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Search for gravitational lens candidates in the XMM-LSS/CFHTLS common field

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ABSTRACT

Our aim was to identify gravitational lens candidates among some 5500 optical counterparts of the X-ray point-like sources in the medium-deep ∼11 deg^2 *XMM*-LSS survey. We have visually inspected the optical counterparts of each QSOs/AGN using CFHTLS T006 images. We have selected compact pairs and groups of sources which could be multiply imaged QSO/AGN. We have measured the colours and characterized the morphological types of the selected sources using the multiple point spread function fitting technique. We found three good gravitational lens candidates: J021511.4−034306, J022234.3−031616 and J022607.0−040301 which consist of pairs of point-like sources having similar colours. On the basis of a colour–colour diagram and X-ray properties we could verify that all these sources are good QSO/AGN candidates rather than stars. Additional secondary gravitational lens candidates are also reported.

Key words: gravitational lensing: strong.

1 INTRODUCTION

Gravitational lensing remains a powerful tool for studies of dark matter distribution in the Universe. One important application of gravitational lens statistics is to provide strong constraints on the cosmological models and parameters since the lensing optical depth depends on the cosmological volume element (Surdej, Remy & Haubold 1992; Mitchell et al. 2005; Oguri et al. 2008; Jullo et al. 2010; Rozo, Wu & Schmidt 2011).

An ideal set of observations to carry out extragalactic research and especially for searching gravitational lens systems is the CFHTLS photometric survey.[1] Previous investigators have mainly set up automatic procedures to search for gravitational lens systems. Cabanac et al. (2007) have presented 40 strong lens candidates over 28 deg^2 of the CFHTLS field, which consist of galaxy/group deflectors producing conspicuous gravitational arc systems. More et al. (2012) have reported about 127 lens system candidates (Strong Lensing Legacy Survey-ARCS) over 150 deg^2 in the CFHTLS. In that work, they applied semi-automatic techniques to find gravitational arcs with the help of some additional visual inspection. Maturi, Mizera & Seidel (2013) studied the statistical colour properties of gravitational arcs over 37 deg^2 in the CFHTLS-Archive-Research Survey and found 73 new arc candidates. Sygnet et al. (2010) have found three good candidates for edge-on galaxy lens applying their automatic/visual procedure to 30 444 individual CFHTLS relatively bright spirals $18 < i < 21$. Shan et al. (2012) have performed a weak lensing analysis over 64 deg^2 of the CFHTLS fields.

We propose here to search for multiply imaged QSOs/AGN among the counterparts of X-ray point-like sources detected with *XMM*. Therefore contrary to the previous approaches, we have been searching for gravitationally lensed QSOs/AGN at much smaller angular scales (typically 1–4 arcsec).

The search for gravitational lens candidates among the optical counterparts of X-ray-selected QSOs/AGN looked a priori very promising as, first of all, it allows the selection of a sample of QSOs/AGN with very few contaminants. Moreover, as the X-ray QSOs/AGN are bright and distant sources (observed up to a redshift $z \sim 4$), they have a high probability of being multiply imaged due to the presence of a deflector near their line of sight.

From lensing probability calculations over a mock catalogue of X-ray sources (reproducing the redshift distribution and differential number counts of the COSMOS X-ray sources as a function of their flux), where we have assumed a constant comoving density of deflector galaxies modelled as singular isothermal spheres, we expect ∼15 QSOs/AGN among the *XMM*-LSS soft X-ray sources

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[1] Canada France Hawaii Telescope Legacy Survey: http://www.cfht.hawaii.edu/Science/CFHLS/

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to have a deflector sufficiently close to their line of sight to lead to the formation of multiple lensed images of their optical counterpart (Surdej et al. 2011; Finet, Elyiv & Surdej 2012).

The contiguous ∼11 deg^2 medium–deep *XMM*-LSS field has been surveyed at high galactic latitudes with the *XMM–Newton* satellite, centred on RA $2^h 18^m 00^s$ Dec. $-7^\circ 00' 00''$ (J2000). It provides the identification of a homogeneous sample of galaxy clusters and QSOs/AGN (Pierre et al. 2011) and reaches a sensitivity near 10^{-18} W m^{-2} for point-like sources in the soft band (Elyiv et al. 2012). About 80 per cent of the 6000 point-like *XMM*-LSS X-ray sources have (an) optical CFHTLS DR6 counterpart(s) (Chiappetti et al. 2013). Visual inspection of all counterparts led us to classify the sources as being either extended or point-like and reject the wrong associations (Melnyk et al. 2013). In this paper, we describe separately the results of our gravitational lens search among the CFHTLS counterparts of X-ray sources.

In Section 2, we detail the method used to identify multiply imaged QSOs/AGN in the *XMM*-LSS field. In Section 3, we describe the adopted procedure to search for multiply imaged QSOs/AGN, discuss each individual candidate and report their colour measurements as well as their morphology. Section 4 contains the main conclusions.

2 THE SAMPLE OF GRAVITATIONAL LENS CANDIDATES

Our sample of X-ray point-like sources and their optical counterparts consist of objects which have been detected in the soft and/or the hard X-ray band and coming from the multiwavelength catalogue of Chiappetti et al. (2013). The ∼5500 optical counterparts of the X-ray sources were visually inspected on 10 arcsec × 10 arcsec CFHTLS optical images centred on the X-ray sources. The angular separations between the lensed images for a typical galaxy deflector and cosmological redshifts of the source (QSO/AGN) and the lens are typically of the order of 1 or several arcsec (Refsdal & Surdej 1994). Knowing that lensed components should be point-like sources and should have rather similar colour properties (colour difference smaller than 0.1–0.2 mag.), this selection was also carried out using these strict criteria. Contamination by the lens, intrinsic colour variation plus time delay(s) and/or microlensing acting may cause colour differences above typical CFHTLS photometric errors.

The point spread function (PSF) of the *XMM–Newton* telescopes provides a resolution near 4–6 arcsec for a point-like source. A detected point-like X-ray source may therefore be sometimes identified with multiple (more than one) optical counterparts. We have made an in-depth study of these particular cases in order to detect new gravitational lens systems (mostly multiply imaged QSOs/AGN).

We inspected g, r and i CFHTLS direct CCD frames whenever they were available. For visual inspection we used the monochromatic images in logarithmic scale for each band as well as the colour composed images. For better objectivity four independent members of the present team (called hereafter ‘inspectors’) ranked each counterpart in the following way: 1 – very good candidate, 2 – good lens candidate, 3 – possible lens candidate and 0 – definitely not a candidate. A similar approach has been followed by More et al. (2008) when searching for gravitational lenses in the Extended *Chandra* Deep Field South and by Jackson (2008) in the COSMOS field. We finally retained nearly 300 candidates which were marked with the 1, 2 or 3 rank by at least one inspector. Next we added the ranks from all inspectors and formed a top list of 72 probable lens candidates. We visually inspected this list several times and removed very faint objects, objects which are obvious stars according to their spectra and so on. At the end, we finally selected 18 multiply imaged QSO/AGN candidates which could be potentially strong lens systems, see Fig. 1 and Table 1. They are ranked there from the best to worst according to final morphological and colour selection.

Most of them consist of double sources. For five pairs with an angular separation larger than 3 arcsec we considered their photometry in the g, r and i bands directly from the CFHTLS catalogue. We used available spectroscopic or photometric redshifts from SDSS[2] (Abazajian et al. 2009) and Melnyk et al. (2013). For the remaining more compact systems, we performed a multiple PSF fitting analysis to precise their morphology (point-like or extended source) and accurate magnitude measurement of each component. We adopted the same PSF fitting technique as that used for the analysis of the gravitational lens systems HE 0435−1223 described in Ricci et al. (2011) and UM673 in Ricci et al. (2013).

3 DESCRIPTION OF THE INDIVIDUAL CANDIDATES

3.1 The best candidates

Candidate J021511.4−034306 is seen as a wide pair. Therefore, we took the magnitudes of the two point-like sources from the CFHTLS data base. The components show similar colours: $g - r = 0.39$ and 0.38 for the A and B components, $r - i = 0.00$ and 0.08, respectively. Photometric redshift determination for the A component indicates $z = 0.94$ (Melnyk et al. 2013). We did not find any SDSS spectra but just a note that these two sources are point like. This system thus consists of a good gravitational lens candidate according to the PSF analysis. The components are bright and slightly saturated. Therefore, we encountered some problems when performing the PSF fitting.

Candidate J022234.3−031616 consists of two close faint sources. We have just r- and g-band observations. We performed a PSF fitting analysis and found that this system consists of two point-like sources with very similar colours: $g - r = -0.46$ and -0.36 for A and B, respectively, see Fig. 2. This system thus consists of a good gravitational lens candidate.

Candidate J022607.0−040301 consists of one bright and one faint source. We performed a PSF fitting analysis and found that both of them are point-like sources. However, they have slightly different colours. Note that the presence of a nearby lens, microlensing and/or intrinsic variations with time delay acting could of course account for such different colours. Photo-z for the A component is 0.086 (Rowan-Robinson et al. 2008).

3.2 Candidates found with extended images or with different colours

Candidate J021844.4−044825 contains one bright optical component near the centre of the X-ray emission and two symmetric faint components. The system is wide and we took the magnitudes of each component from the CFHTLS catalogue. The colours of the two symmetric sources are similar: $g - r = 0.78$ and 0.94 for the B and C components, $r - i = 0.53$ and 0.65, respectively. Akiyama et al. (in preparation) on the basis of spectroscopic observations claim that component A is a QSO/AGN with $z = 4.55$. Since the

[2] www.sdss.org

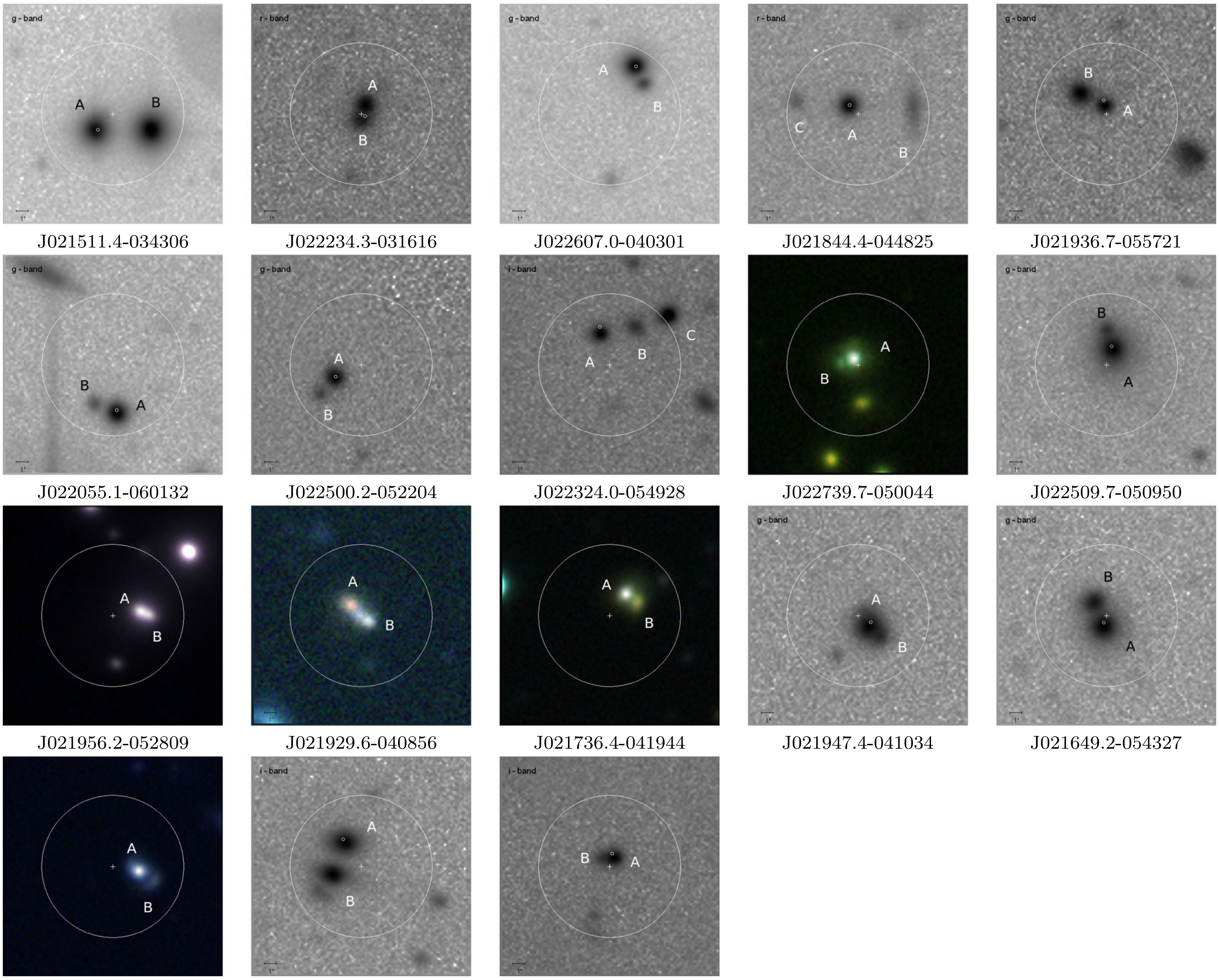

Figure 1. Images of 18 gravitational lens candidates. The cross indicates the centre of the X-ray emission. The radius of the circle around the centre of X-ray emission is 6 arcsec. Here we chose the best illustrative band or colour image for each candidate.

central component A has very high redshift, we do not consider it as a potential deflector. Moreover, the symmetric components B and C are extended, the system J021844.4−044825 does not therefore constitute good gravitational lens candidate.

Candidate J021936.7−055721 consists of two components with an angular separation near 3 arcsec. For these, we took the magnitudes from the CFHTLS data base. The components have similar colours: $g - r = 0.59$ and 0.66 for the A and B components, $r - i = 0.15$ and 0.18, respectively. We performed a PSF fitting analysis of this system. It shows that component A is point like and that B is an extended source.

Candidate J022055.1−060132 also consists of one bright and one faint components. We performed PSF fitting and found that both components are point-like sources. However, they also show very different colours. Given the very different colours and high flux ratio, we do not consider this system to be a good gravitational lens candidate.

Candidate J022500.2−052204 consists of one bright and one faint components. We performed PSF fitting and found that both components are point-like sources. However, they have very different colours. Given the very different colours and high flux ratio, we do not consider this system to be a good gravitational lens candidate.

Candidate J022324.0−054928 is composed of one faint and two symmetric bright components. The system is wide and we took the magnitudes of the components from the CFHTLS catalogue. The colours of those components are very different.

3.3 Candidates found to be extended or not classifiable sources

Candidates J022739.7−050044, J022509.7−050950, J021956.2−052809, J021929.6−040856, J021736.4−041944, J021947.4−041034, J021649.2−054327, J021902.8−054109, J021634.8−043302 and J022646.2−045156 consist of pairs of extended sources according to our PSF fitting analysis.

Candidate J021634.8−043302 consists of a wide pair and we took their magnitudes from the CFHTLS data base. The components show similar colours: $g - r = 1.41$ and 1.33 for the A and B components, $r - i = 0.59$ and 0.62, respectively. From the SDSS data base, the estimated photo-z is 0.38 ± 0.04 and 0.33 ± 0.04 for the A and B components, respectively. In the SDSS data base there is just a note that the two components are galaxies. We performed the PSF fitting of these two components and confirm that they are both extended, see Fig. 2.

Table 1. Properties of the potential strong lens candidates.

ID		Xcatname[a]	RA	Dec.	g	r	i	$g-r$	$r-i$
1	A[e]	J021511.4−034306	2: 15: 11.49	−3: 43: 07.94	18.15	17.76	17.76 ± 0.001	0.39	0.00
	B[e]		−4.69″	+0.03″	17.24	16.86	16.78	0.38	0.08
2	A[e]	J022234.3−031616	2: 22: 34.33	−3: 16: 17.14	21.59 ± 0.02	22.05 ± 0.03		−0.46	
	B[e]		+0.37″	−1.25″	22.28 ± 0.03	22.64 ± 0.04		−0.36	
3	A[e]	J022607.0−040301	2: 26: 06.86	−4: 02: 57.09	19.35 ± 0.01	19.08 ± 0.01	19.00 ± 0.01	0.27	0.08
	B[e]		−1.39″	−2.95″	21.82 ± 0.02	21.47 ± 0.03	21.18 ± 0.02	0.35	0.29
4	A[e]	J021844.4−044825	2: 18: 44.46	−4: 48: 24.69	22.62 ± 0.01	20.81 ± 0.01	19.98 ± 0.002	1.81	0.83
	B[b]		−5.41″	−0.16″	22.97 ± 0.03	22.19 ± 0.03	21.66 ± 0.02	0.78	0.53
	C[b]		+4.51″	+0.44″	24.11 ± 0.05	23.17 ± 0.05	22.52 ± 0.03	0.94	0.65
5	A[e]	J021936.7−055721	2: 19: 36.80	−5: 57: 20.26	22.83 ± 0.02	22.24 ± 0.02	22.09 ± 0.02	0.59	0.15
	B[b]		+2.00″	+1.03″	22.21 ± 0.01	21.55 ± 0.01	21.37 ± 0.01	0.66	0.18
6	A[e]	J022055.1−060132	2: 20: 55.17	−6: 01: 36.51	21.10 ± 0.01	20.44 ± 0.01	20.67 ± 0.02	0.66	-0.23
	B[e]		+1.86″	+0.77″	23.55 ± 0.06	23.47 ± 0.07	23.43 ± 0.06	0.08	0.04
7	A[e]	J022500.2−052204	2: 25: 00.41	−5: 22: 05.50	22.20 ± 0.02	21.73 ± 0.02	21.35 ± 0.03	0.47	0.38
	B[e]		+1.17″	−1.38″	23.90 ± 0.05	23.55 ± 0.06	23.59 ± 0.07	0.35	-0.04
8	A[b]	J022324.0−054928	2: 23: 24.12	−5: 49: 25.13	21.69 ± 0.004	21.64 ± 0.01	21.32 ± 0.01	0.05	0.32
	B[e]		−3.05″	+0.56″	23.11 ± 0.02	22.74 ± 0.04	22.06 ± 0.02	0.37	0.68
	C[e]		−5.76″	+1.53″	21.05 ± 0.003	20.83 ± 0.01	20.76 ± 0.01	0.22	0.07
9	[b]	J022739.7−050044	2: 27: 39.83	−5: 00: 42.99					
10	[b]	J022509.7−050950	2: 25: 09.72	−5: 09: 49.21					
11	[b]	J021956.2−052809	2: 19: 56.12	−5: 28: 08.28					
12	[b]	J021929.6−040856	2: 19: 29.66	−4: 08: 56.75					
13	[b]	J021736.4−041944	2: 17: 36.35	−4: 19: 43.20					
14	[b]	J021947.4−041034	2: 19: 47.40	−4: 10: 34.83					
15	[b]	J021649.2−054327	2: 16: 49.22	−5: 43: 28.45					
16	[b]	J021902.8−054109	2: 19: 02.66	−5: 41: 10.13					
17	A[b]	J021634.8−043302	2: 16: 34.93	−4: 33: 00.13	21.93 ± 0.01	20.52 ± 0.01	19.93 ± 0.004	1.41	0.59
	B[b]		+1.14″	−2.82″	21.77 ± 0.01	20.44 ± 0.01	19.82 ± 0.01	1.33	0.62
18		J022646.2−045156	2: 26: 46.26	−4: 51: 55.45	21.37 ± 0.02[c]	[d]	[b]		

Notes. [a]Identifiers are from Chiappetti et al. (2013). In order to shorten the ID names, we systematically omitted the prefix 2XLSSd before the names of the objects. [b]Extended source. [c]Only for the bright A component. [d]Possibly affected by a cosmic ray. [e]Point-like source.

Candidate J022646.2−045156 looks very different in the various bands. In the g band, it looks like a single point-like source according to the PSF fitting results. In the r band, we see a faint secondary component. However, the bright component looks more compact than the reference star (PSF). This could hint on the presence of a defect or cosmic ray in the r band. It was therefore not possible to correctly define the r magnitude. In the i band, the bright component appears as an extended source according to PSF fitting. The SDSS SED analysis shows that it is a QSO/AGN with z=1.085. It could be that the host galaxy of this QSO/AGN has been detected in the i band.

3.4 Discussion

Using the multiple PSF fitting technique, we found 11 gravitational lens system candidates which consist of extended components: J021844.4−044825, J022739.7−050044, J022509.7−050950, J021956.2−052809, J021929.6−040856, J021736.4−041944, J021947.4−041034, J021649.2−054327, J021902.8−054109, J021634.8−043302 and J022646.2−045156. The candidate J021936.7−055721 consists of two components which have similar colours but one of the components is extended and the other one is point-like. Using magnitudes from the CFHTLS survey or from PSF fitting for the case of compact systems, we found that the following candidates have very different colours: J022055.1−060132, J022500.2−052204 and J022324.0−054928.

The two candidates J021511.4−034306 and J022234.3−031616 consist of pairs of point-like sources having very similar colours. Candidate J021511.4−034306 is very bright in X-ray, 1.1×10^{-13} and 1.5×10^{-16} W m^{-2} in the soft and hard bands, respectively. It corresponds to a hardness ratio $HR = -0.60$ which points to a source being likely an unobscured AGN. Candidate J022234.3−031616 is faint in X-ray and is only seen in the soft band, 6.8×10^{-18} W m^{-2}. The optical counterparts of the J022607.0−040301 candidate have slightly different colours but it could be caused by the presence of a lens, intrinsic colour variation of the AGN combined with a time delay and/or microlensing effects. The system is bright in X-ray, about 1.5×10^{-17} W m^{-2} in both the soft and hard bands. Its corresponding hardness ratio −0.63 indicates that it is a likely unobscured AGN.

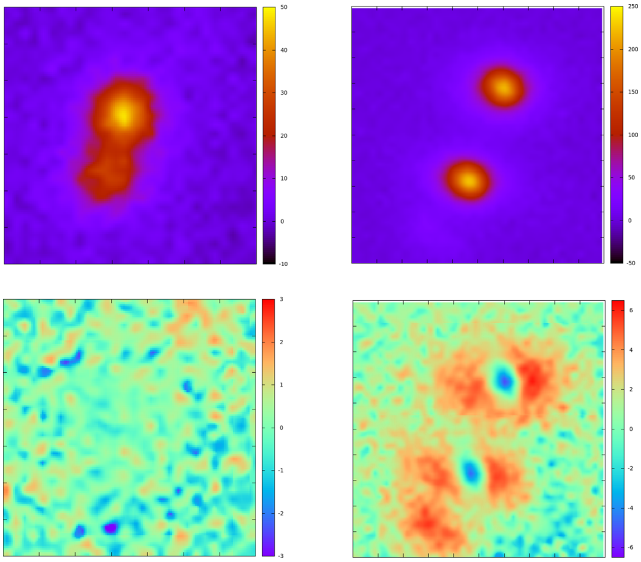

Figure 2. The CFHTLS images are shown at the top and the residuals after subtraction of a double PSF at the bottom. The latter residuals have been normalized to the noise image, in σ unit.

These last three systems (J021511.4−034306, J022234.3−031616 and J022607.0−040301) constitute the best gravitational lens candidates.

From the *XMM*-LSS source catalogue (Chiappetti et al. 2013), we have constructed the colour–colour diagram ($r - i$ versus $g - r$; see Fig. 3) for all spectroscopically confirmed stars and QSO/AGN counterparts of *XMM*-LSS point-like sources (see classification of sources in Melnyk et al. 2013). From this plot we suggest that the J021511.4−034306 and J022607.0−040301 candidates are probably AGN. For the candidate J022234.3−031616 we have only magnitudes in g and r bands and we cannot classify them as QSOs/AGN or stars on the sole basis of the colour–colour diagram.

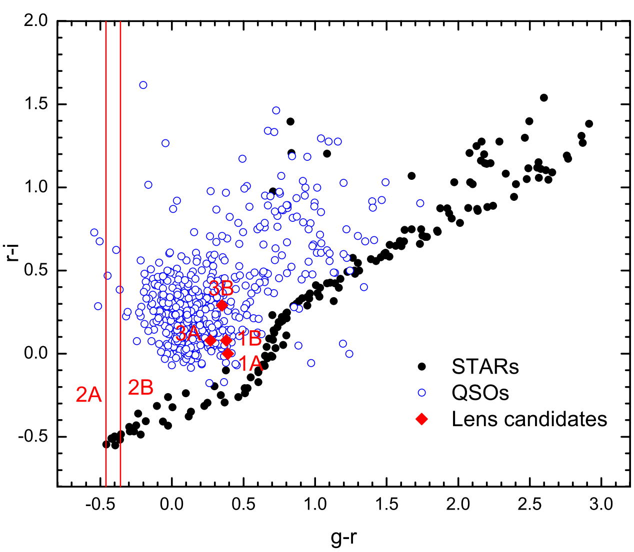

Figure 3. Colour–colour diagram from the templates of stars and spectroscopically confirmed QSOs/AGN in the *XMM*-LSS field, 131 templates are from Pickles (1998), 4 from Bohlin, Colina & Finley (1995), 19 from Bixler, Bowyer & Laget (1991). The components of the three best lens candidates are indicated in red: 1A – J021511.4−034306A, 1B – J021511.4−034306B, 2A – J022234.3−031616A, 2B – J022234.3−031616B, 3A – J022607.0−040301A, 3B – J022607.0−040301B.

4 CONCLUSION

We have performed a visual inspection of some 5500 optical counterparts of X-ray point-like sources in the *XMM*-LSS/CFHTLS common field. Four independent inspectors have identified 18 compact systems which could be multiply imaged QSO/AGN. Using the PSF fitting technique we have characterized the morphology and colours of the components. As a result, we found three systems (J021511.4−034306, J022234.3−031616 and J022607.0−040301) which met our colour and morphological criteria and are the best gravitational lens candidates. They are point-like source pairs with similar colours. With a high probability they could be QSO/AGN. For a final confirmation we need spectroscopic observations of the multiple components of the selected systems.

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