ARSENAL: intermediAte Redshift Sz clustEr NikA2 time fiLler: a demo run

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Abstract – Clusters of galaxies are invaluable tools for measuring cosmological parameters. The SZ effect directly measures the baryon pressure inside clusters. We suggest to optimize the use of the 30m with a Time Filler proposal that will span several years. Here we only request time (20 hours) to demonstrate the usefulness of such a survey. The survey is a direct follow-up of the *Planck* clusters. It consists in mapping the SZ effect at 2 mm, on a selected sample of intermediate redshift clusters (typically 0.15 to 0.3) for which many complementary data are available. The published end products would be calibrated maps of the y Compton parameter and a point-source catalog per cluster. Derived parameters include the cluster pressure profile, the presence of shocks, substructures, and possibly, the total mass and the baryonic mass.

Scientific context – Clusters of galaxies are the most massive collapsed structures in the Universe. They have been used as a probe of the matter content on large scales. As early as in 1933, Zwicky (1933) demonstrated that there was a lot more matter than meets the eye (of optical observers) in clusters of galaxies. Since then, it has been established that dark matter dominates the mass budget of clusters of galaxies, the hot gas being the major baryonic component and the galaxies being a minor constituent. The hot gas has been thoroughly observed with X-ray telescopes, the later ones being XMM and Chandra. The interaction of the Cosmic Microwave Background with the hot electrons is called the Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zeldovich (1972)). It produces a brightness decrement at the cluster location at the NIKA2 wavelength of 2 mm. The *Planck* satellite (Planck Collaboration et al. (2015)), ACT (Hasselfield et al. (2013)) and SPT (Bleem et al. (2014)) have produced the biggest catalogs of SZ observations, with thousands of clusters being measured. The millimetre observations are complementary to X-rays. The X-ray emissivity is mostly proportional to the square of the density, whereas the SZ effect is directly sensitive to the pressure along the line-of-sight and globally, to the total thermal energy of the cluster. In combination, the two measurements allow disentangling the density and temperature parameters. At intermediate redshifts (0.15 to 0.3), the clusters have been well observed by X-ray satellites. But the SZ picture offers a less biased view of the baryonic content of a cluster. Fig. 1 shows all the clusters of galaxies detected by *Planck*: they are everywhere on the sky and therefore constitute perfect targets for a time-filler ground-based follow-up survey which is considered here. The large majority of *Planck* clusters are in the redshift range we are targetting. For many clusters, the millimetre data are scarce and the complementarity of that survey with data from reference 2000-2030 missions like *Herschel*, *XMM*, *Chandra*, *Euclid*, *eRosita*, *LOFAR*, *SKA*, *Athena* is clear. Fig. 3 (right) shows the lack of SZ maps in the center of clusters of intermediate redshift. The core radius of intermediate redshift clusters is about 1-2 arcminutes (corresponding to few hundreds kilopc). The 2 mm signal follows a $(1 + \frac{\theta^2}{\theta_c^2})^{-0.8}$ law, where θ is the angular radius to the center and θ_c is the angular core radius. This is represented in Fig. 3. Mapping the center of clusters would reveal their dynamical state and, in particular, if they are perturbed or not, and if they posess a cool-core (the cooling time is shorter than the Hubble time) or not (see *e.g.* Hudson et al. (2010)).

Main scientific goals – The proposed SZ mapping of clusters of galaxies will directly provide: 1– high angular resolution (18 arcsecond) y Compton parameter maps of well-known clusters. So far, the SZ maps were obtained with a low to mid resolution beams. For example, the *Planck* beam at 2 mm is 7 arcminute, barely resolving even the biggest clusters. ACT and SPT have also provided catalogs of clusters of galaxies which also suffer from mid angular resolution. An impressive catalog of SZ maps has been obtained by Carlstrom et al. (right side of Fig. 1) at 15 GHz (OVRO/BIMA, 1.7 to 2.8 arcmin resolution, Reese et al. (2002)). We want to extend that pionneer survey in terms of the number of clusters, the frequency and the angular resolution. The proposed maps would cover only the central part of the clusters. The external part has already been mapped with unprecedented accuracy by *Planck*. 2– A catalog of 2 mm sources. They will be mostly radio sources (e.g. the Brightest Cluster Galaxy). The submillimetre galaxies cannot be detected with the poor sensitivity expected at 1 mm. Herschel catalogs will be used in any case to take into account potential contaminations. 3– Central pressure profiles of a large sample of clusters. From these profiles and X-ray data from XMM-Newton, one can infer the baryonic mass (dominated by the hot plasma outside the galaxies) and the total mass of the cluster, via the hydrostatic hypothesis, in combination with X-ray and *Planck* data. 4– Inhomogeneities can reveal AGN feedback, shocks, X-ray bubbles and substructures which can be correlated with X-rays and low-frequency radio surveys (relics, and so on) as LOFAR, and, in the future, SKA. This is revealing the dynamics and agregation of clusters within their supercluster environment. The main goal of this proposal is to make a *Planck* ground-based followup, with maps at high angular resolution of a large sample of the center of individual clusters. The *Planck* measurement suffers from the very imperfect knowledge of the cluster size and central details (Planck Collaboration et al. (2013)). This could potentially improve the accuracy of the *Planck* cosmological constraints coming from clusters of galaxies. Other outputs of this survey include serendipitous ones: odd sources, map features. A sure output will be a complementary dataset on clusters, which are studied at many other wavelengths (including deeper maps with NIKA2 at 1 and 2 mm). In that respect, we intend to publish the survey results in an open database. Cluster maps would be public within a year of observations. In relation to the ongoing Guaranteed Time NIKA2 SZ Large Program on clusters of galaxies, we think that it is very complementary because: here we aim at intermediate redshift clusters (0.15 to 0.3) which are more extended and in shallow mode observations, whereas the LPSZ survey aims at high redshift ($z \geq 0.5$) clusters observed with high sensitivity down to their edges, and with a thorough control of sources that can perturb the maps (hence the importance of the 1 mm channel). Other instruments have already followed-up on *Planck* clusters in order to make SZ maps at better resolutions: AMI (a UK 15 GHz interferometer) in particular has been used and provided observations of 123 clusters, including 99 detections (Perrott et al. (2015)), each observation requiring 60 hours of integration with a limited angular resolution of 3 arcminutes.

Feasability and Sample selection – Observing intermediate redshift clusters requires to map angular scales of the order of the NIKA2 field-of-view. The findings within the NIKA2 collaboration is that scales mapped within less than 3 seconds can be recovered while larger scales suffer from various low-frequency noises (sky noise and electronic noise mostly) that are difficult to remove with decorrelation techniques. Scanning fast "freezes" the atmosphere. With a FOV diameter of 390 arcseconds, it becomes important to map at a speed larger than about 100 arcsecond/s. With 150, the sampling of NIKA2 (at the standard 23 Hz acquisition) is 6.5 arcseconds which is not really compatible with Nyquist sampling of the 12 arcseconds 1 mm beam. Whenever necessary, we should therefore go to the fast acquisition rate (46 Hz) which is used in the polarimetric mode, without enabling the half-wave plate here. Operationnally, the switching time is of a few minutes. A speed of 160 arcseconds/s is within the 30 m capabilities without loss of pointing accuracy. We show in Fig. 2 an example of such a scanning speed capability. In this proposal, we request observing the targets given in the Table in order to have a demonstration opportunity. We want to show that that survey can be done with the requirements that we need: 1) the scan speed can increase the recovery of large angular scales and the images are reproducible, even though the opacity is mediocre, 2) the pointing does not need to be accurate at all (4 arcseconds) 3) the sky noise has been discussed above, 4) the survey is insensitive to the 1 mm conditions, 5) the beam must not be perfect but reproducible, 6) anomalous refraction should be limited. 7) opacity correction does not limit the calibration accuracy.

We need to achieve a y sensitivity below 10^{-4} for one beam so that the center of the cluster (typically with a central y of 3×10^{-4}) can be well mapped. The size of the clusters being below 8 arcminutes, scans of 20 by 12 arcminutes at 4 different orientations (0, 45, 90, 135 degrees) in Ra-Dec coordinates are required to obtain a central 12 arcminute diameter map and enough blank fields around to set the zero level. With a maximal azimuth speed of the telescope of 170 arcsecond/s, an effective scanning speed of 120 (resp. 83) arcsec/s can be achieved at an elevation of 45 (resp. 60) degrees. The trade-off between speed and opacity (due to the low elevation) will have to be made on a cluster-to-cluster basis. The integration time can be roughly estimated by assuming an average mediocre zenith opacity of 0.5 at 2 mm (0.75 for the 225 GHz IRAM taumeter!) and an elevation of 45 degrees so that the sensitivity becomes $20\,\mathrm{mJy.s}^{1/2}$ per detector. The conversion from Jy to y involves a factor 12 so that the y 1 σ sensitivity for 1 hour is $20 \times 10^{-3}/12/\sqrt{3600 \times 0.7} = 2.3 \times 10^{-5}$ for one field-of-view and adopting 0.7 for the number of valid Kids. The scan involves an area of $20 \times 12\,\mathrm{arcmin}^2$ which covers 7 FOV, so the final sensitivity of the central 12 arcmin map, after 2 hours (total integration time), will be, in y terms, of $2.3 \times 10^{-5}\ \sqrt{7/2} = 4.3 \times 10^{-5}$. Even after accounting for diffuse vs. point-source sensitivities, this is well below the target sensitivity of 10^{-4}. It would provide a Signal-to-Noise ratio at the peak of 10 per beam (depending on the central strength of the cluster), while the signal covers several square-arcminutes. Fig. 3 shows a typical profile and error bars in annuli that are expected for massive clusters. Including an overhead of 2 for calibration and pointing, the demonstration of the time-filler proposal could be done with the observation of 5 clusters, each of them with a duration of 4 hours. We therefore request **20 hours** of observations with NIKA2, using only the weather conditions where standard NIKA2 proposals cannot be scheduled. This project could be a pathfinder projects for other large-scale 2 mm mapping projects. The team has a lot of experience in the data reduction of SZ observations of clusters of galaxies with NIKA and NIKA2, and reuse of available IDL sofware is planned (NIKA2 consortium publications).

The table of clusters for the whole survey is made of 400 entries (Fig. 4 right). Of course, any source which is being scheduled for other open time proposals would be withdrawn from this proposal, but we do not expect to see many cases of fencing. Fig. 4 (left) illustrates that the opacity is between 0.4 and 0.7 for 25 % of the 30 m time (0.25, 0.5 at 2 mm). Accounting for typically 3 months of NIKA2, the expected total integration time for this survey could be of 500 hours per year, allowing to map hundreds of clusters in several years (with a rolling proposal). The demo time-filler proposal is here intended to show the capability of recovering the diffuse emission of clusters of galaxies. It will allow to ascertain the feasability of the complete time-filler proposal that we will then submit, if the results are satisfactory. It stems from our (slight) frustration, as regular NIKA2 observers, of not using NIKA2 for some lenghty duration because of the opacity constraints. This survey does not "cost" much and would optimize the use of the NIKA2 instrument with a direct public legacy.

References

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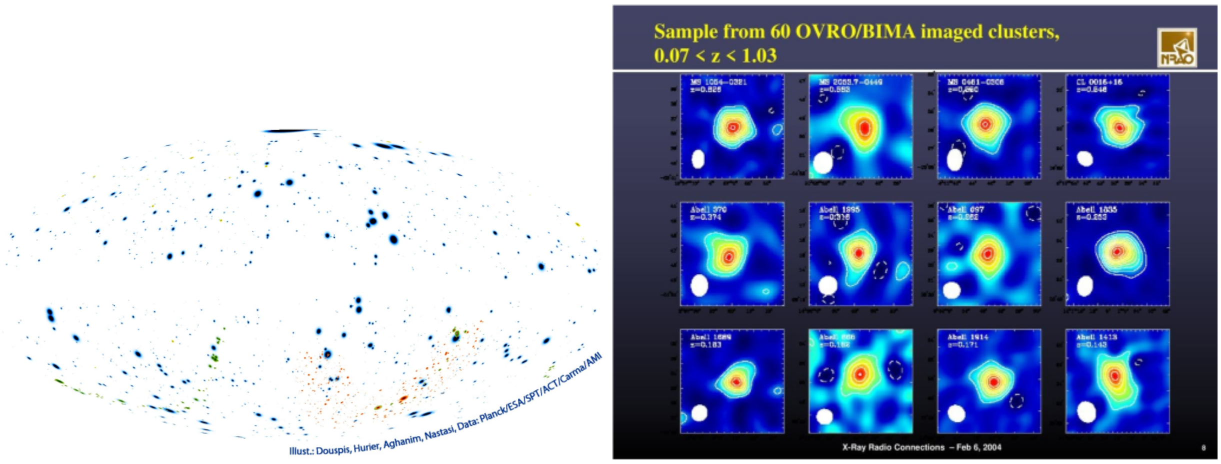

Figure 1: **Left:** Visualization of an all-sky map of SZ clusters of galaxies, in galactic coordinates. Each dot is a cluster. Bigger dots are too extended for the present program. **Right:** A sample of SZ maps obtained with OVRO/BIMA. Reese et al. (2002)

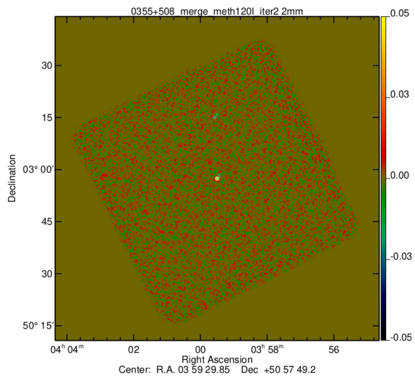

Figure 2: One square-degree NIKA2 map obtained with a fast raster scan. It is centered on a typical 30 m pointing source. The map covers more a one-degree square. It is made by co-adding 4 scans, each scan covering the total area either at +45 or -45 degrees from azimuth. This test case was obtained, just before enabling a polarization commissionning session, when the opacity was 0.57 at 1 mm and 0.33 at 2 mm for an elevation of 34 degrees, conditions which are far from acceptable for normal scientific observations. The scan speed was 150 arcsecond/s to cover 60 arcminutes per subscan (times 21 subscans to cover 60 arcmin in the cross direction). The scan duration was 10 minutes. The central source is well detected with a 2.8 Jy flux at 2 mm and a FWHM of less than 18 arcseconds, *i.e.* no beam smearing effect from the scan speed and the same flux as with a normal intensity speed map. A serendipitous source of about 46 ± 6 mJy is found within 5 arcsecond of a Radio and WISE Source (WISEA J035933.92+511521.2 has a 1.4 GHz flux of 24 mJy)

Table of clusters (unfenced according to CDS), among which, 5 will be selected for the Demo proposal
name, redshift, coordinates (J2000)
A520, 0.202, 04h54m19s, +02d56.8m, 73.579133, 2.946893
A665, 0.182, 08h30m45s, +65d52.9m, 127.688306, 65.882026
A773, 0.216, 09h17m59s, +51d42.4m, 139.497459, 51.706411
A1413, 0.142, 11h55m18.9s, +23d24m31s, 178.828750, 23.408611
A1689, 0.183, 13h11m29.5s, -01d20m17s, 197.872917, -1.338056
A1835, 0.252, 14h01m02.3s, +02d52m48s, 210.259583, 2.880000
A2163, 0.202, 16h15m34s, -06d07.4m, 243.892221, -6.123970
A2218, 0.176, 16h35m52.4s, +66d12m52s, 248.968333, 66.214444

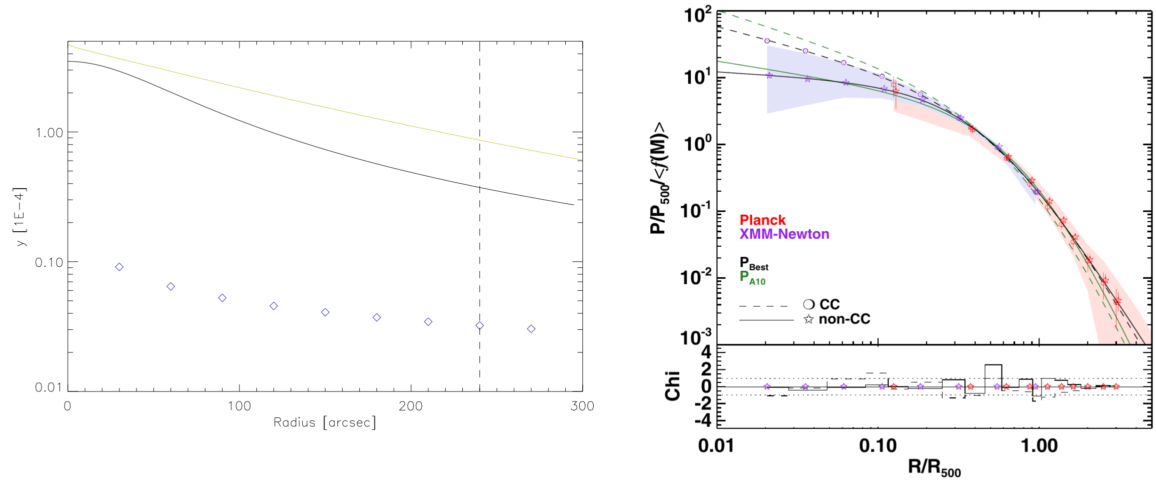

Figure 3: **Left** Radial profile of the SZ effect for a massive cluster (typically A2163) with a core radius of one arcminute. Two models are shown, the β one being in black (derived from SZ data by Reese et al. (2002)) and the X-ray derived model from Arnaud et al. (2010) in yellow. Error bars for NIKA2 measurements in annuli are shown as diamonds (after 2 hours of observations). The recovery of large angular scales will be more difficult beyond the dashed line (8 arcmin diameter). *Planck* clusters are on average less bright (2 to 10 times) than the example shown (A2163). The integration time will be modulated with each cluster. **Right** Radial profile of the pressure in a standard *Planck* cluster. The inner part is not well-known in SZ mode. The horizontal axis corresponds to 5 arcmin at R_{500}. Cool core clusters differ in the center from non-cool-core clusters.

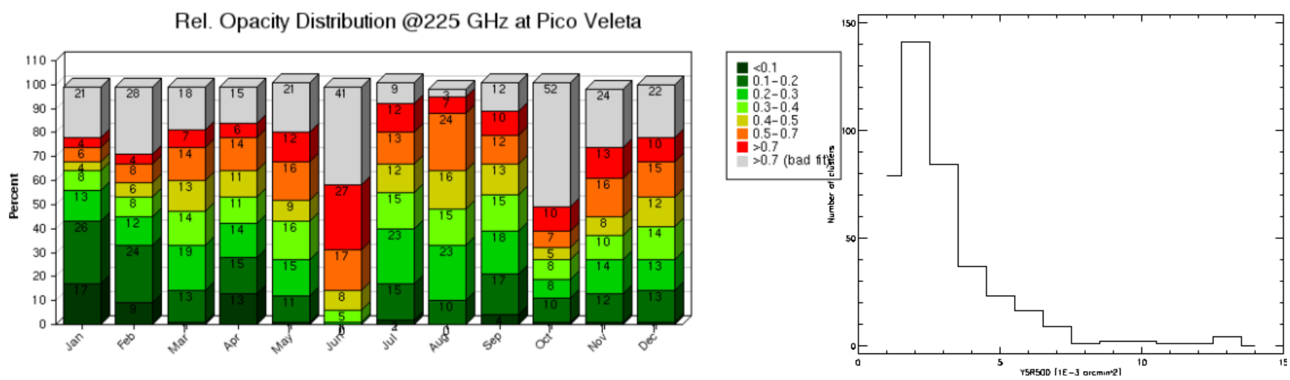

Figure 4: **Left** Relative distribution of 225 GHz taumeter opacities during the 2003/2004 period. IRAM document. **Right** Distribution in the integrated Compton parameters of the 400 *Planck* clusters detected above 3 σ and with a declination above -15 degrees. No redshift selection was made here.