Selecting Lens Candidates (via Variability)

Schmidt, et al.

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Abstract

The selection of the lens candidates which will be observed with the ESO 2.2m and the GROND instrument on december 11-17 2010 is presented. The candidates consist of three kinds of objects: 1) Extended objects and 2) Spectroscopically confirmed QSOs from SDSS Stripe 82 selected via variability and their UV excess colors and 3) spectroscopically confirmed Stripe 82 quasars failing the variability+UVX selection but marked as 'personal favorites'. Each object has been assigned a priority ID. Based on these IDs 5 'personal favorites', 20 Stripe 82 QSOs (which are not in M. Oguri's catalogue of rejected lens candidates) and 362 extended UVX objects have been selected to be observed. Of these an estimated total of ∼200 objects will be observed with the time awarded.

1 Introduction

In this short document the selection of the lens candidates which will be observed at La Silla in mid december 2010 is described. The purpose of this work is to identify the first lensed quasars selected based on the quasar's intrinsic variability. The idea is to look for unresolved lenses in SDSS Stripe 82 where the average time sampling (on average 60 epochs over 8 years) is good enough for a solid variability selection. The applied variability cut is described in detail in Schmidt et al. (2010).

The total number of lensed QSOs expected in Stripe 82 ($i_{\rm lim} = 21.3$) is $\simeq 8$ Oguri & Marshall (2010). Having shown in Schmidt et al. (2010) that the QSO selection algorithm approach 90% completeness at $i > 19.5$, 5-7 of the selected candidates are expected to be confirmed as QSO lenses. So far only two lenses are known in Stripe 82 (Lacki et al., 2008; Jackson et al., 2008) so any increase in the number of lenses with the time sampling of Stripe 82 is desirable. Furthermore, confirming *any* of the candidates as actual lenses will, despite previous efforts, be the first time that a gravitational lens has been selected based on variability.

2 Initial Samples

Below we describe the initial data samples. It is these samples which have been cut down by color, variability, redshift, etc. to create the samples from which the objects to observe have been selected.

2.1 Extended Objects

The initial sample of extended objects was selected from Stripe 82 by asking for all objects with the SDSS DR7 type keyword set to 3, i.e., extended/galaxy morphology. This is done to look for unresolved small-separation lenses. The hope is that the lenses hide in the relatively poor SDSS seeing (which nevertheless goes down to $\sim 0.7 - 0.8$ for the best seeing (gri) epochs in Stripe 82) and can be found on their QSO variability and their multiple point sources in great seeing follow-up. Furthermore the objects have been asked to satisfy the color cuts shown in table 1 (table 1 in Schmidt et al., 2010), which is where the main QSO locus is located in color space, eliminating the majority of stellar contaminants. Furthermore the objects have a brightness of $17 < i < 21$. This returned an initial sample of 39,657 objects.

Table 1: The UV excess (UVX) color box.

-0.4 <	$u-g$	< 0.6
-0.5 <	$g-r$	< 0.7
-0.4 <	$r-i$	< 0.4

2.2 Spectroscopically Confirmed SDSS Stripe 82 QSOs

The initial sample of spectroscopically confirmed QSOs used here is the sample of the 9157 quasars described in Schmidt et al. (2010). This sample correspond to all spectroscopically confirmed quasars in the DR5 QSO catalog (Schneider et al., 2007) located in Stripe 82.

3 Candidate Selection

From the initial samples described above a series of different cuts were applied to select the most interesting candidates for spectroscopic follow-up. The following cuts were applied:

- **Schmidt et al. (2010) variability cut**: The A and γ values defined in Schmidt et al. (2010) has been calculated for each object. 93% of the 9157 quasars (the cut it is defined based on them) and 2.6% (1027 of 39,657) of the extended objects survive this cut.
- **Removing obvious non-quasars by visual inspection**: This has only been done for the extended variability selected objects, since the variability selection was developed on point sources and hence the contaminants ('normal' AGN, defects, variable blue galaxies etc.) are not understood as well for extended objects as for point sources.
- **UV excess cut (table 1) on colors**
- $z_{\mathbf{spec}} > 1$ **or** $z_{\mathbf{phot}} > 1$ **when** $z_{\mathbf{spec}}$ **is not available**: One of the major contaminants of unresolved quasar lenses (extended quasar colored objects) are low redshift quasars looking extended because of the host galaxy, hence the candidates need to have an estimated redshift above 1.
- **Extended morphology**: Last but not least the type keyword need to be set to 3 (extended morphology) in the best seeing Stripe 82 epoch where the r-band seeing has to be less than 0.9".

Having done this we were left with a sample of 362 out of 39,657 extended variable UVX objects and 320 out of 9,157 spectroscopically confirmed QSOs. The selection process is illustrated in figure 1.

4 Priority ID

Since we were not awarded enough time to observe all candidates they needed to be prioritized. This was done by creating a 'priority ID' for each object on which the observational order is based. The ID is simply a long (17 digits) integer which indicates several 'properties' of the individual objects. The priority IDs are created based on the following:

1. 'personal favorite'

   This criterion is ranked higher than everything else, i.e., it vetoes the observation of the given object by setting the first digit of the ID to 2. The personal favorites selected here are described in a bit more detail in section 5.1

2. QSO spectrum (with $z > 1$) available

   If a quasar spectrum with a redshift larger than 1 is available the first digit of the ID is set to one.

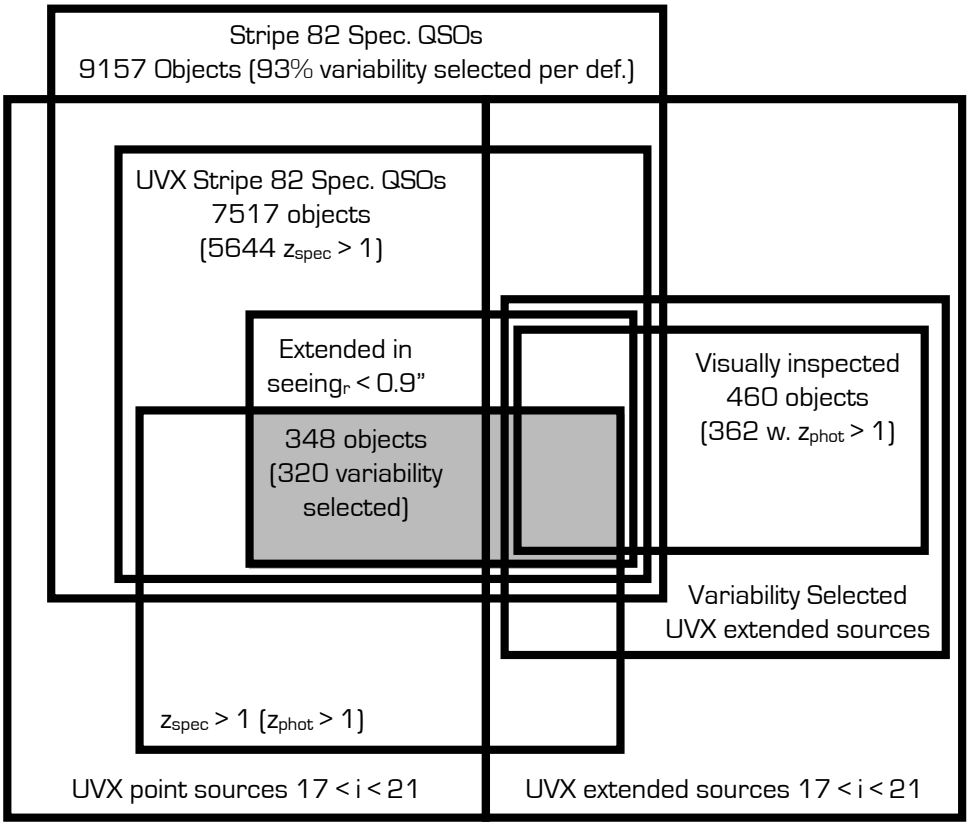

Figure 1: Illustration of cuts made on the QSO and extended UVX sample as described in the text.

3. UKIDSS H-band magnitude

   In the case of cross-matched objects in UKIDSS the H-band magnitude (or rather the maximum of all the H band magnitudes - 100 if not defined - minus the individual magnitudes) is written to the next 4 digits with the dot removed and two decimals.

4. $\frac{\chi^2_{\rm star}}{\chi^2_{\rm phot}}$

   This fraction estimates how 'close' the object is to the stellar locus compared to the quasar locus in color-color space. The 'distances' to the two loci is indicated by the $\chi^2_{\rm star}$ and $\chi^2_{\rm phot}$ respectively. These are obtained when estimating the photometric redshift of the object (see Hennawi et al., 2010, for more details). The fraction is rounded of to nearest integer an occupies the next four digits.

5. $z_{\rm phot}$

   The following 4 digits of the priority ID contains the photometric redshift estimated as described in Hennawi et al. (2010) (dot removed and two decimals).

6. $\frac{{\rm type}_{\rm gal}+1.0}{{\rm type}_{\rm star}+1.0}$

   This fraction compares the number of epochs where the object was flagged as extended (${\rm type}_{\rm gal}$) with the number of epochs where the object was point source like (${\rm type}_{\rm star}$). The fraction is rounded of to nearest integer an occupies the next four digits.

Thus for a given object the priority ID might be 18142001518520018 corresponding to:

- A QSO spectrum with $z > 1$ (and not a 'personal favorite'):	**1**8142001518520018
- A UKIDSS H-band magnitude of 100-81.42 = 18.58:	1**8142**001518520018
- 15 times 'closer' to the quasar locus than the stellar locus	18142**0015**18520018
- An estimated photometric redshift of 1.852:	181420015**1852**0018
- 18 times as many Stripe 82 epochs with galaxy morphology (type = 3) than epochs where the object is point source like (type = 6):	1814200151852**0018**

Hence a large priority ID gives the object a high priority.

One flaw or limitation with this kind of priority ID is that each property contributes to the ID independently, meaning that a lower ranked property is only effective if several objects has the same values of the higher ranked property(ies); for instance the χ^2 criteria is effectively only used when no H-band magnitude is known (or if two or more objects have the same H-band magnitude to within a percent).

5 The final sample for GROND follow-up

By creating the priority ID for each object in the samples resulting from the cuts described in section 3, we were now able to make the final list of objects to observe. We decided to select 5 'personal favorites' which didn't pass all cuts (more about these below), the 20 spectroscopically confirmed QSOs with the highest priority ID (which didn't have a match in M. Oguri's catalogs of rejected lens candidates) and all the 362 extended variability selected objects.

5.1 personal favorites

The five objects selected as 'personal favorites' failed the variability cut, but show interesting (bimodal?) morphologies in the Stripe 82 postage stamps. The reason they fail our variability cut is probably related to messy/'noisy' light curves such that the underlying intrinsic variability (of the multiple QSO images?) is smeared out. For the lens ULAS J234311.93-005034.0 described in Jackson et al. (2008), which also falls outside our variability selection box, this is indeed the case. In figure 2 the r-band 'light curve' created from the Stripe 82 epochs is shown. It is clear that the underlying intrinsic quasar variability completely drowns in the messy photometric data. Whether the messy data is a consequence of the lensing nature (time delay of QSO variability, micro lensing etc.) or not is unclear. Nevertheless, a messy light curve

will make a variability selection difficult and might be the reason that the extended bimodal(?) personal favorites fail our variability cut.

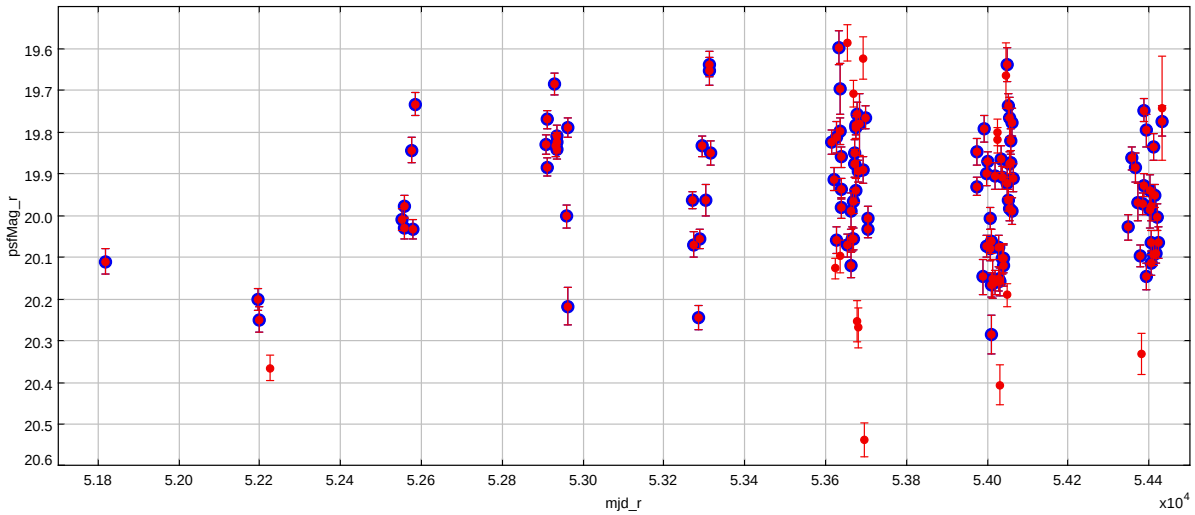

Figure 2: The photometric r-band 'light curve' for the Stripe 82 lens ULAS J234311.93-005034.0 (Jackson et al., 2008). The messy light curve washes out the variability signal from the underlying intrinsic quasar variability of the two images, causing the object to fall outside the variability selection cut from Schmidt et al. (2010). This might also be the reason that the 5 'personal favorites' also fail our variability cut ... and be an indication of a lens nature?

5.2 sample

The final list of objets for photometric follow-up is shown below (priority IDs with less than 17 digits should be thought of as having zeros in front (i.e. no spec and/or no H-band mag and/or $\chi^2_{\rm star} < \chi^2_{\rm phot}$ smaller than 0.5).

# index	objid	priorityid	ra	dec
1	587730847424905311	28307024710390038	314.46866	0.10980109
2	588015508755775570	28223052419080255	53.20213	-0.3653704
3	587731172232135333	28198010123940667	313.38757	-1.0162246
4	587734305413726557	28184014016370613	331.25497	0.52302201
5	587731512076075139	28164010819880032	35.201385	-0.47599432
# index	objid	priorityid	ra	dec
6	587731513141559419	18376002311520013	16.2803823	0.41126949
7	588015509270495301	18319003126990003	2.56871133	0.20768695
8	587731186191237426	18319000828350003	331.03966347	-0.13770241
9	587731185662951500	18318021115240003	350.60691496	-0.46557767
10	587731185668194449	18312148931960003	2.59227832	-0.61700182
11	587730845818683704	18295000427890024	324.52846301	-1.13821544
12	588015507663683725	18276000507450250	11.31436324	-1.22159835
13	587731513145950268	18266007922250005	26.33675498	0.27844314
14	587731186202181850	18266000528230004	356.07654605	-0.14918738
15	587731186191106371	18264001027670009	330.79126123	-0.05476811
16	587731513695338778	18261000131170005	54.98491555	0.74094738
17	587731173843141315	18260000821680100	314.30536647	0.34196573
18	587731185666883640	18259022710160003	359.63513674	-0.54471111
19	587731513142673569	18258037111630003	18.90717437	0.34129864
20	587731187282935899	18249010323490004	12.02523834	0.77324401
21	587734303265521855	18244001226760003	329.47267164	-1.06699208

22	587731512069193830	18243016610500005	19.43621533	-0.50922581
23	587731513151586516	18238000035570008	39.22277877	0.40554146
24	587731511533633570	18237034314450006	22.42771056	-0.93304814
25	587731185116512658	18234000741220007	328.87087805	-0.86667065
# index	objid	priorityid	ra	dec
26	587731185649844313	18289020220100019	320.67921931	-0.44823529
27	587731511548051657	18253000216713650	55.41522299	-0.9305844
28	587731511546413317	18150003520218300	51.59492157	-0.93060182
29	587730846887903261	8499000128010022	314.13792241	-0.32785762
30	587731513160499326	8368000721000278	59.49807353	0.21947222
31	587730847426937208	8363002221232200	319.20750215	0.18337412
32	588015509287076033	8358000821573900	40.5198754	0.13737578
33	587730846349656754	8350000134780400	311.0127548	-0.79229016
34	588015508744175661	8347002021340077	26.68992988	-0.30831431
35	588015510357606468	8343000228350136	33.08143591	0.97796328
36	587731513147785320	8339012421004300	30.5985167	0.31552293
37	587731513154797670	8336000821460041	46.48088427	0.36476759
38	587731512081514575	8326000515921333	47.57941789	-0.51895294
39	588015508208287957	8324000518520229	28.98552678	-0.8355823
40	587731185665179793	8306001220100875	355.76767567	-0.56417785
41	587734304878362816	8304000518520106	334.6089575	0.00358132
42	587731185661313236	8298000427897600	346.95847999	-0.50080682
43	587734304876396906	8285000415360045	330.20091782	0.09621753
44	587731511548838044	8284000215920010	57.13492648	-0.90031382
45	587734303802589408	8281002718523400	329.92277966	-0.77728322
46	587730847964332566	8279000315920278	320.40150042	0.56287791
47	588015508733624396	8276000216830438	2.53962976	-0.24894871
48	587731513160564968	8272000134903300	59.64656503	0.27817405
49	587731513697370521	8272000133881600	59.62061801	0.71050234
50	587734304875151606	8267000916150076	327.31382478	0.05119274
51	587731186733351039	8263002920447000	342.94927851	0.27793996
52	587731173841633816	8257002517620065	310.93381413	0.29493685
53	587731511549755695	8256000035126700	59.32960586	-1.00863174
54	587731513146081322	8254000615818500	26.69367325	0.39718462
55	588015509295268047	8247001217731017	59.21982537	0.12025366
56	588015507679936910	8245000413100273	48.43967501	-1.11547378
57	588015508221526343	8242000035240633	59.22716971	-0.72473727
58	588015509829779619	8240000215920169	53.78393564	0.47095532
59	587731511549493558	8240000134780173	58.63604141	-0.96547939
60	587731513160368403	8240000115360278	59.34605541	0.37801641
61	587731513149292677	8238000626540429	33.97354788	0.30745282
62	587731174381257370	8235000128127500	317.19443538	0.69220297
63	587730846886200909	8231000134900039	310.2969856	-0.22724373
64	587731513160564920	8228000034446700	59.65532312	0.36049748
65	587731513159975206	8226000134902267	58.43069538	0.33322058
66	588015508758397216	8226000034223200	59.11949103	-0.32329802
67	587734305412023026	8224000128120385	327.37109131	0.44621311
68	587731513159254241	8223000115473750	56.68708635	0.29622657
69	587731512086233546	8221000134906700	58.43803043	-0.53917304
70	587731513697042711	8220000141563350	58.87042553	0.67164754
71	587731512620548263	8219001416040425	52.54430662	-0.12571542
72	588015508193476871	8216000215920025	355.14216357	-0.74241339
73	587734305413661075	8212000416043250	331.00978471	0.42840843

74	587731513696321913	8210000134677200	57.1507037	0.69316917
75	587731512623104241	8209000115367000	58.41231406	-0.1021376
76	587731186203492548	8208000915470690	359.03272438	-0.13177073
77	588015507684786413	8207000115243100	59.49140514	-1.15768651
78	587731513154404751	8207000034110127	45.6382539	0.22525097
79	588015509806383318	8204000115360600	0.28134042	0.4404782
80	587731513159254285	8203000033657000	56.65311597	0.29550801
81	588015508758462676	8202000139873200	59.29353774	-0.29290781
82	587731512606851264	8201000115920730	21.18745158	-0.11899497
83	587731185653252727	8199000216710689	328.45076296	-0.49241653
84	588015508758462628	8196000720100012	59.38294514	-0.37495876
85	588015509831877068	8196000135240663	58.56111494	0.53564565
86	587731186726470168	8194000115360226	327.30862891	0.39783338
87	588015509825126671	8194000034333850	43.17498245	0.44043288
88	587731512086757648	8193000134446700	59.53757794	-0.50116709
89	588015508221460870	8192000044270900	58.98617812	-0.67585814
90	587734304339198809	8191000215470253	329.47084958	-0.40949876
91	588015507656409329	8191000134330775	354.67771397	-1.24065329
92	588015508207828998	8189000417730700	27.82587352	-0.79557914
93	587731513690292410	8189000127220286	43.32938887	0.81778804
94	587731513697304999	8189000115476700	59.3975202	0.67716281
95	588015510358458608	8188000115920427	35.04298921	1.01970783
96	587731511549559087	8188000115363400	58.87078743	-0.91100662
97	587731513964495202	8187000035123700	56.62906936	0.66774582
98	587731512623628539	8185000115366700	59.49679676	-0.13496326
99	588015509801664770	8185000115360610	349.48809333	0.5748918
100	587730846352409836	8184000035800325	317.38168232	-0.70777331
101	588015509281964328	8182000315360012	28.77326408	0.05285465
102	587731185671930420	8181000015360888	11.19816342	-0.58054176
103	587731513159516396	8180000215920159	57.25131914	0.36703432
104	587734304344113619	8180000213100060	340.67748562	-0.30502157
105	588015508753285444	8179000140882600	47.42559754	-0.24083923
106	588015509831745823	8179000135461017	58.25954888	0.58006054
107	588015508215234812	8178000034900438	44.82696638	-0.75716066
108	588015509289632089	8177000516710259	46.34723584	0.08097379
109	587731187265372311	8177000215810700	331.956594	0.68745054
110	587731174380471444	8176000216710172	315.39371955	0.79036522
111	587731512623431999	8176000210615500	59.15970642	-0.20052501
112	588015509832335717	8176000134670091	59.6614699	0.43801391
113	588015509273117045	8176000035013300	8.54317644	0.1391726
114	587731511545299205	8175000135690938	49.02232469	-1.03599468
115	588015507684524310	8175000035123050	58.92980723	-1.21081217
116	588015508732051682	8174000315470763	358.93532029	-0.32688323
117	588015508742144300	8173000134902267	21.99672073	-0.34916142
118	587731513150341377	8172000215810231	36.31586499	0.30134035
119	587731512080531877	8172000133200017	45.35428357	-0.60279308
120	587731513160040734	8171000033200610	58.54230901	0.31968225
121	588015509295137044	8170000035805000	58.8276544	0.0845214
122	587731511537041702	8169000215470480	30.22219146	-0.89729309
123	587731512622055894	8167000034447300	55.9861992	-0.09513339
124	587734303802917334	8166000714570037	330.69295078	-0.6965352
125	588015508219035851	8166000028351375	53.52409235	-0.71314309
126	587731512623366502	8165000234676600	59.03555463	-0.0536828

127	588015508196950177	8164000128460196	3.10111897	-0.80628799
128	587730847960924753	8162000134783200	312.63502143	0.59111235
129	587731513696584077	8162000034227600	57.78296332	0.72911735
130	588015509285896326	8161008319880010	37.79431145	0.06472738
131	587731186728173973	8161000127220667	331.23216805	0.28880648
132	587731512086757696	8161000114682167	59.62101297	-0.57216759
133	588015509814444402	8160003020890075	18.76360994	0.57122385
134	587734303269519654	8158005121460067	338.69686764	-1.20383202
135	587731512086167921	8158000415367000	58.21106073	-0.45101632
136	588015508740178139	8158000115360146	17.50382877	-0.30823647
137	588015509822505291	8157000420440381	37.13839876	0.56612756
138	587730847964529079	8157000315701267	320.75744239	0.42708932
139	588015508757676279	8157000215477100	57.53712747	-0.40963053
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146	588015508205863402	8154000033200097	23.3779105	-0.82782683
147	587731513159909592	8153000035123350	58.15865136	0.29197695
148	587731173845566506	8153000034330100	319.84713021	0.36313935
149	588015508221198797	8152000135126200	58.41196708	-0.72514849
150	587731187283394828	8152000113100900	13.13491772	0.76231608
151	588015507675939143	8152000031400433	39.33287343	-1.17832153
152	587731185654301192	8151000115470387	330.82967835	-0.43041495
153	588015509831680310	8151000115366700	58.13388328	0.60079205
154	587731513692520692	8150000221570161	48.4386123	0.66266778
155	588015509830238543	8149000127890722	54.87987994	0.48490571
156	587731187264258598	8148000115366900	329.382684	0.77930676
157	588015508221198760	8148000034901575	58.38595437	-0.74178315
158	587731513678168565	8147000128123650	15.7209482	0.72841514
159	587731512067686775	8146000215470295	16.05285909	-0.60336083
160	587734305417003445	8146000113100172	338.75240093	0.50843897
161	587731511548903804	8146000034780067	57.36230746	-0.92830303
162	588015509295268053	8146000034443100	59.10137589	0.14827754
163	587731187265831421	8144003419650300	332.9891467	0.74197576
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