Reverberation Mapping in the Era of MOS and Time-Domain Surveys: from SDSS to MSE

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AGN Reverberation Mapping

- Measuring the broad line lags $\rightarrow$ RM BH mass
- Calibrations for Single-epoch BH masses at high-z

Primary (direct) method to measure BH mass in AGN/quasars.

\[ M_{\text{BH}} = f \left( \frac{\Delta V^2 R}{G} \right) \]

\[ R = c \tau \]
Limitations of the current RM AGN sample

- 60 AGN with RM lag measurements
  - almost exclusively at z<0.3
  - Most are Hβ lags with some C IV lags and few/no Mg II lags
  - Sample heterogeneous, and does not uniformly sample the AGN parameter space (luminosity, emission line properties, Eddington ratios)

The limitations of the current RM sample severely impact the reliability of the single-epoch BH mass estimators at high-redshift.

Need to substantially improve the RM sample, in a more efficient way.
SDSS-RM in a nutshell

• Simultaneous monitoring a uniform sample of 849 quasars at 0.1<z<4.5 in a single 7 deg$^2$ field with the SDSS-BOSS spectrograph; 32 epochs taken in 2014A; 12 epochs taken in 2015A; plan to continue through 2019 at 6-12 epochs/year

• Dense photometric light curves (~2-4 day cadence) since 2010 (PanSTARRS 1 + SDSS-RM imaging)

The SDSS-RM Project (PI: Y. Shen): http://www.sdssrm.org
Science from SDSS-RM

**Primary Science**
- BLR RM lags and BH masses at $z>0.3$
- Structure and kinematics of the BLR
- The R-L relations for different lines
- Better calibrations of SE BH mass estimators for quasars

**Ancillary Science**
- Photometric and spectral quasar variability
- Quasar/host decomposition of coadded spectra and imaging
- BALQSO trough variability
- Quasar narrow metal absorption lines

Pathfinder RM program for future MOS-RM projects such as MSE-RM (Sarah’s talk)
SDSS-RM: Promises and Challenges

Expected lag detections from SDSS-RM

Shen et al. (2015a)
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>RM quasar targets</td>
<td>~850</td>
<td>~5000</td>
</tr>
<tr>
<td>Quasars w/ lag detections</td>
<td>~250</td>
<td>~2500</td>
</tr>
<tr>
<td>Quality of lag detections</td>
<td>Average lags</td>
<td>Average lags and velocity-resolved lags</td>
</tr>
<tr>
<td>Limiting $i$ magnitude</td>
<td>21.7</td>
<td>~23-24</td>
</tr>
<tr>
<td>Wavelength coverage</td>
<td>0.36-1 micron</td>
<td>0.36-1.8 micron</td>
</tr>
<tr>
<td>Spectroscopic baseline</td>
<td>2-6 yr</td>
<td>5 yr</td>
</tr>
<tr>
<td>Total epochs</td>
<td>~60</td>
<td>~100</td>
</tr>
<tr>
<td>spectrophotometry</td>
<td>5% (w/o ADC)</td>
<td>3-4% (w/ ADC)</td>
</tr>
<tr>
<td>Fiber diameter (average seeing)</td>
<td>2” (1.4”)</td>
<td>1.2-1.7” (0.6”)</td>
</tr>
<tr>
<td>Photometry options</td>
<td>Dedicated (e.g., CFHT)</td>
<td>LSST</td>
</tr>
<tr>
<td>Coadd depth</td>
<td>up to 120 hr x (2.5 m)$^2$</td>
<td>*100 hr x (10 m)$^2$</td>
</tr>
</tbody>
</table>

*up to 15,000 galaxies in spare fibers with 100 hrs each, over 7 MSE fields*
Some SDSS-RM early science papers

<table>
<thead>
<tr>
<th>#</th>
<th>Date</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06/2015</td>
<td>Sun, Mouyuan; Trump, Jonathan R.; Shen, Yue; Brandt, W. N.; Dawson, Kyle; Denney, Kelly D.; Hall, Patrick B.; Ho, Luis C.; Horne, Keith; Jiang, Linhua; and 7 coauthors</td>
<td>The Sloan Digital Sky Survey Reverberation Mapping Project: Ensemble Spectroscopic Variability of Quasar Broad Emission Lines</td>
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<tr>
<td>2</td>
<td>06/2015</td>
<td>Matsuoka, Yoshiki; Strauss, Michael A.; Shen, Yue; Brandt, William N.; Greene, Jenny E.; Ho, Luis C.; Schneider, Donald P.; Sun, Mouyuan; Trump, Jonathan R.</td>
<td>The Sloan Digital Sky Survey Reverberation Mapping Project: Post-Starburst Signatures in Quasar Host Galaxies at z &lt; 1</td>
</tr>
<tr>
<td>3</td>
<td>06/2015</td>
<td>Grier, C. J.; Hall, P. B.; Brandt, W. N.; Trump, J. R.; Shen, Yue; Vivek, M.; Filiz Ak, N.; Chen, Yuguang; Dawson, K. S.; Denney, K. D.; and 15 coauthors</td>
<td>The Sloan Digital Sky Survey Reverberation Mapping Project: Rapid CIV Broad Absorption Line Variability</td>
</tr>
<tr>
<td>4</td>
<td>06/2015</td>
<td>Shen, Yue; Greene, Jenny E.; Ho, Luis C.; Brandt, W. N.; Denney, Kelly D.; Horne, Keith; Jiang, Linhua; Kochanek, Christopher S.; McGreer, Ian D.; Merloni, Andrea; and 9 coauthors</td>
<td>The Sloan Digital Sky Survey Reverberation Mapping Project: No Evidence for Evolution in the M* - sigma* Relation to z~ 1</td>
</tr>
<tr>
<td>5</td>
<td>01/2015</td>
<td>Shen, Yue; Brandt, W. N.; Dawson, Kyle S.; Hall, Patrick B.; McGreer, Ian D.; Anderson, Scott F.; Chen, Yuguang; Denney, Kelly D.; Eftekharzadeh, Sarah; Fan, Xiaohui; and 29 coauthors</td>
<td>The Sloan Digital Sky Survey Reverberation Mapping Project: Technical Overview</td>
</tr>
</tbody>
</table>
Early science results: first lag detections at $z > \sim 0.3$

Based on 6-month spectroscopy only

• Example detections (<6 months) reported
• Including several MgII lag detections
• Exploring a L-z regime for the first time.

• MOS RM is promising
• Photometric LCs are crucial
• There is much room to improve these detections with more time allocation (e.g., higher spectro-cadence).

Paper to be posted soon
Early science results: stellar velocity dispersion (sigma) in high-z quasar hosts

Coadded spectra from 32 epochs: ~ 6-8 hrs on 6-8m telescopes – hundreds of them!
Improvement over previous samples

88 quasars at 0.1<z<1 (<z>=0.6) with sigma measurements.

46 are at z>0.6, where no sigma has been measured in quasars before.

Shen et al. (2015b)
A M-sigma relation at $z \sim 0.6$

The much shallower slope is consistent with selection biases; no evidence for evolution in the M-sigma relation to $z \sim 1$

First robust detection at $z > 0.3$

Shen et al. (2015b)
Ultra-deep AGN host (and galaxies in general) spectroscopy

- Dynamical BH mass
- Quasar virial BH mass
- host $\sigma_*$ measurements

- SDSS 2.5m
- PFS 8m Subaru
- MSE 10m
- SDSS–RM [60 hr]
- SDSS–RM [100 hr]
- MOBIE
- IRIS
- IRMS
- TMT

- Magnitude [1 hr exp]
- Restframe 5000 Å
- Redshift

- ★ degree FoV, hundreds to thousands of AGN
Summary

• **SDSS-RM (2010-2019):**
  – more efficient RM with MOS surveys
  – expanding the redshift-luminosity range of the RM AGN sample
  – new insights on AGN physics and galaxy-BH co-evolution
  – what we learn from SDSS-RM (and ozDES-RM, King et al. 2015) will help us better design future multi-year MOS-RM programs

• **MSE-RM (~2025-2030)**
  – much more and much better detections; deeper sample; broader wavelength coverage
  – synergy with other science programs: transient follow-up, ultra-deep galaxy spectroscopy, etc.
General considerations for MOS-RM

- **Total epochs:** both time baseline (> several x lag) and cadence (temporal resolution) are critical, requiring a large number of epochs over multiple years.

- **Spectrophotometry and depth:** AGN variability is typically 10%, so in general need (relative) spectrophotometry at the few percent level (e.g., 5% for SDSS-RM), as well as good S/N per epoch.

- **Supporting photometry:** quasi-simultaneous and earlier photometry (e.g., a few years earlier) is always useful. LSST synergy is important.

- **Caveats, e.g.,**
  - Real AGN light curves are messier than simulated ones (especially the emission-line LCs or at high-z). SDSS-RM will help.
  - Fiber positioning accuracy important for achieving the desired spectrophotometry.