SDSS and Future Spectroscopic Surveys

Jo Bovy (University of Toronto; Canada Research Chair)
Spectroscopic complements to wide-field photometric surveys

• Spectroscopy essential to elucidate physical processes in ~all areas of observational astrophysics

• Current wide-field spectroscopic surveys still busy targeting objects from previous generation of photometric surveys (SDSS-I/II, 2MASS, …)

• Next generation photometric surveys (Gaia, LSST, …) >> previous & fainter —> need to move to faster follow-up: larger mirrors, larger spectrographs, fiber positioners, better data processing to get more information out of limited data
What you get from spectroscopy

- Low/Medium resolution:
  - Redshifts
  - Masses, metallicities, and star-formation histories of external galaxies
  - Line-of-sight velocities of stars
  - Stellar parameters (temperature, gravity, overall metallicity)

- Higher resolution
  - Elemental abundances —> different nucleosynthetic pathways
  - Peace of mind
What you get from *wide-field* spectroscopy

- Large statistical samples:
  - Allow studies of sampled populations, not just individual objects —> statistical studies of large-scale structure, Milky Way structure, galaxy population
  - (Need to carefully design sample selection to be reproducible, easiest when simple)
  - Legacy database for future studies, e.g., time-domain discoveries
  - Opportunities for developing new, big-data techniques —> e.g., machine learning/deep learning
Current: SDSS-IV

MaNGA: 10,000 galaxies with spatially resolved spectroscopy

APOGEE-2: Massively expanded Galactic archaeology for all Milky Way regions

eBOSS: Studying cosmic acceleration in a new redshift regime with the largest ever quasar sample

BOSS + eBOSS quasar absorption

BOSS + eBOSS quasar clustering

BOSS galaxies

eBOSS galaxies

Sloan Foundation Telescope

du Pont Telescope

Slide from Michael Blanton
Highlights from SDSS-III/IV spectroscopy
Chemical structure of the Milky Way

Majewski et al. (2017)

Hayden, Bovy, et al. (2015)
Highlights from SDSS-III/IV spectroscopy

Dynamics of the Milky Way

Rotation curve

Vertical mass distribution
+ local DM density

Disk mass distribution
Break disk-halo degeneracy

Bovy & APOGEE (2012)

Zhang et al. (2013)

Bovy & Rix (2013)
Highlights from SDSS-III/IV spectroscopy
Cosmology with large-scale structure

$>5\sigma$ BAO detection in LyA forest

Delubac et al. (incl. Bovy; 2015)

BAO “Hubble diagram”

Aubourg et al. (incl. Bovy; 2015)
Highlights from SDSS-III/IV spectroscopy

Large-data-driven approaches to stellar astrophysics

Ness et al. (2015)

Leung & Bovy (2018)

Fabbro et al. (2018)
Questions for the future of near-field cosmology

- Fine-grained dynamics in the Milky Way disk & halo:
  - nature of spiral structure and resulting secular evolution
  - properties of the bar and its interaction with the DM halo
  - History of disturbances to the disk
  - detailed radial profile and shape of the DM halo
  - constraints on the DM sub halo mass function down to $\sim 10^6 \, M_\text{sun}$

- Chemical tagging: identifying dispersed star-formation sites in the disk and halo to obtain detailed archaeological picture

- Co-evolution of the disk, bulge/bar, stellar and DM halo

- Statistical surveys of stellar populations across the HR diagram to better understand stellar evolution

Antoja et al. (2018)

Bovy (2016)
**SDSS-V**  
PI: Juna Kollmeier

- 5-year program beginning mid-2020 in both hemispheres

- 3 Science Programs:
  - Milky Way Mapper, Black Hole Mapper, Local Volume Mapper

- 2 hemispheres: high-res IR spectra, moderate-res optical spectra + O echelle, massively multiplexed wide-field IFU

Credit M. Seibert  
Slide from Juna Kollmeier
### SDSS-V’s 3 “Mappers”

<table>
<thead>
<tr>
<th>Program</th>
<th>Science Targets</th>
<th>(N_{\text{Objects and/or Sky Area}})</th>
<th>Primary Spectral Range and Hardware</th>
<th>Primary Science Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way Mapper (MWM)</td>
<td>Stars across the Milky Way</td>
<td>&gt;6M stars; all-sky</td>
<td>IR; APOGEE ((R \sim 22,000)) with fiber-positioning system</td>
<td>Understanding the formation of the Milky Way and the physics of its stars</td>
</tr>
<tr>
<td>Black Hole Mapper (BHM)</td>
<td>Primarily supermassive black holes</td>
<td>&gt;400,000 sources; all-sky</td>
<td>Optical; e.g., BOSS ((R \sim 2000)) with fiber-positioning system</td>
<td>Probing black hole growth and mapping the X-ray sky</td>
</tr>
<tr>
<td>Local Volume Mapper (LVM)</td>
<td>ISM &amp; stellar populations in the MW, Local Group, and nearby galaxies</td>
<td>&gt;25M contiguous spectra over 3,000 (\text{deg}^2)</td>
<td>Optical; new integral field spectrographs covering 3600-10000Å at (R \sim 4000)</td>
<td>Exploring galaxy formation and regulation by star formation; feedback, enrichment, &amp; ISM physics</td>
</tr>
</tbody>
</table>

Slide from Juna Kollmeier
Galactic Archaeology: 2020

4.3 million stars; (G − H) > 3.5 and H < 11.2

Chemical tagging → large sample size

Pairs of birth sibling stars are rare, but the number of such pairs in a survey of sample size N, will scale as $N^2$
## SDSS and future spectroscopic surveys

<table>
<thead>
<tr>
<th>Survey (facility)</th>
<th>$N_{\text{target}}$</th>
<th>$R_{\text{spec}}$</th>
<th>$N_{\text{res}}$</th>
<th>$\lambda [\mu m]$</th>
<th>$\Omega_{\text{sky}}$</th>
<th>$N_{\text{epoch}}$</th>
<th>Timeframe</th>
<th>$m_{\text{primary}}$</th>
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<tbody>
<tr>
<td>SDSS-V</td>
<td>$7 \times 10^6$</td>
<td>22,000</td>
<td>500</td>
<td>1.51-1.7</td>
<td>4$\pi$</td>
<td>4 – 60</td>
<td>2020-2024</td>
<td>$m_H \leq 12$</td>
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<tr>
<td></td>
<td></td>
<td>2,000</td>
<td></td>
<td>0.37-1</td>
<td></td>
<td></td>
<td></td>
<td>$m_G \leq 18$</td>
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<tr>
<td>Gaia (RVS)</td>
<td>$2 \times 10^6$</td>
<td>8000</td>
<td>270</td>
<td>0.85-0.87</td>
<td>4$\pi$</td>
<td>$\sim 60$</td>
<td>2013-2020</td>
<td>$m_G \leq 12$</td>
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<tr>
<td>Gaia-ESO</td>
<td>$0.1 \times 10^6$</td>
<td>17,000</td>
<td>140</td>
<td>0.55 &amp; 0.85</td>
<td>0.02$\pi$</td>
<td>$\sim 1$</td>
<td>2013-2018</td>
<td>$m_G \leq 17$</td>
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<tr>
<td>GALAH</td>
<td>$0.8 \times 10^6$</td>
<td>28,000</td>
<td>400</td>
<td>0.40 - 0.85</td>
<td>$\pi$</td>
<td>$\sim 1$</td>
<td>2015-2020</td>
<td>$m_G \leq 13$</td>
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<td>$</td>
<td>b</td>
<td>\geq 10$</td>
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<td>WEAVE</td>
<td>$0.8 \times 10^6$</td>
<td>5,000 &amp; 20,000</td>
<td>1000</td>
<td>0.37-0.9</td>
<td>$\sim \pi$</td>
<td>$\sim 1 - 2$</td>
<td>2018-2023</td>
<td>$m_G \leq 19$</td>
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<tr>
<td>DESI</td>
<td>$8 \times 10^6$</td>
<td>3,000</td>
<td>5000</td>
<td>0.36-0.98</td>
<td>$\sim \pi$</td>
<td>$\sim 1 - 2$</td>
<td>2019-2024</td>
<td>$m_G \leq 19$</td>
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<tr>
<td>LAMOST</td>
<td>$8 \times 10^6$</td>
<td>1,800</td>
<td>4000</td>
<td>0.4-0.9</td>
<td>0.5$\pi$</td>
<td>$\sim 1$</td>
<td>2010-2020</td>
<td>$m_G \leq 16$</td>
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<tr>
<td>4MOST</td>
<td>$10 \times 10^6$</td>
<td>5,000 &amp; 20,000</td>
<td>1600 &amp; 800</td>
<td>0.4-0.9</td>
<td>1.5$\pi$</td>
<td>1 – 2</td>
<td>2023-2028</td>
<td>$m_g \leq 21$</td>
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<td></td>
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<td>$m_v \leq 16$</td>
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<tr>
<td>APOGEE-1 &amp; -2</td>
<td>$5 \times 10^5$</td>
<td>22,000</td>
<td>300</td>
<td>1.51-1.7</td>
<td>0.5$\pi$</td>
<td>$\sim 4$</td>
<td>2011-2019</td>
<td>$m_H \leq 12$</td>
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<tr>
<td>PFS</td>
<td>$1 \times 10^6$</td>
<td>3,000</td>
<td>2400</td>
<td>0.4-1.6</td>
<td>0.05$\pi$</td>
<td>1</td>
<td>2018-2021</td>
<td>$m_g \leq 22$</td>
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<tr>
<td>MOONS</td>
<td>$2 \times 10^6$</td>
<td>5,000 &amp; 20,000</td>
<td>1000</td>
<td>0.6-1.8</td>
<td>0.05$\pi$</td>
<td>1</td>
<td>2020-2025</td>
<td>$m_{\text{H}} \leq 22$</td>
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Table from Juna Kollmeier
### SDSS and future spectroscopic surveys

<table>
<thead>
<tr>
<th>Class</th>
<th>Facility / Instrument</th>
<th>First light (anticipated)</th>
<th>Aperture (M1 in m)</th>
<th>Field of View (sq. deg)</th>
<th>E tendue</th>
<th>Multiplexing</th>
<th>Wavelength coverage (nm)</th>
<th>Spectral resolution (approx)</th>
<th>IFU</th>
<th>Dedicated facility</th>
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<tbody>
<tr>
<td>Comparison</td>
<td>SDSS I - IV</td>
<td>Existing</td>
<td>2.5</td>
<td>1.54</td>
<td>7.6</td>
<td>640</td>
<td>0.38 - 0.92</td>
<td>1800</td>
<td>Yes</td>
<td>Yes</td>
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<td>4-m</td>
<td>Guo Shoujing / LAMOST</td>
<td>Existing</td>
<td>4</td>
<td>19.6</td>
<td>246</td>
<td>4000</td>
<td>0.37 - 0.90 windows</td>
<td>1000 - 10000</td>
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<td>Yes</td>
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<td>AAT / HERMES</td>
<td>2015</td>
<td>3.9</td>
<td>3.14</td>
<td>37.5</td>
<td>392</td>
<td>0.37 - 1.00 windows</td>
<td>28000, 50000</td>
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<td>WHT / WEAVE</td>
<td>2017</td>
<td>4</td>
<td>3.14</td>
<td>39.5</td>
<td>1000</td>
<td>0.39 - 0.95 windows</td>
<td>5000</td>
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<td>Yes</td>
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<td>VISTA / 4MOST</td>
<td>2017</td>
<td>4</td>
<td>2.5</td>
<td>31.4</td>
<td>2400</td>
<td>0.39 - 0.95 windows</td>
<td>18000</td>
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<td>Yes</td>
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<td>Mayall / DESI</td>
<td>2018</td>
<td>4</td>
<td>7.1</td>
<td>89.2</td>
<td>5000</td>
<td>0.36 - 0.98 windows</td>
<td>4000</td>
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<td>8-m</td>
<td>VLT / MOONS</td>
<td>2018</td>
<td>8.2</td>
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<td>1000</td>
<td>0.8 - 1.8 windows</td>
<td>4000</td>
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<td>No</td>
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<td>Subaru / PFS</td>
<td>2019</td>
<td>8.2</td>
<td>1.25</td>
<td>66</td>
<td>2400</td>
<td>0.71 - 0.89 windows</td>
<td>5000</td>
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<tr>
<td>10-m</td>
<td>MSE</td>
<td>2024</td>
<td>11.25</td>
<td>1.5</td>
<td>149</td>
<td>3468</td>
<td>0.36 - 1.8 windows</td>
<td>3000</td>
<td>Second generation</td>
<td>Yes</td>
</tr>
</tbody>
</table>

MSE Science book
Canadian funding and large spectroscopic surveys

- SDSS-IV & -V funded by private foundations (Sloan) + institutional membership fees (~$300k / participant for SDSS-V)
- DESI: similar setup I believe
- WEAVE / 4MOST: ESO surveys open to ESO members
- No (to me) obvious source of funding in Canada to join these efforts, leading to:
  - Small number of Canadian scientists part of this —> little influence, no seat on collaboration councils
  - Scrambling to get funding together —> join late, little influence on project
  - MSE-like observatory perhaps a future possibility, but to gain expertise and position ourselves well, need to get involved in 2020–2025 generation of surveys