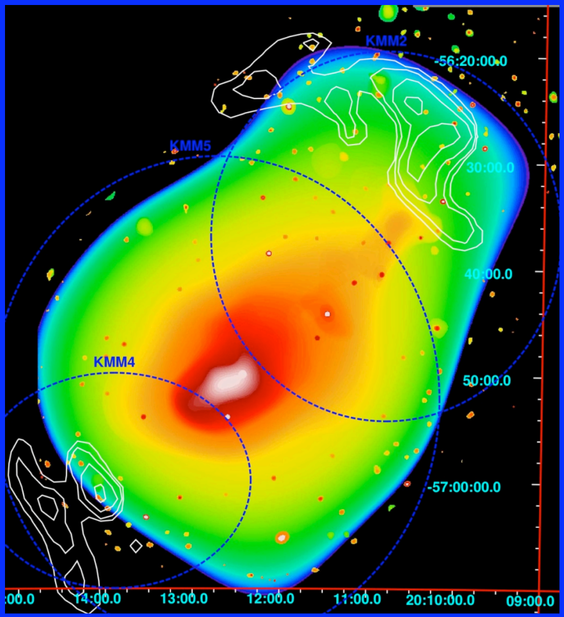
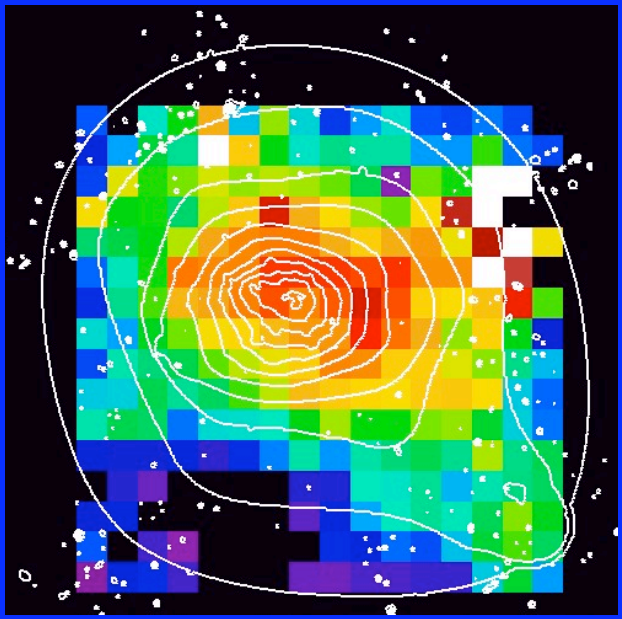
Nonthermal Emission and the Dynamical State of Clusters



A3667 XMM X-ray image and radio contours

Craig Sarazin

University of Virginia



Coma temperature map and PIN FOV

Collaborators

Daniel R. Wik (Univ. Virginia) - Coma

Kazuhiro Nakazawa (Univ. Tokyo) - Abell 3667

Alexis Finoguenov (MPE, UMBC) - XMM-Newton A3667, Coma

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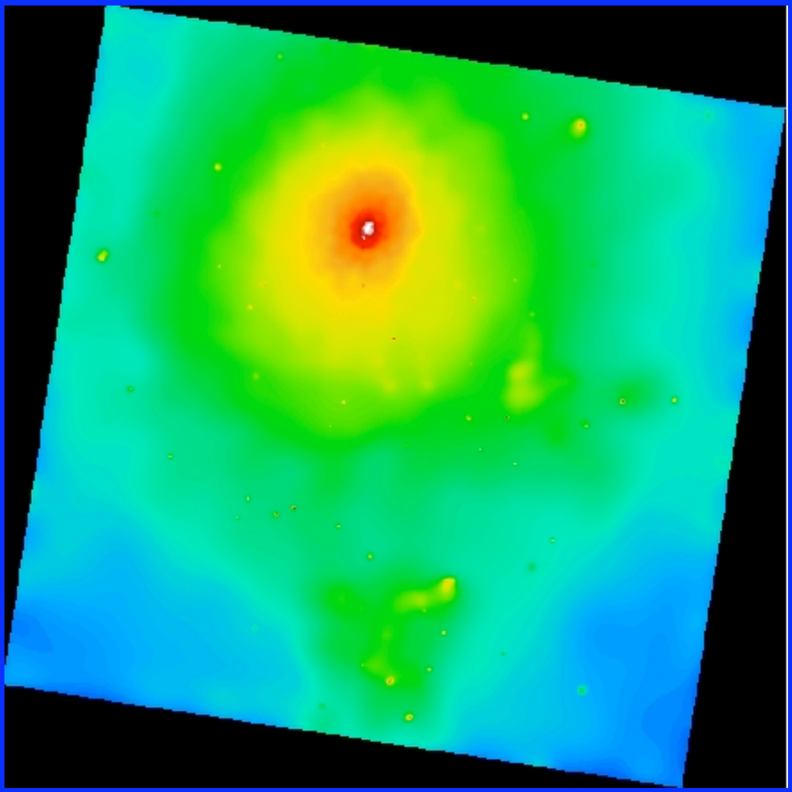
Richard Mushotzky (Univ. Maryland)

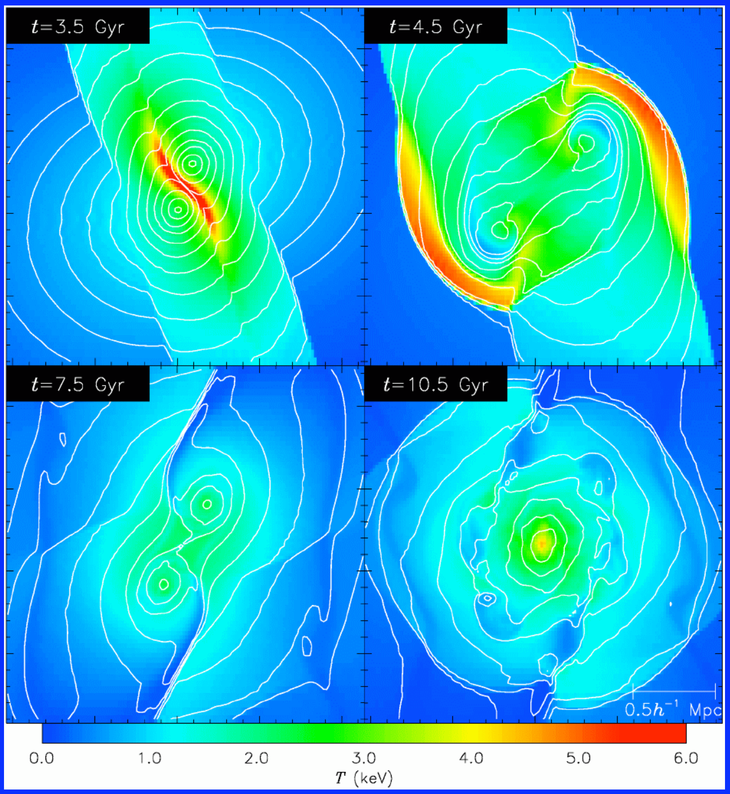
Takashi Okajima, Jack Tueller (NASA Goddard)

Motokazu Takizawa (Yamagata Univ.)

Cluster Mergers & Shocks



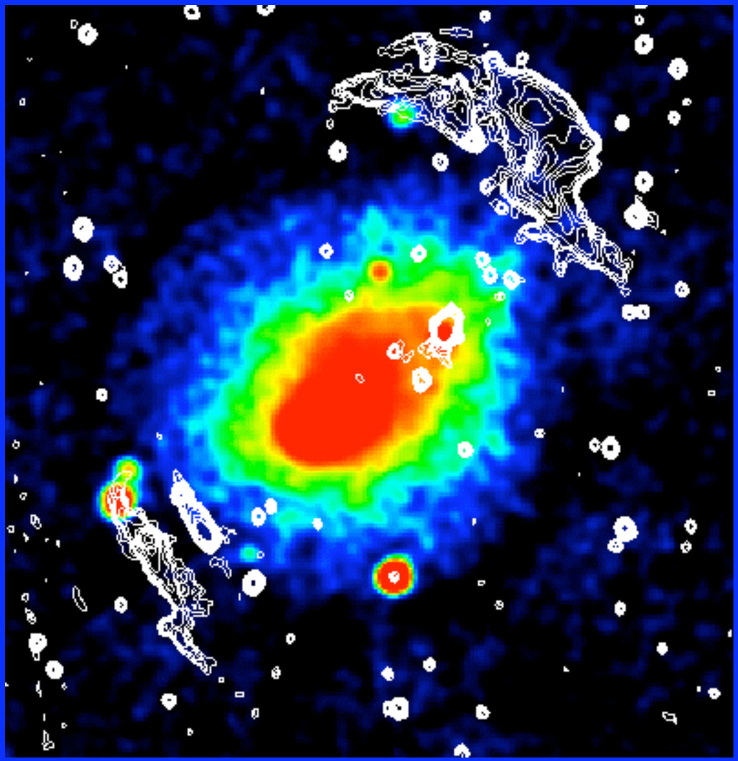
Abell 85 Chandra



Simulations with merger shocks

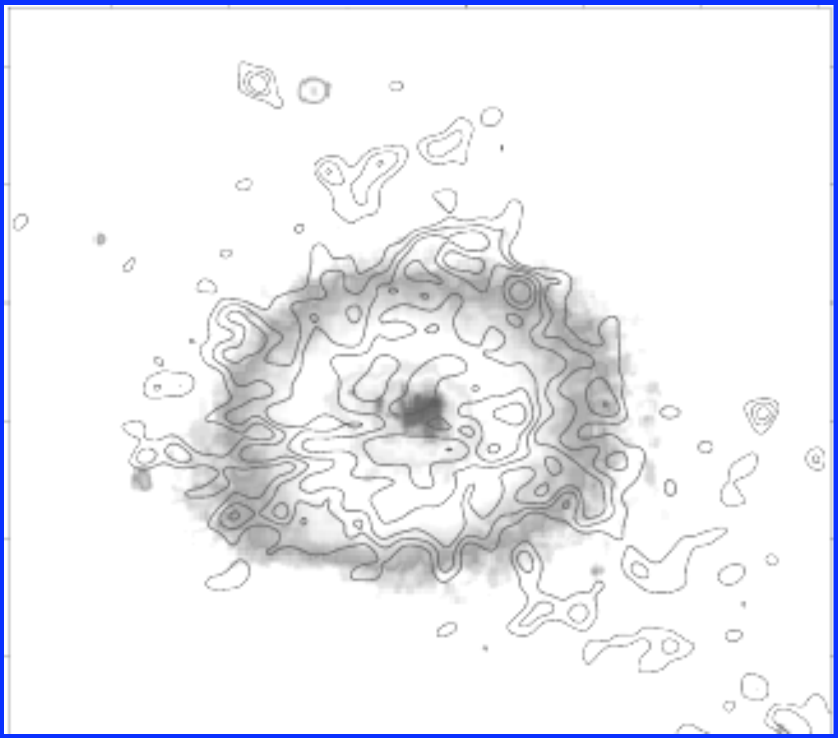
Cluster Radio Halos and Relics

Radio Relics
(shock acceleration?)



Abell 3667
Röttgering et al.

Radio Halo
(turbulent acceleration?)



Coma
Govoni et al.

Cluster Radio Relics and Halos

- Diffuse, cluster-scale radio emission without associated radio galaxy
- Steep radio spectra
- Only in merging clusters
- Cluster radio halos: central and symmetric
    - Due to turbulent acceleration behind shocks (?)
- Cluster radio relics: peripheral and elongated
    - Due to merger shock (re)acceleration (?)
- Should also emit hard X-rays by Inverse Compton scattering of CMB

Measuring or Limiting the Magnetic Field

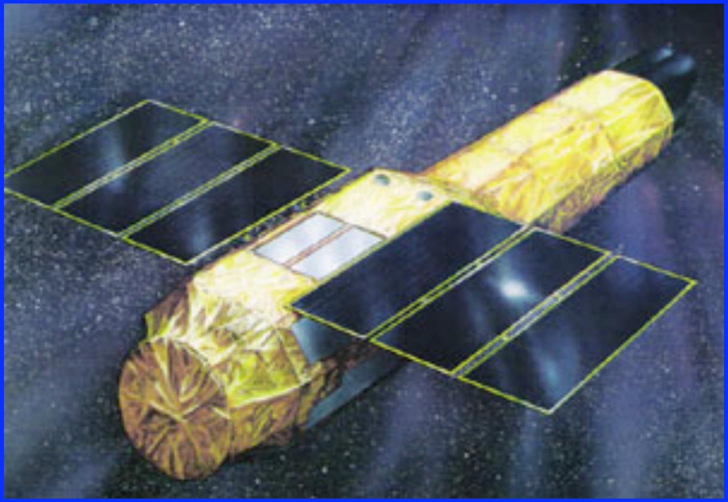
- Measure both IC X-rays and synchrotron radio
  - Radio ∝ E (rel. e) x U_B
  - HXR IC ∝ E (rel. e) x U_{CMB}
  - Detect both → E (rel. e) & B
- Upper limit IC → upper limit E (rel. e).
  → lower limit B

Suzaku

Japan-US X-ray Observatory

- XIS: 4 X-ray telescopes with ccd detectors
- HXD: Hard X-ray Detector:
  - Silicon PIN diodes (10-70 keV)
  - GSO crystal scintillators (40-600 keV)

➡ PIN is the most sensitive hard X-ray detector yet flown



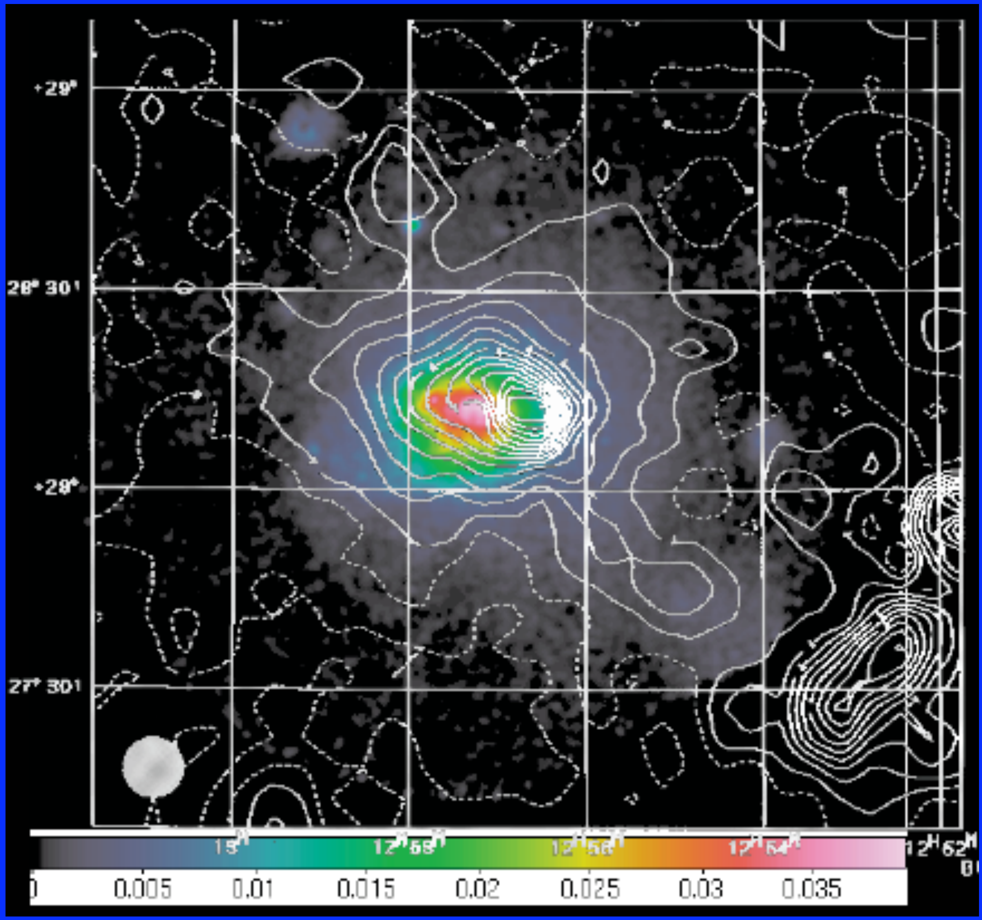
Coma Cluster

Brightest non-cooling core X-ray cluster

Brightest radio halo

Color: X-ray ROSAT

Contours: Radio
(Deiss et al. 1997)



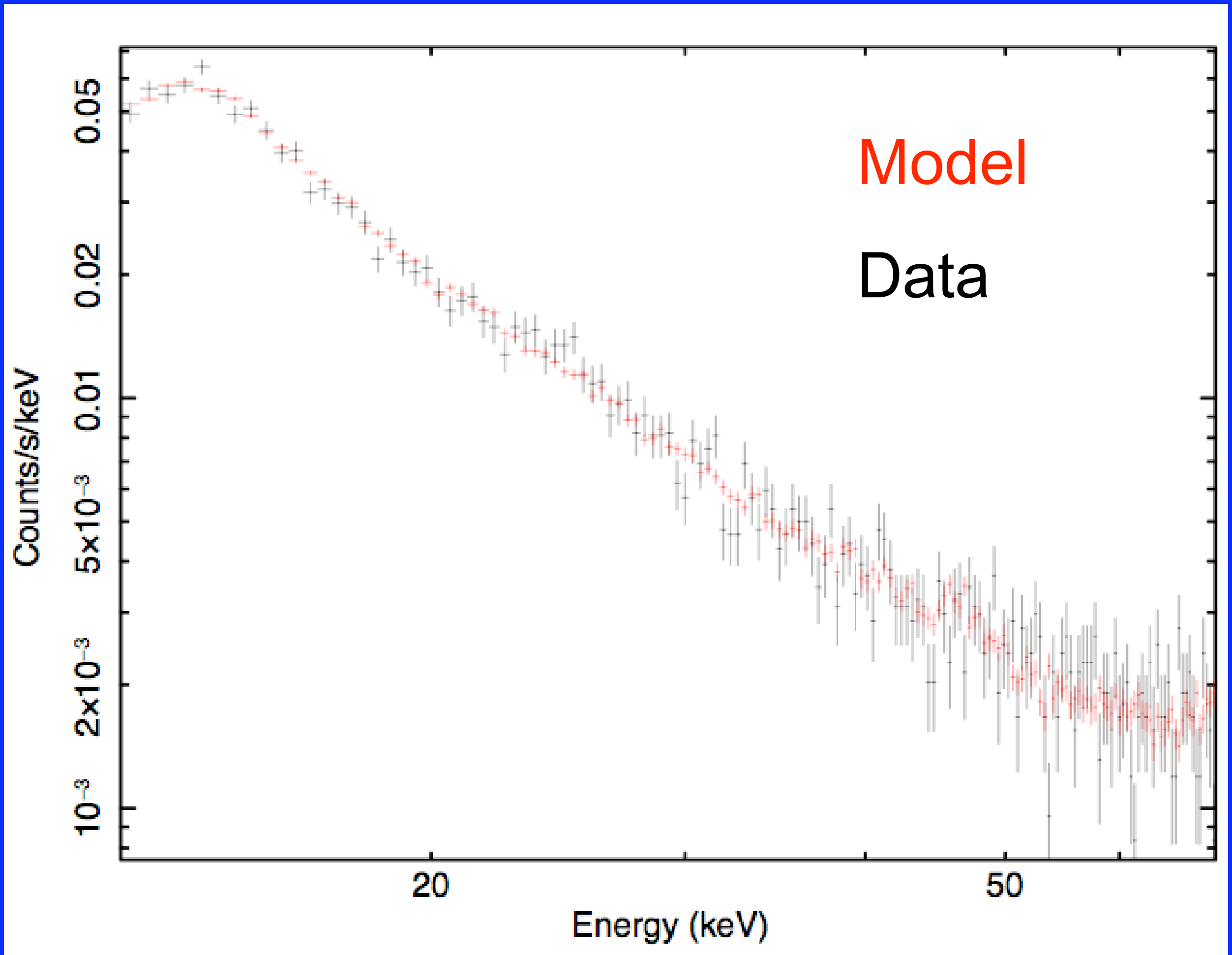
Coma Cluster – IC Hard X-rays?

- Long history of searches
- Recent detections
  - BeppoSAX: $F_X = 1.5 \times 10^{-11}$ ergs/cm^2/s, 20-80 keV
    (Fusco-Femiano et al. 2004, 2007)
  - RXTE: $F_X = 1.6 \times 10^{-11}$ ergs/cm^2/s, 20-80 keV
    (Rephaeli & Gruber 2002)
- But, very controversial
  - BeppoSAX: $F_X < 8.1 \times 10^{-12}$ ergs/cm^2/s, 20-80 keV
    (Rossetti & Molendi 2004, 2007)
  - INTEGRAL: hard X-rays purely thermal
    (Renaud et al. 2006, Eckert et al. 2007)
  - INTEGRAL/RXTE/ROSAT: hard X-rays purely thermal
    (Lutovinov et al. 2008)
  - Swift/BAT: hard X-rays purely thermal
    (Ajello et al 2008; Okajima et al. 2008)

Suzaku Observation of Coma

- 156 ksec (PIN), 31 May – 4 June 2006
- NXB model agrees well with Earth-blocked flux and spectrum

NXB Model vs. Earth-Blocked Data



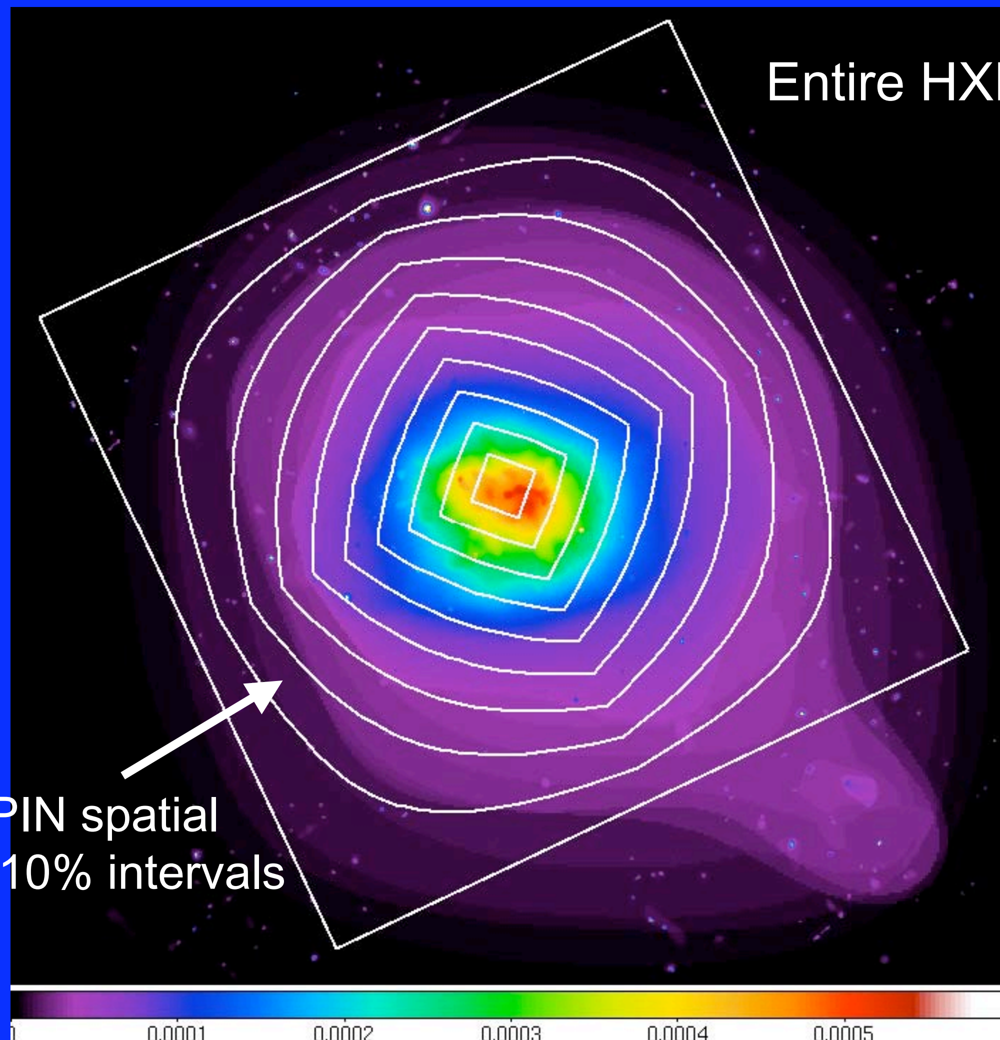
Suzaku Observation of Coma

- 156 ksec (PIN), 31 May – 4 June 2006
- NXB model agrees well with Earth-blocked flux and spectrum
- Model CXB
- Model AGN point srcs (small effect)
- Joint fit with XMM/Newton and/or Suzaku XIS to model thermal emission – key!

Joint XMM - PIN Analysis

To ‘’PIN’’ down the thermal emission . . .

- Mosaic of XMM/Newton exposures to cover cluster (Schuecker et al. 2004; Finoguenov 2010)
- Extract XMM spectra in regions of ~constant PIN area



XMM 2-7.5 keV image, Schuecker et al. 2004

Joint XMM - PIN Analysis

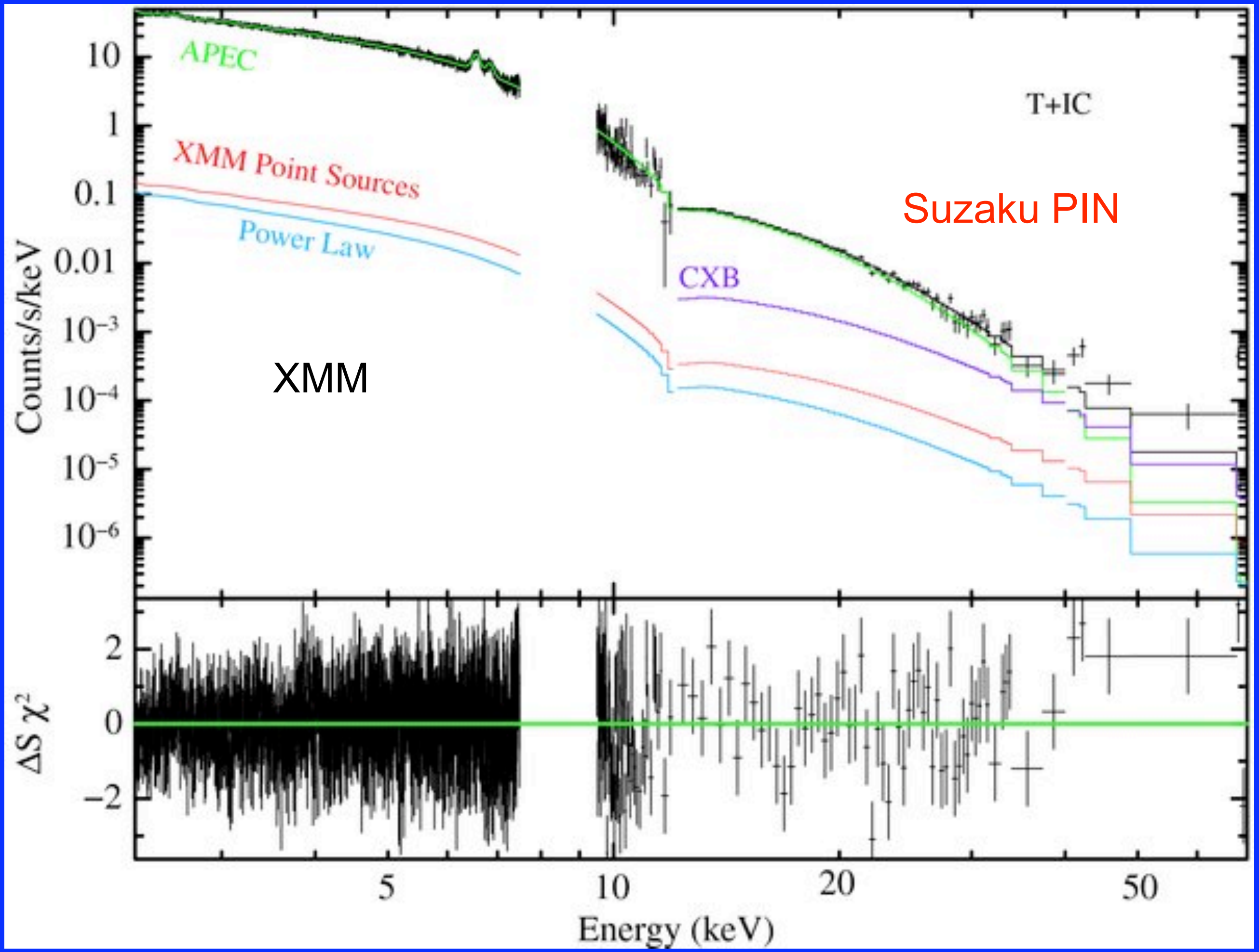
To ‘’PIN’’ down the thermal emission . . .

- Mosaic of XMM/Newton exposures to cover cluster (Schuecker et al. 2004; Wik et al. 2009)
- Extract XMM spectra in regions of ~constant PIN area
- Weight by PIN area, combine
- Gives thermal spectrum as seen by PIN, correct shape and flux
- Fit PIN and XMM jointly

Coma: Spectral Fitting Results

- Single temperature model with no second component is an OK fit $\rightarrow$ no strong hard X-ray excess
- Addition of power-law improves fit, but only for photon spectral index $\Gamma < 0$, not astrophysically sensible

Best-fit Single Temperature plus Power Law



Coma: Spectral Fitting Results

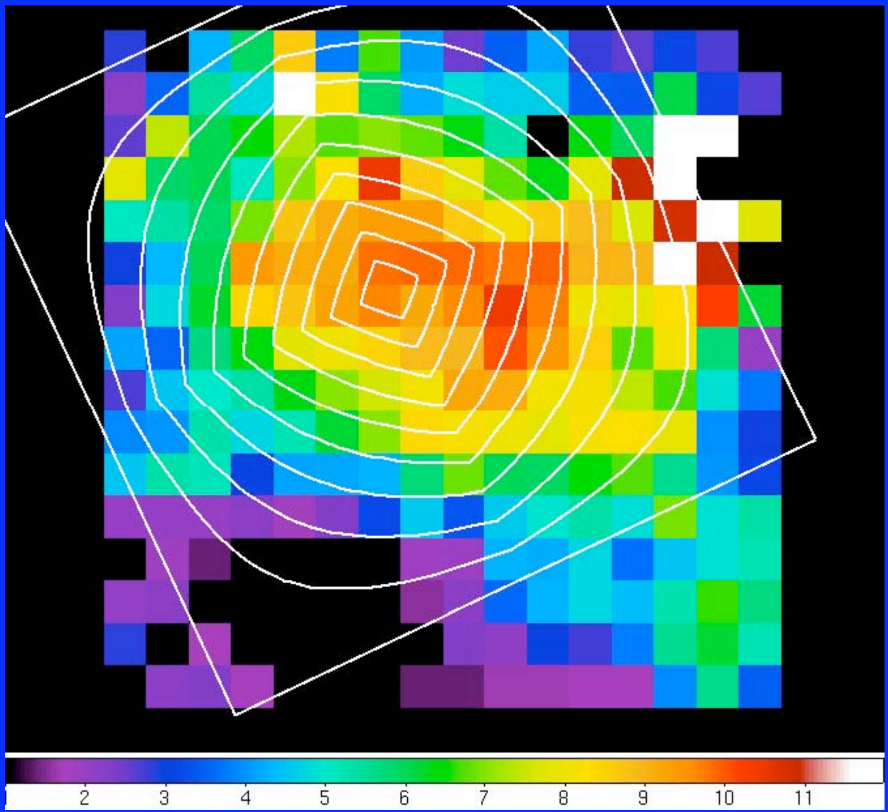
- Single temperature model with no second component is an OK fit $\rightarrow$ no strong hard X-ray excess
- Addition of power-law improves fit, but only for photon spectral index $\Gamma < 0$, not astrophysically sensible
- Two-temperature model better than one temperature + power-law

Hard excess due to thermal structure in gas?

Multi-Temperature Model

- XMM-Newton mosaic used to construct temperature map
- Combine models for regions weighted by PIN effective area
- Provides OK "fit" to data with no adjustment of models

Hard X-rays probably thermal



Coma: Spectral Fitting Results (Cont.)

Doesn't include systematic errors

- NXB (non-X-ray background)
  - 2.3% 12-40 keV
  - 4% 40-70 keV
- CXB
- XMM/Suzaku cross-calibration

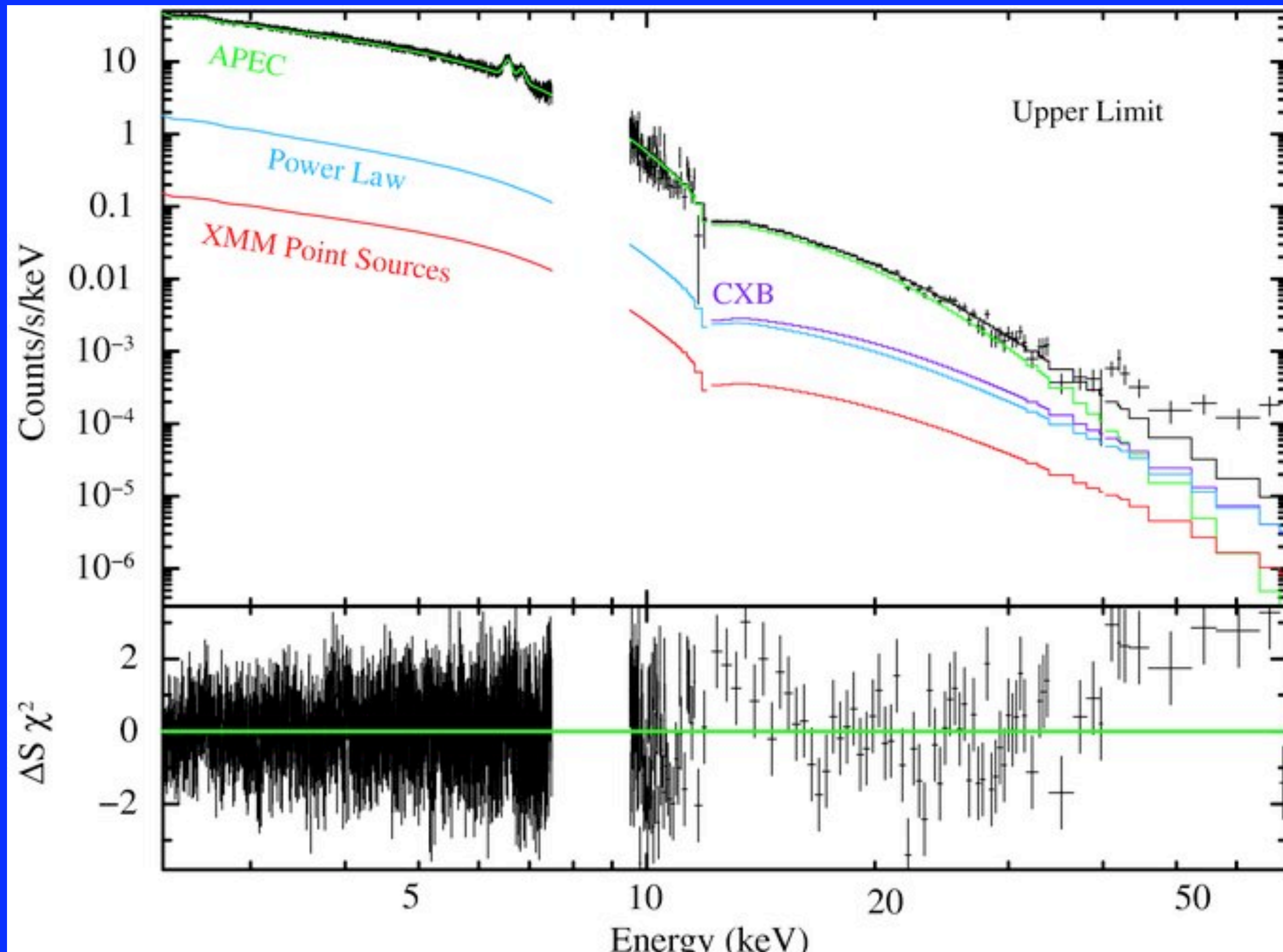
Coma: Spectral Fitting Results (Cont.)

Doesn't include systematic errors

- NXB (non-X-ray background)
  - 2.3 % 12-40 keV
  - 4 % 40-70 keV
- CXB
- XMM/Suzaku cross-calibration

Take 90% errors, combine

Power-law not required



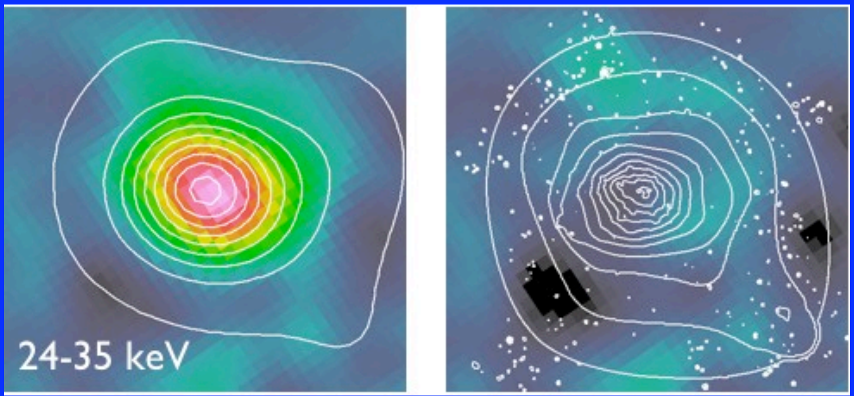
APEC
Power Law
XMM Point Sources
CXB
Upper Limit
Counts/s/keV
10
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Delta S\ \chi^2$
2
0
−2
5
10
20
50
Energy (keV)

Upper Limit on IC

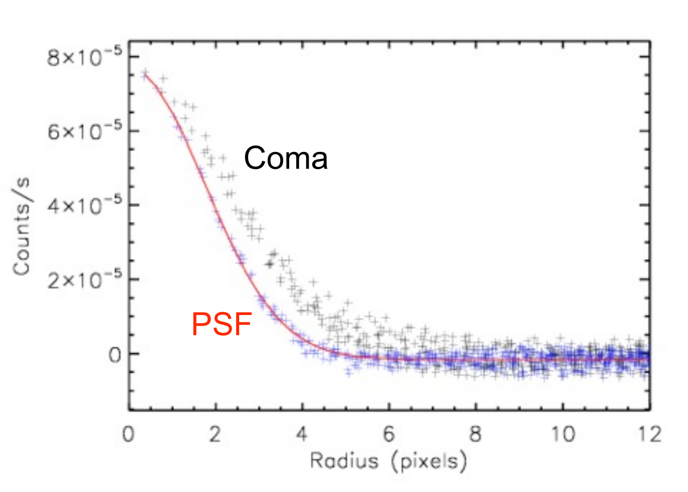
- For $\Gamma = 2.0$ (from radio)
  F_X(20-80 keV) < 6.0 x 10^{-12} ergs/cm^2/s
  (90% confidence),
- Factor of 2.5 below
  - BeppoSAX (Fusco-Femiano et al. 2004) and
  - RXTE (Rephaeli & Gruber 2002) detections
  - These detections inconsistent for any sensible Γ
  - Due to thermal hard X-ray emission?
- Lower limit B > 0.15 μG
  - Consistent with B_{eq}~0.5 μG (Giovannini et al. 1993)
- PIN FOV smaller than BeppoSAX, detections and our limit might be consistent if IC much more extended than radio halo

Limiting Very Extended Hard X-ray Emission from Coma with the Swift/BAT

- Swift/BAT hard X-ray detector, scans sky, provides huge exposure ~ all locations
- Coded Mask images
- Hard X-rays extended



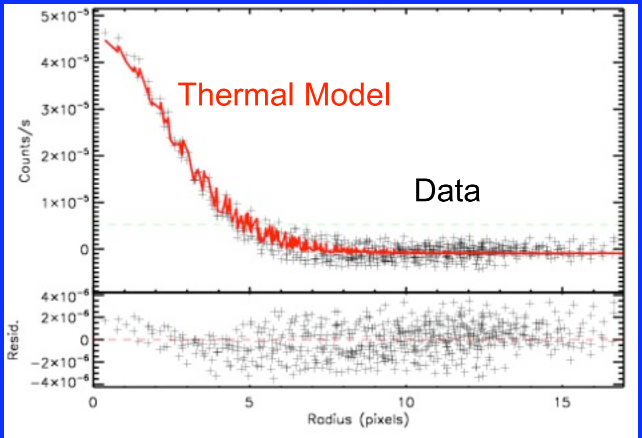
Residual after thermal emission removed

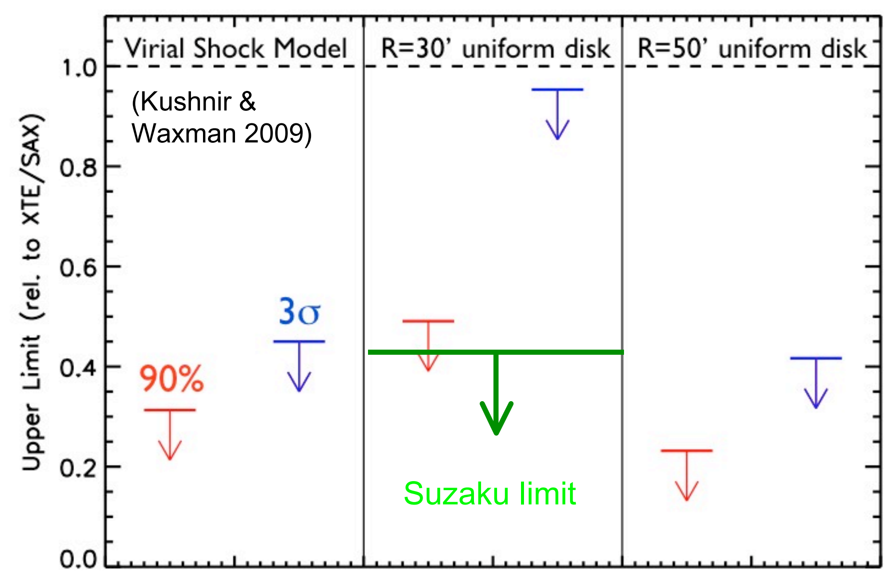


Limiting Very Extended Hard X-ray Emission from Coma with the Swift/BAT

- Emission completely consistent with thermal emission from XMM mosaic
- No evidence for extended nonthermal emission
- Unlikely that very extended nonthermal emission reconciles BeppoSAX and RXTE detections with Suzaku limits

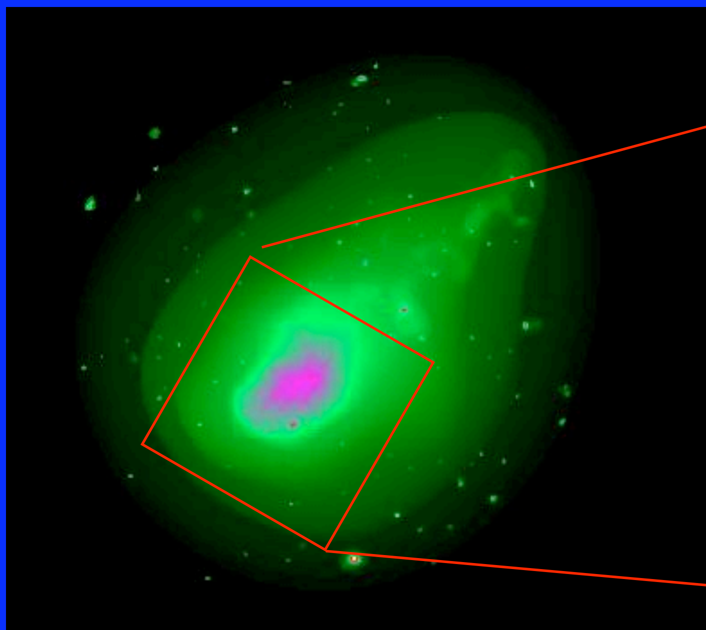
(Wik et al. 2010)





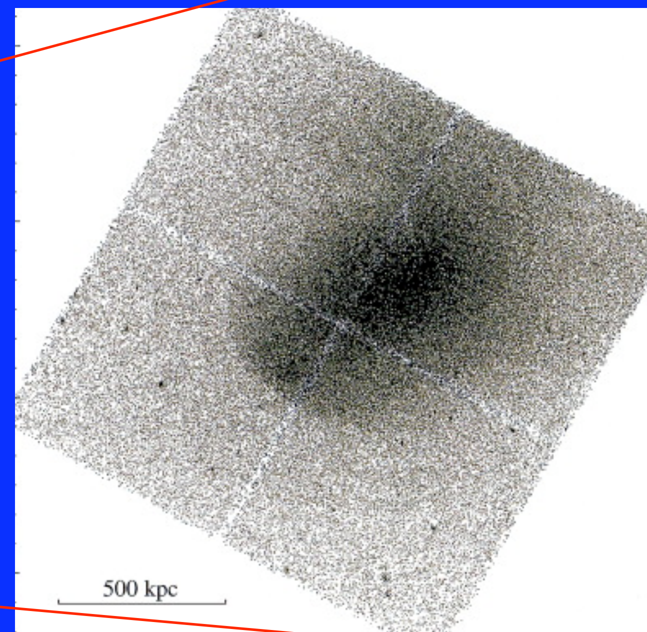
Abell 3667 – Merging Cluster

XMM



Briel et al. 2004; this work

Chandra



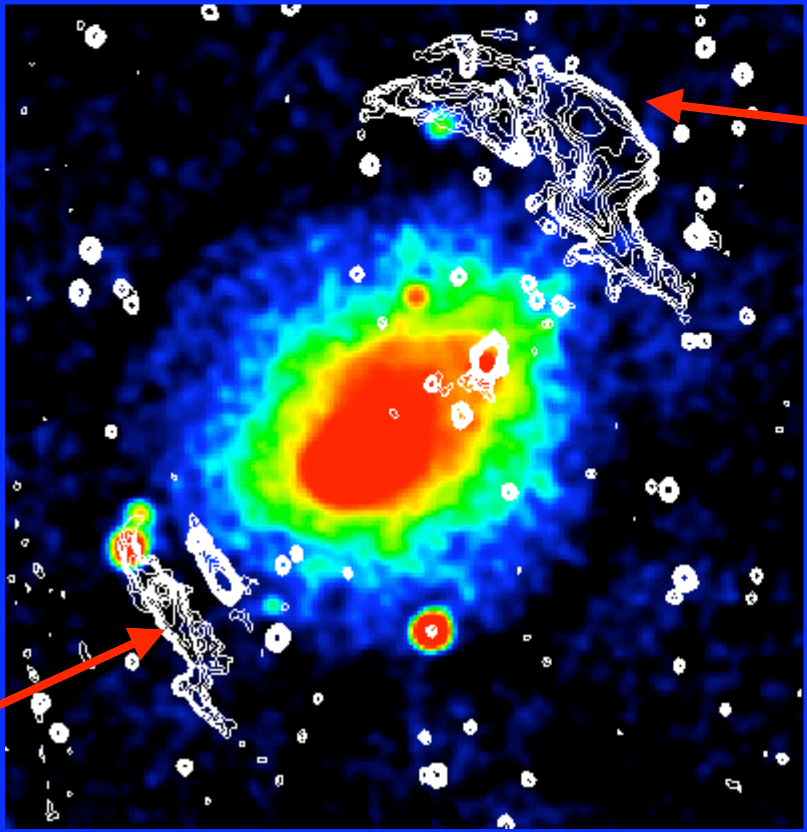
Vikhlinin et al. 2000

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

- Cold front, remnant of cool core of one subcluster

Double Radio Relics

ROSAT (color), radio contours



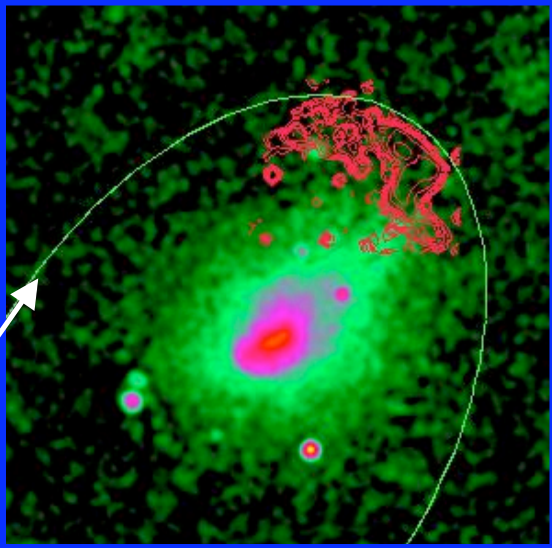
Röttgering et al. 1997

NW Radio Relic

SE Radio Relic

NW Radio Relic in Abell 3667

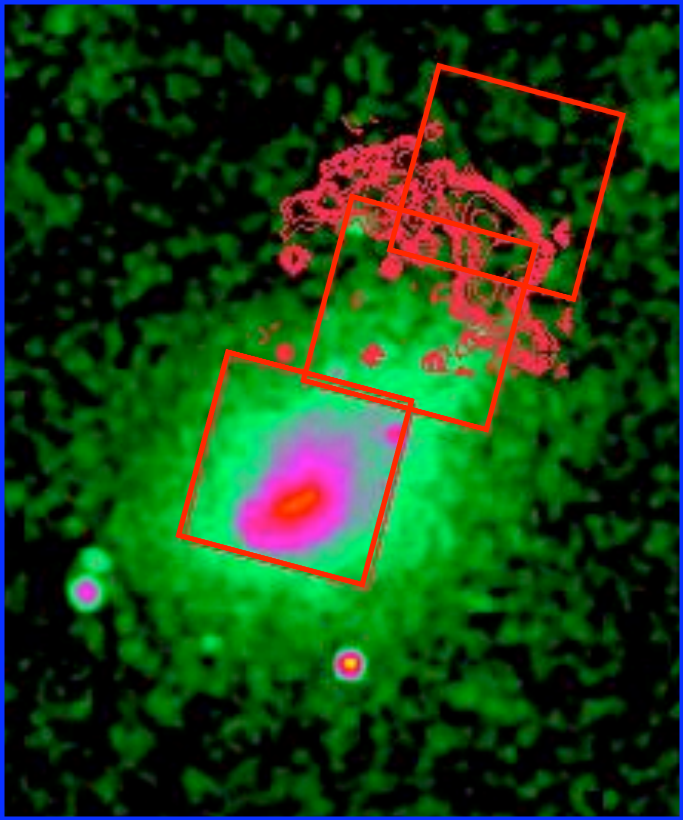
- Brightest diffuse cluster source
  - 3.7 Jy at 20 cm (Johnston-Hollitt 2004)
- Located at large projected radius ~2.2 Mpc → expect weak B field
- Should be a very strong IC HXR source!



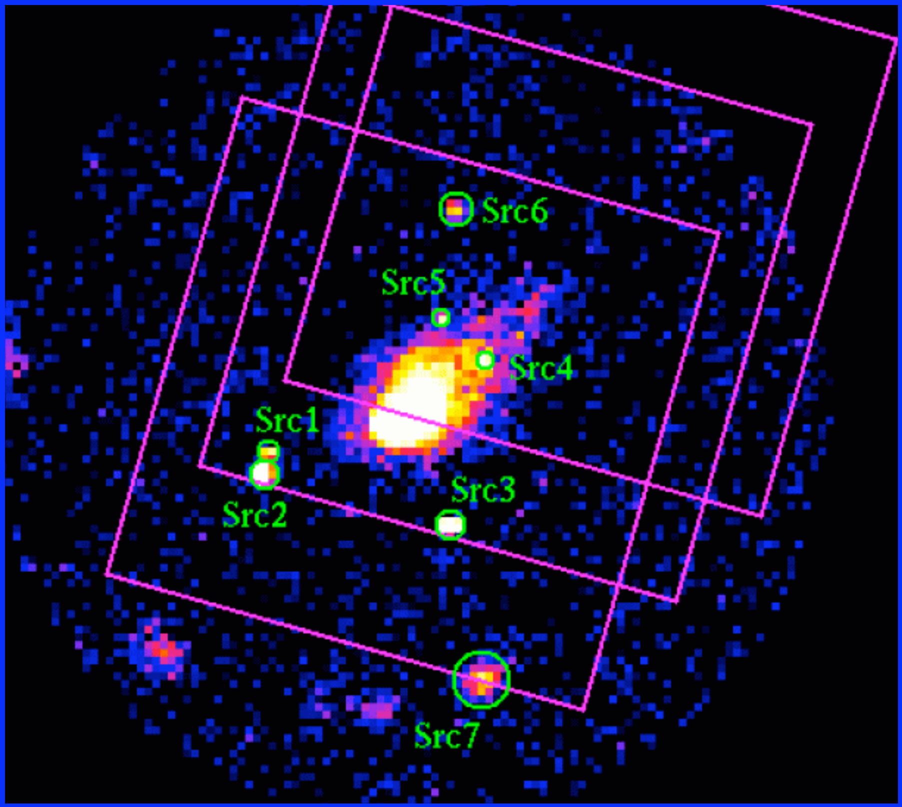
Merger shock?

Radio vs. ROSAT X-rays

3 Suzaku Observations



XIS FOVs



HXD/PIN FOVs

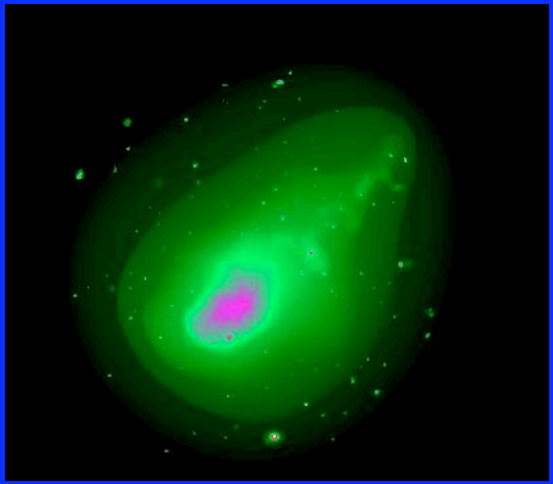
- 3 observations, 3-7 May 2006
- Exposures of ~20, ~17, ~78 ksec

Suzaku General Cluster Results

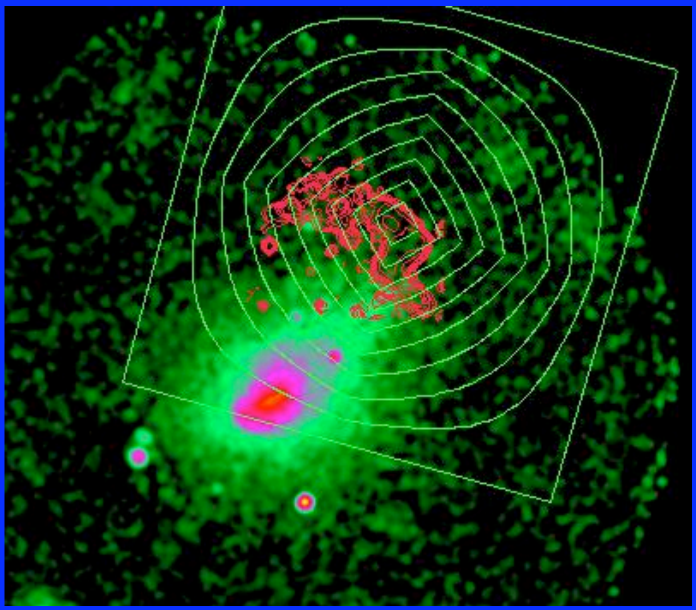
- Hot gas out to ≈ 42 arcmin = 2.6 Mpc ≈ virial radius
  - but, along merger axis of merging cluster
- Very hard emission from cluster center (hot gas at > 13 keV?)

Joint XMM - PIN Analysis

- Mosaic of XMM/Newton exposures to cover cluster (Briel et al. 2004; Finoguenov et al. 2010)
- Extract XMM spectra in regions of ~constant PIN area
- Weight by PIN area, combine
- Gives thermal spectrum as seen by PIN, correct shape and flux
- Fit PIN and XMM jointly

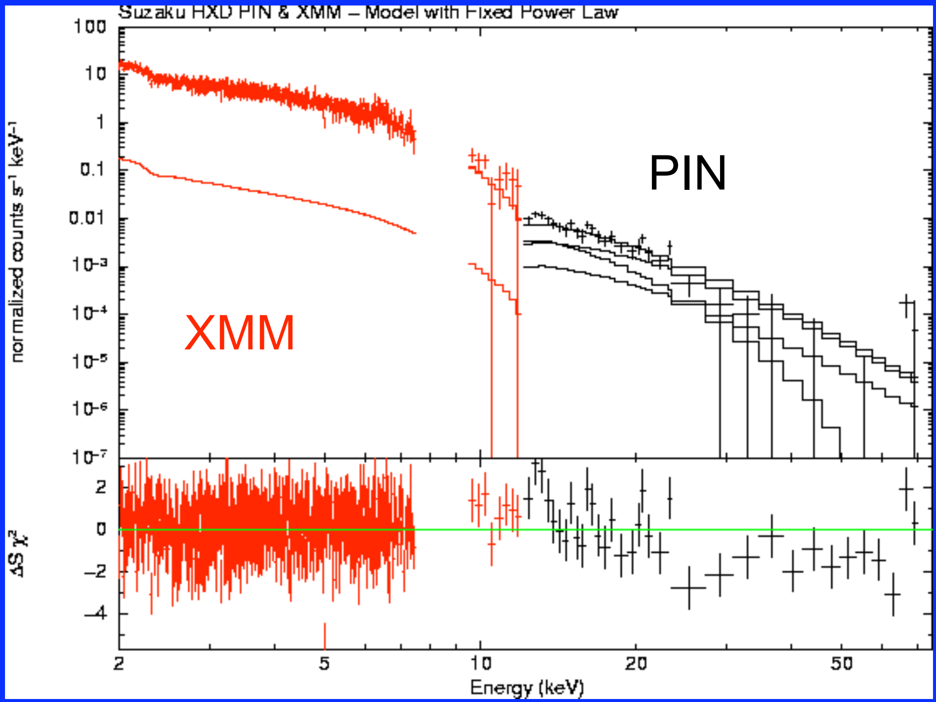


XMM Image from mosaic



Hard X-rays: PIN-XMM Results

- Detection of excess HXR
- Best-fit power-law $\Gamma = 3.2$, much steeper than radio → really thermal?
- Assuming power-law with $\Gamma = 2.1$ (radio)
  $F_X = 3.4 \times 10^{-12}$ ergs/cm^2/s
  12-70 keV
- Doesn't include systematic errors



Hard X-rays: PIN-XMM Results (Cont.)

Systematic Errors:

- NXB: ±4.5%
- CXB: ±18% (HXR flux, cosmic variance)
- XMM/PIN calibration: ±25%

→ $F_X < 7.1 \times 10^{-12}$ ergs/cm^2/s 12-70 keV

BeppoSAX PDS

$F_X < 9.3 \times 10^{-12}$ ergs/cm^2/s 12-70 keV

(Nevalainen et al. 2004)

Lower limit on B

→ $B > 0.6\ \mu G$

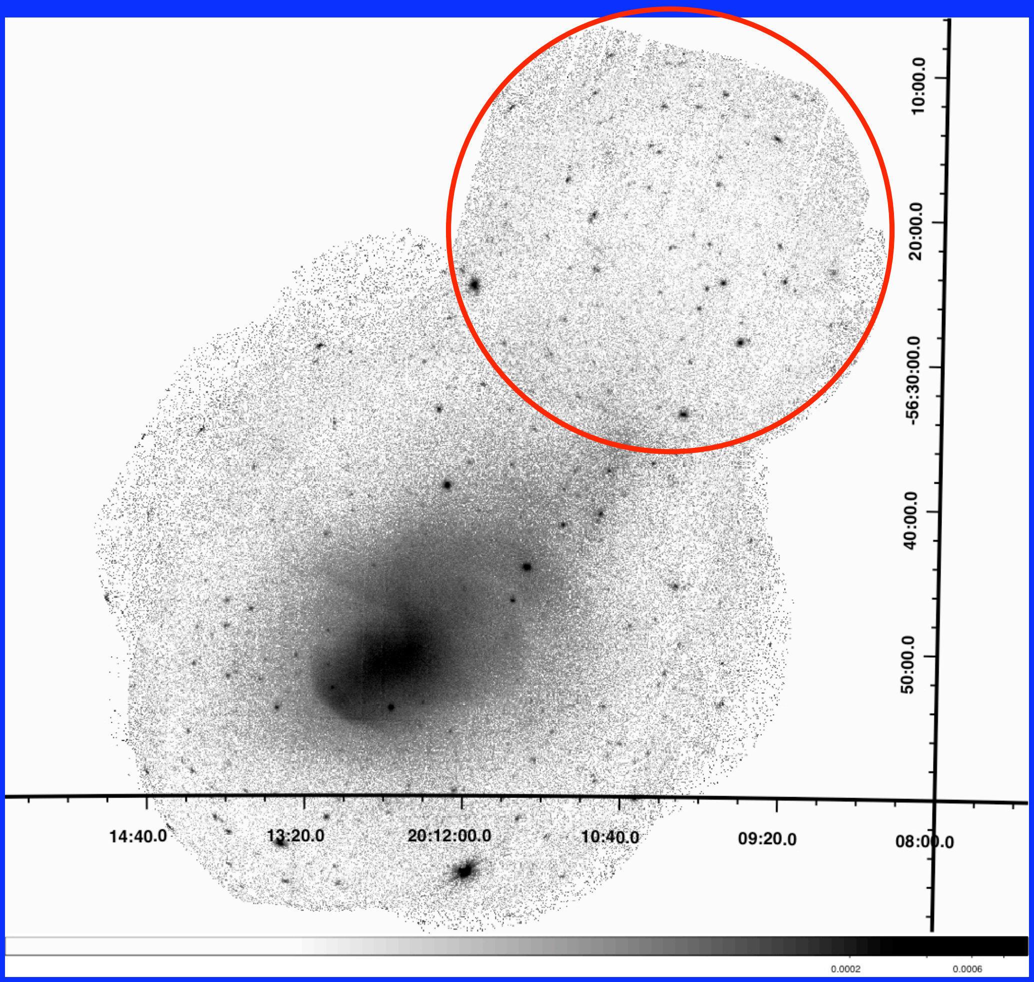
New XMM Observation of Radio Relic

Existing XMM mosaic has only short exposure in relic region

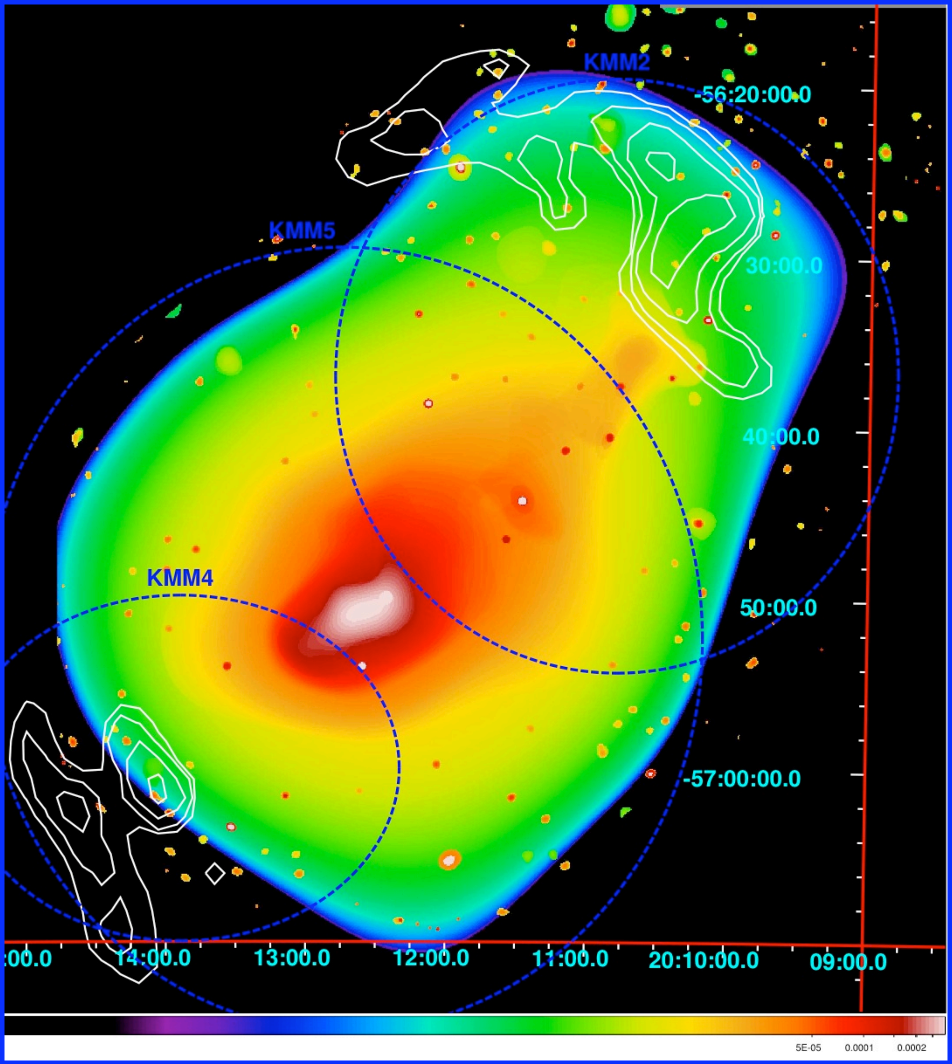
New XMM-Newton Observation

- 12-13 October 2008
- OBSID = 0553180101
- PN exposure 55 ks (37 ks clean)
- MOS exposure 50 ks (47, 44 ks clean)

New XMM Observation of Radio Relic



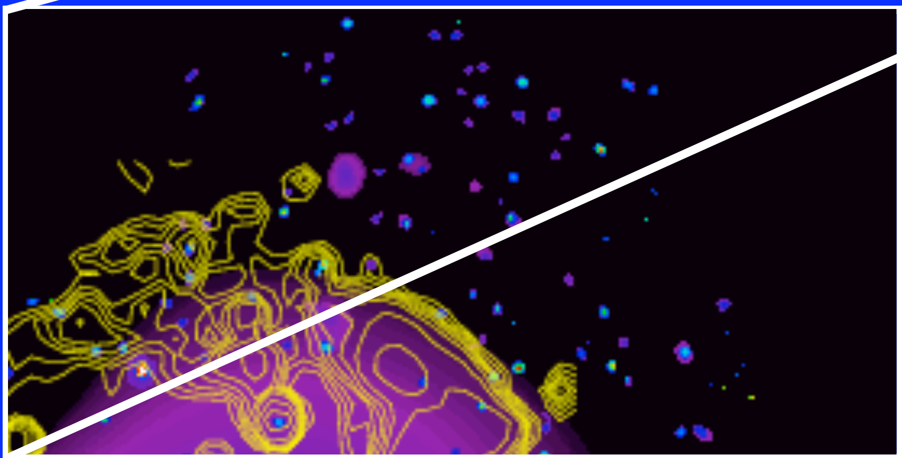
New XMM Observation of A3667 Radio Relic

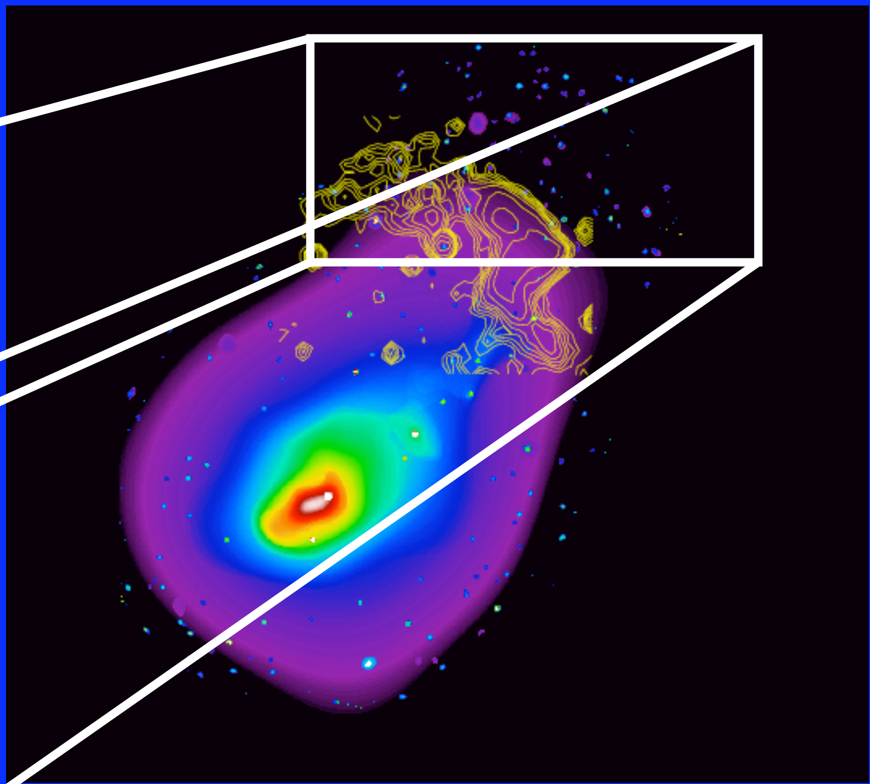


New XMM Observation (Cont.)

Smaller PSF really helps!

- Lots of sources beyond relic (not resolved in Suzaku XIS)



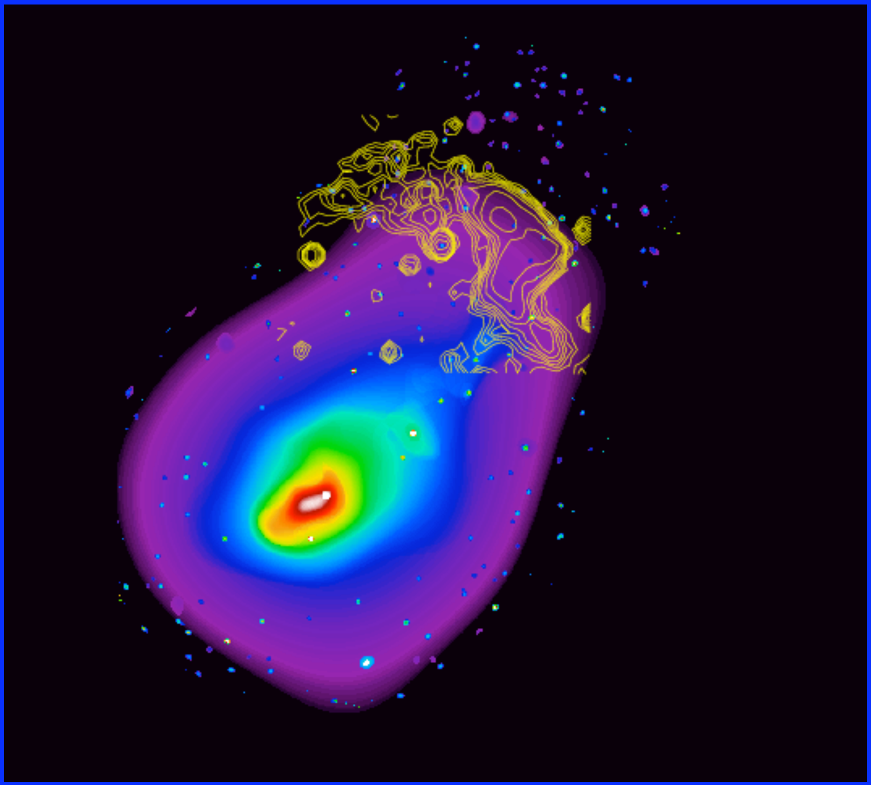


XMM-Newton mosaic with new observation

New XMM Observation (Cont.)

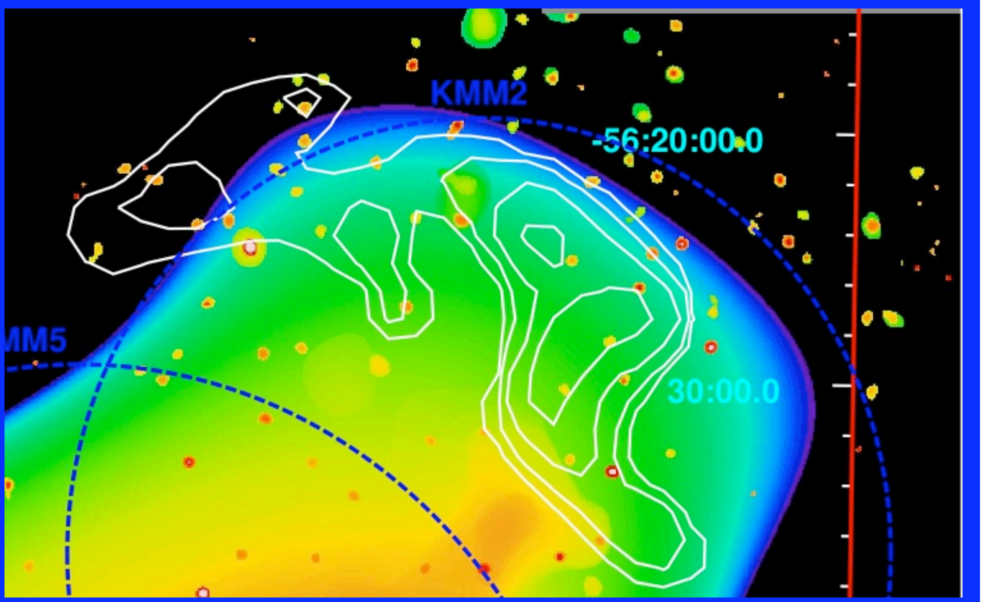
Smaller PSF really helps!

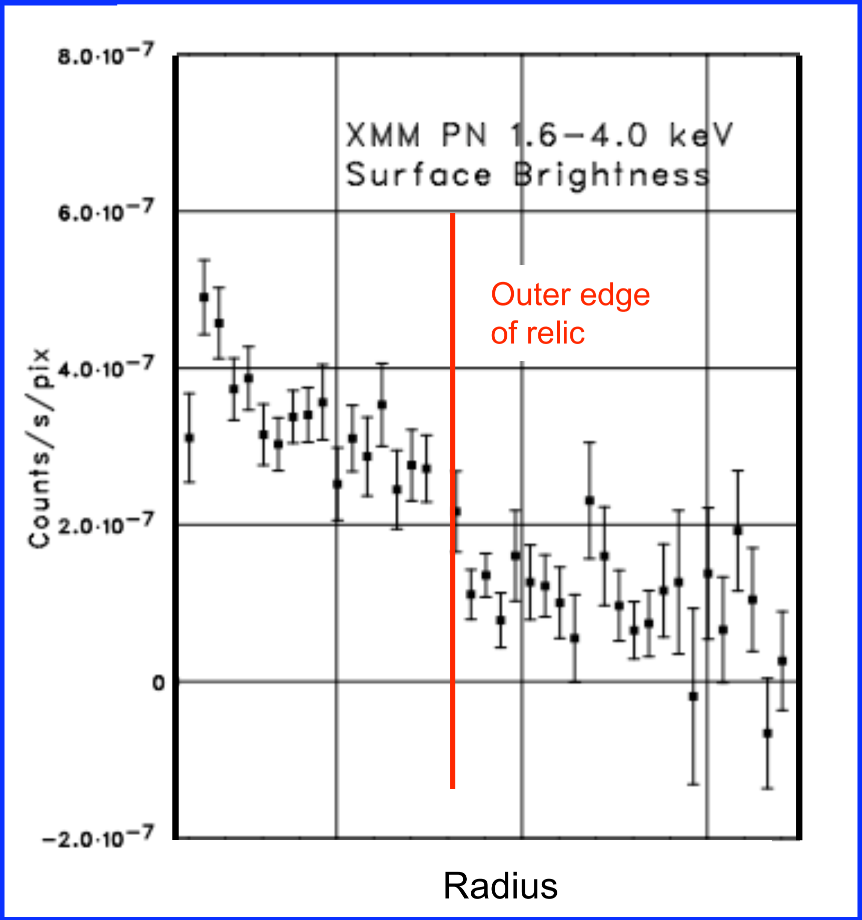
- Lots of sources beyond relic (not resolved in Suzaku XIS)
- Less scattered X-rays from bright core than Suzaku XIS



XMM-Newton mosaic with new observation

X-ray Surface Brightness Discontinuity at Outer Edge of Relic





Discontinuity at Outer Edge of Relic

- Jump in X-ray Surface Brightness (outside relic to inside)
- Jump in X-ray hardness (harder inside)
- Mixture of thermal shock & IC nonthermal emission from relic?
  - Too few photons to fit combined thermal and nonthermal

Merger Shock

Density jump

n_{e1} = (6.81±0.55) x 10^{-5} cm^{-3}

n_{e2} = (1.32±0.08) x 10^{-4} cm^{-3}

Compression C = n_{e2}/ n_{e1} = 1.94 ± 0.19

Temperature jump

T_1 = 1.9 ± 0.6 keV

T_2 = 4.0 ± 0.8 keV

Mach number M = 1.71 ± 0.16

Compression C = 1.97 ± 0.19

v_s = 1210 ± 220 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

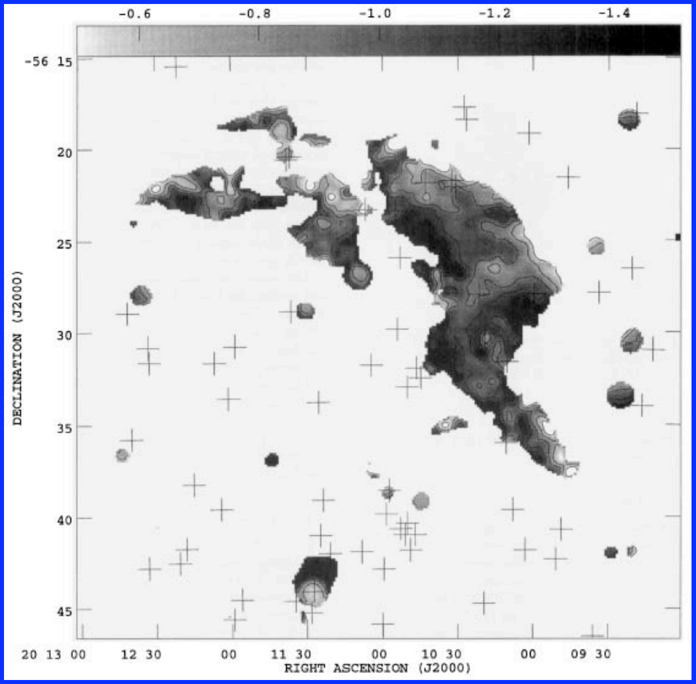
- Sharp outer edge (= location of shock acceleration)
- Radio spectrum steepens away from edge

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

$$t_{rad} = 1.3 \times 10^8 \left(\frac{\nu_b}{1.4\,\mathrm{GHz}} \right)^{-1/2} \left(\frac{B}{3\,\mu\mathrm{G}} \right)^{-3/2} \times \left[1 + \left(\frac{3.6\,\mu\mathrm{G}}{B} \right)^2 \right]^{-1} \mathrm{yr}$$

$$v_2 = v_s / C \approx 610\,\mathrm{km/s}$$

$$\theta_{\mathrm{rad}} \approx 1.3'$$



- Radio spectrum too flat at outer edge given shock compression?

Properties of NW Radio Relic

- Spectrum only steepens by ~1
- Relic doesn't fade immediately as spectrum steepens

  Three-dimensional object

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

XMM Large Project

Cycle 9

311 ksec (new) plus 55 ksec (old) on NW relic and merger shock

Conclusions

- Coma Hard X-rays (Wik et al. 2009, 2010)
  - Upper limit on IC, below BeppoSAX & RXTE detections
  - Hard excess probably thermal
  - Swift/BAT → hard X-rays not very extended
- A3667 Hard X-rays (Nakazawa et al. 2009)
  - PIN has hard excess, but < systematic uncertainty
    - $F_X < 7.1 \times 10^{-12}$ ergs/cm^2/s 12-70 keV
    - E(rel. e) $< 9 \times 10^{61}$ ergs
    - B > 0.5 μG
- New XMM image shows discontinuity at outer edge of relic (Finoguenov et al. 2010)
    - Shock, Mach number ~ 1.7, v_s ~1200 km/s
    - Shock could accelerate rel. e's, explain shape, surface brightness, and spectral variation of relic
    - Inverse Compton → B ≥ 3 μG, very strong at large radius
  - Significant nonthermal pressure support in radio relic?