Cosmology with high (z>1) redshift galaxy surveys

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Ph. D. thesis defense talk, 17 May 2010
Cosmology with HETDEX

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The concordance cosmological model

- Our universe is flat, and dominated by cosmological constant.

From “WMAP+BAO+H_0” in Komatsu et al. (2010):

\[
H_0 = 70.4^{+1.3}_{-1.4} \text{ km/s/Mpc}
\]

\[
\Omega_\Lambda = 0.728^{+0.015}_{-0.016}
\]

\[
\Omega_m h^2 = 0.1349 \pm 0.0036
\]

\[
100\Omega_b h^2 = 2.260 \pm 0.053
\]

\[
\Omega_r h^2 = 4.174 \times 10^{-5}
\]

\[
\tau = 0.087 \pm 0.014
\]

\[
n_s = 0.963 \pm 0.012
\]

\[
\Delta^2_R(k_0) = \left(2.441^{+0.088}_{-0.092}\right) \times 10^{-9}
\]

where, \(k_0 = 0.002 \text{ Mpc}^{-1}\)
Four biggest challenges in cosmology

We do not know the nature of the building blocks!

- **Inflation**
  How does our Universe begin, or what drives inflation?
- **Dark Matter**
  What is/are the dark matter(s) made of?
- **Dark Energy**
  What drives the current acceleration?
  Is this really the cosmological constant?
- **Dark Matter, Dark Energy**
  Is General Relativity a valid theory in the cosmological scales?
The answer will come from galaxy surveys

• On-going, near future surveys
  – Baryon Oscillation Spectroscopic Survey ($0.2 < z < 0.7$, 10,000 sq. deg.)
  – WiggleZ ($0.2 < z < 1.0$, 1,000 sq. deg.)
  – **Hobby-Eberly Telescope Dark Energy eXperiment ($1.9 < z < 3.5$, 420 sq. deg.)**: Start observing from Fall 2011!!

• Surveys which may happen in the future
  – BigBOSS ($0.2 < z < 0.7$)
  – Euclid ($0 < z < 2.0$)
  – Cosmic Inflation Probe ($1 < z < 6$)
  – SUMIRE/LAS ($?? < z < ??$)
  – and more to be proposed
HETDEX and other surveys

- **HETDEX** will provide a unique window to high-z!

![Diagram showing the comparison of different surveys](image)

- SDSS LRG: \(\sim 1.3 \text{ [Gpc}/h]^3\)
- BOSS LRG: \(\sim 6 \text{ [Gpc}/h]^3\)
- WiggleZ: \(\sim 1.5 \text{ [Gpc}/h]^3\)
- HETDEX: \(\sim 3 \text{ [Gpc}/h]^3\)

Survey areas:
- 2dF GRS: 1000 sq. deg.
- SDSS LRG: 7600 sq. deg.
- BOSS LRG: 10,000 sq. deg.
- HETDEX: 420 sq. deg.
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Evolution of density fluctuations

- In synchronous comoving gauge,

\[ CMB \text{ decoupling}\ (z = 1091.36 \pm 0.91) \]

\[ \frac{1}{aH} \]

\[ \delta \propto a^2 \quad \delta \propto a \]

\[ \text{Outside of 'comoving Horizon'} \]

- 500 Mpc/h
- 34.7 Mpc/h
- 1 Mpc/h

- CMB decoupling
  \( z = 1091.36 \pm 0.91 \)

- Quantum fluctuations

- Radiation Dominated
- Matter Dominated
Linear matter power spectrum

Primordial density $P(k)$

Power spectrum $[\text{Mpc}/h]^3$

Wavenumber $[h/\text{Mpc}]$
Linear matter power spectrum

Primordial density $P(k)$

Transfer function $T(k)$

Power spectrum $[\text{Mpc}/h^3]$ vs. wavenumber $[h/\text{Mpc}]$.
Linear matter power spectrum

Primordial density $P(k)$

Transfer function $T(k)$

Baryon Acoustic Oscillation

$k_{eq}$
Baryon Acoustic Oscillation in WMAP7

- Cosmic Microwave Background temperature map (WMAP7)
  
  Acoustic scale $\sim 0.6^\circ$  
  ($l_A = 302.69 \pm 0.076$)

$\langle T \rangle (\theta) = \int \frac{dl}{2\pi} (W_l^TT)^2 (\bar{\theta} + \bar{\zeta} l^2) C_l^{TT} J_0(l\theta)$

Komatsu et al. (2010)
The acoustic (sound horizon) scales

- Comoving distance traveled by the sound waves from the Big-bang to decoupling epochs \textbf{(MEASURED FROM CMB!!)}
  - CMB decouples from baryon at $z=1091.36 \pm 0.91$
    \[ d_{\text{CMB}} = 146.8 \pm 1.8 \text{ Mpc} \]
  - Baryon decouples from photon at $z=1020.5 \pm 1.6$
    \[ d_{\text{BAO}} = 153.3 \pm 2.0 \text{ Mpc} \]
BAO and dark energy

• $d_{\text{BAO}}$ is a standard ruler!
• We can measure the angular diameter distance, $d_A(z)$ and Hubble parameter, $H(z)$:

$$d_{\text{BAO}} = d_A(z) \Delta \theta = c \frac{\Delta z}{H(\tilde{z})}$$

• $d_A(z)$ and $H(z)$ depend on dark energy:

$$H^2(z) = H_0^2 \left[ \Omega_m (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_{DE} (1 + z)^3(1+w) \right]$$

$$d_A(z) = \frac{\chi(z)}{1 + z} \left[ 1 - \frac{k}{6} \frac{\chi^2(z)}{R^2} \right] \quad \chi(z) = c \int \frac{dz}{H(z)}$$
From matter to galaxy $P(k)$: bias

- Galaxies are biased tracers:
  The distribution of galaxies is not the same as that of matter fluctuation.

- On large scales, we may assume that galaxy formation is a local process:

  $$\delta_g(x) = \epsilon + b_1 \delta(x) + \frac{1}{2} b_2 \delta^2(x) + \frac{1}{6} b_3 \delta^3(x) + \ldots$$

- In linear regime, where matter density contrast is small, we may truncate the expansion in linear order (linear bias):

  $$P_g(k) = b_1^2 P_L(k) + P_0$$
The galaxy $P(k)$ in redshift space

- Peculiar velocity, which further shift the redshift of the galaxy induces yet another change in power spectrum (Kaiser effect)
- As a result, power spectrum becomes anisotropic: increase in clustering along line of sight direction

\[ P_{\text{red}}(k, \mu) = P_0 + \left[ b_1^2 + 2b_1 f \mu^2 + f^2 \mu^4 \right] P_L(k) \]

\[ f = \frac{d \ln D_+(a)}{d \ln a} \]
Distances from full power spectrum

- In galaxy surveys, we chart galaxies by $(\theta, \phi, z)$.
- **Observed power spectrum** using reference cosmology is rescaled and shifted (in log scale) relative to the **true power spectrum**: 

\[
P_{\text{obs}}(k_{\text{ref} \perp}, k_{\text{ref} \parallel}) = \left( \frac{D_A, \text{ref}}{D_A} \right)^2 \left( \frac{H}{H_{\text{ref}}} \right) P^g_s(k_{\perp}, k_{\parallel})
\]
Not just BAO: Alcock-Paczynski test

- From a spherically symmetric object, we can measure
\[
\frac{c\Delta z}{\Delta \theta} = d_A(z)H(z)
\]

- By measuring distance from the full power spectrum, we are effectively doing AP test at every points in Fourier space:
\[
\frac{k_{\perp,\text{ref}}}{k_{\parallel,\text{ref}}} = \frac{d_A(z)H(z)}{d_{A,\text{ref}}(z)H_{\text{ref}}(z)} \frac{k_{\perp}}{k_{||}}
\]

- [Important] We need to know the correct angular dependence!
BAO vs. full power spectrum

- It will improve upon the determination of both $D_A$ and $H$ by a factor of two, and of the area of ellipse by more than a factor of four!

Shoji, Jeong & Komatsu (2008)
More information from growth

- Let’s talk about \( f = \frac{d \ln D}{d \ln a} \)
- In principle, we can constraint dark energy from the growth:
  \[
  \frac{d^2 g}{d \ln a^2} + \left[ \frac{5}{2} + \frac{1}{2} (\Omega_k(a) - 3w_{\text{eff}}(a)\Omega_{\text{de}}(a)) \right] \frac{dg}{d \ln a} + \left[ 2\Omega_k(a) + \frac{3}{2}(1 - w_{\text{eff}}(a))\Omega_{\text{de}}(a) \right] g(a) = 0
  \]
  where \( g(a) = \frac{D(a)}{a} \).
- As normalization of power spectrum is degenerate with growth factor and bias, we may not able to extract the growth information from them.
- However, from the angular dependence in redshift space distortion, we can measure \( f = \frac{d \ln g}{d \ln a} + 1 \)!
- This can be a consistency check for General Relativity!
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Everything becomes non-linear!

1. non-linear gravity
2. non-linear galaxy bias
3. non-linear redshift space distortion

Reid et al. (2009)
Perturbation Theory calculation

- Next-to-leading order perturbation theory with local bias yields a following theoretical template (Ch2. of dissertation)

\[
P_{gs}(k, \mu, z) = P_0 + b_1^2 \left[ P_m(k, z) + b_2 D^4(z) P_{b2}(k) + b_2^2 D^4(z) P_{b2b2}(k) \right] \\
+ 2 f \mu^2 b_1 b_\theta P_\delta\theta(k, z) + f^2 \mu^4 b_\theta^2 P_{\theta\theta}(k, z) \\
+ D^4(z) \left[ P_{gs, 22}^{rest}(k, \mu; b_1, b_2) + 2 P_{gs, 13}^{rest}(k, \mu; b_1) \right]
\]

- Now we have 4 free ‘bias’ parameters: \(b_1, b_2, b_\theta, P_0\)
- This template can model the non-linear galaxy power spectrum of HETDEX!
- Let me show it one by one.
Non-linear matter clustering

Real space matter power spectrum

\[ P_{gs}(k, \mu, z) = P_0 + b_1^2 \left[ P_m(k, z) + b_2 D^4(z) P_{b2}(k) + b_2^2 D^4(z) P_{b22}(k) \right] \]

\[ + 2 f \mu^2 b_1 b_\theta P_{\delta\theta}(k, z) + f^2 \mu^4 b_\theta^2 P_{\theta\theta}(k, z) \]

\[ + D^4(z) \left[ P_{gs,22}^{(rest)}(k, \mu; b_1, b_2) + 2 P_{gs,13}^{(rest)}(k, \mu; b_1) \right] \]
Non-linear matter power spectrum

Jeong & Komatsu (2006)
BAO in nonlinear matter $P(k)$

Based on this study, we have decided to design HETDEX such that we measure $P(k)$ well at $k<0.3 \, h \, \text{Mpc}^{-1}$.
Non-linear redshift space distortion

Redshift space matter power spectrum

\[ P_{gs}(k, \mu, z) = P_0 + b_1^2 \left[ P_m(k, z) + b_2 D^4(z) P_{b2}(k) + b_2^2 D^4(z) P_{b_{22}}(k) \right] \]
\[ + 2 f \mu^2 b_1 b_\theta P_{\delta\theta}(k, z) + f^2 \mu^4 b_\theta^2 P_{\theta\theta}(k, z) \]
\[ + D^4(z) \left[ P_{gs, 22}^{(rest)}(k, \mu; b_1, b_2) + 2 P_{gs, 13}^{(rest)}(k, \mu; b_1) \right] \]

- We introduce a Lorentzian suppression for “Finger of God” effect

\[ P_s^{total}(k_\perp, k_\parallel) = P_s^{coherent}(k_\perp, k_\parallel) \frac{1}{1 + f^2 k_\parallel^2 \sigma_p^2} \]
Finger of God effect

• Velocity dispersion will **suppress** the power along the line of sight!

• In simulation, pair-wise velocity is observed to follow the exponential profile. (Scoccimarro 2004)
2D redshift space matter $P(k)$

Jeong (2010)

$\sigma_p^2 = 1.39 \pm 0.12 \, [\text{Mpc/h}]^2$

$\chi^2 = 1.079 / \text{DoF} = 318$

$\sigma_p^2 = 3.44 \pm 0.13 \, [\text{Mpc/h}]^2$

$\chi^2 = 1.144 / \text{DoF} = 318$

$z = 3$

$z = 2$

- $k_{\parallel} [\text{h Mpc}^{-1}]$
- $k_{\perp} [\text{h Mpc}^{-1}]$

- N-body
- Perturbation Theory
- PT + Finger of God
redshift space matter $P(k)$

Power spectrum, $P(k)$ $[h^{-3} \text{Mpc}^3]$

- Perturbation Theory
- Perturbation Theory + FoG
- N-body Data
- Linear Spectrum (Kaiser)

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

Jeong (2010)
BAO in redshift space matter $P(k)$

$\frac{P(k)}{P_{\text{no-osci}}(k)}$ vs. wavenumber, $k$ [$h/\text{Mpc}$]

$z = 3$

$z = 2$

Jeong (2010)

HETDEX

- Linear Theory
- Perturbation Theory
- PT + Finger of God
- N-body data (512 [Mpc/h])
- N-body data (256 [Mpc/h])
Finally, non-linear galaxy bias

Real space galaxy power spectrum

\[ P_{gs}(k, \mu, z) = P_0 + b_1^2 \left[ P_m(k, z) + b_2 D^4(z) P_{b2}(k) + b_2^2 D^4(z) P_{b22}(k) \right] \]

\[ + 2 f \mu^2 b_1 b_\theta P_{\delta \theta}(k, z) + f^2 \mu^4 b_\theta^2 P_{\theta \theta}(k, z) \]

\[ + D^4(z) \left[ P_{gs,22}^{(rest)}(k, \mu; b_1, b_2) + 2 P_{gs,13}^{(rest)}(k, \mu; b_1) \right] \]
Non-linear galaxy power spectrum

Jeong & Komatsu (2009a)

Millennium power spectrum: nonlinear bias + linear $P(k)$

$z=3$

$z=2$

$P(k)$ [Mpc$/h^3$]

wavenumber [h/Mpc]

$k_{\text{max}}$
BAO in galaxy $P(k)$

- $\sigma_8=0.9$ of the Millennium Simulation is too high compare to the concordance value $\sigma_8=0.814$.
- That’s why we have a smaller $k_{\text{max}}$ here.
The HETDEX galaxy power spectrum

- Perturbation Theory correctly models the non-linearities in the galaxy power spectrum! *I believe we are ready for data.*
BAO from HETDEX

- galaxy power spectrum in redshift space
- galaxy power spectrum in real space
- nonlinear matter power spectrum in real space
- linear matter power spectrum in real space

Baryonic acoustic oscillation $P(k)/\alpha - \alpha_{nw}$

wavenumber $k$ [h/Mpc]
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HETDEX is different from N-body

- N-body = constant number density, cubic box
- HETDEX = a lot of complications
  - Selection + Masking + Survey geometry
  - CCD sensitivity, Sky scanning pattern, Cloud
The thing I will Fourier transform

- What we will measure is the estimated density contrast, but it is different from the "real" density contrast!!

\[ F(r) = w(r) \left[ n_g(r) - \alpha n_s(r) \right] = w(r) \bar{n}(r) \left[ \delta_g(r) - \delta_s(r) \right] \]

\[ \equiv W(r) \left[ \delta_g(r) - \delta_s(r) \right] \]

- LAE selection function, \( n(z) \)
- HET shot centers
- Sky scanning pattern
- Shot weight (cloud, etc)
- IFU masking pattern
- Weight for each IFU unit

Window function

\[ W(r) \equiv \bar{n}(r) w(r) \]

- White noise from random catalogue
- Density contrast of LAE
Number density of HETDEX

- is determined by “shot”+”masking”+”selection”
  \((x, y = \text{angular}, z = \text{radial})\)

\[
\bar{n}(\mathbf{r}) \equiv S(x, y) \otimes M(x, y)n(z) \quad \rightarrow \quad W(\mathbf{k}) = \tilde{S}(k_x, k_y)\tilde{M}(k_x, k_y)n(k_z)
\]
Angular-window (const. weighting)

\[
d^2 \frac{\text{sinc}(k_x d/2) \text{sinc}(k_y d/2)}{\text{sinc}(k_x \Delta_m/2) \text{sinc}(k_y \Delta_m/2)} [100 \text{sinc}(5k_x \Delta_m) \text{sinc}(5k_y \Delta_m) - 4 \text{sinc}(k_x \Delta_m) \text{sinc}(k_y \Delta_m)]
\]

\[
\log_{10} \left[ \tilde{M}(k_x, k_y)^2 \right]
\]

16.528 Mpc $\sim$ 11'  \hspace{1cm} d = 1.252 Mpc $\sim$ 50"

$\Delta_m = 2.337$ Mpc

Shot has to be "as uniform as possible"!
Effect on power spectrum

\[ \frac{\langle |F(k)|^2 \rangle}{W^2} = \int \frac{d^3q}{(2\pi)^3} \frac{|W(k - q)|^2}{W^2} P(q) \]
Result I. constant number density
Result II. After angular selection

Theoretically convolved power spectrum

Nyquist/2

aliasing??

power spectrum $[\text{Mpc}^3]$

wavenumber $[1/\text{Mpc}]$
Things to do by the mid August

- 2D angular-window function from direct FT
- “more” uniform shot? Or “more” random shot?
- angular + radial selection
- Including FKP optimal weighting
- Effect of IFU dependent weighting
- Effect of stochastic things (cloud, etc)
- Effect of HET scanning pattern (inducing correlation?)
- Effect of survey geometry (42*10? 84*5?)
- 2D (perpendicular, parallel) power spectrum
- Effect of anisotropic window to measure velocity power spectrum
- Effect of window function in the galaxy bispectrum
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Primordial non-Gaussianity

- Well-studied parameterization is “local” non-Gaussianity:
  \[ \Phi(x) = \phi(x) + f_{NL}(\phi^2(x) + \langle \phi^2 \rangle) \]

- Any detection of \( f_{NL} \) would rule out all the single field models regardless of the details of the model!

Current best measurement of \( f_{NL} \)
- From CMB (Komatsu et al, 2010)
  \[ f_{NL} = 32 \pm 21 \ (68\% \ C.L.) \]
- From SDSS power spectra (Slosar et al, 2009)
  \[ f_{NL} = 31^{+16}_{-27} \ (68\% \ C. \ L.) \]
Non-Gaussianity from HETDEX $P(k)$

\[ P_g(k, \mu) = P_0 + \left[ b + \frac{2f_{NL}\delta_c(b-1)}{M(k, z)} + f\mu^2 \right]^2 P_L(k) \]

\[ M(k, z) = 2D(z)k^2T(k)/(3H_0^2\Omega_{m0}) \]

$\Delta f_{NL} = 21$, comparable to WMAP7!!
The galaxy bispectrum: definition

- Probability of finding three galaxies at separation \((r, s, t)\) is given by the two, and three-point correlation function

\[
P_3(r, s, t) = \bar{n}^3 (1 + \xi(r) + \xi(s) + \xi(t) + \zeta(r, s, t)) dV_1 dV_2 dV_3
\]

- \(B(k, k')\) is the Fourier transform of \(\zeta(r, s)\).

\[
B(k, k') = \int d^3r \int d^3s \zeta(r, s) e^{-i r \cdot k} e^{-i s \cdot k'}
\]

- Or, in terms of density contrast,

\[
\langle \delta(k_1)\delta(k_2)\delta(k_3) \rangle = (2\pi)^3 B(k_1, k_2, k_3) \delta^D(k_1 + k_2 + k_3)
\]
The galaxy bispectrum: theory

- The galaxy bispectrum consists of four pieces
  I. Matter bispectrum due to primordial non-Gaussianity
  II. Matter bispectrum due to non-linear gravitational evolution
  III. Non-linear galaxy bias
  IV. Non-Gaussianity term from peak correlation

\[ B_g(k_1, k_2, k_3, z) = 3b_1^3 f_{NL} \Omega_m H_0^2 \left[ \frac{P_m(k_1, z)}{k_1^2 T(k_1)} \frac{P_m(k_2, z)}{k_2^2 T(k_2)} \frac{k_3^2 T(k_3)}{D(z)} + (2 \text{ cyclic}) \right] + 2b_1^3 \left[ F_2^{(s)}(k_1, k_2) P_m(k_1, z) P_m(k_2, z) + (2 \text{ cyclic}) \right] + b_1^2 b_2 \left[ P_m(k_1, z) P_m(k_2, z) + (2 \text{ cyclic}) \right] + b_1^3 \frac{\delta_c}{2\sigma_R^2} \int \frac{d^3 q}{(2\pi)^3} T_R(q, k_1 - q, k_2, k_3) + (2 \text{ cyclic}) \]
Triangles

(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
\( k_1 = k_2 = k_3 \)
Bispectrum of Gaussian Universe

- We can measure bias from Equilateral and Folded triangles:
  \[ \Delta b_1/b_1 = 0.01, \, \Delta b_2/b_2 = 0.05 \]

Bispectrum from non-linear gravitational evolution

Bispectrum from non-linear galaxy bias
Squeezed limit is the cleanest window to primordial non-Gaussianity

Jeong & Komatsu (2009b)
Bispectrum of non-Gaussian Universe II

• From HETDEX bispectrum, we can measure primordial non-Gaussianity better than Planck, $\Delta f_{NL} = 4.5$!

Bispectrum from primordial non-Gaussianity

Jeong & Komatsu (2009b)
Conclusion

• **Theory is ready for analyzing HETDEX power spectrum.**
• I am working on making a pipeline from HETDEX data to the power spectrum and bispectrum.
• Beyond power spectrum, we can extract more information from the galaxy bispectrum: e.g. bias parameter, primordial non-Gaussianity.
• **Theory is not (yet) ready for analyzing HETDEX bispectrum. This will be my next work.**
What’s next?

• Cahill Center for Astronomy Astrophysics at Caltech
Thank you!
Zheng Zheng effect

- Recent Lyman-alpha Radiative transfer simulation shows the environment (density, velocity gradient) dependence effect

Note!!!!
Number density of LAEs = 50 HETDEX
Zheng et al. (2010)
Is this effect important for HETDEX?

- The effect is smaller for small number density of LAEs! n(LAEs) for HETDEX is **2.4E-4 [Mpc/h]^3**
- What about at HETDEX redshifts, and on large scales?
- A working group inside of HETDEX collaboration formed: DJ, Eiichiro Komatsu, Jens Niemeyer, Ariel Sanchez
HETDEX and CMB lensing

Unlensed

Lensed

Picture from Hu & Okamoto (2001)
HETDEX is at the sweet spot!

- Convergence power spectrum of CMB is given by

$$C_{\ell}^{\kappa\kappa} = \frac{9}{4} \Omega_m^2 H_0^4 \int \frac{dz}{z} D(z) \left(1 + \frac{z}{H(z)} \right)^2 \left(\frac{d_A(z; z_{LSS})}{d_A(z_{LSS})}\right)^2 P_m \left(k = \frac{l}{d_A(z)}\right)$$

$$\equiv \frac{9}{4} \Omega_m^2 H_0^4 \int \frac{dz}{z} K(z) P_m \left(k = \frac{l}{d_A(z)}\right),$$
HETDEX-lensing cross correlation

- We can measure the linear bias parameters with $\Delta b_1/b_1 \sim 0.1$, but may not be useful for $f_{NL}$ as $\Delta f_{NL} \sim 200$

But, this figure is for Full-sky HETDEX! For $f_{\text{sky}}=0.01$ (real HETDEX), $\Delta b_1/b_1 \sim 1$. It will be reduced as more “effective lens redshifts” are included!