Fundamental cosmology from the galaxy distribution
What we learn from LSS

Fundamental:

• Matter content (CDM, baryons, neutrino mass)
• Properties of dark energy
• Testing gravity with peculiar velocities
• Character of primordial fluctuations (non-Gaussianity)

Astrophysical:

• Calibrating the halo-galaxy connection
• Environmental effects on galaxy formation (cosmic web)
• Finding the gas (x-corr with CMB & X-ray)
Outline

• Achievements and goals

• Observational outlook

• Tensions
  – Current situation
  – Modelling issues and outlook
A SURVEY OF GALAXY REDSHIFTS. II. THE LARGE SCALE SPACE DISTRIBUTION

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ABSTRACT

We have finished a redshift survey of galaxies complete to 14.5 m in the north and south galactic polar caps above declination =0° and containing some 2400 galaxies. We present here various projections of the resulting redshift-space maps. While different in detail, the statistical nature of the redshift-space distribution is very similar between the north and south. The space distribution of galaxies is frothy, characterized by large filamentary superclusters of up to 60 Mpc in extent, and corresponding large holes devoid of galaxies. We also present redshift-space maps generated from n-body simulations, which very roughly match the density and amplitude of the galaxy clustering but fail to match the frothy nature of the actual distribution. Our results present a severe challenge to all theories of galaxy and cluster formation.

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

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ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto k^\gamma$. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, $m$, if $m \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.
CDM rapidly became the leading model

- Included DM but preserved galaxy-scale structure

- Predictive (linear relics plus N-body)
  - (so were baryon-only models, but little data then)

![Graphs showing varying matter density times Hubble constant and varying baryon fraction](image)
1990: APM $w(\theta)$

$\Omega_m h \simeq 0.2$ (and hence $\Lambda$ via lack of small-scale CMB expected in open models)
Establishment of standard model as we know it today

- only subsequent new ingredient is $n=0.96$ tilt (WMAP 2006)
Current BSM science aims with LSS:

(0) Neutrino mass

(1) Non-Gaussianity

(2) Evolution of dark energy?

(3) Build-up of DM structures as test of gravity
Neutrinos

Normal or inverted hierarchies fit oscillation data
Free-streaming erases neutrino fluctuations

Reduced growth rate for $k > \sim 0.05$  – reduced $\sigma_8$

Claims of detection at $m = 0.36 \pm 0.10$ eV (1403.4599)

Planck 2015: $m < 0.23$ eV (0.06 eV smallest possible)
Non-Gaussianity

Potentially deepest impact of LSS on initial conditions

$\Phi \rightarrow \Phi + f_{NL}(\Phi^2 - \langle \Phi^2 \rangle)$

$\Rightarrow b(k) \rightarrow b(k) + O\left(f_{NL} \left(\frac{k_c}{H_0}\right)^{-2}\right)$

Scale-dependent bias limits $f_{NL}$ with precision $\sim 25$

- less strong than Planck, but CMB will get no more modes
But DE & MG are the prime BSM targets

- and BAO & RSD are the main tools

- and SDSS LRGs are the enabler
SDSS

- Current state of the art
- 2M z’s 2002-present
SDSS: Luminous Red Galaxies
Baryon Acoustic Oscillations

The (comoving) distance that sound waves travel by recombination sets the length of the BAO cosmic ruler at $t = 380,000$ years:

$$l_{\text{BAO}} = \int_0^{t_{\text{rec}}} \frac{c_s}{a} dt \approx \frac{c}{\sqrt{3}} \frac{t_{\text{rec}}}{a_{\text{rec}}}$$

$$a_{\text{rec}} = 1/1100$$

‘Baryon wiggles’ at 1 degree (& 0.3, 0.2, 0.1...): 150 Mpc at 13 Gpc

Oscillations of baryonic gas and radiation before decoupling
Acoustic Peak from BOSS

- SDSS-III BOSS gives a strong BAO detection, measuring the acoustic scale to 1% at $z=0.57$.

Anderson et al. (2014)
The Cosmic Distance Scale

Planck curve is a Prediction, not a Fit

Anderson et al. (2014)
Sensitivity to Dark Energy

\[
D(z) = \frac{c}{H_0} \int_0^z \frac{dz}{\left[ \Omega_v (1+z)^{3+3w} + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 \right]^{1/2}}
\]

Dark Energy affects $H(z)$, $D(z)$ and perturbation growth $g(z)$

Effects of $w$ are:

1. Small (need $D$ to 1% for $w$ to 5%)

2. Degenerate with changes in $\Omega_m$

Rule of 5

Future target should be <1% on BAO scale, requiring much larger redshift surveys

Solid: vary $w$  Dashed: vary $\Omega_m$
BAO limits on DE equation of state
(w = P / ρc²)

\[
w(a) = w_0 + (1-a)w_a
\]

\[w = -1 \pm 0.06\]
if unevolving:

DE looks like cosmological constant

Planck 2015
Redshift-space distortions as a probe of gravity

\[ D \approx \frac{cz}{H} \rightarrow \left( cz_{\cos} + \delta v \right)/H \]

Mass: measure \( f_g \equiv d \ln \delta/d \ln a \quad (\sim \Omega_m^{0.55} \text{ for standard gravity}) \)

Galaxies: measure \( \beta \equiv f_g/b; \quad b \) unknown, but \( f_g \sigma_8 \) observable

\[ P(k) \text{ approximately Kaiser-Lorentz: } P(k, \mu) = P_{\text{real}}(1 + \beta \mu^2)^2(1 + k^2 \sigma_p^2/2)^{-1} \]

Infer \( \beta \) from quadrupole-to-monopole ratio in anisotropic power spectrum

Use simulations to assess deviations from simple distortion model (and to assign errors)
14 years of RSD

Split 2-point correlations in transverse and radial directions

2001: 2dFGRS 8% on $f_g$

2014: SDSS LRG 2.5% on $f_g$
Direct peculiar velocities

Davis & Nusser: exquisite match of TF v with 2MRS gravity:

$$\beta = \frac{f_g}{b}$$

$$= 0.33 \pm 0.04$$

- cf. 1980s POTENT $$\beta = 1$$
Growth rate: Einstein OK at 10%

DESI (BigBOSS), eBOSS (SDSS-IV), Sumire-PFS (WFMOS), Euclid will push towards <1% precision at higher z
Improving the data

- Reducing nonlinearity
- Robustness from different tracers
- Suppression of cosmic variance
Clipping the nonlinearities

F. Simpson: choose threshold at top ~10% of density and set $\rho = \rho_{\text{max}}$ above threshold

GAMA 1505.03865:
Clipped DM matches linear growth to $k=0.5$
- but works less well for galaxies.

In progress: clipped VIPERS
(Mike Wilson)
Future LSS probes
Subaru PFS

- 2400 Fibres over 1.3-deg field on 8.2m
- R=3000 spectra from 0.4 to 1.3 microns
- Multinational project led by IPMU Tokyo
- Planned first light 2017
- 4m OII emitters over 1400 deg² in 0.6 < z < 2.4
DESI

DOE project for KPNO 4m over 2018-2022:

5000 Fibres; 3-deg field

30M galaxies

- LRGs to $z = 0.9$
- OII ELGs to $z = 1.7$
- QSOs to $z = 3$
DESI redshift coverage

3 million QSOs
17 million ELGs
4 million LRGs
10 million BGs (r < 19.5)
DESI target photometry

14,000 deg$^2$ in grz to 24.0, 23.4, 22.5 – complete mid-2017
DESI targets

Multicolour grz selection including WISE new data
DESI corrector and positioner
DESI positioner

5000 twin r-theta epicyclic positioners, mounted in petals
DESI spectra ($R \sim 3000$)

OII flux limit $8 \times 10^{-17}$ cgs in 20-min exposures (5m for BGS)
Euclid slitless spectroscopy

NIS Instrument:

- ~ 25M redshifts in 1 < z < 2
- 15,000 deg²
- H < 19.5
Outlook: 0.1% cosmology
Precision is challenging
Vulnerability to mocks

Observational strategy causes $O(1)$ raw systematics, which must be corrected to 0.1% precision
The chimera of unbiased estimators

VIPERS: first RSD at z=1 (Pezzotta et al. in prep)

Fit $f_g$ using analytic models – is there any difference between applying a bias correction or hoping for zero bias?
Mocks by occupying haloes

1950s Neyman-Scott idea reborn with simulation results on DM haloes
The halo model in SDSS

Fitting SDSS: Guo et al. 1505.07861

Halo model: \[ \rho = \bigcirc + \bigcirc \]
N(M+++)? Assembly bias

- Not just that haloes collapsing early are more clustered
  - Always present in Kaiser (1984)
  - Halo model averages over such effects:

\[
b(M,z_f) + N(M): \langle b \, N \rangle = \langle b \rangle \, \langle N \rangle
\]

- But galaxy contents(M) can couple to formation z:
  - Early formation yields older stars
  - But deeper potential: harder to quench?
  - Early formation gives fewer subhaloes (= satellites)

\[
b(M,z_f) + N(M,z_f): \langle b \, N \rangle \neq \langle b \rangle \, \langle N \rangle
\]
Galactic conformity

SFRs correlated within and between haloes (Kauffmann et al. 1209.3306)

Tidal forces correlate halo accretion rates (Hearin et al. 1504.05578)
Haloes are not passive spectators

- Large potential effects on mass profile from feedback
  - Major problem for gravitational lensing
    - Can plausibly fit empirically with few parameters (1505.07833)
  - But lensing’s headache is good news for galaxy formation

Van Daalen; Schaye

Power spectrum ratio
RSD and fine details of velocity field

e.g. Reid et al. (2014): central galaxy velocity offset matters in RSD modelling at % level
“There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know”
Vulnerability to Bayes

Will we believe any detections of new ingredients?

\[ P(\text{model} \mid \text{data}) \sim L(\text{data} \mid \text{model}) \cdot P(\text{model}) \]

- Moderate prior belief in simplest neutrino hierarchy
- Strong prior belief in \( \Lambda \)
- Even stronger prior belief in Einstein gravity

Already plenty of papers with ‘detections’ that are ignored: e.g. Bean 2009 GR disproof, 2014 Beutler massive neutrino detection. Unlikely that DESI or Euclid will reach 5sigma level
e.g. the lensing-CMB $\sigma_8$ tension

Systematics or evidence for MG?

1606.05338
Conclusions

• LSS has a proud record in fundamental cosmology
  – Establishing $Λ$CDM as the standard model
  – Validation of fundamentals of model at 10% level

• Huge surveys in prospect for the next decade
  – Prospect of factor 10 improvement in precision
  – Much hard work to nail systematics underway

• Will we have the theoretical courage to believe radical results?