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Distant Clusters of Galaxies

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The information we receive from astronomical objects is, thanks to the finite speed of the electromagnetic radiation, related to their past status. Such differentiation between past and present becomes meaningful only on a large scale or, equivalently, over long times. The clock and time unit are set by the stellar evolution and by the dynamical time.

A glance at Figure 1 shows indeed that at z = 0.5 the look back time for $\Omega_o = 1.0$ and H_o = 50 km sec^{-1} Mpc^{-1} is about $6 \cdot 10^9$ years, a time which is long enough to allow the evolution off the main sequence of some stars and comparable to the free-fall time of large and massive clouds of gas. The collapse time of a cluster of galaxies (Gunn and Gott, *Ap. J.* **176,** 1, 1972) is of the same order of magnitude, however, it is independent of the particular cosmological model. It is striking, indeed, to consider what Figures 1 and 2 tell us. At $z \geqslant 0.5$ and depending on the values of q_o and H_o we may look at the Universe before cluster formation, or we may look only at extremely rich clusters of galaxies (since these have a much shorter collapse time). To us seem fundamental not only the fact that the observations of distant clusters of galaxies give information on the evolution of galaxies but also the awareness that searches and statistics on distant clusters may give constraints on the geometry of the Universe in a simple and straightforward way. This observational work must be allowed and must be done since it is within the state of the art of modern observations.

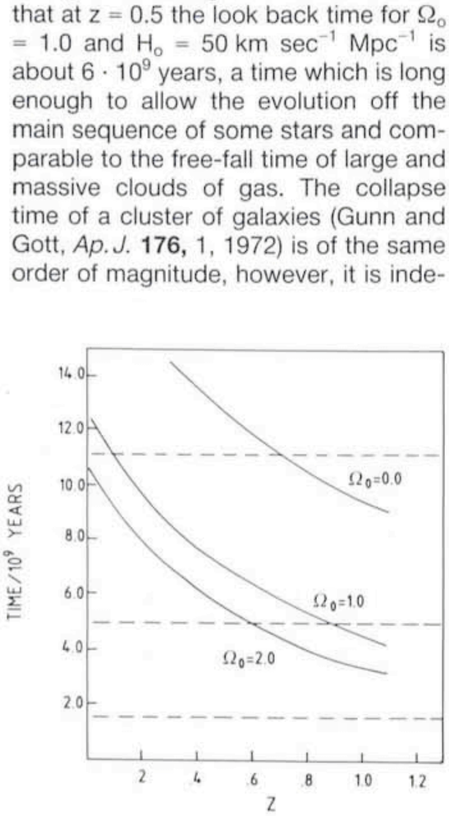

Figure 1: *Cosmic time as a function of redshift for H_o = 50 km sec^{-1} Mpc^{-1} and values of Ω_o as marked (continuous line). The dashed lines mark the cluster collapse time for a cluster which is 5 times less dense than Coma ($t_c \simeq 11.2\ 10^9$ years, top line), as dense as Coma ($t_c \simeq 5\ 10^9$ years, central line) and 10 times denser than Coma ($t_c \simeq 1.6\ 10^9$ years, bottom dashed lines).*

The geometry of space, indeed, remains one of the fundamental tasks of observational cosmology. The classical tests: magnitude-redshift and angular diameter-redshift, need to be investigated up to z = 0.9/1.0 and the evolution effects must be understood before any conclusion can be drawn.

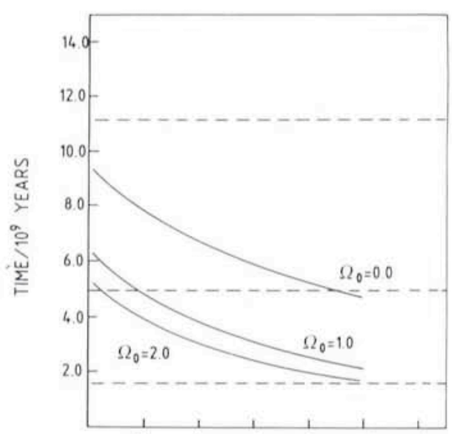

Figure 2: *Same as Figure 1 for H_o = 100 km sec^{-1} Mpc^{-1}. For Ω_o = 0.0 a cluster like Coma would form at about z = 0.9.*

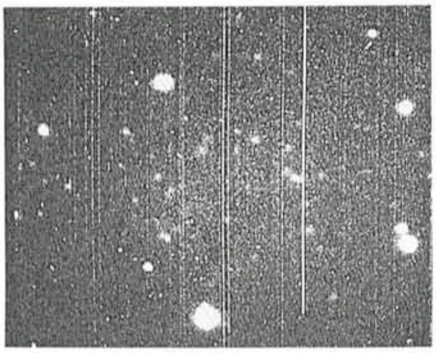

Figure 3: *CCD image (3.6 m telescope + EFOSC) of a cluster at z = 0.69.*

The standard candle for these tests is generally taken to be the first ranked cluster galaxy. This is, however, the one galaxy that is most affected by statistical fluctuations and luminosity and/or dynamical evolution. Often it is a radio source and it is unclear yet to what extent we are dealing with a well defined and low intrinsic dispersion standard candle. As stressed also by Tammann, the use of the 5th brightest galaxy is a better choice, and we must try to measure more, and fainter, magnitudes.

The deep knowledge we have today on stellar evolution and the present and planned instrumentation allows a realistic approach to the fundamental and fascinating field of cosmic evolution. Signs of detection can be found in the early work by Butcher and Oemler (*Ap. J.* **219,** 18, 1978) and by Dressler and Gunn (*Ap. J.* **270,** 7, 1983). Such signs are however inconclusive and only mark the beginning of a set of new observations which can now be done in a systematic way.

To detect evolution means to evaluate the differences between the same object at two different epochs. The astronomical equivalent is to observe what we believe to be the realization of the same object (or even better the realiza-

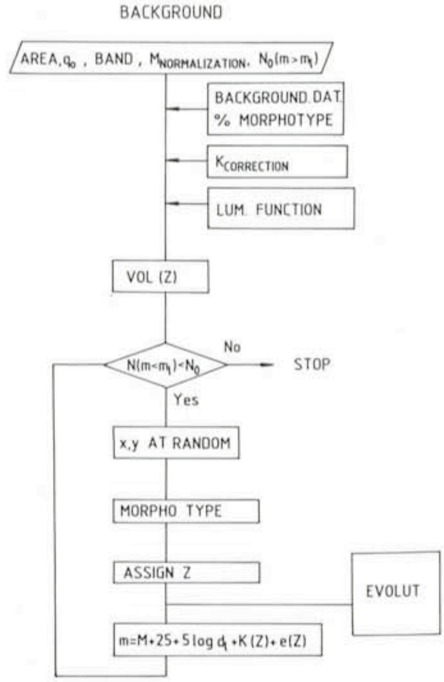

Figure 4a: *Flow diagram for the creation of non-cluster galaxies ("background").*

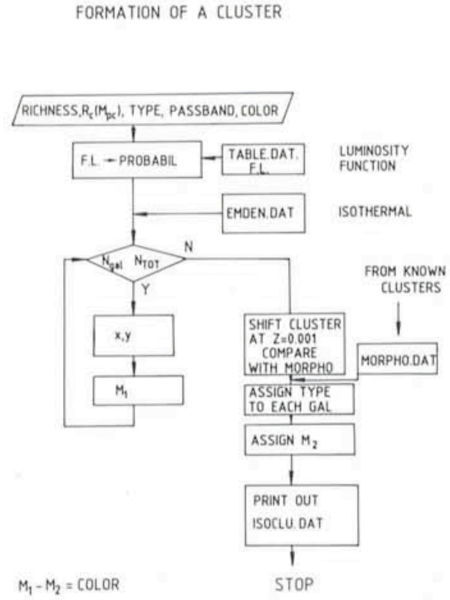

Figure 4b: *Flow diagram for the creation of a cluster of galaxies.*

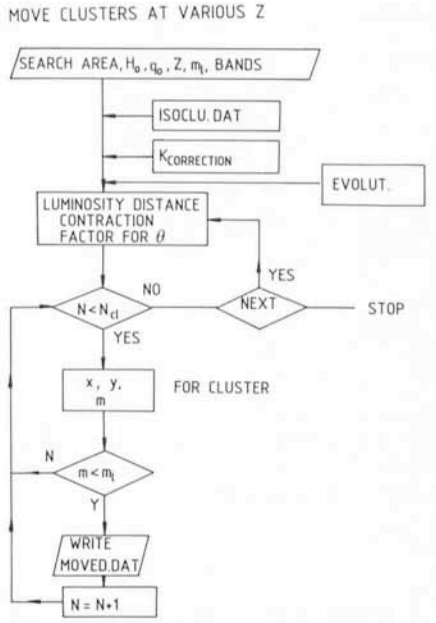

Figure 4c: *Flow diagram for the creation of a cluster at a selected z superimposed on a "background" of galaxies.*

tion of the same class of objects) at two different epochs. Such an approach, therefore, requires a good morphological knowledge, in the context we are dealing with, of nearby and distant clusters of galaxies. The first step is the availability of fair samples; that is catalogues.

Catalogues of Clusters of Galaxies and the Detection of Distant Clusters

The northern sky has been searched systematically for clusters of galaxies by George Abell and the result is his perused catalogue (*Ap.J. Suppl. Series* **3**, 211, 1956). The catalogue is very incomplete for clusters at $z > 0.3$ but forms, however, a fundamental listing for detailed and statistical studies of the nearby present epoch universe. George Abell was not able to complete the survey of the southern sky he initiated in collaboration with Harold Corwin (Abell, G., and Corwin, H., 1983, in *Early Evolution of the Universe and its Present Structure,* p. 179, edited by G. Abell and G. Chincarini, Reidel). The catalogue of the southern Sky is now being completed (Abell, Corwin and Olowin, in preparation). This catalogue will be similar in various aspects to its northern counterpart and therefore practically useless for studies of very distant clusters, $z > 0.4$. The need for deeper surveys – as we have said we must study the log N_c – cz relation and the effects of evolution – motivated the search conducted by Gunn, Hoessel and Oke (*Ap.J.* **306,** 30, 1986), who observed a limited region of the northern sky detecting 418 galaxy clusters in the redshift range $0.15 \leq z \leq 0.92$. We observed one of these clusters, at $z = 0.69$, with the EFOSC attached to the Cassegrain focus of the 3.6-m ESO telescope at La Silla. The analysis of the data has just begun; a preliminary and not yet fully corrected CCD image is reproduced in Figure 3. We do not know yet which kind of a cluster we are dealing with, indeed before we know it we must have a sizeable sample so that we can study the characteristics of clusters at high redshifts. A first hint, however, of the kind of objects we can observe at high z is given (a) by the considerations related to cluster formation (see Figures 1a, 1b) and (b) by the probability of detecting a cluster at a given z.

The eye, or any devised algorithm, recognizes a cluster of objects as a den-

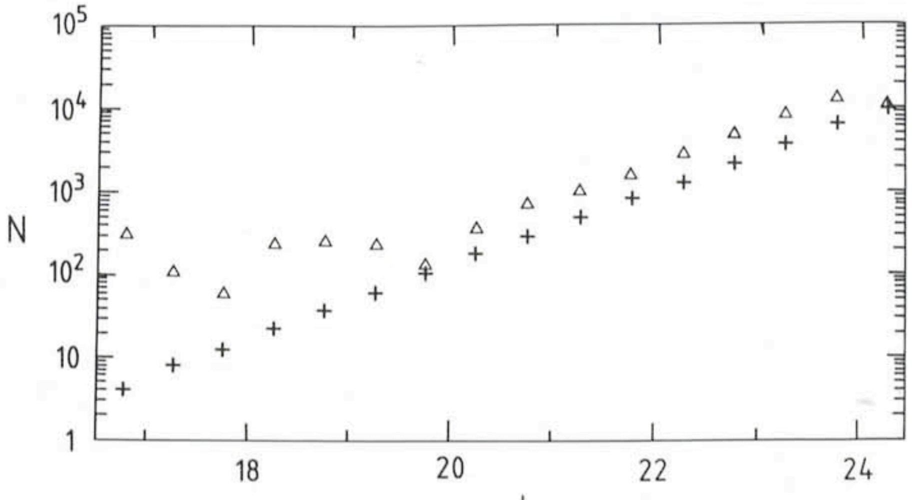

Figure 5: *Counts of galaxies by Jarvis and Tyson (crosses) and by Koo (triangles).*

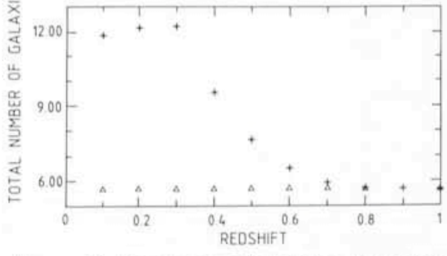

Figure 6: *"Background" galaxies (triangles) and total number of cluster galaxies (crosses) expected in a 10′ × 10′ field. The magnitude limit is J = 25 and the cluster is of richness class R = 2 (R2) and population type E dominant (T1).*

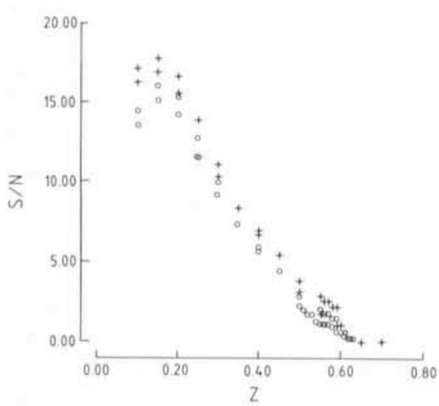

Figure 7: *Signal to noise ratio (searching area with diameter 0.250 Mpc) as a function of redshift (z) for an R2, T1 cluster (without evolution) for 2 simulations.*

sity enhancement over a background of objects. The probability of detection is therefore a strong function of the signal to noise ratio, s/n. The problem has been studied by simulating the universe using our present knowledge. The ingredients are illustrated in Figure 4a for the creation of the background, in Figure 4b for the creation of a cluster and in Figure 4c for what should simulate an area of the sky observed (1) in a selected passband (for now we have used J and F colours), (2) to a given limiting magnitude (we have used $m\ell$ (J, K) = 23 and 25, and (3) without taking into consideration the detector noise (which will be the next ingredient). Naturally we are faced with various uncertainties and approximations, some of which are:

1. At very faint magnitudes the galaxy counts are uncertain by about a factor 2 (Koo, Ph.D. thesis, Univ. of California, 1981; Jarvis and Tyson, *A.J.* **86,** 476, 1981), Figure 5.
2. At large redshifts the K correction plays a dominant role and may indeed completely bias the observed population in the clusters and in the background. We urgently need, indeed, to know the far ultraviolet energy distribution of a statistically valid sample of spiral and elliptical galaxies.
3. For the non-cluster galaxies we placed the galaxies at random. We believe this is a reasonable approximation for the galaxy distribution over a small area of the sky. Non-cluster galaxies were added, with the constraint given by the observed counts, up to z = 2.0.
4. The cluster galaxies were assumed to satisfy an isothermal distribution. The population (galaxy type) was assigned according to a mean derived from observations of nearby clusters.

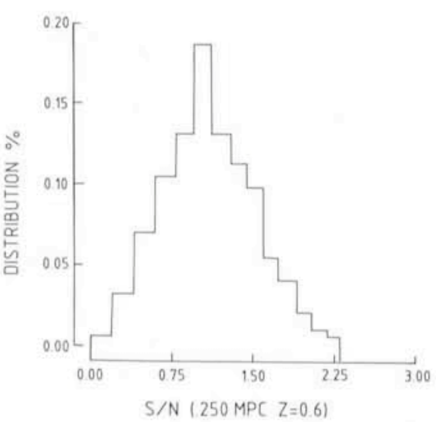

Figure 8: *Distribution of the s/n ratio derived for a cluster R2, T2 (spiral-poor). The histogram is based on 800 simulations.*

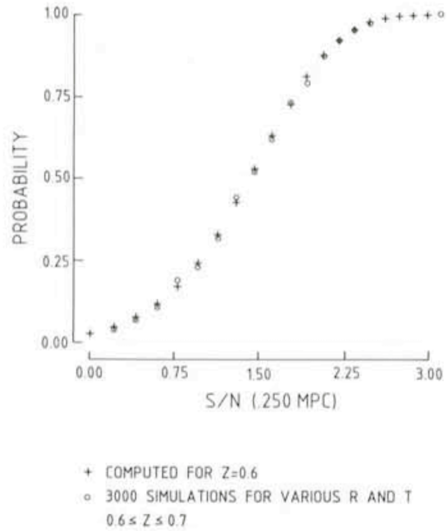

Figure 9: *Probability of detection as a function of s/n. Open circles as derived numerically using 3000 simulations, crosses as computed analytically.*

It is clear that at large z we may face a different distribution (clusters may be forming) and population (galaxy may show signs of cosmic evolution). But this is, indeed, the scope of the simulations. The difference between what we expect and what we observed should be due (assuming we have full control of the observational effects) to the phenomena we want to understand: (1) geometry, (2) formation epoch and (3) cosmic evolution.

On a 10′ × 10′ area the number of background and cluster galaxies (R2 → richness class 2, T1 → rich in elliptical/lenticular galaxies, J25 → m^{ℓ}_{J} = 25.0) as a function of redshift is illustrated in Figure 6. The definition of a search area (0.250 Mpc diameter for instance) allows then a measure of the ratio s/n as a function of the redshift z, Figure 7. Note that due to various realizations of

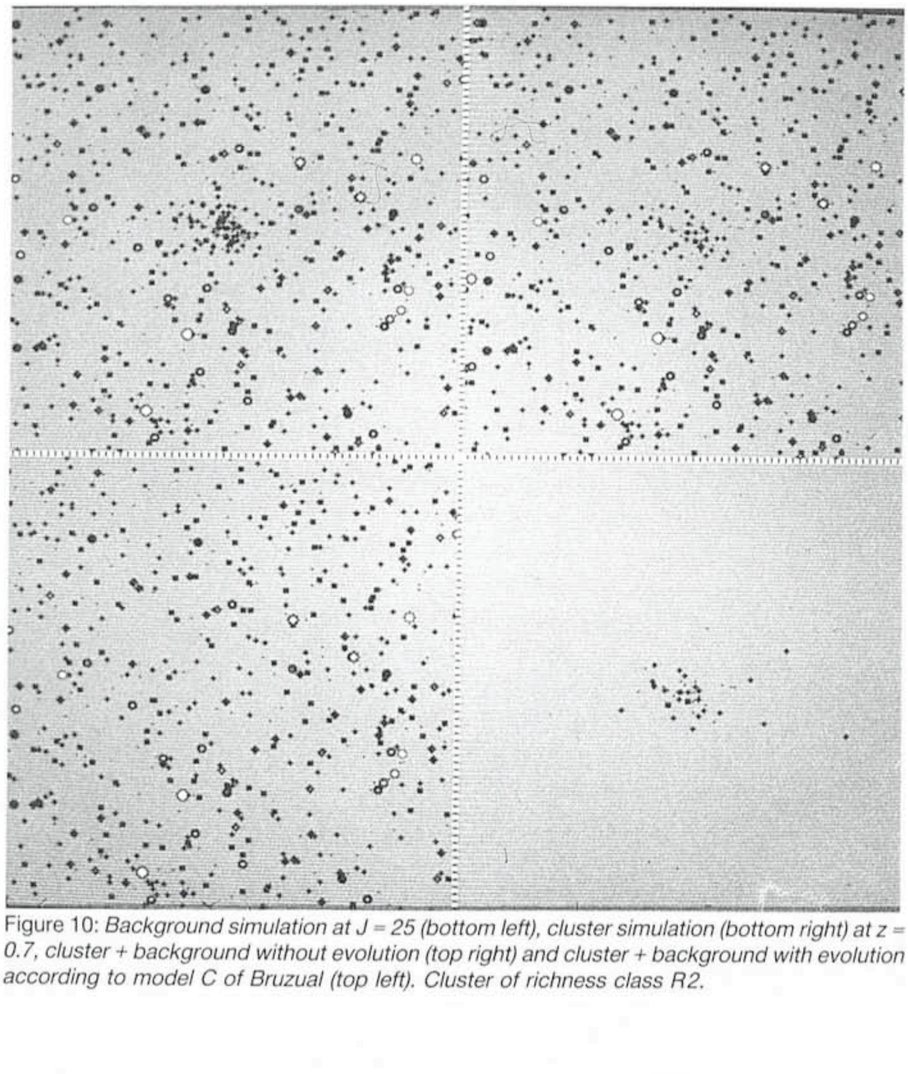

Figure 10: *Background simulation at J = 25 (bottom left), cluster simulation (bottom right) at z = 0.7, cluster + background without evolution (top right) and cluster + background with evolution according to model C of Bruzual (top left). Cluster of richness class R2.*

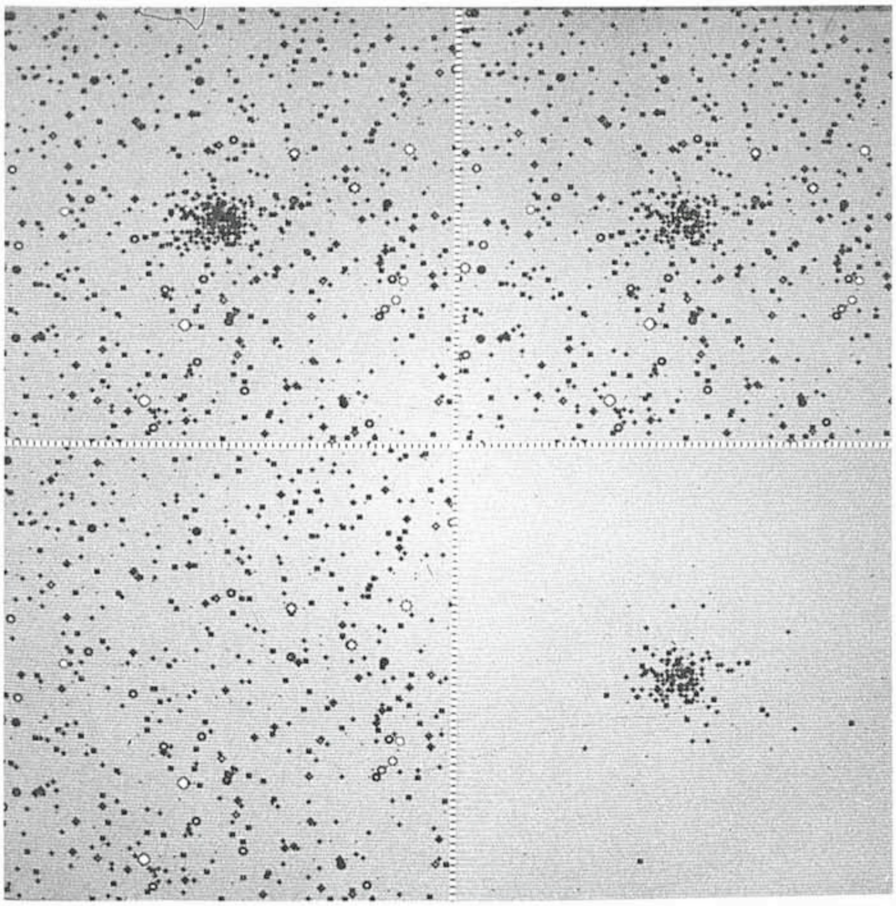

Figure 11: *Same as for Figure 10 for a cluster of richness class R4.*

the same model we have a dispersion of s/n at a given z, an effect which is illustrated in Figure 8 for a cluster at z = 0.6 (the histogram has been derived from the analysis of 800 simulations). Such dispersion must be accounted for when we determine the probability of detecting a cluster at a certain z, and indeed it may reflect the statistics playing in the real universe in the process of cluster formation. A first important result is that, without taking into account any form of evolution, a cluster (in this case of richness class R = 2) is already lost in the background at z = 0.6.

The probability of cluster detection has been computed as a function of the signal to noise s/n (and therefore as a function of z) both analytically and using 3,000 simulations for clusters of various richness and population. The result is illustrated in Figure 9 where the agreement between theory and numerical experiments is excellent. As we have said earlier, however, such probability of detection is a curve of mean values which should be convolved, at each s/n, with the dispersion histogram of Figure 8.

The result of what we have described so far (note that the addition of the detector noise will make detection even morre difficult) is that even unevolved clusters of richness class 4 are hardly detectable for $z \geq 0.6/0.7$ (there is some difference between elliptical dominated clusters [T1] and spiral rich clusters [T3]). Since clusters have been detected at $z > 0.8$, then either we are detecting only extremely rich clusters or evolution plays an important role in making a cluster more visible at large z. We may be dealing with a combination of the two effects. (Note that some detection could be due to a projection effect, that is an enhancement of density when two clusters are seen along the same line of sight).

An idea of how the evolution may increase the probability of detection is depicted in Figures 10 and 11. In each figure is reproduced the simulated background (bottom left), the simulated cluster (bottom right), the cluster superimposed on the background (top right) and the evolved cluster superimposed on the background (top left). In each case the evolution has been illustrated by using model C of Bruzual (*Ap. J.* **273,** 105, 1983); that is a burst of star formation lasting about 10^9 years. The limiting magnitude of the simulated sample is J = 25 and the area $10' \times 10'$. Each galaxy point is coded, even if not marked in the figure to avoid confusion, in magnitude, colour, galaxy type, position and redshift. Figure 10 refers to a spiral-poor cluster (T2) of richness class 2 (R2) at a redshift z = 0.7 while Figure 11 refers to a spiral-poor cluster of richness class 4 (R4) at a redshift z = 0.7.

The evolution of galaxies enhances the cluster visibility!

The new evolutionary models which are being completed by Buzzoni (Brera Astronomical Observatory, Milano) and the observations and analysis of a fair sample of clusters of galaxies will certainly allow important cosmologiccal conclusions to be drawn.

The Giant Luminous Arc in the Centre of the A 370 Cluster of Galaxies

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Recently, people have been very excited by the announcement of the discovery of two giant luminous arcs in the centre of distant clusters of galaxies, namely A 370 and Cl 2242-02 (1). These structures lie in the proximity of giant E galaxies and extend over about 100 kpc. Their origin is still unknown and controversial, and their nature can be understood in terms of strong star formation in the cluster core (by galaxy/galaxy interactions or by cooling flows from the dense Intra-Cluster Medium) or eventually a gravitational lensing configuration.

Indeed, the arc in A 370 was first discovered by a team from the Toulouse Observatory (B. Fort, G. Mathez, Y.