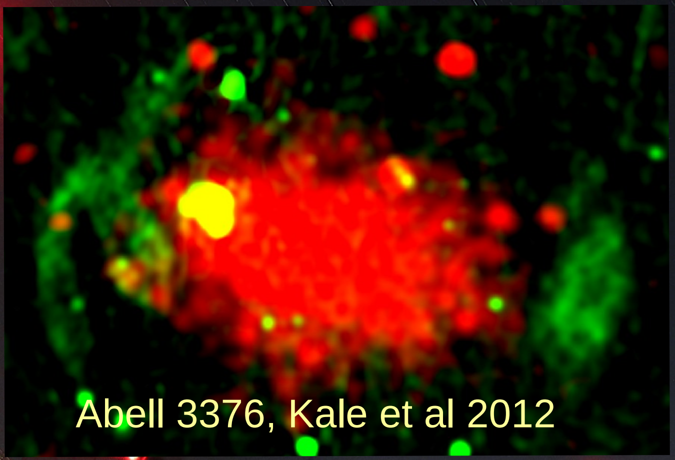
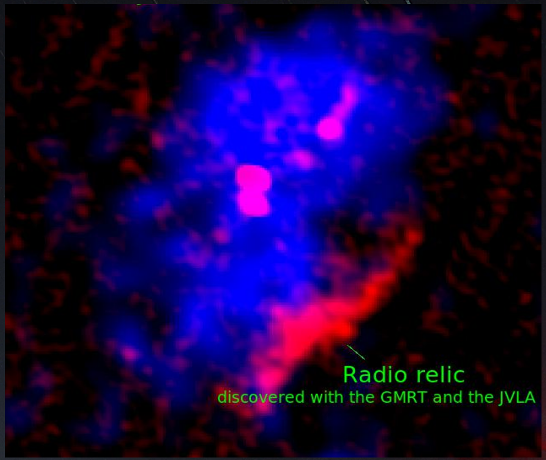
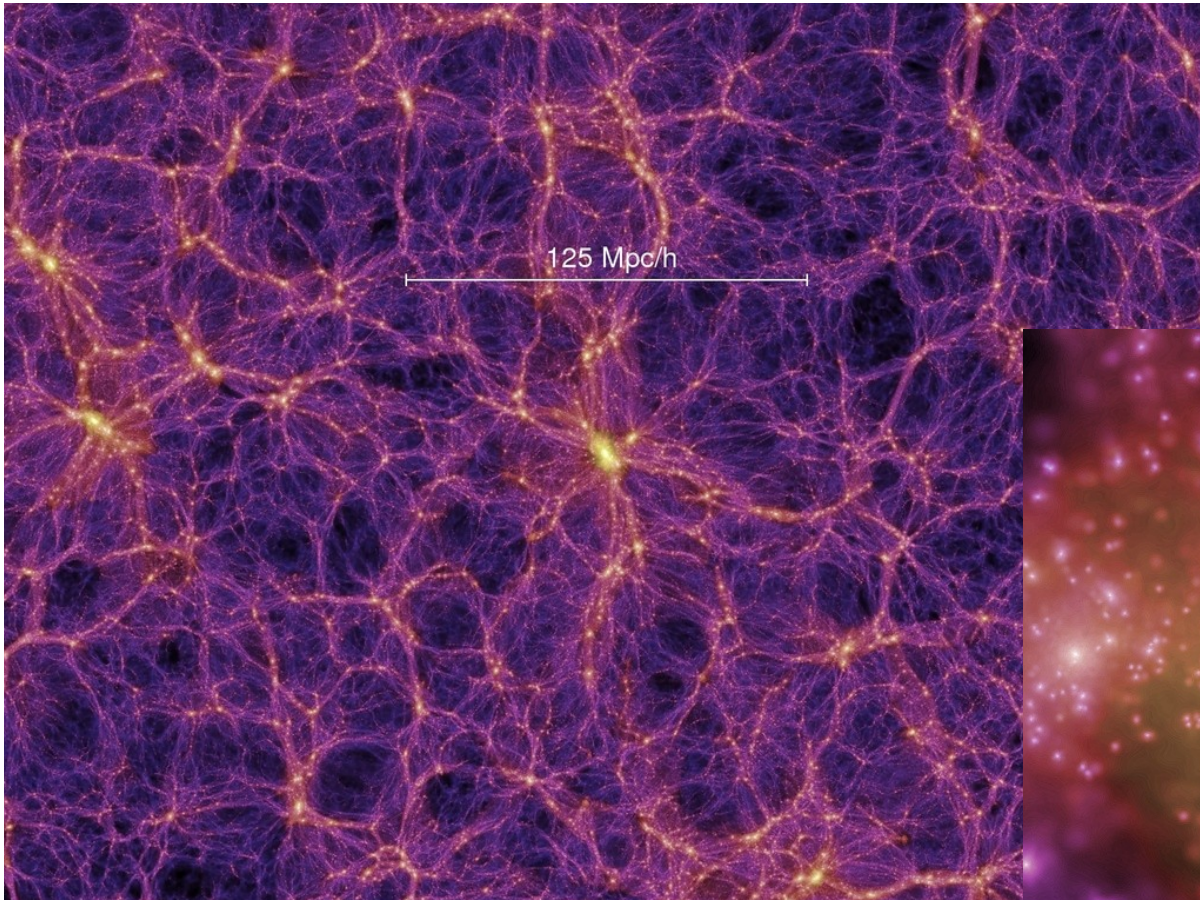
Clusters of Galaxies

Ruta Kale

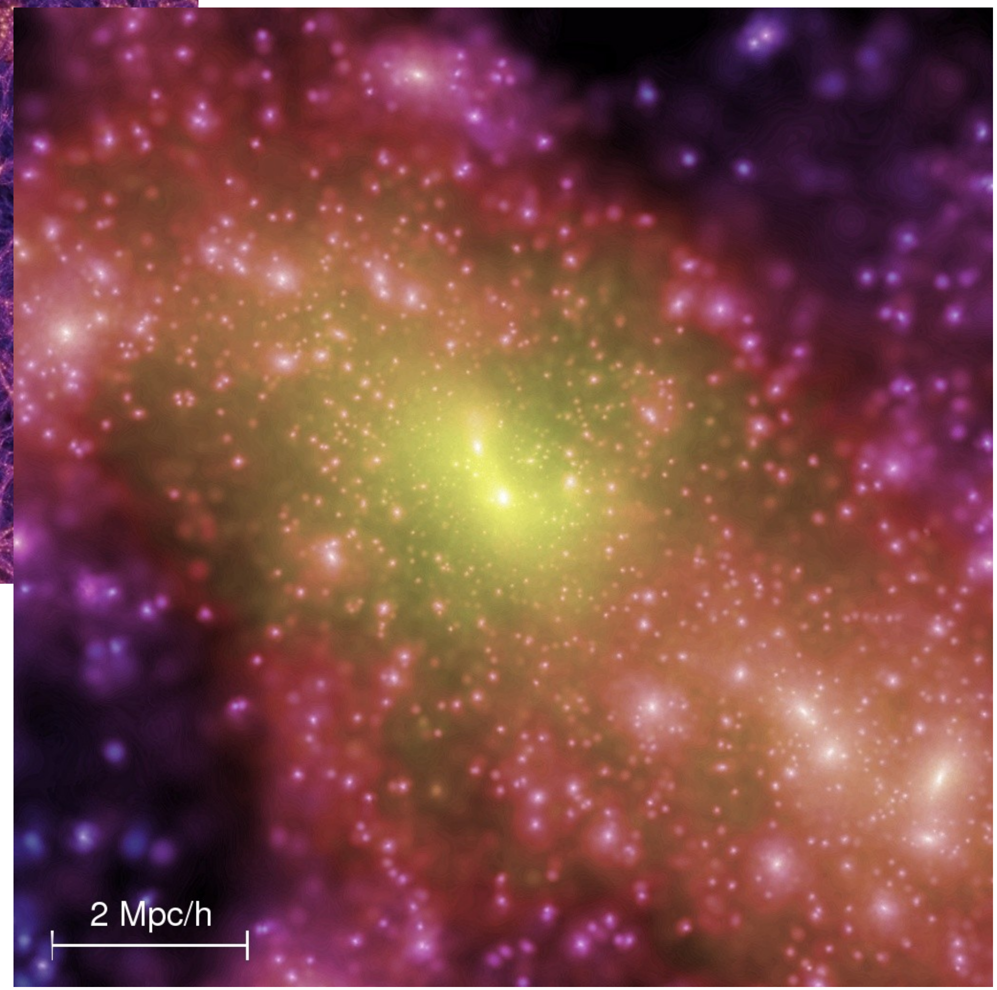




GMRT picture courtesy: Shilkumar Meshram and Divya Oberoi



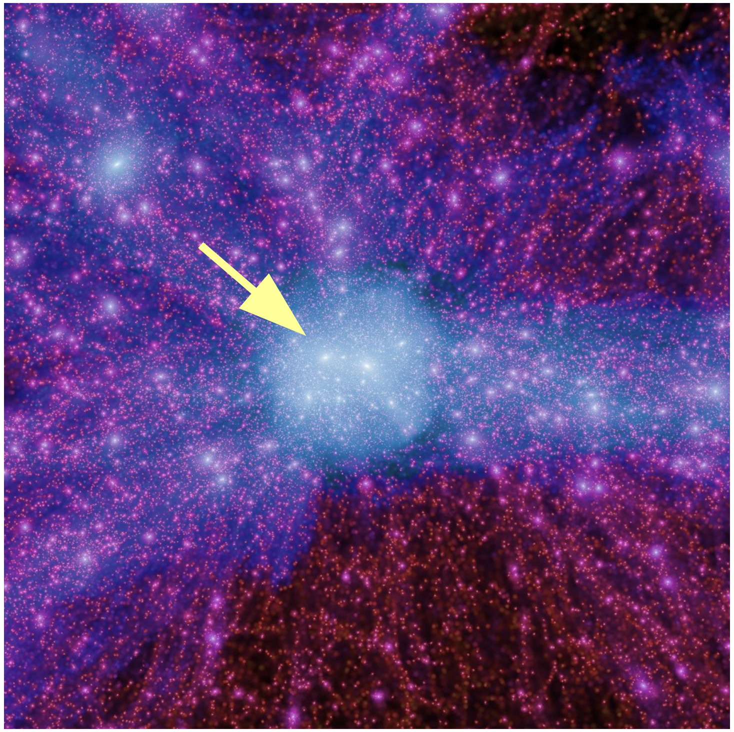
Large scale structure
Millenium simulation
Springel et al 2005



Galaxy cluster size ~ 1 Mpc

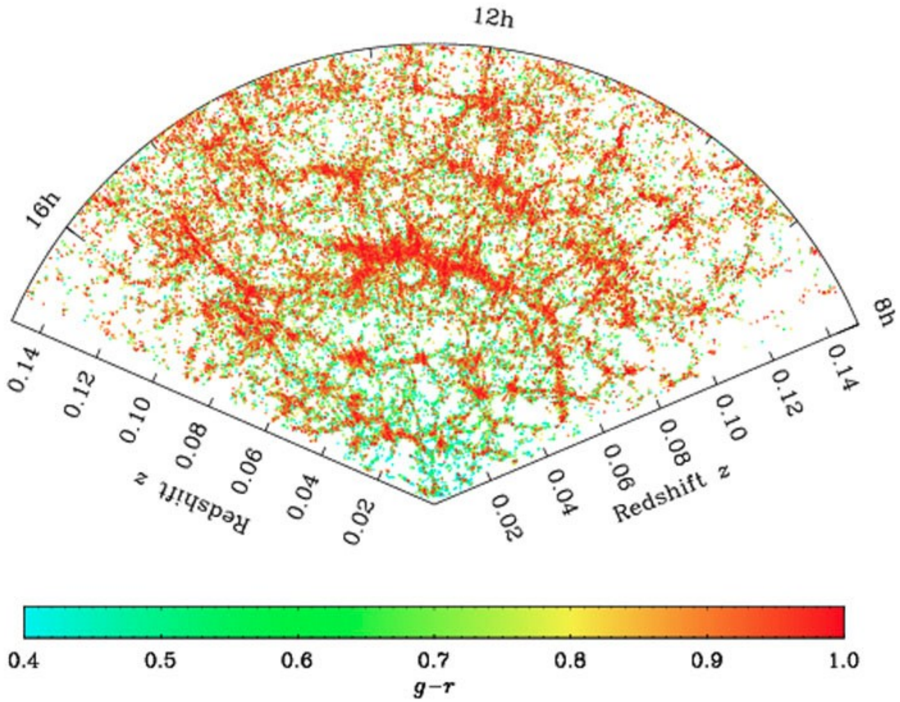
1 parsec = 1pc = 3.26 light years
Sun to Earth = 1 AU = 5 x 10^{-6} pc

Large scale structure of the Universe



15 Mpc/h

Millenuim simulation
V. Springel



Sloan Digital Sky Survey
Zehavi et al. 2011

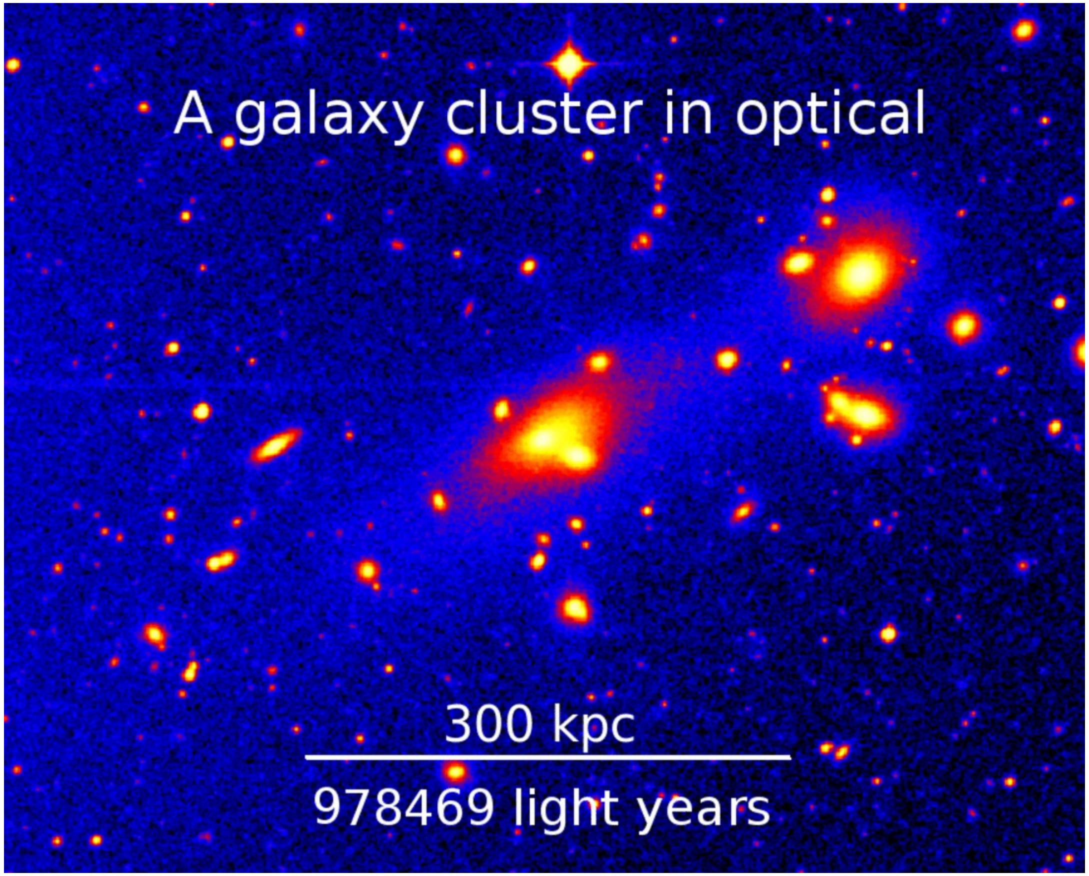
Outline

- Constituents of galaxy clusters
- Deductions from early optical studies: existence of dark matter
- Galaxies in clusters
- Intra-cluster medium: radiation mechanisms
- Sunyaev Zel'dovich effect
- Intra-cluster medium in radio bands: tracing cluster mergers
- Superclusters

Galaxy clusters: as we know today

Observationally identified as regions of overdensities in the projected distribution of optically detected galaxies (eg. Zwicky 1938; Abell 1958).

Masses ~ 10^{14} - 10^{15} $M_{\odot}$



- Contain 100s to 1000s of galaxies in regions of linear size ~Mpc
- Velocity dispersion ~ 1000 km s^{-1}
- X- ray luminosities ~ 10^{44} – 10^{45} erg s^{-1}

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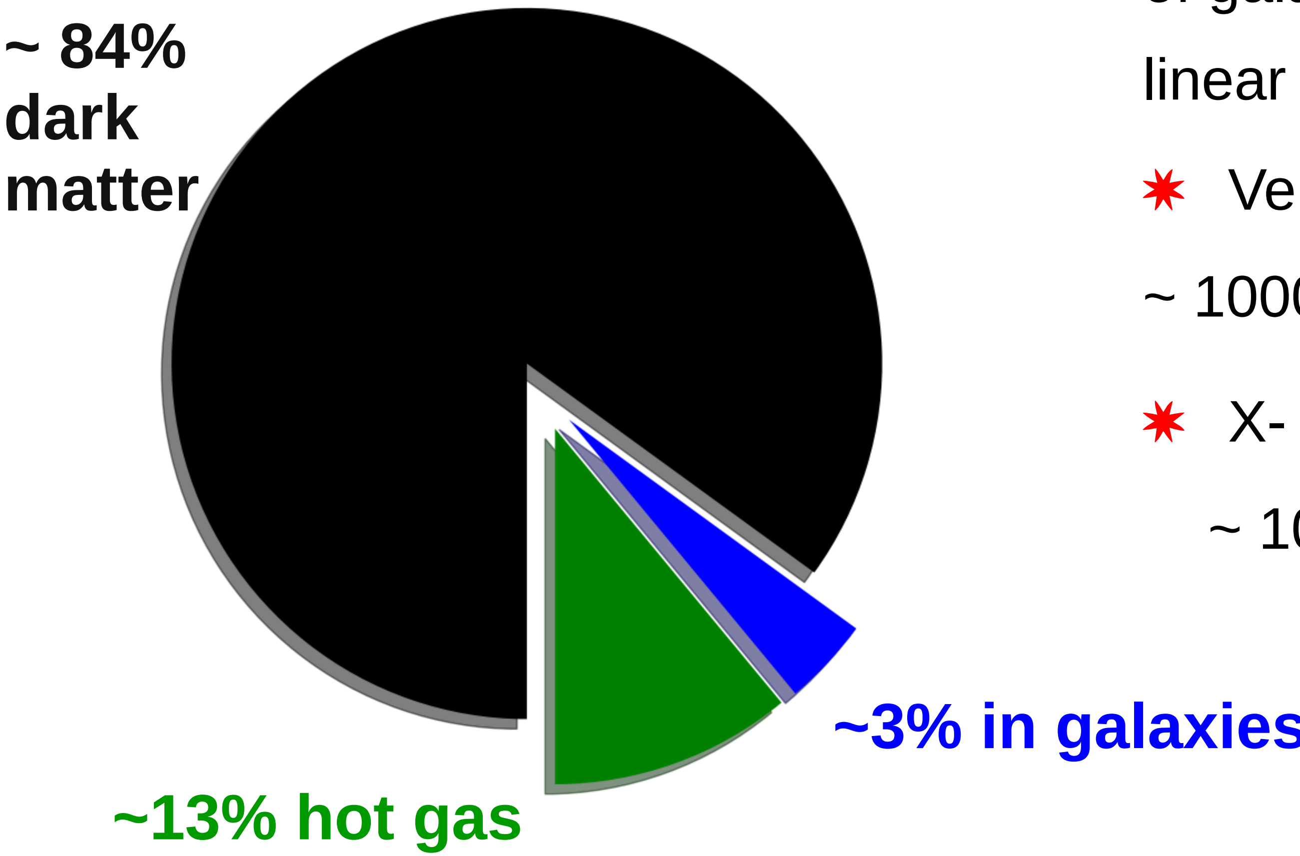

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Intra-cluster medium

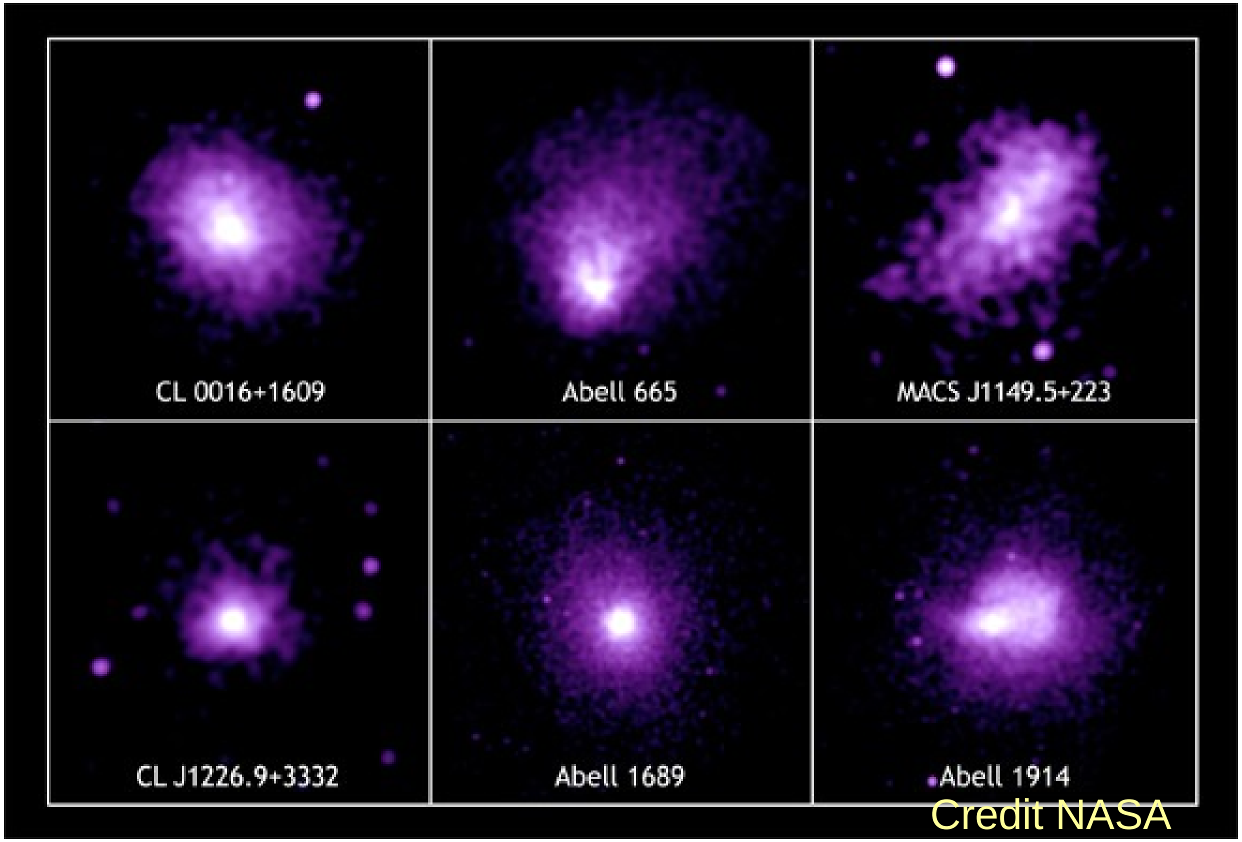
- Thermal plasma

Thermal

Bremsstrahlung

T ~ 10^8 K;

Core density, n_e ~10^{-1} – 10^{-3} cm^{-3}



- **Relativistic particles (cosmic rays)**
- **Magnetic fields (~ 0.1-a few μG)**

CRe in the ICM

- Relativistic particles
- Magnetic fields

(~ 0.1- a few μG)

→ Not detectable in most observing bands

- **Synchrotron radiation from ~GeV electrons in microGauss magnetic fields: detectable in radio frequency bands.**

Intra-Cluster Medium: a plasma

$$n_e \sim n_p = 0.01 \ \ \mathrm{cm}^{-3}, \ kT = 5 \ \ \mathrm{keV} \ \ \mathrm{and} \ \ B = 1 \ \ \mu\mathrm{G}$$

Zuhone and Roediger 2016

Intra-Cluster Medium: a plasma

Mean free path

Debye length: is the scale over which charges screen out electric fields in plasmas

Electron skin depth: the depth in a plasma to which electromagnetic radiation can penetrate

Electron Larmor radius: the radius of the circular motion of an electron in the plane perpendicular to the magnetic field

Comparison of these with the size of galaxy cluster.

$$n_e \sim n_p = 0.01 \ \text{cm}^{-3}, \ kT = 5 \ \text{keV} \ \text{and} \ B = 1 \ \mu\text{G}$$

Intra-Cluster Medium: a plasma

Length scale	Value	
Debye length	100 fpc	~3 km
Electron skin depth	2000 fpc	~62 km
Electron Larmor radius	0.05 npc	~1.5 Mm
Mean free path	1 kpc	~3.086 x 10^{19} m

Cluster size ~ 1 Mpc

$$n_e \sim n_p = 0.01 \ \text{cm}^{-3}, \ kT = 5 \ \text{keV and } B = 1 \ \mu\text{G}$$

Zuhone and Roediger 2016

Why are clusters important to study ?

- Most massive laboratories: gravitationally dominated by dark matter (80-85%)
- Probes of structure formation: precise values of cosmological parameters can be derived
- Most massive reservoirs of baryons in the form of intra-cluster medium
- Probes of large scale (~Mpc) magnetic fields
- Host to the most massive galaxies in the Universe
- Record keepers of nucleosynthesis in the Universe: distribution of elements

How did it all begin ?

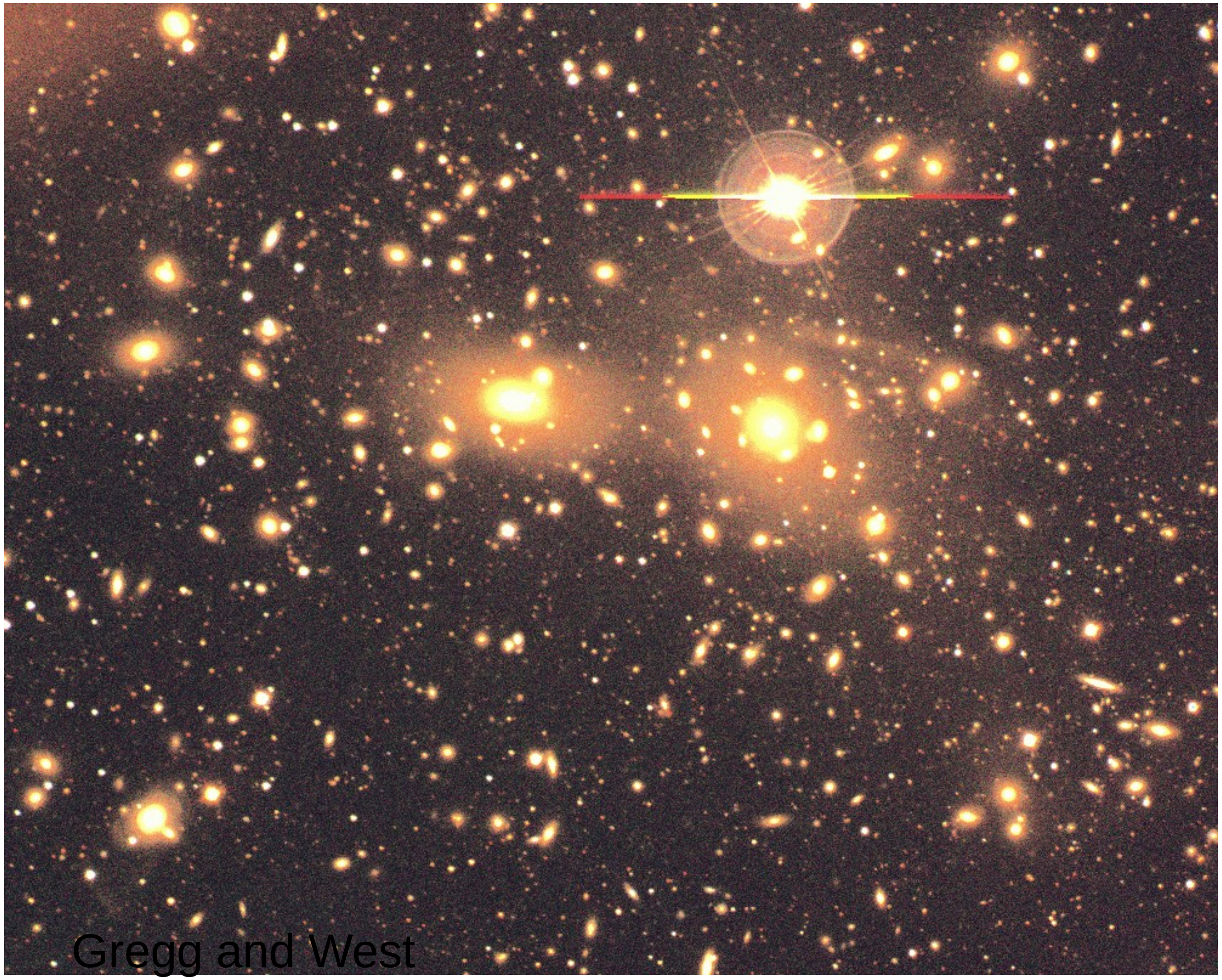
The Coma cluster

Discovered and described by Wolf 1902

RA 12h59m48s
Dec +27d58.8m

Redshift ~ 0.023
D~ 100 Mpc

1 pc = 3.26 ly



The nearest large galaxy cluster.

The Coma cluster

Discovered and described by Wolf 1902

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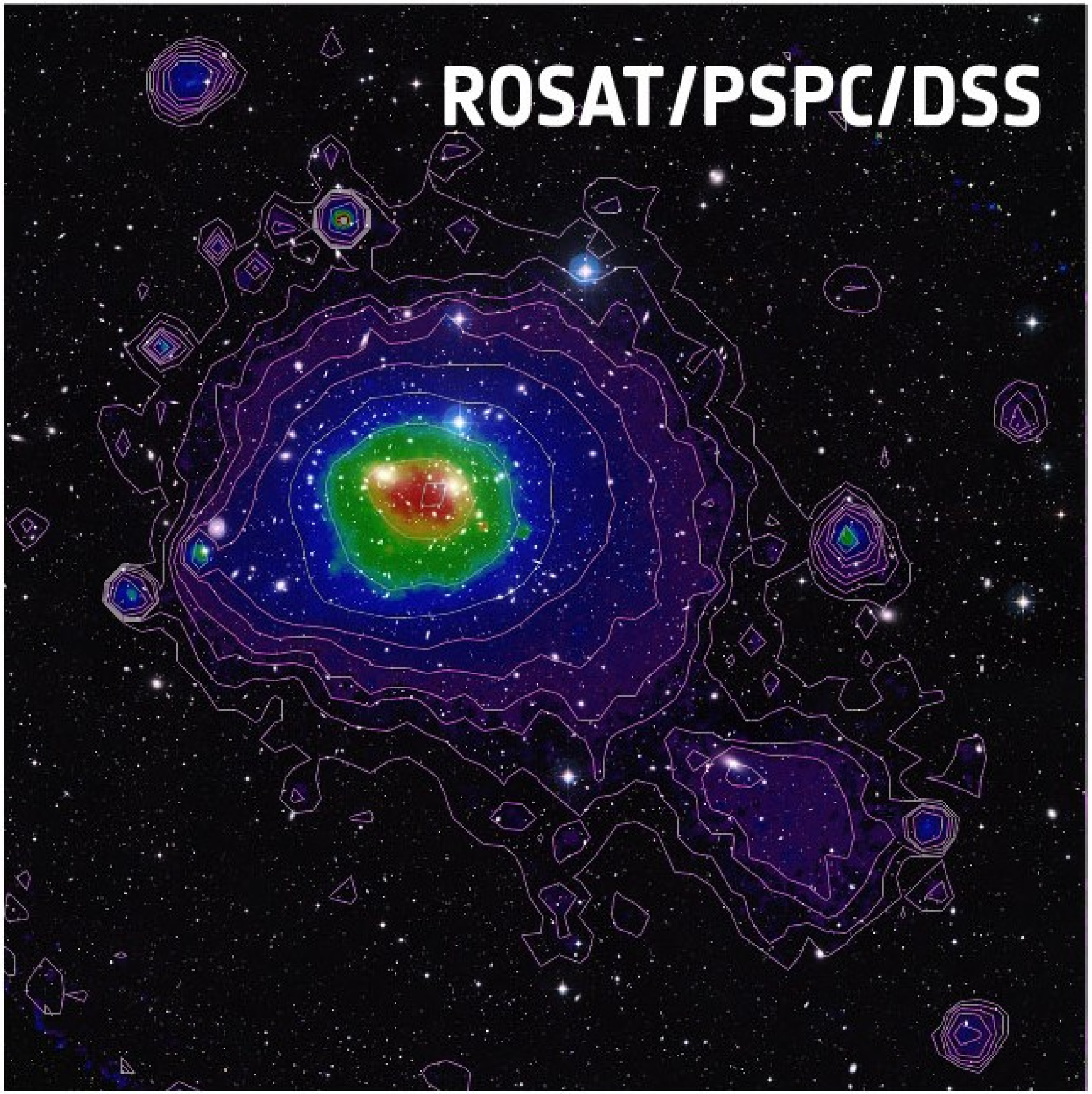


Existence of dark matter
proposed to explain the high velocity dispersion of galaxies in the Coma cluster

F. Zwicky, “Die Rotverschiebung von extragalaktischen Nebeln”, Helv. Phys. Acta 6, 110–127 (1933)

Virial Theorem

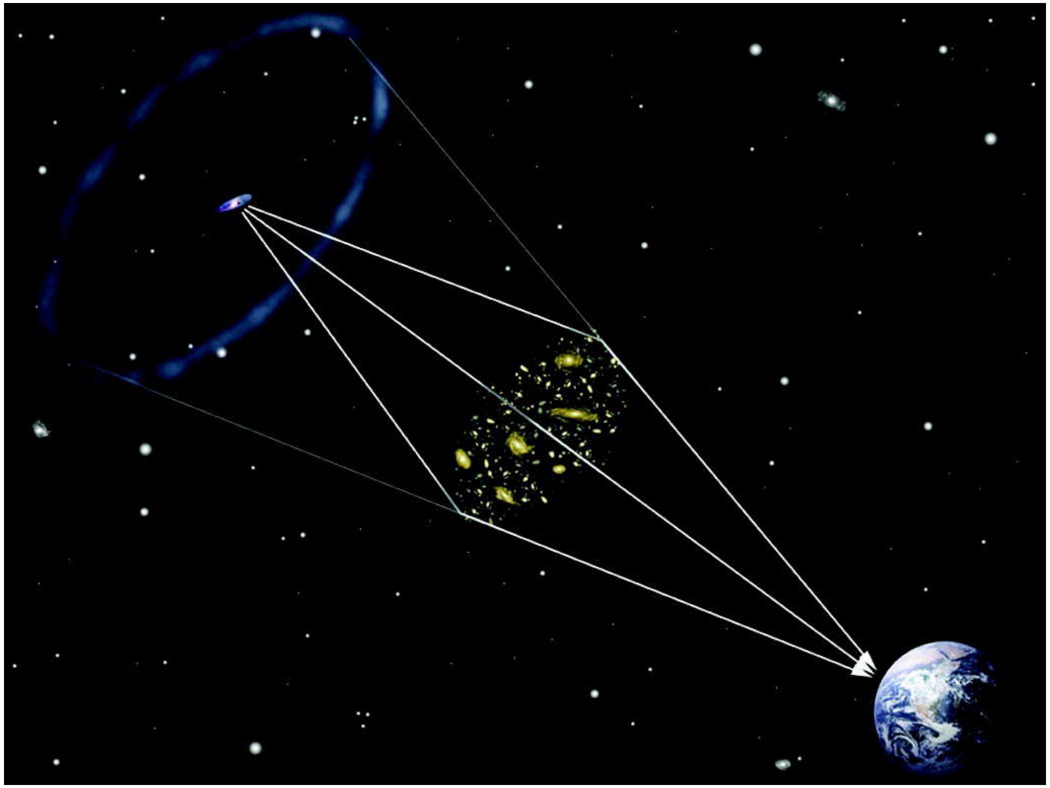
$$\bar{\varepsilon}_k = \overline{v^2}/2 \sim -\bar{\varepsilon}_p/2 = 32 \times 10^{12}\ \mathrm{cm}^2\mathrm{s}^{-2}$$

$$\left(\overline{v^2}\right)^{1/2} = 80\ \mathrm{km/s}. \qquad (8)$$

In order to obtain the observed value of an average Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times larger than that derived on the grounds of observations of luminous matter.[8] If this would be confirmed we would get the surprising result that dark matter is present in much greater amount than luminous matter.

Gravitational lensing

"Nebulae as Gravitational Lenses", Physical Review, 51 (4): 290, Bibcode: 1937PhRv...51..290Z



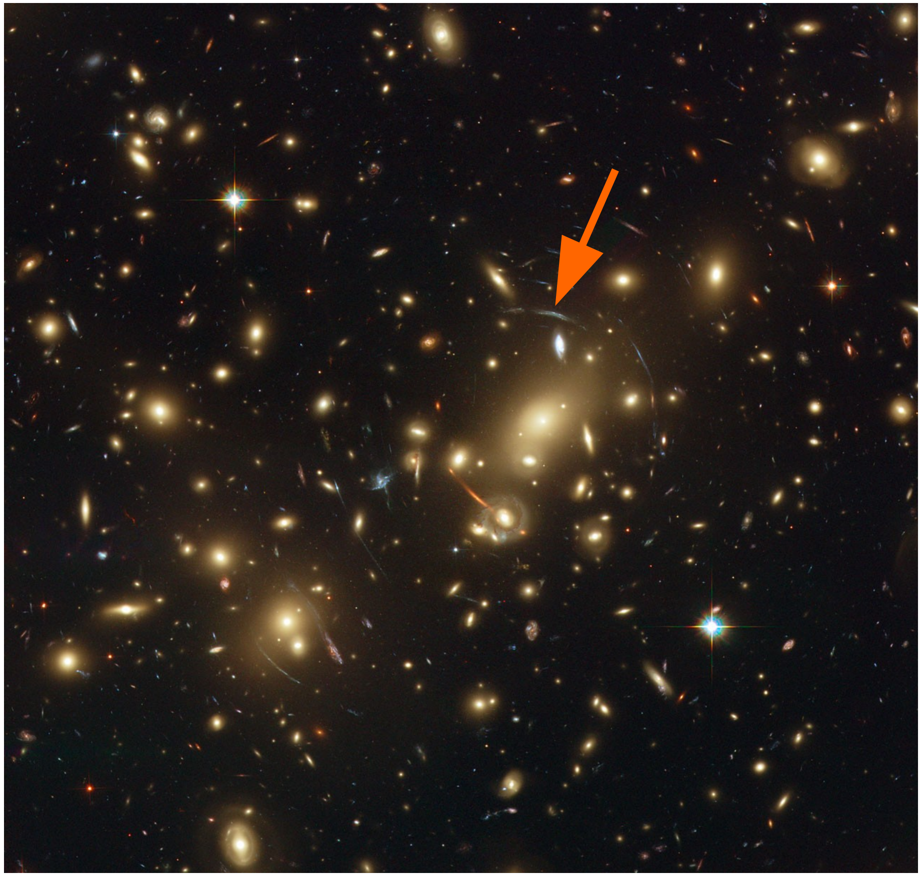
http://astro.wsu.edu/worthey/astro/html/lec-darkmatter.html

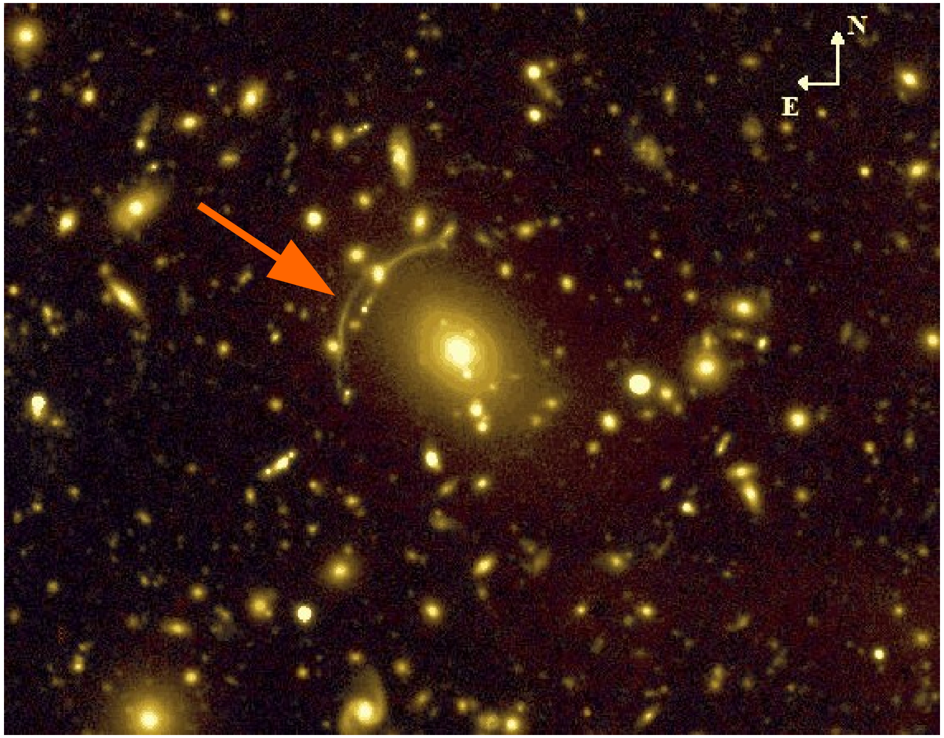
Hubble Space Telescope : Einstein ring

Gravitational lensing

Abell 2218

Abell 611



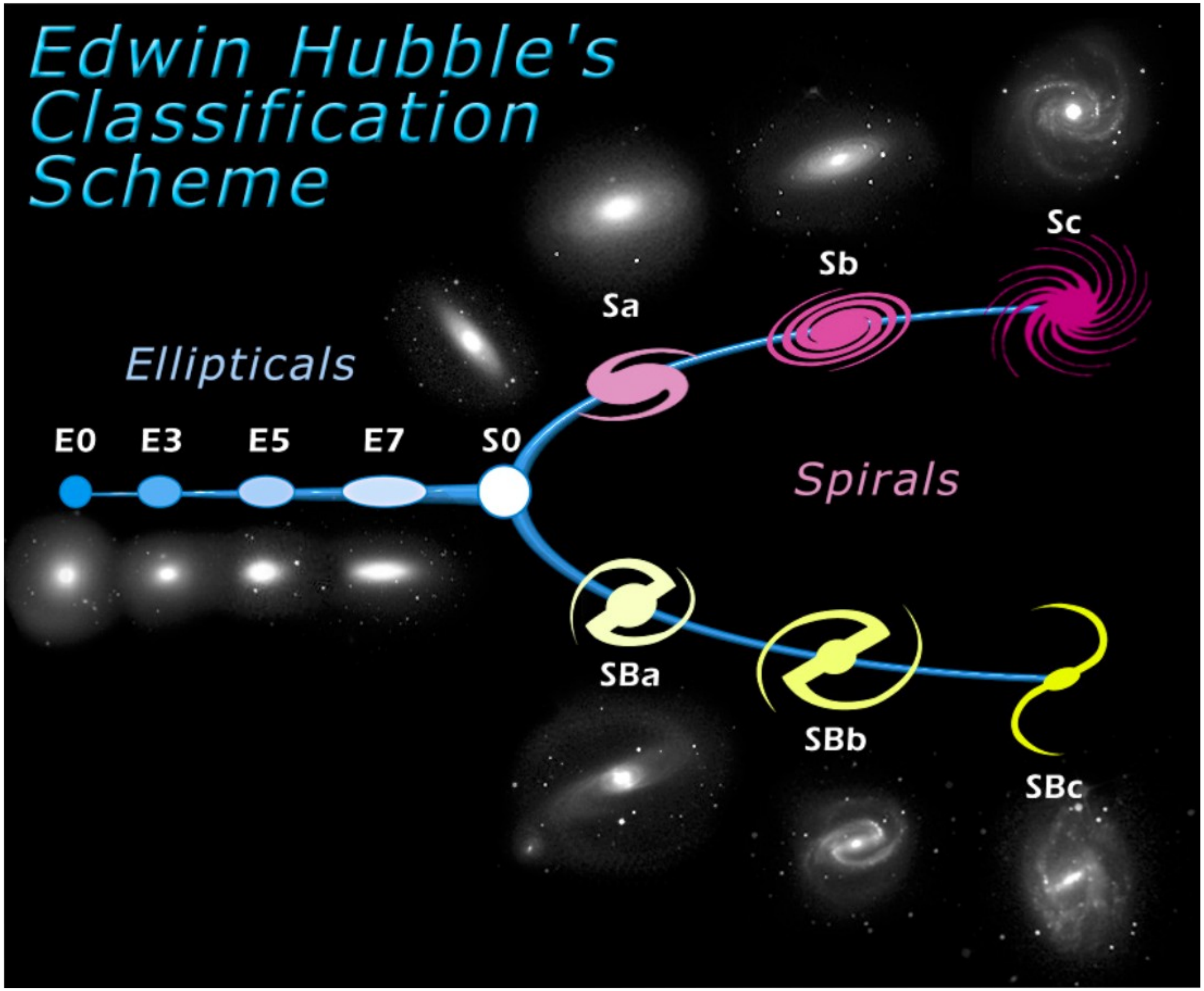


Machacek et al. 2002

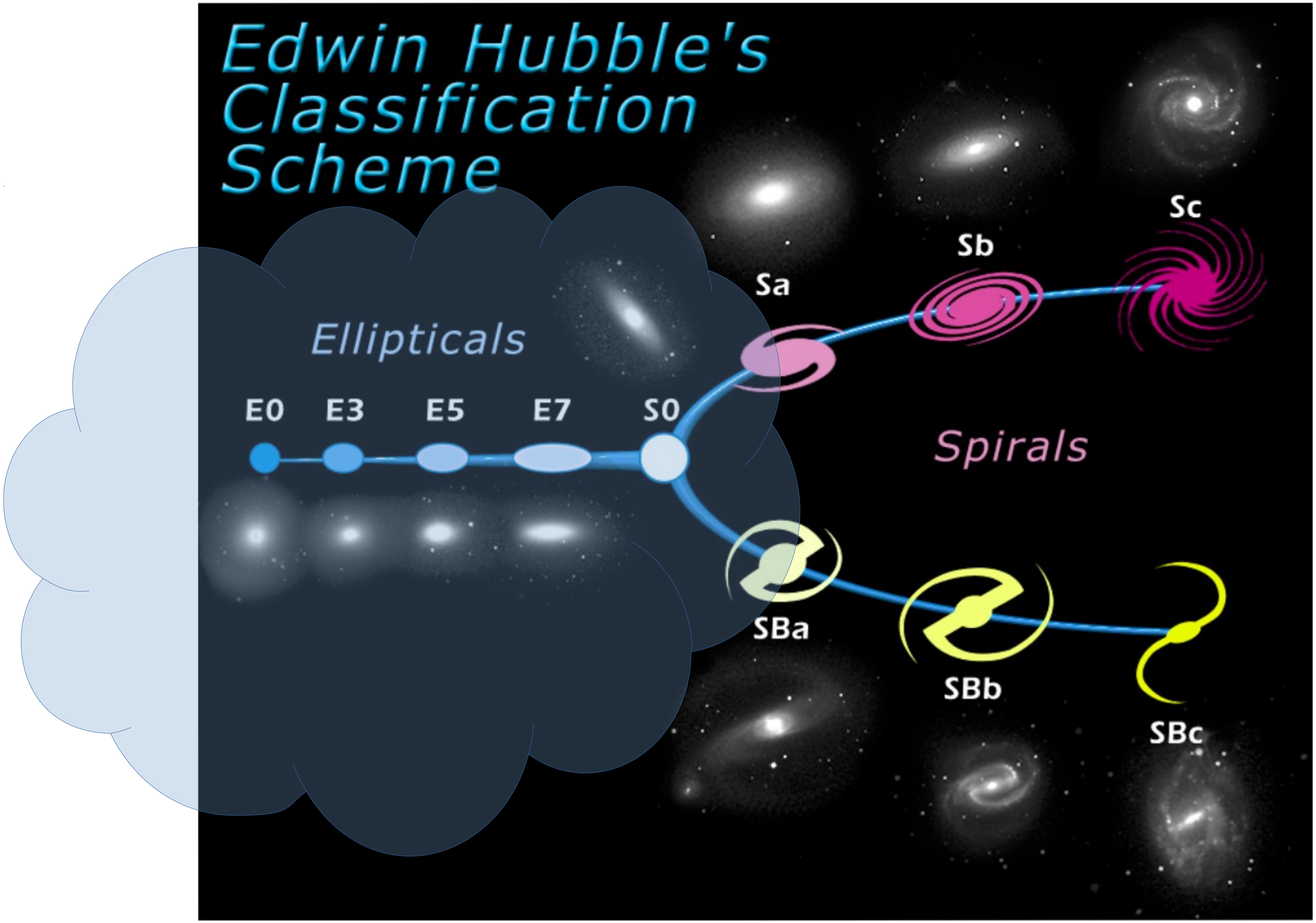
Romano et al. 2010

Gravitational lensing by clusters is an effective method to constrain the masses of galaxy clusters.

Galaxies in galaxy clusters

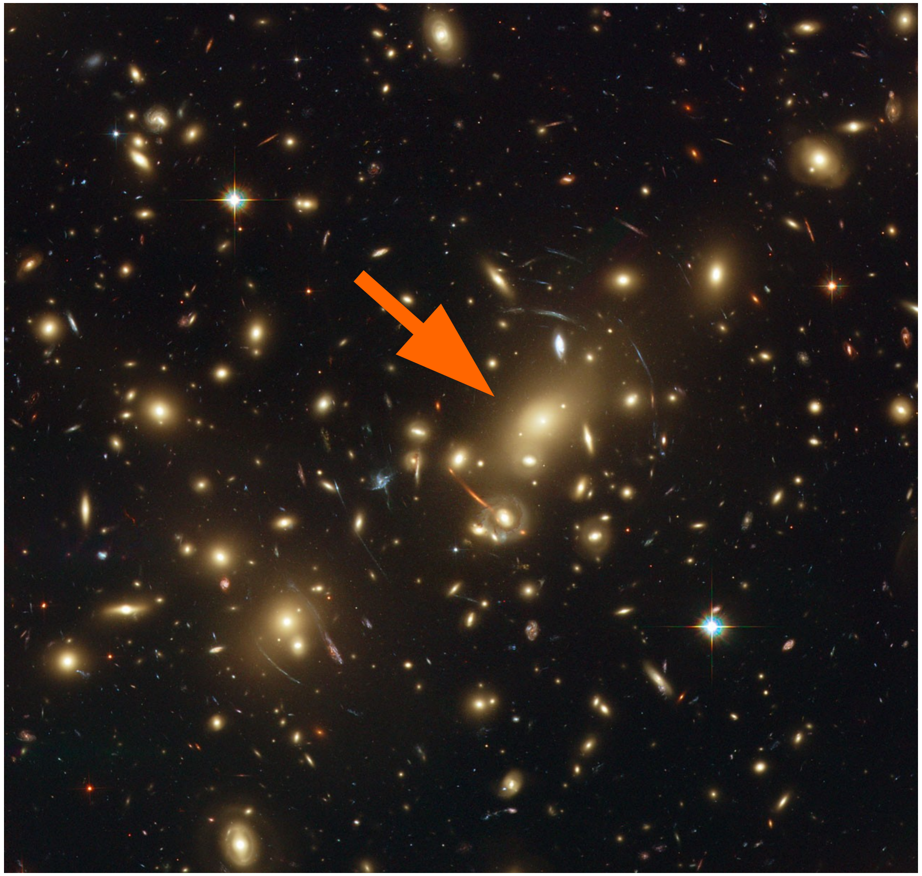


Galaxies in galaxy clusters



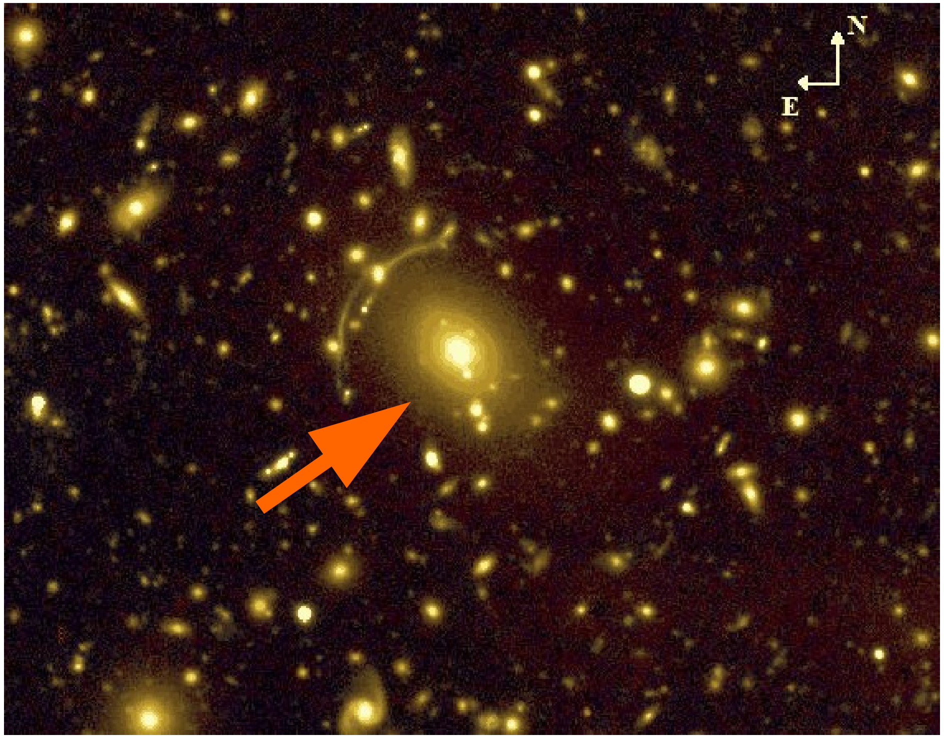
Brightest Cluster Galaxies (BCGs)

Abell 2218



Machacek et al. 2002

Abell 611



Romano et al. 2010

These are the brightest among all galaxies.

Galaxy types and environments

Fraction of population
Vs
Projected galaxy density

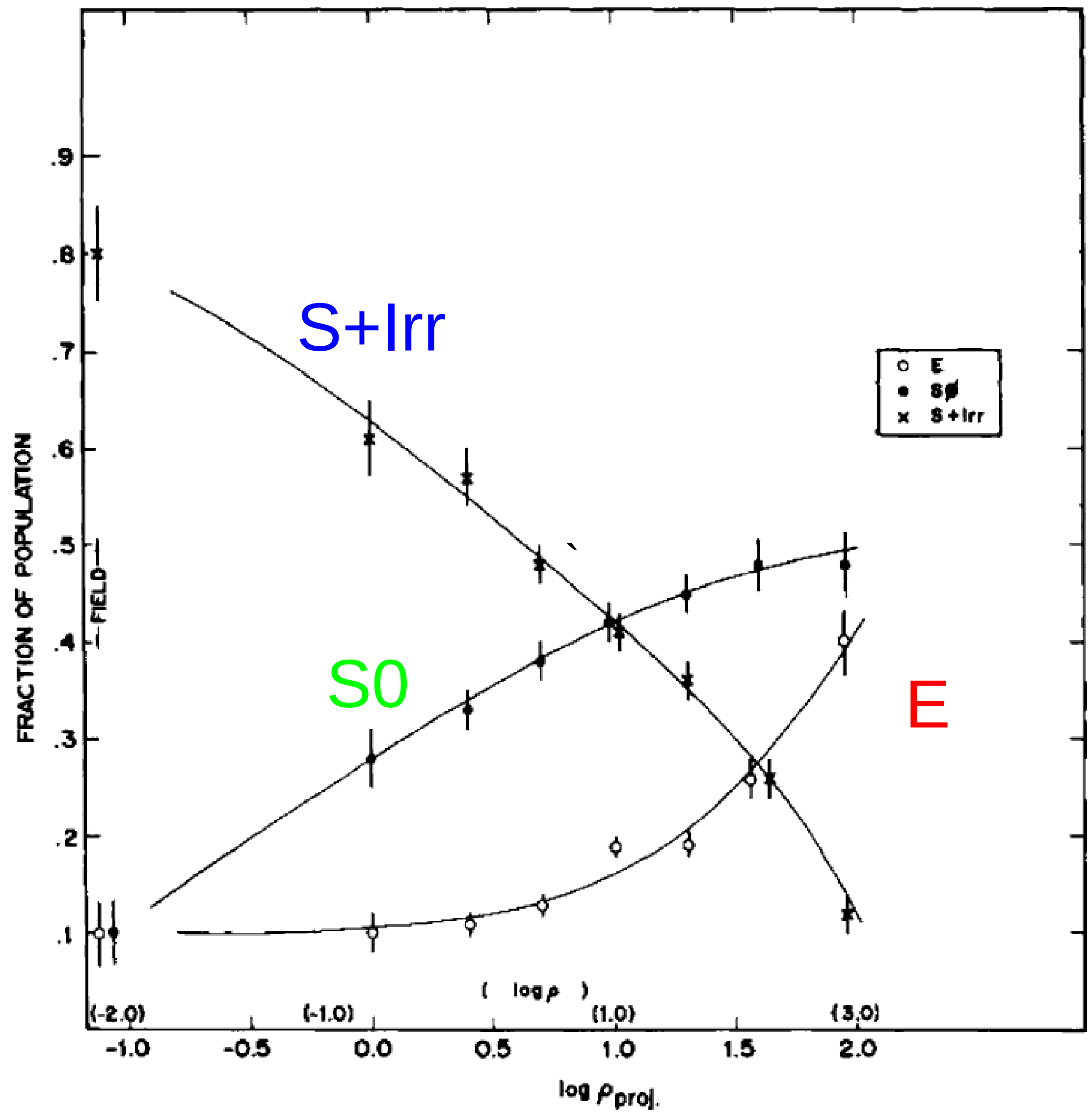


Fig. 3.4. The fractions of different morphological types of galaxy found in different galaxy environments. The local number density of galaxies is given as a projected surface density, $\varrho_{\rm proj}$ of galaxies, that is, numbers Mpc^{-2} (Dressler, 1980)

Brightest Cluster Galaxies (BCGs)

-Larger than typical ellipticals (50-100 kpc halo)

-Have higher velocity dispersion (300-400 km/s)

-Larger fraction of dark matter

-Different fundamental plane projections

- More likely to be radio loud

Burns 1990, but see also Best et al 2005b

e.g. Sandage & Hardy 1973

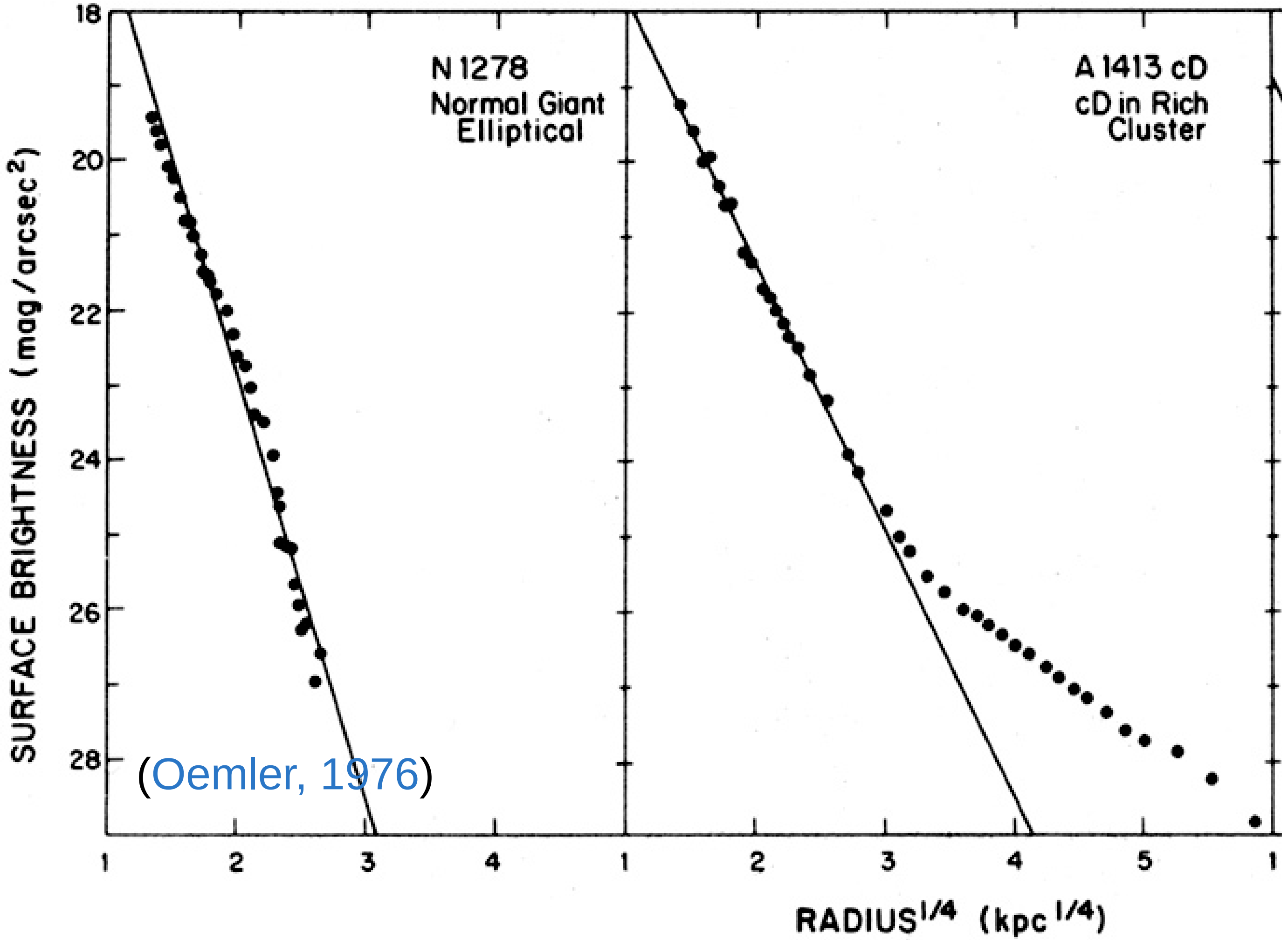
(von der Linden et al 07)

Are BCGs special? (Yes ?)

BCG environment: ~100 galaxies / Mpc^3

Galaxies outside clusters: < 10 galaxies / Mpc^3

BCGs include cD galaxies and Es



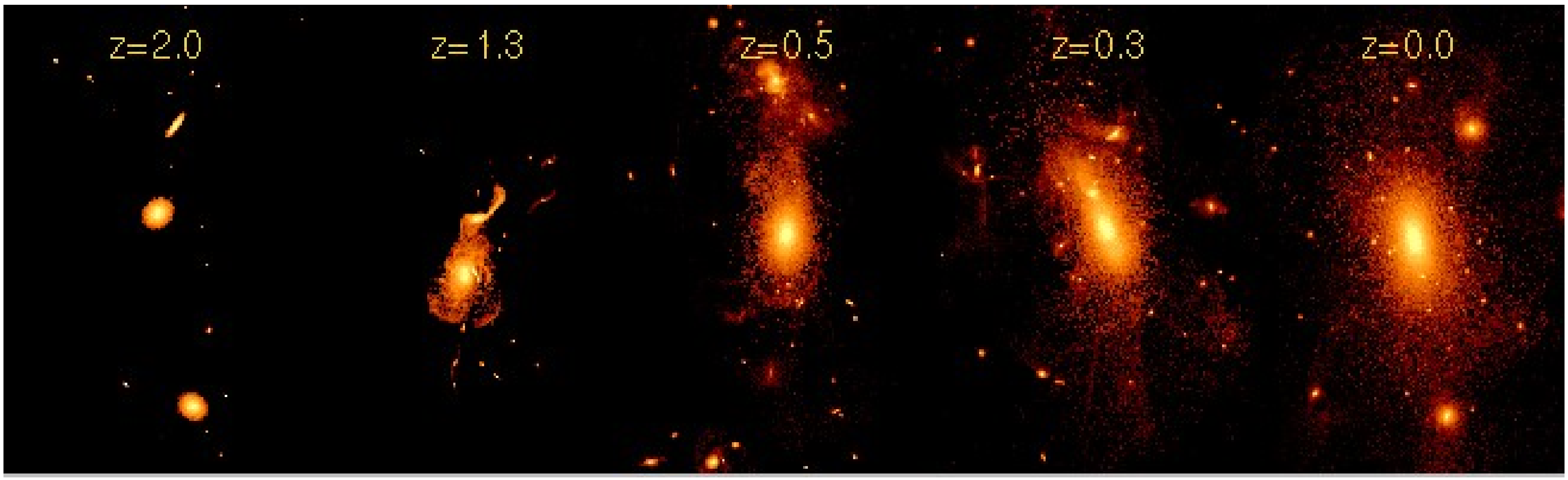
Magnitudes per square second of arc Vs one-fourth power of the radius. The dots are the observed points, and the straight lines are de Vaucouleurs fits to the inner points.

Figure reproduced from the book 'X-ray emission from clusters of galaxies ' by Sarazin.

Formation and evolution of BCGs

Connected to the formation of the cluster itself

Snapshots of the evolution of the cluster and BCG



Dubinski et al 1998

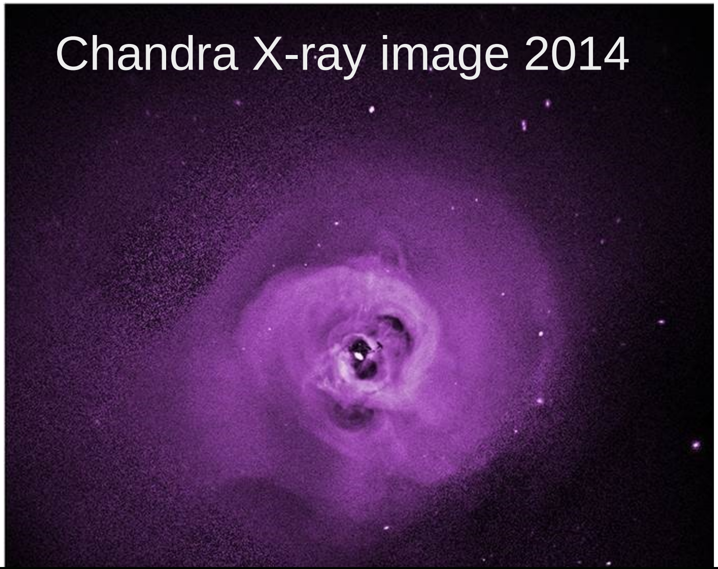
Each strip is 1 Mpc wide. The top strip shows the view perpendicular to the chain of 3 galaxies which fall together to make the BCG.

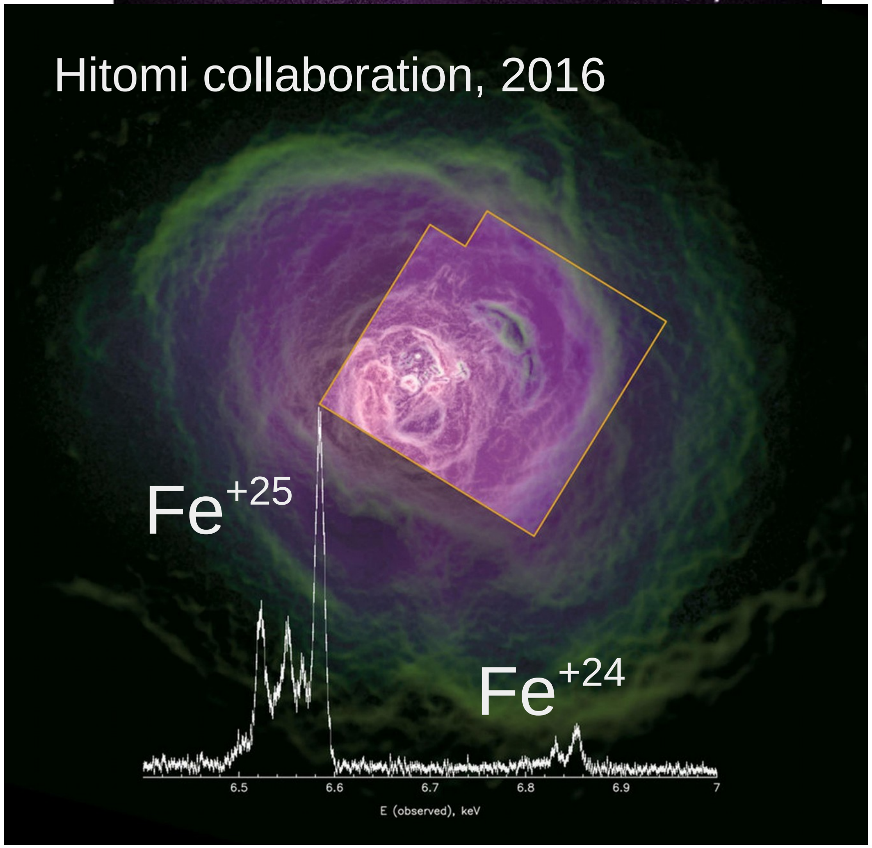
What about cluster X-rays ?

- X-rays are not visible from Earth so the discovery of X-rays from clusters happened much later.
- Felten (1966) : Thermal Bremsstrahlung as the mechanism behind the X-ray emission from the Coma cluster. The one they chose to explain turned out to be spurious, but later there were confirmed detections.
- Temperatures of 10^8 K predicted.

Confirmation

- Fe^{+24} and Fe^{+25}, 7 keV line confirmed the state of the ICM Perseus cluster: Mitchell et al 1976
- Cavaliere et al. 1971 first proposed that extended X-ray sources are groups and galaxy clusters.

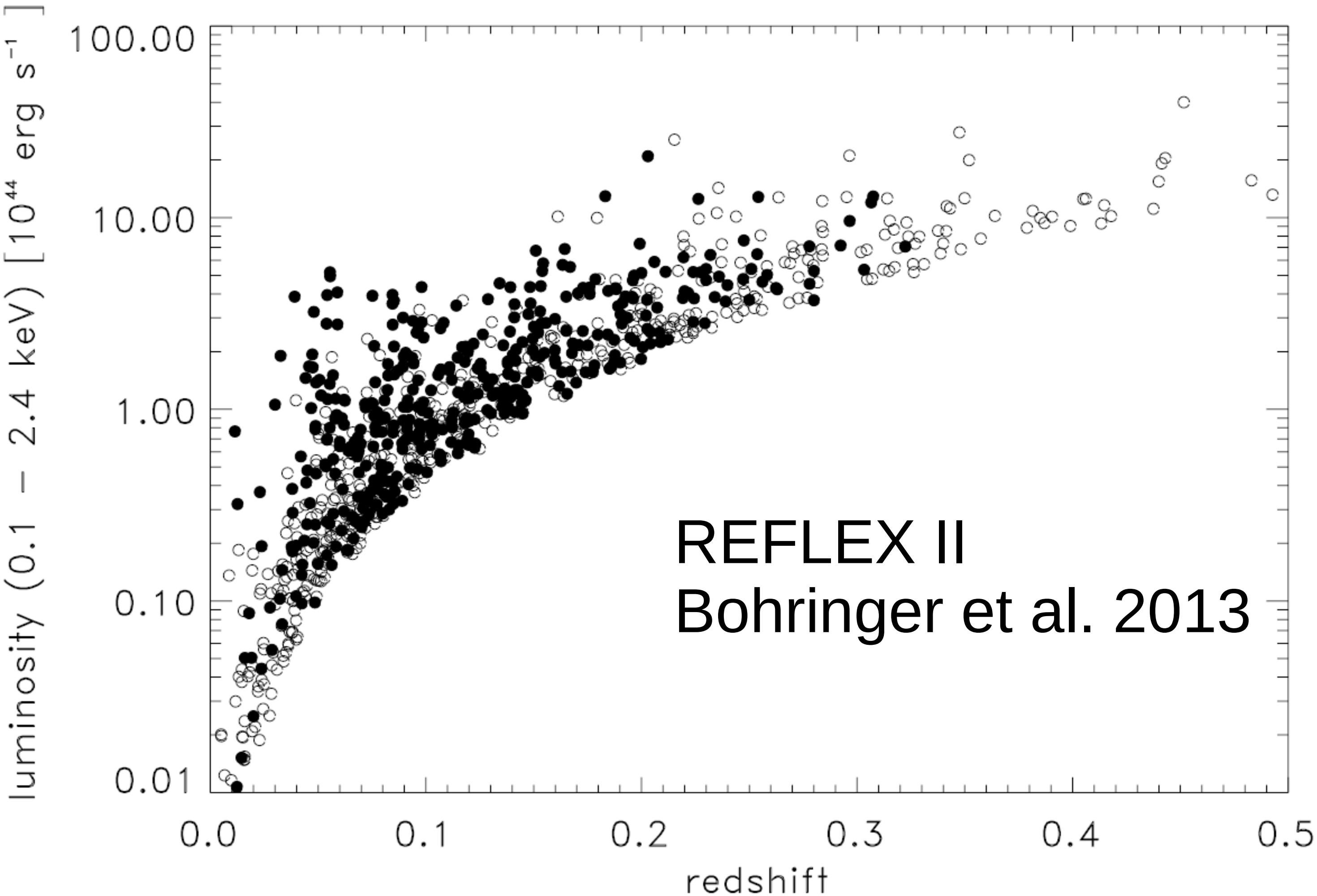




Perseus cluster: X-ray observations providing detailed structure of the ICM

X-ray surveys: ROSAT

Operational in 1990s



Soft X-rays 0.1 – 2.4 keV: About 4000 clusters detected.

Cooling of X-ray gas

- Thermal Bremsstrahlung emissivity

$$\epsilon^{ff} = 1.435 \times 10^{-27} \bar{g} T_g^{1/2} n_e \sum_i Z_i^2 n_i \,\mathrm{ergs\,cm^{-3}\,s^{-1}}$$

$$\approx 3.0 \times 10^{-27} T_g^{1/2} n_p^2 \,\mathrm{ergs\,cm^{-3}\,s^{-1}}$$

$$t_{cool} = 8.5 \times 10^{10}\,\mathrm{yr} \left(\frac{n_p}{10^{-3}\,\mathrm{cm}^{-3}} \right)^{-1} \left(\frac{T_g}{10^8\,\mathrm{K}} \right)^{1/2}$$

Compare with Hubble time (or age of the Universe)

Sarazin 1999
Rybicki and Lightman

Cooling of X-ray gas

- Accumulation of cool gas at the cluster core- run away cooling.
- Such cool gas should start to form stars at rates of 100s to 1000 of solar masses per year.
- Proposed in 1990s
- But no evidence for such cool gas :

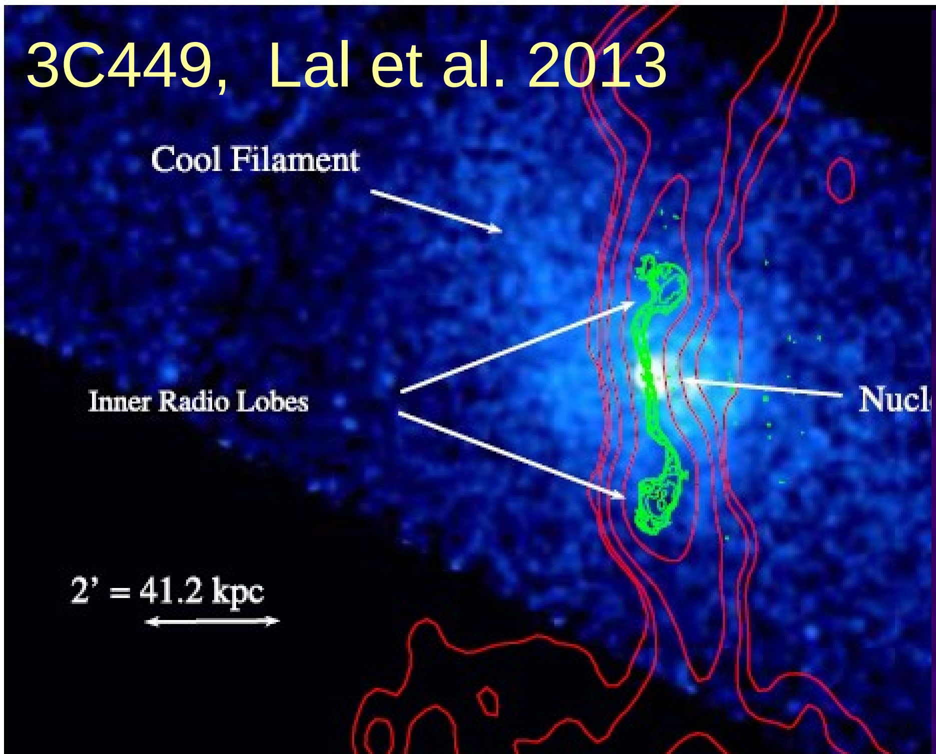
  Chandra and XMM Newton satellites in early 2000s solved the cooling flow problem.

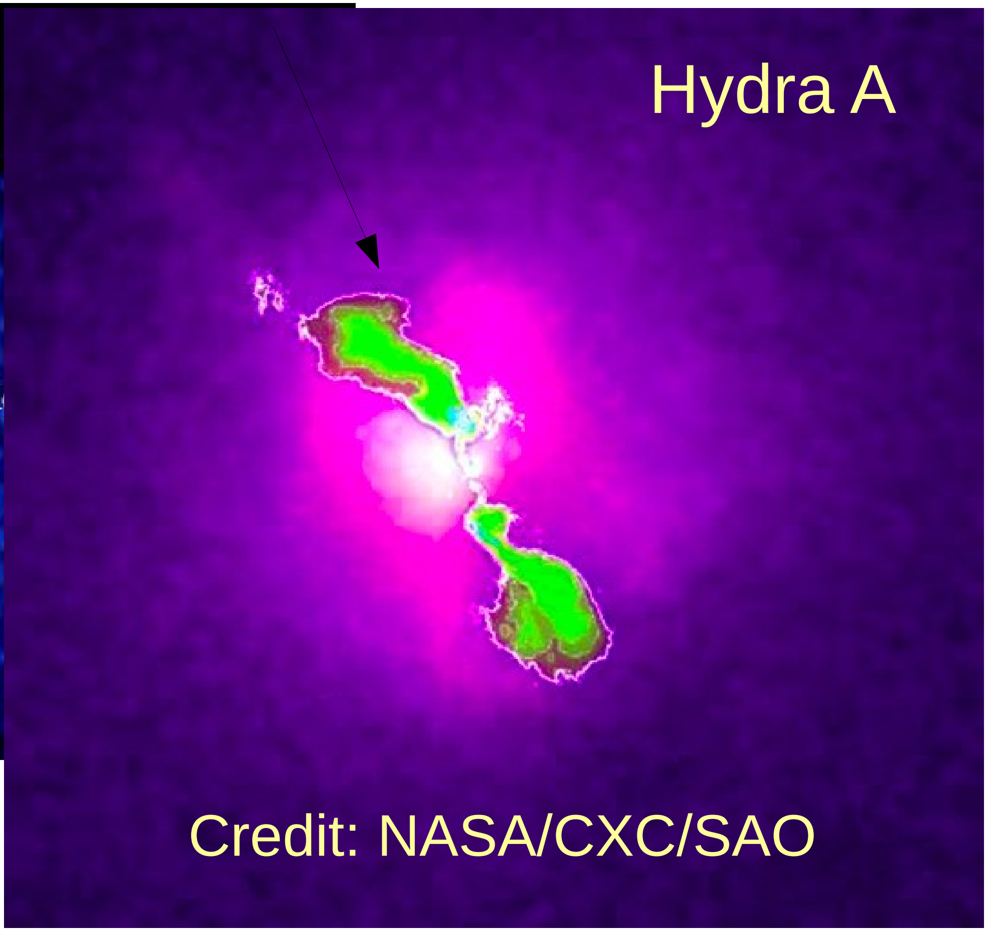
Cooling of X-ray gas

- What keeps the gas at cluster cores from cooling ?
- Feedback ? !

Feedback by central galaxies

Cavities in X-ray gas by jets and lobes from galaxies



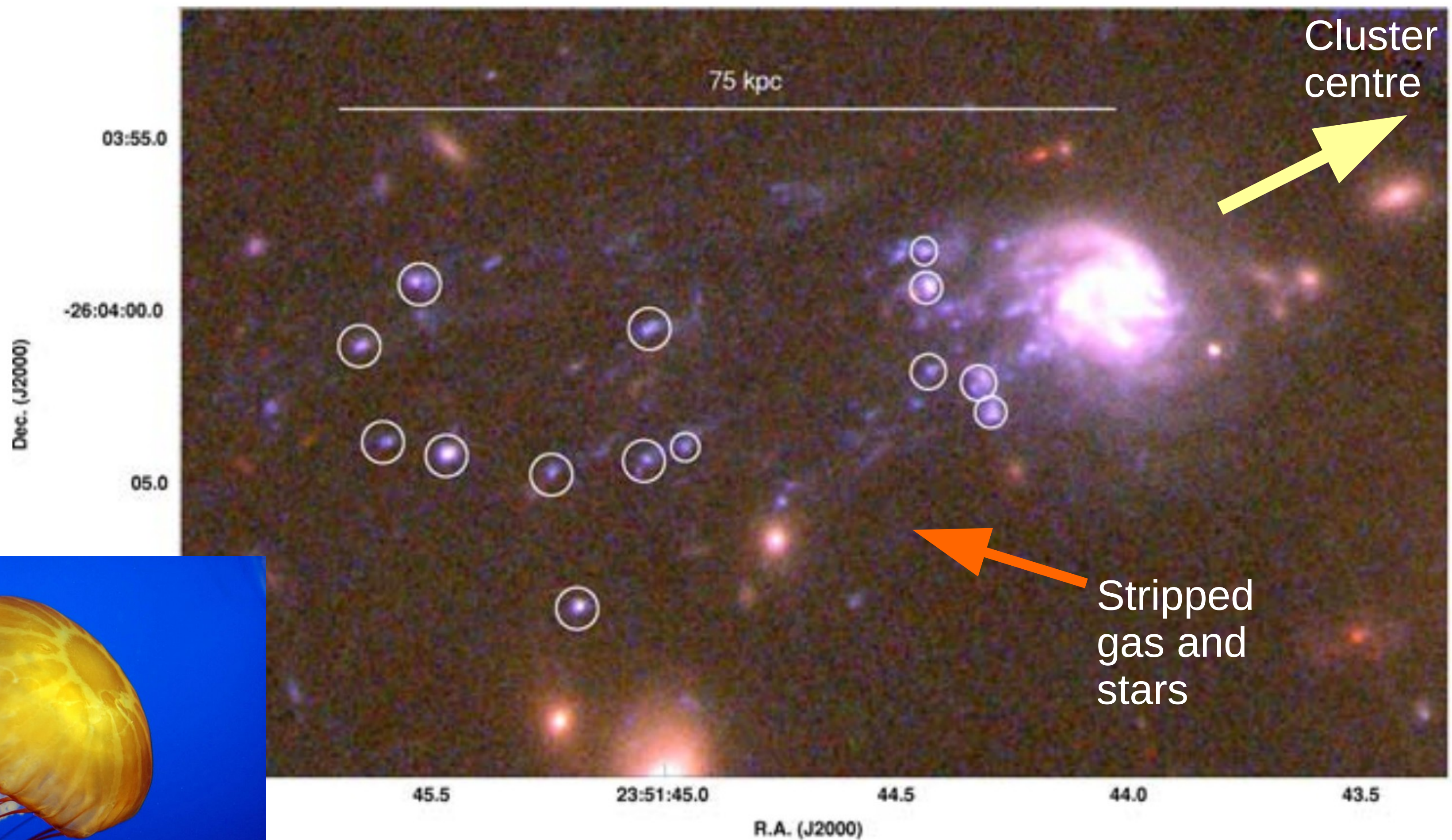


Open issues: Is this enough to keep the cluster cores hot? Or are there other contributors to the heating ?

Transformation of galaxies during infall

Galaxies falling into cluster potential experience extreme ram pressure stripping

Example:
Jellyfish
galaxies



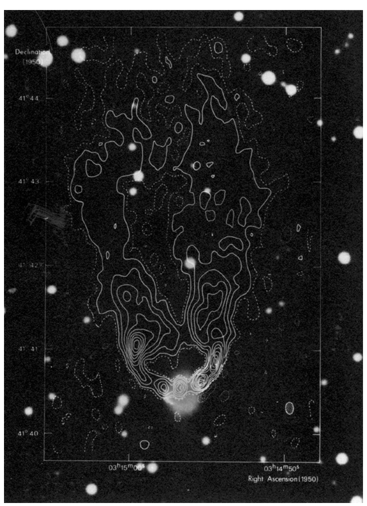
e. g. Poggianti et al Nature 2018

Transformation of galaxies during infall

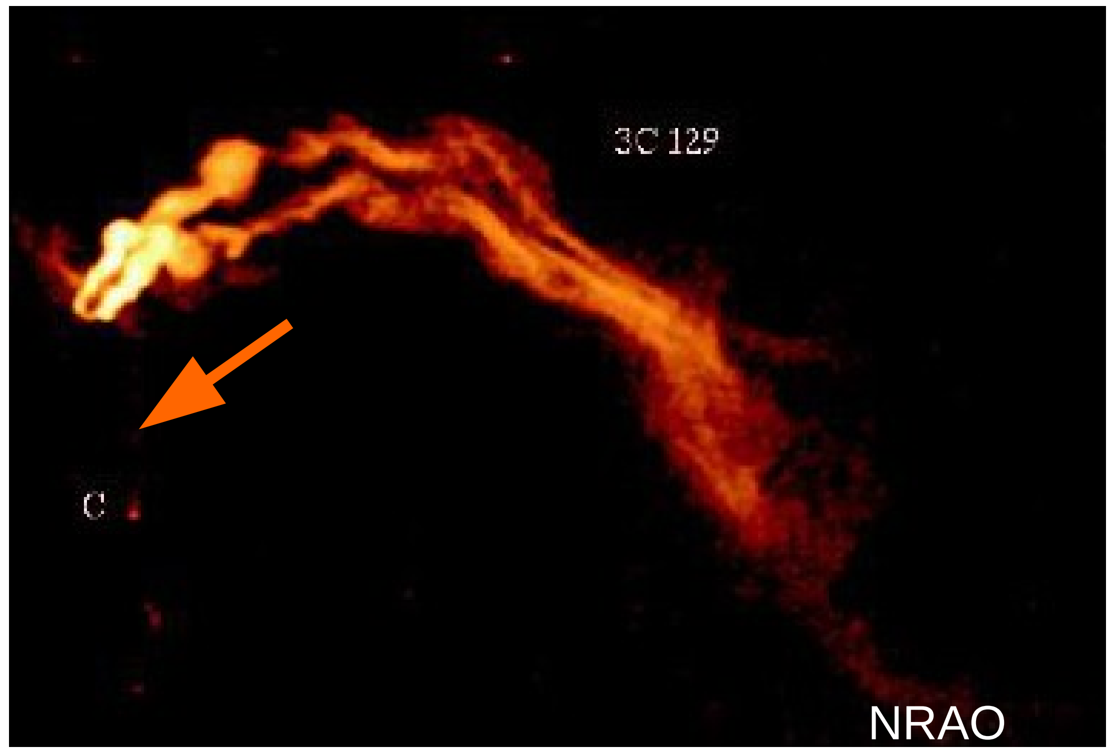
Galaxies falling into cluster potential experience extreme ram pressure stripping

Example:

Head-tail galaxies: bending of radio jets



NGC 1265

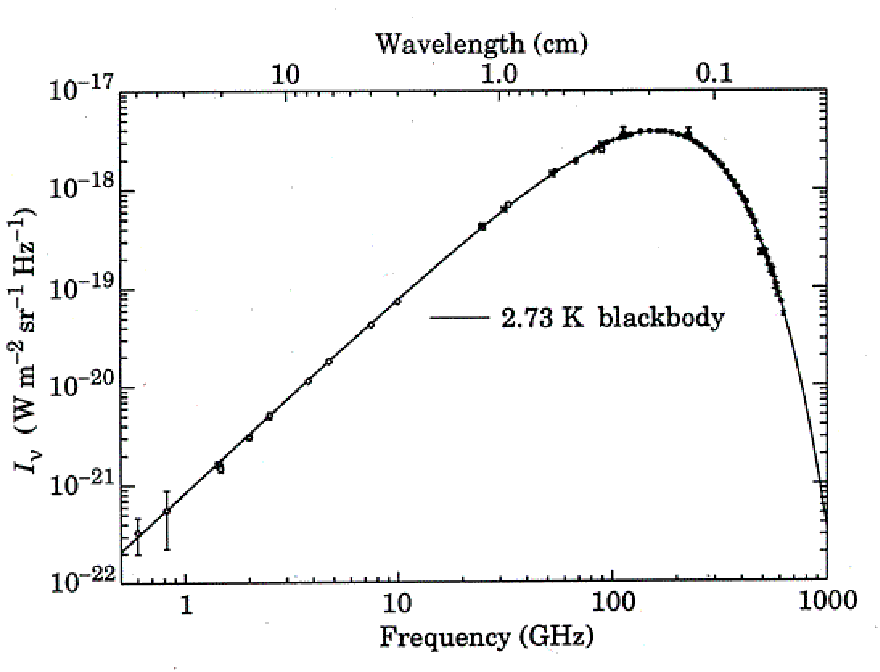


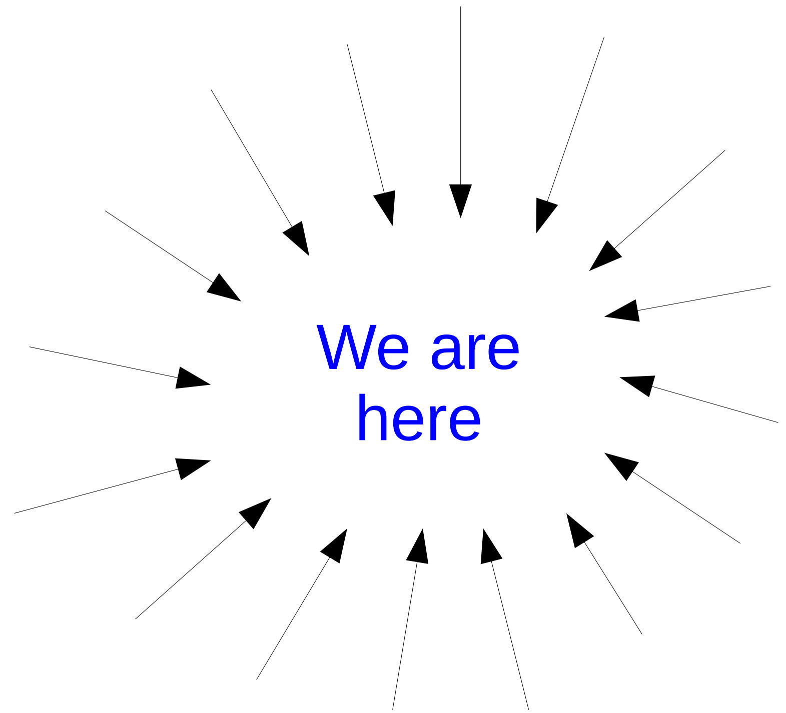
e. g. Poggianti et al Nature 2018

Detecting clusters through their effect on the Cosmic Microwave Background Radiation

Cosmic Microwave Background

- Cosmic Microwave Background Radiation
- 2.73 K black body

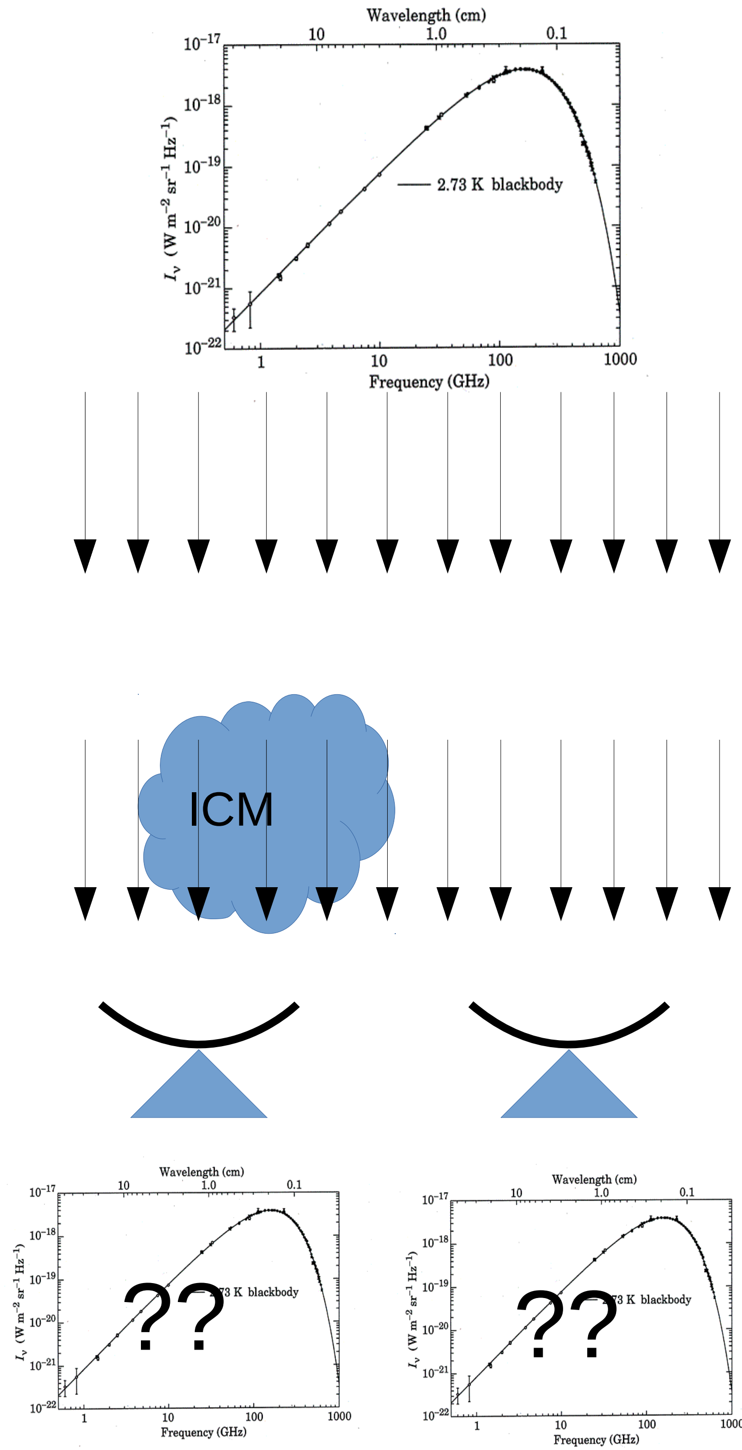




Forms a background to everything that we observe

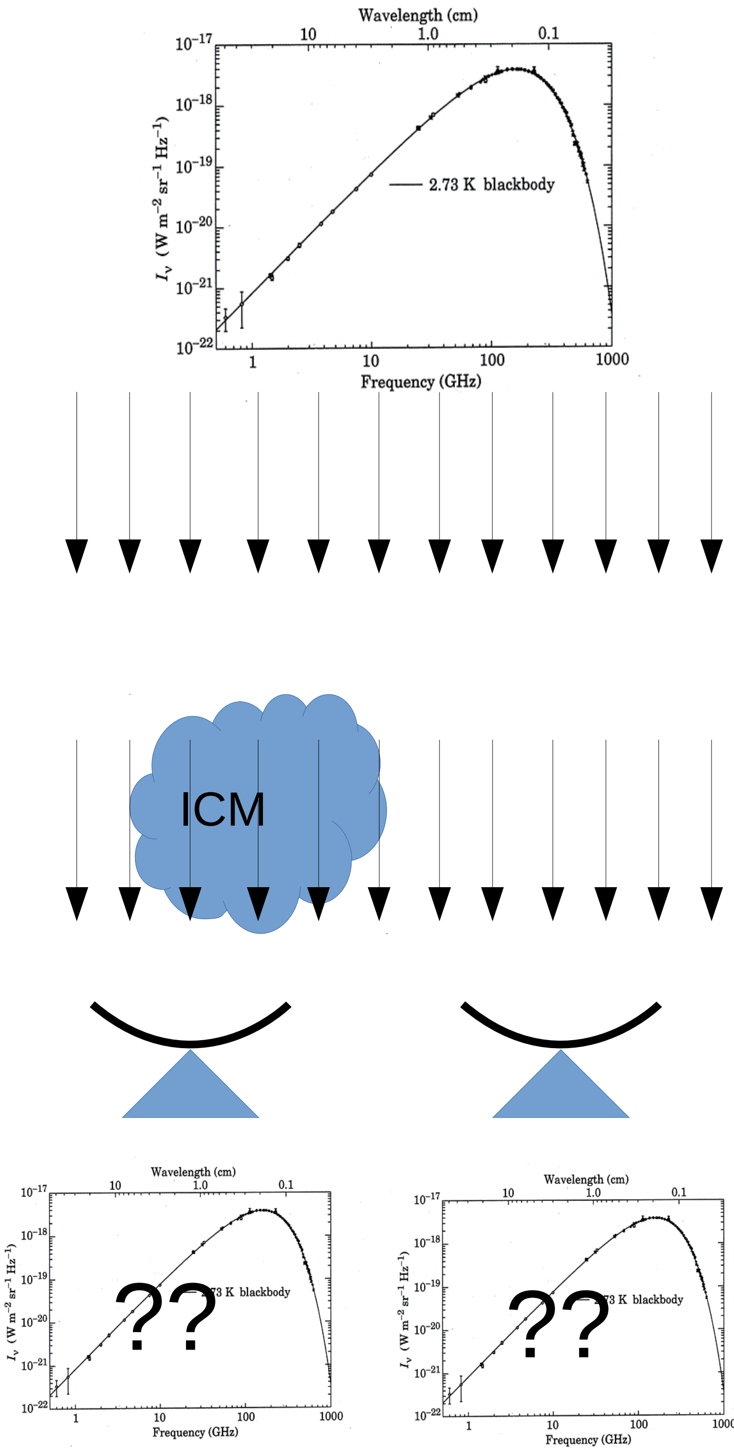
CMB: through ICM ?

- Cosmic Microwave Background Radiation
- 2.73 K black body



CMB: through ICM ?

- Cosmic Microwave Background Radiation
- 2.73 K black body
- CMB photons upscattered by the electrons in the ICM
- Decrement in the CMB at low frequencies and an increment at higher frequencies



Sunyaev and Zel'dovich 1972

Sunyaev-Zel'dovich effect

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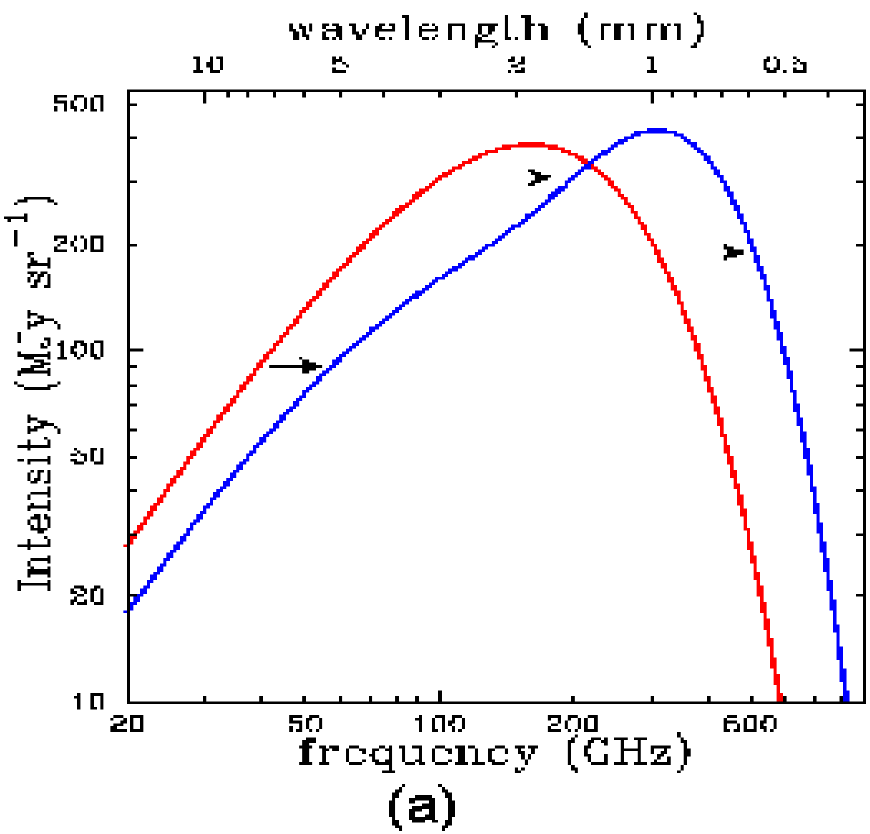

Image:Bertoldi 2002

Sunyaev and Zel'dovich 1972

Sunyaev-Zel'dovich effect

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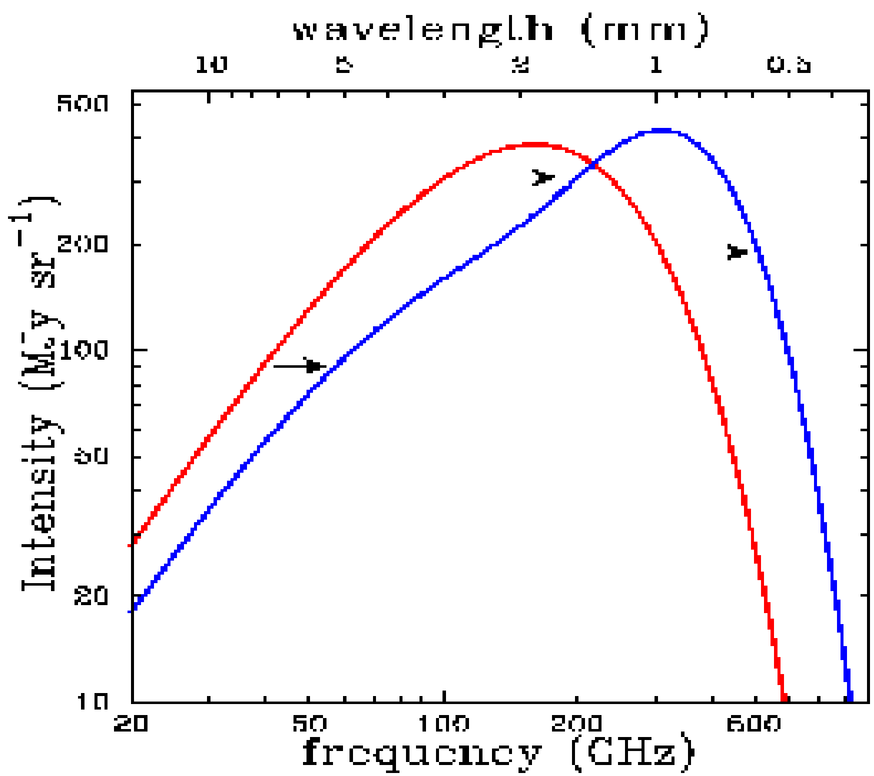


(a)

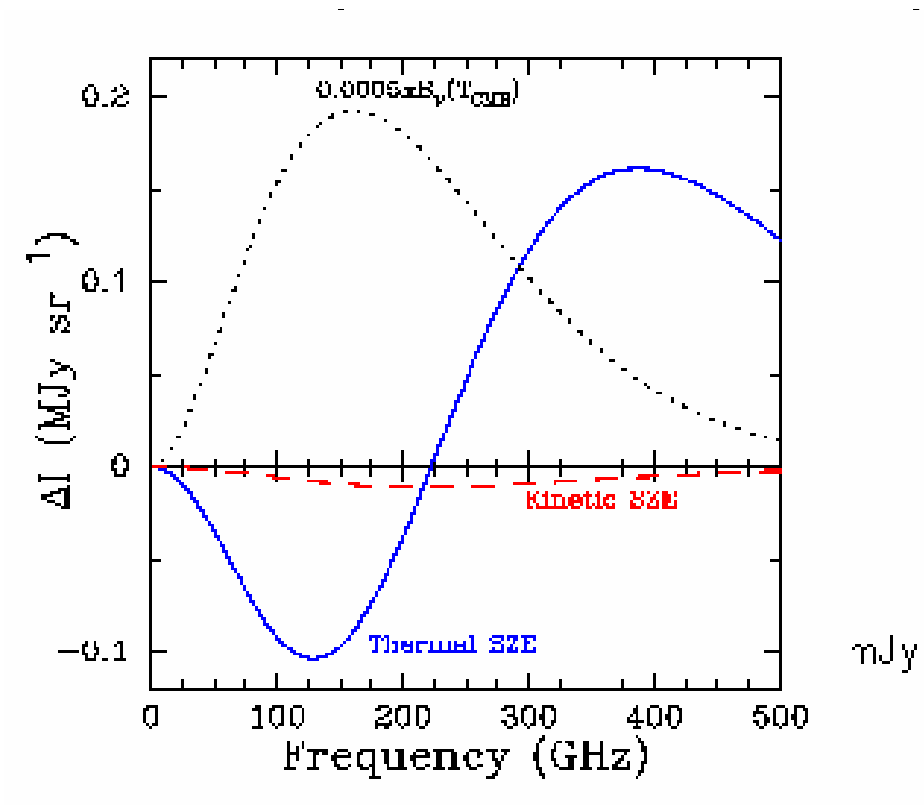
Image:Bertoldi 2002

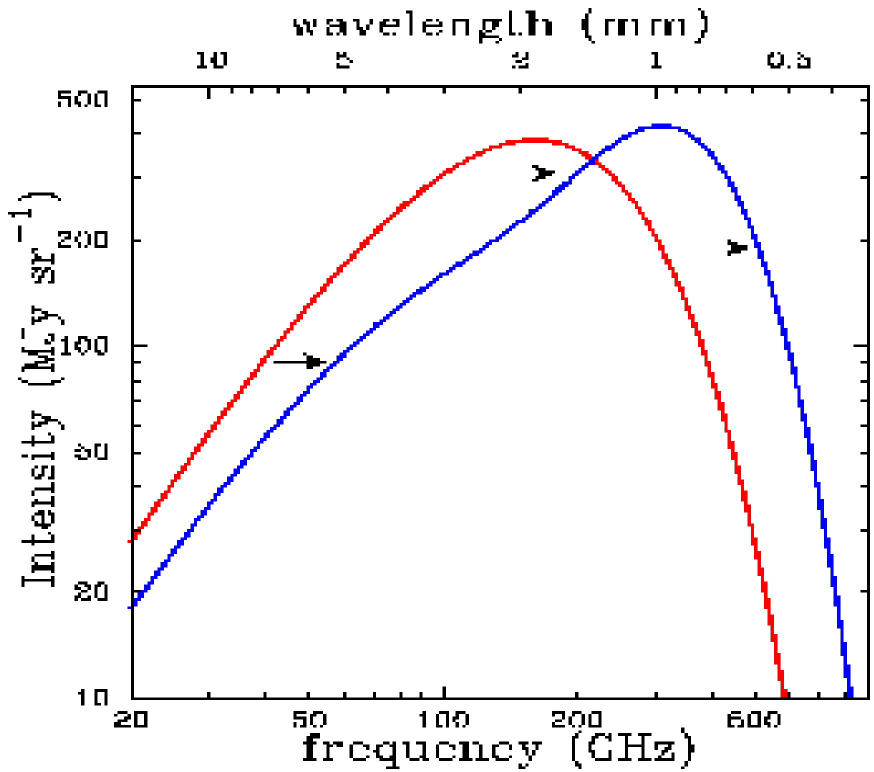
$$\frac{\Delta T}{T_{\rm CMB}} = g(x) \int dl\, n_e(l)\, \frac{k_B\, T_e(l)}{m_e c^2}\, \sigma_T$$

Sunyaev and Zel'dovich 1972

Sunyaev-Zel'dovich effect

- Cosmic Microwave Background Radiation
- 2.73 K black body





(a)

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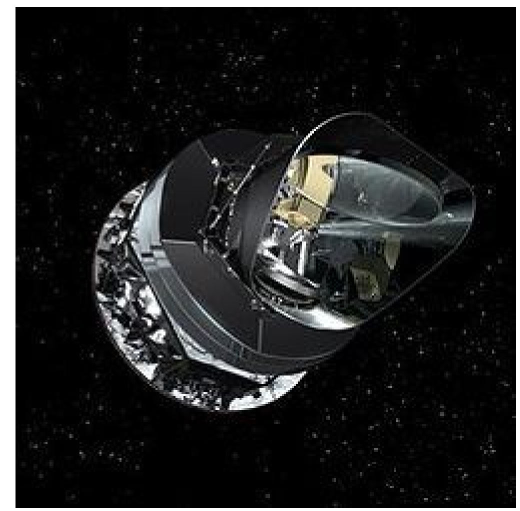
Sunyaev and Zel'dovich 1972

Sunyaev-Zel'dovich effect

- First detections of clusters using this effect in ~1983

Atacama Cosmology Telescope

South Pole Telescope



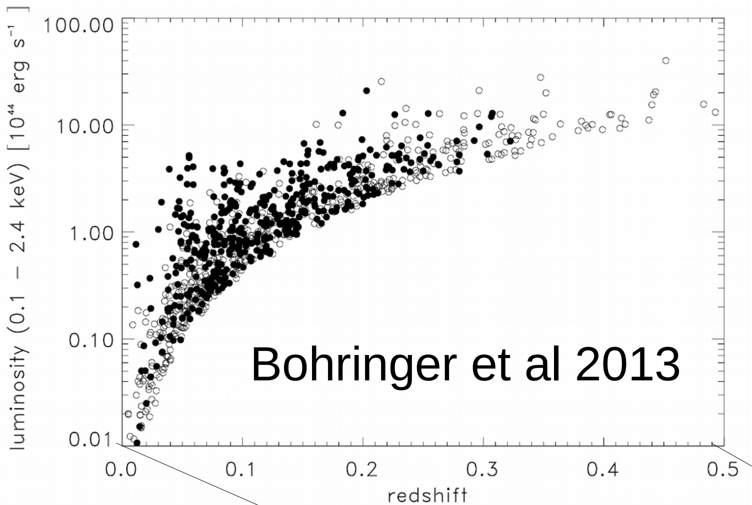
Planck satellite

These have started operations in the last 10 years and are ongoing experiments.
Hundreds of new clusters have been detected using the SZ effect.

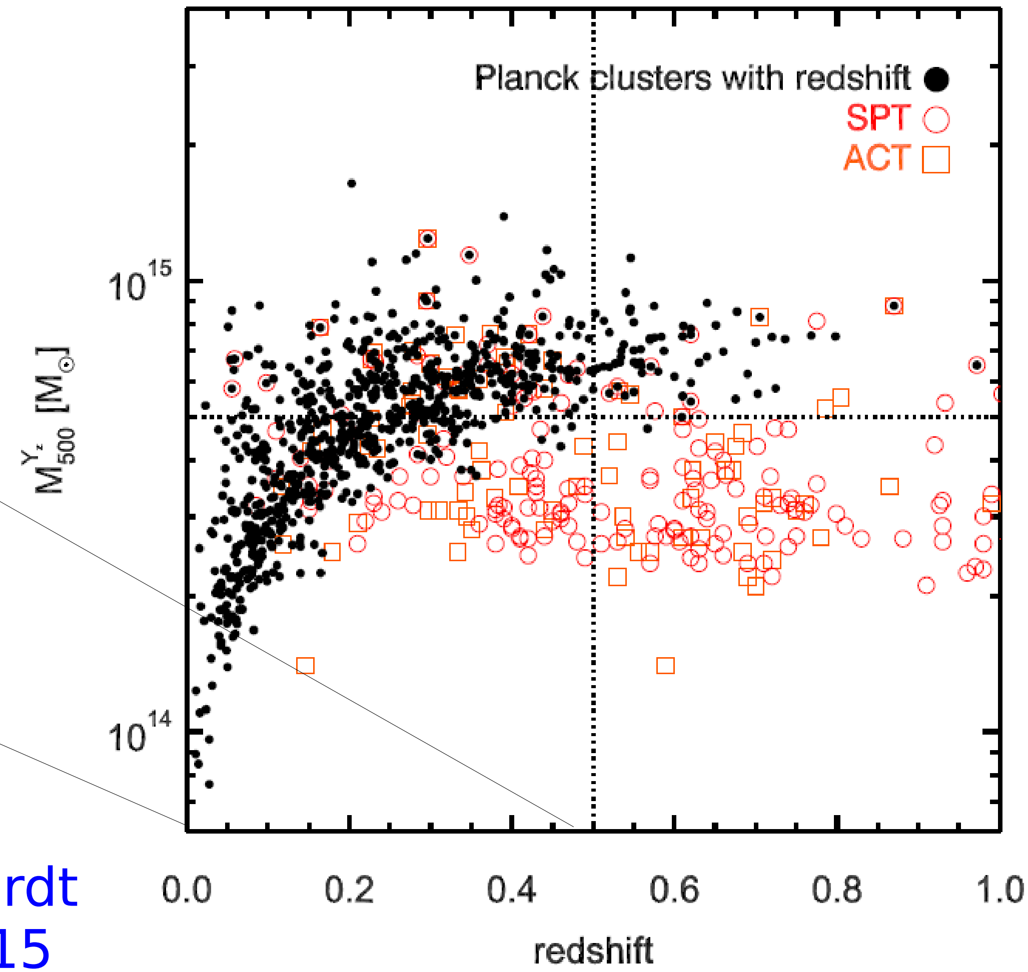
Sunyaev-Zel'dovich effect

- Pressure profiles of ICM possible up to distances of more than a Mpc from cluster centers- about 1.5 – 2 more times that possible with X-rays.
- Measure of mass of the cluster

Clusters from SZ surveys: Planck, SPT, ACT



Planck collaboration 2014



South Pole Telecope: Reichardt et al. 2013; Bleem et al. 2015
Atacama Cosmology Telescope: Marriage et al. 2011; Hasselfield et al. 2013

Clusters in radio bands ?

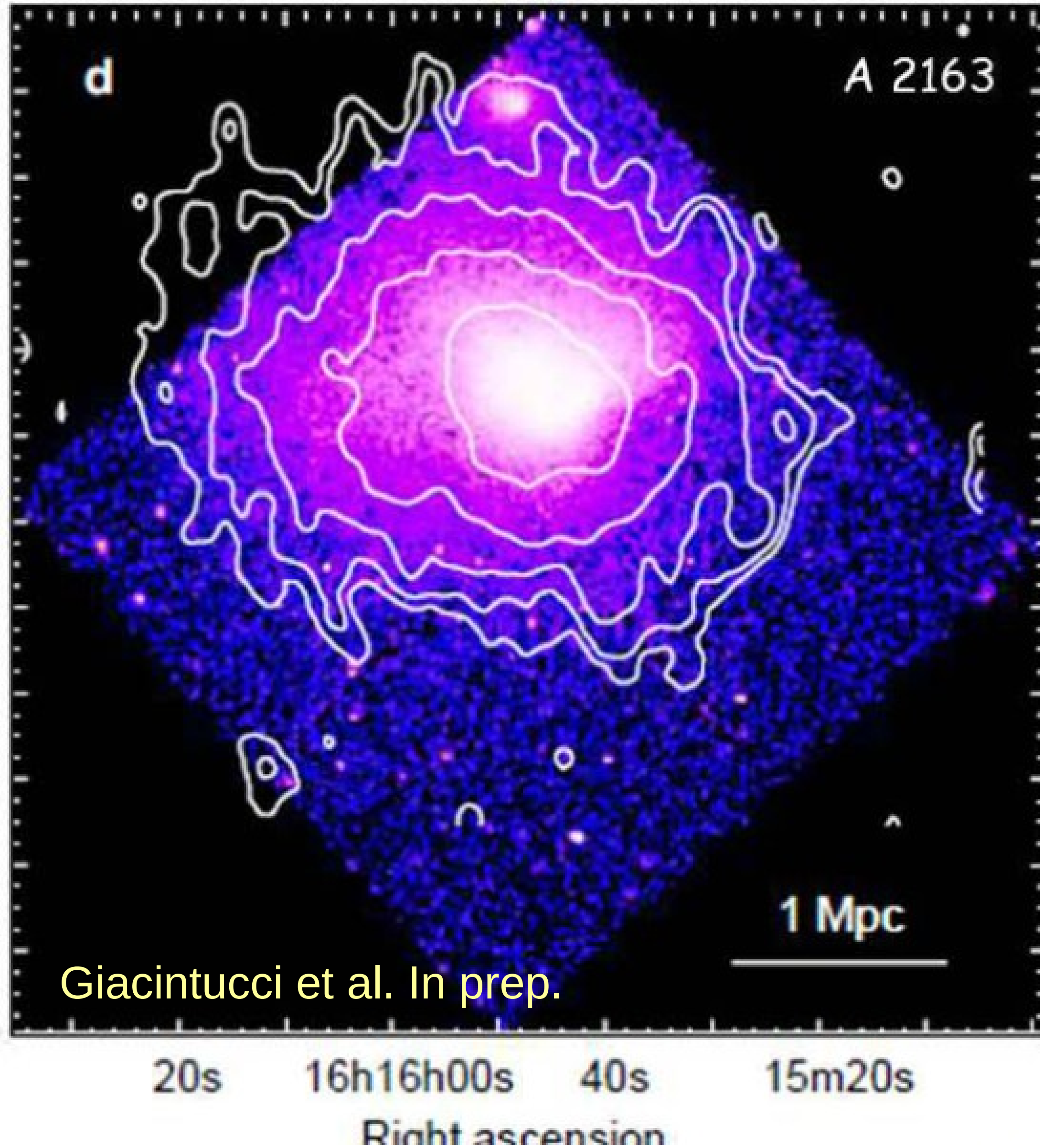
Cluster scale sources: Radio halos

700 kpc - 2 Mpc sizes: Several **arcminutes to a degree** for clusters in redshift range 0.5 – 0.02

Radio power at 1.4 GHz ~ $10^{24\text{-}26}$ W/Hz

Low surface brightness:
1- few μJy arcsec^{-2}

Nearly unpolarized



See Feretti and Giovannini 2012 for a review

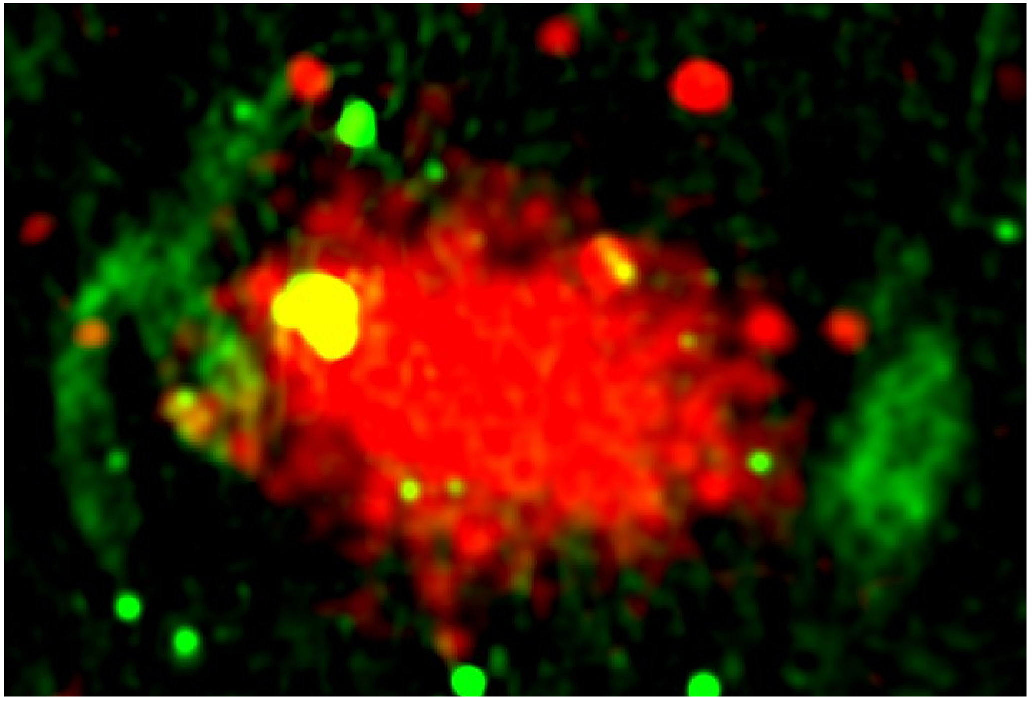
Radio relics

100s kpc to 2 Mpc sizes

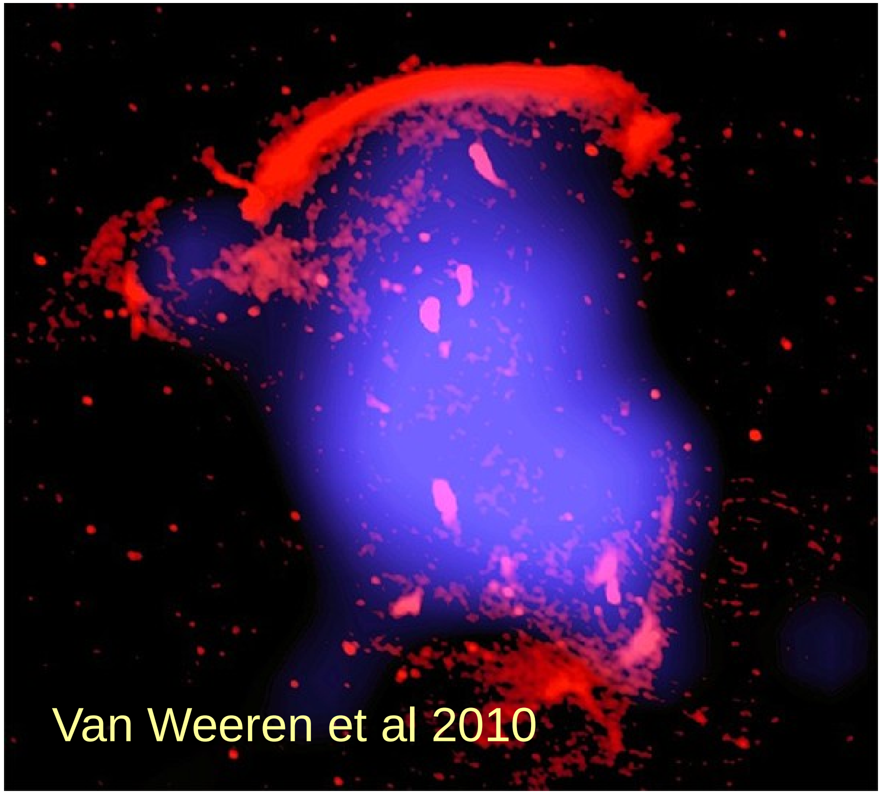
Polarized ~ few to 30%

Occur as single or in pairs

at cluster periphery



A3376 Bagchi et al 2006; Kale et al 2012
Colour: X-rays; Red: X-rays; Green: GMRT 330 MHz

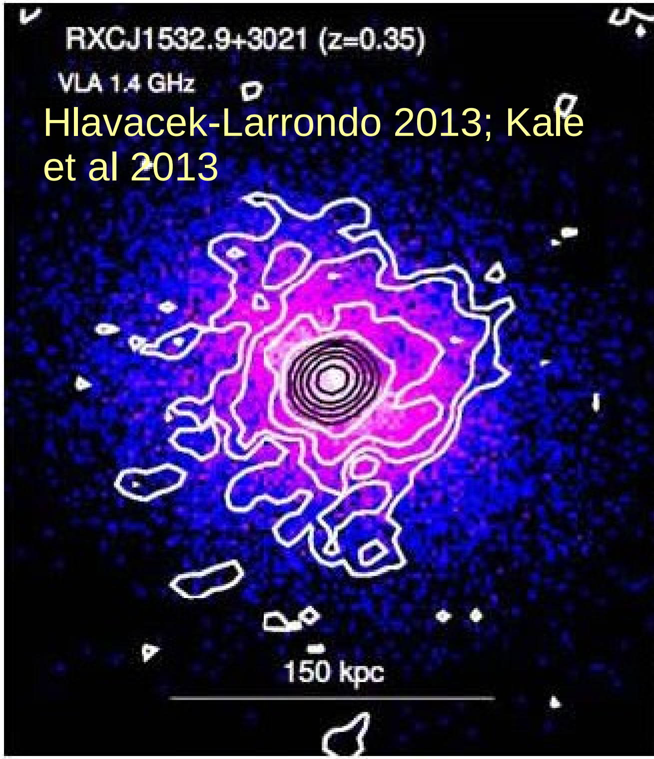


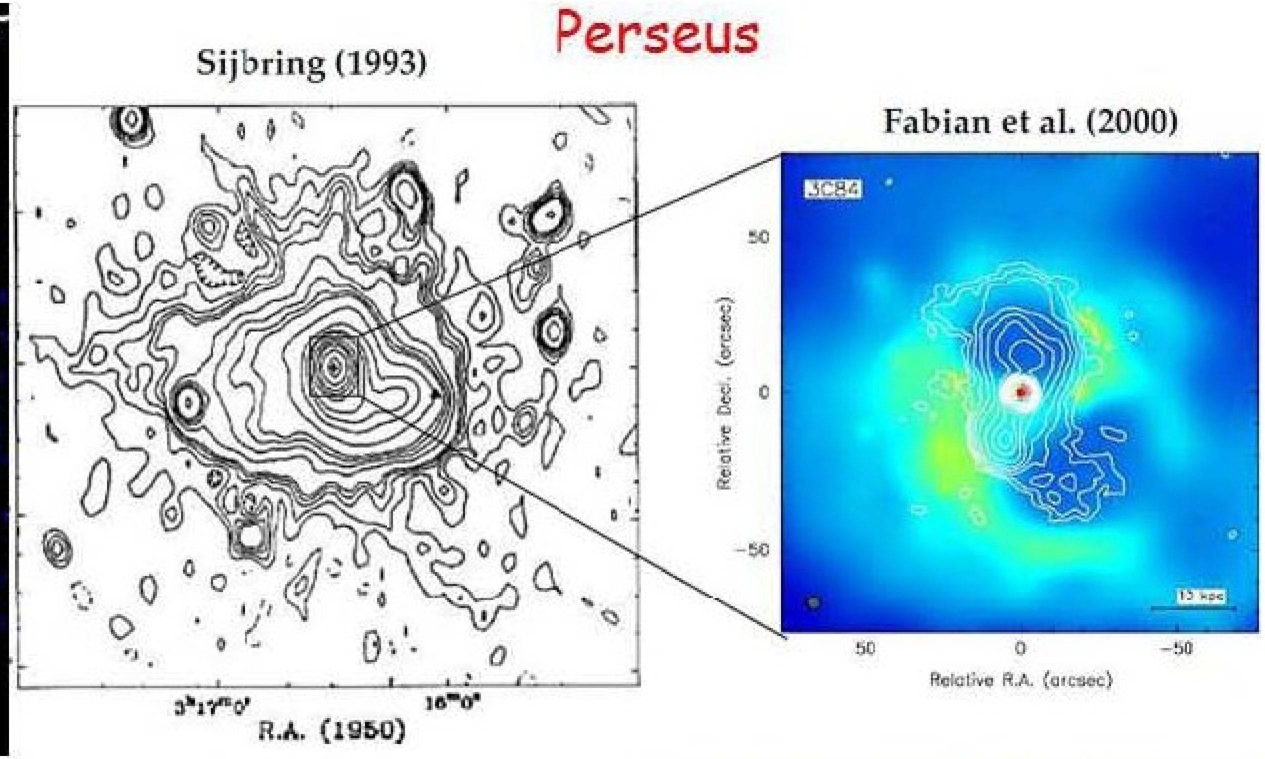
Located along elongation axis of X-ray emission (van Weeren et al. 2011)

Tracers of merger shocks (M<4)

Spectral steepening from outer to inner edge.

Radio mini-halos: cool-core clusters





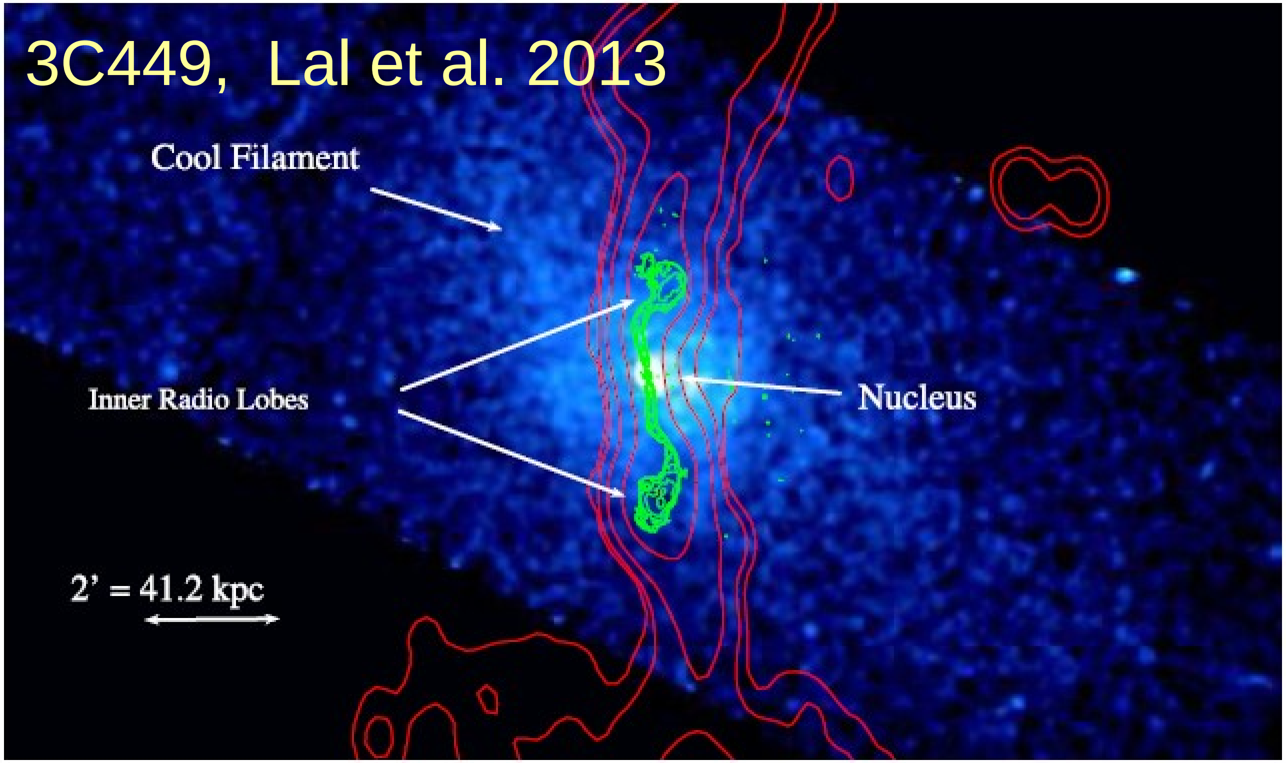
90 – 500 kpc sizes; surround central elliptical galaxy in cool-core clusters.

Central galaxy not sufficient to sustain the mini-halo in most cases; alternative source of relativistic electrons is needed. The radio activity of the galaxy certainly plays a role in providing the seed relativistic electrons.

Gitti et al 2002; Giacintucci & Mazzotta 2008;
Zuhone et al 2011;2014;2015

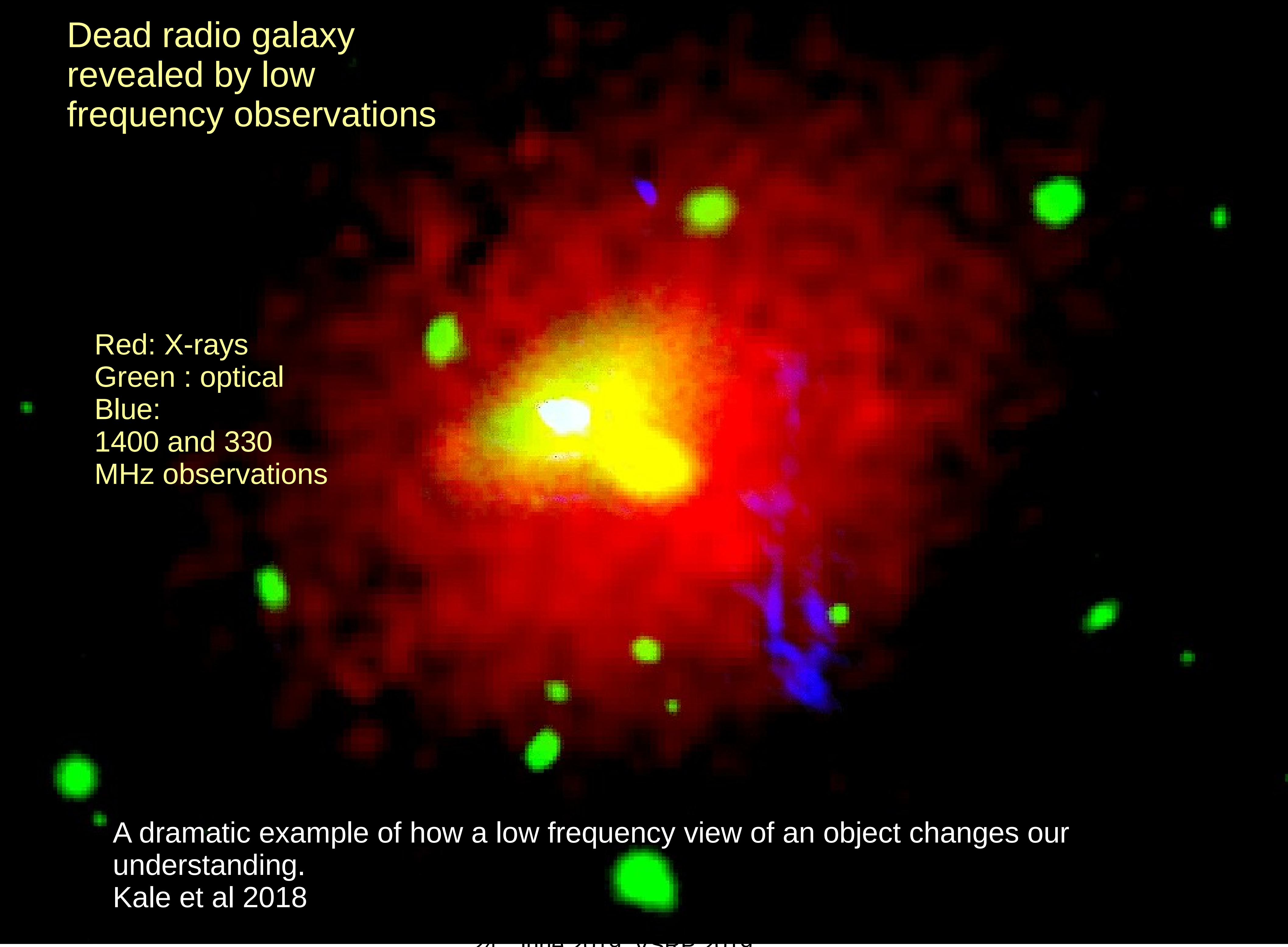
Dead radio galaxies: remnants

What happens after the central AGN switches off ? The jets and lobes will fade by losing energy to radiation and expansion. Can we detect such sources ?



Low frequency observations such as with the GMRT are ideal to detect such source.

Dead radio galaxy revealed by low frequency observations



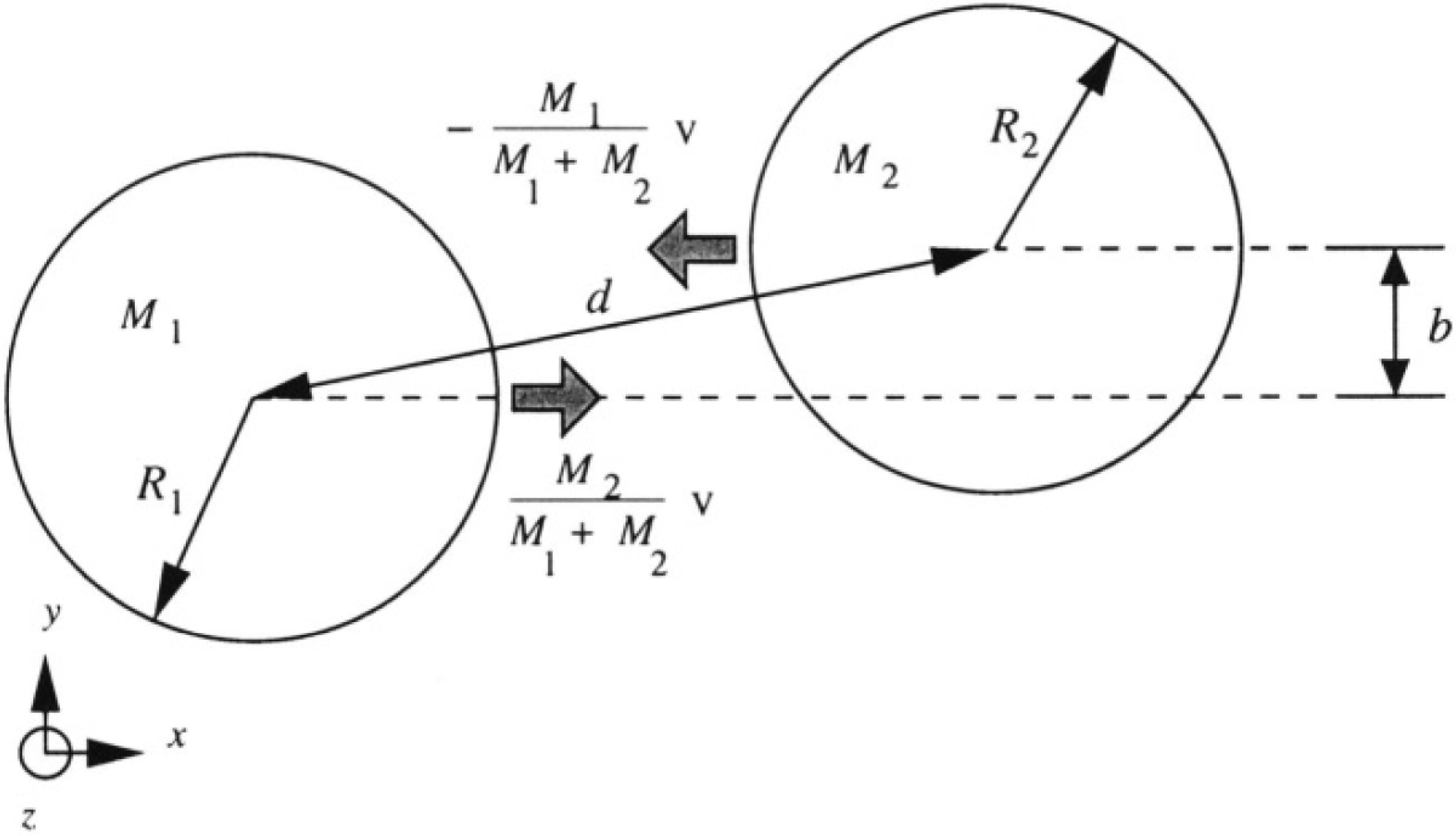
Red: X-rays
Green : optical
Blue:
1400 and 330
MHz observations

A dramatic example of how a low frequency view of an object changes our understanding.
Kale et al 2018

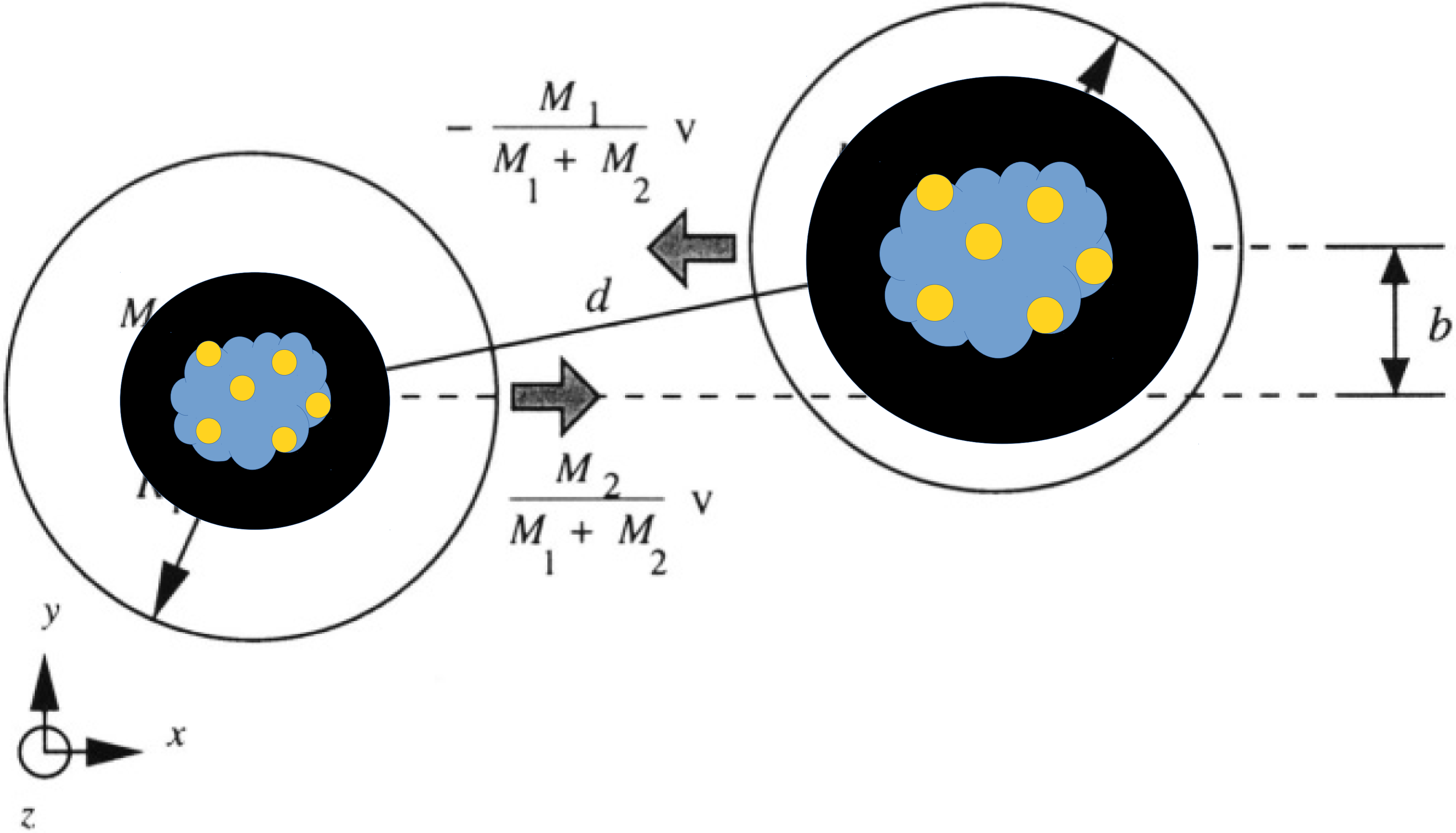
Open questions:

- What is the origin of the diffuse radio sources – how do the relativistic electrons attain those energies, what is the magnetic field ?
- Among all merging clusters why only a fraction (~50 %) have detectable level of radio emission ?
- Merging drives shocks and turbulence that may re-accelerate charged particles – but under exactly what conditions does this happen ?
- Energy content, magnetization, CR acceleration in the diffuse medium ?

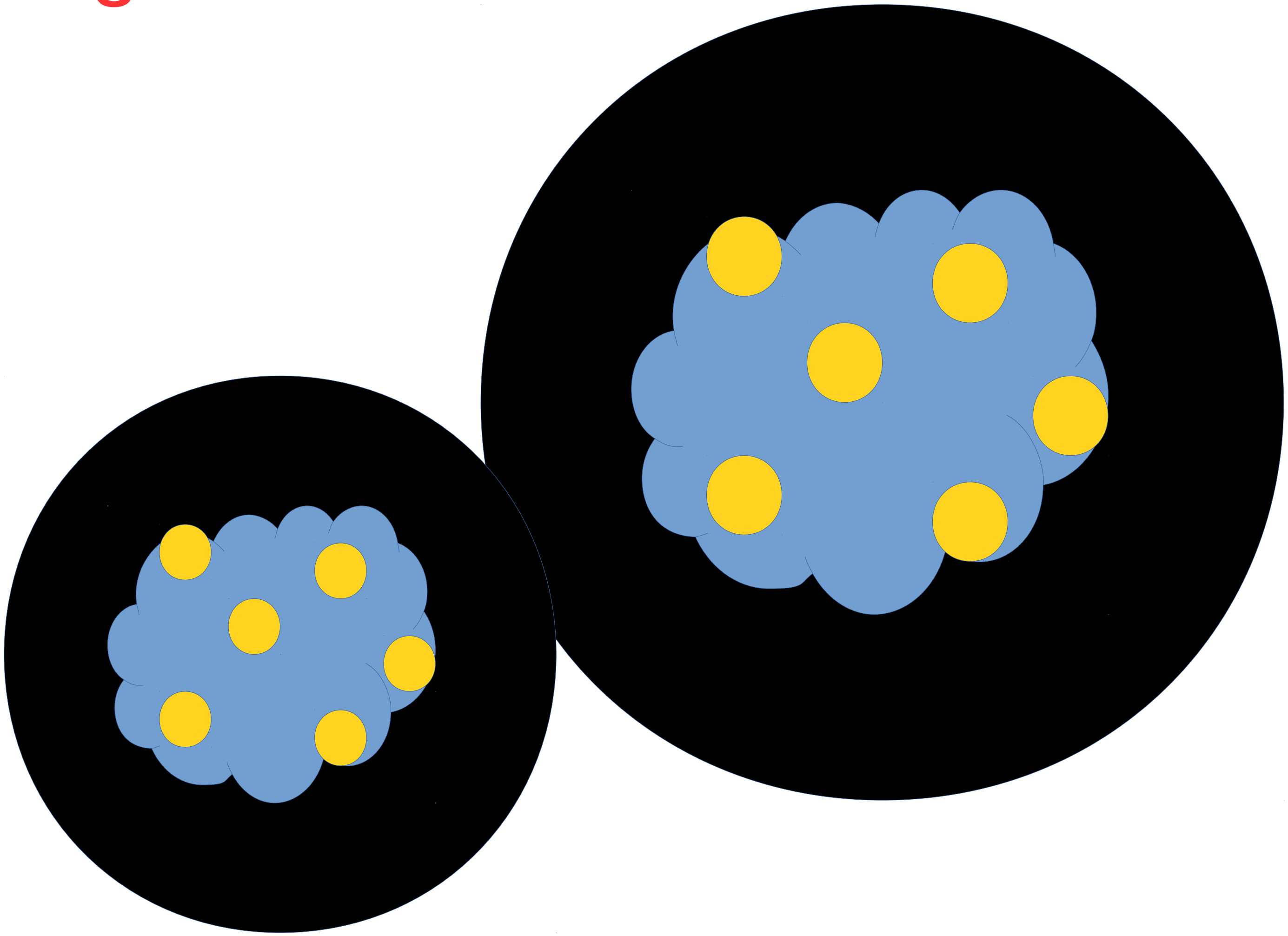
Colliding spheres



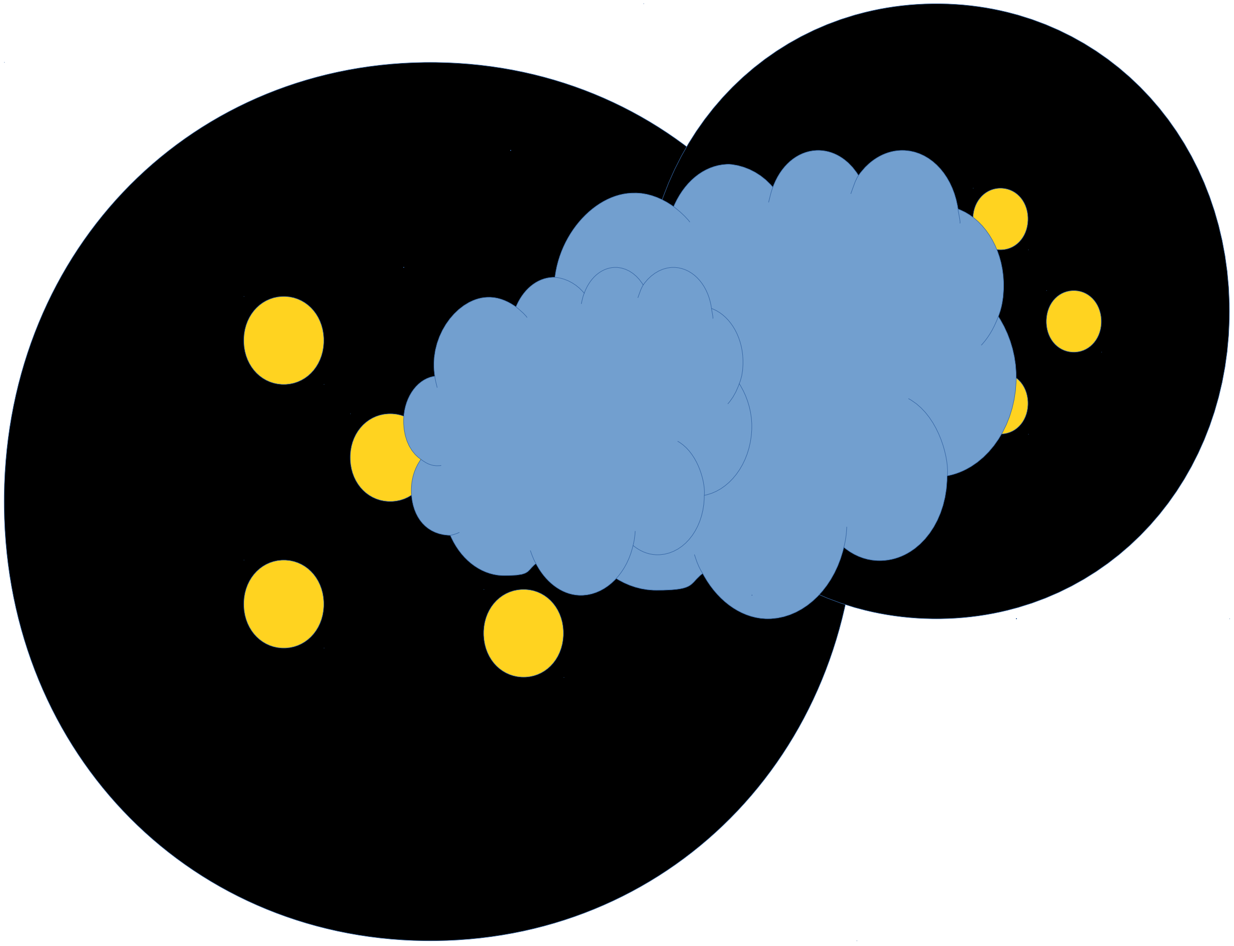
Colliding clusters



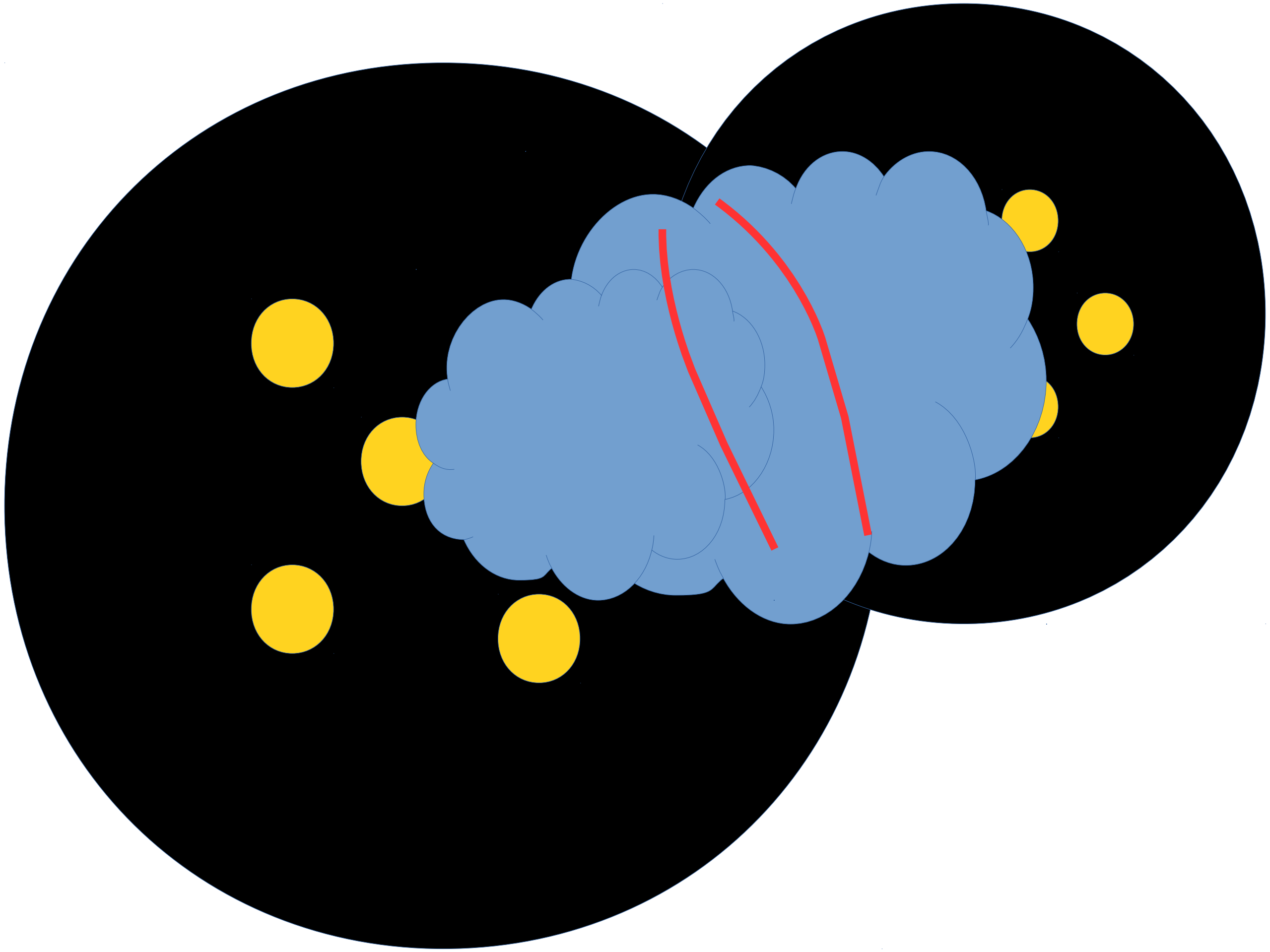
Colliding clusters



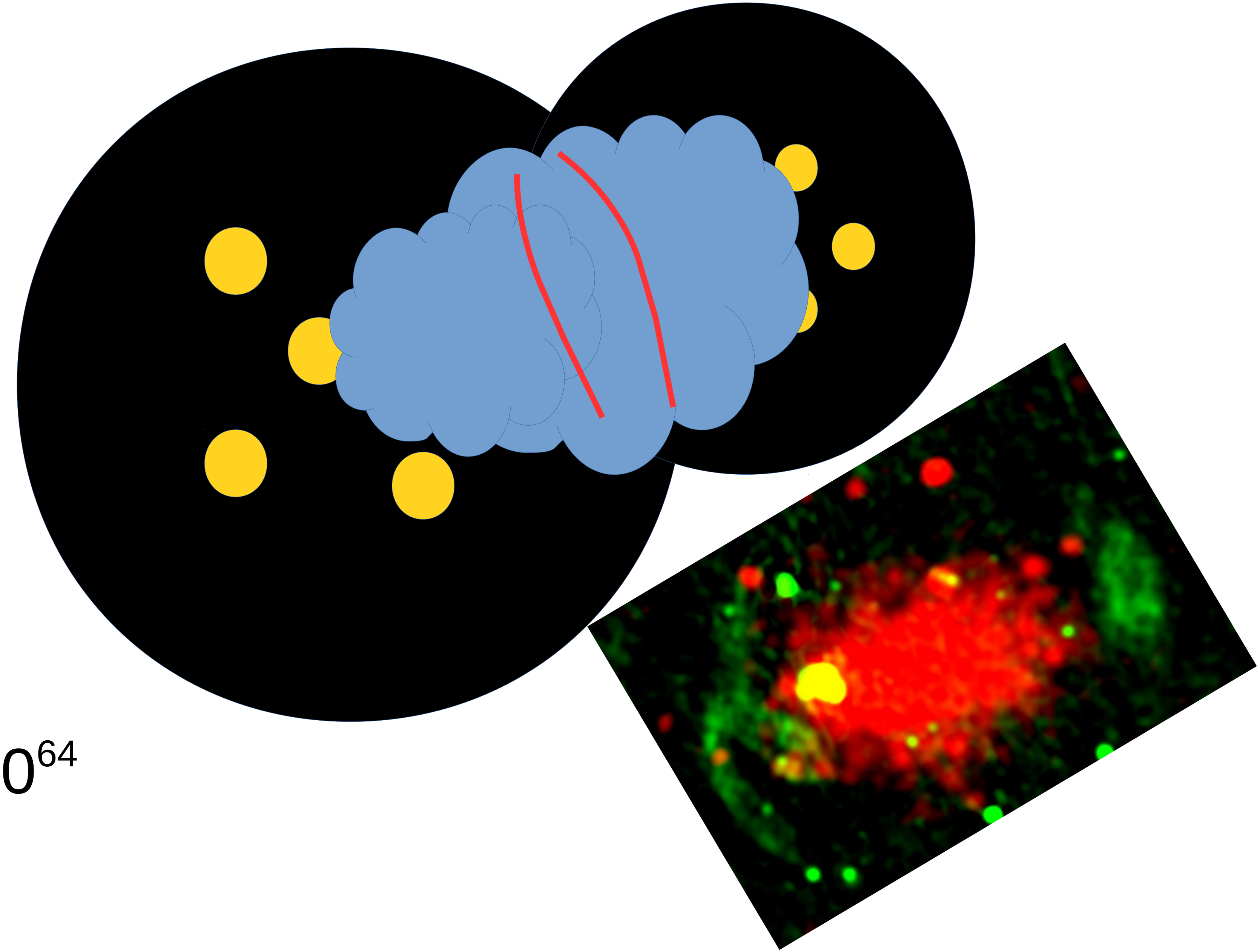
Colliding clusters



Colliding clusters



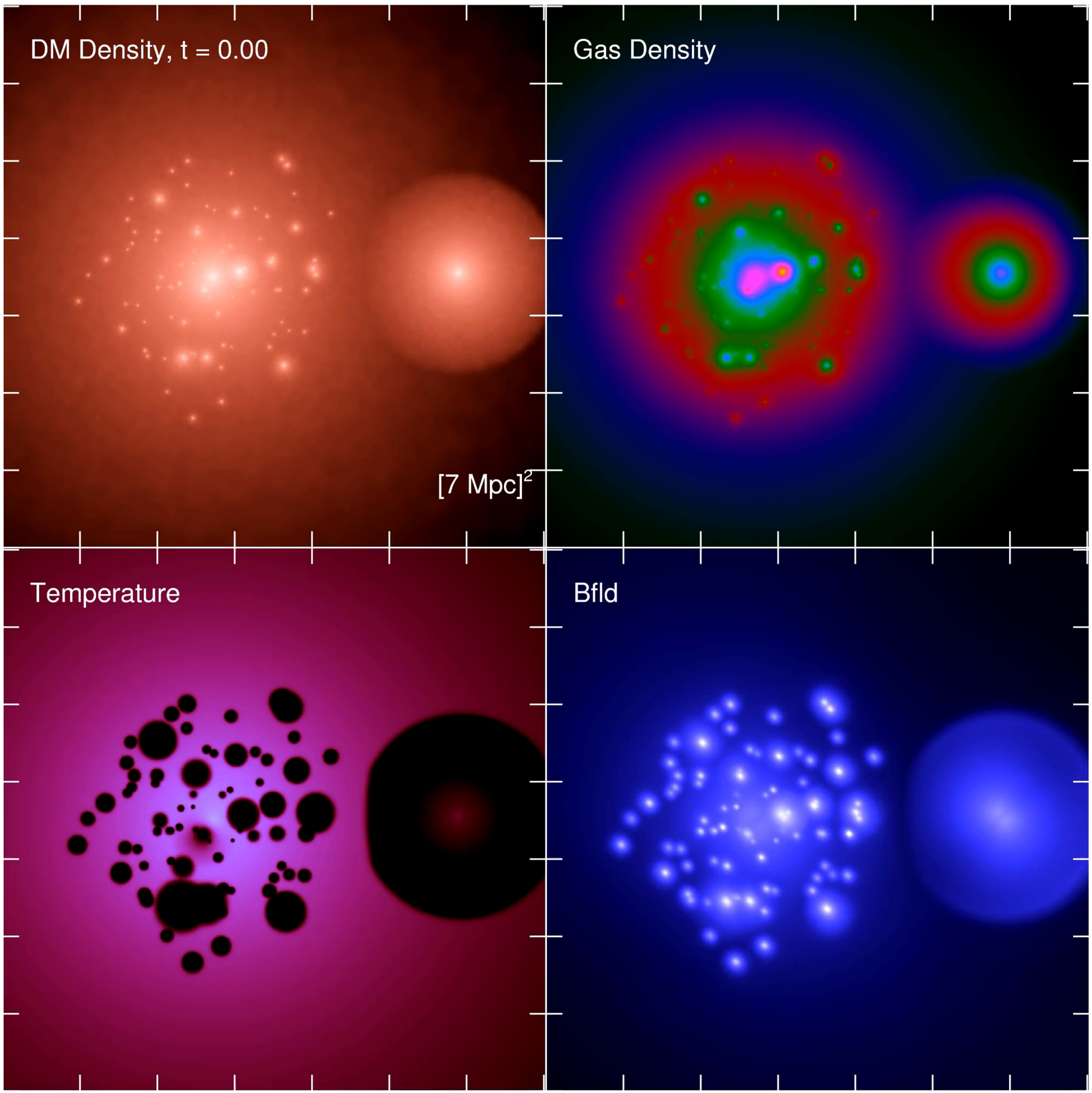
Colliding clusters



$10^{63} - 10^{64}$
erg !!

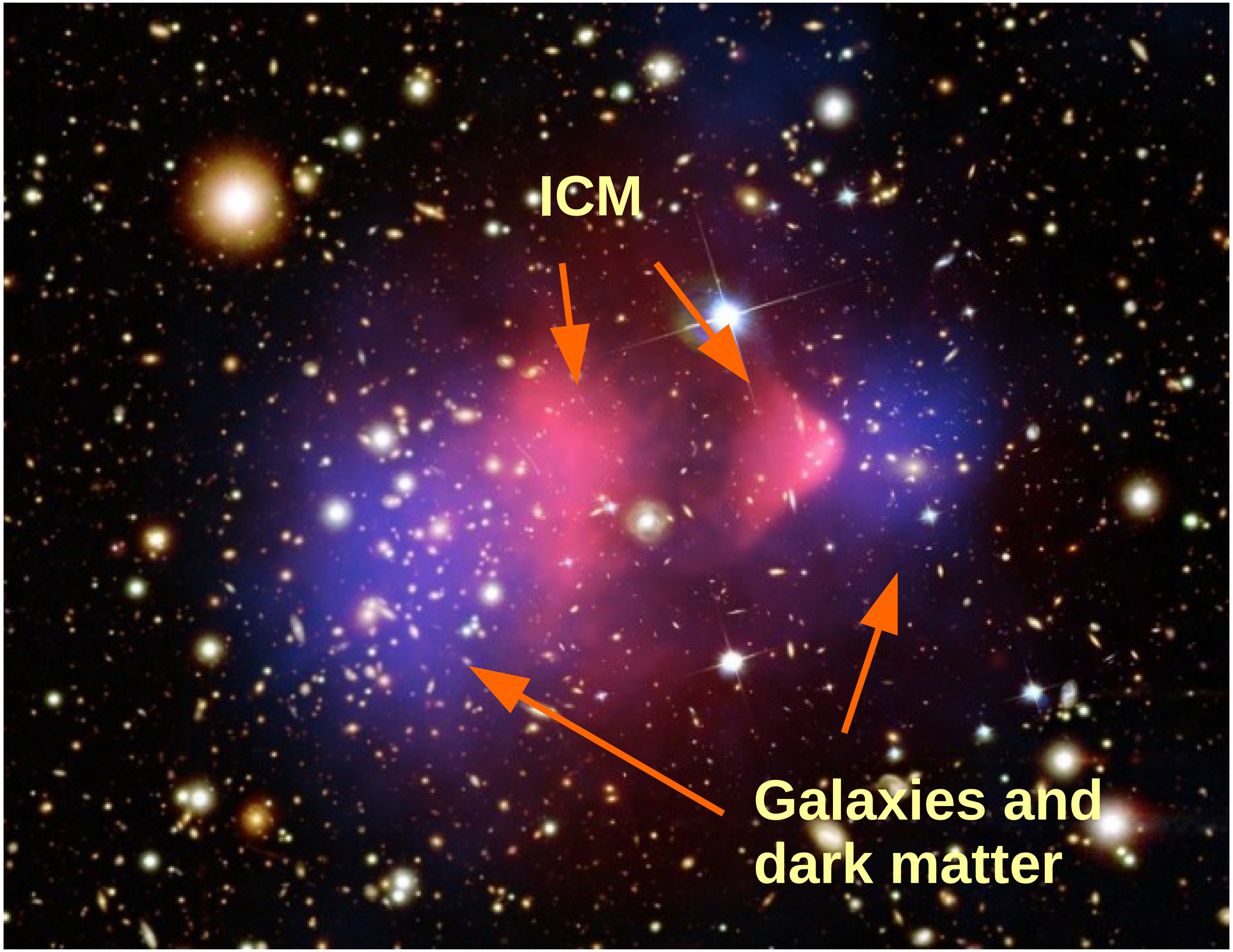
Simulation example

Donnert et al 2014, 2016, 2017



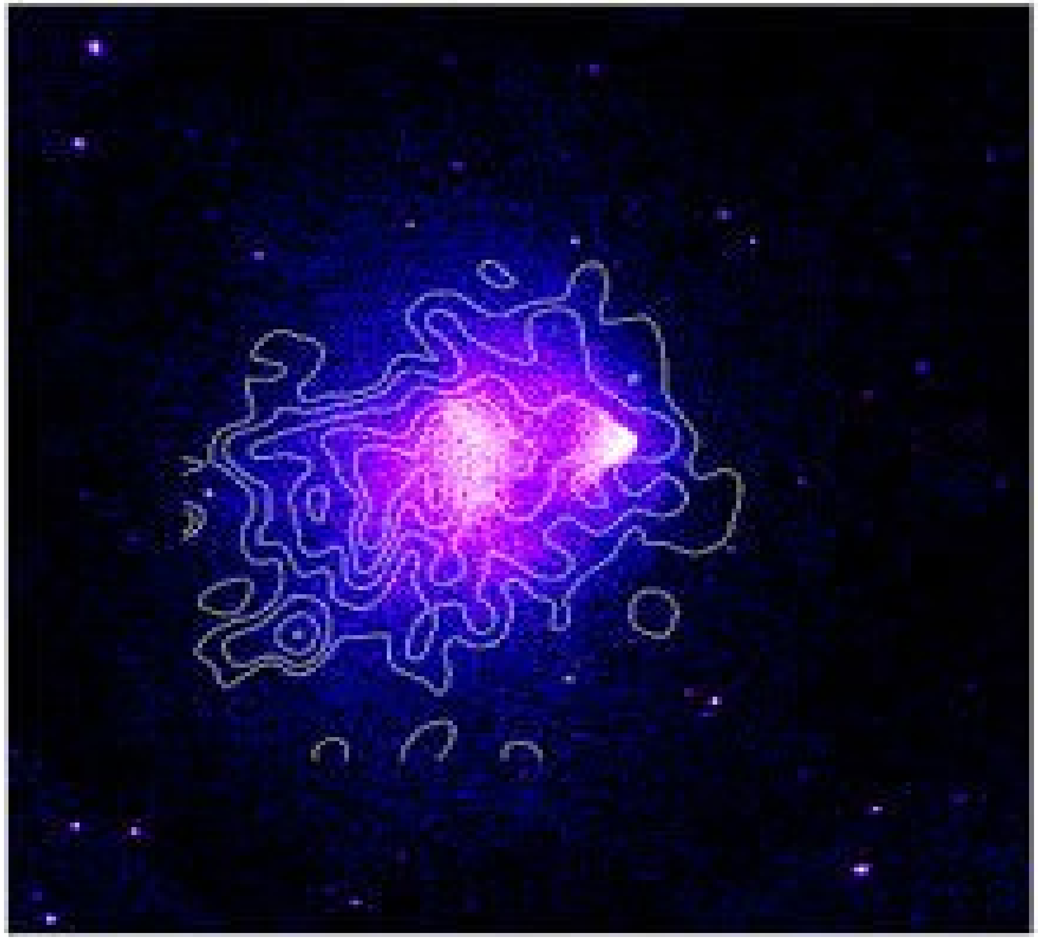
Donnert et al 2014; 2016; 2017

Illustration: Bullet cluster



https://apod.nasa.gov/apod/ap060824.htm
l

Illustration: Bullet cluster

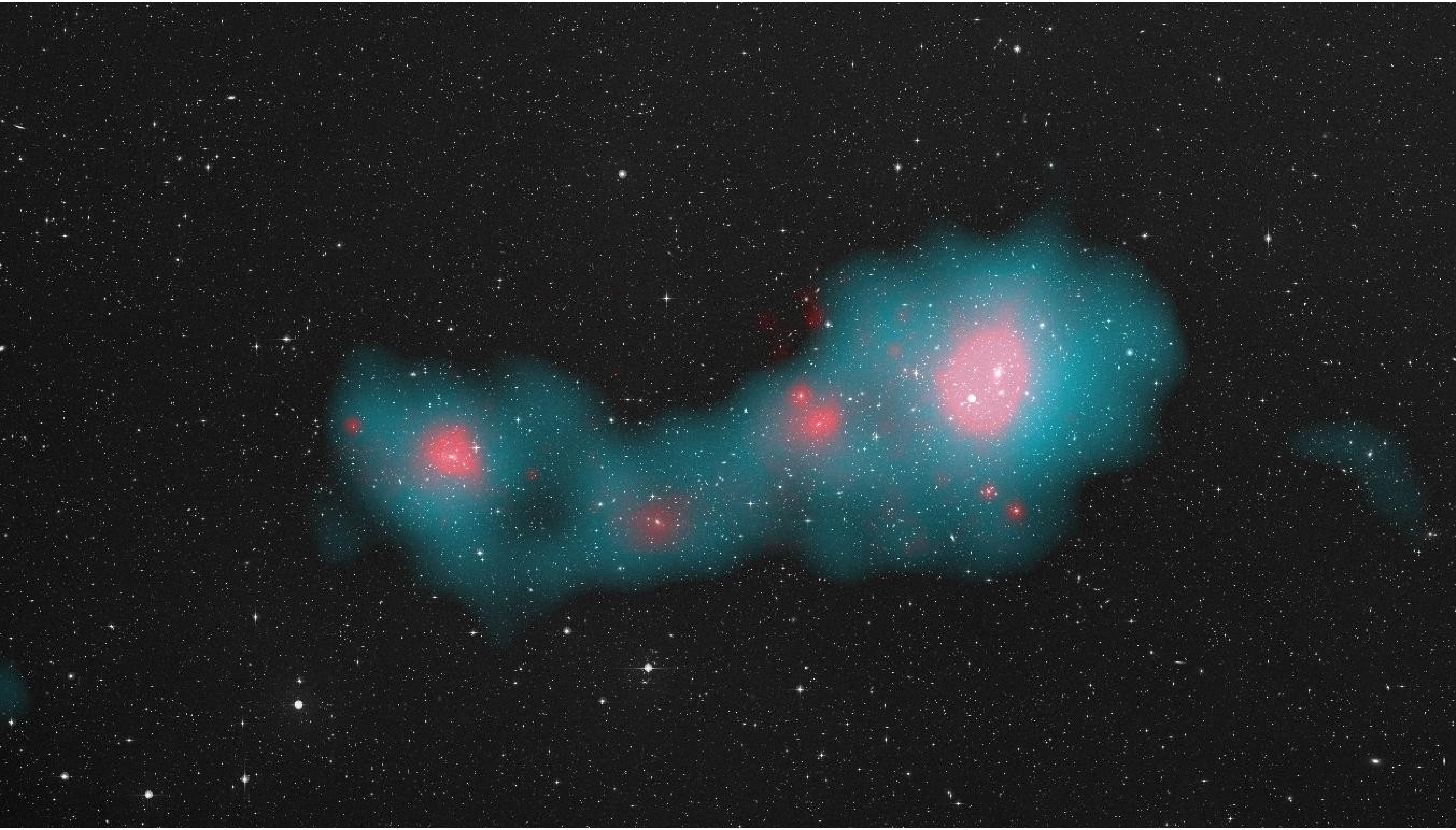


A radio halo

Markevitch et al
2005

Superclusters: e. g. Shapley SC

ESA & Planck Collaboration / Rosat/ Digitised Sky Survey

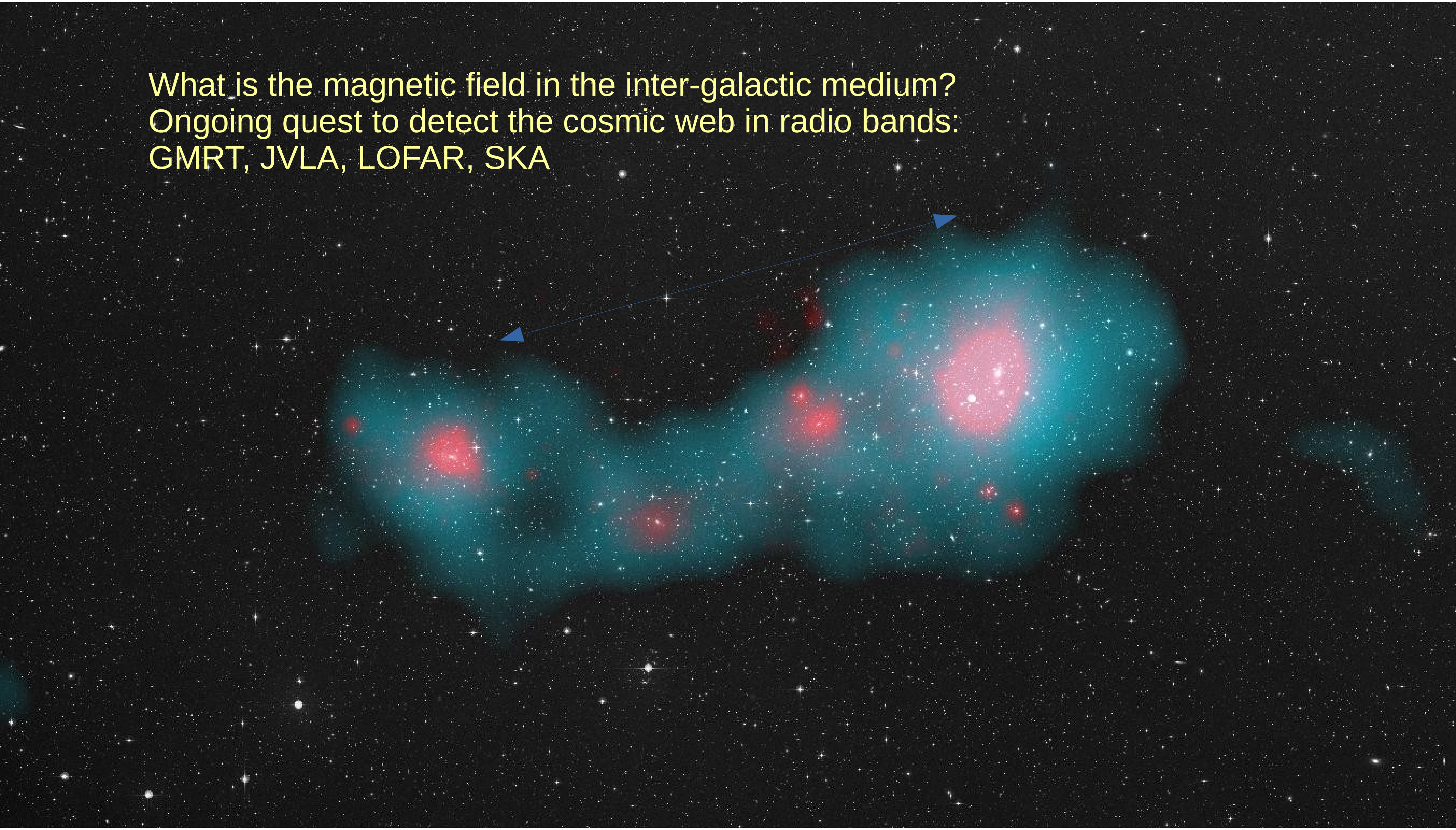


Z= 0.046

3.2 x 1.8 square degrees

Superclusters: e. g. Shapley SC

ESA & Planck Collaboration / Rosat/ Digitised Sky Survey

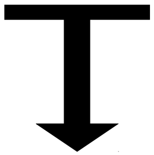


Z= 0.046

3.2 x 1.8 square degrees

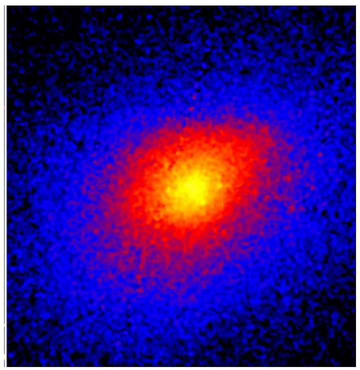
Galaxy clusters across the EM spectrum

Gamma rays



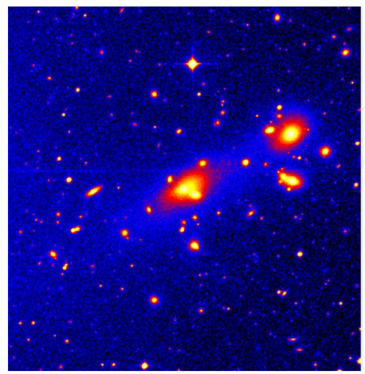
Hadronic collisions

X-rays



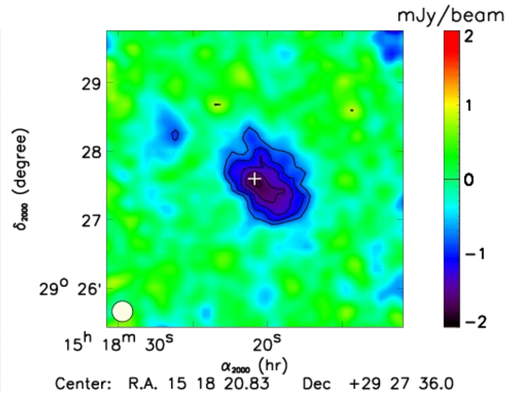
Thermal Bremsstrahlung
$10^7 - 10^8$ K plasma

Optical



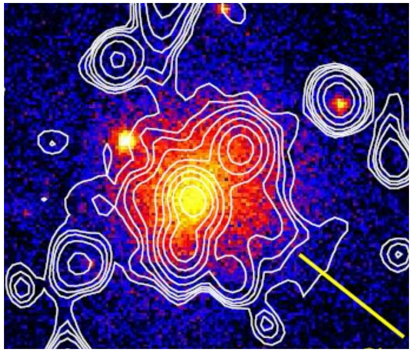
Stars

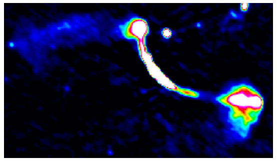
mm



Sunyaev-Zel'dovich effect: inverse Compton scattering of CMB by the ICM

RADIO





GeV cosmic ray electrons and μG magnetic fields

ICM is a high $\beta \sim 10\text{-}10^3$ plasma

Brunetti and Jones 2014; van Weeren et al 2019; Huber et al 2013, Ackermann et al 2013; Rippin et al 2017; Sunyaev and Ze'ldovich 1979; Kale et al 2018; Giacintucci et al 2013

Reading material (mainly graduate level textbooks):

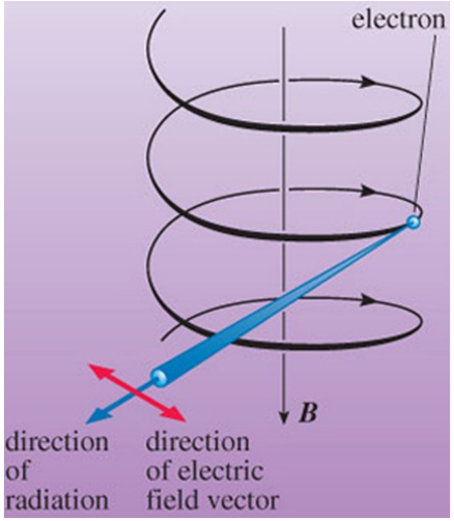
1. Extra-galactic Astronomy and Cosmology by P. Schneider.
2. High energy Astrophysics by M. Longair.
3. Radiative Processes in Astrophysics by Rybicki and Lightmann.
4. X-ray emission from clusters of galaxies by Sarazin (old but still relevant for fundamentals).
5. https://ned.ipac.caltech.edu/level5/March11/Peterson2/Peterson2.html
6. https://ned.ipac.caltech.edu/level5/March15/Roos/Roos3.html
7. http://hosting.astro.cornell.edu/academics/courses/astro201/vt.htm

Summary

- ICM is a unique plasma in the Universe that we can study: no other laboratory available to create this physical system.
- Gravitational lensing by clusters important to study dark matter and distant galaxies.
- Clusters transform galaxies: galaxy evolution.
- The ICM can distort the spectrum of the CMB- powerful probe to discover clusters, to study ICM physics.
- Mergers of galaxy clusters lead to the largest energy release after the Big Bang: radio bands probe the shocks and turbulence in the ICM. Laboratories to study plasma and fluid dynamics.
- Clusters are young systems with many open problems to study.

Synchrotron emission

$$P = -\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{9}\frac{e^4 B^2 \gamma^2}{m_e^2 c^3}$$



$$t_{\mathrm{cool}} = \frac{E}{P} = 2.4 \times 10^5 \left(\frac{\gamma}{10^4}\right)^{-1} \left(\frac{B}{10^{-4}\,\mathrm{G}}\right)^{-2} \mathrm{yr}$$

Synchrotron cooling time << diffusion time (~1-10 Gyr)
- Requirement of in-situ sources of acceleration such as shocks and turbulence

Ref: Extragalactic Astrophysics and cosmology by P. Schneider