Science White Paper for LSST Deep-Drilling Field Observations
LSST Deep Drilling for Galaxies

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1 Science Goals

1.1 Concise List of Main Science Goals

1. Identification and study of large samples of star-forming galaxies at redshifts $z > 3$ at flux limits $\sim 5\times$ fainter than for the wide survey.

2. Identification of star-bursting progenitors of high-redshift quasars at $z > 5$.

3. Identification and study of passively evolving (or otherwise red) galaxies at redshifts $z > 2.5$ enabled by deep observations through the y, z filters.

4. Identification and study of high-redshift clusters and proto-clusters of galaxies identified via the galaxy red sequence.

5. Characterization of ultra-faint supernova host galaxies.

6. Characterization of variability-selected AGN host galaxies.

7. Identification of nearby isolated low-redshift dwarf galaxies via surface-brightness fluctuations.

8. Characterization of low-surface-brightness extended features around both nearby and distant galaxies.

9. Deep "training sets" for characterizing completeness and bias of various types of galaxy measurements in the wide survey (e.g. photometry, morphology, stellar populations, photometric redshifts).

1.2 Details of Main Science Goals

The LSST deep-drilling fields are comparable to the deepest fields currently observed with ground-based 8-10 meter telescopes, but cover much larger area. The deepest fields currently available from Subaru and CFHT cover a combined area of approximately 5 square degrees (CFHTLS, COSMOS, SXDF, and the Subaru deep field), albeit not generally to LSST deep-field depth over the full span from the near-UV to the near-IR. With HypersuprimeCam on Subaru and large cameras on other large telescopes, it is likely that 10-20 square degrees will be covered depths comparable to the LSST deep fields in at least the g, r, i, z bands by the time of commissioning.

For galaxy science, the larger area is the main selling point for the LSST deep-drilling fields, particularly if it is weighted a bit more heavily toward the u, z and y-band than the main survey. These bands are especially valuable for improving photometric redshifts and for identifying high-redshift ($2 < z < 6$) galaxies at flux limits far below the sensitivities of the main survey. Figure 1 shows some possible limiting depths for the deep-drilling fields compared to the spectral-energy distributions of high-redshift star-forming galaxies (left panel) and passively evolving red-sequence galaxies (right panel). The points of the triangles are the depths for the deep-drilling fields, and

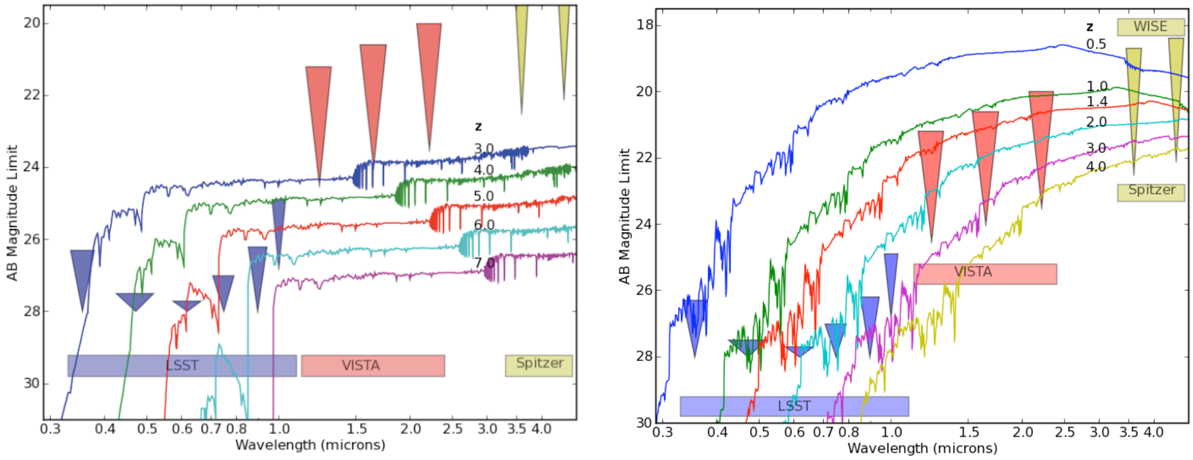

Figure 1: **(a)** Caption for panel a. **(b)** Caption for panel b.

in this example, we have invested significantly more time in the u, z, y filters. For the star-forming galaxies, the main survey is deep enough to reach a L^* out to $z \sim 5$, but identification of Lyman-break galaxies at $z \sim 3$ will be somewhat hampered by the relatively shallow u-band depth of the main survey, to the extent that the $z \sim 4$ samples are likely to probe further down the luminosity function than the $z \sim 3$ samples. For passive galaxies, the deep-drilling fields could in principle provide detections in z and y of L^* passive galaxies out to $z \sim 3$.

The table below lists the co-moving volume enclosed in different redshift ranges for a single deep-drilling field, the age of the universe at the mean redshift of the interval, and the number of galaxies with $L > L^*$. Estimates of the number of galaxies with luminosities $L > L^*$ were computed from the UV luminosity functions of star-forming galaxies given in Oesch et al. 2010 (for $z < 2$), Reddy et al. 2008 (for $2 < z < 3$), and Bouwens et al. (2010) for higher redshifts. For ten deep-drilling fields, the sample sizes are roughly a million galaxies with $L > L^*$ per unit redshift. A y-band depth of AB=26.5 would be required for 5σ detection of L^* galaxies out to $z \sim 6$. Also shown in the table are the stellar masses for galaxies with a number density $n = 2 \times 10^{-4}\mathrm{Mpc}^{-3}$ from Papovich et al. (2011) for $z > 1$ and from van Dokkum et al. (2010) for $z < 1$.

Table 1:

z	Volume (Gpc)	Age (Gyr)	$N(> L^*) \times 10^5$	$\log M_*$
0.1-1	0.03	8.6	0.9	11.4
1-2	0.10	4.2	2.3	11.2
2-3	0.11	2.5	1.2	10.7
3-4	0.11	1.8	1.4	10.3
4-5	0.10	1.3	1.0	9.3
5-6	0.09	1.0	1.3	9.0
6-7	0.08	0.8	0.72	8.7

The capsule summary of these numbers is that one is likely to be moving from samples of order 10^5 to samples of order 10^6 galaxies per unit redshift for fields of this depth, which is comparable to the gain from the 2df redshift survey to SDSS. The larger samples enable higher precision for correlation functions and other meausures of clustering, luminosity functions, and other types of distribution functions or parameter correlations, which are the essential measurements against which theories of galaxy evolution are tested. This is discussed in more detail in the Galaxies chapter of the LSST Science Book.

The high-redshift red-sequence galaxies are interesting as markers of clusters and protoclusters of galaxies. Locally there is about one Coma-like cluster per 0.01 Gpc, which means that a ten deep fields will have roughly one hundred progenitor overdensities per unit redshift. These overdensities may not yet be evolved enough to be identified via the S-Z effect, but the progenitor groups may have well-developed red sequences that can be identified with LSST photometry and confirmed with followup IR photometry and spectroscopy.

Roughly $20-50\%$ of the integrated extragalactic background light arises from the faint outskirts of galaxies, from intergalactic stars (e.g. in groups and clusters of galaxies) and from low-surface-brightness galaxies. Even if such low-surface-brightness populations are old, they can still host type Ia supernovae. Thus looking at the locations of "hostless" type-Ia supernovae in the deep fields should some insight into how the low-surface brightness stellar populations are distributed relative to the denser stellar populations (e.g. is the diffuse light all associated with the halos of bright galaxies and galaxy groups, or is there a large amount of diffuse light in low-density regions?). According to the science book we can expect about 2500 SNe Ia per deep field per year, yielding a sample of 250000 for 10 deep fields over 10 years, which ought to be spectacularly good for statistical studies of faint/invisible hosts.

Conservatively, one could probably expect at least 30,000 Active Galactic Nuclei per deep field, and most of these will be identified as variable in the time-series image subtractions (Science Book AGN chapter). Because the deep fields will have the most complete AGN catalogs and the deepest and likely the highest resolution images of their host galaxies, they will be an important resource for studying the connection between the AGN and their host morphologies, stellar populations, and environment.

For the nearby universe, the LSST deep fields provide the opportunity to study the low-surface-brightness outskirts of galaxies (e.g. tidal tails and fine structure left over from mergers), and also to search for dwarf and LSB galaxies. The volume enclosed out to $z = 0.1$ for 10 deep-drilling fields is 6.3×10^5 Mpc^3. Within this volume there are ~ 4000 galaxies brighter than L^* for which one can search for much fainter extended features than the wide survey. The predicted number of dwarf galaxies is very uncertain, but a straight extrapolation of the Croton et al. (2005) early-type-galaxy LF to $M_V = -8$ would predict $\sim 10^3$ galaxies within 7.5 Mpc. Distances to such galaxies are difficult/impossible to obtain spectroscopically, but can be determined to $\sim 20\%$ precision using surface-brightness fluctuations from the LSST images themselves. This is likely to be the best measurement of the early-type dwarf-galaxy luminosity function, unbiased by whether or not they are satellites of a nearby luminous galaxy.

1.3 Supplementary Science

2 Description of Proposed LSST Observations

2.1 List of Proposed Fields

The proposed deep fields are listed in the table below, in rough order of preference. The first four are in common with the LSS white paper and are probably the best in terms of multi-wavelength coverage.

The VIDEO-1 field is one of the VLT/VISTA infrared-survey pointings and has been observed spectroscopically in the VVDS redshift survey. The ADFS is the Akari Deep Field South, a carefully selected field near the south ecliptic pole.

Table 2: Deep Fields for Galaxies Science

	Field	RA	Dec	l, b	Ecliptic Latitude	$(E(B-V)$ mean (95% range)
1	GOODS-S/ECDF-S	03 32 28	-27 48 26	223, -54	-45	0.010 (0.007-0.016)
2	COSMOS	10 00 24	+02 10 55	236, +42	-9	0.025 (0.018-0.045)
3	UKIDSS/UDS/XMM-LSS	02 21 00	-04 30 00	171, -58	-18	0.025 (0.020-0.033)
4	ELAIS-S1	00 37 48	-44 00 00	311, -72	-43	0.008 (0.006-0.012)
5	SSA22	22 17 30	00 15 00	63, -44	10	0.064
6	Fornax Cluster	03 38 29	-35 27 03	237, -54	-53	0.011 (0.006-0.017)
7	NGC 1068 group	02 42 40	-00 00 48	172, -52	-15	0.034 (0.026-0.051)
8	VIDEO-1/VVDS	14 00 00	05 00 00	342, 62	16	0.028 (0.023-0.034)
9	ADFS	04 41 24	-53 22 12	261, -41	-73	0.004

2.2 Motivation for Proposed Fields

The motivation for the deep fields for distant-galaxy science are well known: we would like fields that have low extinction, low IR cirrus, low $N_{\rm HI}$, low foreground star contamination, and extensive deep multi-wavelength observations. The list above includes the best southern fields, with the only problem being that most of the multiwavelength data is in areas much smaller than 10 square degrees. Nevertheless, these are the fields receiving the most attention and so are the obvious places for LSST to point.

The deep-drilling fields are too small to provide a fair sampling of the overall density field in the nearby universe. It might make sense to put a nearby group or cluster of galaxies in one of the deep-drilling fields, because otherwise there will be nothing at low redshift and high density in the deep-drilling fields. This would benefit both the nearby-galaxy science and transient science and perhaps AGN science. For reference, table 3 provides a list of nearby groups with Galactic Latitude $|b| > 30$ degrees, taken from http://www.atlasoftheuniverse.com/galgrps.html. Perhaps the most interesting are the Sculptor Group, which would be close enough for searching for ultra-faint dwarf galaxies, and the Fornax Cluster, which is the largest overdensity within 20 Mpc in the Southern hemisphere. The Sculptor group subtends an area on the sky much larger than the LSST field of view, and so is probably not an ideal target. The Fornax Cluster is probably better suited for LSST; a single field of view encompasses more than half of the known cluster galaxies, but would miss the outskirts. The field would encompass the Seyfert galaxy NGC1365, which has an active nucleus from which variability has been detected (Fig. 2). Also of potential interest is the NGC1068 group at ~ 14 Mpc, which is close enough to search for dwarf companions and also possibly of interest for dense time-series sampling on the AGN. (Fig. 3).

2.3 Observing Plan, Cadence, Filters, and Expected Depth

Our most important suggestion is to change the balance from the main LSST survey to favor u, z, y. Obviously the depths are a trade with other science. For the galaxies science, reaching $AB = 28$ at 5σ uniformly in all bands would be better than going much deeper in g, r, i. The y, z filters are most important for z $2-3$ red-sequence galaxies and for detecting $z > 5$ Lyman-break galaxies. It is likely that Subaru HyperSuprimeCam will do well in these filters, so some of this ground will already be ploughed. The u band is most important for $z \sim 3$, and perhaps for the low-redshift transients. HyperSuprimeCam will not include u.

2.4 Observation-Time Cost

The calculations below assume 10 deep fields, and assume that these will use 5% of the total survey time. The total survey is estimated to consist of 5.6 million 15-second images (Science Book), so

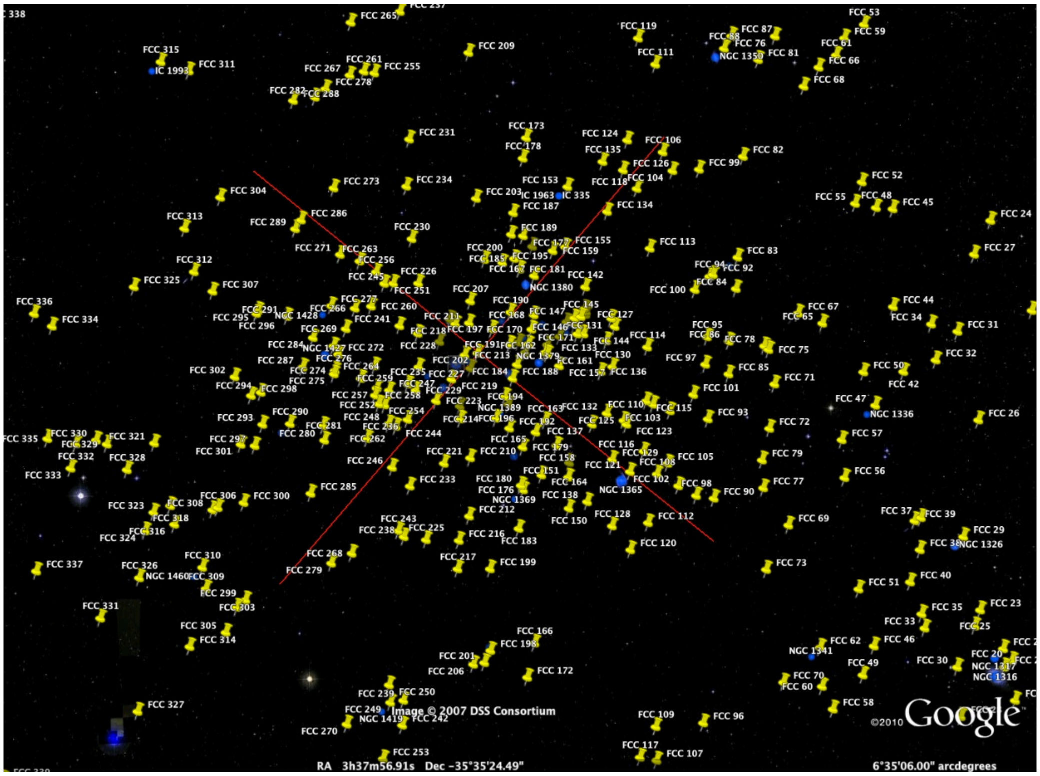

Figure 2: Positions of Fornax Cluster members from Ferguson & Sandage (1990) with the size of the LSST field of view shown via the red lines centered on the central galaxy NGC1399.

5% of that is 280000, giving an allocation of 28000 to each of the 10 deep fields.

In the strawman program below, we propose to go to $AB = 28$ in u, g, r, i, z. Because of crowding, one reaches rapidly diminishing returns trying to go deeper than this, at least for the distant-galaxy science goals. We propose to go to $AB = 27.0$ in the $y4$ band to enable the distant-galaxy science. The required exposure times to reach these limits at 5σ for a point source are shown in the table below, from the LSST exposure time calculator. We have chosen to allow observations out to 7-days from new moon for the redder filters at the expense of some observing time, to maximize the schedulability. The bluer bands should be observed during dark time

Table 3: Required Exposure Times

Band	Limit	Moon	Nexp	Time (s)
u	28.0	3	2281	34215
g	28.0	3	659	9885
r	28.0	3	1040	15600
r	28.0	7	1612	24180
i	28.0	7	3258	48870
z	28.0	7	11658	174870
$y4$	27.0	7	7818	117270
total			28386	

With 50 exposures in each of 4 filters per night, it will take 142 nights to complete each field. For the purpose of the galaxy science, it does not matter how these are scheduled, although it would certainly be preferable to complete the observations on a few of the deep fields early, rather than stretching them all out the full length of the survey.

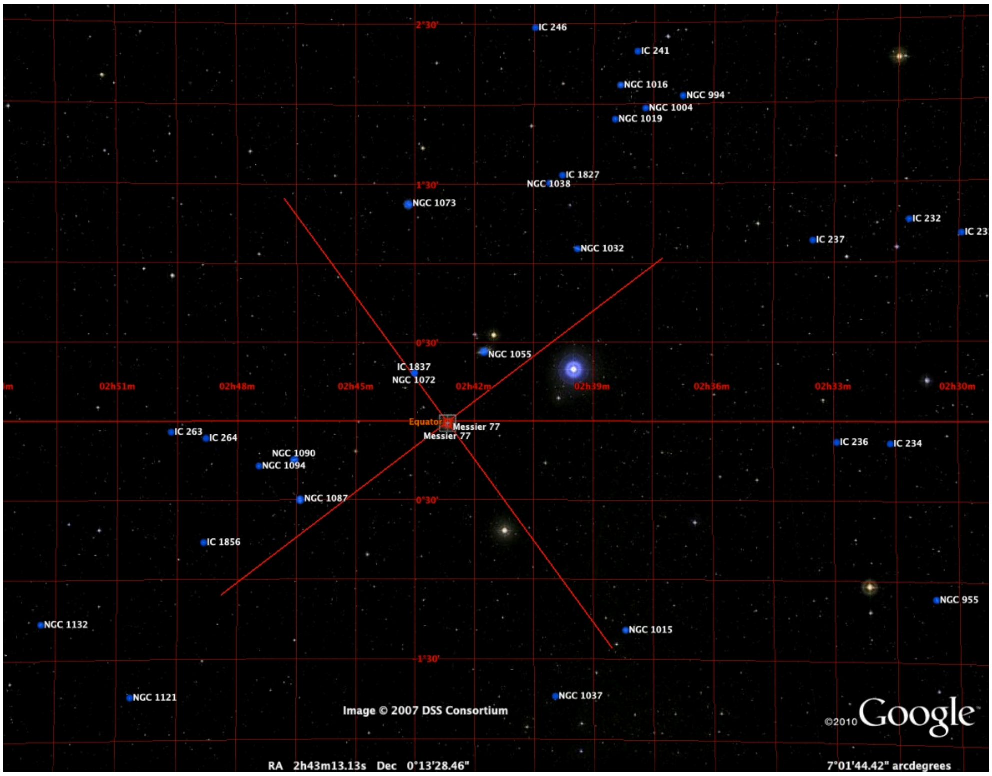

Figure 3: Positions of bright galaxies surrounding NGC1068, with the size of the LSST field of view shown via the red lines.

3 Other Required or Relevant Observations

3.1 Other Required Observations

3.2 Other Relevant Observations

The high-redshift science will rely heavily on multi-wavelength data from other facilities, and would benefit greatly from extensive redshift surveys. A summary of the existing data for the first four fields is given in the LSS white paper (Gawiser et al.) and will not be repeated here. A few notes on the remaining fields are below. A bit more digging needs to be done on some of these.

SSA22:
HST: Deep imaging in one field in uv,g, r, i, y, j, h
Chandra: ?
Spitzer: No
Herschel: No?
Spectroscopy: Fairly extensive over a portion of the field (e.g Steidel)

Fornax Cluster:
HST: Extensive pointed imaging on individual Fornax-Cluster galaxies
Chandra: observations of the cluster
Spitzer: IRAC & MIPS
Herschel: ?
Spectroscopy: Fairly extensive surveys of cluster candidate galaxies

NGC 1068 group:

HST: Images centered on NGC1068 itself. Not much else.
Chandra: Pointed observations at NGC1068
Spitzer: IRAC & MIPS
Herschel: ?

VIDEO-1/VVDS:
HST: No
Chandra: ?
Spitzer: No
Herschel: Hermes survey

ADFS: HST: No
Chandra: ?
Spitzer: IRAC(?) & MIPS
Herschel: Hermes survey
Akari: Deep field

4 Specific Needs for LSST and for Deep Drilling

4.1 Need for LSST

As mentioned earlier, the expectation deep fields to about the same depth over the area of one or two LSST deep fields will be available prior to LSST. At the moment, there does not appear to be a facility on the horizon that would provide the deep u band imaging, and it is somewhat unlikely that the y band depth proposed here will be achieved before LSST. Other than that, the main advantage is an order of magnitude gain in area.

4.2 Need for Deep Drilling

The science goals outlined above are those for which the main survey is insufficiently deep, by definition.

5 Feasibility

5.1 General Feasibility

5.2 Bright Objects and Extinction

These are all low-extinction, high Galactic Latitude fields. We have not yet evaluated the variation of foreground extinction across the fields. It is unlikely that this would be a deciding factor for the galaxy science described above.

5.3 Unresolved Feasibility Issues

6 Other Issues

6.1 Relevance to LSST Commissioning

It will be very important to observe one field to the final deep-field depths during commissioning or the first year thereafter. This will provide an assessment of the final depth and image quality for the full survey, and an investment of 10% of the time. This is both early science and a sensible insurance policy.

6.2 Other Relevant Information

7 References Cited

Ferguson, H. C. & Sandage, A., 1990, AJ, 100, 1.

Oesch, P., et al., 2010, ApJ, 725, 150

Reddy, N., 2008, ApJS, 175, 48

Bouwens, R. , 2010, astro-ph/1006.4360

Papovich, C. , 2010, astro-ph/1007.4554

van Dokkum, P. , 2010, ApJ, 709, 1010

Croton, D. 2005, MNRAS, 356, 1155

Table 4: Nearby Groups of Galaxies

Group	RA	Dec	N gal	RV (km/s)	D (Mpc)	*l*	*b*
Sculptor	00:36	-31.0	8	177	2.8	343	-84
NGC45	00:13	-23.4	3	503	6.1	54	-80
NGC3115	10:05	-7.7	3	494	9.2	247	36
NGC1800	05:09	-32.2	3	717	10.7	234	-34
NGC7713	23:36	-36.9	3	690	10.7	356	-71
NGC1792	05:07	-37.7	4	939	15.3	241	-36
NGC4546	12:36	-4.1	3	949	15.3	295	58
NGC4594	12:40	-11.1	8	957	15.3	298	51
NGC4666	12:45	-1.2	4	1485	15.3	299	61
NGC4179	12:11	+2.0	3	1188	16.9	280	63
NGC4697	12:53	-7.4	25	1191	16.9	303	55
NGC4753	12:55	+0.6	9	1084	16.9	304	63
NGC4856	13:04	-15.4	4	1182	16.9	307	47
NGC1097	02:45	-29.7	3	1229	18.4	225	-64
NGC1433	03:51	-46.3	10	916	18.4	253	-49
NGC1947	05:27	-64.1	3	1012	18.4	273	-33
NGC7424	23:00	-40.8	4	1008	18.4	354	-63
Dorado	04:18	-55.8	19	1000	19.9	265	-43
Fornax I	03:32	-35.5	49	1446	19.9	236	-54
NGC1052	02:40	-8.1	9	1438	19.9	181	-58
NGC1672	04:49	-59.4	4	1161	19.9	268	-38
NGC908	02:23	-21.0	6	1495	19.9	201	-68
NGC1068	02:43	+0.3	6	1126	21.5	171	-51
NGC1532	04:13	-32.4	3	1124	21.5	232	-46
NGC3166	10:14	+3.4	3	1127	21.5	238	45
NGC3585	11:13	-26.8	3	1203	21.5	277	31
NGC4038	12:00	-19.0	14	1502	21.5	286	42
NGC5364	13:55	+5.0	5	1185	21.5	340	63
NGC936	02:28	-1.2	4	1393	21.5	168	-55
NGC3923	11:50	-28.8	7	1497	24.5	287	32
NGC4643	12:43	+1.8	3	1292	24.5	298	64
NGC5566	14:21	+3.6	5	1511	24.5	349	58
Eridanus	03:34	-21.5	34	1533	26.1	213	-52
NGC3640	11:21	+3.3	5	1273	26.1	256	57