The Radio/X-ray Interaction in Abell 2029

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Background

Abell 2029:

– z = 0.0767, D=320 Mpc, scale = 1.44 kpc/”

– typically listed as a cooling flow cluster (> 100 $M_{\odot}$ /yr)

• considered to be the one of the most relaxed clusters

– optical data show cD halo to > 600 kpc (Uson et al. 1991)

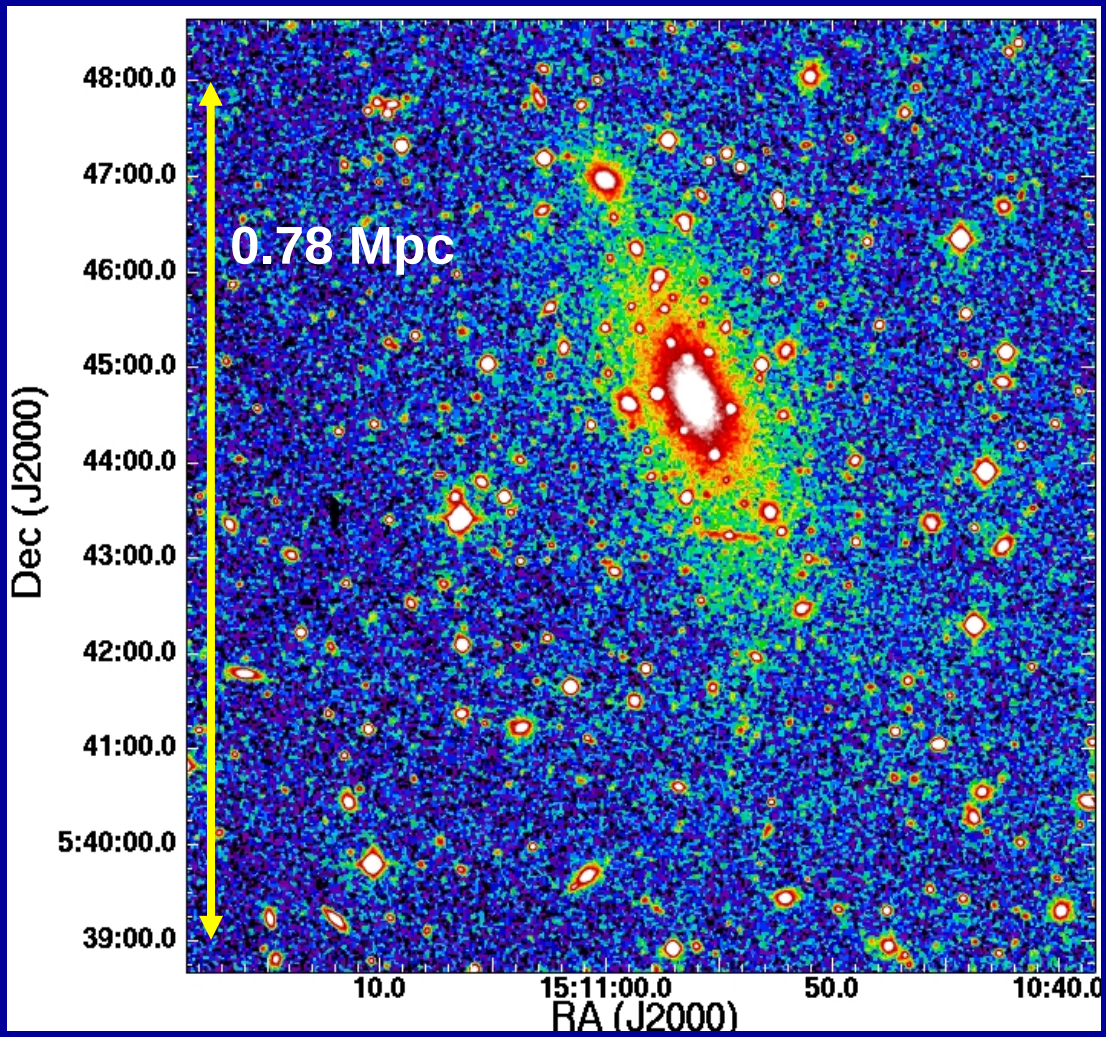
– no optical evidence of a merger

– X-ray surface brightness shows no large distortions

– contains a ‘C’ shaped central radio source which has steep spectrum outer lobes

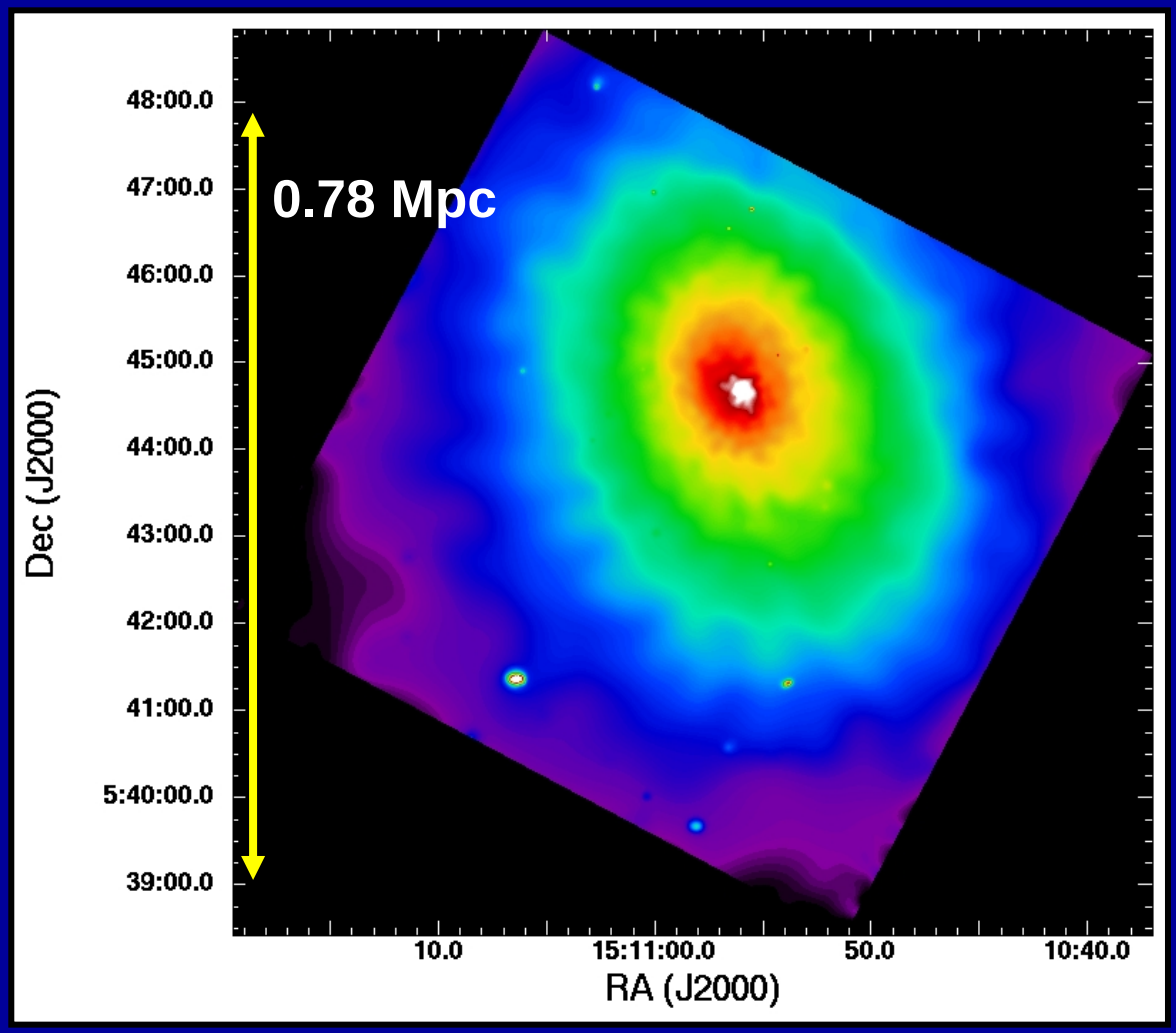
– contains no evidence of recent star-formation in the core ([OII] or blue stellar colours) ➔ unusual for cooling flow

Big Fuzzy Halo



- z = 0.0767, 1.44 kpc/"
- second generation DSS red image
- cD halo to r > 600 kpc (Uson et al. 1991)
- no evidence of optical emission lines or blue stellar continuum in core
- no evidence of merging

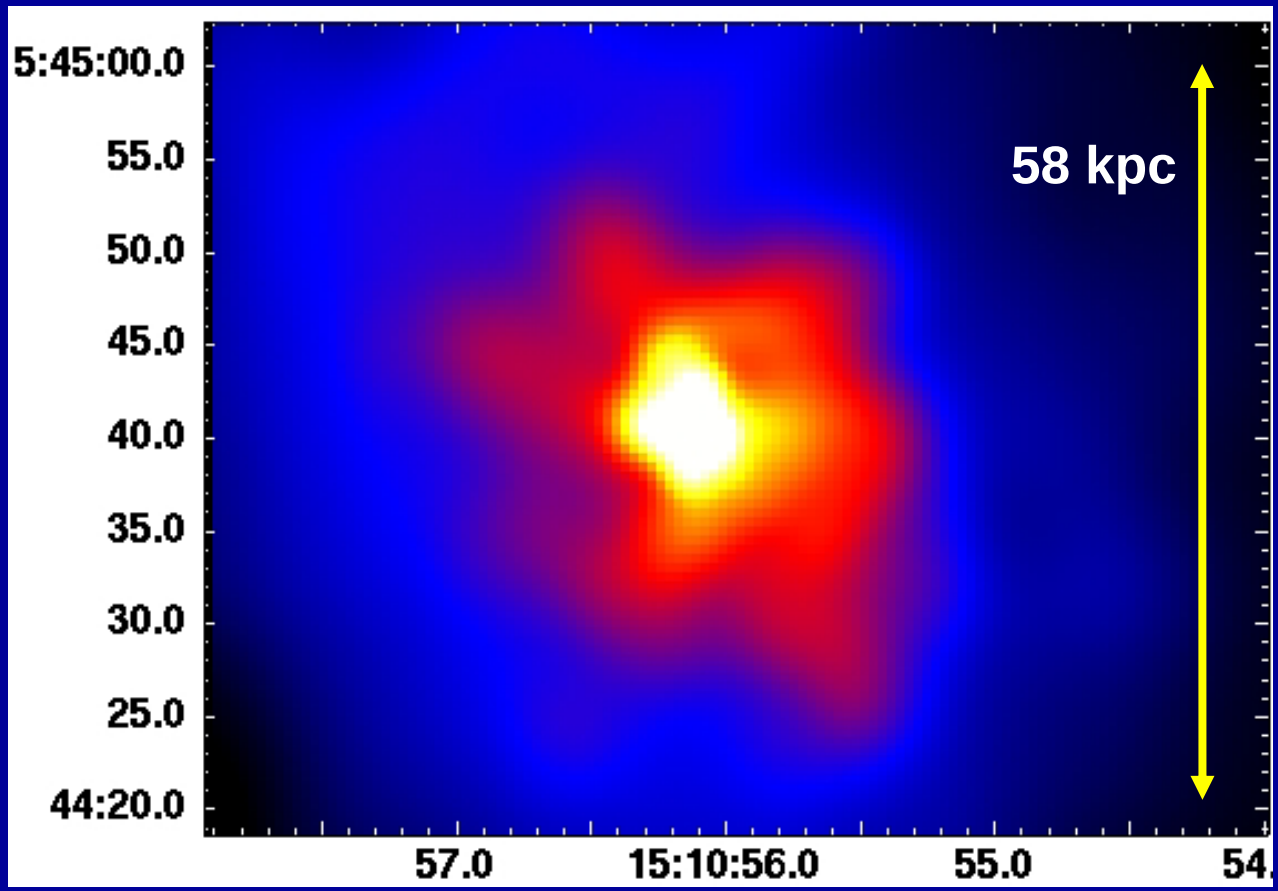
Chandra View



- considered to be one of the most relaxed clusters
- elongated along same PA as optical
- cooling flow (>100 $M_{\odot}$/yr)
- no evidence of a major merger, consistent with the presence of a cooling flow

- 19 ksec Chandra 0.3 - 10.0 keV adaptively smoothed image of the ACIS S3 ccd

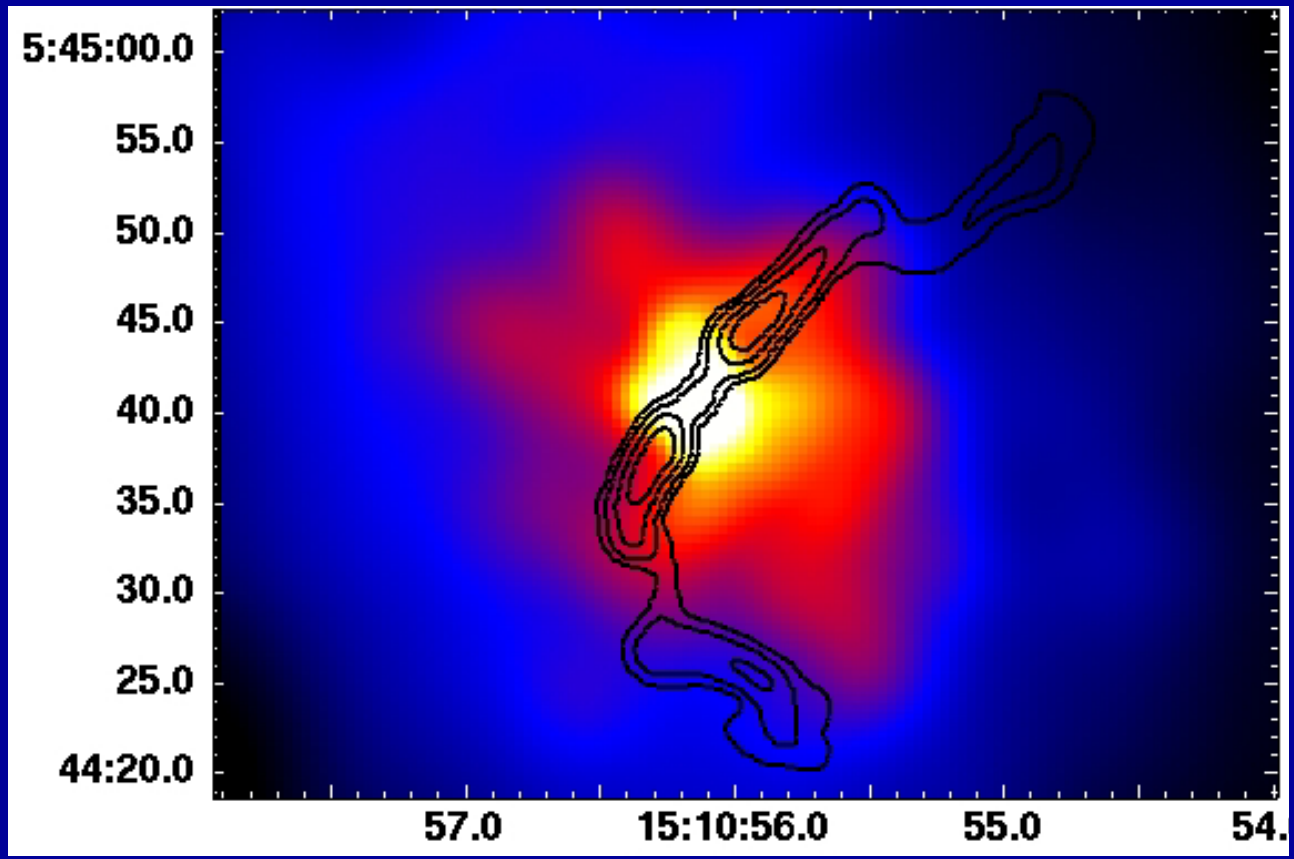
Central Cluster Filaments



- ROSAT HRI data revealed filaments (Sarazin et al. 92)
- Chandra shows LOTS of structure with many radial filaments
- broad X-ray core

- 19 ksec Chandra 0.3 - 10.0 keV adaptively smoothed image

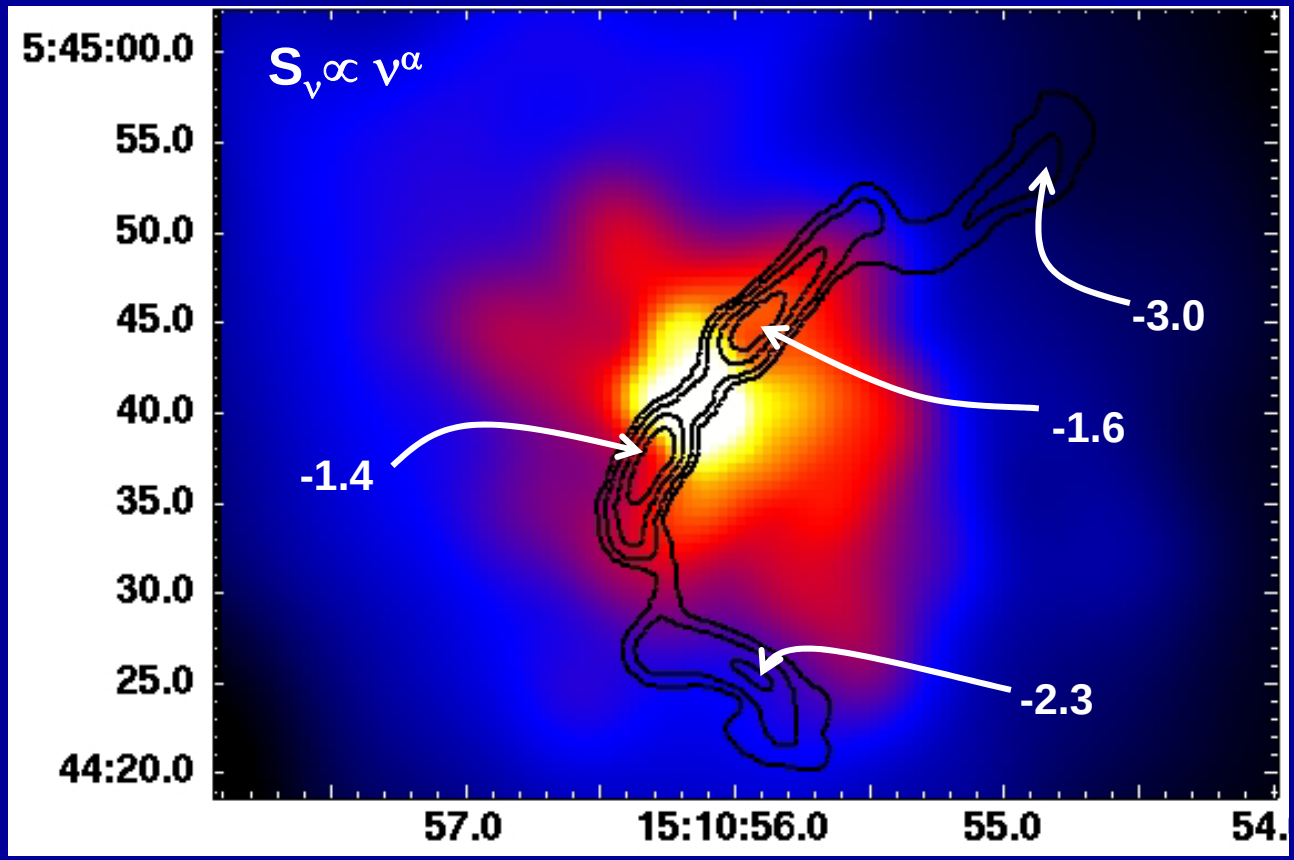
Radio Connections?



- central WAT radio source – often associated with merger where cD and/or ICM is moving
- south tail is traced by partial rim of bright X-ray emission
- filaments to NE unrelated to currently active radio source

- 1.4 GHz radio contours of PKS 1508+059 from Taylor et al. (1991)
- Southern X-ray filament ~ 9σ deviation

Radio Connections?



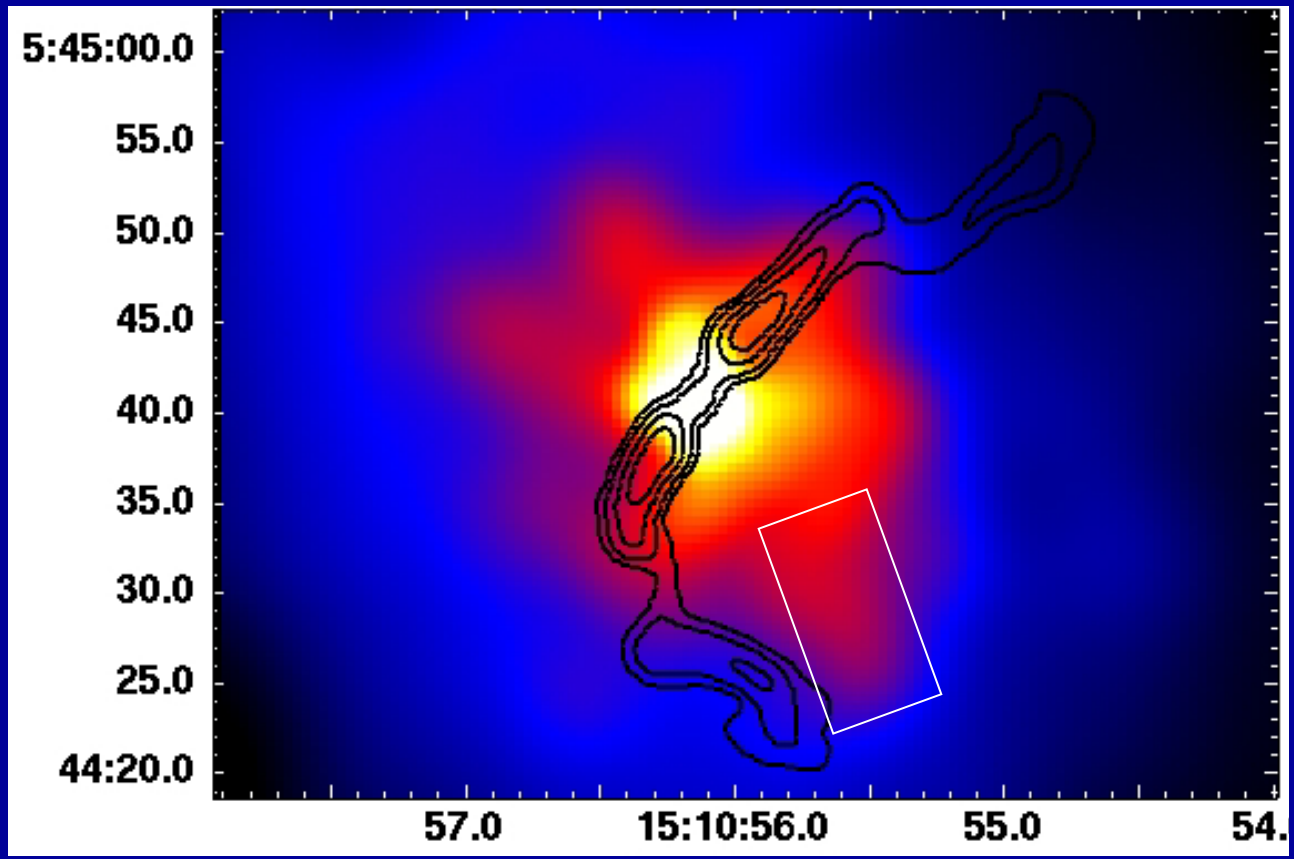
- steep spectrum inner jets and very steep outer tails
- consistent with confinement by the thermal ICM

$\tau_{jet} \sim 1.6 \times 10^6$ yr,

$\tau_{tail} \sim 1.7 \times 10^7$ yr

- 1.4 GHz radio contours and 1490- 4860 MHz spectral index (Taylor et al. 1991)
- 'typical' extragalactic radio source has $\alpha \sim -0.7$

Pressure Balances

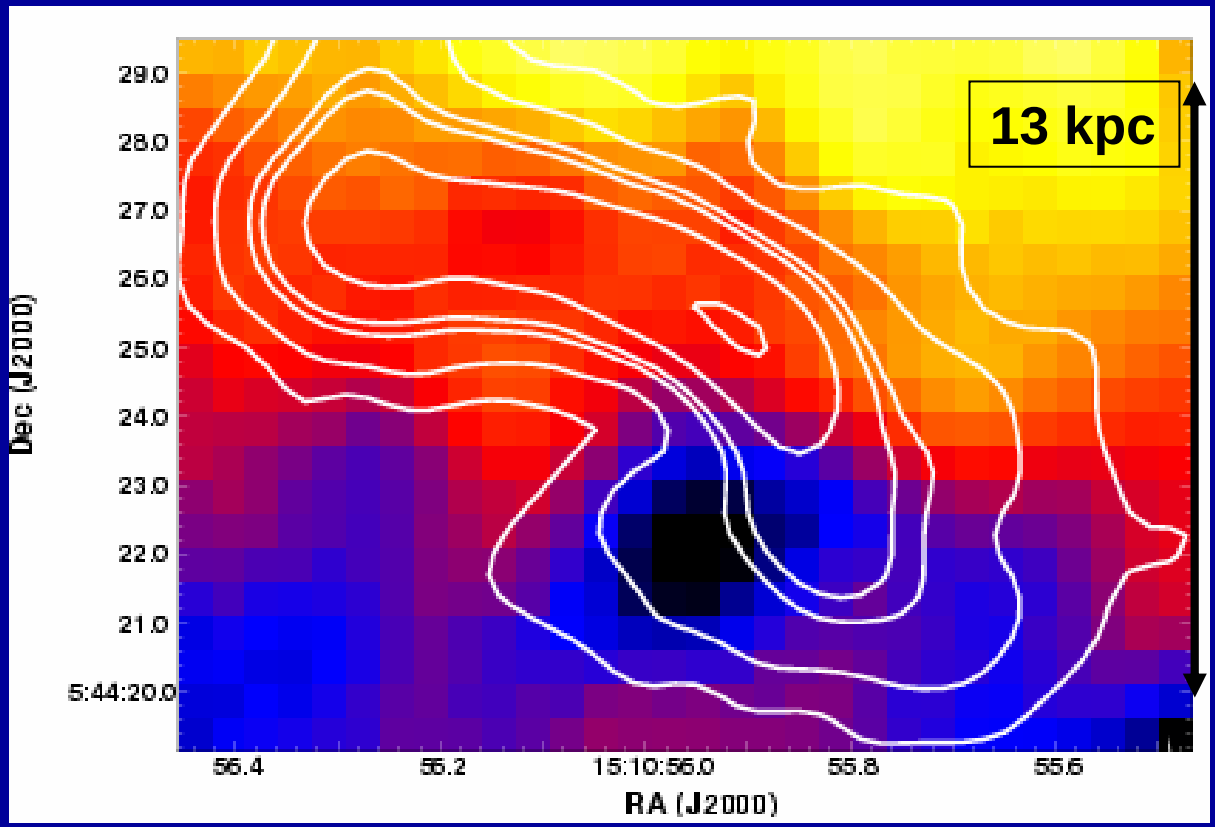


- without P balance the cavities would quickly collapse
- several systems show P_{th} exceeds P_{me} by factors of 10 or more
- additional P from relativistic particles or hot thermal gas

$P_{th}/P_{me} = 60$

- Thermal pressure in filament = 1.6×10^{-9} dyne cm^{-2}
- Minimum energy radio pressure = 2.6×10^{-11} dyne cm^{-2}

Central Cluster Region: South Tail

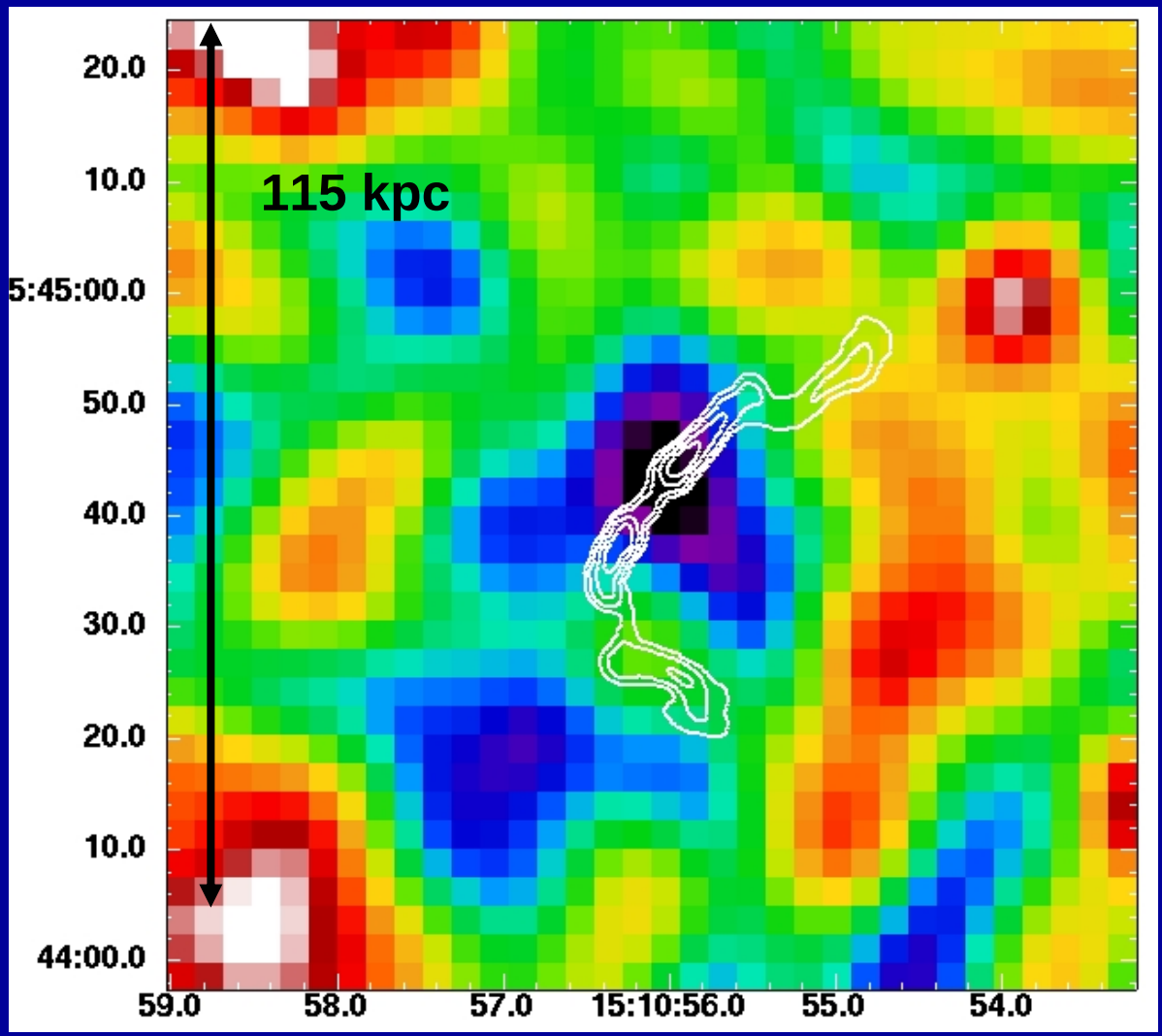


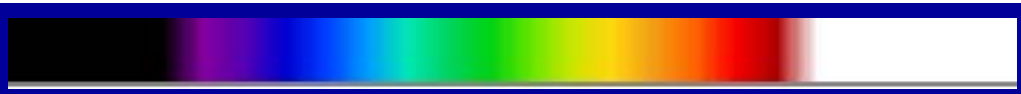
- Compact X-ray depression co-incident with the steep spectrum end of southern radio tail

(~ 4σ depression)

- much more compact than other holes

Temperature Structure

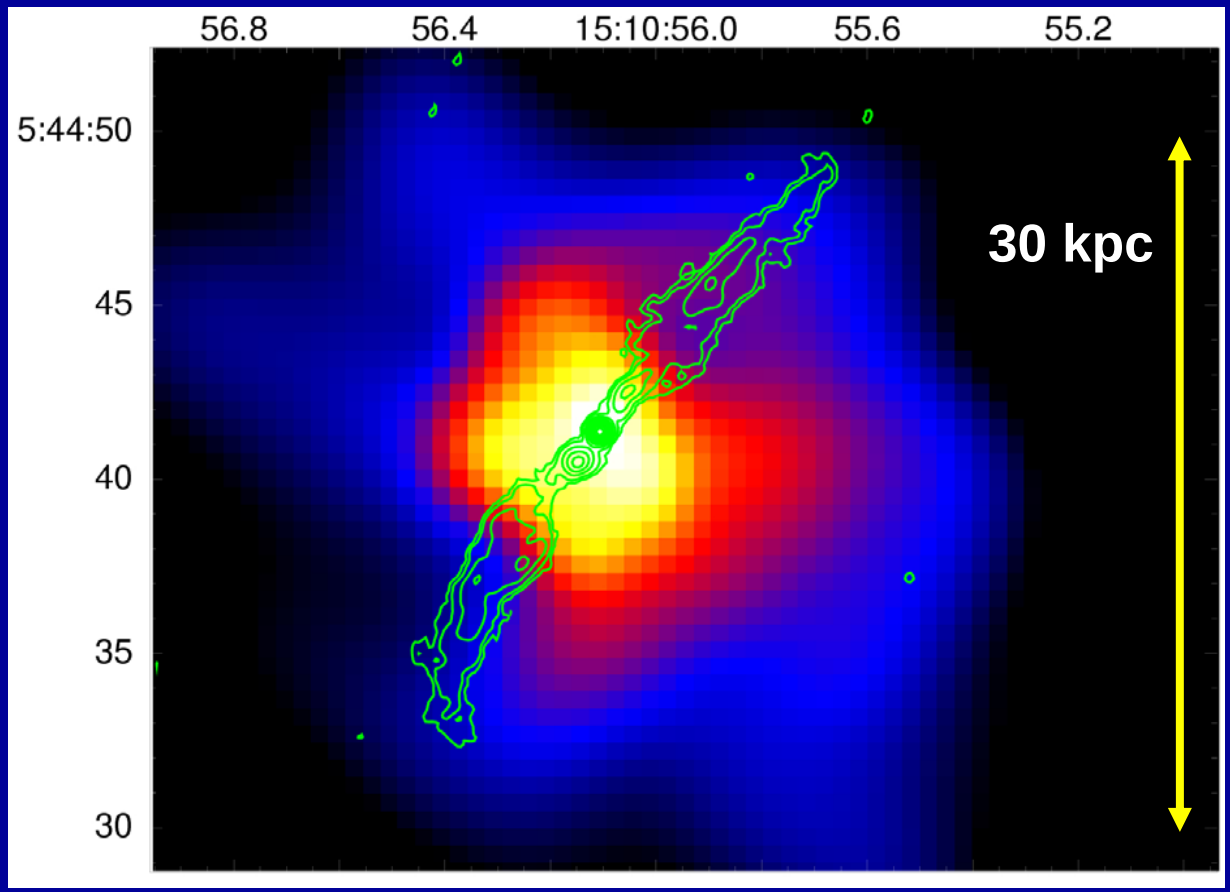




- cool core (~1 keV)
- average cluster emission has kT~ 7.4 keV
- cool gas around southern radio tail
- no obvious cool region for northern tail, appears to be in a region of average gas temperature

- 1.4 GHz radio contours of PKS 1508+059 from Taylor et al. (1991)

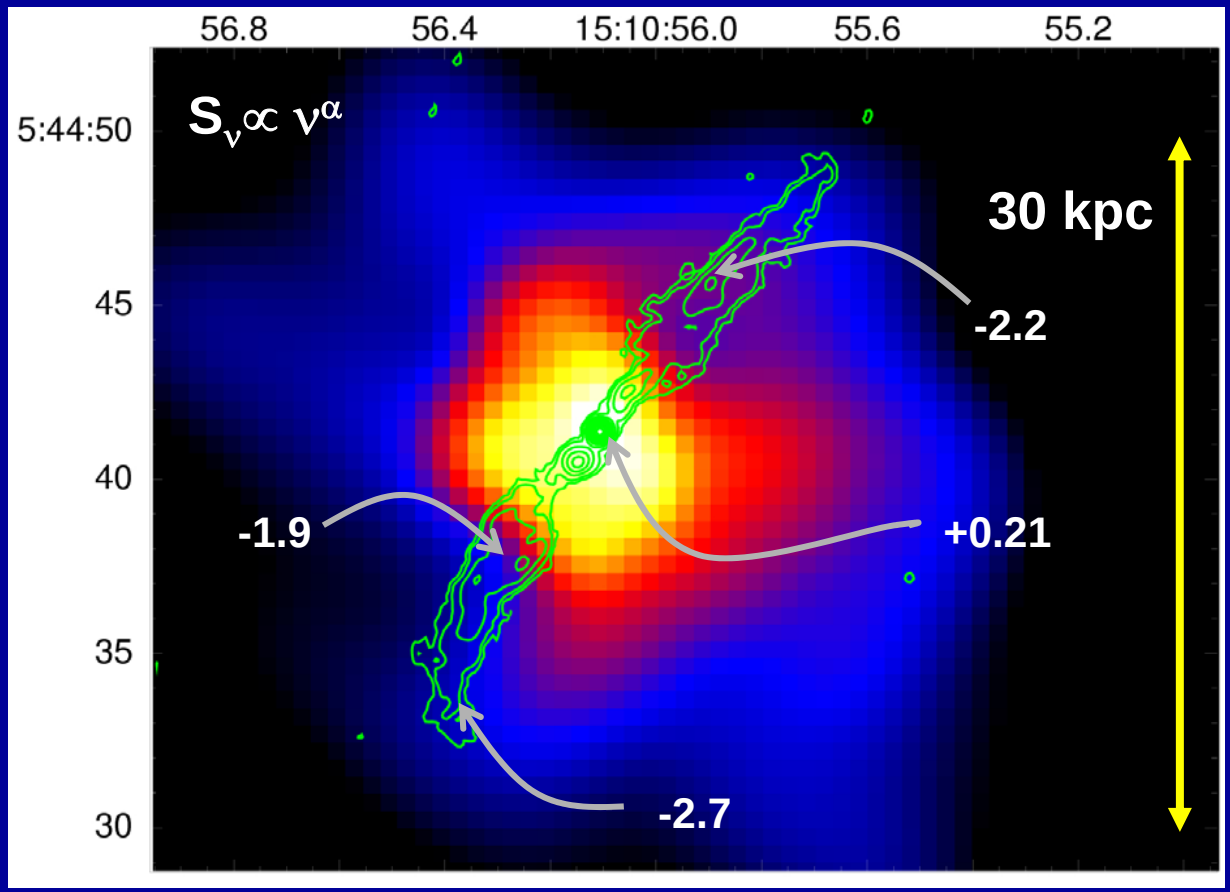
Cluster Core Region



- Chandra shows broad core with hourglass shape
- filaments visible
- no evidence of AGN point source
- well collimated jets propagate along pinch axis
- jets flare at 3kpc and decollimate at sharp X-ray gradient

- 8.4 GHz radio contours of PKS 1508+059 from Taylor et al. (1991)

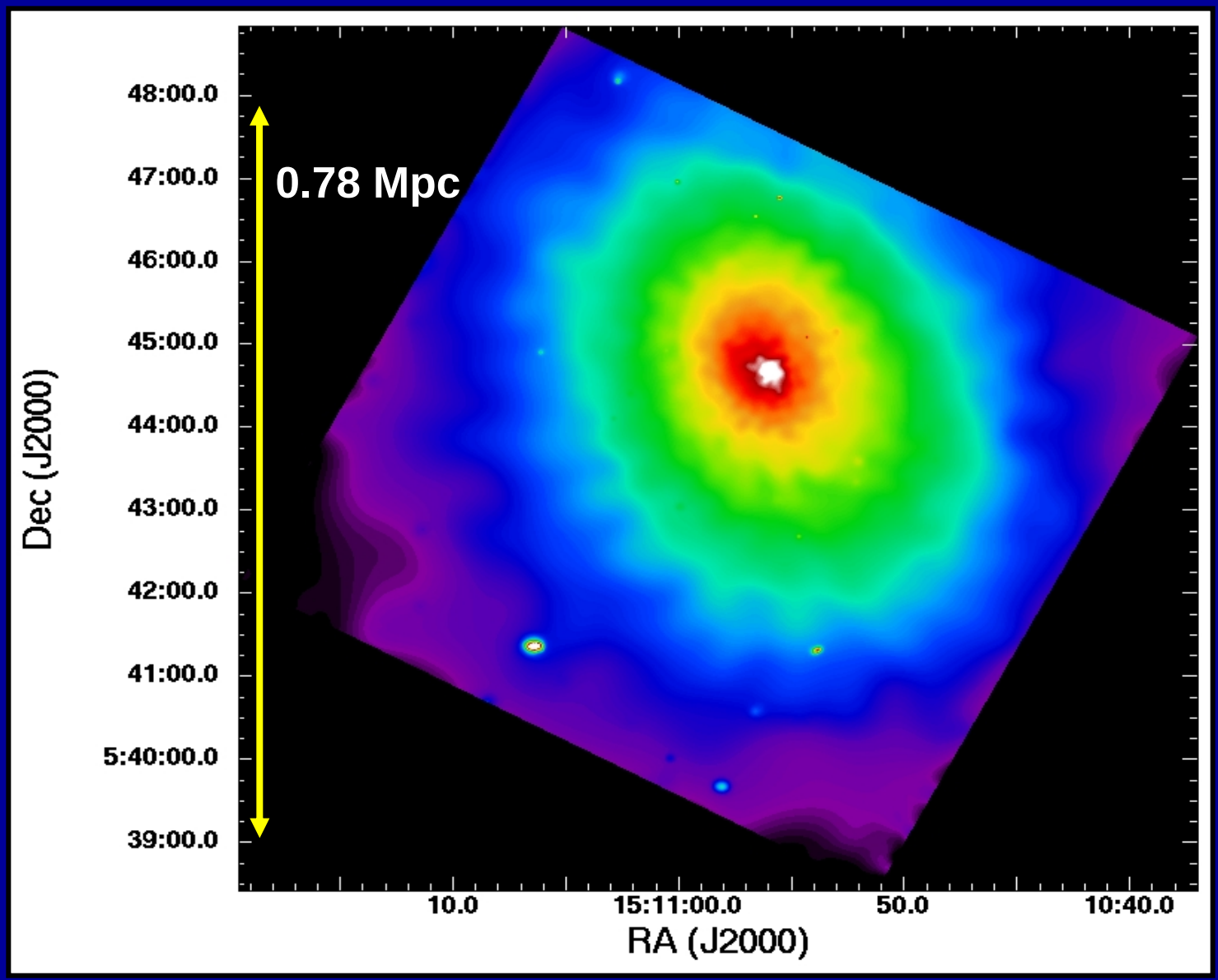
Cluster Core Region



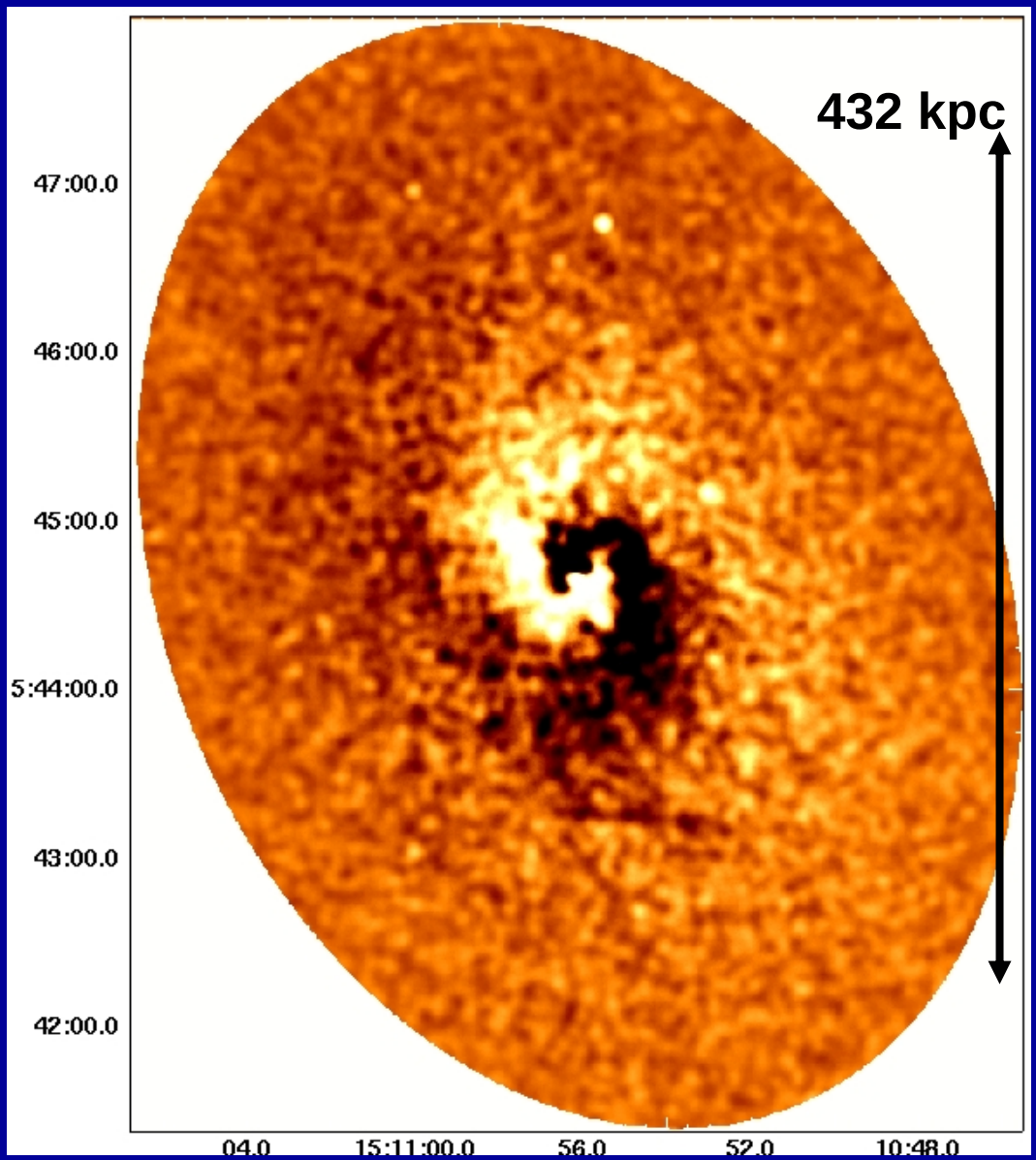
- inverted radio core and steep spectrum jets
- small size and steep spectrum are consistent with confinement by external ICM
- northern jet follows linear path, tip of the southern jet bends along the broad edge of the X-ray core

- 8.4 GHz radio contours and 4860-8515 MHz spectral index (Taylor et al. 1991)

Chandra View



Chandra Residual Image



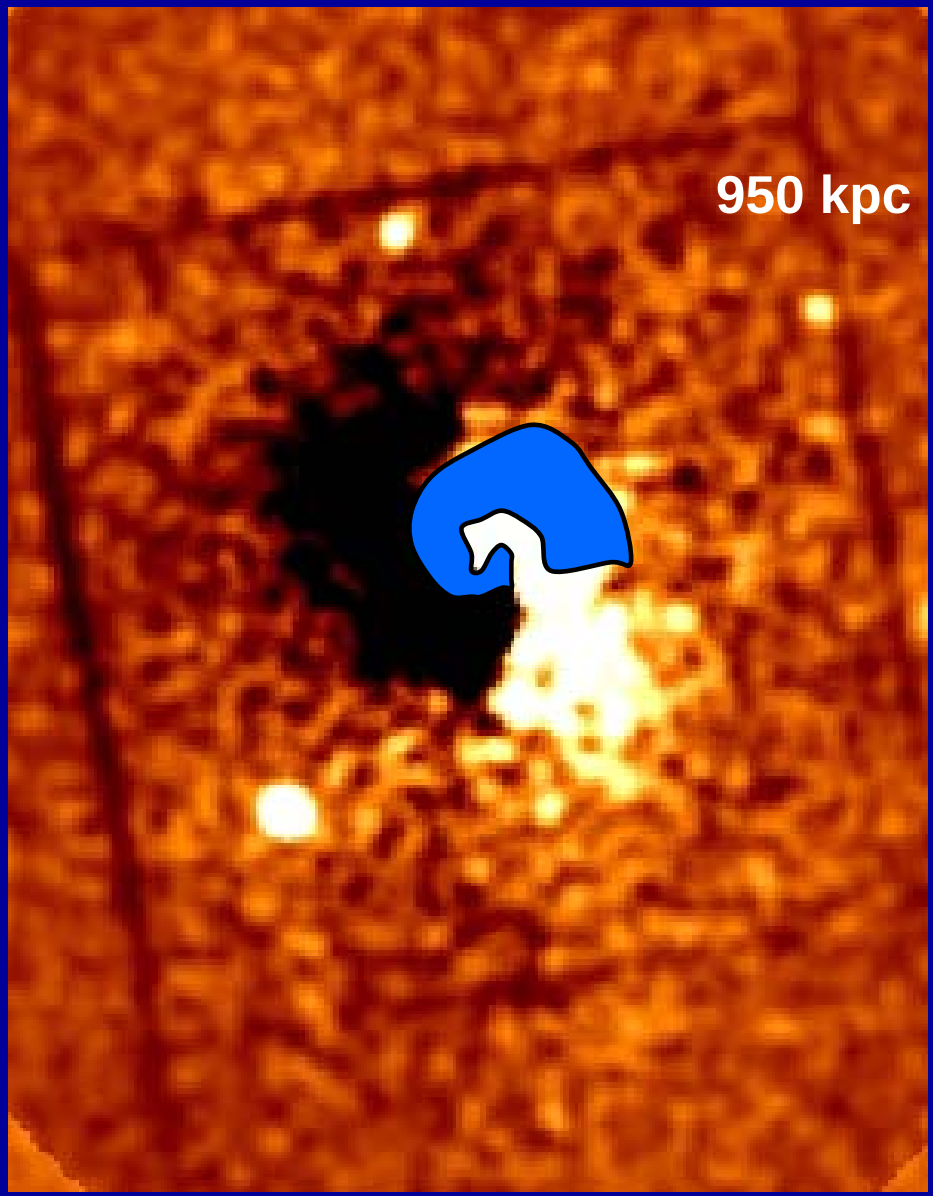
- Chandra image showed asymmetric surface brightness distribution
- fit an elliptical model to the 0.7-8.0 keV X-ray data and subtracted it
- residuals show a striking dipolar spiral pattern
- linear feature south of core is absorption from a foreground edge-on spiral galaxy (Clarke et al. 2004)

Spectral fits give:

T_{bright} = 5.4 keV

T_{dark} = 6.2 keV

XMM Residual Image

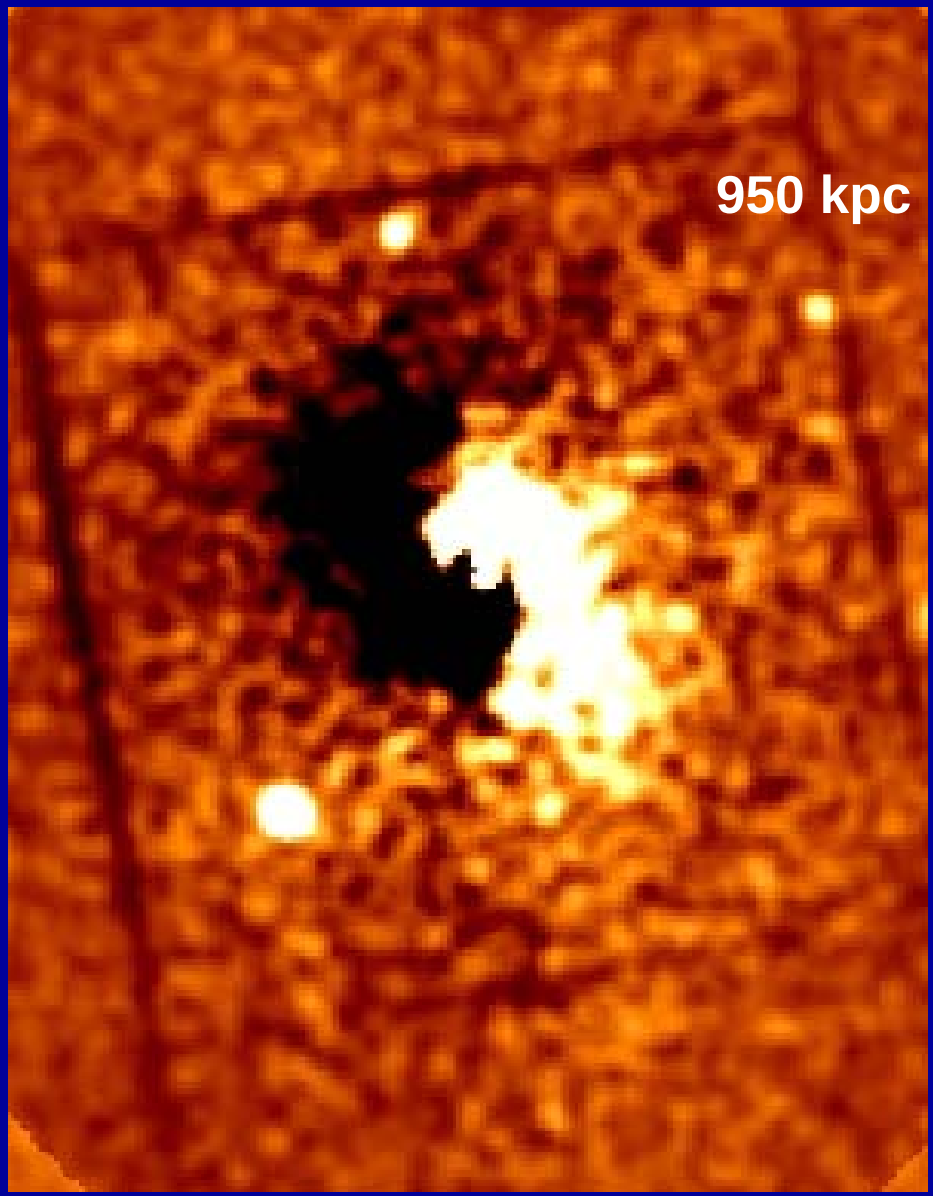


- independent fit of an elliptical model to the XMM data results in similar ellipticity and PA
- XMM reveals that dipolar excess extends well beyond region visible in Chandra image

Possibly due to infalling cold system? Other mechanisms?

- investigate the excess further with a new 80 ksec Chandra observation received one week ago

XMM Residual Image



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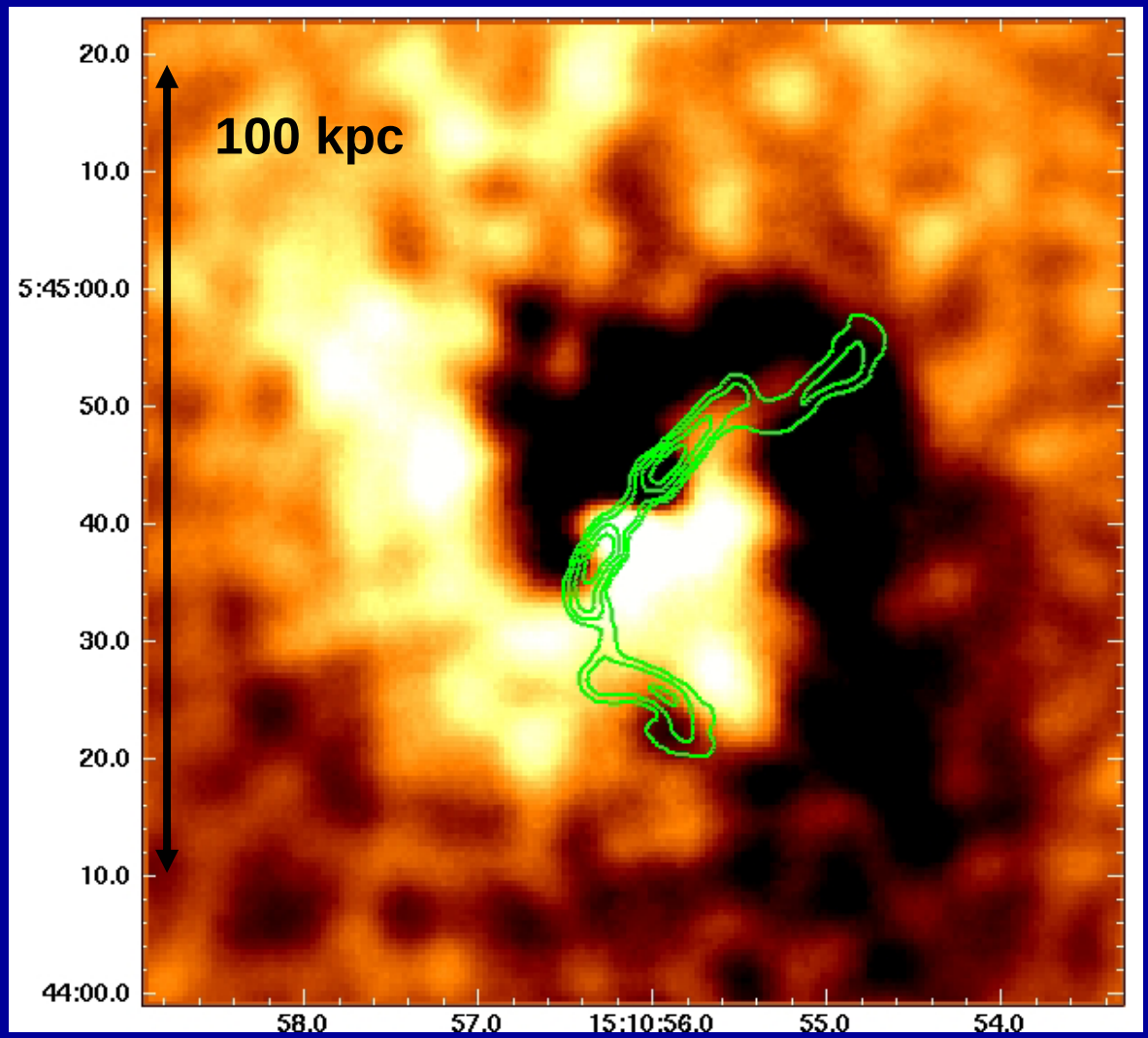
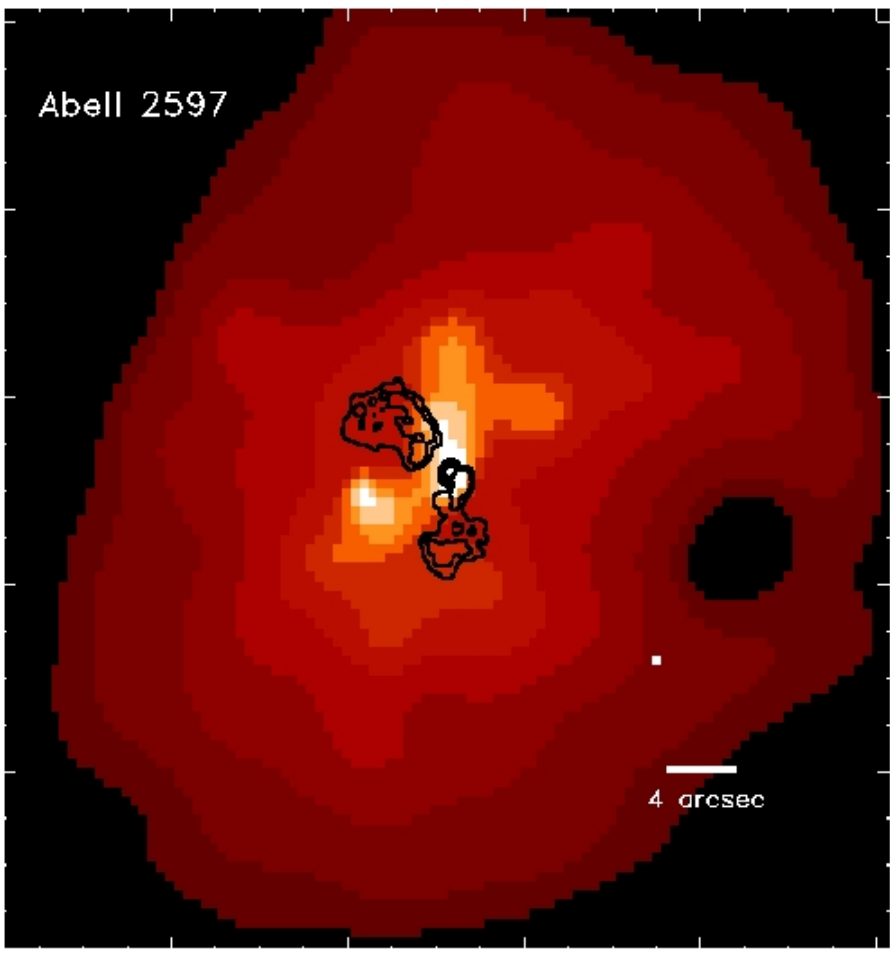
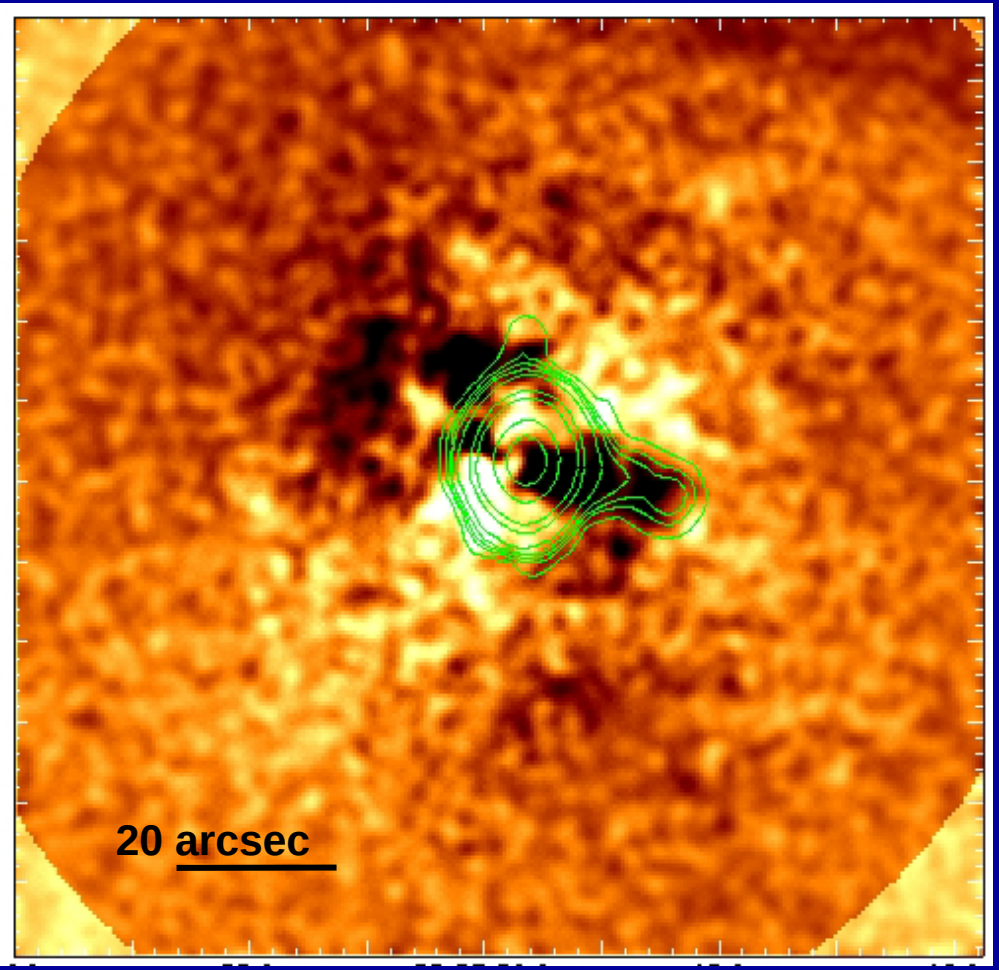
Chicken or Egg?



- X-ray excess appears to cut directly between the southern jet and tail
- wide angle tail radio morphology is common to mergers
- Is the bend in the south jet due to interaction?
- Is the displacement of the south tail a result of the merger?
- What causes the displacement of the north tail?
- Is there a bubble in the southern tail?

Abell 2597





- Chandra image with 8 GHz radio contours overlaid (McNamara et al. 2000)
- **ghost holes** visible at radii larger than central radio source

- residual Chandra image with VLA 330 MHz radio contours
- low frequency emission shows radio extension from core to western hole

Summary

- Abell 2029 is very relaxed but there is significant activity in the central regions
- X-ray data show a broad, hourglass – shaped core with the jets of a wide angle tail radio source propagating along the pinch axis
- steep radio spectrum and small size are consistent with confinement by external thermal ICM
- southern tail surrounded by cool gas, northern in average T region
- inner jets begin well-collimated, then flare at distance of 3 kpc where there is likely an X-ray pressure gradient (similar to results from study of M31 by Laing & Bridle 2002) beyond that the southern jet bends along the edge of an X-ray filament
- partial shell around southern outer tail has $P_{th}/P_{me} \sim 60$
- residual image shows dipolar pattern which may be the results of an infalling cold system

Is the X-ray structure determined by the radio source or is the radio source structure a result of the 'merger' seen in X-rays?

New 80 ksec Chandra observation should help us unravel this complex system