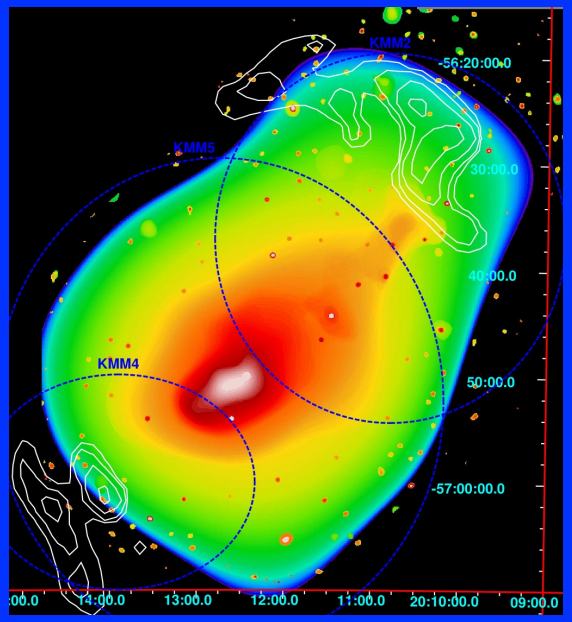
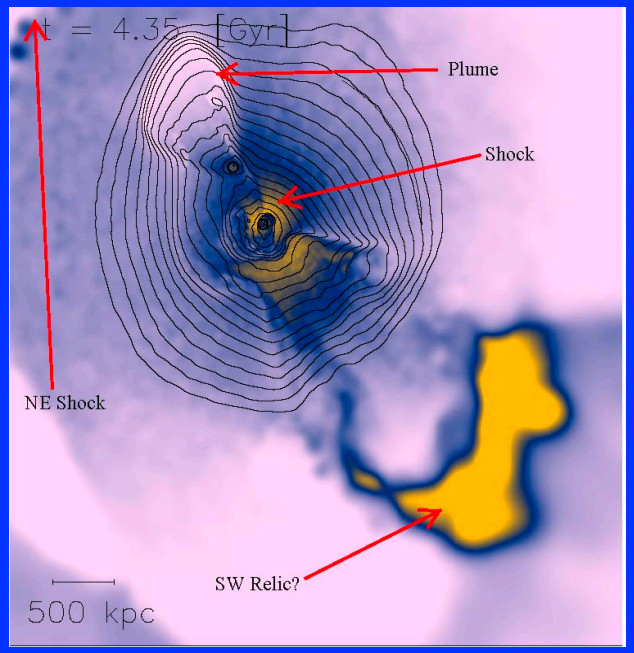
Mergers and Radio Sources in Abell 3667 and Abell 2061



A3667 XMM X-ray image and radio contours

Craig Sarazin

University of Virginia



SLAM Simulation of A2061

Collaborators

Alexis Finoguenov (MPE, UMBC) - Abell 3667

Avery Bailey, Taylor Hogge (Univ. Virginia) – Abell 2061

Marios Chatzikos (Univ. Kentucky) - Simulations

Shea Brown (Univ. Iowa)

Tracy E. Clarke (NRL)

Damon Farnsworth, Larry Rudnick (Univ. Minnesota)

Melanie Johnston-Hollit (Victoria University, New Zealand)

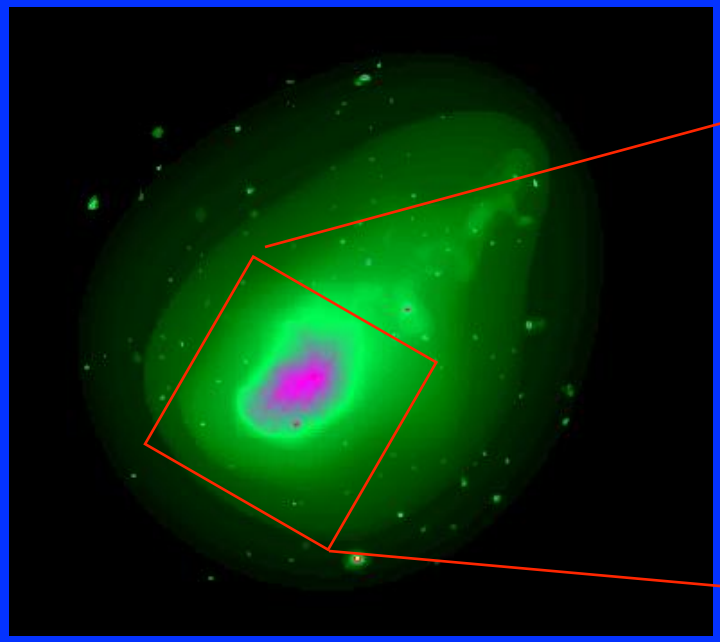
Kazuhiro Nakazawa (Univ. Tokyo)

Reinout van Weeren (Harvard CfA)

Dan Wik (NASA Goddard)

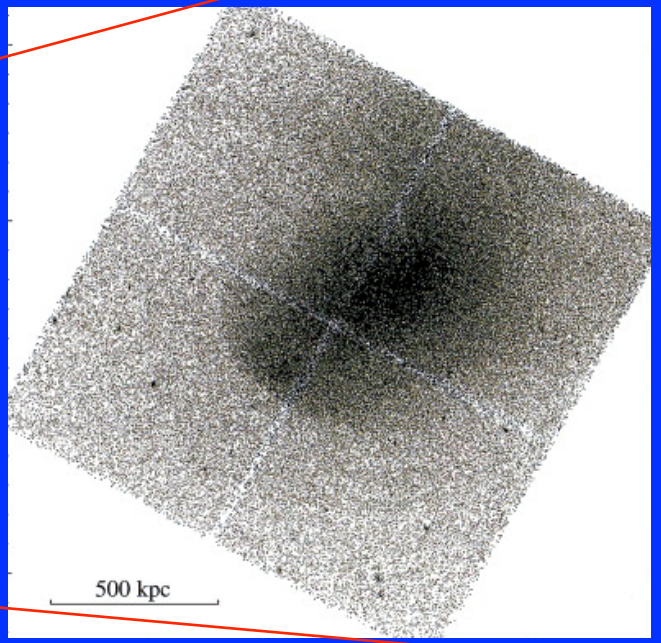
Abell 3667 – Merging Cluster

XMM



Briel et al. 2004; Nakazawa et al. 2009

Chandra



Vikhlinin et al. 2000

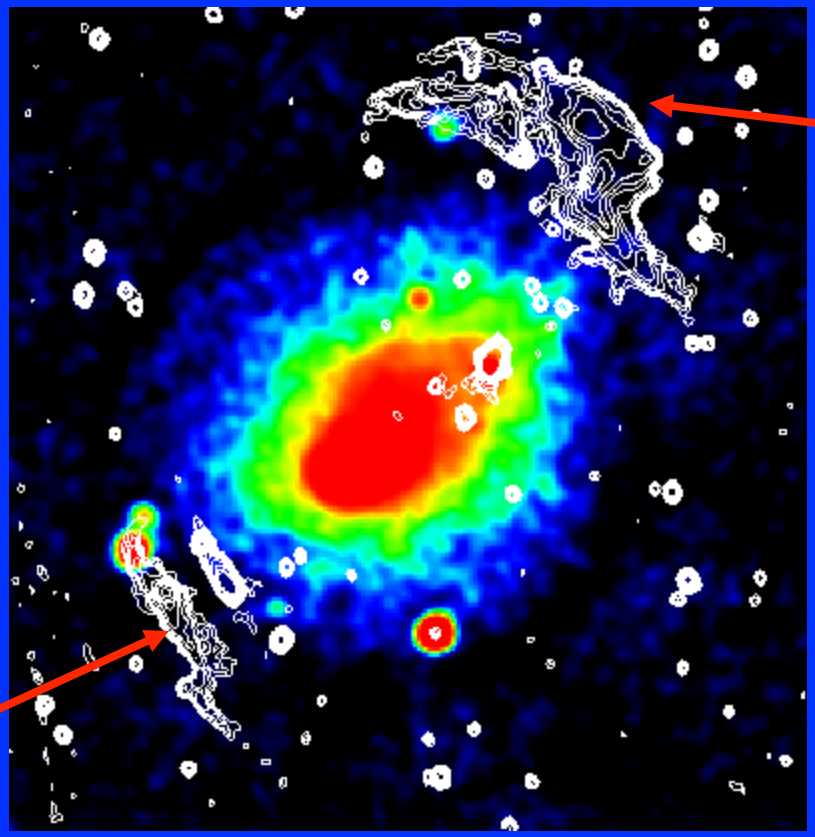
- Major merger along NW-SE axis
- z = 0.0552

- Cold front, remnant of cool core of one subcluster

Finoguenov et al. 2010; Sarazin et al. 2013, 2014

Double Radio Relics

ROSAT (color), radio contours



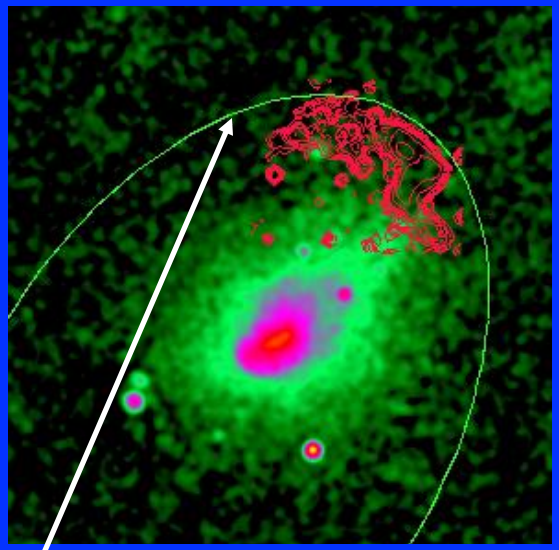
NW Radio Relic

SE Radio Relic

Röttgering et al. 1997

NW Radio Relic in Abell 3667

- Brightest diffuse cluster source
  3.7 Jy at 20 cm (Johnston-Hollitt 2004)
- Located at large projected radius ~2.2 Mpc
- Due to merger shock acceleration?



Radio vs. ROSAT X-rays

Merger shock?

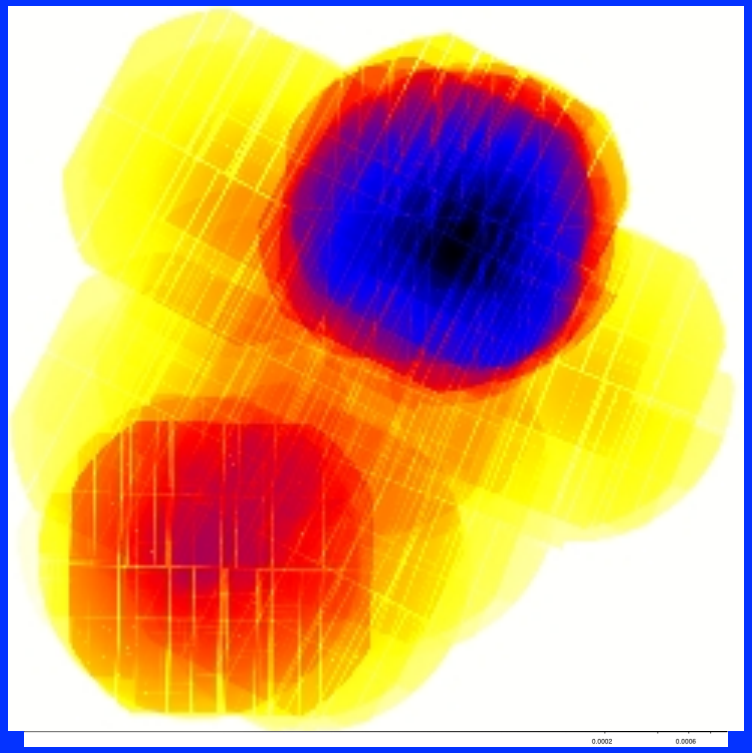
XMM Observations of Radio Relic

- 7 previous observations of Abell 3667

  (Briel et al. 2004)

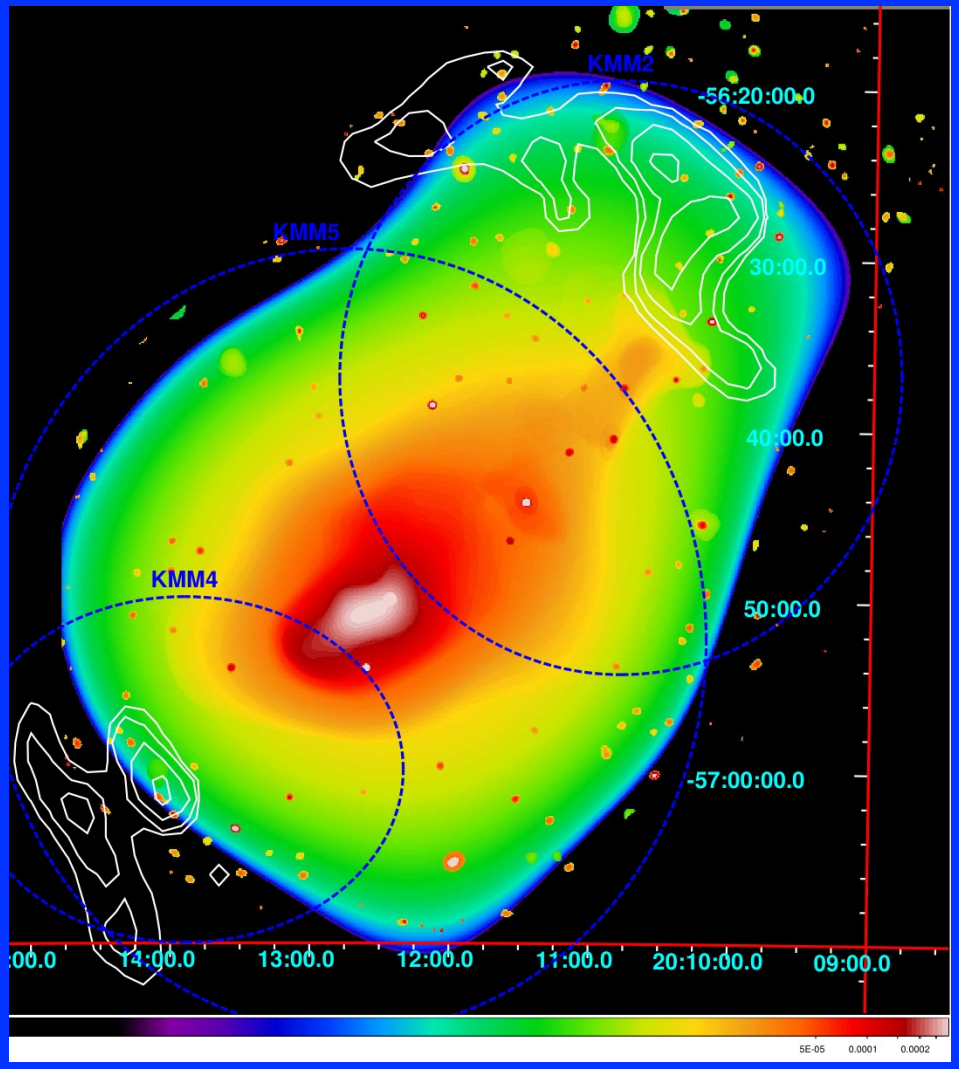
  But, misses radio relic region
- XMM AO-7 observation 55 ksec
- XMM AO-9 Large Project 311 ksec

  Coverage of relic and regions beyond and to the side

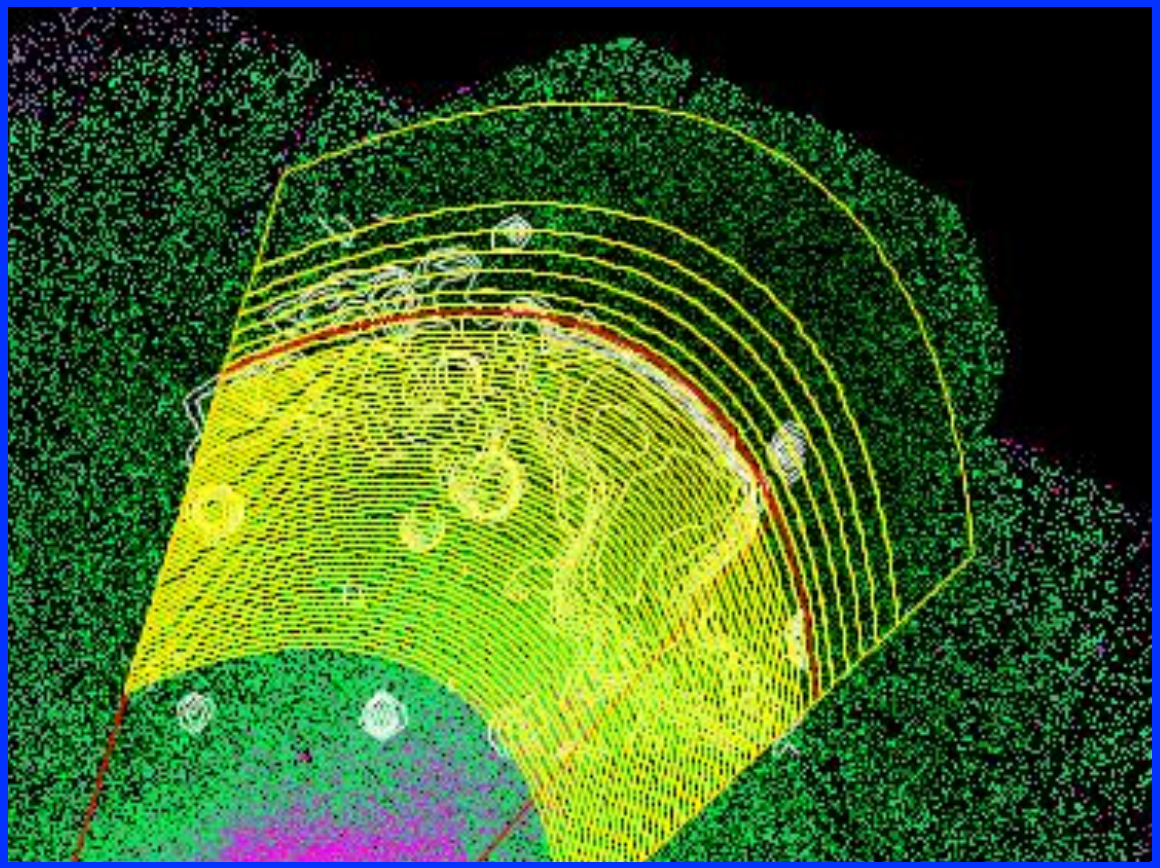


Total exposure map

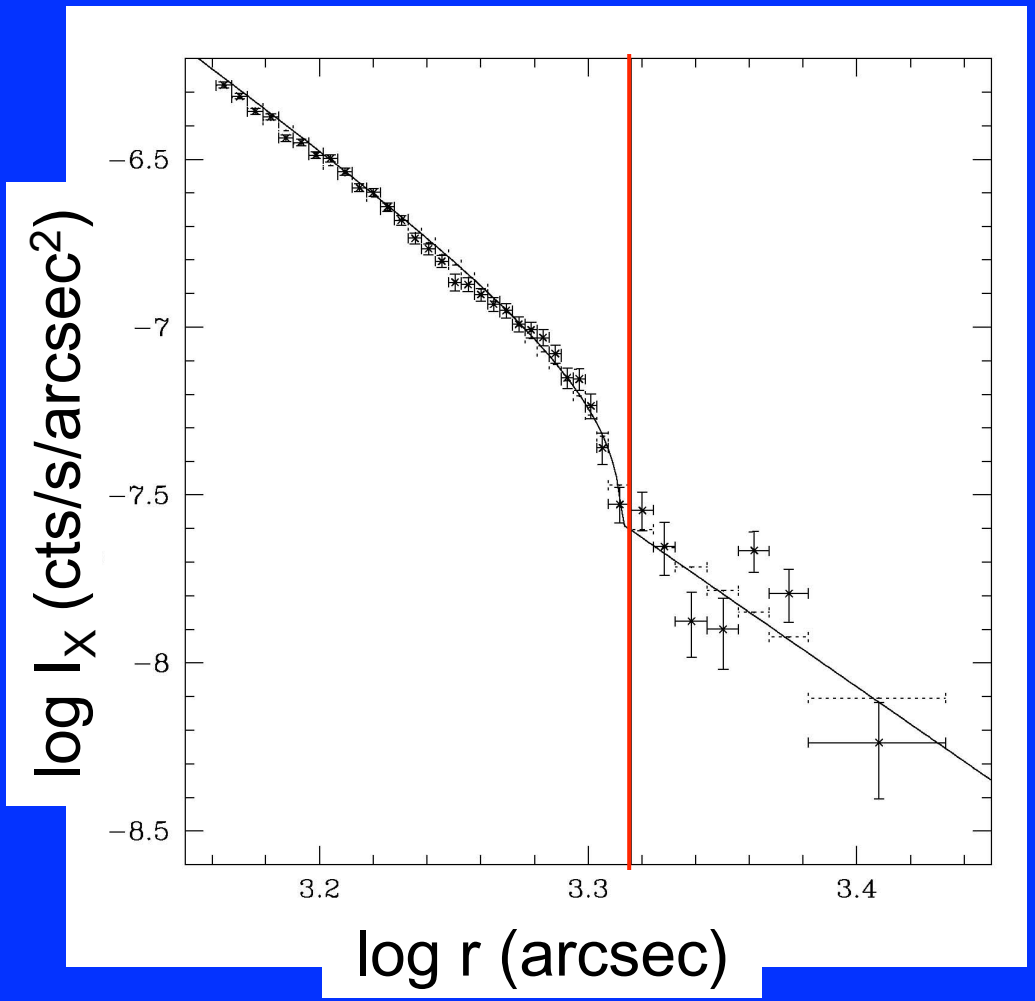
XMM Image


KMM2
KMM5
KMM4
-56:20:00.0
30:00.0
40:00.0
50:00.0
-57:00:00.0
14:00.0
13:00.0
12:00.0
11:00.0
20:10:00.0
09:00.0
5E-05
0.0001
0.0002

X-ray Surface Brightness Discontinuity at Outer Edge of Relic



X-ray Surface Brightness Discontinuity at Outer Edge of Relic



0.5-2 kev

Shock SB model

$$\varepsilon = \varepsilon_0 r^{-p}$$

$$r = \left[\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 \right]$$

Shock = ellipsoid, a, b, c

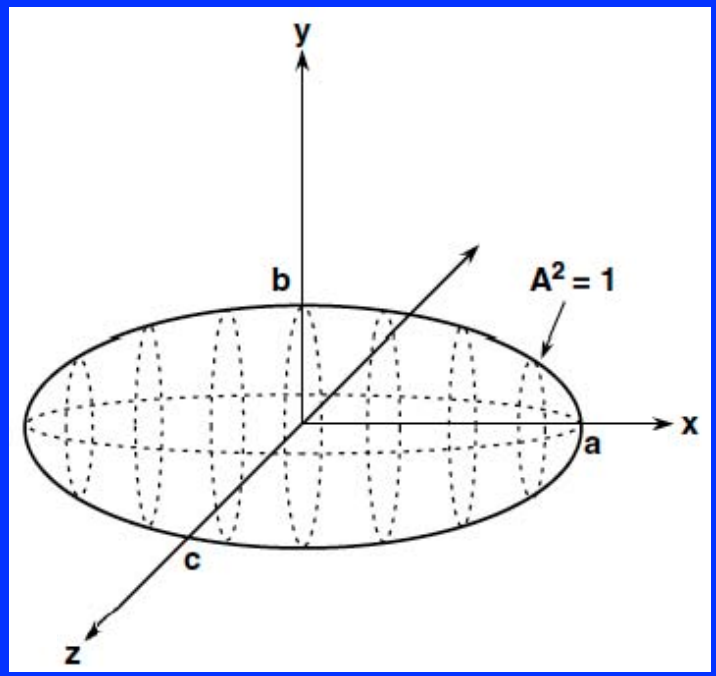
$$I(x,y) = I_{in} + I_{out}$$

$$I(x,y) = \frac{\varepsilon_0 c}{4\sqrt{\pi}(1+z)^{\eta}} \frac{\Gamma(p-1/2)}{\Gamma(p)} A^{-2p+1} \phi$$

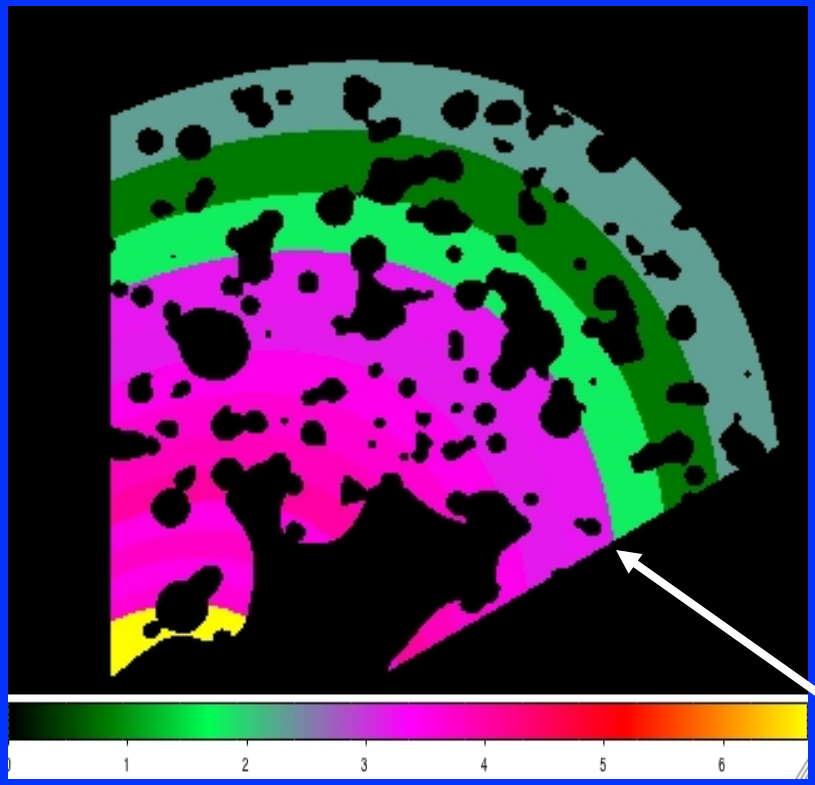
$$A(x,y) = \left[\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 \right]$$

$$\phi_{in} = \begin{cases} 1 - I_{A^2}(p-1/2,1/2) & A < 1 \\ 0 & A \geq 1 \end{cases}$$

$$\phi_{out} = \begin{cases} I_{A^2}(p-1/2,1/2) & A < 1 \\ 0 & A \geq 1 \end{cases}$$



Temperature Discontinuity at Outer Edge of Relic



kT_{in}= 4.23 ± 0.31 keV

kT_{out}= 1.95 ± 0.10 keV

outer edge of relic

Merger Shock

Density jump

n_{e1} = (6.81±0.25) x 10^{-5} cm^{-3}

n_{e2} = (1.62±0.04) x 10^{-4} cm^{-3}

Compression C = n_{e2}/ n_{e1} = 2.38 ± 0.11

Temperature jump

T_1 = 1.95 ± 0.10 keV

T_2 = 4.23 ± 0.31 keV

Mach number M = 2.09 ± 0.09

Compression C = 2.36 ± 0.09

v_s = 1500 ± 105 km/s

$$\frac{1}{C} = \frac{3}{4M^2} + \frac{1}{4}$$

$$\frac{T_2}{T_1} = \frac{5M^4 + 14M^2 - 3}{16M^2}$$

Merger Acceleration in Relic?

Is the merger shock accelerating the relativistic electrons in the radio relic?

$$\Delta F_{KE} = \frac{1}{2}\rho_1 v_s^3 \left(1 - \frac{1}{C^2}\right)$$

$$\frac{dE_e}{dt} = L_{radio}\left[1 + \left(\frac{3.6\,\mu\mathrm{G}}{B}\right)^2\right]$$

Acceleration efficiency of electrons ~ 0.2%

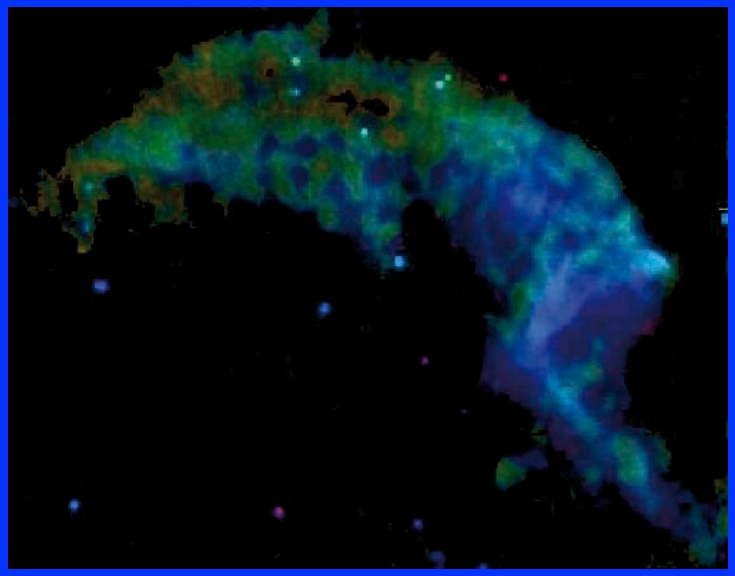
Lower than supernova remnants, but lower Mach number

Properties of NW Radio Relic

- Sharp outer edge (= location of shock acceleration)
- Radio spectrum steepens away from edge

  α = - 0.7 at edge, -1.9 far from edge

$$t_{rad} = 1.3\times10^{8}\left(\frac{\nu_b}{1.4\,\mathrm{GHz}}\right)^{-1/2}\left(\frac{B}{3\,\mu\mathrm{G}}\right)^{-3/2}$$
$$\times\left[1+\left(\frac{3.6\,\mu\mathrm{G}}{B}\right)^{2}\right]^{-1}\ \mathrm{yr}$$
$$v_2 = v_s / C \approx 640\,\mathrm{km/s}$$
$$\theta_{\mathrm{rad}} \approx 1.'3$$



Properties of NW Radio Relic

- Radio spectrum too flat at outer edge given shock compression?
  - α = - 0.7 observed
  - α = - 3/[2(C-1)] $\approx$ -1.10 expected, First Order Fermi acceleration, relativistic particles and magnetic field weak
  - True of several other relics, assuming expected merger shock Mach numbers

Does the shock re-accelerate a pre-existing population of low energy relativistic particles?

(Kang & Ryu 2011; Pinzke et al. 2013; Sarazin et al. 2013)

Limit on Relic Magnetic Field

Limit on Inverse Compton from relic - assume all of X-ray emission is IC

- Lower limit on B if emission is not IC
  - $B \geq 3\ \mu G$

A very large field at 2.2 Mpc from the cluster center!

Significant nonthermal pressure support in relic

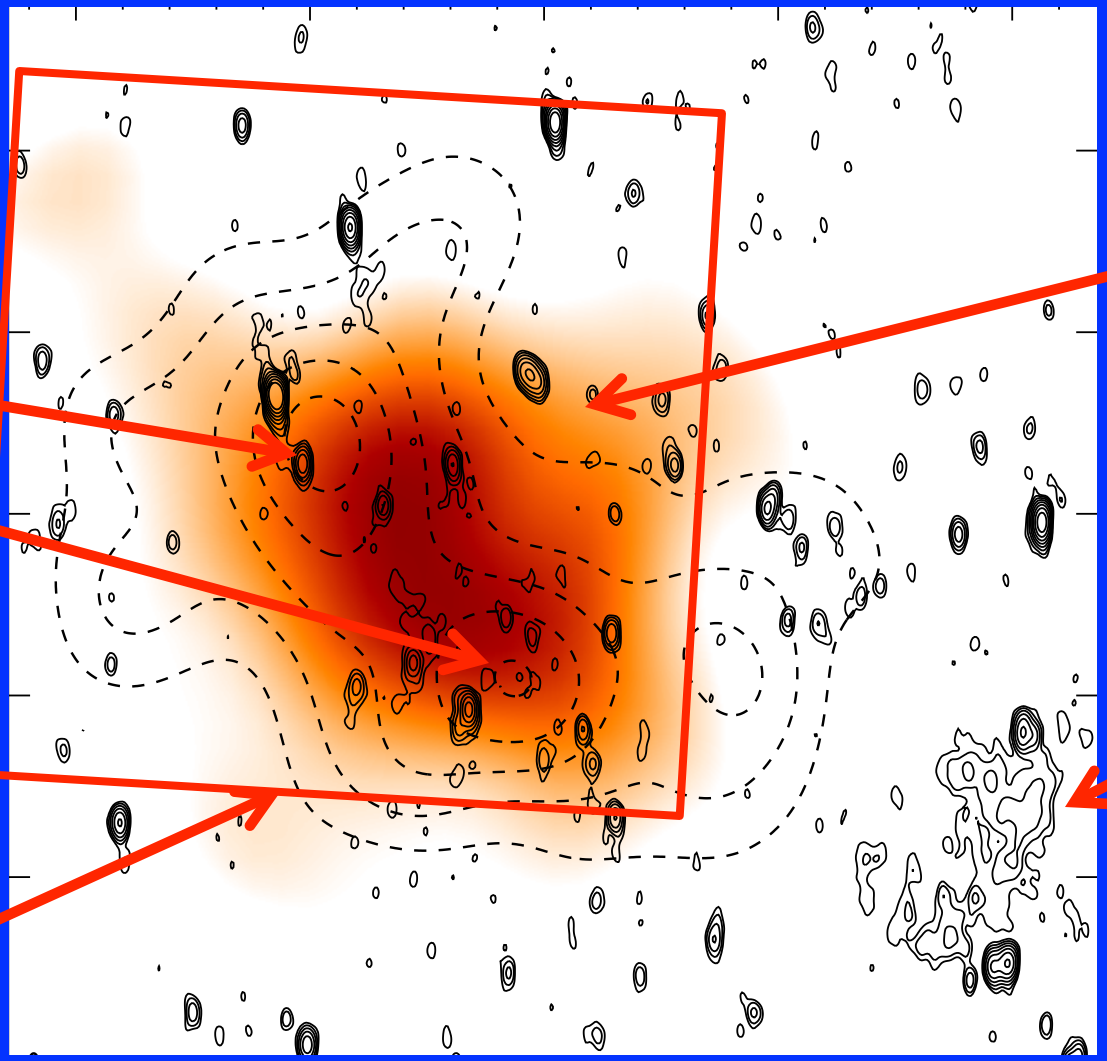
- $P_{Nonthermal} / P_{Thermal} \sim 20\%$
- But, in brightest radio relic in violent merger cluster

AbeII 2061: Unusual Structures in Merging Cluster

Hogge et al. 2014

- Merging cluster, Cor Bor supercluster, elongated
- Bimodal galaxy distribution, 2 cD galaxies
- SW radio relic (Kempner & Sarazin 2001)

Abell 2061



2 galaxy peaks

ROSAT orange

SW radio relic

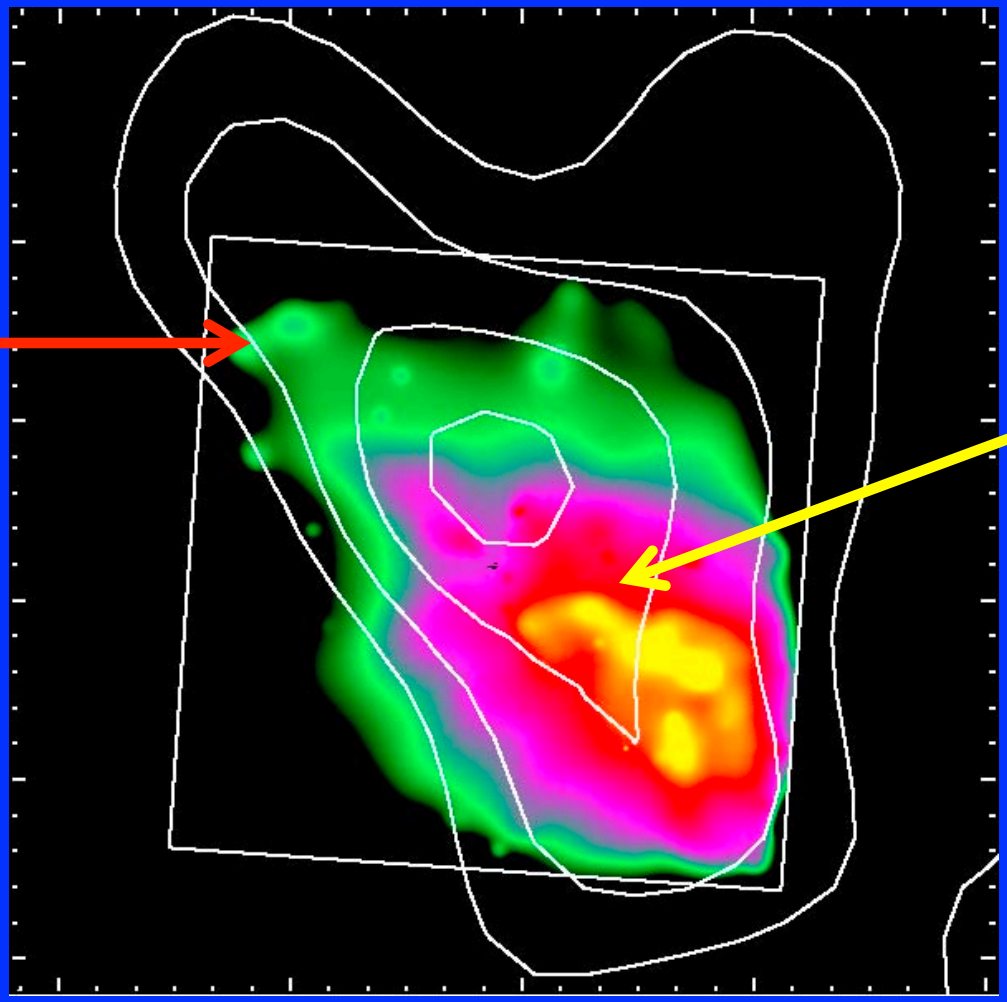
Chandra FOV

Abell 2061: Unusual Structures in Merging Cluster

Hogge et al. 2014

- Merging cluster, Cor Bor supercluster, elongated
- Bimodal galaxy distribution, 2 cD galaxies
- SW radio relic, central radio halo/relic (Rudnick et al. 2006, 2009; Farnsworth et al. 2013)

Example – Abell 2061



Chandra X-ray Intensity

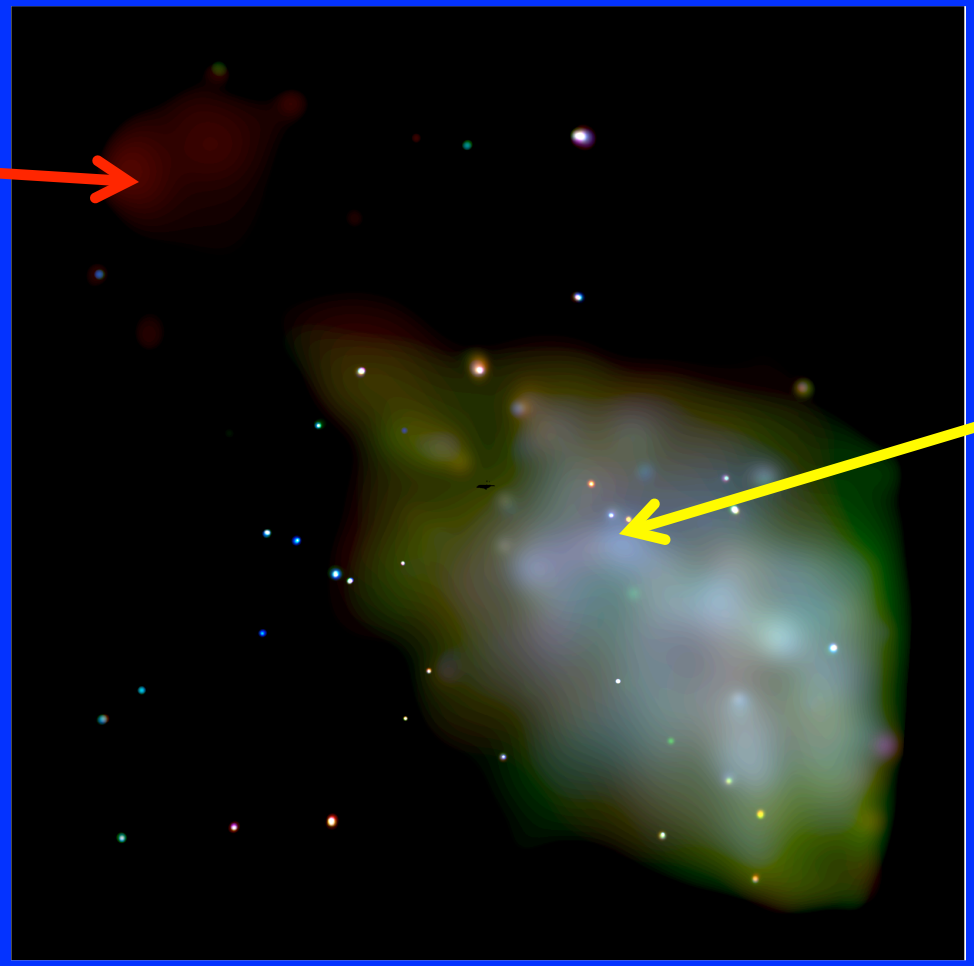
Abell 2061: Unusual Structures in Merging Cluster

Hogge et al. 2014

- Merging cluster, Cor Bor supercluster, elongated
- Bimodal galaxy distribution, 2 cD galaxies
- SW radio relic, central radio halo/relic
- Chandra Image

  Complex X-ray image, cold Plume, inner Shock, extended ridge

Abell 2061 X-ray Color Map



AbeII 2061: Unusual Structures in Merging Cluster

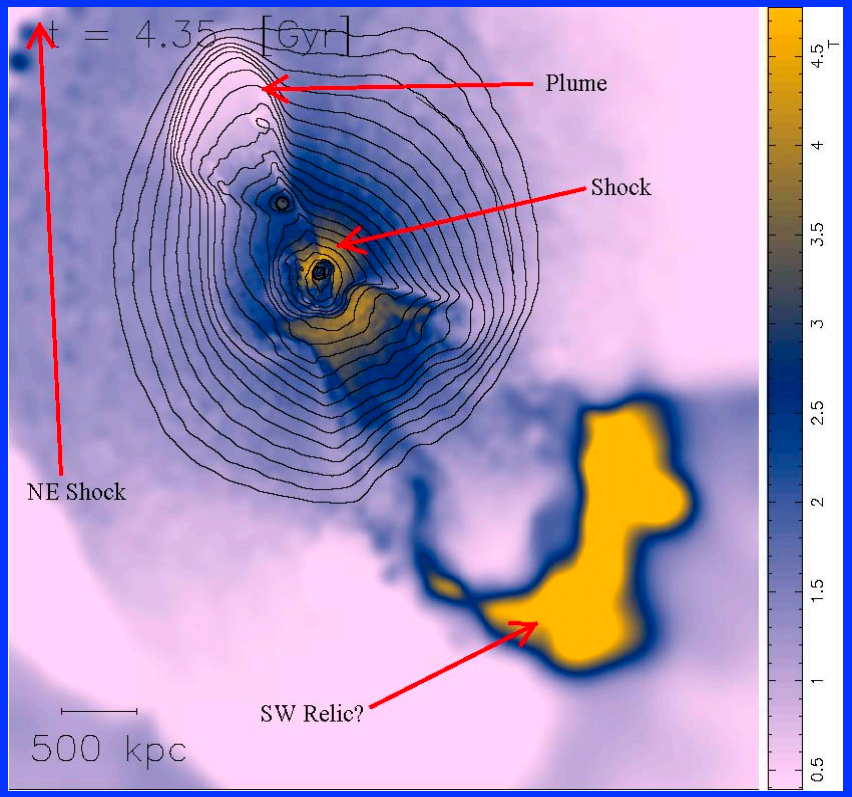
Hogge et al. 2014

- Merging cluster, Cor Bor supercluster, elongated
- Bimodal galaxy distribution, 2 cD galaxies
- SW radio relic, central radio halo/relic
- Complex X-ray image, cold Plume, inner Shock
- Why the internal Shock?
- Why is the Plume cold?
- Are radio sources due to shocks?

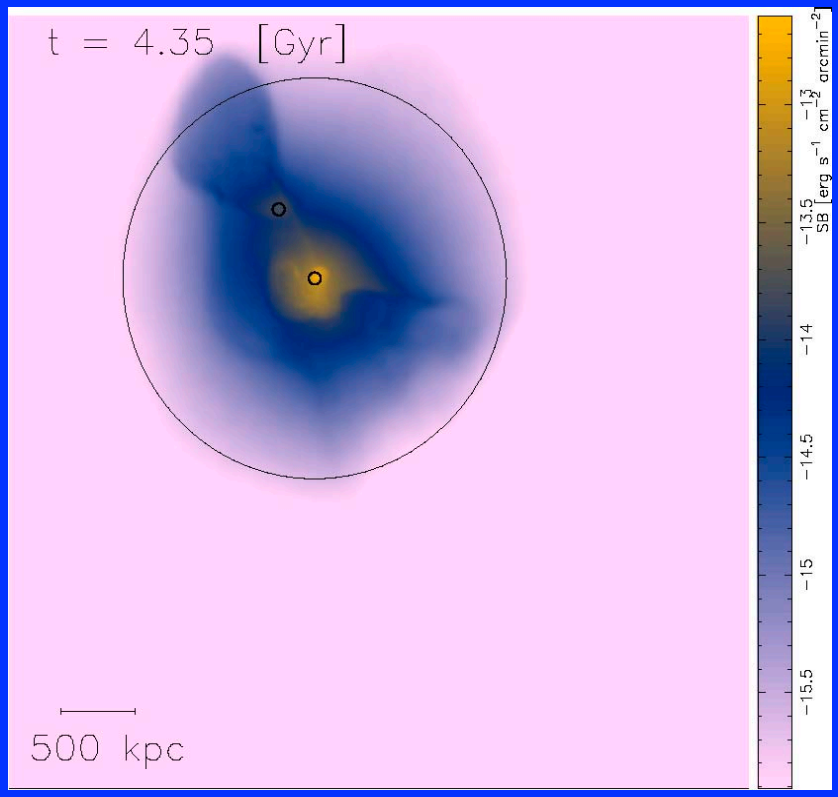
SLAM Simulations

- SLAM = Simulation Library of Astrophysical
  Chatzikos, Sarazin, & O'Shea 2014a,b,c
- 156 binary cluster mergers (hydro + N-body)
- Resemble A2061 for:
  - Mass ratio 5-10 (2×10^{14} / 4×10^{13} $M_{\odot}$)
  - Offset mergers $\lambda \approx 0.075$
  - After first core crossing
  - Subcluster merged from SW

SLAM Simulation



Temperature



X-ray SB

SLAM Simulations

- Plume is cool core gas of smaller subcluster
  - Initially, gas lagged behind DM
  - Slingshot effect = thrown out beyond DM
    (Hallman & Markevitch 2004)
    - Accelerated outward by
      - Gravity of DM
      - Running down cluster pressure gradient
  - Cool because
    - Cool core of low mass cluster
    - Adiabatic expansion
  - Now falling back into cluster center

SLAM Simulations

- Central Shock region is Plume gas hitting cluster core
- Merger shock beyond Plume = extention of radio source to NE ?
- Very strong merger shock to SW = SW radio relic?
  - Subcluster cleared channel in main cluster during infall
  - Merger shock rushed out this channel

Conclusions

- A3667 XMM X-ray Data

  (Finoguenov et al. 2010, Sarazin et al. 2013, 2014)

  - Merger shock at outer edge of radio relic
  - Radio relics due to merger shocks
- A2061 = complex X-ray and radio structure due to offset merger

  (Hogge et al. 2014)