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Registration n°: **P395042**
Date: **15-MAR-2021**

PROPOSAL FOR THE 30M TELESCOPE

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

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Proposal category: Standard
Scientific category: Cosmic Microwave Background (CMB)/Sunyaev-Zel'dovich Effect (SZE), Galaxy Clusters
Observing requirements: Observing requirements

Total requested time: 20.0 (Nika2)

Abstract:
Clusters of galaxies are invaluable tools for measuring cosmological parameters. The SZ effect directly measures the baryon pressure inside clusters. We suggest optimizing the use of the 30~m telescope with a Time Filler proposal that may span several years (called the survey). Here we only request time (20~hours) (called the Demo) 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 with NIKA2, on a Planck 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, in combination with other datasets.

Sources:

Id	Epoch	RA	DEC	z (redshift)	
A520	J2000	04:54:19.000	02:56:48.000	0.202	edit/delete
A665	J2000	08:30:45.000	65:52:55.000	0.182	edit/delete
A773	J2000	09:17:59.000	51:42:23.000	0.216	edit/delete
A1413	J2000	11:55:18.900	23:24:31.000	0.142	edit/delete
A1689	J2000	13:11:29.500	-01:20:17.000	0.183	edit/delete
A1835	J2000	14:01:02.300	02:52:48.000	0.252	edit/delete
A2163	J2000	16:15:34.000	-06:07:26.000	0.202	edit/delete
A2218	J2000	16:35:52.400	66:12:52.000	0.176	edit/delete

Technical sheet "Nika2 technical sheet":
Id: 11
Proposal: P395042
Time: 20.00 hours
Observing parameters:

Id	Source type	Map size	Pwv	Time	Repetition	Remark	1.3mm flux	1.3mm rms	2mm flux	2mm rms	Band priority
1	Extended	240.0	7	4.0	5		1.0	10.0	3.0	0.5	2mm

Scheduling constraints:
None

PI note:
A demo run to test the idea of a time-filler survey proposal that will be submitted later.

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

F.-X. Désert (IPAG), et al.

Abstract – Clusters of galaxies are invaluable tools for measuring cosmological parameters. The SZ effect directly measures the baryon pressure inside clusters. We suggest optimizing the use of the 30 m telescope with a Time Filler proposal that may span several years (called the survey). Here we only request time (20 hours) (called the Demo) 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 with NIKA2, on a *Planck* 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, in combination with other datasets.

Scientific context – Clusters of galaxies are the most massive collapsed structures in the Universe. 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 (Hilton et al. (2021)) and SPT (Bleem et al. (2015)) have produced todate 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, being only proportional to the density. Fig. 1 (left) 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 2 mm signal typically 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. The core radius of intermediate redshift clusters is about 1-2 arcminutes (corresponding to few hundred kilopc). This is represented in Fig. 3 (left). 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 survey of SZ mapping of clusters of galaxies will directly provide: 1– high angular resolution (18 arcsec) 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 early impressive catalog of SZ maps has been obtained by Carlstrom et al. (Fig. 1 right) at 15 GHz (OVRO/BIMA, 1.7 to 2.8 arcmin resolution as shown as a white beam, Reese et al. (2002)). We want to increase by an order of magnitude 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 will probably not be detected with the poor sensitivity expected at 1 mm. *Herschel* catalogs will be used, wherever available, 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), like LOFAR, and, in the future, SKA. The main goal of the time-filler survey 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. A sure output will be a complementary dataset on clusters, which are be studied at many other wavelengths. For instance, the observed clusters will largely overlap with the targets of the large *XMM* heritage programme by The CHEX-MATE Collaboration et al. (2020), a *Planck* selected sample of 118 clusters in our range of redshifts. Another program, with *Chandra*, is dealing with 169 clusters (ESZ sample with $z < 0.35$)). Most clusters have available optical data too. 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 observed in a shallow mode, 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 their importance for 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 scanned 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 and other noises. With a FOV diameter of 390 arcsec, it becomes important to map at a speed larger than about 100 arcsec/s. With 150 arcsec/s, the sampling of NIKA2 (at the standard 23 Hz acquisition) is 6.5 arcsec which is not really compatible with Nyquist sampling of the 12 arcsec 1 mm beam. Whenever necessary, we should therefore go to the fast NIKA2 acquisition rate (46 Hz) which is used in the polarimetric mode, without enabling the half-wave plate here. Operationnally, the time for switching to the fast rate is of a few minutes, with the restart of the acquisition system. A speed of 160 arcsec/s is within the 30 m capabilities without loss of pointing accuracy (J. Peñalver, private comm.). We show in Fig. 4 an example of such a scanning speed capability. In this Demo proposal, we request observing the targets given in the Table in order to have a demonstration opportunity. The chosen clusters all have deep X-ray data both from *XMM* (of similar angular resolution to NIKA2) and *Chandra* (of better angular resolution, and useful for identifying bubbles, ripples, cold fronts, and other subtle features that might be picked up by NIKA2). All clusters (but A1413) show diffuse low frequency radio emission. With this Demo proposal, we want to show that the full time-filler 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 can have very relaxed requirements with only 4 arcsec 3) the sky noise can be tackled with (as 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. This Demo program must quantify to which extent the clusters can be mapped in a snapshot mode. They contain a fair sample of 'canonical' clusters to be published in a standalone article .

We need to achieve a y sensitivity below 10^{-4} for one beam (FWHM of 18 arcsec) 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 arcmin, scans of 20 by 12 arcmin at 4 different orientations (0, 45, 90, 135 degrees) in Ra-Dec coordinates are required to obtain a central 12 arcmin diameter map and enough blank fields around to set the zero level (in agreement with the IRAM recommendations). With a maximal azimuth speed of the telescope of 170 arcsec/s, an effective sky 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 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 20×12 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 (left) 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 different datasets: X-rays, *Planck*, optical, and SZ maps of clusters of galaxies with NIKA and NIKA2, with a planned reuse of available IDL sofware (NIKA2 consortium publications). *According to the published commissioning results of the NIKA2 instrument, the total observing time using the NIKA2 2 mm band to map a region of 240.0 [arcmin^2] to reach an rms of 0.4 [mJy/beam], assuming 9.0 [mm] pwv, 45.0 [deg] elevation, Filter = 1.0, Overhead = 2.0, was estimated to be 3.8 hours, using the time estimator v 2020.JUL.22. The rms of 0.4 mJy is slightly below the above* $y_{rms} = 4.3 \times 10^{-5}$

The initial table of clusters for the whole survey is made of 400 entries (Fig. 2 right) from the *Planck* catalog. Of course, any source which is being scheduled for other open time proposals would be withdrawn from the whole time-filler proposal, but we do not expect to see many cases of fencing. Some *ACT* clusters may also be included. Fig. 2 (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 operations, 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 survey time-filler proposal that we will then submit, if the results are satisfactory. This survey would optimize the use of the NIKA2 instrument with a direct public legacy.

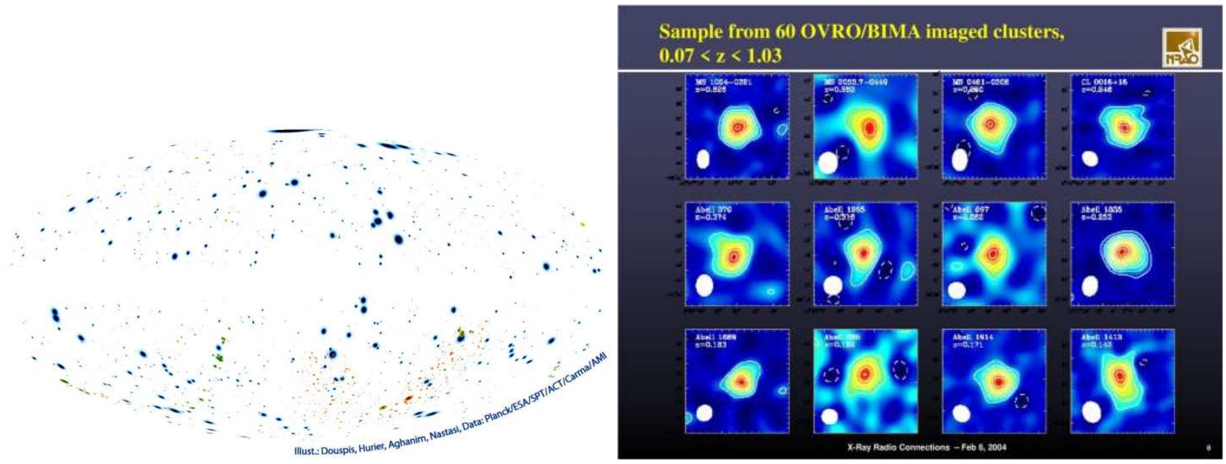

Figure 1: **Left:** Visualization of an all-sky map of SZ clusters of galaxies, in galactic coordinates. Each dot is a cluster. Bigger dots are too extended for the present program. **Right:** A sample of SZ maps obtained with OVRO/BIMA. Reese et al. (2002)

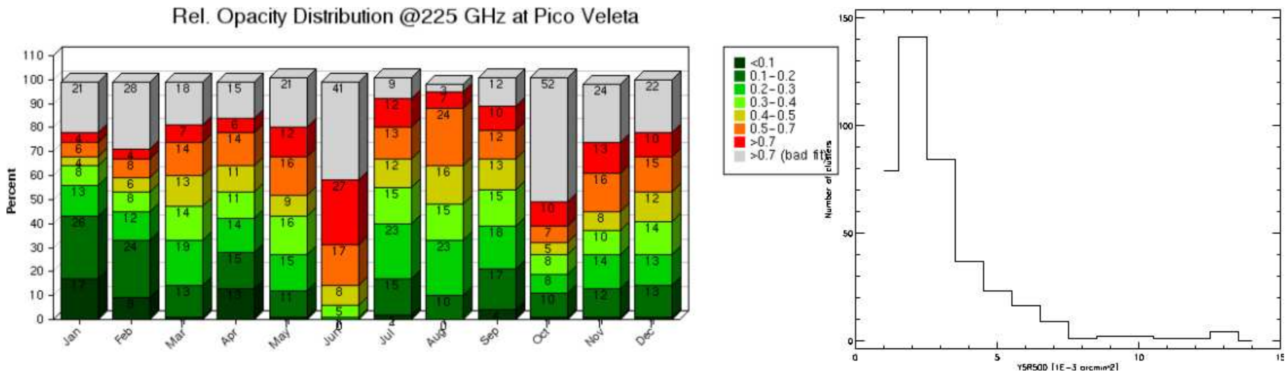

Figure 2: **Left** Relative distribution of 225 GHz taumeter opacities during the 2003/2004 period. IRAM document. **Right** Distribution in the integrated Compton parameters of the 400 *Planck* clusters, with a signal-to-noise ratio above 3 and with a declination above -15 degrees. No redshift selection was made here. An extensive use of this IAS cluster database is/will be made.

References

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Zwicky, F. 1933, Helvetica Physica Acta, 6, 110

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

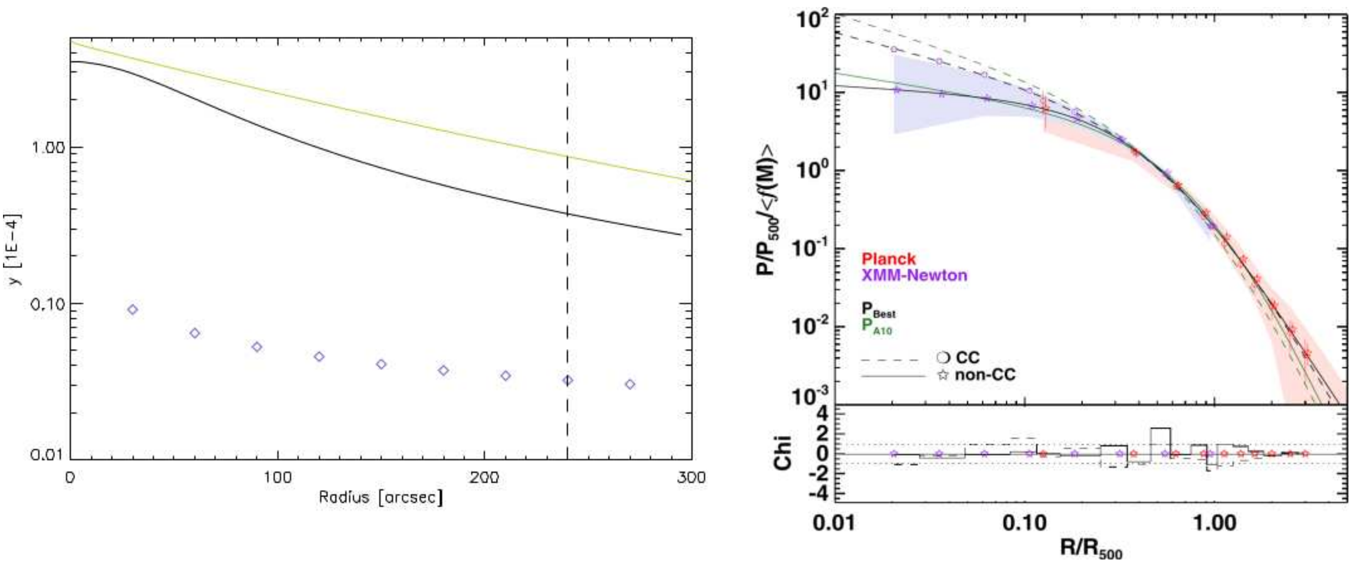

Figure 3: **Left** Radial profile of the SZ effect for a massive cluster (typically A2163) with a core radius of one arcminute. Two models are shown, the β one being in black (derived from SZ data by Reese et al. (2002)) and the X-ray derived model from Arnaud et al. (2010) in yellow. Error bars for 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** Average radial pressure profile obtained from several *Planck* clusters. The inner part is not well-known in SZ maps. The horizontal axis corresponds to 5 arcmin at R_{500}. Cool core clusters differ in the center from non-cool-core clusters.

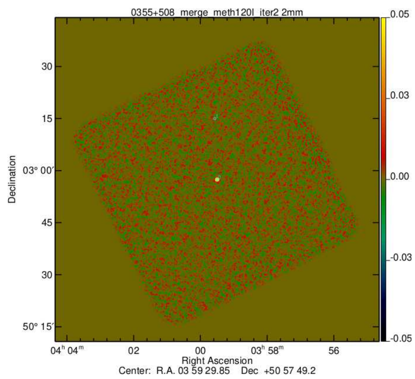

Figure 4: One square-degree 2 mm NIKA2 map obtained with a fast raster scan (color scale in Jy/beam). It is centered on a typical 30 m pointing source. The map covers more a one-degree square. It is made by co-adding 4 scans, each scan covering the total area either at +45 or -45 degrees from azimuth. 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 arcsec/s to cover 60 arcmin 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 arcsec, *i.e.* no beam smearing effect from the scan speed and the same flux as with a standard scan speed map. A serendipitous source of about 46 ± 6 mJy is found within 5 arcsec of a Radio and WISE Source (WISEA J035933.92+511521.2 has a 1.4 GHz flux of 24 mJy)