4. The CFHTLS Wide Synoptic Survey

The CFHTLS wide survey is based on u,g,r,i and z observations of three uncorrelated fields, with exposure times of about one hour per field, covering 8x9 , 7x7 and 7x7 deg$^2$ respectively. The main scientific goals are cosmic shear, clusters of galaxies and galaxy dynamics with stellar proper motions. Its design also provides to the CFHTLS wide a very high legacy value and several new wide survey follow up started over the past year. Important scientific results, for example in the cosmic shear survey, have already been obtained that demonstrate the feasibility and the considerable interest of the science drivers, putting the CFHTLS wide in a unique position with respect to competition. The survey will keep its promising scientific potential only if its size is not cut and if each field is observed in all filters. 

Due to technical problems and the fact that CFHTLS wide survey goals do not demands time constraints, wide observations are often put in low priority or have been delayed and the data rate has been much slower than expected. As it stands, the data flow will never keep the CFHTLS wide in position to achieve its scientific goals in the expected time scale and competing surveys may make up for their lost soon. To avoid this situation, we propose a survey strategy that takes into account the needs of all science drivers. Three scenarios are presented in this report. They are all based on a scheme that organizes observations as function of filters: the $i$, $r/2$ and $g$ observations have the highest priorities, then the $z/2$ and $u^*/2$ observations, and eventually the remaining $z/2$, $u^*/2$. The pre-survey is postponed to the end of the survey and the $r/2$ observations keep going until the very end of the survey in order to cover the whole field on the largest time baseline for proper motions. The total amount of hours is kept to 927 hrs for each strategy, only the time-scale organization changes, that is the amount of allocated hours per semester and the length of the survey. We believe however, that the fastest survey strategy (see the “best scenario” presented on Table 6) is indeed the best to keep the competitiveness of each survey component and the persons involved motivated and funded accordingly, and to provide as fast as possible wide data to CFHTLS and non-CFHTLS registered users that are willing to start CFHTLS follow up.

4.1. Wide Synoptic Status and Future Planning

4.1.1. Wide Synoptic Survey Design

The Wide Survey has been designed to meet the data requirements of its scientific components. Four main drivers have been identified at the time of the survey definition:

- Cosmic shear
- Galaxy clusters
- Galactic studies
To this list must be added the Legacy dimension of the CFHTLS. It was hoped that new applications of the data would appear during the course of the survey.

4.1.1.1. Cosmic Shear requirements
The science based on the cosmic shear measurement aims at determining the properties and evolution with look-back time of the power spectrum of the dark matter. The five main requirements (see the cosmic shear section, 4.2.1) are:

1) Depth of $i=24.5$ with good photometry and shape measurements, i.e. a S/N larger than 12.
2) Image quality better than 0.9” in order to allow for the measurements of
3) Contiguous area larger or equal to 7º x 7º in each field in order to probe the power spectrum at scales larger than $l = 20$ and to constrain several cosmological parameters and dark energy properties (see the cosmic shear report)
4) Total effective (i.e. accounting for 20% of loss due to bright stars and defects) area of at least 130 square degree spread over 3 fields to cross check the cosmic shear signal in case there are disagreements between two fields.
5) Color information to produce photometric redshifts in order to separate the sources.

4.1.1.2. Galaxy Cluster requirements
The aim of the Wide Synoptic galaxy cluster component is to measure the cluster number counts, luminosity and correlation function and their evolution out to $z=1$. This allows for placing strong constraints on cosmological parameters. The 3 main requirements (see the cluster section) are:

1) At least 4 colors: $g$, $r$, $i$ and $z$ at a depth allowing for the detection of galaxies two magnitudes fainter than bright cluster elliptical at any redshift out to $z=1$. These filters constrain the position of the 4000Å break in early-type galaxies from redshift $z=0.0$ out to $z = 1.1$. This results in the following depths: $z = 24.4$, $i=25.5$, $r=25.9$, $g=26.6$
2) Contiguous area of at least $10º\times10º$ in one field to probe the super-cluster scale of $100h^{-1}\text{Mpc}$ at redshift unity (corresponding to $4º$) and at least $6º\times6º$ in the other fields.
3) X-ray coverage of one of the fields to compare X-ray and optical cluster selection and assess the completeness of the optical catalogs.

4.1.1.3. Galactic Studies requirements
The aim of galactic studies in the Wide Synoptic is to search for white dwarfs that could contribute a significant fraction of the dark matter in the Galaxy, to search for brown dwarfs, and to constraint population models of the Galaxy. The 2 main requirements for Galactic studies (see the stellar science section) are:

1) Two epochs of observation separated by at least 3 years in the $r$ band to select stars from their proper motions.
2) At least 4 colors: g, r, i, z

4.1.1.4. Wide Survey requirements

The requirements of the four main scientific drivers have been merged in the following requirements:

1) 4 fields covering a total area of 208 square degree, with 3 7°x7° fields and a 9°x8° field.
2) An image quality better than 0.9"
3) 5 filters reaching the following depth (AB magnitude for a point source detected at a S/N of 5, with 0.8" seeing):
   a. u* = 26.4
   b. g = 26.6
   c. r = 25.9
   d. i = 25.5
   e. z = 24.8
4) two epochs in r band separated by 3 years
5) a shallow pre-survey in r band designed to rigidify the astrometric and photometric solutions across an entire wide field and strengthen the legacy value of the survey.

These requirements allow for attaining the scientific goals of each scientific component of the Wide Survey.

4.1.1.5. Wide Survey Allocation and Implementation

The Wide component of the Canada France Hawaii Telescope Legacy Survey has been awarded a total of 162 nights with seeing better than 0.9" over 10 semesters, following the CFHT Board of Directors (hereafter BoD) decision of December 2001 (see [http://www.cfht.hawaii.edu/Science/SAC/Nov01/Board_2001.html](http://www.cfht.hawaii.edu/Science/SAC/Nov01/Board_2001.html)) and the recommendation of the Scientific Advisory Committee (hereafter SAC, recommendation #8 in the report of the 61st SAC meeting, (see [http://www.cfht.hawaii.edu/Science/SAC/May02/report.html](http://www.cfht.hawaii.edu/Science/SAC/May02/report.html)). This amounts to 34% of the total CFHTLS time, with the Deep component being awarded 210 nights (44%) and the Very Wide 102 nights (22%).

To accommodate the reduction of the time awarded to the Wide Survey with respect to the requested allocation, and following the SAC recommendation, the CFHTLS Steering Group decided in early 2003 to reduce the area of the Wide Survey to 3 fields, covering a total of 170 square degrees and to preserve the 5 bands of the survey at the requested depth.

The three Wide Survey fields have been pre-selected in a sample of targets that have low extinction amplitude and small extinction fluctuation over the total fields (difficult for very large sky areas), a visibility spread over the two semesters, that are visible from
southern ESO/VLT telescopes (for a fraction of them) and, for a fraction of them, that are part of ongoing surveys with other observatories (legacy value). Note that we did not impose that all targets are already surveyed by other telescopes. This flexibility allows us to avoid observing periods that are strongly oversubscribed by CFHT follow up carried out by PI programs or other agencies having access to CFHT (this issue turned out to be a critical point for the genuine visibility of W1 fields).

The final selected fields are:

- **W1**: field centered at $\alpha = 02:18:00.0$, $\delta = -07:00:00$ (J2000) with an area of 9ºx8º. This field covers partially the XMM-LSS that provides X-ray coverage. The overlap is not complete because of the presence of a bright star (Mira Ceti) in the Northern region of XMM-LSS that had to be avoided for the MegaCam observations. The D1 deep field is encompassed by the W1, and both are parts of the GALEX deep and wide UV survey. The W1 field also overlaps with the ESO/VLT VVDS spectroscopic redshift survey that will provide unique redshift samples of $i=22.5$, $i=24$ and (for a very small fraction) $i=26$ galaxies, over a very large field. They will be used to constrain the redshift distribution of sources and to calibrate photometric redshifts.

- **W2**: field centered at $\alpha = 08:54:00.0$, $\delta = -04:15:00$ (J2000) with an area of 7ºx7º. This field was selected in order to match the visibility criterion, the low extinction and small extinction fluctuation and the oversubscription constraint. At the beginning of the survey, W2 offered the option to have a target in a sky region where almost no other surveys was carried out. The COSMOS survey is now very close, keeping oversubscription high in this region. However, it does not overlap. So, we expect to use the COSMOS data jointly with CFHTLS Wide and Deep for cosmic shear studies, when these data will be public.

- **W3**: field centered at $\alpha = 14:17:54.0$, $\delta = +54:30:31$ (J2000) with an area of 7ºx7º centered on the Groth strip. Hence a large HST galaxy sample is available in this region. This field has the smallest extinction amplitude and extinction fluctuation of all wide targets. It is visible from GEMINI North and is part of on going DEEP2 spectroscopy surveys. Its position matches well the visibility criterion with respect to W1 and W2.
Table 1 presents the total integration time per wide synoptic pointing and the resulting depth, according to the exposure time calculator. The total integration time on the 170 square degree of the Wide synoptic is of 1038.9 hours, or 159.8 nights, assuming 6.5 hours of integration time per night of MegaCam run. The pre-survey requires 38.7 hours or 5.9 nights. The total amount is of 165.8 nights, that is 3.8 nights in excess of the allocation (or 2% of the allocation, well within the uncertainties of the QSO efficiency).

4.1.1.6. The Night versus QSO Hours allocation problem

The BoD and SAC allocation has been made in terms of nights. The scheduling at the CFHT level (QSO) is made in hours. During the preparation of the survey, a factor of 6.5 hours of science exposure per MegaCam night has been assumed. This factor takes into account the overheads of the observations (including the calibration) and the weather.

Moreover, the BoD and SAC allocation were understood by the Steering Group as being an “open shutter, scientific validated exposure time” while the QSO accounts for a 40s overhead per exposure. While a 40s seems to be a small hit, it is in fact a very significant hit given the large number of exposure that the Wide Synoptic entails. This is especially the case for the pre-survey because of its short exposures, and in u* and z for the survey itself, where the single exposure time had to be reduced to 600s and therefore the number of exposures had to be increased (see table 1, the Proposed Dither and Observed Dither rows). The survey is being charged by CFHT the amount of time appearing on the Accounted Time in table 1, while the survey was designed using the Exposure Time. This results in an increase of the time necessary to complete the survey of 80.4 hours or 12.4 nights. The total amount of QSO accounted time necessary to complete the survey is 178.2 nights, 10% in excess of its allocation of 162 nights. This percentage is bound to increase if the QSO efficiency is below 6.5 hours per night.
4.1.2. Wide Survey Progress
The CFHTLS has begun on May 30th 2003, during the last Queue Run of the semester 03A. During this first year and half of the survey, the MegaPrime/MegaCam system has come into a mature instrument.

4.1.2.1. The Image Quality Problem
It was soon realized after the operations with MegaPrime/MegaCam started that the image quality delivered by the system was worse than its specifications. Since image quality (IQ) is a critical factor for the success of the cosmic shear component of the Wide, the TERAPIX team has dedicated a lot of effort in assessing the impact of the IQ on their science, and in providing quick analysis of the PSF size, ellipticity and of their variations across the field as the instrument team was adjusting the Wide Field Corrector (WFC) setup.

The analysis of the data before the L3 flip gave the following results that are detailed in the Cosmic Shear section (4.2.2.1):

1) The best configuration obtained led to a loss of 11% of the field usable for weak lensing studies because the PSF ellipticity was too high to recover a 1% amplitude lensing signal with a 10% relative accuracy.
2) When the 11% lost due to optical distortion is combined with the area lost to bright stars, the final effective area of the survey would be 120 square degrees, below the minimum requirement of 130 square degrees.
3) As the instrument team was investigating the IQ, the PSF was very unstable during a QSO run and between runs, making the correction of the PSF anisotropies difficult.

Given this situation, the Wide coordinators had decided to begin the survey at a reduced pace, expecting that CFHT would solve this issue. This has indeed been the case, when it was found out in semester 04B that a flip the L3 lens of the WFC did improve the IQ of the data. The situation after the L3 flip is the following (see 4.2.2.1):

1) The average seeing in the MegaPrime/MegaCam data has improved by 0.1 to 0.2′′
2) The PSF anisotropy has improved, and 93% of the instrument field is now useful for weak lensing studies.
3) When combined with the area lost to bright stars and with the area already observed in the previous WFC configuration, the effective area of the Wide survey for cosmic shear studies is now of 130 square degree, equal to the minimum requirement of this scientific driver.
4) The PSF anisotropy is now more stable and uniform, allowing for a better and more homogeneous correction of its effect over the whole field.
5) The requirements on the seeing have to be reduced from 0.9″ to 1.0″.

Given these results, we consider that the decision to hold back the pace of the Wide Synoptic survey during the first three semesters was justified, since the effective total area would have been smaller than the minimum requirements for cosmic shear studies if we had proceeded to the normal pace. Now that the system delivers data that allows for these studies to be made, we expect that the Wide Synoptic Survey will ramp up to obtain its full share of the CFHTLS time.
4.1.2.2. Semesters 03B-04A-04B

Our goals during the first semesters of the survey have been:

1) To start the gathering of data in order to assess the feasibility of the various scientific goals of the survey.
2) To ensure that the IQ in the complete survey would ensure its scientific returns.
3) To ensure that data on specific portions of the survey were acquired in a timely fashion in order to preserve the scientific edge of the CFHTLS.

Point 2. is somewhat contradictory with points 1. and 3. Given the IQ problem discussed above, if too much data whose quality is below the scientific requirements of the survey is collected, the final coverage will not allow for the completion of the Cosmic Shear program. It was therefore deemed important to reduce the speed of the data gathering with respect to the initial plan, in order to wait for a solution. Such a solution has been found during semester 04B with the flip of the L3 lens of the WFC.

Meanwhile, it was important for some components of the survey to have some coverage of part of the fields quickly in order not to hold back important scientific outputs of the CFHTLS. This was especially the case in the W1 field that has already been partly covered in X-ray by the XMM-LSS survey, and in the infrared by the Spitzer SWIRE legacy survey. The French component of this legacy (Pierre et al.) was eagerly expecting the Wide data in order to proceed to the identification of the IR sources for their spectroscopic followup.

It was therefore decided to provide a full coverage of the SWIRE area of W1 in the 5 bands during semester 04B, despite the fact that the IQ was not yet within the specifications. The coverage of the 3 Wide fields at the end of semester 04B is given on figure 1.

As expected, the W1 field has obtained the best coverage, where the SWIRE Spitzer area has been observed in u*, g, r, i, z, with half the final survey exposure time in u* and r (because one epoch has so far been obtained for the latest), and the full final depth in g, i, and z.

The W3 field has received some coverage in g, r and i, allowing for a contiguous area of 12 square degrees for weak shear studies.

The W2 field as so far not received enough coverage for useful studies. This field is visible in winter and has suffered a lot of the bad weather that has prevailed in 04A, and has been mostly observed in the pre-survey configuration that is less demanding in terms of IQ.

One important aspect of the Wide strategy is to provide contiguous coverage. For example, the data collected on W2 at pointing w2.-1+3 or on W3 on pointing w3.-3-1 cannot be used for the assessment of the feasibility of the Cosmic Shear program, where an important aspect is to calibrate the photometry and PSF anisotropy on scales larger than the MegaCam field. These data were obtained during the first two semester. During the course of 04B, the interface between the QSO team and the Steering Group has been noticeably improved as priorities are provided to the QSO on a run to run basis by the survey coordinators. This has led to avoid any more problems with non contiguous pointings.
As of the end of 04B, it is now possible to test the feasibility of the Cosmic Shear program, and to start the identification of the clusters in the XMM-LSS/SWIRE area. The results of these tests are positive, as illustrated in the Cosmic Shear section where the weak lensing signal is detected up to scales of 2.5º with negligible B modes (see 4.2.3.2). Various algorithms for the detection of clusters have been implemented using the Deep data (see Cluster section, 4.3.4.1) and will be applied to W1 as soon as this data are released to the community (release T0002).

Figure 1. Status of the coverage of the CFHTLS Wide Synoptic survey at the end of semester 04B. Each pointing of the survey is drawn in black, the pre-survey pointings are outlined in dashed line. Observed pre-survey pointings are shaded in grey. For each survey pointing, a vertical line shows the amount of data that has been collected in each filter, with the following color code: u in cyan, g in blue, r in green, i in red and z in purple. The height of the bar indicates the fraction of data collected. For example, the r bar (green) cover only half the pointings, as only the first epoch of data has been collected. The dashed red area in W1 (a) shows the coverage of the SWIRE Spitzer observations.
4.1.2.3. Semester 05A

With the flip of the L3 lens of the WFC, the MegaPrime/MegaCam system now delivers data that allow for attaining the Wide Synoptic Survey goals. There is no reason to hold back the Wide scheduling anymore, and the observations of the survey should resume to their normal pace. This has been agreed within the Steering Group where it was decided that each of the survey component would receive their nominal share in 05A. Assuming an efficiency of 4.7 hours per night, and 50 nights of CFHTLS observations, we can reasonably expect to gather 80.0 hours of data for the Wide component.

The scheduling of the semester 05A observations has been made with the following constraints:

1) The area coverage needs to increase fast for the Cosmic Shear science.
2) If the survey ends in 08A (nominal duration of the survey), we need to finish gathering the first epoch of r band data before the end of 06A. This calls for fast area coverage in r.
3) u and z band data is needed for galaxy and clusters studies.

Point 3 is in conflict with points 1 and 2. This is clearly seen in table 1 where the amount of time needed to cover a Wide pointing in both g, r/2 and i is 2.3 hours, against 1.8 hours in u* and 2.1 in z (the notation r/2 signify that half the final exposure time in r is gathered). After consultation with the user base of the CFHTLS (cfhtls-w mailing list), we decided to schedule 42.75 hrs on W3 to gather g, r/2 and i only, hence covering a large area, and 37.25 hours in u*/2, g, r/2, i, z/2 on W2. Moreover, a pointing in W2 (w2.+2+2) will receive its full depth in u* and z.

The expected coverage in each of the fields is plotted on figure 2, to be compared to their actual coverage in figure 1. By the end of 05A, we expect about 28 square degrees will be available for weak lensing studies in W3 and 13 in W2, while 13 square degrees in W2 will be available for clusters studies, although with shallower depth in u* and z.
4.1.3. Wide Survey Future Scheduling

4.1.3.1. The Queue Efficiency Problem

In the course of the semesters 03B, 04A and 04B, a critical problem has arisen that can potentially endanger the whole CFHTLS. While the survey was designed with an expected efficiency of 6.5 hours per night (see sections 4.1.1.5 and 4.1.1.6.), the actual efficiency of the observations has proved much smaller.

This is illustrated in table 2 taken from the wide report, where various quantities relevant to this topic have been compiled on a semester per semester basis. The efficiency derived in row 3 is only of 4.3 hours per QSO night. This number is in agreement with the numbers derived by the QSO team (see slide 17 at http://TERAPIX.iap.fr/cplt/oldSite/SlidesAll/CFHTLS040205/Cuillandre040205.pdf).

Starting with a night of 9.5 hours, and after losing 20% to weather, 10% to technical problems, a further 15% to out of specifications conditions and a further 2 hours to overheads (not counting the readout since they are charged to the survey), we are left with $9.0 \times 0.70 \times 0.85 - 2.0 = 3.6$ hours. An efficiency of 4.3 hours per night represents a loss of 35% of the allocation of the CFHTLS.

It is interesting to note that the QSO report for 04B (section C.1 last bullet of the remarks, see http://www.cfht.hawaii.edu/Instruments/Queue/2004b_report.html) mention a goal of 6.0 hours per night of observed time, i.e. a time that contains all the instrument calibrations and overheads. This is clearly in contradiction with the value of 6.5 hours per night for validated science open shutter time that was adopted for the survey definition.

The CFHT is trying to improve the efficiency of the system, but according to CFHT (see the CFHT report) there is little room for large improvement in the current design. About one hour might be gained with the implementation of the autofocus and by using a set of tertiary standards in the CFHTLS fields themselves. If these modifications are successful, the CFHTLS operation team and the Steering Group feel that a realistic achievable efficiency is of 5.0 hours per night. This corresponds to a loss of 23% of the allocation of the CFHTLS. The initial allocation of 474 nights for the CFHTLS could be obtained by either:

1) Extend the duration of the CFHTLS over 14 semesters.
2) Increase the fraction of time of the CFHTLS from 50% to 73% of the MegaCam time.

The other alternative consisting in revising the CFHTLS allocation to the effective time observed using 50% of the nights over 10 semester would lead to the descoping of part of the survey amounting to 26% of its original allocation.

The total CFHTLS allocation is of 474 nights or 3081 hours, assuming the 6.5 hours per night factor. This corresponds to 308.1 hours per semester. The accumulated balance of the CFHTLS at the end of 04B is therefore of $158.5 + 122.4 + 247.0 - 3 \times 308.1 = -396.4$
hours. The amount of time remaining to be observed at the start of 05A is of 2553.1 hours. If the share of the CFHTLS is maintained to 50% of the dark and grey time (option 1), or 50 nights a semester, and using an efficiency of 5.0 hours per night, this can be observed in \( \frac{2553.1}{50 \times 5.0} = 10.2 \) semesters. This would bring the total duration of the survey to 13.2 semesters, until the end of semester 10A.

Keeping the duration of the legacy survey at 10 semesters (option 2) would require allocating \( \frac{2553.1}{5.0 / 7.0} = 73 \) nights per semester to the CFHTLS.

<table>
<thead>
<tr>
<th>1 Semester</th>
<th>03B</th>
<th>04A</th>
<th>04B</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Number of QSO nights (^a)</td>
<td>104,0</td>
<td>118,0</td>
<td>116,0</td>
</tr>
<tr>
<td>3 Total Validated Exposure Time (hrs) (^a)</td>
<td>340,0</td>
<td>282,0</td>
<td>500,4</td>
</tr>
<tr>
<td>4 Queue Efficiency (hrs/night) (^b)</td>
<td>3,3</td>
<td>2,4</td>
<td>4,3</td>
</tr>
<tr>
<td>5 CFHTLS Validated (hrs) (^c)</td>
<td>158,5</td>
<td>122,4</td>
<td>247,0</td>
</tr>
<tr>
<td>6 CFHTLS Allocated fraction (^d)</td>
<td>45,0%</td>
<td>44,0%</td>
<td>50,3%</td>
</tr>
<tr>
<td>7 CFHTLS Validated fraction (^e)</td>
<td>46,6%</td>
<td>43,4%</td>
<td>49,4%</td>
</tr>
<tr>
<td>8 Wide Survey Validated (hrs) (^c)</td>
<td>42,4</td>
<td>19,3</td>
<td>66,1</td>
</tr>
<tr>
<td>9 Fraction of Wide w/r CFHTLS</td>
<td>26,8%</td>
<td>15,8%</td>
<td>26,8%</td>
</tr>
<tr>
<td>10 Balance of Wide w/r other components (hrs) (^f)</td>
<td>-11,5</td>
<td>-22,3</td>
<td>-17,9</td>
</tr>
<tr>
<td>11 Balance of Wide w/r to its allocation (hrs) (^g)</td>
<td>-61,0</td>
<td>-95,4</td>
<td>-62,8</td>
</tr>
</tbody>
</table>

Table 2: Queue Efficiency and CFHTLS Wide progress per semester.

Notes:
- \(^b\): equal \((3) / (2)\)
- \(^e\): equal to \((5) / (3)\)
- \(^f\): equal to \((8) – 34\% \times (5)\)
- \(^g\): equal to \((8) - (2) \times 6.5 \times (6)\)

### 4.1.3.2. The Queue Efficiency Problem for the Wide

The Queue Efficiency problem is critical for the Wide survey, because it is already late with respect to the other components. Given the problem of the IQ, the wide coordinators have not pressured the SG to obtain 34% of the time during the first three semesters. As a result, the cumulated deficit of the Wide at the end of 04B is of 51.7 hours with respect to the time that the CFHTLS has effectively obtained (row 10 of table 2). The cumulated deficit over the same period with respect to what its allocation should have been is of 219.2 hours. These numbers have to be compared to the expected allocation of the Wide during a semester that amounts to 162 x 6.5 / 10=105.3 hours.
After 3 semesters, the deficit of the Wide survey amounts to 2 semesters. Now that the IQ problem is solved with the L3 lens flip, the Wide Survey is expecting to obtain its full allocation over the remaining of the survey. This means that the wide has to get its full 34% survey fraction, at least, and must define an optimal strategy that prioritizes the primary science goals over the next semesters that preserves their competitiveness in front of other on going or planned surveys.

4.1.3.3. Scenarii for the future of the Wide Survey

We have investigated possible scenarii for the Wide Synoptic. These are based on the following sets of requirements:

1) The area of the Wide survey cannot be reduced below the present 170 square degree, because its effective area is already very close to the minimum area for the Cosmic Shear program (see 4.2.4).
2) The two epochs of r band observations must be preserved in order to be able to perform the Galactic science program (see 4.4).
3) The g, r, and i band depth are needed by all programs to perform their science.
4) Some programs can still perform their science with a loss of 0.5 magnitude in u* and z.
5) The pre-survey in r is required by all programs to ensure the proper astrometric and photometric calibration across the entire fields. It is a full part of the Legacy Value of the survey. Note that these exposures can also be useful for stellar proper motion studies since they are all done in r-band and provide a third epoch.

Based on these assumptions, we can compute the duration in hours of the Wide Synoptic under a set of possible hypothesis, were the integration time is reduced to half the initial schedule in u and/or z in some or all of the fields. The results are displayed on table 3. The thick lines of the table delineate sets of hypothesis where:
- the full scientific program can be done (A)
- all the main scientific drivers can still be completed (B-M)
- some main scientific drivers will not be possible (N-S)

A second issue is the need of obtaining the data in timely manner if the scientific components are to keep their edge over competing projects. It is important to note that the Wide Synoptic survey has no time constraint in its observations, except in the r band where the two epochs have to be separated by at least 3 years. Therefore we can predict accurately how long it will take for us to complete the program to a given level, since our observing time does not depend on the possible loss of an epoch that needs to be recovered. This is clearly an advantage in terms of planning, but it is a disadvantage in terms of execution, since time critical observations of the SNLS Deep and Very Wide have so far often taken the precedence over the Wide observations. The main parameter playing a role in the relative competition of the three CFHTLS components is the amount of time dedicated to the survey per semester. The less the pressure between the three components, the easiest it is for the Wide to advance rapidly toward completion. This amount of time is in turn governed by two parameters:
- The fraction of time allocated to the CFHTLS with respect to PI programs
- The Queue efficiency
If the time fraction and the queue efficiency remain the same as the one of semester 04B, we can expect at least 65 hrs of observation per semester for the Wide (see table 2, row 8). Under this assumption, and given the priority to quickly obtain full coverage in g and i for the cosmic shear (see 4.2.4), a first epoch in r (see 4.4) but also a good coverage in z on W1 (see 4.3.3) we can produce a first minimal scenario described in table 4, where a tentative schedule of the remaining 927 hours required to complete the survey has been laid down. This is indeed a bare minimum! Where none of the reduced main objective (hypothesis M in table 3. With u/2 and z/2) is completed before 2009B, one year and a half after the nominal end of the survey. If the survey were to finish in 08A, only z/2 could be gathered on W2 and W3, half of it missing on W1 in contradiction to the clusters requirements. Moreover, no u band would be gathered. We would have only the u/2 data already obtained in W1 (see 4.1.2.2), and we could not meet the minimum photometric redshift requirements of the Cosmic Shear program (see 4.2.4). Note also that in order to complete the whole Wide Synoptic Survey in 2010A, a large allocation of time is requested for the wide on semesters 09A, 09B and 10A, after the completion of the SNLS Deep program.

<table>
<thead>
<tr>
<th>H</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
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Table 3. Duration of the Wide Synoptic Survey in hours, depending on the amount of exposure time in the u and z filter per field. If data has already been acquired on a field beyond the hypothesis limit, their exposures have been added to the final sum. For example, 11 square degrees in W1 have full z coverage already. In the hypothesis were W1 were to receive only z/2 (hypothesis F, G, L and M) the time already used to gather the remaining half of the z band on these pointings has been added to the final total.
time do take into account the scheduled observations of semester 05A for 85 hrs that contain a significant amount on time on W2 in u and z (26 hrs, see 4.1.2.3).

The situation described in the “Minimal” scenario of table 4, is disastrous for all scientific components of the Wide survey. In order to mitigate it, more time per semester must be allocated to the CFHTLS. A first step in this direction is our “Average” scenario described in table 5., where we assume that the Wide Synoptic can use 20 supplementary hours per semester. This is possible for example if the QSO efficiency rises to 5.0 hours per night, assuming 110 nights of MegaCam per semester and a CFHTLS share of 52%.

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Table 4. Minimal Scenario for the Wide Synoptic Survey completion. Each cell list the amount of hours spent per semester on each field for a given goal. The various goals are prioritized as obtaining the full g and i coverage plus the first epoch in r (first 3 rows, denoted g, r/2, i), then half the exposure time in z (denoted z/2), then half the exposure time in u (u/2), then the full z band coverage (z), the full u band coverage (u) and finally the second epoch of r (r) and the pre-survey. At the end of semester 05A, the amount of observing time (taking into account the 40 seconds readout per frame) required to complete fully the Wide is of 927 hrs (last column). A given goal on a given field is highlighted in red when no observation has been taken, in green while A Queue observations are in progress and in blue once they are completed.
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Table 5. Average Scenario for the Wide Synoptic survey completion. Legend is the same as table 4., with additional B queue time highlighted in yellow.

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Table 6. Best Scenario for the Wide Synoptic survey completion. Legend as table 5.
In order to show the effect of these supplemental 20 hours, we have noted them as “B Queue” and highlighted in yellow in table 5. However, the validity of this scenario supposes that 100% of this “CFHTLS B Queue” will be observed, and not 65% as for the PI B queue program. These B queue is to be understood as a lower ranking than the time critical observations of the other components of the CFHTLS.

The benefits for the Wide Synoptic survey are immediate: this gives 140 hrs spread on semesters 05B to 08B. The minimum hypothesis M (u/2, z/2) can be attained in semester 08B, one semester later than the CFHTLS original design. Note however that if this minimal hypothesis were to be retained, 22 more hours would be required in semester 09B to obtain the second epoch of the r band. This is mandatory for the galactic science case.

The coverage at full depth of all the fields in u and z is possible if the time awarded to the Wide component increase in semesters after semester 08B, once the SNLS survey has been completed.

Finally, increasing the share of the CFHTLS with respect to PI programs to its maximum of 60% allowed by the BoD would relieve even more the pressure on the Wide Synoptic. We compute that 40 hours per semester would be available as CFHTLS B Queue. This “Best” scenario is described in table 6. And would allow critical scientific research to be performed in a timely manner. By semester 07B, all the minimum requirements for Cosmic Shear and high-z cluster would be met. The survey could be completed in semester 09B with a small ramp down during the last 2 semesters.

### 4.1.4 Scientific Return of the Wide Synoptic

Before examining the current scientific return of the Wide Synoptic survey, an important caveat must be kept in mind: at the time of the writing of this report, no release (image and catalogue) has been delivered to the CFHTLS community on the Wide. The first data release containing Wide data will be T0002. The results regarding wide data come from image processing done by teams that may have used TERAPIX weight map and flag map images sent to CADC (step1 of TERAPIX processing; see the TERAPIX report), but not TERAPIX stacks of wide data. Yet, a number of teams have prepared their tools for the analysis of the Wide data, using the images and catalogues of the Deep stacks that were delivered in the T0001 release on November 24, 2004.

#### 4.1.4.1. Cosmic Shear

We refer here to the section of the report on the Cosmic Shear (see 4.2.3). The main results are so far:

- The detection of the weak lensing signal in the T0001 stacks of the Deep data up to scales of 20’. The S/N is still low because of the small coverage of the field, but the results are promising because the B-modes amplitude is statistically zero, a proof that the PSF anisotropies are well controlled.
- The use of the full color information to compute photometric redshifts and select the source planes of the lensing signal. Results on Deep T0001 data show the
weak lensing amplitude increases as function of redshift as predicted. It demonstrates this is cosmological lensing signal and that weak lensing with CFHTLS data can explore the growth rate of perturbation and probe dark energy properties. This indicates that indeed, the coverage in u*, g, r, i, z of the field is necessary.

- The tentative detection of the weak shear signal up to scales of 2.5 degrees in the Wide data with negligible B-modes. This proves that the MegaCam field-to-field variations are also well understood and that the Cosmic Shear science will succeed on the total survey area. On smaller scales, the W1 and W3 cosmic shear signal is remarkably similar to VIRMOS-Descart.

4.1.4.2 Clusters
We refer here to the section of the report on the Clusters (see 4.3). This work as been so far conducted on the Deep stacks of the T0001 release and on the Wide stacks of the TERAPIX pre-release of March 2003.

- Two teams (Benoist et al., Marmo et al.) have devised pipelines to find clusters in the optical data and optimized them to deal with the inhomogeneous depth across a given field. Both pipelines have been validated on simulated data and used on Deep stacks. Their automated cluster detection has provided a cluster list. Clusters were checked by eye and validated. The tools are now ready for cluster analysis in Deep stacks and both teams are waiting for the wide stacks of the T0002 release.

- Several giant arcs have been detected in the W3 field, using sub-arc-second seeing i-band data of the CFHTLS pre-release. The discovery was done by visual inspection and revealed 4 giant arcs spread over 4 deg². If this detection rate was confirmed with the T0002 wide data, we expect about 30 new giant arcs soon and about 200 once the whole 170 deg² will have been observed in i-band. The visual inspection is however not a reliable technique and new detection algorithms are under development to produce a fair sample of arcs automatically detected.

4.1.4.3 Stars
We refer here to the section of the report on the Galactic Science (see 4.4). This work as been so far conducted on the Deep stacks of the T0001 release as benchmark for the wide studies.

- The team at Besançon observatory explored colour-colour diagrams derived from T0001 deep stack to locate galaxies, stars and quasars. The star-galaxy separation together with the inspection of colour-colour diagram works well.

- The photometric data provided by T0001 turns out to be good enough to separate spheroid, thick disc and thin disk stars of the Galaxy.
• A first attempt to constrain the luminosity functions of low mass stars using D1, D2 and D3 data revealed it is steeper than previously thought.

• Detection and counts of brown dwarfs in deep stacks are in good agreement with Besançon’ models. Further confirmations using near infrared data is however needed.

• Detection of white dwarfs reveal very efficient with CFHTLS data sets. Proper motions are needed.

Overall, the T0001 shows the CFHTLS will be unique for stellar and dynamical studies. The photometric accuracy is good, but not yet as good as expected, so deep and wide T0002 stacks are important to improve photometric precision and find the first fast moving objects.

4.1.4.4 Legacy Aspects of the Wide Synoptic Survey.

The legacy dimension of the CFHTLS is a very important aspect of this project, and the Wide survey has already started to spawn new research projects. For example, the W1, W2 and W3 fields have attracted new observations at various wavelengths:

• W1 has been or will be partly followed-up with:
  o SIRTF with the SWIRE legacy survey in the mid and far infrared
  o GALEX with the Deep Survey in the near and far UV.
  o UKIDSS in the near infrared that has both part of its Deep Extragalactic Survey and it’s Ultra Deep Survey in W1.

• W2 will be followed up by:
  o the ESO KIDS Public Survey. The ESO KIDS is a wide field public survey proposal lead by the AstroWise consortium. The project plan is to cover 1500 deg² with Omegacam on the ESO/VST. Its main science drivers are cosmic shear, clusters of galaxies, and AGNs. This project has not been accepted by ESO.
  o APEX. The Max-Planck-Institut fr Radioastronomie in Bonn is seriously considering an SZ follow up of the W2 field using the Atacama Pathfinder Experiment" (APEX). They plan do build a complete cluster sample from the W2 optical data in collaboration with CFHTLS teams working on clusters of galaxies and weak lensing in order to provide a complete SZ survey of these cluster. No formal agreement has been signed yet that would involve the French and Canadian agencies and CFHT.

The quality of the CFHTLS Wide data such as the area and the u band have also lead to the creation of some new projects. We describe two of them in the following section.

4.1.4.4.a. The Red-Sequence Cluster Survey (RCS2, Hoekstra et al.)

The second generation Red-Sequence Cluster Survey (RCS2) aims to obtain imaging data in g', r' and z' for a total area of 1000 square degrees. Of this area, 150 square degrees are contained within the CFHTLS wide survey, whereas the remaining data are taken in PI mode, using allocations from the Canadian and Taiwanese communities.
The aim of the survey is to find a large sample of galaxy clusters out to high redshifts \((z<1.4)\) which provide us with a powerful probe of the growth of structure in the universe. The main science driver of the survey is the use of cluster abundances to constrain dark energy models, but a secondary goal is the discovery of a large number of new, extreme, strong lensing clusters. RCS2 is currently the largest cluster survey, and will result in a sample of more than 10,000 clusters at redshift ranges that have been relatively unexplored. The overlap with the CFHTLS is crucial for the use of clusters as probes of cosmology. The RCS2 PI observations are shallow, aimed at detecting clusters. The CFHTLS wide data, however, provide the low to intermediate redshift calibration of cluster masses (this cannot be done well from the RCS2 data alone). The wide survey will yield a large sample of galaxy clusters (only second to the RCS2) but thanks to its depth we can determine masses of individual massive clusters out to \(z\approx0.6\) and study the scatter in the mass-observable relation. This will provide important insights in the properties of galaxy clusters, but is also a crucial ingredient in cosmological applications.

4.1.4.4.b The CFHTLS u’ band as a unique tool in cosmic star formation studies: access to UV continuum over a huge redshift range. (Millard et al.)

The CFHTLS u’ band is of primary interest in the domain of galaxy evolution, because it traces the rest-frame space UV continuum, thus the star formation activity (once extinction is accounted for), in the critical redshift range 0.7-2.2. Homogeneous data in u’ over significant areas at the required depth are still extremely scarce, though they give access to a redshift range which encompasses the well known “redshift desert”, while it is a key period where the cosmic star formation was nearing its maximum value.

In terms of history of star formation, the CFHTLS u’ band data bridges studies in the distant universe from the LBGs to those achieved in the nearby Universe from GALEX observations, with the same technique, thus minimizing differential effects that hamper many evolutionary studies today.

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\[ z = 0.5 \]
\[ z = 1.0 \]

\[ \lambda = 6 \times 10^{-21} \times 10^{-4} \]
\[ \delta = 0.010 \]

\( \theta \) (deg)

(a)  
(b)

Figure 3. (a) Illustration of GALEX dropouts. (b) Correlation function of galaxies detected in their rest frame UV at redshift of unity. Heinis et al., 2005
On the technical side, the travel of the Lyman break through the u’ band sets strong constraints in the photometric derivation of redshifts and objects classification. The extreme case of “GALEX dropouts” which are located in the z-range 1.5-2.2 is of particular interest. Incidentally, the u’ band position is also an excellent prior for identification and photometry issues of the GALEX observations.

We have used the CFHTLS u’ bands data to derive the correlation lengths of rest-UV selected galaxies near z~1 (Heinis, Milliard Arnouts et al 2005, presented at the CFHTLS workshop this year). The results show from samples with very close rest-frame selection criteria, that the clustering of the bulk of the star formation does not evolve significantly from z~0 to z~3 (figure 4.). We have derived the evolution of the rest-FUV luminosity function from z~0 to z~1 with GALEX, (Arnouts et al 2005, Schiminovich et al 2005), and have extended this analysis to larger redshifts with the CFHTLS u’ bands (Ilbert, Arnouts et al 2005, in prep). In combination with the GALEX bands, the u’ band will allow a homogeneous study of star formation properties, extinction, and evolution of galaxy populations over a huge z-range. It offers a unique possibility to understand the links between star formation and the distribution of the underlying mass derived from the cosmic shear and galaxies studies in GALEX-CFHTLS common fields.

Furthermore in many respects the u band data (with CFHTLS resolution!) will give us our best measure of the physical size of the star forming regions allowing us to determine the star formation 'intensity' as a function of redshift. Additionally the u’ band will provide some insight into the structure of star formation. There's considerable gain in obtaining these measures in a relatively local sample (e.g. z~0.8) as opposed to higher z in longer wavelength bands where significant k-dimming is taking place. For example there will be numerous (~10-20,000) Lyman break galaxy analogs (Heckman et al 2005) at redshifts close enough that the u’-band data would give us considerable insight into their morphologies.

Getting enough statistics requires a significant area to be covered in the u’ band. The planned overlap with GALEX is 10 square degrees in the CFHTLS Wide, in addition to the ~3 square degrees in common in the CFHTLS Deep. The full 5 bands coverage (and specially keeping the u) of at least this common area would bring a science return of primary interest for a relatively modest additional cost, providing the Canada France community with unique, first rank science data.

4.2. Cosmic shear

The CFHTLS cosmic survey team has demonstrated the MegaPrime instrument can be used for weak lensing studies. First measurements based on T0001 data and by using around 30 deg$^2$ of W1+W3 fields demonstrate that the cosmic shear signal has been measured on angular scales between one arc-minute to two degrees and B-modes can be eliminated on these scales. At larger scales we do not have enough data yet to make
a measurement. Cosmic shear signal has also been measured for two different source redshift distributions, showing that this survey will soon be able to probe the growth rate of perturbations. Cosmological interpretations of the dark matter power spectrum derived by weak lensing and analyses of constraints on cosmological parameters are in progress, and two papers will be submitted soon. The sky coverage (170 deg²) of the Wide survey is unique and makes the CFHTLS the most competitive cosmic shear survey ever done; for the survey to remain competitive we cannot tolerate a reduction of this area. The queue efficiency is however too low and it will be very challenging to reach the full sky coverage rapidly and keep the survey at the forefront of weak lensing studies if the data rate is not increased. We propose a three step observing strategy to improve the survey efficiency for cosmic shear: first, getting all i-band data before the end of 2006B; second, observing 10 deg² in u*,g,r,i, z and also with WIRCAM data to determine accurately the source redshift distributions; and third, getting data with other filters over the full wide field.

4.2.1. Science goals

Weak gravitational lensing on distant galaxies provides a cosmological signal dominated by the properties of the dark matter power spectrum at rather low redshift (<5) and its evolution with look-back time. Because it is primarily sensitive to the projected matter density, the lensing signal can be correlated with galaxy light in order to derive also relation(s) between light and mass distributions and on the properties of the galaxy biasing as well. Weak lensing also depends on the geometry of the universe, through angular distances, and on the underlying theory of gravity that relates the mass density contrast to the gravitational potential.

The main scientific objectives of weak lensing surveys are therefore the following:

- **Power spectrum:** properties and evolution with time
  - Probe the details of gravitational instability mechanism,
  - Properties of the dark matter power spectrum,
  - Properties of dark energy and its evolution with time,
  - Tests of inflation scenarios (running spectral index),

- **Properties of halos**
  - Galaxy-Galaxy lensing (size and shape of halos),
  - Detection and mass profile of clusters of galaxies,
  - Strong lensing studies in clusters (giant arcs; see the section on clusters of galaxies),

- **Relation between light and mass**
  - Biasing and its evolution with angular scale, environment and redshift,

- **Gravity**
  - Alternative gravitation theories.

Because gravitational weak lensing is directly sensitive to matter, regardless the light distribution, it is the best suited tool to probe the universe with the scientific goals listed above. The Canadian and French weak lensing teams, that are indeed among the world leading teams in the field, decided to join together in order to propose the biggest and most ambitious cosmic shear survey ever done on ground based and space observatories.
Both Canadian and French teams led CFH12k weak lensing surveys, and already collaborate since several years. Their past experience is a strong guarantee they are able to carry out this project.

The weak lensing signal is mostly dominated by gravitational distortion that modifies the shape of galaxies. The properties of lensing signal can be derived from the statistical analysis of correlated galaxy ellipticity distribution, as, for example, in the RCS and the VIRMOS-Descart cosmic shear surveys.

The CFHTLS cosmic shear survey has been designed in order to go one step further the RCS (see Hoekstra et al 2004 and reference therein) and the VIRMOS-Descart (see van Waerbeke et al 2005 and reference therein) surveys and to supersede all on going competing cosmic shear surveys. The CFHTLS will

- Improve the statistic by increasing the number of galaxies by a factor 10,
- Improve the $k$-space coverage by increasing the field of view of each patch and probe all angular scales up to 7 deg.,
- Improve redshift estimate by using 5 optical filters and, in a near future, near infrared data. Using photometric redshift information, the survey will be divided into several source/lens planes (at least two) in order to probe the growth rate of mass density fluctuations. Assuming galaxies up to $z \approx 1$ will be used, as for VIRMOS-Descart, the survey depth should be $i=24.5$. In order to be able to measure photometric redshift for about 70% of these galaxies, the limiting magnitude required for other bands are $u^*=24.5$, $g=25.5$, $r=24.7$, and $z=23.0$ (5-sigma, 3 arc-second aperture).
- Benefit from the CFHTLS photometric calibration plan in order to get weak field to field photometric Zero Point fluctuations on angular scale larger than one Megacam field. This will guarantee the photometric homogeneity of the whole sky coverage, which is an important requirement in order to compute light-mass cross correlations for biasing studies on angular scales beyond the Megacam field size.

The CFHTLS Wide survey will cover $170 \text{ deg}^2$, spread over three uncorrelated fields. The shape of the survey was motivated by

- the need to probe linear scales as large as possible in order to minimise the sensitivity of cosmological interpretations to non-linear effects and to overlap with CMB angular scales,
- the intrinsic limitation due to cosmic variance that dramatically increases for angular scales beyond 9-7 degrees ($l=20-25$), as can be seen of the figure below. Also, it is in this angular scale domain that realistic $w$-models start to separate. And finally,
- by the need to get redundant information obtained from several uncorrelated fields, in order to cross check the cosmic shear signal in case of contradiction between two of them. The minimum number of fields is therefore 3.
Hence, when used jointly with the cosmic variance constrain, the survey shape should roughly have a maximum size $3 \times 9 \times 9 = 243 \text{ deg}^2$ and a minimum size $3 \times 7 \times 7 = 147 \text{ deg}^2$. We initially proposed to get 4 patches and cover about $208 \text{ deg}^2$, but we finally de-scoped the survey by removing one of them. We therefore have the minimum survey configuration. Note that taking into account the area lost due to masks, an effective $150 \text{ deg}^2$ sky coverage corresponds to a total survey size of about $170 \text{ deg}^2$.

Power spectrum of the gravitational convergence $\kappa$ for three cosmological models with non-zero dark energy contribution to curvature ($\Omega_X$) and different equation of state ($P = \rho c^2$). The blue line corresponds to the linear theory of growth rate of perturbation. The filled cyan area shows the one-sigma cosmic variance. For $l < 20$, its contribution to error budget strongly increases. The separation between models is stronger when $l > 20$, but becomes more and more sensitive to the non-linear evolution of the power spectrum which is poorly known. Hence, medium sized surveys covering angular scale between 20 arc-min. and 10 degrees are optimum (From Huterer 2002).

To date, the most serious survey in competition is the on going SUBARU cosmic shear survey that covers $30 \text{ deg}^2$. The CTIO survey covers a large field of view ($75 \text{ deg}^2$), but it is shallower ($R = 23.5$) and is rather similar to RCS. Knowing that the SUBARU data are of excellent quality and deeper than the CFHTLS, the main strengths of the CFHTLS are the total sky coverage (6 times the SUBARU survey) and the wave-number range, up to 5-10 degrees where the $C_l$'s of most popular dark energy models start separating ($2 \times 7 \text{ deg}^2 + 1 \times 9 \text{ deg}^2$ patches), over three uncorrelated fields and at a depth of $i = 24.5$, like VIRMOS-Descart. In this respect, the CFHTLS Cosmic shear survey is unique. It is however important to notice that the SUBARU cosmic shear survey already covers $30 \text{ deg}^2$ and may now change its strategy and extend to a larger field of view soon. Knowing that the first CFHTLS wide data will be public in one year from now (therefore the
SUBARU cosmic shear survey team will have access to them), it is therefore of primary importance CFHTLS Wide covers the total field of view as soon as possible, in at least one filter useful for cosmic shear.

Simulations of the estimated relative gains on the cosmological parameters $\omega_b$, $(\Omega_b h^2$, where $\Omega_b$ is the baryon density parameter), $h$ (Hubble parameter), $n_s$ (spectral index), $\alpha_s$ (running spectral index), $\sigma_8$ (normalisation of the power spectrum) and $\Omega_m$ (density parameter) for survey size of 10 deg$^2$ (VIRMOS-Descart), 60 deg$^2$ (about twice SUBARU) and CFHTLS-170 deg$^2$ have been carried out. They show the gains are 0.24, 0.59 and 1.00 respectively. We therefore expect to be about at least twice better than SUBARU (even assuming 60 deg$^2$, it would not cover 3 fields of 7x7 deg$^2$ each, so the error budget of SUBARU will be worse than estimated here. On the other hand it will go deeper).

Following predictions done by Tereno et al (2005), the joint use of CFHTLS 170 deg$^2$ cosmic shear survey with the WMAP+CBI+ACBAR results will improve constraints on the $\omega_b$, $h$, $n_s$, $\alpha_s$, $\sigma_8$ and $\Omega_m$ parameters as compared to CMB data alone by a factor 1.2, 2.9, 2.0, 2.1, 2.5 and 2.8 respectively. The figures below compare the results of a join CMB+Weak lensing analysis with VIRMOS-Descart (left) and CFHTLS 170 deg$^2$ (right). The blue ellipses are constraints derived from CMB data only, the red-orange-green ellipses are constraints from weak lensing data only. Because degeneracies between CMB and weak lensing are perpendicular for these parameters, the gain in using both data sets is important, provided the weak lensing survey size exceeds significantly 100 deg$^2$.

Similar join analyses with the SNLS results will permit spectacular progress on the equation of state of dark energy and on its evolution with look back time. While SNIa’s are sensitive to the geometry of the universe only, cosmic shear is also sensitive to the
growth rate of perturbation. Benabed & van Waerbeke (2004) have explored how CFHTLS could benefit of this property which is a unique advantage of cosmic shear as compared to any other ways to probe the power spectrum. They have demonstrated that the CFHTLS Wide survey will constrain the quintessence field, even with a limited knowledge on other important cosmological parameters, with a precision as good as SNLS.

The figure below shows the expected Map variance for a CFHTLS-like cosmic shear survey (170 deg$^2$, n$_{gal}$=20/arcmin$^2$, $\langle z \rangle$=0.9, $\sigma_\epsilon$=0.44), for two different dark energy models, both having $\Omega_\Lambda$=0.7, $\Omega_m$=0.3, $\sigma_8$=0.9 and $\Gamma$=0.24, but with a different parameterisation for the equation of state.

Predictions of Map statistics for a CFHTLS survey ((170 deg$^2$, n$_{gal}$=20/arcmin$^2$, $\langle z \rangle$=0.9, $\sigma_\epsilon$=0.44), for two different dark energy models. The red curve has ($\Omega_\Lambda$=0.7, $\Omega_m$=0.3, $\sigma_8$=0.9, $\Gamma$=0.24 , $w_0$= -0.8 , $w_1$=0.32), the blue curve has ($\Omega_\Lambda$=0.7, $\Omega_m$=0.3, $\sigma_8$=0.9 , $\Gamma$=0.24 , $w_0$= -0.8 , $w_1$=0.). The separation between these two models in the range 1 arc-minute to 10 arc-minutes is sufficient to be detected by CFHTLS with a high significance level.

The blue line shows a $w_0$=-0.8 and $w_1$=0 model (no evolution). The red line has $w_0$=-0.8 and $w_1$=0.32. It illustrates a dark energy component with a strong variation with time that mimics a $\alpha$=6 SUGRA model. The models have significant difference in amplitude in the range 1-10 arc-minutes that can easily be explored with CFHTLS data.

Assuming the dark energy can be parameterised by a constant part, $w_0$, and a varying part, $w_1$, the constraints that can be obtained on the two models are shown below. Top panel is the pure $\Lambda$-model and bottom panel is a SUGRA-like model. From left to right, a likelihood analysis has been done using strong priors (left), marginalisation over
\( \Omega_m \in [0.1;0.5] \) and \( \sigma_8 \in [0.6;1.1] \) or a marginalisation over \( \Gamma \in [0.1;0.4] \). These plots show that a CFHTLS cosmic shear survey can recover information on \( w_1 \) and eventually rule out a pure lambda model.

This panel also locates the SNIa degeneracy direction. Clearly, by using together the SNLS and the CFHTLS Wide cosmic shear survey can probe the dark energy with its evolution. The ultimate use of these two data sets together with WMAP+CBI+ACBAR will therefore provide unique results on cosmological parameters and the properties of the power spectrum that will have no competitors over the next 3 years.

\[
\begin{array}{c}
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\text{Constraints obtained on } w_0 \text{ and } w_1 \text{ with the CFHTLS Wide survey (see text). Green, orange and red areas are the 3-, 2- and 1-sigma confidence levels respectively. The blue line locates the SNIa degeneracy direction. Together with the 700 SNIa’s analysed by the SNLS team, strong constraints on both } w_0 \text{ and } w_1 \text{ are expected from the CFHTLS Deep and Wide data.}
\end{array}
\end{array}
\]

It is worth noticing that the predictions shown above are only based on 2-point statistics. High order statistics like the skewness of the gravitational convergence or the 3-point shear functions will provide useful information on non-gaussianity and will permit to break some degeneracy regardless the constraints from SNIa and CMB (see Bernardeau et al 1997, 2002, 2003, Pen et al 2003). The gain of a factor of 10-20 in sky coverage as compared to VIRMOS-Descart will be of primary importance for high-order statistics.

The CFHTLS cosmic shear survey involves 7 faculty, 2 Post-docs (another one soon) and 3 PhD students (another one expected this year), 5 in Canada and 7 in France. The persons involved are F. Bernardeau (CEA/SPhT), Fu L. (IAP, PhD Student), R. Gavazzi (Obs. Toulouse, Post-doc), S. Gwyn (U.Vic), H. Hoekstra (U.Vic), M. Hudson (U. Waterloo),
R. Maoli (IAP), Y. Mellier (IAP), L. Parker (U. Waterloo), E. Semboloni (IAP, PhD student), I. Tereno (IAP, PhD student, Post-doc by May 2005), S. Vafaei (UBC, Master degree), L. van Waerbeke (UBC). Several of the team members already have strong experience in cosmic shear studies with CFH12k data. The French and Canadian researchers involved collaborate together since more than three years and already have published join papers on weak lensing. The results discussed below results from works done on Megacam data by the cosmic shear groups over the past two years.

The French and Canadian teams run two different pipelines to process the data and to measure weak lensing signal, so systematic effects are controlled at two different levels: the pixel data processing and the ellipticity analysis from object catalogues.

4.2.2. Impact of MegaPrime image quality on the survey

4.2.2.1. PSF analysis before the L3 lens flip

After the discovery that the WFC image quality was below specifications, we investigated its impact on cosmic shear survey by comparing the shape of the PSF anisotropy to the VIRMOS-Descart CFH12k data.

Based on past experience, we expect that a 1% amplitude lensing signal can be recovered with a 10% relative accuracy, if the star ellipticity keeps below 10%. We then mapped the PSF of MegaPrime and derived which fraction of the fields has star elongation below 10%. This experience was done in collaboration with the CFHT staff, who provided several sets of Megacam images done at different air mass and with different filters. During the test phase, we checked the performances of the instrument for different WFC configurations and sent the full data set to CFHT, so that CFHT was in position to setup the best WFC configuration.
The PSF analysis of MegaPrime done with the help of CFHT during the test period. The left panels show the stellar ellipticity in two high density star fields. The right panels show the image quality assessments for cosmic shear studies. The two axes of each box of left panels are the raw stellar $e_x, e_y$ ellipticity components. Each box is a Megacam CCD. The dashed circle locates the critical radius. Points outside these circles have very strong stellar ellipticity and we cannot guarantee we will measure weak lensing signal with sufficient accuracy to achieve the scientific goals. The top panels show an unacceptable WFC optical configuration, with too much CCDs having stars located outside the critical circles.

The figures above show two examples based on a PSF analysis of a stellar field. The left hand figures show the elongation of stars over the field, the right figures show the amplitude of the stellar $(e_x, e_y)$ ellipticity components, before corrections. Each stick indicates the length and the orientation of the stellar ellipticity at that position. There are 36 ellipticity plots, one per Megacam CCD. The dashed critical circle inside each plot shows the 10% amplitude limits: if star ellipticity is located inside the circle, then we know that a shear amplitude of 1% can be measured with a 10% accuracy. The top panel is an example of unacceptable WFC configuration: 22/36 CCDs only have most stars inside the critical circle. In terms of lensing surveys, it means that only 61% of the total sky coverage of the survey can be used for cosmic shear. In other words, the survey reduced to 103 deg$^2$ effective area, before any kind of masking. The bottom panel shows the best WFC configuration (before the L3 lens flip): 32/36 CCDs show most stars inside the circle. Hence 89% of the Megacam field can be used for cosmic shear, and the total sky coverage reduced to 150 deg$^2$.

The best configuration keeps all survey goals feasible. When the survey was designed, we took into account the fraction lost by the masking process. Over 170 deg$^2$, about 20% will be lost due to bright stars, satellites tracks, CCD defects and systematic elimination of CCD boundaries. The expected effective survey size was therefore 140 deg$^2$. With the best WFC configuration, the effective survey size would be at least 120deg$^2$, and likely higher than this because the CCDs that are most affected by the bad image quality are at the extreme bottom right part of the Megacam camera that are part of image boundaries and will be partly masked anyway.

In conclusion, the WFC image quality partly degrades the efficiency of cosmic shear survey with MegaPrime but its impact does not question the scientific goals of the
CFHTLS cosmic shear survey. First results that are discussed in the next section used wide and deep data sets obtained with this WFC configuration. It shows the WFC image quality problem has indeed a small impact. The CFHTLS cosmic shear survey could start, even with rather degraded performances of the instrument. However, because CFHT decided to spend a lot of efforts in understanding and improving the WCF, we proposed to start the Wide field survey at lower speed that initially proposed in order to wait for better image quality in the future.

4.2.2.2. Gain with the WFC L3 lens flip
The recent flip of the L3 lens produced a spectacular improvement of image quality. Its impact on weak lensing analysis can be seen on the figures below. They show the PSF analysis done with the help of CFHT at TERAPIX on i-band images with the same seeing (0.55''), before (top) and after (bottom) the L3 flip.

*PSF comparison of the MegaPrime WFC before (top) and after (bottom) the L3 lens flip. The two data sets have exactly the same averaged seeing and are both obtained in i-band and at low airmass, so the PSF interpretation of the two samples is directly comparable. The histograms clearly show the PSF distribution is more compact since L3 was flipped. The PSF mapping on the right panels may give the impression data are worse now. This is an illusion produced by the much larger number of stars in the second data set.*
that increased the visual correlation. In fact, the PSF is more homogeneous over the field now, while the area with unacceptable stellar elongation is smaller.

The improvement is clear on two points:

- The stellar ellipticity exceeds the critical 10% amplitude limit on a smaller Megacam field of view than before. As compared to previous configuration, 33.5/36 CCDs have PSF inside the critical circles; that is 93% of the Megacam field. The translation into sky coverage must take into account the field of view already observed with Megacam and the previous WFC. Taking into account only i-band, 30 deg$^2$ have already been observed, that is an effective area of 30*88% = 26.4 deg$^2$. For the rest of the survey we then expect (170-30)*0.93 = 130.2 deg$^2$. So, if we assume the survey configuration keeps stable now, the expected effective sky coverage should be about 160 deg$^2$. Assuming 20% lost due to masking, the final effective field of view should still be 130 deg$^2$.
- The second point is the stability and uniformity of the stellar PSF anisotropy: tests done by CFHT and TERAPIX show that the WFC seems stable with time. The PSF looks also much more uniform than before over the field. Moreover, in most of the central field were the PSF looks uniform, the amplitude of stellar anisotropy is smaller than with the previous WFC configuration. We then expect the PSF correction will be easier, with less residual fluctuations and more robust than before.

4.2.3. Weak lensing with CFHTLS data

The discussion above shows that with the recent improvement of L3, MegaPrime is among the most effective instrument for cosmic shear done so far. However, the feasibility of the survey must still be demonstrated from real data analysis. In the following section we show the first results obtained from wide and deep data analyses. The results will be published soon in two papers (Semboloni et al 2005, Hoekstra et al 2005). These papers assess the CFHTLS data quality for cosmic shear studies, demonstrate weak lensing signal is detected, provide first measurements, explore first constraints on cosmological parameters based on the whole range of angular scales analysed with present-day CFHTLS data, and finally make first tentative of tomography studies.

4.2.3.1. Deep data set from the T0001 release

The cosmic shear signal has been analysed using the T0001 released data sets on D1, D3 and D4 (D2 is still too shallow). The seeing of stacked images is between 0.85 to 0.95 arc-second.

The signal was analysed using the same weak lensing analyses as for VIRMOS-Descart data, starting from the masking process, source extraction, PSF anisotropy analysis with IMCAT, and analyses of shear variance, Map variance and shear correlation function as function of angular scale. Both E and B modes have been explored and we checked the reliability of the signal by using the r and i band data set independently.
The results are shown on the figures below. The first figure show the joint D1+D3+D4 r-band top-hat shear variance, Map variance and shear correlation function. The signal to noise is not very high because the sky coverage is still small, but we see the B-mode values are statistically zero.

Weak lensing analysis of the Deep data, released by November 2004, of D1, D2 and D3 fields in r-band. From top to bottom: E- (red) and B- (black) modes derived from the 2-point shear correlation function, the Map variance and the top-hat shear variance.

On the second plot below, both i and r bands top hat shear variance are shown together. Both images and catalogues have been processed independently. This plot shows that the PSF anisotropy correction method and the shear detection technique are robust and reliable and that errors of individual galaxy shape measurement do not produce strong fluctuations.
Two point shear correlation function analysis of Deep data derived independently from r-band and i-band data in D1 and D3. Both E and B modes have similar shape and amplitude. This demonstrates the signal is robust and reliable.

Finally, we used the full deep u,g,r,i and z data of the D1 and D3 fields in order to derived photometric redshifts of the galaxy sample. If the signal is indeed produced by gravitational lensing, we expect its amplitude be higher for high-z lensed sources than for the others. We used the hyper-z software to separate galaxies into z<0.7 and z<2.0 galaxies. We did not try to measure redshifts with high accuracy, but just built two reliable populations with minimal controls done by comparing the photo-z of the bright populations with existing redshift surveys.

The two-point shear correlation function derived from Deep D1 and D3 data in r-band for z<0.7 and z<2.0 galaxies. The amplitude of E-modes varies as expected if the signal is of cosmological nature and produced by weak lensing by large-scale structures of the universe.

The figure above shows the top hat shear variance of both E and B modes for the low-z and high-z galaxy samples (galaxies are spread equally in the two redshift bins). The difference is very significant, and is a strong demonstration we observe a cosmological signal produced by large-scale structures of the universe. It also demonstrates that the CFHTLS cosmic shear survey is readily in position to measure the growth rate of dark matter perturbation, a cosmological information that only weak lensing data can probe.

One important need for this goal is a robust estimate of source redshift distribution, at least in two redshift bins. Near infrared data sets that can provide WIRCAM will be necessary to better constraint redshift of the high-z galaxy population.

### 4.2.3.2. Analysis of Wide data
The i-band W1 and W3 data cover 19 and 12 deg$^2$ respectively. This is sufficient to derive reliable shear signal and to draw conclusions regarding the scientific potential of Wide data for the CFHTLS cosmic shear survey.

As for the deep, data have been processed the same way as CFH12k data. However, a fraction of W1 has been analysed by two independent teams, using both the VIRMOS-Descart and the RCS pipelines. The results have been compared on small fractions of W1 and W3 and are similar.

The whole sample has only been completely analysed by the RCS pipeline, without using CFHTLS release data sets, but by processing Wide i-band images on its own. The PSF anisotropy analysis and weak lensing studies are based on a CCD-by-CCD exploration of stacked data and follow the processing schemes described in Hoekstra (2004), Hoekstra et al (2004) and van Waerbeke et al (2005).

Up to now, 31 pointings observed in i-band have been used, corresponding to an effective sky coverage of 22 deg$^2$. They are show in the figure below.

Overview of the W1 and W3 fields that have been used for the CFHTLS Wide cosmic shear survey presented in this report.

A typical PSF anisotropy of a stacked Wide image is shown below.
Image of the Megacam PSF derived from the W1+3+3 stack. Each stick shows the local orientation and ellipticity of stars. The average ellipticity has been subtracted in order to show the large scale variations.

The catalogues used for weak lensing studies contain all galaxies brighter than $i=24.5$ and result in a galaxy number density of $20 \text{ gal/arcmin}^2$ over the effective area. The first CFHTLS cosmic shear results on Wide data are show below. The three common weak lensing 2-point statistics show a strong signal, with B-modes consistent with 0 at all scales.
Cosmic shear signal derived from $E$- (black) and $B$-mode (red) analyses on angular scales below Megacam field size. The left panel shows the 2-point shear correlation functions, and the right panels show the Map variance (top) and the top-hat shear variance (bottom). The analyses show $B$-modes are negligible.

The comparison with the VIRMOS-Descart data shows that both data sets are very consistent and clearly demonstrates the potential of CFHTLS Wide for weak lensing studies.

Comparison of VIRMOS-Descart cosmic shear signal obtained with CFH12k data (blue) and W1 (black) and W3 (red) obtained with CFHTLS Wide data at the same depth. The amplitude and the shape as function of angular scales are identical. The top panel shows the Map variance and the bottom shows the $B$-modes, derived by computing the Map variance after rotating all galaxies by 45 deg.

A more innovative aspect of CFHTLS data as compared to past surveys at CFHT concerns large scales. The compact $7 \times 7 \text{ deg}^2$ fields provide a unique opportunity to explore cosmic shear beyond one degree, in the transition regime between linear and non-linear scales. With the W1 and W3 data in hands, large scales have been analysed very recently. The plots shown below describe preliminary studies of the top hat shear variance in W3 (left) and W1 (right) respectively, up to 2.5 degrees. The signal is strong
and is also confirmed from the Map variance and the shear 2-point correlation functions. Clearly, B-modes are still negligible up to these scales.

First top-hat shear variance measurements done on angular scales beyond 1 degree (i.e., beyond a Megacam field size), obtained from CFHTLS wide data on W3 (left) and W1 (right). The signal is strong and dominates B-mode residuals that are statistically zero between 1 arc-minute and 2.0 degrees.

These results are very encouraging and promising for the future since it demonstrates that CFHTLS is able to probe lensing signal where sensitivity to non-linear structures will be small. Constraints on cosmological parameters should therefore be more robust and easier than in the past.

The deep and wide weak lensing studies shown in the previous sections demonstrate that weak lensing studies with Megacam are feasible. The technical performances of the MegaPrime/Megacam instrument are at least as good as CFH12k, despite the WFC defects. The lensing signal is strong, does have the expected shape and amplitude as function of angular scales and of source redshifts, and does not show B-modes. Therefore, we believe MegaPrime/Megacam, the CFHTLS weak lensing survey tools and its teams are now fully operational. We are convinced the performances of the instrument, as described in the previous sections, will permit to reach the scientific goals, keeping cosmic shear as a top science driver of CFHTLS.

4.2.4. Strategy for the next periods of CFHTLS Wide field observations

The investigation of the MegaPrime image quality and the cosmic shear signal in the Deep and Wide data show that the performances of instrument are now acceptable for the scientific goals of the CFHTLS cosmic shear survey. Stacked data with median seeing ranging between 0.85 to 1.0 arc-second provide good enough data for cosmic shear analysis. There is therefore no more reason to slow down the Wide component of the survey. In the following, an observing strategy for the wide survey is proposed that would optimise the competitiveness and the scientific return for cosmic shear science with CFHTLS. No de-scoping is proposed, since all filters are ultimately necessary, but a change in filter priorities over the next observing periods.
With the instrument as it stands now, the main issue for the cosmic shear survey is the gain in sky coverage. By the end of the 05A period (that is 2 years after the survey started), we expect to have 50 deg$^2$ in i-band. In view of the competition, having the largest field of view as possible, and as fast as possible, is still the main priority. Due to the masking process, we expect the final effective sky coverage will be about 160 deg$^2$. Assuming we have 50 deg$^2$ in i-band by end of July 2005, we propose to get the remaining 120 deg$^2$ in i-band within the period 05B, 06A and 06B. This strategy would keep the CFHTLS cosmic shear survey the most competitive lensing survey in the world. It is important to stress again that the field of view is even more critical for all studies involving higher order statistics than 2-point functions.

From a CFHTLS operation and queue observation point of view, the strategy proposed above correspond to 40 deg$^2$ per semester, over three semesters, in i-band, that is 51.3 hrs (including 40 sec. readout per exposure), or 50% of the Wide time allocated per semester.

The redshift information is the second priority. As shown in the previous section, we used the redshift information to demonstrate lensing nature of the signal. It is also important to scale the cosmic shear amplitude and derive cosmological parameters. For the biasing, redshift information is used to separate galaxies into foreground and background samples.

The first step is to get a global redshift distribution derived from photometric redshift with a reasonable accuracy. This information need at least the data obtained with the 5 MegaPrime optical filters, but only on a fraction of Wide fields. More important is to get NIR data using WIRCAM on a small CFHTLS Wide field fraction in order to get photo-z of z=1 galaxies with enough accuracy. It is therefore important to get 10% of the total Wide area in u,g,r,i and z, plus WIRCAM H and K data. Since we use the broad shape of the redshift distribution, this part of the survey can be done on only one Wide field and can use jointly Deep data. For example, we could use 10 deg$^2$ on W1. Since the i-band, part of the r-data and some g bands data have already been collected, this is mainly u and z data that are necessary. Assuming we focus on the remaining r/2, plus the full u and z over 10 deg$^2$, this strategy corresponds to 41.3 hrs of CFHTLS Wide observation (including 40 sec. readout time per exposure). We believe this can be easily scheduled of 05B, 06A and 06B.

The final step is to get full photo-z information for each galaxy. This information is needed to get multiple lens plane information and constrain some properties of dark energy in our universe from tomography techniques. This is also useful to study the galaxy biasing as well as to down-weight the contribution of physical pairs that may contaminate the weak lensing signal by intrinsic B-mode. This step has a lower priority, so, for cosmic shear surveys, we propose to put the 5-color information over the whole Wide fields with a lower priority, once the two steps described above be terminated. Note that NIR data will be also very useful, but it is impossible to observe the full Wide sky coverage with WIRCAM.
The table shown below summarises the proposed scheduled, based on cosmic shear requirements, and taking into account the needs of r/2 exposures for stellar proper motions over the full duration of the CFHTLS wide survey.

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The CFHTLS cosmic shear team thanks CFHT, especially Jean-Charles Cuillandre and the QSO team, for their remarkable work and continuous support.
4.3. The CFHTLS and Galaxy Clusters

A systematic study of the cluster population in the CFHTLS Wide fields has been undertaken by a French consortium. In this report, we describe: (1) the unique potential of the CFHTLS cluster sample for cosmology; (2) the work organization; (3) the proposed scheduling of the W observations; (4) preliminary results obtained in the D1 field.

4.3.1. Scientific motivation

With the W1 (72 deg²), W2 (49) and W3 (49) patches covered in 5 bands, the Wide component of the CFHTLS will constitute a unique sample of galaxy clusters out to a redshift of 1 and will enable the detection of possible massive clusters (if any) out to a redshift of 1.5. There is no on-going other cluster survey providing such depths over such a large contiguous area; this lay-out is essential for cosmological investigations (the RCS covers only ~ 4 deg² patches in 2 bands out to z~1 (Gladders & Yee 2005), the RCS2 is complementary: it already covers 300 deg² and will cover 850 deg², in three filters, but will be shallower - exp. time of 6 minutes in z, instead of 120 minutes for CFHTLS Wide -, and the 2dF survey and SDSS are limited to z~0.2). The goal of our consortium is to fully exploit this opportunity.

The Wide survey is ideally suited for Large Scale Structure studies (LSS): clusters constitute the deep potential wells of the universe, i.e. the “nodes” of the cosmic structures and so, present the necessary complement to SN, CMB and weak shear analysis (e.g. Bahcall et al 1999, Fig. 2). Cluster properties are particularly sensitive to the density parameter ($\Omega_m$) and to the slope of the initial power spectrum ($n$). We have presented the expected cluster number density and cosmological constraints in detail in the CFHTLS document; we recall here the main points on which we focus our activities.
a. **Map the space distribution of the clusters out to z ~1 over a cosmologically significant single area (8 deg ~ 250 Mpc, commoving, at z=1, Λ-CDM).**

So far, this has been done only out to a redshift of 0.2-0.3, with e.g. the Abell and SDSS catalogues in the optical and the REFLEX sample in the X-ray (RASS data).

We shall for the fist time obtain the *cluster correlation function* in 2 redshift bins (in 2D and 3D).

b. **Systematic search for superclusters**

Less than 5 are known above z>0.5; they are essential entities to investigate the process of hierarchical structure formation.

c. **Calibration of the mass-luminosity relation for clusters above z>0.5**

Cluster Mass is the primary theoretical parameter, but not a direct observable. We thus need to develop a dedicated approach in order to estimate cluster masses

i. Recent results from the SDSS (Popesso et al 2004) have shown that optical cluster luminosities can be as good as X-ray parameters for estimating masses. We shall extend this study out to z~1

ii. We shall correlate the optical cluster LSS matter distribution with the weak lensing detected clusters, to obtain (1) an alternative mass estimate, (2) a measurement of the bias (DM over light) as a function of scale.

### 4.3.2. Core Programme: construction of the CFHTLS cluster catalogue

In order to achieve our science goals, it is essential to obtain a complete cluster catalogue, i.e. a catalogue for which selection effects are under control. This will be achieved by the following steps:

a. Using the multi-band galaxy catalogue with the matched filter (Nice, Saclay) and red sequence (Nice) techniques (see Sec. 4)

b. Using weak lensing detections: KSB (IAP), shapelets (Saclay)

c. Estimate the cluster redshifts with ugriz photometry. For each cluster candidate position, this is principally achieved using probability functions as described by Pierre et al 2004 (Fig. 7)

d. Calculate the corresponding selection functions with n-body simulations from the GALICS programme (Lyon). This is a key point for the subsequent cosmological studies.

e. Perform the spectroscopic follow-up

The catalogue so obtained – with controlled selection functions - will constitute a *truly legacy* and a unique data set\(^1\). In addition to the applications listed above, it will also

\(^1\) Shall we recall here the innumerable applications of the Abell catalogue that was based on simple eye-bolled detections?
a. be the reference catalogue for the future identification of the PLANCK clusters (detected by Sunyaev Zel’dovich effect)
b. provide an homogeneous data set for the study of the evolution of clusters and galaxy clusters out to $z = 1$ (i.e. morphology, B-O effect etc...). This will be a natural “by-product” of the determination of the selection functions as the optical cluster detection algorithms heavily rely on the galaxy properties.

The CFHTLS cluster catalogue will be hosted in the extended L3SDB developed in Saclay for the purpose of the XMM-LSS cluster catalogue. This is an object-oriented database that allows: the management of the various catalogue versions, displaying multi-band cluster data, the on-line characterization of the cluster candidates and quality check by registered “evaluators”, the real-time monitoring of the spectroscopic follow-up and subsequent redshift assignment, the selection of cluster sub-samples according to a wide range of parameters. It is a secured database (data are encoded) and also designed for the use by the world community (release follows the granularity set on objects and parameters by the manager).

We plan to spectroscopically measure at least 20% of the cluster redshifts. Final cosmological constraints will be derived by means e.g. of Fisher matrices including the various error types on [M-L relation, spectro-z, photo-z, no redshift, etc...].

4.3.3. Proposed scheduling for the Wide survey

Our primary working area is W1 because it is covered by a number of other surveys (XMM, Galex, UKIDSS, SWIRE) that will provide invaluable information to check and calibrate our cluster detection procedures as well as optical mass estimators; moreover some 50 spectroscopic XMM-LSS cluster redshifts are already available. It is also the largest Wide field, thus best suited for LSS studies.

With a cluster density of $\sim 15 \text{ deg}^2$, some 1000 clusters$^2$ are expected, with roughly 500 at $z<0.5$ and 500 at $z>0.5$. Out of these clusters, our first results show that we get some 3 clusters/deg$^2$ weak lensing detections, corresponding to the most massive clusters; these are cD type clusters and for them, useful photometric redshifts can be rather easily achieved with the available ugriz bands at the nominal depths. A further important principle here, is that we plan to use the fact that clusters of galaxies are “balls” (= potential wells) clearly separated from each others in the 3-D space, in order to rely as much as possible on the mean cluster photo-z for the computation of the 3D cluster correlation function. The mean separation between clusters more massive than $10^{14}\text{Mo}$ is the order of 30 Mpc (HVS simulations, Evrard et al 2002), which is comparable to the comoving length encompassed by a $\Delta z$ of 0.01 at $z = 0.5$ (33 Mpc) in the $\Lambda$-CDM cosmology. Predicted numbers of clusters more massive than $10^{14}\text{Mo}$ are 1, 2.5, 10 for the $z<0.2, 0.2<z<0.5$ and $0.5<z<1.2$ ranges (HVS, $\Lambda$-CDM).

From this, it is obvious that the highest possible photometric accuracy is necessary in order obtain good cluster characterization. In addition, the $z'$ band is precious not only for detecting $z>0.8$ clusters (red sequence method) but also for constraining their redshift

$^2$Cosmological constraints reachable with these numbers are available in the CFHTLS document.
along with the other bands; Photometric accuracy is also critical above \( z > 0.7 \) for the galaxy background subtraction. Hence, the need to keep the nominal CFHTLS depths in all bands. On the other hand, constraints on seeing are not as stringent as for the weak lensing analysis and a mean value of 1.1” is acceptable. We therefore propose the following schedule for the W programming

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1. **W1 : all bands, nominal depths ASAP**
   - first estimate of the 2D and 3D cluster correlation function out to \( z = 1 \) (15 clusters/deg2)

2. **W2, W3 : all bands, if possible nominal depths**
   - detection and \( z \)-phot of only the most massive clusters (3 clusters/deg2): impact of the cosmic variance on the W1 results.

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**References**


**4.3.4. Preliminary results**

In the past months the aspects that were addressed were mainly related to understanding of the data, the setting of the various parameters for the detection algorithms, as well as the construction of several simulated data sets to mock the "Deep" and "Wide" galaxy catalogues in such a way that at least several cluster properties are represented. The data used are the Deep T0001 release of December 2004.

The optical detection algorithms that were selected are two-folded: first the so called *matched filter* where one searches for overdensities assuming a luminosity function and a radial profile, and then an approach based on the assumed colour properties of the cluster galaxies, mainly the red-sequence produced by the elliptical galaxies in clusters cores. The first method requires only one pass band, whereas the second at least two, the choice of the bands allowing the access to a particular redshift domain. If the five UGRLz pass bands are available it is also possible to look for overdensities in the 3-dimensional space...
given by the position on the sky and the photometric redshift. This approach is currently being addressed using the software "Lephare" developed by S. Arnouts.

The works that were initiated and the first results related to galaxy clusters within the CFH-LS are presented below:

4.3.4.1. Optical Cluster detection
C. Benoist (Obs. Nice), C. Marmo (CEA/SAP Saclay; Post-doc), L. Olsen (Obs. Nice; Post-doc), E. Sleazak (Obs. Nice)

Matched filter
Two matched filter algorithms are used. The first one, very similar to the one used by Postman et al. (1996), has been originally developed and applied on the 15 sq.deg. of the ESO Imaging Survey by Olsen et al. 1999. The second one, being currently tested, has been developed by C. Marmo in order to be able to deal with locally varying galaxy counts, reflecting depth variations, particularly important for the mosaics of the Wide fields.

For the time being the matched filter algorithm has been applied on the I band data of the Deep 1 and Deep 3 fields, with configuration files and filtering methods similar to the ones of Olsen et al. 1999. The resulting cluster counts are presented in Figure 1, and are compared to the ones obtained with the EIS cluster catalogue. Even if preliminary one can notice a good match between the two sets of data. As an example the GRI colour image of two systems at different redshifts are presented in Figure 2.

![Normalized redshift distribution of cluster candidates detected by the matched filter algorithm applied on the I band of Deep1 and Deep3 compared to those detected over the 15 sq.deg of the EIS Cluster Survey (Olsen et al. 1999).](image-url)
GRI colour images of two cluster candidates detected by the Matched Filter algorithm applied on the Deep1 field, with the matched filter redshift being $z=0.3$ on the left and $z=0.6$ on the right.

To obtain a good understanding of the differences between the two matched filter implementations we have produced a number of simulated cluster catalogues. We are using catalogues with galaxies uniformly distributed (even though not realistic useful for comparing the different algorithms) and adding simulated cluster galaxy distributions on top. The clusters are built to cover a range of richness and redshifts and also to investigate the ability to separate clusters along the same line of sight. Besides the comparison of the two programs the simulations will be used to choose optimal parameters for the matched filter program as well as a posteriori filtering balancing the false-positive and positive-false detection rates. In turn this work together with the work on GALICS data (described below) will be used to determine the selection function essential for scientific exploration of the cluster catalogue.

**Colour filtering**

The other approach that has been initiated on the Deep 1 field is the detection of overdensities in both position on the sky and colour. Assuming that the systems of interest are composed by a large fraction of early type galaxies presenting a tight sequence in a well chosen colour-magnitude diagram (red-sequence), projected overdensities in a given colour slice may indicate the presence of a cluster whose redshift is given by some assumed evolutionary tracks as shown in Figure 3.

We proceed in the following way: for a given redshift we choose the best set of consecutive filters to constrain the position of the 4000 A break (see Fig. 3), filter the galaxy catalogue assuming a redshift bin of 0.1 (which is enough to account for the photometric uncertainties), and produce a probability density map for this particular
redshift. Then, pics are extracted using SExtractor. The maps themselves are built following an approach based on signal theory assuming the presence of a statistical noise that has to be characterized and filtered (Slezak & Benoist 2005, in preparation). We have chosen multi-scale technique allowing for a local hierarchical analysis of the point distribution. The advantages of this method is that 1) the relevant scales are directly selected through thresholding; 2) the measured amplitudes have a statistical meaning; 3) the approach is valid even for a small number of events and finally 4) this method allows a good administration of regions presenting a superposition of structures of different sizes and amplitudes.

In Figure 4 two such maps, corresponding to $z=0.3$ (from a G-R slicing) and $z=0.6$ (from a R-I slicing) are presented. At low redshift the brightest pics match well with the Matched filter detections, whereas at larger redshifts comparisons between the methods and with simulations are still going on.

*From the left to the right: the colour tracks of an elliptical galaxy (from Coleman Library) seen through three pairs of filters GR, RI and Iz. The coloured lines show the redshift intervals best covered by each combination to optimally constrain the position of the 4000A break.*
4.3.4.2. Simulations: mocking the Wide & Deep fields for cluster searches

The analysis of the selection biases related to each detection method will be performed with a set of GALICS simulations that offer the possibility to construct catalogues mocking with high precision the CFHTLS galaxy catalogues. A first set of such catalogues will be ready around mid-March. Those are constructed in the following way: large scale (cubes of 1000Mpc) N-body simulations are performed within several cosmologies ($\Lambda$ and quintessence); galaxies and clusters are then added in following the GALICS techniques (Hatton et al. 2003) and/or MOLUSC (Sousbie et al. 2005). Such a technique allows galaxy clusters to have proper luminosity functions, colour distributions and radial profiles.

The next stage that is already being addressed is the introduction at small scales of the formation and evolution processes of cluster sub-structures based on N-body re-simulations and high resolution hydrodynamics in individual clusters (Lanzoni et al. 2005).

4.3.5. WIRCAM follow up
The nominal depth of the K-band proposed by the UKIDSS survey in the XMM-LSS area (DXS : 35 sq.deg with K=21) is optimum for cluster search up to $z=1.5$ and to compute precise photometric redshifts for the clusters detected within the CFH-LS data. An extension of this survey with WIRCAM would therefore be the best option for galaxy clusters.
4.3.6. Searching for giant arcs in clusters of galaxies

B. Fort (IAP), Y. Mellier (IAP), M. Dantel-Fort (IAP), J.P. Kneib (LAM, Marseille), O. Le Fèvre (LAM, Marseille), R. Gavazzi (OMP, Toulouse; Post-doc), G. Soucail (OMP, Toulouse).

Mellier has shown at the 2004 CFHT users meeting several giant arcs he discovered in CFHTLS wide fields. These giant arcs were found during the hand-made masking process of wide data that were delivered with the TERAPIX CFHTLS pre-release of March 2003. Four examples found in W3 are shown below.

Four image of giant arcs found on i-band images of W3. All these clusters show at least one arc and most also have several typical lensing features. None have been confirmed using spectroscopy, but their morphology is typical of gravitationally distorted objects. These arcs have been discovered on a field covering only 4 deg$^2$.

A remarkable point is that these four arcs are spread over 4 deg$^2$ only. Because of cosmic variance, it is too early to derive the amount and number density of giant arcs in the wide survey, but it is likely the total number of giant arcs in clusters of galaxies will be between 30 and 200. This sample will be unique, at that depth.

The primary scientific use of these arcs will be a mass estimate of innermost regions of these clusters of galaxies using strong lens modelling. Because CFHTLS Wide i-band images are obtained in similar seeing conditions and the survey will contain u,g,r,i and z-band images, the selection function of giant arcs on a i-band selected sample should be under control. If so, statistics of arcs in the CFHTLS Wide data can be used to explore
the statistical properties of dark matter distribution in the innermost regions of clusters of galaxies and to compare the results with mass reconstruction from weak lensing or X-ray studies. Because weak lensing reconstruction using Wide data is limited to cluster having enough lensed galaxies behind, this joint analysis is limited to intermediate redshift clusters (z<0.5 – 0.8), but will still be the widest strong lensing cluster sample ever observed at that depth.

The fraction of clusters of galaxies with arcs depends on the geometry of the universe and on the cluster mass distribution (mass density profile, ellipticity, sub-structures). The interpretation of the giant arc fraction is unfortunately complex (cluster dynamical evolution) and degenerated (mixing the role of geometry of the universe and growth rate of perturbation with non-linear evolution of clusters), so it must be compared with numerical simulations. If extreme numbers were found (i.e. a very small or a very large fraction of giant arcs), its interpretation in a cosmological context will be interesting and may be challenging.

The eye-detected arcs shown above have been discovered by looking at each Wide field of the CFHTLS pre-release twice, each time by spending about 5h/deg², so the detection rate and the “completeness” are likely reliable for this small sample. Although each arc candidate must be confirmed by a visual inspection, using this detection tool systematically is a questionable method to find all arcs. A team led by B. Fort started to setup an automated arc detection tool that should supersede eye detection. This tool is under development and will use the giants arcs already detected and HST data as benchmarks. Using this more rigorous and faster method, we expect that smaller, fainter and thinner arcs will be detected automatically, with limited biases. If successful, it will be generalised to find extended lensing features around smaller and more compact systems than rich clusters of galaxies.

The statistics of giant arcs needs first a large sky coverage with sub-arcsecond seeing images in order to derive statistically significant numbers. In a second step, two more filters are necessary to find counter images attached to each arc, using morphology+color information. These multiple systems will improve the mass reconstruction and will confirm the gravitational lensing nature of the arc candidate. Then, other optical filters and at least H and K band images will be necessary to constrain redshifts of all clusters of galaxies, of the arc population as well as the redshift distributions of foreground and background galaxies, for weak lensing studies.

4.4. Stellar populations in the CFHTLS

4.4.1. Objectives

The main objectives of the survey regarding stellar populations and galactic structure are twofold:
the search for very faint luminosity objects on which little is known (brown dwarfs and old white dwarfs mainly) galactic structure and kinematics, specially for old populations (spheroid and thick disc).

These objectives rely on accurate photometry and astrometry. At present no detailed analysis has been performed on astrometry. This is planned to be done with the first release of Wide data. Astrometry calibration will be checked to have an absolute astrometric accuracy at the level of the pixel, and a relative accuracy of several hundred of pixels should be possible. The present limit for absolute astrometry is that the comparison is done with the USNO-B which is not accurate enough. Relative astrometric accuracy is being evaluated using several epochs of Deep field observations, results are expected before the end of the year (Schultheis, Goldman, et al.).

4.4.2. Photometric analysis of the T0001 release

While stellar population analysis will be conducted using all 3 parts of the CFHTLS, the first release T0001 contained data only from the Deep. It gives an overview of what populations are present and to check the reliability of the data compared with the objectives. The photometric analysis will be similar either for the Deep, the Wide or the Very Wide. The first release covers only 1 epoch. No proper motions are yet possible. Preliminary studies of stellar object detected in the D1, D2 and D3 fields led to the following analysis:

4.4.2.1 Star/galaxy separation
The release provides catalogues of objects detected, including an indicator for unresolved objects. The indicator is based on the half-light radius computed in the i' band. This indicator is given for objects of magnitude less than 21. Hence the star/galaxy separation is insured for only bright objects for which a morphological classification is possible. In this stellar objects catalogues we emphasize the presence of extra-galactic compact objects, either quasars or compact galaxies.

The stellar objects catalogues up to 21 magnitude have then been analysed using colour-colour diagrams, efficient tools to identify the populations, such as the spheroid (in the blue part of the diagram), thick disc stars (in the middle), and thin disc population towards the red. Quasars are expected to lie on the blue side, but their sequence is shifted with regards to the stellar locus in the u*-g'/g'-r' diagram, and also a bit in the g'-r'/r'-i' diagram (see fig. 1).
Roser Pello provided us with a set of synthetic colors of galaxies in the Megacam photometric system. Checking the position of galaxies with various redshift in the colour-colour diagram allows us to estimate that a number of compact galaxies may contaminate the sample, outside of the stellar locus, but also possibly in the stellar locus. In order to eliminate this contamination, one must rely on proper motions (for the closest objects), when available, and on complementary observations, either in the near-infrared (for example with WIRCAM), or by spectroscopic follow-up. If such complementary observations are available for at least a part of the sample, it may be possible to establish the degree of contamination and to statistically correct the star counts for the regions where no complementary observations exist.

4.4.2.2. Galactic stellar populations

When the stellar sample is cleaned up and corrected for extragalactic contaminants, a comparison with a Galactic model may help to interpret the data. The Besançon model of the Galaxy provides a tool to identify the different stellar populations in the colour-colour and colour-magnitude diagrams. It has been adapted to produce colours in the Megacam photometric system (Schultheis et al, 2005). Figure 2 gives the position of the spheroid, thick disc and thin disc stars in the colour-colour diagrams and in the $i'$ vs $r'$-$i'$ diagram for the D3 field. Positions are about the same in other deep fields, apart from the stellar densities which may differ due to variation of the position in the Galaxy.
The photometric accuracy provided by the TERAPIX processing reveals to be sufficient to separate the 3 main populations using several colour-colour diagrams. A further analysis of the stellar densities in all deep fields will allow us to derive constraints on scale heights of the disc population and on the shape of the stellar halo. This analysis requires good statistics in several fields well separated on the sky. It will perform using all 3 surveys together, with the future releases.

4.4.2.3. Low mass stars

![Figure 2: Colour-colour diagrams of field D3 (left) as compared with the Besançon Galaxy model predictions (on the right). Stellar population are identified by their colours: spheroid (magenta), thick disc (green), thin disc (red). Star symbols indicate the expected locus of white dwarfs + red dwarfs binaries.](image)

The CFHTLS gives a new insight on the low mass stars. The volume scanned by it for these rather close stars is large enough for competing the deep star counts obtained from the HST. The latter are more remote counts where the binaries may not be resolved. The CFHTLS data allow to detect intrinsically faint stars in the solar neighbourhood in a larger volume than in the HST, thanks to the area covered. Schultheis et al (2005) have attempted to constrain the local luminosity function using D1, D2 and D3 field. They find that, to account for the number of M dwarfs in the survey, the Initial Mass Function (IMF) has to be steeper than previously thought. Moreover the number of M dwarfs observed is much larger than in the HST counts as given by Zheng et al. (2002). This implies that a large number of non-resolved systems in the HST are resolved in the CFHTLS, giving new constraints on the statistics of binarity. This preliminary analysis
will be redone with a better statistics from the Wide release. It would also benefit from a more efficient star-galaxy separation at faint magnitudes.

4.2.2.4. Brown dwarfs
Brown dwarfs are expected to be found in the CFHTLS selected from their $i'$-$z'$ colour. Figure 3 shows their position in the $r'$-$i'$ vs $i'$-$z'$ diagram as expected from NextGen atmosphere models, as well as superimposed the stellar objects detected in D1, D2 and D3. Apart from the slight shift of the D1 field (probably due to a not accurate zero point, off by 0.06 magnitude from the other fields), the model predicts colours in good agreement with the data. Spectral types indicated are from the Golimowski et al (2004 AJ, 127, 3516) temperature/spectral type relation. 3 objects are found redder than L0 stars. Near-infrared data are needed to confirm their identification, as quasars at very high redshift may have similar colour in $i'$-$z'$ but are significantly redder in the infrared.

Figure 3: D1, D2 and D3 data in the $r'$-$i'$ vs $i'$-$z'$ colour diagram. Solid line indicates the location of the theoretical dwarfs with log g=5 and solar metallicity from NextGen
models computed specifically in the CFHTLS photometric system. The spectral types come from the temperature/spectral type relation from Golimowski et al (2004). Star symbols indicate possible brown dwarfs or high redshift quasars.

4.2.2.5. White dwarfs

White dwarfs (WD) are expected to be present in the stellar sample as blue objects. Among objects bluer than the spheroid turnoff are hot white dwarfs together with horizontal branch stars from the thick disc and the spheroid. Horizontal branch stars are generally brighter than $i'=21$. In most colour-colour diagrams WD are mixed up with subdwarfs, especially the cool ones. However using a $u^*-g'$ vs $g'-r'$ diagram it may be possible to identify white dwarfs better in the CFHTLS than from the SDSS photometric system in similar colours, the $u^*$ being wider in the UV than the $u'$. Figure 4 shows the sequence of DA white dwarfs in the $u^*-g'/g'-r'$ of the SDSS and in the $u^*-g'/g'-r'$ in the CFHTLS system. Plus signs indicate the location of the subdwarfs (including random photometric errors). White dwarf models are from Bergeron, Leggett & Ruiz (2001, ApJS 133, 413) and have been kindly computed by Pierre Bergeron in the CFHTLS system. The separation between the subdwarf sequence and the WD one is better using the CFHTLS photometric system.

Figure 4: Theoretical location of DA white dwarfs (WD) in the $u^*-g'/g'-r'$ diagrams from CFHTLS photometric system and SDSS photometric system. Models are for DA white
Most of the ancient halo white dwarfs would be too faint to be observed at i’<21 where the morphological classification applies. To separate them from quasars, and, at fainter magnitudes from galaxies, one would need proper motions. They will be searched when several CFHTLS epochs will be released. One expects to be able to better constrain the fraction of the baryonic dark halo made in white dwarfs. The present upper limit has been pushed down to 4% by Crézé et al. (2004, A&A 426, 65). But this leaves place for discovering several tenth of these objects in the CFHTLS, giving new constraints on their physics, as well as on the initial mass function at early ages of the Galaxy.

4.2.2.6. Variability studies
Among the blue objects (bluer than the spheroid turnoff r'-i’<0.1) short period variable stars are expected. The identification of RR Lyrae is possible in the CFHTLS-Deep using Real Time Data, thanks to the sequence of timed observations. A team of astronomers searching for orphan afterglows is also extracting the short period variables from the RTA however it is not their priority. At present a handful of variable stars have been identified. We expect that astronomers interested in variables will join this group to analyse the real time data as well as the Very Wide for variables.

4.2.2.7. White dwarf + red dwarf pairs
Outside the mean stellar locus in the colour-colour diagrams, one may also find some stellar systems, such as the binary pairs white dwarf + red dwarf. These objects are particularly interesting for constraining the stellar physics as well as the binary probability for high initial mass ratio, hence the star formation process. These objects are expected to lie in a part of the diagrams where galaxies are, and potentially compact galaxies contaminating the stellar sample (see figure 2). However they are expected to have a measurable proper motions on a 3 year period, hence will be identified in all the 3 parts of the CFHTLS in the coming years.

4.2.3. Conclusions
On the stellar population point of view, the CFHTLS promises to be a very efficient tool. The photometric accuracy is however not at the expected level, we expect it to improve in the future, as well as the star-galaxy morphological classification. The photometric system is adequate to separate the interesting populations: u*-g’ is very useful for detecting white dwarfs, and i’-z’ for detecting brown dwarfs. However, we are waiting for getting astrometric data, and for the reliability of the proper motions. Before the end of the year, one expects to have detected the first fast moving objects.

Near-infrared follow-up would be very interesting to insure the star-galaxy classification which is at the moment a problem for analysing data at faint magnitudes. The i’-K colour index will be most useful and one encourages the follow-up of at least a part of the fields with WIRCAM. Moreover, a follow-up in z’ of the Very Wide survey has been asked on
both the Canadian and French side. This follow-up is dedicated to search for very high redshift quasars as well as brown dwarfs with i'-z' larger than 1.5 and it would allow to distinguish both type of objects from each other. It would add significantly to the legacy value of this survey.