COSMOLOGY
CURRENT SURVEYS AND INSTRUMENTATION
MATTHEW COLLESS
MULTI-OBJECT SPECTROSCOPY IN THE NEXT DECADE
SANTA CRUZ DE LA PALMA
2-6 MARCH 2015
Why Surveys? Why MOS?

- Astronomy is an observational science dealing with large populations of complex objects that form structures in space and evolve in time.

- Surveys allow us to study large populations, to map structures, and to track evolution.

- “A picture is worth a thousand words”, but, to an astronomer, “a spectrum is worth a thousand images”.

- Multi-Object Spectroscopy (MOS) is the most efficient way to gather astrophysical information for large populations scattered over time and space.

- So... in the last few decades MOS surveys have transformed observational cosmology.
COSMOLOGY SURVEYS TIMELINE

1980s
- CfA, 0, 4.0

1990s
- LCRS, 2.0, 4.4
- PSCz, 0, 4.2

2000s
- DEEP, ~2, 4.0
- 2dFGRS, 2.6, 5.3
- SDSS, 2.8, 5.9
- 6dFGS, 2.2, 5.1
- WiggleZ, 2.6, 5.5

2010s
- BOSS, 3.0, 6.2

Survey, logM, logN
- non-MOS
- slit MOS
- fibre MOS
MOS INSTRUMENTS FOR COSMOLOGY

- **1D (MULTI-FIBRES)**
  - Las Campanas Fibre System (LCRS)
  - 2dF (2dFGRS, 2QZ) → AAΩ (WiggleZ, GAMA, OzDES)
  - 6dF (6dFGS) → TAIPAN (TAIPAN)
  - SDSS (SDSS-I, SDSS-II) → BOSS (BOSS, eBOSS)

- **2D (MULTI-SLITS)**
  - DEIMOS (DEEP, DEEP-2)

- **3D (MULTI-IFUS)**
  - MUSE(?)
  - HET/VIRUS (HETDEX)

Fibres dominate MOS cosmology surveys because science drivers are multiplex and area
Redshift Surveys: US surveys, European surveys, Australian surveys; celestial sphere is at CMB
AAO z-SURVEYS

Movie by Simon Driver

2dFGRS, 2QZ, 2SLAQ-LRG, 2SLAQ-QSO, 6dFGS, GAMA, WIGGLEZ; CELESTIAL SPHERE AT Z=1
GAMA: THE VERY MODEL OF A MODERN REDSHIFT SURVEY

- **Galaxy and Mass Assembly Survey**
- **Federative, multi-λ, and multi-facility**
  - Galaxy SEDs from UV to radio using existing surveys & new observations
  - Also multi-z when ASKAP provides HI redshifts
RICH SURVEY DATABASE
...COMPLEX INFORMATION STRUCTURES
<table>
<thead>
<tr>
<th>Telescope : Instrument</th>
<th>Survey(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAT : AAΩ, HERMES, SAMI</td>
<td>WIGGLEZ, GAMA, GALAH, SAMI</td>
</tr>
<tr>
<td>UKST : 6DF, TAIPAN</td>
<td>RAV - CCPGS, TAIPAN</td>
</tr>
<tr>
<td>SDSS 2.5m : SDSS, BOSS, MANGA</td>
<td>SDSS, BOSS, eBOSS, MANGA</td>
</tr>
<tr>
<td>WHT : ISIS, WEAVER</td>
<td>VEAVE</td>
</tr>
<tr>
<td>GTC : OSIRIS, EMIR, MEGARA</td>
<td></td>
</tr>
<tr>
<td>VLT : VIMOS, KMOS, MUSE, VACONS</td>
<td>VANDELS, VIPERS, LEGA-C,…</td>
</tr>
<tr>
<td>VISTA : HST</td>
<td>4MOST, WAVES</td>
</tr>
<tr>
<td>LAMOST</td>
<td>LEGUE</td>
</tr>
<tr>
<td>CALAR Alto : ALFRA</td>
<td>CALIFA</td>
</tr>
<tr>
<td>Magellan : PRIMUS</td>
<td>PRIMUS</td>
</tr>
<tr>
<td>Subaru : FMOS, PFS</td>
<td>FAST, MANGA, HETDEX</td>
</tr>
<tr>
<td>HET : VIRUS</td>
<td>GAIA</td>
</tr>
<tr>
<td>GAIA</td>
<td>GAIA</td>
</tr>
<tr>
<td>KPNO 4m : DESI</td>
<td>DESI</td>
</tr>
<tr>
<td>Euclid</td>
<td>Euclid</td>
</tr>
<tr>
<td>LSST: MOS / MSE / WFIRST</td>
<td>…</td>
</tr>
</tbody>
</table>
IMPACT OF MOS SURVEYS - 1

- LITERATURE ANALYSIS BY TRIMBLE & CEJA (2008) LOOKED AT 11,831 PAPERS PUBLISHED IN 2001-3 (DATED, BUT RESULTS STILL APPLICABLE)
- THE MOST-CITED OPTICAL/INFRARED FACILITIES…

<table>
<thead>
<tr>
<th>FACILITY</th>
<th>CITATIONS</th>
<th>PAPERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST</td>
<td>15390</td>
<td>1063.1</td>
</tr>
<tr>
<td>Keck</td>
<td>8122</td>
<td>365.6</td>
</tr>
<tr>
<td>SDSS</td>
<td>7235</td>
<td>161</td>
</tr>
<tr>
<td>VLT</td>
<td>5696</td>
<td>345.5</td>
</tr>
<tr>
<td>AAT</td>
<td>4592</td>
<td>170.2</td>
</tr>
<tr>
<td>Schmidts</td>
<td>3430</td>
<td>247.8</td>
</tr>
<tr>
<td>2MASS</td>
<td>2937</td>
<td>182.9</td>
</tr>
</tbody>
</table>
## Impact of MOS Surveys - 2

<table>
<thead>
<tr>
<th>Citations</th>
<th>Journal</th>
<th>Subject</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2770</td>
<td>ApJS</td>
<td>Cosmology</td>
<td>WMAP, ACBAR, CBI, AAT, HST, other optical</td>
</tr>
<tr>
<td>1301</td>
<td>ApJS</td>
<td>Cosmology</td>
<td>WMAP, optical &amp; X-Ray unidentified</td>
</tr>
<tr>
<td>632</td>
<td>ApJ</td>
<td>Cosmology</td>
<td>HST</td>
</tr>
<tr>
<td>466</td>
<td>ApJS</td>
<td>Cosmology</td>
<td>WMAP</td>
</tr>
<tr>
<td>450</td>
<td>MNRAS</td>
<td>Galaxies</td>
<td>JKT, Siding Spring 2.3m, SDSS, IUE</td>
</tr>
<tr>
<td>397</td>
<td>ApJ</td>
<td>Cosmology</td>
<td>CFHT, CTIO-4, Keck II &amp; I, CTIO-1.5, VLT, UKIRT, UHi 2.2, Vatican, WIYN, HST, SDSS</td>
</tr>
<tr>
<td>383</td>
<td>ApJS</td>
<td>Cosmology</td>
<td>WMAP, CBI, ACBAR, AAT, other optical</td>
</tr>
<tr>
<td>380</td>
<td>A&amp;A</td>
<td>Service</td>
<td>XMM</td>
</tr>
<tr>
<td>375</td>
<td>AJ</td>
<td>Service</td>
<td>SDSS</td>
</tr>
<tr>
<td>370</td>
<td>A&amp;A</td>
<td>Service</td>
<td>XMM</td>
</tr>
<tr>
<td>313</td>
<td>AJ</td>
<td>Service</td>
<td>SDSS</td>
</tr>
<tr>
<td>309</td>
<td>Nature</td>
<td>GRB</td>
<td>VLT 1 &amp; 2</td>
</tr>
<tr>
<td>306</td>
<td>A&amp;A</td>
<td>Service</td>
<td>XMM</td>
</tr>
<tr>
<td>298</td>
<td>ApJLett</td>
<td>GRBs</td>
<td>VLA, Keck, Palomar 5-m</td>
</tr>
<tr>
<td>281</td>
<td>ApJS</td>
<td>Cosmology</td>
<td>WMAP</td>
</tr>
<tr>
<td>281</td>
<td>ApJLett</td>
<td>GRBs</td>
<td>MMT, Magellan, Whipple-1.5</td>
</tr>
<tr>
<td>279</td>
<td>MNRAS</td>
<td>Galaxies</td>
<td>AAT</td>
</tr>
<tr>
<td>277</td>
<td>AJ</td>
<td>Service</td>
<td>Schmidt surveys (USNO catalogue)</td>
</tr>
<tr>
<td>275</td>
<td>ApJ</td>
<td>Cosmology</td>
<td>Boomerang</td>
</tr>
</tbody>
</table>

Trimble & Ceja (2008)
SURVEY IMPACT BY FIELD

The diagram illustrates the impact of various fields in astrophysics, measured by normalized citations and papers in each field. Notably, Cosmology is highlighted with a high citation count (2.61,478). The fields are categorized into different regions, such as Stars, AGN, Normal Galaxies, NS / BH, Interstellar Medium, Solar System, Clusters of Galaxies, Milky Way, GRBs, Service, Exoplanets, Brown Dwarfs, White Dwarfs, Planetary Nebulae, Cataclysmic Variables, Other Binaries, and SN/Remnants, each with its own normalized citation and paper count.
PHYSICS FROM LARGE-SCALE STRUCTURE

Information from geometry
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

Information from power spectrum shape
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum

Information from large scale bias
- $f_{NL}$

Information from structure growth
- amplitude of power spectrum
- Redshift-Space Distortions

$$P_{gg}^s(k, \mu, z) = k^n T^2(k) G^2(z) \left[ b(z, k) + f(z) \mu^2 \right]^2$$

- $k$ = comoving wavenumber
- $\mu$ = cos(angle to line-of-sight)
- $a$ = cosmological scale factor
- $b$ = galaxy bias factor
- $G$ = linear growth rate
- $f =$ dlnG/dlna
SIDEBAR: SPECTRO-Z’S VS PHOTO-Z’S

- PHOTO-Z’S ARE POTENTIALLY A CHEAP WAY TO MEASURE MANY GALAXY REDSHEFFTS AND HENCE THE BAO PEAK
- PROBLEM IS LARGE ERRORS - FOR Z-ERRORS >1000 KM/S, BAO PEAK IS SMEARED OUT & H(Z) CANNOT BE MEASURED; FULL INFORMATION REQUIRES Z-ERRORS <300 KM/S
- TO MEASURE DA(Z), A PRECISION OF σz/(1+z) ≲ 4% IS REQUIRED; WORSE PRECISION CAUSES CATASTROPHIC CANCELLATION OF BAO SIGNAL OVER WIDTH OF Z-SHELL
- HOWEVER 3-4% PRECISION YIELDS POOR CONSTRAINTS ON THE BAO PER UNIT VOLUME; A PHOTO-Z SURVEY NEEDS ~10X MORE VOLUME THAN A SPECTRO-Z SURVEY
- BETTER PRECISION HELPS, BUT AT Z<0.7, SPECTRO-Z SURVEYS ARE ALREADY COVERING LARGE FRACTION OF SKY, SO PHOTO-Z SURVEYS ONLY COMPETITIVE AT HIGHER Z’S
- PHOTO-Z SURVEYS REQUIRE STRINGENT CALIBRATION AND MORE EXTENSIVE MODELING THAN SPECTRO-Z SURVEYS
COSMOLOGY FROM 2dFGRS

- **2dFGRS** measured 221,000 z’s over 2000 deg$^2$
- **Large-scale structure of the galaxy distribution** precisely mapped on scales of $10^6$–$10^9$ light-years.
- The form of large-scale structure is consistent with growth by gravitational instability ⇒ quantum fluctuations from the Big Bang are amplified by gravity to become galaxies, clusters & superclusters.
- The total density of all types of matter is $\Omega_M = 0.23$ ⇒ there is only 23% of the matter needed to make a critical-density (i.e. flat = zero-curvature) universe.
- The total density in ordinary matter is $\Omega_B = 0.04$ ⇒ baryons are 17% & CDM 83% of the total matter.
- Neutrinos make up less than 13% of all matter ⇒ total mass of 3 neutrino species is less than 0.7 eV.
- Baryon Acoustic Oscillations detected at 2.5σ.
COSMOLOGY FROM MOS – BAO

- BARYON ACOUSTIC OSCILLATIONS (BAO) PROVIDE STANDARD RULER
- BAO RESULT FROM PRESSURE WAVES IN PRE-RECOMBINATION PHOTON-BARYON FLUID IMPRINTING THE SOUND HORIZON SCALE ON THE MATTER DISTRIBUTION
- GALAXY REDSHIFIT SURVEYS YIELD ANGULAR DIAMETER DISTANCES $D_A(z)$ & EXPANSION RATES $H(z)$
- BAO MAP EXPANSION HISTORY BOTH ALONG AND ACROSS THE LINE OF SIGHT, PROBING BOTH DARK ENERGY AND GRAVITY
- A WELL-UNDERSTOOD, PRECISE TOOL; MAIN LIMITATION IS THE SCALE OF THE SURVEYS REQUIRED
BAO SURVEYS

- BAO first detected in galaxy distribution (at 2.5σ) by 2dFGRS and SDSS (Cole+ 2005, Eisenstein+ 2005)

- The WiggleZ survey observed $2 \times 10^5$ emission-line galaxies over 800 deg$^2$ and measured BAO at 0.5<$z$<1 with 3.8% precision at $z=0.6$ (Blake+ 2011)

- Beutler+ (2011) used 6dFGS to make a low-redshift ($z<0.1$) BAO distance measurement with 4.5% precision

- Kazin+ (2010) used the full LRG sample from DR7 to measure the galaxy correlation function and obtain a 3.5% measurement of the BAO scale at $z = 0.35$

- Percival+ (2010) used 900,000 galaxies over 9100 deg$^2$ from the combined 2dFGRS, SDSS DR7/LRG samples to obtain the BAO scale at $z=0.27$ with 2.7% precision

- Padmanabhan+ (2012) showed that density field reconstruction could improve these BAO measures by about a factor of 2
Redshift-Space Distortions result from peculiar motions due to gravity and measure the growth of structure.

RSD measure the combination $f(z) \sigma_8(z)$, where $f(z) = \Omega_m(z)^{\gamma}$ and $\sigma_8$ is fluctuation in 8 Mpc/h sphere.

RSD constraints come for free with any large galaxy $z$-survey.

Main uncertainty is theoretical modeling of the non-linear gravitational evolution and non-linear bias; currently this limits application of RSD method to co-moving separations $r > 10$ Mpc/h (or $k < 0.2$ h/Mpc)
LOW-Z COSMOLOGY SURVEYS

- 6dFGS, though smaller than 2dFGRS & SDSS, gives valuable constraints on cosmology at low z, notably a direct measure of $H_0$ and growth of structure.

- The Taipan Survey (Hopkins talk) will have 4x the sample size & volume of 6dFGS and give $H_0$ with ~1% precision and growth of structure to 5% at $\langle z \rangle \approx 0.1$.

- Dark Energy is a late-time (low-redshift) phenomenon!
HIGH-Z COSMOLOGY SURVEYS


**BAO: DEVIATIONS FROM $\Lambda$CDM GEOMETRY**

**RSD: GROWTH RATE OF STRUCTURE**
**COSMOLOGICAL POWER OF MOS**

- **The added information given by MOS surveys is quantified by the tighter constraints on dark energy and modified gravity relative to those from the CMB alone.**

![Graphs showing constraints on dark energy and modified gravity parameters](Planck Collaboration (Paper XIV, 2015))
**BOSS: THE STATE OF THE ART**

- **Goal:** Measure BAO over larger volume and z-range than all previous z-surveys
- **Final dataset is SDSS DR12 (to July 2014)**
- **Galaxies:** $1.4 \times 10^6$ at $z<0.7$ ($i<19.9$) over $10^4$ deg$^2$
  - Forecast: $D_A$ to 1.0% and $H(z)$ to 1.8% and 1.7% at $z=0.3$ and $z=0.57$
- **Ly$\alpha$:** $1.6 \times 10^5$ QSOs with $g<22$ at $2.15<z<3.5$
  - Forecast: overall dilation factor to 1.9% at $z<2.5$
BOSS AND eBOSS

BOSS + eBOSS quasar absorption

eBOSS quasar clustering

BOSS galaxies

eBOSS galaxies

Redshift z

2.5
2.0
1.5
1.0
0.5
0.5
1.0
1.5
2.0
2.5
BOSS: THE STATE OF THE ART

- BOSS detects BAO feature at 7σ in galaxies and 5σ in Lyα forest.
- BAO alone yield a high confidence detection of dark energy and, with the CMB acoustic scale, BAO imply a nearly flat universe.
- BAO+CMB+SN data jointly give $H_0 = 67.3 \pm 1.1 \text{ km/s/Mpc} (1.7\%)$ robust to assumptions about dark energy or space curvature.
- For constant dark energy ($\Lambda$), BAO+CMB+SN yields $\Omega_M = 0.301 \pm 0.008 (2.7\%)$ and $\Omega_K = -0.003 \pm 0.003$.
- For evolving forms dark energy, BAO+CMB+SN data are always consistent with flat $\Lambda$CDM at ~1σ.
- BAO+Planck-WL gives a summed mass of neutrinos $\Sigma m_\nu < 0.25 \text{ eV}$. 
COSMOLOGY - PECULIAR VELOCITIES

- MOS cosmology is not just about redshifts!
- Peculiar velocity surveys (V-surveys) can provide additional information removing some degeneracies intrinsic to Z-surveys (e.g. between $\beta$ and $r_g$).
- V-surveys are necessarily low-redshift due to fixed fractional distance errors.
- Distance errors are typically significant (e.g. 20-25% for TF and FP, but 5-8% for SNe).
- 6dFGRS is the current state-of-the-art Z+V-survey:
  - 125,000 redshifts and 9000 peculiar velocities (using fundamental plane distances for early-type galaxies).
  - V-survey covers 17000 deg$^2$ to depth of $\sim$16000 km/s.

Z-ONLY
Z+V
$1\sigma$ contours on pairs of parameters
**V-SURVEY COSMOLOGY**

- **Johnson et al.** (2014) use the power spectrum of the 6dFGS peculiar velocities to obtain first scale-dependent measurements of the growth rate of structure $f \sigma_8$ (in combination with $z < 0.07$ SNe).

- Measured the growth rate in $\Delta k = 0.03$ h/Mpc bins to $\sim 35\%$ precision, incl. a measurement on scales $> 300$ h/Mpc, the largest-scale measurement of the growth rate to date.

- No evidence for a scale dependence in growth rate or variation from predictions of Planck $\Lambda$CDM model.

- Combining all scales, the growth rate at $z = 0$ is measured with $\sim 15\%$ precision, independent of galaxy bias & in good agreement with RSD growth rate measurements from 6dFGS z-survey.

- Future peculiar velocity surveys will allow us to understand in detail the growth of structure in the low-redshift universe, providing strong constraints on the nature of dark energy.
**DARK ENERGY – FUTURE PROGRESS**

- **ALL OBSERVATIONS** TO DATE OF THE COSMIC EXPANSION HISTORY AND THE GROWTH OF STRUCTURE ARE CONSISTENT WITH A FLAT $\Lambda$CDM + GR MODEL WITH $\Omega_M \approx 0.3$ AND $\Omega_\Lambda \approx 0.7$

- **Z-SURVEY METHODS** (BAO, RSD) ARE EXPECTED IN FUTURE TO PROVIDE 10X BETTER CONSTRAINTS ON THE DARK ENERGY EQUATION OF STATE
CONSTRANTS FROM MOS SURVEYS

- FISHER MATRIX PREDICTIONS FOR PRECISION OF BAO DISTANCE SCALE MEASUREMENTS AS A FUNCTION OF REDSHIFT
- THE BOSS SURVEY ACHIEVES ~2% FOR Z<1 AND AT Z~2.5
- THE DESI & EUCLID SURVEYS WILL ACHIEVE 0.5-1% OUT TO Z=2

Percival (2013)
MOS COSMOLOGY IN 2025

□ WHAT WILL MOS COSMOLOGY LOOK LIKE IN 2025?
SOME SAFE PREDICTIONS…

1. Redshift surveys exist totaling a few $\times 10^7$ galaxies out to $z \sim 1.7$ and a few $\times 10^6$ galaxies/QSOs out to $z \sim 3$

2. Peculiar velocity surveys (optical and HI) exist totaling $>10^5$ galaxies in the nearby universe

3. LSST provides ultimate target list for MOS surveys; how can we fully exploit this? Need dedicated 8M MOS!

4. A common federated database system has emerged from a heterogeneous set of surveys and software

5. Many more papers are based on archival MOS spectra and databases than on fresh observations

6. ‘Data Scientists’ outnumber ‘Observers’ (and have more kudos and better career prospects)

7. Team leaders are still complaining that science outputs from their surveys are person-/brain-power-limited
Future MOS Instruments

- Every self-respecting general-purpose 4m or 8m-class telescope needs MOS capability.
- MOS is expanding in new directions: not just high-multiplex but also high-resolution and multi-IFUs (& eventually MOAO multi-IFUs).
- In the ELT era, most 8m-class telescopes will have a MOS instrument of some variety as their cutting-edge facility.
- GMT to have highly versatile MOS/multi-IFU capability provided by the MANIFEST facility:
  - Coupled to large optical/NIR spectrographs (both medium and high resolution)
  - AΩ = 25m aperture x 20 arcmin diameter field
  - Operating in natural seeing and GLAO modes
IN MEMORIAM

THIS TALK IS DEDICATED TO

PROFESSOR PETER MCGRGOR

A FINE ASTRONOMER, A SUPERB INSTRUMENTALIST
AND A WONDERFUL COLLEAGUE
AT THE AUSTRALIAN NATIONAL UNIVERSITY
WHO PASSED AWAY 5 MARCH 2015