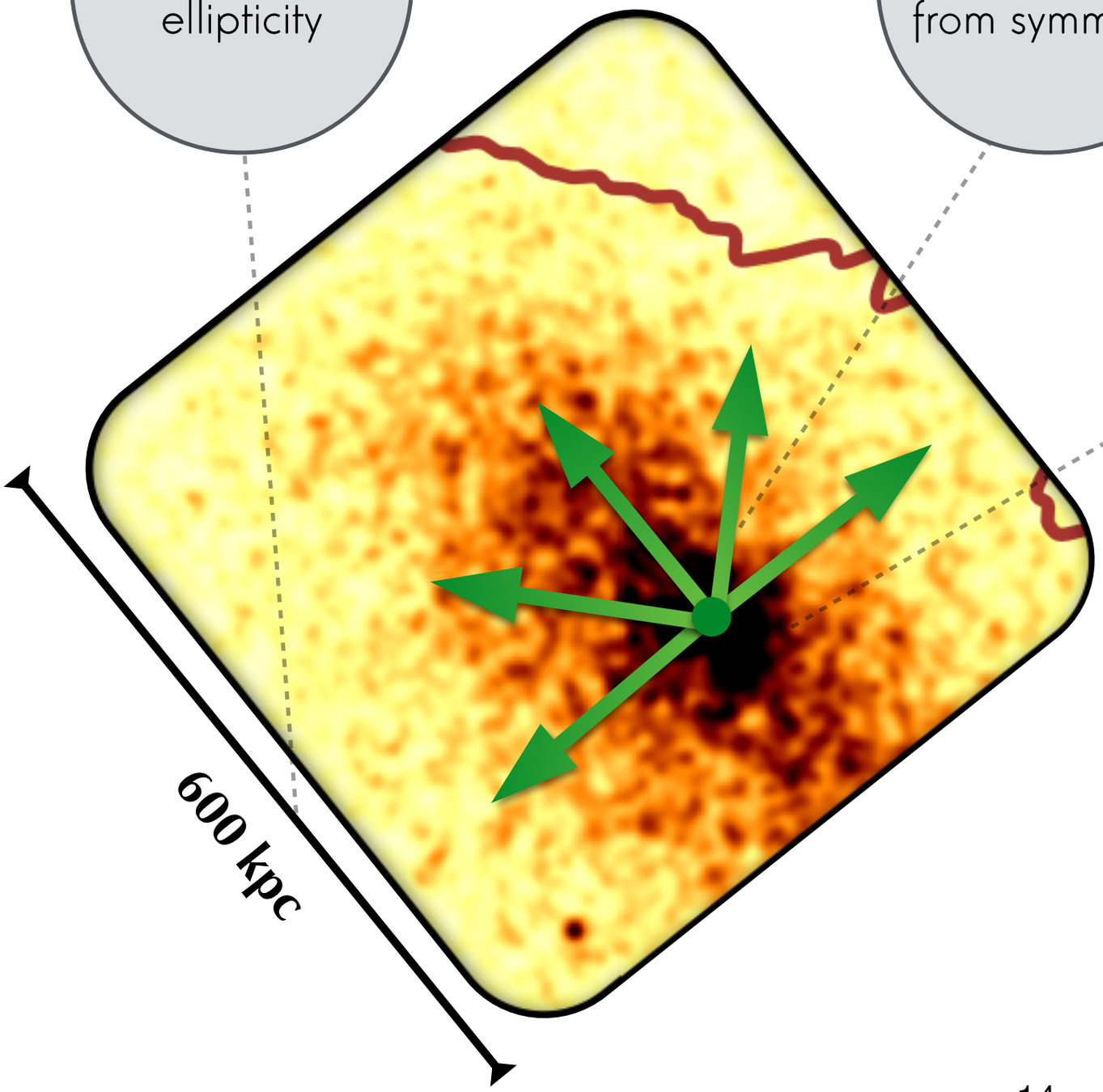
Sanderson et al. (2009)

Peaked central brightness BUT...

High ellipticity

Deviations from symmetry

Hot, high-entropy core



Peaked central brightness BUT...

High ellipticity

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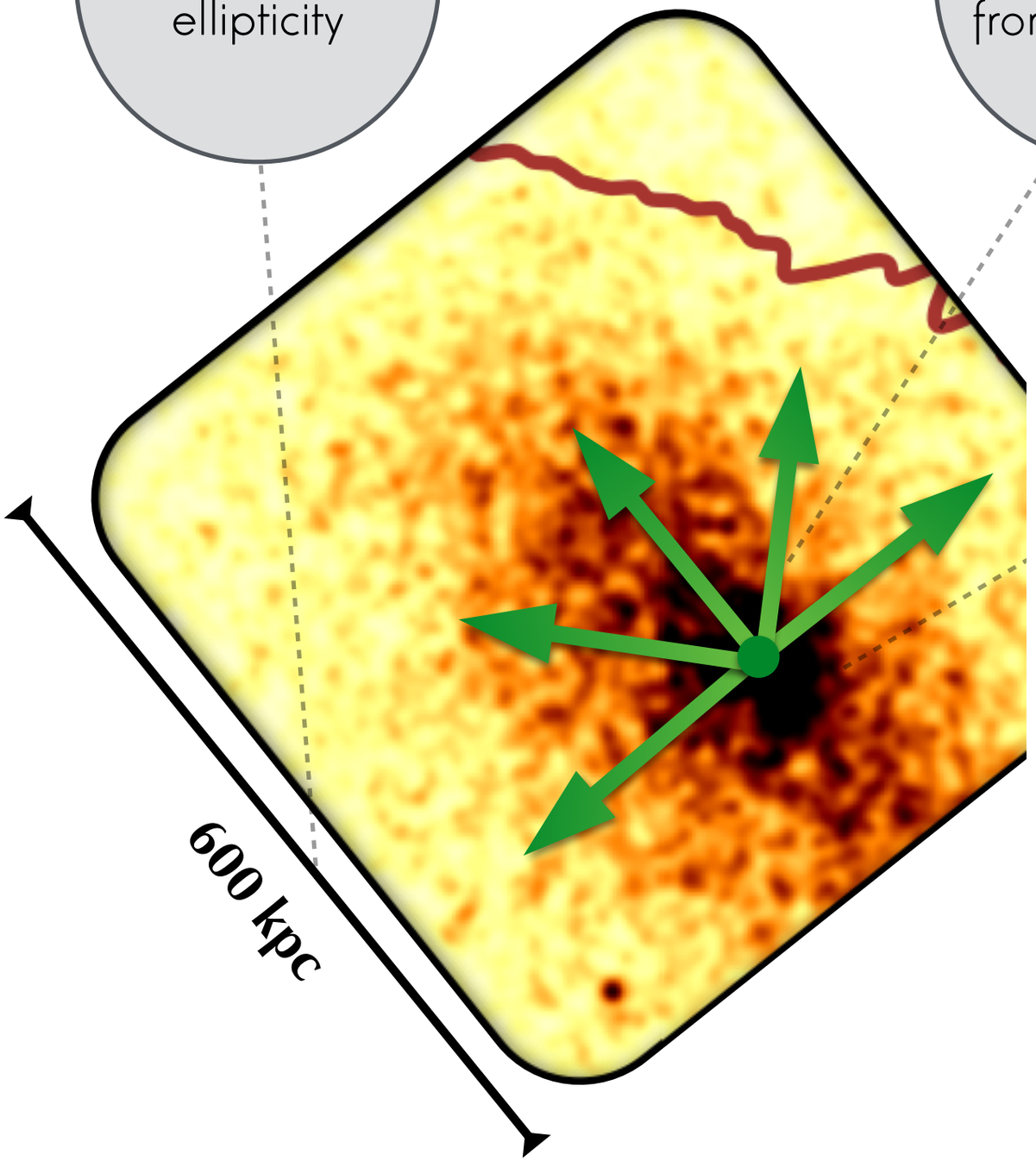
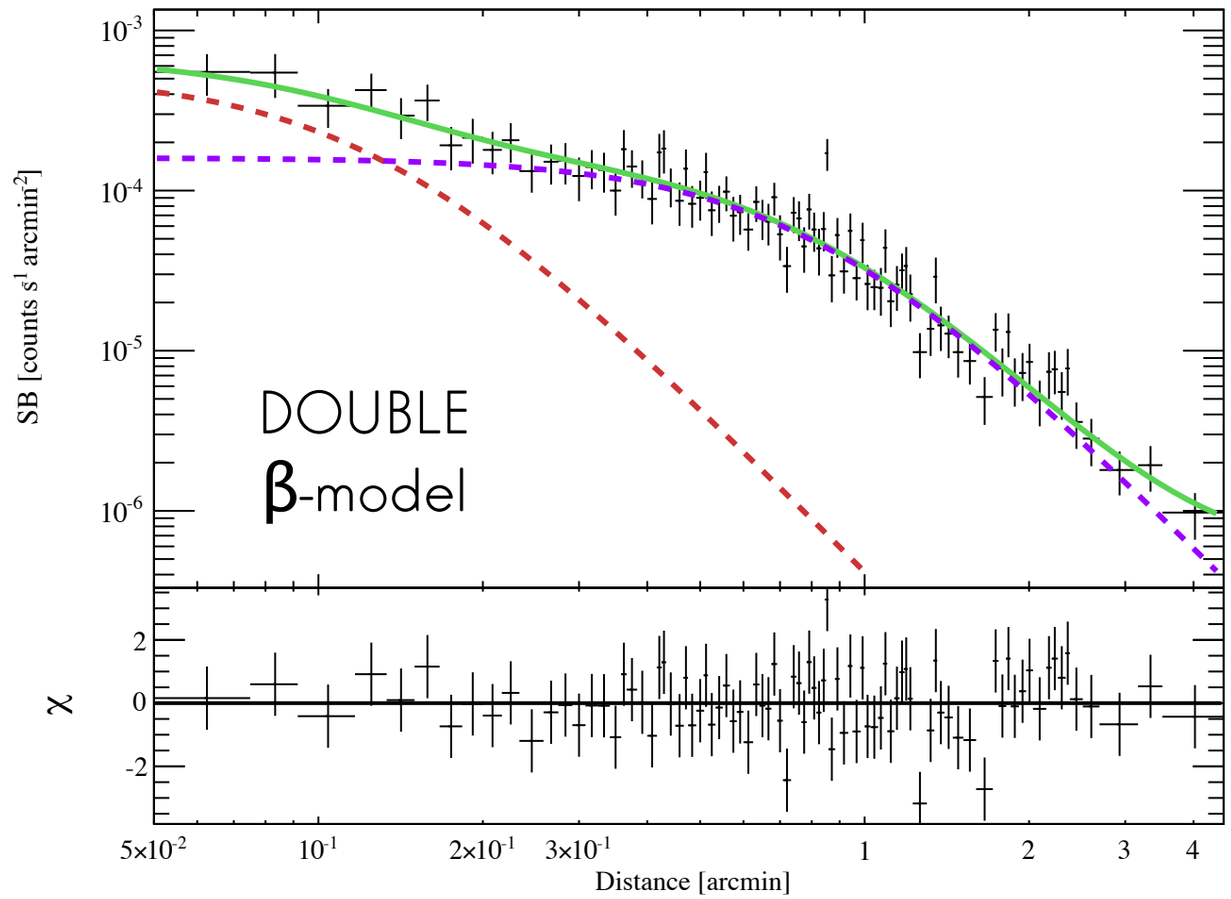
Hot, high-entropy core



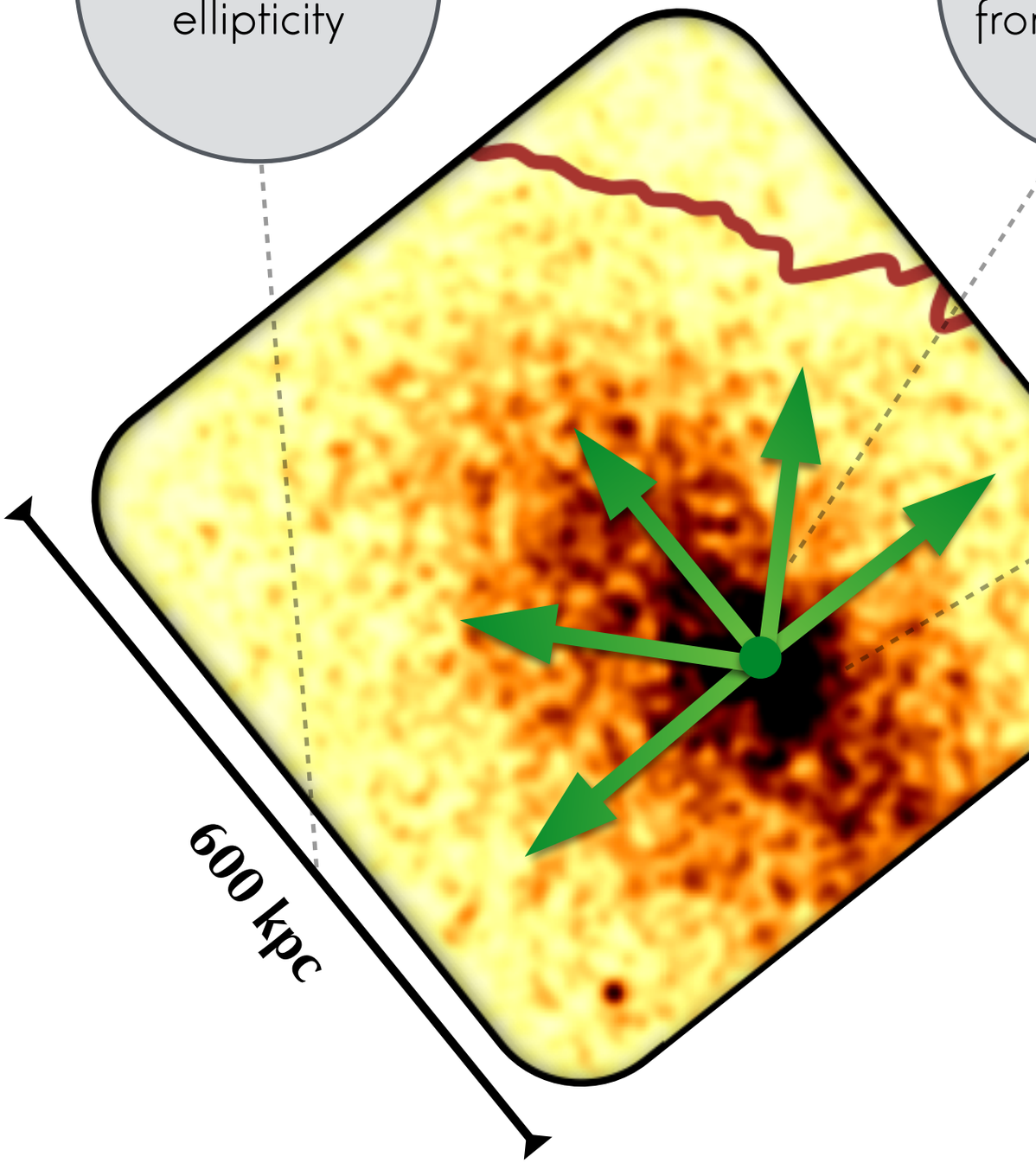


Peaked central brightness BUT...

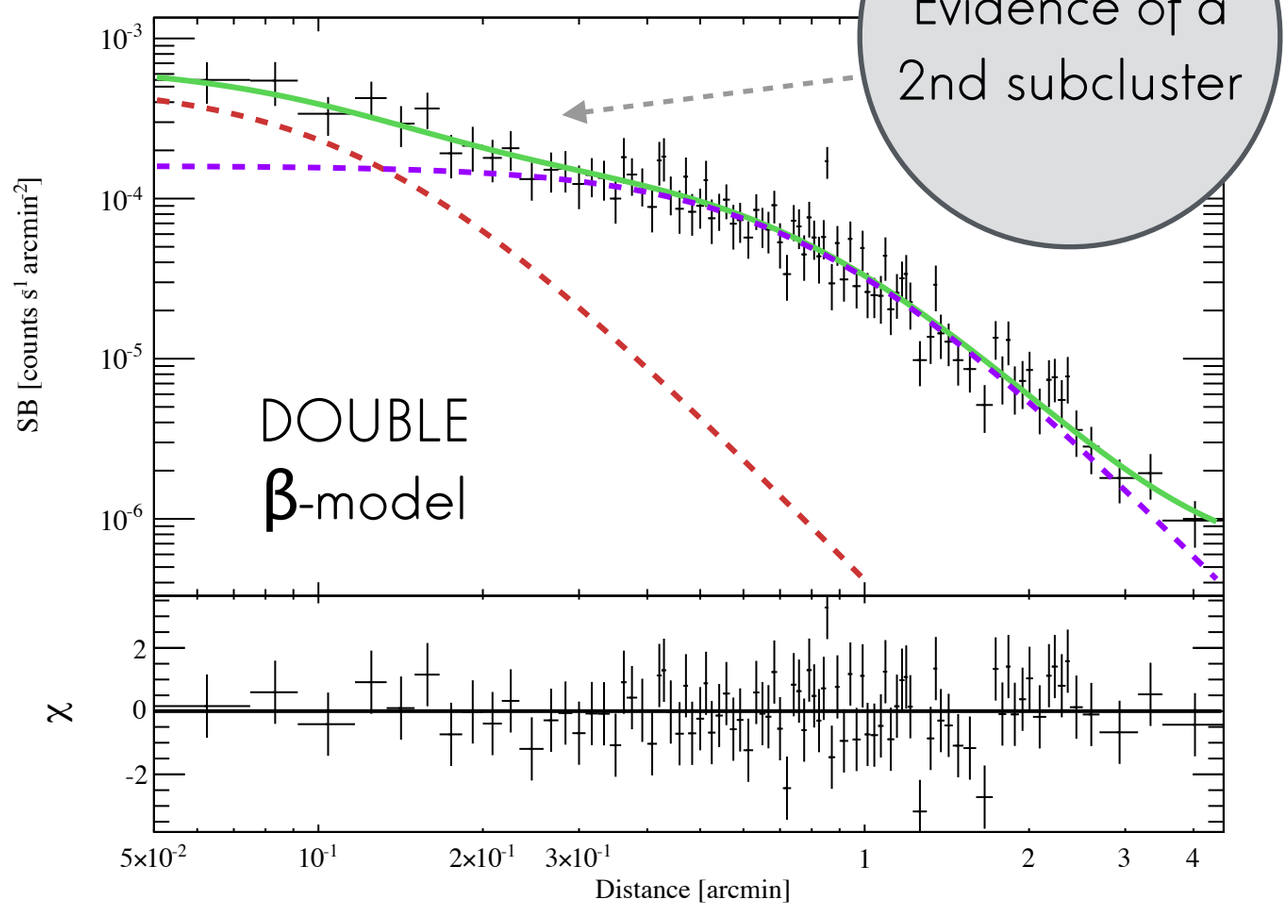
High ellipticity

Deviations from symmetry

Hot, high-entropy core



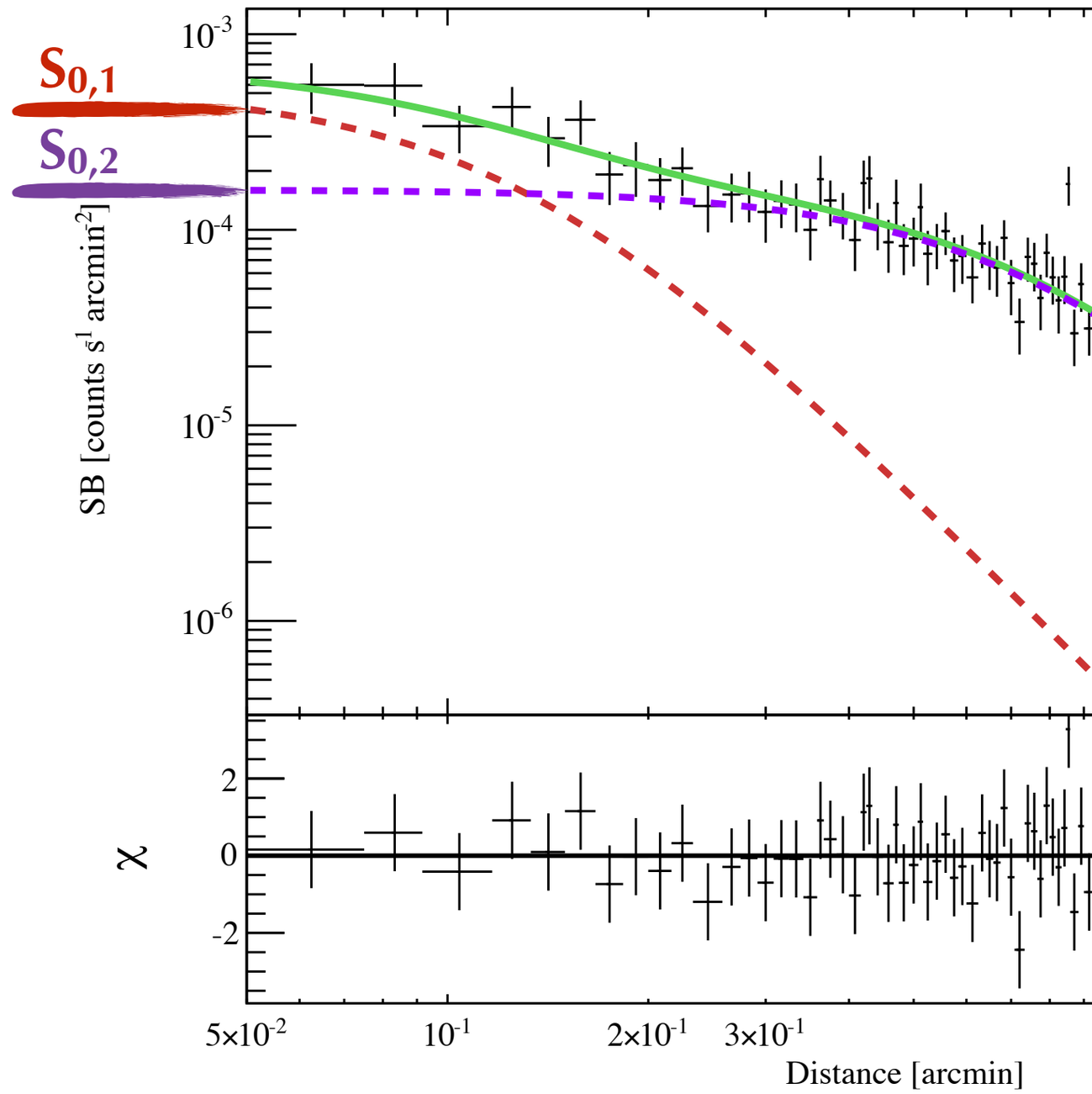
Evidence of a 2nd subcluster

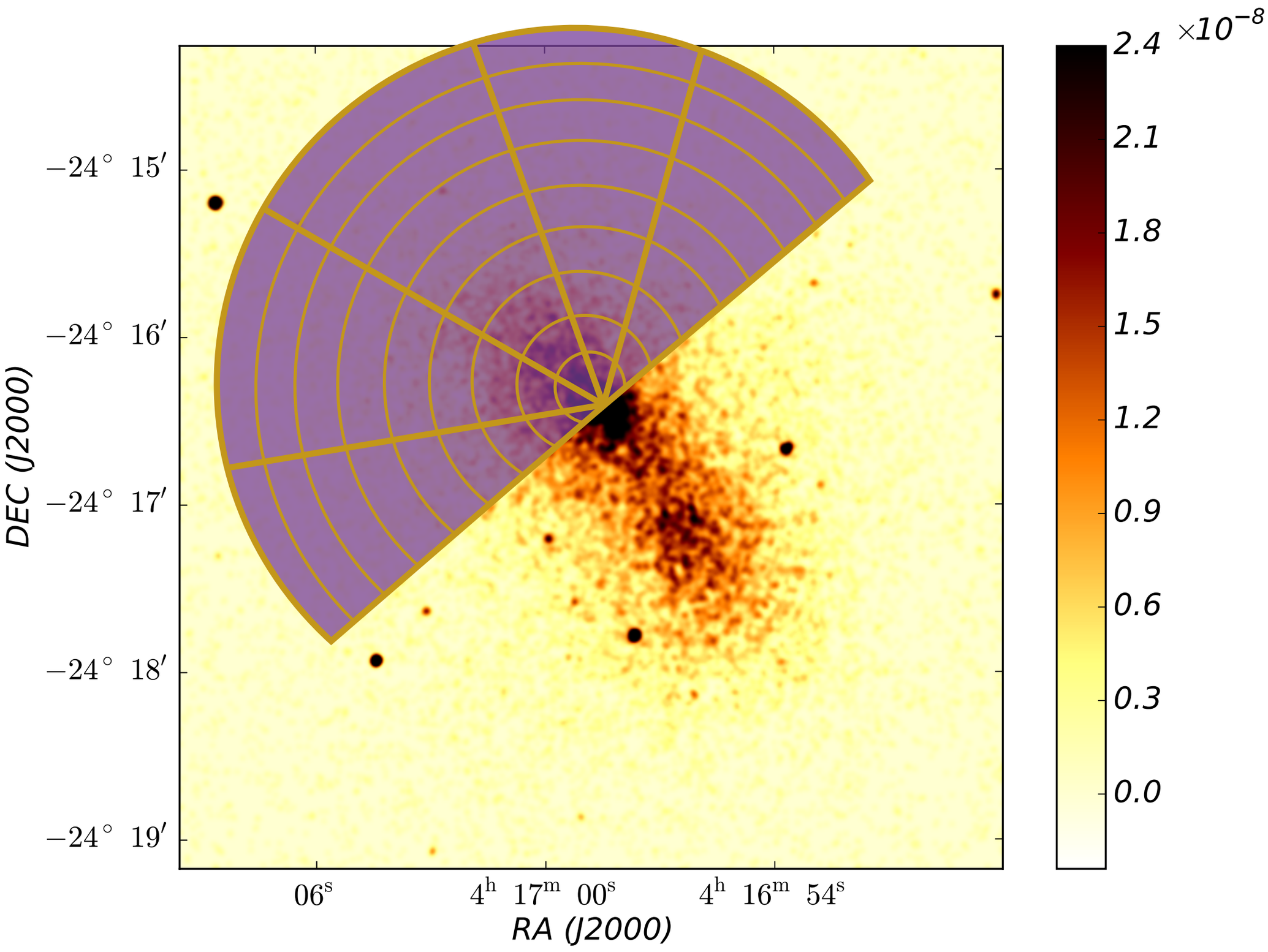


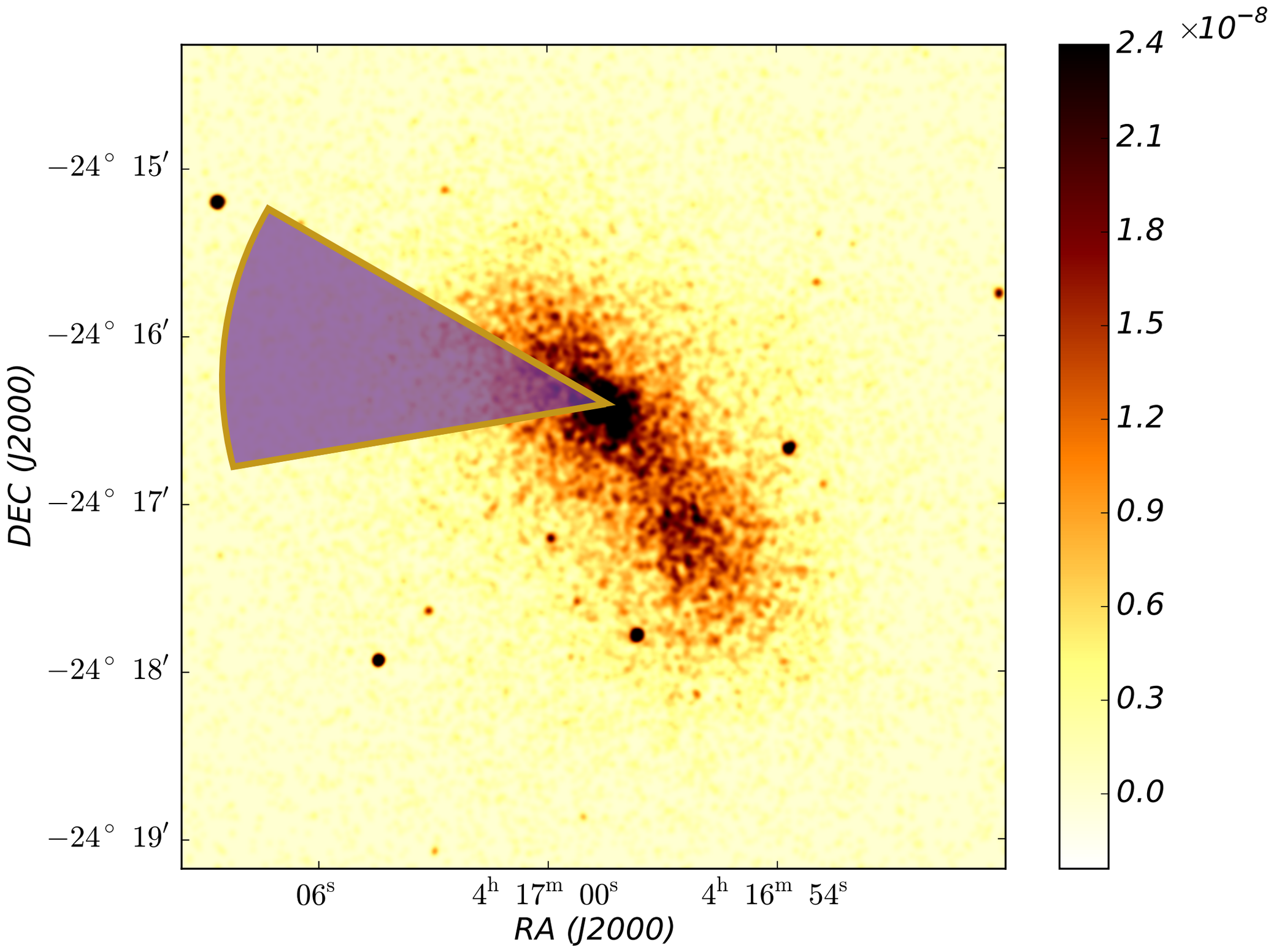
The ratio:

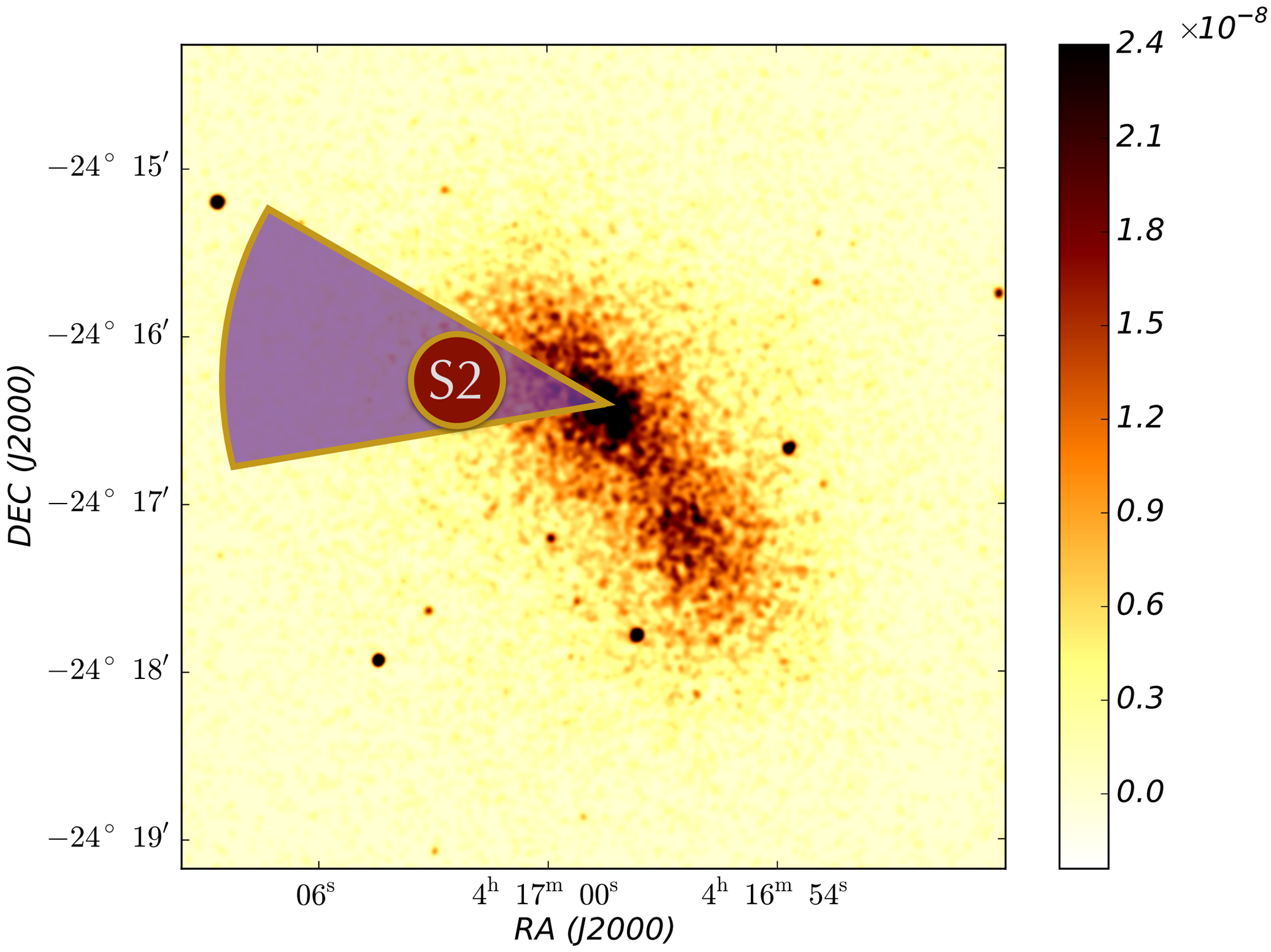
$R_S = S_{0,1}/S_{0,2}$

is closest to 1 in the direction of the " hidden" subcluster.

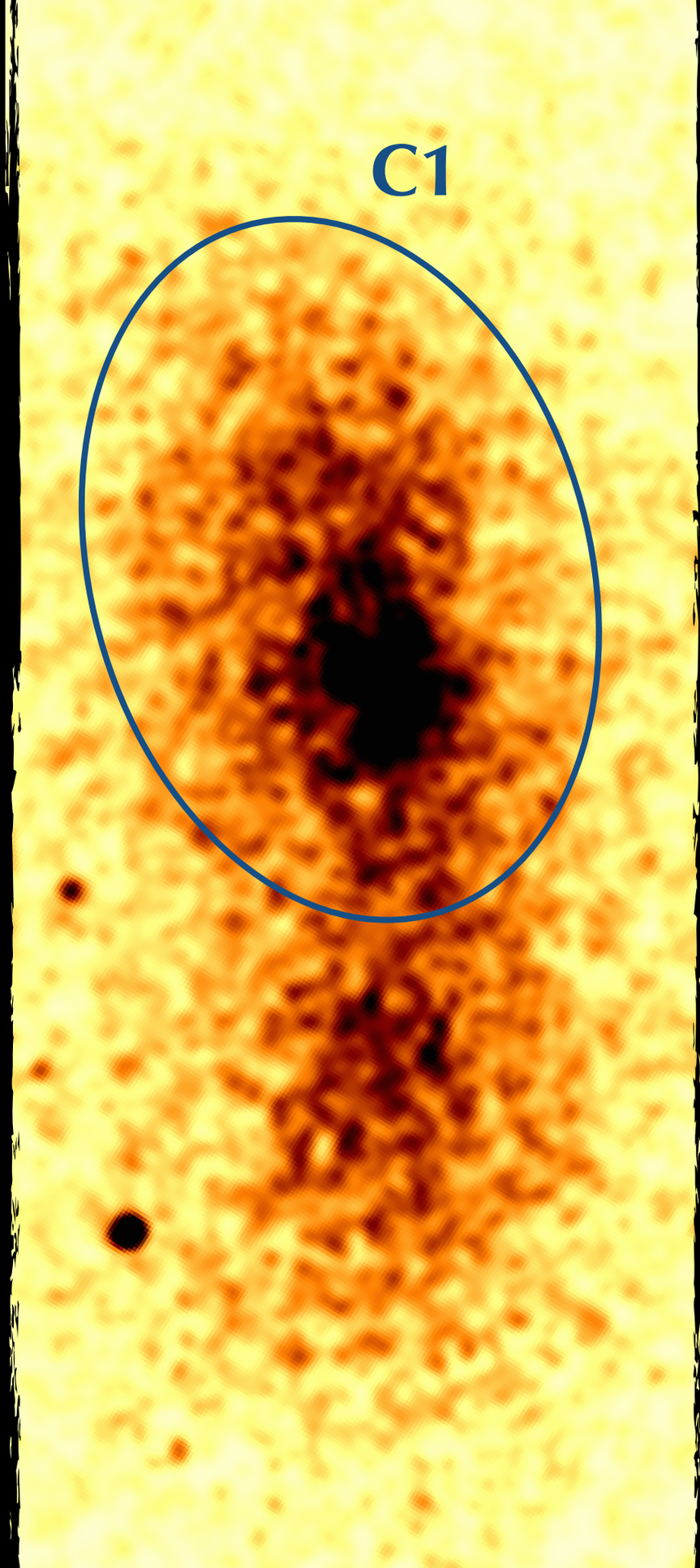



−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
DEC (J2000)
06s
4h 17m 00s
4h 16m 54s
RA (J2000)
×10−8
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0

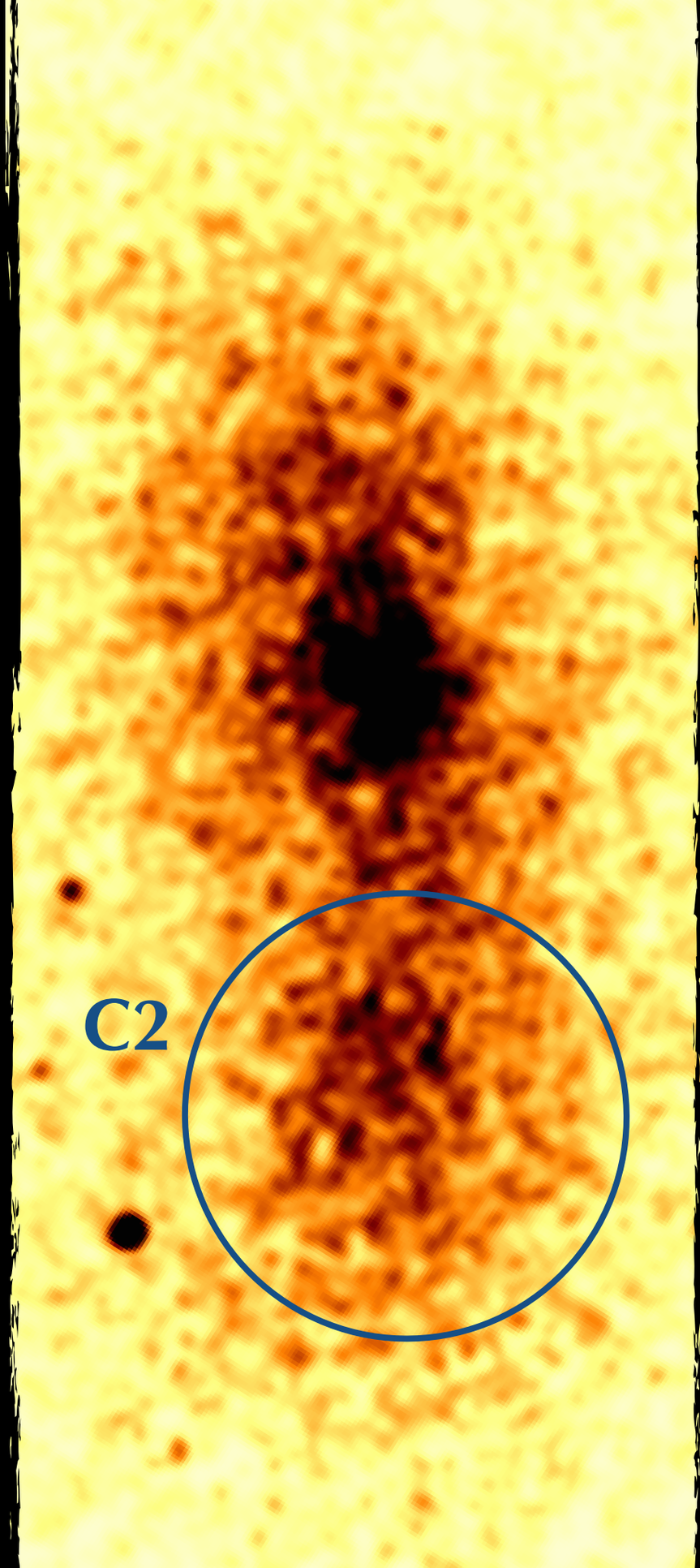

$-24^\circ\ 15'$
$-24^\circ\ 16'$
$-24^\circ\ 17'$
$-24^\circ\ 18'$
$-24^\circ\ 19'$
DEC (J2000)
06^s
$4^h\ 17^m\ 00^s$
$4^h\ 16^m\ 54^s$
RA (J2000)
$\times 10^{-8}$
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0

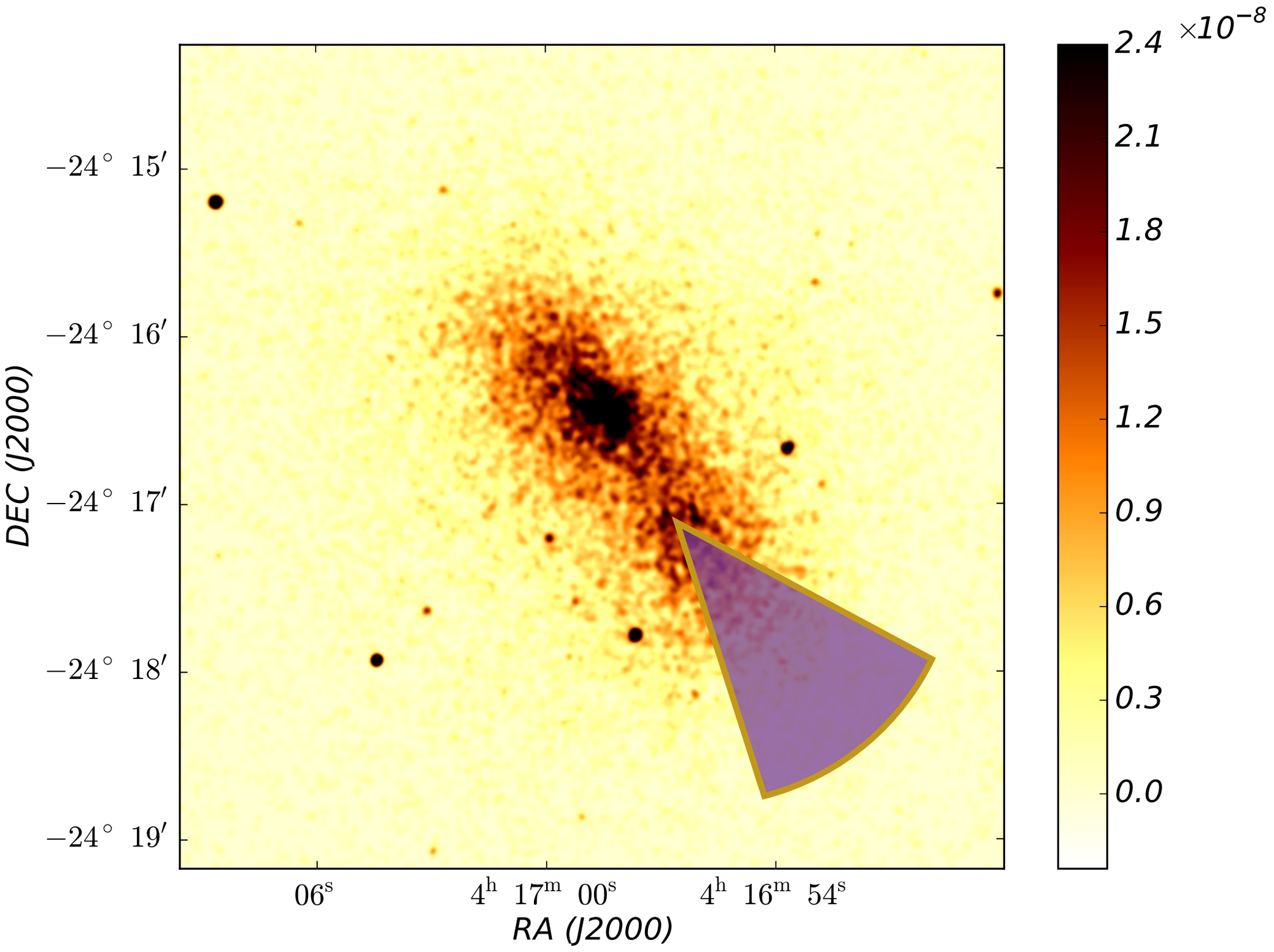

S2
−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
DEC (J2000)
06s
4h 17m 00s
4h 16m 54s
RA (J2000)
×10−8
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0

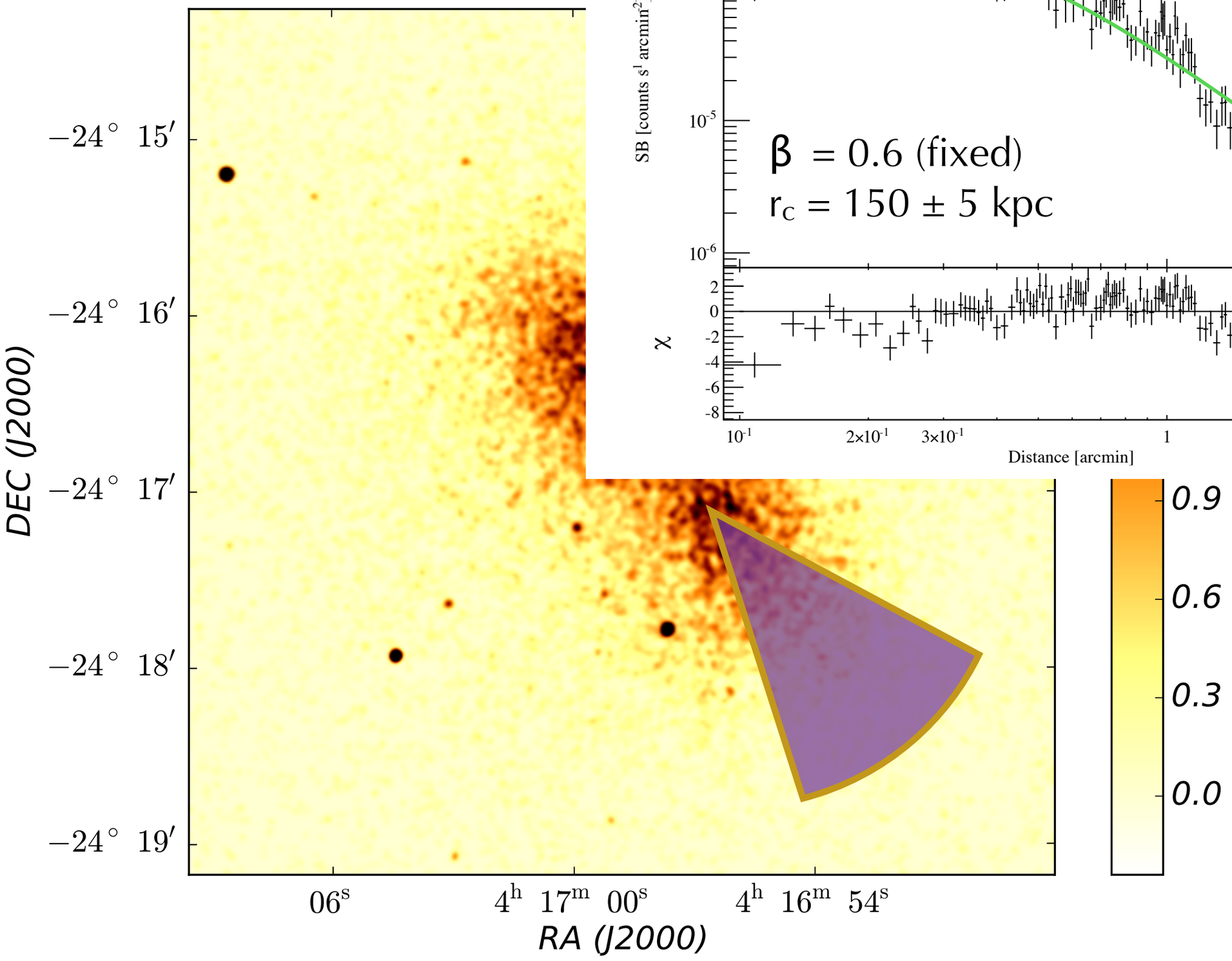
C1 is undergoing a merger with a less massive cluster not immediately visible in the X-ray map.

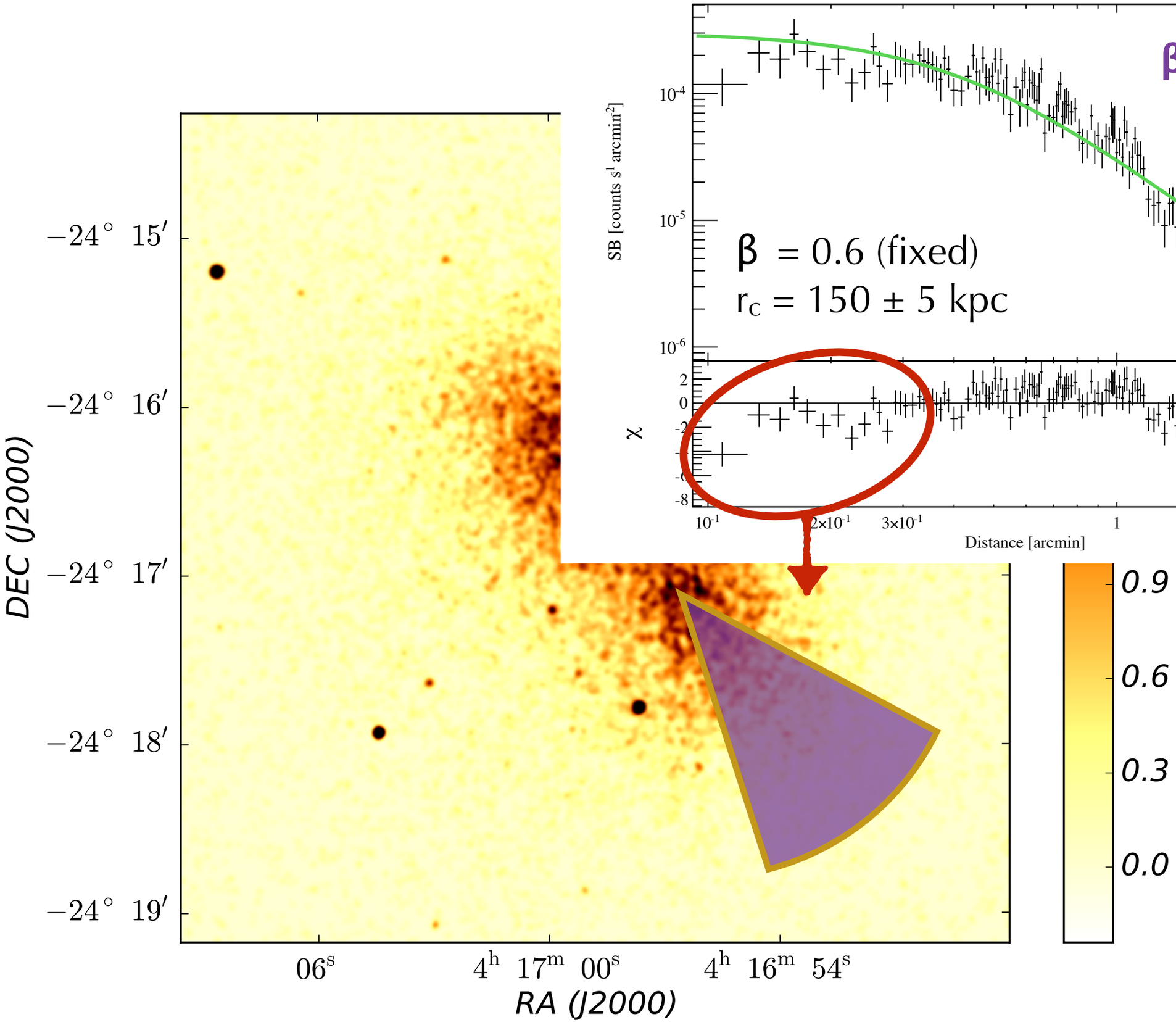


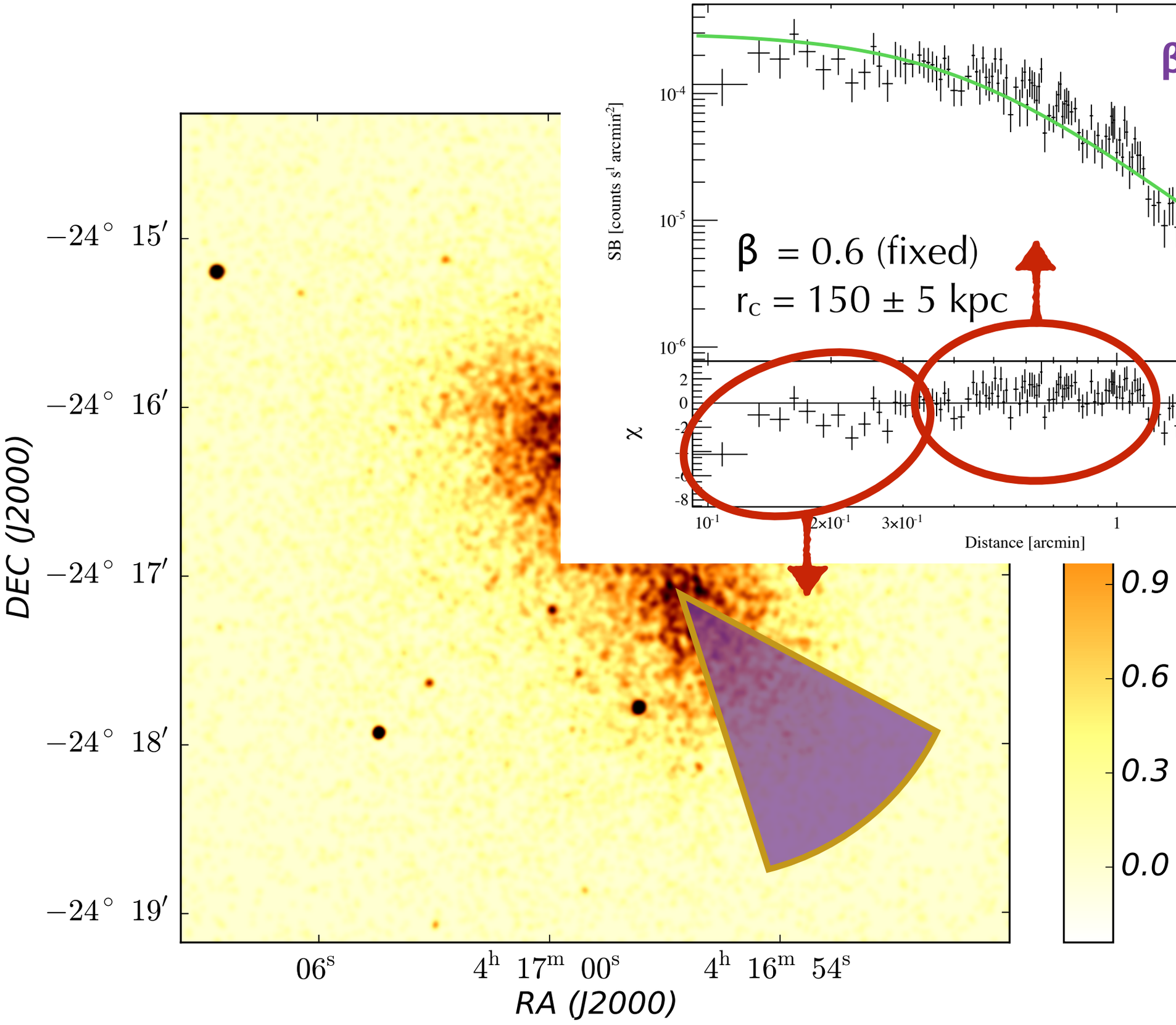
Is C2 a relaxed cluster?

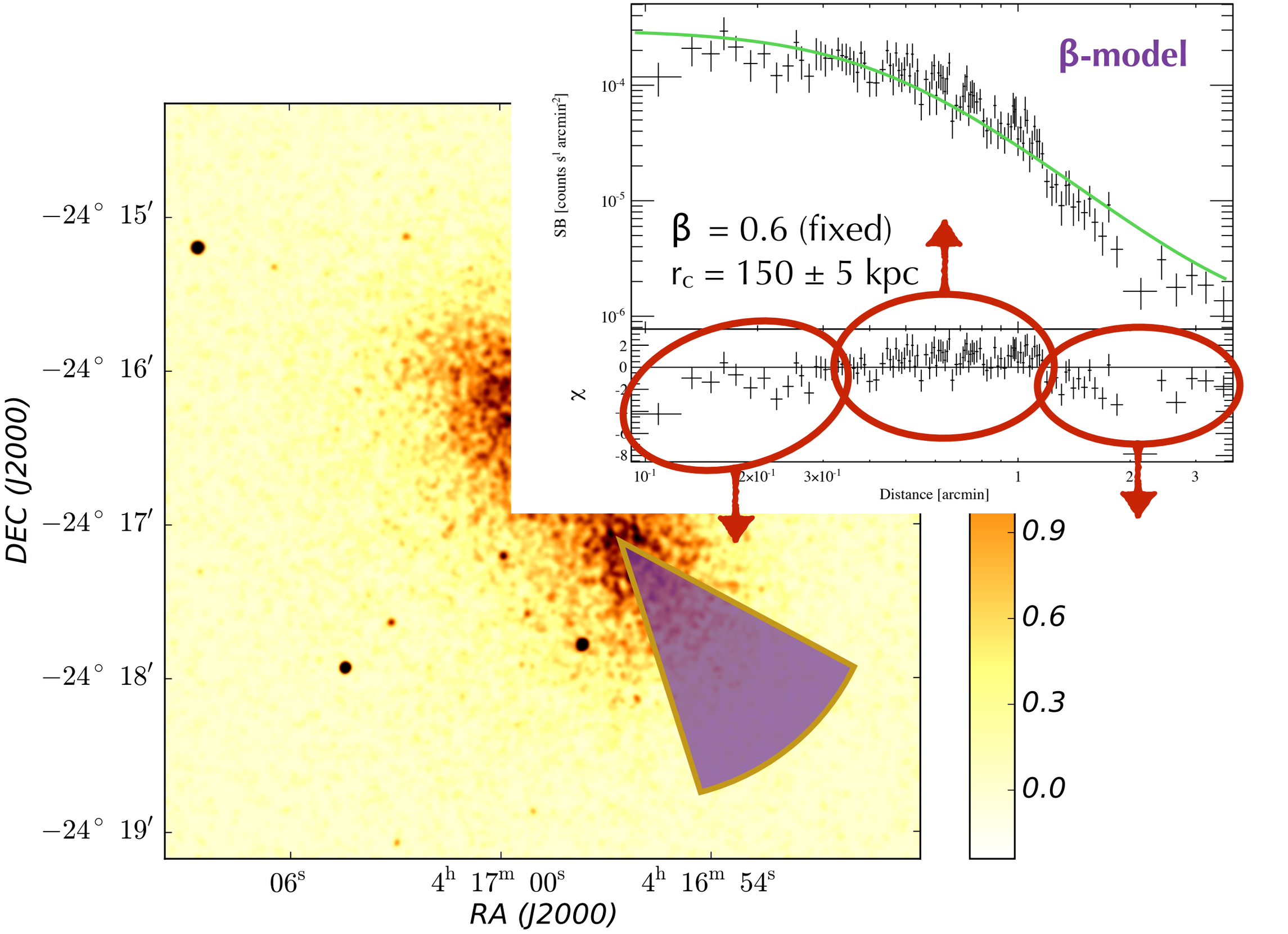


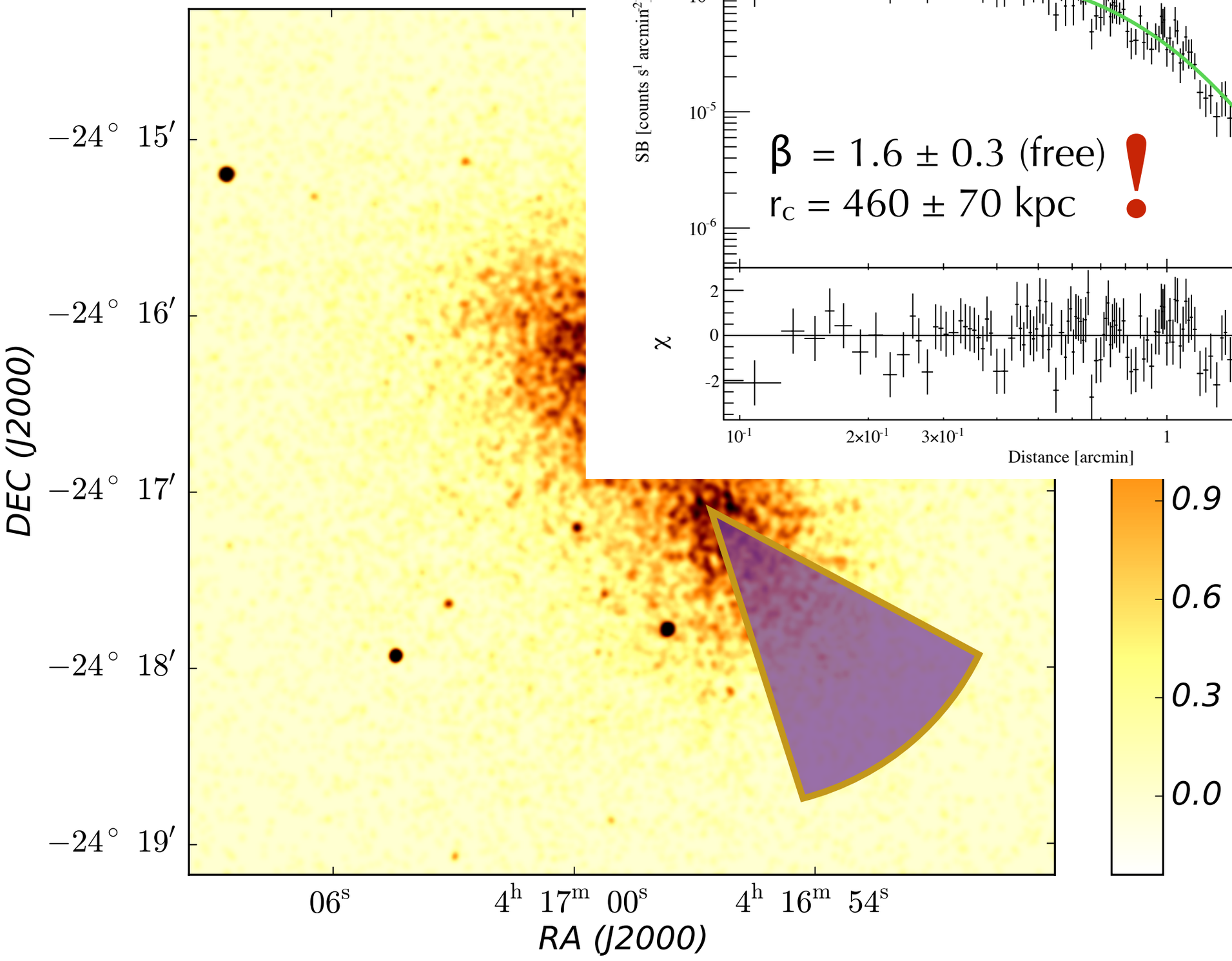

−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
DEC (J2000)
06s
4h 17m 00s
4h 16m 54s
RA (J2000)
×10−8
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0

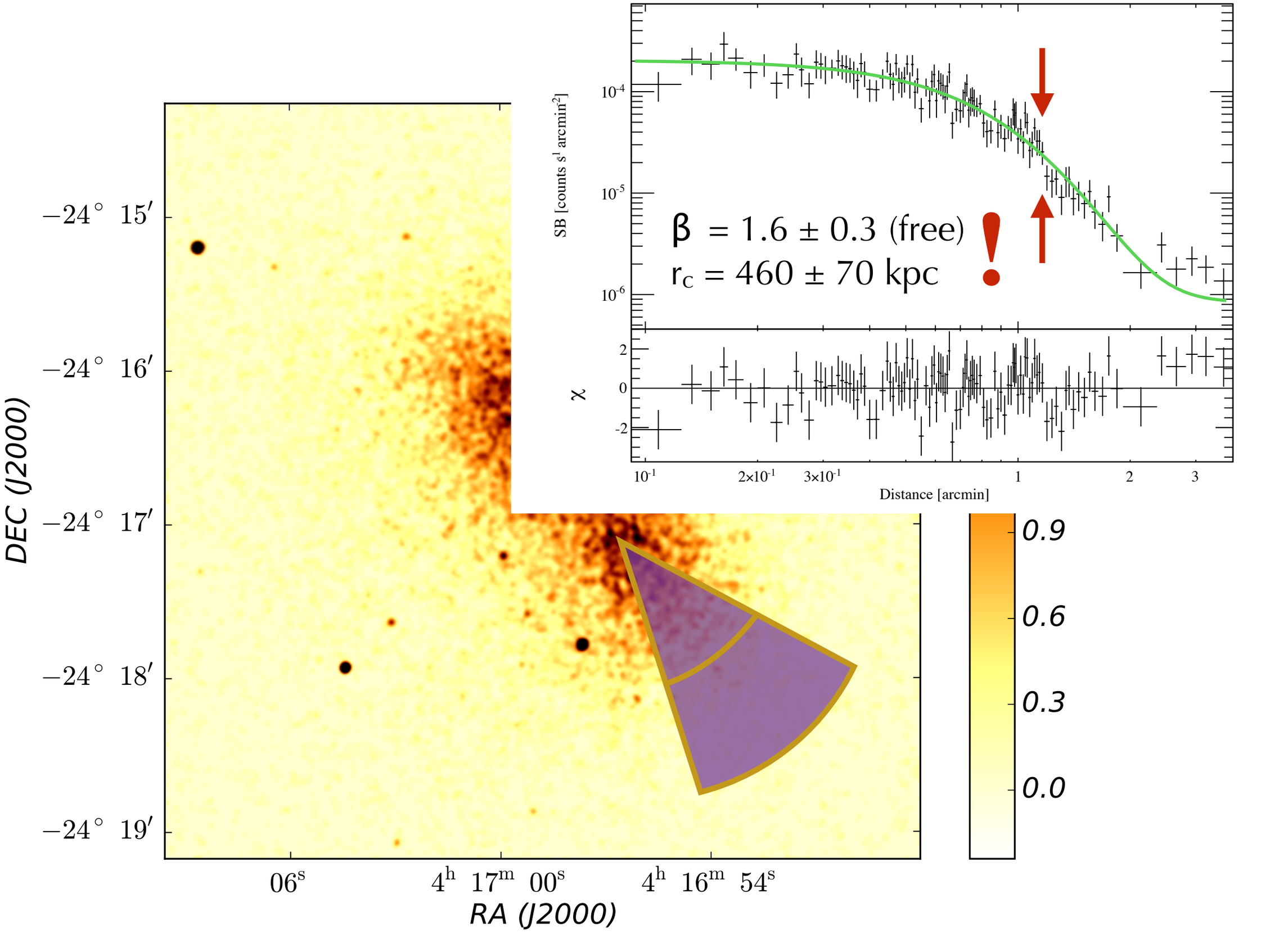

β-model
β = 0.6 (fixed)
r_c = 150 ± 5 kpc
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
10^{-6}
χ
2
0
-2
-4
-6
-8
10^{-1}
2×10^{-1}
3×10^{-1}
1
2
3
Distance [arcmin]
0.9
0.6
0.3
0.0
DEC (J2000)
$-24^\circ\ 15'$
$-24^\circ\ 16'$
$-24^\circ\ 17'$
$-24^\circ\ 18'$
$-24^\circ\ 19'$
06^s
$4^h\ 17^m\ 00^s$
$4^h\ 16^m\ 54^s$
RA (J2000)

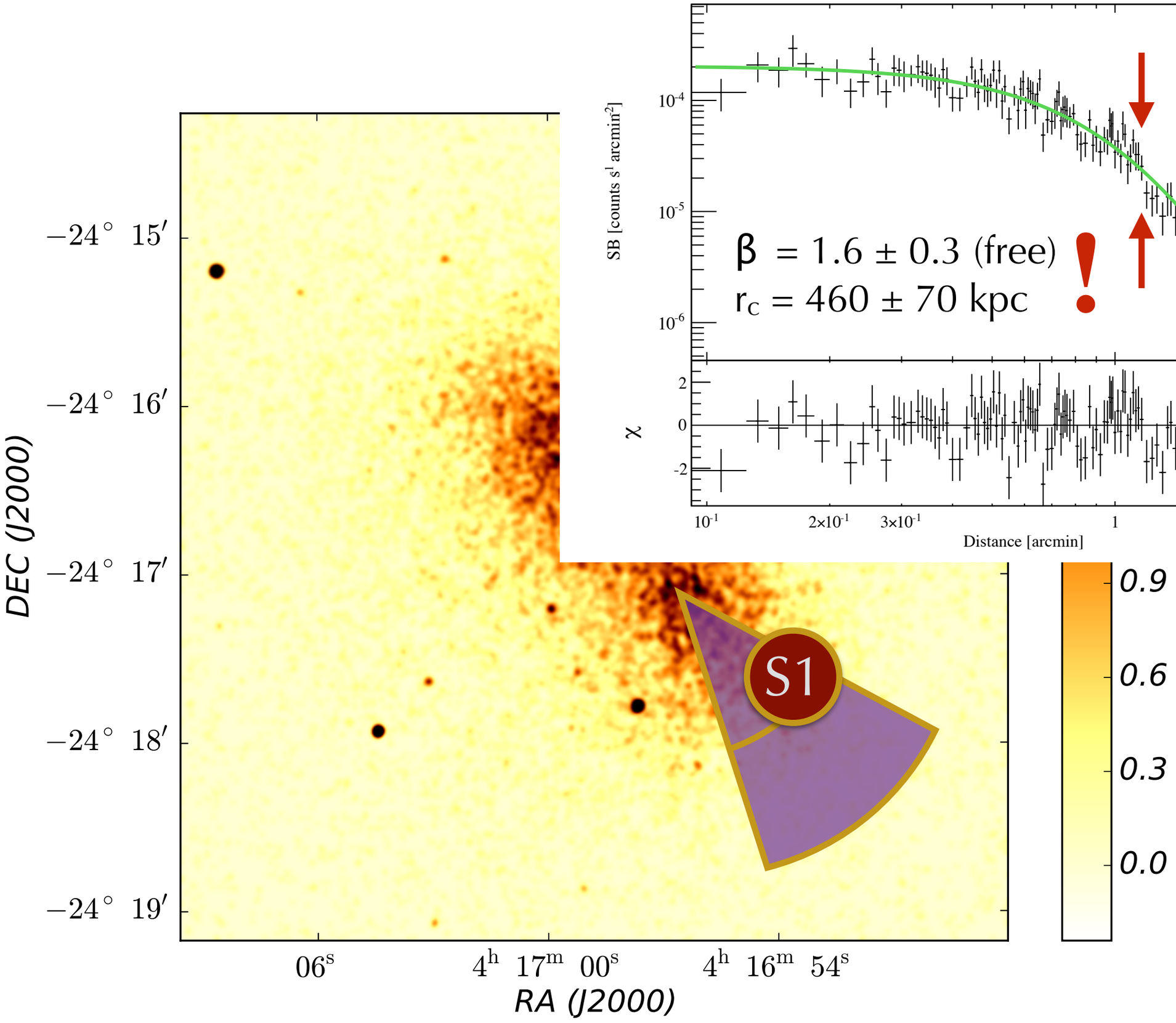

β-model
β = 0.6 (fixed)
r_c = 150 ± 5 kpc
SB [counts s^-1 arcmin^-2]
χ
Distance [arcmin]
DEC (J2000)
RA (J2000)
−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
06^s
4^h 17^m 00^s
4^h 16^m 54^s
0.9
0.6
0.3
0.0


β-model
β = 0.6 (fixed)
r_c = 150 ± 5 kpc
SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
10^{-6}
χ
2
0
-2
-8
10^{-1}
2×10^{-1}
3×10^{-1}
1
2
3
Distance [arcmin]
0.9
0.6
0.3
0.0
DEC (J2000)
$-24^\circ\ 15'$
$-24^\circ\ 16'$
$-24^\circ\ 17'$
$-24^\circ\ 18'$
$-24^\circ\ 19'$
06^s
$4^h\ 17^m\ 00^s$
$4^h\ 16^m\ 54^s$
RA (J2000)

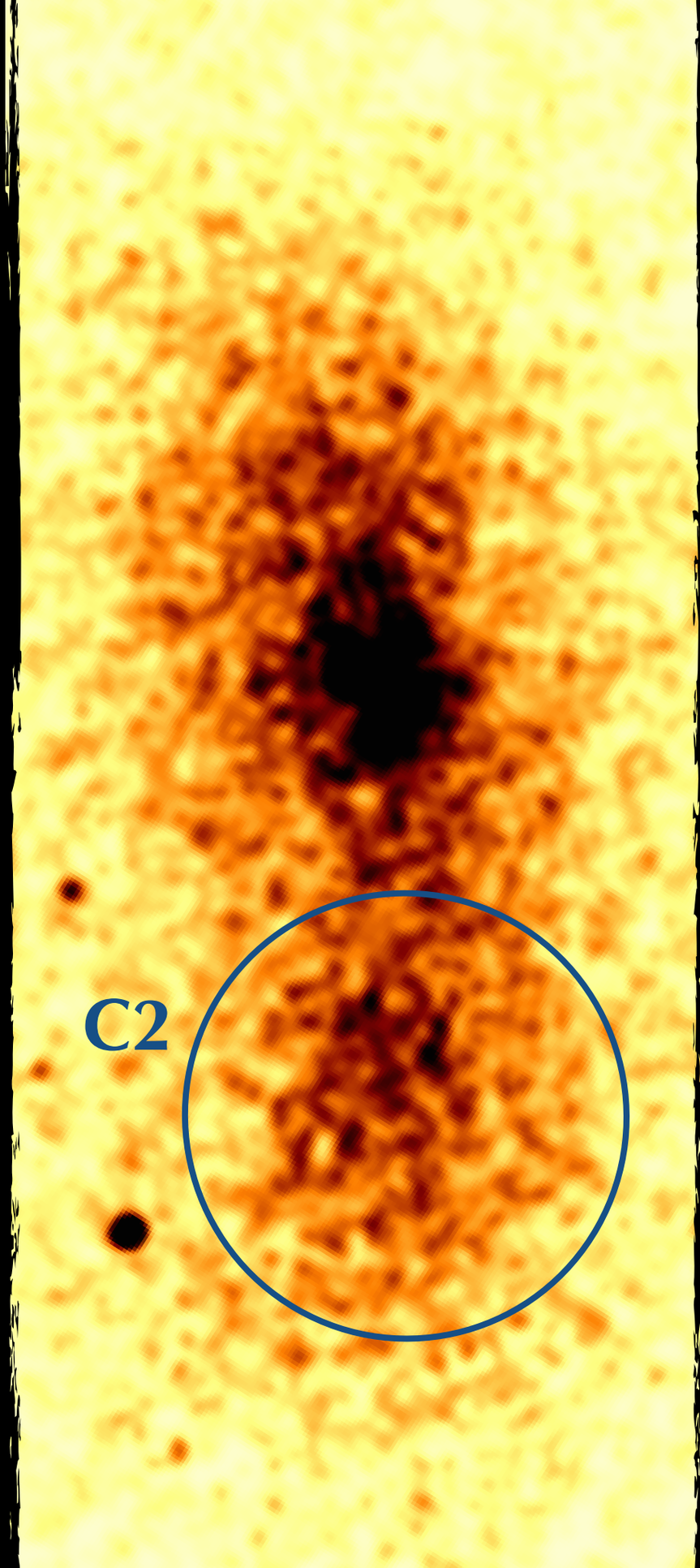

β-model
β = 0.6 (fixed)
r_c = 150 ± 5 kpc
SB [counts s^-1 arcmin^-2]
χ
Distance [arcmin]
DEC (J2000)
RA (J2000)
−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
06^s
4^h 17^m 00^s
4^h 16^m 54^s
0.9
0.6
0.3
0.0


β-model
β = 1.6 ± 0.3 (free)
r_c = 460 ± 70 kpc
SB [counts s^-1 arcmin^-2]
χ
Distance [arcmin]
DEC (J2000)
RA (J2000)
−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
06^s
4^h 17^m 00^s
4^h 16^m 54^s
0.9
0.6
0.3
0.0


β = 1.6 ± 0.3 (free)
r_c = 460 ± 70 kpc
SB [counts s^-1 arcmin^-2]
χ
Distance [arcmin]
DEC (J2000)
RA (J2000)
−24° 15′
−24° 16′
−24° 17′
−24° 18′
−24° 19′
06^s
4^h 17^m 00^s
4^h 16^m 54^s
0.9
0.6
0.3
0.0


SB [counts s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
10^{-6}
β = 1.6 ± 0.3 (free)
r_c = 460 ± 70 kpc
χ
2
0
-2
10^{-1}
2×10^{-1}
3×10^{-1}
1
2
3
Distance [arcmin]
S1
0.9
0.6
0.3
0.0
DEC (J2000)
$-24^\circ\ 15'$
$-24^\circ\ 16'$
$-24^\circ\ 17'$
$-24^\circ\ 18'$
$-24^\circ\ 19'$
06^s
$4^h\ 17^m\ 00^s$
$4^h\ 16^m\ 54^s$
RA (J2000)

C2 is also undergoing a merger with a smaller cluster not immediately visible in the X-ray map.



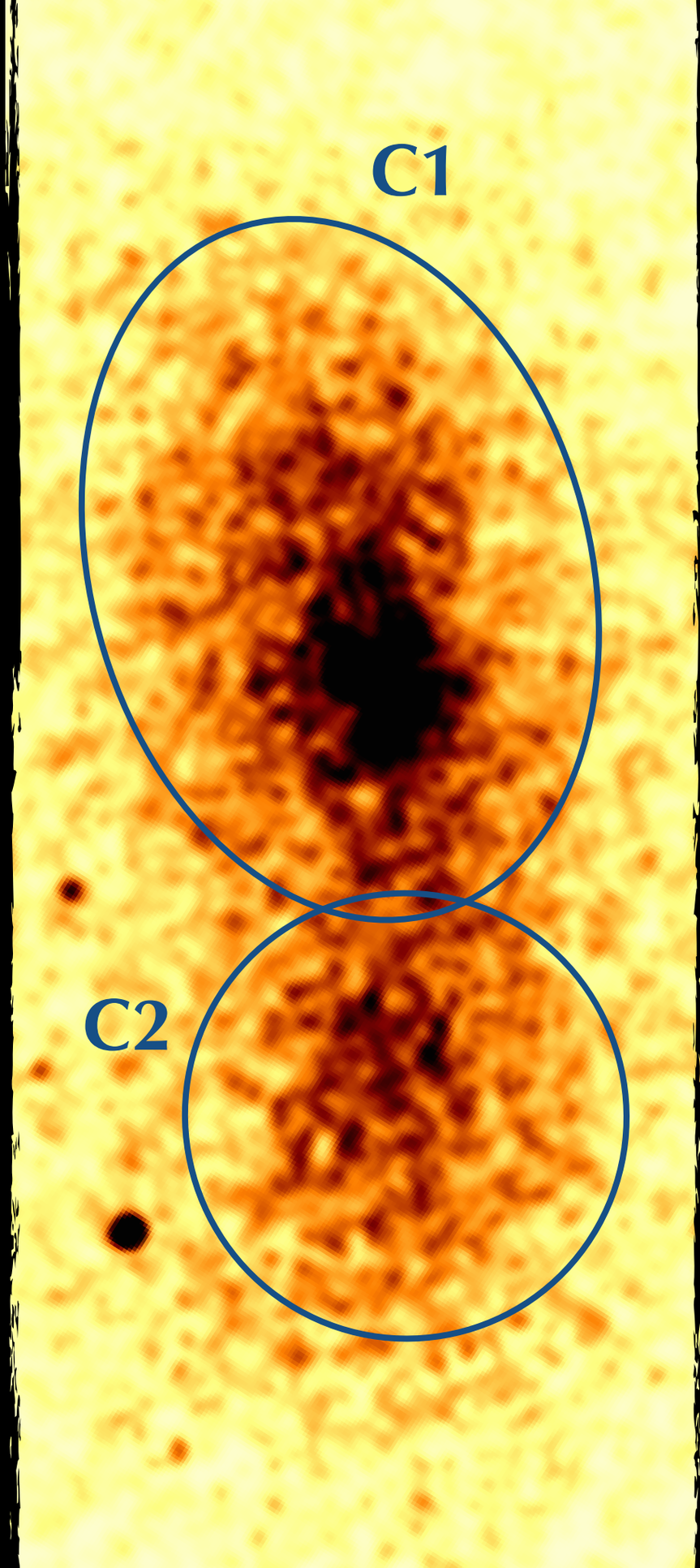
Provisional Summary

C1 is merging

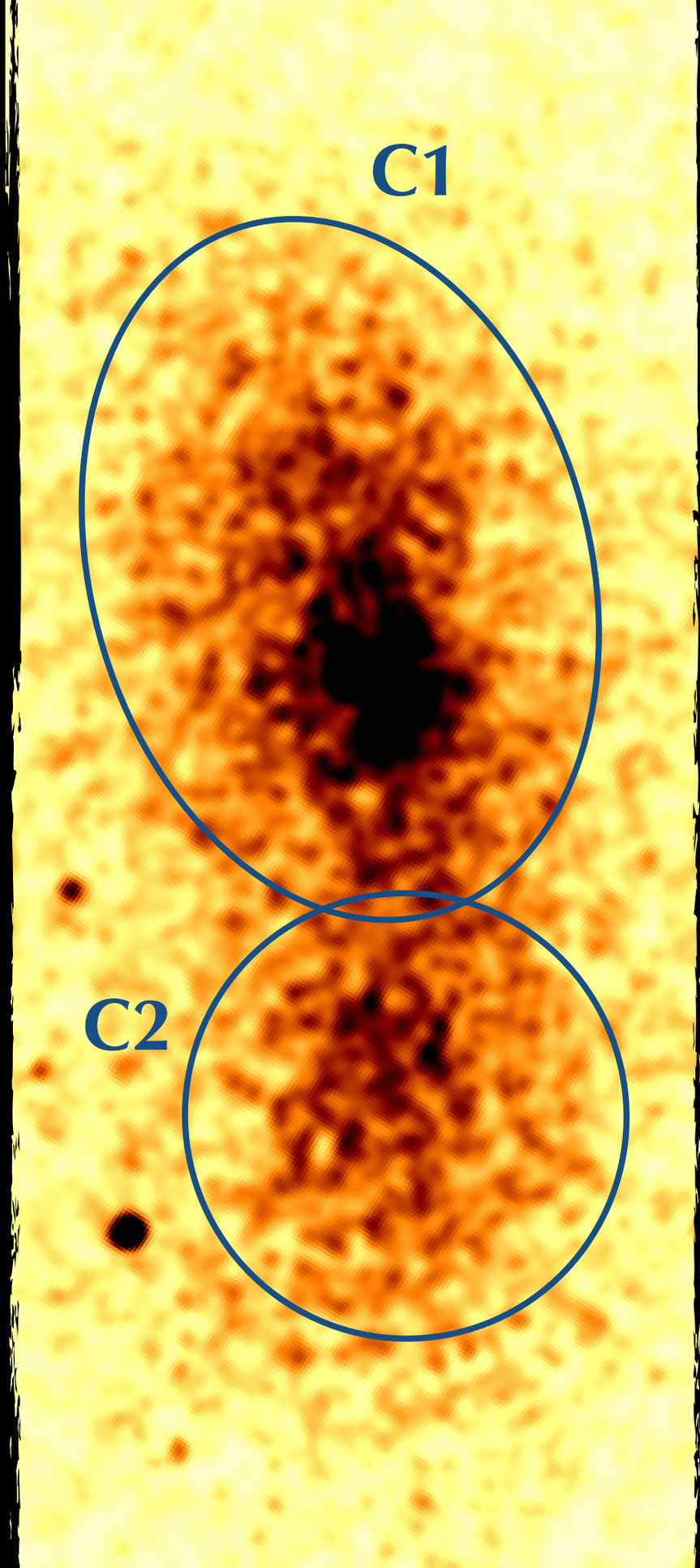
- strongly elongated
- hot core
- high central entropy
- ICM substructure
- C1 = multiple subclusters

C2 is merging

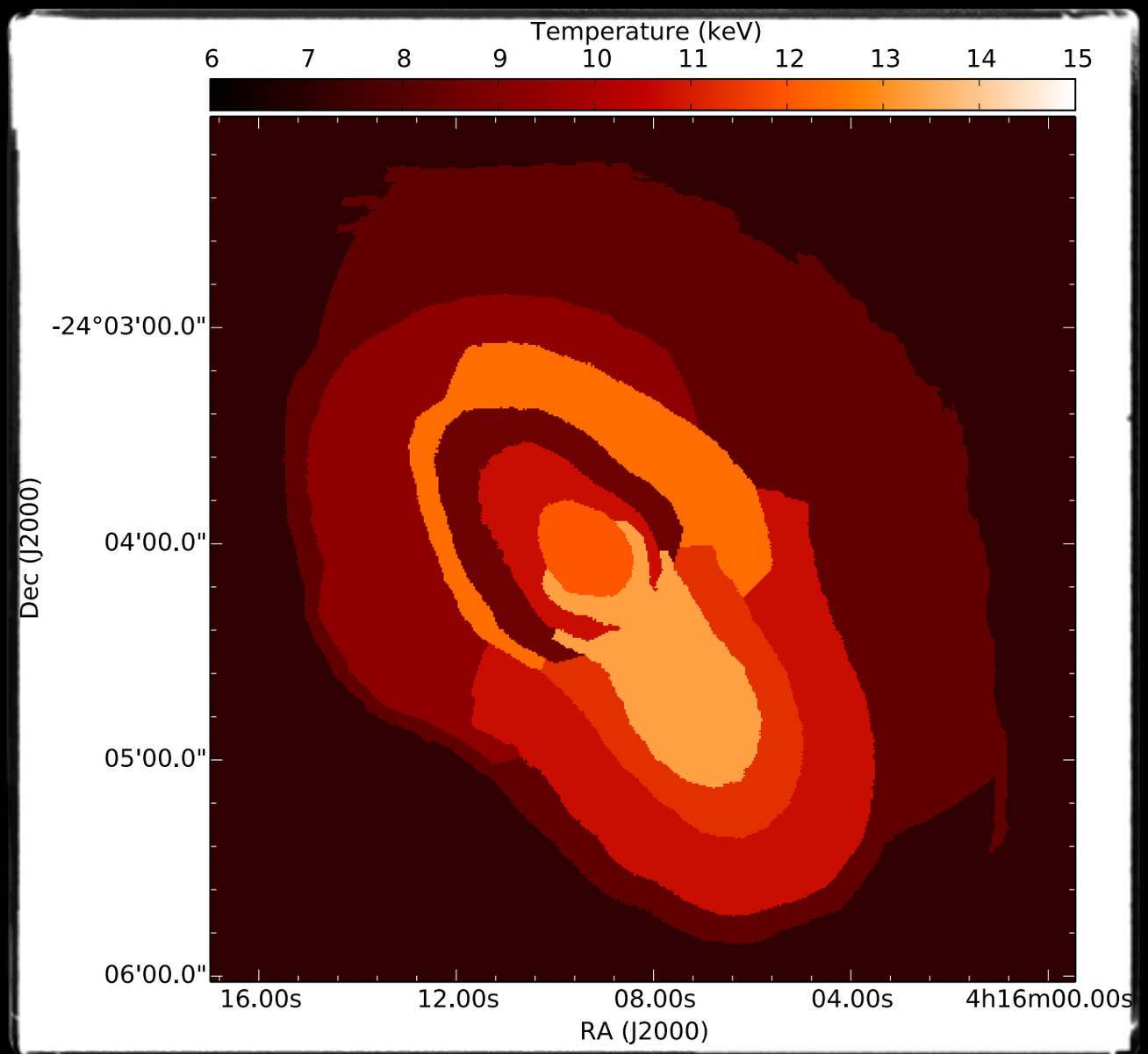
- flat X-ray brightness
- poor/unphysical β-model fit
- density discontinuity in the ICM

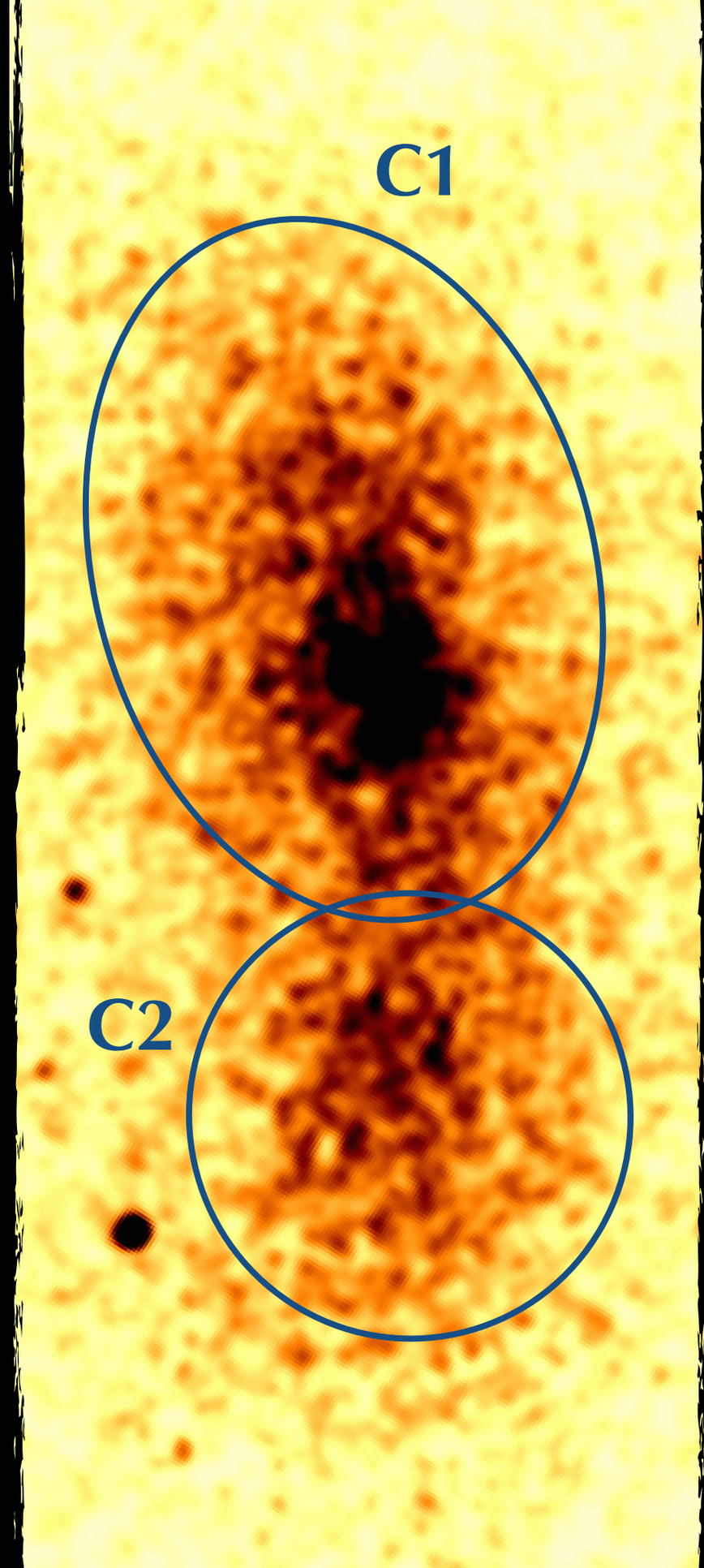


Are C1 and C2
interacting with
each other?

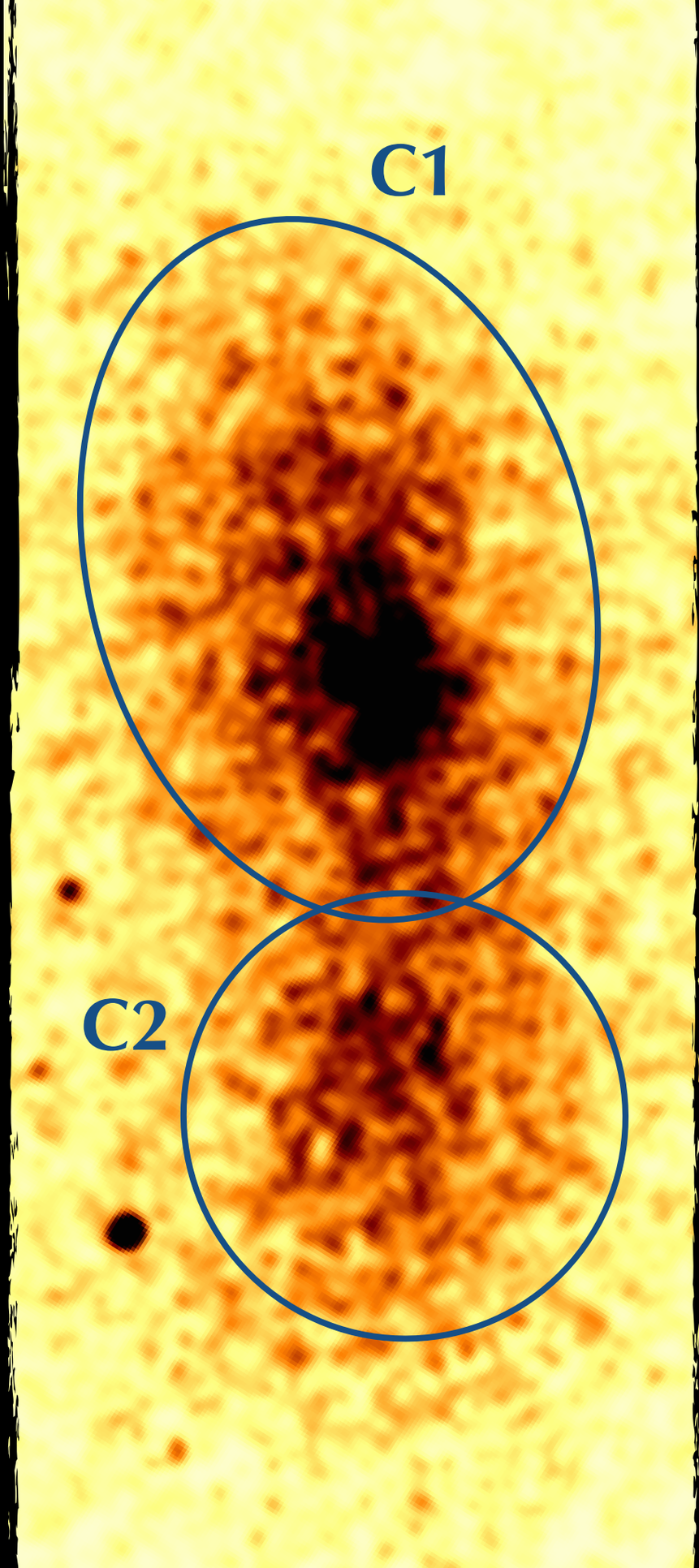


- no clear evidence of typical merger shocks

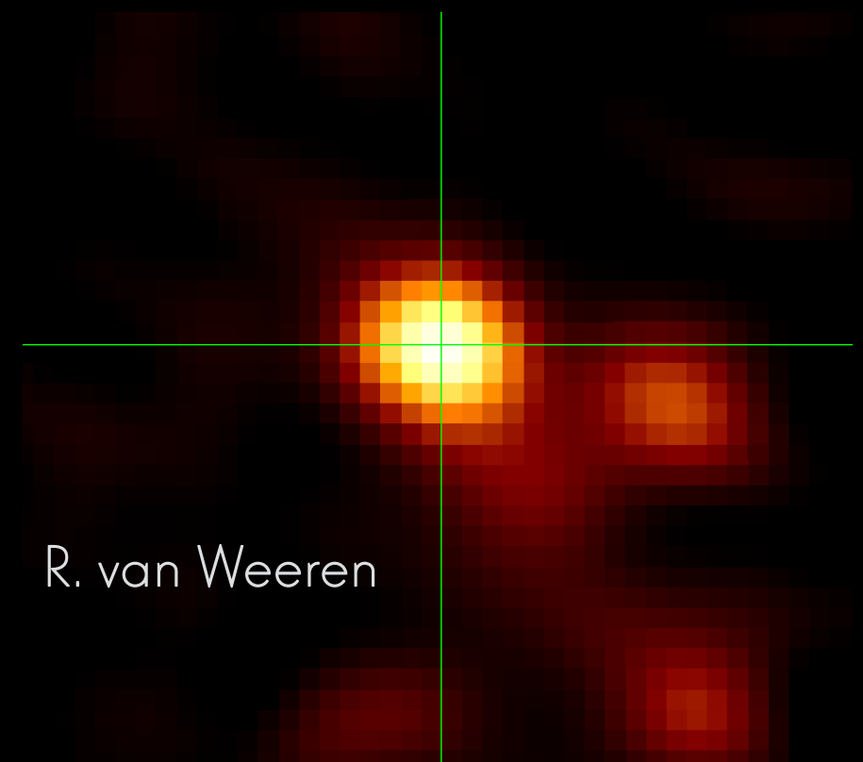




- no clear evidence of typical merger shocks
- no evidence of diffuse radio emission like, e.g., in the Bullet Cluster or A3667

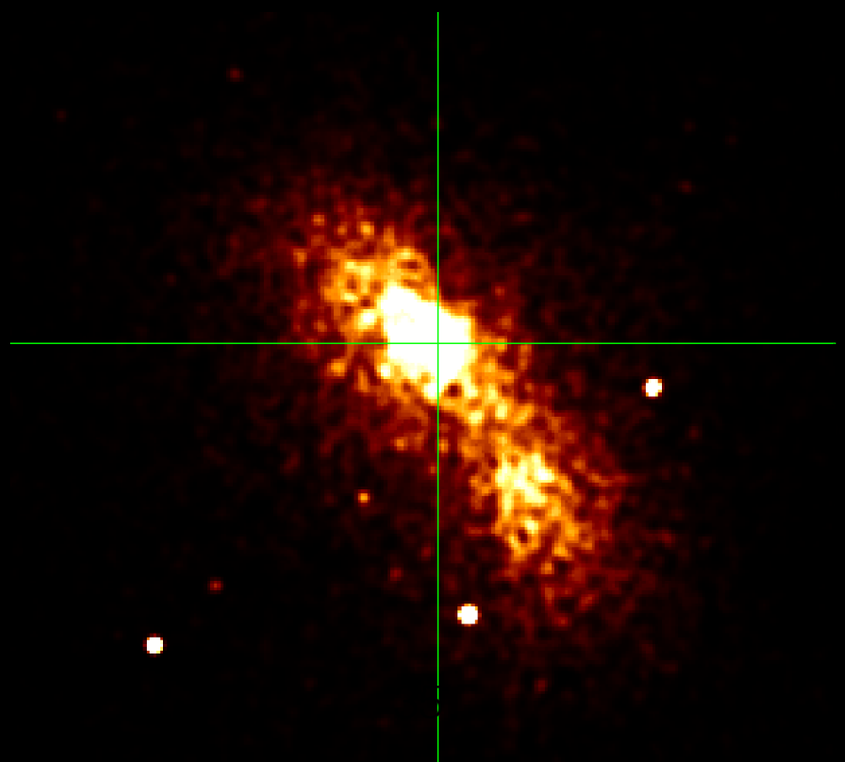


VLA low resolution

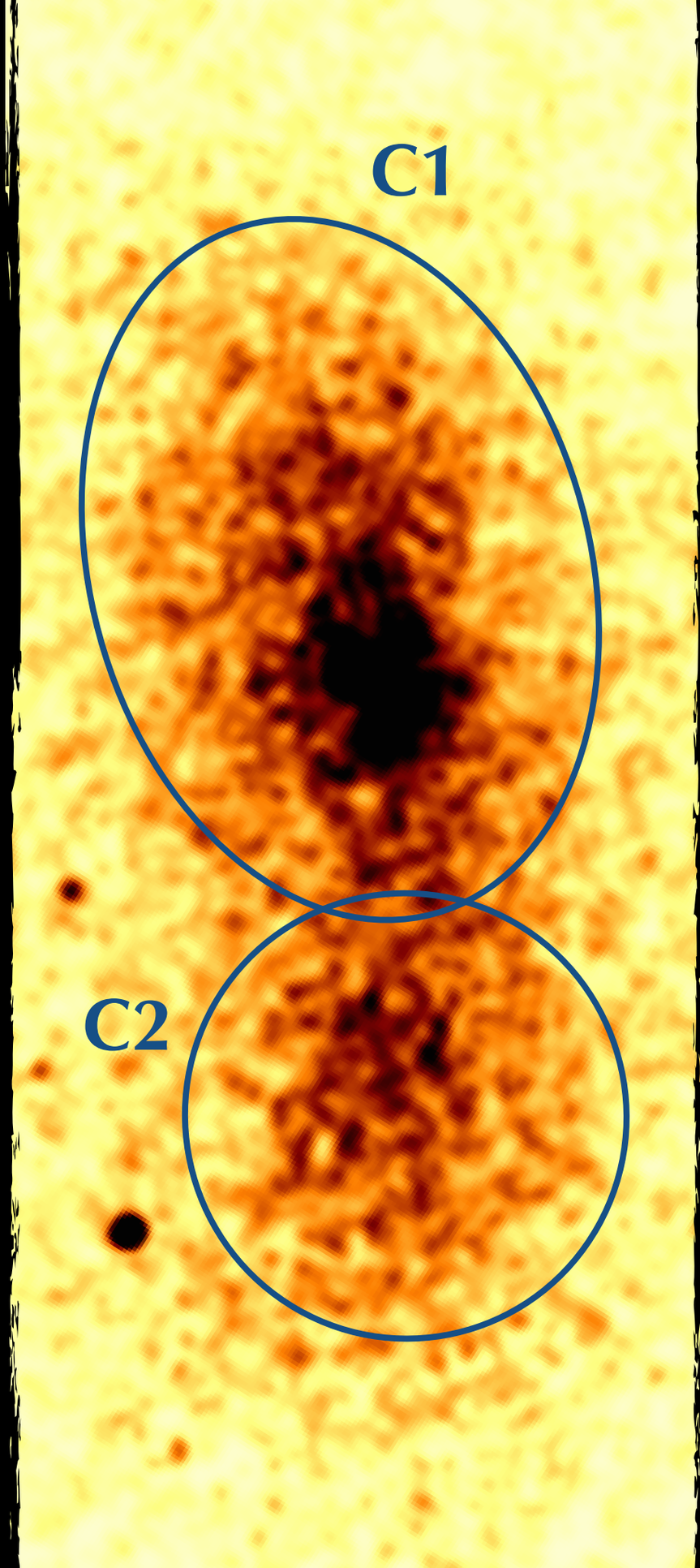


R. van Weeren

Chandra 0.5-3 keV

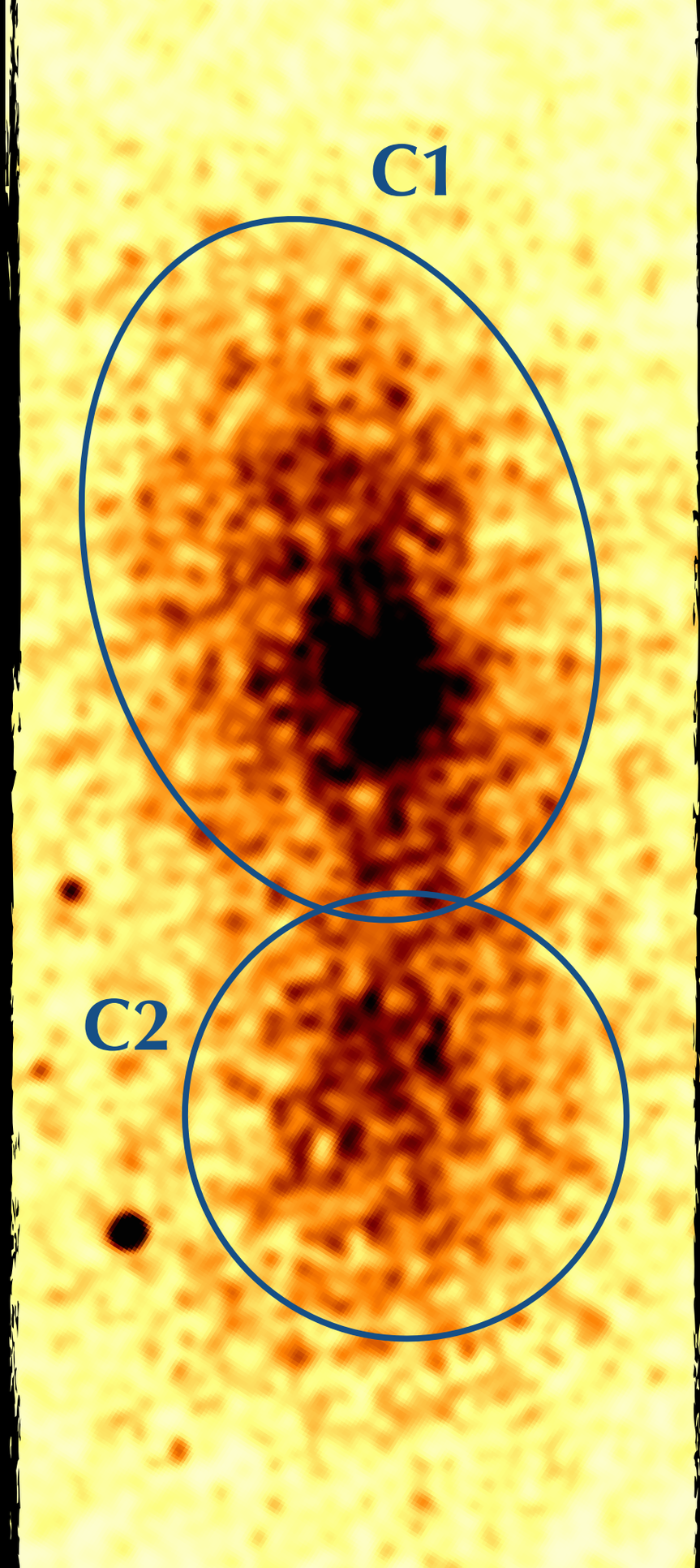


- no clear evidence of typical merger shocks
- no evidence of diffuse radio emission like, e.g., in the Bullet Cluster or A3667
- no large dissociation between the DM and the gas components (Jauzac et al. 2014)



- no clear evidence of typical merger shocks
- no evidence of diffuse radio emission like, e.g., in the Bullet Cluster or A3667
- no large dissociation between the DM and the gas components (Jauzac et al. 2014)

C1 and C2 have not yet merged with each other



Summary

- The HST Frontier cluster MACS J0416.1-2403 is a hot (T ~ 10 keV), massive (M ~ 1e15 $M_{\odot}$) merging cluster.

- The main subclusters are interacting with less massive galaxy groups, as evidenced by substructure and weak density discontinuities in the ICM.

- However, *no clear evidence of interaction between the two main subclusters*.

- **Likely scenario:** MACS J0416.1-2403 is a place of active cosmic structure growth. We are witnessing a pre-merging system.

Surface Brightness Modeling

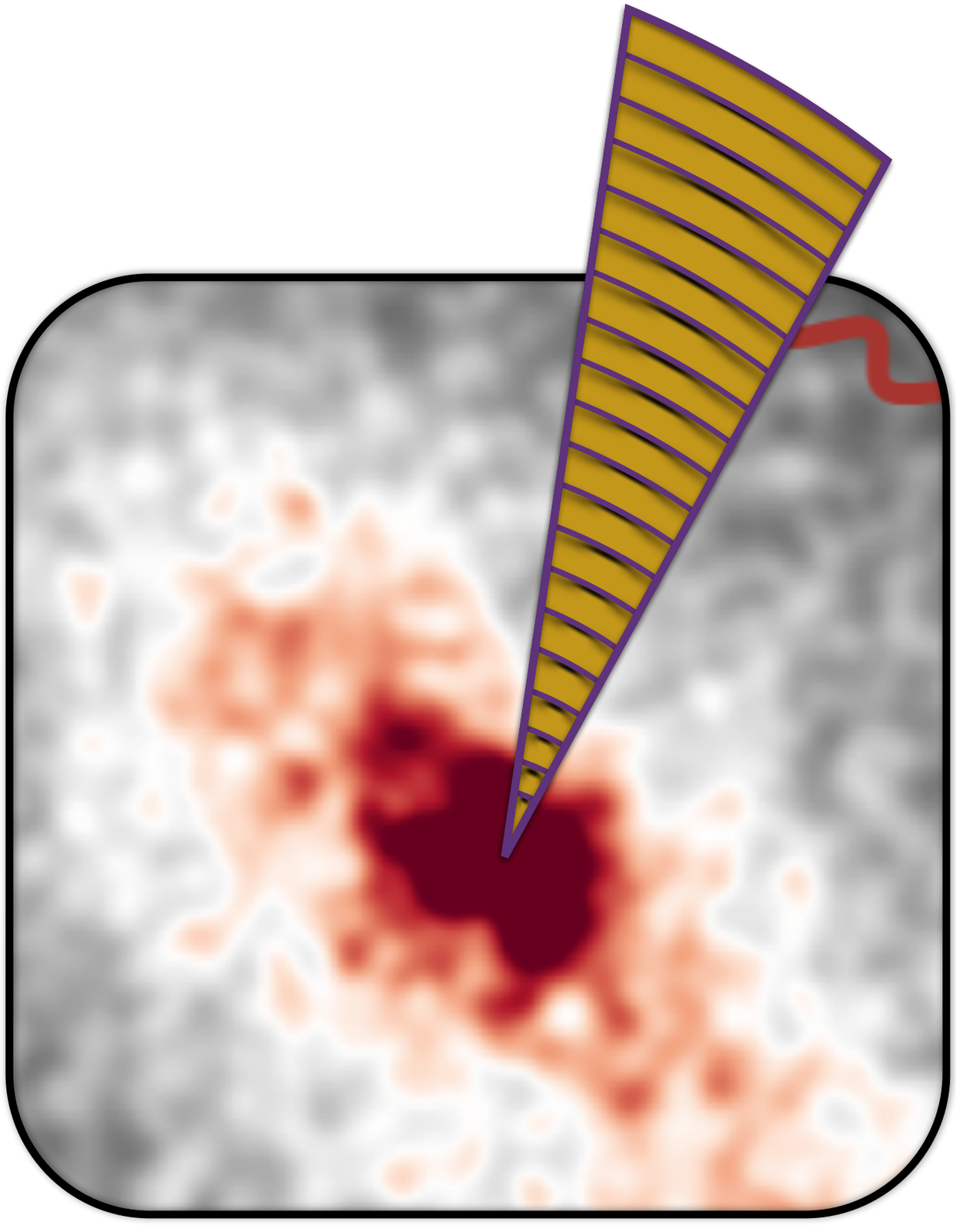


Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.

Calculate the local sky background surface brightness from the outer bins of the profile.

Keeping the sky background fixed to its best-fitting value, fit the inner part of the profile.

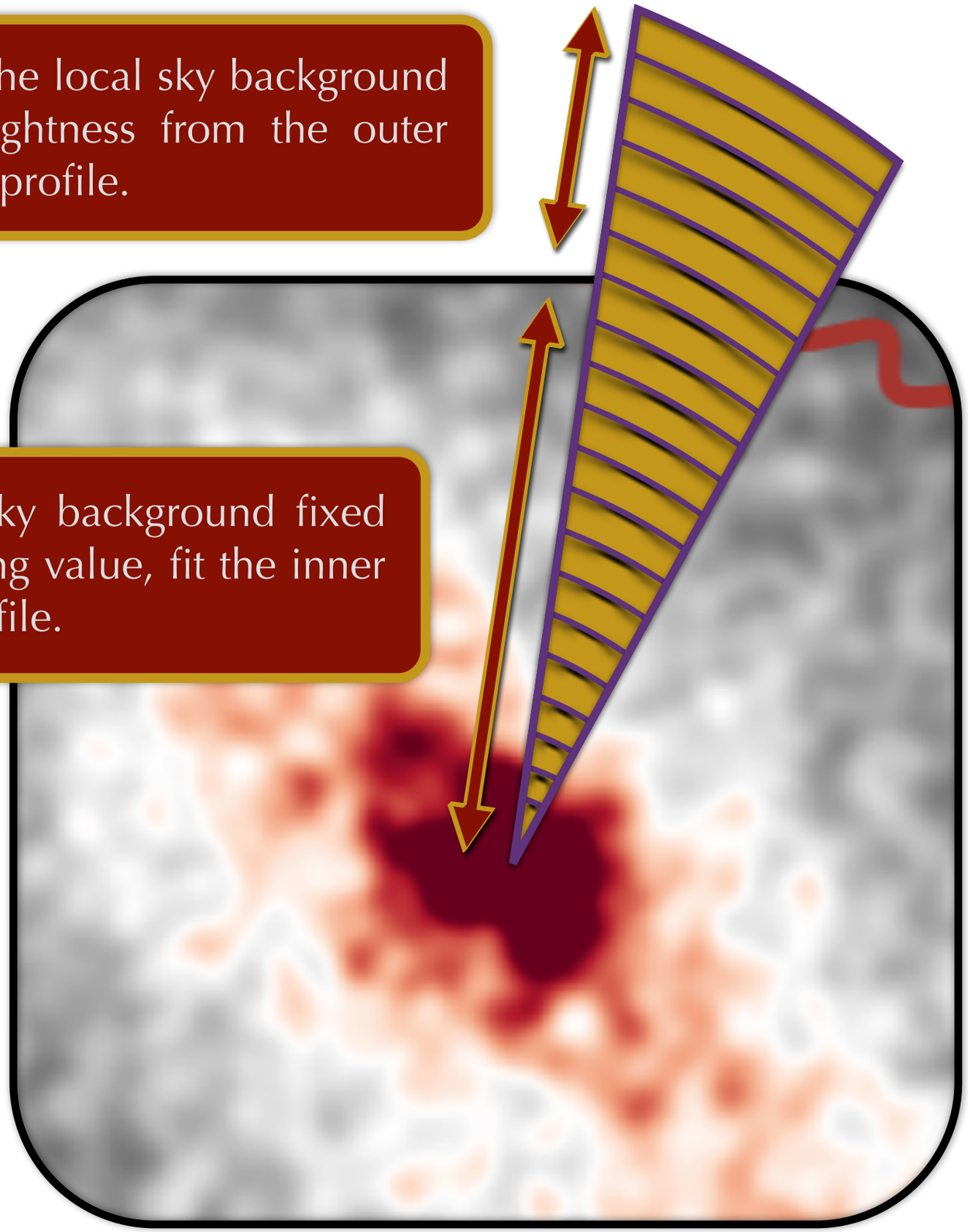


Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.

Surface Brightness Modeling

Subtract the **stowed** background profile from the surface brightness profile across the "cavity".

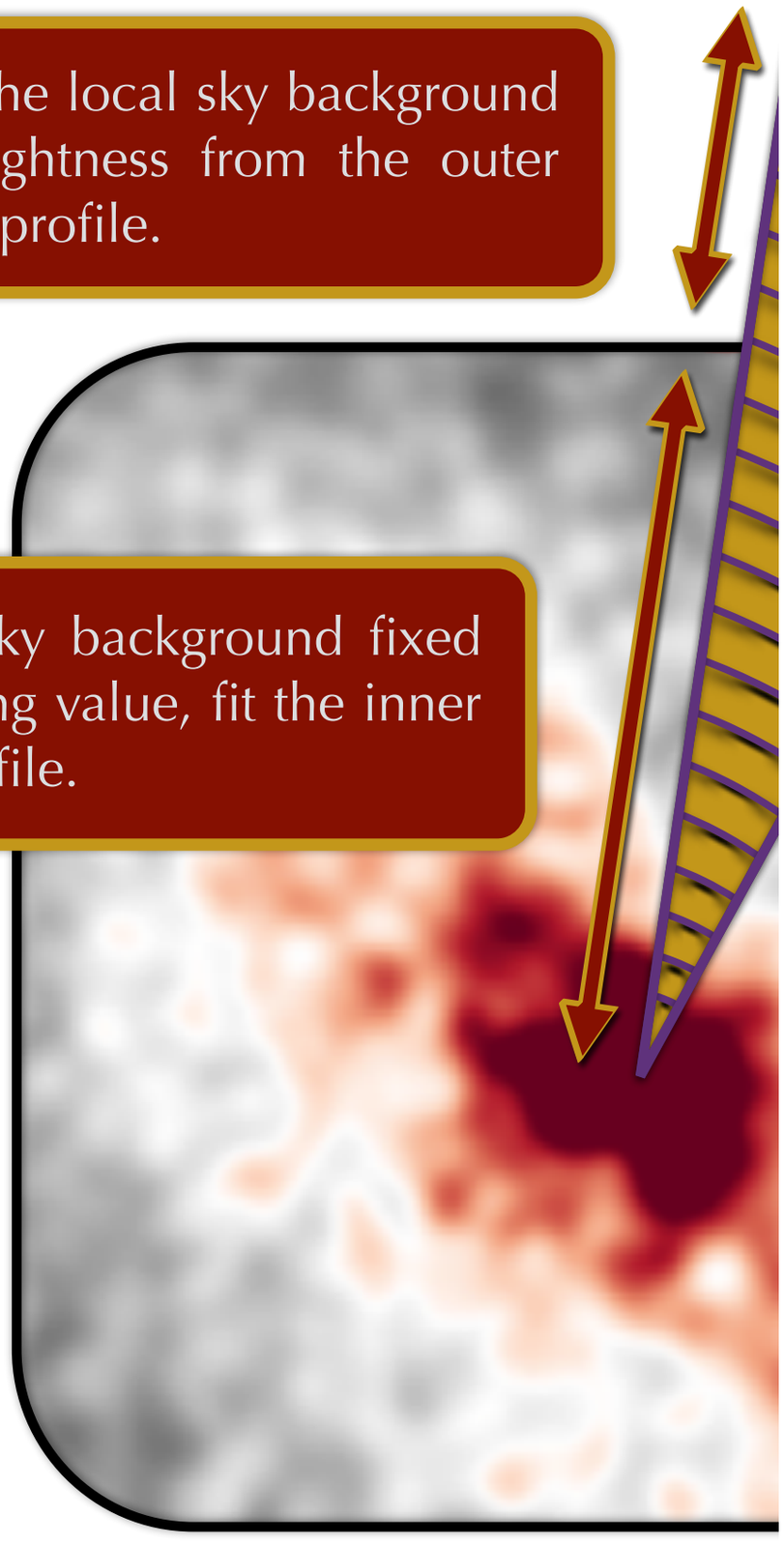
Bin the net profile to have at least 1 count/bin.

Use **Cash statistics** for the fits, rather than chi-squared statistics.

Fit various underlying density models to the data, assuming that the plasma is isothermal.

Calculate the local sky background surface brightness from the outer bins of the profile.

Keeping the sky background fixed to its best-fitting value, fit the inner part of the profile.



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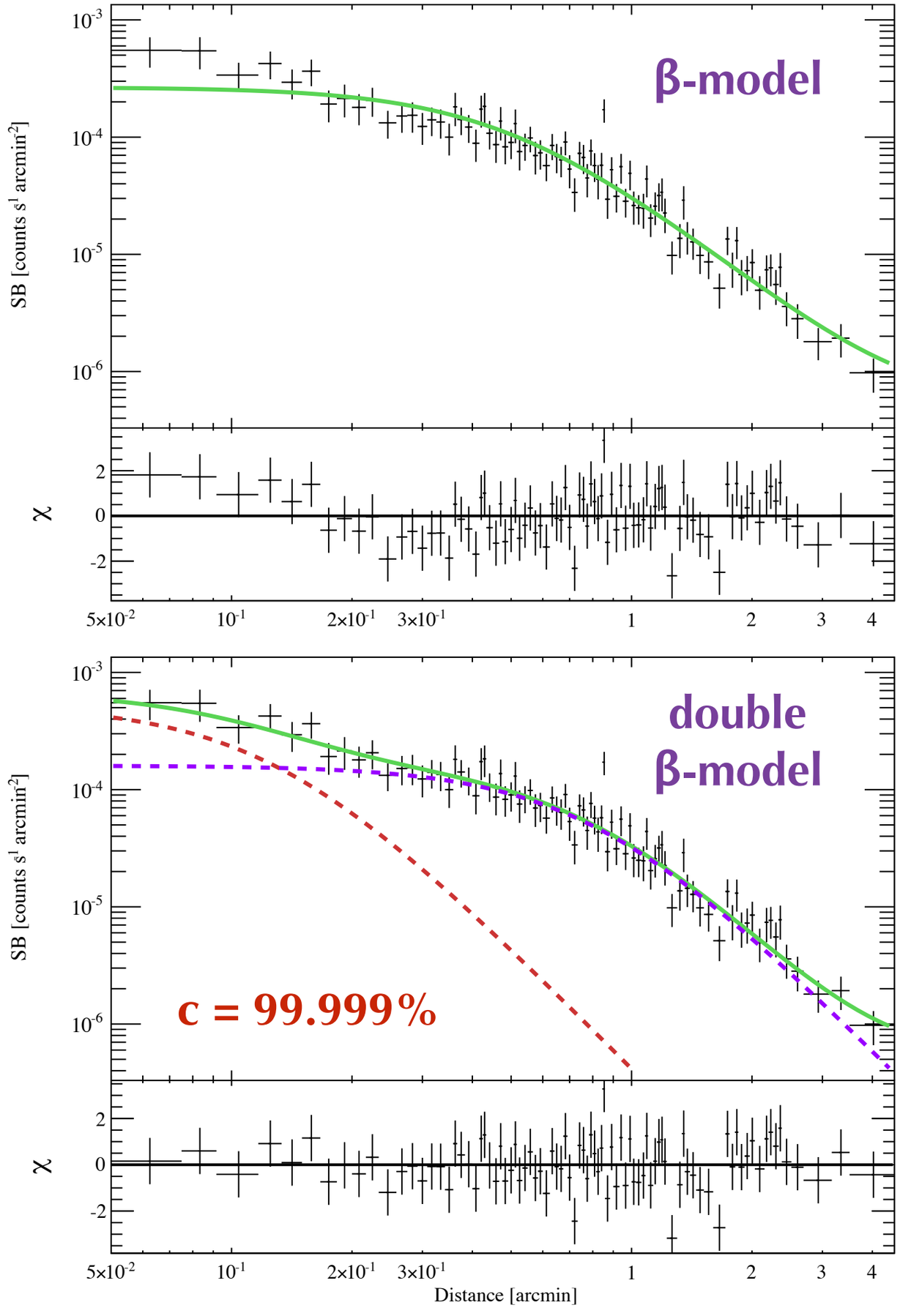

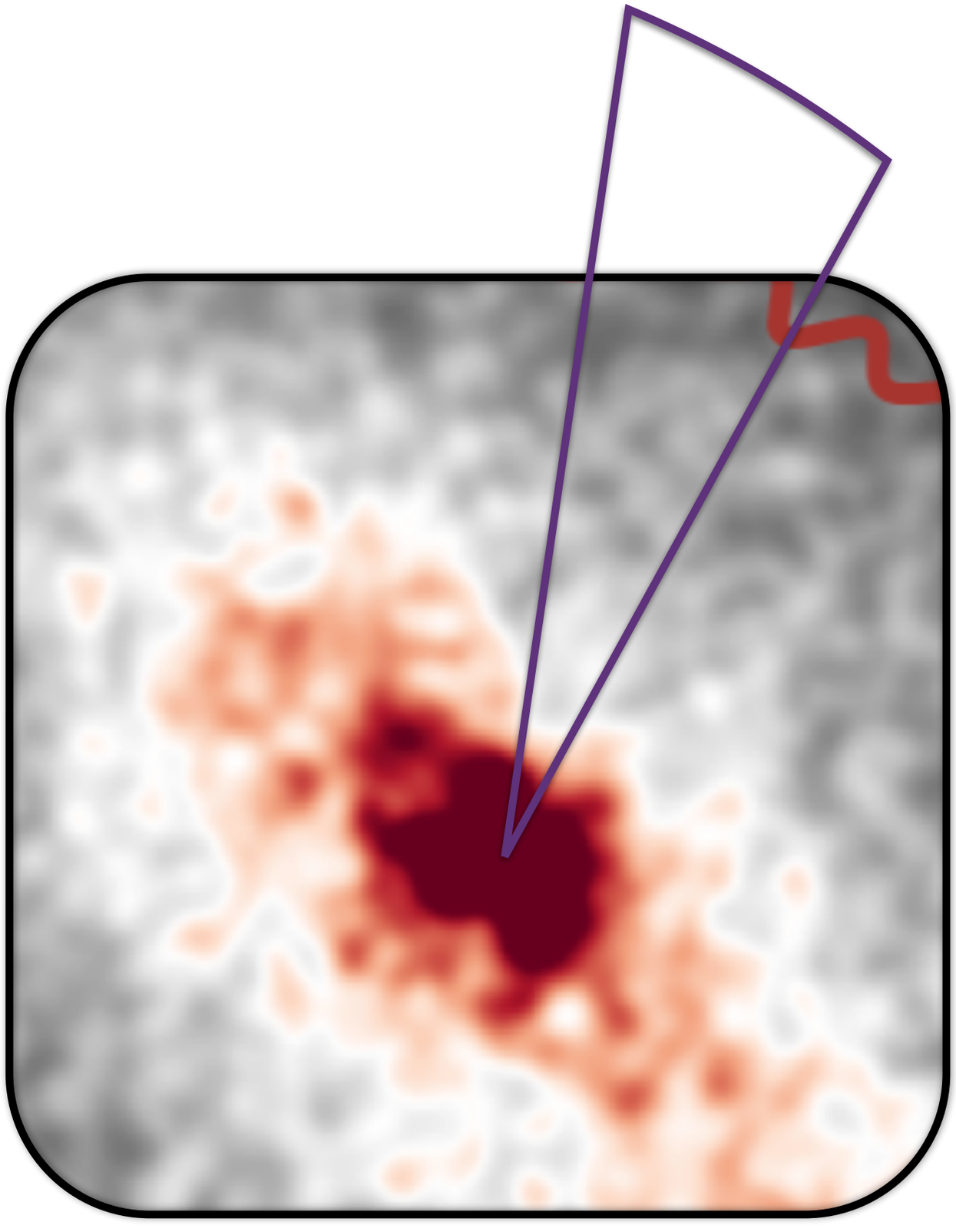

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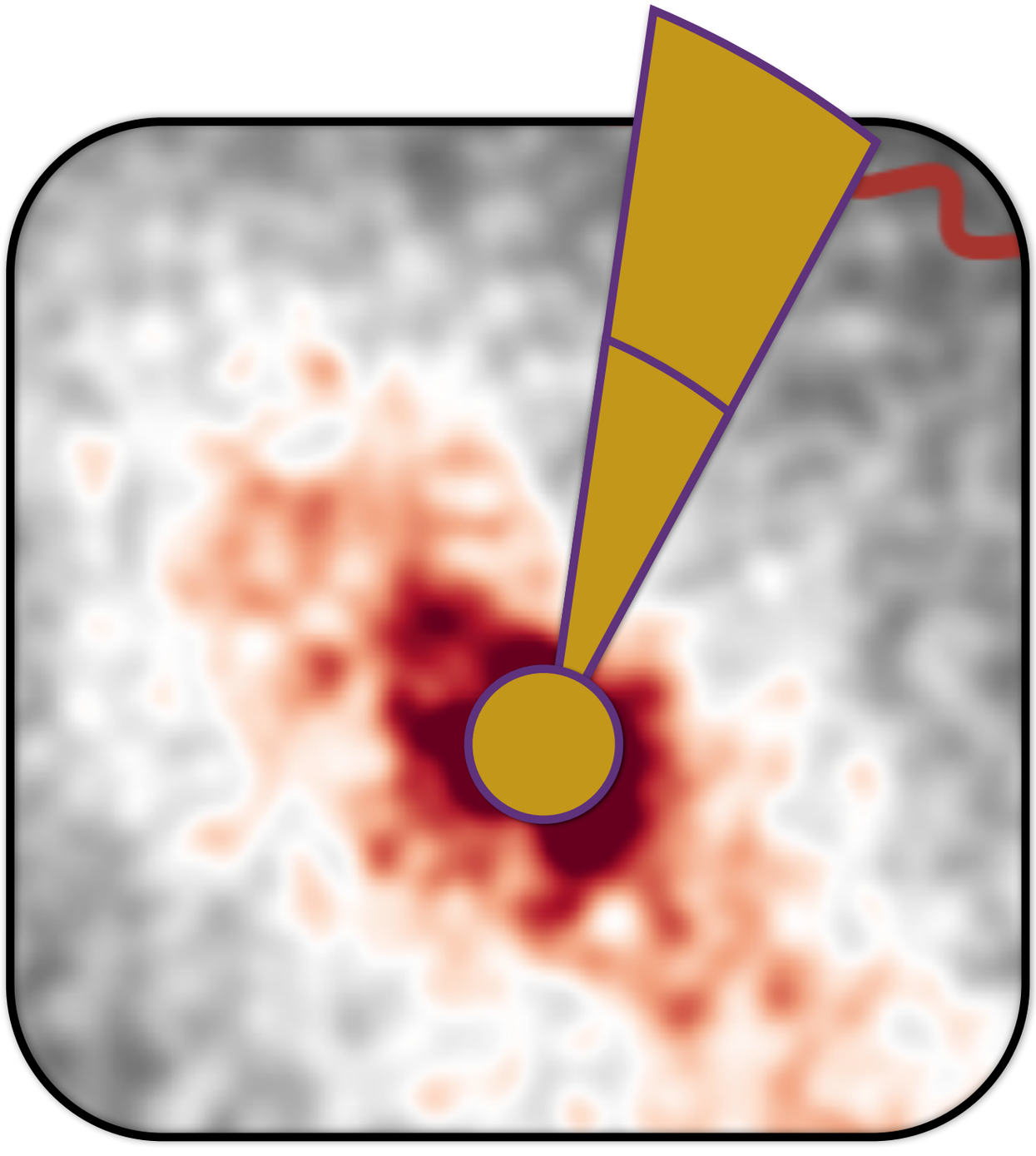

Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.

Model the local sky background.

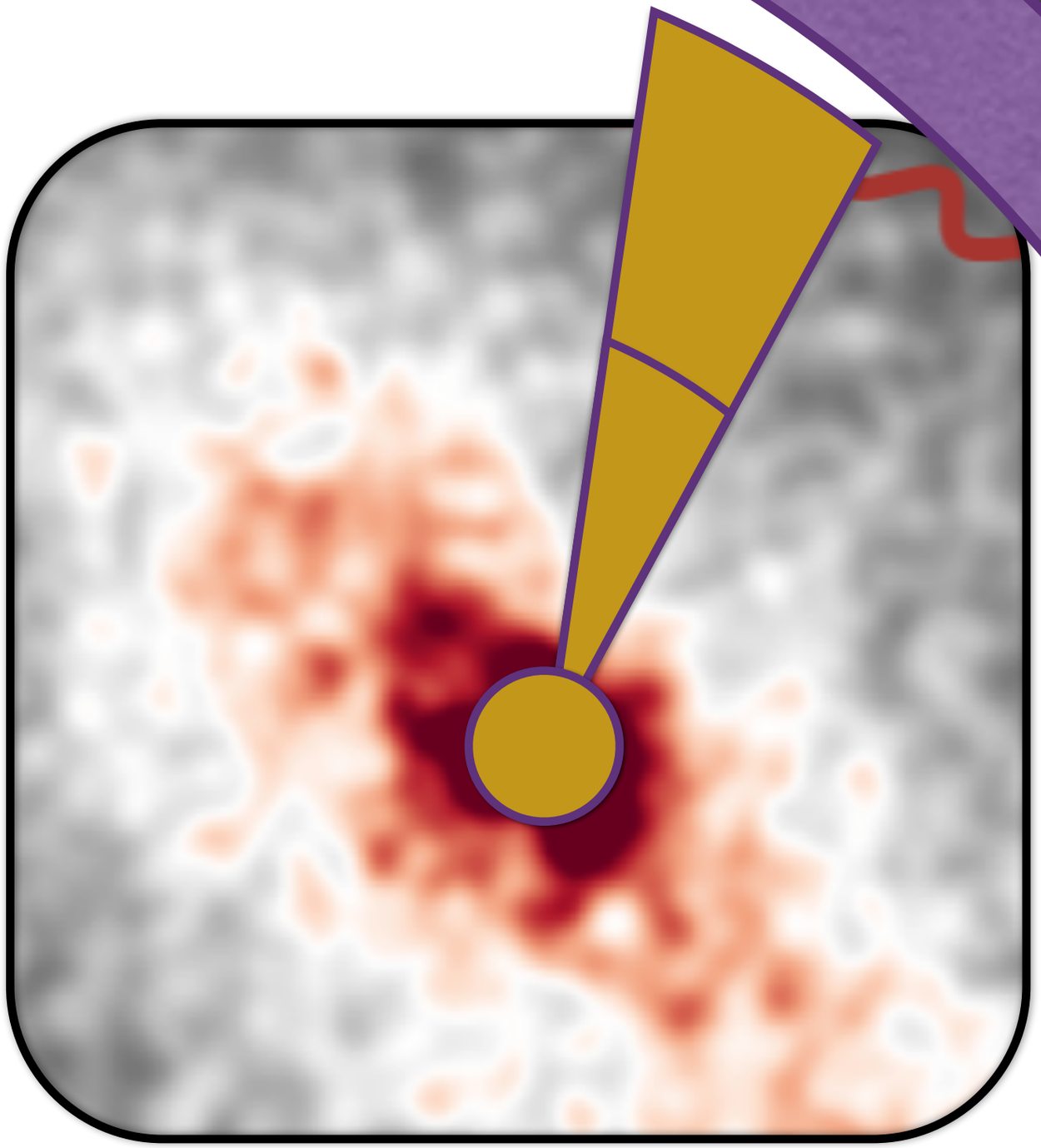

Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.

Spectroscopic Analysis

From the total spectrum of a partial annulus, subtract the stowed background spectrum from the same region.

Bin the spectra to have at least 1 count/bin.

Use **Cash statistics** for the fits, rather than chi-squared statistics.

Keeping the sky background model fixed, fit the net source spectra with single-temperature APEC models.

Spectroscopic Analysis

Model the local sky background.

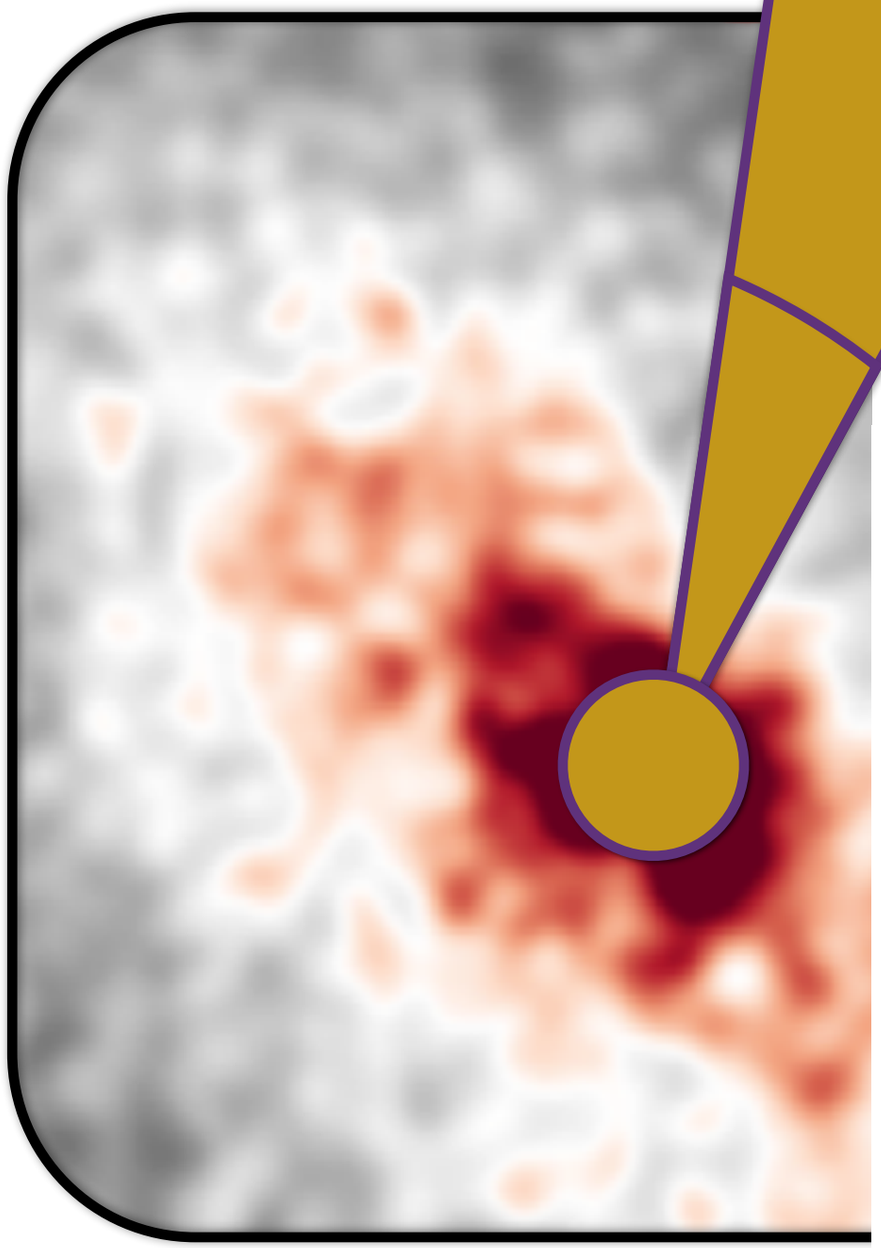

Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.

Fig. 3: Temperature profile across the NW "cavity."