Galaxy Clustering (inc. BAO) with AFTA-WFIRST

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(with input from Chris Hirata & David Weinberg)

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How We Probe Dark Energy

• *Cosmic expansion history* $H(z)$ or *DE density* $\rho_X(z)$
tells us whether *DE is a cosmological constant*

$$H^2(z) = \frac{8\pi G[\rho_m(z) + \rho_r(z) + \rho_X(z)]}{3} - \frac{k}{a^2}$$

• *Growth history of cosmic large scale structure* [growth rate $f_g(z)$ or growth factor $G(z)$]
tells us whether *general relativity is modified, given $H(z)$*

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Measuring the Metric

In the conformal Newtonian gauge (the longitudinal gauge), the perturbed Robertson-Walker metric is given by

$$ds^2 = a^2(\tau)[-(1 + 2\phi)d\tau^2 + (1 - 2\psi)\gamma_{ij}dx_idx_j]$$

• Applicable only for scalar mode of the metric perturbations
• $\phi$: the gravitational potential in the Newtonian limit
• $\gamma_{ij}$: the three-metric for a space of constant spatial curvature

WL: probe $\phi + \psi$

GC/RSD: probes $\phi$ (peculiar velocities follow gradients of the Newtonian potential)

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BAO as a Standard Ruler

Blake & Glazebrook 2003
Seo & Eisenstein 2003

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BAO “wavelength” in radial direction in slices of $z : H(z)$

$\Delta r_{||} = (c/H)\Delta z$

BAO “wavelength” in transverse direction in slices of $z : D_A(z)$

$\Delta r_{\perp} = D_A\Delta \theta$

BAO systematics:

- Bias
- Redshift-space distortions
- Nonlinear effects
Spherically-averaged galaxy correlation function (top) and galaxy power spectrum (right).

Anderson et al. (2012)
First Measurements of $H(z)$ & $D_A(z)$ from Data

LasDamas mock catalog  SDSS LRG catalog

$x_h(z) = H(z)s = 0.04339 \pm 0.00178$ (4.1%); $x_d(z) = D_A(z)/s = 6.599 \pm 0.263$ (4.0%)

$r(x_h, x_d) = 0.0604$  ($z=0.35$, $s$: BAO scale, i.e., sound horizon at the drag epoch)


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Mode-coupling

- Small scale information in $P(k)$ destroyed by cosmic evolution due to mode-coupling (nonlinear modes); intermediate scale $P(k)$ also altered in shape
- Its effect can be reduced by:
  1. Density field reconstruction (Eisenstein et al. 2007)
  2. Extracting “wiggles only” constraints (discard $P(k)$ shape info)
  3. Full modeling of correlation function (Sanchez et al. 2008)

Ratio of nonlinear and linear $P(k)$
Horizontal line: no nonlinearity
Dashed lines: model
Dark matter only
(Augulo et al. 2008)
BAO Reconstruction With SDSS DR7 LRGs

Padmanabhane et al. (2012)

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BAO Systematic Effect: Redshift-Space Distortions

- Artifacts not present in real space
  - Large scales: coherent bulk flows (out of voids and into overdense regions). These boost BAO; can be used to probe growth rate $f_g(z)$
  - Small scales: smearing due to galaxy random motion ("Finger of God" effect)

Left: Ratio of redshift-space and real-space power spectra. Horizontal lines: coherent bulk flows only. Dashed lines: model (Angulo et al. 2008)

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**BAO Systematic Effect:**

*Galaxy Clustering Bias*

- How galaxies trace mass distribution
  - Could be scale-dependent
  - Only modeled numerically for a given galaxy sample selection (Angulo et al. 2008)

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**Ratio of galaxy power spectrum over linear matter power spectrum**

Horizontal lines: no scale dependence in bias. Dashed lines: model

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Advantages:
- Observational requirements are least demanding among all methods (redshifts and positions of galaxies are easy to measure).
- Systematic uncertainties (bias, nonlinear clustering, redshift-space distortions) can be made small through theoretical progress in numerical modeling of data.

Challenges:
- Full modeling of systematic uncertainties
- Translate forecasted performance into reality
The Use of Galaxy Clustering to Differentiate Dark Energy & Modified Gravity

Measuring redshift-space distortions $\beta(z)$ and bias $b(z)$ allows us to measure $f_g(z) = \beta(z)b(z)$

$[f_g = d\ln \delta / d\ln a]$

$H(z)$ and $f_g(z)$ allow us to differentiate dark energy and modified gravity.

Wang (2008)

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Forecast Methodology

• Method from Wang, Chuang, & Hirata (2012), arXiv:1211.0532
  – Use dewiggled $P(k)$ (inc NL, RSD), with $b(z)=0.9+0.4z$
  – $k_{\text{max}}=0.2h/\text{Mpc}$, $k_*=0.12h/\text{Mpc}$ (100% nonlinearity)
  – Marginalize over $k_*$ and $\sigma_z/(1+z)$
  – Exponential pdf for $v_{\text{pec}}$ with dispersion 290km/s

• Survey assumptions
  – 4000 sq deg, $\sigma_z/(1+z)=0.001$, FoV=0.281(deg)$^2$
  – Exposure times (1.3-2$\mu$m and 1.5-2.1$\mu$m):
    • 6x150s : 148.3 days, 5.2M (4.6M) H$\alpha$ galaxies;
    • 6x300s : 296.6 days, 22.1M (19.3M) H$\alpha$ galaxies;
    • 6x600s : 593.1 days, 49.4M (42.9M) H$\alpha$ galaxies
Preliminary & Conservative Forecasts

AFTA-A: 4000 (deg)$^2$

DRM1: 3313 (deg)$^2$

Euclid: 15000 (deg)$^2$

WFIRST DRM1/AFTA:
nominal depth is 6 exposures, but most of the area is deeper
$\rightarrow$ ~20% more galaxies

Euclid:
nominal depth is 2 exposures, but some of the sky gets only 1 exposure
$\rightarrow$ ~18% less galaxies
Preliminary Forecasts

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[Graph showing AFTA - A with different wavelengths and time intervals]
Preliminary Forecasts

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Preliminary Forecasts

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Note that \( f_g(z)G(z) \) is scaled by \( s^\alpha, \alpha \sim 4 \).
The scaling can be optimized such that \( \Delta \ln [f_g(z)G(z)] \sim \Delta \ln \beta(z) \) (see Wang 2012).
Discussion: Science trades

• Key considerations
  – Complementarity to Euclid
  – Significance of dark energy science

• Possibilities:
  – Go deeper over smaller area: better reconstruction of density field to reduce NL effects
    • $nP_{0.2} \sim 2$ might be sufficient, use extra time to go wider
  – Explore capability for multi-tracer approach
Advantage of Multi-Tracer Approach: I

AFTA-A, 0.11" pixel, 6x3 chips, FoV=0.281 (deg)^2; Telescope temperature: 250K

<table>
<thead>
<tr>
<th>λ</th>
<th>Hα: z range 656.28nm</th>
<th>[OIII]: z range 500.7nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3-2 µm</td>
<td>0.980-2.046</td>
<td>1.595-2.993</td>
</tr>
<tr>
<td>1.5-2.1 µm</td>
<td>1.285-2.199</td>
<td>1.995-3.192</td>
</tr>
</tbody>
</table>

- The z range is complementary to Euclid if [OIII] emission lines can be reliably detected and the [OIII] luminosity function is known
- Study ongoing by Colbert et al. using WFC3 grism data

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Mapping the Cosmic Expansion History

\( H_0 \): Blue: Riess et al. (2011)

BAO/GC:
Filled blk sq: Xu et al. (2012) [SDSS DR7 LRGs]
Open blk sq: Chuang & Wang (2012) [SDSS DR7 LRGs]
Cyan sq: Reid et al. (2012) [BOSS CMASS galaxies]
Green: Blake et al. (2011, 2012) [WiggleZ]
Red sq: Busca et al. (2012) [Ly\(\alpha\) forest of BOSS quasars with \( z=2.1-3.5 \)]
*4% with WMAP7 priors
*15% w/o WMAP priors

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Advantage of Multi-Tracer Approach: II

Hamaus, Seljak, & Desjacques (2012)
Single tracer: use all halos
Multi-tracer: use two density fields obtained via weighting the halo catalog with its principal components.

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Discussion: Requirements for the telescope

- $\sigma_z/(1+z)=0.001 \rightarrow$ dispersion requirements?
- Uniformity of galaxy selection
- Longer wavelengths (more complementary to Euclid)
- Identify H$\alpha$ and [OIII] lines reliably (more complementary to Euclid and enable multi-tracer approach)
Conclusions: I

- For 1.5-2.1 μm, Hα redshift range \( z = 1.3-2.2 \) extends beyond the \( z=2 \) cutoff of Euclid.
- [OIII] emitters could extend the survey to \( z\sim3 \).
- For 6x300s over 4000 sq deg (~300 days), the BAO precision is significantly better than Euclid and DRM1 at all redshifts in the survey.
- For 6x150s over 4000 sq deg, the precision is substantially worse than both Euclid and DRM1.

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Conclusions: II

• With ~300 days of observing time, the AFTA galaxy redshift survey would be a substantial advance in dark energy discovery potential. With ~150 days of observing time, it would be much less of an advance.

• These observing time numbers will scale with the FoV of the focal plane array.

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The End
\( x_h = H(z) s \), \( x_d = D_A(z) / s \)  
\( \Delta z = 0.1 \)  
Wang (2012)
Use Baryon Acoustic Oscillations to Probe Dark Energy

Galaxy 2-pt correlation function

Galaxy power spectrum

Eisenstein et al. (2005)

Percival et al. (2009)

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Results from WiggleZ

Top: spherically averaged.

Right: background cosmology fixed.

Blake et al. (2011ab)

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Challenge in 2D:
Proper Modeling of SDSS Data

Okumura et al. (2008)

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Evaluating the Modeling

Average of 160 LasDamas mock catalogs

Chuang & Wang, arXiv:1209.0210

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Reid et al. (2012) measured $H(z)$, $D_A(z)$, $f_g(z)\sigma_8(z)$ assuming WMAP7 priors

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