Clusters of Galaxies

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Outline

- Introduction
- Cluster masses, dark matter
- Evolution and dynamical state
- Distance determination
- Interaction of cluster components
- Magnetic fields, radio haloes, cooling flows

Clusters of Galaxies

- Largest bound structures
- Size ~ a few Mpc
- Mass ~ 10^{15} M_{sun}
- “Closed systems“
- Crossing time ~ Hubble time
- Observable out to large redshifts

→ Ideal tools for cosmology

Some cosmological parameters

Ω_m = matter density (in units of the critical density)

Ω_{baryon} = baryon density (in units of the critical density)

Ω_Λ = contribution to the total mass-energy density associated with cosmological constant

(in units of the critical density)

$$\Omega_m = \Omega_{baryon} + \Omega_{dark}$$

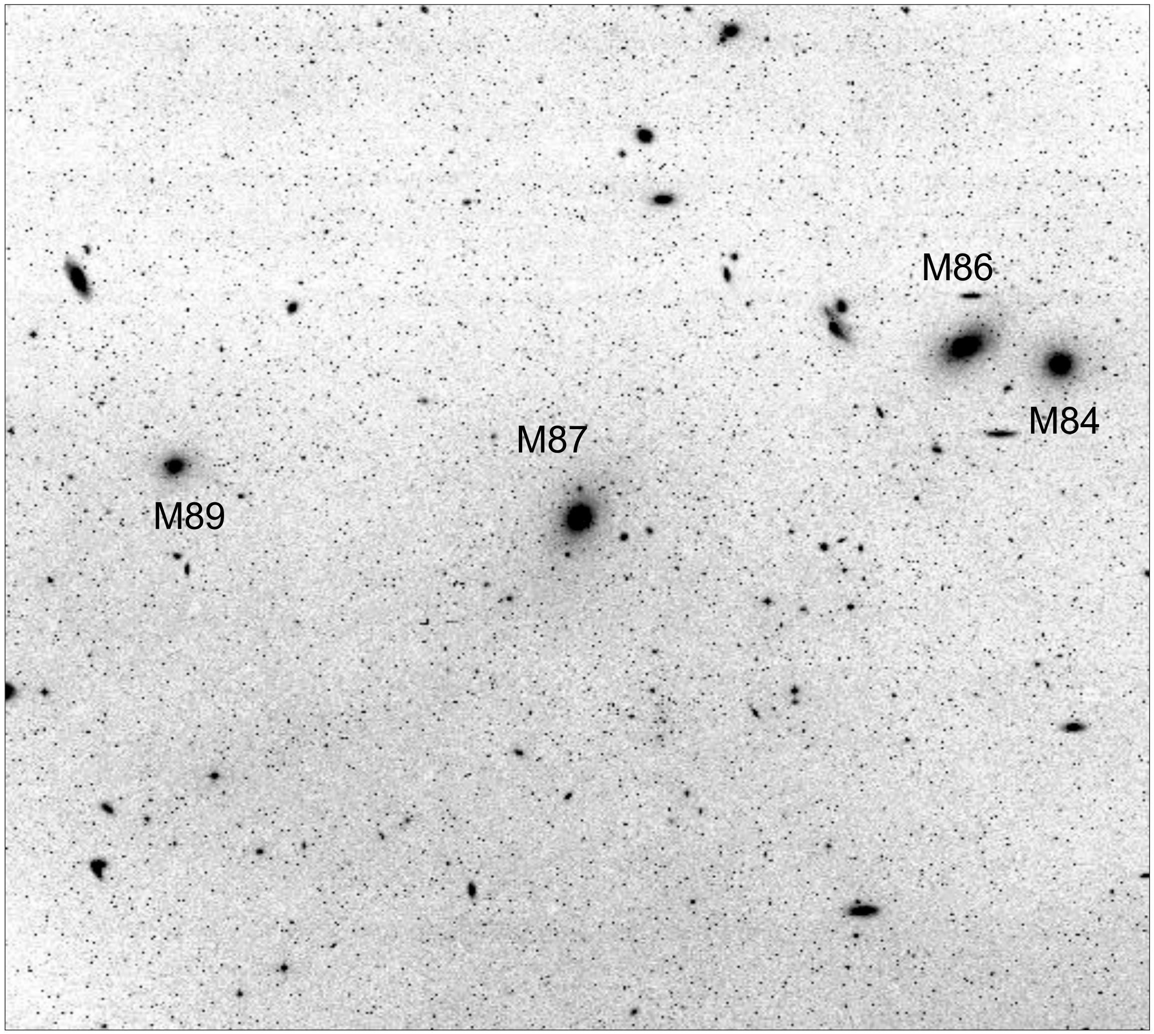
$$\Omega_{tot} = \Omega_m + \Omega_\Lambda$$

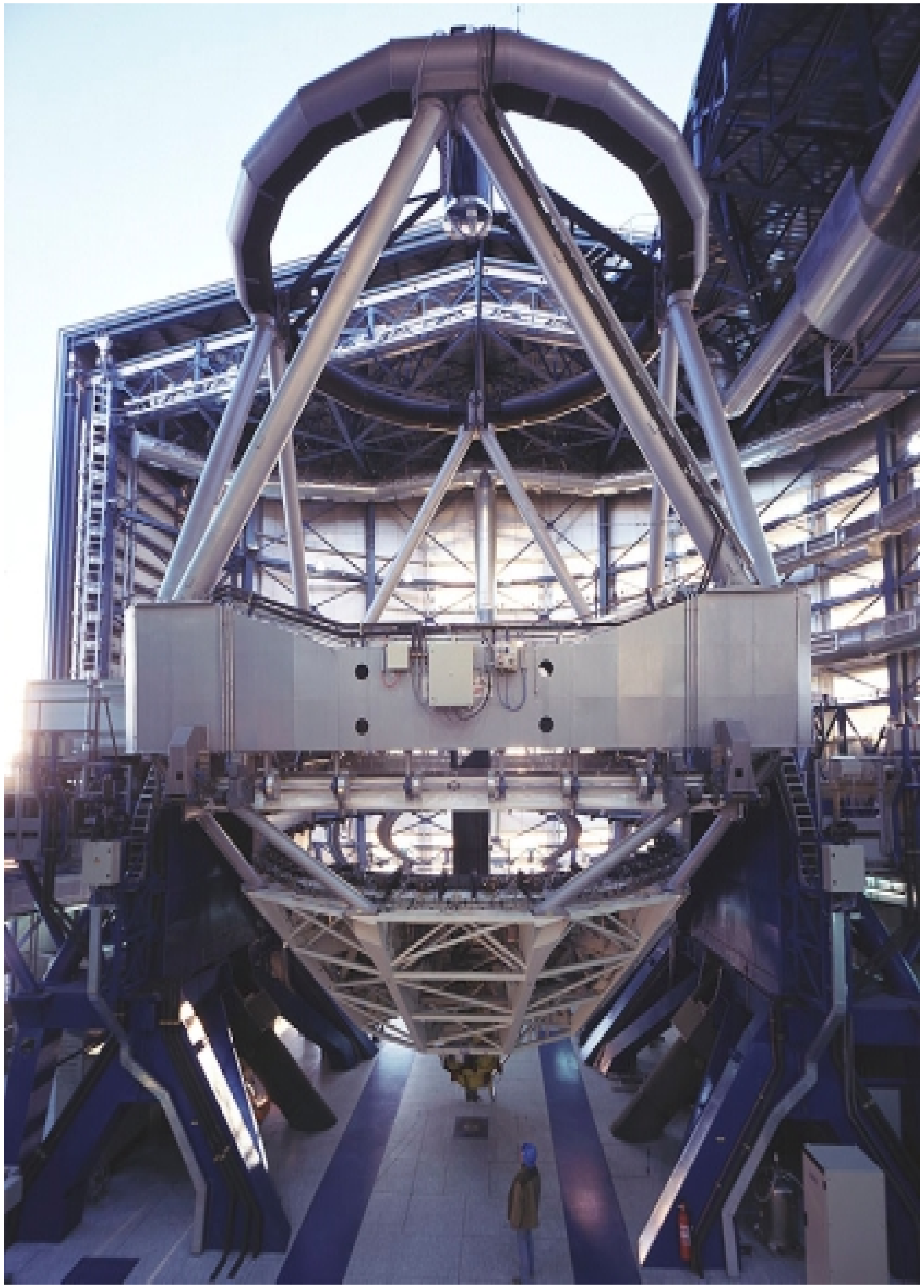
H_0 = Hubble constant (proportionality factor between expansion velocity and distance)

Cluster components

- Galaxies
  - A few hundreds to thousands
  - Velocity dispersion ~ 1000 km/s
  - Excess of elliptical galaxies

Virgo Cluster





Very Large Telescope

- 4 Telescopes
- 8.2-m mirrors (22 tons)
- Active optics
- Adaptive optics
- Interferometer (VLTI)

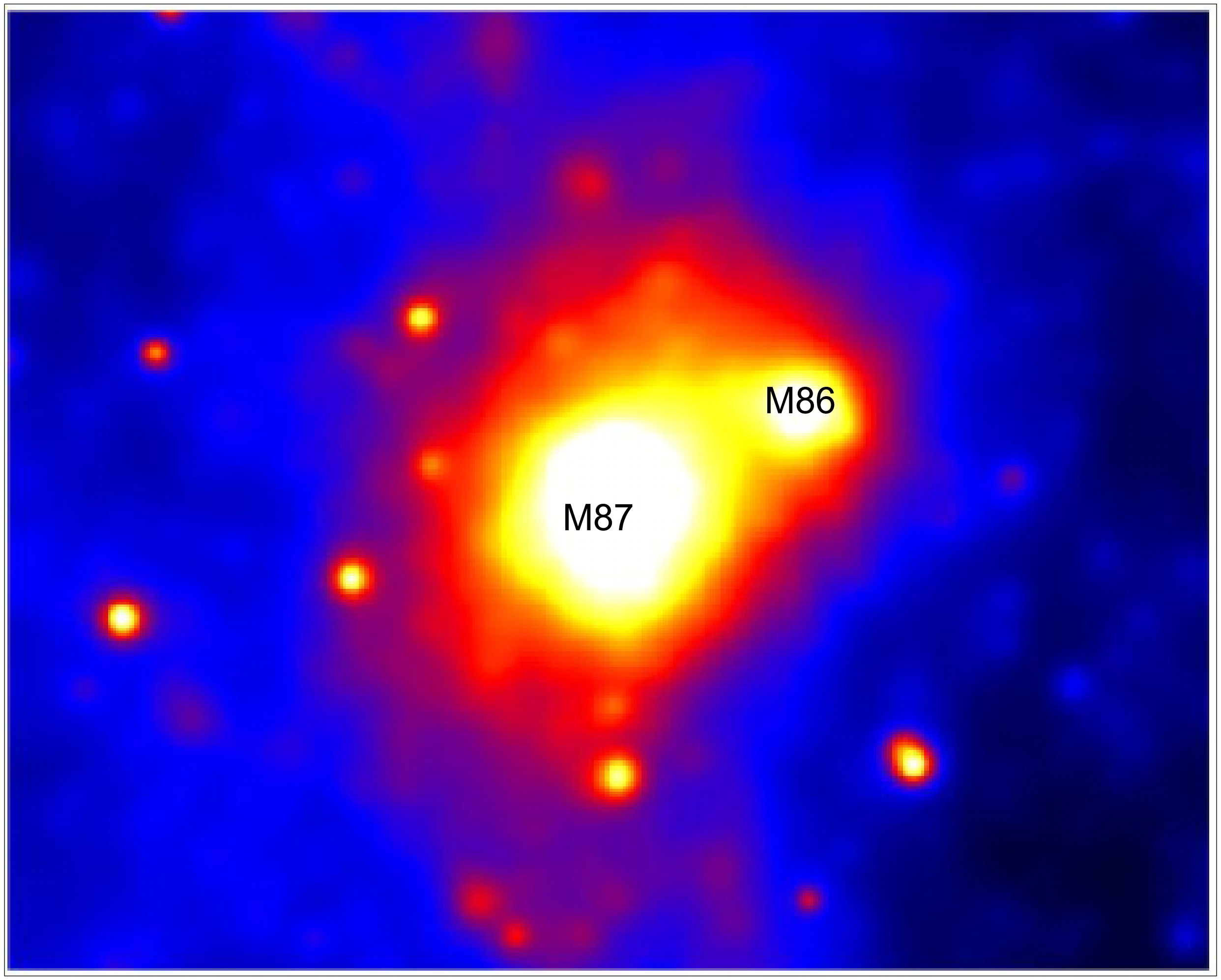
Cluster Components

- Galaxies
- Intra-cluster gas
  - density ~ 10^{-2} – 10^{-4} cm^{-3}
  - temperature ~ 10^{7}-10^{8} K (1-10keV)
  - metallicity ~ 0.2-0.4 solar
  - fully ionised
  - thermal bremsstrahlung

    → X-ray emission (~ density^2)

    luminosity ~ 10^{43-45} erg/s

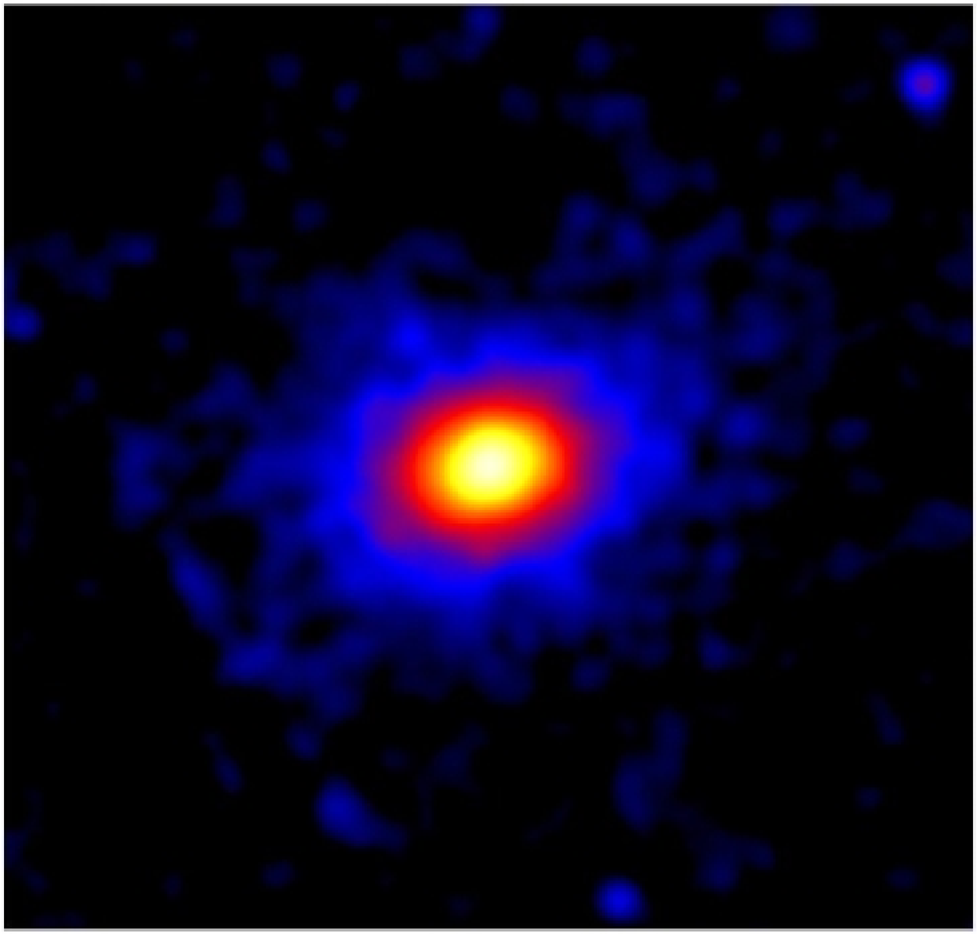
Virgo Cluster in X-rays



Schindler et al. `99

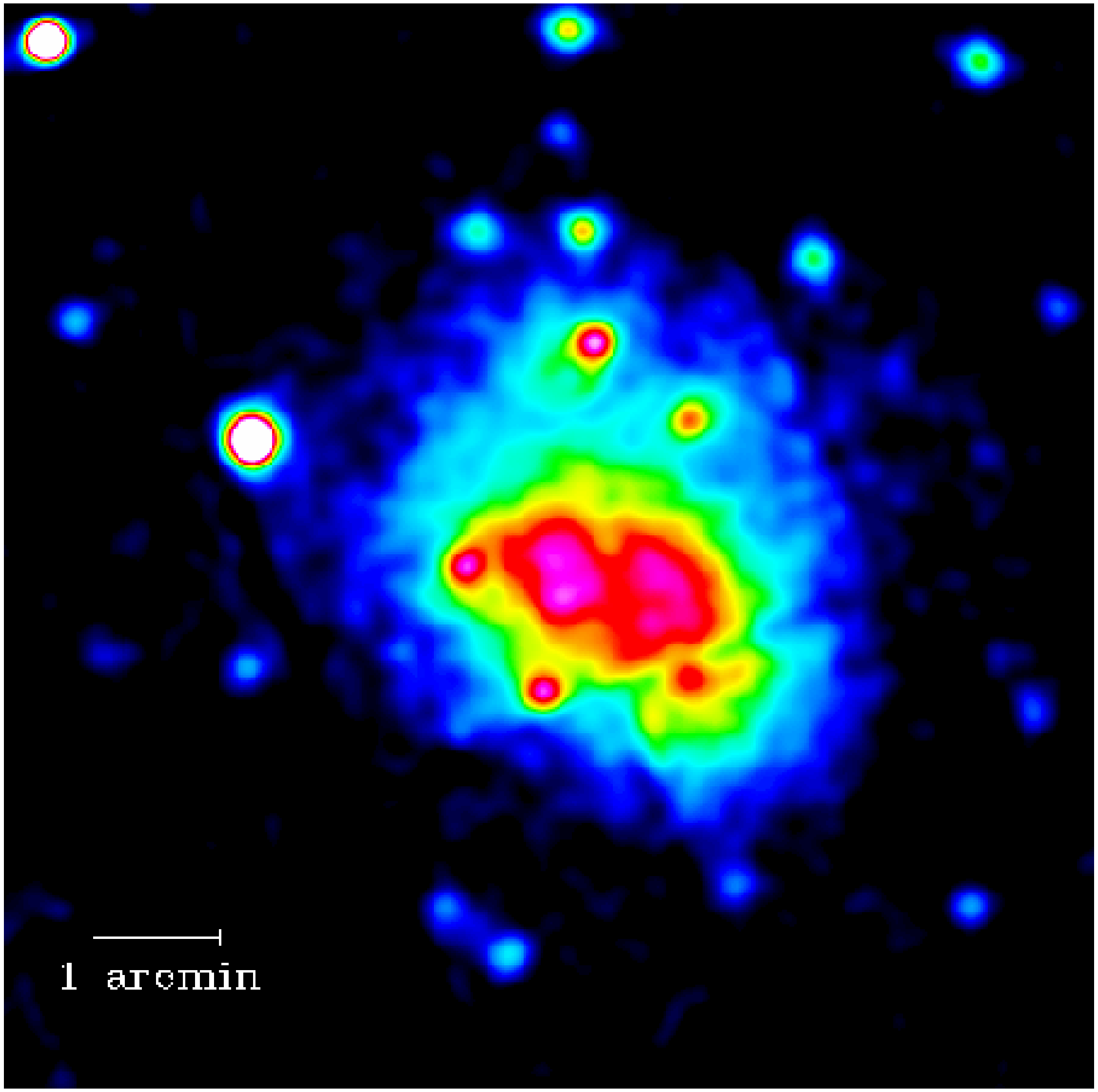
RBS797 (z = 0.35, $T = 7.7^{+1.2}_{-1.0}$ keV)

CHANDRA (0.5 – 7 keV)



Schindler et al. 2001

CL0939+4713 (XMM)

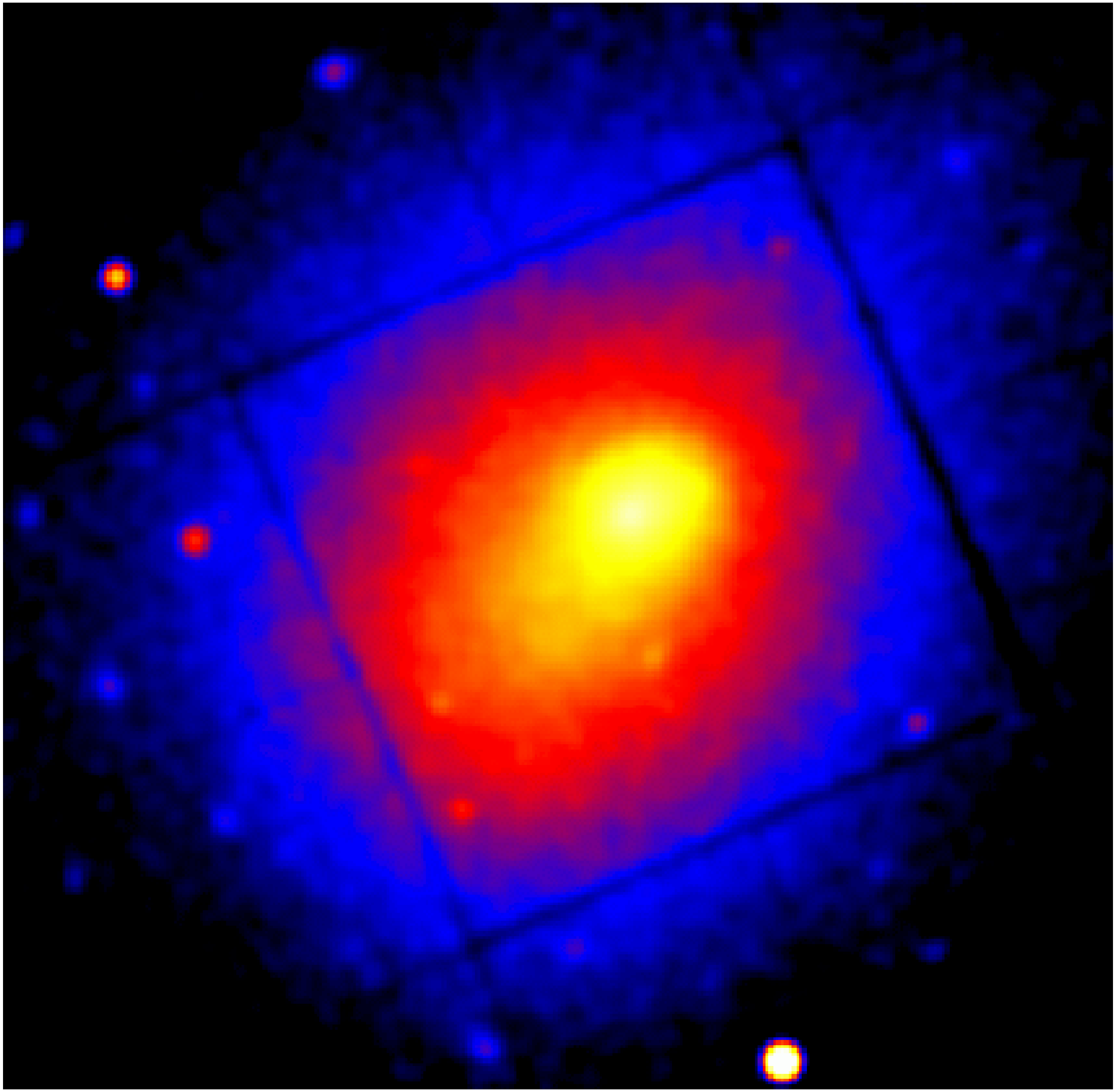


distant cluster

z = 0.41

consisting of two
merging subclusters

De Filippis, Schindler,
Castillo-Morales 2003



A3558 -
the centre of the Shapley Supercluster

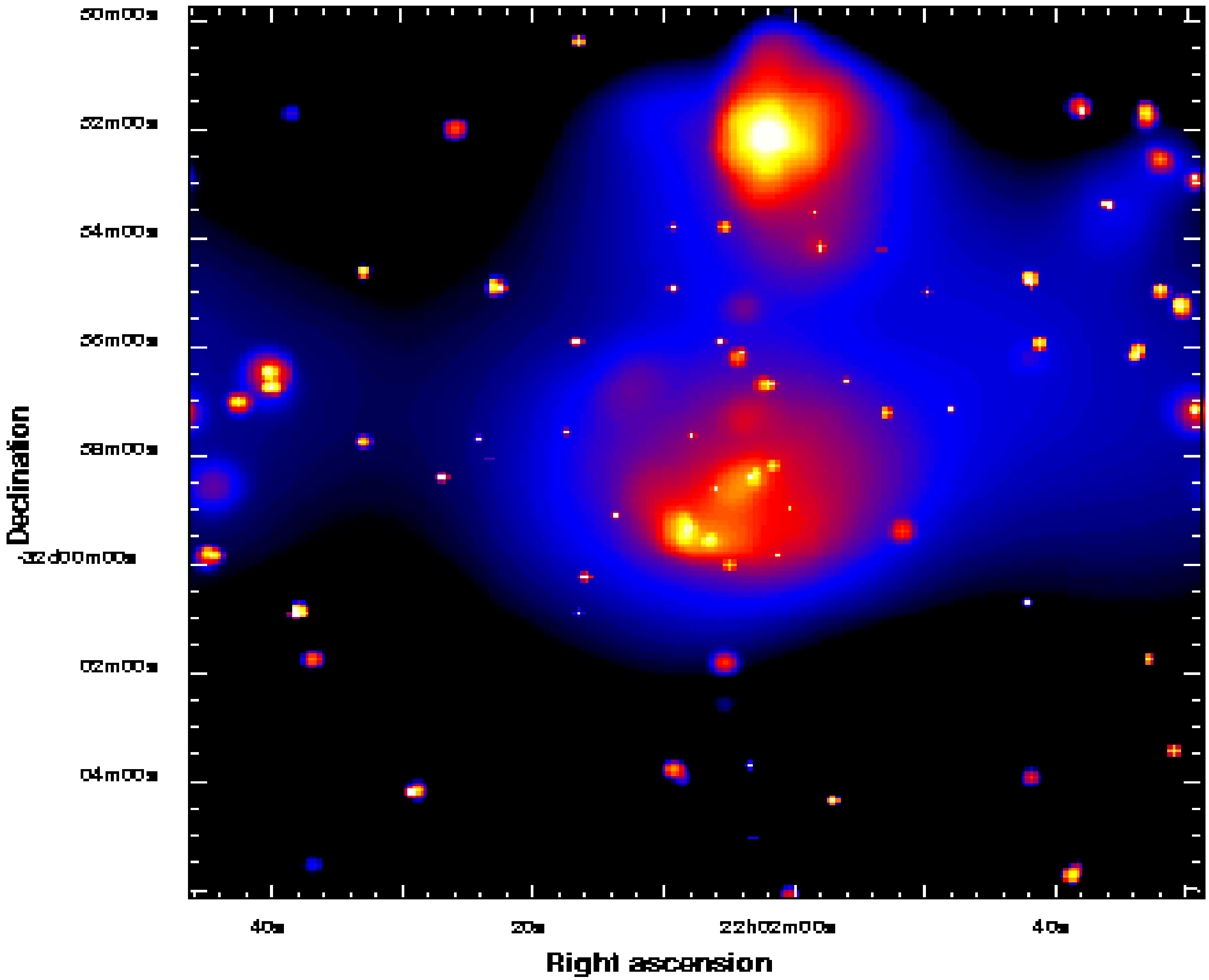
XMM
(0.3-10keV)

z = 0.048
T = 5keV
m=0.3solar

Sukonthachat et al., in prep.

Galaxy Groups

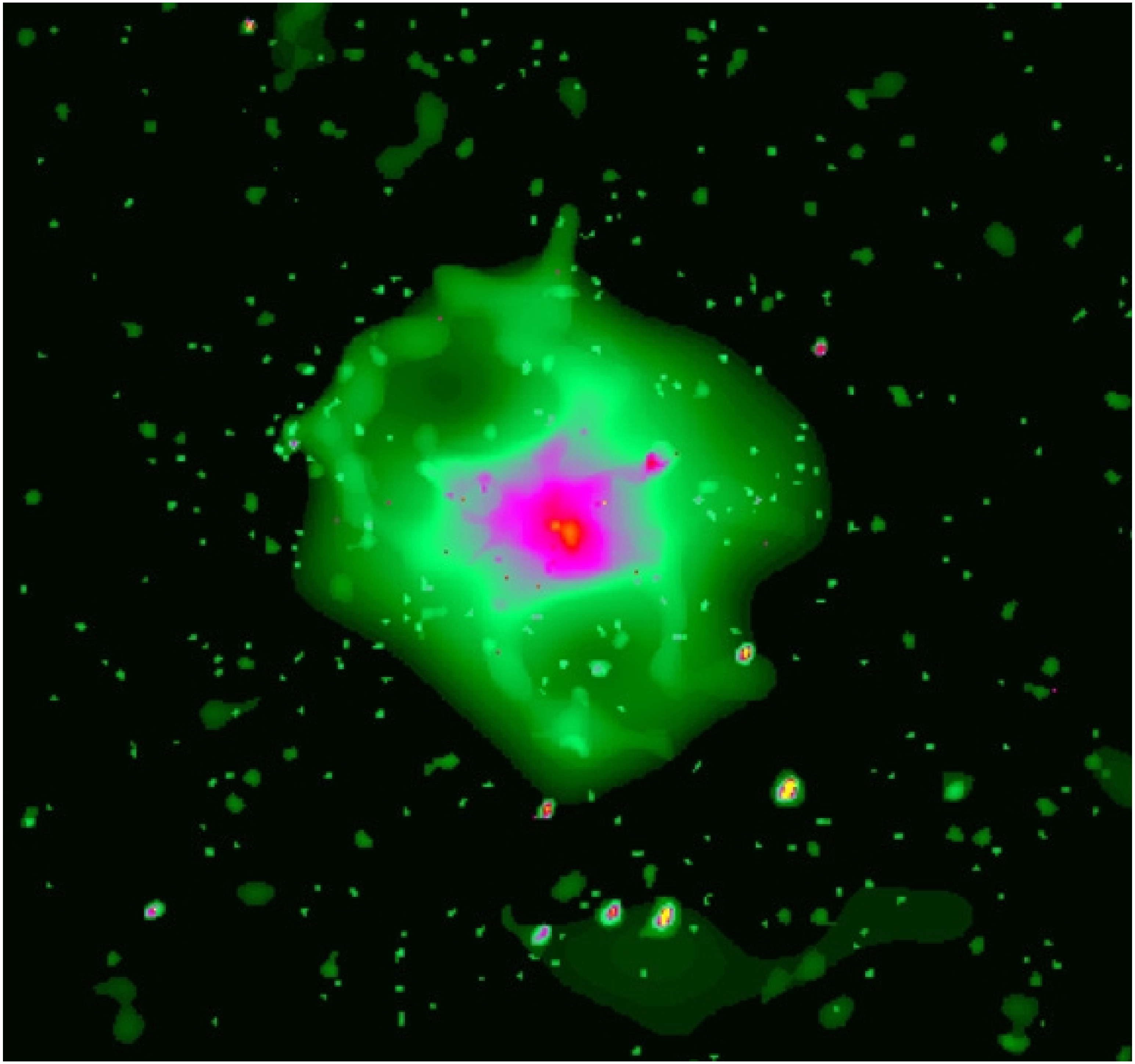
HCG90 (CHANDRA)



Longo,
Paolillo,
De Filippis
(in prep.)

HCG62

CHANDRA



X-ray satellites

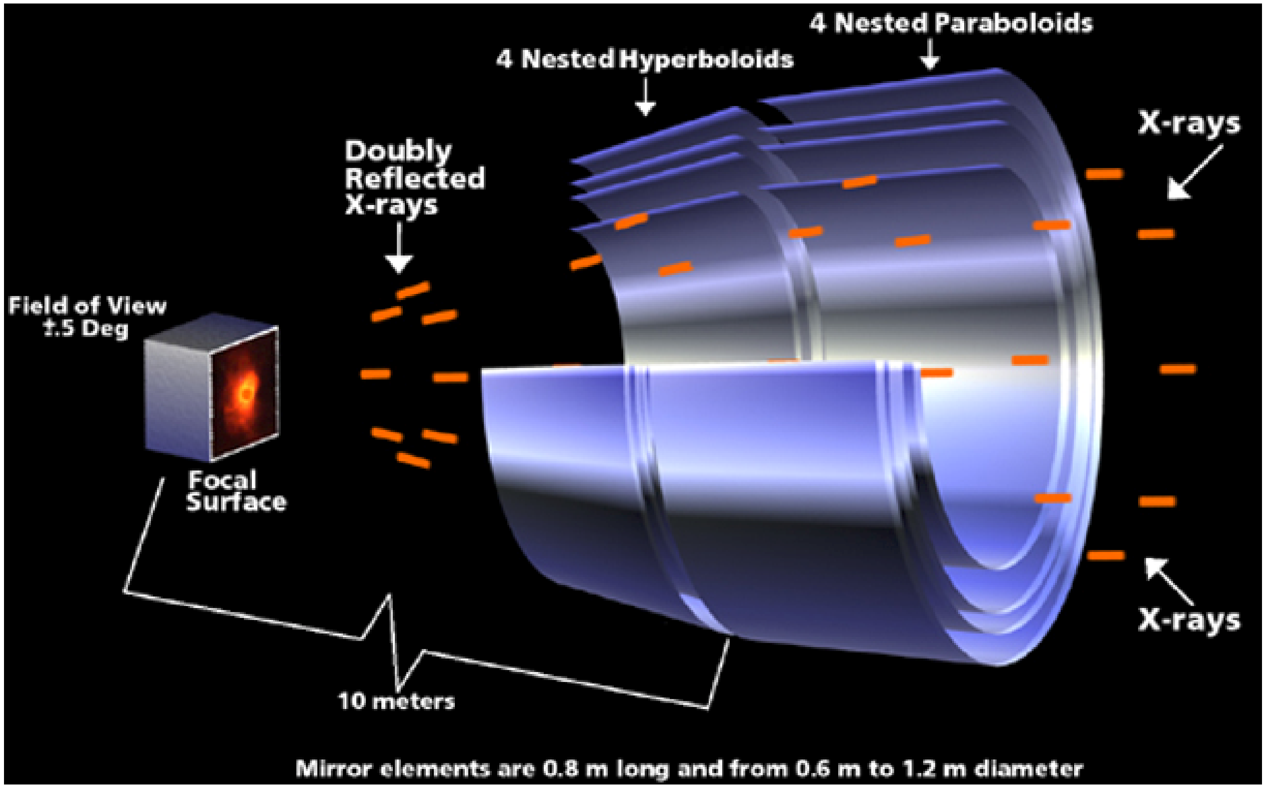
XMM

- ESA
- large collecting area

CHANDRA

- NASA
- high spatial resolution

Röntgenteleskop

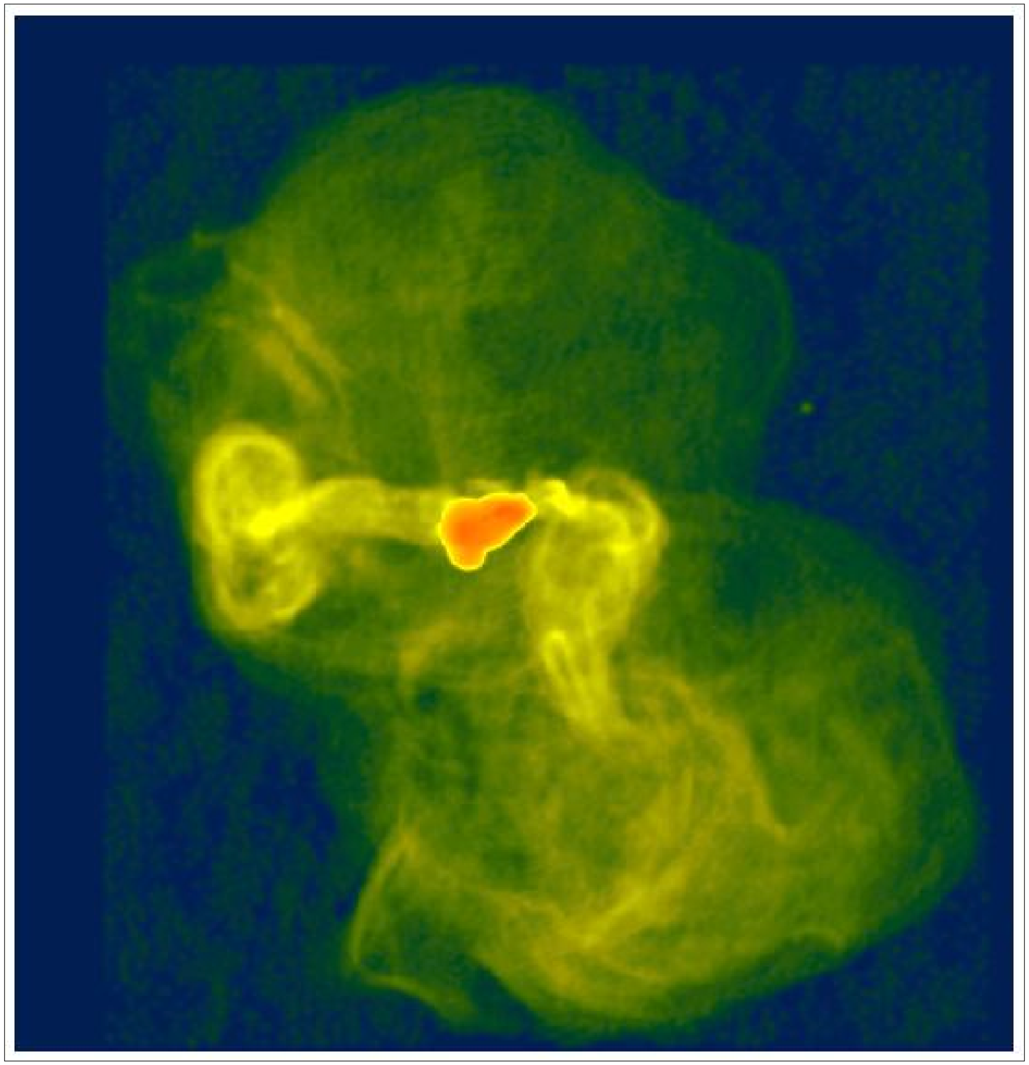


- Infall at small angles (< 1°)
- Reflection at paraboloid and hyperboloid
- Several nested mirror shells

Cluster Components

- Galaxies
- Intra-cluster gas
- Relativistic particles
  - radio synchrotron emission
    → magnetic field ~ 10^{-6} G
  - accelerated in active galaxies
    or in shock from cluster mergers

Radio image of M87



Centre of the Virgo cluster

VLA

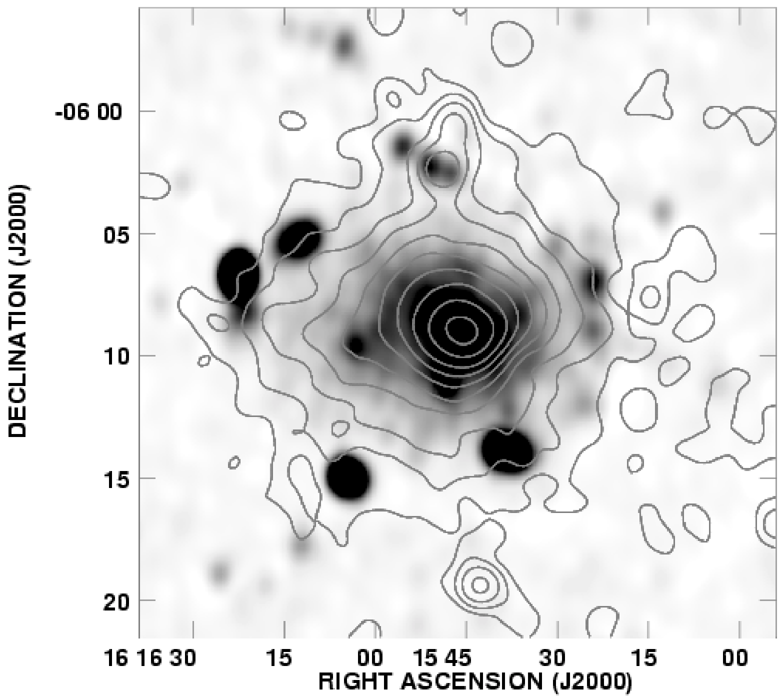
Owen et al. 2000

Radio emission has been found in many galaxies clusters

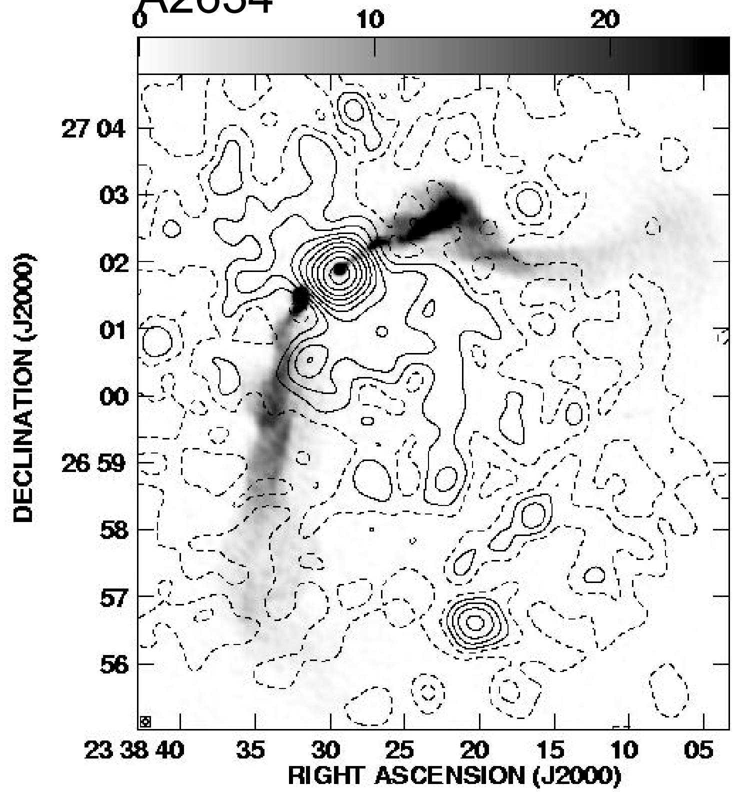
Diffuse emission
(Radio haloes, relics)

Emission associated with galaxies

A2163 Feretti et al. 2001



A2634



Radiotelescope

Very
Large
Array

Interferometry

	Mass fraction	Observable in
Galaxies	3 – 5 %	Optical
Intra-cluster gas	15 – 20 %	X-rays
Relativistic particles	-	Radio
Dark matter	Rest	-

Mass Determination

Three independent methods:

1. X-ray method
2. Gravitational lensing
3. Galaxy velocities

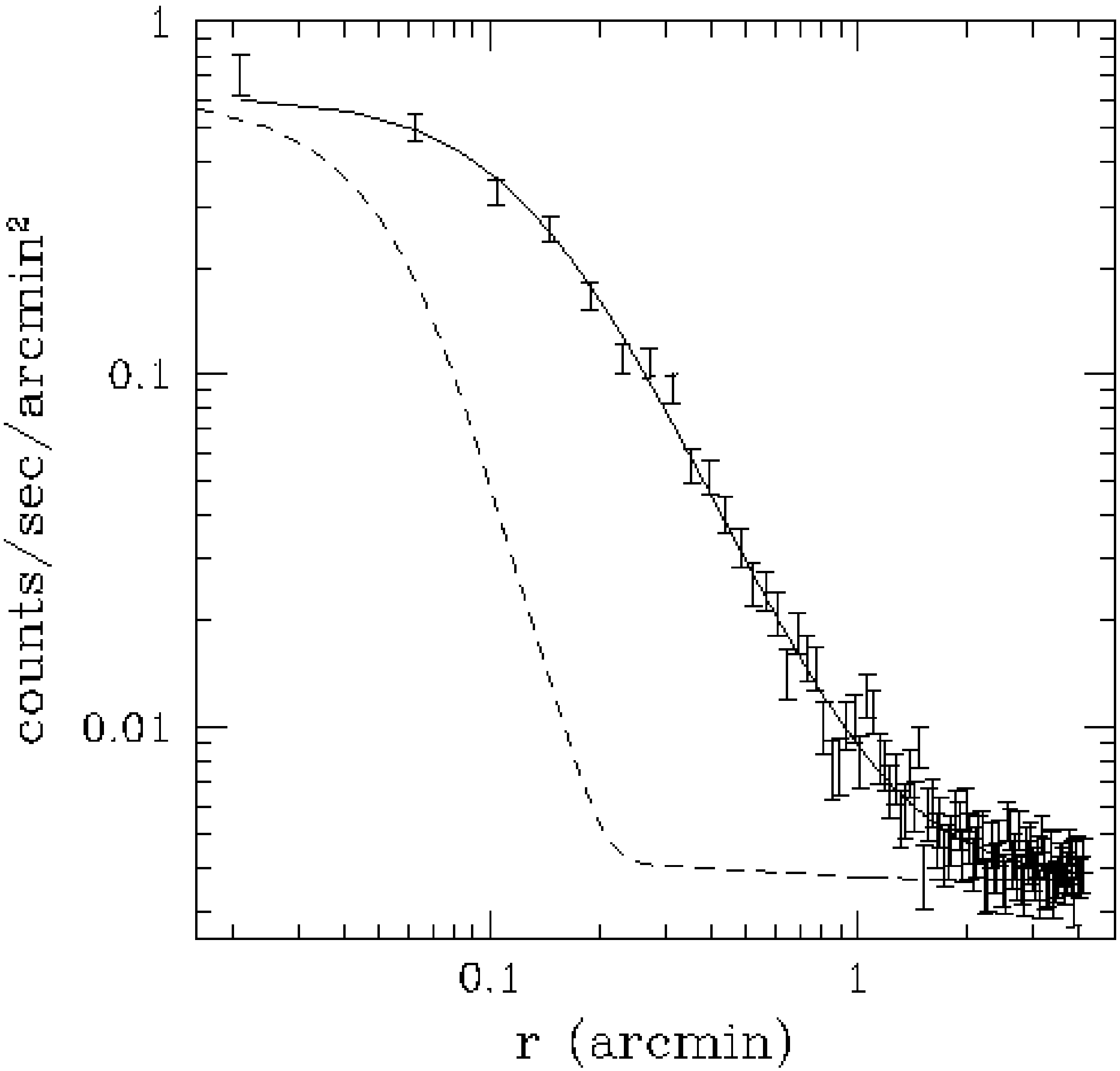
Mass Determination with X-ray Observations

Gas is used as tracer for potential

- spherical symmetry
- hydrostatic equilibrium

$$M(r) \propto T\left(\frac{d\ln\rho}{d\ln r}+\frac{d\ln T}{d\ln r}\right)$$

X-ray profile



Fit with

β model

Deprojection

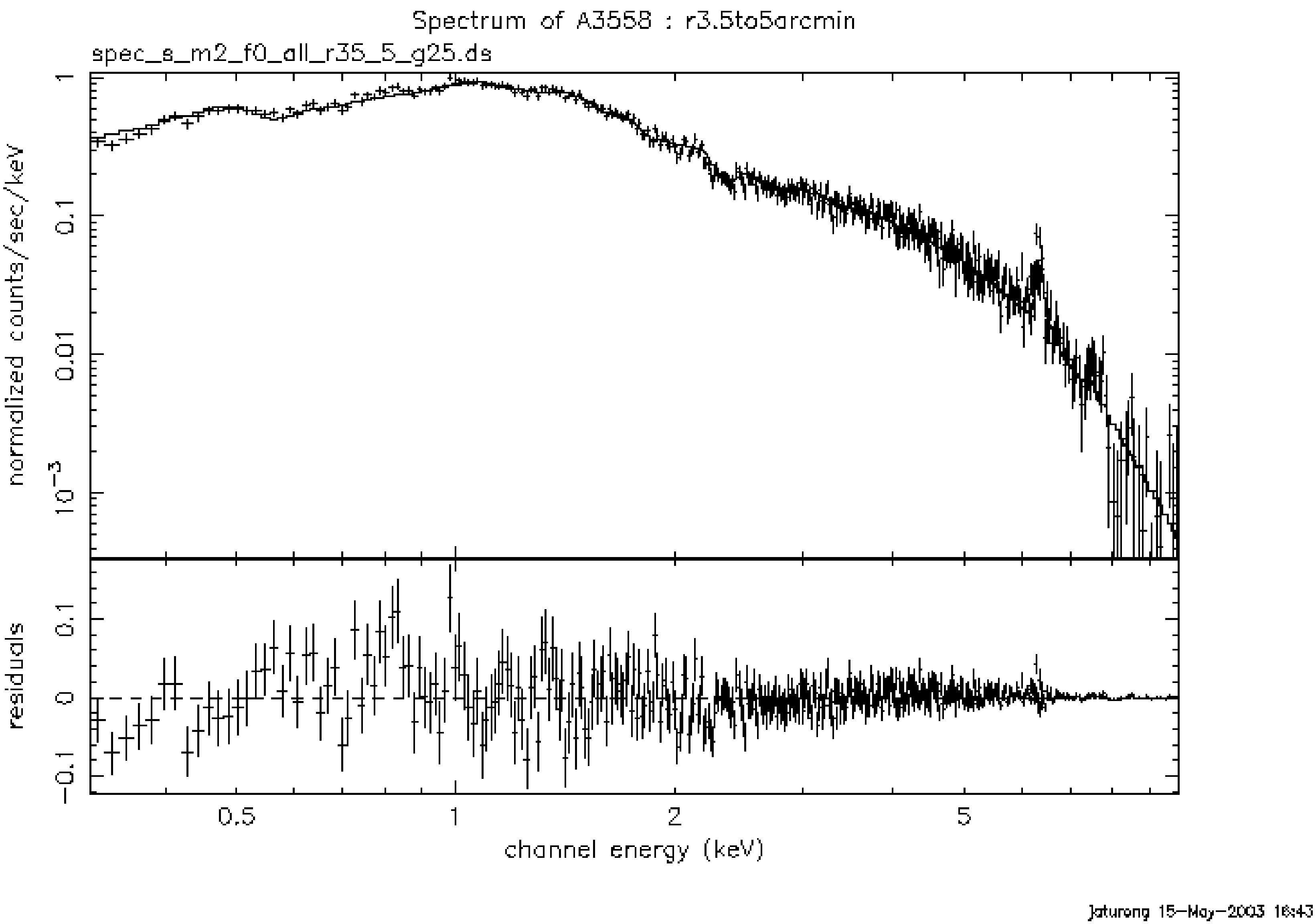
gas density (3D)

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2}$$

surface brightness (projected)

$$S(r) = S_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta+1/2}$$

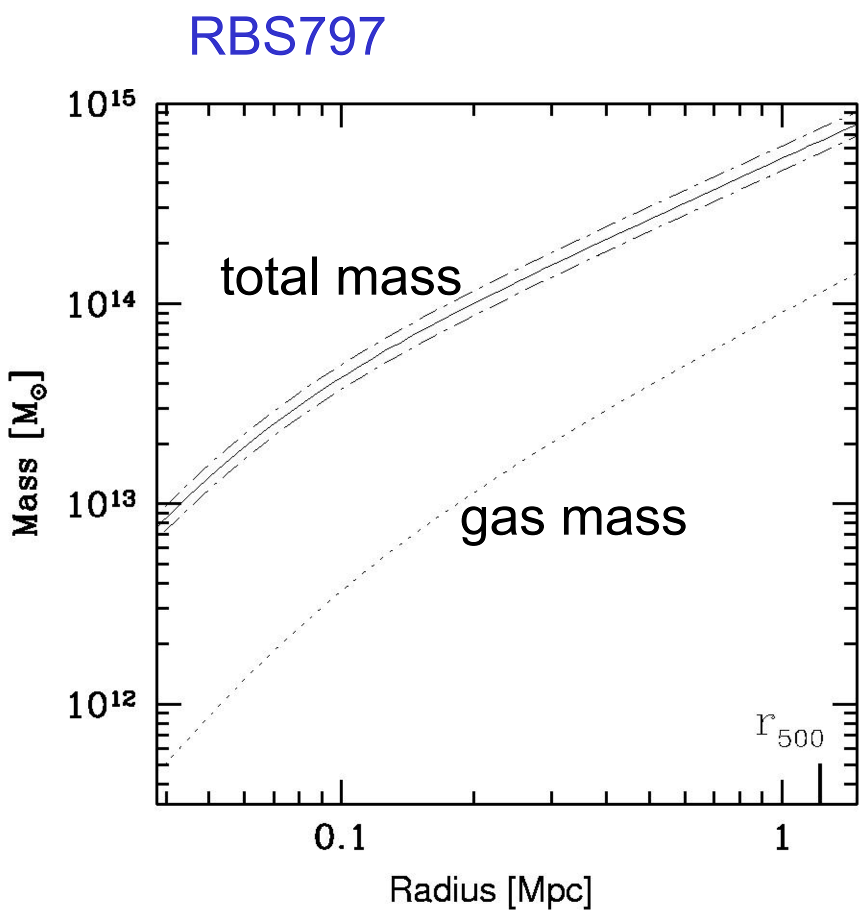
XMM spectrum of A3558



needed:

- good spatial resolution (Chandra)
- high sensitivity (XMM)
- spatially resolved spectroscopy (both)

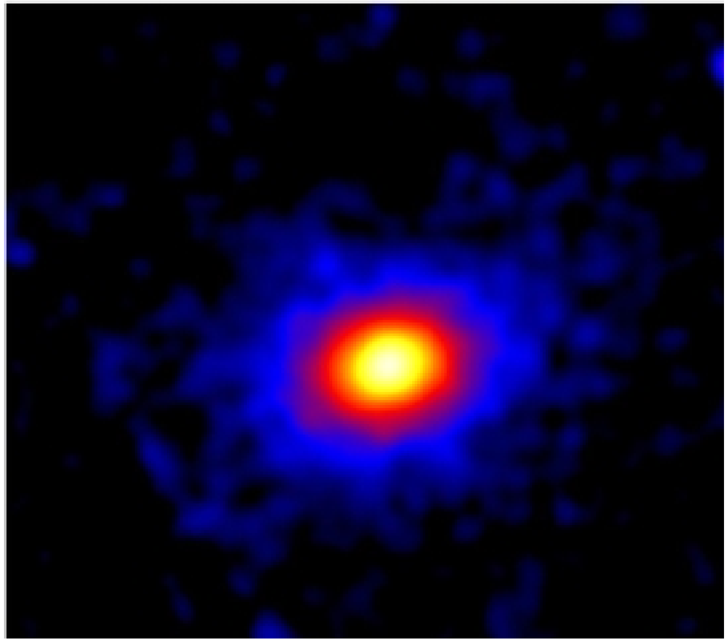
Mass Determination with X-rays



Integrated profiles of

- total mass
- gas mass
- gas mass fraction

Schindler et al. ´01



Mass Determination

Three independent methods:

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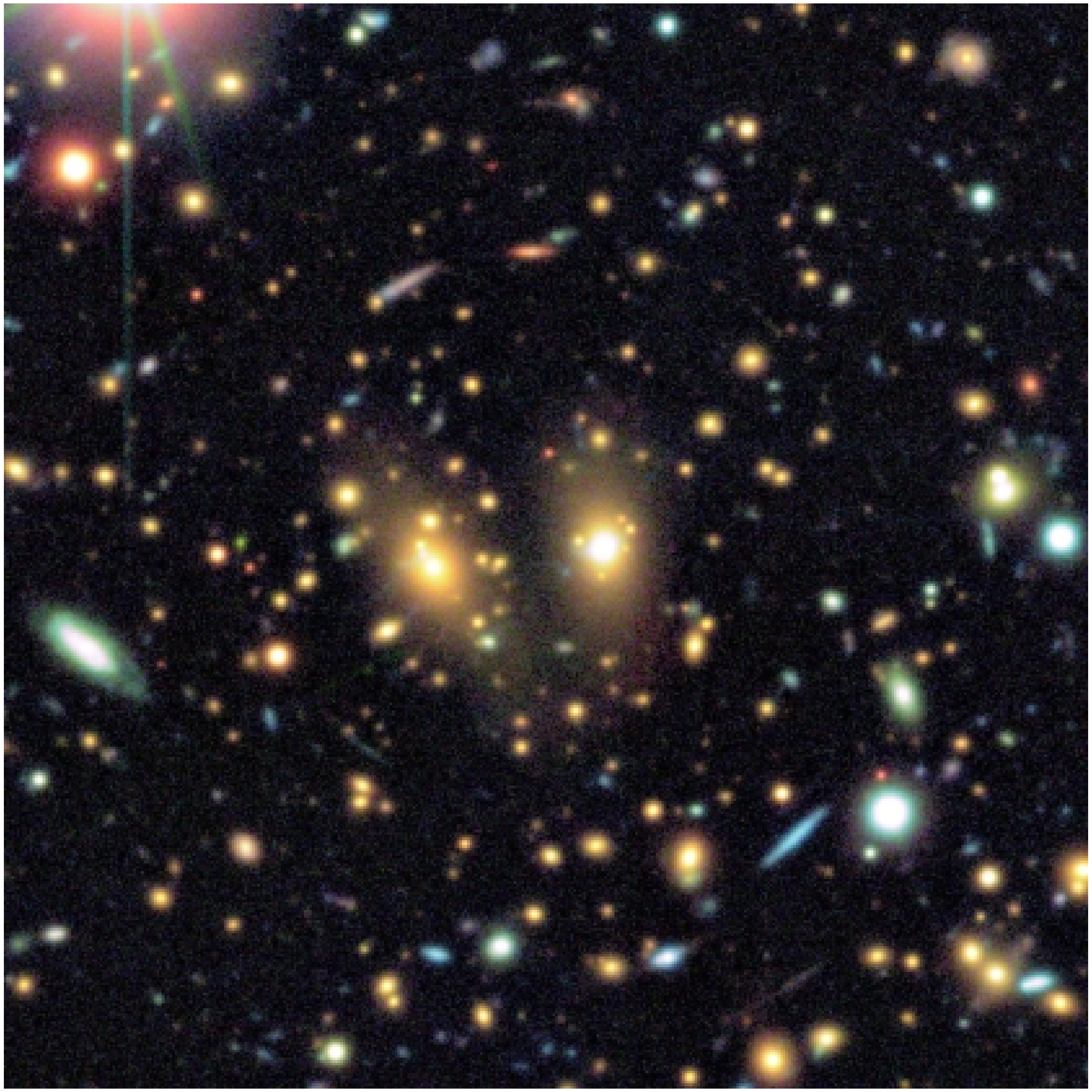
Gravitational lensing



- Strong lensing (giant arcs)
- Weak lensing (statistical evaluation of elongation of many galaxies)

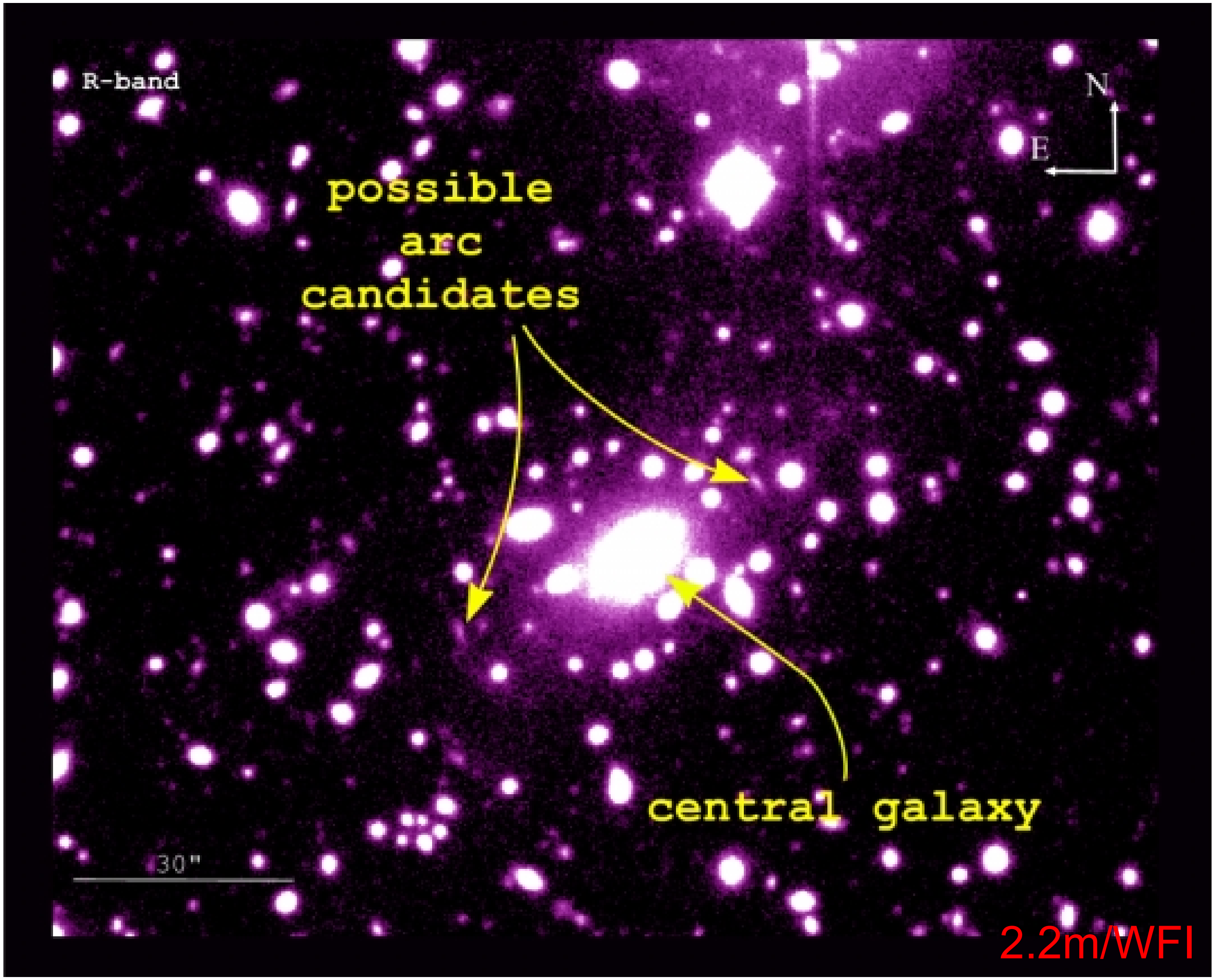
RXJ1347 (VLT)   Miralles, Erben, Schindler, Schneider, in prep.

A1689

HST

Arc search programme at ESO telescopes

Search in the most luminous X-ray clusters



2.2m/WFI

Kausch et al., in prep.

Mass Determination

Three independent methods:

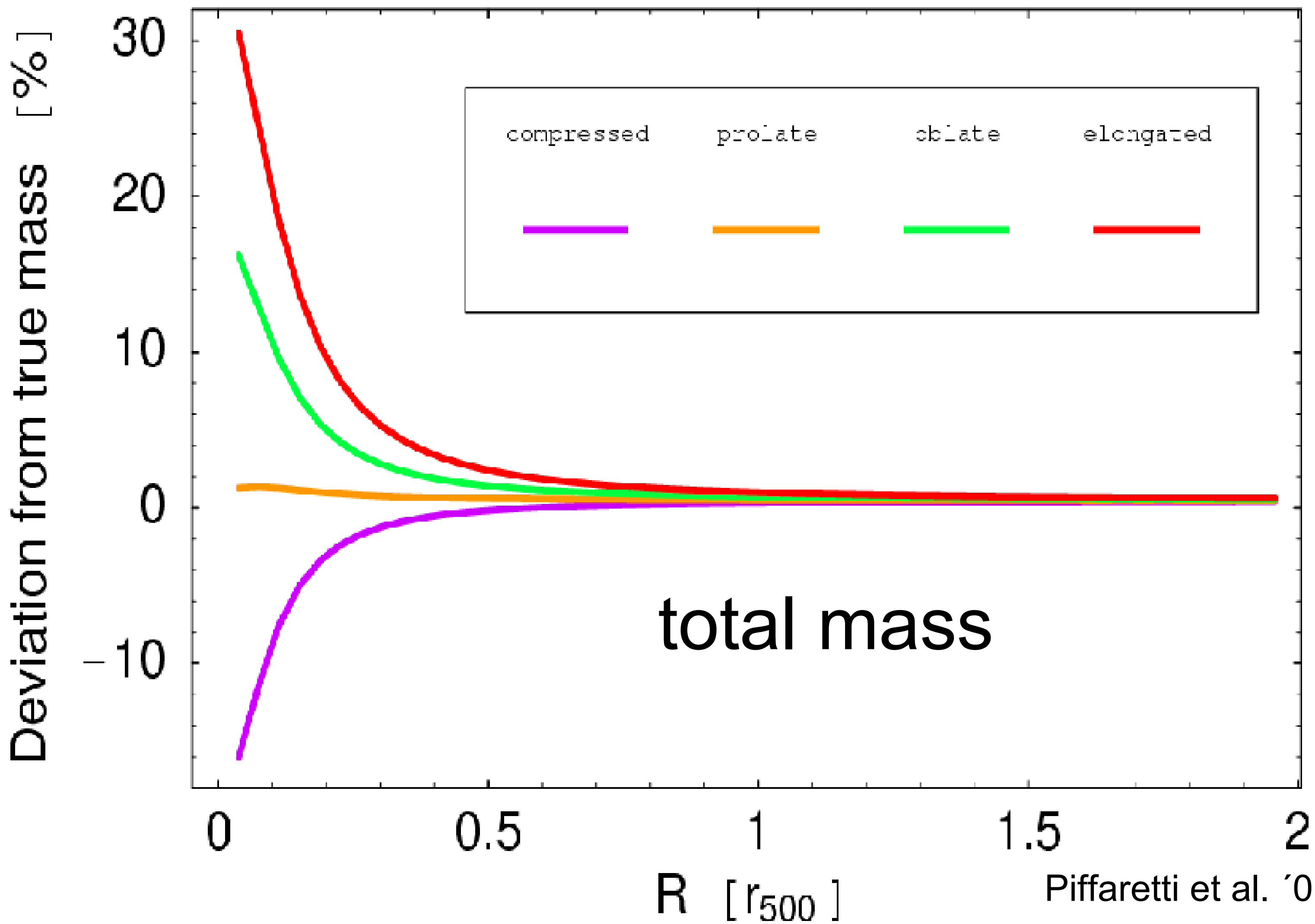
1. X-ray method
2. Gravitational lensing
3. Galaxy velocities

$$M_X \approx M_{vel} \le M_{weak\ lens.} \le M_{strong\ lens.}$$

How good is the X-ray method?

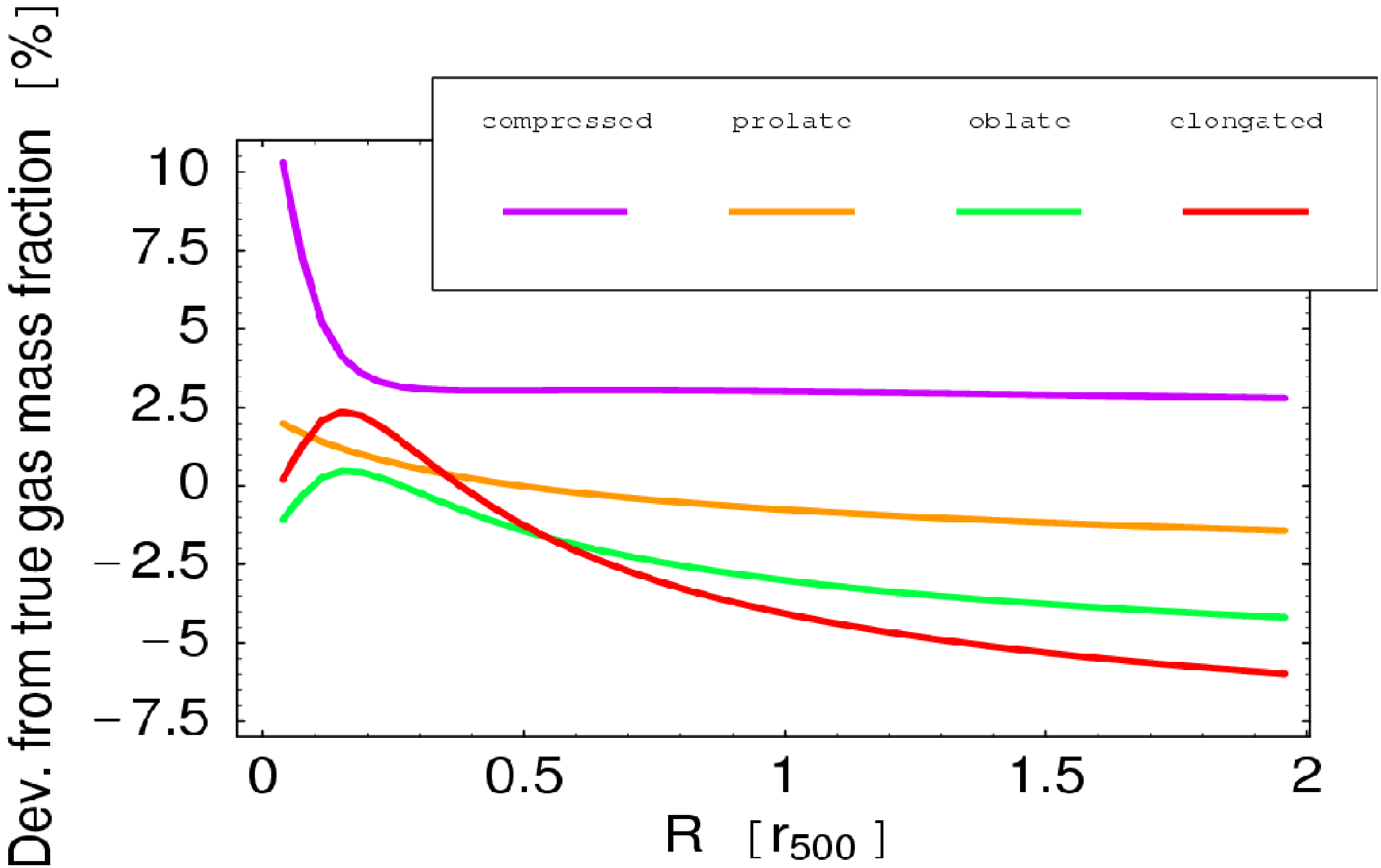
- hydrostatic equilibrium ?
  - good assumption for relaxed clusters
    (Schindler ´96)
- spherical symmetry ?
  - good assumption
    (Piffaretti, Jetzer, Schindler ´03)
- non-thermal pressure ?
  - magnetic pressure is not a problem
    (Dolag & Schindler ´00)

Total mass of elongated clusters

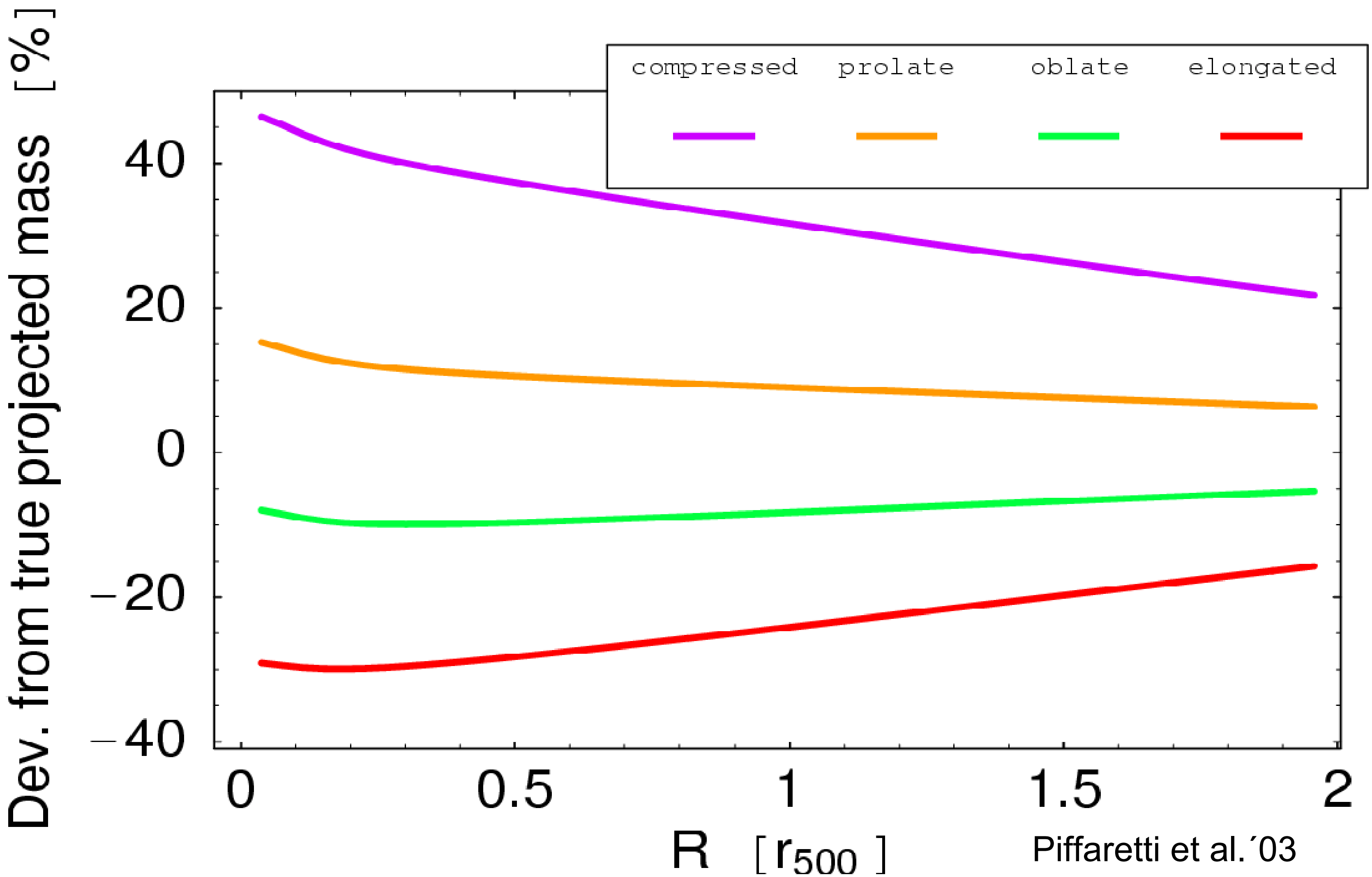


Piffaretti et al. ´03

Gas mass fraction of elongated clusters



Projected mass of elongated clusters



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Magnetic fields –
do they affect the mass determination ?

- X-ray mass uses only thermal pressure
- additional magnetic pressure could lead to an underestimate

- ➢ effect is negligible in normal clusters
- ➢ only important in mergers

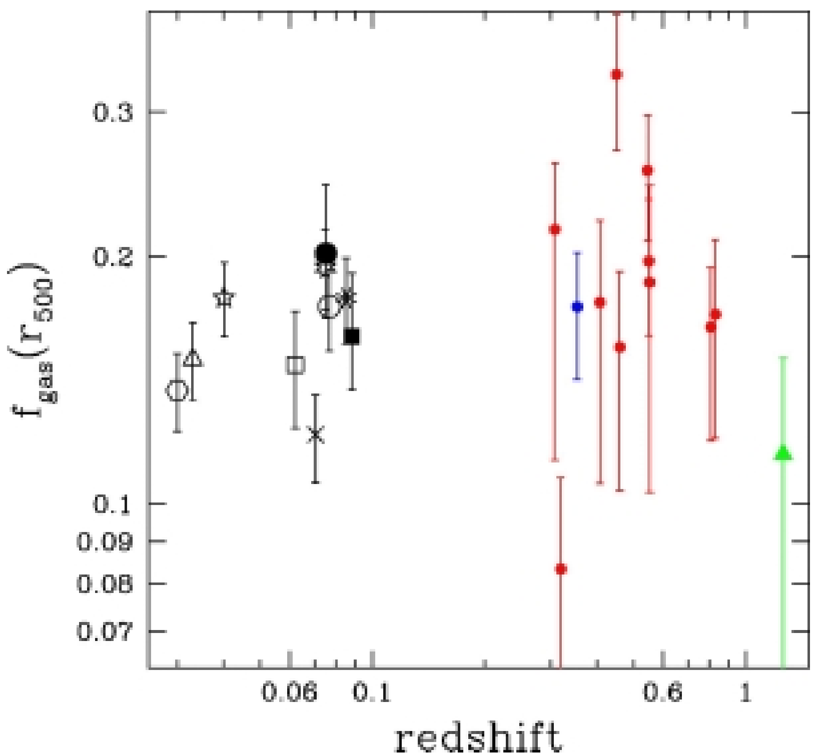
Dolag & Schindler 2000

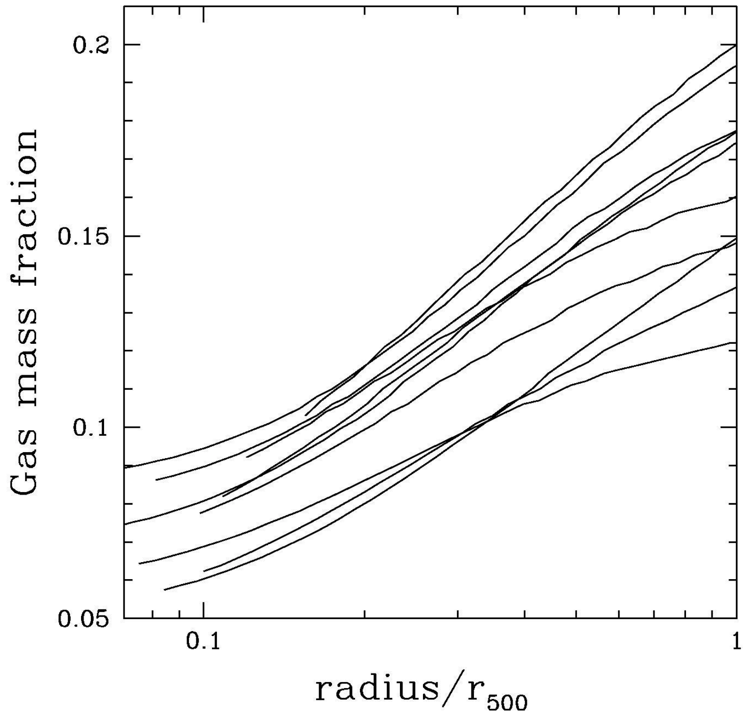
Most likely reasons for mass discrepancy:

- projection effects
- non-equilibrium

Gas mass fractions

- $\langle f_{gas} \rangle = 0.16 \pm 0.03$





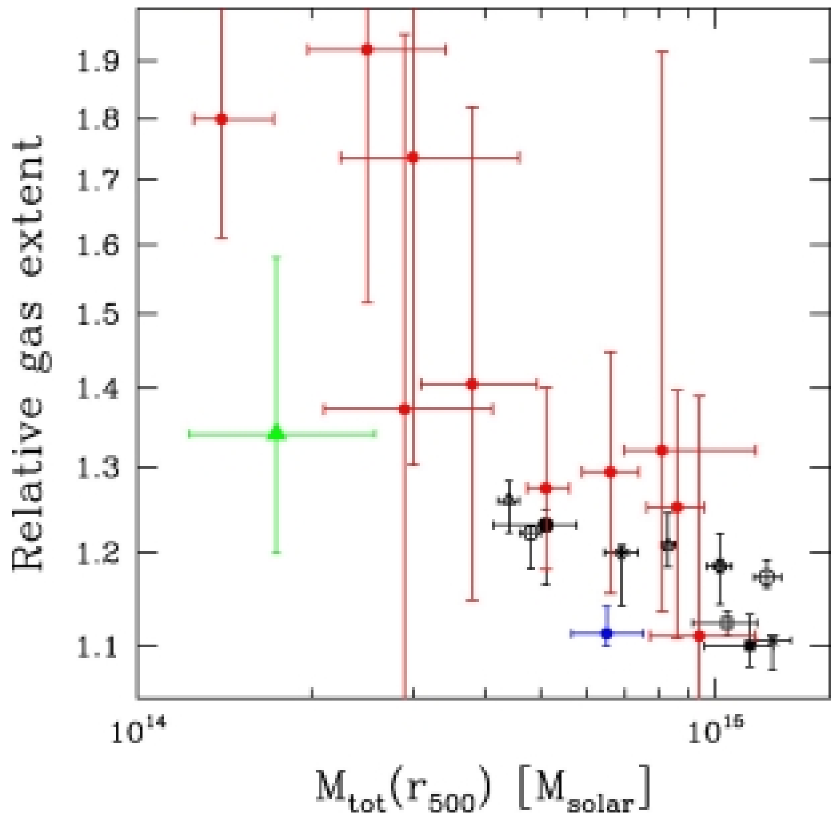
- No clear trend with redshift
- Variation of gas mass fraction ?

Castillo-Morales & Schindler ´03

Relative Gas Extent

- Gas distribution is more extended than the dark matter distribution

$$E = \frac{f_{gas}(r_{500})}{f_{gas}(r_{500}/2)}$$



- Relative gas extent shows a mild dependence on the total mass

↓

additional heating processes

Castillo-Morales & Schindler ´03

Dark matter

We can determine

- the amount of dark matter
- the distribution of dark matter

We cannot determine

- the nature of dark matter

Matter Density Ω_m

- X-ray observations
  - baryon fraction (f_{gas} ~ 0.15-0.20)
- primordial nucleosynthesis
  - upper limit for $\Omega_{baryon} < 0.06$

$$\Omega_m \le \frac{\Omega_{baryon}}{f_{gas}} \approx 0.3 - 0.4$$

Dynamical State

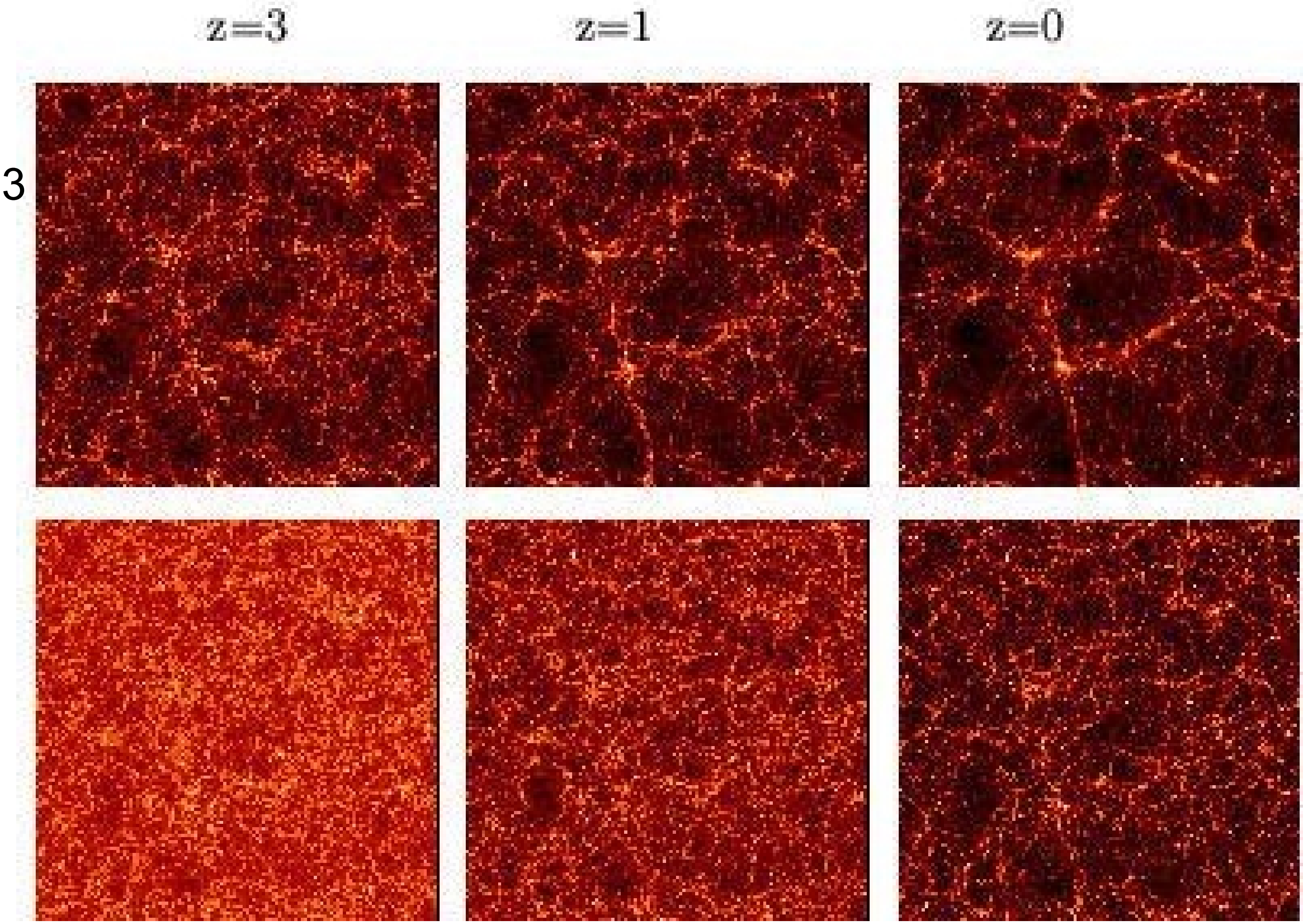
Determination of dynamical state is very important, because ...

matter density Ω_m depends sensitively on the dynamical state

Simulation

$\Omega_m = 0.3$

$\Omega_m = 1$



Virgo Consortium

How do we determine the dynamical state ?

Observations only snapshots

↓

Numerical simulations follow the evolution

Different components

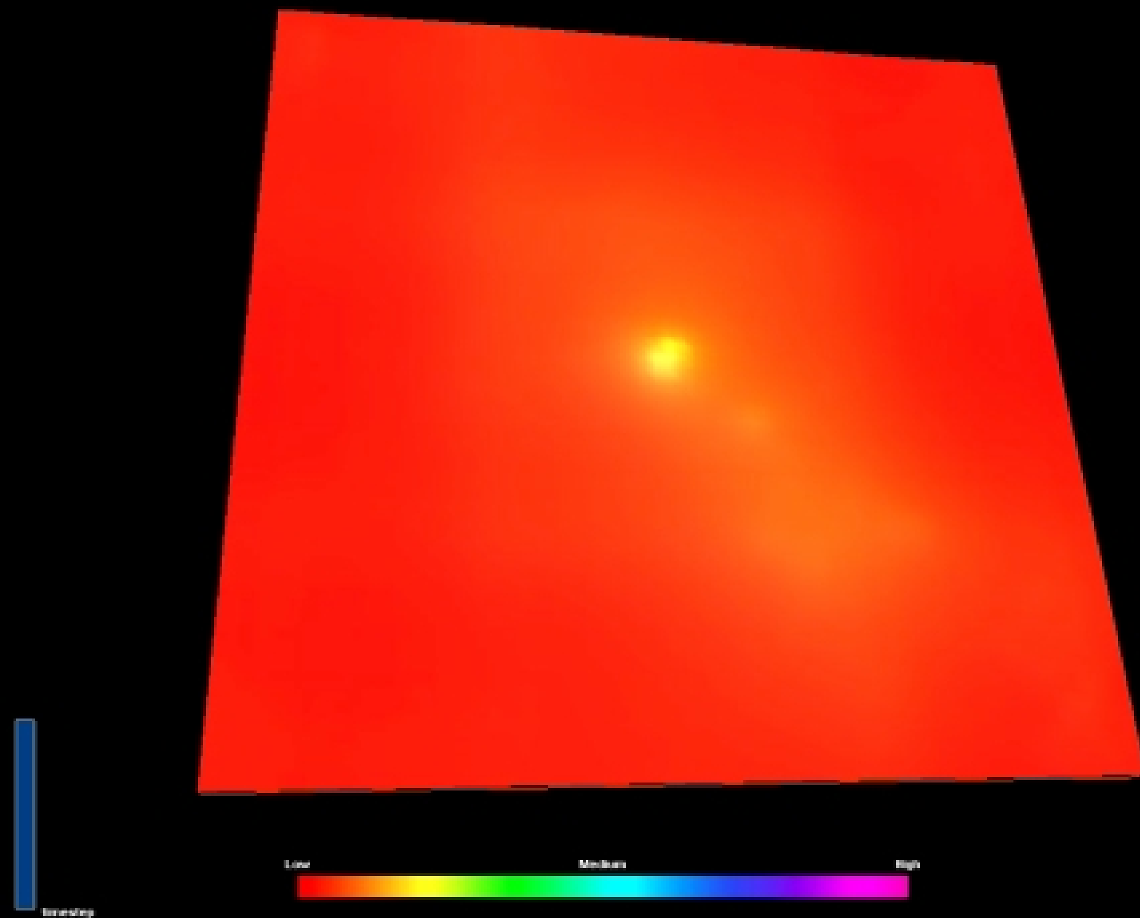
- galaxies, dark matter ⟶ N-body
- gas ⟶ hydrodynamic

Collaboration between

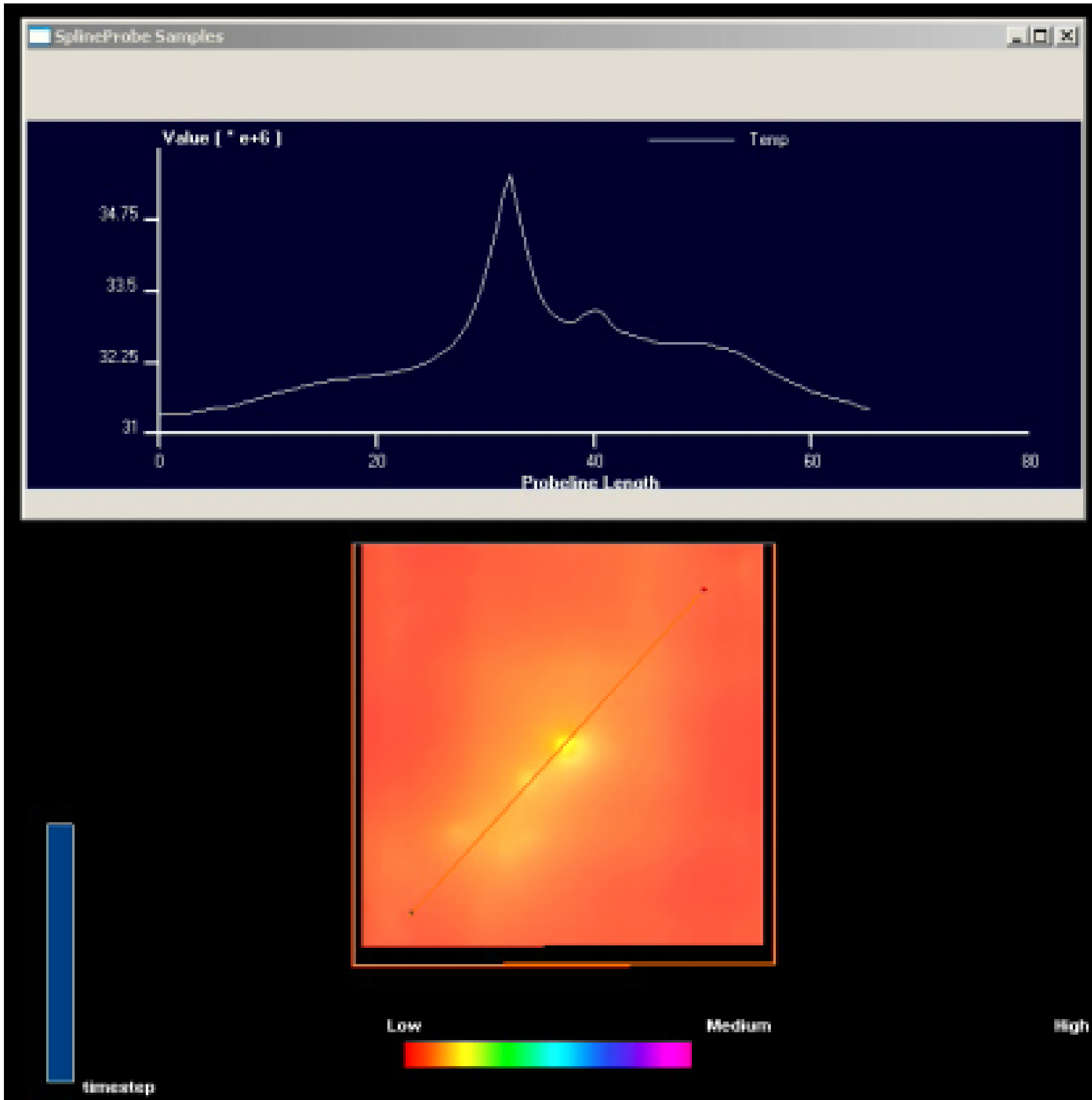
- **Innsbruck** (Domainko, Kapferer, Kimeswenger, Mair, Schindler, van Kampen)
- **Edinburgh** (Mangete, Ruffert)
- **Potsdam** (Benger)

So far only test runs!!!

Evolution of a subcluster merger (X-ray emission)



Movies are available at http://astro.uibk.ac.at/astroneu/hydroskiteam/index.htm

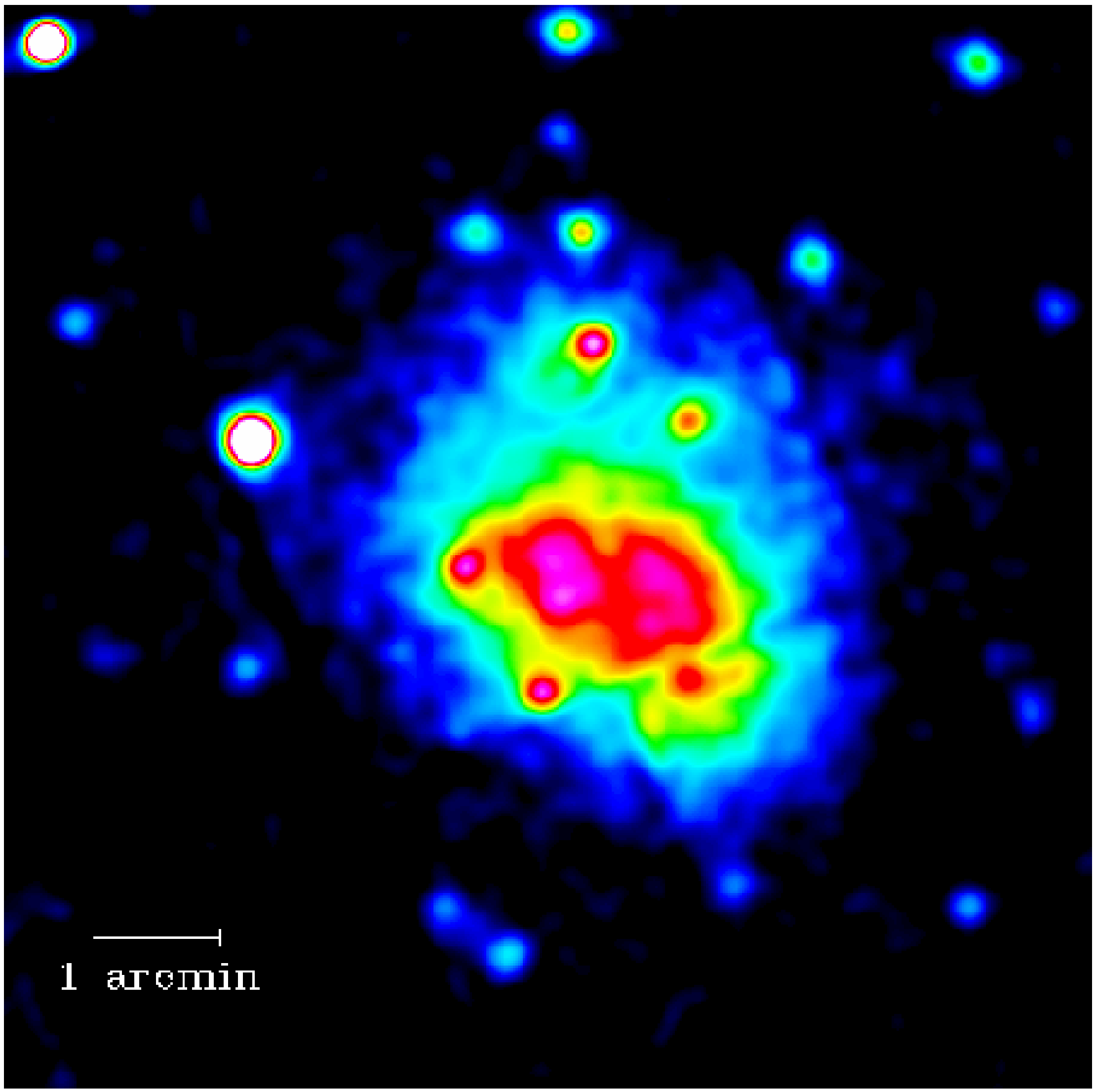


Temperature

Movies are available at http://astro.uibk.ac.at/astroneu/hydroskiteam/index.htm

CL0939+4713 (XMM)

De Filippis, Schindler, Castillo-Morales, 2003

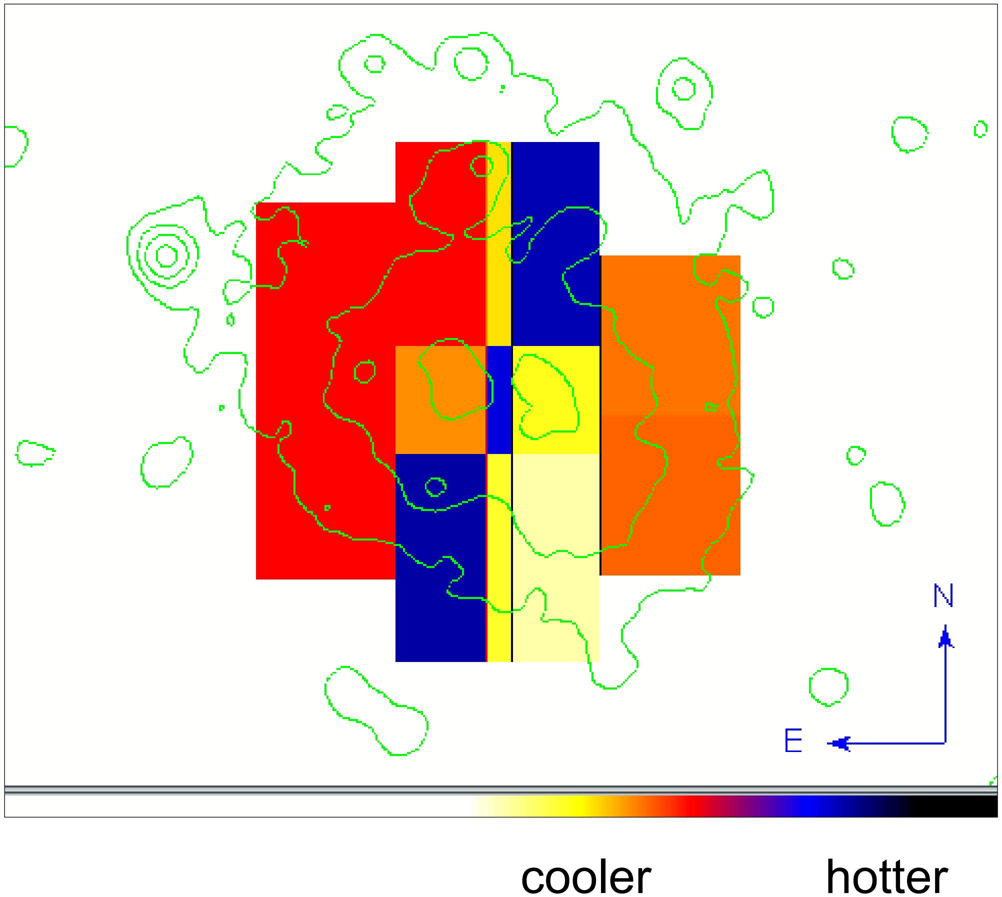


distant cluster

z = 0.41

consisting of two merging subclusters

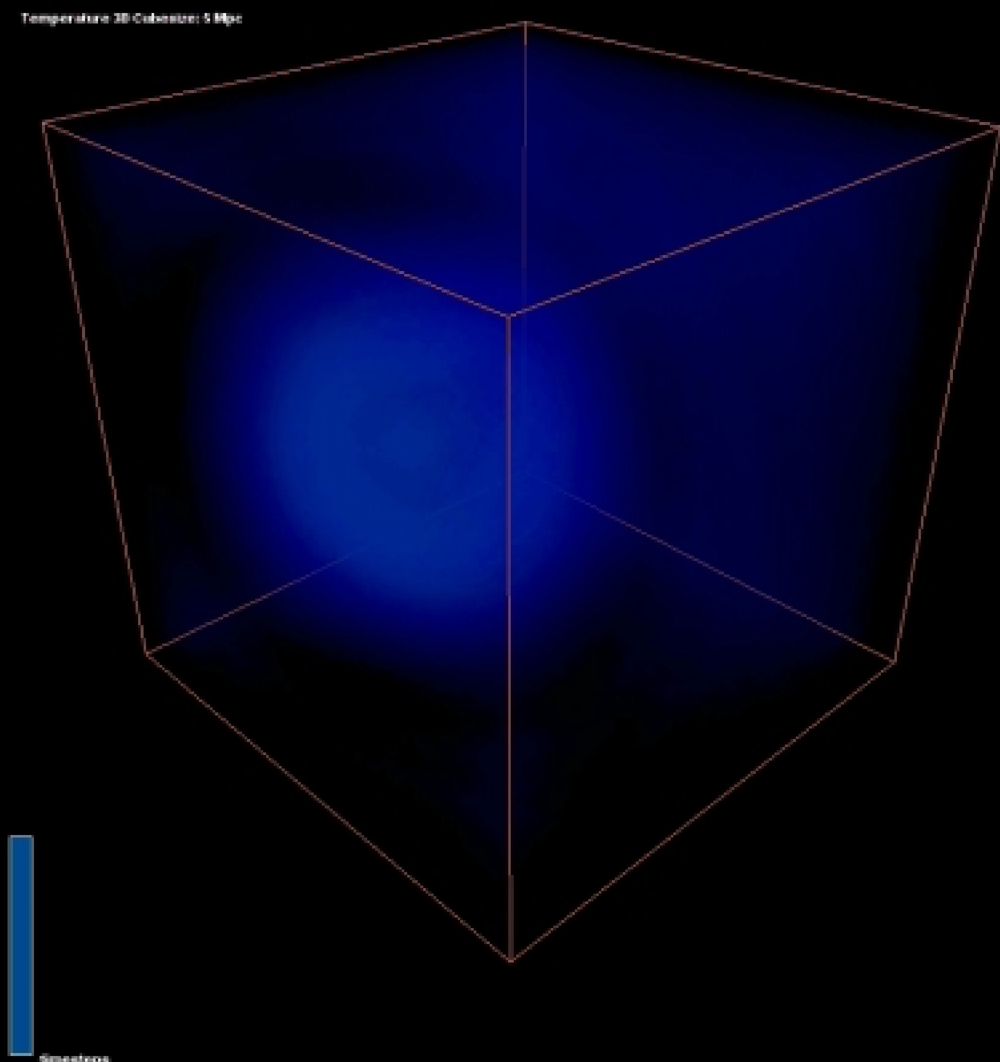
Temperature Map



CL0939+4713 (z = 0.41),
XMM (MOS1+MOS2+PN)

- Hot region between two subclusters

Temperature



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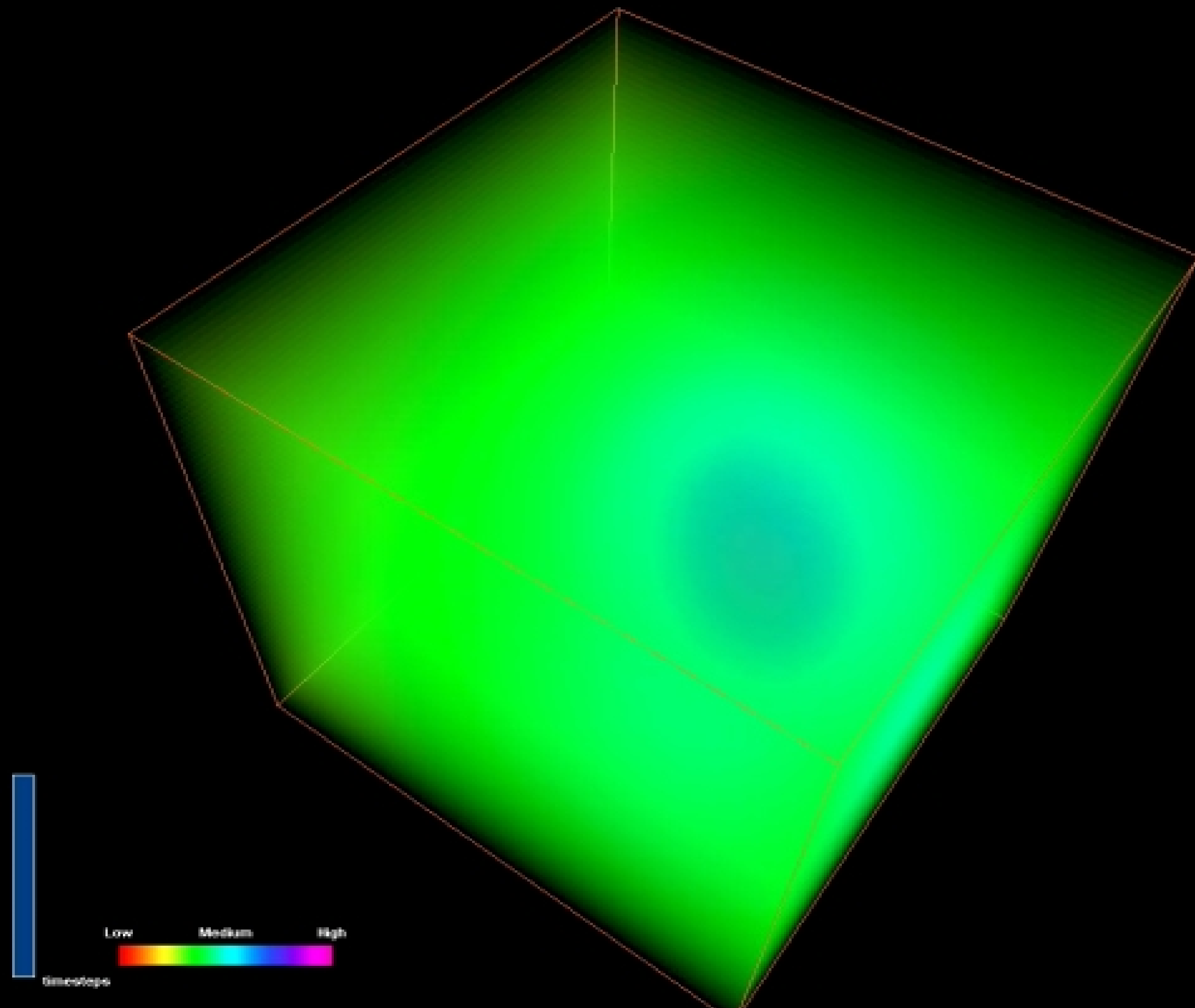
Density



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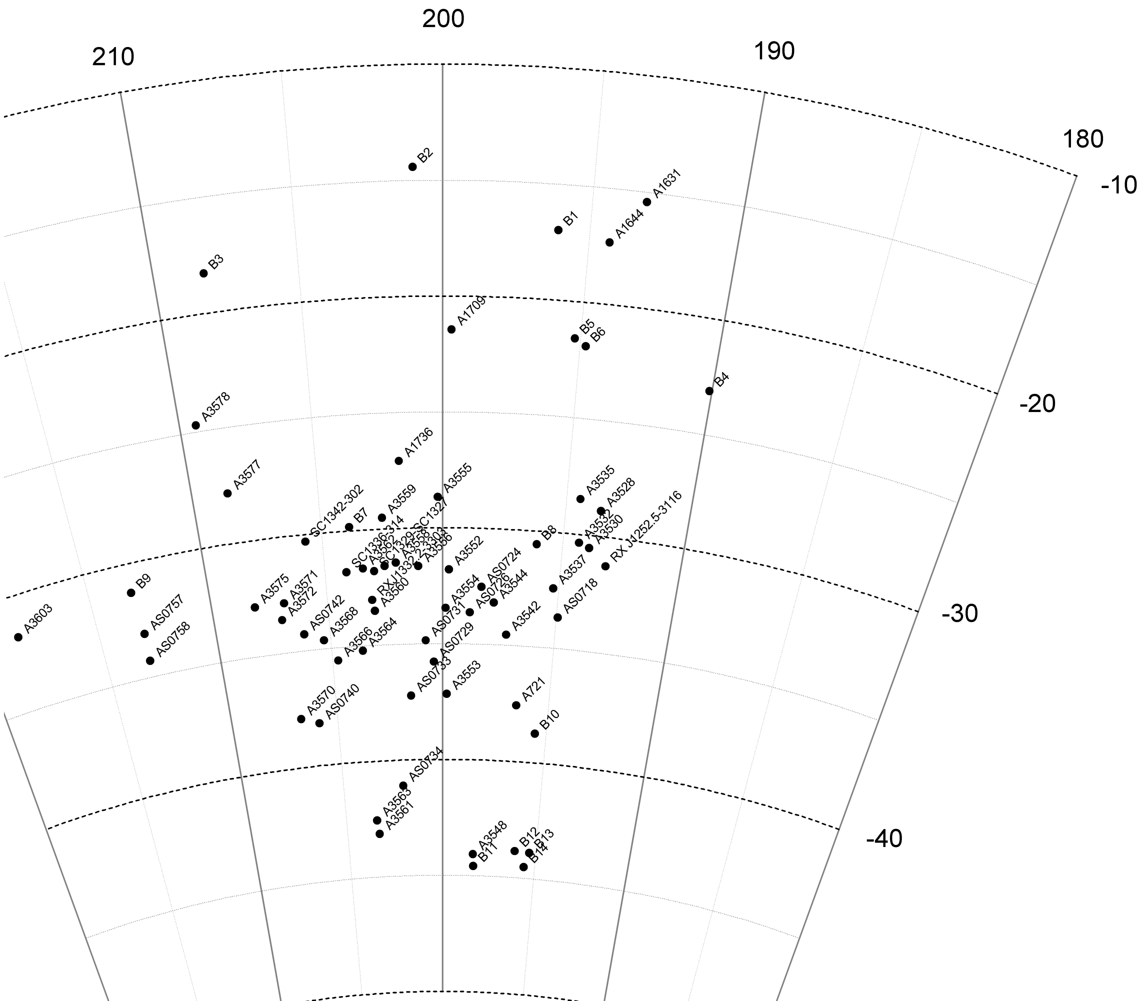
The Shapley Supercluster



De Filippis, Schindler, in prep.

Region with very high cluster density

First complete analysis of the region in X-rays (ROSAT All-Sky Survey)

Development of a new detection algorithm optimised for clusters

The Shapley Supercluster

- cluster density in Shapley 1.7 10^{-5} Mpc^{-3}
- average cluster density 1.2 10^{-6} Mpc^{-3}

high-density environment →
higher merging rate