Spectroscopic
Future of $\Lambda$ Galaxy Surveys

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Cosmology from spectroscopic galaxy surveys

Use galaxies \((\theta, \phi, z)\) to trace the matter field

Future Galaxy Surveys
Recent progress
extended BOSS / SDSS-IV

- Ongoing cosmological galaxy survey within SDSS
- Use the Sloan telescope and MOS to observe to higher redshift than BOSS
- Basic parameters (cmpr BOSS 10,000deg^2, 1.1M galaxies)
  - $\Omega = 1,500$deg^2 – 5,800deg^2
  - 230k 0.6<z<0.9 LRGs (direct BAO, RSD)
  - 210k 0.8<z<1.0 ELGs (direct BAO, RSD)
  - 340k 0.9<z<2.2 QSOs (direct BAO, RSD)
  - 60k QSOs (BAO, RSD from Ly-\alpha forest)
- Survey 2014-2019

Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216
DR14 eBOSS QSO footprint (data now public)

~2,000 deg$^2$ split in the NGC and SGC regions

Ata et al. 2017; arXiv:1705.06373
DR16 eBOSS footprint (data public early 2020)

Cosmological measurements will be announced at the Jan AAS meeting

5,800$^\circ$ split in the NGC and SGC regions
BAO as an absolute ruler

Radial direction

\[ \alpha_{||} \propto H(z) r_d \]

Angular direction

\[ \alpha_{\perp} \propto \frac{D_A(z)}{r_d} \]

Ata et al. 2017; arXiv:1705.06373

eBOSS DR14 quasars at z=1.52
BAO as an absolute ruler

De Sainte Agathe et al. 2019; arXiv: 1904.03400
Current BAO measurements

(e)BOSS Lyα-quasar
SDSS MGS
6dFGS
(e)BOSS quasars
(e)BOSS Galaxies

Cosmological Implications of the absolute ruler


Verde, Treu & Riess 2019; arXiv:1907.10625
Relative BAO: position vs line-of-sight

The Alcock-Paczynski effect

\[ \frac{\alpha_{||}}{\alpha_{\perp}} \propto H(z) D_A(z) \]

STANDARD SHAPE
[Minimum scale – cosmological expansion can still be recovered]
Relative BAO: evolution with redshift


Ata et al. 2017; arXiv:1705.06373

Strong requirement that $H(z)/H_0$ looks like $\Lambda$CDM (6.6$\sigma$ requirement for $\Lambda$)
Structure growth

Linear amplitude of $\delta_k$ depends on peculiar velocities: additive term

$$\mu^2 f(z)\sigma_8(z) \propto \mu^2 \frac{dG}{d\log a}$$

RMS amplitude of velocities of structure growth

Samushia et al. 2013; MNRAS, 439, 3504
Current RSD measurements from galaxy 2-point

Zarrouk et al. 2018; arXiv:1801.03062
Voids – galaxy cross-correlations

\[ D_A(z)H(z)/c = 0.436 \pm 0.005 \]

\[ Voids + gals: f(z)\sigma_8(z) = 0.450 \pm 0.019 \]

\[ BAO: \quad D_A(0.57)H(0.57)/c = 0.463 \pm 0.017 \]

\[ Gals: \quad f(z)\sigma_8(z) = 0.444 \pm 0.038 \]
“we use a complete perturbation theory model that properly takes into account the non-linear effects of dark matter clustering, short-scale physics, galaxy bias, redshift-space distortions, and large-scale bulk flows”
Future concern: Assembly bias

- Haloes align with tidal fields
- Gives biased anisotropic clustering for objects selected by shape or $\sigma_v$
- So far BOSS & eBOSS galaxy selections are ~isotropic in halo properties

- Selecting groups in redshift-space gives strong LOS clustering dependence

Obuljen, Dalal & Percival 2019; arXiv:1906.11823
DESI (2020-2025)
Dark Energy Spectroscopic Instrument (DESI)

- New fibre-fed MOS for Mayall
- On course for 2019 first-light and 2020 survey start
- DESI will survey
  - $\Omega = 14,000 \text{deg}^2$
  - ~20,000,000 high redshift galaxies (direct BAO)
  - ~10,000,000 low redshift ($z<0.5$) galaxies
  - ~600,000 quasars (BAO from Ly-$\alpha$ forest)
  - Cosmic variance limited to $z \sim 1.4$
- Also WEAVE (WHT, 2020 start?) and 4MOST (VISTA, 2022 start) but fewer fibers, so less optimized for stand-alone spectroscopic galaxy surveys for cosmology
DESI – the build
DESI – the build
DESI cosmological predictions

DESI collaboration 2016; arXiv:1611.00036

<table>
<thead>
<tr>
<th>Data</th>
<th>$\sigma_{\Sigma m_\nu}$ [eV]</th>
<th>$\sigma_{N_{\nu,\text{eff}}}$</th>
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<tbody>
<tr>
<td>Planck</td>
<td>0.56</td>
<td>0.19</td>
</tr>
<tr>
<td>Planck + BAO</td>
<td>0.087</td>
<td>0.18</td>
</tr>
<tr>
<td>Gal ($k_{\text{max}} = 0.1 h\text{Mpc}^{-1}$)</td>
<td>0.030</td>
<td>0.13</td>
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<tr>
<td>Gal ($k_{\text{max}} = 0.2 h\text{Mpc}^{-1}$)</td>
<td>0.021</td>
<td>0.083</td>
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<tr>
<td>Ly-(\alpha) forest</td>
<td>0.041</td>
<td>0.11</td>
</tr>
<tr>
<td>Ly-(\alpha) forest + Gal ($k_{\text{max}} = 0.2$)</td>
<td>0.020</td>
<td>0.062</td>
</tr>
</tbody>
</table>

Total mass $>0.059\text{eV}$ $>0.10\text{eV}$
Euclid (2022-2028)
Euclid

M2 mission in ESA cosmic visions program
due to launch 2022

Wide survey:
- 15,000deg²
- NIR Photometry
  - Y, J, H
  - 24m mag, 5σ point source
- NIR slitless spectroscopy for redshifts
  - red: 1.25-1.85μm (0.9<z<1.8 Hα)
  - ~25M galaxies
- wide-band visible image for WL

Deep survey:
- 40deg²
- 12 passes, as for wide survey
- additional blue spectra: 0.92-1.25μm
- dispersion directions for 12 passes >10deg apart
A panchromatic survey

* NISP simulation does not include cosmic rays

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<thead>
<tr>
<th></th>
<th>VIS</th>
<th>Y</th>
<th>J</th>
<th>H</th>
<th>GRISM</th>
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<tr>
<td>Wide</td>
<td>24.5</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>$2 \times 10^{-16} \text{ erg/s/cm}^2$</td>
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<tr>
<td>Deep</td>
<td>26.5</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>$2 \times 10^{-17} \text{ erg/s/cm}^2$</td>
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</tbody>
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Slitless spectroscopy

Pushing the detection limit:
- Line misidentification
- Spectra confusion
- Detector persistence
- Foregrounds
Euclid galaxy clustering predictions

From BAO

From RSD
The next generation ...
Astro2020 papers on spectroscopic surveys

- The Sloan Digital Sky Survey as an Archetypal Mid-Scale Program (Blanton et al.)
- SDSS-V: Pioneering Panoptic Spectroscopy (Kollmeier et al.)
- The Dark Energy Spectroscopic Instrument (DESI) (Levi & Allenet al.)

- The MegaMapper: a $z > 2$ Spectroscopic Instrument for the Study of Inflation and Dark Energy (Schlegel & Kollmeier et al.)
- Next Generation LSST Science (Jha et al.)
- FOBOS: a Next-Generation Spectroscopic Facility (Bundy et al.)
- The Maunakea Spectroscopic Explorer (Marshall et al.)
- SpecTel: A 10-12 Meter Class Spectroscopic Survey Telescope (Ellis & Dawson et al.)
- HD GRS: Illuminating the dark universe with a very high density galaxy redshift survey over a wide area (Wang et al.)

- Towards a Spectroscopic Survey Roadmap for the 2020s and Beyond (Abbott et al.)
- The End of Galaxy Surveys (Rhodes et al.)
Survey improvement

Rhodes et al. astro2020 white paper: “The end of galaxy surveys”

Goal: all of the information

2dFGRS
The Maunakea Spectroscopic Explorer
Maunakea Spectroscopic Explorer

- Proposed as replacement for CFHT
- New 11.25m telescope (similar profile dome to CFHT!)
- 4332 fibres, 1.5deg² FOV, current design has Echidna style positioner
- 3249 fibres
  - R~2500 (optical, J, H)
  - R~6000 spectroscopy (optical)
- 1083 fibres
  - R~20,000 – 40,000 optical windows
- Many science cases from stars to cosmology

https://mse.cfht.hawaii.edu
Why do we need MSE for cosmology?

- Focus on:
  - neutrino mass
  - Inflation (the very early Universe)
  - Cosmology survey case: arXiv:1903.03158

- Other ideas for surveys with cosmological aims:
  - A deep survey for LSST photometric redshift training
  - Pointed observations of z=1 galaxy clusters
  - An IFU-based peculiar velocity survey
  - Low redshift very dense (& faint) survey

https://mse.cfht.hawaii.edu
The High-z Cosmology Survey

Probing primordial Universe with SF galaxies and quasars

- Primordial non-Gaussianity and neutrino masses
- Wide survey: 10,000 deg²
- Emission Line Galaxies: 1.6<z<2.4, Lyman Break Galaxies: 2.4<z<4.0
- Covering a volume 280 Gpc³
- 8000 pointings with 30 minute exposure
- 100 nights per year for a 5-year MSE program
Forecast for \( f_{NL} \) and \( \sum m_\nu \)

A picture of primordial Universe
- \( f_{NL} \): 3 tracers (ELG, LBG, QSO), each significantly better than CMB alone
- Total accuracy \( \sigma(f_{NL}) \sim 1.8 \)
- With CMB(S4), accuracy on neutrino masses \( \sum m_\nu \sim 8 \text{ meV} \)
- Neutrino mass hierarchy at \( 5\sigma \) as precise as DUNE \((\nu \text{ beams})\)
Discussion

- Current large-scale structure observations agree with the Planck \( \Lambda \)CDM model

- Future projects will push further out in redshift, number of galaxies and volume covered
  - Next generation of surveys (DESI, Euclid) will get \(~20x\) more galaxies
  - Factor \(~4\) improvement on fundamental physics measurements
  - More BAO, more relative expansion measurements, but lots more beyond BAO as well
  - Continue to focus on confirming \( \Lambda \)CDM / finding late-time deviations

- Next step after this – MOS on 10m class telescope
  - Science more focused on inflation, neutrinos (large volume)
  - Many other science cases, including a possible extension to high density low redshift sample (MOS with large number of fibres)