Fundamental Physics and Large-scale Structure II: "Hobby-Eberly Telescope Dark Energy Experiment"

Eiichiro Komatsu (Texas Cosmology Center, UT Austin) on behalf of HETDEX collaboration  
Coming Opportunities in Physical Cosmology, January 27, 2012
Cosmology: Next Decade?

- Astro2010: Astronomy & Astrophysics Decadal Survey
- Report from *Cosmology and Fundamental Physics* Panel (Panel Report, Page T-3):

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Cosmology: Next Decade?

- Astro2010: Astronomy & Astrophysics Decadal Survey
- Report from *Cosmology and Fundamental Physics* Panel (Panel Report, Page T-3): **Translation**

**TABLE I  Summary of Science Frontiers Panels’ Findings**

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Large-scale structure of the universe has a potential to give us valuable information on all of these items.
What is HETDEX?

• Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) is a *quantum-leap* galaxy survey:
  
  • The **first** blind spectroscopic large-scale structure survey
    • We do not pre-select objects; objects are emission-line selected; huge discovery potential
  
  • The **first** 10 Gpc$^3$-class survey at high z [1.9<z<3.5]
    • The previous big surveys were all done at z<1
    • High-z surveys barely reached $\sim 10^{-2}$Gpc$^3$
Who are we?

• About ~50 people at Univ. of Texas; McDonald Observatory; LMU; AIP; MPE; Penn State; Gottingen; Texas A&M; and Oxford

• Principal Investigator: Gary J. Hill (Univ. of Texas)

• Project Scientist: Karl Gebhardt (Univ. of Texas)
Glad to be in Texas

- In many ways, HETDEX is a Texas-style experiment:
  - Q. How big is a survey telescope? A. 10m
  - Q. Whose telescope is that? A. Ours
  - Q. How many spectra do you take per one exposure? A. More than 33K spectra – at once
  - Q. Are you not wasting lots of fibers? A. Yes we are, but so what? **Besides, this is the only way you can find anything truly new!**
Hobby-Eberly Telescope
Dark Energy Experiment (HETDEX)

Use 10-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in $z=1.9–3.5$
Many, MANY, spectra

• HETDEX will use the new integral field unit spectrographs called “VIRUS” (Hill et al.)

• We will build and put 75–96 units (depending on the funding available) on a focal plane

• Each unit has two spectrographs

• Each spectrograph has 224 fibers

• Therefore, **VIRUS will have 33K to 43K fibers on a single focal place** (Texas size!)
HETDEX Foot-print (in RA-DEC coordinates)
“Fall Field” 28x5 deg² centered at (RA,DEC)=(1.5h,±0d)

“Spring Field” 42x7 deg² centered at (RA,DEC)=(13h,+53d)

Total comoving volume covered by the footprint ~ 9 Gpc³
HETDEX: A Quantum Leap Survey

Figure 12.— The redshift-space power spectrum recovered from the combined SDSS main galaxy and LRG sample, optimally weighted for both density changes and luminosity dependent bias (solid circles with 1-σ errors). A flat Λ cosmological distance model was assumed with Ω_M = 0.24. Error bars are derived from the diagonal elements of the covariance matrix calculated from 2000 log-normal catalogues created for this cosmological distance model, but with a power spectrum amplitude and shape matched to that observed (see text for details). The data are correlated, and the width of the correlations is presented in Fig. 10 (the correlation between data points drops to <0.33 for ∆k > 0.01 h Mpc^−1). The correlations are smaller than the oscillatory features observed in the recovered power spectrum. For comparison we plot the model power spectrum (solid line) calculated using the fitting formulae of Eisenstein & Hu (1998); Eisenstein et al. (2006), for the best fit parameters calculated by fitting the WMAP 3-year temperature and polarization data, h = 0.73, Ω_M = 0.24, n_s = 0.96 and Ω_b/Ω_M = 0.174 (Spergel et al. 2006). The model power spectrum has been convolved with the appropriate window function to match the measured data, and the normalisation has been matched to fit the large-scale (0.01 < k < 0.06 h Mpc^−1) data. The deviation from this linear power spectrum is clearly visible at k > ∼ 0.06 h Mpc^−1, and will be discussed further in Section 6. The solid circle with 1σ errors in the inset show the power spectrum ratioed to a smooth model (calculated using a cubic spline fit as described in Percival et al. 2006) compared to the baryon oscillations in the (WMAP 3-year parameter) model (solid line), and show good agreement. The calculation of the matter density from these oscillations will be considered in a separate paper (Percival et al. 2006). The dashed line shows the same model without the correction for the damping effect of small-scale structure growth of Eisenstein et al. (2006). It is worth noting that this model is not a fit to the data, but a prediction from the CMB experiment.

Small Scale

Large Scale
HETDEX: A Quantum Leap Survey

HETDEX vs SDSS
- **10x** more galaxies observed
- **3x** larger volume surveyed
- Will survey the previously unexplored **discovery space**
Low-z bin \((1.9 < z < 2.5), 434 \text{deg}^2, 380K\) galaxies

High-z bin \((2.5 < z < 3.5), 434 \text{deg}^2, 420K\) galaxies

Fractional Error in \(P_{\text{galaxy}}(k)\) per \(\Delta k = 0.01 h \text{Mpc}^{-1}\)

3\% uncertainty

Wavenumber, \(k [h \text{ Mpc}^{-1}]\)
What do we detect?

- $\lambda=350$–$550$nm with the resolving power of $R=800$ would give us:
  - $\sim0.8M$ Lyman-alpha emitting galaxies at $1.9<z<3.5$
  - $\sim2M$ [OII] emitting galaxies
  - ...and lots of other stuff (like white dwarfs)
One way to impress you

• So far, about ~1000 Lyman-alpha emitting galaxies have been discovered over the last decade

• These are interesting objects – relatively low-mass, low-dust, star-forming galaxies

• We will detect that many Lyman-alpha emitting galaxies within the first 2 hours of the HETDEX survey
What to measure?

• **Inflation**
  - Shape of the initial power spectrum ($n_s; \frac{dn_s}{d\ln k};$ etc)
  - Non-Gaussianity ($3\text{pt } f_{NL}^{\text{local}}; 4\text{pt } \tau_{NL}^{\text{local}};$ etc)

• **Dark Energy**
  - Angular diameter distances over a wide redshift range
  - Hubble expansion rates over a wide redshift range
  - Growth of linear density fluctuations over a wide redshift range
  - Shape of the matter power spectrum (modified grav)
What to measure?

• **Neutrino Mass**
  • Shape of the matter power spectrum

• **Dark Matter**
  • Shape of the matter power spectrum (warm/hot DM)
Shape of the Power Spectrum, $P(k)$

Matter density fluctuations measured by various tracers, extrapolated to $z=0$

- CMB, $z=1090$ ($l=2–3000$)
- Galaxy, $z=0.3$
- Non-linear $P(k)$ at $z=0$
- Linear $P(k)$
- Gas, $z=3$

$P(k,z=0)$ [Mpc$^{-3}$]

- SDSS DR7 (Reid et al. 2010)
- LyA (McDonald et al. 2006)
- ACT CMB Lensing (Das et al. 2011)
- ACT Clusters (Sehgal et al. 2011)
- CCCP II (Vikhlinin et al. 2009)
- BCG Weak lensing (Tinker et al. 2011)
- ACT+WMAP spectrum (this work)

Hlozek et al., arXiv:1105.4887

$k$ [Mpc$^{-1}$]
Shape of the Power Spectrum, $P(k)$

- **Primordial spectrum**, $P_{\text{prim}}(k) \sim k^{n_s}$
- **CMB, $z=1090$ (l=2–3000)**
- **Matter density fluctuations measured by various tracers, extrapolated to $z=0$**
- **Galaxy, $z=0.3$**
- **Gas, $z=3$**

**Non-linear $P(k)$ at $z=0$**

**Linear $P(k)$**
$P(k) = A \times k^{n_s} \times T^2(k)$

**T(k):** Suppression of power during the radiation-dominated era.

The suppression depends on $\Omega_{cdm}h^2$ and $\Omega_{baryon}h^2$.

Primordial spectrum, $P_{prim}(k) \sim k^{n_s}$

$P(k,z=0)$ at $z=0$

linear $P(k)$ asymptotes to $k^{n_s}(\ln k)^2/k^4$
Current Limit on $n_s$

- Limit on the tilt of the power spectrum:
  - $n_s=0.968\pm0.012$ (68%CL; Komatsu et al. 2011)
  - Precision is dominated by the WMAP 7-year data

- Planck’s CMB data are expected to improve the error bar by a factor of $\sim4$. 
• Joint constraint on the primordial tilt, $n_s$, and the tensor-to-scalar ratio, $r$.

• Not so different from the 5-year limit.

• $r < 0.24$ (95%CL)

• Limit on the tilt of the power spectrum: $n_s = 0.968 \pm 0.012$ (68%CL)
Role of the Large-scale Structure of the Universe

• However, CMB data can’t go much beyond k=0.2 Mpc$^{-1}$ ($l=3000$).

• **High-z** large-scale structure data are required to go to smaller scales.
Shape of the Power Spectrum, $P(k)$

Matter density fluctuations measured by various tracers, extrapolated to $z=0$

- Galaxy, high-$z$
- CMB, $z=1090$ ($l=2-3000$)
- Gas, $z=3$

$k [\text{Mpc}^{-1}]$

$P(k,z=0) [\text{Mpc}^3]$
Measuring a scale-dependence of $n_s(k)$

- As far as the value of $n_s$ is concerned, CMB is probably enough.

- However, if we want to measure the scale-dependence of $n_s$, i.e., deviation of $P_{\text{prim}}(k)$ from a pure power-law, then we need the small-scale data.
  - This is where the large-scale structure data become quite powerful (Takada, Komatsu & Futamase 2006)

- Schematically:
  - $\frac{dn_s}{d\ln k} = \frac{[n_s(\text{CMB}) - n_s(\text{LSS})]}{\ln k_{\text{CMB}} - \ln k_{\text{LSS}}}$
Probing Inflation (3-point Function)

Can We Rule Out Inflation?

- Inflation models predict that primordial fluctuations are very close to Gaussian.
- In fact, **ALL SINGLE-FIELD** models predict a particular form of **3-point function** to have the amplitude of $f_{NL}^{\text{local}}=0.02$.
- Detection of $f_{NL}>1$ would rule out **ALL** single-field models!
Bispectrum

- Three-point function!

- $B_\zeta(k_1, k_2, k_3) = \langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = (\text{amplitude}) \times (2\pi)^3 \delta(k_1 + k_2 + k_3) F(k_1, k_2, k_3)$

Primordial fluctuation
(a) squeezed triangle 
\(k_1 \approx k_2 >> k_3\)

(b) elongated triangle 
\(k_1 = k_2 + k_3\)

(c) folded triangle 
\(k_1 = 2k_2 = 2k_3\)

(d) isosceles triangle 
\(k_1 > k_2 = k_3\)

(e) equilateral triangle 
\(k_1 = k_2 = k_3\)
Single-field Theorem
(Consistency Relation)

- For **ANY** single-field models*, the bispectrum in the squeezed limit is given by

\[
B_\zeta(k_1 \sim k_2 < k_3) \approx (1 - n_s) \times (2\pi)^3 \delta(k_1 + k_2 + k_3) \times P_\zeta(k_1)P_\zeta(k_3)
\]

- Therefore, all single-field models predict \( f_{NL} \approx (5/12)(1 - n_s) \).

- With the current limit \( n_s = 0.968 \), \( f_{NL} \) is predicted to be 0.01.

* for which the single field is solely responsible for driving inflation and generating observed fluctuations.
Probing Inflation (3-point Function)

- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limit is:
  - $-10 < f_{\text{NL}}^{\text{local}} < 74$
- The 68% CL limit: $f_{\text{NL}}^{\text{local}} = 32 \pm 21$
- The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{\text{NL}}$
- The Planck’s expected 68% CL uncertainty: $\Delta f_{\text{NL}}^{\text{local}} = 5$

Komatsu et al. (2011)
Trispectrum

\[ T_\zeta(k_1, k_2, k_3, k_4) = (2\pi)^3 \delta(k_1 + k_2 + k_3 + k_4) \]
\[
\{ g_{NL} \left[ (54/25)P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3) + \text{cyc.} \right] \\
+ \tau_{NL} \left[ P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|k_1 + k_3|) + P_\zeta(|k_1 + k_4|)) + \text{cyc.} \right] \}
\]
The current limits from WMAP 7-year are consistent with single-field or multi-field models.

So, let’s play around with the future.
Case A: Single-field Happiness

- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).
Case B: Multi-field Happiness

- $f_{NL}$ is detected. Single-field is dead.
- But, $\tau_{NL}$ is also detected, in accordance with multi-field models:
  \[ \tau_{NL} \geq \left( 6 \frac{f_{NL}^{local}}{5} \right)^2 \]
  [Sugiyama, Komatsu & Futamase (2011)]

\[ \ln(\tau_{NL}) \]
\[ \ln(f_{NL}) \]
Case C: Madness

- $f_{NL}$ is detected. Single-field is dead.

- But, $\tau_{NL}$ is not detected, inconsistent with the multi-field bound.

- (With the caveat that this bound may not be completely general) BOTH the single-field and multi-field are gone.
Beyond CMB: Large-scale Structure!

• In principle, the large-scale structure of the universe offers a lot more statistical power, because we can get 3D information. (CMB is 2D, so the number of Fourier modes is limited.)
Beyond CMB: Large-scale Structure?

- Statistics is great, but the large-scale structure is non-linear, so perhaps it is less clean?
- Not necessarily.
(a) squeezed triangle 
\(k_1 \approx k_2 \gg k_3\)

(b) elongated triangle 
\(k_1 = k_2 + k_3\)

(c) folded triangle 
\(k_1 = 2k_2 = 2k_3\)

(d) isosceles triangle 
\(k_1 > k_2 = k_3\)

(e) equilateral triangle 
\(k_1 = k_2 = k_3\)

MOST IMPORTANT

\[
\begin{align*}
\frac{k_2}{k_1} &< 0.5 & \text{elongated triangle} \\
\frac{k_2}{k_1} &> 0.5 & \text{isosceles triangle}
\end{align*}
\]
Non-linear Gravity

For a given $k_1$, vary $k_2$ and $k_3$, with $k_3 \leq k_2 \leq k_1$

$F_2^{(s)}(k_1, k_2) P_m(k_1, z) P_m(k_2, z) + (\text{cyclic})$

- For a given $k_1$, vary $k_2$ and $k_3$, with $k_3 \leq k_2 \leq k_1$
- $F_2(k_2,k_3)$ vanishes in the squeezed limit, and peaks at the elongated triangles.
Non-linear Galaxy Bias

- There is no $F_2$: less suppression at the squeezed, and less enhancement along the elongated triangles.

- Still peaks at the equilateral or elongated forms.

\[ b_1^2 b_2 \left[ P_m(k_1, z) P_m(k_2, z) + \text{(cyclic)} \right] \]
Primordial Non-Gaussianity

This gives the peaks at the squeezed configurations, clearly distinguishable from other non-linear/astrophysical effects.
Bispectrum is powerful

• $f_{\text{NL}}^\text{local} \sim O(1)$ is quite possible with the bispectrum method.

• This needs to be demonstrated by the real data – we will certainly do this with the HETDEX data!
• The acoustic oscillations should be hidden in this galaxy distribution...
• The existence of a localized clustering scale in the 2-point function yields oscillations in Fourier space.
A really nice thing about BAO at a given redshift is that it can be used to measure not only $D_A(z)$, but also the expansion rate, $H(z)$, directly, at that redshift.

- BAO perpendicular to l.o.s
  
  $$\Rightarrow D_A(z) = \frac{153\text{Mpc}}{[(1+z)\theta]}$$

- BAO parallel to l.o.s
  
  $$\Rightarrow H(z) = \frac{c\Delta z}{153\text{Mpc}}$$
Transverse $= D_A(z)$; Radial $= H(z)$

Two-point correlation function measured from the SDSS Luminous Red Galaxies (Gaztanaga, Cabre & Hui 2008)

$\theta = 153 \text{Mpc}/[(1+z)D_A(z)]$
\[ D_V(z) = \left\{ (1+z)^2 D_A^2(z) \left[ cz/H(z) \right] \right\}^{1/3} \]

Since the current data are not good enough to constrain \( D_A(z) \) and \( H(z) \) separately, a combination distance, \( D_V(z) \), has been constrained.

\( \Omega_m = 0.278, \Omega_\Lambda = 0.722 \)
Beyond BAO

• BAOs capture only a *fraction* of the information contained in the galaxy power spectrum!

• The full usage of the 2-dimensional power spectrum leads to a *substantial* improvement in the precision of distance and expansion rate measurements.
BAO vs Full Modeling

- Full modeling improves upon the determinations of $D_A$ & $H$ by more than a factor of two.
- On the $D_A$-$H$ plane, the size of the ellipse shrinks by more than a factor of four.

Shoji, Jeong & Komatsu (2008)
Alcock-Paczynski: The Most Important Thing For HETDEX

- Where does the improvement come from?
- The Alcock-Paczynski test is the key. *This is the most important component for the success of the HETDEX survey.*
The AP Test: How That Works

- The key idea: (in the absence of the redshift-space distortion - we will include this for the full analysis; we ignore it here for simplicity), the distribution of the power should be **isotropic** in Fourier space.
The AP Test: How That Works

- **DA**: (RA, Dec) to the transverse separation, \( r_{\text{perp}} \), to the transverse wavenumber

\[ k_{\text{perp}} = \frac{(2\pi)}{r_{\text{perp}}} = \frac{(2\pi)}{\text{[Angle on the sky]}} / D_A \]

- **H**: redshifts to the parallel separation, \( r_{\text{para}} \), to the parallel wavenumber

\[ k_{\text{para}} = \frac{(2\pi)}{r_{\text{para}}} = \frac{(2\pi)}{H / (c\Delta z)} \]

If \( D_A \) and \( H \) are correct:

If \( D_A \) is wrong:

If \( H \) is wrong:
The AP Test: How That Works

- **\(D_A\):** (RA,Dec) to the transverse separation, \(r_{\text{perp}}\), to the transverse wavenumber
  \[
  k_{\text{perp}} = (2\pi)/r_{\text{perp}} = (2\pi)[\text{Angle on the sky}] / D_A
  \]

- **\(H\):** redshifts to the parallel separation, \(r_{\text{para}}\), to the parallel wavenumber
  \[
  k_{\text{para}} = (2\pi)/r_{\text{para}} = (2\pi)H/(c\Delta z)
  \]

If \(D_A\) and \(H\) are correct:

If \(D_A\) is wrong:

If \(H\) is wrong:

If \(D_A\) and \(H\) are wrong:
So, the AP test can’t be used to determine $D_A$ and $H$ separately; however, it gives a measurement of $D_A H$.

Combining this with the BAO information, and marginalizing over the redshift space distortion, we get the solid contours in the figure.
Redshift Space Distortion

- Both the AP test and the redshift space distortion make the distribution of the power anisotropic. Would it spoil the utility of this method?

- Some, but not all!
Marginalized over the amplitude of $P_{\text{galaxy}}(k)$

Alcock-Paczynski: $D_A H = \text{const.}$

Standard Ruler: $D_A^2 / H = \text{const.}$
HETDEX and Neutrino Mass

- Neutrinos suppress the matter power spectrum on small scales ($k>0.1\;h\;\text{Mpc}^{-1}$).

- A useful number to remember:
  - For $\sum m_\nu=0.1\;\text{eV}$, the power spectrum at $k>0.1\;h\;\text{Mpc}^{-1}$ is suppressed by $\sim7\%$.

- We can measure this easily!
Expected HETDEX Limit

- ~6x better than WMAP 7-year + $H_0$
Summary

• Three (out of four) questions:
  • What is the physics of inflation?
    • $P(k)$ shape (esp, $dn/d\ln k$) and non-Gaussianity
  • What is the nature of dark energy?
    • $D_A(z), H(z)$, growth of structure
  • What is the mass of neutrinos?
    • $P(k)$ shape

• **HETDEX is a powerful approach for addressing all of these questions**