Clustering and redshift-space distortions as probes of dark energy: present and future

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• The renaissance of redshift-space distortions (in a new context)

• Improving the data: the VIPERS project at ESO

• Improving the modelling: RSD in the precision cosmology era, predictions and systematic errors

• A glimpse of the distant future: Euclid
Redshift-Space Distortions (RSD) and cosmic acceleration: what’s all the fuss about?
Cosmic concordance: a $w=-1$ Universe?

Amanullah et al. 2010 (Union supernovae)
However, lambda (or dark energy) is not the end of the story...

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu} \]

Modify gravity theory [e.g. $R \rightarrow f(R)$]  
Add dark energy

“…the Force be with you”
To distinguish, look at how linear density fluctuations grow in the expanding Universe.

\[ \frac{d}{dt} \delta + 2H(t)\delta = 4\pi G \langle \rho \rangle \delta \]

\[ \delta^+(x, t) = \hat{\delta}(x) D(t) \]

\[ f = \frac{d \ln D}{d \ln a} \]

(Image credit: V. Springel)
• The growth equation (and thus the growth rate) depends not only on the expansion history $H(z)$ (and thus on $w(z)$) but also on the gravitation theory.

• Measuring $f(z)$ we can break the degeneracy between models with same effective $H(z)$, but completely different physics (unless DE clusters, Kunz & Sapone 2007).

For a wide variety of models:

$$f(z) = [\Omega_m(z)]^\gamma$$


e.g.

$\gamma = 0.55$ for standard $\Lambda$

$\gamma = 0.68$ for DGP braneworld

How do we measure $f(z)$?

Growth produces motions: galaxy peculiar velocities

Figure by K. Dolag
In galaxy redshift surveys, peculiar velocities manifest themselves as \textit{redshift-space distortions} (Kaiser 1987).
In galaxy redshift surveys peculiar velocities manifest themselves as *redshift-space distortions* (Kaiser 1987)

*redshift space*
• E.g. 2dFGRS, $z \sim 0.1$, Peacock et al. 2001, Hawkins et al. 2003

$$\beta = 0.49 \pm 0.09$$

• Essentially used to obtain an estimate of $\Omega_M$ once the bias is known or derived (e.g. from the bi-spectrum, Verde et al. 2001):

$$\beta \approx \frac{\Omega_M^{0.55}}{b_L}$$

(Definitive 2dFGRS measurement: Hawkins et al. 2003)
A test of the nature of cosmic acceleration using galaxy redshift distortions

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$\beta=0.70\pm0.26 \quad (@ \ z=0.77)$

(LG et al. 2008, Nature 451, 541)
VVDS-Wide @ z=0.77:

\[ f = b_L \beta = 0.91 \pm 0.36 \]

Where \( b_L = 1.3 \pm 0.1 \) is measured combining VVDS and CMB (e.g. Marinoni et al. 2005)

The signature of linear growth at \( z \sim 1 \)

Guzzo et al. 2008, Nature 451, 541
Baryonic Acoustic Oscillations imprint in the galaxy distribution

$P(k) (h^{-3} Mpc^3)$

$2\pi/k (h^{-1} Mpc)$

$\Lambda$CDM ($\Omega_m = 0.35$)

$\Omega_B =
\begin{cases}
0.005 \\
0.02 \\
0.05 \\
0.10
\end{cases}$

D. Eisenstein 2007
Baryonic Acoustic Oscillations: measure $H(z)$ from redshift surveys

Give $D_A(z)$ and $H(z)$: see Percival et al. 2011 for most recent application to SDSS and 2dFGRS
Waiting for Euclid...
Improving the data: the VIPERS survey
Which survey? BAO-oriented surveys (as e.g. Wigglez or BOSS) aim at huge volumes with sparse sampling. However, highly-sampled surveys like 2dFGRS provided us with a much more comprehensive and detailed view of large-scale structure and its relation to galaxies...
VIPERS: exploiting VIMOS Multi-Object Spectroscopy at the VLT (440 hours)

(see http://vipers.inaf.it)
VIPERS Team

- **MILANO OAB (Project Office)**: L. Guzzo, B. Granett, A. Iovino, A. Marchetti, U. Abbas (Turin)
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- **PORTSMOUTH**: W. Percival, R. Tojeiro, R. Nichol
- **WARSAW**: A. Pollo, K. Malek, J. Krywult (Kielce)
VIPERS in a nut-shell

- 440.5 VLT hours
- $\sim 24$ deg$^2$ over W1 and W4 CFHTLS wide fields ($\sim 16 + 8$)
- $I_{AB} < 22.5$, LR Red grism, 45 min exp.
- 288 VIMOS pointings
- $z > 0.5$ color-color pre-selection
- PSF + SED –based star-galaxy separation (AGN color recovery)
- $\sim 100,000$ redshifts, >40% sampling
- Density and volume comparable to 2dFGRS, but at $z \sim 0.8$
Location of VIPERS fields

CFHT Legacy Survey Areas
VIPERS coverage (as of Dec 2011): ~55,000 spectra observed; ~35,000 redshifts reduced and validated (v2.0 internal release)
VIPERS redshift distribution

34,922 redshifts
(40% of total survey)
Early results: The real-space galaxy $P(k)$ at $<z> \sim 0.8$ from the full CFHTLS-Wide data, “sliced” using VIPERS $N(z)$ and color selection


CFHTLS-Wide:
- $\sim 140$ deg$^2$
- 5-bands (ugriz)
- 2.1 million galaxies

- VIPERS mag/color criteria work very well in selecting $0.5<z<1.2$
- Characterize VIPERS parent sub-catalogue
- Accurate $N(z)$ crucial for de-projection: provided by VIPERS
- Exploits currently largest available volume of CFHTLS-Wide areas
- Recent Cl angular Thomas
Real space $P(k)$ at $z \sim 0.7$ from CFHTLS-Wide + VIPERS $N(z)$

1) $C_l$ spectrum using Tegmark 1997 quadratic estimator

2) Deconvolved following Efstathiou & Moody 2001

Complementary to recent $C_l$ estimate at $z \sim 0.5$ from SDSS LRGs (Thomas, Abdalla & Lahav 2011)

B. Granett & VIPERS Team, arXiv 1112.0008
Early $\xi(r_p, \pi)$ from first $\sim12,000$ high-quality VIPERS redshifts at $0.5<z<1$

Data

Best-fitting model ($\beta=0.62$)

2 parameter fit of the full shape of $\xi(r_p, \pi)$ on $0<r_p<20$ scale (S. de la Torre, & the VIPERS Collaboration)
f(z) from redshift distortions, recent developments


- ~152,000 redshifts (aim at 200,000 gals), over 5000 deg²
- UV-selected emission-line galaxies from GALEX: complex selection function
- Original main goal: BAOs
- Large volume, very low-density sample
- VIPERS will provide comparable precision, but also allow us to select multiple populations
- Reduce errors (McDonald & Seljak, 2009, JCAP) and control systematics
Summary of VIPERS status

- VIPERS finally exploits VIMOS capabilities for LSS study, filling a specific niche $z \sim 1$: volume $6 \times 10^7 \ h^{-3} \ Mpc^3$, sampling $\geq 40\%$

- Study large-scale structure, clustering and growth at $0.5 < z < 1$, to an accuracy comparable to local state-of-the-art surveys

- Efficient survey pipeline: automatic data calibration, redshift measurement and database archiving: $\sim 22,000$ spectra secured in 2009 season, further $\sim 10,000$ from 2010 under reduction

- Pre-refurbishment data required heavy human review of the automatic redshifts: BIG TEAM EFFORT. Situation improved with new VIMOS CCDs (installed/commissioned in June-September 2010), but full potential still to be reached

- With current observing rate, completion expected by end 2013

- More photometry ongoing/planned (GALEX, WIRCAM, VISTA)

- Public survey: raw data public immediately, redshifts released in regular tranches
Improving the tool: RSD in the precision cosmology era
Kaiser/Hamilton linear redshift-distortion model

\[ P(k_{||}, k_{\perp}) = P(k) \left(1 + \beta \mu^2 \right)^2 D(k\mu\sigma_p). \]

\[ D(k\mu\sigma_p) = \frac{1}{1 + (k\mu\sigma_p)^2 / 2} \]
Based on BASICC simulation halo catalogues (Angulo et al): 3 billion particles in a 1340 $h^{-1}$ Mpc side box

**RESULT:** ~5-10% systematic underestimate

Hints that larger-mass halos do perform better (e.g. LRGs)

See also Okumura & Jing 2011 using ratios of moments and Kwan et al. 2011

Calls for improved description of RSD

Improving the linear model: role of galaxy bias

De la Torre & LG 2012, arXiv:1202.5559
Predicting statistical errors: can we trust Fisher Matrix predictions?

Predicting statistical errors: a handy and accurate scaling formula describing the behaviour found in the Monte Carlo experiments

\[ \frac{\delta(\beta)}{\beta} \approx C b^{0.7} V^{-0.5} \exp \left( \frac{B}{b^2 n} \right) \]

Accounting for the Alcock-Paczyński effect?

A glimpse of the distant future
Growth with Euclid: RSD

- Redshift-space distortions map motions due to structure growth

\[ \sigma_z = 0.001(1+z) \]
\[ \sigma_z = 0.0 \]

EUCLID lightcone (100deg²)
\[ S_{50}<1\times10^{-16}\text{erg/s/cm}^2 \]
(sims from Durham group)
Euclid will image the

- best 1/3 of the sky (15000 deg$^2$)
- similar resolution at HST in optical
- NIR imaging in 3 filters
- Images for $2 \times 10^9$ galaxies

and carry out an unprecedented redshift survey with

- NIR spectra for $5 \times 10^7$ galaxies
  ($0.7 < z < 2$)

The Euclid “Red Book”

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#
Summary

- Explaining the origin of cosmic acceleration is plausibly the most compelling problem in cosmology: did Einstein have the last word on gravity?
- A brilliant future for galaxy redshift surveys: measure both \( w(z) \) and \( f(z) \) using BAOs/P(k) and z-distortions (plus clusters...) \( \rightarrow \) test dark energy vs modified gravity
- A renaissance for redshift-space distortions: not considered in this context before 2008, now accepted as standard “dark energy probe” (EUCLID)

1) RSD: Improving the data
- Exciting \( z \)-distortions results from WiggleZ. More expected soon come from BOSS
- VIPERS: a 2dFGRS at \( z \sim 0.8 \), \( \sim 100,000 \) highly-sampled redshifts; early measurement of real-space \( P(k) \) in combination with CFHTLS
- EUCLID is approved and plans to couple a massive (slitless) redshift survey with a high-resolution imaging survey, to combine galaxy clustering and weak lensing (launch 2019)

2) RSD: Improving the estimators
- Need to go beyond Kaiser-Hamilton formalism, if we aim at precision cosmology on \( f(z) \)
- A lot of work ongoing in the community, very promising results, exciting times ahead
- DARKLIGHT: an ERC Advanced Grant program to improve estimators and apply to early data: look for jobs in this area
"ILLUMINATING DARK ENERGY WITH THE NEXT GENERATION OF COSMOLOGICAL REDSHIFT SURVEYS"

ERC Advanced Research grant 5 years, 1.7 Meuro

5 postdoc positions + 3 PhD positions

Starting summer 2012

- Improve modelling and estimators of clustering and redshift distortions, preparing for precision cosmology
- Apply them to ongoing new surveys (e.g. VIPERS)
- Combine with other probes of LSS (clusters of galaxies) and CMB measurements (Planck)