Galaxy Cluster Collisions

Gastão B. Lima Neto

IAG/USP – São Paulo/Brazil

Rubens Machado, Rogério Monteiro, Eduardo Cypriano, Joydeep Bagchi, Florence Durret, Tatiana Laganá, Hugo Capelato

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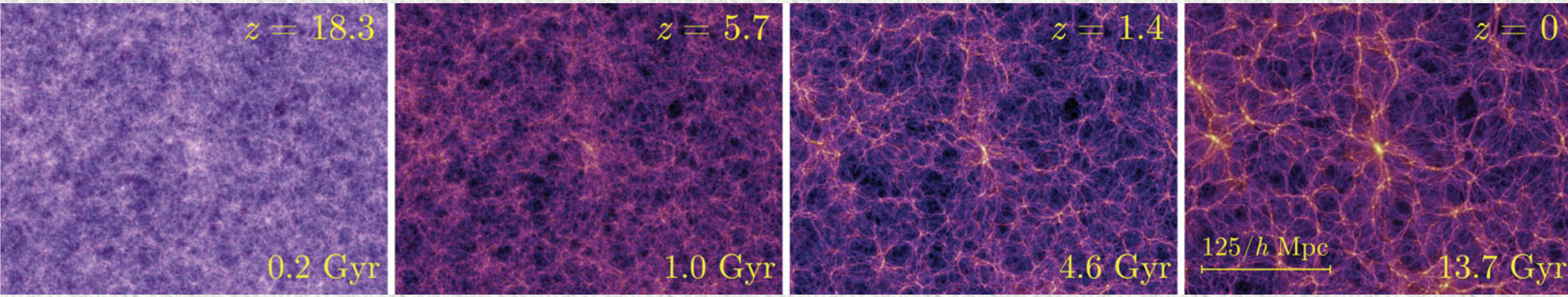
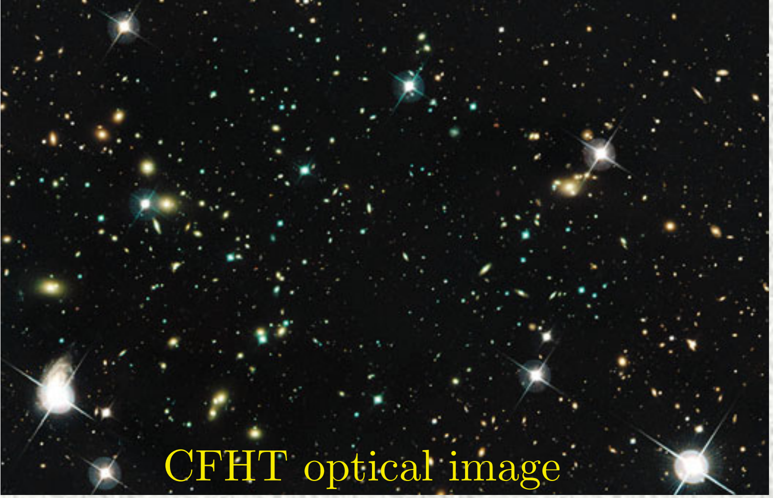
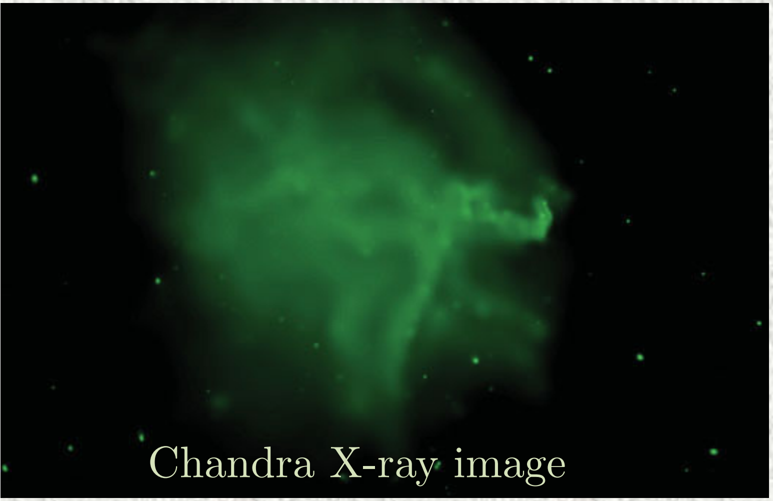
Galaxy Clusters

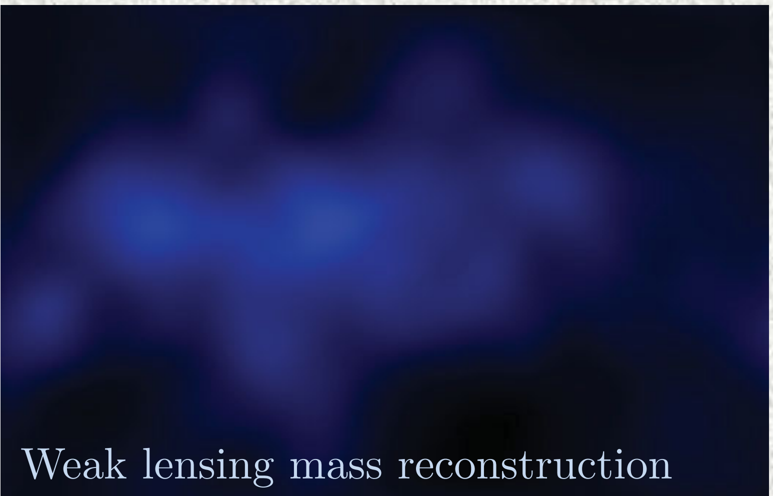
- Intersection/nodes in cosmic filaments
- Large scale structure formation:
  - Hierarchical (ΛCDM)
  - Clusters are still accreting mass falling through filaments.



ΛCDM "millenium simulations"(Springel et al. 2005, 2009, 2011; `www.mpa-garching.mpg.de/galform/virgo/millennium/`)


CFHT optical image


Chandra X-ray image


Weak lensing mass reconstruction

Mass composition of a cluster

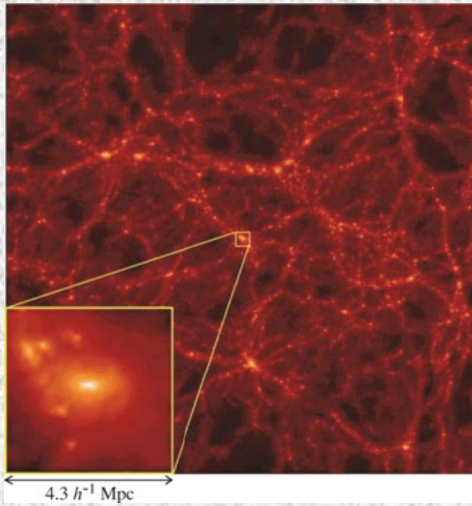
~ 2% galaxies but also stars in the intracluster medium (ICL);

~ 13% hot plasma (kT ~ keV);

~ 85% dark matter.

(mass ratio depends on the total mass: low mass clusters have more stars and less hot plasma)

DM N-body simulation

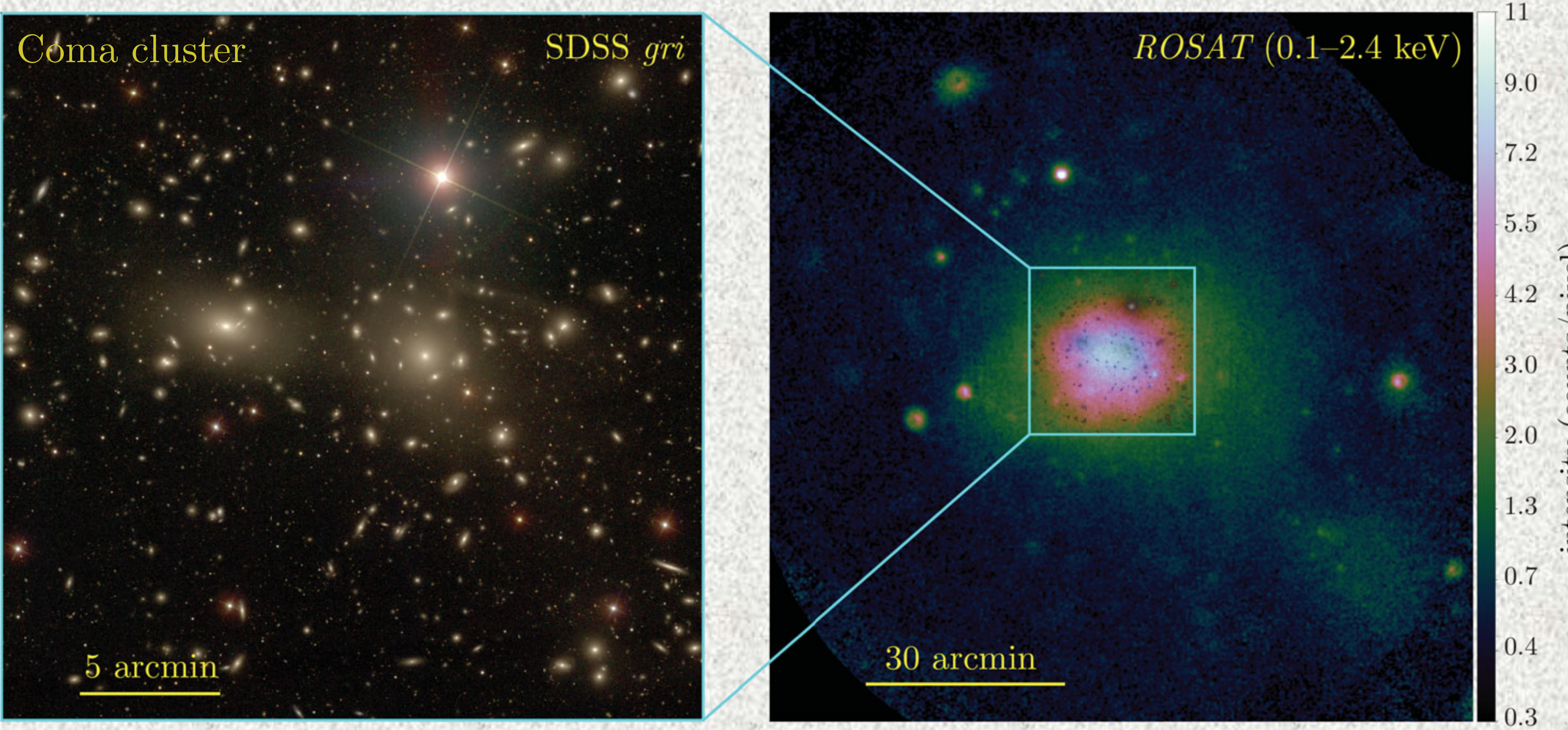


VIRGO Consortium Cosmological Simulation

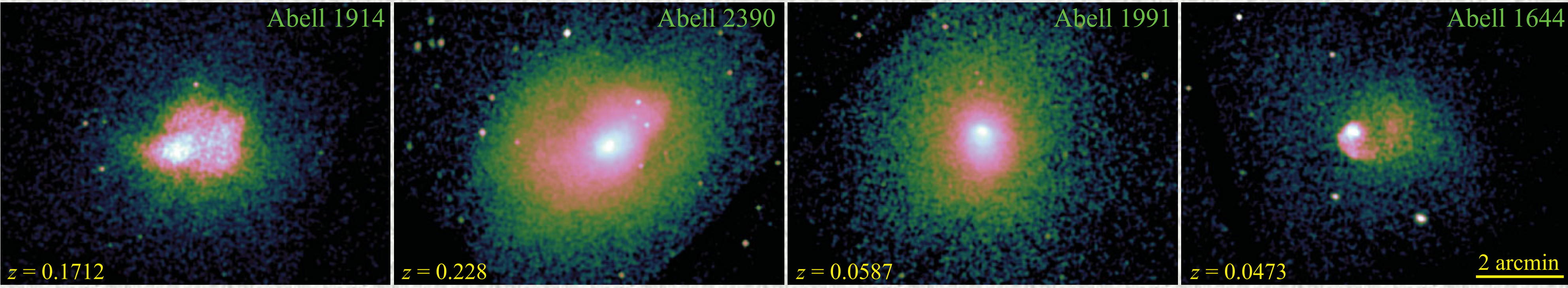
Abell 520 (*Train Wreck Cluster*): NASA, ESA, CFHT, CXO, Jee M.J. & Mahdavi A.

Intracluster medium

- About 12–15% of cluster mass is in the form of a hot (10^7–10^8K), rarefied (10^{-2}–10^{-3} cm^{-3}) plasma.
- Strong X-ray emitter (bremsstrahlung, recombination lines).
- Tracer of cluster gravitational potential (short relaxation time-scale).



Deep X-ray imaging shows dynamical activity in clusters

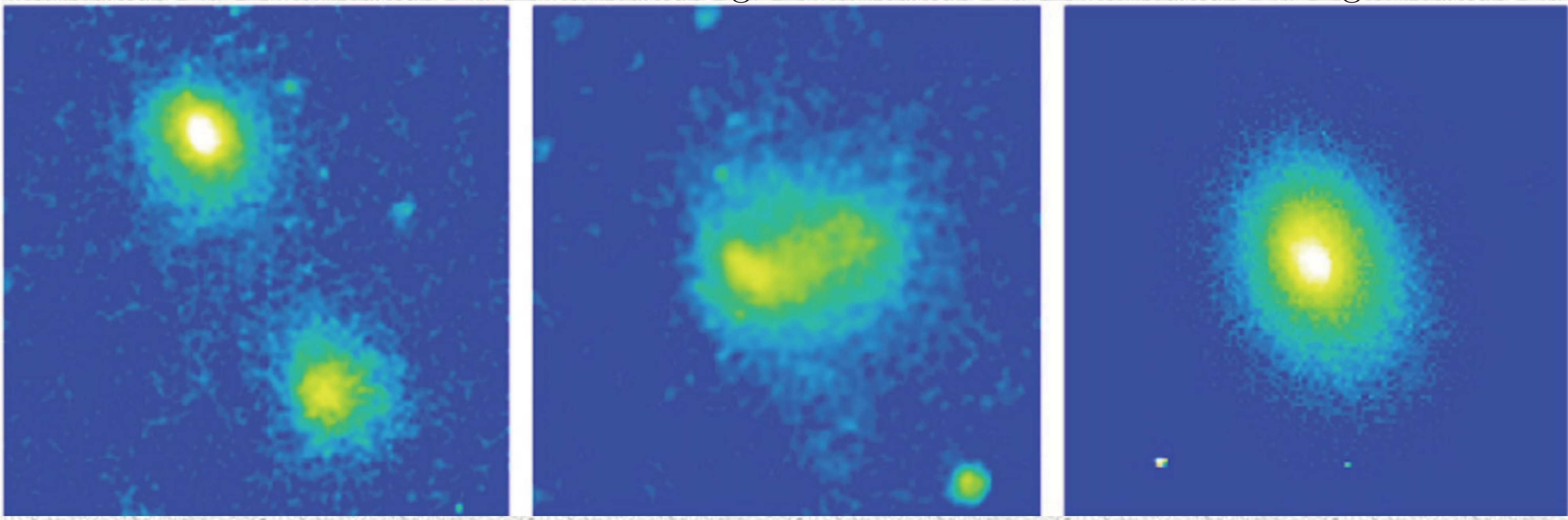


- Superficial brightness ($\propto n^2$ projected) of nearby clusters.
- X-ray imaging may reveal past or on-going collisions/mergers.
  - Multiple X-ray peaks, off-centered compared with galaxy distribution
  - Lack of symmetry, substructures.
- Some substructures are not due to gravitational effects only.

➔ AGN activity, shocks.

Snapshots of a cluster merger

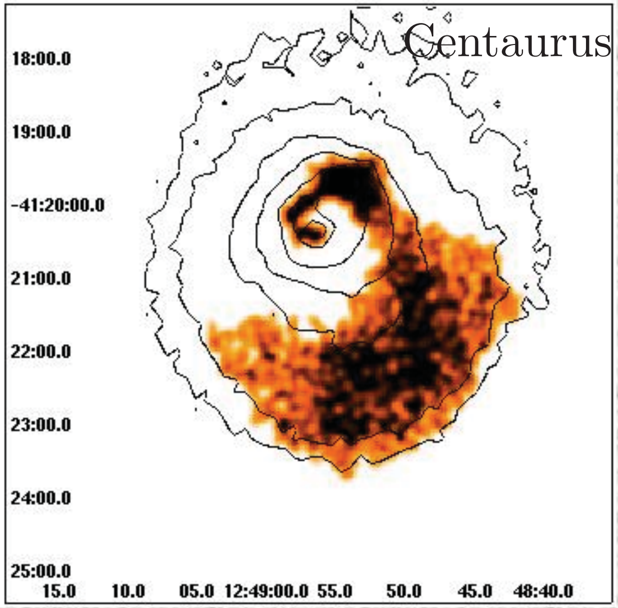
Before | During the collision | Relaxing

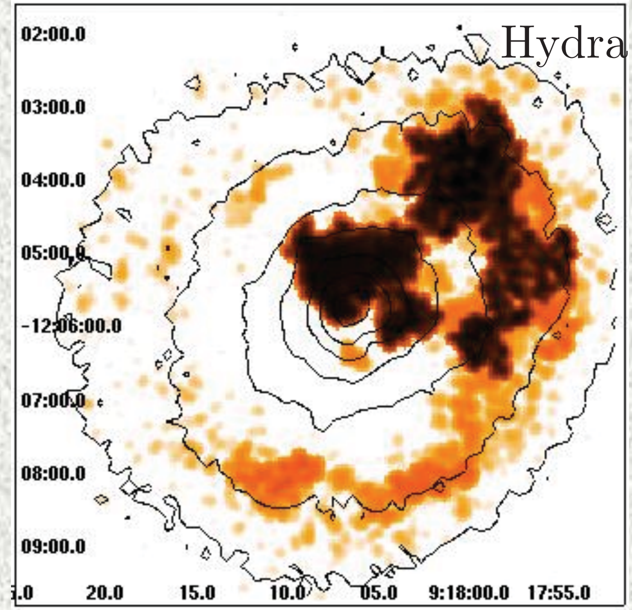


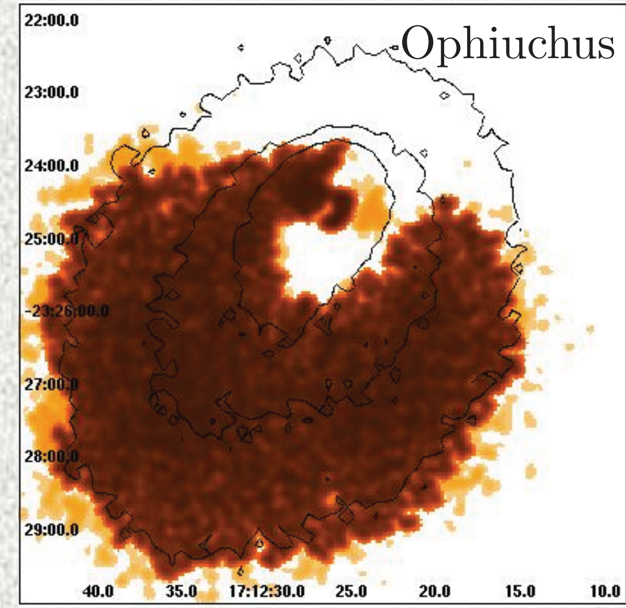
Markevich & Vikhlinin (2007)

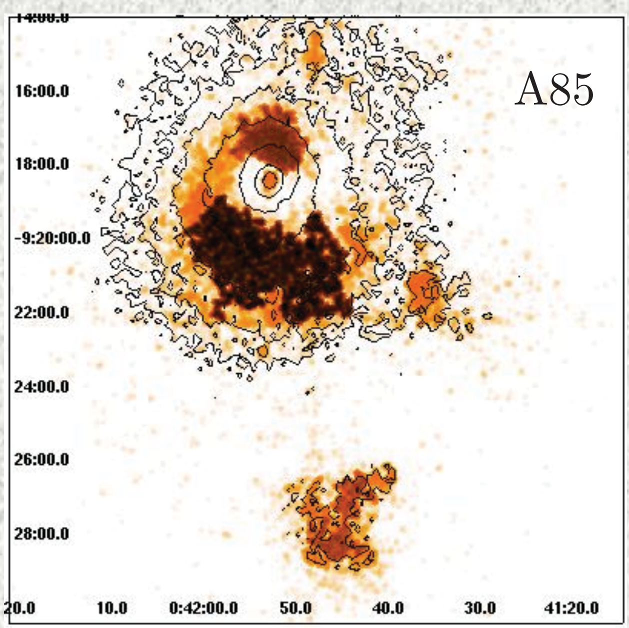
- X-ray observations give us snapshots of the dynamical evolution.
- The interpretation is not obvious
  → numerical modelling is usually necessary.
- Short relaxation time-scale makes
  → X-ray gas emission can be used as a gravitational potential tracer.

Minor collisions





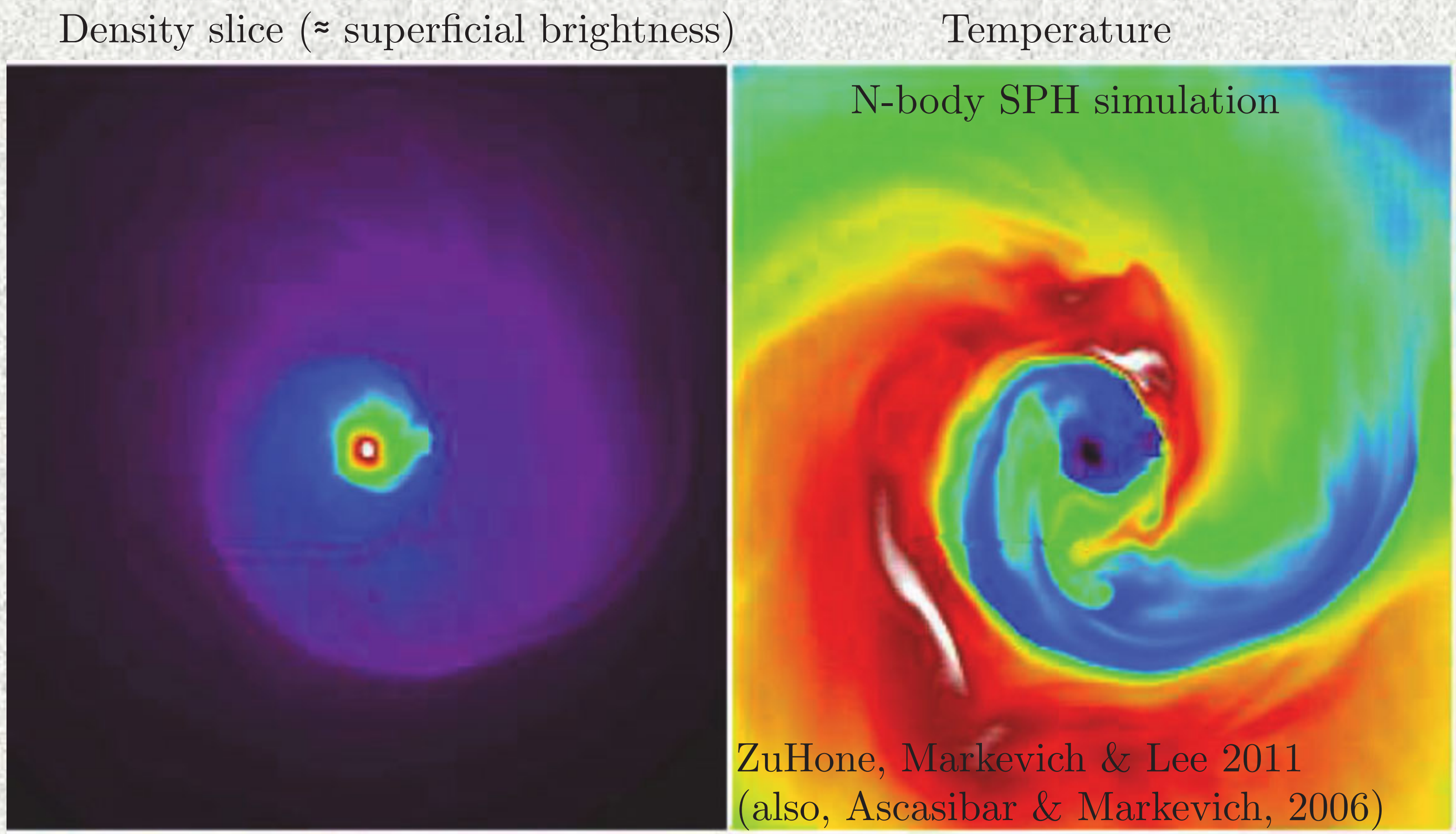




- Substructure map obtained by subtracting a symmetrical 2D β-model or Sérsic. [Laganá +10; Andrade-Santos +12].

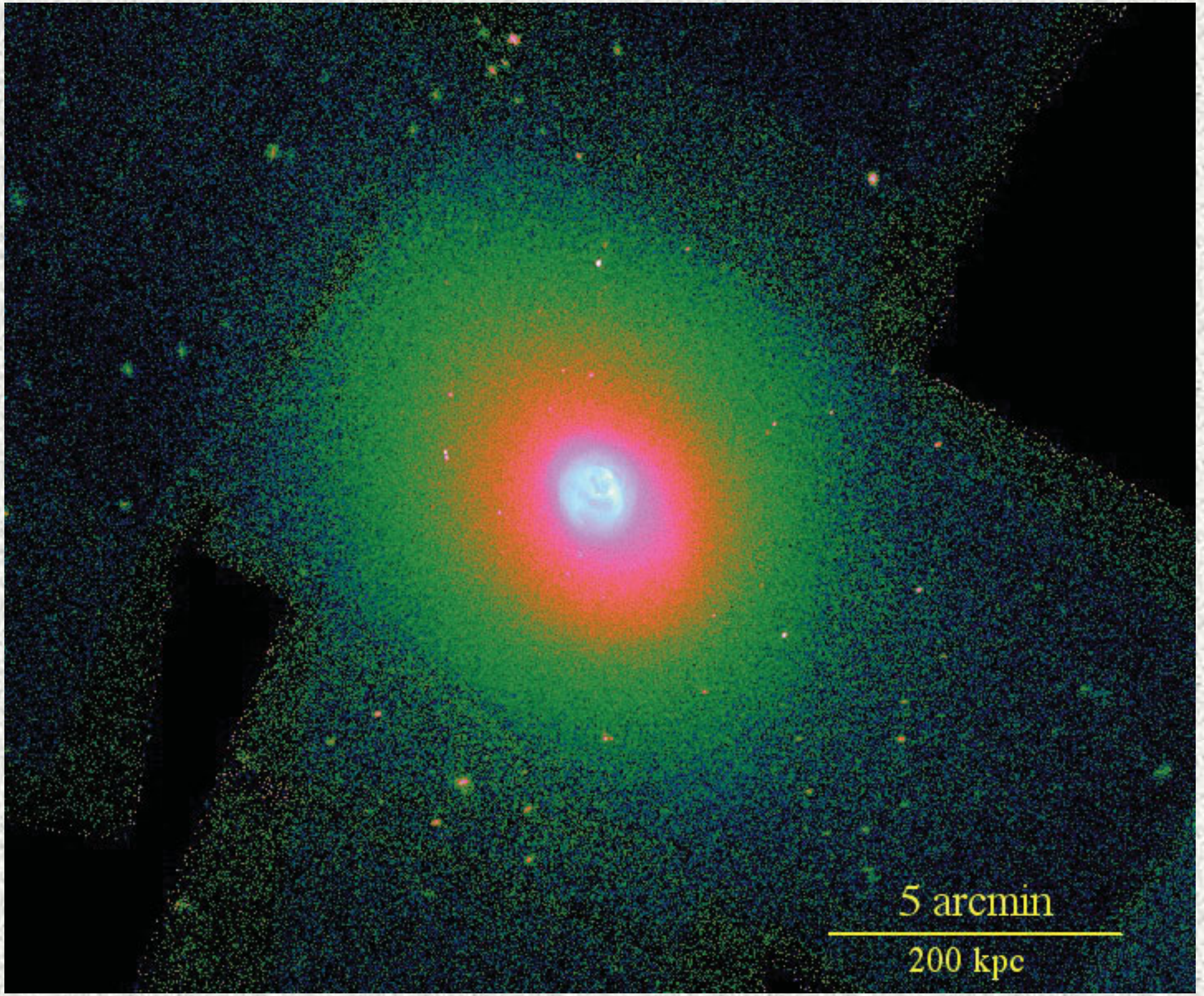
- Spiral "arm" feature detected in 7/15 nearby clusters observed with Chandra, selected only by their proximity and deep exposure.

Offsef collision: Sloshing



- Sloshing happens in a collision with orbital angular momentum.
- Mass ratio roughly between 1/2 to 1/10;
- Cooler gas in the center pushed in a spiral (like an spiral arm).
- No heating of the cool-core: it is not a mechanism to prevent cooling-flows.

Abell 2052



Deep X-ray image with Chandra (PI. E. Blanton)

Abell 2052

Residue after subtracting smooth symetrical model.

Small scale near the center: cavities (bubbles) blown by the central AGN activity.

Larger scales: Spiral structure, probably due to sloshing.

Test the dynamics with N-body simulation.

Blue: residue from X-ray emission map

E. Blanton +11

Abell 2052

gadget-2 (Springel):
resolution 5 kpc, 2.4x10^6 particles

Initial conditions based on X-ray observation

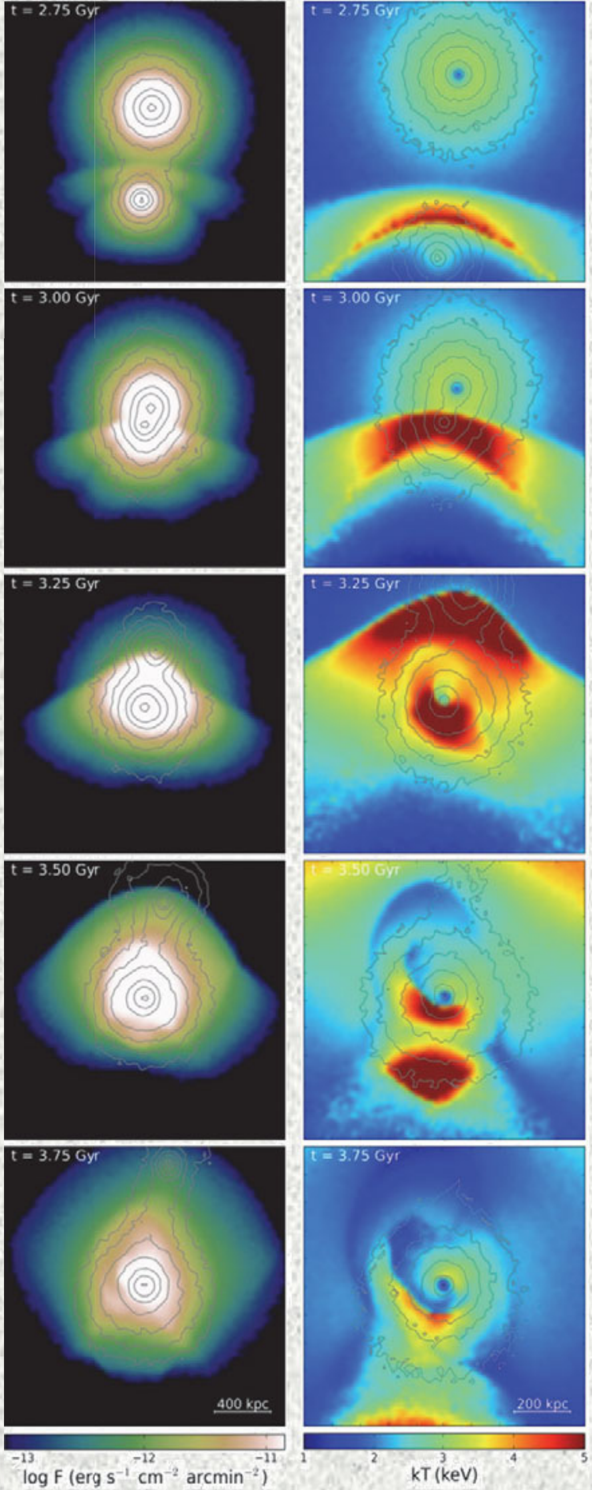
0 Gyr

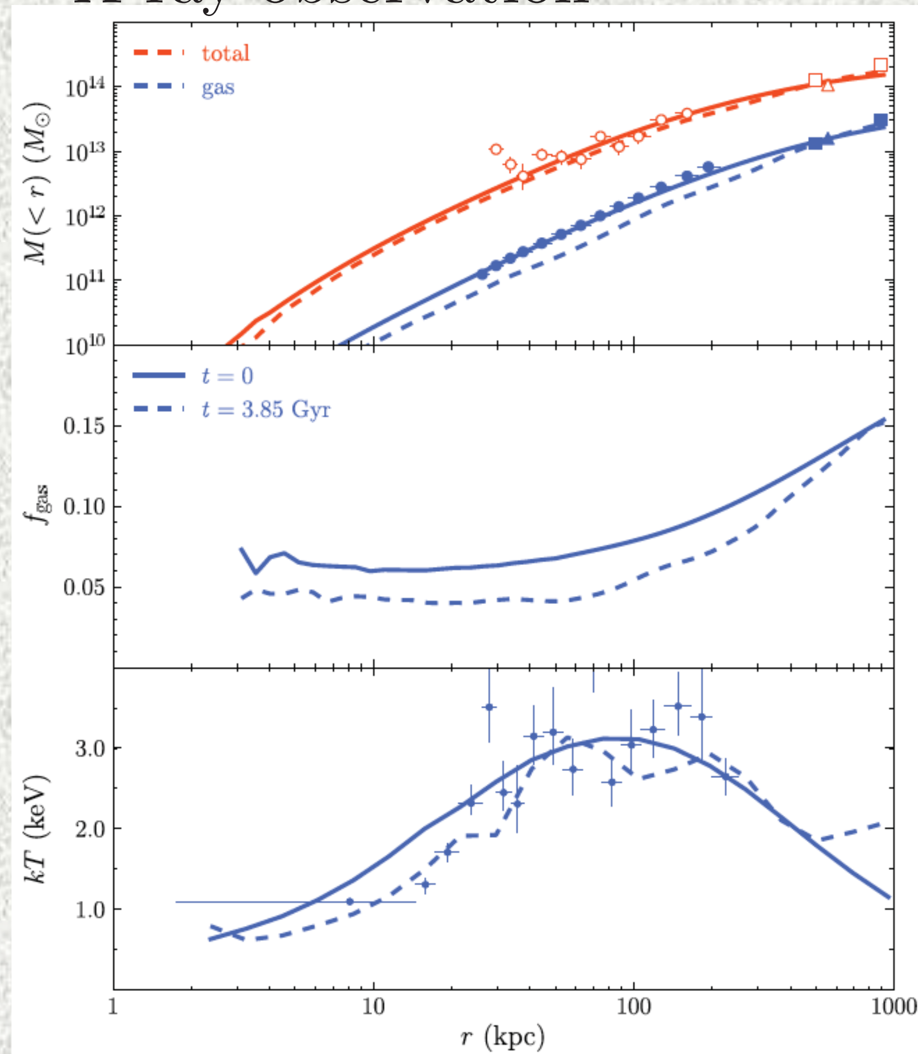
0.25 Gyr

0.50 Gyr

0.75 Gyr

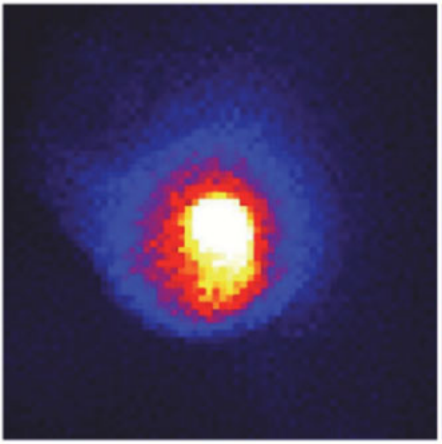
1.0 Gyr



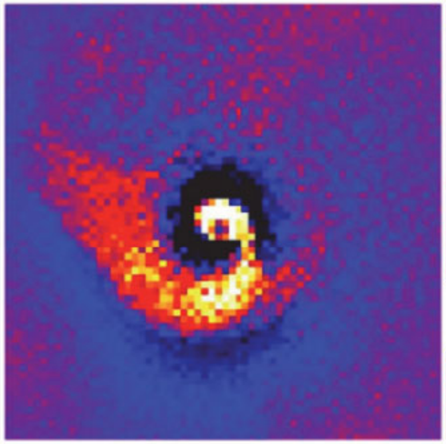


Abell 2052

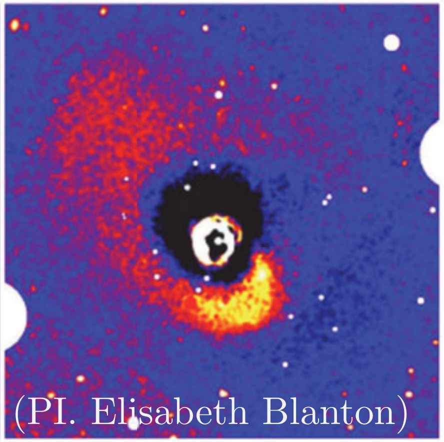
X-ray emission simulated map



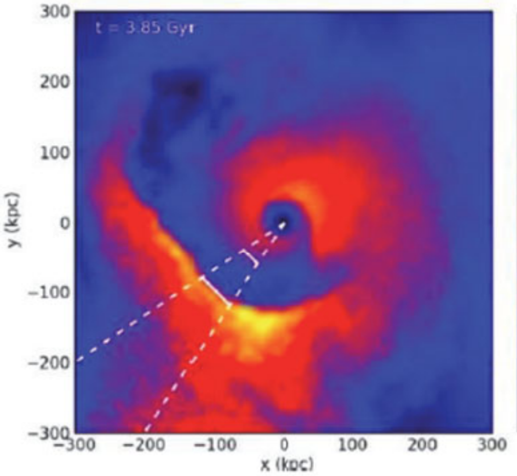
Simulated residue



Chandra observation



Simulated temperature map

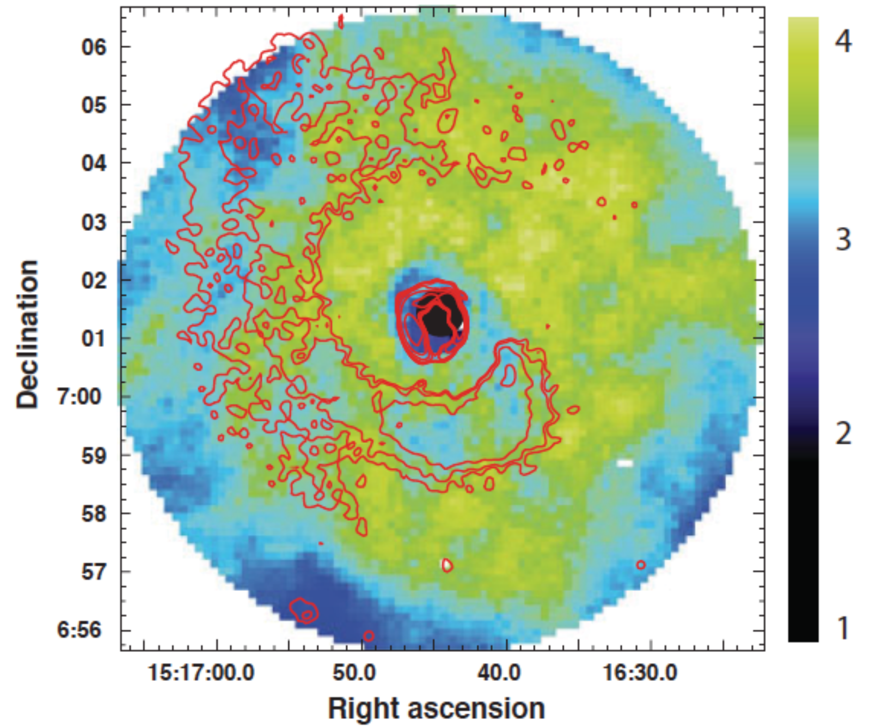


Machado & Lima Neto 2015

- Dealing with projection effects on the temperature map is not trivial.
- Temperature projection is emission weighted (gas emissivity).

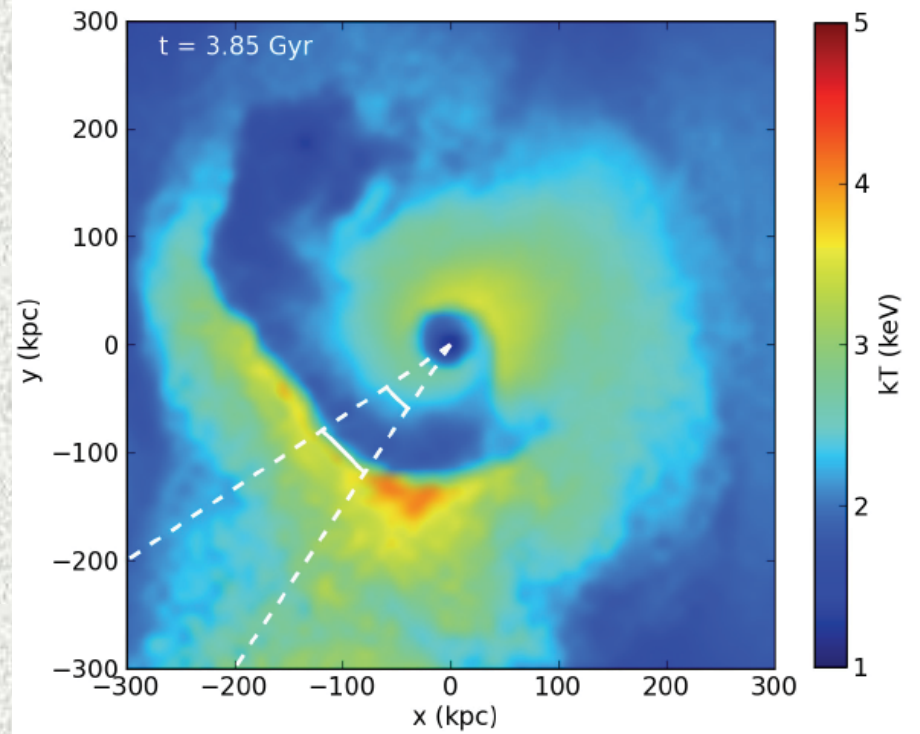
Abell 2052

Temperature map
(Blanton +2011)



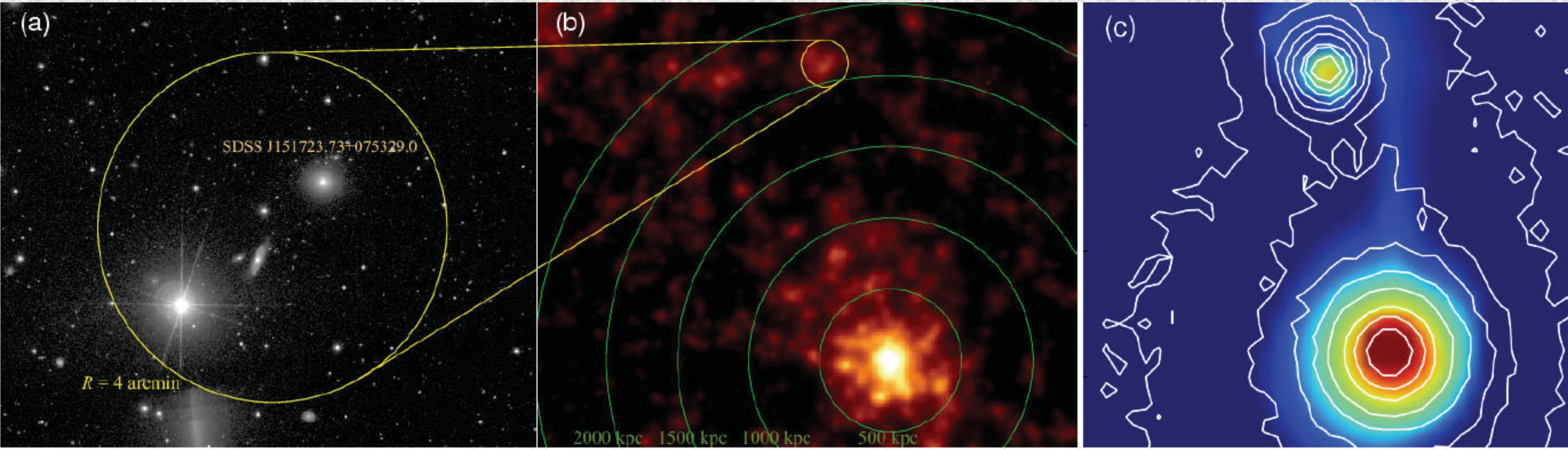
"Cold" gas from the core acquires angular momentum and leaves the center with a spiral pattern.

Simulation
(Rubens Machado)



Looking for the secondary cluster

The N-body simulation also predicts the probable location of the group/cluster that causes the sloshing



SDSS r-band

projected light mass using galaxies in a redshift slice centered on A2052

Simulation (projected mass map)

– Selection of SDSS galaxies using photo-z → brightness map.
– N-body simulation gives the position of the secondary in a number of possible scenarios.
– Best candidate at about 2.1 Mpc: group dominated by an elliptical galaxy with same (spectroscopic) redshift of A2052.
– In very few systems with sloshing where the secondary is known.

Major collisions: Dissociative clusters in which the gas has been detached from the collisionless components

- 1E 0657-56 (Markevitch et al. 2004), "Bullet Cluster"
- MACS J0025.4-1222 (Bradac et al. 2008), "Baby Bullet"
- Abell 520 (Mahdavi et al. 2007), "Train Wreck"
- Abell 2744 (Merten et al. 2011), "Pandora Cluster"
- Abell S1063 (Gomez et al. 2012)
- Abell 2163 (Okabe et al. 2011)
- Abell 1758N (Ragozzine et al. 2011)
- DLSCL J 0916.2+2951 (Dawson 2012), "Musket Ball Cluster"
- ACT-CL J0102-4915 (Jee et al. 2014), "El Gordo"

This is only a small subsample of colliding/merging clusters

Most famous example: the bullet cluster

- Massive cluster at redshift $z = 0.3$.

Image NASA/STScI, Magellan/U.Arizona/D.Clowe et al. 2006

Most famous example: the bullet cluster

- X-ray emission map → diffuse gas ($kT \sim 14$ keV, $n \sim 10^{-2}$ cm^{-3}).
- Bow-shock → supersonic collision of 2 clusters.

X-ray NASA/CXC/CfA/M.Markevitch et al.

Most famous example: the bullet cluster

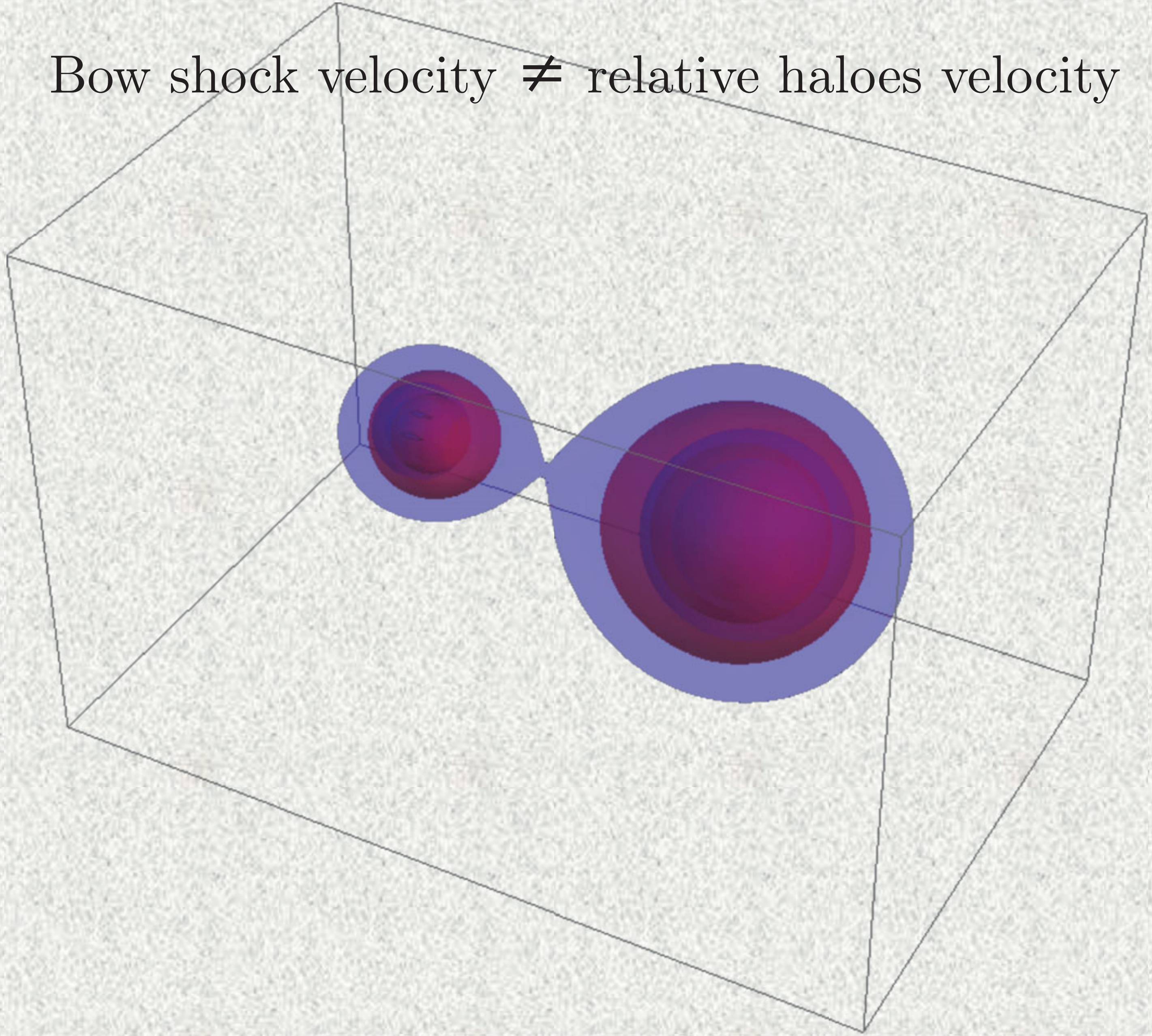
In clusters the gas mass is ~6x larger than the mass in galaxies.

One of the best evidences of dark matter.

- Mass distribution through weak-lensing effect.
- Mass distribution does not coincide with gas distribution (almost the same as the galaxy distribution).

Weak lensmass map: NASA/STScI, ESO WFI, Magellan/U.Arizona/Clowe et al.

Bow shock velocity $\neq$ relative haloes velocity



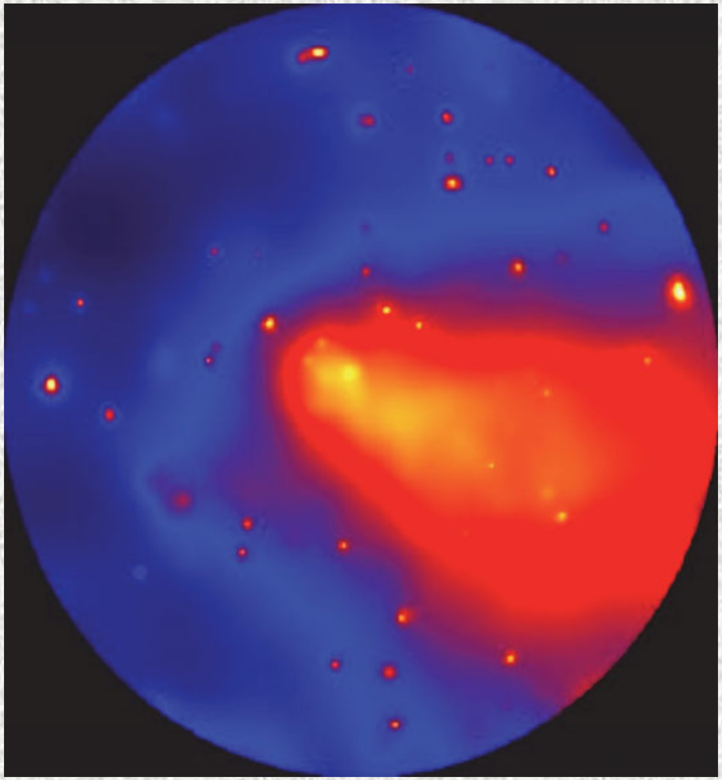
blue: Dark matter; red: gas. Bullet Cluster (1E 0657-56) Springel & Farrar, 2007

Abell 3376

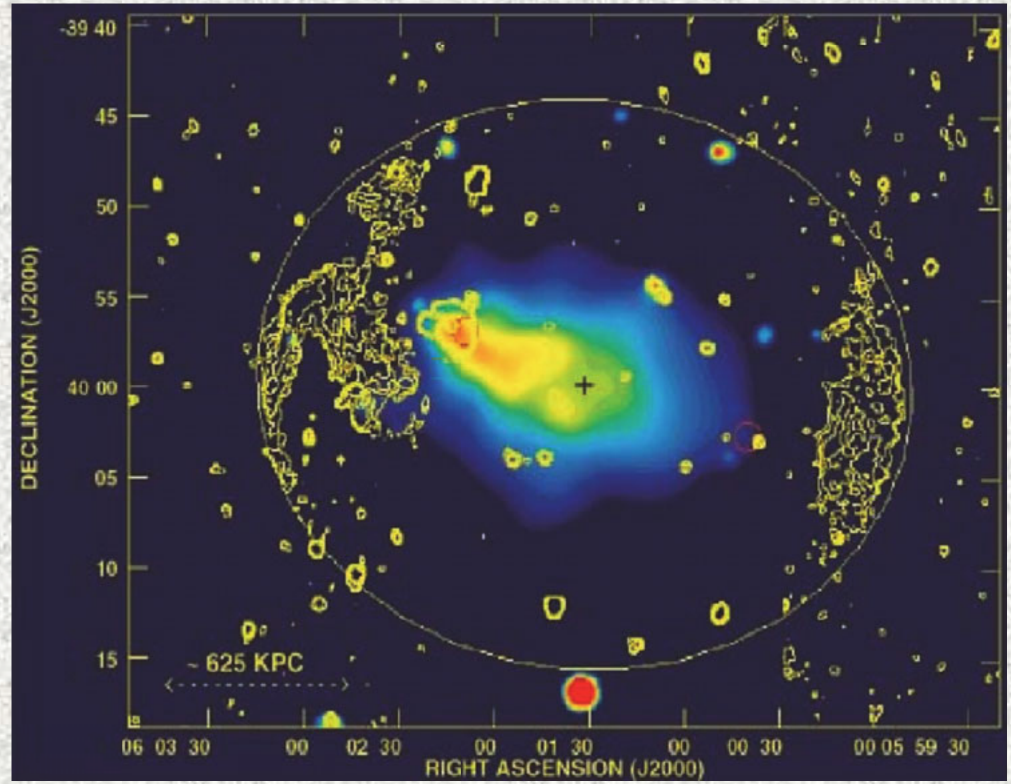
z = 0.0456; “true-color” *grz* DECam/Blanco/CTIO image

A local bullet cluster

XMM-Newton



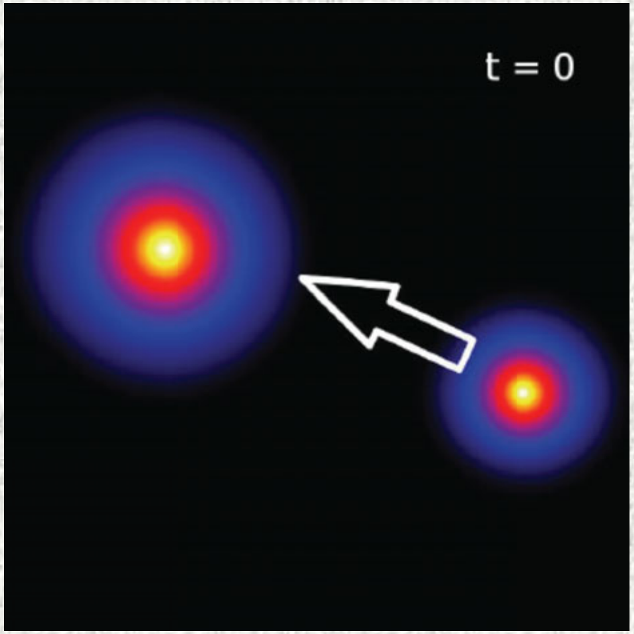
ROSAT(X-ray image) + VLA (radio contours)

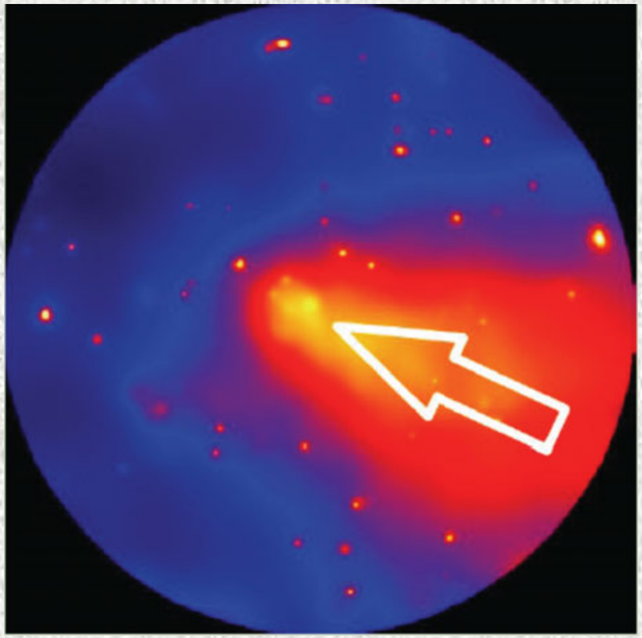


- Abell 3376, $z = 0.046$
- The gas has a bullet-like morphology.
- Radio emission from reaccelerated electron (Fermi process) in a shock (radio relics).

Bagchi et al. 2006

N-body: initial conditions





- Dark matter radial density profile ➔ Hernquist (similar to NFW);
- Gas density profile ➔ Dehnen $\gamma=0$ (similar to β-model);
- Clusters relative initial velocity ➔ ?
- Mass ratio➔ ?
- Impact parameter ➔ ?
- Gas fraction ➔ 0.18 (e.g. Laganá + 11, 13);
- Gas temperature ➔ From hydrostatic equilibrium.

Trial and error

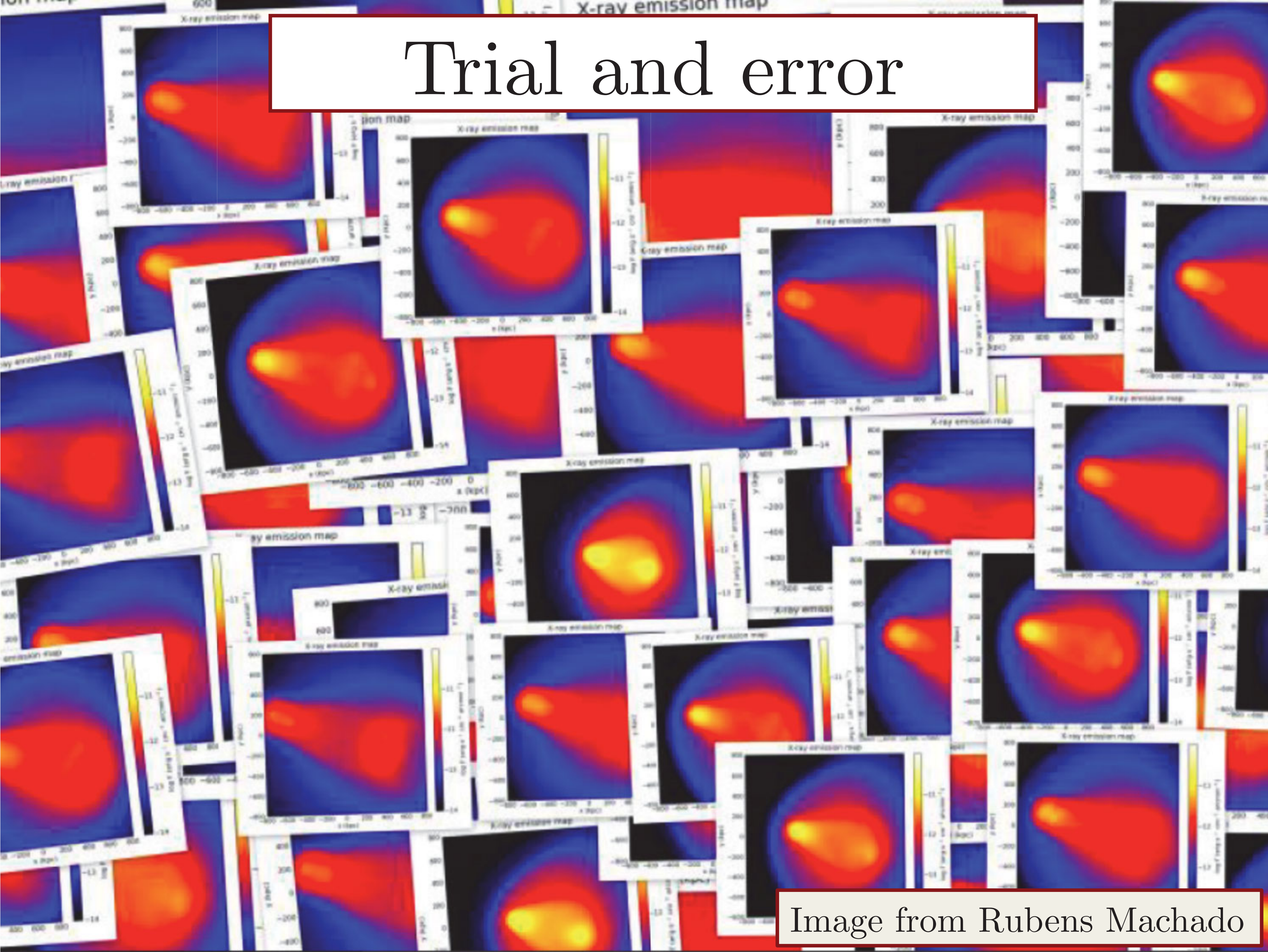
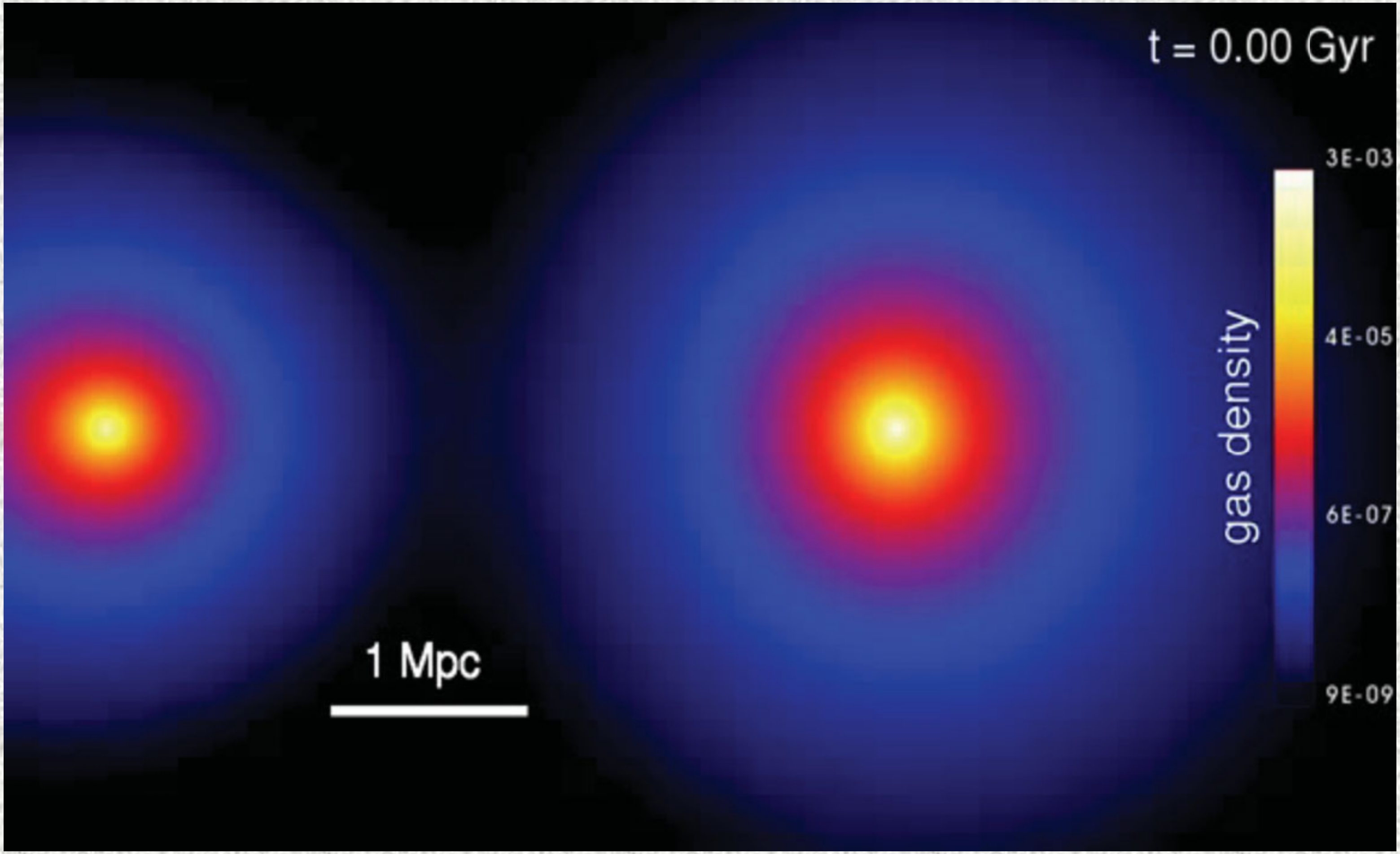


Image from Rubens Machado

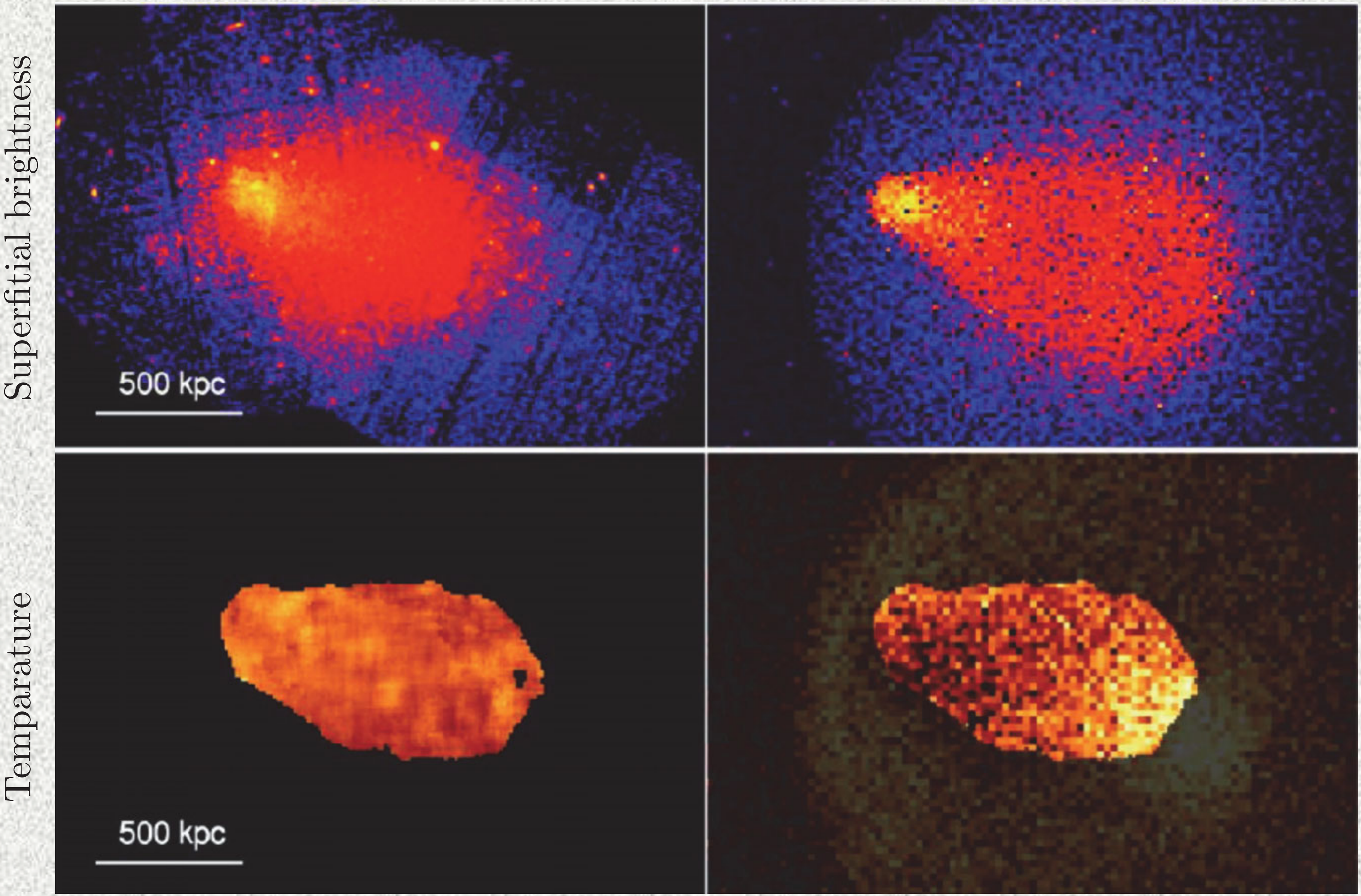
N-body simulation



- Tree-code + SPH (Gadget-2, Springel 2005)
- 9 million particles, head-on collision ($b = 0$ kpc) of 2 clusters with mass ratio 1/3 and $v_{\text{rel.}} = 1500$ km/s.

Rubens Machado et al. 2013

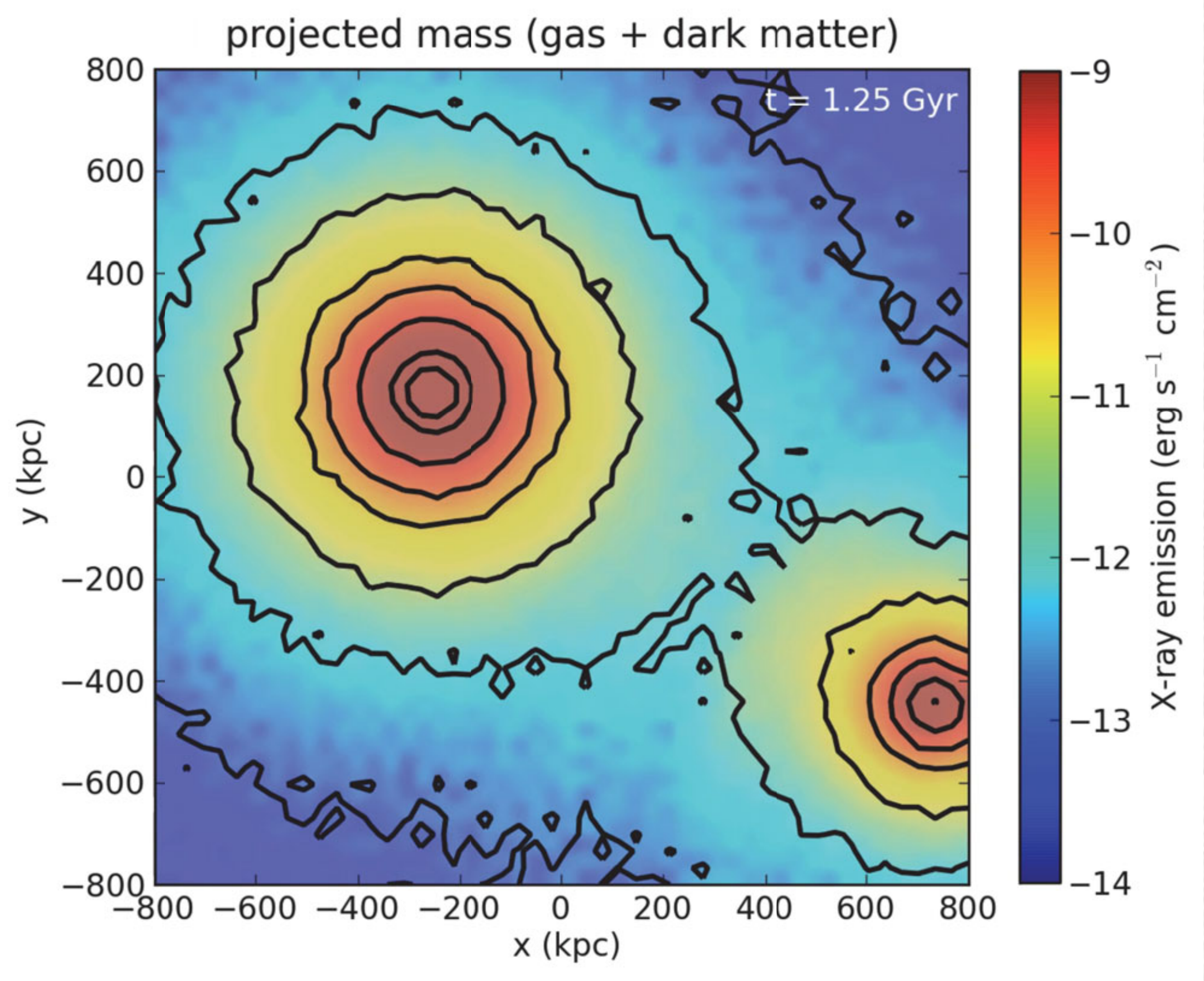
Observation × Simulation



Mock XMM image and temperature maps

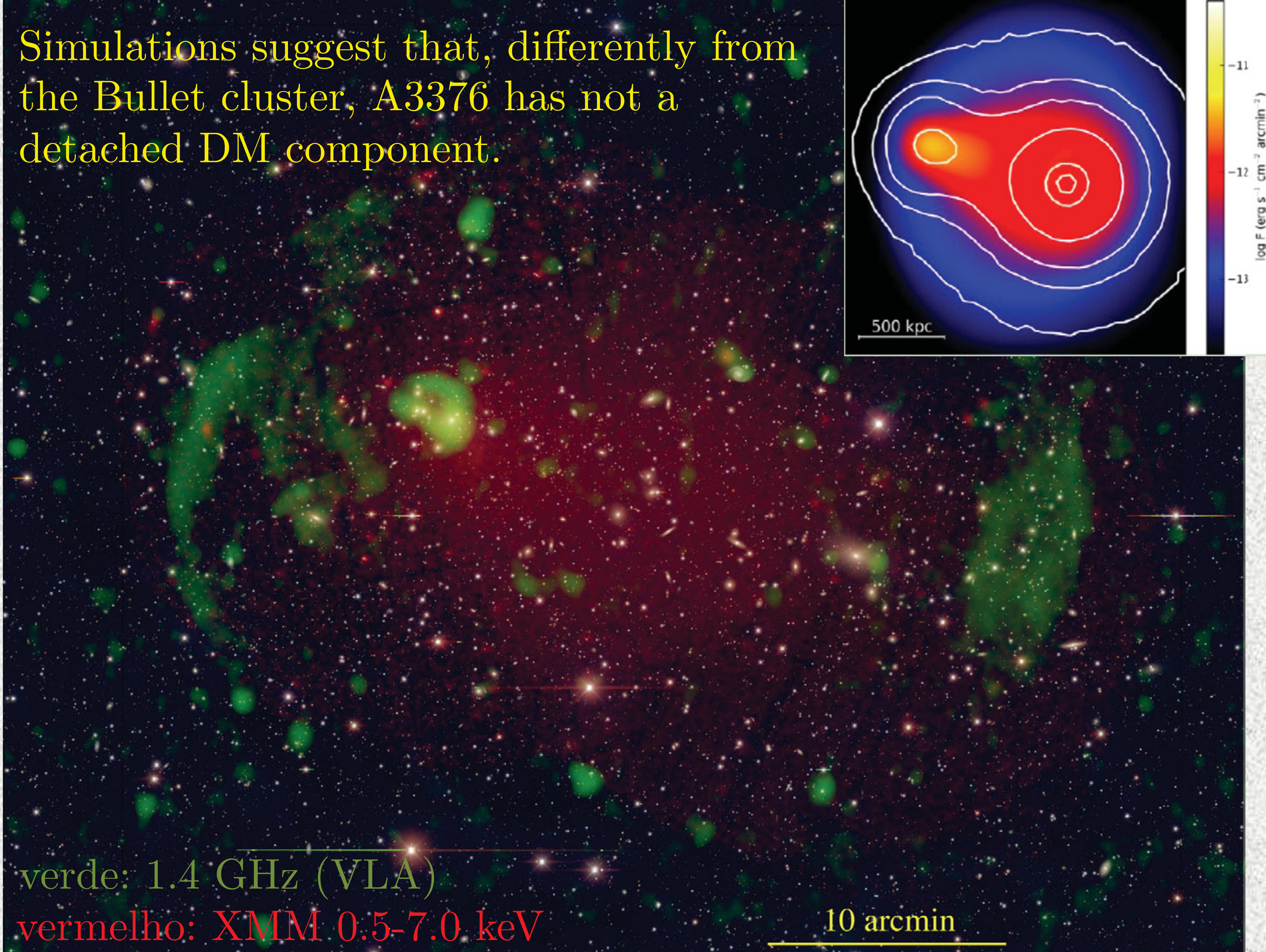
Abell 3376: mass and gas distributions

Simulation showing X-ray emission and projected mass density (black contours).



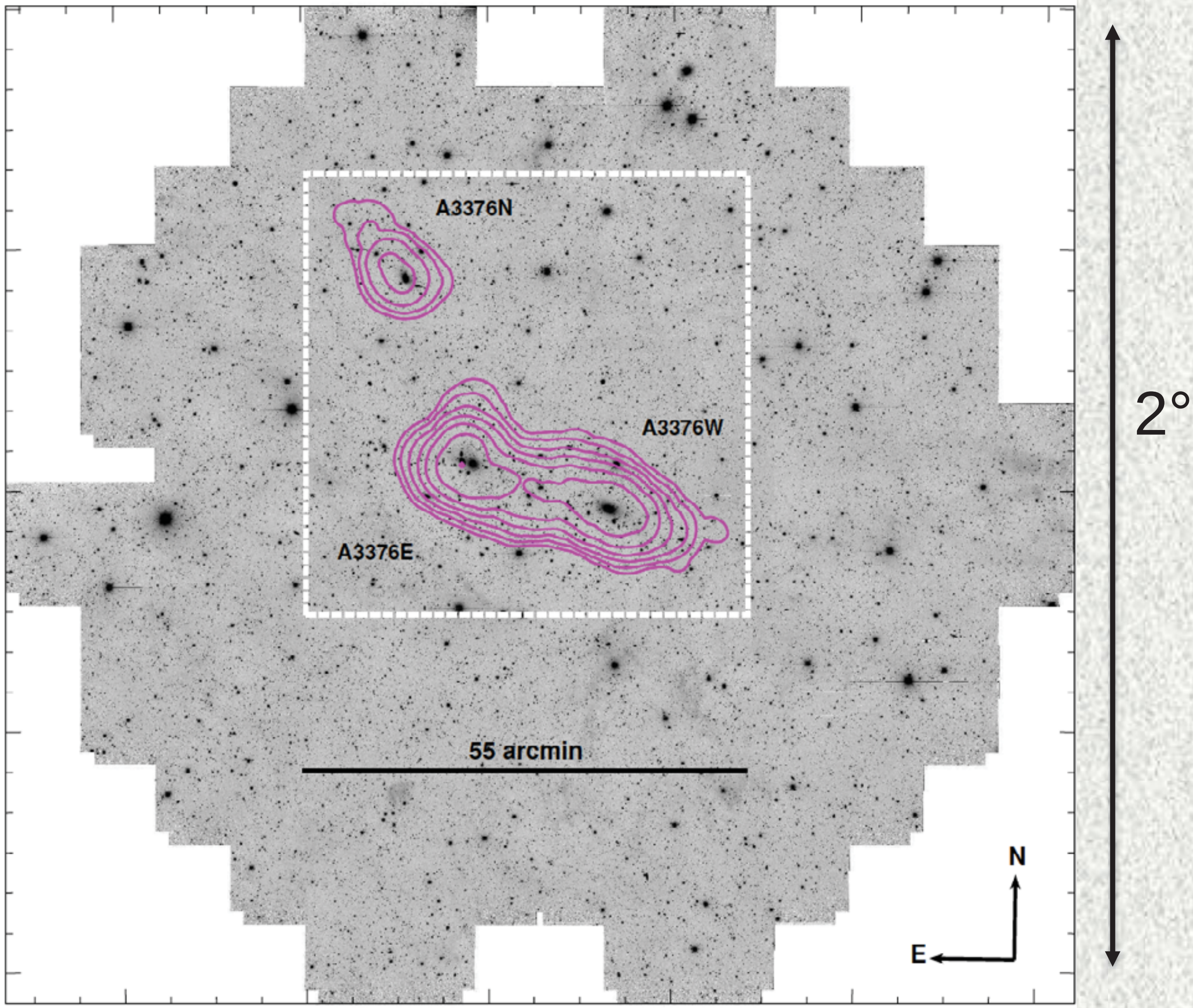
Rubens Machado +2013

Simulations suggest that, differently from the Bullet cluster, A3376 has not a detached DM component.



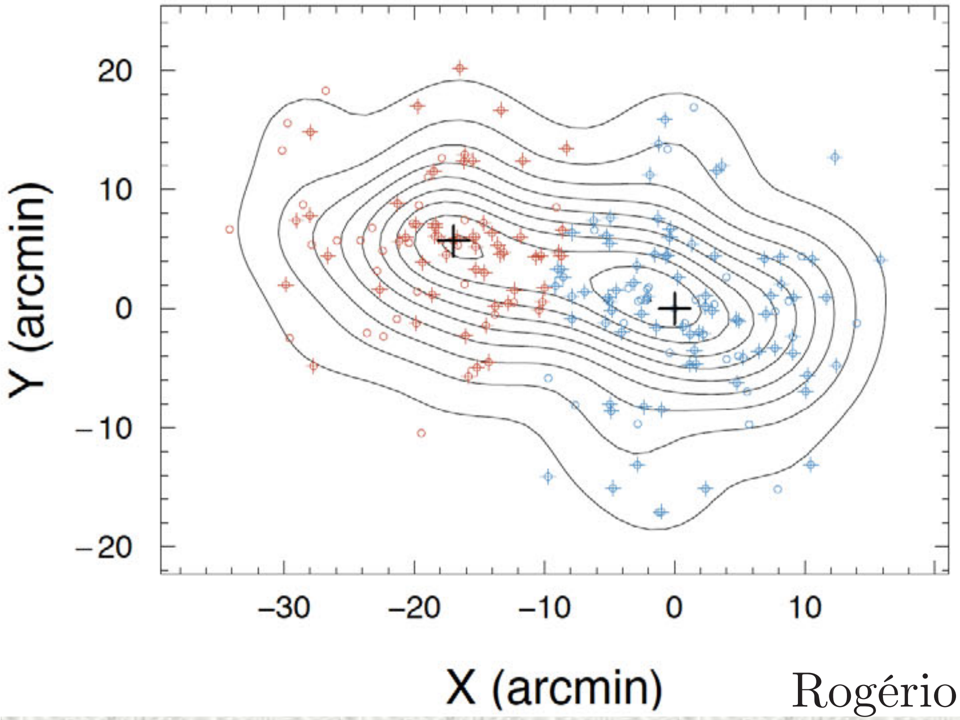
A3376: DECam observation

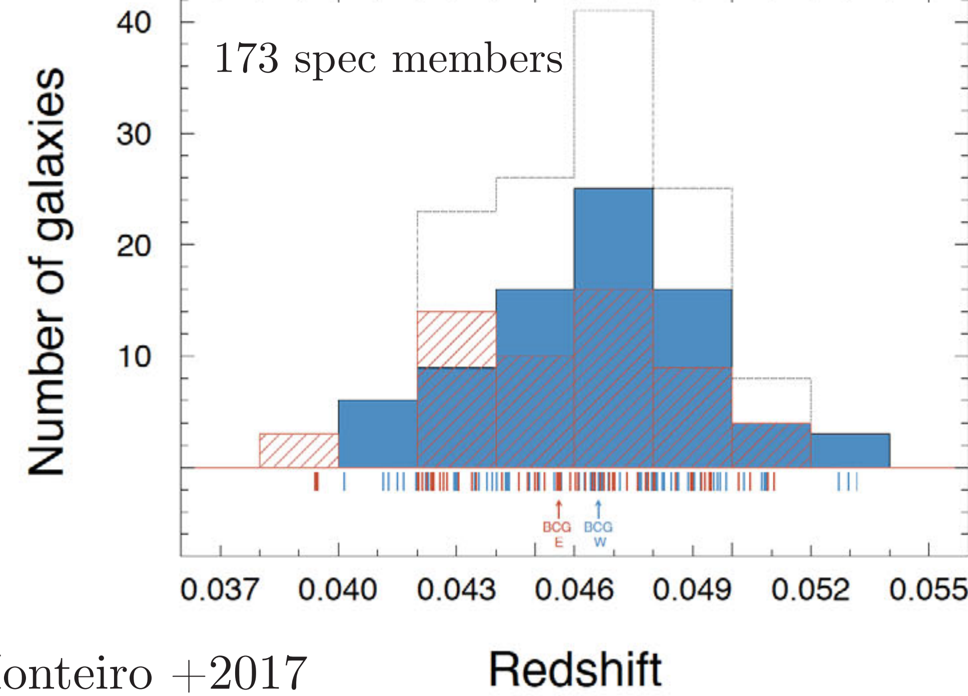
Magenta contours correspond to the numerical density distribution weighted by the r' luminosity for the red sequence galaxies selected through colour-colour statistical subtraction



- r,g,i deep observation with a large field of view (02/2014).
- Necessary for mapping and constraining lensing.

Dynamical analysis: A3376



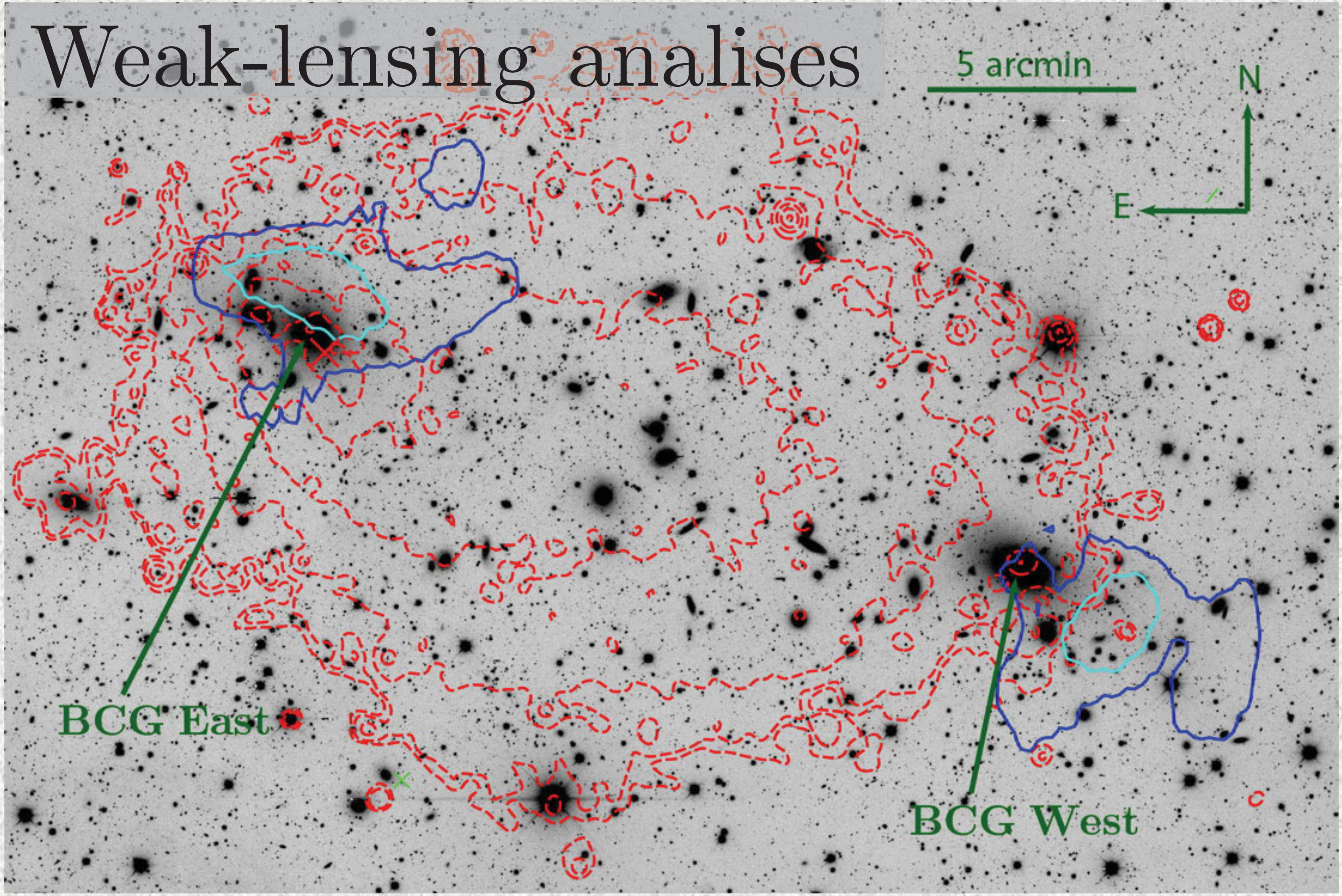


Rogério Monteiro +2017

– Disentangle a collision occurring almost on the plane of the sky.
– Both substructures have almost Gaussian velocity distribution almost superimposed in redshift space

redshifts: Dressler +1988, Russell + 2004, WINGS (Cava +2009) [source: NED]

Weak-lensing analises



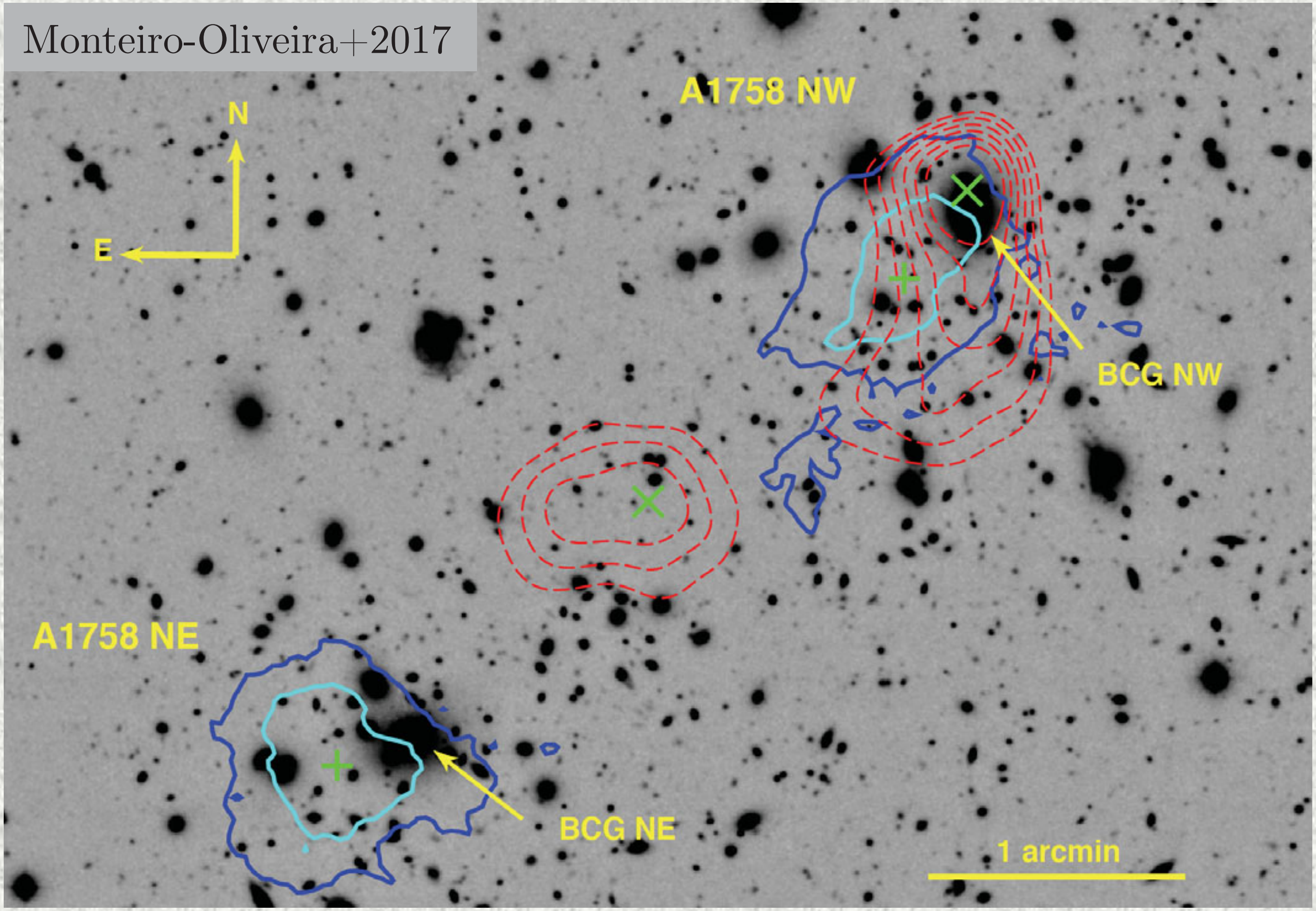
Red: X-ray emission (gas)
Blue: 68% and 95% confidence level position of mass centers

- Comparing mass, galaxy and gas distributions.
- Possible offset in the western component, no offset with eastern component ➔ as predicted in N-body simulations.

Summary

- X-ray observations are particularly useful to detect and characterize colliding/merging clusters.
  - *Chandra* and XMM-*Newton* are 17 years old and the next generation of X-ray telescopes such as ATHENA may or may not be launched only in 2028.
- Optical observations are needed for lensing and galactic dynamical analysis.
- Sloshing in clusters are frequent due to fast collisions of unequal bodies (mass ratio 1/2 to 1/10).
- Depending on the impact details, there may be or not detachment of DM and gas.
  - In the case of detachment, we have one of the best constraint on the DM self-interaction cross section (e.g. Abell 1758, Monteiro-Oliveira+2017)
- Difficult, but not impossible to disentangle clusters colliding near the plane of the sky in redshift space.

Abell 1758



Red: x-rays; blue: 68% and 95% c.l. position of mass centers

Highly dissociative collision, we can put an upper limit to the DM self-interaction cross section: 5.8 $cm^2 g^{-1}$.

$$\tau_s = \frac{\sigma}{m} \Sigma_s < 1$$

Markevich+2004