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Detection and characterization of distant galaxy clusters in the near infrared

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Thanks

I wish to thank in a first time all the team of the cosmologic group of the IAS for their work and for the good ambience, as well as all people concerned by the admission process.

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I thank especially Clement Martinache, for his confidence, his advices, his good mood, all the work, his advices achieved during my training, and simply to accept me like trainee.

I- Introduction

A- Context

The study of galaxy clusters can bring answers in several domains of research, like for example Cosmology, or Astrophysics.

1 – In Cosmology

Since the beginning of the last century, the cosmology has known a revolution. In this vision, the matter is distributed around some patterns ; the Universe has a structure, stars, galaxies... Hubble's observations of first extragalactic objects in 1929 proved that not only that our Universe contains different galaxies, but that it is expanding. The recent model of Cosmology possess some parameters : the dark matter, the dark energy... And, we want to know more about these parameters, like their evolution for example. Galaxy clusters are the largest structures of the Universe. These objects interest us because they can teach us the matter distribution in the Universe. The properties of these objects early in the Universe (we set the notion of redshift which tends to infinity when the time goes to zero) are still unknown, i.e. for a Universe with less than three gigayears old. These properties could be real answers for some issues of modern Cosmology. Indeed, the now so-called standard model of cosmology, dubbed LambdaCDM, explains with only 6 parameters a wide range of observations (CMB, cluster counts, ...) and is yet to be challenged. In this model, ordinary matter represent only 4.6% of the energetic content of the Universe, the rest being present in the 'dark component', i.e dark matter and dark energy, whose nature is still unknown and cannot be observed directly. In the primordial Universe, only the dark matter can explain the formation of structures. With its uncoupling with the ordinary matter, it is able to create important potential well before the uncoupling of the ordinary matter. With the Universe expansion, the matter is uncoupled and so can falls in the pre-existing well, and creates the overdensities which interest us, like for example the galaxy clusters. Thus, to know the matter distribution and particularly, the dark matter distribution at the largest scales, the study of the repartition of galaxy clusters is necessary. Such a study of these objects could set constraints on several cosmologic parameters like the amplitude of density fluctuations. For example, the Cosmic Microwave Background brings us informations about some cosmologic parameters at only one redshift (z=1100). The Cosmic Microwave Background is the best measure done ever. It confirms lots of models. The study of clusters distribution, and so the dark matter distribution, could give us information about these parameters at others redshifts.

2 – In Astrophysics

The study of clusters can teach us about the star formation. Indeed, at z=0, i.e. today, we don't observe lots of star formation, and the recent observations of the sky and the potential clusters show us that the majority of stars were formed for redshift around 2. So our subject is the birth and the evolution of stars and galaxies in clusters. Their study is necessary to understand the mechanism of formation of stars in a galaxy cluster.

Beyond the answers brought in Cosmology, the study of clusters can solve others important questions which remain unanswered in astrophysics : What is the comportement of a gas in a well of potential ? How are stars formed in a cluster ? And what is the link between the cluster environment and the evolution of galaxies ? Where are located the star formation in a cluster ?

The subject of the next pages and of my internship is to characterize a galaxy cluster. But, it stays a major question how can we identify the galaxy cluster in their star forming phase ?

3 – Identify them

According to the theory, there are few of such objects in all the sky (approximatively one thousand), and to characterize the process of stellar formation and the gas collapse, data in infrared and submillimetric are necessary.

Indeed, stars born in the giant molecular clouds. In these overdensities of the interstellar medium, the gravitationnal collapse takes place when the local mass is bigger than the Jeans mass. Such regions of the sky can form lots of stars, and some, very massive (up to 200 Sun mass). We know that the most massive stars have a very small duration of life, at the order of 10 Myr, at the opposite to the lightweight, which can be considered like immortal. Hence, the most massive stars are surrounded by dust, and observing these stars teaches us about the star formation, because they are necessary young, compared to the lightweight, and indicate . By different gravitational mechanism, the stars are ejected of their gas cocoon, but, the most massive die before they leave it. So, we can consider that there are only massive and young stars in these clusters. Moreover, the most massive stars are the brightest ($L \alpha M^{3,5}$). These stars have an emission peak in the ultraviolet. But, the energy of this peak excites the surrounding dust, which emits in the infrared (~100µm) during its desexcitation. A study in the infrared is thus necessary to detect star formation.

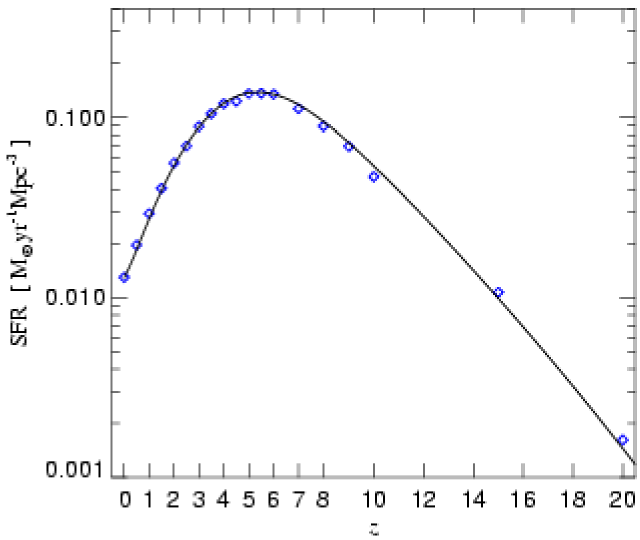

Illustration 1: Star Formation Rate (SFR), the most of stars formed are at a redshift between 1,5 and 2

B- Origin of data

1 – A multiwavelength selection

All our study is based on the data collected by three telescopes, Planck, Herschel and Spitzer, and the instruments associated, HFI, SPIRE and IRAC.

Thanks to the satellite Planck of the ESA which observes the integrity of the sky in the submillimetric and the millimetric wavelengths we can detect the brightest objects and so the most massive in these spectral area ; two type of objects are expected, clusters in star formation phase and lensed galaxies. Curently, we have a lot of candidates with redshifts bigger than 2, whose nature is unknown.

With the Planck resolution of 4,5 arcmin, we are unable to confirm our sources as clusters, and we can't differenciate the two types of objects. If we use the instrument SPIRE of the telescope

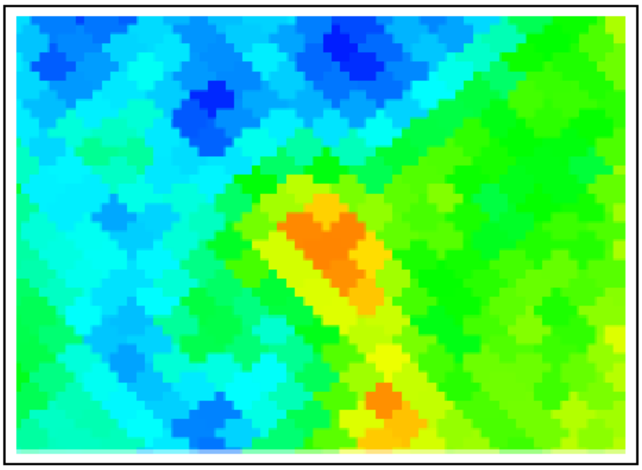

Illustration 2: Candidate from HFI of Planck (350 µm) 30 arcmin x 30 arcmin

Herschel (distant infrared : 250-350-500 µm) and the instrument IRAC of the telescope Spitzer (near infrared : 3,6-4,5 µm), we can study these objects in more details. Indeed, Herschel and

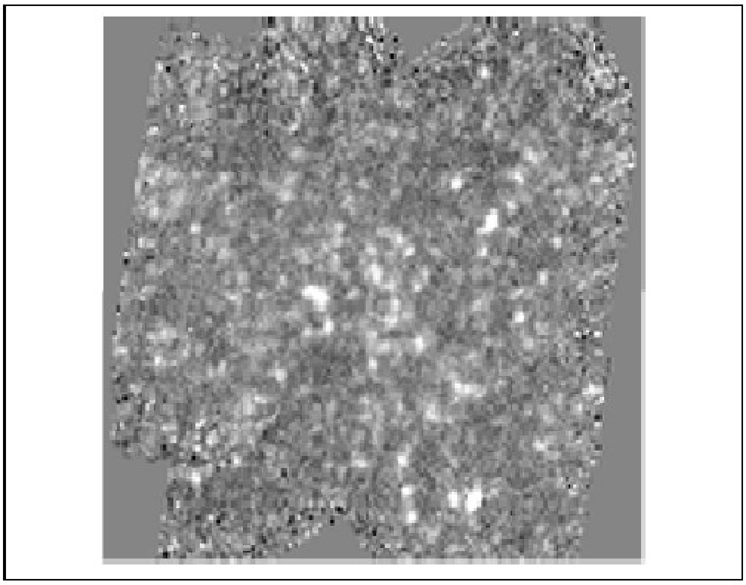

Illustration 3: Same candidate from SPIRE of Herschel (350 µm) 30 arcmin x 30 arcmin

Spitzer have a better angular resolution than Planck (10 arcmin). An analysis with these instruments permits to better characterize our candidates.

a- Planck, a set of more than one thousand candidates

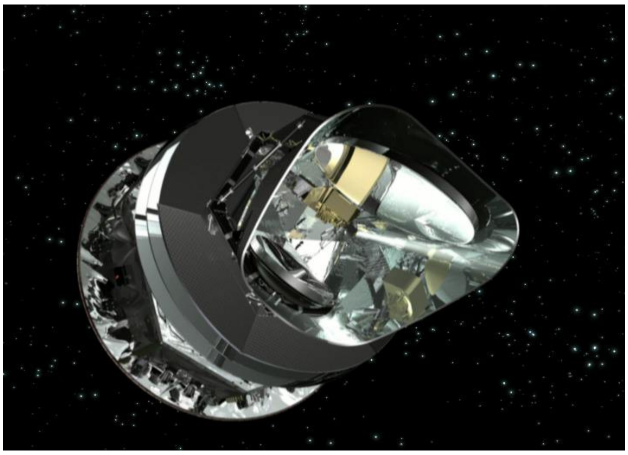

Illustration 4: Planck

Planck allows to have a first detection and location of the object. This detection is made on the entire sky, indeed there are few bright candidates, it is necessary to observe all the sky to find a maximum of objects. Herschel, has a better resolution than Planck and permits to make a better study of the object. Spitzer gives us a better and more detailled study than the two others.

The telescope Planck is a spatial observatory developed by the European Spatial Agency (ESA) which has for aim to map the temperature variations of the Cosmic Microwave Background (CMB). Its spectral area is the micrometric wavelength (100-900 GHz). It was launched in 2009 on a heliocentric orbit and has two instruments to map the sky, LFI and HFI (Low Frequency Instrument, respectively High). The instrument which interest us is HFI which work between high micro-waves and infrared. The first data published of its main mission has given the best possible map of the CMB. An important result is the position of the brightest object of the sky, which are necessary to find to clean the map of the CMB, and to realize our study about the clusters. Others results are the observation of the Sunyaev-Zel'dovich effect, which concerns the distortion of the CMB by high-energized electrons thanks to the Compton diffusion. We can notice that Planck observed gravitational lensing too, and evidences of inflation.

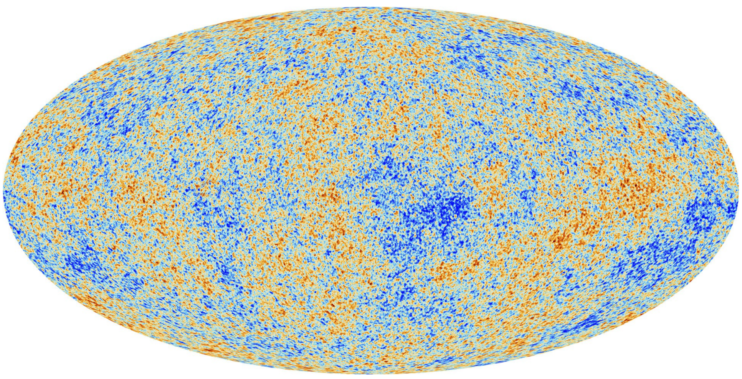

Illustration 5: Cosmic Microwave Backgroud, the best map of Universe

So, Planck allows us to find the brightest object of a region in the sky in the spectral area of millimetric and submillimetric. However like we have seen it, Planck is inefficient to identify exactly a cluster among all bright sources. In deed, there are two types of objects among the sources, the lensed infrared galaxies and the clusters which are wanted. Thus, we need to have data imaging more detailled in near and distant infrared.

b- Herschel : SPIRE, 250, 350, 500 µm

Illustration 6: Herschel

The telescope Herschel is a spatial telescope, launched in 2009, and which observes in the distant infrared and the submillimetric. It has for aim to study the galaxies formation and their evolution. There are three instruments on Herschel, HIFI, PACS and SPIRE. SPIRE permits to create the pictures of the sky in the distant infrared at the wavelength 250, 350 and 500 µm. After the primordial detection by Planck, SPIRE permits to obtain a more detailled picture of the object and its environment. This telescope allows to probe the star formation in infrared, in areas where there are more than one thousand stars created by year.

c- Spitzer : IRAC, 3,6 and 4,5 µm

Illustration 7: Spitzer

The telescope Spitzer launched in 2003, has for aim to observe the formation and the evolution of primordial galaxies, a phenomenon better seen in the infrared. Its instrument IRAC works in the wavelength 3,6 and 4,5 µm and permits to obtain a picture more detailled than the picture coming from SPIRE and Herschel. Thanks to this satellite we can make a redshift selection and estimate the stellar mass.

To resume, we work with three telescopes, Planck which works in millimetric wavelength and finds the brightest objects. The preceeding part of sky found by Planck (1000 objects) is studied by SPIRE, to obtain a more detailled picture (228 objects) of the environment and star formation. Finally, with IRAC, we do exactly the same thing (80 objects).

d- The Very Large Telescope (VLT)

Illustration 8: The Very Large Telescope (VLT) at Hawaï

The VLT is a set of eight telescopes based in the northern Chile. It studies the sky on the wavelength from the ultraviolet to the infrared. After the detection by the others telescopes, the VLT takes pictures of the part of sky concerned.

2 -Our data

However, the picture is not enough to characterize a potential cluster, an analysis is necessary. The first question could be about the certainty of the nature of the object. Is it really a cluster ? Can we characterize it with the redshift, and what is its redshift ? The last but not the least question is, where are formed stars in a cluster ? For all these reasons we need to have a better characterization of these overdensities.

Hence, thanks to the VLT we have obtained some pictures in two bands, J and K (near infrared) to analyse.

In the next paragraphs, we make a follow-up in infrared of a candidate already confirmed coming from Herschel in J-band and K-band. The idea is to constrain the magnitude to constrain the redshift, indeed we want to study a redshift bigger than 2. To select them, we make use of J and K.

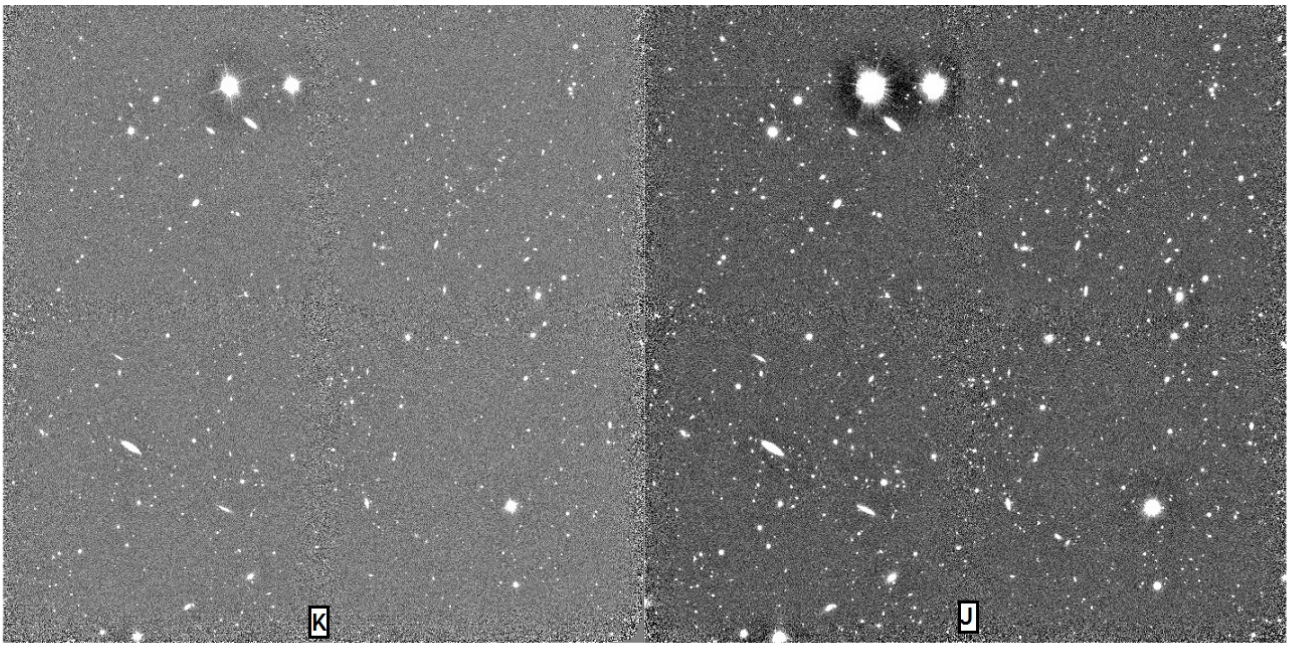

Illustration 9: Part of sky studied in K (left) and J (right)

Although we want to find a candidate, the real objective of our study and my internship is to test a method to characterize a cluster. So, we'll study a candidate already treated by another team, but with another method in paper Santos 2011.

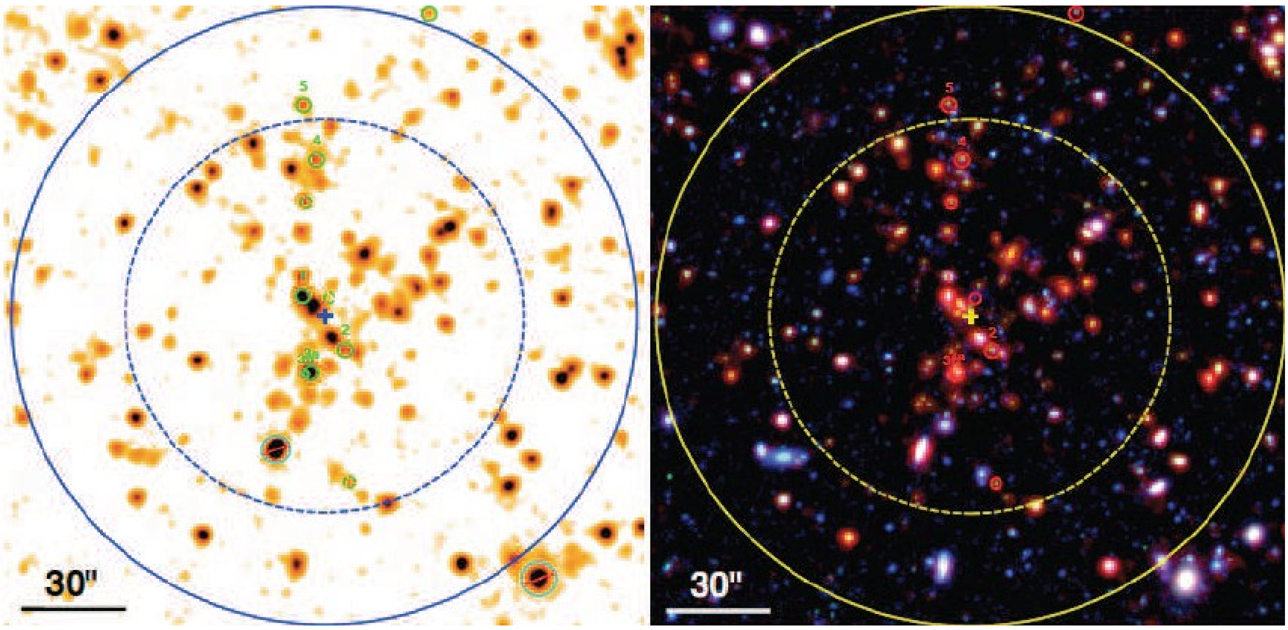

Illustration 10: The confirmed galaxy cluster

This cluster has been confirmed by the Santos team at a redshift of 1,58. Its mass is of the order of the tera solar mass. Its angular radius is 1 arcmin, corrsponding to a physical distant of 250 kpc for a redshift around 1,58.

Our study will be base on a redshift seclection. To do this, we can use the Balmer Break, called 4000 Angström Break too, to identify the objects which shine more in K-band than in J-band. The object in K-band interest us if they aren't in the J band. The study of the luminosity for the two different wavelengths brings us important information about the nature of the object. Indeed, J concerns mainly the old stellar populations, whereas K the youngest. K informs us about the stellar

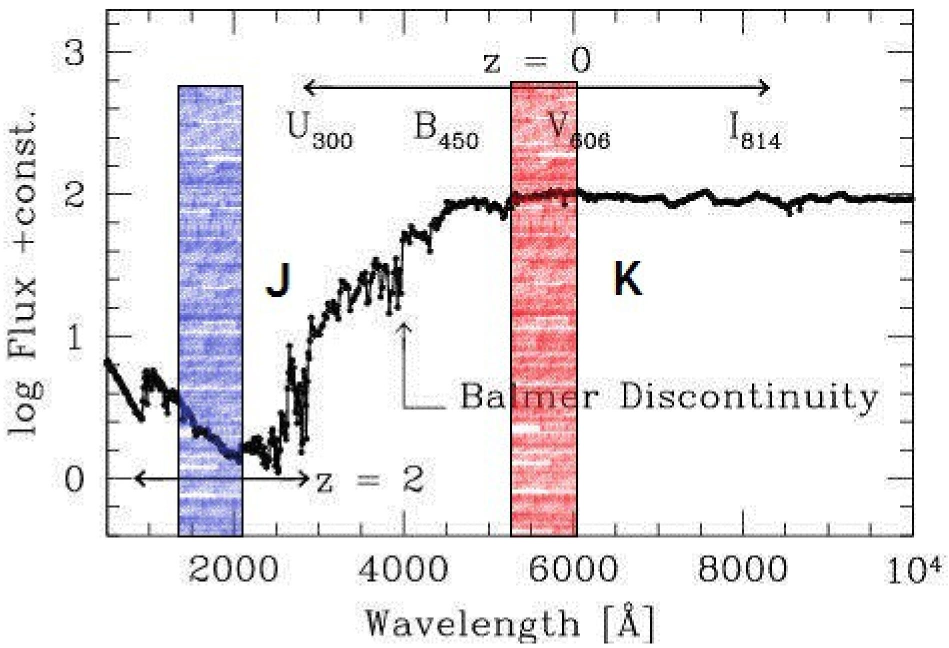

Illustration 11: 4000 Angström break or Balmer break

mass. For redshifts around 2, bands J and K are markers of the stellat birth and evolution. This break can allow us to identify old populations (z=2). The idea of our study is thus to constrain redshift.

From the two bands, J and K, we want to build the catalogs of the sources present on the picture. For this, we need a method to detect a source.

II- Data, methods and sources detection

A- Source detection

The idea to detect a source in the image is to set a threshold. In deed, if a point of the sky is brighter than the threshold, we can consider it to belong to a source. If not, it is not a source for us, but it belongs to the background. So a first study can be done with our eyes and detect in a first time what can be a bright source. A good scheme to find sources could start by determining the background to substract it to the original picture. The background is considered like the overal systematic error of the instrument, and all the objects that the eye and the instrument can't see. In deed, the aperture of the instrument permits to collect more luminosity. A little part of the background could come from the environnant noise. To determine it, we can consider all the points and study locally their mean value. With some threshold, we are able to keep a good number of sources. After this, we need to identify if the sources are alone or if it's two near sources, and classify them giving a number for example. To separate two near sources, we can calculate the flux of the pixels with a limit distant. Finally, we obtain a catalog of sources, with several parameters like their position, number, magnitude (calculated according to the flux), and all errors associated on position and magnitude.

This method is used by the software Source Extractor (SExtractor), and we will use it to create catalogs. Thanks to the software we can obtain a catalog of bright sources for the two bands, J and K.

B- Creation of catalogs by SExtractor

During the analysis of the data, SExtractor can give us several parameters about the sources. For our study, we'll use the position in Right ascension (RA) and declination (DEC), a number attribuated at the sources to differenciate them, their magnitude and the error on the magnitude. In deed, all our work is around the position on the map of the objects and their magnitude.

Another important result given by Sextractor, is the noise of the map. In deed, the software is able to detect the noise with a function background and segmentation, and to plot the noise distribution. Moreover, we can see that the noise is gaussian and according to SExtractor it has for mean-value and sigma, -0,066216 and 0,445253 respectively.

We have now our two catalogs, in J and in K. However, like the threshold detection is a parameter fixed by the user of the software, we need to check if it's a good threshold, i.e. if the map without detected sources is noise.

C- Checks : Characterization of the noise

The previous part explained that we should characterize the noise and the background of the picture to find the sources. But how can we find this noise ?

We consider in a first part all the pixels. To start, we can determine approximatively what can be a bright source to substract it of the original image. We obtain a map of the sky without the potential sources, and so a set where every pixel has a value of brightness, or simpler, flux. The

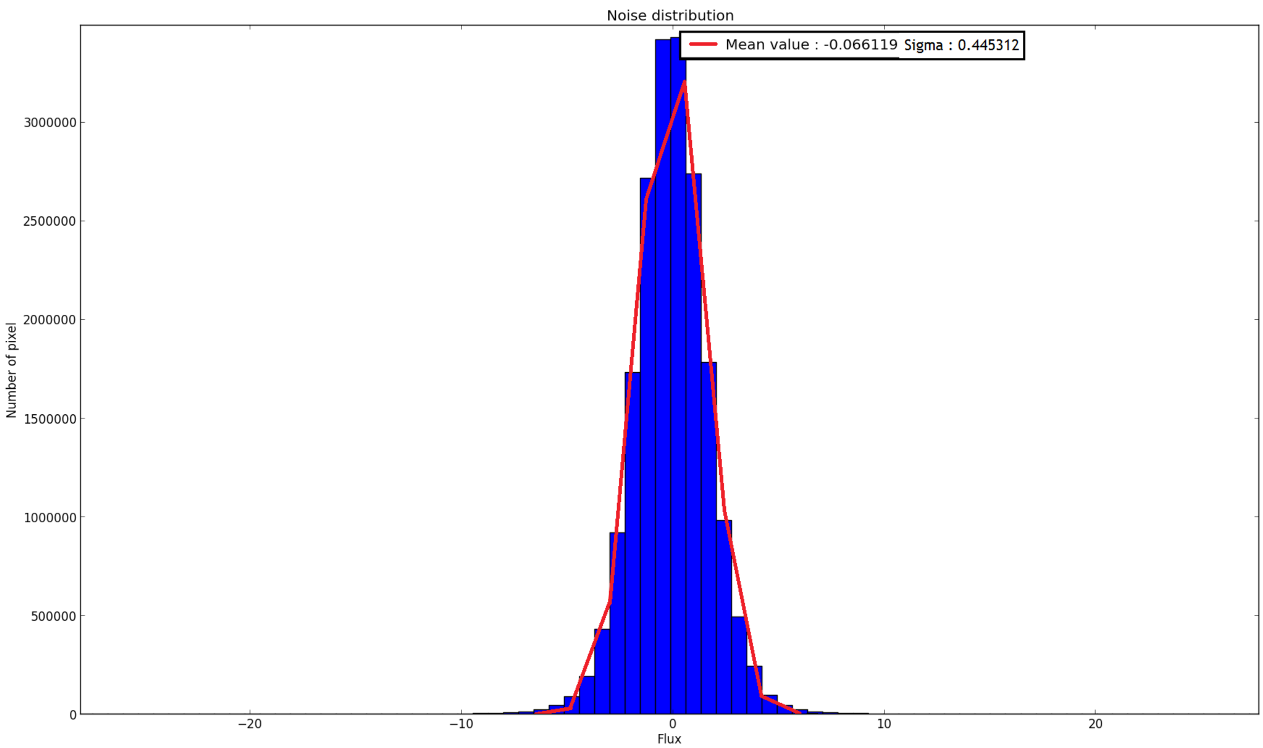

Illustration 12: Noise Distribution

points of sky where there is a potential source are now consider like a pixel with a value of bright equal to zero. Now, we can plot the distribution of all pixels of the sky what we don't consider to belong to a source.

Indeed, these pixels are under a threshold defined approximatively at the beginning, we can consider this set like the noise of the sky. If we want to consider a real noise, we need to consider among the sources or the potential sources, the bright points on the border of the picture. Like we have seen before, there exists some points on the border of the map where the flux is non negligible and are over the threshold. So, we'll substract these pixels of the map too, to avoid to interfer with our distribution.

The illustration 11 is the noise distribution. We can see that this last one seems to be a gaussian distribution, which will confirm our hypothesis of the noise. After a fitting in a gaussian, we can obtain the mean value of the distribution and its sigma.

Henceforth, we can now plot the total distribution of all pixels of the map. If we do that, we obtain something that seems to be a gaussian but not symmetric. In deed, if we substract the noise distribution to the total distribution, we can see the existence of some points with a flux more important than the noise, whose the position (in flux on the plot) is far from the gaussian mean-value, around two or three sigmas. That shows us there exists something which is not an error or

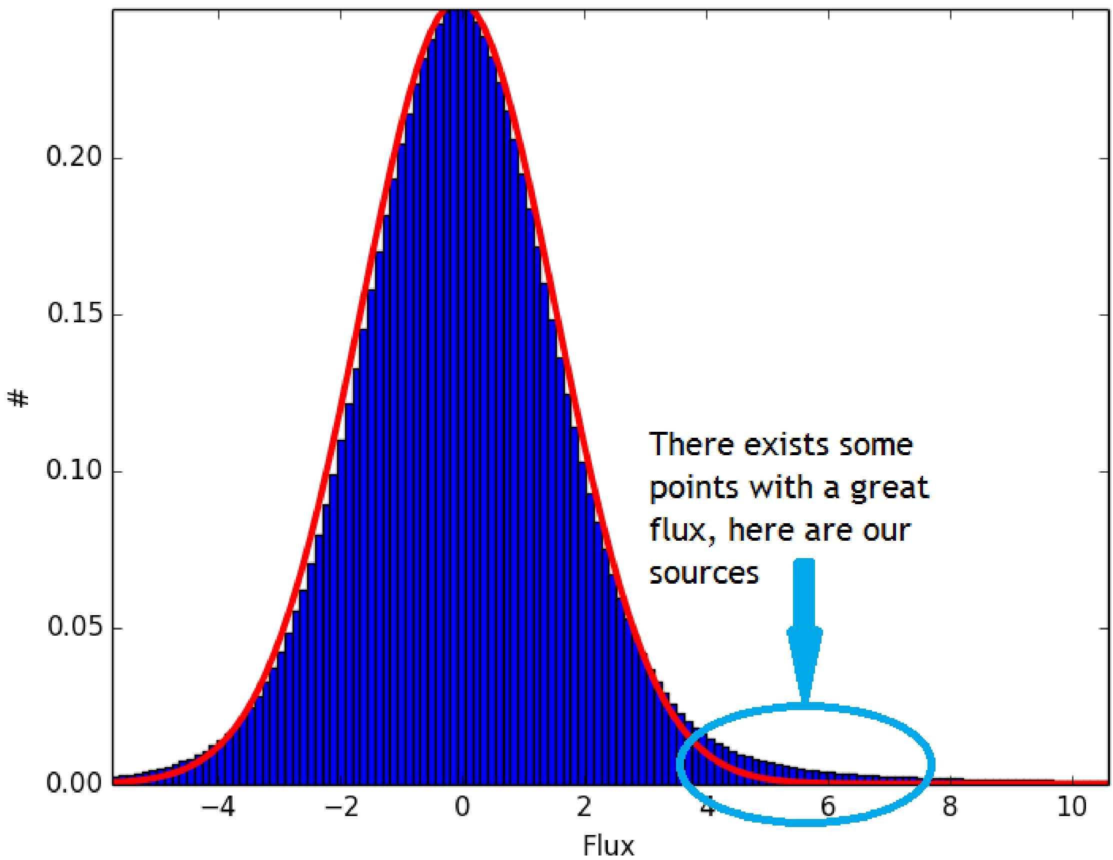

Illustration 13: The total distribution in flux of all the pixels, we can see the gaussian like before which is the background of our picture. There exists a tail for bigger flux, which could be the sources.

just noise on the map. So the existence of sources is confirmed by the way.

Thus, with the values of the sigma and the mean-value, we can see that our method is a good method, because that confirms us our expected results.

However, the map is full of objects and points more or less bright, and we want to determine real sources among the set of all potential sources. We know there exists some systematic error due to the instrument. Indeed, the instrument has some inhomogeneities, and can observe residual luminosity. Moreover, the calculation of the flux of a pixel is done in taking the mean value of the four neighbours. All points are the superposition of several local pictures at different time of the point. But, we can see that there exists an issue for the point located on the border of the picture, because there is less time of aperture for these points. So, on the border we can't consider the eventual sources found like real sources, because the errors of the instrument are too big.

Moreover, in their quality these catalogs are not very useful because we can't see the differences between the two bands J and K.

D- Review of catalogs

1 – Cleaning catalogs

With the two catalogs, in J and K, we have to create new catalogs to exploit them. Like we have seen before, there exists some points on the border which are not sources, due to the calculation of the flux value. A solution to identify these points is to plot the distribution of the sources (and not the pixels), in function of their magnitude. The following diagram is made with the J-band. We can consider that the treatment is exactly the same for the K-band.
Look at magnitude distribution of all sources. We can see there is a problem. Indeed, there exists

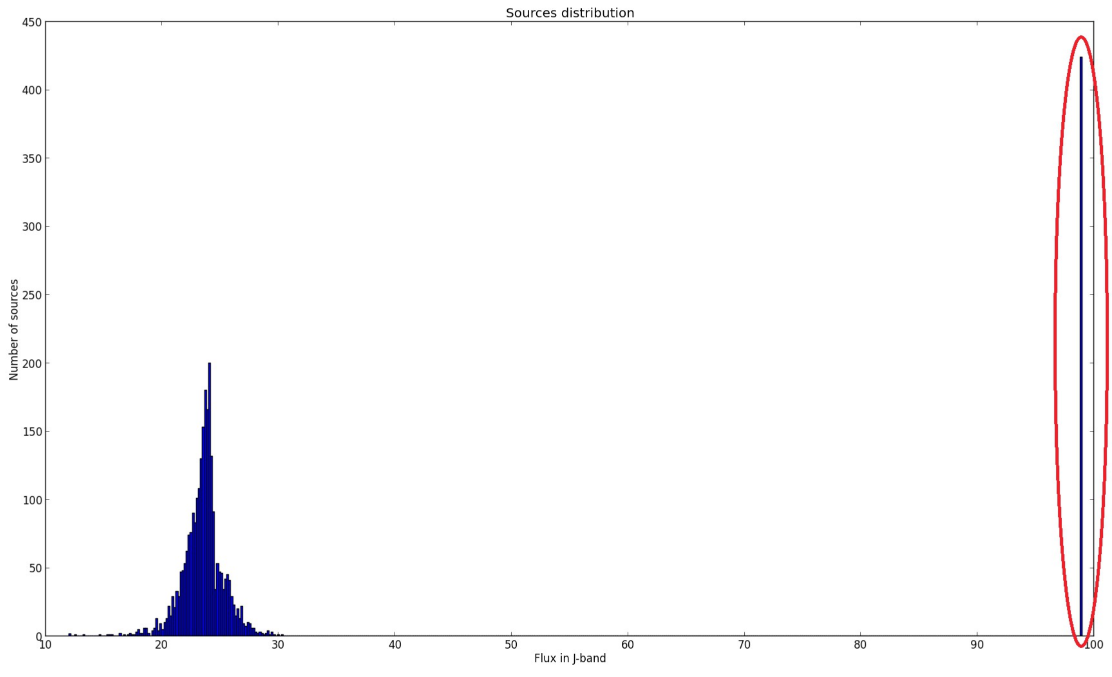

Illustration 14: Source distribution, there are objects with few bright for a flux around 100

some sources with a magnitude of 99. That is unphysical.

Moreover, we recall that the magnitude is growing up while the intensity is decreasing. So, the points on the border of the plot, around 100 in magnitude, and generally, more than 30 are not very bright. If we want to see where are these sources, we can plot the map of these sources. On the border of the picture there is less signal than the others part of the map.

All the points are on the border of the map, so we can forget them like real sources. However, there exists some points on the center of the map. This is not a problem because the sky map is the addition of four smaller maps. And, we have the same problem of calculation on the border of these maps, so on the center of the global map. All these points are due to the border effect, and we don't have to take them in our study because they represent something unphysical.

The following picture shows the position of the problematic points. They are indeed on the border.

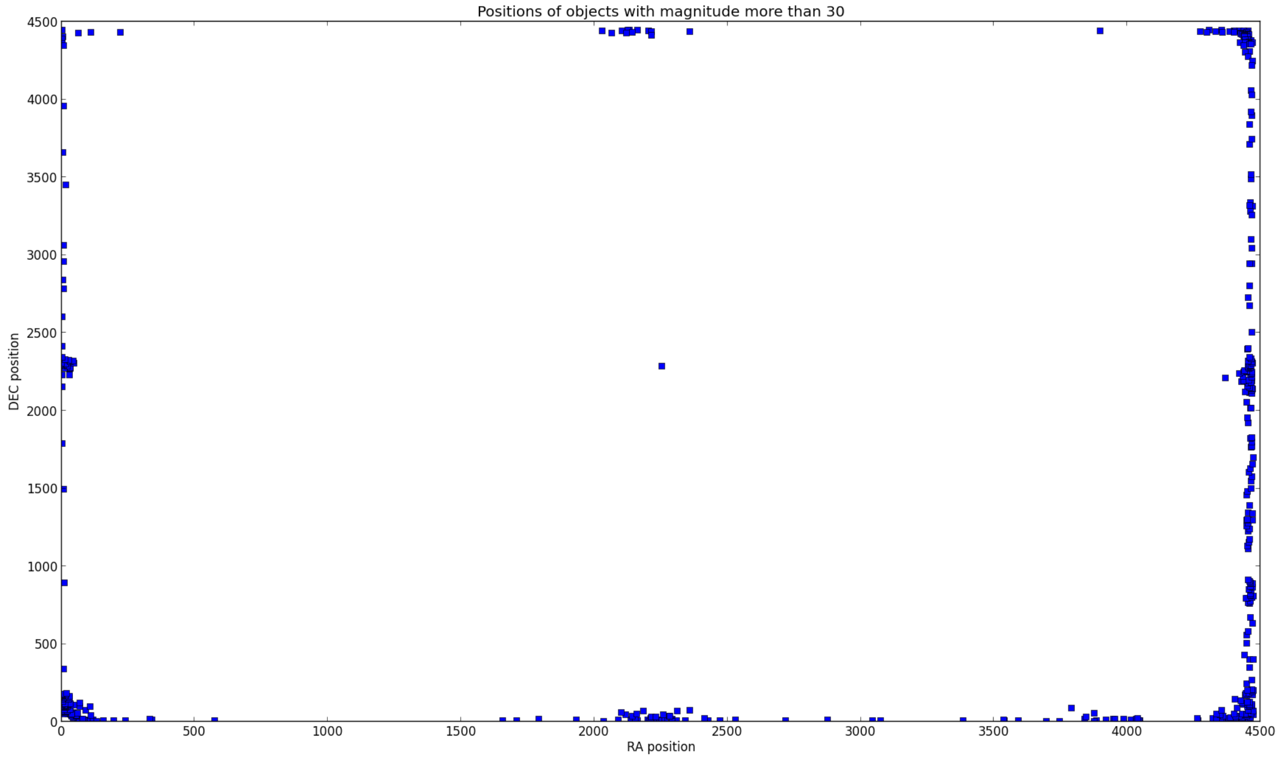

Illustration 15: Positions of "sources" with strange magnitude on the map. All these points are on the border and should be considered like errors due to the instrument.

2 – Band merging catalogs

The two images, in J and in K, are not the same. Indeed, the positions of bright objects are not really the same, because the instrument has some systematic errors when the filter is changed. Another explanation comes from SExtractor, indeed, it sets the position of source in the centre of a circle, so there could be for a same object, two different centres. The idea is so to see all sources corresponding between the two catalogs. Thanks to the software Topcat, we can merge several catalogs to compare them. We want to obtain one in J and K, called J+K, and an other K without J, called K/J. J+K corresponds to the sources seen in J and in K, K/J corresponds to the sources seen only in K and not in J. The new first catalog has now more parameters for each sources, and more sources too. There are a parameter of magnitude for the sources seen in J, and for the sources seen in K. Thus, we can create a new parameter in our catalog, the color defined by the difference of magnitude between J and K.

To match the sources, Topcat takes a source, and take the near source of it inside a circle of 1 arcsec. This radius is determined by the user and by a previous analysis, the value seems be good.

To conclude this part, we have two new catalogs, cleaned from the noise and all bad points coming from the border. We can now make the analysis of our new catalogs.

All the previous parts had for aim to explain us the maneer to obtain a good data catalog. The next part is about the analysis of the data collected in the preceeding part.

III- Analysis

A- Color-Magnitude Diagram

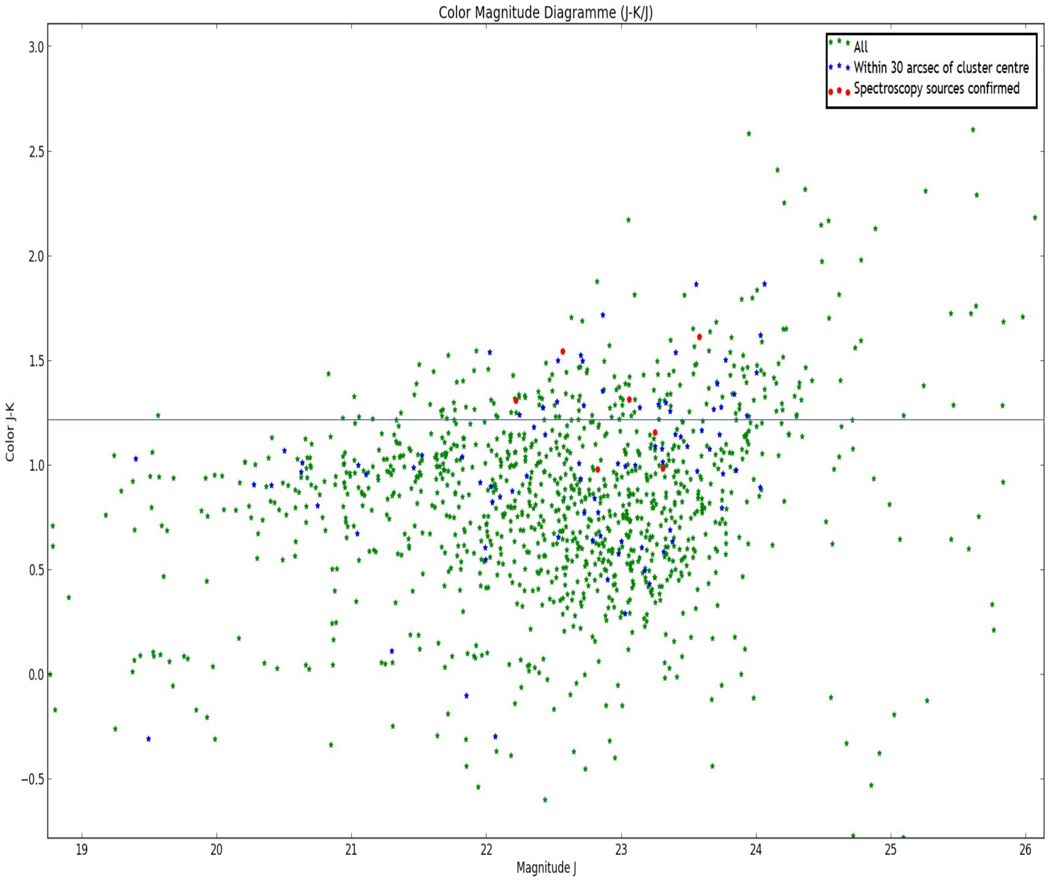

Illustration 16: Color Magnitude Diagram, with a cut in color at 1,3, which corresponds to a cut in redshift at 2.

We want to study the confirmed source in magnitude and color to see if the cluster has a particular color. To recall, the color is a difference of magnitude. A solution to study that is to plot the Color-Magnitude Diagram, i.e. the diagram where the color J-K is ploted in function of the magnitude J. So, our work consists to see if the confirmed source takes a particular place in the (J-K, J) space. We do that because this is a diagnostic about the redshift, and particularly, we are interested by a redshift bigger than 2. That can teach us about the Balmer Break and allow us to characterize the redshift of the cluster, cf Franx (2003), because more J-K is big, more K has a weak magnitude and intensity. If we report that on the Balmer Break, we can see that this object is seen in K and not in J, and the redshift is around 2. Indeed, for K-band z=0, for J-band, z=2 according tio the Balmer Break. A study in color permits us to constrain the redshift because we are interested by the objects seen in J but not in K, i.e. the old objects. The last illustration shows us the result.

The green points represent all the sources found with our method. The blue points are all sources within a circle around a radius of 30 arcsec of the confirmed cluster centre. The study driven by Santos brings us an important result, the redshift of all points in the cluster. All points in the cluster are on the illustration in red and have a redshift around 1,57.

We can confirm this result because for a redshift bigger than 2, that corresponds to a color bigger than 1,3. This is ploted on the illustration. We can see that there are four points confirmed by spectroscopy which have a enough big color.

Hence, a cut in color is a good maneer to find the candidates, because we know that the redshift of the cluster is less big than 2. So we can consider that all the points of the confirmed cluster are found by our method. Moreover, it is possible to observe some errors on the position of the points on the diagram due to the instrument.

It is why a better and more detailled study is necessary. The next part will present the Color-Color Diagram of our confirmed candidate cluster.

Moreover, there exists an empirical relation observed in the cluster confirmed between redshift and color. This is a characteristic of old populations. Can we see this relation ? The next step is to established the color-color diagram to highlight this relation, because with it we can better constrain the redshift. This relation is called the Red Sequence, it is a link between the color and the redshift, which exists for elliptical galaxies and for some clusters. Is it true for all clusters, and particularly for our cluster? The color-color diagram allows us to know it.

The following diagram shows the Red Sequence. The models 1 and 2 are two different models of Red Sequence. Like this is an empirical relation, there exists some sources which are not in the area constrained in redshift, indeed, there exist some systematic errors or contaminations.

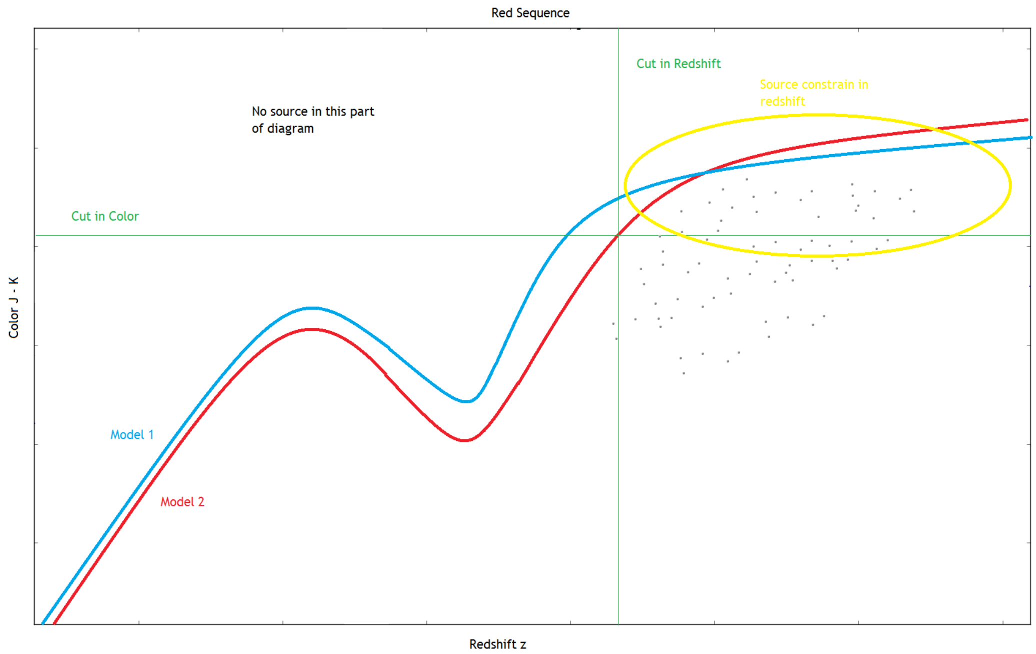

Illustration 17: Red Sequence

The general idea of the Red Sequence is to use a constrain on the color to constrain the redshift.

B- Color-Color Diagram

We want to plot the Color-Color diagram. The idea is to obtain another color than J-K and more detailled in the infrared. If we recall all our study, the only telescope not used is Spitzer and itsinstrument IRAC which has a better resolution than SPIRE.

IRAC works in 3,6 µm and 4,5 µm, we notice ch1, respectively ch2, the band associated. Exactly the same treatment of the picture is done, creation of catalogs with our method and SExtractor, cleaning of catalogs and merging of catalogs. So, we obtain a color ch1-ch2.

We have ploted J-K in function of ch1-ch2. The same reasoning about the Balmer Break can be done than for only J-K. More ch1-ch2 is big, more the magnitude in ch2 is weak. We have done the same cut in color for J-K than before. For a redshift bigger than 1,5, a cut in color can be done for ch1-ch2 at -0,1. We can see that the four points found before are in the area defined by the limits in the color. However, the same problem than before is still here. Indeed, the cut for J-K is not precise, and so, the possibility to find more points of the confirmed source in the area is possible.

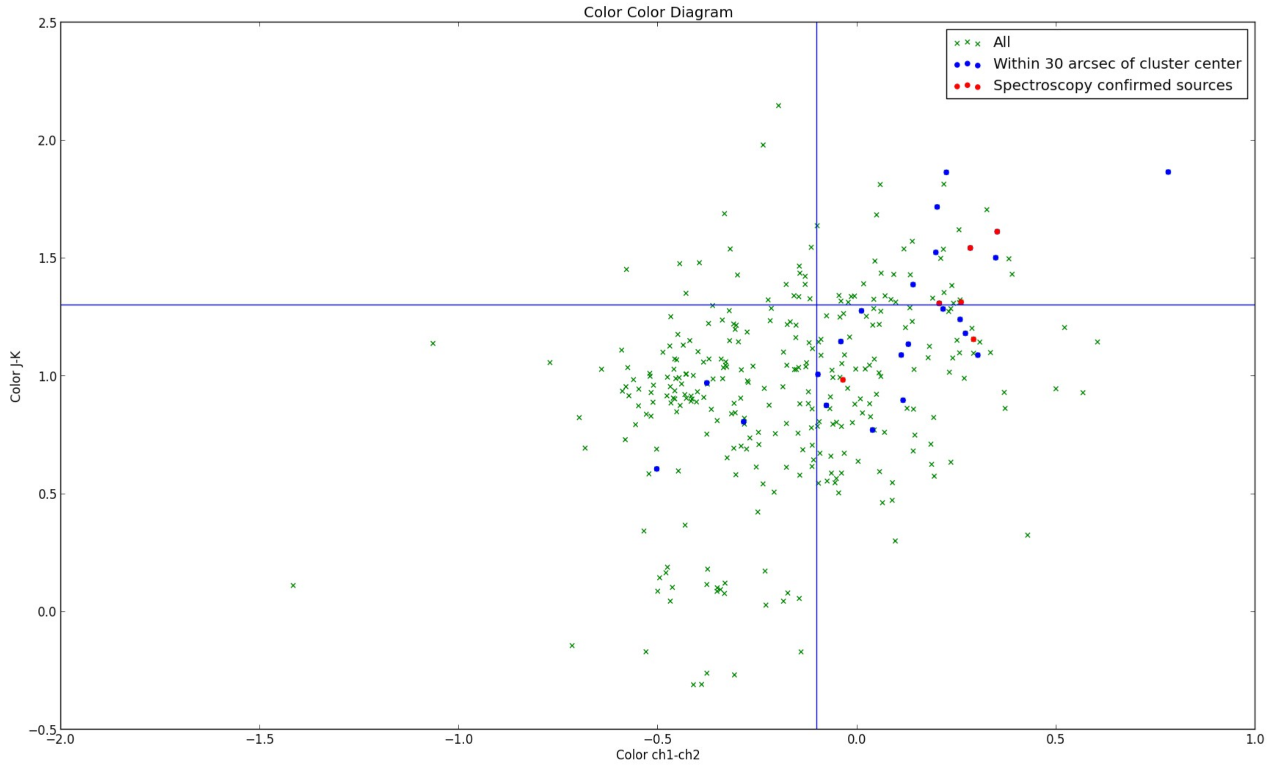

Illustration 18: Color Color Diagram, with a cut in color J-K at 1,3, which corresponds to a cut in redshift at 2, and a cut in color ch1-ch2 at -0,1, which corresponds to a cut in redshift of 1,5

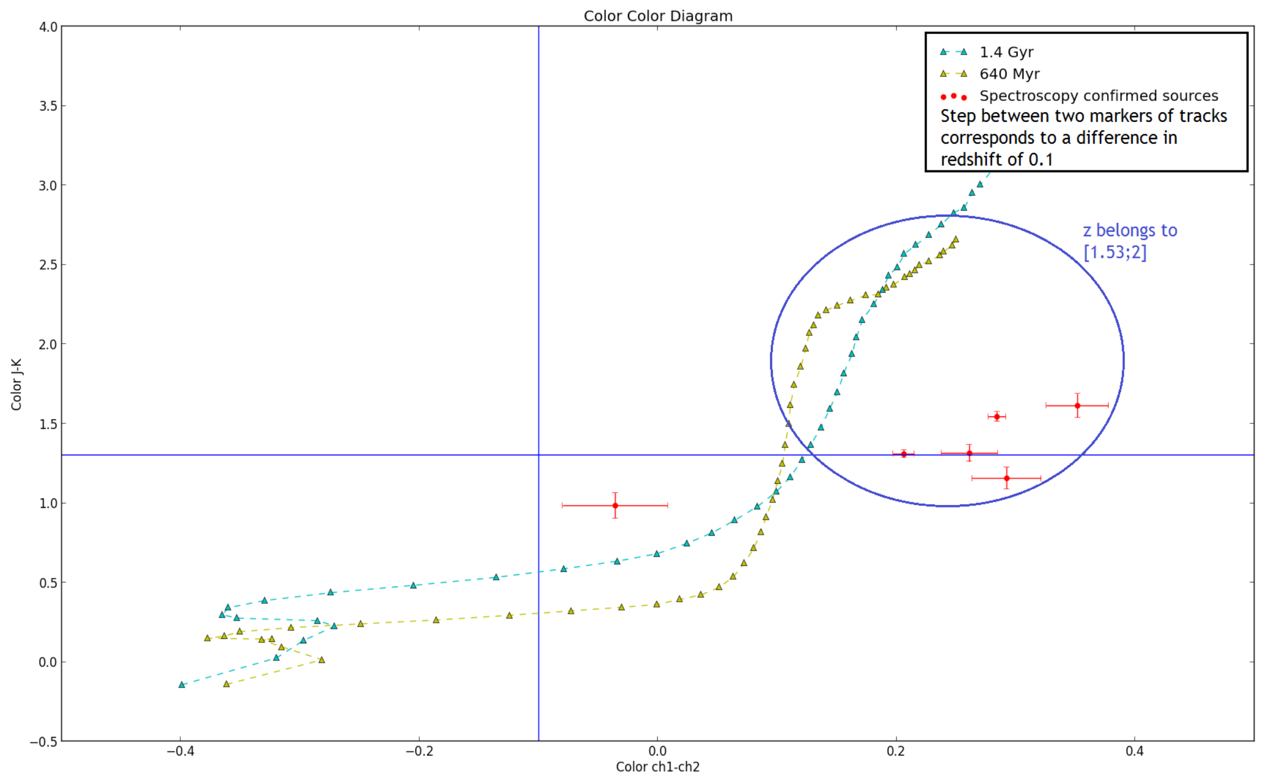

Illustration 19: Color-Color Diagram with tracks, the cluster is at a redshift around 1,6

On the preceeding plot, we have use tracks, which are models of stellar evolution in redshift, to see if our cluster has a particular place in redshift. We can see that a major part of it follows the evolution after 1,4 Gyr, and with the cut in color, that corresponds to a redshift around 2. So, the relation quoted before is seen here, because our cluster is around 2 in redshift and takes a particular place in the color-color plane. So, a study in color can be a good method to detect, or characterize, a cluster.

V- Conclusion

The last part shows us that our method is a good pattern to find a galaxy cluster. Indeed, our study was based on the work of the Santos' team, which had confirmed the position of our cluster. So, we can find new supposed clusters with cuts in color at redshift around 2. With our method, we have found a characterization for clusters which are at a redshift around 2, a next study will be to apply this on others clusters and establish the relation expected between the redshift and the color.

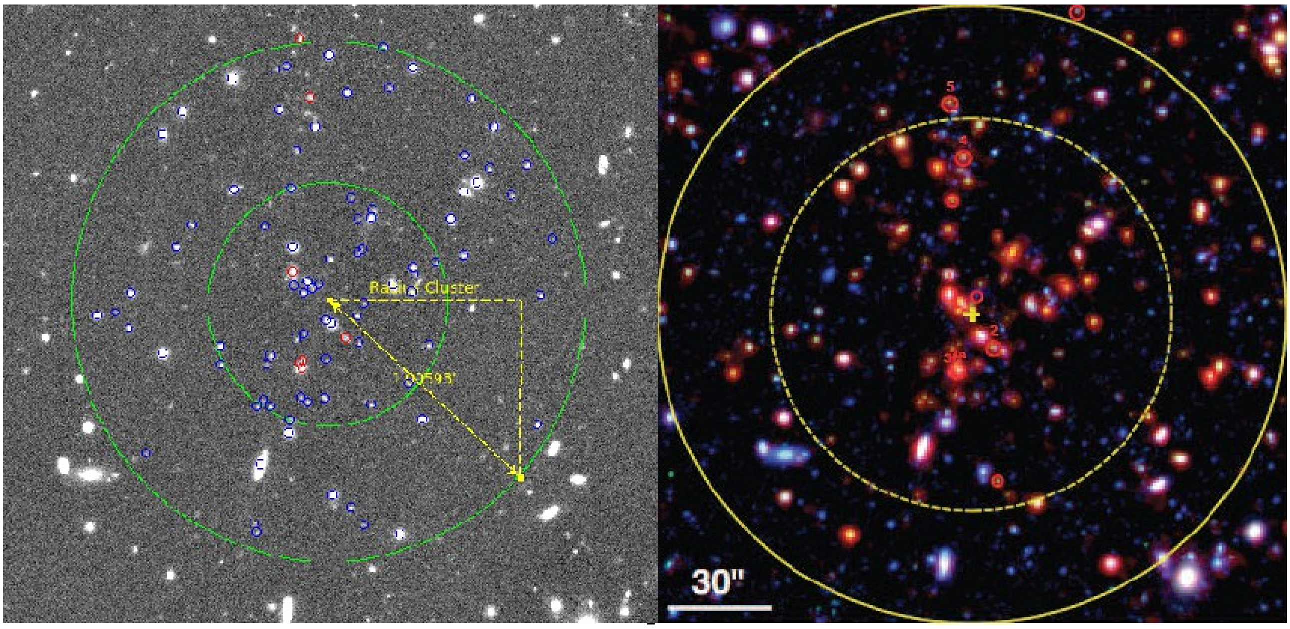

Illustration 20: The cluster identified by us (left), identified by Santos' team (right)

VI- Annex

Position in the sky

We have two data imaging, one in the J-band and the other in the K-band, of the same part of the sky. We consider that the sky is a surface in two dimensions whose every point are locatable with two coordinates, the right ascension (RA) and the declination (DEC). The RA is defined from the equator and corresponds to a deplacement orthogonal to a meridian. The DEC is a transverse deplacement compared the previous. However, we need to keep in mind that the sky evolves in the time. The simplest example is the example of the Sun, which goes from the East to the West. So the position in RA and DEC evolves too, and to take a good image, or several images of the sky, we need to follow a fixed point.

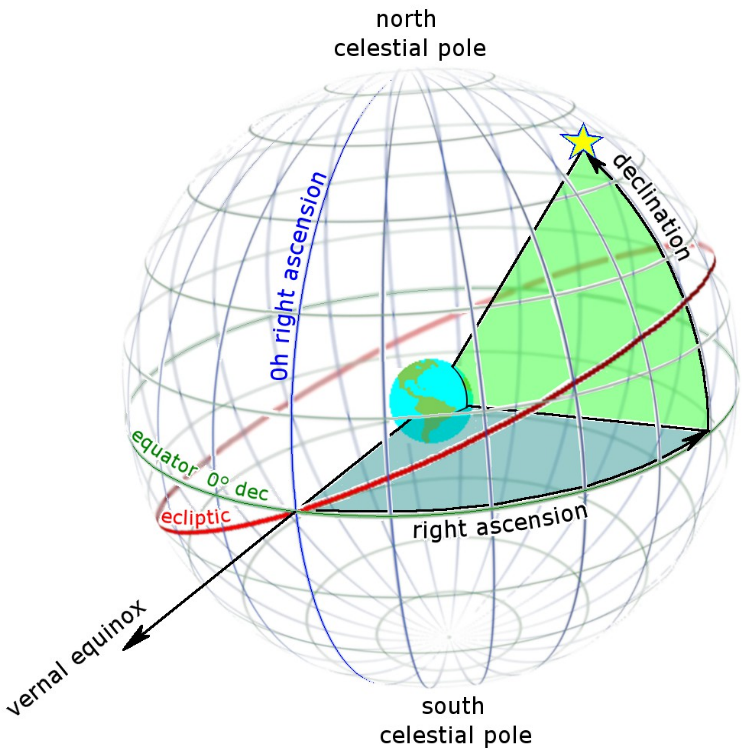

Illustration 21: Explanatory diagram for the declination and the right ascension

We can consider that the surface is a plan because the part of sky studied is very small compared the total surface of the sky which mesures 40000°², and our sample is 60 arcmin², we recall that 1 arcmin² is equal to 1/3600 °². The picture represents only 0,00004 % of the entire sky, so our approximation like a plane is a good approximation.

VII- Bibliography

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