HETDEX
Hobby-Eberly Telescope Dark Energy Experiment

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The HOBBY-EBERLY TELESCOPE DARK ENERGY EXPERIMENT

The solution to the problem of dark energy will require a fundamental shift in our understanding of the universe, and acceptance of any model will require significant corroboration with observations. The Hobby-Eberly Telescope Dark Energy Experiment, HETDEX, offers a technically clean and observationally robust approach to measuring the effects of dark energy. The project has three parts: upgrade of the HET to have a $22'$ diameter field-of-view, deployment of the VIRUS integral field spectrograph, and completion of a wide field survey to constrain the evolution of dark energy. In 1400 hours of observations on the Hobby-Eberly Telescope, we will obtain approximately 0.8 million redshifts of Lyman-α emitting galaxies. This survey will determine the local Hubble expansion at $z = 2.4$ and angular diameter distance out to $z = 2.4$ to 0.8% each and the growth of structure at $z = 2.4$ to 2%. Our approach is to observe 420 contiguous square degrees with a 1/7 fill factor with the instrument VIRUS, composed of 75 integral field units feeding 150 spectrographs. With a spectral range of 350–550 nm and spectral resolution of 6.4Å, we can identify Lyman-alpha emitting galaxies at $1.9 < z < 3.5$. HETDEX further will measure curvature of the universe to about 0.1%, which is over a factor of ten better than current projects; this measurement of curvature will then be leveraged by all late-time dark energy experiments since there is a degeneracy of curvature with dark energy. Thus, HETDEX strongly complements future and on-going studies. With no theoretical guidance as to the nature of dark energy, HETDEX takes the approach of exploring a new part of parameter space as well as significantly reducing uncertainties on the effect of dark energy at late times. HETDEX is optimized for measures of the expansion history, but there is significant additional science from the survey (e.g., spectra of a 0.25 million stars and 1.4 million other galaxies); given its capability, VIRUS will remain the primary instrument for HET for many years after completion. VIRUS will also be operated in a parallel mode with the other HET instruments, so that after 10 years of HET operation, we have the ability to increase the area surveyed by VIRUS by a factor of 5–10. This mode will have very strong scientific implications for a large variety of science, for example, direct detection of the cosmic web, new regimes for studying Galactic structure, finding the most metal poor stars, constraints on non-Gaussianity, and probes of outer regions of nearby galaxies for measures of dark matter and star formation. All of these investigations are enabled by VIRUS and HETDEX but will require additional organizational structure and data analysis not currently budgeted.

The significant insights on dark energy, the large database with substantial overall science, and the availability of a unique and powerful integral field spectrograph that takes at least 33,600 spectra per exposure on the HET will have a broad impact on the astronomy community. The large, blind spectroscopic capability opens new regions of phase space (such as the emission-line universe) for general use. Also, given the importance of dark energy and the financial investment from the public, we must reach beyond the science community. With dark energy, the astronomical community has an extraordinary opportunity to engage the public in a way that is rarely possible. We are creating a significant outreach component involving the McDonald Observatory Visitors Center and Stardate radio. We also have a popular webpage (hetdex.org, which has 0.4M visits as of March 2009) that we continually update. We plan to exploit fully HETDEX in this manner.

1 Science Case Overview

HETDEX will be able to determine the Hubble expansion, $H(z)$, at $z = 2.4$ and angular diameter distance, $D_A(z)$, out to $z = 2.4$ to a precision of $\sim 0.8\%$ each, and the growth of structure at $z = 2.4$ to 2%. Additionally, HETDEX will be able to measure the curvature of the universe to around 0.1%, over a factor of ten better than currently known. Since the observable property—the expansion rate—is determined by both dark energy and curvature, HETDEX's measure of curvature will break the degeneracy and improve constraints provided by all lower redshift measurements. By observing in the redshift range $1.9 < z < 3.5$, HETDEX will provide unique information on the evolution of dark energy. Since nearly all other dark energy experiments target lower redshifts, HETDEX is an excellent complement to the dark energy landscape. The fully calibrated HETDEX dataset will be available to the public.

Despite the gross difference in magnitude from the theoretical prediction (providing too large a value by a factor ranging from 10^{56} to 10^{120}), the most promising candidate for dark energy remains the vacuum energy, or Einstein's "cosmological constant". Nevertheless, although the measurements provide strong support for the existence of the cosmological constant, the present uncertainties remain large enough to encompass a plethora of alternative models. There are two obvious strategies for moving forward: improve the accuracy of measurements of present day cosmic expansion, or investigate the history of expansion at a previously unexplored epoch. Both approaches seek to measure the properties of dark energy and its potential evolution while avoiding a host of systematic effects, and, given the importance of the problem, any robust plan must encompass both strategies. The goal of HETDEX is to obtain the most accurate measure to date of the expansion history of the universe from $1.9 < z < 3.5$.

The basic question the science community must ask itself is whether they want the combined dark energy program, across all space-based and ground-based efforts, to be a null result. By focussing solely on the epoch where we already have solid evidence that we do not understand the expansion history, reducing this accuracy may serve to only enforce what we have already assumed, the cosmological constant. This approach may not, however, bring us any closer to understanding the nature of dark energy; i.e., knowing the cosmological constant to 8% or less than 1% is theoretically irrelevant. We must always remember that dark energy has not been detected at $z > 2$: we only believe its existence based upon the extrapolation of our knowledge at $z < 2$. Given our ignorance of the nature of dark energy, such an extrapolation is not justified. HETDEX takes the approach of studying a new epoch in the universe and measuring the expansion history as well as possible. There are no experiments on-going or planned that provide as stringent a measure of the expansion rate at $z > 2$. Thus, HETDEX will make a fundamental and long-lasting impact on dark energy, curvature, and its significant amount of ancillary science.

1.1 HETDEX in the Dark Energy Landscape

HETDEX will employ a large set of integral field unit spectrographs to determine the positions and redshift of approximately 0.8 million Lyα emitting galaxies at redshifts between 1.9 and 3.5. Our baseline survey involves 1400 hours of observations, distributed over three years on the 10-meter Hobby-Eberly Telescope (HET). In the parlance of the Dark Energy Task Force (DETF), this “Stage III’ experiment is designed to provide an increase in the DETF Figure of Merit (FoM) of a factor greater than 5 over a “Stage II” survey. We are currently designing a parallel mode for instrument VIRUS, which will allow a substantial increase in the survey area. Estimates show that, over 10 years of operation of HET, we could increase our survey by a factor of 10, with no new hardware or extra allocated observing on the telescope. HETDEX then becomes a “Stage IV” dark energy mission.

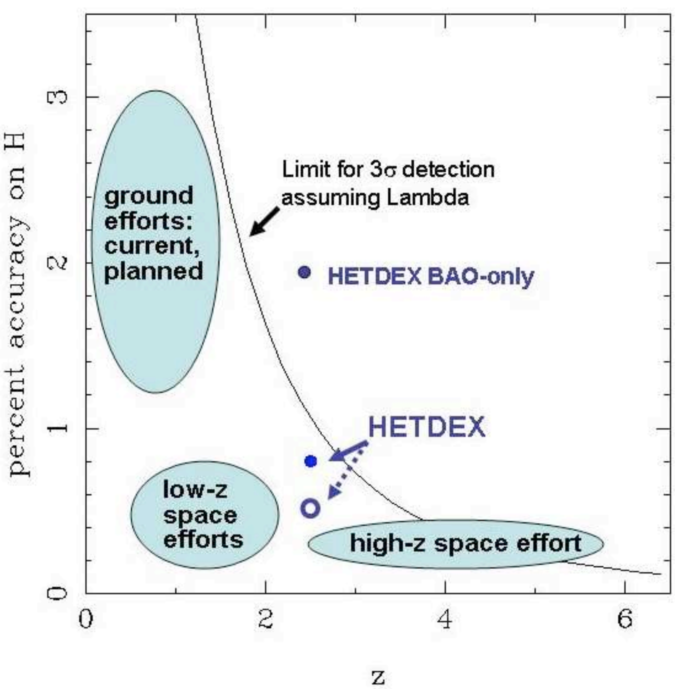

Figure 1: Accuracy on the Hubble expansion rate, $H(z)$, versus redshift. The black line is the accuracy that is required for a direct detection of dark energy (at 3-sigma) assuming a cosmological constant; in other words, this curve represents what is required in order to measure that dark energy has an effect on the expansion rate. We include expected results from planned ground-based experiments. The low-z and high-z space efforts represent expectations from a space mission (e.g., JDEM, Euclid, CIP). HETDEX is included 3 times, with results using baryonic acoustic oscillations only (solid point at 2%), using the full power spectrum analysis with the baseline survey (solid point at 0.8%), and results from a possible survey extension (open symbol at 0.5%).

The main driver for HETDEX is to provide a significant (3-sigma or better) direct detection of dark energy over an unexplored epoch, under the assumption that dark energy is a cosmological constant. With this goal, HETDEX must obtain constraints on the expansion history to better than 1%, specifically on the distance measures of the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$. This analysis is focussed on redshifts z=1.9 to 3.5 using the power spectrum of galaxies. This goal requires an accuracy of 1.0% on $H(z)$ at $z = 2.5$; this in turn requires a survey volume of 9 Gpc^3 for a density of tracers of $\sim 10^{-4}$ objects per Mpc^3. Our approach is to obtain redshifts for 0.8 million LAE galaxies in the redshift range $1.9 < z < 3.5$ with a survey of 420 deg^2.

Figure 1 places results from HETDEX in context with other ground-based and space-based dark energy experiments. The solid line in the figure shows the accuracy needed on $H(z)$ to provide a 3-sigma direct detection of dark energy. Of course, dark energy is already required to explain the expansion rate at low redshifts, and the current focus at those redshifts is to measure potential evolution. In that case, one is not concerned so much to have a direct detection (the solid line), but to look for evolution across a small redshift range (as the low-z ground experiments target). However, there are no measurements at high redshift that demonstrate that dark energy is required. Thus, the main result for dark energy research from HETDEX will be a high-precision measure of the expansion rate at $z > 2$, providing crucial constraints on any cosmological model, including dark energy evolution. In terms of raw accuracy on the expansion rate, HETDEX competes with the space-based experiments. The fundamental parameter for any dark energy study should be the accuracy on the expansion rate as opposed to constraining a particular model for dark energy, since it is the misunderstanding of the observed expansion rate that is causing us to re-evaluate our basic model of the universe.

1.2 HETDEX and Curvature of the Universe

In addition to a direct detection of dark energy from $H(z)$, a 0.8% measure of D_A at $z = 2.4$ (which the HETDEX baseline will provide) will fix the curvature of the universe to about 0.1%. The calculation is fairly straight-forward: if dark energy is not important at $z > 3$ (for example, if it is a cosmological constant), then the *difference* between HETDEX's measure of D_A out to $z = 2 - 4$ and D_A out to $z = 1090$ given by the CMB (via the measurement of the locations of the acoustic peaks) depends, to a good approximation, only on the sum of the matter density and curvature. Moreover, CMB experiments accurately measure the matter density via the ratios of the height of the acoustic peaks, and therefore HETDEX's measure of D_A will directly relate to the curvature. If dark energy is important at $z > 3$, it will be detected by HETDEX's $H(z)$ measurement. Either way, HETDEX will make a fundamental contribution to the study of the expansion history and dark energy. The present constraint on curvature from WMAP is about 2% (with the assumption that dark energy is a cosmological constant). Thus, HETDEX will measure curvature over a factor of ten better than previously known. Note that nearly all other dark energy missions require some knowledge of curvature to measure dark energy, simply because curvature affects the observed expansion rate. The curvature constraint derived from HETDEX can therefore be used to enhance all low redshift studies. For some experiments, the factor of ten increase in precision in the curvature will be a significant advance.

1.3 Constraints on Expansion History

There have been many papers and reports dedicated to designing a Figure-of-Merit (FoM) for a dark energy program. All have their own sets of advantages and disadvantages. With little to no theoretical guidance as to the nature of dark energy, it is not a surprise that there is no uniform design of a FoM. The most recent FoM comes from a panel convened by NASA and DoE, called the JDEM FoMSWG (Joint Dark Energy Mission Figure-of-Merit Science Working Group). The FoMSWG FoM represents $w(z)$ via 36 principal components (piecewise continuous redshift bins), and uses the uncertainties in each bin in a Fisher matrix to determine the DETF FoM. The DETF FoM assumes that w is represented by a linear function (i.e., two parameters). Thus, while the FoMSWG utilizes 36 parameters, the main result comes from translation to a two-parameter model. To calibrate, the FoMSWG assumes that all current ground-based experiments combined will provide a DETF FoM of 116 (by the year 2016), and JDEM has a value greater than 300. A very important aspect of the JDEM FoMSWG is that they provide the code to calculate the resulting DETF FoM, and also provide the Fisher matrices for current/planned ground-based experiments and for Planck. This allows everyone to have a uniform set of priors. The two additional required pieces of information are the accuracy on H and D_A for a given survey and how those accuracies translate into uncertainties in the 36 redshift bins used for w. The baseline HETDEX accuracies on H and D_A are 0.8% for each at $z = 2.4$ (our average redshift weighted by the number of LAEs). These accuracy numbers come from our analysis of the expected full power spectrum. Combining with Planck and current ground-based dark energy experiments, these yield a DETF FoM of 170. The JDEM FoMSWG's value for all "Stage III" dark energy experiments is 116. They include HETDEX in their estimate but use only the distance accuracies as measured from the baryonic acoustic oscillation signal. As shown in Figure 1, this result is over two times worse than using the full power spectrum. For an extension of the HETDEX survey via a parallel mode or directed observations, accuracies on the distances go below 0.5%, and the FoM increases to more than 300.

The full constraints from HETDEX are based on using the shape of the galaxy power spectrum to measure the distance indicators. Most approaches to studying dark energy that are based on large scale structure rely on using only the baryonic acoustic oscillation signal (BAO). The reason for this is that the BAO provides a robust signal that is subject to minor corrections from non-linear effects in galaxy clustering. These corrections are small, around 0.5% at $z = 0.3$ to 0.2% at $z = 1.5$, and can be corrected by using cosmological simulations. Of course, the predicted correction is only as good as the simulation, but since the bias is small to begin with, the correction should be fairly accurate. The effect of biases in the BAO scale position is currently a topic of great interest to the community, as it is thought to be important for redshifts $z < 2$. For $z > 2$, however, the non-linearities in the BAO scale length are small enough so that most observational approaches will be limited by statistics, rather than systematics. In order to extract information from the full shape of the power spectrum, we need to understand the importance of non-linear effects in the growth of cosmic structure to a higher degree than what is required for BAO. We use 3rd order linear perturbation theory and numerical cosmological simulations to correct for non-linearities in the matter power spectrum, the redshift-space distortion, and the bias, to 1% for inverse scales of $k < 0.3$ Mpc^{-1}.

As designed, HETDEX is focussed at $z > 1.9$; this allows exploitation of a different set of information contained in the large-scale structure of galaxies. Rather than just measuring BAO, we can use the full shape of the power spectrum, including the Alcock-Paczynski test. Figure 2 demonstrates how we will use the power spectrum to measure cosmological parameters. In the figure, the solid line represents the theoretical model for the galaxy power spectrum (calculation explained below). We then take our observed galaxy power spectrum (the expected uncertainties are shown in the figure) and match the two profiles. There is both a vertical shift and a horizontal shift made during this fit. A horizontal shift is a geometric measure since it is only shifting the scale of the profile.

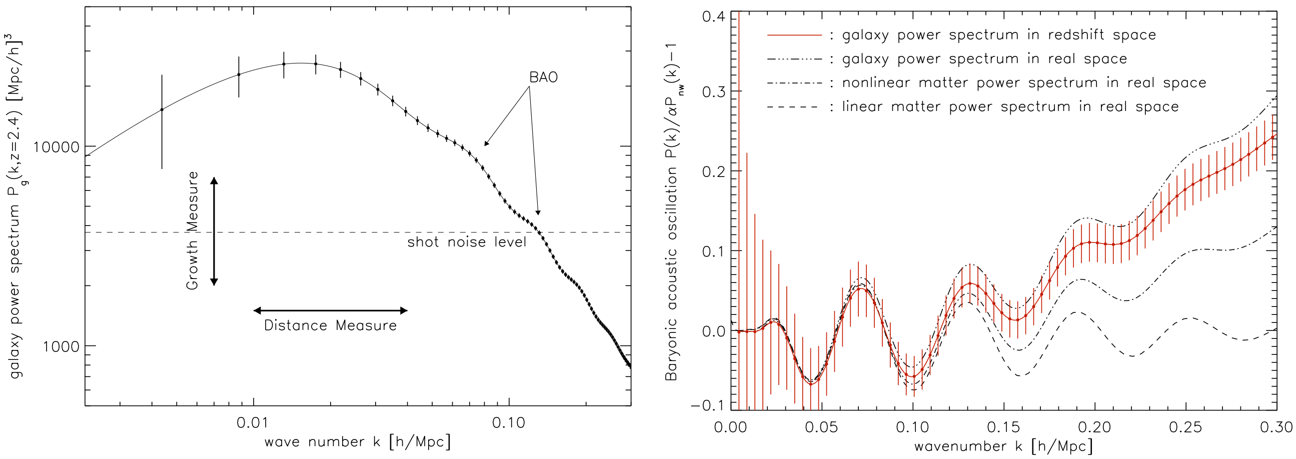

Figure 2: Theoretical power spectrum that will be measured by the baseline HETDEX survey. **LEFT:** The solid line is the theoretical model of the galaxy power spectrum at $z = 2.4$. Points represent the locations in k-space where HETDEX will provide independent measures of the power. The shot noise level is shown; for $k > 0.13$ the uncertainties are dominated by shot noise and for $k < 0.13$ they are dominated by cosmic variance. Using the full shape of the power spectrum, the horizontal shift from the fiducial model is mainly related to the distance (i.e., geometric) indicators D_A and H, and the vertical shift relates to the growth of structure (i.e., dynamical), and the galaxy bias factor. The wiggles in the spectrum are the BAO. **RIGHT:** Same model as on the left, but with the no wiggle power spectrum removed. We show different aspects of the non-linear corrections, with linear only (bottom), then including non-linearity in clustering of dark matter (second from bottom), then including non-linearities in galaxy bias (top), and finally including redshift space distortion due to peculiar velocity (3rd line from bottom, with error bars that we expect from HETDEX).

In Fig. 2 we plot the one dimensional power spectrum, where we have combined information from both the radial (H) and angular (D_A) profiles. A vertical shift provides a measure of growth of structure since it is related to the amount of power at a given scale; the vertical shift also depends on the galaxy bias parameter. We will use the three-point function (bispectrum) suitably normalized by the power spectra, which depends primarily on the bias, to measure and fix the bias to 2% accuracy. This allows us to extract the growth of structures at the same level of accuracy, i.e., 2%. Obviously, there is some degeneracy between the orthogonal shifts (for example, if the power spectrum is a pure power law, they would be have a perfect correlation), requiring a simultaneous fit. BAO techniques rely solely on a horizontal shift, after removing an underlying smooth profile (represented by the graph on the right). However, the BAO signal is a very small part of the information contained in the power spectrum, as is obvious in the left panel in Fig. 2. Thus, HETDEX relies on having an accurate theoretical estimate of the fiducial power spectrum, which then allows us to fit $H(z)$, $D_A(z)$, and growth of structure, $G(z)$. Given the uncertainties as expected from the detailed simulations we have done and the uncertainties from non-linear corrections, a simultaneous fit provides uncertainties on H and D_A to about 0.8% and G to about 2%, at $z = 2.4$.

1.4 Other Science

We have optimized HETDEX, both the instrument and survey, to maximize our ability to constrain the expansion history of the universe from $1.9 < z < 3.5$. The result, however, will be a database that presents a multitude of additional significant science. We also expect VIRUS to become the primary HET instrument for years after completion of the baseline survey. We are working closely with the HET and HETDEX consortium members in order to optimize the additional science that will be enabled. We organized a workshop (Feb 17-18, 2009) designed specifically to discuss these science topics, which was well attended by all consortium members. The ways in which additional science is achieved are 1) data on the objects that lie within the main HETDEX survey, 2) other science enabled with the instrument VIRUS, 3) parallel science when other instruments on the HET are being used since VIRUS is able to take data simultaneously, and 4) through possible modifications with future upgrades to VIRUS. The list of ancillary science is long and we provide only a partial listing of the exciting possibilities:

1. HETDEX can detect the cosmic web by summing specific fibers across the full survey (both HETDEX fields and the full parallel fields). Based on theoretical models, we will provide a positive detection of the Lyman-alpha emission from the cosmic web.
2. With at least a million stars at S/N=10 per resolution element down to R=22, the parallel data will trace new regimes for Galactic structure models. Most of the stellar work on other facilities focusses on larger area coverage with much brighter stars. VIRUS will open up new avenues of research for Galactic structure.
3. The same stellar data will be used to find the most metal-poor stars. Again, given the faint magnitudes probed, this survey will be unique for this exploration.
4. Combining the LAE spectra with a multi-wavelength imaging survey will allow us to uncover the physical nature of these systems.
5. The larger area covered by the parallel mode allows constraints better than those expected from Planck on non-Gaussianity. This constraint, combined with the increase that HETDEX provides for curvature, allows for some of the best measures on inflation.
6. The faint surface brightness limit offered by VIRUS allows measure of the dark matter profile and star formation rate at the outer edges of nearby galaxies.
7. The HETDEX survey will detect more than 25000 AGN up to $z = 3.5$ without any preselection biases. Taken together with the one million galaxies, this will provide a very significant increase in sample size for AGN-galaxy correlation studies. For all parallel observations, these numbers increase by 5–10 times.
8. By combining the VIRUS spectra of the LAEs, detection of the HeII 1640 line would signify population III stars at redshifts from $1.9 < z < 3.5$.
9. With over a million local [OII] emitters, HETDEX will provide the best estimate (by a significant amount) of the local star formation rate.
10. Millions of spectroscopic redshifts, many of which will have photometric redshifts, will provide the best calibration for photo-z studies over redshifts that are little explored.

The above exciting science and significant amount of additional science not listed here enabled by VIRUS and HETDEX is currently not budgeted. As we develop the software for HETDEX, we are cognizant of the needs for the full community, but we need additional financial and organizational support for it to work. We will explore options as we progress, and it is our intention to make all data available to the public.

2 Technical Overview

2.1 Survey Design

For HETDEX, we will cover 420 square degrees with a 1/7 fill factor using a blind spectroscopic survey. To cover 420 square degrees with the HET 22′ diameter field requires about 4000 pointings. Sensitivity estimates predict a limit of 3.5×10^{-17} ergs/cm^2/s in 20 minutes of observation for each pointing which then requires about 1400 clear hours (including overhead). Given the pointing constraints of HET, the most efficient location is a spring field at high declination (centered at $\alpha = 11^{\mathrm{h}}$, $\delta = +58°$). Including overheads and using all of the time available for this field during a year, this survey will take 3 years, although even the first year's data will provide interesting results. Our field dimension is rectangular, being 6 degrees in declination by 70 degrees in RA. This footprint optimizes HET observing efficiency while not having an impact on the measure of the power spectrum. Going to a larger aspect ratio would only slightly further help the observing efficiency, but would start to impact our ability to measure power on large scales. Another option that we are exploring is to include a fall field. There are a variety of advantages for doing this (e.g., accessible field for both northern and southern telescopes), but the details have to be worked out before we change the baseline program. Having one 6x70 or two 6x35 square degree fields will give nearly identical results for the uncertainties on H and D_A. Splitting the fields will allow us to finish the baseline program by 2012. We have identified a fall field that is efficient for HET to observe and has low enough extinction to be useful (centered around 2^{h},0°). A Fall field will benefit substantially from other current and planned efforts (e.g., DES, LSST).

We do not need to cover completely the 22′ field with IFUs, since LAEs are numerous enough that this would produce significantly more galaxies than we require. The number of tracers required for optimum constraints is well understood and above a certain density, there is little gain. Thus, there is a trade on number of spectrographs, number of fibers, spacing of the integral field units, and exposure time, since these directly influence the number of objects detected and field size. Our final design has taken all of these trades into consideration. The one trade that relates directly to cost is number of spectrographs, which is set at 150. This number is designed to provide a direct detection of dark energy. By increasing the number of spectrographs, we then are able either to provide a more accurate measure of dark energy or to mitigate both instrumental and observational risk. Thus, we have designed all aspects of the upgrade to accommodate up to 192 spectrographs. The goal of 192 spectrographs will only be realized if additional funding for this enhancement is secured.

Our final configuration for the HETDEX survey is to cover 420 square degrees with about 4000 pointings of the 22′ field. Within each pointing, we have 75 IFUs each with 448 fibers of 1.5″ diameter. In a dither pattern of three pointings the IFU covers an effective sky area of 50x50 square arcsec accounting for gaps and edge effects. The 75 IFUs will be spread evenly over the 22′ field, which after dithering fills the field by 1/7 or 60 square arcmin per dithered pointing. Over the full 420 square degrees, the HETDEX survey will have covered 60 square degrees. Using 192 spectrographs (96 IFUs) allows us to cover 77 square degrees in the 420 square degree field. We have done extensive simulations using cosmological models to determine whether the sparse sampling will have an affect, and there is no concern at the level of constraint that HETDEX will obtain.

2.2 Instrumental Overview

The HET is an innovative telescope with an 11 m hexagonal-shaped spherical mirror comprising 91 identical 1 m hexagonal segments that are supported by a steel truss. The mirror sits at a fixed zenith angle of 35 degrees and can move 360 degrees in azimuth to access about 70% of the sky visible at the observatory. Images of astronomical objects are acquired and followed across the spherical focal surface of the primary mirror by means of a tracker which is mounted on top of the telescope. The tracker carries the 4-mirror spherical aberration corrector, as well as instrumentation to position it, aligned with the primary mirror, and science instrument feeds. The Wide Field Upgrade (WFU) will improve system performance and add new capabilities. A new Wide Field Corrector (WFC, being constructed by the University of Arizona College of Optical Sciences) will increase the field of view from 4 to 22 arcminutes diameter. The new tracker is being constructed in collaboration with the University of Texas Center for Electromechanics (CEM), and the new instrument package will include wavefront sensing and metrology to provide complete feedback on all degrees of freedom of the system. Figure 3 shows the upgraded HET.

VIRUS uses industrial-scale replication to break the cost-curve associated with large instruments on the next-generation large telescopes. Purchase of components such as detectors and optics in large batches minimizes cost and amortizes the engineering development costs over many units. Performance and cost can be proven during prototype development and the parallel nature of the instrument also allows the software to be developed and tested ahead of deployment of the full instrument. This approach reduces risk, speeds deployment, and cuts cost relative to large monolithic astronomical instruments.

In preparation for HETDEX, a prototype building block of the VIRUS, VIRUS-P, has been constructed and has been operating on the McDonald Observatory 2.7-meter telescope since October 2006, undertaking a pilot survey of LAEs. VIRUS-P has met or exceeded all requirements needed for the final VIRUS replicated units, including image quality, throughput, and stability. The design is now being evolved for production, minimizing the cost. We have made some significant changes to the design, based on experience with the prototype and the engineering of the HET Wide Field Upgrade. The most significant change has been to double the spectrographs so that each pair shares a single IFU, a common collimator housing, and a common cryostat. The motivation for this came first from fiber cable handling: it is more efficient in terms of weight and cross-sectional area to double the number of fibers in a cable. Note that the fiber itself is not the dominant weight in a bundle. Although this does not produce a large cost-savings for the IFUs, it does make the cable handling significantly easier with 75. (The ultimate goal is to have 92 cables, and the IFU handling system is being designed for this number.) The other advantage of doubling the spectrographs is that two cameras can share a vacuum, with single connection to the LN2 cooling.

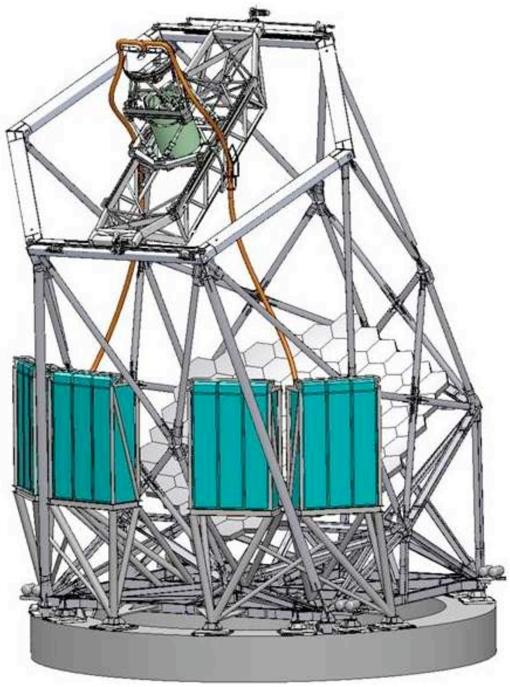

Figure 3: Drawing of the upgraded HET with all components, the new Tracker, PFIP, WFC. The boxes (blue-green) on the sides of the telescope house the suite of spectrographs for VIRUS. The two cables (orange) contain the fibers which run from the IFUs to the spectrographs.

The VIRUS production schedule has a pre-production prototype design phase extending to mid 2009 and a manufacturing phase that follows. Five units (with 10 spectrographs) are currently funded. The VIRUS-P prototype confirmed the optical and engineering performance, and the pre-production design phase has concentrated on simplifying the design with emphasis on streamlining the assembly and optical setup of the units. As part of the design development we are prototyping critical components, particularly those in the camera, and the major castings so as to remove any uncertainty in the manufacturability prior to mass production. The production design of the collimator assembly is now be frozen. The optics design is frozen and we are in the process of procuring optics sets for the pre-production prototypes. The camera design is well advanced but the final design of the detector heads will be done as NRE with the selected detector vendor. While the detector system procurement is not part of the funding sought in this grant proposal, the development schedule for the detector system is the pacing item in the overall production schedule and the design of the CCD package is an important part of that procurement. Discussions with vendors indicate that the current conceptual design for the CCD package and the detector head is manufacturable, and details will be resolved with the delivery of a non-functioning detector head assembly early in the contract (estimated Q3 2009). The second deliverable is a fully-functioning pair of detectors with electronics integrated into their detector head assemblies, and is expected in Q1 2010. These detectors will be integrated into a camera cryostat and used for a final verification of the alignment procedures on the camera and an evaluation of the performance of the five collimator assemblies. At that point full production of the detectors will start. The first batch of detectors and readout electronics are due in Q2 2010, at which point the first five production cameras will be integrated and those spectrograph units will be evaluated. Full production will continue for the following year with delivery of the last components in Q1 2011 at the same time as the new Wide Field Corrector will be delivered and the WFU will be ready to deploy on HET. Spectrographs will be available for mounting at the same time as the WFU is installed, and the full compliment will be installed by mid 2011.

2.3 Project Oversight and Reviews

HETDEX is being carried out by the University of Texas at Austin McDonald Observatory in cooperation with HETDEX partners and the HET consortium.

The HET Board provides primary oversight of the HETDEX project. The HET Board, made up of representatives of the HET consortium member institutions, carries out its oversight through the following: 1) the project provides the HET Board with regular reports at its bi-annual meetings. 2) The project provides regular status updates, in writing and via periodic teleconferences, to a HET Board appointed HETDEX Standing Oversight Committee. This committee reports to the HET Board on progress and coordinates the resolution of issues requiring Board or HET community input. 3) the HET Board selects external panels and defines the charge for a series of external project reviews. Major reviews currently planned are shown in the table above.

In addition, each major subsystem will have appropriate subsystem design reviews. Where major subsystems or components are procured by external contract, these reviews will be defined in the Statement of Work for the contract.

Finally, the DEX Coordination Committee (DCC), chaired by the Project Scientist with members from each HETDEX partner institution, oversees the use of the allocated telescope time for the project and establishes guidelines for publication and exploitation of the dataset. The DCC provides representation for partners of HETDEX who are not members of the HET consortium.

Science Requirements Review: The HETDEX Science Requirements Review was held on two days in June 2007. The review panel consisted of Gary Bernstein (Chair, U. Penn), Roland Bacon (CRAL, Lyon), Gerry Gilmore (Cambridge), Rocky Kolb (Chicago), and Steve Rawlings (Oxford). HETDEX received a very positive response from the committee. The committee highlighted that 1) HETDEX offers excellent discovery space by focussing on a previously unexplored epoch, 2) a direct detection of dark energy at $2 < z < 4$ would be a very significant gain in our understanding of dark energy, and 3) the measure of curvature of the Universe from HETDEX will be unparalleled and extremely important for other dark energy experiments. The committee was enthusiastic about HETDEX and strongly desires to see this project succeed.

Preliminary Design Review: The HETDEX Preliminary Design Review was held at the McDonald Observatory on 10-11 April 2008. The review panel included Bruce Bigelow (UC Santa Cruz), Gary Chanan (UC Irvine), Richard Kurz (ESO), Adrian Russell (NRAO, Chair) and Ray Sharples (University of Durham). In addition to the two days of presentation, the project provided more than 1000 pages of documents to the panel for their review.

The panel submitted a written report to the HET Board and the panel chair briefed the Board on their recommendations and conclusions. The Board accepted the panel report and the project's response, reaffirming the Board's strong endorsement for the project. The panel made the following general observations:

"HETDEX is a compelling project, addressing what is arguably one the most exciting areas of astrophysical research today. The Panel was very impressed with the quality of the HETDEX personnel, who are clearly both very talented and highly motivated.

Whilst the PDR Charge does not call for a pass fail analysis, it is clear to the panel that the project has successfully reached PDR level and is ready to move on to the next phase. Of course there remains a lot of work to complete the project, but we believe that the foundations are strong."

Based on the recommendations of the panel, the project has made a number of changes to the project scope, initiated specific additional analysis tasks, and created an explicit means of making tradeoff decisions that impact science other than dark energy.

3 Technical Development

The technical development phase is largely over and we are now focussed on the implementation and testing phase. Below is the project status on the major components.

Following the Successful system Preliminary Design Review, the project has moved rapidly into detailed design. We have executed contracts for the major subsystems of the Wide Field Upgrade, begun detailed design of those WFU subsystems being completed in-house and are beginning fabrication of prototype VIRUS Unit Spectrographs.

The Center for Electromechanics (CEM), a research center of the University of Texas, has been contracted to complete the detailed design and fabrication of the new Tracker. CEM has completed two design reviews for the Tracker and will hold a Critical Design Review in May 2009. They have executed a contract for the Tracker Hexapod, the longest-lead tracker procurement. CEM will begin to fabricate and assemble the Tracker in their high bay facility in Austin beginning after CDR. The tracker will be tested at their facility and integrated with the Telescope Control System software prior to installation at the HET.

The College of Optical Sciences (COS) of the University of Arizona is building the Wide Field Corrector. COS has completed a Preliminary Design Review and will hold a Critical Design Review in June 2009. The four mirror corrector will be fabricated in the COS facilities. Factory testing will include complete optical testing at all operating angles. The WFC, the critical path of the project, is scheduled for delivery in the first quarter of 2011.

The remaining major Wide Field Upgrade subsystem, the Prime Focus Instrument Package (PFIP), is being designed in-house. PFIP includes the ensemble of metrology instruments used to maintain pointing and image quality. Most of the metrology instruments are based on existing designs from the current HET. The design of the PFIP support structure is developing in parallel with the mechanical designs of the Tracker and WFC to which it interfaces.

The production design of the VIRUS Unit Spectrographs is also being completed in-house in collaboration with Texas A&M University. A request for proposals is underway for the detectors system which includes CCDs and readout electronics. A prototype camera assembly, including aluminum and Invar castings, will be completed in July 2009. A prototype of the liquid nitrogen distribution system used to cool the detectors has been assembled and is currently undergoing performance testing.

The first production run of Integral Field Unit (IFU) fiber bundles has been completed in collaboration with the Astronomical Institute of Potsdam and the Max Planck Institute for Extraterrestrial Physics. Nine complete IFUs, supporting nine pairs of spectrographs, have been produced commercially using technology transferred from AIP. A tenth IFU will be used to conduct accelerated life testing.

Initial pipelined software have been developed independently at MPE and UT for reduction of the pilot survey data. MPE has the responsibility for the pipeline of the full HETDEX survey, and the pilot survey reductions show excellent progress. We will continue to run both pipelines for the pilot survey in order to refine and improve the emission-line detections.

While not technical, a main focus is to understand the observational and astrophysical risks. The most pressing issues are determining the bias of the LAE population, the ability to discriminate Lyman-alpha emission from [OII] emission, understanding the redshift evolution of LAEs, and quantifying our ability to correct for the non-linearities in the power spectrum. The pilot survey, which has been on-going for two years and will continue for at least one more, is designed to address the observational and data analysis concerns. The current results suggest that, including a modest imaging survey, we can confidently discriminate LAEs and that the redshift evolution is as previously assumed. A robust estimate of the bias will require an additional year of pilot survey data and, for now, we use a conservative estimate of the LAE bias. We have an aggressive theoretical effort on-going in order to quantify all non-linear corrections. Our goal is to have these concerns understood by early 2011.

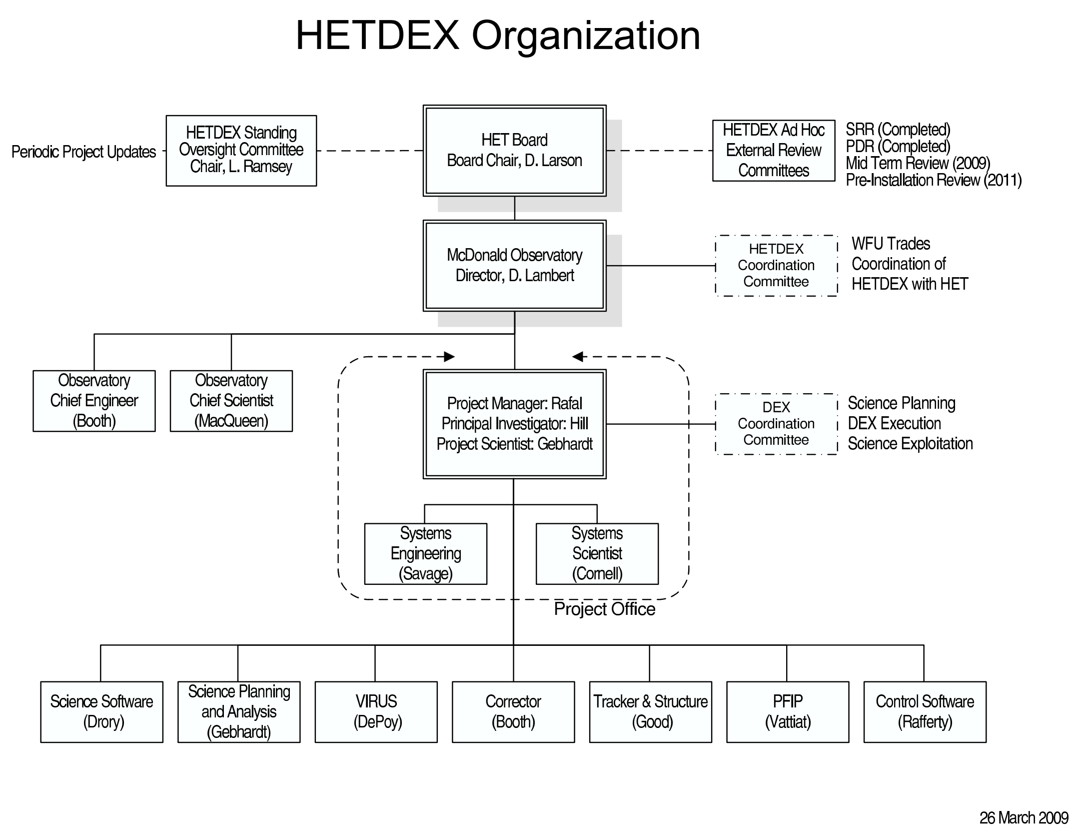

Figure 4: Organizational chart for HETDEX.

4 Organization

HETDEX is led by The University of Texas McDonald Observatory with the participation of Pennsylvania State University, Universitaets-Sternwarte Muenchen, Max-Planck-Institut fuer Extraterrestrische Physik, Astrophysikalisches Institut Potsdam, and Texas A&M University. HET is a collaboration of the University of Texas at Austin, Pennsylvania State University, Stanford University, Universitaets-Sternwarte Muenchen, and Georg-August Universitaet Goettingen. The HET Board of Directors has endorsed HETDEX and will authorize the necessary modifications to HET, installation of VIRUS, and the execution of the DEX Survey subject to its oversight through a series of formal project reviews. The HET Board of Directors is kept informed of progress through regular reports and through a Standing Oversight Committee chaired by L. Ramsey.

The HETDEX management team has been working together since before the project officially started in September 2007. They have responsibility for the full scope of HETDEX from the HET Wide Field Upgrade and VIRUS to the delivery of science results. HETDEX is managed by a Project Manager (PM) Marc Rafal, Principal Investigator (PI) Gary Hill, and Project Scientist (PS) Karl Gebhardt, each of whom report to the Director of McDonald Observatory. Together, they share responsibility for the budget, schedule and scientific goals of the project. The Systems Engineer, Richard Savage, and Systems Scientist, Mark Cornell, join these three to form the HETDEX Project Office. Collectively, they are responsible for meeting the scientific goals of the project and delivering the project within the schedule and budget. Figure 4 shows the organizational chart for HETDEX.

5 Cost Estimate

The full budget for HETDEX is $36.1M (in real year dollars) in direct costs. The top level budget includes the Wide Field Upgrade ($13.8M), VIRUS ($13.1M), Data Analysis ($2.8M), Science Support ($0.8M), Survey Execution ($1.3M) and Management ($1.9M).

To date we have received commitments and pledges of $24.3M for the project. The pacing item for the project is the HET Wide Field Upgrade, which is now fully-funded. VIRUS is partly funded. The remaining funds to be raised cover completion of VIRUS, science support and remaining management. We seek to raise the total project funds with our private and State fund raising efforts. However, we accept the reality of what we can obtain privately, even though we have been very successful. We therefore are asking for funds from the NSF.

The budget estimates are based on contract costs for those procurements underway, vendor estimates for preliminary designs and realistic extrapolations from previous projects. We are currently in the process of building the first set of 10 VIRUS spectrographs and acquiring the entire detector system of 150 units.

We do not include in the budget the required additional science support for the data analysis and interpretation in terms of the dark energy constraints from HETDEX. This entails mainly providing an accurate measure of the power spectrum from the velocities and position. Other needs are, for example, night-to-night observational planning, pipeline maintenance, quantifying the window function given the actual observing conditions and footprint, reconstruction of the density field to improve the constraints, measuring growth of structure, integrating other dark energy experiments for combined constraints, follow-up spectroscopy of LAE and [OII] galaxies, larger numerical simulations including galaxies and Lyman-alpha emission. We estimate that we will require an additional $2–3 million from the US partners in terms of science support in order to reach final publication of HETDEX results. This additional support is a relatively robust estimate based on experience from the pilot survey and tests with the numerical modeling to date.

We also do not include support for parallel observations, including pipeline data analysis, distribution and interpretation. We will seek additional support for this aspect.

6 Schedule

The table below shows our current schedule:

Project Event	**Scheduled Date**	**Status**
Science Requirements Review	Q2 2007	Completed
Preliminary Design Review	Q2 2008	Completed
Tracker Contract Executed	Q3 2008	Completed
WFC Contract Executed	Q4 2008	Completed
IFU Production Run 1	Q4 2008	Completed
Tracker PDR	Q4 2008	Completed
WFC PDR	Q1 2009	Completed
Tracker CDR	Q2 2009	
WFC CDR	Q3 2009	
VIRUS CDR	Q3 2009	
Mid-Term and VIRUS Production Review	Q4 2009	
Pre-Production Unit Spectrograph Complete	Q1 2010	
Tracker Delivered to Integration and Test	Q2 2010	
PFIP Delivered to Integration and Test	Q3 2010	
WFC Delivered to HET	Q1 2011	
Pre-Installation Review	Q1 2011	
HET Taken Offline	Q2 2011	
HET Returned to Science Operations	mid 2011	
Main DEX Survey	2011–2014	

We also track risks, both technical and observational, through regular meetings, formal updates and reviews. Since we are updating a facility that has been very well characterized, with both HET and SALT (an HET-like facility), and we have built a prototype instrument which is being used for a large pilot survey, we have a strong grasp of the important issues to focus on. The pilot survey, in particular, has been a tremendous help in terms of characterizing and improving the instrument, defining the observational strategy, refining the software, and organizing the collaboration. When we start the HETDEX survey, we will have taken four years of pilot survey data, and expect most of the major observational and analysis issues will have been resolved.