Hobby-Eberly Telescope Dark Energy Experiment

Gary J. Hill
HETDEX Principal Investigator
Overview

- HETDEX Motivation
  - Dark Energy evolution
  - but really a vast blind integral field spectroscopic survey
- What HETDEX comprises
- VIRUS and the VIRUS prototype
- HETDEX Pilot Survey – LAEs, [OII] emitters
- The HETDEX survey and example science
- HETDEX ∩ SDSS
- Status of the HET Wide Field Upgrade and VIRUS
## HETDEX and VIRUS Consortium

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<th>University of Texas</th>
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<td>Yi-Kuan Chiang</td>
<td>Ralf Bender</td>
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<td>Lutz Wisotzki</td>
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Hobby Eberly Telescope Dark Energy Experiment

- HETDEX is:
  - Upgrade of HET to have a new wide 22’ field of view
  - Deployment of the hugely replicated spectrograph, VIRUS, putting >33,000 fibers on sky, per exposure
  - 3-5 year blind spectroscopic survey
- HETDEX will:
  - Map 0.8 million LAEs (1.9 < z < 3.5) and a million [OII] emitters (z < 0.5)
  - Measure expansion history to 1% precision at z~2.5
    - Determine if dark energy evolves, looking back 11 billion years
    - Measure curvature of the universe to 0.1%
- Very complementary to BOSS and DES
- HETDEX is a unique blind spectroscopic survey with many other applications
  - In particular in galaxy evolution
What Controls the Expansion Rate

Different components dominate as follow the arrow of time

\[
\left( \frac{H(z)}{H_{100}} \right)^2 = \omega_r (1 + z)^4 + \omega_m (1 + z)^3 + \omega_k (1 + z)^2 + \omega_\Lambda (z)
\]

- Observing different epochs allows us to see the influence of different components
- HETDEX probes early epochs, where DE evolution and curvature are important
- HETDEX helps break degeneracies inherent in lower redshift measurements
Realization of BAO in HETDEX

\[ \frac{P(k) - P_0(k)}{P(k)} \]

vs.

\[ k \text{ (Mpc}^{-1}) \]
The power of the power

Entire shape of power spectrum in 2-D (Alcock-Paczynski Effect) constrains $H, d_A$ and contains information about structure growth – if non-linear growth and redshift space distortion at high $k$ can be understood (Shoji, Jeong & Komatsu, 2009)
Three Non-linearities to Worry About

- Non-linear evolution of the density field
  - Non-linearity in continuity and Euler equation
- Non-linear bias
  - Non-linearity in the way that galaxies trace matter
- Non-linear redshift space distortion
  - Non-linearity in peculiar velocity along the line of sight

Solid framework: Perturbation Theory (PT)
- Validity of the cosmological linear perturbation theory has been verified observationally (WMAP!)
- So, we go beyond the linear theory, and calculate higher order terms in perturbations.
- 3rd-order perturbation theory (3PT)
Non-linearity in Matter Clustering

Simulation

3rd-order Perturbation Theory

Linear theory

HETDEX
Hobby-Eberly Telescope Dark Energy Experiment

McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN
Non-linear bias

- Galaxies not distributed same as matter fluctuations
- Usually, this fact is modeled by a “linear bias”, or $P_g(k)=b_1^2 P(k)$, where $b_1$ is scale-independent.
- Extending this to a non-linear form, we have to assume something about galaxy formation
- Assumption: galaxy formation is a local process, at least on scales that we care about
  - Non-linear bias can be modeled with 3PT (Jeong and Komatsu 2009)
  - or constrained by the bi-spectrum (e.g. Sefusatti & Komatsu 2007)
Non-linear Bias

Using: \[ \delta_h(x) = b_0 + b_1 \delta(x) + \frac{b_2}{2} \delta^2(x) + \frac{b_3}{6} \delta^3(x) \]
Redshift Space Distortion

- (Left) Coherent velocity field => Clustering *enhanced* along the line of sight
  - “Kaiser” effect
- (Right) Virial-like random motion => Clustering *diminished* along the line of sight
  - “Finger-of-God” effect
Non-Linear Redshift Space Distortion
(Jeong & Komatsu 2009, unpublished)

- Virial motion is parameterized by the velocity dispersion, which is included as an unknown free parameter
- We need a better way to model this without any free parameters, or with a parameter that can be measured by other means
Full power spectrum modeling
(Shoji, Jeong, & Komatsu 2009)

- 2-D power spectrum modeling including the effects of
  - structure growth
  - non-linear bias
  - redshift-space distortions
  - shape of PS
  - 0.8 M tracers $b=2.5$

- Comparison of constraints on $H/D_A$ for BAO vs. full PS
  - Up to factor of 4 improvement
  - depending on what parameters are marginalized over

- Technique recovers $H/D_A$ for Millennium simulation

Ongoing and proposed efforts

- HETDEX: 2014-2017, 1.9 < z < 3.5
- BOSS: 2009-2014, z = 0.35, 0.6, 2.5
- WIGGLEZ: done, 0.5 < z < 0.8
- DES: 2012-2016, 0.3 < z < 1.0
- eBOSS: 2015-2018, z ≤ 2.5
- EUCLID: 2019-2025, 0.8 < z < 2.0
- WFIRST: > 2020
Curvature

\[
\left( \frac{H(z)}{H_{100}} \right)^2 = \omega_r (1 + z)^4 + \omega_m (1 + z)^3 + \omega_k (1 + z)^2 + \omega_\Lambda (z)
\]

- Expect curvature very close to flat \((10^{-5})\) in inflationary universe
  - Often assumed flat, but currently only known to 1-2%
  - Can become a dominant unknown in high precision dark energy experiments at low z
- Comparison of \(d_A\) between \(z \sim 2-3\) and recombination can measure \(k=\Omega_k h^2\) to \(\sim 0.2\%\) (Knox 2006)
  - Which depends mainly on \(k\) in the matter dominated era
  - Due to the much smaller contribution of dark energy between \(z \sim 2-3\) and recombination, compared to lower redshift.
The HET Wide Field Upgrade and VIRUS
Wide Field Corrector

- Four mirror corrector with meter-sized optics and large aspheric departures
  - 22 arcmin diameter field of view
  - 10 m pupil diameter
- Subcontracted to the University of Arizona College of Optical Sciences
- Challenge for polishing, testing, mounting, and alignment
- Reflective coatings cover 350 to 1800 nm
- Unit is sealed and purged with nitrogen to protect coatings
New HET tracker

UT Austin Center for Electromechanics and McDonald Observatory

- Need to increase tracker payload 4-fold
- Tracker locates payload to 5 μm accuracy within a 7x7x4 m³ volume
- X,Y linear axes
- Hexapod for other degrees of motion

- We are now testing the tracker meets its requirements
- Effort will be complete in late July
- Tracker will be packed and shipped by end of September

Tracker assembled in CEM high bay in Austin
VIRUS is a simple spectrograph replicated on large scale
- 150 channel fiber-fed IFS placing >33,600 1.5” dia fibers on sky
- 350-550 nm coverage and R~700
- Optimized to detect LAEs via blind integral field spectroscopy
- VIRUS prototype has been used at McDonald 2.7 m for 5 years
  - Used for HETDEX Pilot Survey (Adams et al 2010, Blanc et al 2010)
  - Proved the optical design, principles of the mechanical design, and the data reduction software
VIRUS hardware components

- Fiber IFU production led by AIP
- Collimator production led by TAMU
- Camera production led by UT Austin
- Data pipeline lead by MPE
- Many mechanical parts produced by Oxford and IAG

- Three fiducial spectrographs used to ensure interchangeability of parts
IFU Production @ AIP

- Leibniz Institut Potsdam (AIP)
- 18 m average length; 448 fibers per IFU (1.5 arcsec diameter on sky)
- Production IFU cables are being assembled at two vendors plus at AIP
Collimator Production @ TAMU

- Collimators being assembled at TAMU
  - Many parts supplied by Oxford

Complete Collimator assemblies

VPH gratings being assembled into cells
VIRUS camera assembly @ UT

Camera mirror in mount
Detectors and CMA integrated into housing

Complete Camera Mirror Assembly
x 150
Thousands of parts in hand

Invar “spider” support with CCD and field flattener installed
Units undergoing testing in lab

AIP Potsdam

UT Austin
VIRUS production unit in lab
Proving HETDEX: the VIRUS Prototype
HETDEX Pilot Survey (HPS)

- Mitchell Spectrograph (VIRUS-P) observations on the McDonald 2.7 m Smith Telescope
  - 200 nights
  - 166 sq. arcmin.
  - 350-580 nm R~900
- Executed by Graduate students Josh Adams and Guillermo Blanc
- Tests the fundamentals of HETDEX
- First “wide field” integral field spectroscopic survey
  - Blind spectroscopy complements narrow band imaging
  - Much larger volume probed than NB imaging
- Mitchell Spectrograph has been used for many other investigations, especially where low surface brightness sensitivity is required

HETDEX Pilot Survey

- Survey volumes
  - $1.03 \times 10^6$ Mpc$^3$ for Ly-$\alpha$
  - $4.24 \times 10^4$ Mpc$^3$ for [OII]
- 104 bright LAEs and 293 [OII] emitters detected to 6e-17 erg/cm$^2$/s
- LAEs and [OII] cleanly separated by observed line equivalent width
- 6 AGN among Ly-$\alpha$ detections
- Fields selected to have deep multi-wavelength broad-band imaging

Example Data

- 6 position dither pattern ensures good field coverage
  - 4.1 arcsec dia fibers on 2.7 m
- Three 20 min exposures at each position cover 3 sq. arcmin
- 2 hr of effective exposure time
Example Data

- VIRUS data reduced with two independent pipelines
- **Vaccine** (U. Texas) and **Cure** (USM/MPE Munich)
- $5\sigma$ flux limit of $\sim 6 \times 10^{-17}$ erg/s/cm$^2$ for a point-source and unresolved line
Lyα Luminosity Function

Detected expected number of LAEs and verified methodology and predictions for HETDEX

HETDEX Survey – geometry and example science
Observing footprint of VIRUS

1.5” dia fibers in 1/3 fill hexagonal close pack

IFU Layout

16’ dia

IFUs arrayed on a basic 50 arcsec pitch square grid

50”x50” field covered in 3 dithers in 20 minutes exposure

This shows the layout for 96 IFUs. We expect to deploy 75 and will concentrate them within 16 arcmin field diameter in a roughly hexagonal shape
HETDEX Survey

- Spring field - 300 deg$^2$ with $1/4.5$ fill factor; 600k LAEs $\approx 0.5$ LAE arcmin$^{-2}$.

- Fall field - 150 deg$^2$ with $1/4.5$ fill factor; 300k LAEs $\approx 0.5$ LAE arcmin$^{-2}$.
Window function

- Sparse sampling is a central feature of HETDEX observing strategy
  - Mean density of LAEs is \( \sim 4x \) higher than needed
  - Inefficient to expose shorter due to read noise and overhead
- Separation of IFUs is \( \sim 1 \) Mpc
  - Causes feature in window function at \( k \sim \pi \) [h/Mpc]
  - No effect on scales of interest (\( k < 0.3 \))
- Hole in center of IFUs for other instruments is on a scale that causes a 5% depression of the power spectrum
  - Can be modeled & corrected
- Extensive modeling of WF
  - C-T Chiang et al., in prep
Example science from HETDEX

**Cosmology and Galaxy Evolution**
- Detection of dark energy at an early epoch
- Curvature of Universe to 0.2%
- Shape of matter distribution early in the Universe
- Total neutrino mass
- Detection of cosmic web in emission
- Nature of early galaxies

**Nearby Galaxies**
- Star formation at late times ([OII])
- Dark matter in nearby galaxies
- Stellar populations at large radii
- Galactic structure from stellar kinematics
- Map nearby galaxy clusters
- Study of the first stars in our Galaxy
- White dwarfs
Nearby stars, galaxies, & clusters

HETDEX ∩ SDSS (survey realization)

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<th>Count</th>
<th>Description</th>
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<td>44714</td>
<td>stars with g&lt;22 (S/N ≈ 3)</td>
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<tr>
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<td>galaxies with g&lt;22 (S/N ≈ 3)</td>
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<td>789</td>
<td>stars with SDSS spectrum in IFUs</td>
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<td>galaxies g&lt;17 (rotation curves)</td>
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<td>9101</td>
<td>galaxies g&lt;19 &amp; D&gt;5”</td>
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- VIRUS probes stars deeper and bluer than other galactic structure surveys
  - Will include tens of extremely metal poor stars
- Large sample of resolved galaxies (z<0.1)
  - Rotation curves and dark matter distributions to SDSS surface brightness limit
  - Spatially-resolved star formation rates
  - Cross with new Westerbork APERTIF HI survey
- Continuum spectra of stars and galaxies to ~SDSS photometric limit (at >5σ per resolution element)
- 2000 Abell richness clusters covered (z<0.45)
  - Selected by spectroscopic signature
  - Complements eROSITA X-ray and HSC weak lensing
Summary

- VIRUS is in full production
  - Production will extend through 2013 and be complete in 2014
  - Majority of units will be deployed in time for HETDEX survey in Q2 2014
- HET Wide Field Upgrade is expected to be deployed by early 2014
- The combination of the upgraded 10 m HET and VIRUS will create a unique survey facility
  - Opens up new parameter space in wide-field blind spectroscopy
  - >33,000 fibers each 1.5 arcsec on sky gives huge grasp – 60 sq. arcmin. per exposure
  - Incredible grasp for low surface brightness measurements

Expect 150 LAEs in the first 20 minute observation with VIRUS on HET – more than we detected in 100 nights in the HETDEX Pilot Survey!
HETDEX will set the night on fire!
(apologies to the Doors)