Mem. S.A.It. Vol. 74, 335
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Clusters and groups of galaxies: the interplay between dark and baryonic matter

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Abstract. We present the people involved and the research activities planned in our COFIN 2001-2003 Project.

Key words. galaxies: active – galaxies: general – galaxy: clusters: general – galaxies: intergalactic medium – cosmology: dark matter

1. Introduction

The field of groups and clusters is now entering a new stage of unified astrophysical processes and understanding.

These condensations are long held to grow by hierarchical merging under the dominant gravitational drive of the dark matter (DM). This drives toward closely invariant structure over the scales from small galaxies to rich clusters. On the other hand, the baryons are sensitive to the energy inputs, which drive structures away from scale invariance.

In fact, the baryonic component comprises three coupled phases: the hot gas (i.e., the intracluster medium or ICM), the cooled gas, and the phase condensed into galactic stars or even into supermassive black holes (BHs) in the AGNs. The very formation of groups or clusters liberates gravitational energy on large scales; in addition, the baryonic condensations feed back extra energy affecting temperature and density of the ICM.

The partition and the cycling of the baryons among such phases shifts as the dark structure grows, so driving the baryonic component away from DM's scale invariance. So the dark and the baryonic component are related by a complex network of relationships including actions and back reactions. Understanding and quantifying such interplays has gone beyond the powers of a single researcher or even one professionally focused research team. This Project is intended to join the aims, the expertises and the efforts of four Italians research Teams.

We aim at pinpointing the subtle differences between the DM structures, and at clarifying the behaviour of their baryonic content at scales ranging from galaxies to poor groups and rich clusters. In particular,

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we plan to test to what extent DM structures actually retain self-similarity when M and z change, and to study how the energy feedback from baryons condensing into stars or AGNs strives away from this. These goals will be pursued with observations in the optical, X-ray, radio and microwave bands, with numerical simulations, and with semi-analytic modeling.

2. Overview of the Research Units and of their activities

Principal Investigator: A. Cavaliere.

Bologna Research Unit
Local Coordinator: S. Bardelli
Dynamics of merging clusters.

This Research Unit (RU) will perform multi-wavelength studies of the dynamical phenomena due to merging of, and accretion on clusters. We will study how these phenomena affect the ICM physical state and the galaxy population. In particular, we plan to perform: - Optical observations: to analyse the distribution and dynamics of galaxies, to identify and study substructures, to provide mass estimates, to determine the galaxy spectral and morphological classification and the luminosity function. - X-ray observations: to provide an alternative mass estimate, the analysis of the gas distribution, the construction of temperature maps, the identification of filaments and shock fronts. - Radio observations: to study the influence of merging on the morphology of extended radiosources, to search for relics and radio haloes, to estimate the velocity component perpendicular to the line-of-sight.

Trieste Research Unit
Local Coordinator: M. Mezzetti
Observational properties of groups and clusters of galaxies.

This RU will investigate the baryon properties in galaxy systems as a function of mass. At small z, we will focus on the optical luminosity function of galaxies in different environments, and on the luminosity function of the systems as a whole. We will also obtain the optical mass to luminosity ratio and the X-ray luminosity function, and correlate all these observables. The study of the cluster dynamics will be extended to higher z using spectroscopic data from VLT observations. Of particular interest will be the photometric and spectroscpic study of the cluster 1E 0657-56, for which we plan to evaluate the mass from gravitational lensing.

Padova Research Unit
Local Coordinator: L. Moscardini
Numerical simulations of the formation of galaxy systems.

This RU in Padova/Torino will provide the numerical simulations supporting the activities of the other RUs. These simulations will be used for: - Studies of the ICM dynamics during the process of formation of galaxy clusters and groups (when and how the gas thermalizes; hydrostatic equilibrium; time evolution of the entropy and its distribution in the final object; relation with the LSS); - Simulations of X-ray and mm observations, and of gravitational lensing effects (observational effects; comparison of different mass estimates).

Roma Tor Vergata Research Unit
Local Coordinator: LC: A. Cavaliere
X-ray emission and Sunyaev-Zel'dovich Effect, two probes for the non-gravitational heating of the ICM.

This RU will develop the existing semi-analytic model with energy feedback from SNe, to compute the optical luminosity functions (LFs) of the galaxies in the field and in overdense regions collapsing as groups or clusters. We will relate the optical LF to the X-ray observables and to the SZ effect. We will include the galaxy binary interactions to investigate how these flatten the mass function at small or intermediate masses, how they trigger impulsive star formation (so tuning the LF itself), and how they affect the fueling of central AGNs. We will include the feedback from the AGNs, and investigate how the X-ray luminosity and SZ intensity are determined.

3. The dynamics of merging clusters: the physics of shocks and their influence on the galaxy population

Trieste Research Unit: S. Bardelli, A. Cappi, B. Lanzoni, and E. Zucca.

The aim of this research program is the detailed study of the dynamical phenomena involved in cluster mergings, which are the mechanisms responsible for the formation of rich clusters. In particular, we will work on the modifications of the physical state of the intracluster medium and of the properties of the galaxy population due to the enormous energy release (10^{63} erg) involved in these phenomena.

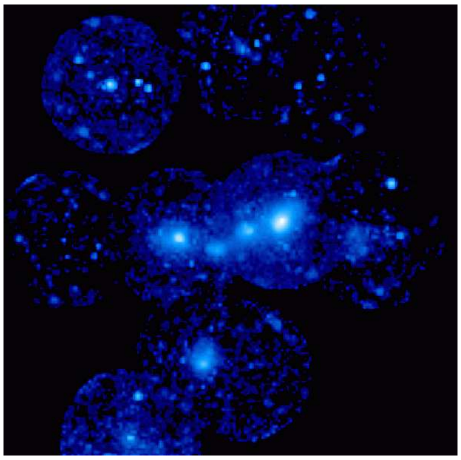

Fig. 1. The soft X-ray emission (ROSAT mosaic from Ettori et al. 1997) in the A3558 cluster complex. We propose that this structure is the remnant of a cluster-cluster collision seen after the first core-core encounter.

In order to obtain complementary information, this study will be done using a multiwavelength approach (optical, X-ray and radio bands):

- The analysis of optical data allows to describe the distribution and the dynamical state of galaxies, with particular attention to the presence of substructures. The estimate of the velocity dispersion of clusters gives information about the virialization degree of the structures and allows to determine the virial mass. Moreover, from the galaxy spectra it is possible to obtain a spectral/morphological classification, which gives the possibility to relate the star formation activity with the local environment.
- The distribution of hot intracluster gas, visible in the X-ray band, is directly related to the potential well of the structures and can be used to estimate the cluster masses. Merging events are expected to modify the gas distribution, and therefore the X-ray isophotes, forming filaments connecting the involved clusters. Moreover, the shock fronts should be visible as enhancements in both temperature and surface brightness distributions.
- The study of extended radio sources constraints the description of the merging, giving a further probe of the relative velocity of the structures and of the gas flows. In particular it should be possible, on the basis of the bending of the lobes of Wide Angle Tail sources, to have information on the velocity component perpendicular to the line of sight, impossible to infer from the redshift distribution. Other important parameters to be derived are the age of the emitting electrons and the difference between the internal pressure of the source and that of the hot cluster gas. Moreover the position of the shock front is detectable in the radio band as relics if electrons left by a pre-existing radiosource are present.

The research program presented in this proposal is mainly aimed to the detailed multiwavelength study of major merging events, which can be found in rich superclusters. Moreover, given the fact that understanding the dynamics of mergings requires the study of a number of systems in different evolutionary phases, we will consider also cluster mergings at higher redshifts. In particular we will focus on the following samples, for which we have multiwavelength data:

1. the complexes of merging clusters in the Shapley Concentration (at $z \sim 0.05$): we found three cluster complexes (dominated by A3528, A3558 and A3571, respectively) which represent a major merging event at different evolutionary stages (Bardelli et al. 1996, 1998, 2000, 2001a, 2001b);
2. two pairs of merging clusters (A2061-A2067 and A2122-A2124) in the Corona Borealis supercluster (at $z \sim 0.07$);
3. the intermediate redshift ($z = 0.247$) cluster A521, which is a young cluster forming at the crossing of two filaments (Maurogordato et al. 2000; Arnaud et al. 2000);
4. the candidate clusters at high redshifts, optically selected from the ESO Imaging Survey (EIS, da Costa et al. 2000).

The final aim of the project is to have a good description of the merging phenomenon from the observational point of view, studying interacting systems in different evolutionary phases, to be compared with the predictions of the simulations and of the semi-analytical models.

Within this context, we plan to dedicate the first year of activity mainly to the data acquisition and reduction and the second year to the interpretation of these data.

4. Observational properties of groups and clusters of galaxies

Trieste Research Unit: A. Biviano, W. Boschin, M. Girardi, F. Mardirossian, A. Mercurio, M. Mezzetti, M. Persic, and M. Ramella.

4.1. Observations of groups and clusters of galaxies

As far as galaxy groups are concerned, the RU proposes to considerably improve the knowledge of groups properties thanks to the new wide catalogs of groups recently published in the literature. At nearby redshift ($z < 0.05$) these catalogs are the NOG sample (Giuricin et al. 2000), the SSRS2 and UZC groups (Ramella et al. 2002) and the RASSCALS groups (Mahdavi et al. 2000). At higher redshift ($z \sim 0.1$) the ESP groups (Ramella et al. 1999) and the LCRS groups (Tucker et al. 2000) are available. The new data will allow to detect signs of cosmological evolution for galaxy groups. The follow-up studies of the EIS clusters (Nonino et al. 1999), both from spectroscopic (ESO 3.6 m) and imaging observations (NTT), represent the main observational effort of the RU in the field of galaxy clusters. In particular, new candidate clusters will be selected in the field of the EIS survey by using a recently developed search algorithm based on the Voronoi tessellation (VT, Ramella et al. 2001). The confirmed clusters will be interesting targets for FORS/VLT spectroscopic observations for the determination of the dynamical properties of medium-distant clusters ($z \sim 0.5-0.7$). In addition, the RU plans to perform a serendipitous search of clusters in the X-ray band applying the VT technique to Chandra archival fields (Boschin 2002).

4.2. Dynamics of clusters of galaxies

Based on the catalog of the ESO Nearby Abell Cluster Survey (ENACS, Katgert et al. 1998), the largest spectroscopic survey of rich nearby clusters, the RU proposes to study the structure and the dynamical status of galaxy clusters by analyzing the anisotropy profiles of member galaxies and searching for substructures and velocity gradients. In addition, the ENACS sample will be complemented with available data of nearby clusters from the literature (e.g., Girardi et al. 1998). The techniques used to study the nearby systems will be extended to the analysis of a sample of about 50 clusters at intermediate redshifts (median $z \sim 0.3$) compiled from different reference sources (Girardi & Mezzetti 2001). The observational effort described in the previous point will allow to increase the number of $z > 0.5$ systems with known redshifts.

4.3. Galaxy systems, galaxies and environmental effects in the nearby universe

The RU proposes to study the dependence of galaxy properties (optical luminosity function, structural properties, nuclear activity, etc.) from the environmental density. The NOG catalog will be used to this purpose. Preliminary results show that there is evidence of an excess of high-luminosity halos in high-density regions and, conversely, an excess of galaxy systems with fainter luminosities in low-density regions. These results are compatible with those suggested by CDM simulations (Lemson & Kauffmann 1997; Mo & White 1996).

4.4. Clusters of galaxies in the mid infrared

The data freely available from the ISO archive will be used to study the properties of medium-distant galaxy clusters in the mid-IR (e.g. Fadda et al. 2000). The aim of this investigation is twofold: 1) investigate the properties of cluster member galaxies in mid-IR; 2) use the gravitational lensing magnification power of these clusters to image distant galaxies beyond the cluster lenses, at an intrinsic flux level which otherwise be unreachable with ISO. The mid-IR images and photometry will allow to set constraints on the presence and importance of dust in cluster and background galaxies.

4.5. Galaxies at optical and X-ray wavelength

Galaxies are the building blocks of groups and clusters. The RU will deal with two key aspects of galaxy physics: a) the relative amounts of visible and dark matter; b) the properties of starburst galaxies (SBGs). About point a), the properties of dark matter halos around galaxies will be investigated by studying the rotation curves (RC) of spiral galaxies (e.g. Persic & Salucci 1995). As far as SBGs are concerned, particular attention will be given to the thermal and non-thermal high-energy processes occurring in these galaxies and their links to the late stages of stellar evolution (e.g. SN explosions, galactic winds, etc.). Preliminary results suggest that the high-energy spectral shapes of SBGs are complex with different components dominating in different X-ray spectral intervals.

5. Numerical models of the formation and evolution of galaxy clusters

Padova/Torino Research Unit: S. Bertone, P. Coiazzi, A. Diaferio, A. Gardini, F. Lucchin, M. Meneghetti, L. Moscardini, M. Negrello, O. Pantano, E. Rasia, P. Reviglio, G. Tormen, and M. Viel.

5.1. Creation of a database of high-resolution Tree-SPH simulation of galaxy clusters

17 clusters;
mass range: 3×10^{14} to 1.5×10^{15} $\mathrm{M}_{\odot}$ h^{-1}
force resolution: 5 kpc h^{-1};
box size: 480 Mpc h^{-1};
ΛCDM cosmology;
50 snapshots from redshift 10 to 0.
See Fig. 2.

5.2. Sunyaev-Zel'dovich effect using hydrodynamical simulations

Analysis of the effect of inhomogeneities and substructures in the gas distribution and their influence on the interpretation of observations at different redshift. See Fig. 3.

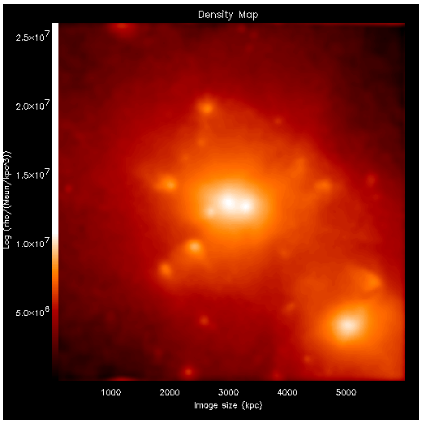

Fig. 2. Density map of a simulated galaxy cluster at $z \sim 0.2$ (Tormen et al. and Rasia et al., in preparation).

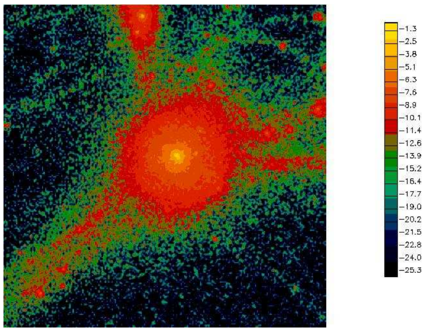

Fig. 3. Inhomogeneities and substructures in the gas distribution (Diaferio et al., in preparation).

5.3. Implementation of software simulating observations with X-ray telescopes

Inclusion of effects present in real observations (background, foreground, cosmic rays, internal noise, counts in pixels, etc.). See Fig. 4.

5.4. Numerical simulations of the strong-lensing properties of galaxy clusters

Special attention to the consequences due to the inclusion of observational effects,

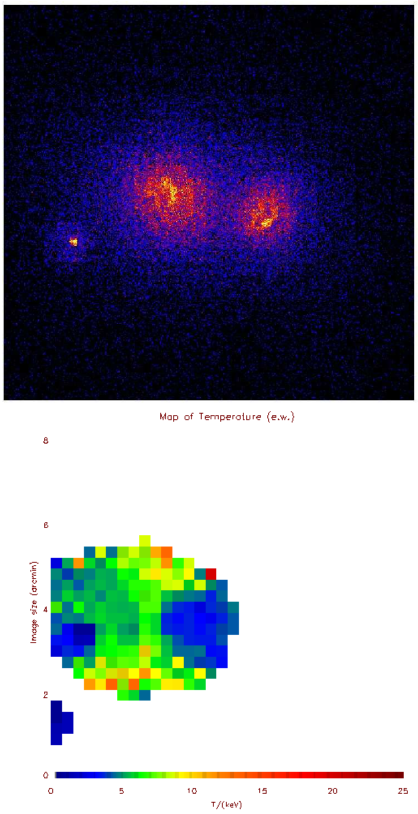

Fig. 4. Simulation of a Chandra-like observation with 30 ksec of exposure time (Gardini et al., in preparation)

as atmospheric seeing, photon noise in the CCD pixels, brightness of the night sky, etc. See Fig. 5.

6. The thermal history of the ICM: feedback from SNe or from AGNs?

Roma Tor Vergata Research Unit: A. Cavaliere, A. Lapi, N. Menci, and V. Vittorini.

6.1. DM vs. Baryons

Groups and clusters under the dominance of the DM evolve hierarchically by repeated *merging* with comparable or smaller

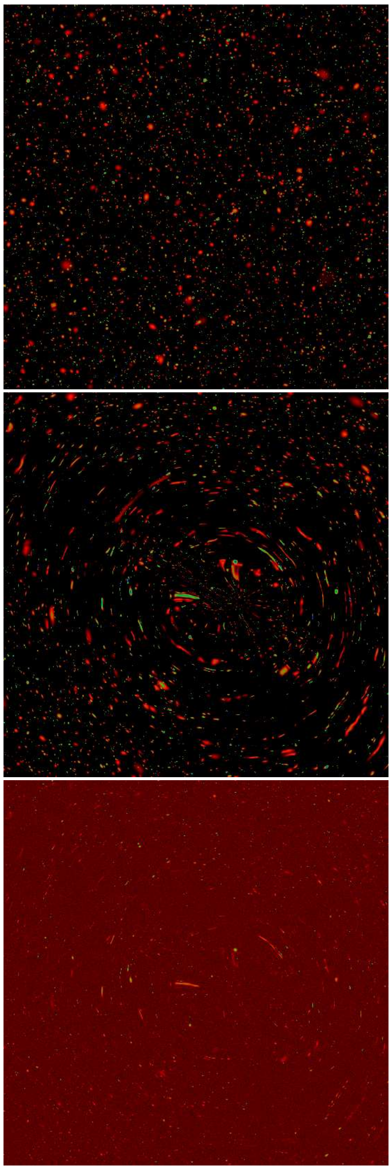

Fig. 5. Unlensed field (upper panel); lensed field without observational effects (middle panel); lensed field with observational effects (lower panel) (Meneghetti et al., in preparation).

clumps. This process is governed only by *weak*, large scale gravity, so closely scale-invariant structures with self-similar profiles are expected. These structures have densities scaling as $\rho \propto 200\,\rho_u$, sizes $R \propto (M/\rho)^{1/3}$ ranging from 0.5 to 3 Mpc, and velocity dispersions $\sigma^2 \propto GM/R$.

Are the baryons scale-invariant, too? They are mostly in a diffuse hot phase, the ICM. This has temperatures $kT \approx 0.6\,(\sigma/300\,\mathrm{km\,s^{-1}})^2$ keV, and total thermal energies $E \approx 10^{60\div63}$ erg. Such large thermal energies are most likely originated through accretion shocks that convert gravitational energy as the baryons fall into the structure during the formation process.

The ICM is probed by its Bremsstrahlung X-ray emission, $L_X \propto n^2\ R^3\ \sqrt{T}$, which for scale-invariant ICM would follow $L_X \approx 10^{45}\ (T/4\,\mathrm{keV})^2$ with typical densities $n \approx 10^{-3}$ cm^{-3}. However, the data for groups with $kT \lesssim 1$ keV (within their considerable scatter) show much *weaker* emissions, i.e., *lower* densities compared with the scale-invariant conditions (see Fig. 6).

Another ICM probe is provided by the Sunyaev-Zel'dovich effect, which yields (secondary) CMB fluctuations $(\Delta T/T)_{CMB} \propto n\,T\,R$. This should follow $(\Delta T/T)_{CMB} \approx -0.5\,(T/4\,\mathrm{keV})^{3/2}$ mK in scale-invariant conditions.

In any case, the departures from scale-invariance of the SZ decrement and of L_X are related by $\Delta T_{CMB} \propto L_X^{1/2}\,T^{3/4}$, that holds model-independently for ICM in hydrostatic equilibrium.

But in groups X-ray data are noisy, and SZ measurements are missing. We plan to derive quantitative predictions by taking a closer look at the ICM heating processes.

6.2. Feedback sources

Non-adiabatic heating must be involved. This is because the X-ray data may be rephrased in terms of the ICM specific entropy $S \propto \ln(T\,n^{-2/3})$; lower values of L_X in groups correspond to a high entropy floor $T\,n^{-2/3} \gtrsim 140$ keV cm^2. Such values require not only additional ICM heating,

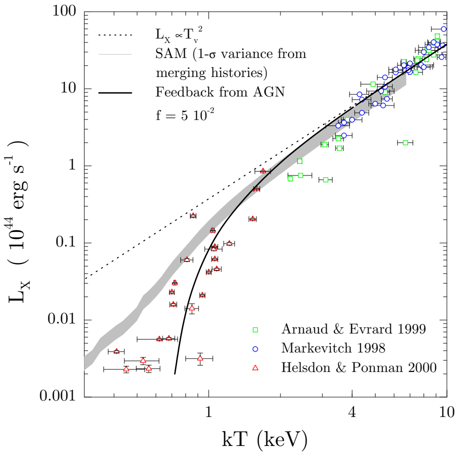

Fig. 6. The $L_X - T$ correlation (from Cavaliere, Lapi & Menci, in preparation).

but also a density decrease, a strongly non-adiabatic behaviour.

Primary candidates to provide feedback are the SNe following the star formation in the member galaxies. These events provide an energy release amounting to $2\,10^{48}$ erg per $M_\odot$ in the IMF. This converts to $\Delta E \approx$ 0.3 keV per affected particle, close to the ICM binding energy E of a poor group.

In 1 keV groups the related $\Delta E/E \approx$ 0.3 is marginally sufficient if SN remnants behave cooperatively to heat and expel an appreciable fraction of the ISM in normal galaxies or smaller.

Such heated gas is re-accreted during the group formation, and its temperature hinders the liberation of gravitational energy during the infall. In this process of *hierarchical* heating, the SN energy provides the scale that breaks the drive toward scale-invariance induced by weak gravity. Note that the amount of cooling consistent with baryon condensation into stars helps to lower the ICM density, by removing the low-entropy gas from the center of groups and clusters.

Alternatively or additionally, the more extreme condensation of baryons under relativistically strong gravity into supermassive black holes energizes central AGNs and provides $\Delta E/E$ attaining unity. A typical AGN discharges during its short lifetime about 10^{61} erg; this is a large energy, but the coupling efficiency f to the surrounding medium is highly uncertain, and may range from 10^{-1} for radio-loud to 10^{-2} in the radio-quiet AGNs.

As $\Delta E/E \propto (kT_v)^{-5/2}$ increases toward unity in moving from clusters to groups, we expect these to be progressively underluminous, and the $L_X - T$ relation to be steepened in agreement with the X-ray data (see Fig. 6).

In galaxies $\Delta E/E$ attains unity, so that the energy feedback is enough to expel a substantial amount of gas and to regulate the accretion itself, setting BH masses $M_\bullet \approx 2 \times 10^9\,(\sigma/300\,\mathrm{km\,s^{-1}})^5\,(f/10^{-2})^{-1}$ $\mathrm{M}_\odot$. We expect this to leave as a specific signature a steep and tight correlation close to $M_\bullet \propto \sigma^5$ (see Fig. 7).

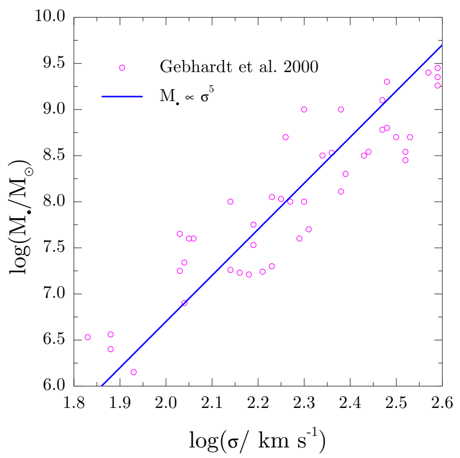

Fig. 7. The $M_\bullet - \sigma$ correlation.

In the extreme, higher values of $\Delta E/E$ over shorter times may cause total evacuation of the ISM and freeze out of the stellar evolution in a number of galaxies, as may have been the case for some of the EROs.

6.3. Summary

To conclude this Section, we put in context and summarize our preliminary views. The baryons behave non-invariantly owing to the energy fed back as part of them condense under *strong* gravity. The latter cooperates with the other fundamental interactions in the star cores that re-explode as type II SNe; but it acts in its pure form in the relativistic dips accreting gas that energizes AGNs at the galactic centers.

In particular, the ICM constitutes an archive of the thermal inputs from stars and BH. The relics of this history include on galactic scales the $M_\bullet - \sigma$ relation from optical measurements, and on larger scales the $L_X - T$ and $\Delta T_{CMB} - T$ correlation from X and microwave observations.

7. Conclusions

This Project is motivated by the need to join the aims, the expertises and the efforts of four Italian research Teams. They have common, long-standing interest in groups and clusters of as systems of galaxies and as containers of ICM. They have an acknowledged background concerning optical observations (Bologna), optical and X-ray observation of groups and clusters (Trieste), numerical simulations (Padova), and modeling of the ICM and its X-ray emission (Roma Tor Vergata).

The field of groups and clusters is now entering a stage of potential unifications of our astrophysical understanding. The basic structures are gravitationally dominated by the DM, and tend to be invariant over the mass scales from small galaxies to rich clusters. But the baryons respond actively to the energy inputs from SNe or AGNs, so striving away from scale-invariance.

Actually, dark and baryonic components are related by a complex network of relationships. Understanding and making quantitative such interplays has gone beyond the powers not only of a single researcher but also beyond those of a professionally focused research team. It rather requires close contact and direct collaborations among many people dealing with such diverse facets as optical and X-ray observations and numerical simulations or semi-analytic modeling.

This project is intended to offer a grant opportunity and a cultural framework to stimulate, foster and make systematic such interactions, and so contribute efficiently to the advancement of the field.

Acknowledgements. Partial grants from MIUR and ASI are acknowledged.

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