Chandra's Clear View of the Structure of Clusters

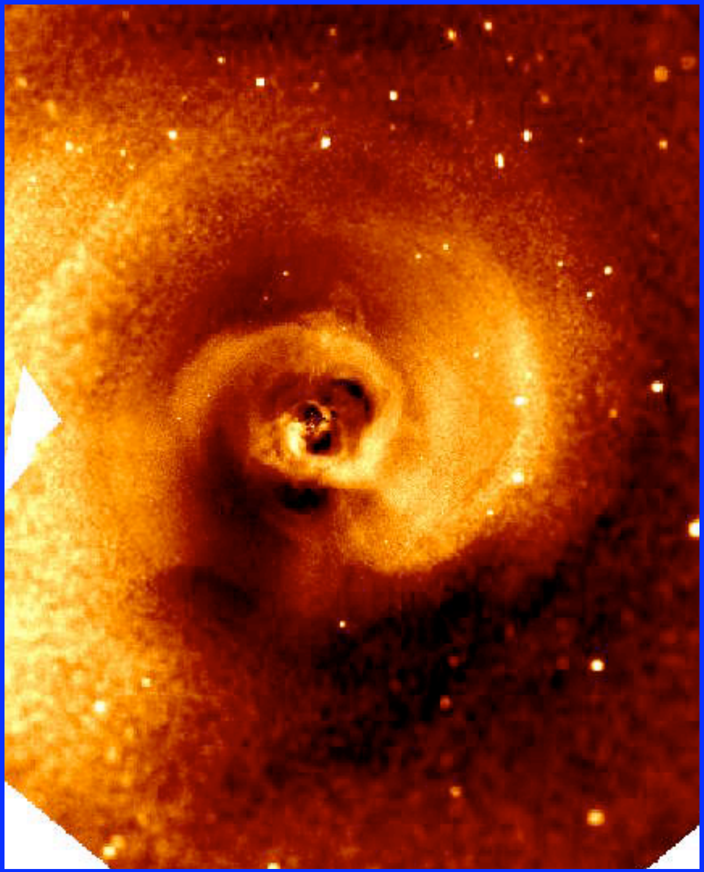
Hydra A Cluster
(Kirkpatrick et al. 2009)

Craig Sarazin
University of Virginia

Bullet Cluster
(Markevitch et al. 2004)

Cool Cores, Radio Sources, & Feedback

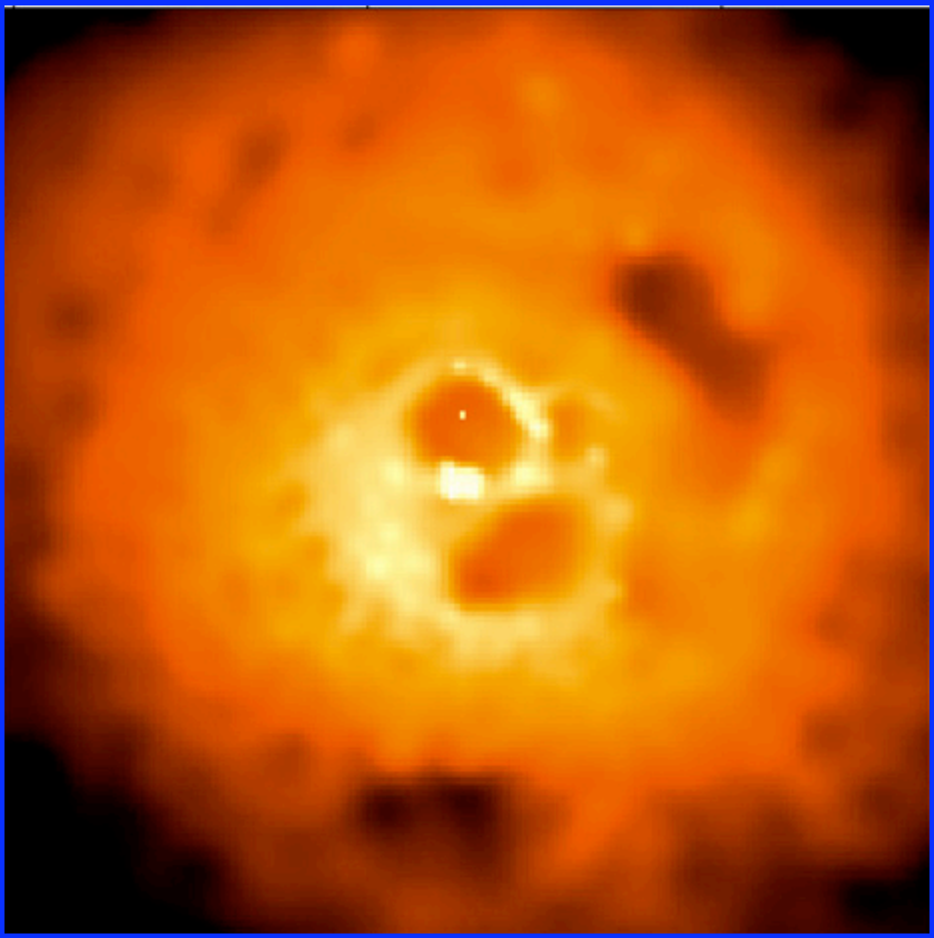
Perseus (Chandra)



Fabian et al. 2011

Radio Bubbles

X-ray Cavities

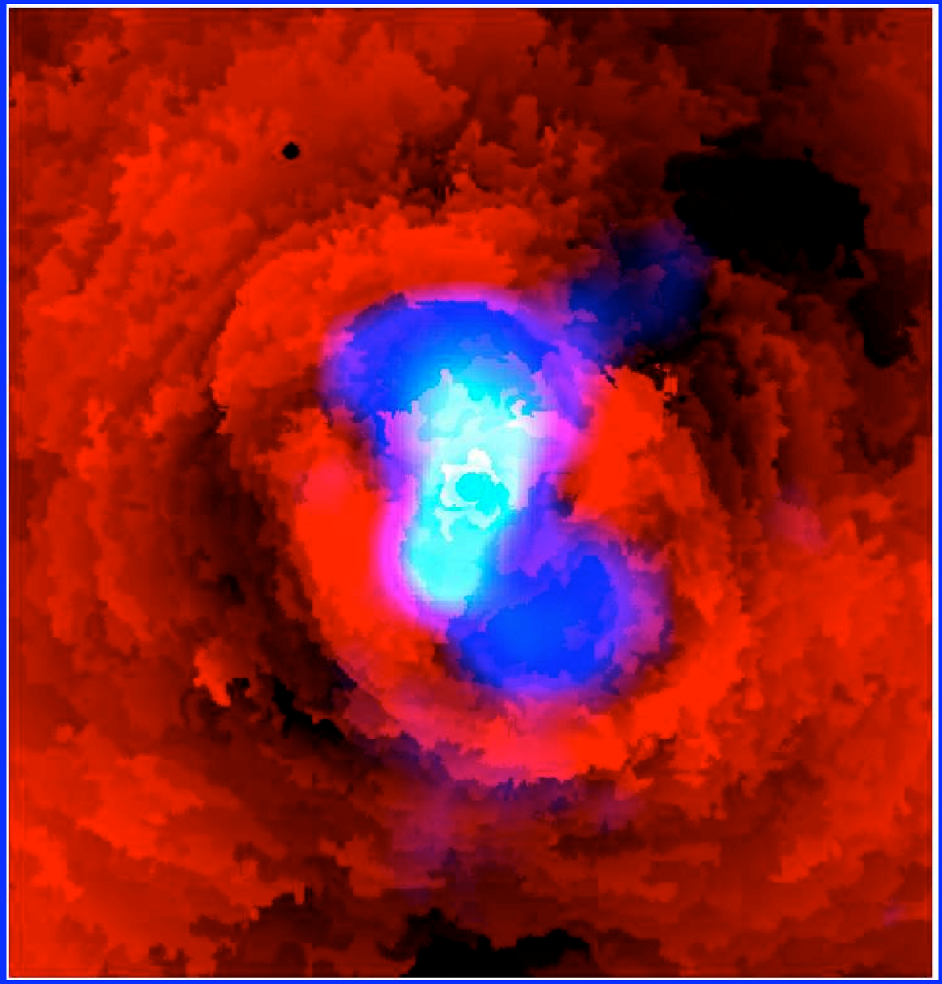


Perseus (Fabian et al. 2000)

Radio Bubbles

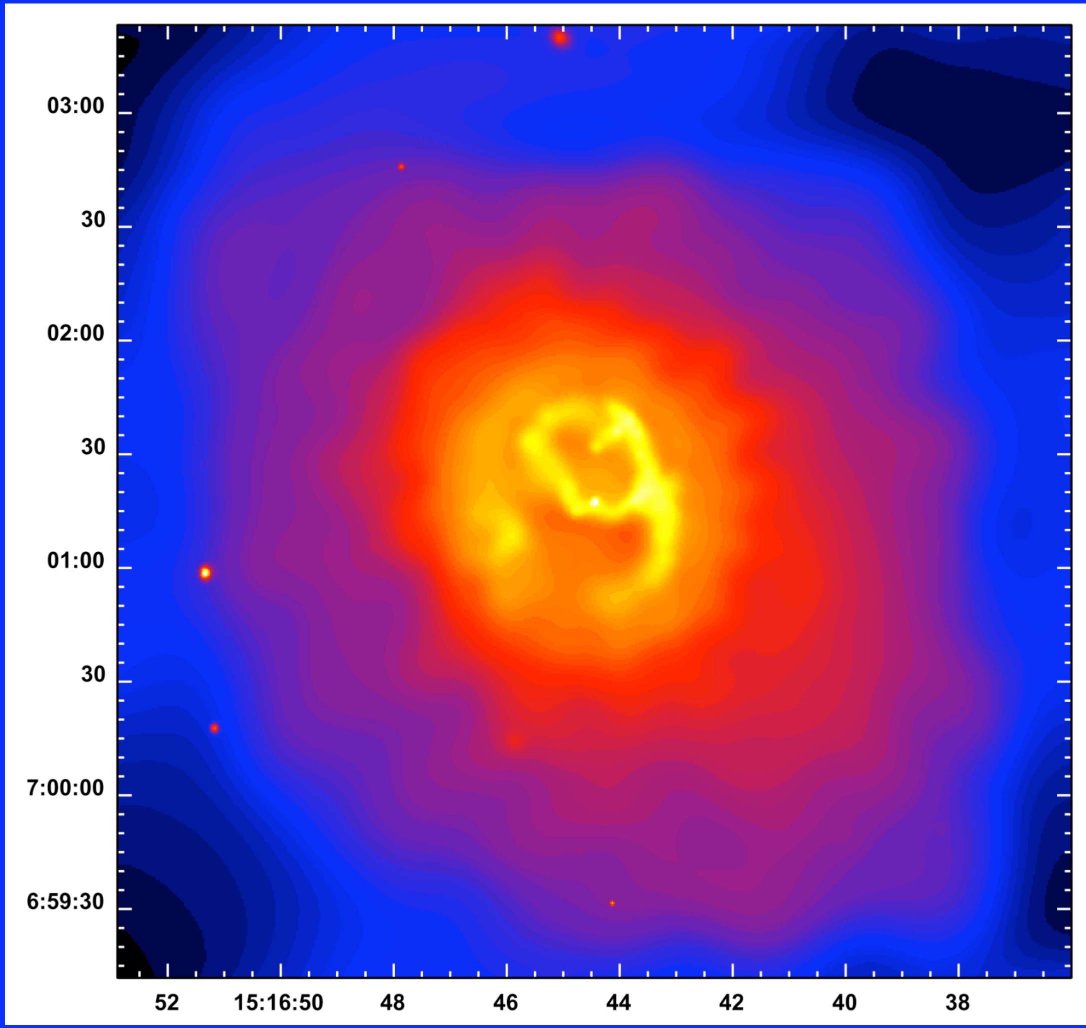
X-ray Cavities Filled by Radio Lobes

Perseus

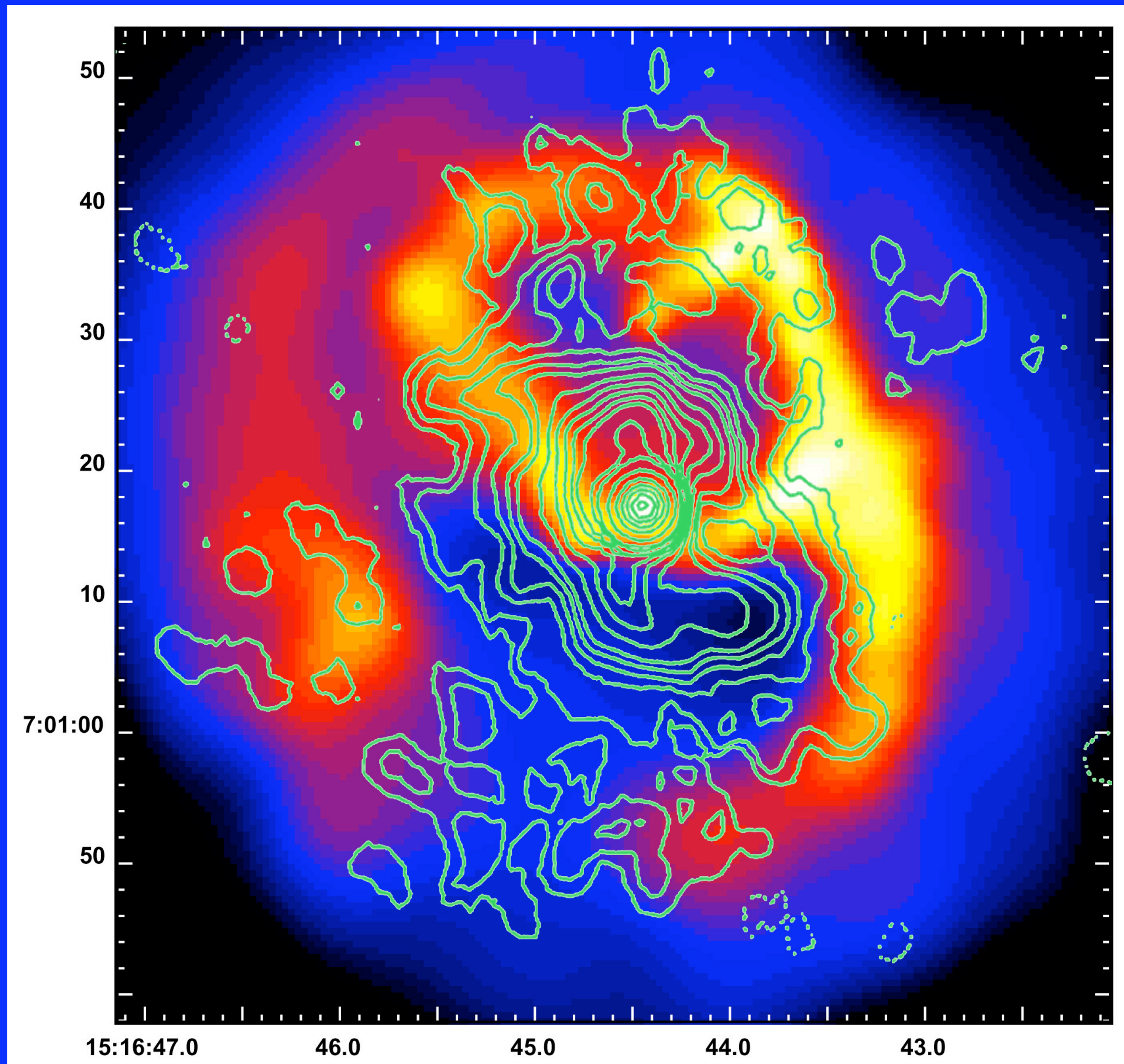


Radio (blue) on pressure structure map (Fabian et al 2006)

A2052 (Chandra)



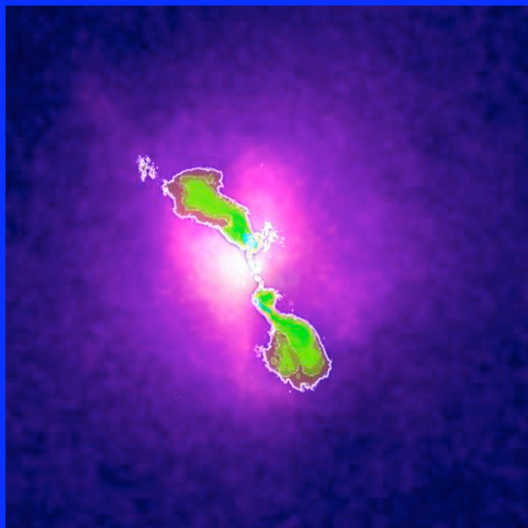
Blanton et al. 2001



Radio Contours (Burns)

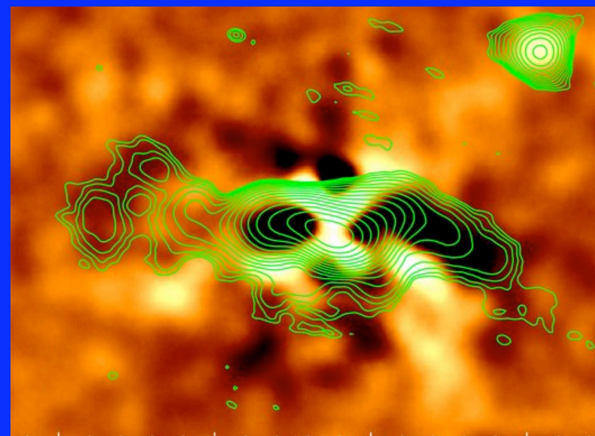
Other Radio Bubbles

Hydra A



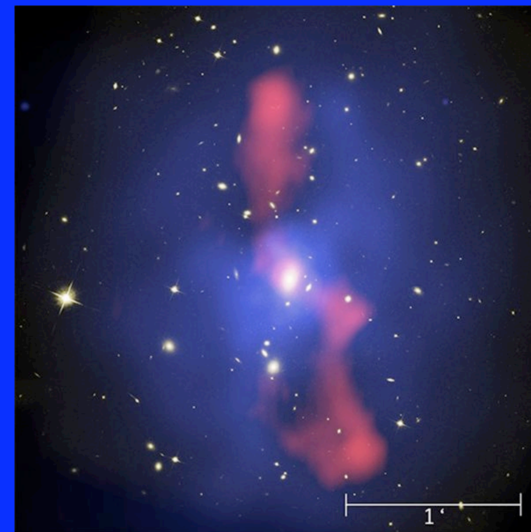
McNamara et al. 2000

Abell 262



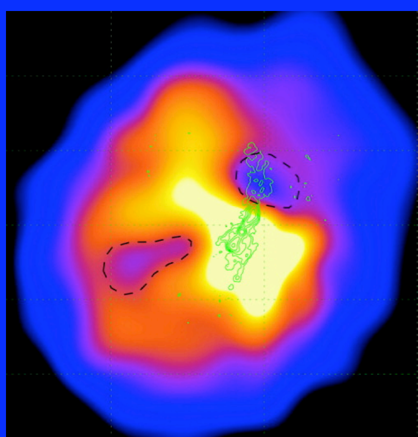
Clarke et al. 2009

MS0735.6+7421



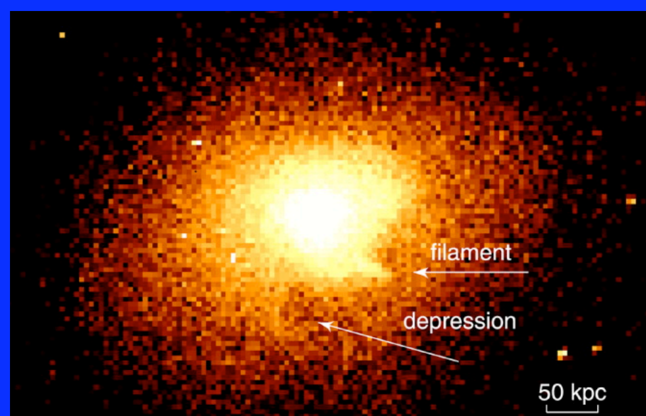
McNamara et al. 2005

Abell 4059



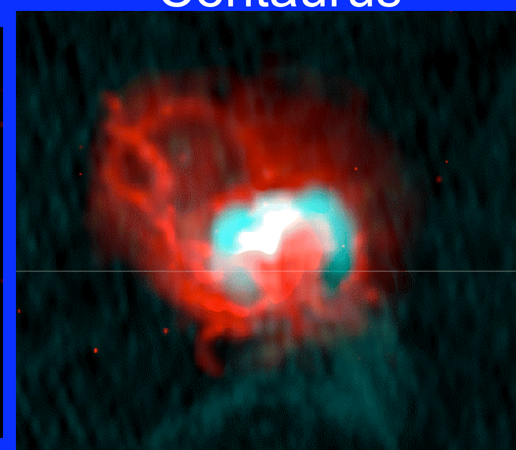
Heinz et al. 2002

MKW3s



Mazzotta et al. 2002

Centaurus



Fabian et al. 2005

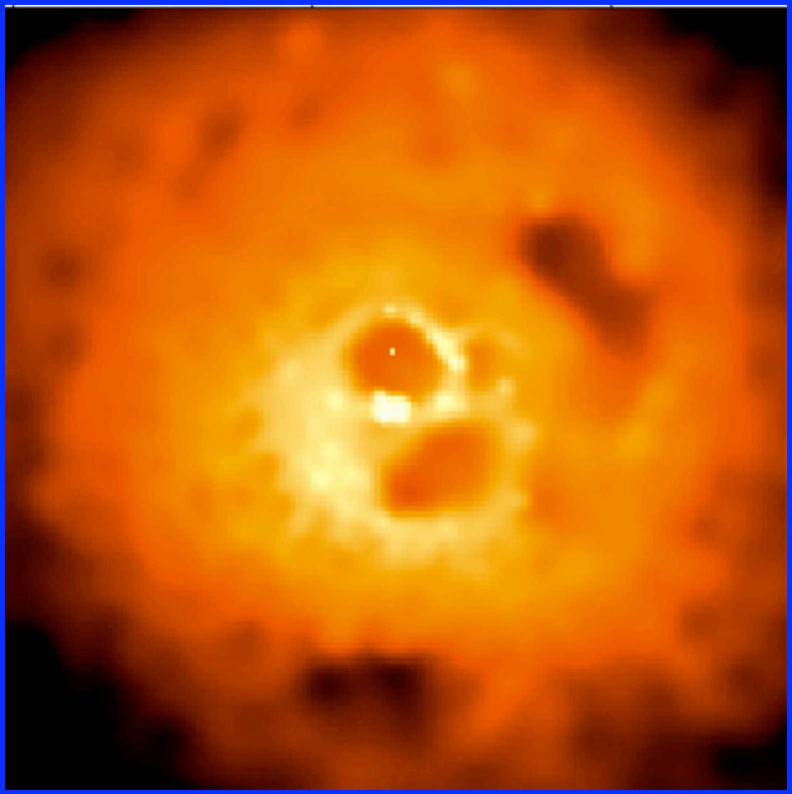
Morphology – Radio Bubbles

- Two X-ray holes surrounded by bright X-ray shells
- From de-projection, surface brightness in holes is consistent with all emission being projected (holes are empty of X-ray gas)
- Mass of shell consistent with mass expected in hole

→ X-ray emitting gas pushed out of holes by the radio source and compressed into shells

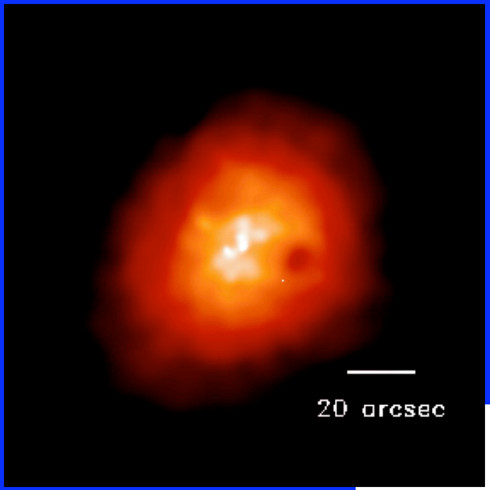
Buoyant "Ghost" Bubbles

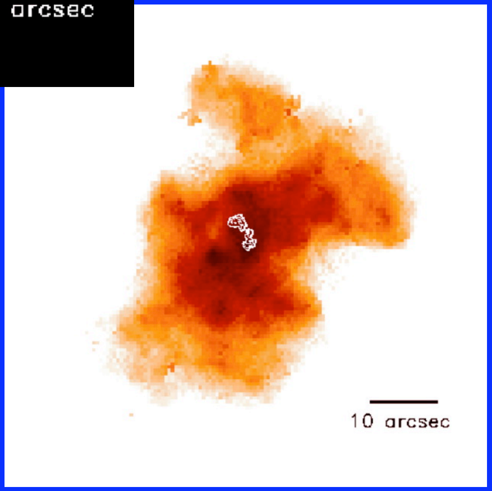
Perseus



Fabian et al. 2000

Abell 2597

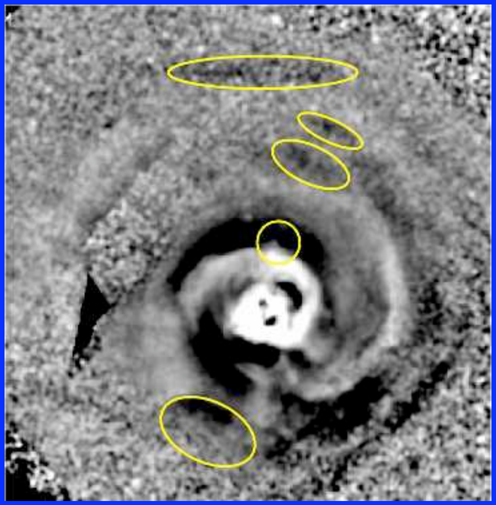




McNamara et al. 2001

Multiple Radio Bubbles

Perseus

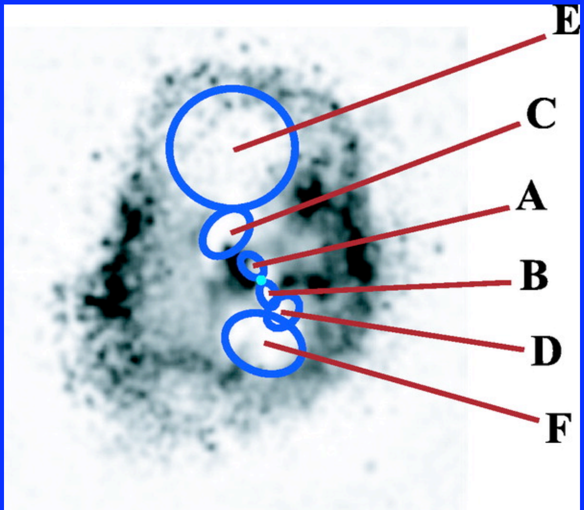


Fabian et al. 2011

Abell 2597

Blanton et al. 2011

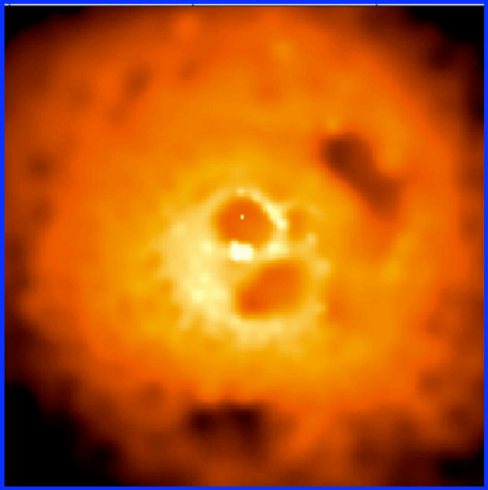
Hydra A Cluster



Wise et al. 2007

Buoyant “Ghost” Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies

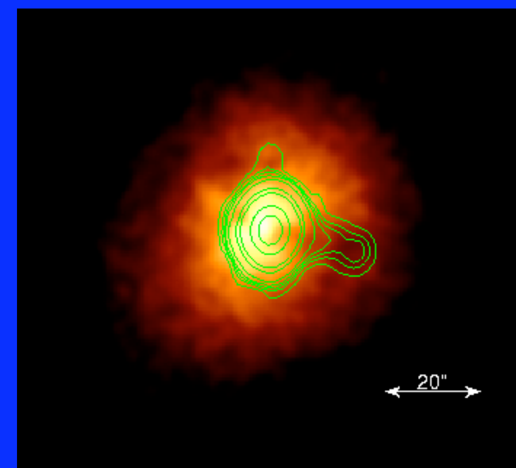


Fabian et al.

Buoyant “Ghost” Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies
- Filled with very low frequency radio

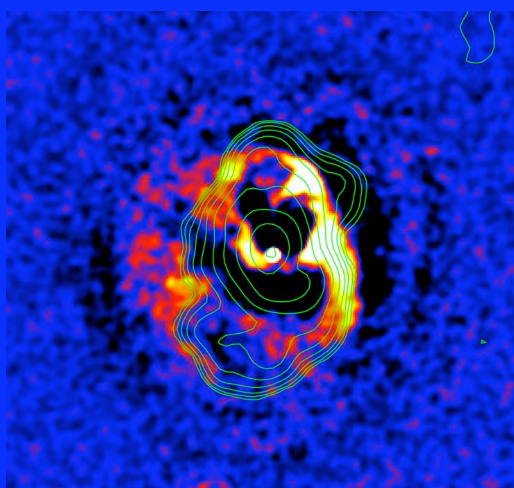
Abell 2597



327 MHz radio green

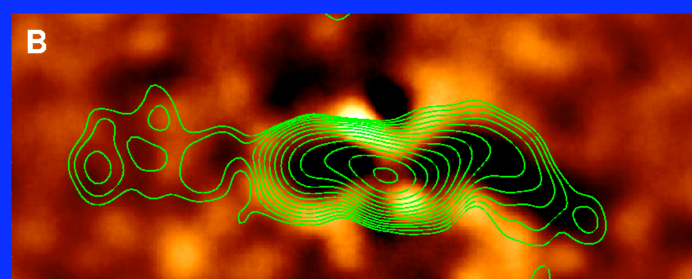
Clarke et al. 2005

Abell 2052



Blanton et al. 2011

Abell 262



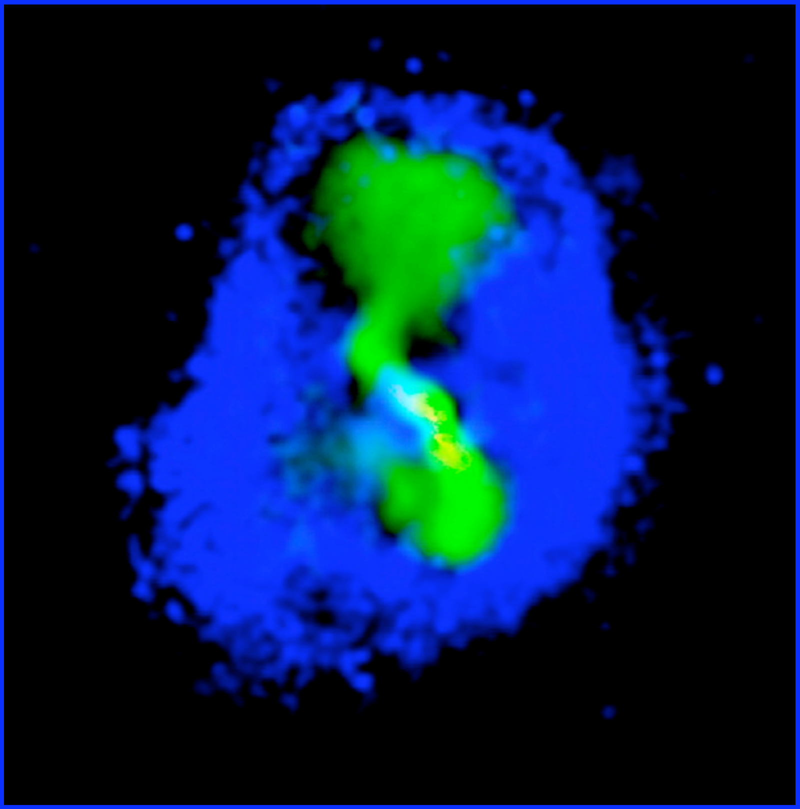
327 MHz radio green

Clarke et al. 2009

Buoyant “Ghost” Bubbles

Filled with very low frequency radio

Hydra A Cluster



330 MHz radio green

Lane et al. 2004

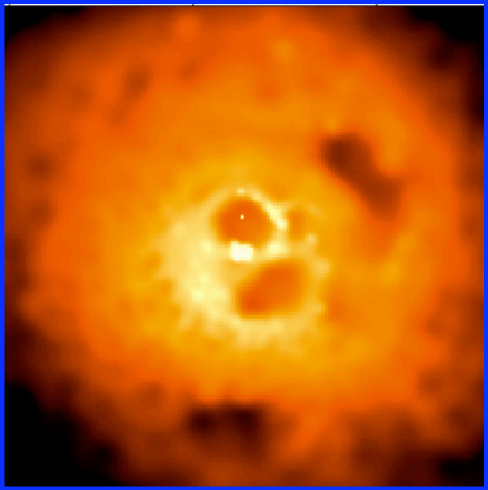
Buoyant "Ghost" Bubbles

- X-ray cavities at larger distances from center
- No radio at high frequencies
- Filled with very low frequency radio

→ Old radio bubbles which have risen buoyantly

Give repetition rate of radio outbursts

($\sim 10^{7\text{-}8}$ yr)

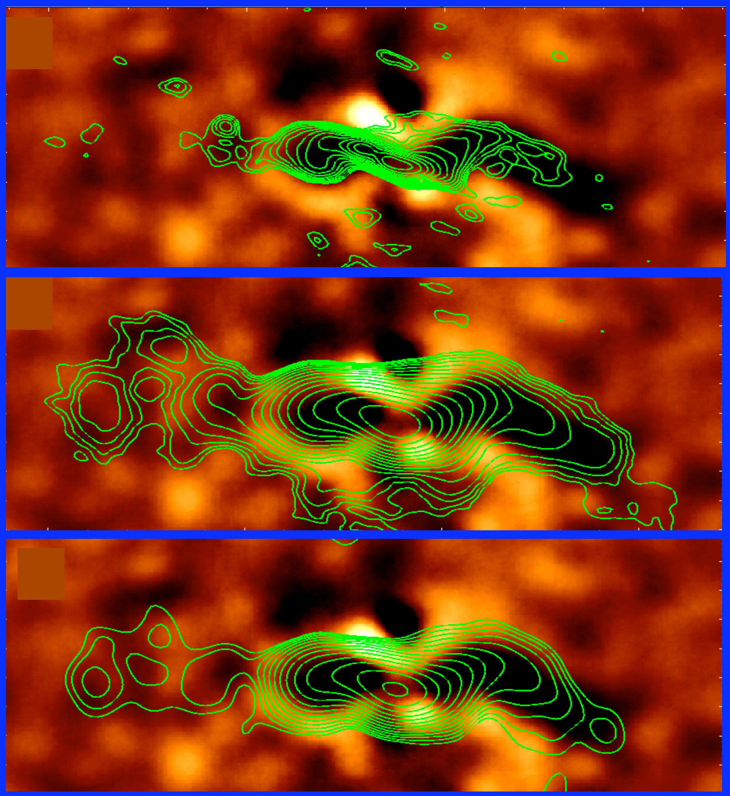


Fabian et al.

X-ray Tunnels?

Continuous channels in X-ray, with steeper radio spectra at large distances

Abell 262

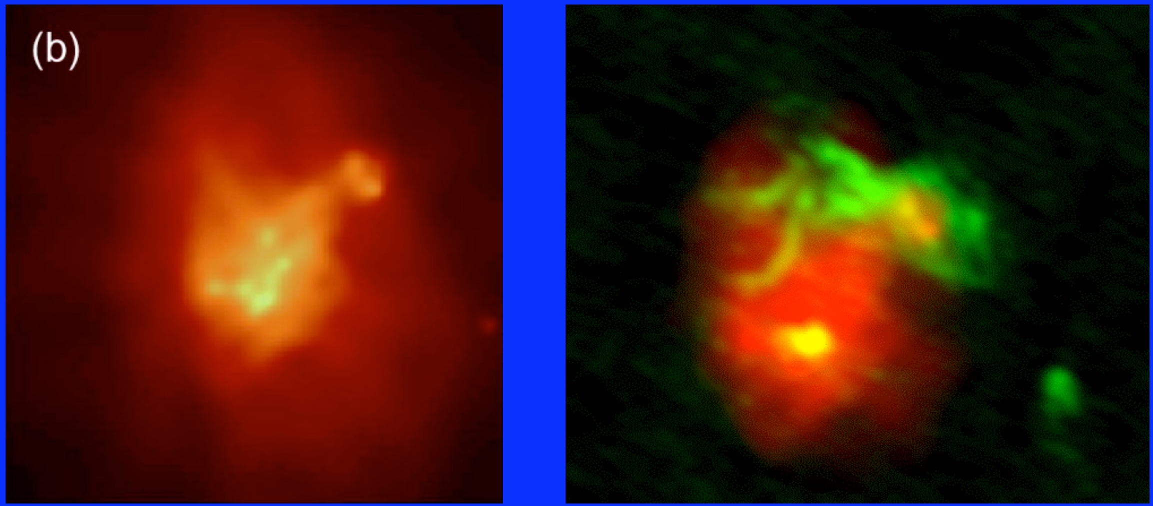


Red = Chandra

Green = low frequency radio

Clarke et al. 2009

Entrainment of Cool Gas

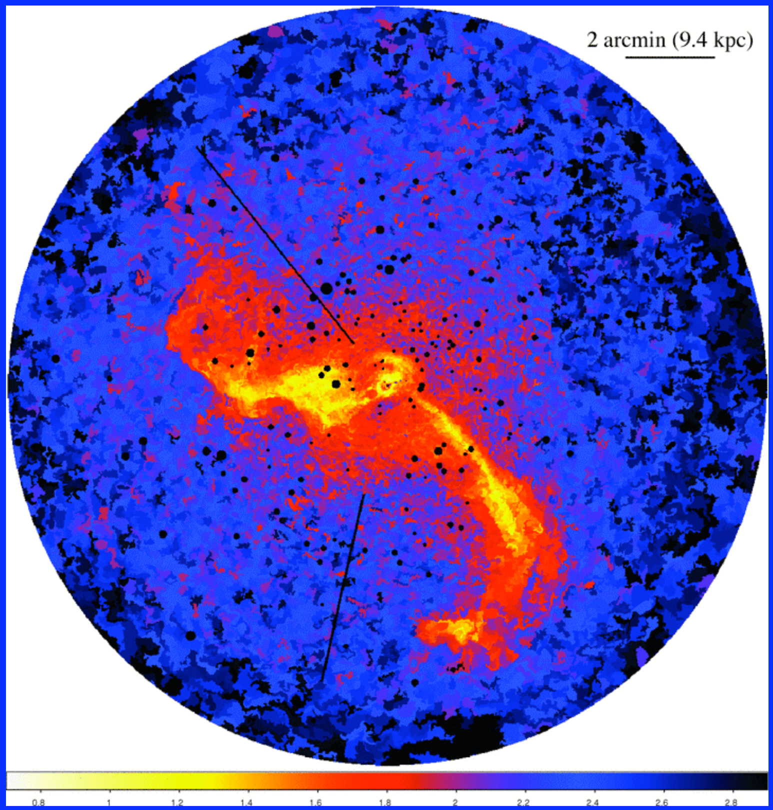


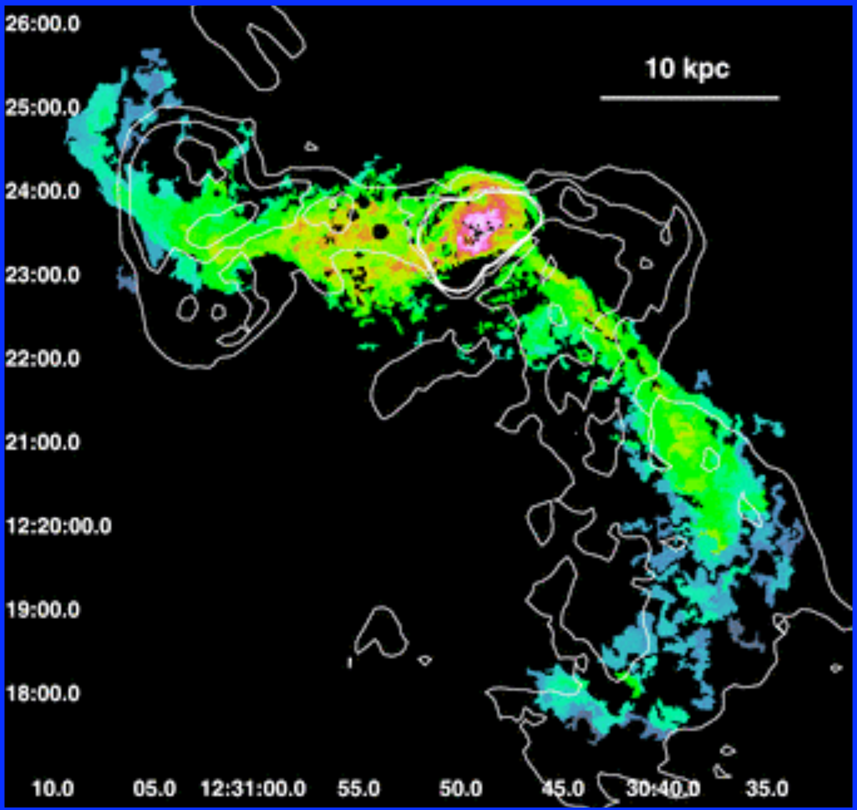
A133

Fujita et al. 2002; Randall et al. 2010

- Columns of cool X-ray gas from BCG center to radio lobe
- Gas entrained by buoyant radio lobe?

Entrainment of Cool Gas





M87/Virgo

Million et al. 2010, Werner et al. 2010

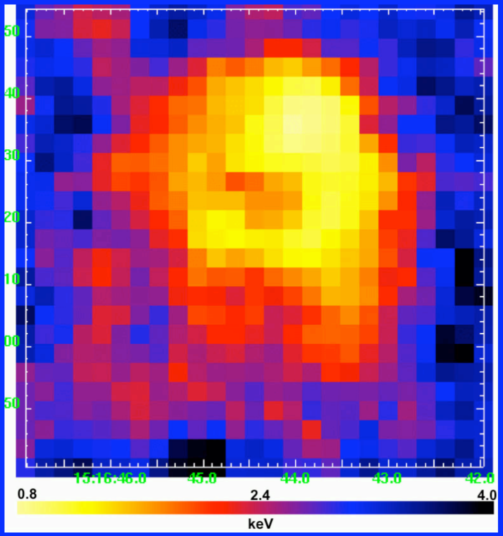
Temperatures & Pressures

In most radio bubbles:

- Gas in shells is cool
- Pressure in shells ≈ outside
- No large pressure jumps (shocks)

  Bubbles expand ≲ sound speed

  Pressure in radio bubbles ≈ pressure in X-ray shells
- Equipartition radio pressures are ~20 times smaller than X-ray pressures in shells!?

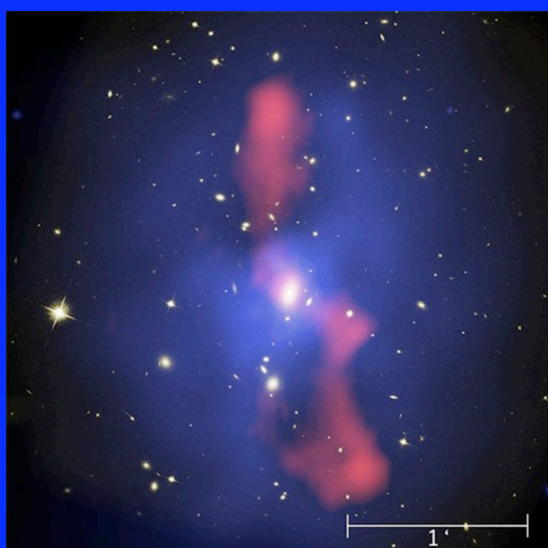


Shocks Around Radio Bubbles

Some radio bubbles surrounded by shocks

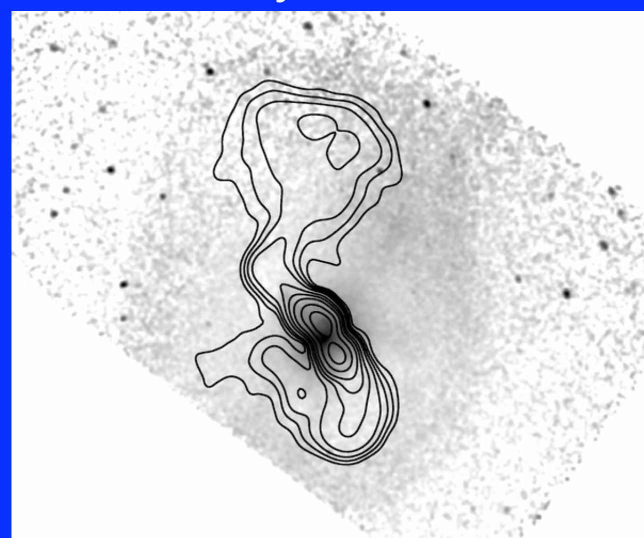
→ supersonic expansion

MS0735.6+7421

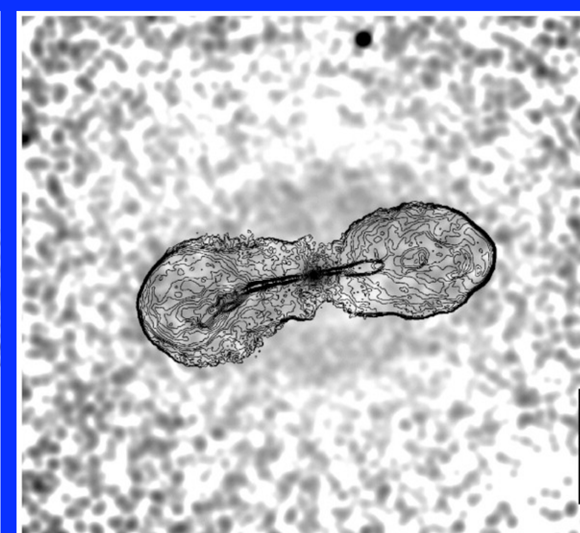


McNamara et al 2005

Hydra A



Hercules A



Nulsen et al 2005a.b

X-ray Shells as Radio Calorimeters

Energy deposition into X-ray shells from radio lobes
(Blanton et al. 2002;Churazov et al. 2002):

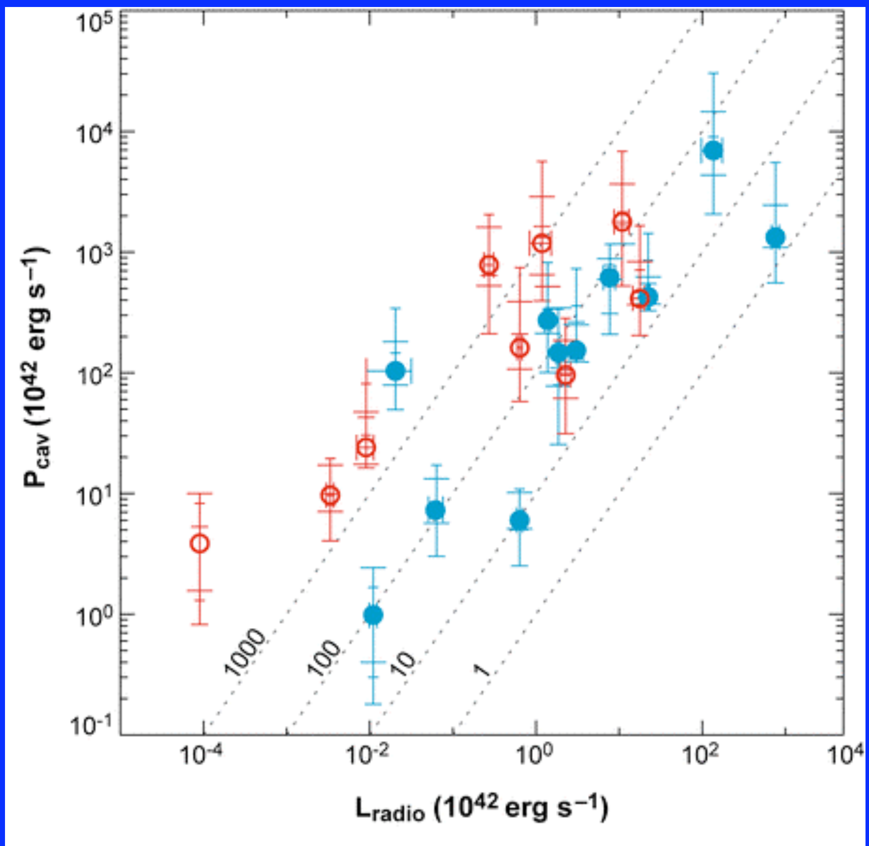
$$\frac{1}{\gamma - 1} PV + PV + \text{ (shock energy)} = \frac{\gamma}{\gamma - 1} PV = (2.5 \text{ to } 4)\, PV$$

Internal bubble energy — Work to expand bubble

- E ≈ 10^{59} ergs in Abell 2052, typical value
- Divide by repetition rate of radio (from buoyant bubbles) = radio jet kinetic power

Compare to Radio Luminosity

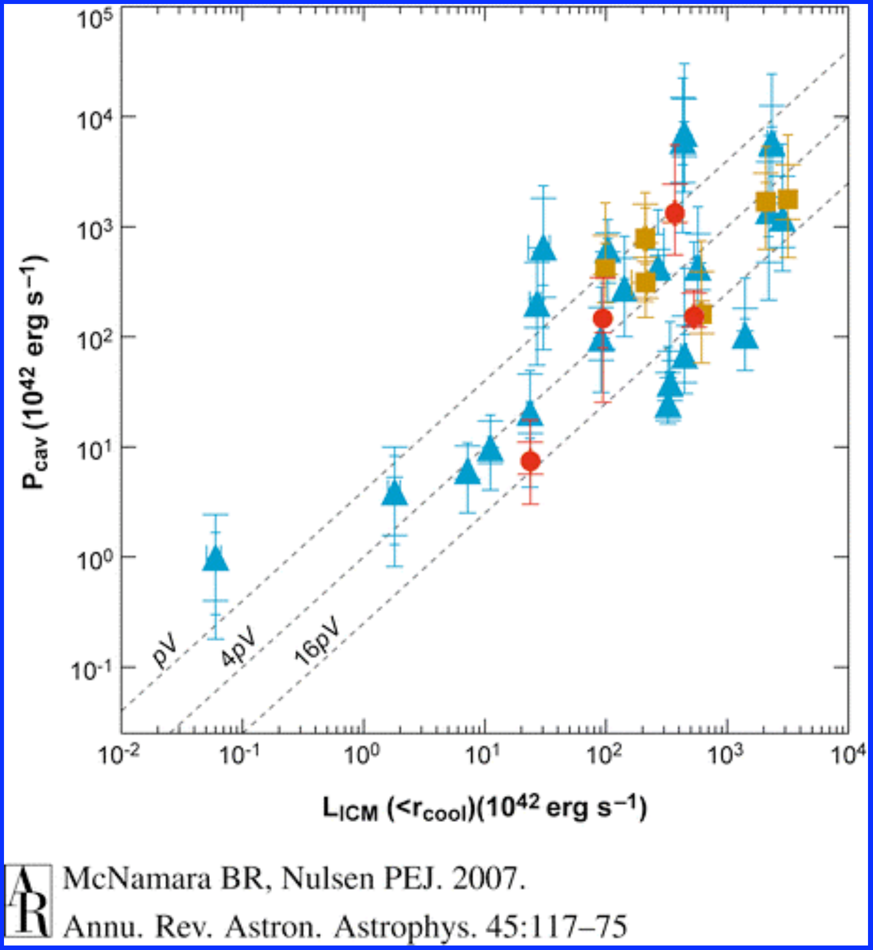
Radio emission is very inefficient



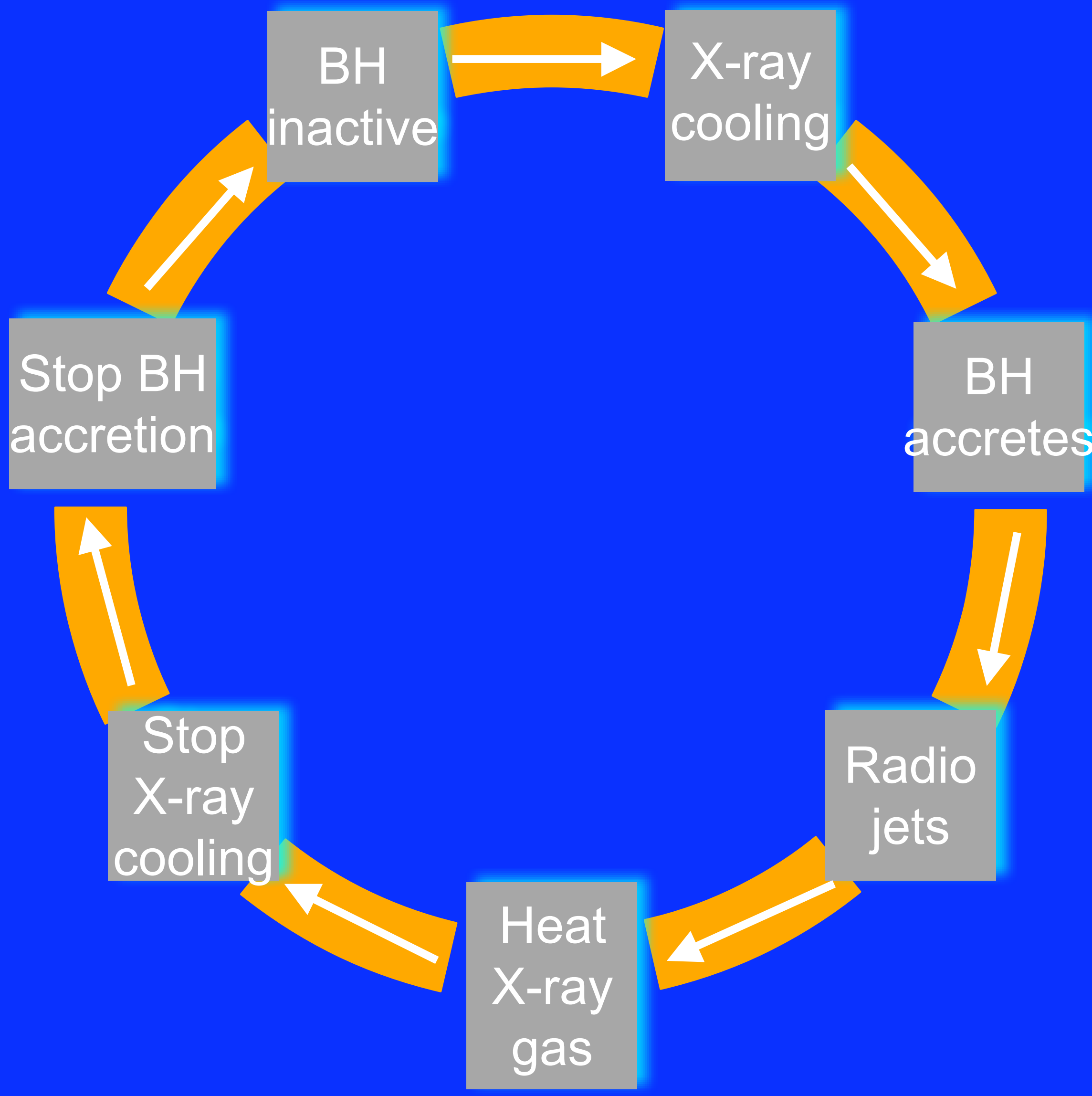
McNamara BR, Nulsen PEJ. 2007.
Annu. Rev. Astron. Astrophys. 45:117–75

Can Radio Sources Offset Cooling?

Works in many cases, but perhaps not all



Feedback Cycle?

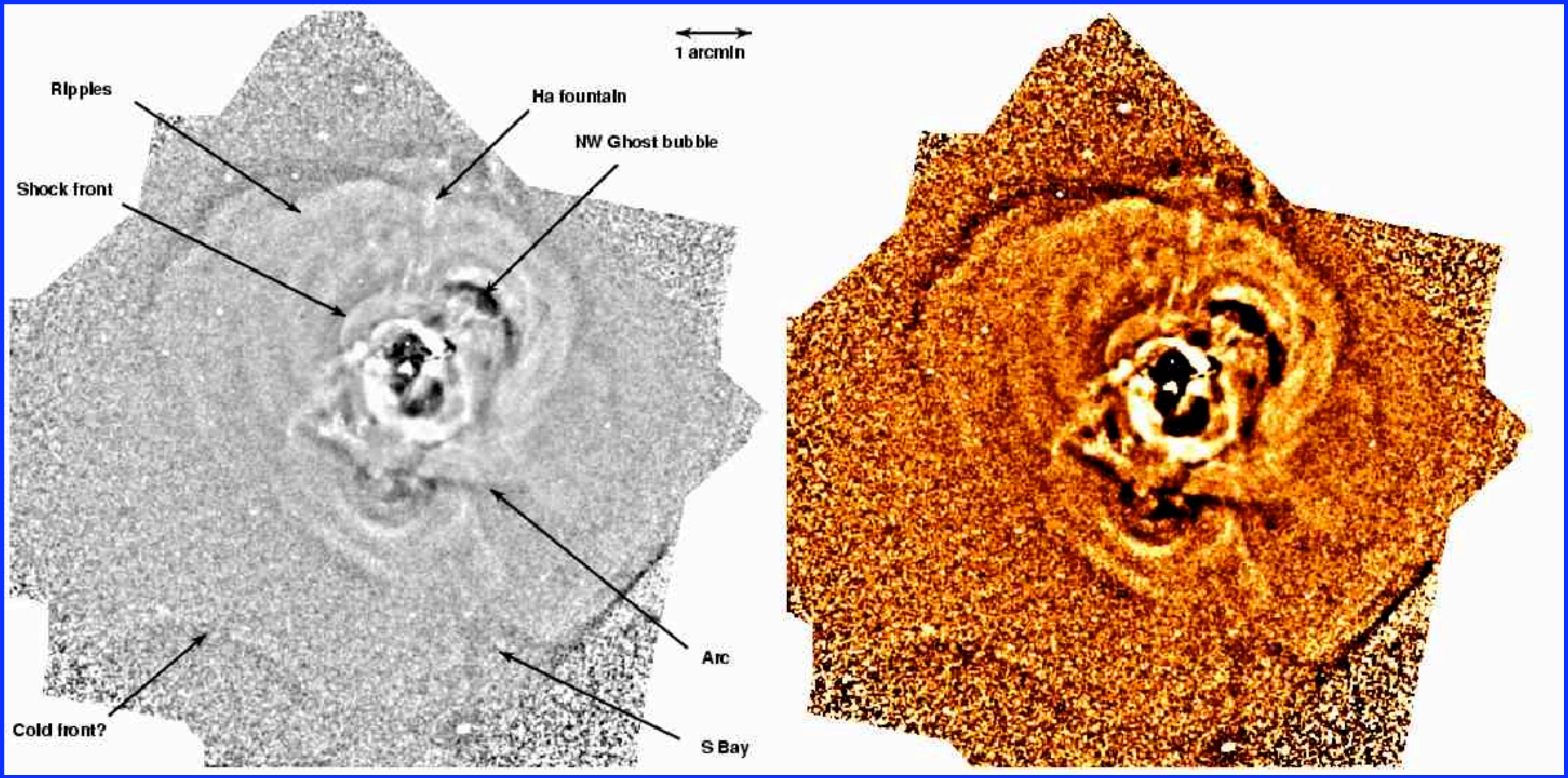


How Do Radio Sources Heat the Cooling X-ray Gas?

Enough energy, but how to get it into the cooling gas?

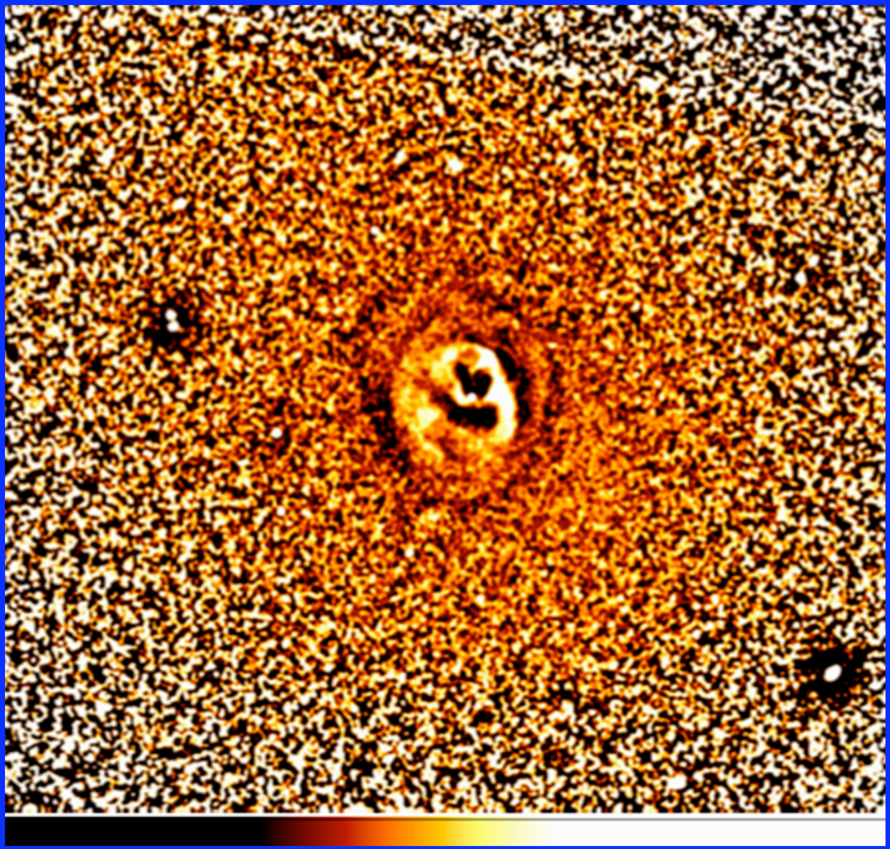
One possibility is sound waves and weak shocks from the radio source

Ripples in Perseus

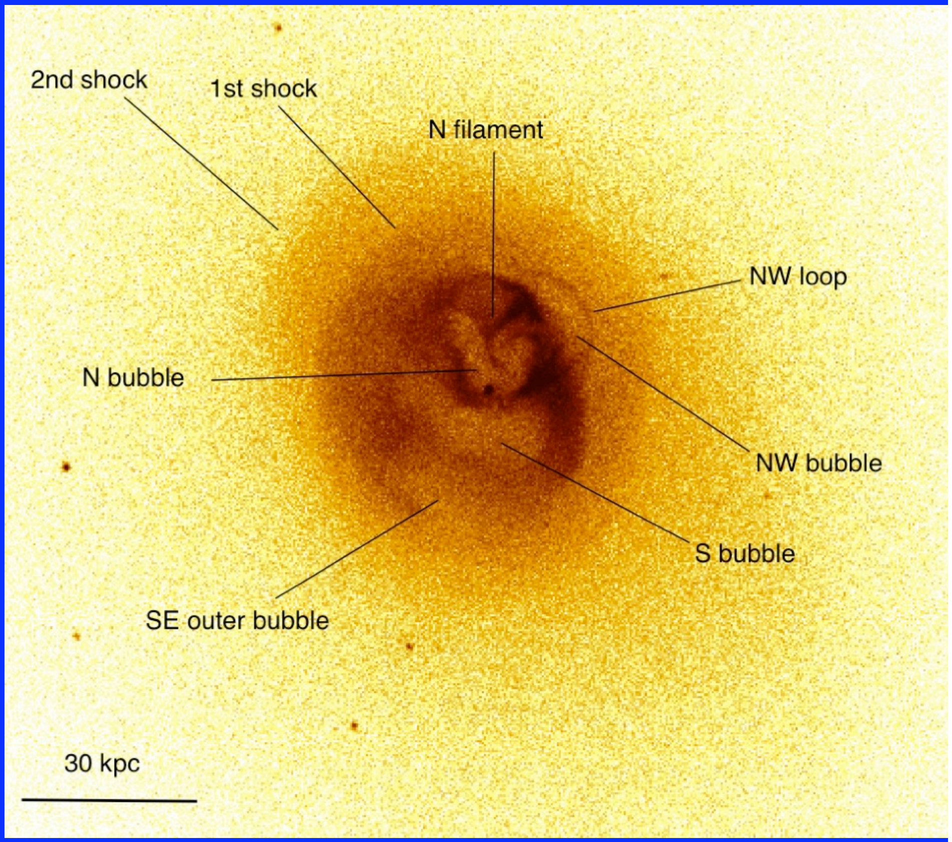


Fabian et al. 2006

Ripples in A2052



Unsharp Masked Chandra Image



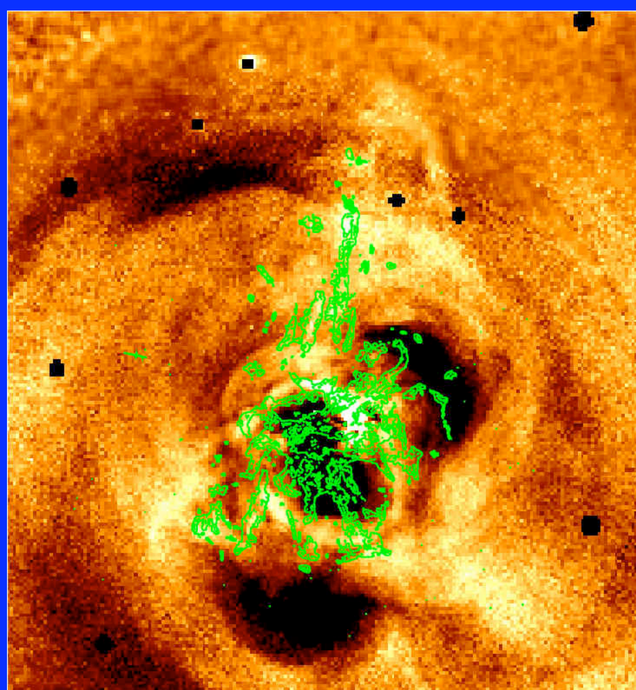
Unsmoothed Chandra Image

Blanton et al. 2008, 2011

X-ray Gas and Cooler Material

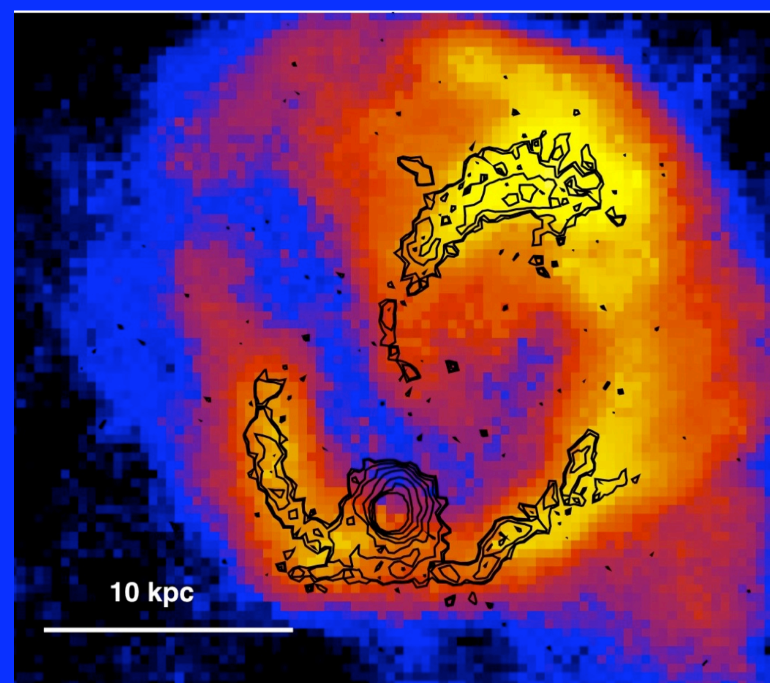
In some cases, association between X-ray filaments and filaments of cooler gas and dust (optical emission lines, CO, star formation)

Perseus



Fabian et al. 2011

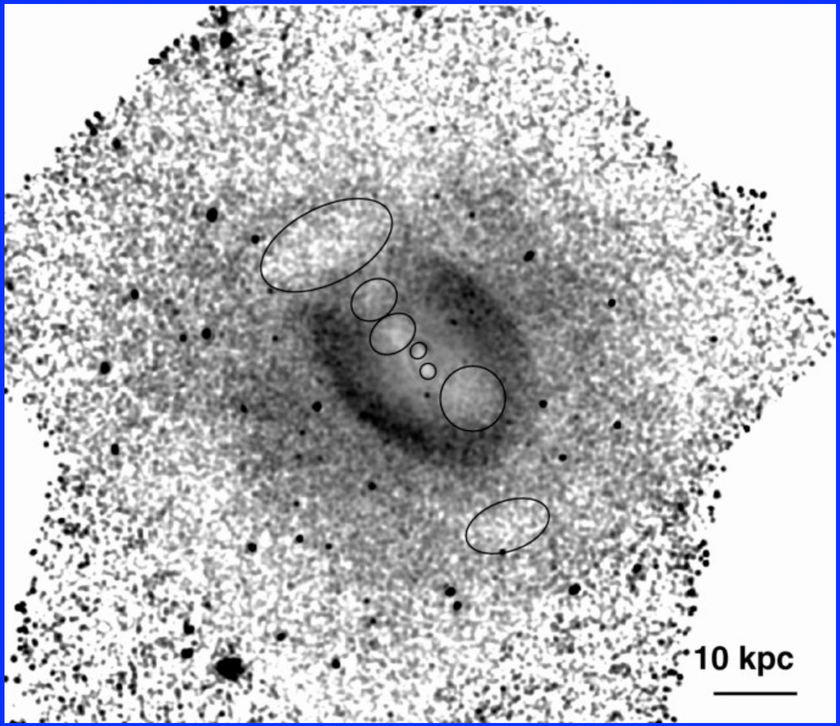
Abell 2052



Blanton et al. 2011

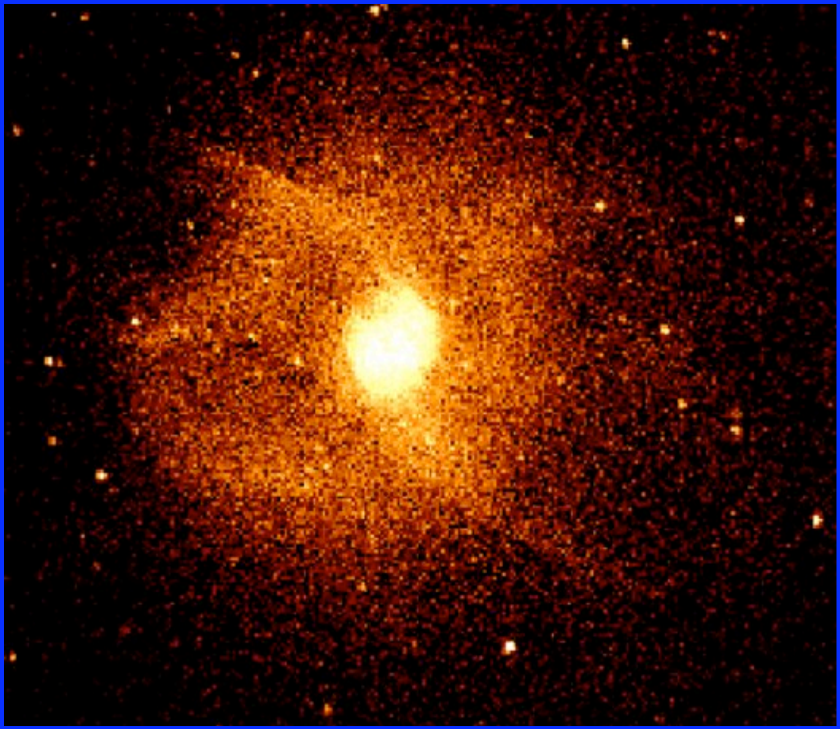
Radio Bubbles and Shocks in Groups and Galaxies

NGC5813 Group



Randall et al. 2011

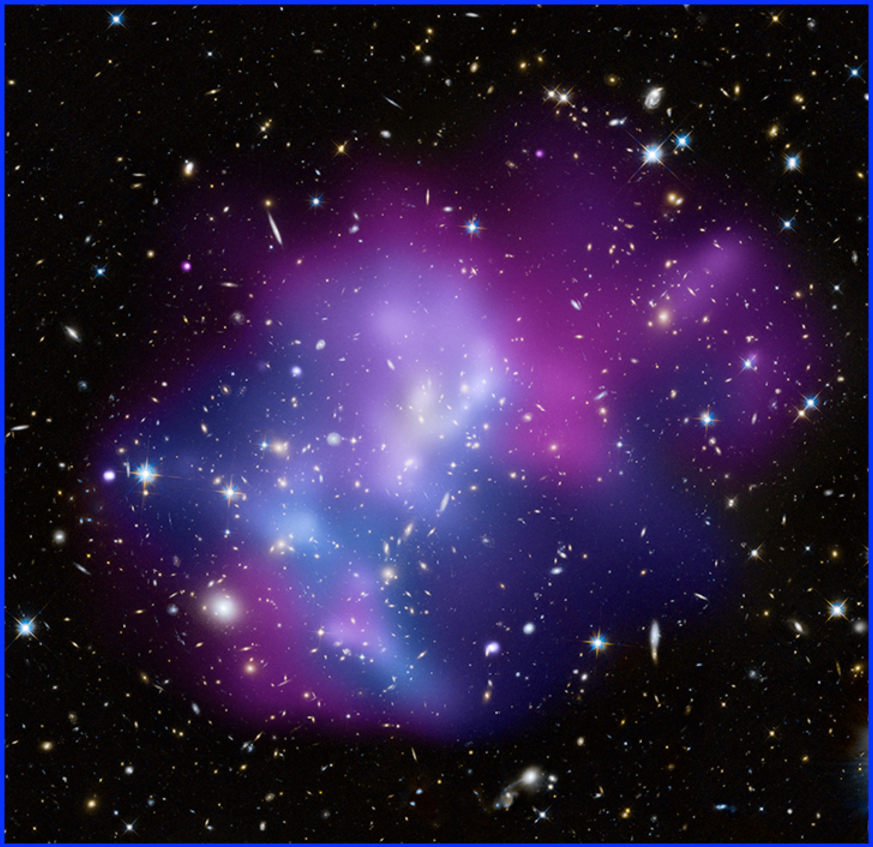
NGC4636



Baldi et al. 2009

Merging Clusters

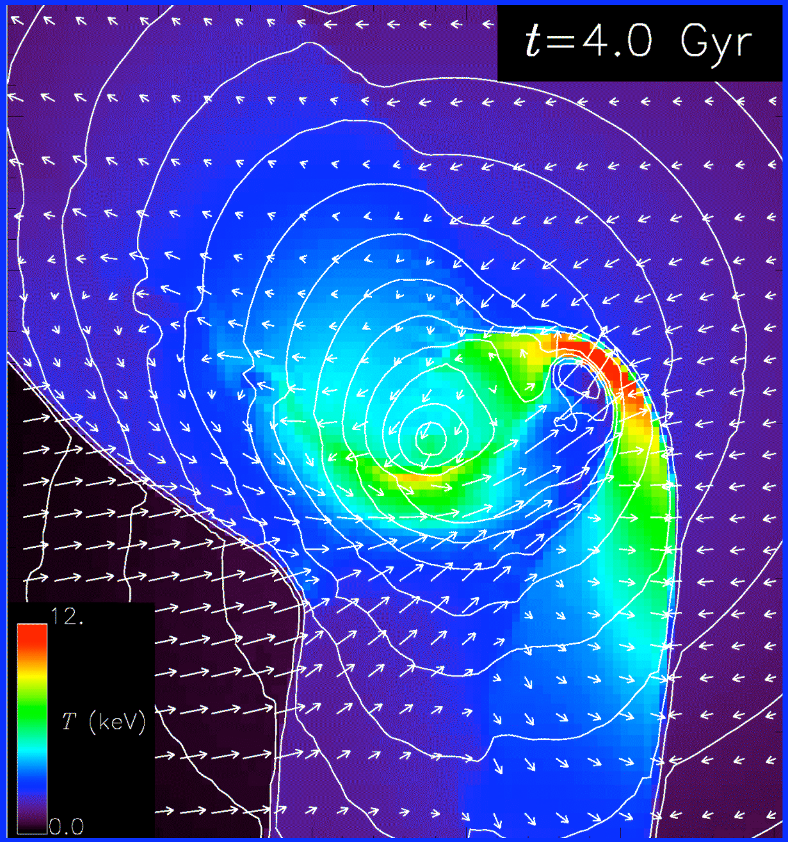
MACSJ0717.7+3745



Ma et al. 2009

Cluster Mergers

- Clusters form by mergers
- Merger shocks heat intracluster gas



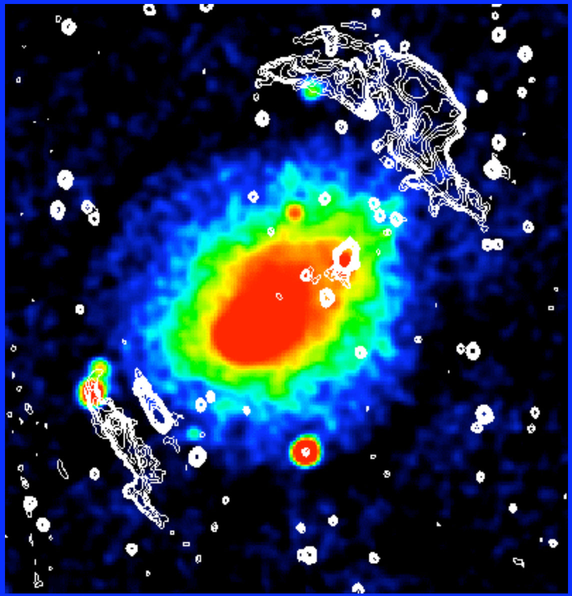
Cluster Merger Simulation

(Ricker & Sarazin 2001)

Cluster Mergers

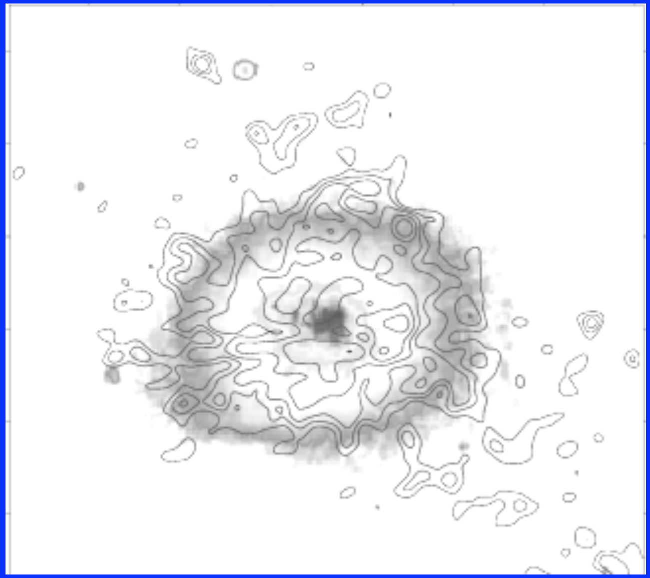
- Clusters form by mergers
- Merger shocks heat intracluster gas
- Mergers may accelerate relativistic particles

Radio Relics



Abell 3667
Röttgering et al.1997

Radio Halo

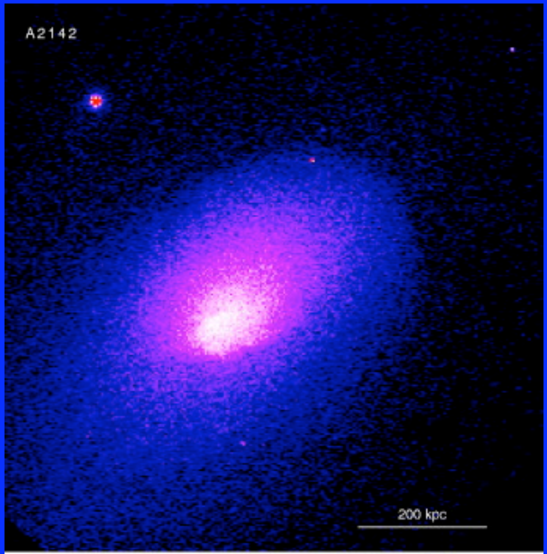


Coma
Govoni et al. 2001

Cold Fronts in Mergers

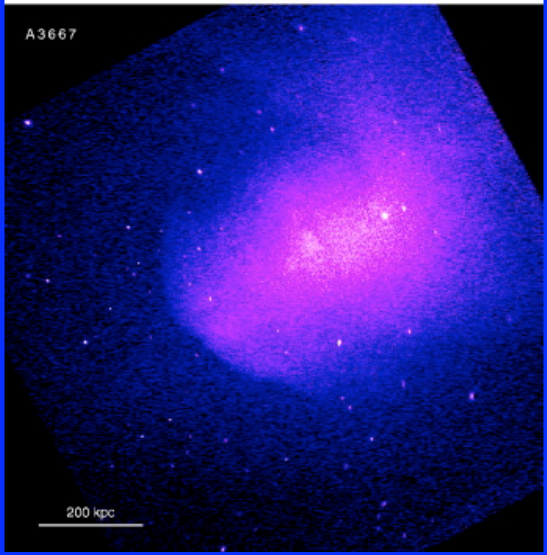
Merger shocks?

No: Dense gas is cooler, lower entropy, same pressure as lower density gas



Abell 2142

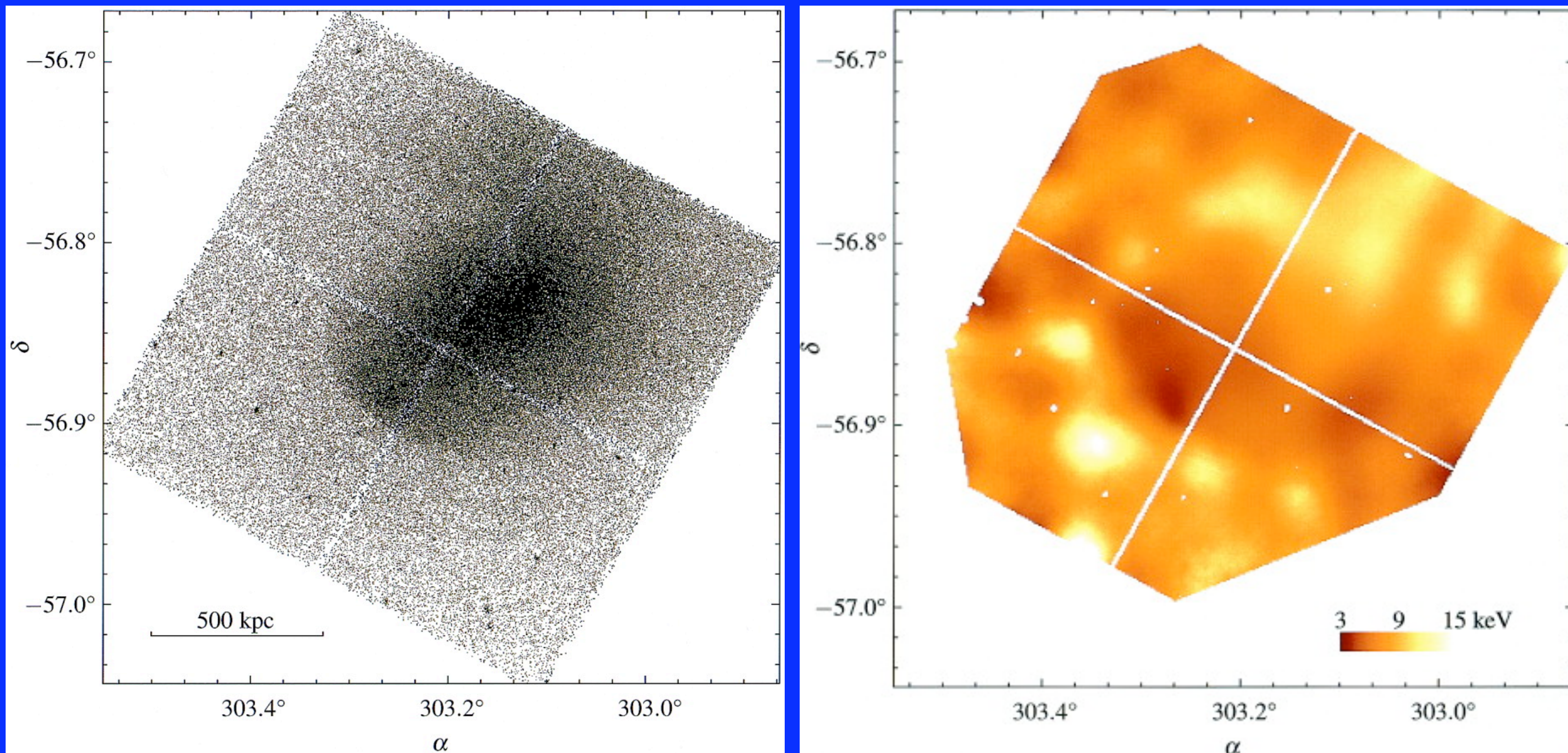
(Markevitch et al. 2000)



Abell 3667

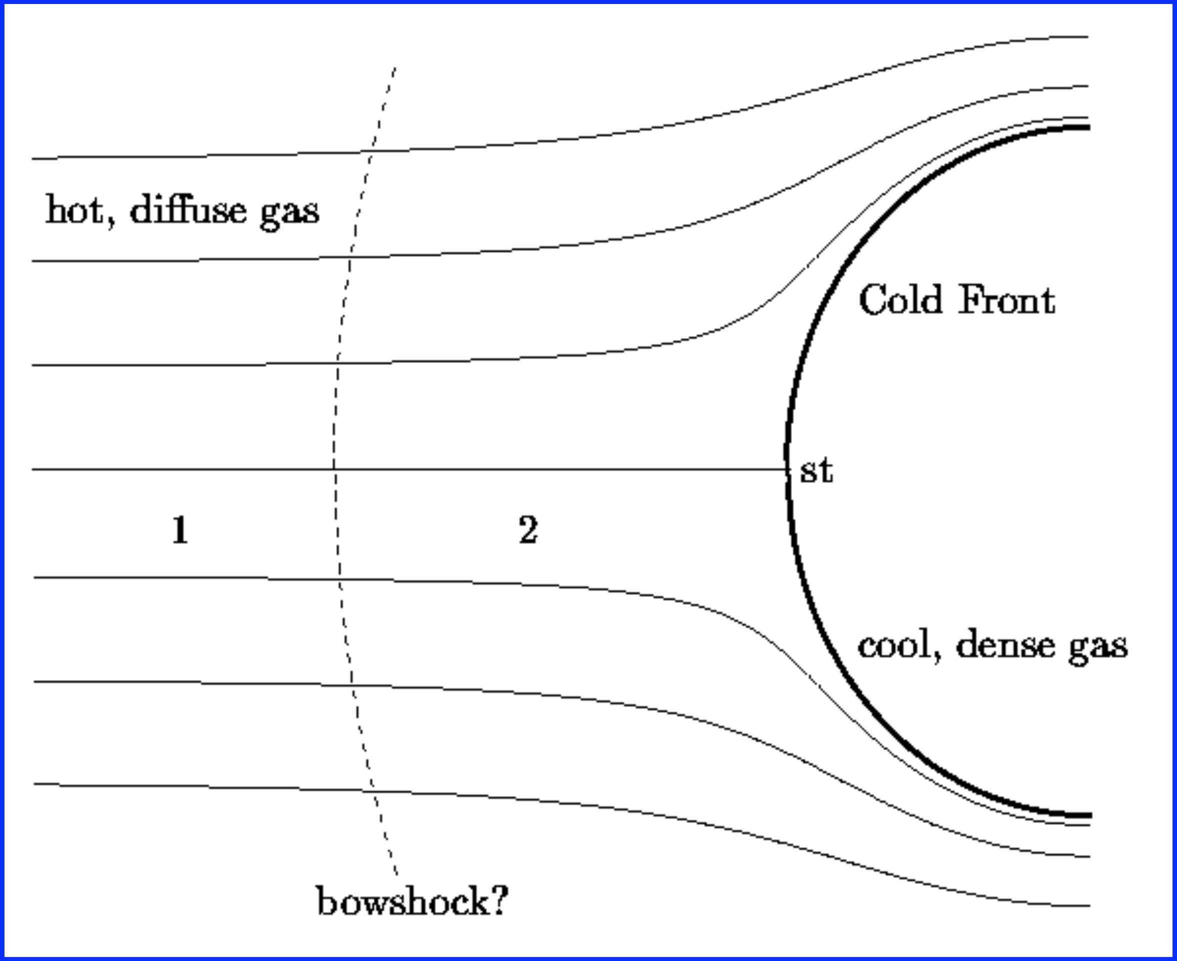
(Vikhlinin et al. 2001)

Abell 3667



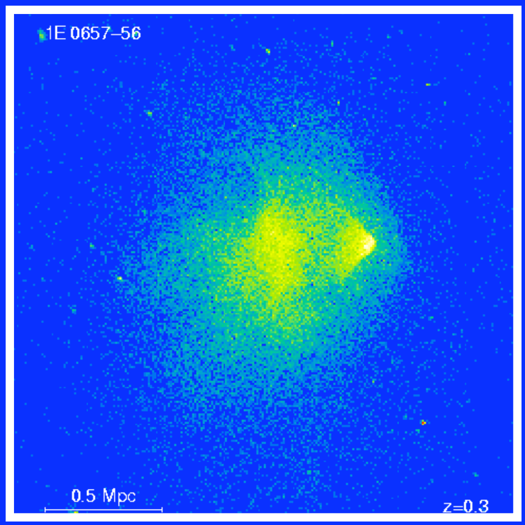
Contact discontinuity, cool cluster cores plowing through hot shocked gas (Vikhlinin et al. 2001)

Merger Cold Fronts & Merger Shocks



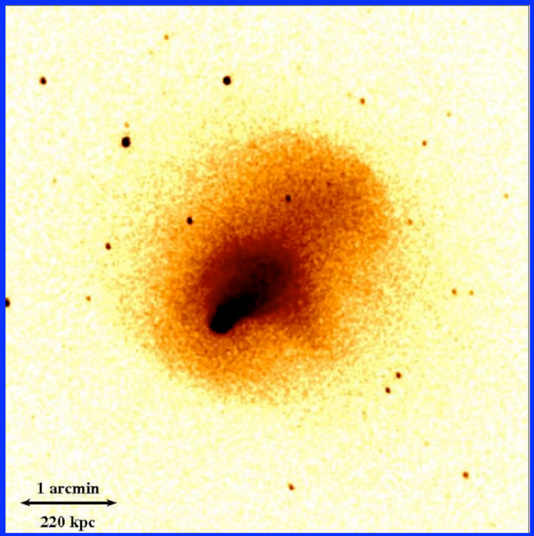
Cold Fronts

1E0657-56



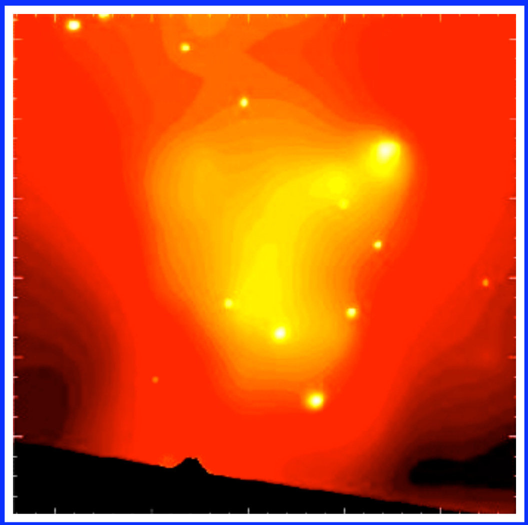
Markevitch et al. 2004

Abell 2146



Russell et al. 2010

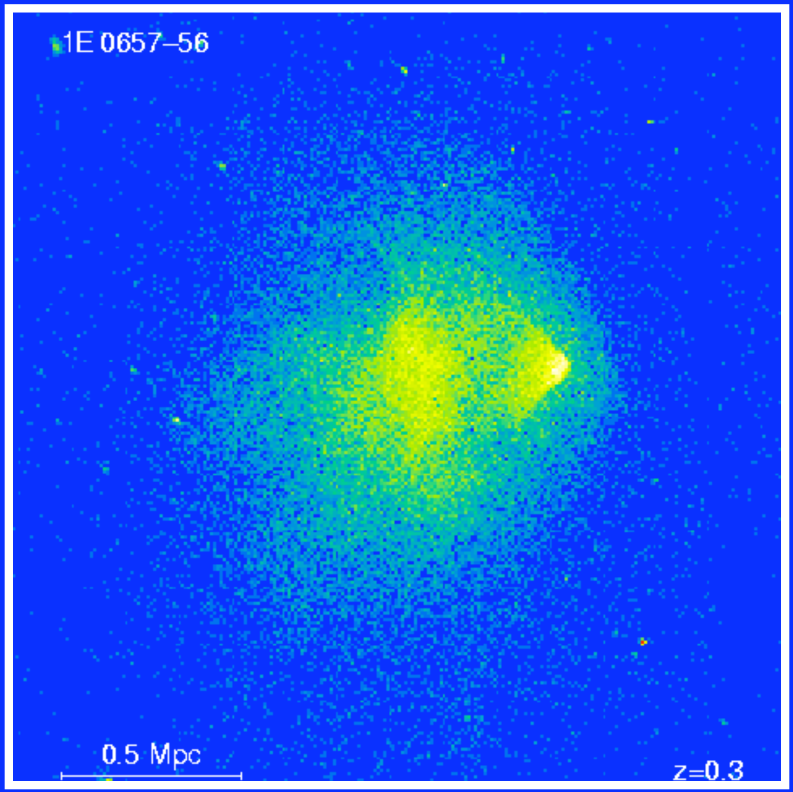
Abell 85 South



Kempner et al. 2002

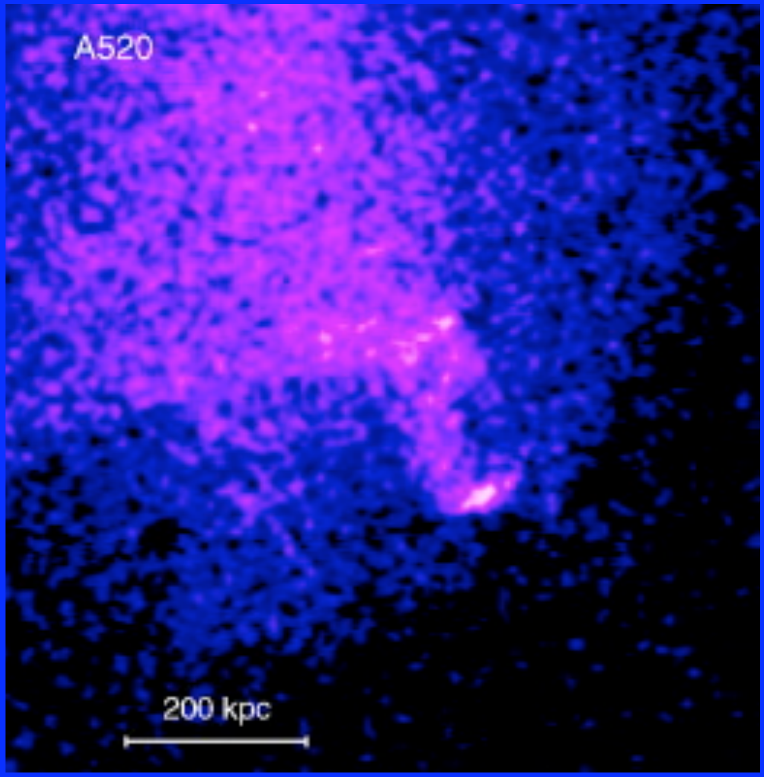
Merger Shock Fronts

1E0657-56 = Bullet Cluster



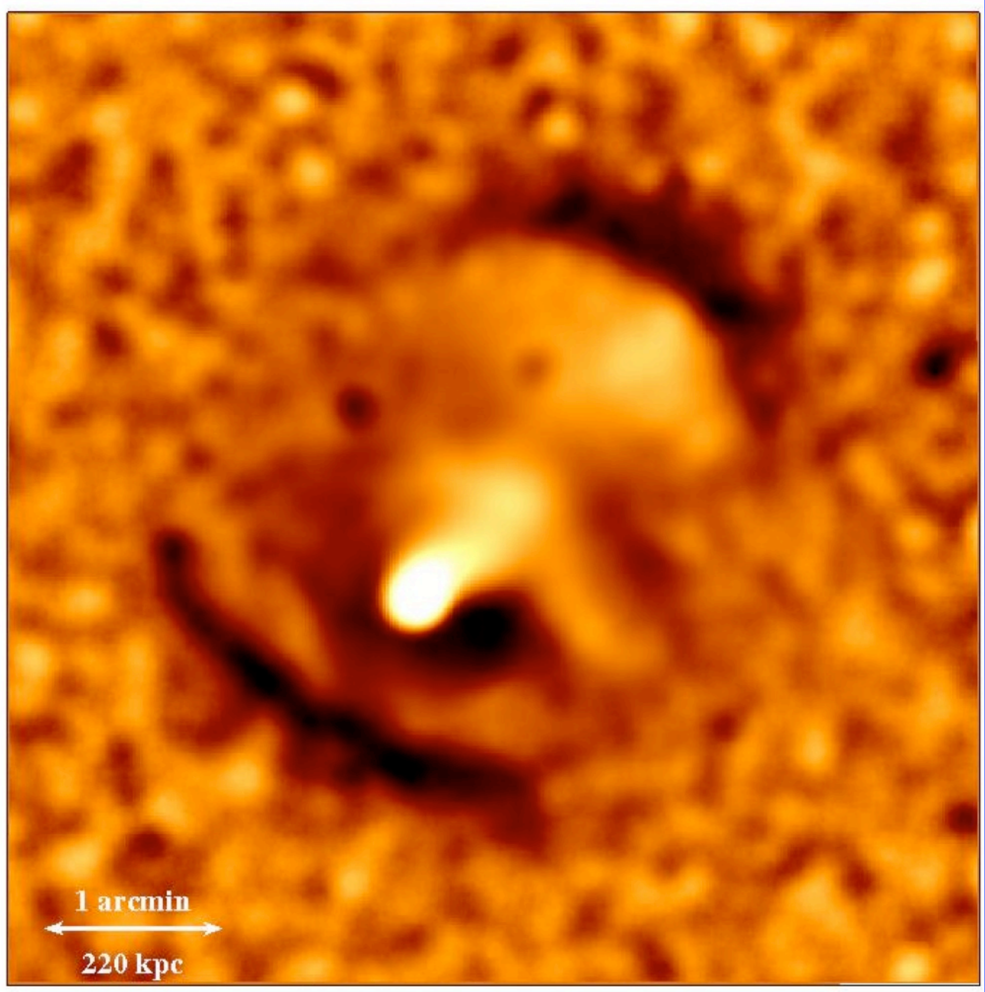
Markevitch et al. 2004

Abell 520



Markevitch et al. 2005

Double Merger Shock Fronts



Abell 2146 (unsharp mask)

Russell et al. 2010

Merger Kinematics

(Markevitch & Vikhlinin 2007)

Give merger Mach number $\mathcal{M}$

- Rankine-Hugoniot shock jump conditions

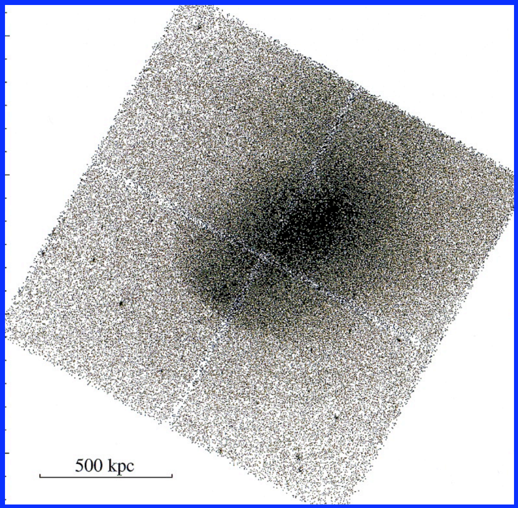
  Density, temperature, or pressure jump

  $P_2/P_1 = 2\gamma/(\gamma+1)\ \mathcal{M}^2 + (\gamma-1)/(\gamma+1)$
- Stagnation condition at cold front
- Stand-off distance of bow shock from cold front

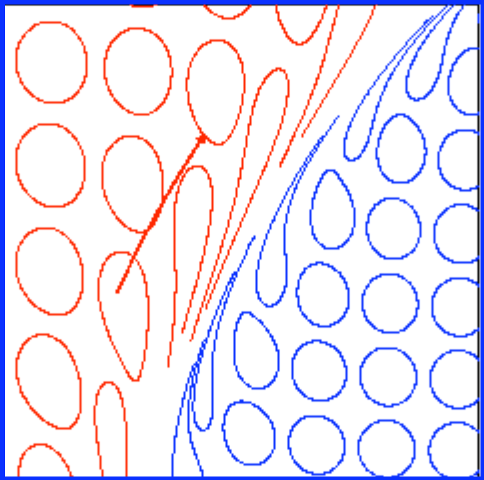
Find $\mathcal{M} \approx 2$, shock velocity ≈ 2000 km/s

Transport Processes – Thermal Conduction

(Ettori & Fabian 2000; Vikhlinin et al. 2001)



- Temperature changes by 5x in $\lesssim$ 5 kpc < mfp
- Thermal conduction suppressed by ~ 100 x
- Kelvin-Helmholtz and other instabilities suppressed
- Due to transverse or tangled magnetic field?



→ Is conduction generally suppressed in clusters?

Mergers: Test of Gravitational Physics

Bullet Cluster

1E0657-56

Image = galaxies

Red = X-rays = gas

Blue = lensing mass = gravity

(Markevitch et al. 2004
Clowe et al. 2004)

→ Gas behind DM ≈ Galaxies

Mergers:
Test of Dark Matter vs. Modified Gravity

- Gas behind DM ≈ Galaxies
- DM = location of gravity
- Gas = location of most baryons
- Whatever theory of gravity, not coming from where baryons are

→ Require dark matter (not MOND)

Mergers:
Test of Collisional Dark Matter

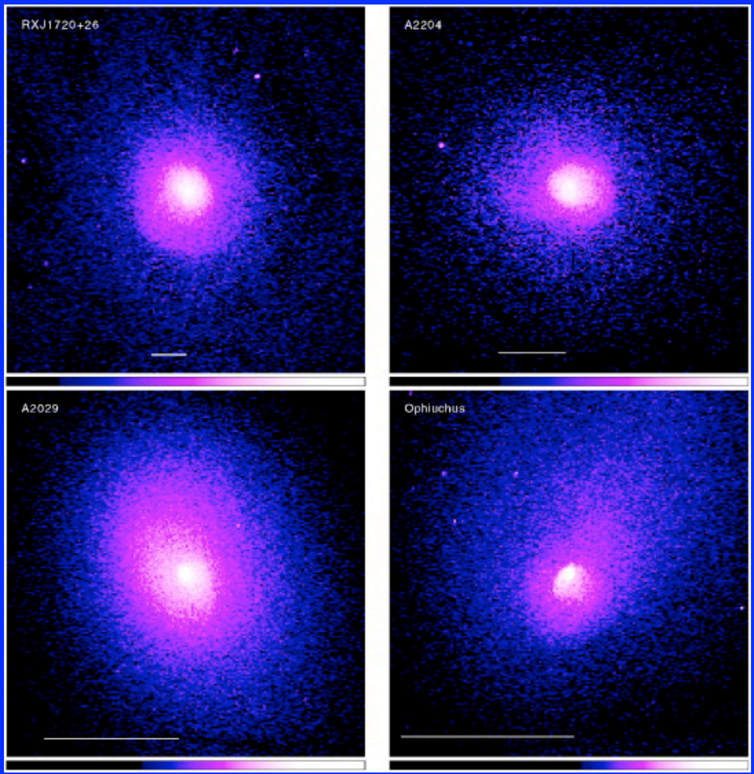
- Gas behind DM ≈ Galaxies
- Gas collisional fluid
- Galaxies collisionless particles
- Limit on self-collision cross-section of DM

→ σ/m (DM) $\lesssim 1\ cm^2/g < 5\ cm^2/g$ required for cores in dwarf galaxies

(Randall et al. 2008)

“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
- Kinematics: lower Mach numbers



(Markevitch & Vikhlinin 2007)

“Sloshing” Cold Fronts

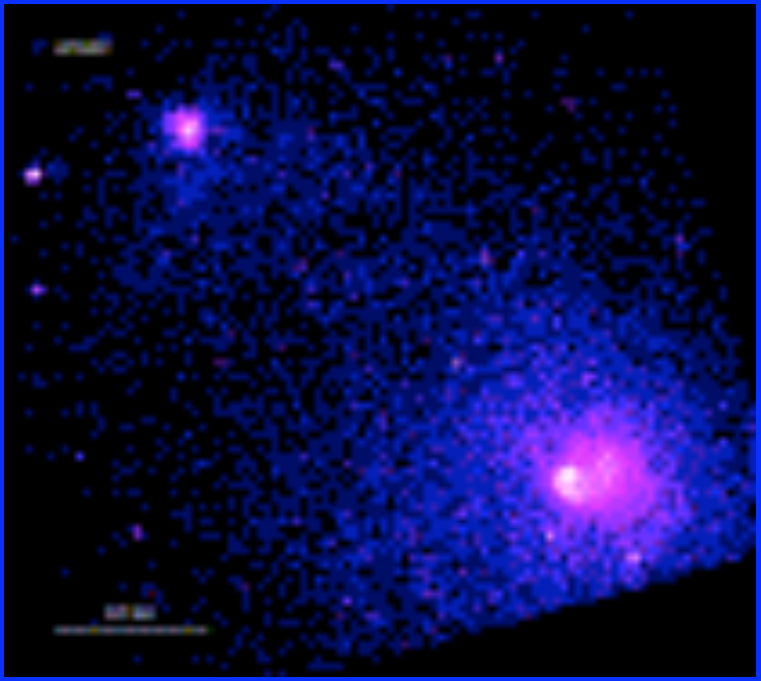
- Cold fronts in regular, cool core clusters
- Kinematics: lower Mach numbers
- Due to gas sloshing due to passage of subcluster near core of main cluster

(Markevitch et al. 2001)

“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
- Kinematics: lower Mach numbers
- Due to gas sloshing due to passage of subcluster near core of main cluster

Abell 1644

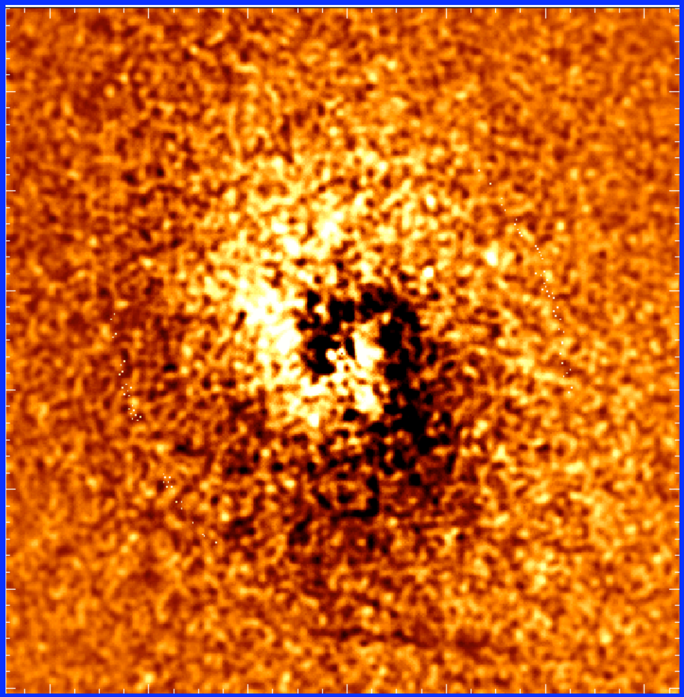


(Johnson et al. 2010)

“Sloshing” Cold Fronts

- Cold fronts in regular, cool core clusters
- Kinematics: lower Mach numbers
- Due to gas sloshing due to passage of subcluster near core of main cluster
- One-arm spiral pattern toward subcluster often

Abell 2029
(difference image)



(Clarke et al. 2004)

Merger Shocks and Nonthermal Particles

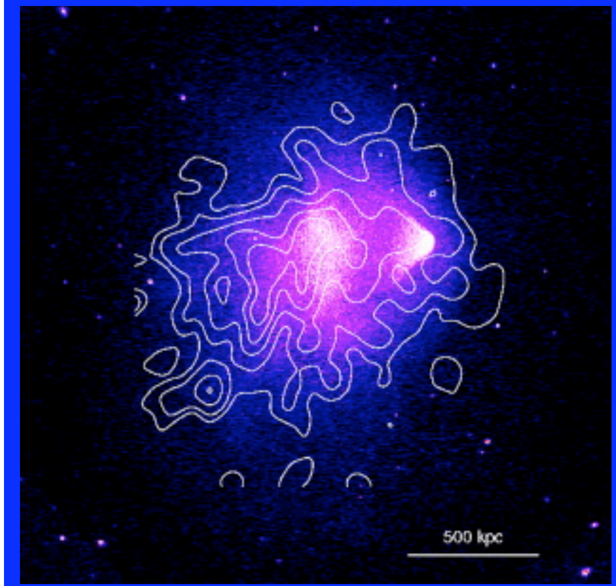
Theory suggests relativistic particles (re)accelerated

- at merger shocks (radio relics)
- behind merger shocks (radio halos)

Merger Shocks and Nonthermal Particles

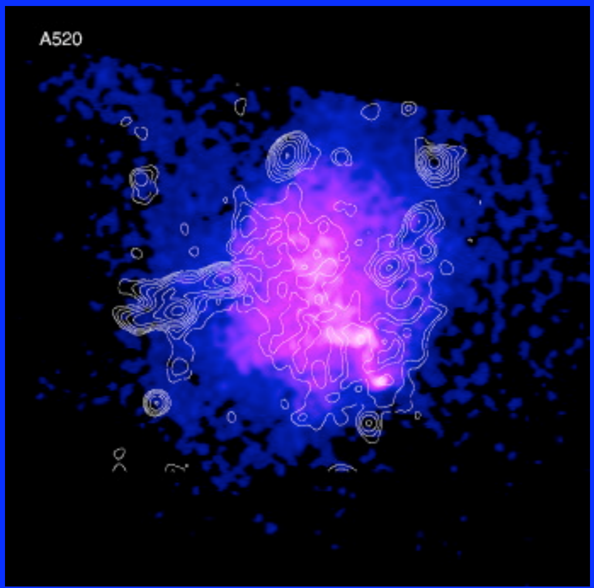
Chandra images support shock/radio connection

Bullet



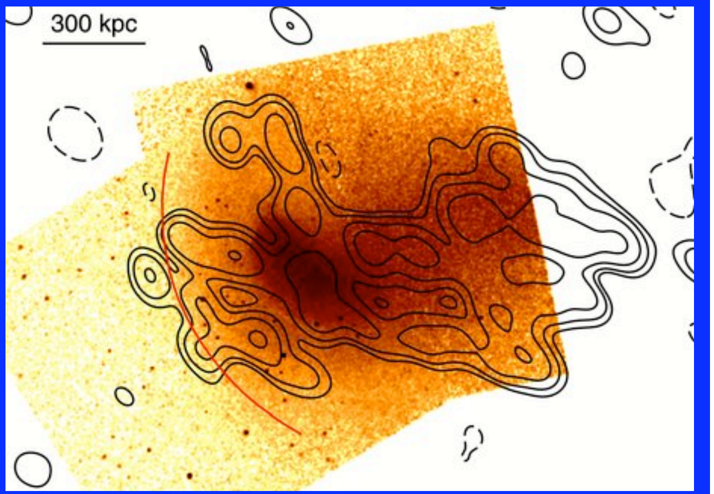
(Liang et al. 2000)

Abell 520



(Govoni et al. 2001)

Abell 754



(Macario et al. 2011)

Summary

- Chandra high resolution observations have transformed our view of clusters
- Cool cores - X-ray cavities, radio bubbles, and feedback
  - Low redshift analogs of high mass galaxy formation at high redshift
- Merging clusters, cold fronts, shocks
  - Physics of cluster formation, transport processes, and particle acceleration
  - Basic gravitational physics