Sloshing, Shocks, and Bubbles in the Cool Core Cluster A2052

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Collaborators

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AGN Feedback in Clusters

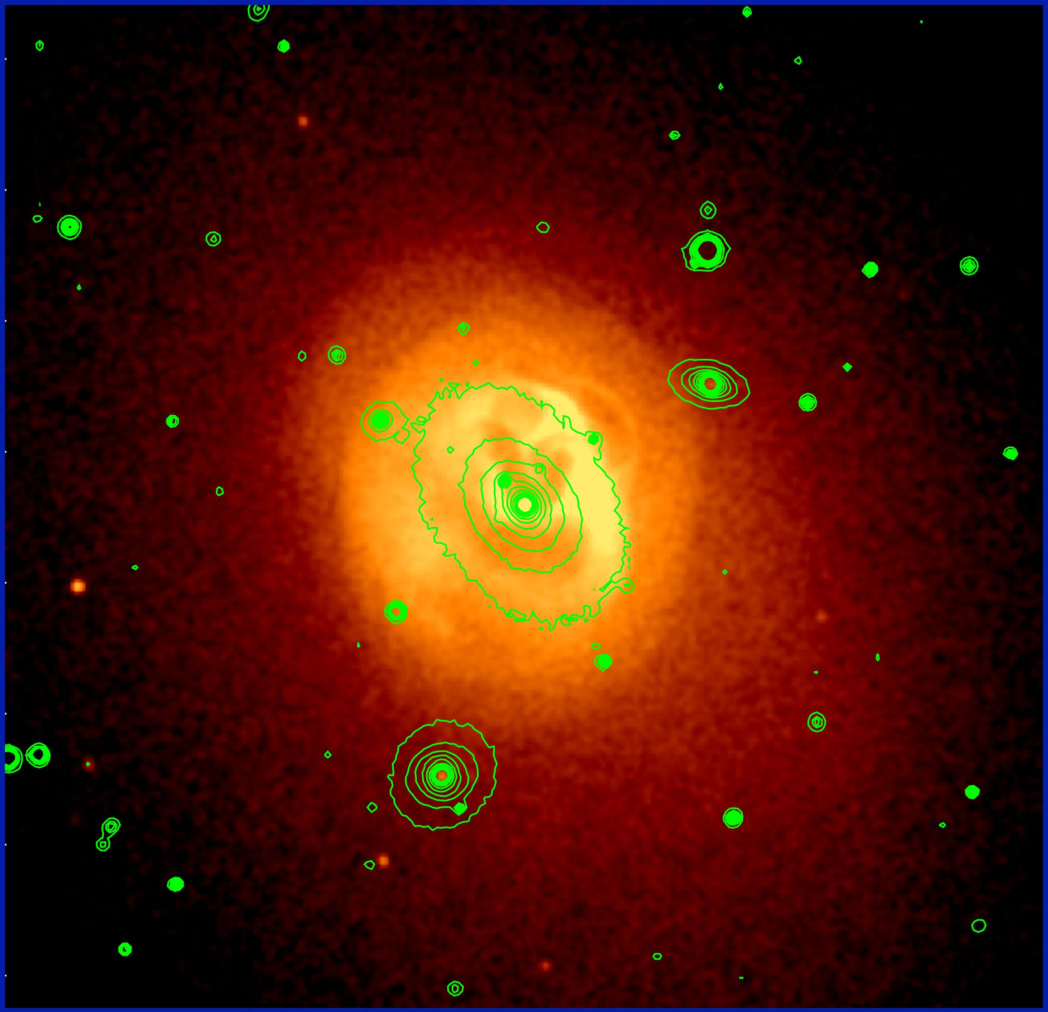
- Simulations (Croton et al. 2006) have shown that feedback is a necessary ingredient to produce the observed luminosity function of galaxies
- Feedback from AGN may set the upper limit to the observed masses of galaxies
- Feedback contributes to cluster preheating
- Feedback plays a role in observed scaling relations (e.g. L_X-T)
- AGN feedback can potentially affect cluster properties that are used for constraining cosmological models, such as the gas mass fraction.

✳ Chandra images over the last 12 years show AGN at work in the centers of cool core clusters, inflating bubbles that rise buoyantly through the ICM, and sometimes producing shocks and sound waves.

Heating by Radio Sources

- Earlier models (e.g. Heinz, Reynolds, & Begelman 1998) predicted that radio sources would heat the ICM through strong shocks. This heating could help to balance the cooling in cooling flows.
- Shock heating models showed that the gas found around the radio sources should be bright, dense, and hotter than the neighboring gas.
- Other models (e.g. Reynolds, Heinz, & Begelman 2001) instead invoke weak shocks to do the heating.
- Buoyantly rising bubbles of radio plasma can also transport energy into clusters.
- Viscously dissipated sound waves are another possibility.

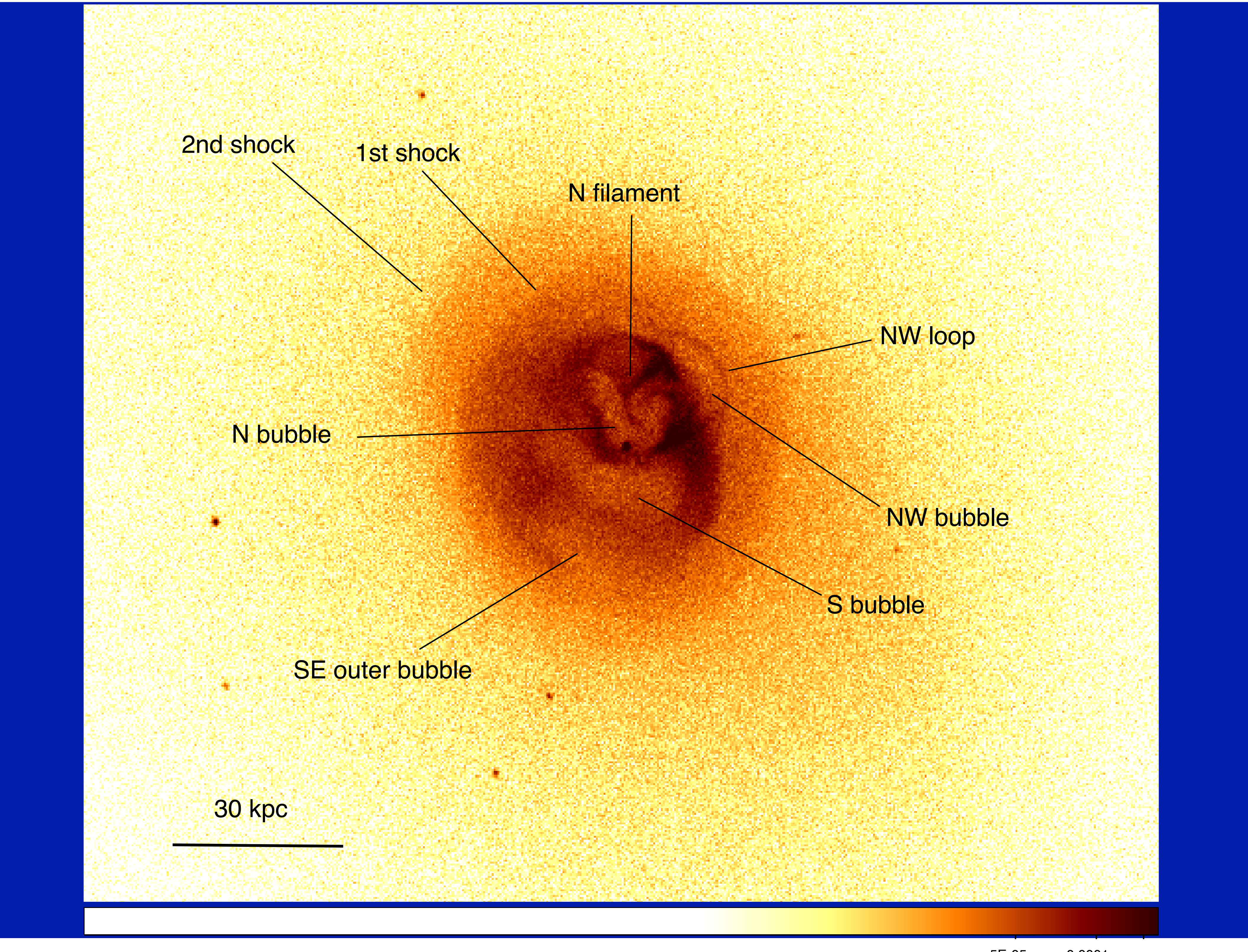
Abell 2052



- Most deeply observed cool core cluster, other than Perseus and Virgo/ M87.
- 657 ksec in Cycles 1, 6, and 10.

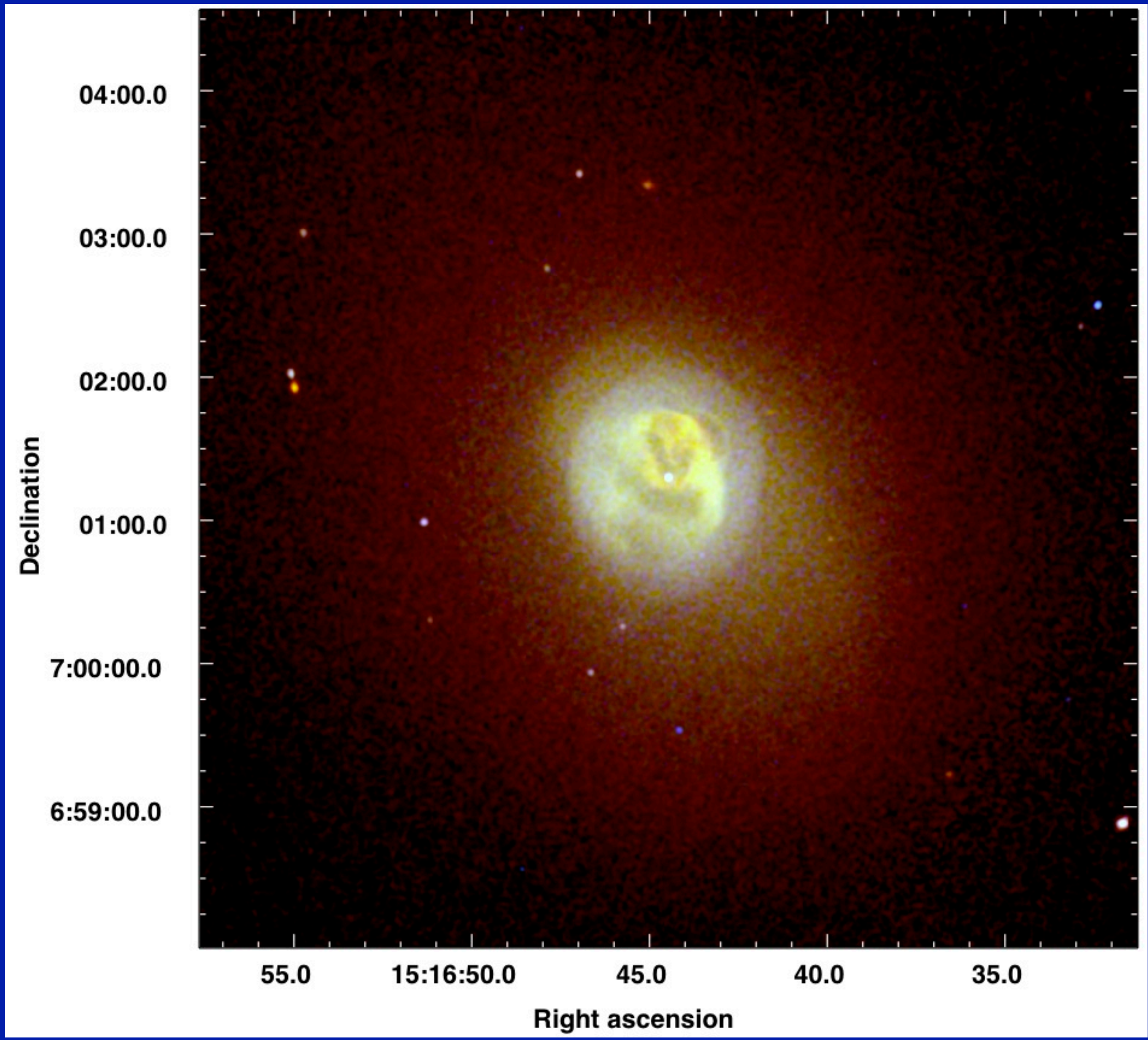
Abell 2052

- Moderately rich cluster at z=0.035.
- Central radio source, 3C 317.


2nd shock
1st shock
N filament
NW loop
N bubble
NW bubble
S bubble
SE outer bubble
30 kpc

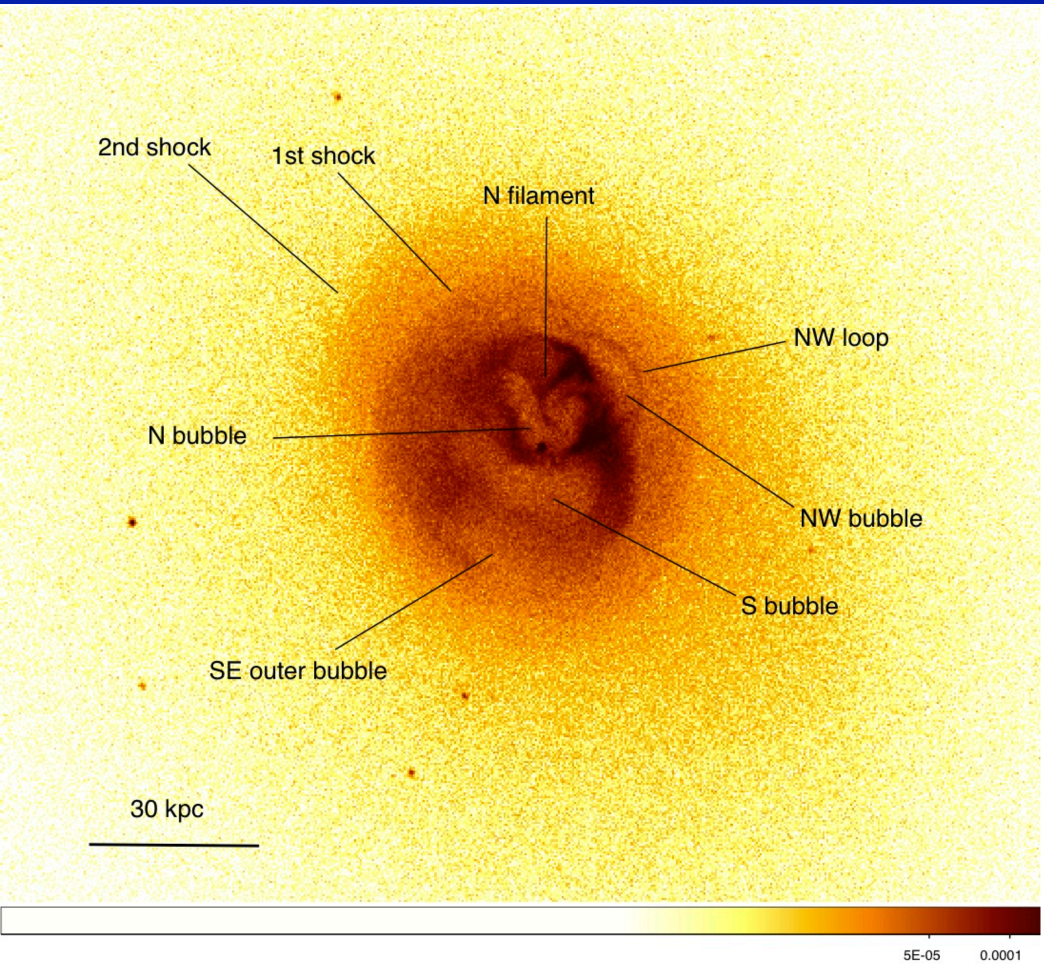
A2052

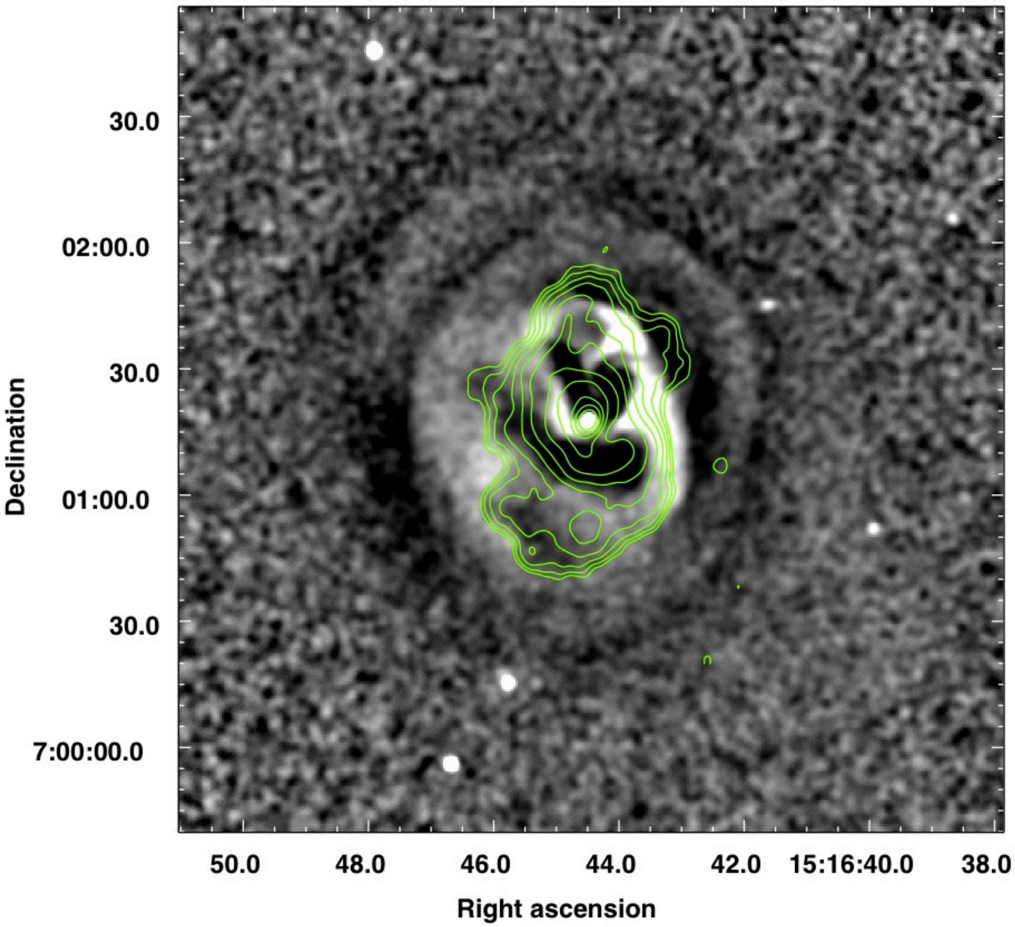
1”=0.7 kpc



Red = 0.3-1 keV, green = 1-3 keV, blue = 3-10 keV

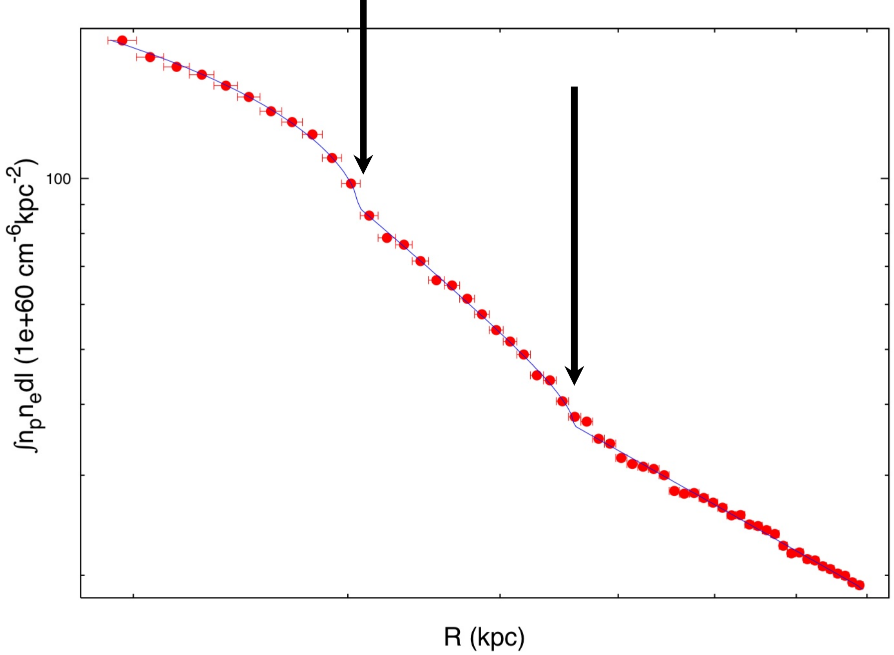
Abell 2052, Shock Heating

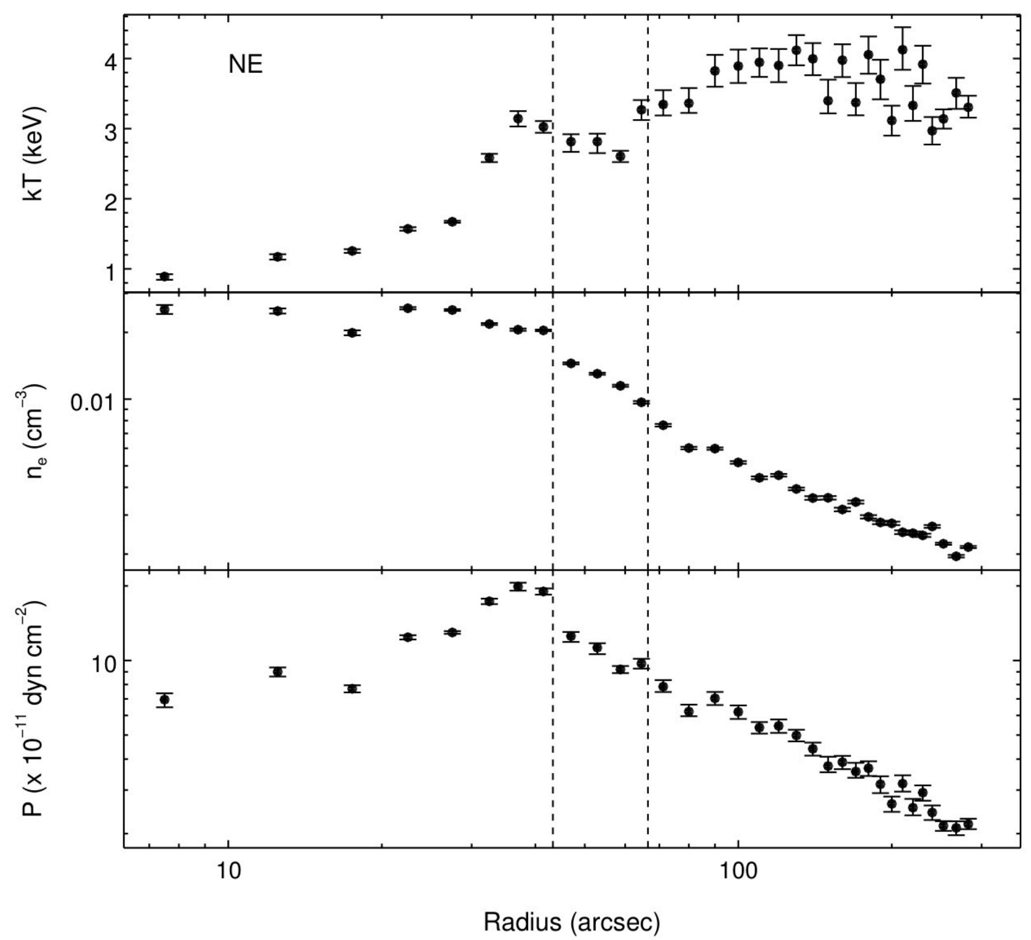




Blanton et al. (2011), 657 ksec Chandra ACIS-S
4.8 GHz radio contours

Abell 2052, Shock Heating

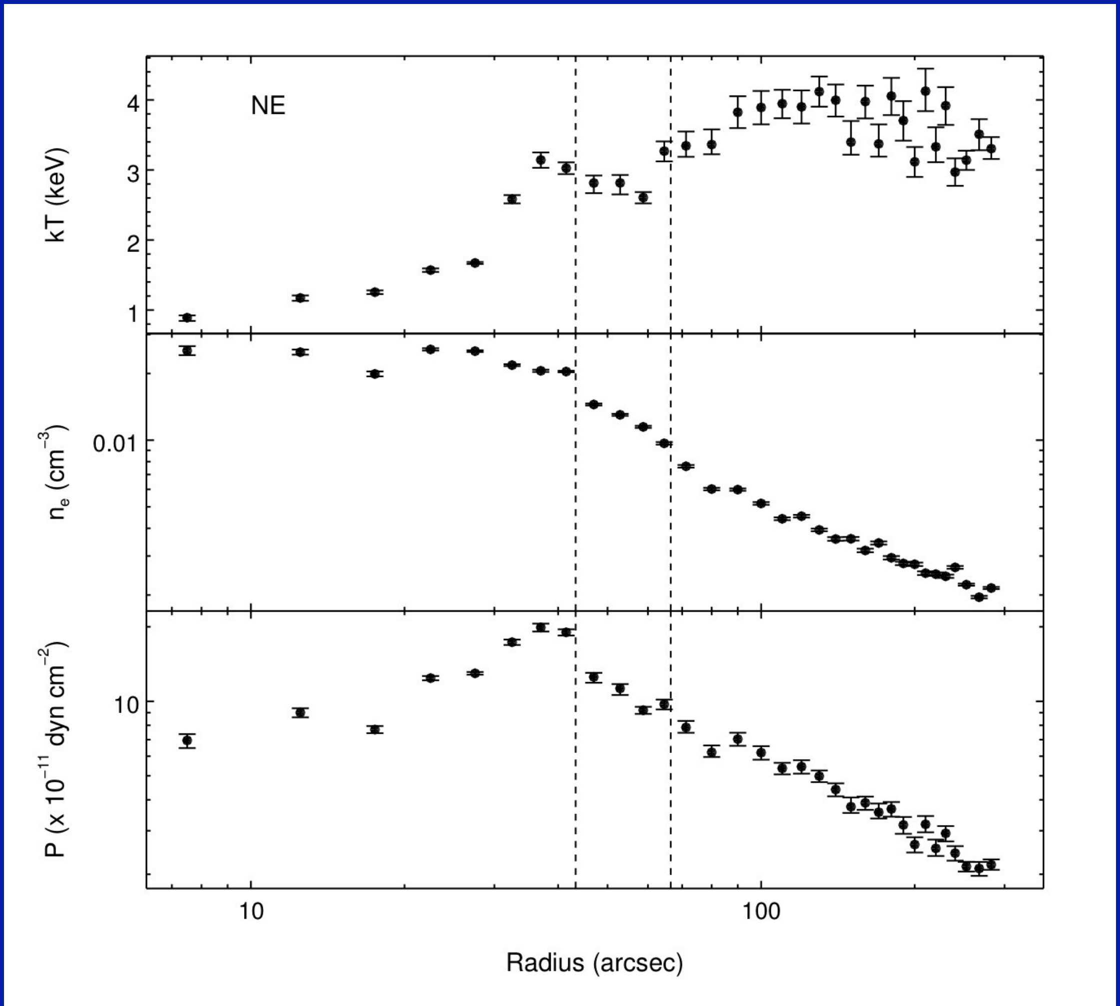




Both shocks (at 31 and 46 kpc from AGN) have Mach ~ 1.2

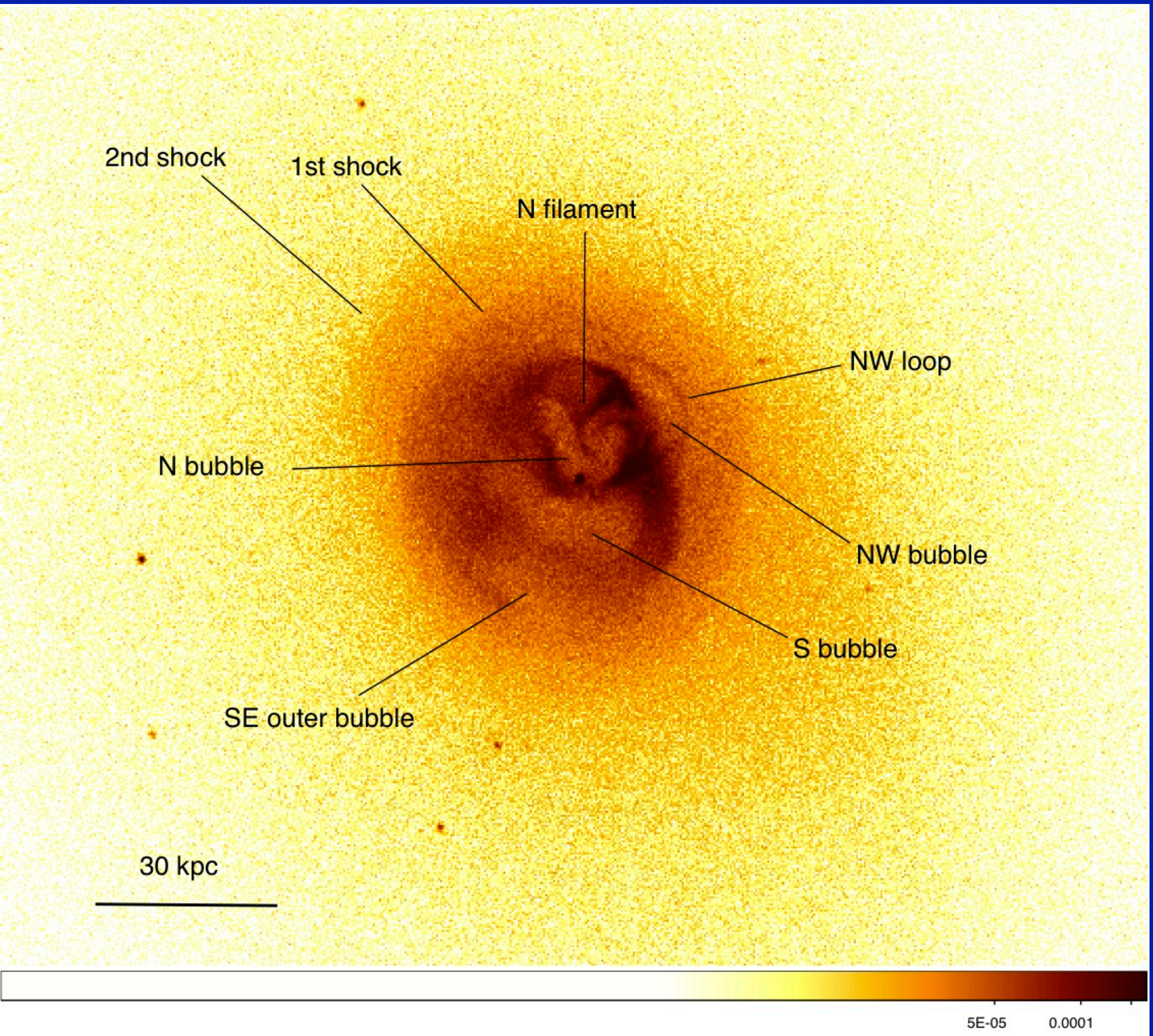
Blanton et al. (2011).

Abell 2052, Shock Heating



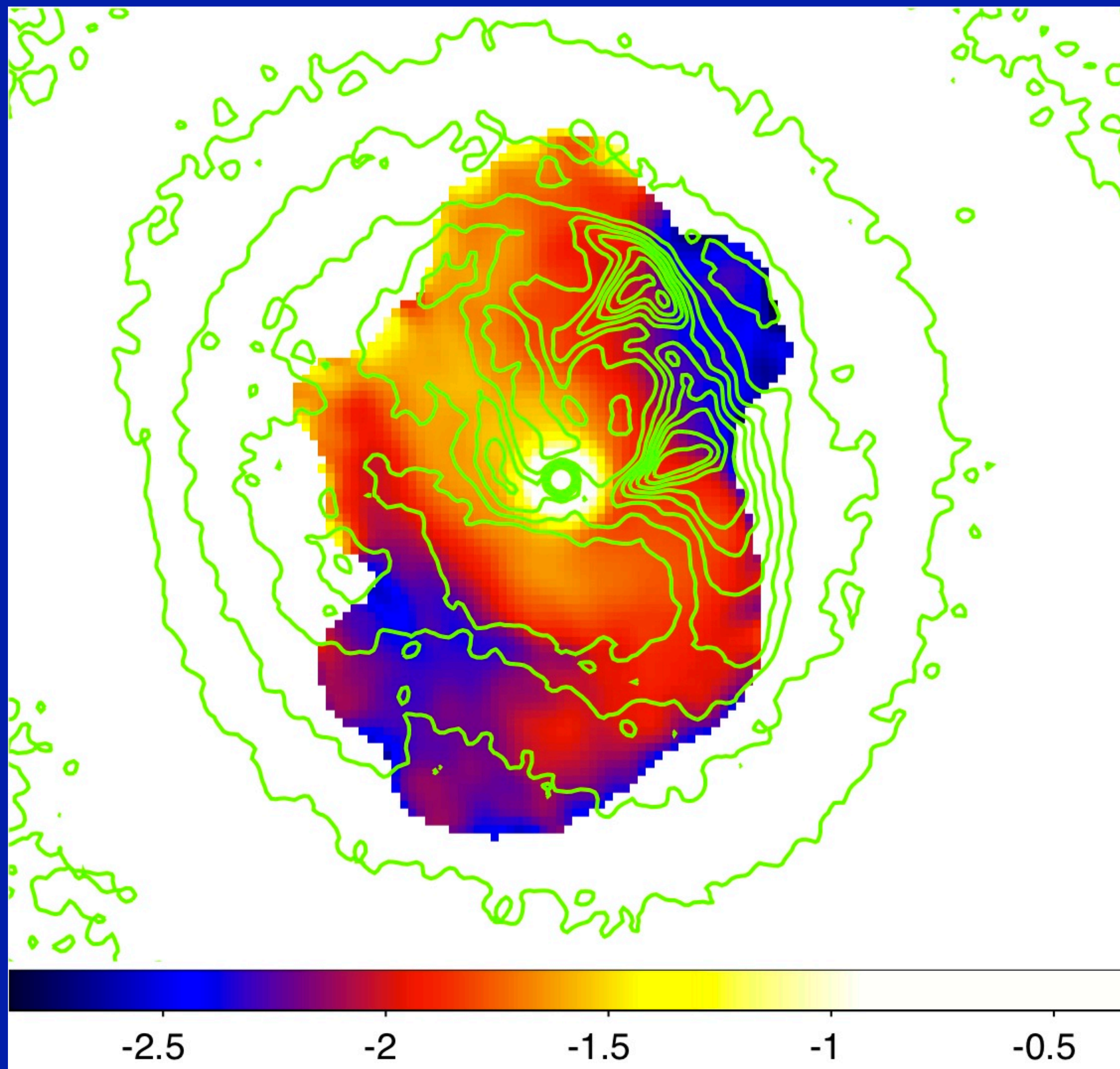
- For the inner shock, the best-fitting temperature rise is a factor of 1.12, and within the errors, is consistent with the expected rise of a factor of 1.16.

Repetition rate of AGN



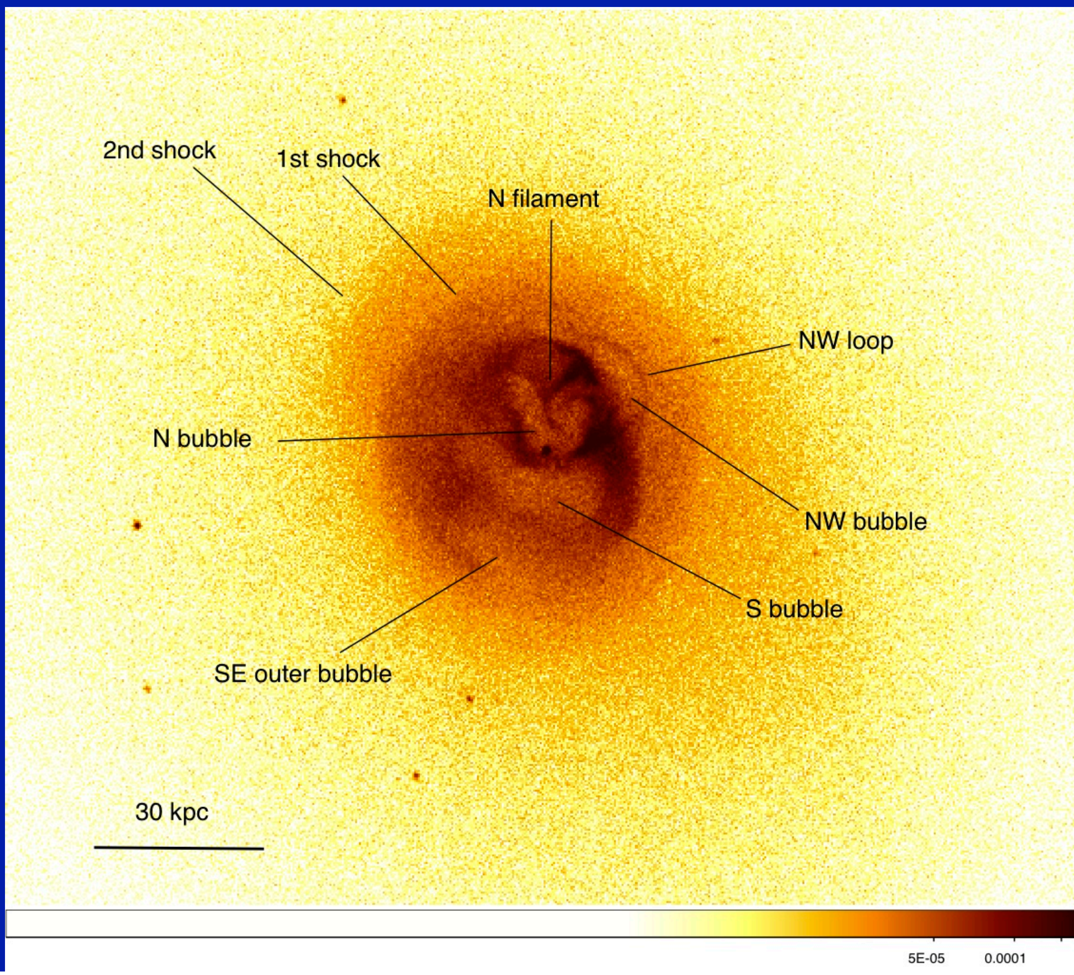
- Estimate cycle time (time between radio source outbursts) using shock velocities and offsets, or buoyantly rising bubbles.
- Both methods give t ~ 2 x 10^7 yr.

Radio Spectral Index Map

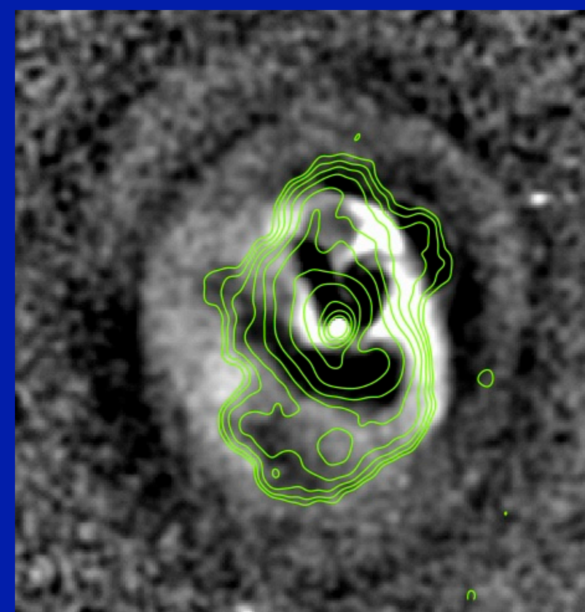


Abell 2052: Bubble Energy Input

$$\frac{1}{(\gamma - 1)} PV + PdV = \frac{\gamma}{(\gamma - 1)} PV$$



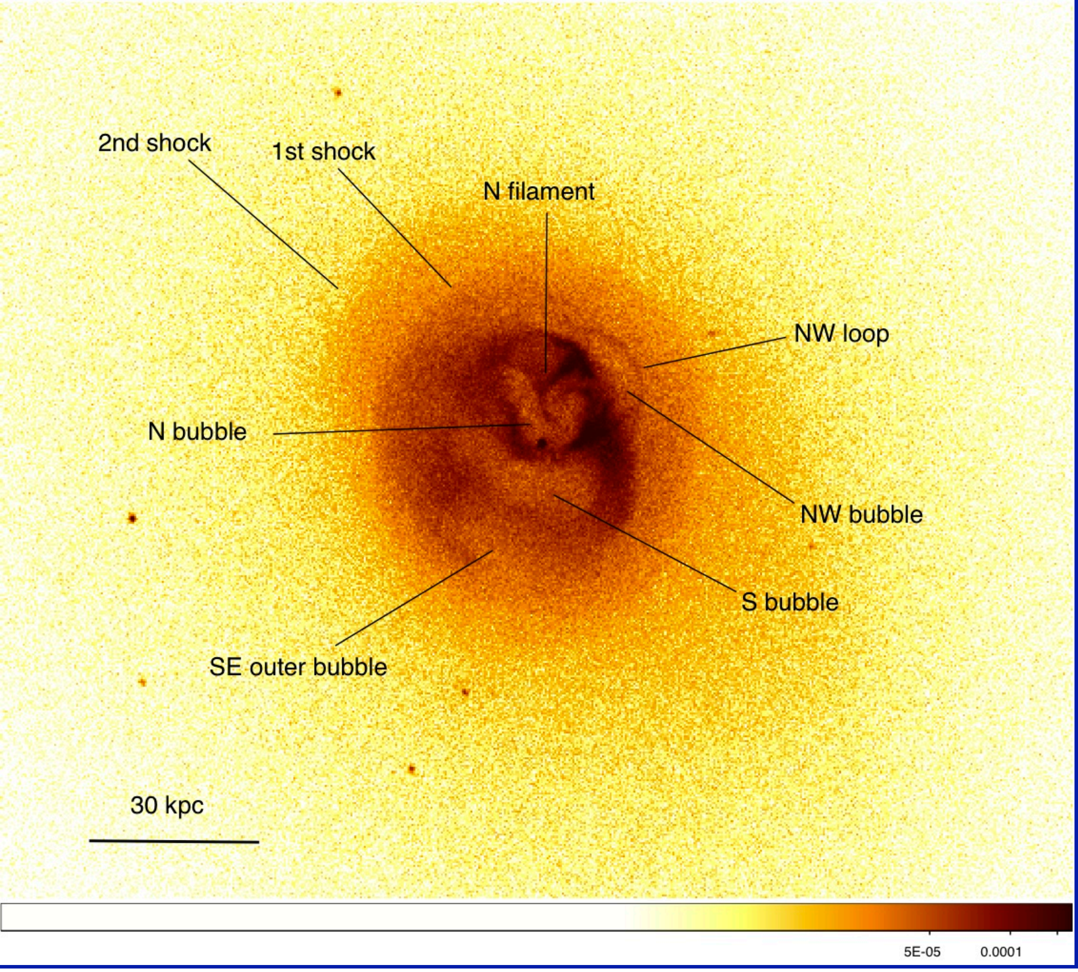
- Using γ=4/3, the energy input rate is 3.2 x 10^{43} erg s^{-1} (6.4 x 10^{43} erg s^{-1}) assuming the bubbles rose at 0.5 (1) times the sound speed



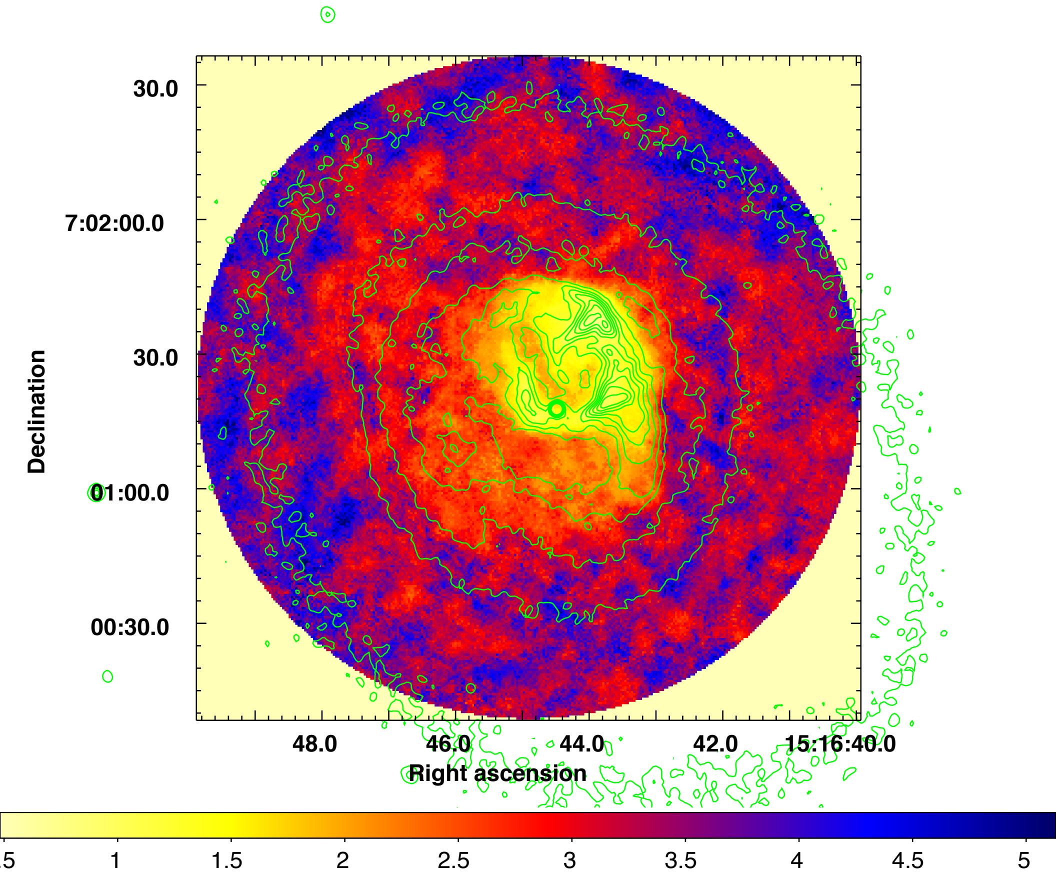
Abell 2052: Shock Energy Input

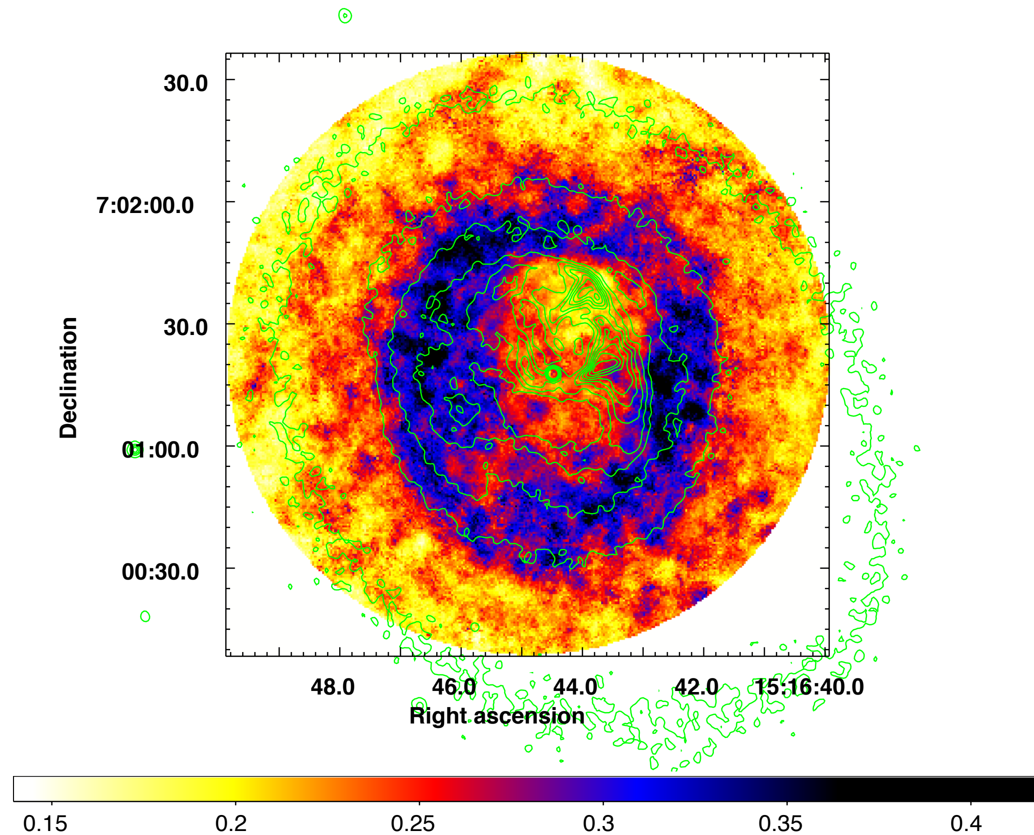
$$\Pi_s = \frac{(\gamma+1)P}{12\gamma^2}\left(\frac{\omega}{2\pi}\right)\left(\frac{\delta P}{P}\right)^3$$

McNamara & Nulsen (2007)



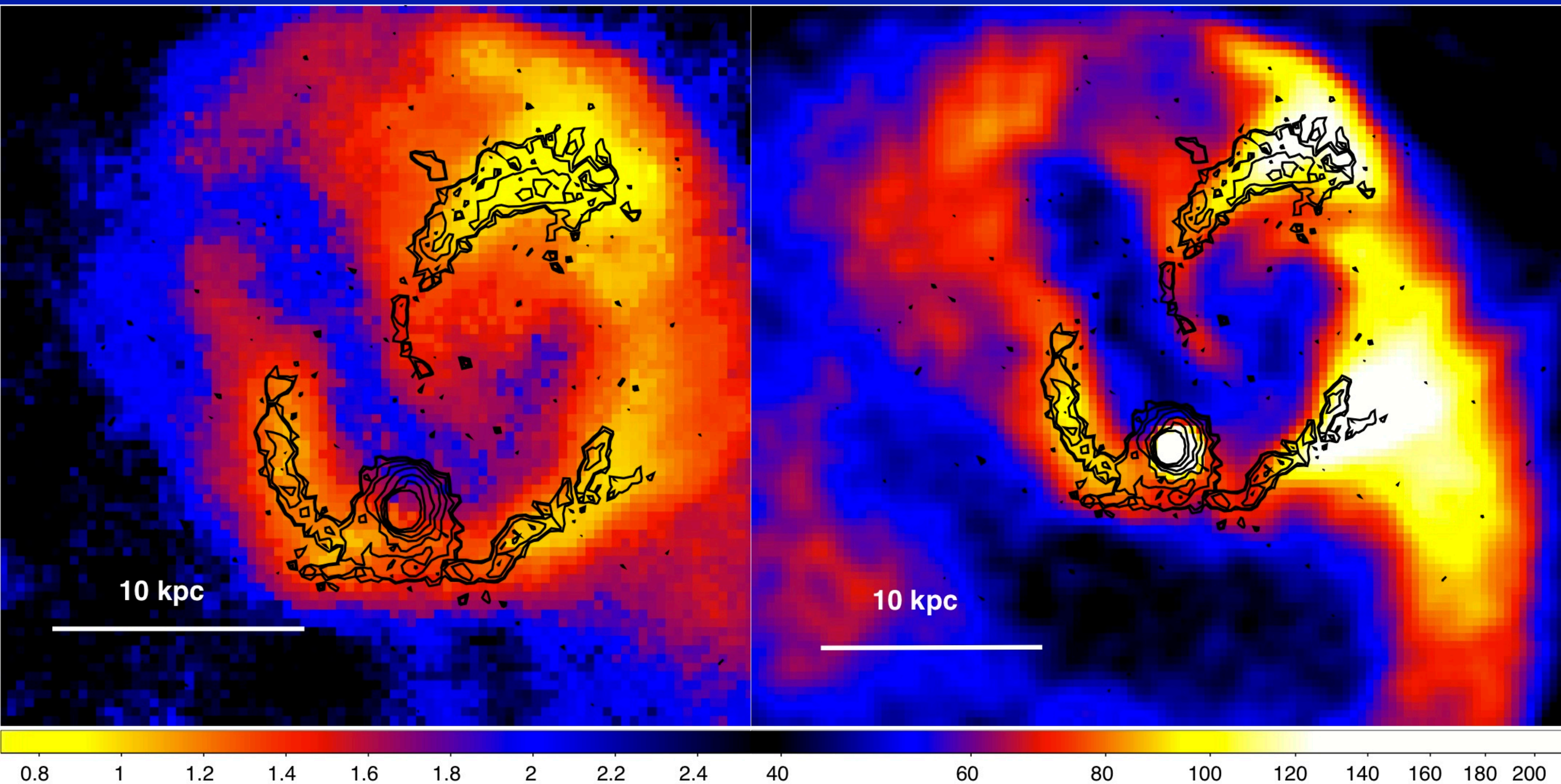
- The shock energy input rate is 1 x 10^{43} erg s^{-1}, a factor of 3-6 lower than the energy input from buoyantly rising bubbles.
- The combination of rising bubble and shock heating offsets the cooling rate of 5.4 x 10^{43} erg s^{-1}





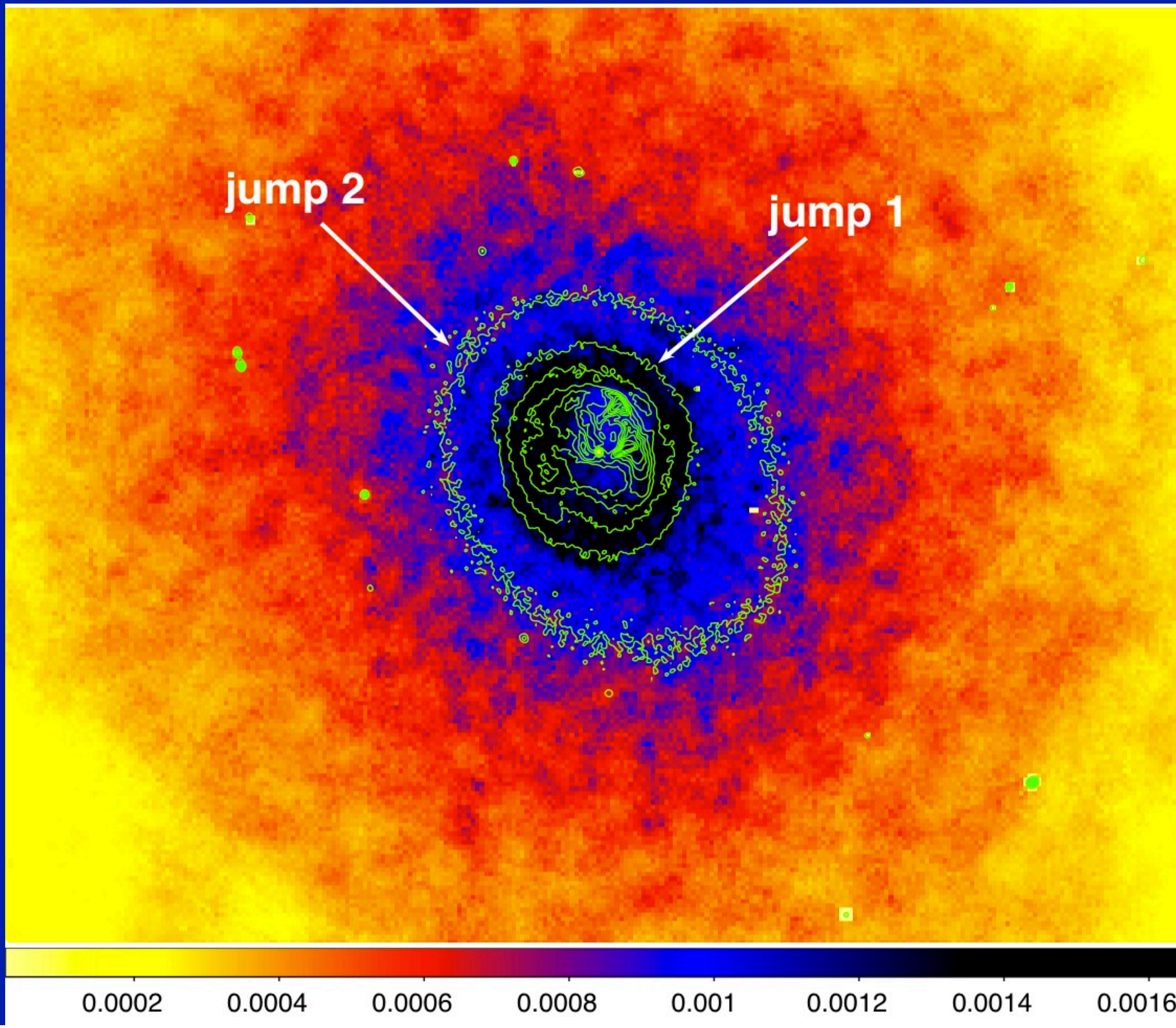
Temp Map

Pseudo-Pressure Map

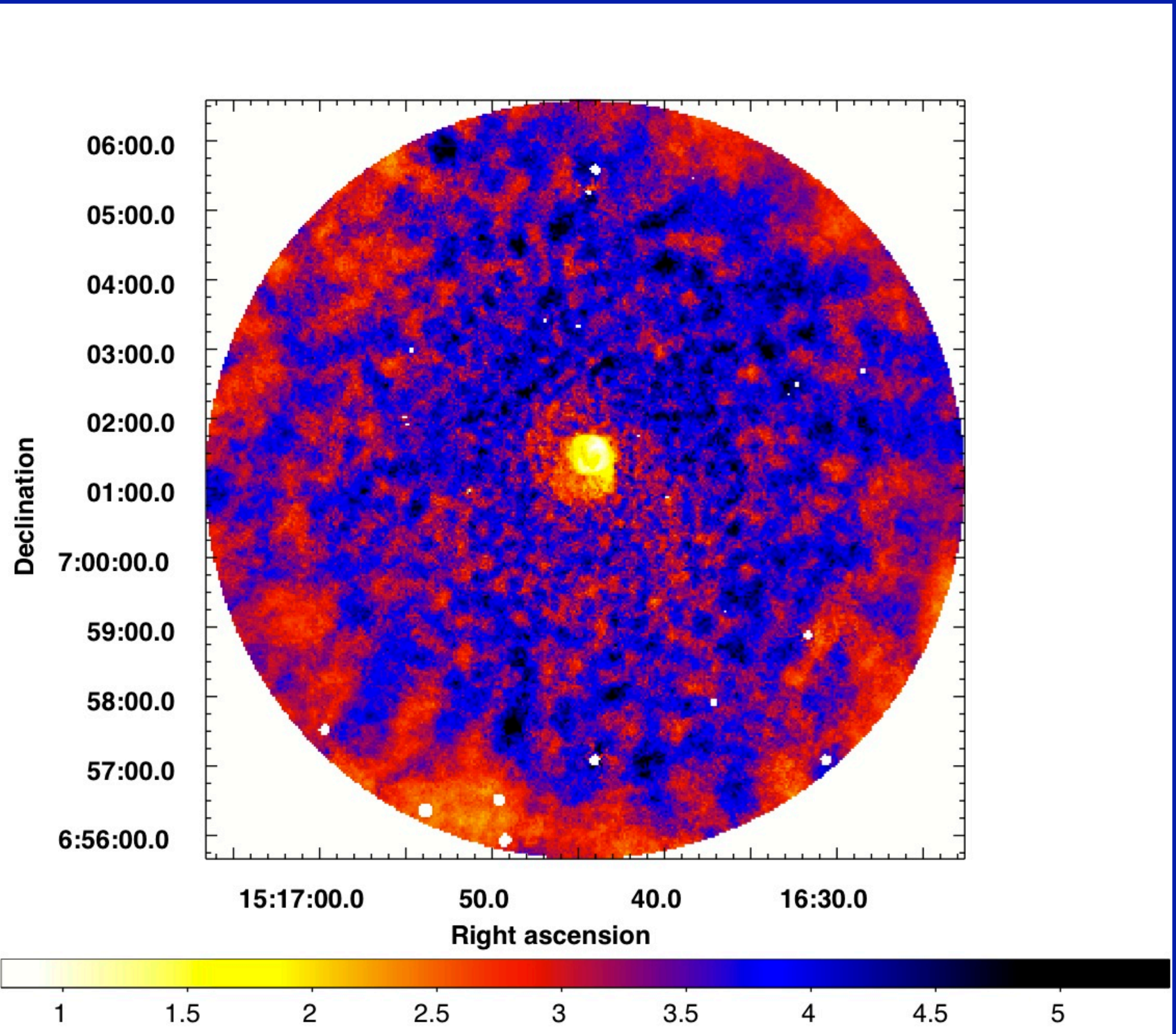


H-alpha/Tmap   H-alpha/image

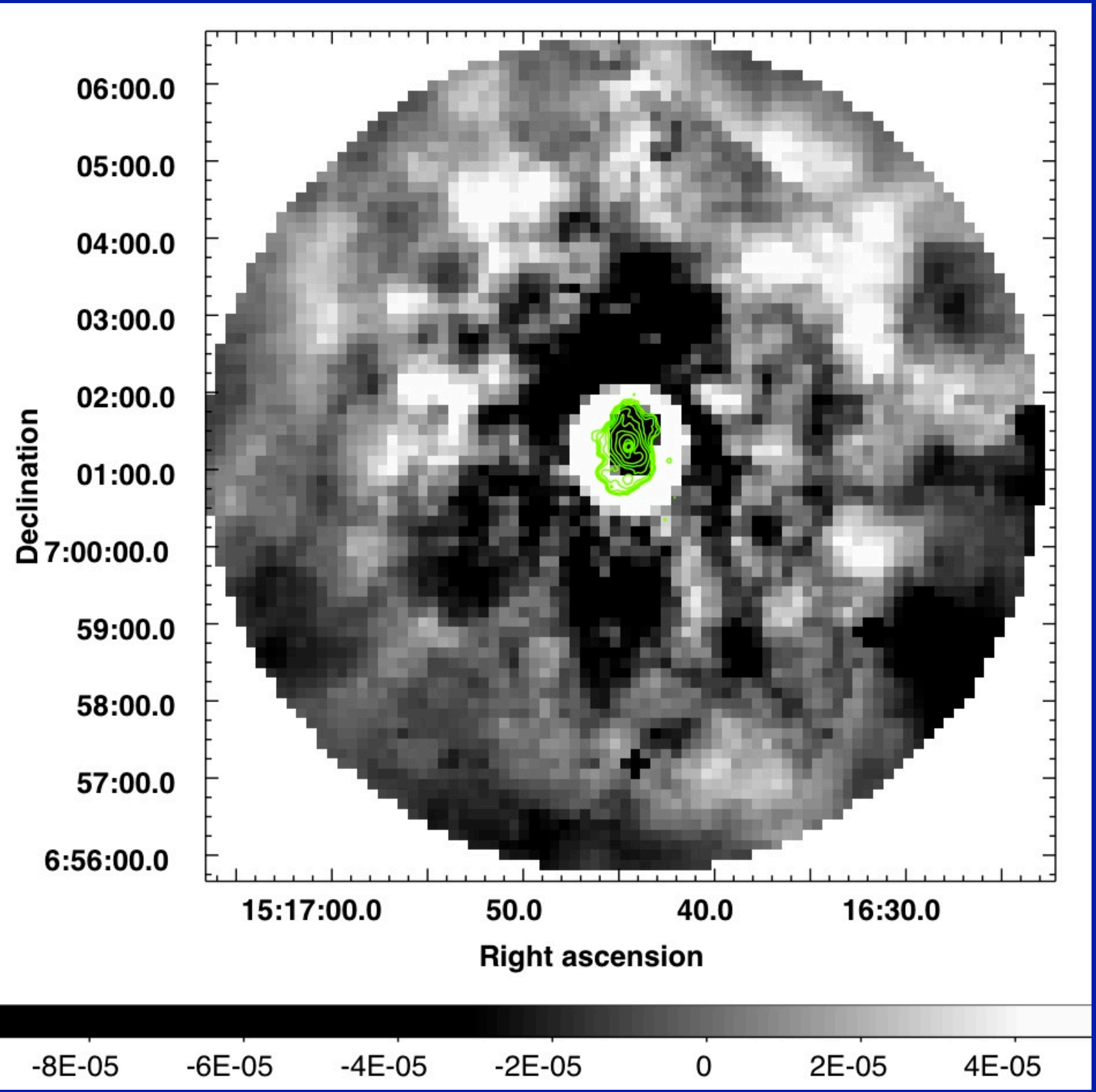
Pseudo-Pressure Map



High-Res Temp Map

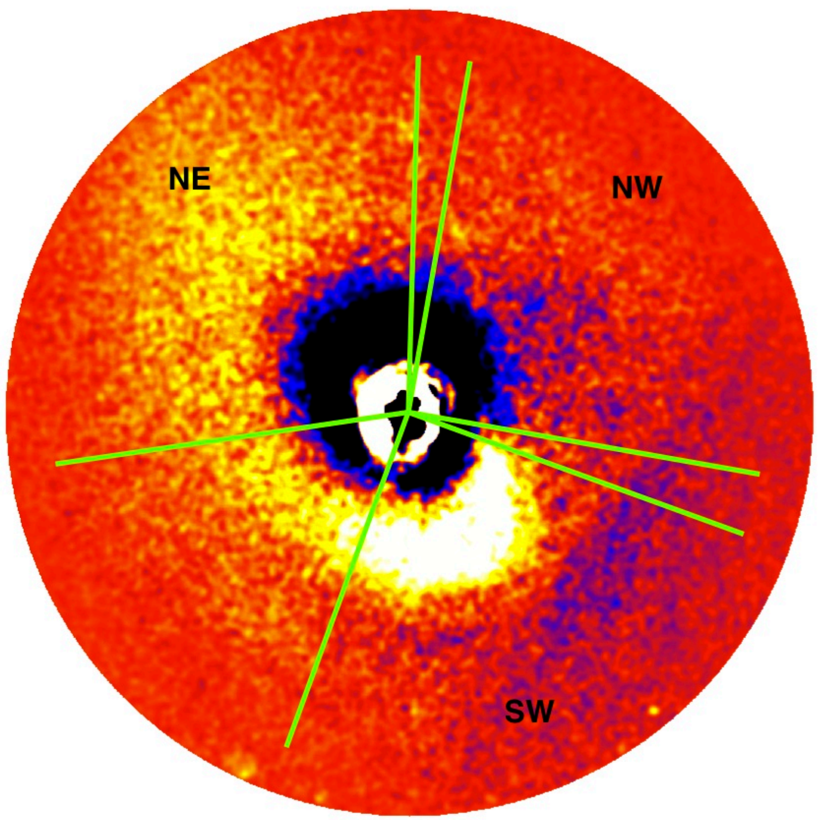


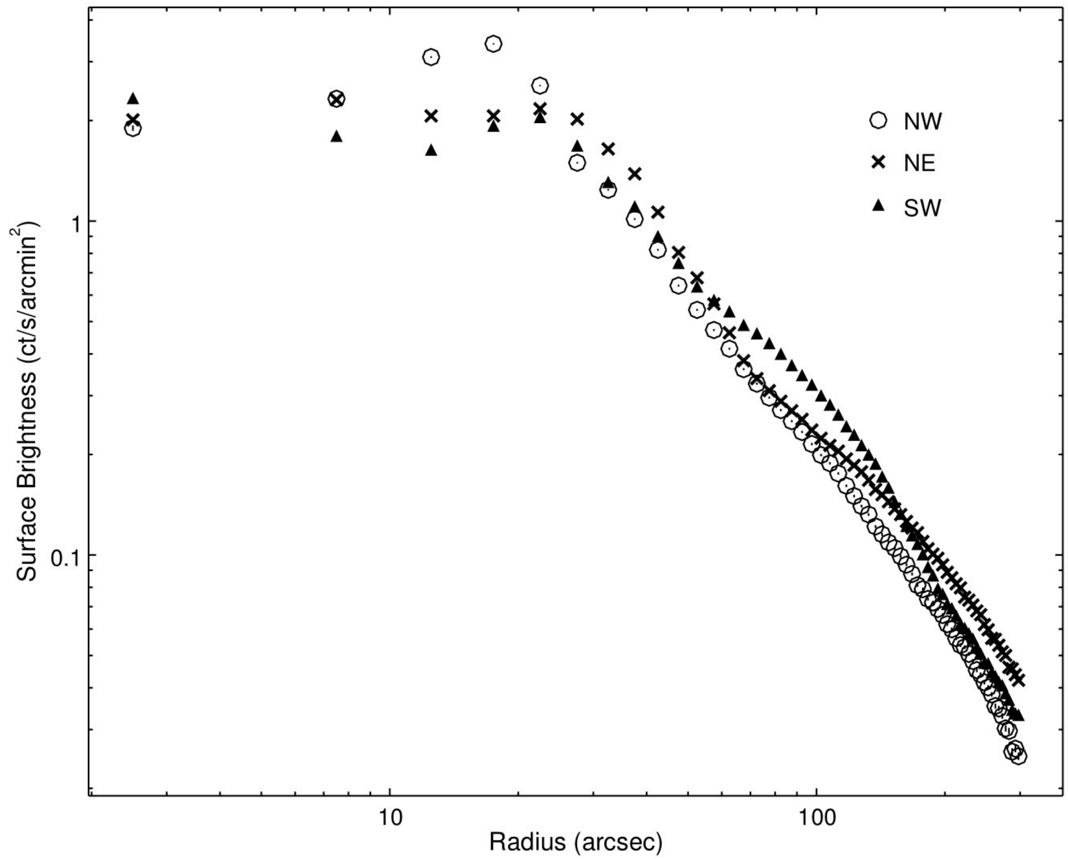
- More than 80,000 spectral fits.
- Small-scale structure in temperature and pressure may be related to turbulence, B-field fluctuations, DM sub-halos… (Randall et al., in prep)



- Residual pseudo-pressure map.
- Outer bubbles to N and S, each with E~10^{60} erg

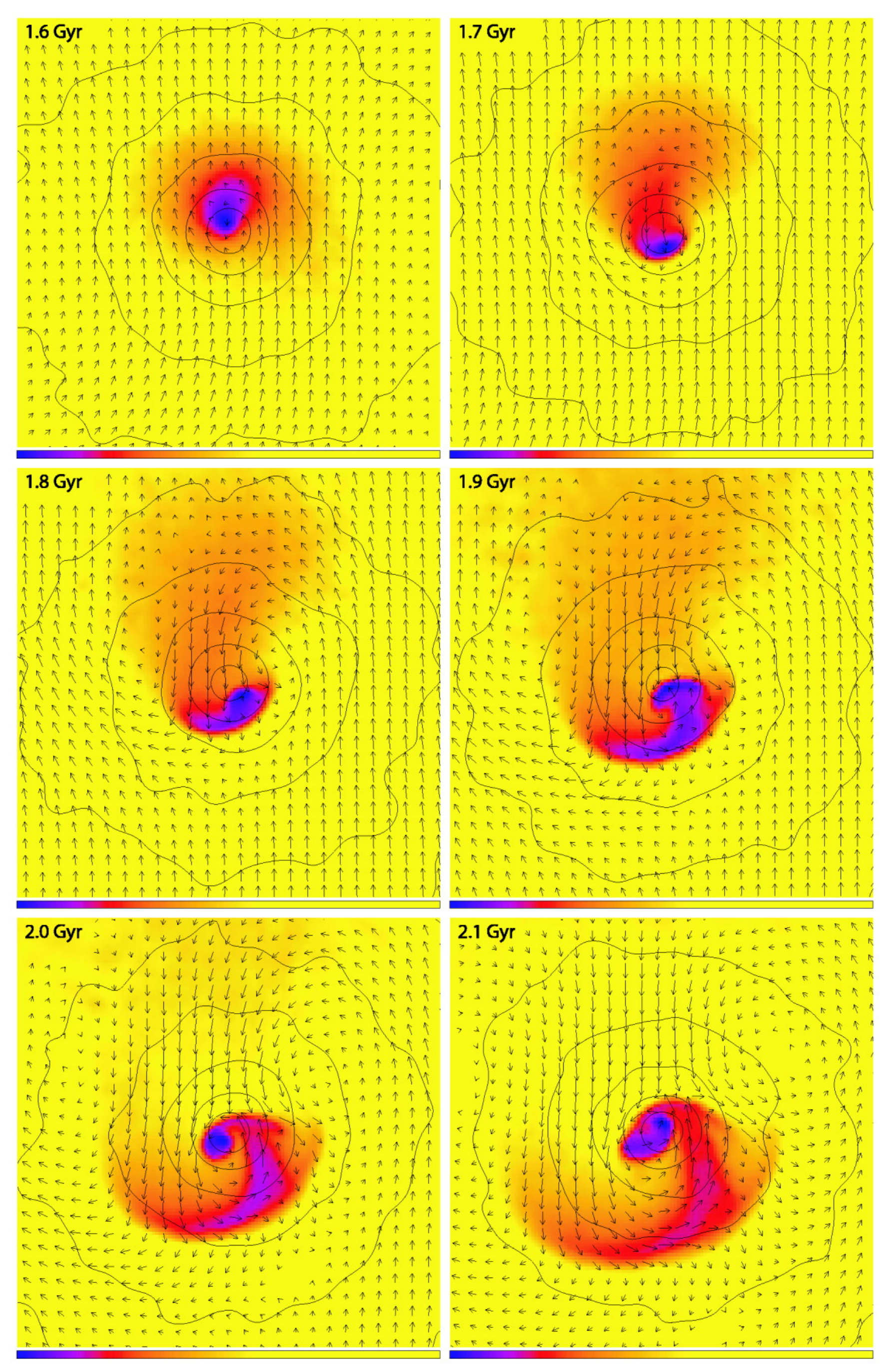
A2052: Sloshing



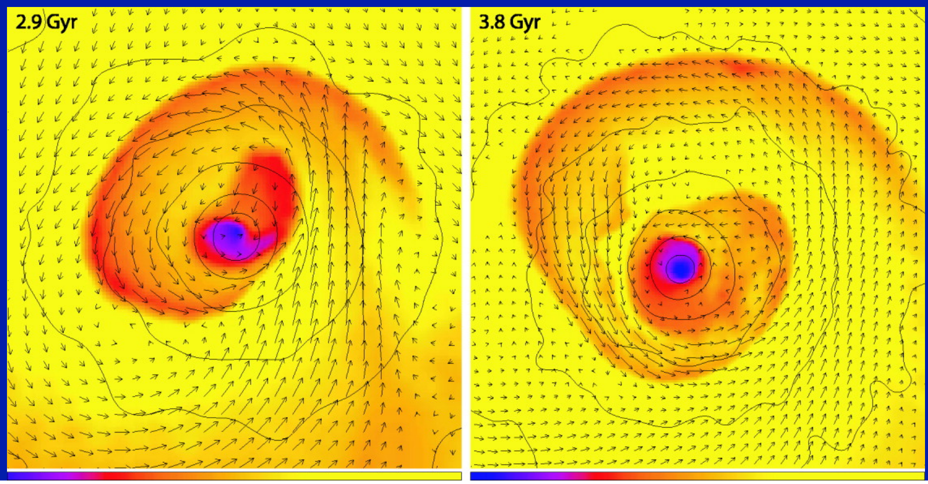


240 kpc radius circle
model-subtracted image

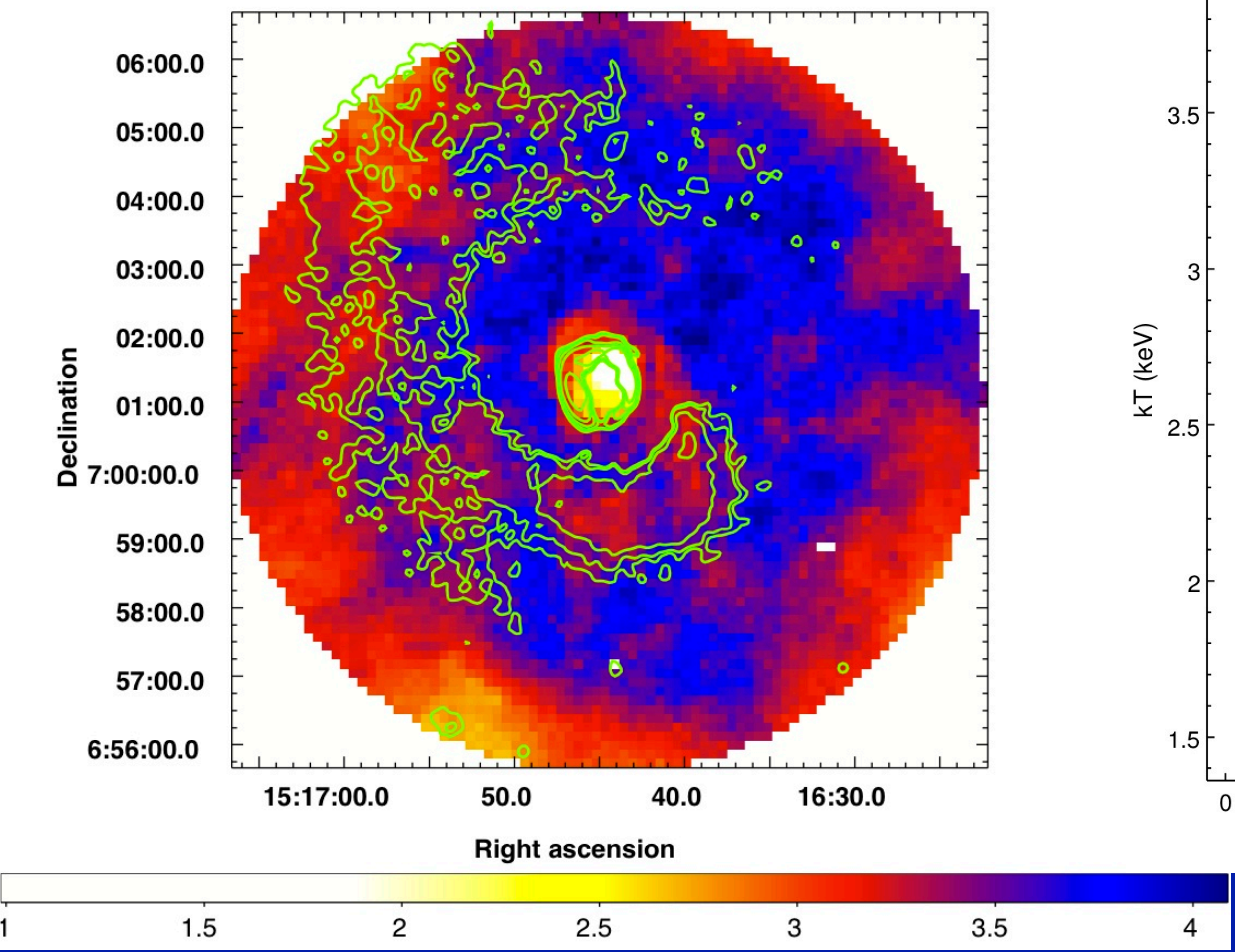
Sloshing Simulations

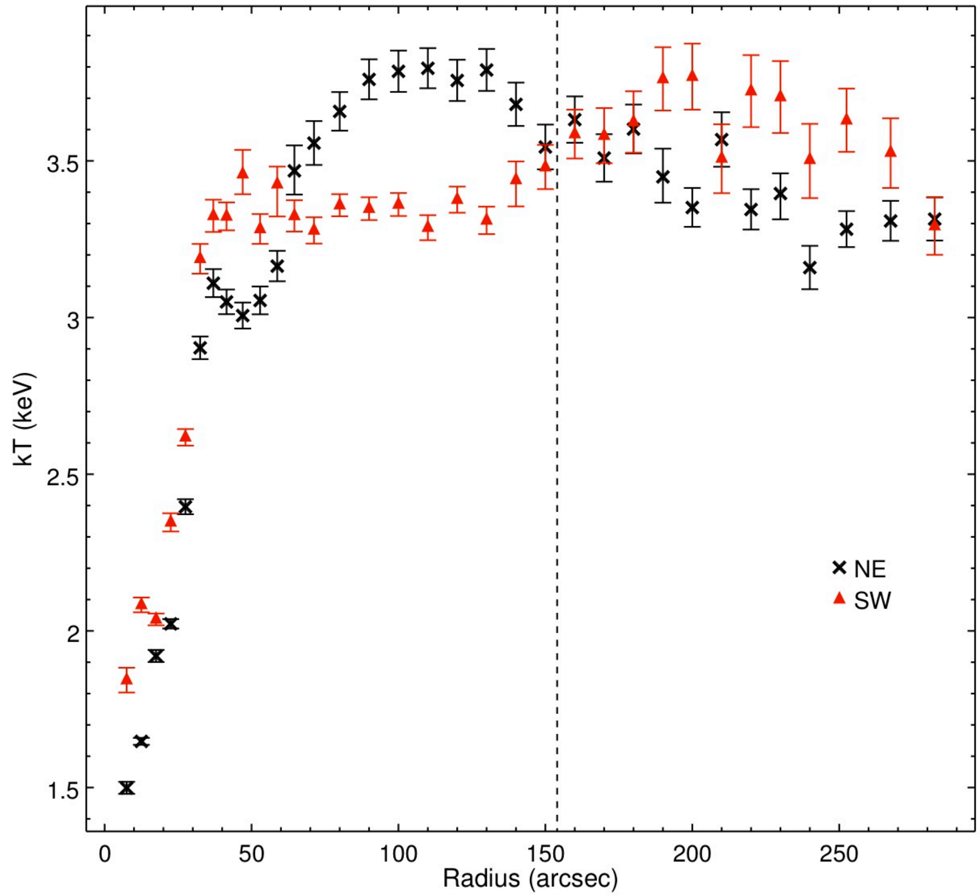


Temperature maps showing cool, spiral feature produced in core gas sloshing (Ascasibar & Markevitch 2006)



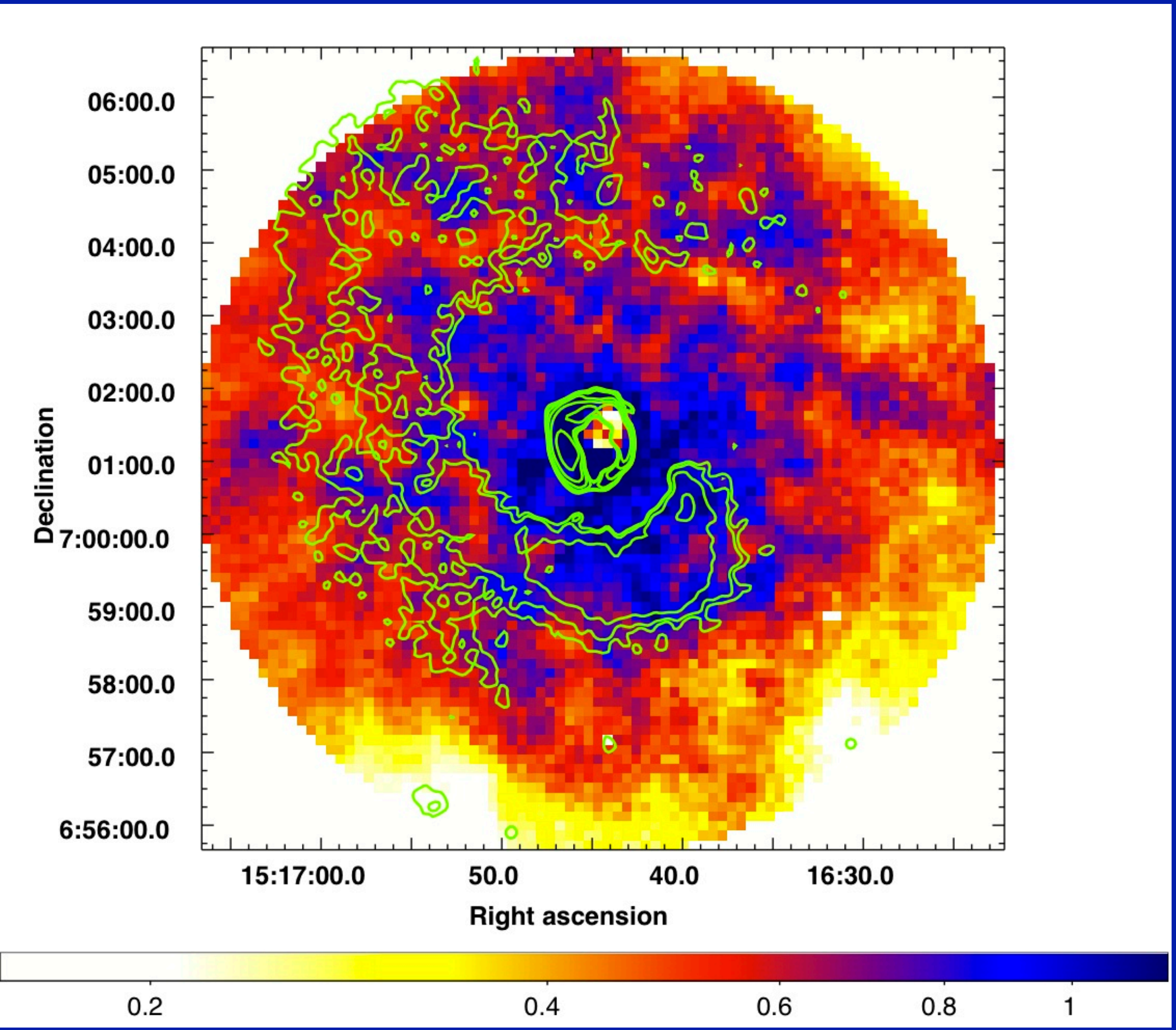
A2052: Sloshing





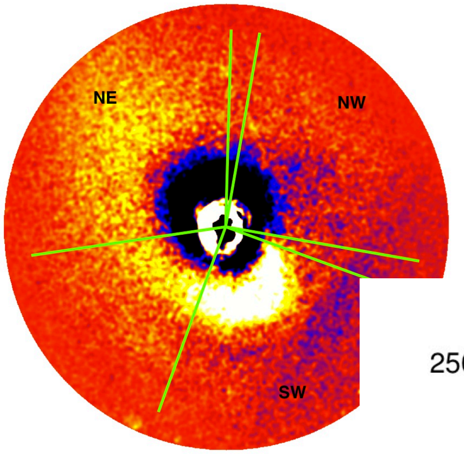
Temperature map

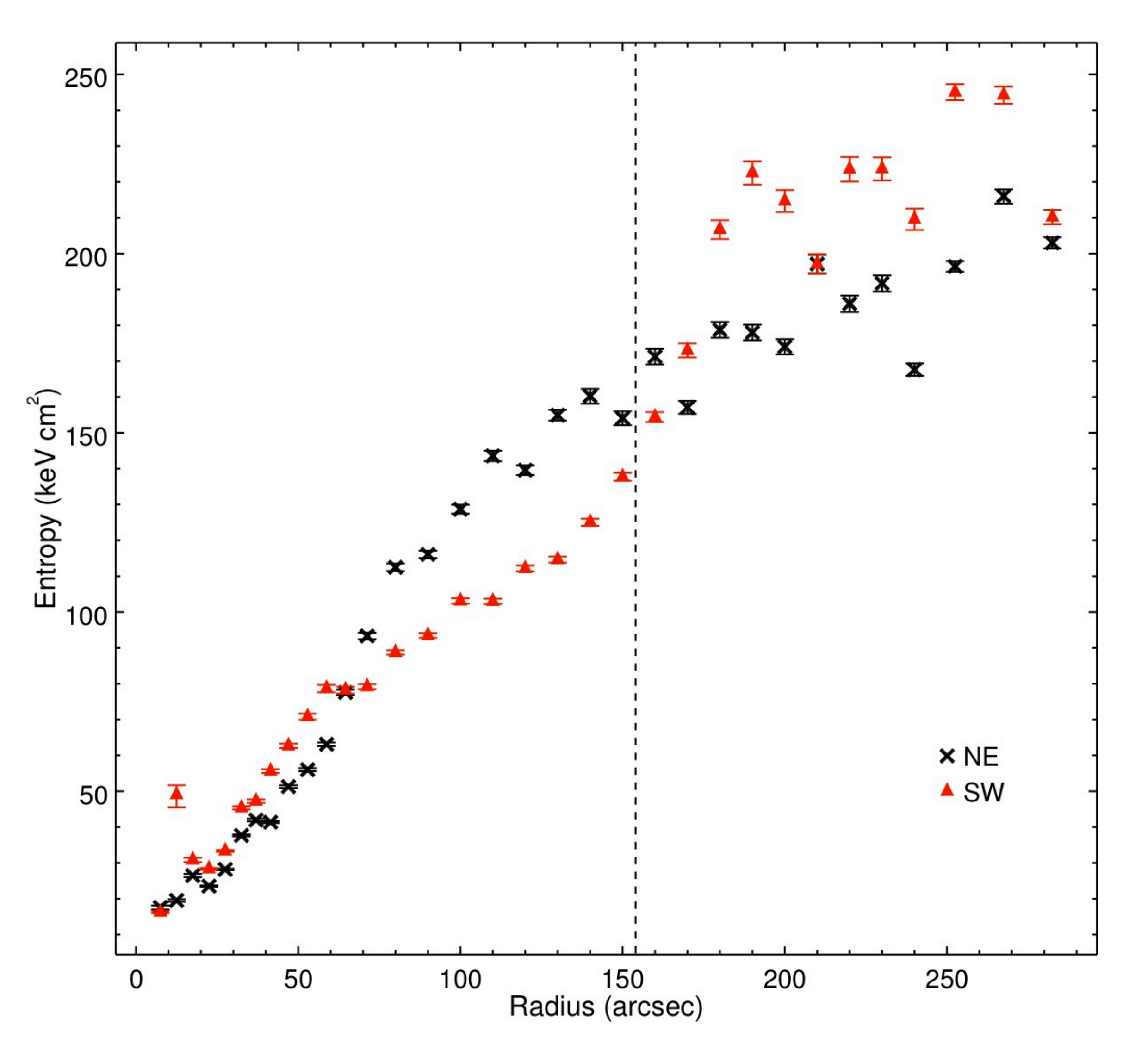
Sloshing



- Sloshing also contributes to core heating, by redistributing cool gas to larger radii.
- Distribution of elements is also affected.

Sloshing / Entropy

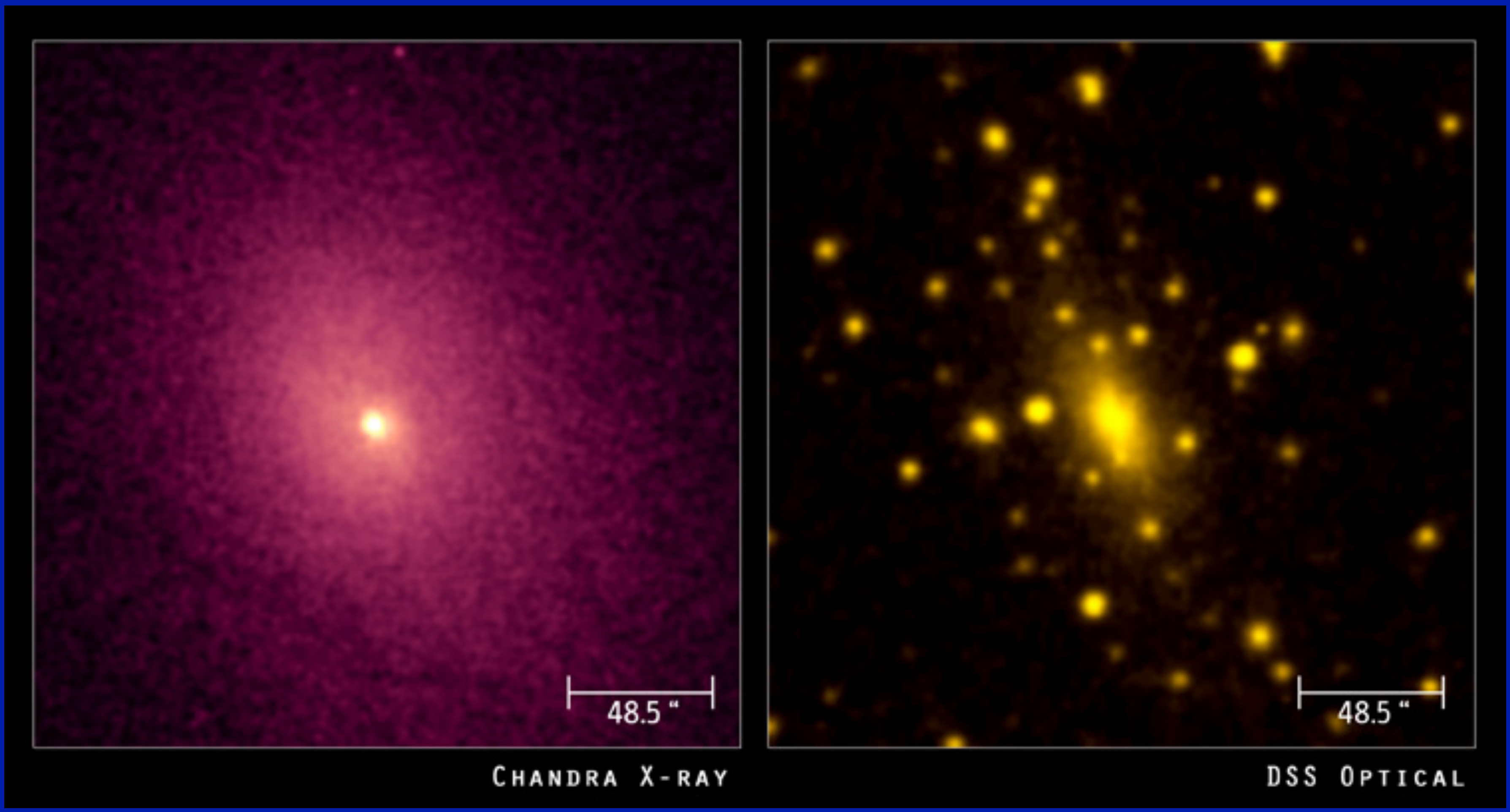




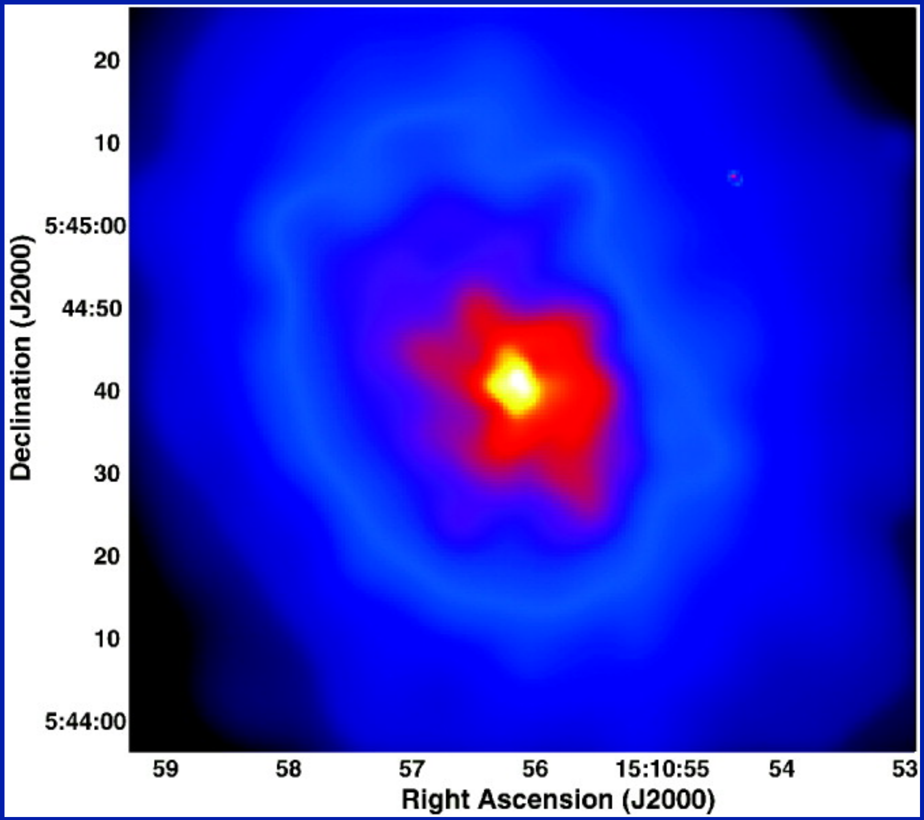
$S = kT / n^{2/3}$

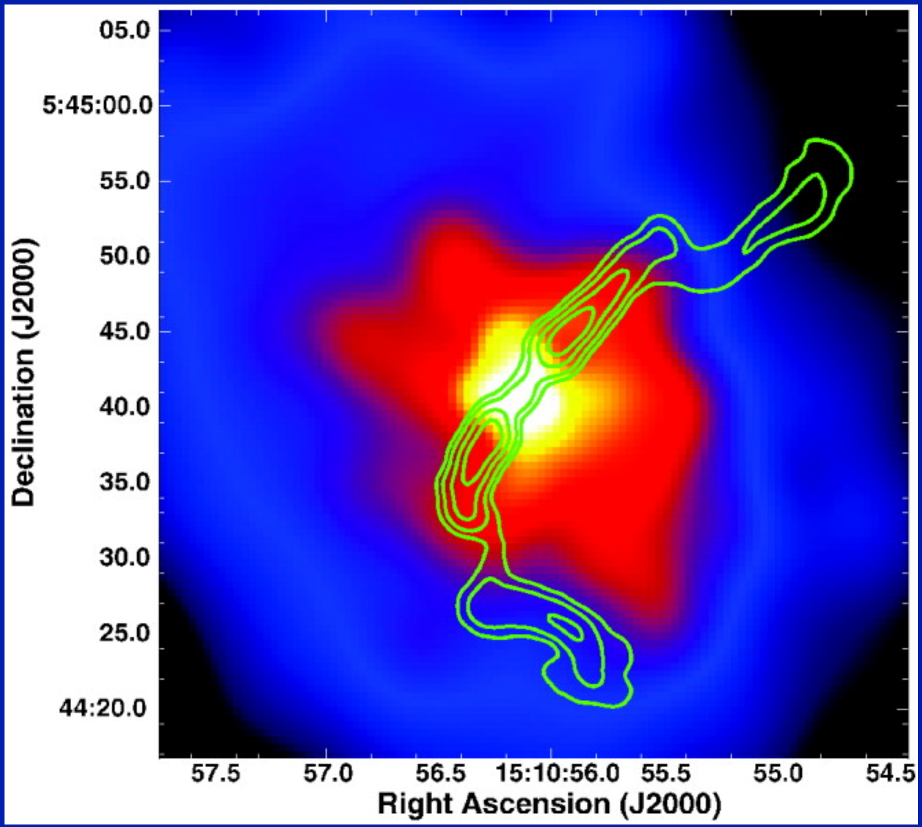
Bonus Material!

A2029: Can Sloshing Bend Radio Lobes?



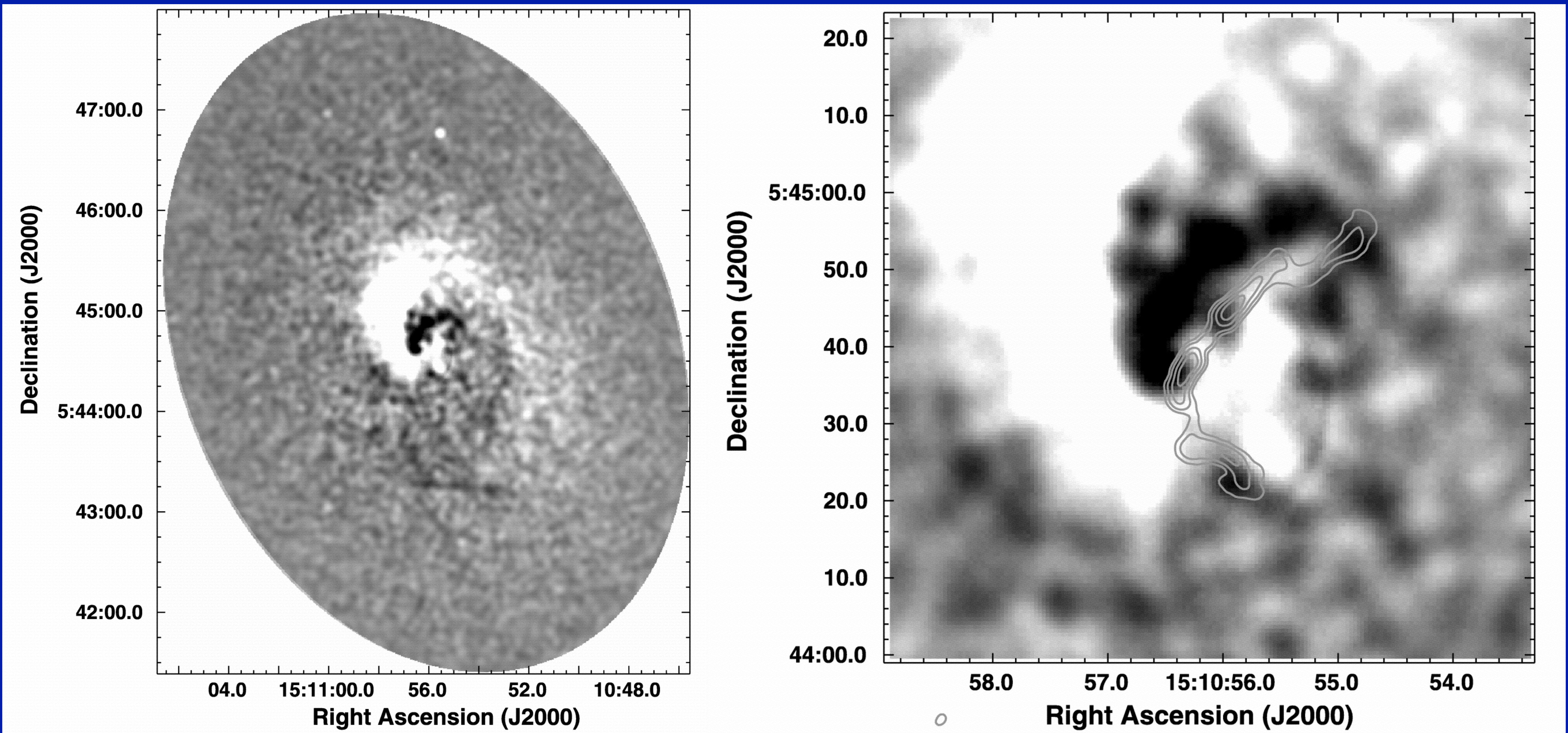
A2029





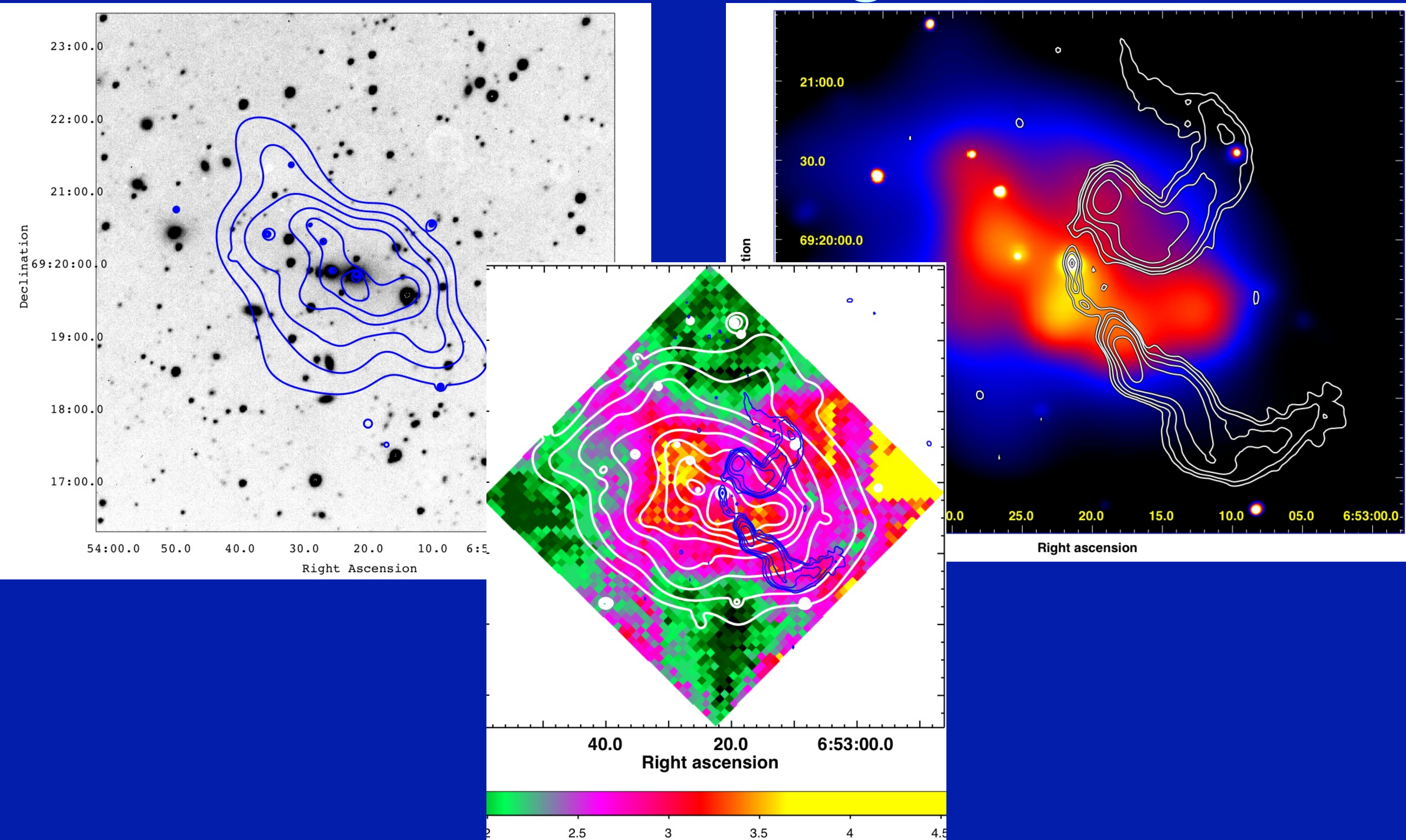
Clarke, Blanton, & Sarazin (2004)

A2029: Sloshing



Clarke, Blanton, & Sarazin (2004)

A562: Merger



Douglass, Blanton et al. (2011)

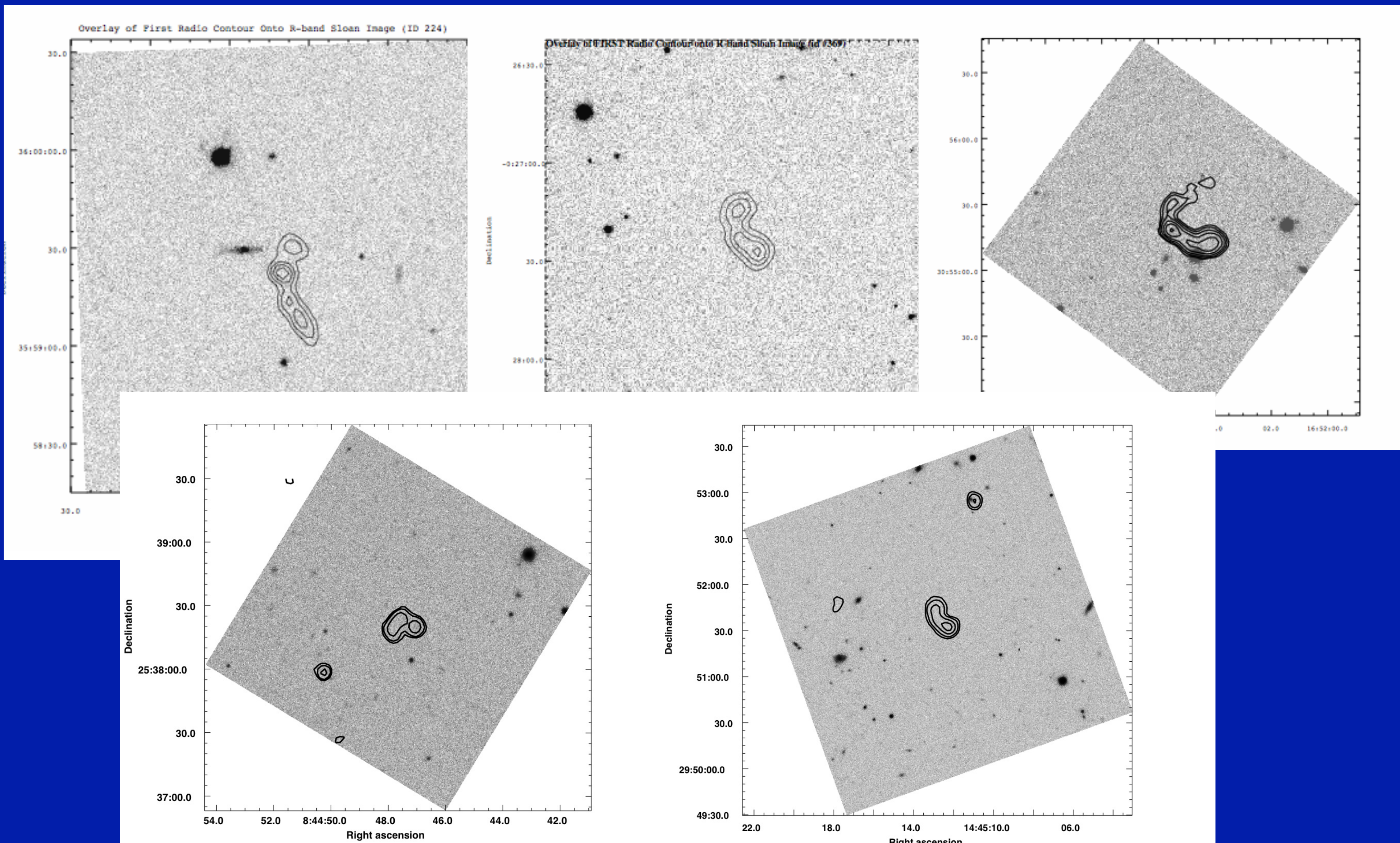
Environments of Radio Sources (FIRST + SDSS)

- Percentage of sources in clusters

	N > 40	N > 20
– Single component	10%	29%
– Straight	24%	43%
– Auto Bent	41%	59%
– Visual Bent	62%	78%

Wing & Blanton (2011)

New Probable High-z Clusters



FIRST 1.4 GHz radio contours overlaid on SDSS r-band images.

- Awarded Spitzer Snapshot program to observe 653 bent-double radio sources without optical ids in SDSS.
- Expect ~400 new clusters with z>0.7.

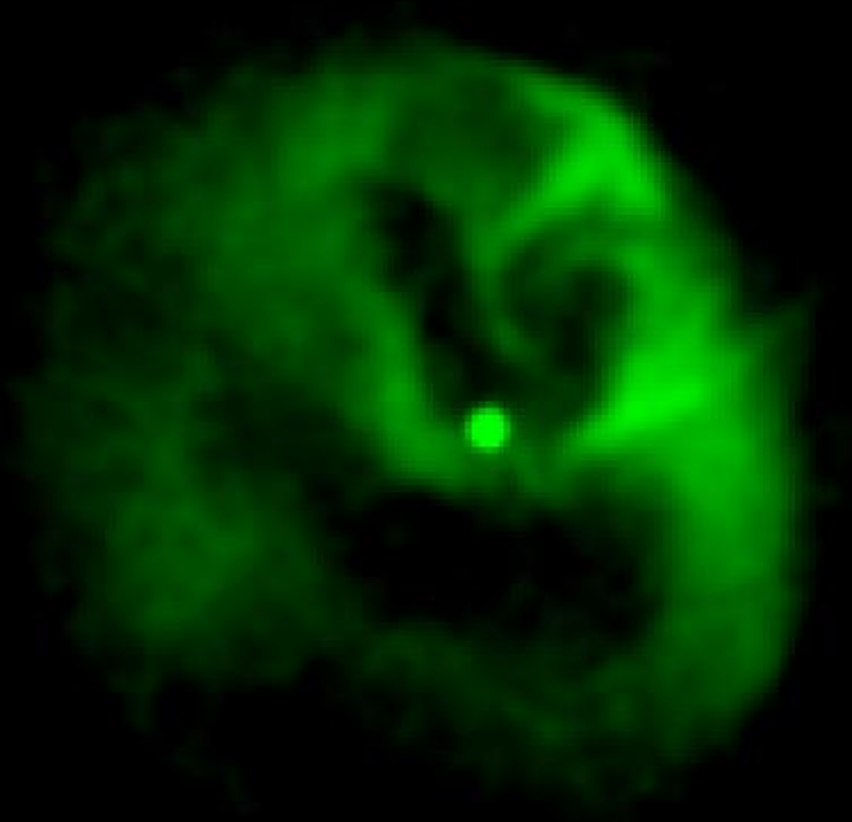
- See posters by Douglass et al. and Wing et al., for environments of bent radio sources.

Conclusions

- Abell 2052 excellent case for studying cluster physics, showing that:
  - Radio sources displace the X-ray-emitting gas in the centers of cool cores, creating cavities or "bubbles."
  - Buoyant bubbles transport energy (and magnetic fields) into clusters.
  - Shocks also transport energy.
  - Sloshing contributes to heating and metal redistribution.
  - Cooling losses can be offset by combination of energy inputs.

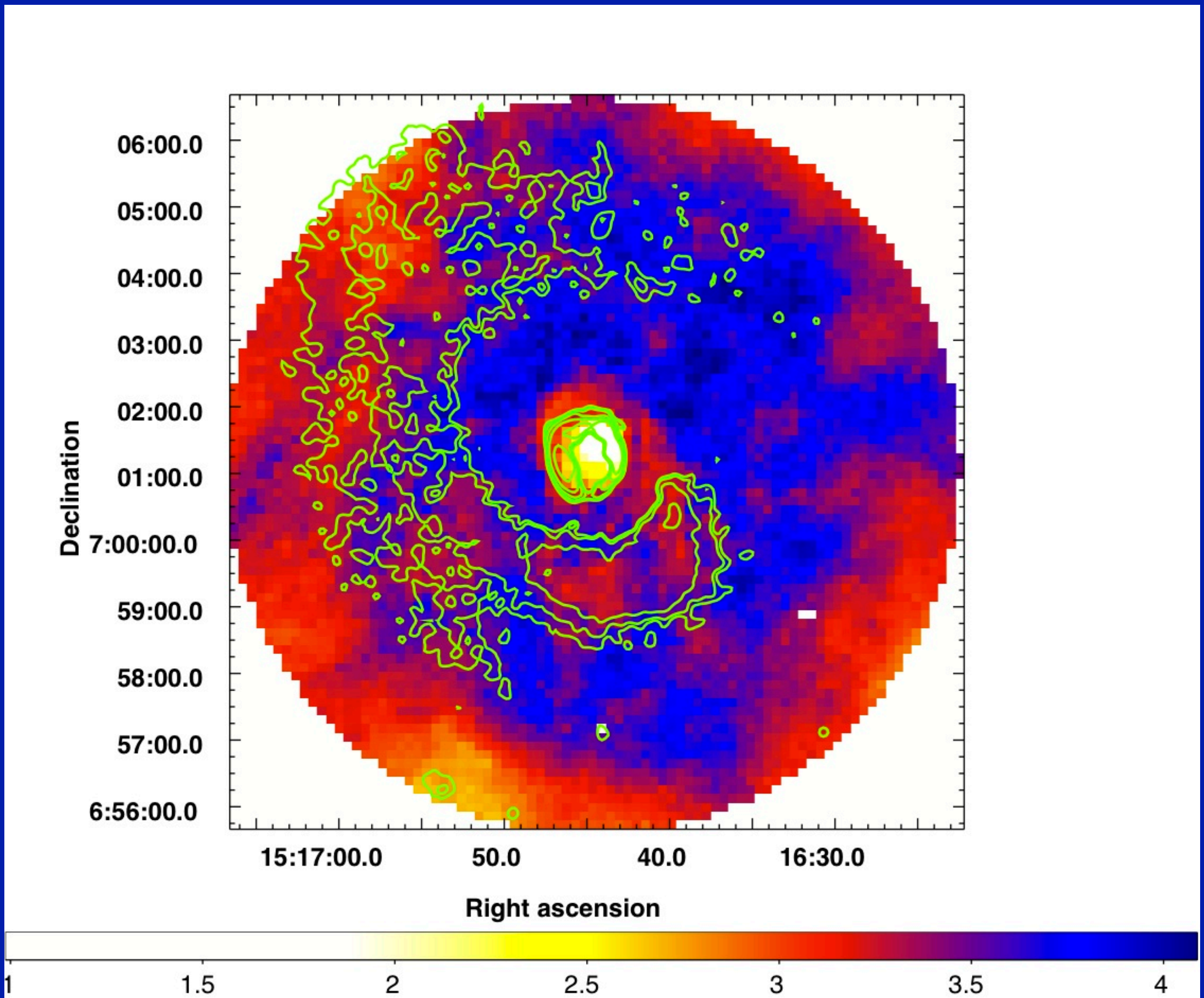
Conclusions

- Since distorted radio sources often attain their morphologies from interaction with the ICM, they can be used as tracers for distant clusters and groups of galaxies.
- Cluster finding technique that is different from, and complementary to, other methods.
- Can locate clusters with wide range of masses.
- May be mergers, or systems with sloshing.
- Good targets for studying feedback at high-z.

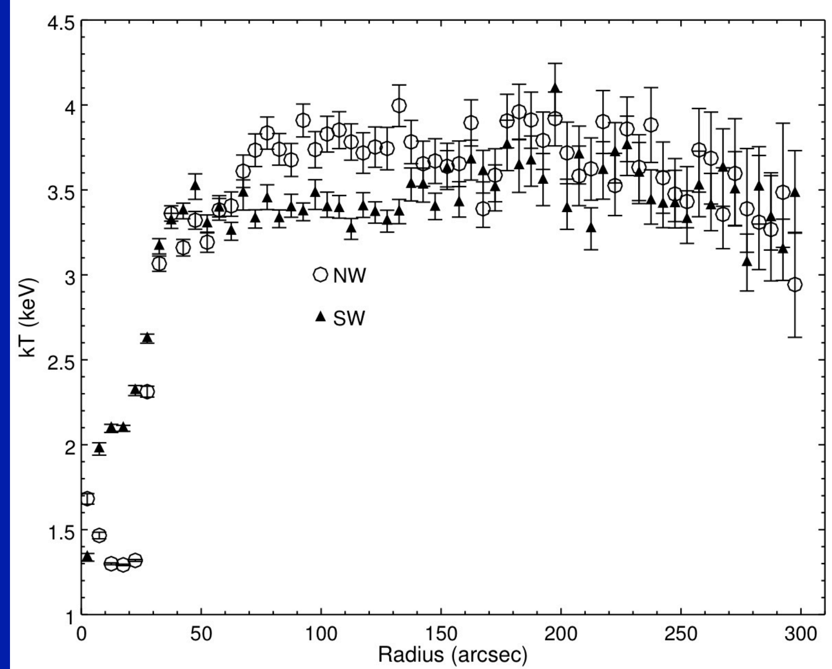


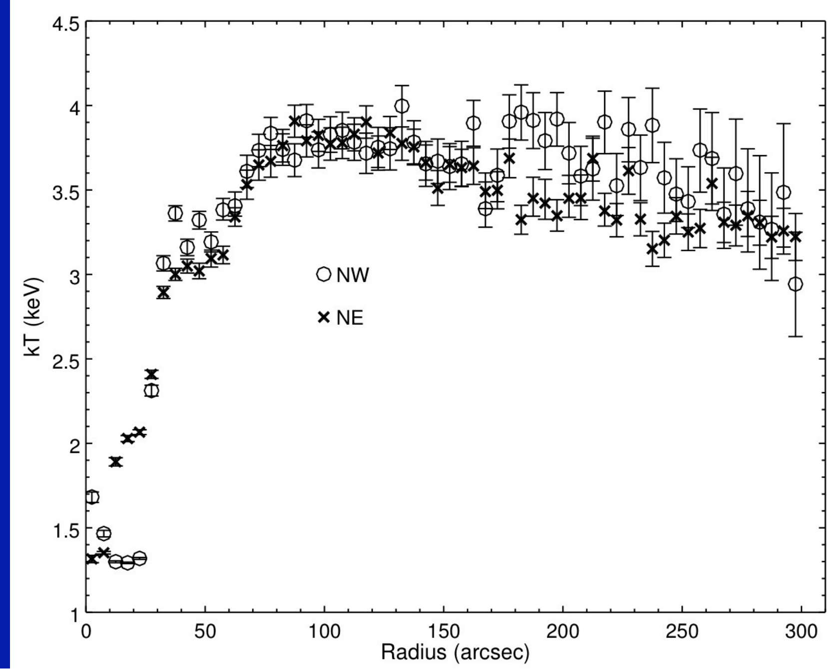
Thanks!

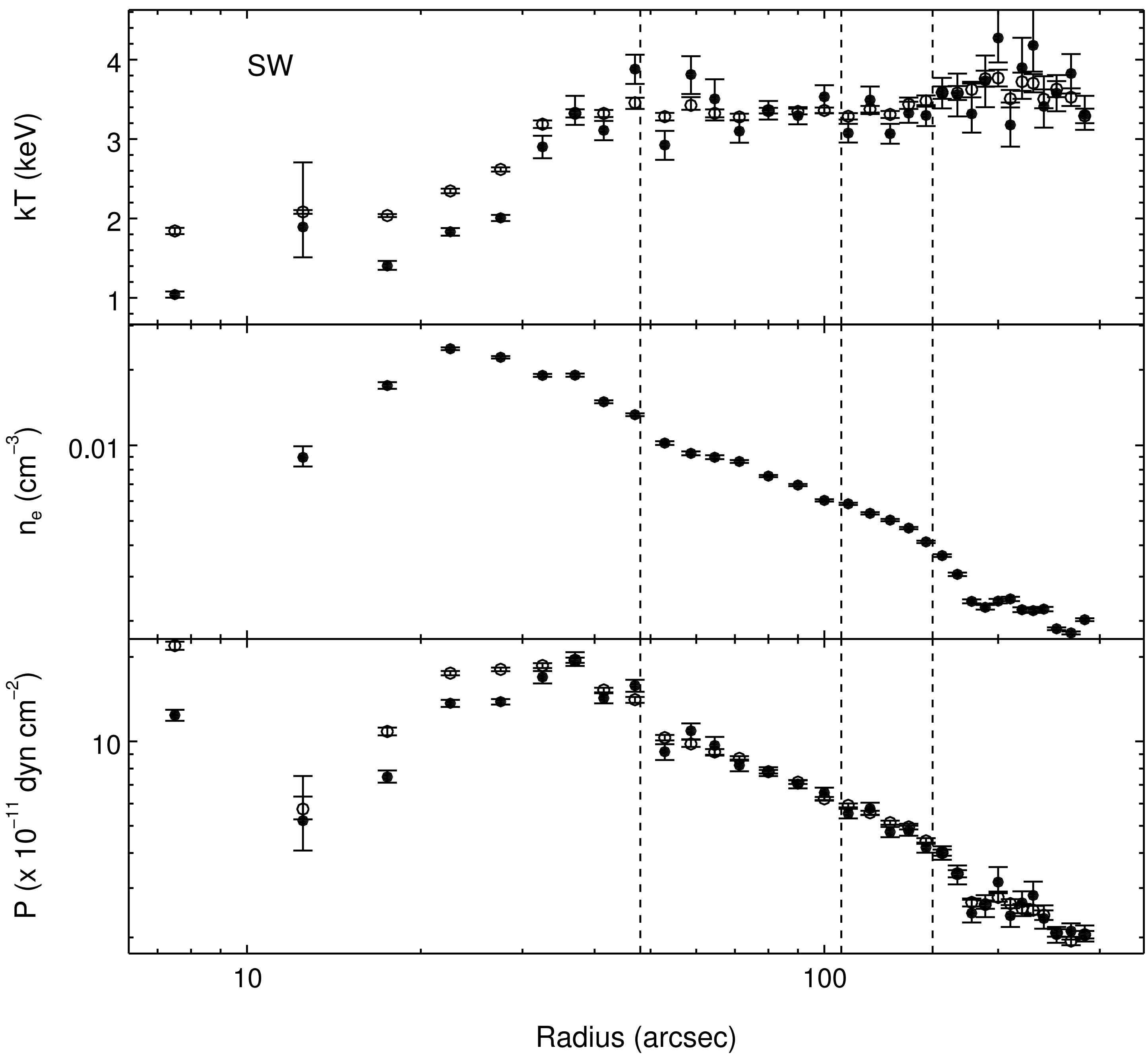
A2052: Sloshing



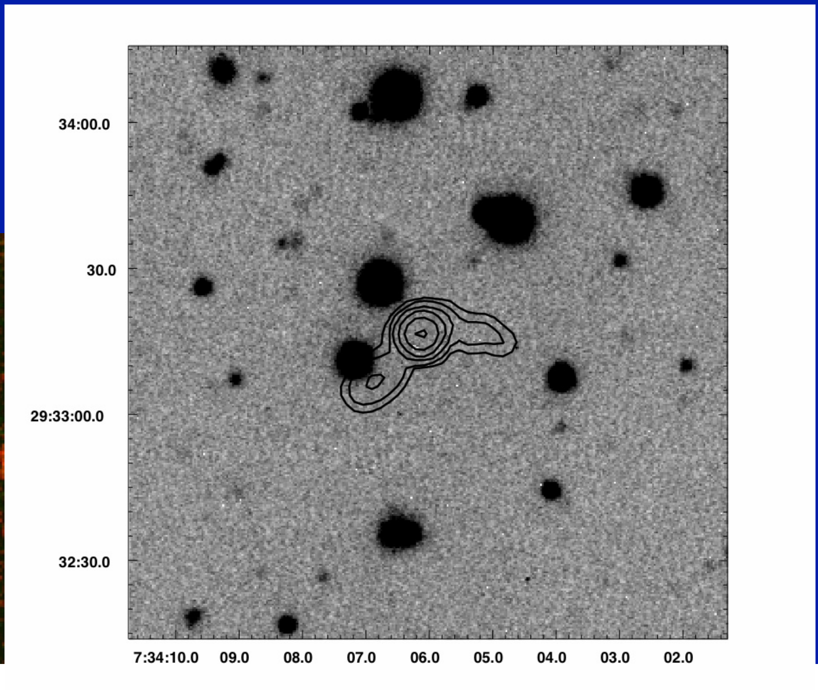
Temperature map

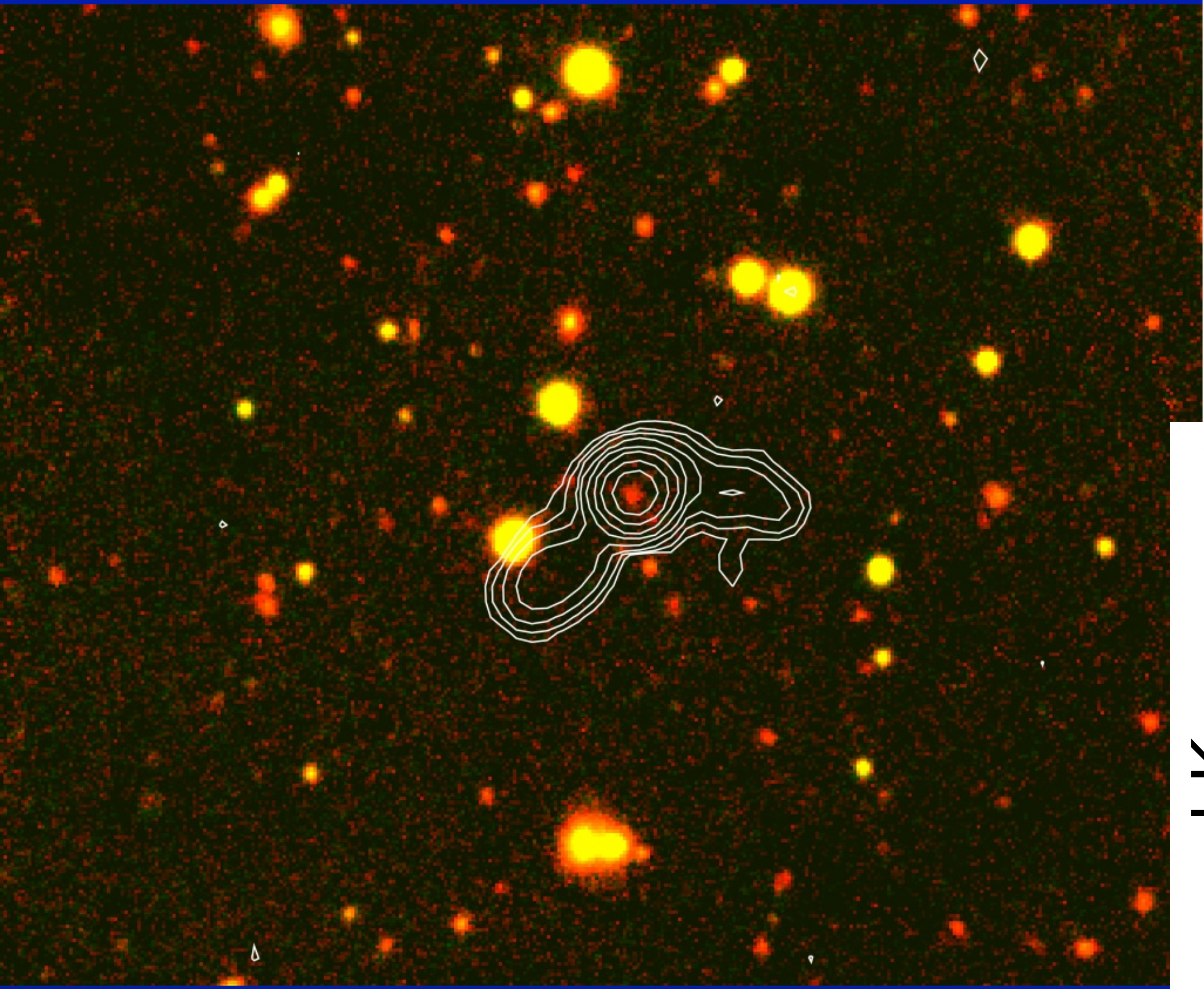


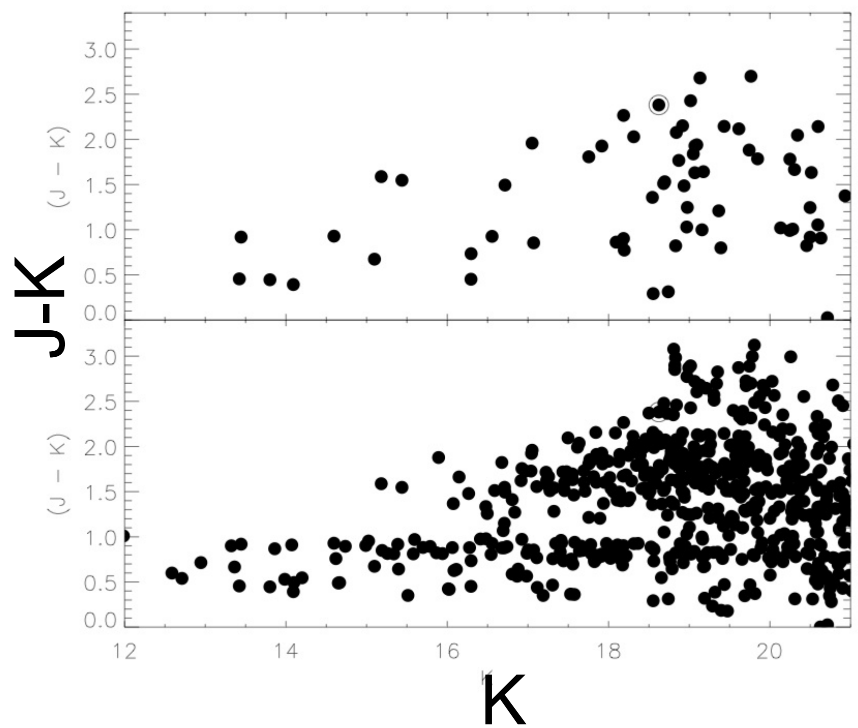



SW
kT (keV)
4
3
2
1
n$_e$ (cm^{-3})
0.01
P (x 10^{-11} dyn cm^{-2})
10
10
100
Radius (arcsec)

Lowell R-band

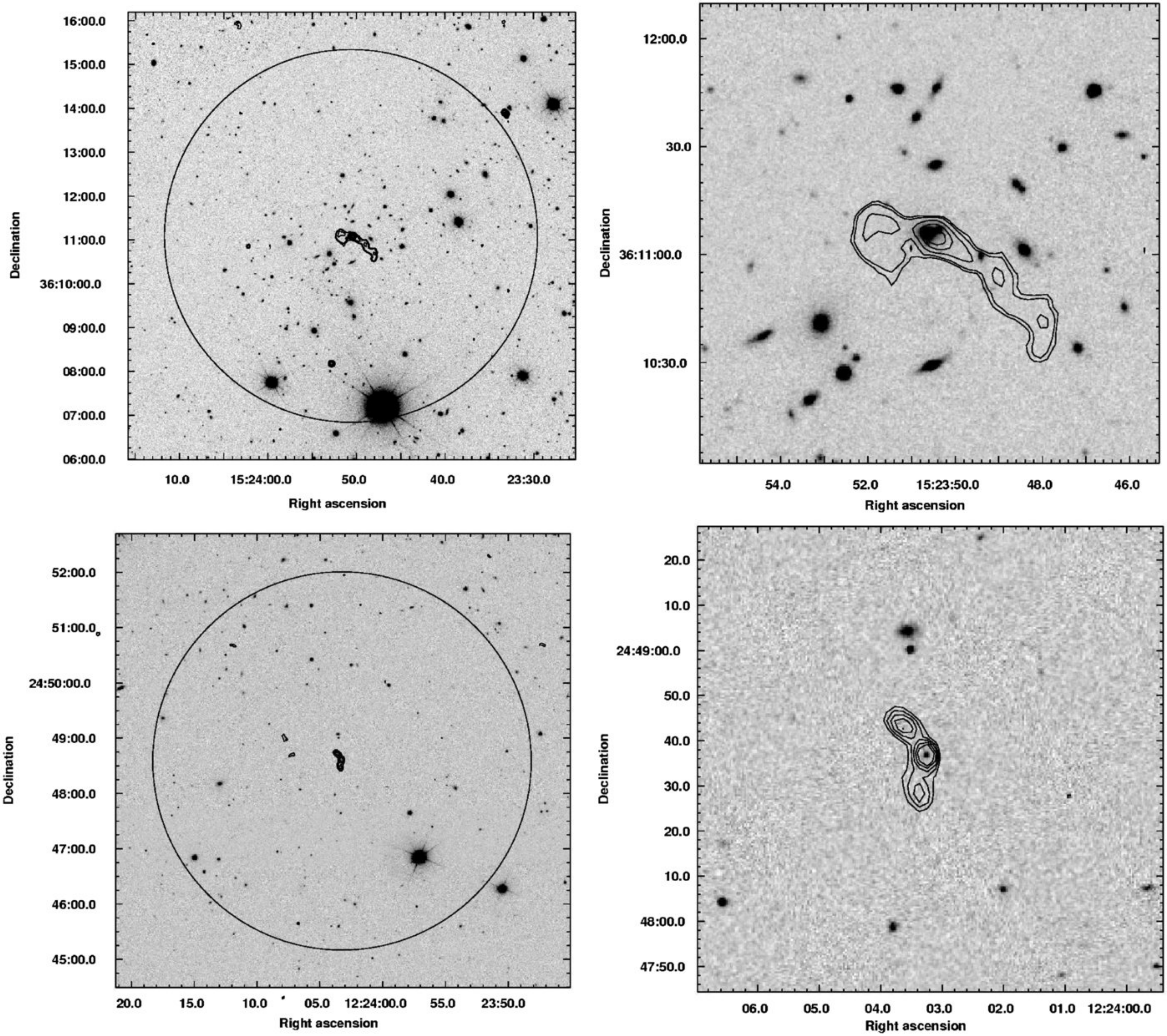






KPNO 4m J+K band

2.5’ x 1.5’ (1.7 x 0.7 Mpc)


16:00.0
15:00.0
14:00.0
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11:00.0
36:10:00.0
09:00.0
08:00.0
07:00.0
06:00.0
Declination
10.0
15:24:00.0
50.0
40.0
23:30.0
Right ascension
12:00.0
30.0
36:11:00.0
10:30.0
Declination
54.0
52.0
15:23:50.0
48.0
46.0
Right ascension
52:00.0
51:00.0
24:50:00.0
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46:00.0
45:00.0
Declination
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Right ascension