Bringing Clusters of Galaxies into Sharp F

Christine Jones


MACS0717+3745 Chandra - HST

1. History – finding clusters

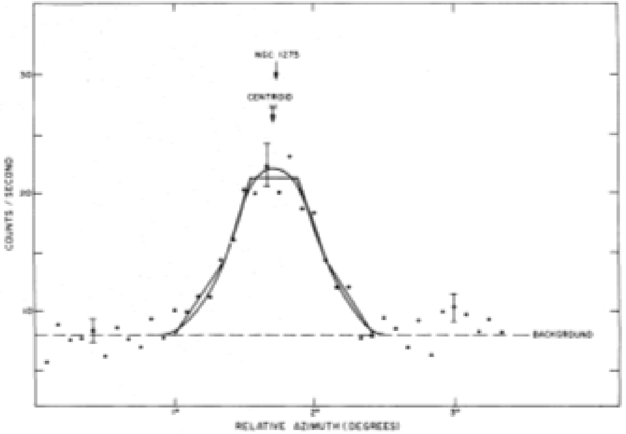
2. The most massive clusters
How they grow and using them as
cosmic telescopes

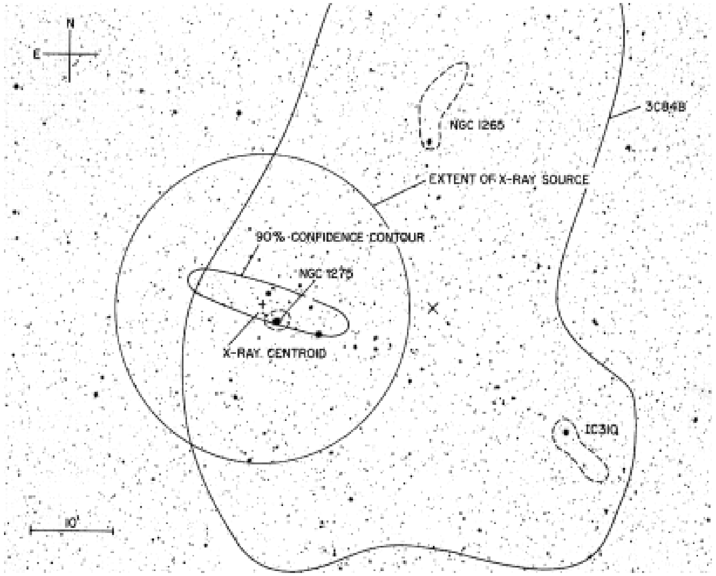
3. AGN feedback in cluster cores

4. The Future -- X-ray Surveyor –
high angular resolution and large
area

Perseus from Uhuru (Forman et al. 1972)

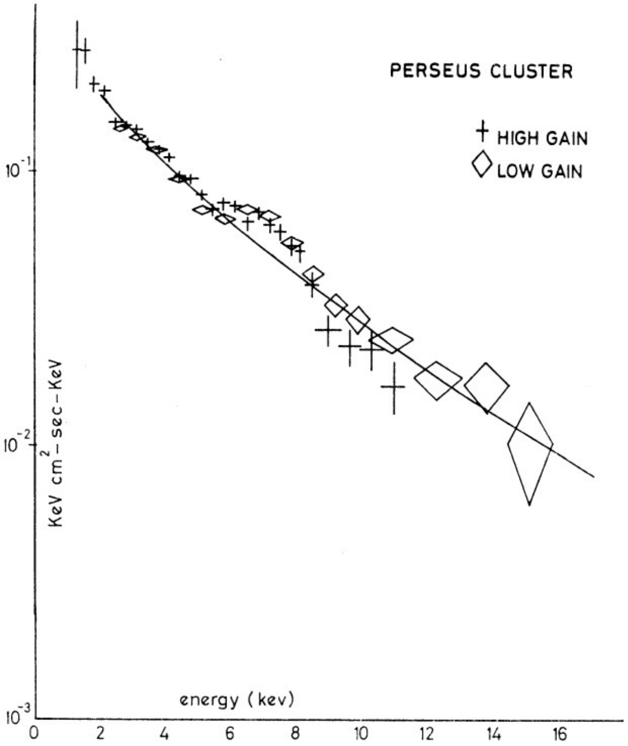
Clearly extended
Nature unknown



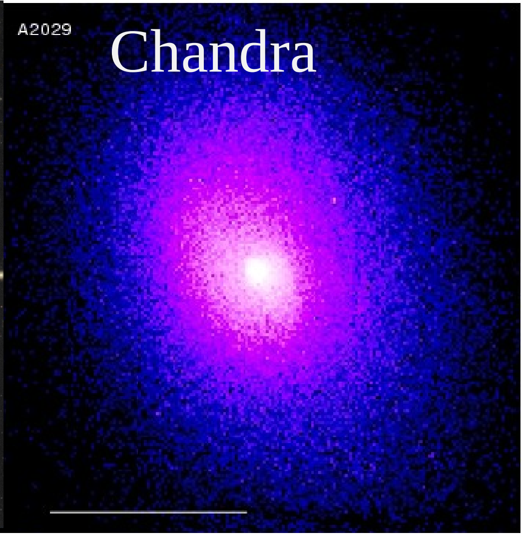


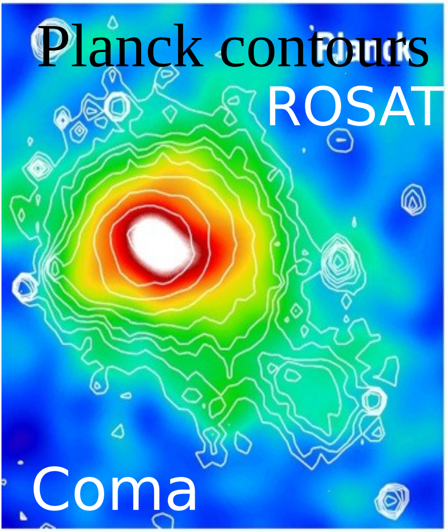
Ariel 5

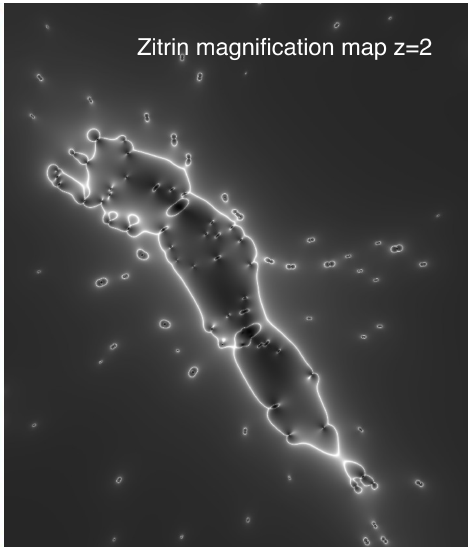
- Mitchell, Charles, Culhane, Davison, Ives et al. 1976, MNRAS, 176, 29
- Emission suggests 6 keV plasma enriched with iron
- Quickly led to “cooling flow problem” e.g., Fabian & Nulsen 1977



Cataloging and Mapping Clusters of Galaxies







GALAXIES

HOT GAS (most of the baryons)

DARK MATTER

Optical/IR
Zwicky 1961-68
Abell 1958,1989
Wen, Han, Liu
2012

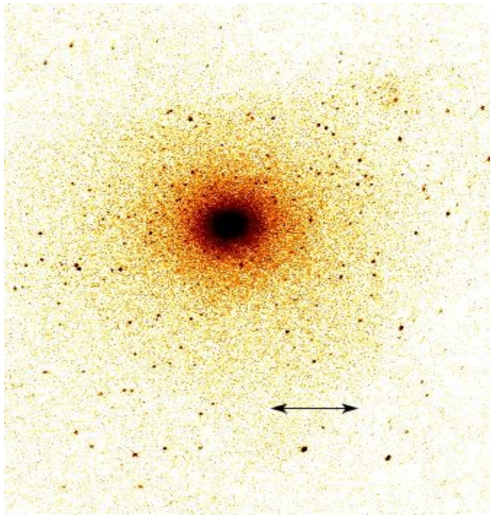
X-ray surveys
Einstein (Gioia et al)
ROSAT (Bohringer, Rosati, Vikhlinin, Ebeling…)
XMM, Chandra
(Mehrtens,Fassbender…)

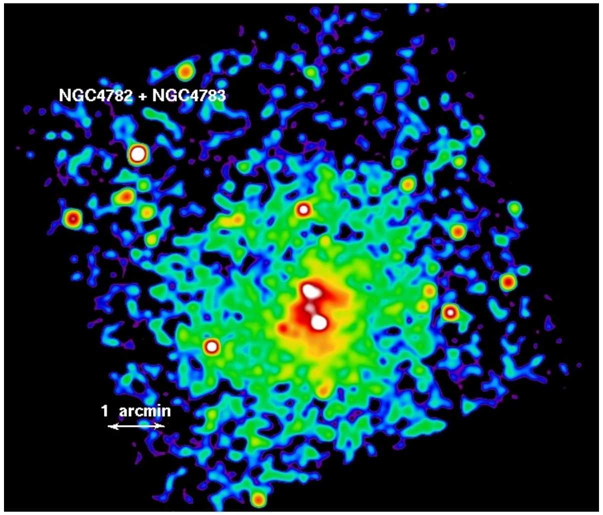
SZ surveys
Planck
SPT
ACT

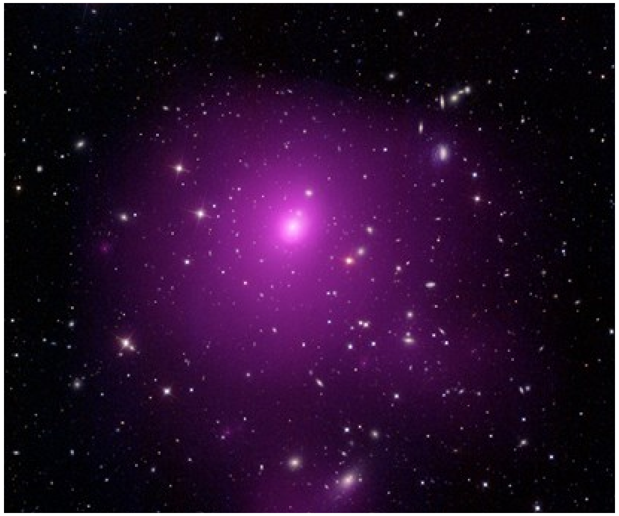
Lensing
HST & ground
Euclid
WFIRST-AFTA

Setting the stage

Family of increasing mass, temperature, and luminosity

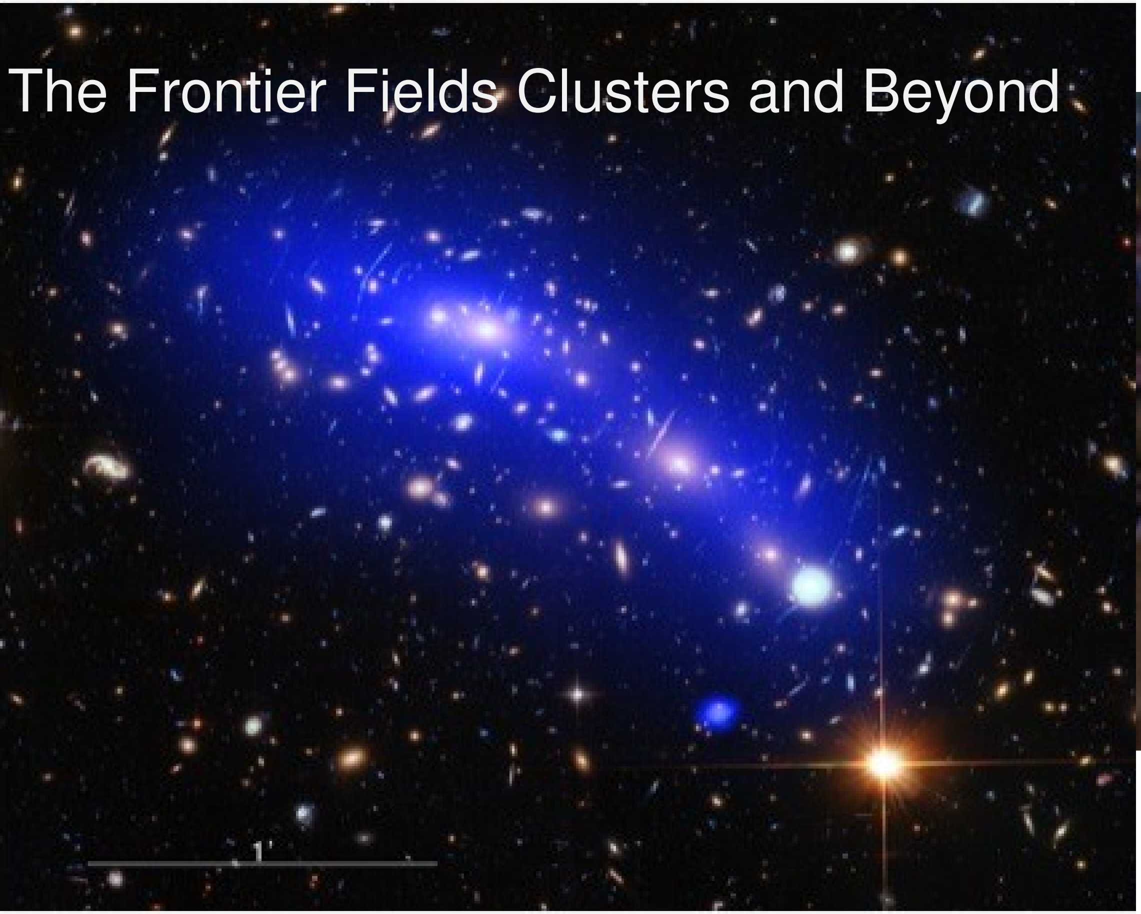






	E/S0 Galaxies	Groups	Clusters
L_x (ergs/sec)	$10^{39\text{-}42}$	$10^{42\text{-}43}$	$10^{43\text{-}46}$
Gas Temp	0.5-1.0 keV	1-3 keV	2-15 keV
$M_{gas}/M_{stellar}$	0.02	1	5

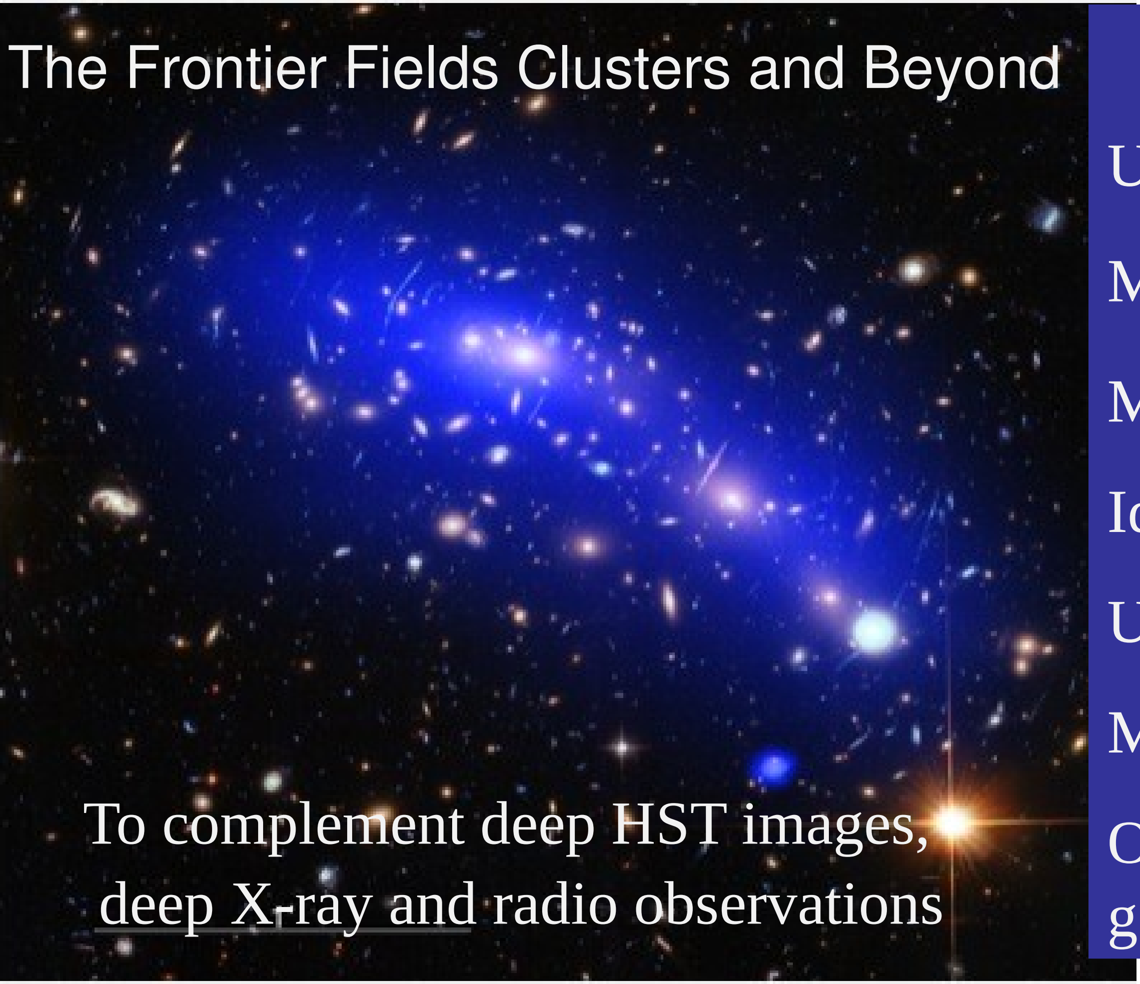
Part 1 – The Growth of Clusters of Galaxies



Stephen S. Murray
1944 - 2015

With thanks to S. Murray, W.Forman, G. Ogrean, R. van Weeren, F. Andres-Santos, A. Zitrin, A. Vikhlinin, L. David, E. Churazov, S. Randall, R. Kraft,
J. DePasquale, E. Bulbul, P. Rosati, M. Donahue, P. Nulsen, A. Goulding, A. Bonafede, B. Mason, T. Mroczkowski, J. Sayers, J. Merten, K. Umetsu, E. Roediger

Part 1 – The Growth of Clusters of Galaxies



The Frontier Fields Clusters and Beyond

To complement deep HST images, deep X-ray and radio observations

Goals

Understand cluster mergers

Measure DM halos $>10^{13}\ M_{sun}$

Measure DM–baryon offsets

Identify merger shocks

Understand particle acceleration

Measure faint radio populations

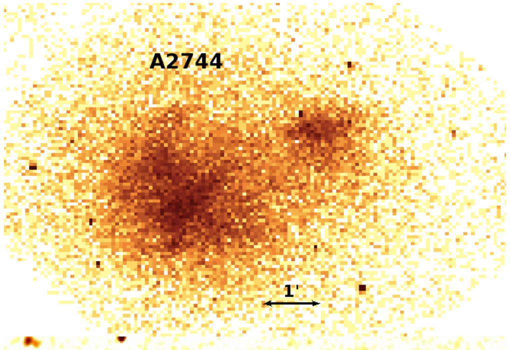
Observe effects of mergers on galaxies

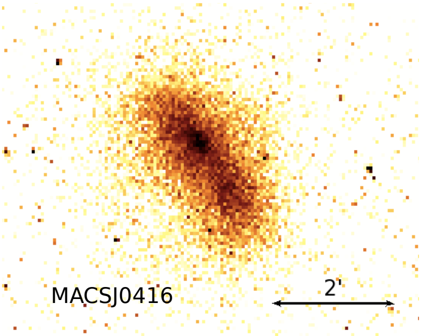
Chandra Frontier Clusters Observing Status

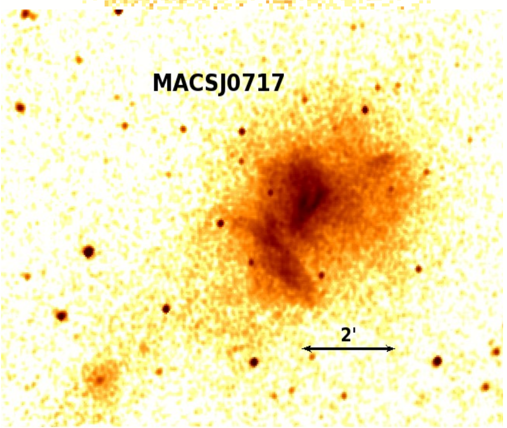
- Abell 2744 (z=0.308) - 125 ks
- MACSJ0416.1-2403 (z=0.396)
- 300 ks
- MACSJ0717.5+3745 (z=0.545)
- 243 ks
- MACSJ1149.5+2223 (z=0.543)
- 370 ks

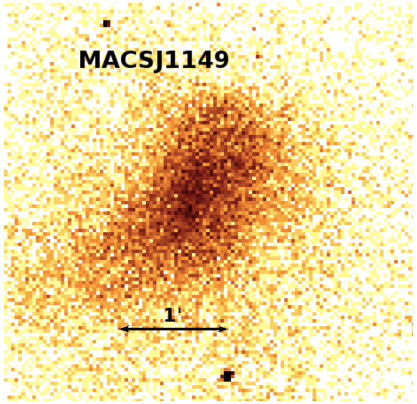
More Chandra/XMM

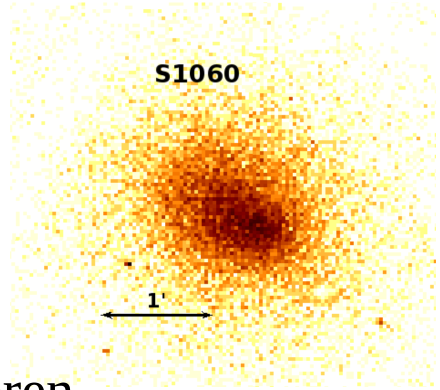
- Abell S1060 (z=0.348) 27 ks (100k SSM)
- Abell 370 (z=0.375) 95 ks (XMM proposed)

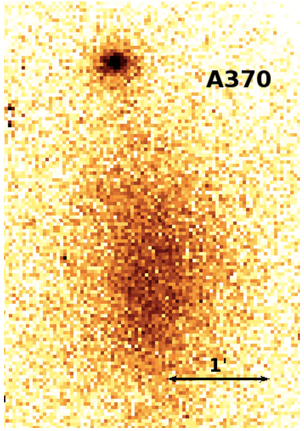




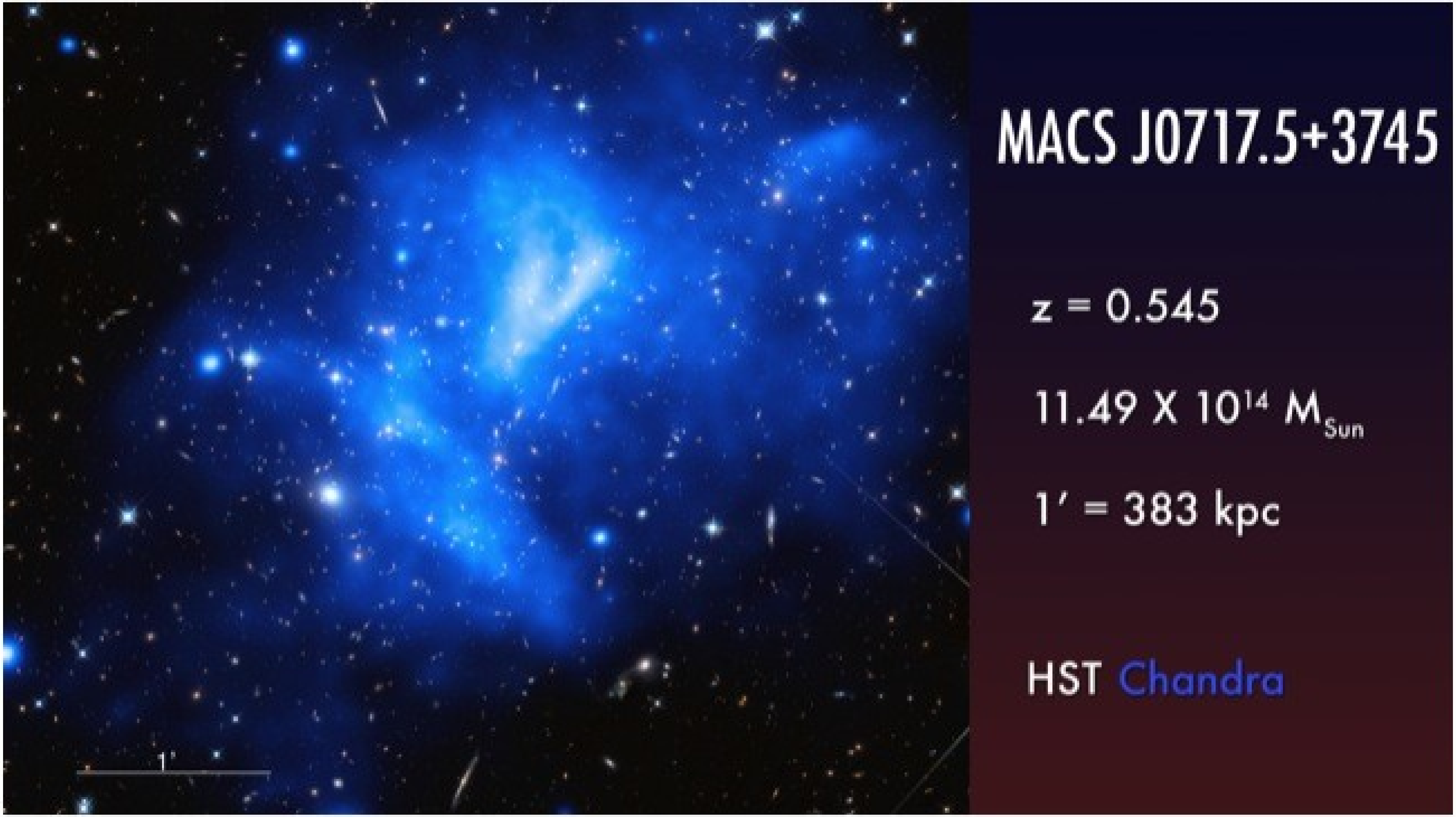








Deep radio observations led by R. van Weeren



Most massive of the Frontier Fields Cluster

Most complicated in terms of structure

Most interesting!

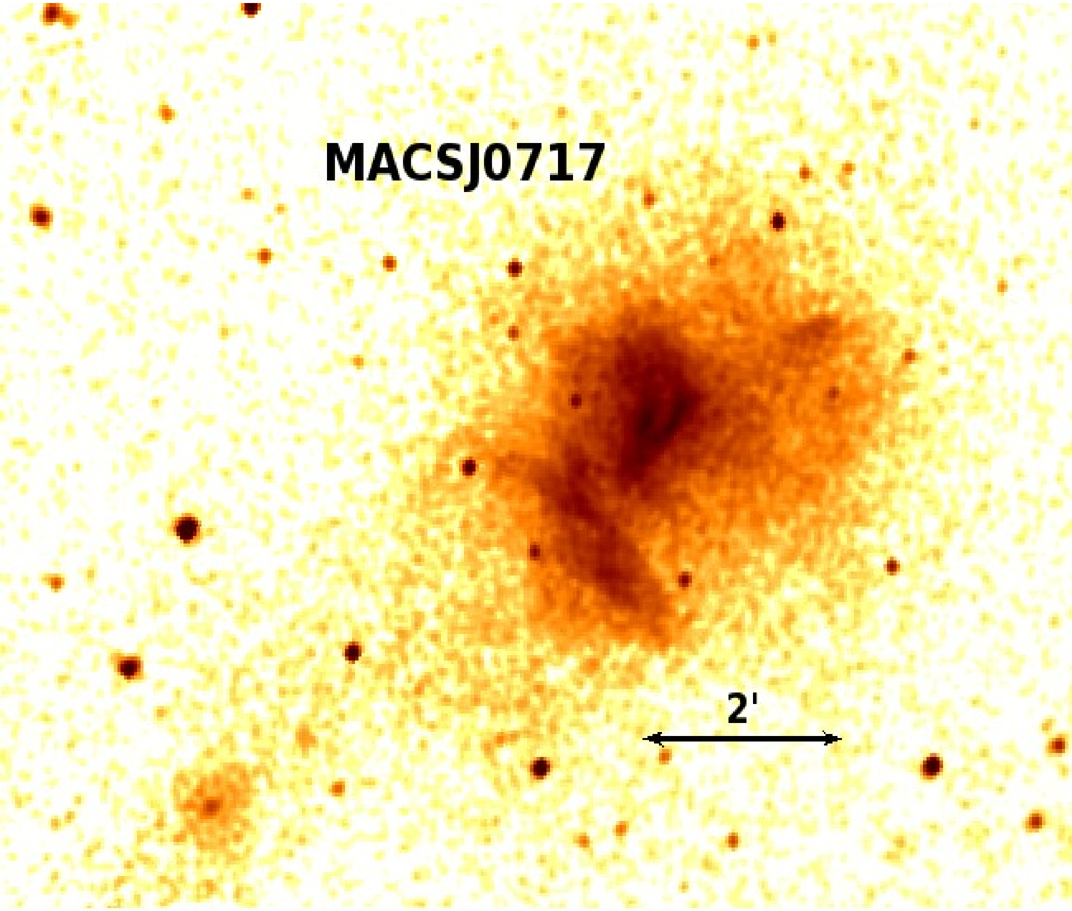
Cluster growth through mass accretion

1)“Steady” infall of matter from filaments (e.g. Ma+ 2009, Whalen+ in prep)

2) Infall of groups

3) Major mergers

In MACS0717 – all of these



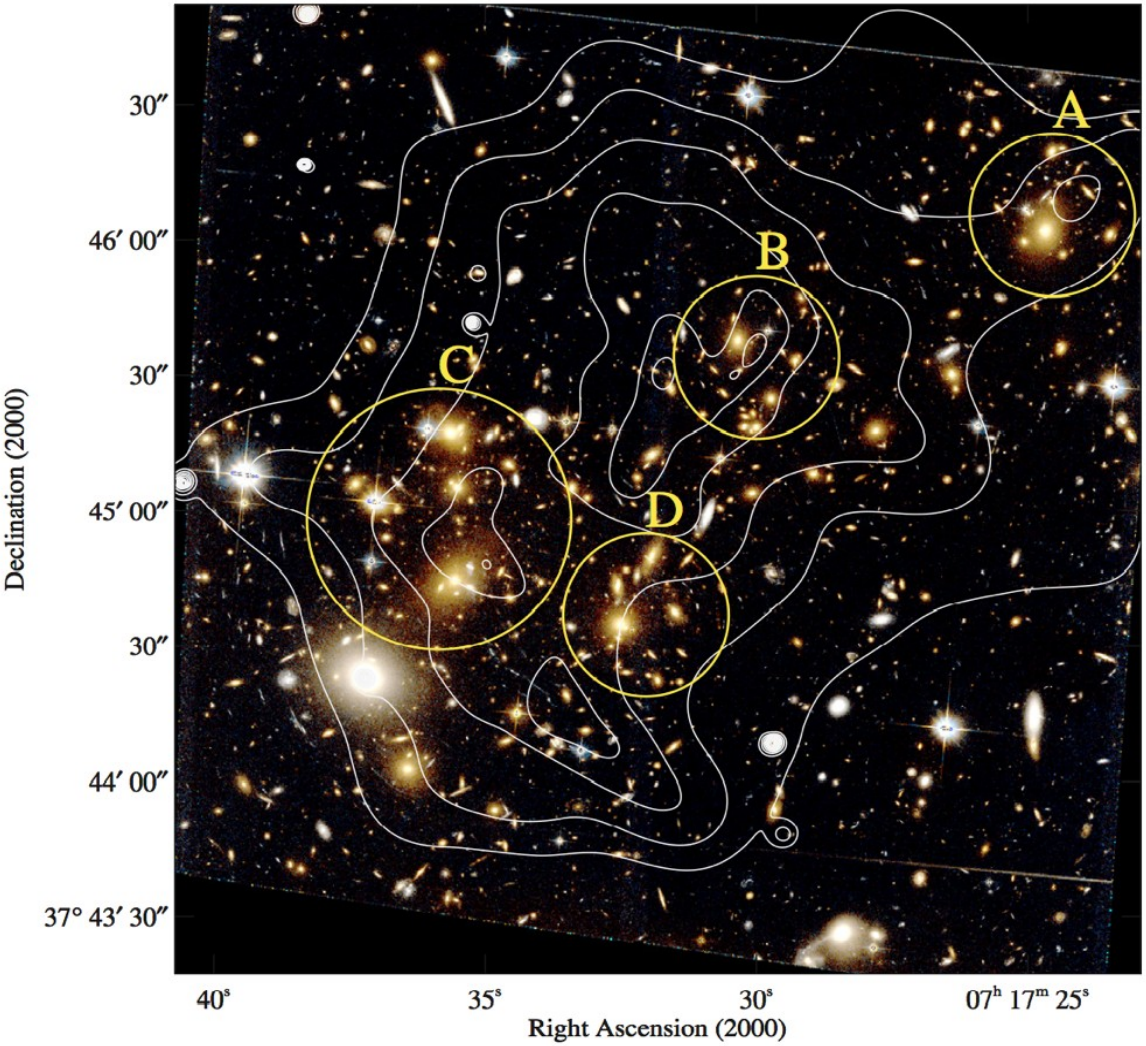
MACS J0717.5+3745

Previous work:

Medezinksi+2013; Jauzac+2012; Ma+2009; Zitrin+2009; Ebeling+200

- $z = 0.545$
- $L_X = 2.5 \times 10^{45}$ erg s^{-1}
- T= 11.6 keV overall
- $M_{vir} = 10^{15} M_\odot$
- Quadruple merger event
- σ_V = 660 - 1760 km s^{-1} (for the subclusters)
- Hints of shock heated regions: ~20+ keV

Ma+2009



MACS J0717.5+3745: Non-Thermal Emission

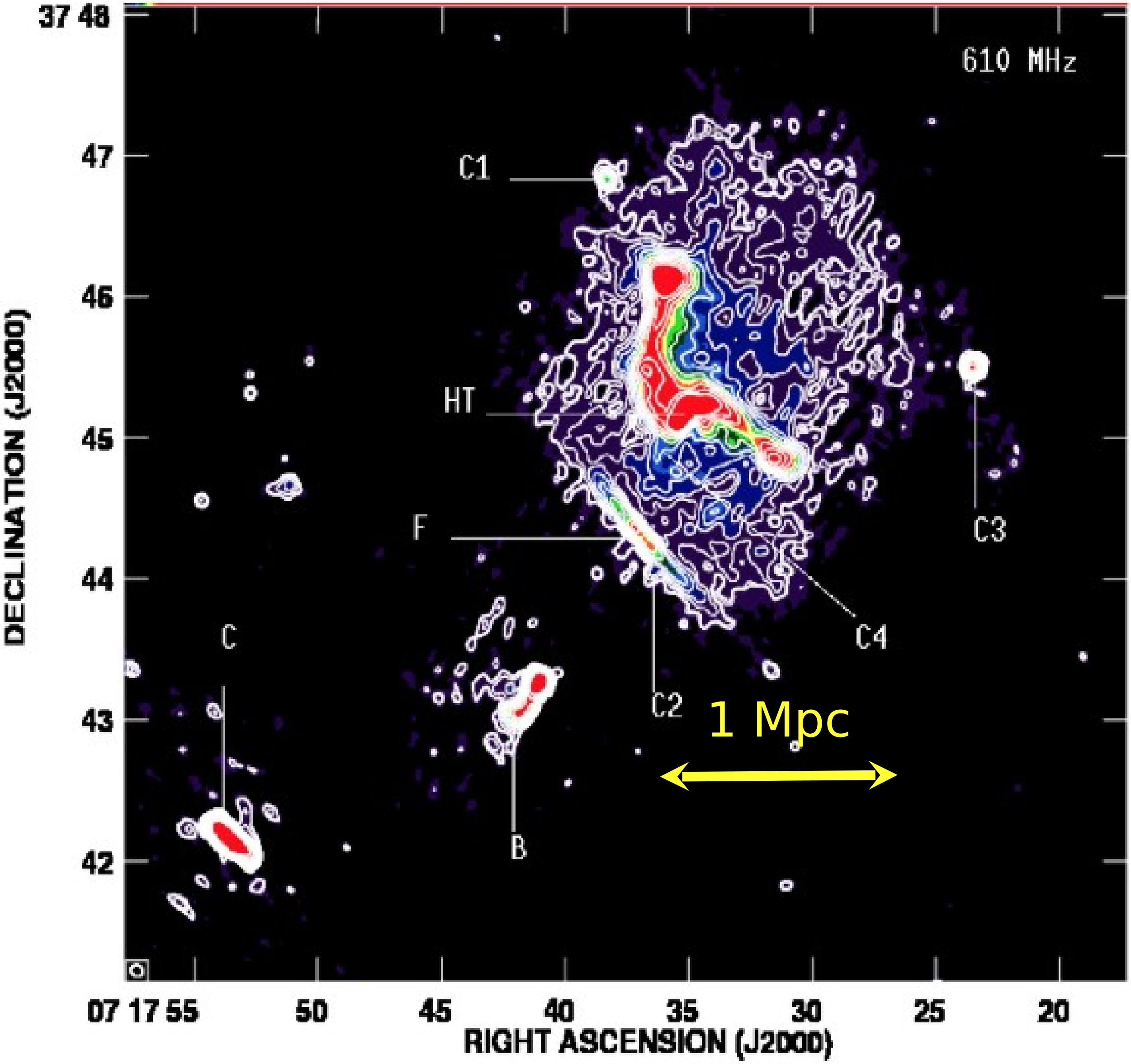
van Weeren+ 2009; Bonafede+2009; Pandey-Pommier+2013

GMRT 610 MH

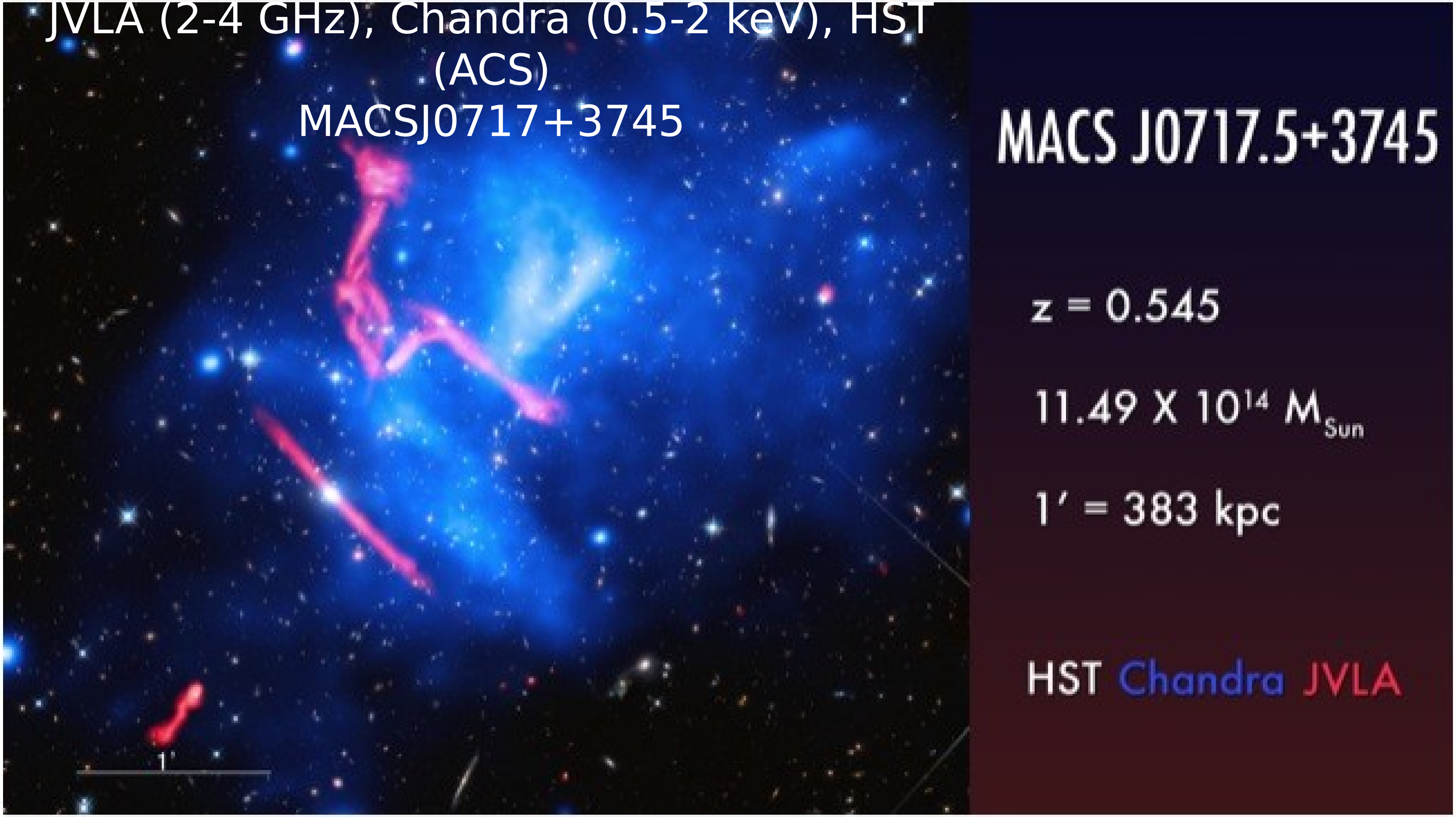
Radio observations:

- 850 kpc radio relic
- 1.5 Mpc radio halo
- *implies: cluster-wide population of cosmic rays and magnetic fields*

Relics reaccelated particles by merger shocks



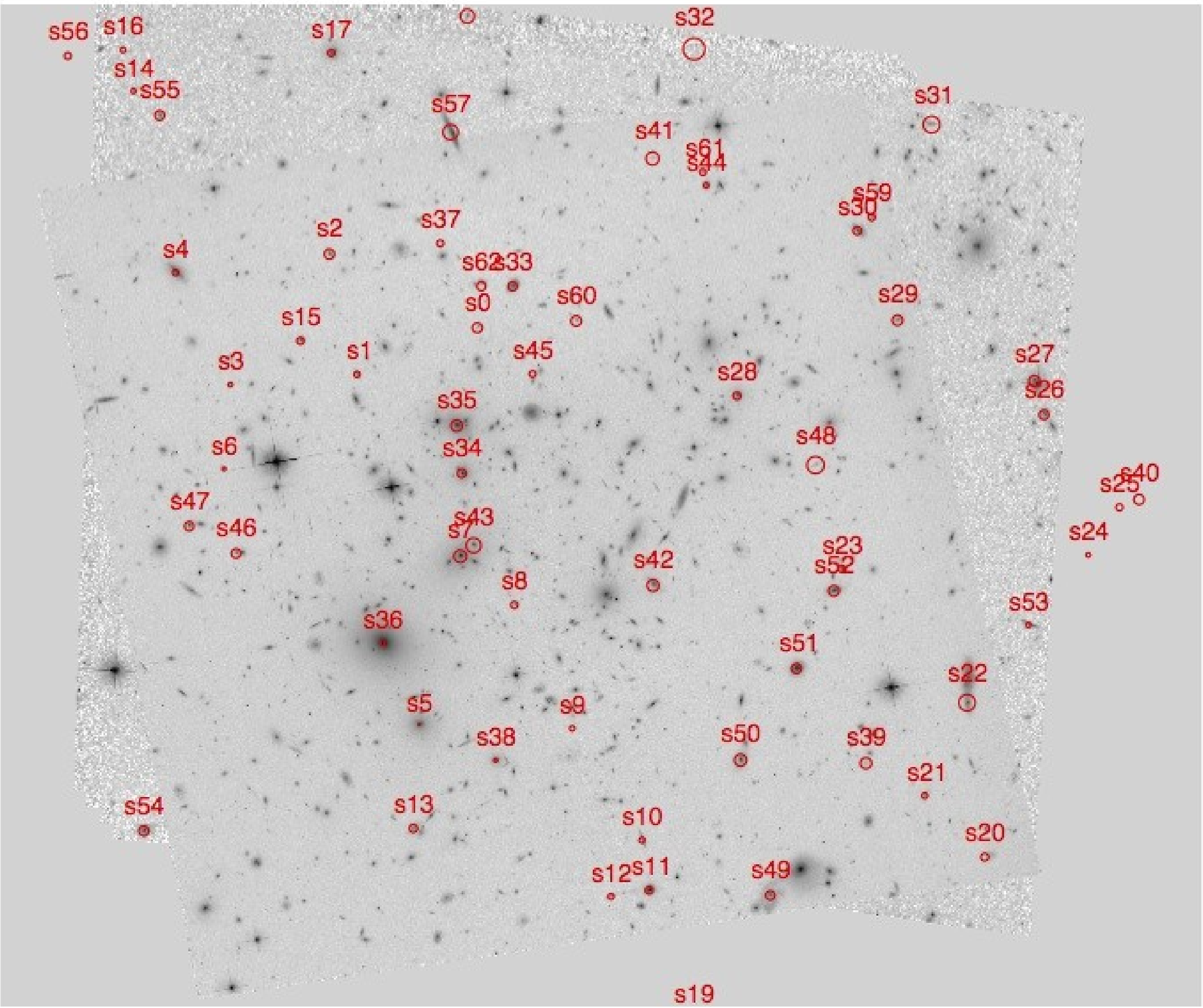
JVLA (2-4 GHz), Chandra (0.5-2 keV), HST (ACS) MACSJ0717+3745



van Weeren+ in prep.

Clusters as cosmic telescopes – not just for galaxies! Also AGN

MACS J0717.5+3745 - Radio Galaxies (X-ray AGN)



Deep JVLA observations

1.0-6.5 GHz in A and B configurations

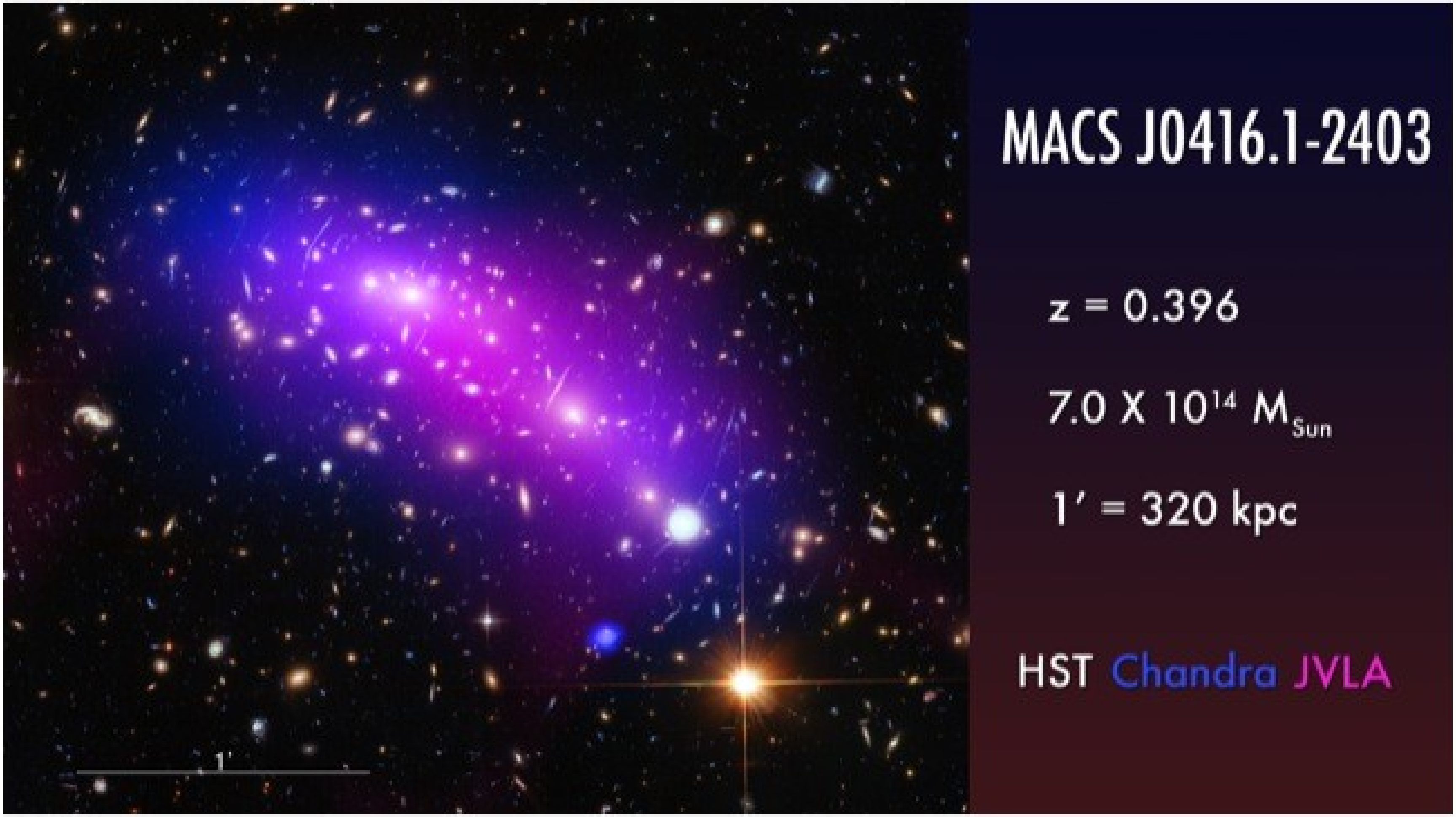
7 sources with magnification factors >2
Two with magnifications >5

Most are likely star forming galaxies (10-50 M_{sun}/yr)

Increase in number density 0.6<z<2 compared to z<0.3

Reaching the SKA detectio
threshold

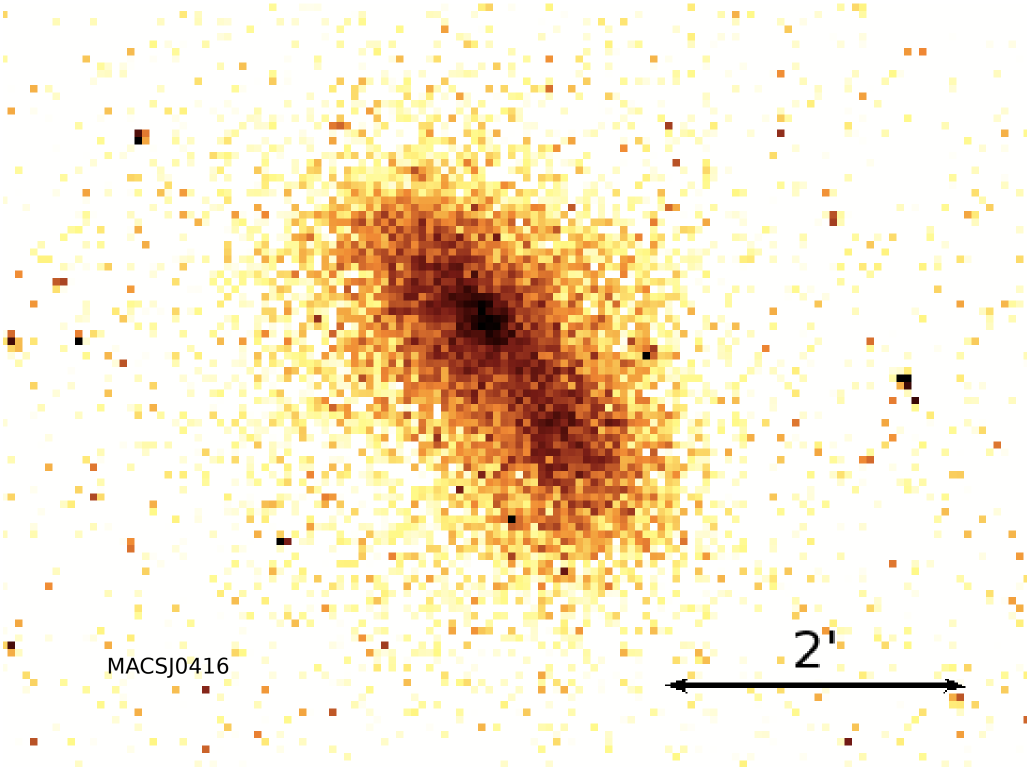
van Weeren et al submitted 2015



324 ks Chandra, observed (June 2009 – December 2014)
Radio - JVLA + GMRT

Ogrean et al. 2015 ApJ 812, 153

MACSJ0416.1-24.3 z=0.396 Chandra

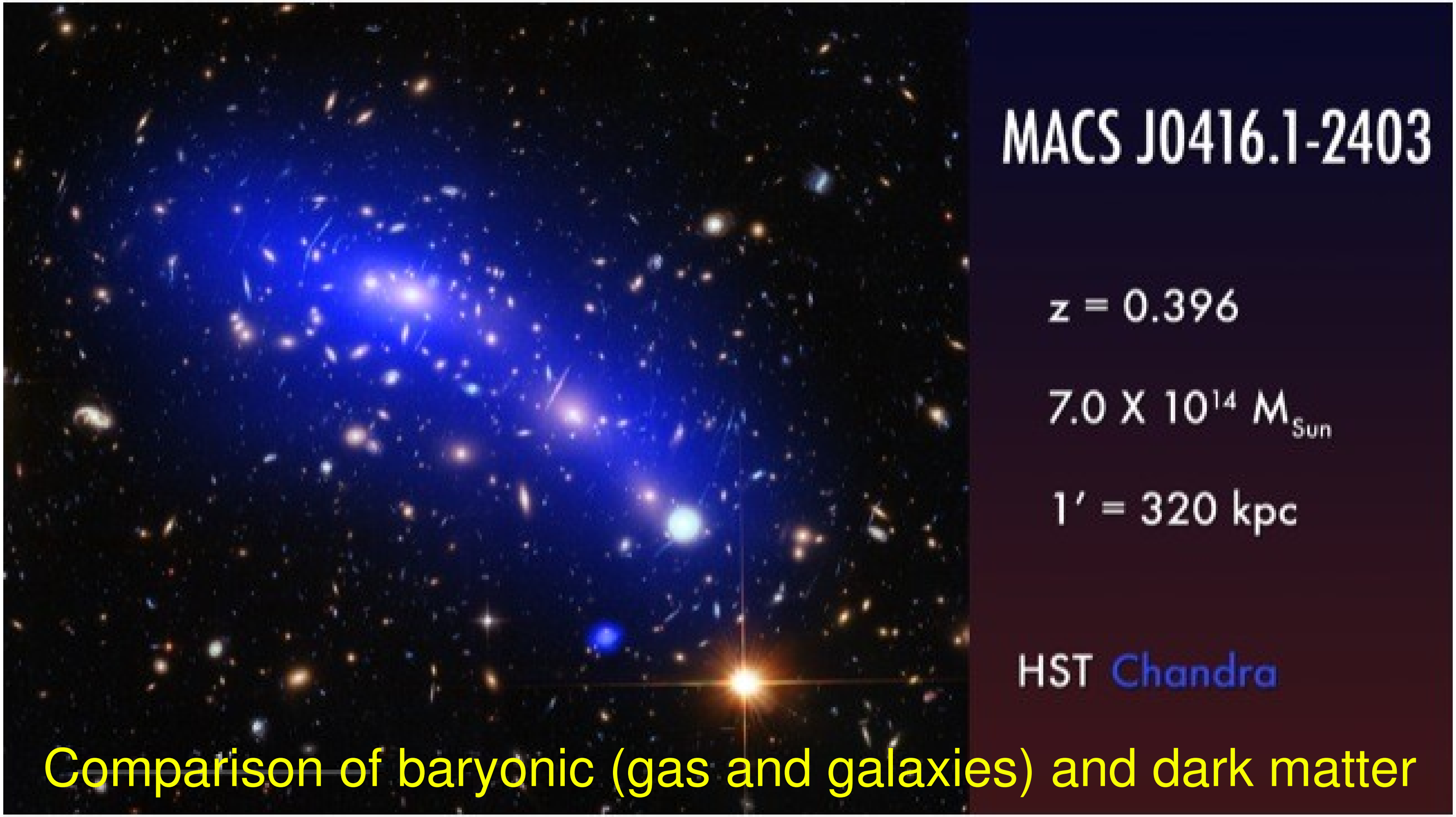


Classed as actively merging, with two primary subclusters, plus two smaller, “X-ray dark” subclusters
(Mann & Ebeling 2012, Jauzac et al. 2014)

Pre-merger state determined from our deep Chandra observations
(Ogrean et al. 2015)

“X-ray dark subclusters” may be filaments in projection.

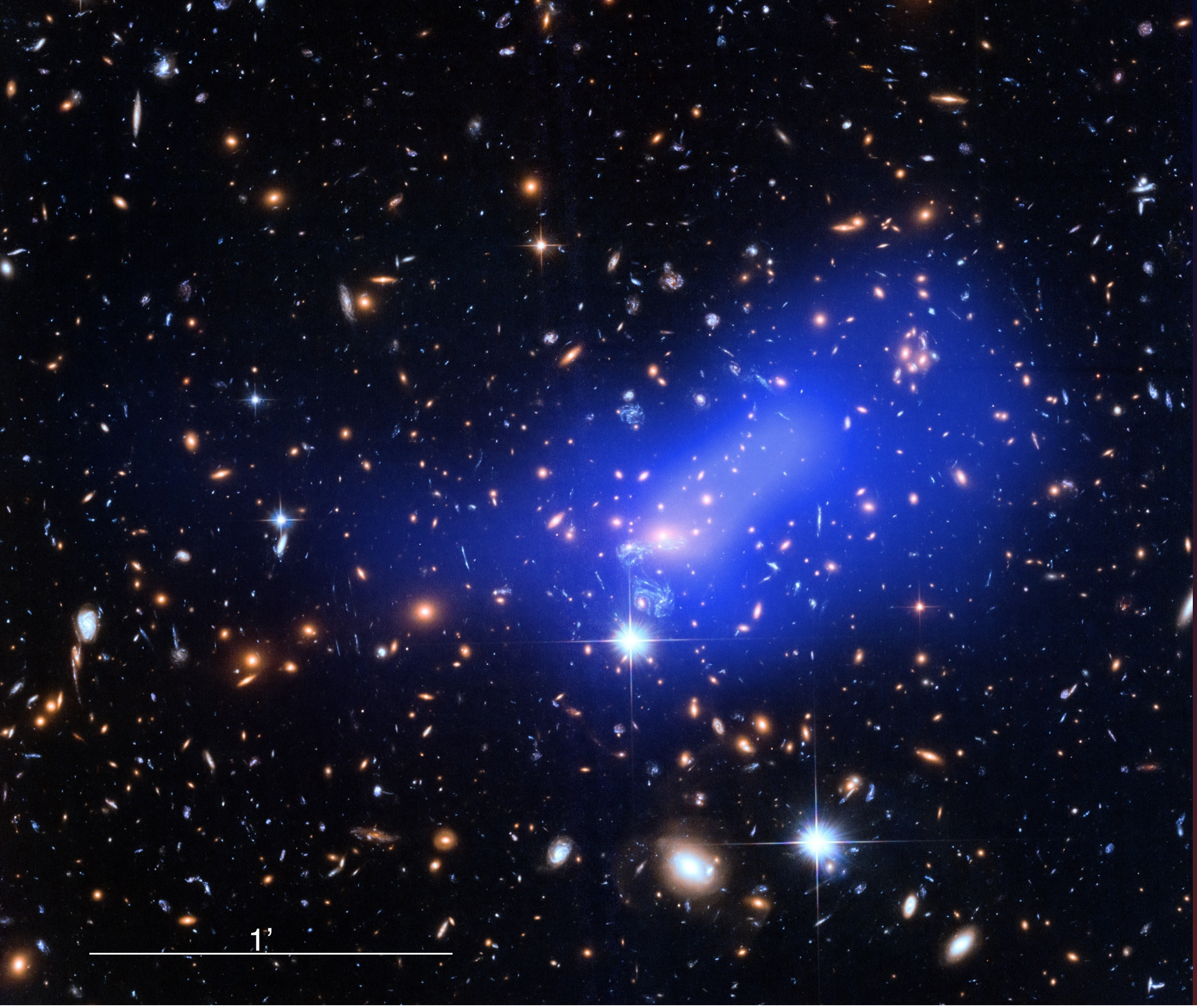
Also CLASH Cluster (Postman et al.)



Comparison of baryonic (gas and galaxies) and dark matter

Ogrean et al.(2015) found good agreement between positions of BCGs in each primary subcluster and peak of gas distribution

Harvey, Massey, Kitching, Taylor, Tittley (2015) found a significant offset, but used southern (blue) galaxy as BCG in southern subcluster.



MACS J1149.5+2223

$z = 0.545$

10.4 X 10^{14} M_{Sun}

1′ = 383 kpc

Optical Chandra

Chandra 365 ks

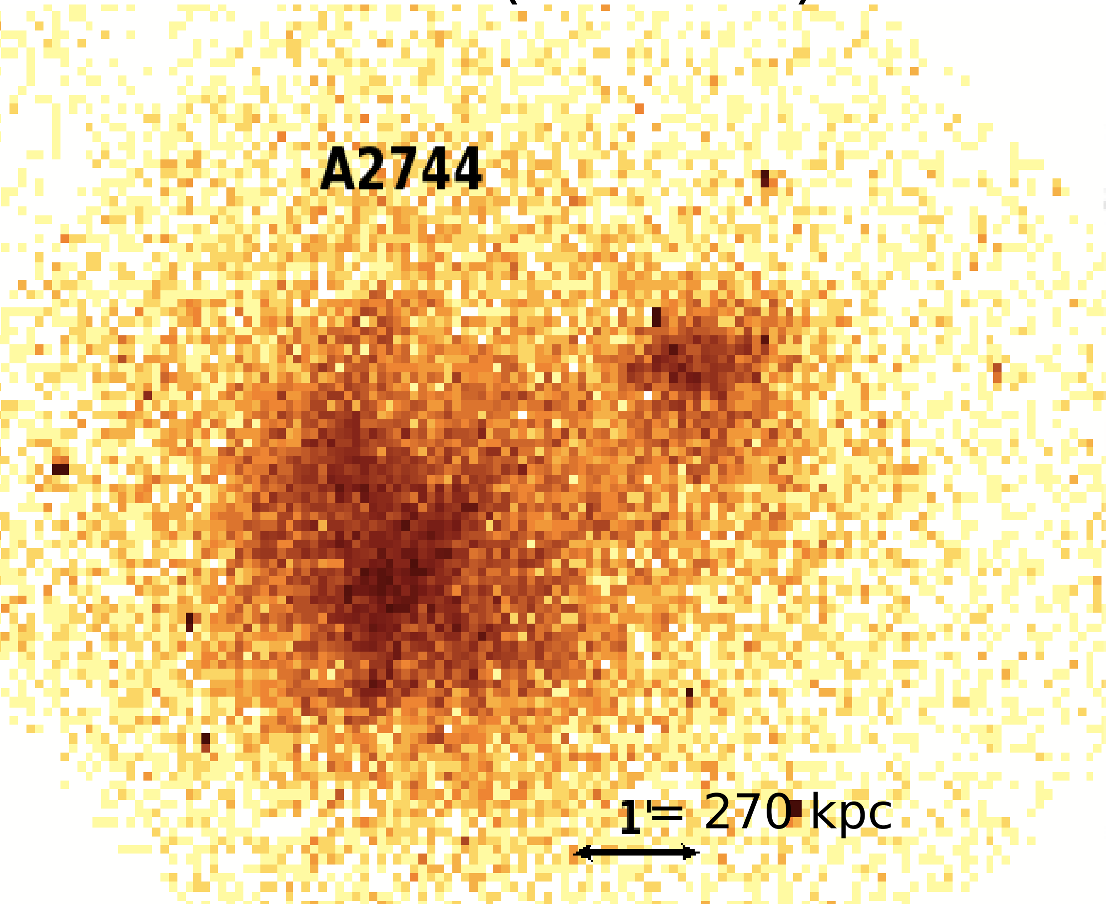
kT = 11 keV   Lx =1.6 x 10^{45} ergs s^{-1}

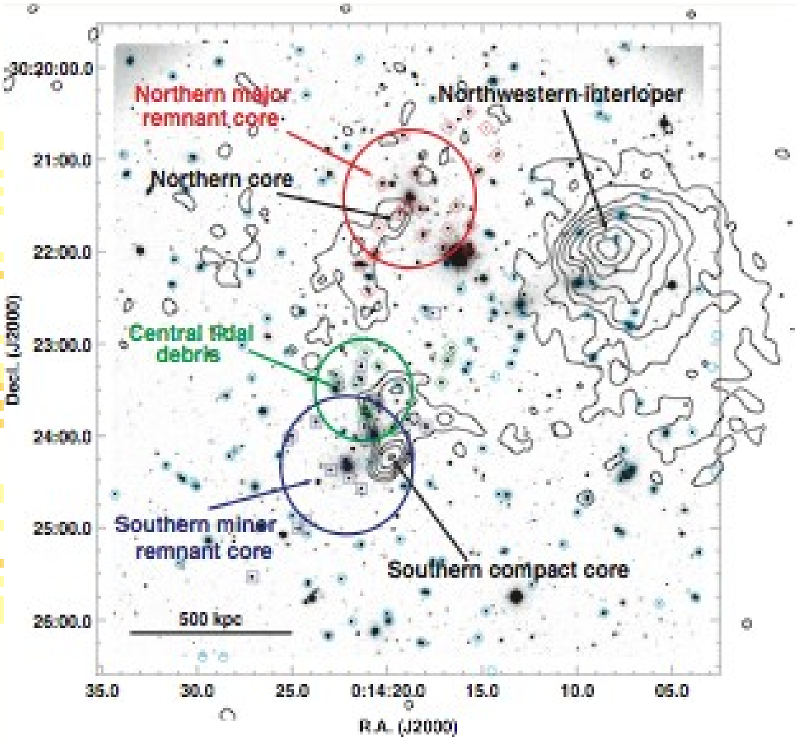
Merger of 4 subclusters

Faint radio halo at 1.4 GHz (steep spectrum? Newly born?)

Ogrean et al. 2015

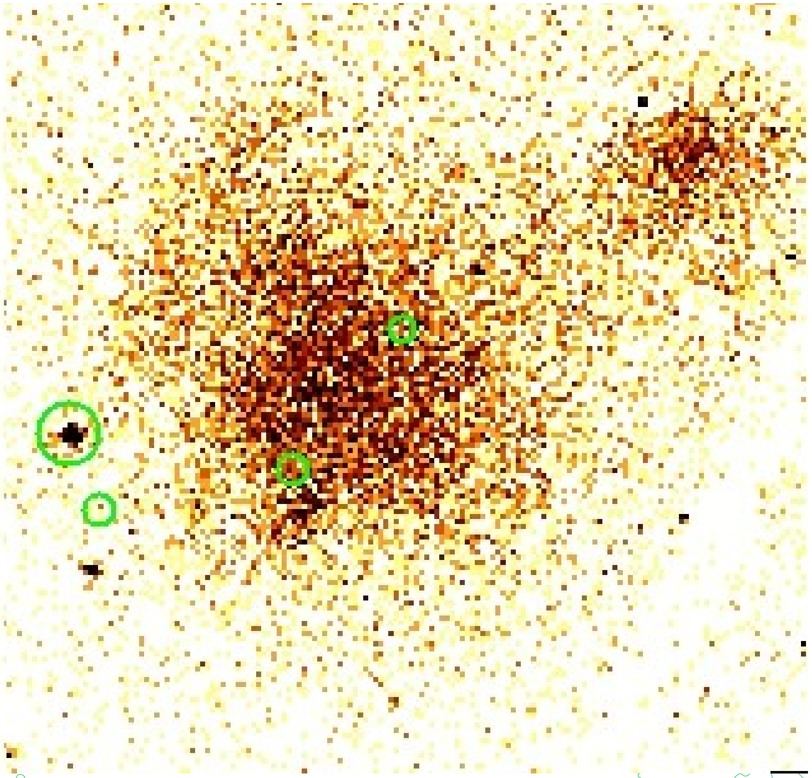
Abell 2744 (z=0.308) 125 ks Chandra - Owers et al 201





- X-ray luminous (10^{46} erg s^{-1} and hot - 9 keV)
- Major post core crossing merger
- North and south cores plus debris
    - X-ray subclusters fully disrupted
    - X-ray peak has no major galaxy concentration
- Northwestern interloping merger moving NW

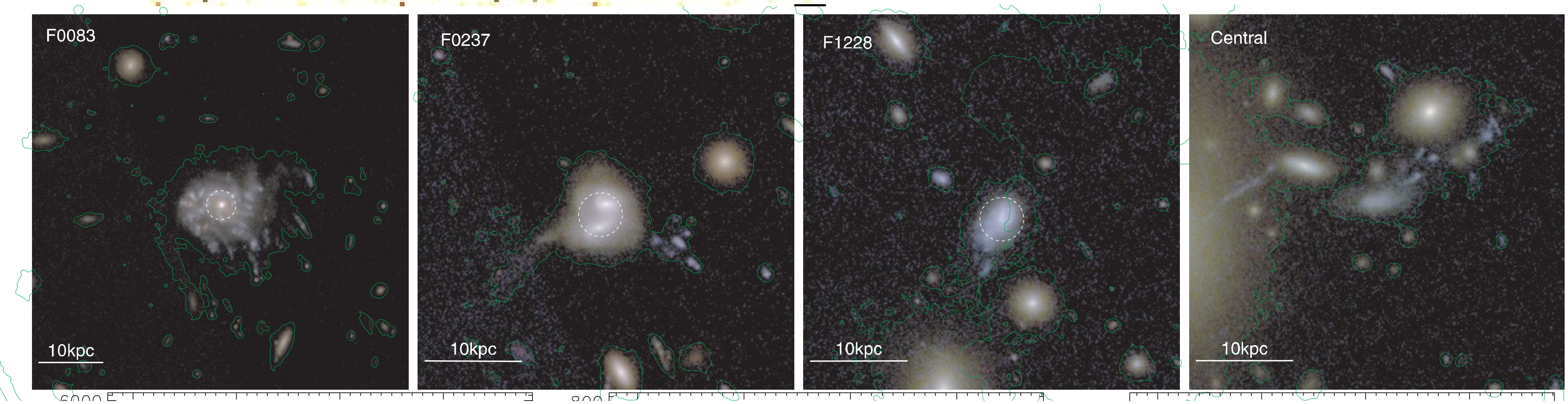
Abell 2744 (z=0.308) 125 ks Chandra



Jellyfish galaxies
induced star formation from
high pressure environment
Owers et al. 2012

First jellyfish galaxies found in A3627
Sun+ 2006, 2010
More than 100 In other clusters (e.g.
Ebeling+ 2014, Poggianti+ 2015)

-



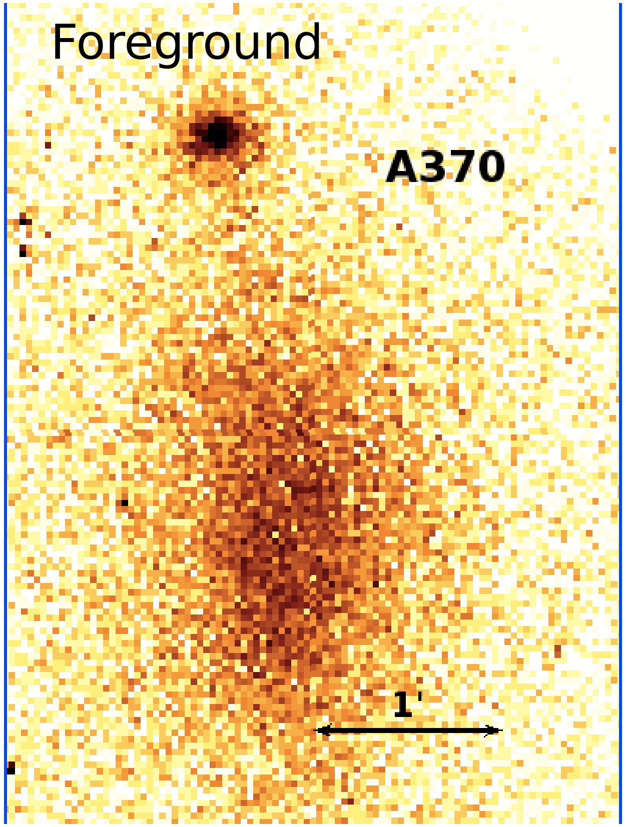
ABELL 370 (Z=0.375) 95 KS CHANDRA

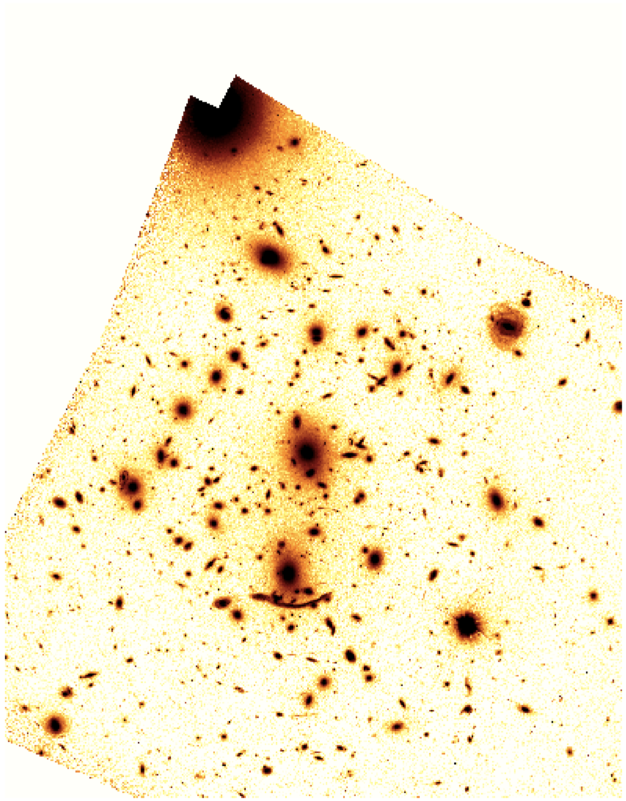
- Two primary BCGs
- N-S Orientation

Bautz et al. (2000)

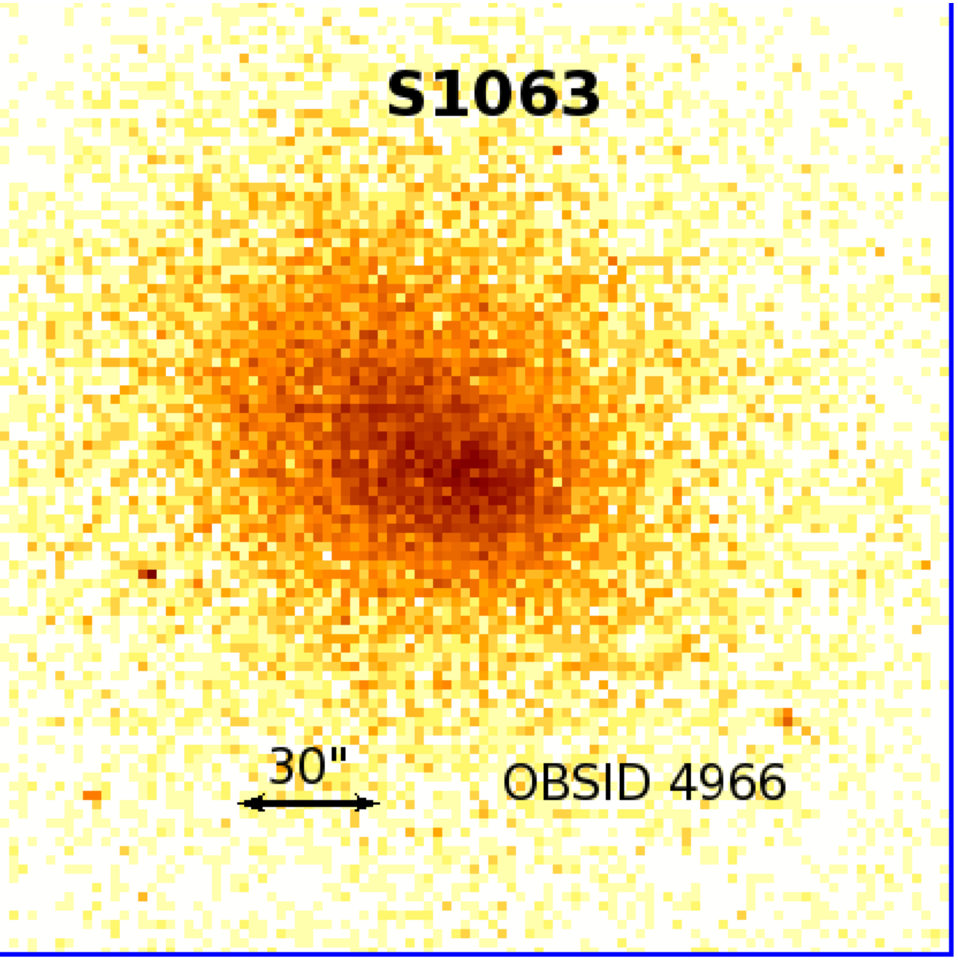
  - Studied triaxiality
  - Detected submm galaxies

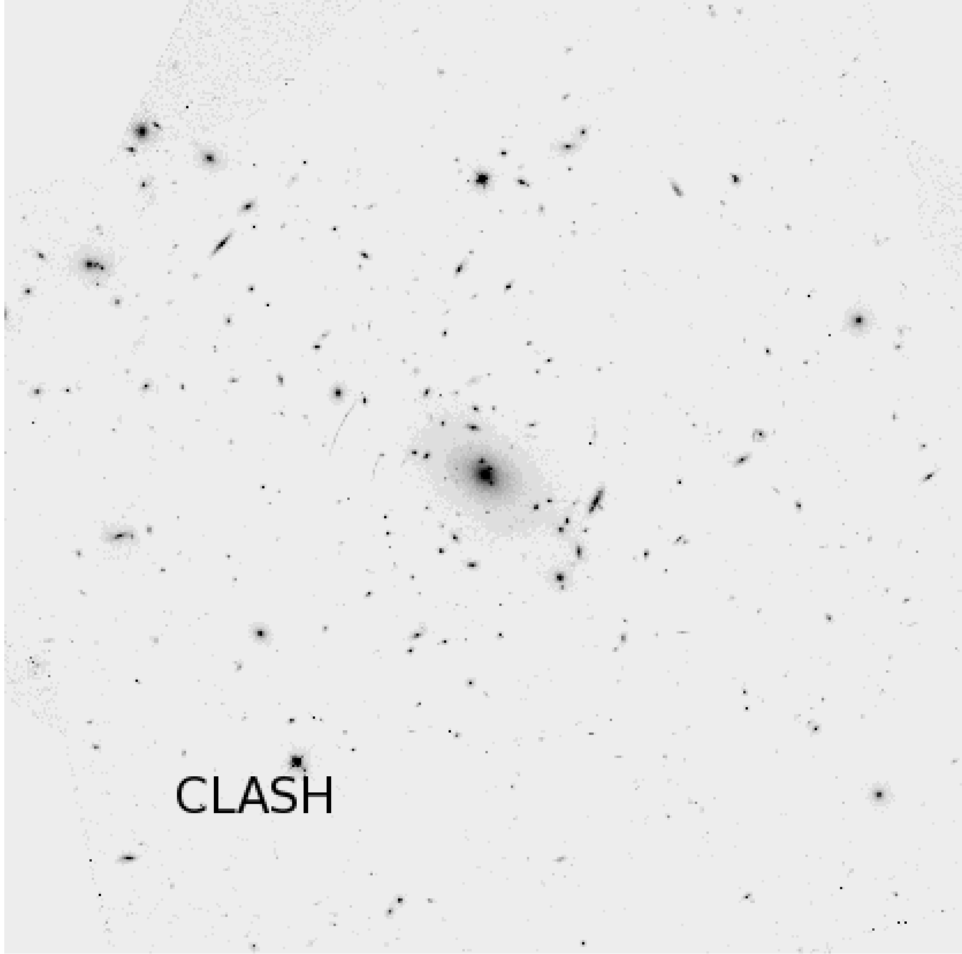
  - Need deeper X-ray observation





- AS1063 (RXC J2248.7-4431) z=0.348 ACIS-I
- Deeper Chandra observations in AO17 (Murray GTO time)



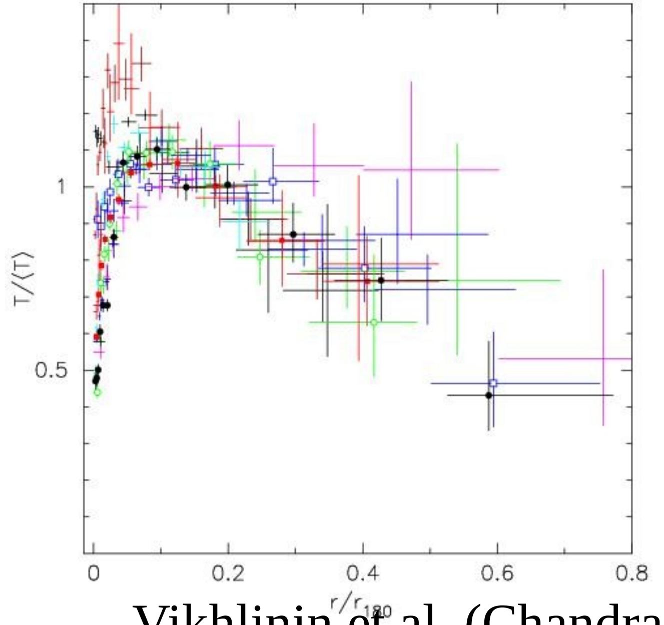


The “most relaxed” of the Frontier Clusters

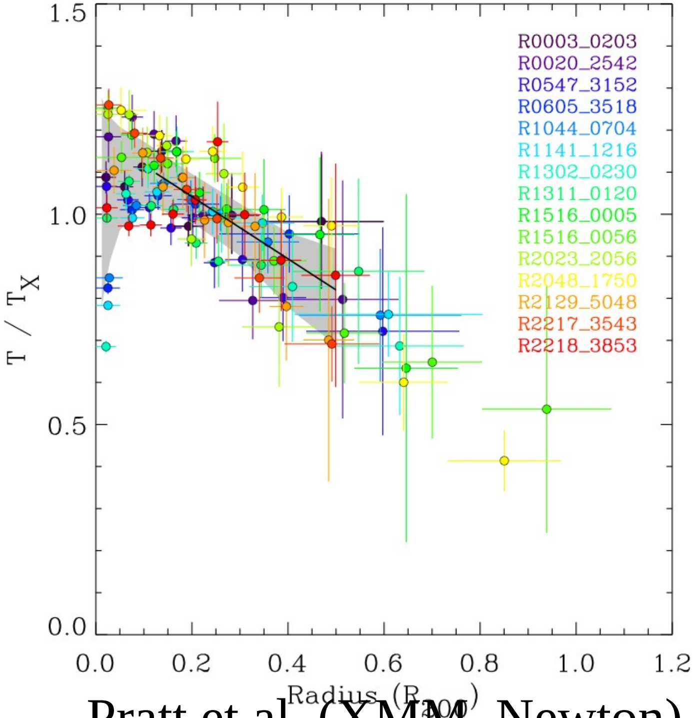
Part 2 – AGN feedback

Cluster temperature profiles - “universal” profile with a central cool-core in undisturbed systems

“Cooling flow problem”
What happens to the cooling gas?
(Fabian & Nulsen 1977)



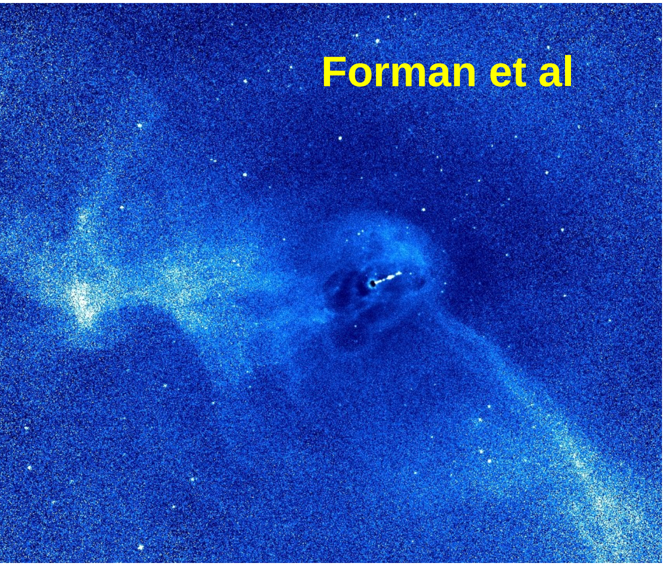
Vikhlinin et al. (Chandra)



Pratt et al. (XMM_Newton)

AGN outbursts in cool-core clusters reheat the gas

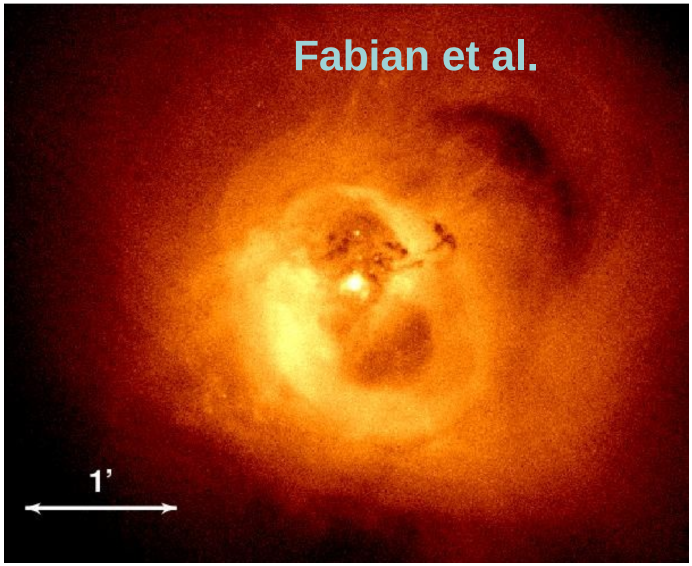
M87 Virgo cluster



Forman et al

1+ kpc
10^{57} ergs
10^{43} erg/s

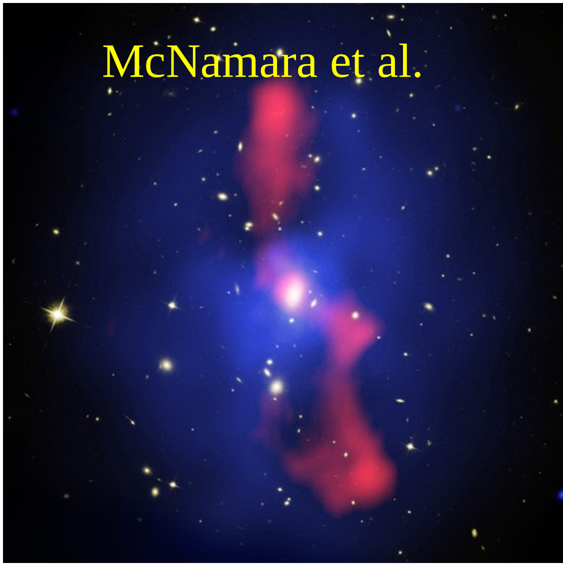
Perseus cluster



Fabian et al.

10+ kpc
10^{59} ergs
10^{45} erg/s

MS0735 cluster



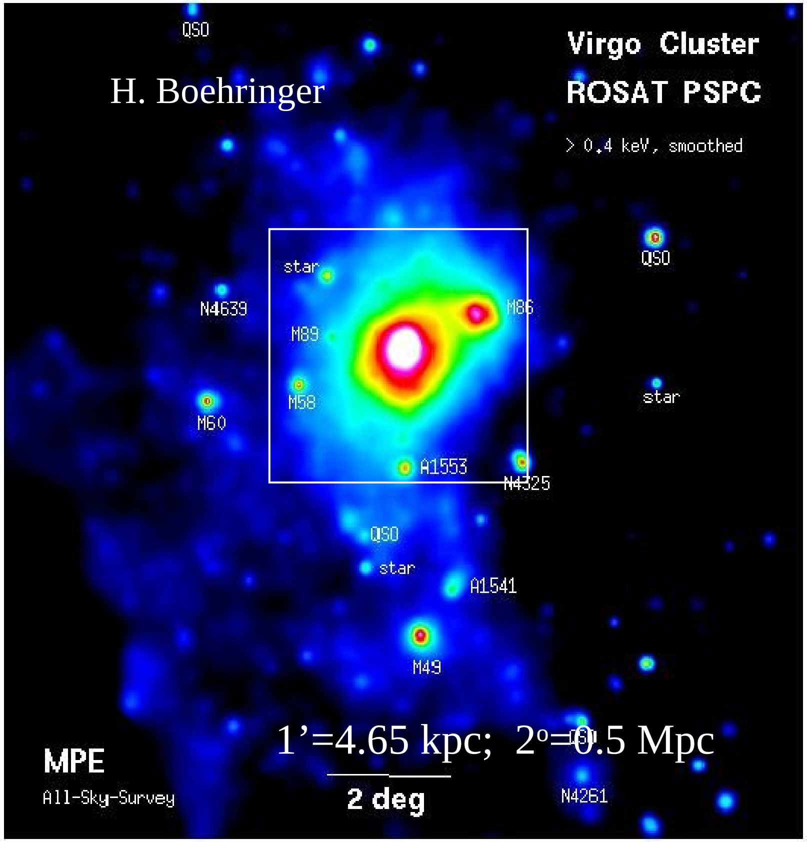
McNamara et al.

100 kpc
10^{62} ergs
10^{46} erg/s

Very powerful outflows, little radiation from the AGN

Churazov et al. 2005 MNRAS …switching from very bright to very dim
McNamara & Nulsen 2007 ARA&A , Fabian 2012 ARA&A

M87 - Virgo Cluster

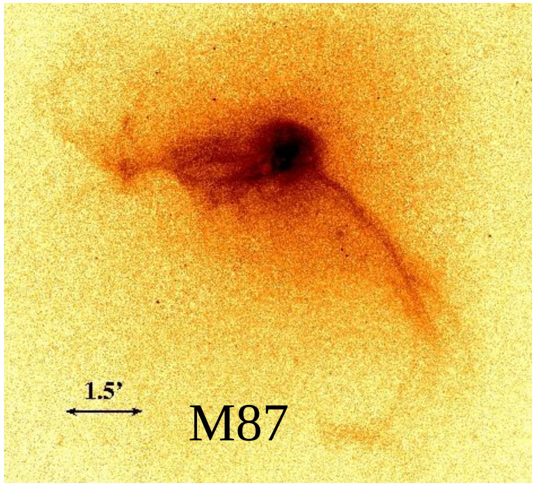


M87 is central dominant galaxy

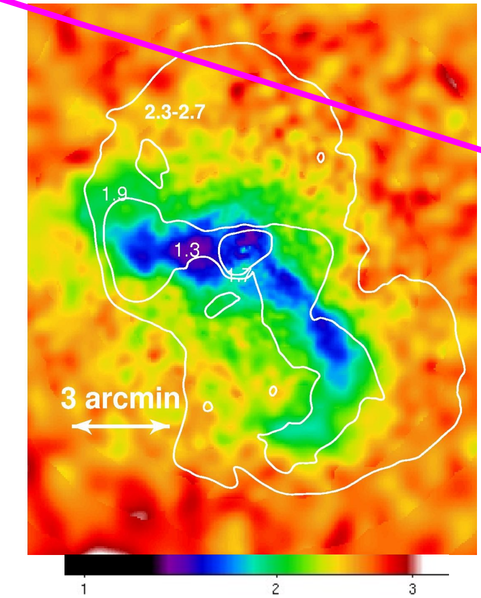
- M87 is 50 x more X-ray luminous than NGC4472 (optically brightest galaxy)
- M87 hosts $6 \times 10^{9} M_{sun}$ SMBH and jet
- Classic cooling flow ($24\ M_{sun}$/yr)
- Ideal system to study SMBH/gas interaction

Chandra-XMM-VLA View

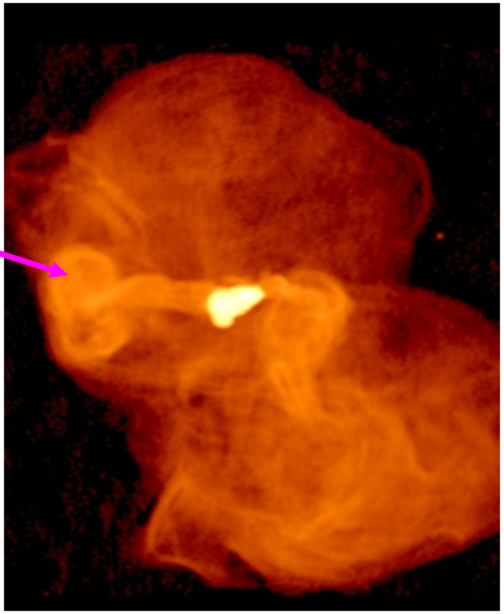
- Two X-ray “arms”
- X-ray (thermal gas) and radio (relativistic plasma) “related”
- Eastern arm - classic buoyant bubble with torus i.e., “mushroom cloud” (Churazov et al 2001)
  - XMM-Newton shows cool arms of uplifted ga (Belsole et al 2001; Molendi 2002)
  - **CLASSIC BUBBLE**
  - **With torus**



Chandra Forman et al

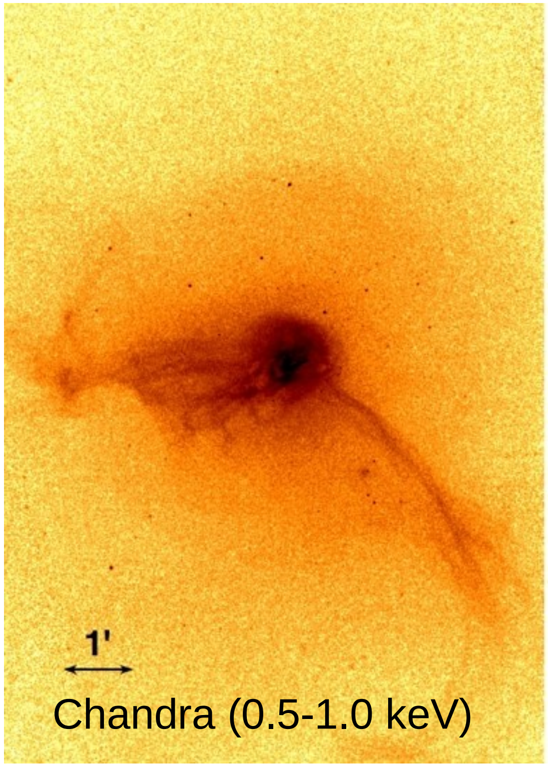


XMM Belsole et al;Molendi

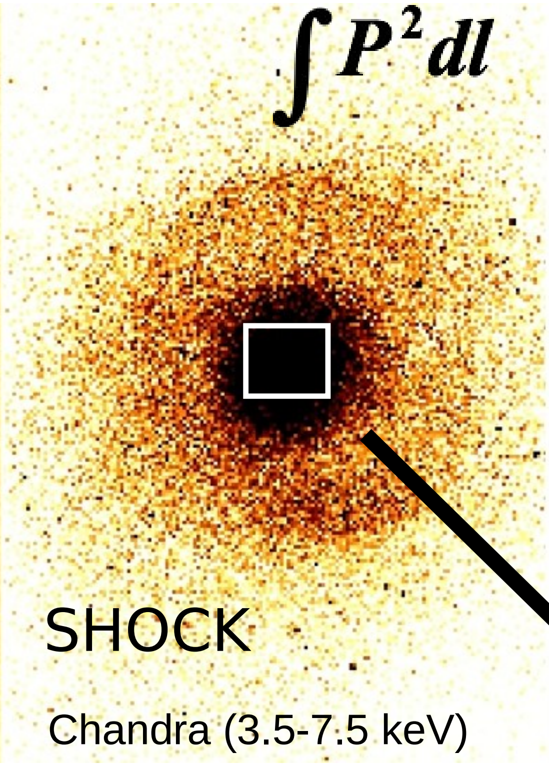


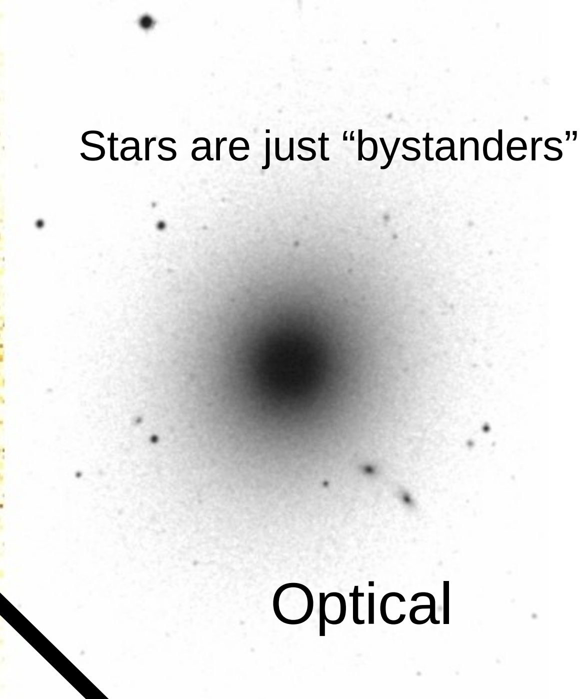
VLA Owen et al.

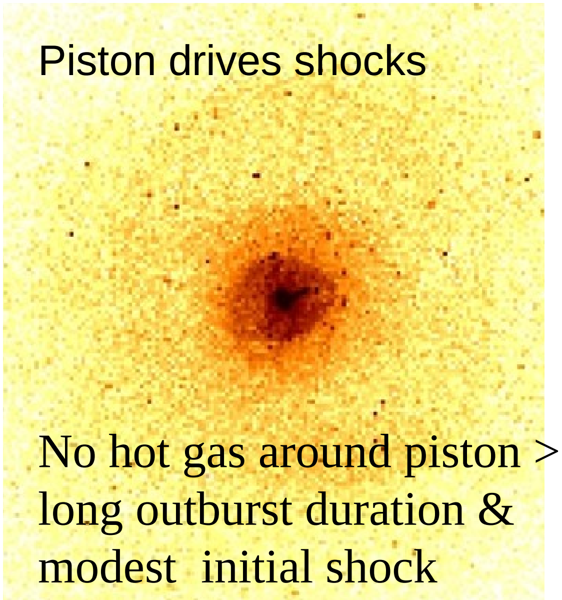
Classical Shock in M87



23 kpc (75 lyr)







Piston drives shocks

No hot gas around piston > long outburst duration & modest initial shock

- Black hole = 6.6×10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates “bubbles” of relativistic plasma
- Bubbles and shock heat surrounding gas
- Model to derive detailed 13 kpc shock properties

Forman et al 2005, 2007, 2012, 2015

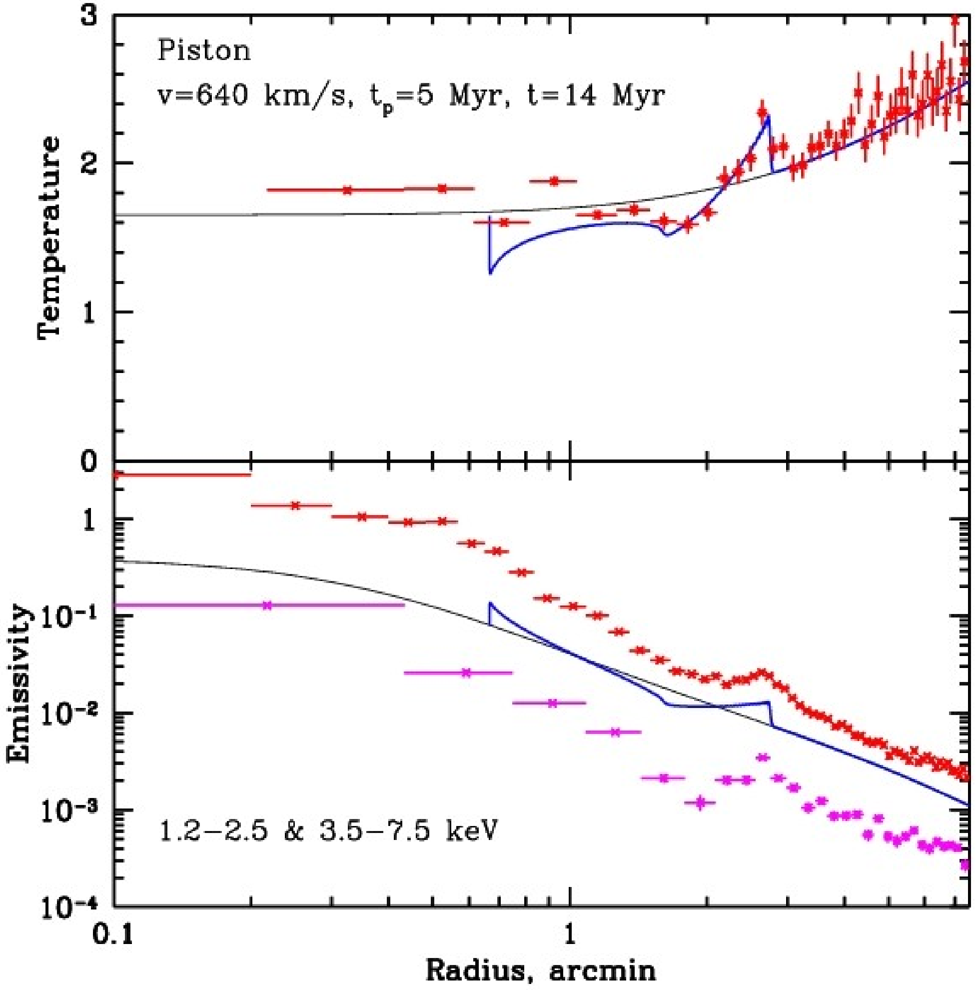
For M87 – Outburst energy and AGN duration measured directly from gas density and temperature

Series of models with varying initial outburst energies and different AGN durations (0.1, 1.1, 2.2, 3.1, 4.4, 6.2 Myrs)

Match to data

- E = 5.5 x 10 ^{57} ergs
- Determined by jumps
- AGN duration ~ 2 Myrs

Forman et al. 2015



M87 Outburst Model

Detect shock (X-ray) and driving piston (radio)

Classical (textbook) shock M=1.2 (temperature and density independently)

Outburst Model

Age ~ 11 - 12 Myr

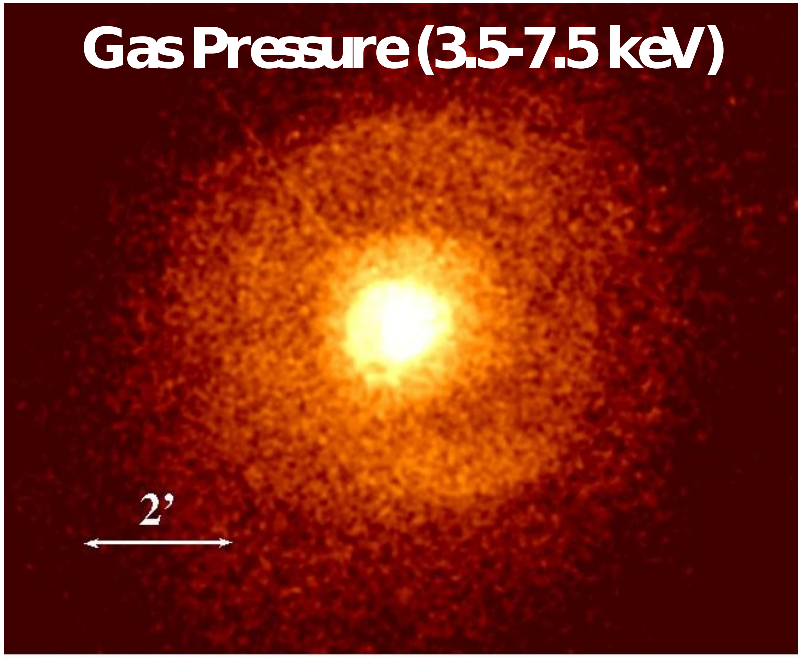
Energy ~ $5x10^{57}$ ergs

Bubbles ~65%

Shocked gas ~10%

(25% carried away by weak wave)

AGN outburst duration ~ 2 Myr



Forman et al 2005,2007, 2012, 2015

Outburst energy "balances" cooling (few 10^{43} erg/sec)

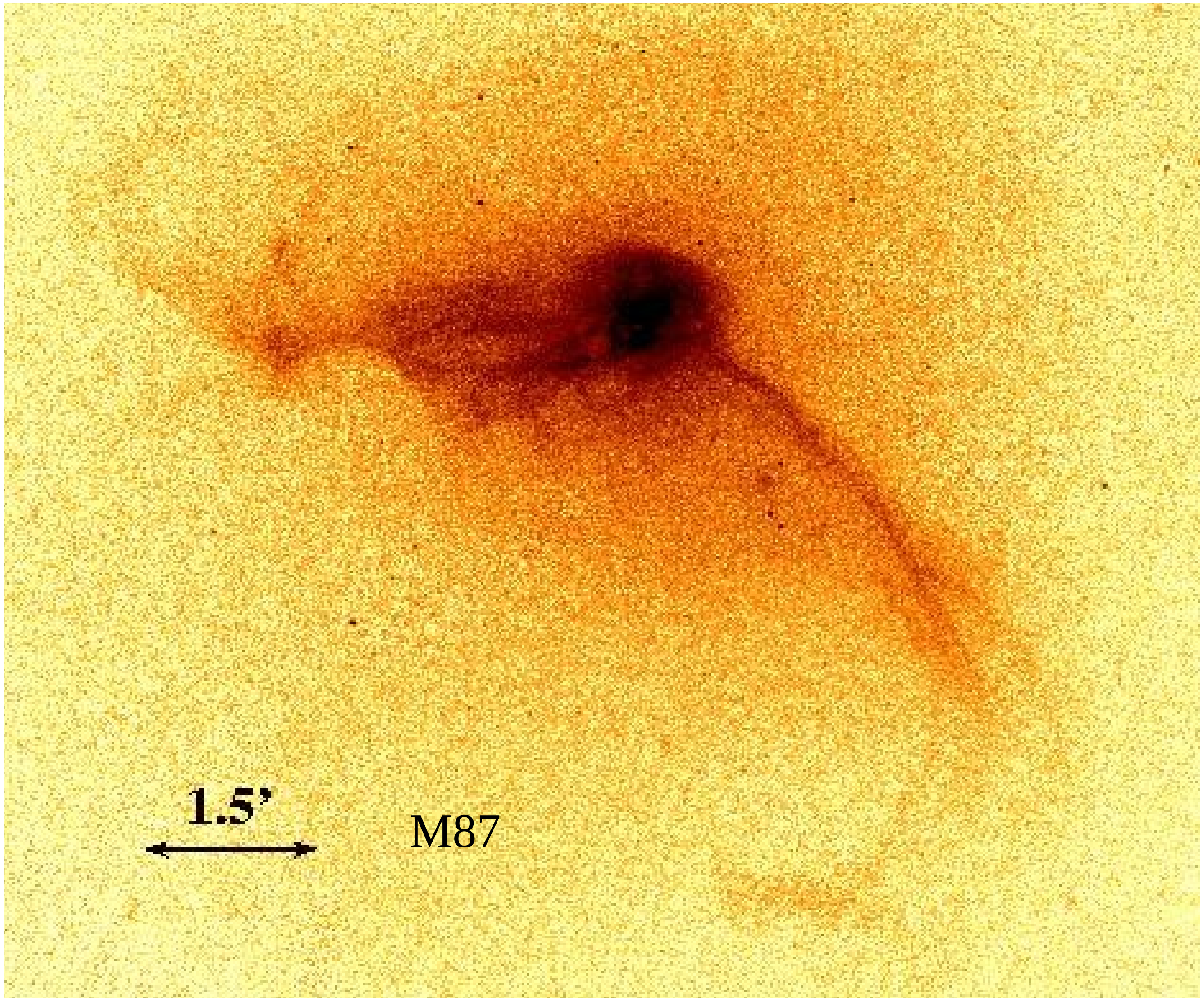
AGN outbursts -key to feedback in galaxy evolution, growth o SMBH

Pass along some advice from Riccardo Giacconi

Really look at the data

In preparing for set of lectures, Bill checks the Chandra archive for an image of M87 to replace the ROSAT image ----

Bill finds this – arms and bubbles galore! The PI of the observation was looking for LMXB’s and emission from globular clusters



Advances in X-ray and optical telescopes

3 inch diameter solar X-ray telescope mirrors

57 feet (with IUS) just fit into shuttle bay)

First imaging solar X-ray Telescope about the same diameter as Galileo’s 1610 telescope

380 years after Galileo, Hubble is **100 million** times more sensitive

In ~40 years X-ray telescope have comparable increase in sensitivity with launch of Chandra

At 16 years, Chandra is operating very well

The future - Athena approved by ESA for 2020‘s
X-ray Surveyor under study for the 2020’s

X-ray surveyor team at SAO, PSU, MIT, GSFC, MSFC, JHU, Stanford, Waterloo, Rutgers, NIST, Dartmouth

- 3 m aperture with high angular resolution

- 30 x Chandra ($A_{eff} = 2.3\ m^2$ at 1 keV)

-sub-arcsec imaging in the inner 8′ (diameter) FOV

-Piezo-electric material on back of thin glass shells shapes figure

-Useful FOV ~ 20′ (diameter); 4″ imaging at the edges

- Possible Science Instruments:
  - 5×5′ microcalorimeter with 1″ pixels

  - 22×22′ CMOS imager with 0.33″ pixels

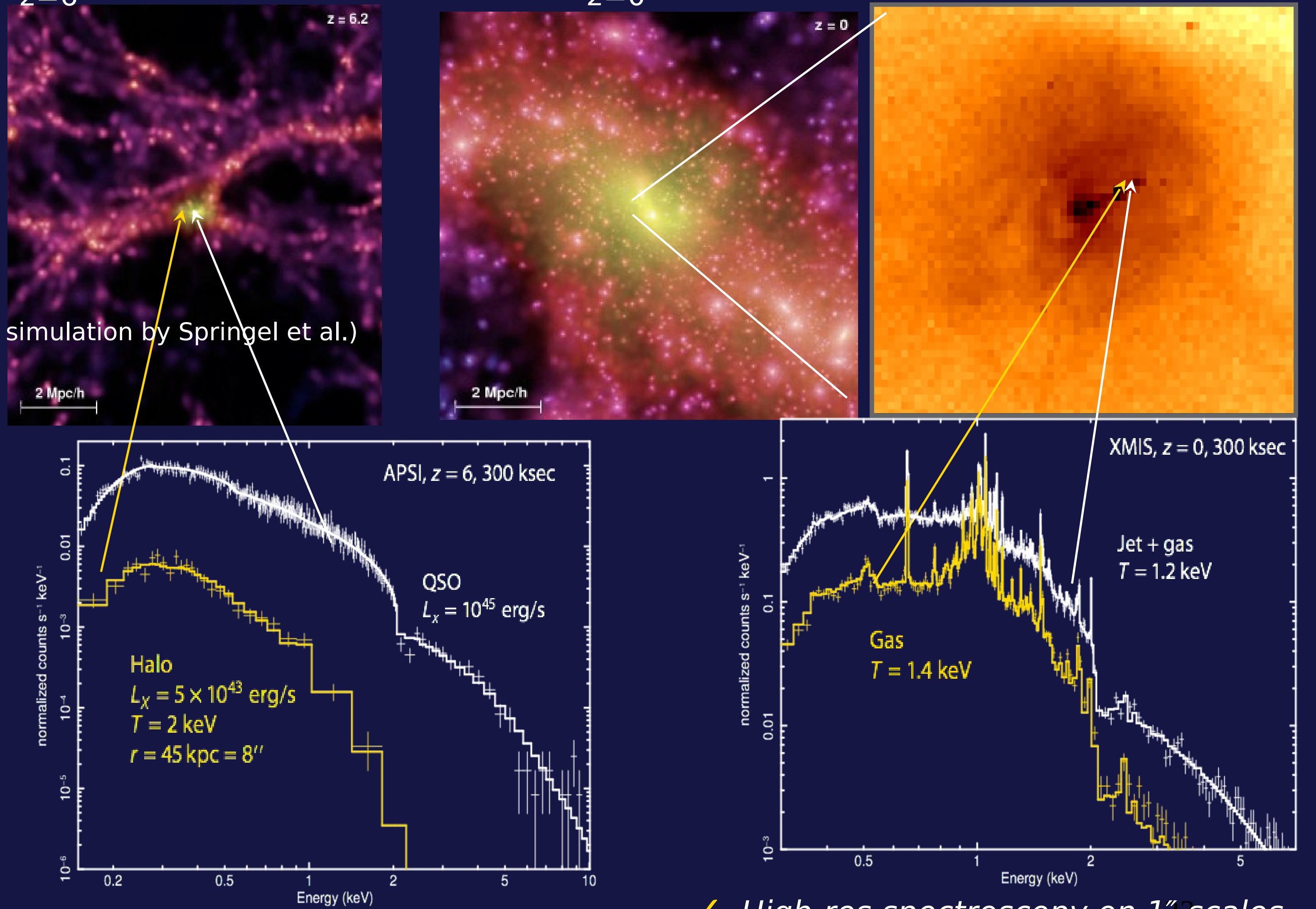
see Vikhlinin et al. 2011 ”High Resolution, High Throughput X-Ray Observatory with Adjustable Optics”

M87‘s youth - Growth of galaxy groups and 10^9 M☉ black holes from z ₌ 6 to the present

Sloan quasar at *z*=6

“nursing home” at *z*=0

M87, *Chandra*, 1″ pixels



(DM simulation by Springel et al.)

- ✓ *Sensitivity + angular resolution — detect and resolve quasar host halos and galaxy*
- ✓ *High-res spectroscopy on 1″ scales — feedback and physics in clusters, galaxies, SNRs*

Very dynamic processes in clusters of galaxies

AGN outbursts reheating cooling gas in the centers of “cool-core” clusters

Subcluster mergers growing clusters and heating the ICM

To understand the physical processes in clusters, we need X-ray plus multiwavelength observations (e.g. lensing, optical imaging and spectroscopy, radio maps of AGN jets/lobes and relics/halos) and simulations.

THANKS! And look at the data!