Weighting a beast: how to measure the mass of an accreting super massive black hole?

Giorgio Calderone – INAF OATs
Accreting super massive black holes \((M \sim 10^6 \div 10^{10} M_\odot)\)

**Black hole “size”**

\[
R_g = \frac{GM}{c^2} \sim 1.5 \times 10^{13} \left(\frac{M}{10^8 M_\odot}\right) \text{ cm} \sim 1 \left(\frac{M}{10^8 M_\odot}\right) \text{ AU}
\]

\[
R_{\text{ISCO}} = 6 \times R_g \sim 1 \left(\frac{M}{10^8 M_\odot}\right) \text{ lh (light hour)}
\]

**Accretion luminosity**

\[
L = \eta \dot{M}c^2 \sim \eta \ 6 \times 10^{46} \left(\frac{\dot{M}}{M_\odot \text{ yr}^{-1}}\right) \text{ erg s}^{-1}
\]

**Eddington luminosity \((F_{\text{rad}} = F_{\text{grav}})\)**

\[
L_{\text{Edd}} = \frac{4\pi Gc \rho}{\sigma_T} M \sim 1.3 \times 10^{46} \left(\frac{M}{10^8 M_\odot}\right) \text{ erg s}^{-1}
\]

**Eddington ratio**

\[
\epsilon \sim 5\eta \left(\frac{\dot{M}}{M_\odot \text{ yr}^{-1}}\right) \left(\frac{M}{10^8 M_\odot}\right)^{-1}
\]
Gravitational sphere of influence (SOI)

- Stars and gas moves in the galactic potential, determined mainly by stars;
- only in the inner part the gravitational potential is dominated by the SMBH;

\[ \Phi = \Phi_{\text{stars}} + \Phi_{\text{BH}} \]

To probe \( M \) we should investigate the spatial region where [Peebles 1972]:

\[ \Phi_{\text{stars}} \sim \Phi_{\text{BH}} \Rightarrow \sigma^2_* = \frac{GM}{R_{\text{SOI}}} \]

- Typical values:

\[ R_{\text{SOI}} \sim 10 \left( \frac{M}{10^8 M_\odot} \right) \left( \frac{200 \text{ km s}^{-1}}{\sigma_*} \right)^2 \text{ pc} \]

\[ \theta_{\text{SOI}} \sim 0.1'' \left( \frac{M}{10^8 M_\odot} \right) \left( \frac{200 \text{ km s}^{-1}}{\sigma_*} \right)^2 \left( \frac{D}{20 \text{ Mpc}} \right) \Rightarrow \text{requires high spatial resolution} \]
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Super massive black hole mass estimation

Primary methods (directly probe gravitational potential):

- Motions of individual test particles:
  - Star motions (Sgr A*);
  - Motion of maser clouds (Type II AGN);
- Spatially resolved ensemble motions (non-active galaxies):
  - Stellar dynamics, gas kinematics;
- Eddington limit (Type I AGN, only mass lower limits);
- Accretion disk fitting (mainly high luminosity Type I AGN);
- 2D reverberation mapping.

Secondary methods (based on primary methods):

- Empirical relations (non-active galaxies):
  - $M - \sigma_*$, $M - L_{\text{bulge}}$, $M - C$, etc.;
- Spatially unresolved, time resolved ensemble motions:
  - Reverberation mapping (Type I AGN, $Z \lesssim 0.3$);
- Spatially and time unresolved ensemble:
  - Single epoch virial method (all Type I AGN);
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Emission line variability

Tohline & Osterbrock 1976

Play movie online

Tohline & Osterbrock 1976
Reverberation mapping

Grier+2012

- line variations correlates with the continuum ones, with time delays of $\sim 10$–100 days;
- different lines respond at different times (stratified BLR);
- correlation plots show “narrow peaks”, i.e. line emitting region is rather small;

$\Rightarrow$ use time lags as a proxy for BLR distance:

$$R_{\text{BLR}} = c \tau$$

Peterson 2002
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Reverberation mapping + virial motion

- line widths ⇒ BLR clouds speed;
- line variability ⇒ BLR distance from BH;

  *virial motion* assumption:

  \[ M \propto \frac{R_{BLR} V^2}{G} \]  
  (virial product)

- Consistency check:
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- Consistency check:

Calibration required!

![Diagram showing correlation between BH mass and virial product]

- LAMP sample
- Other RM AGNs
- non-AGNs

Woo+2010

Consistency check:

![Diagram showing correlation between BH mass and virial product]

- This work
- Gültekin et al. 09

Woo+2010
Reverberation mapping: estimate line width

Use RMS spectrum

![Graph showing NGC 5548 spectrum and RMS spectrum with wavelength in Ångstroms and flux values.](image)

Peterson 2004
Reverberation mapping: estimate line width

Use RMS spectrum

NGC 5548
(JD2448954JD2449255)
mean spectrum

rms spectrum

Estimate FWHM...

Peterson 2004
Reverberation mapping: estimate line width

...or line dispersion

$$\sigma^2_{\text{line}}(\lambda) = \langle \lambda^2 \rangle - \lambda_0^2 = \left[ \frac{\int \lambda^2 P(\lambda) d\lambda}{\int P(\lambda) d\lambda} \right] - \lambda_0^2$$
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Graphs based on FWHM and \( \sigma_{\text{line}} \):

- Year 12
- NGC 5548

Collin+2016
Reverberation mapping: can we get rid of calibration from $M - \sigma$?

Mass estimate

$$M = f \frac{R_{\text{BLR}}(\alpha \sigma)^2}{G}$$
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**Convert: line widths $\rightarrow V$**

We still lack a model for the line profile!

![Diagram showing line profiles for different inclinations and distances.](image)
Reverberation mapping: can we get rid of calibration from $M - \sigma$?

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$$M = f \frac{R_{\text{BLR}} (\alpha \sigma)^2}{G}$$

**BLR geometry and inclination**

- isotropic: $f = \sqrt{\frac{3}{4}} \sim 0.87$
- disk-like: $f = \frac{0.5}{\sqrt{\left(\frac{H}{R}\right)^2 + \sin^2 \theta}}$

- $M - \sigma_*$ calib. $\rightarrow f \sim 4 \div 6$, $\alpha = 1$
- scatter $\sim 0.4$ dex;

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**Velocity–delay maps (2D RM)**

- only 9 sources (Pancoast+2014, Grier+2017);
- i.e., for Mrk50 ($z = 0.023$, Pancoast+2014):
  - $\theta \sim 25^\circ$
  - $\alpha \sim 4^\circ \div 16^\circ$
  - $f \sim 6$;
- All $M < 10^8 M_\odot$;
- $\log \tilde{f}_\sigma = 0.45 \pm 0.32$;
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Weighting a beast

09 Oct. 2018
Reverberation mapping confirms simple photoionization model

**Photoionization model**

- **continuum luminosity ionizes BLR clouds**;
- **ions recombine at some excited level, and emit a photon (emission line)**;
- **a given emission line is emitted in zones with appropriate ionization parameter**:

\[
U = \frac{\text{ionizing photons}}{\text{recombinations}} \propto \frac{L_{\text{ion}}}{R^2 n_e} \\
\Rightarrow R \propto L_{\text{ion}}^{0.5}
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**R – L (Kaspi) relation**

\[
\alpha = 0.546^{+0.027}_{-0.027} \quad \sigma = 0.13^{+0.02}_{-0.02} \text{ dex}
\]

Bentz+2013
Summary

- ~60 AGN have RM measurements, $z < 0.3$ (http://www.astro.gsu.edu/AGNmass/);
- 9 AGN have 2D–RM measurements, $M < 10^8 M_\odot$;
- good correlation with M–$\sigma$;
- self-consistent: different lines and different continuum luminosity $\rightarrow$ single black hole mass;
- confirms photoionization model;
- Accuracy: $\sim 0.4$ dex;
- very time consuming: it can be applied on a small number of nearby sources;
Single epoch virial method

Mass estimate

\[ M = f \frac{R_{BLR} V^2}{G} \]

with the constants \( a \) and \( b \) calibrated using different emission lines:

- \( \text{H} \beta \) (Bentz+2009): \( a=0.83, b=0.519, c=2 \);
- \( \text{MgII} \) (Shen+2011): \( a=0.74, b=0.62, c=2 \);
- \( \text{CIV} \) (Vestergaard+2006): \( a=0.66, b=0.53, c=2 \);

Recent values (Woo+2015, 2018):

- \( \text{H} \beta \) (Woo+2015): \( a=0.47, b=0.533, c=2 \);
- \( \text{MgII} \) (Woo+2018): \( a=1.51, b=0.83, c=1.82 \), (add.unc. \( \sim 0.2 \) dex).
Single epoch virial method

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\[ \log \frac{M_{\text{vir}}}{M_\odot} = a + b \log \left( \frac{\lambda L_\lambda}{10^{44} \text{ erg s}^{-1}} \right) \]

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Single epoch virial method: issues

- Is $f$ unique for all AGNs?
- Radiation pressure (Marconi, 2008, Chiaberge 2010):

$$\frac{M_{\text{RP}}}{M_\odot} = 10^{6.6} \left( \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right)^2 \left( \frac{\lambda L_\lambda}{10^{44} \text{ erg s}^{-1}} \right)^{0.5} + 10^{7.5} \left( \frac{\lambda L_\lambda}{10^{44} \text{ erg s}^{-1}} \right)$$

- $\lambda L_\lambda$ estimates may be affected by host galaxy and/or jet contributions

- Mass estimates on large samples: uncertainty is $0.5$ dex.
  $\Rightarrow$ all SMBHs (in each subsample) share a single value of the mass!
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Summary

- **Simple and straightforward, applicable to all Type I AGN**;
- **Accuracy**: $\sim 0.5$ dex (from RM) + uncertainties on line widths;
- Unclear whether it is biased by BLR geometry, inclination, radiation pressure, selection bias, etc.;
QSFit: Quasar Spectral FITting package

**QSFit (empirical) recipe:**

1. Fit continuum (PL), host galaxy contribution and Balmer continuum;
2. Subtract continuum offset: negative residuals: 50% → 10% (empirical);
3. Fit “known” lines;
4. Fit iron templates (UV and optical);
5. Fit “unknown” lines (to fix residuals);
6. **Free all parameters** and run the final fit.

- **Galaxy template (elliptical):**

- **Emission lines:** Gaussian profile

- **Iron UV template:**

- **Iron optical template:**

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<td>3729.875</td>
<td>N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Ne iii]</td>
<td>3869.81</td>
<td>N</td>
<td>[N ii]</td>
<td>6585.27</td>
<td>N</td>
</tr>
<tr>
<td>Hδ</td>
<td>4102.89</td>
<td>B</td>
<td>[Si ii]</td>
<td>6718.29</td>
<td>N</td>
</tr>
<tr>
<td>Hγ</td>
<td>4341.68</td>
<td>B</td>
<td>[Si ii]</td>
<td>6732.67</td>
<td>N</td>
</tr>
<tr>
<td>Hβ</td>
<td>4862.68</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example: high–Z

![Graph showing Data, Model, Continuum, Cont. + Galaxy, and Balmer lines.](image)
Example: high–Z

![Graph showing luminosity density against rest frame wavelength.](image)

- **Data**
- **Model**
- **Continuum**
- **Cont. + Galaxy**
- **Balmer**

**Lum. density \([10^{42} \text{ erg s}^{-1} \text{ A}^{-1}]\)**

**Rest frame wavelength [Å]**
Example: high–Z

![Graph showing lum. density versus rest frame wavelength.](image)

- Data
- Model
- Continuum
- Cont. + Galaxy
- Balmer
- Iron

Lum. density [$10^{42}$ erg s$^{-1}$ A$^{-1}$]

Rest frame wavelength [Å]
Example: high–Z

Data
Model
Continuum
Cont. + Galaxy
Balmer
Iron
Broad
Narrow
Unknown

Lum. density \([10^{42} \text{ erg s}^{-1} \text{ A}^{-1}]\)
Rest frame wavelength \([\text{A}]\)

Giorgio Calderone – INAF OATs
Weighting a beast
09 Oct. 2018 17 / 28
New quasar spectral catalog: The QSFit catalog

- Start from S11 sample (105,783 Type 1 AGNs):
- Spectra from SDSS/DR10 (~ 3800–9000Å)
- Drop sources with $z > 2$
  (to avoid issues in fitting the Ly$\alpha$ line);
- Drop sources flagged as BAL
  (to avoid issues in fitting absorption lines);

The QSFit catalog

- 71,251 sources;
- QSFit input (SDSS): ~ 18 GB;
- QSFit output (results, plots, logs):
  ~ 35 GB, FITS: ~ 85 MB;
- $\chi_{\text{red}}^2$ ~ 1.09;
- Analysis time (12 CPU INAF–Bo):
  ~ 24 hours;
- Elapsed time/source ~ 7 s;
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**The whole analysis is easily replicable:**

```python
res = qsfit('spec-0752-52251-0323.fits',
            z=0.3806, ebv=0.06846)
qsfit_plot, res
```

Giorgio Calderone – INAF OATs
Quasar Spectral FITting package

QSFit is a software package to automatically perform spectral analysis of Active Galactic Nuclei (AGN) optical/UV spectra. It provides estimates of:

- AGN continuum luminosities and slopes at several rest frame wavelengths;
- host galaxy luminosities (for sources with z < 0.8);
- luminosities, widths and velocity offsets of 20 individual emission lines (Hα, Hβ, MgII, [OIII], CIV, etc.), and luminosity of the blended Balmer lines (n ≥ 7);
- luminosities of iron blended lines at optical and UV wavelengths;
- luminosity of the Balmer continuum;
- several "quality flags" to assess the reliability of the results.

The main purpose of QSFit is to allow anyone to perform AGN spectral analysis in a simple, replicable and shareable way. The code is available on Github and can be easily customized for specific purposes.

Reference Paper


If you make use of the catalog or the code, please acknowledge as: Calderone et al., MNRAS, 72, 4 (2017)

Catalog of spectral properties (ver. 1.2.4)

We used QSFit to analyze 71,251 optical spectra (from SDSS-DR10) of Type 1 AGN at z < 2, and compiled a catalog of spectral properties. See the reference paper.

The catalog can be explored online or downloaded as a FITS file.

The complete data analysis can be easily replicated by running QSFit (as shown in the example above) on all the spectra in the sample.

The old version 1.2 is available here.

Source Code (Github)

The source code can be downloaded from Github. The software is written in IDL and released under the GPL license.

The prerequisites to run QSFit are IDL (ver. >= 8.1) and Gnuplot (ver. >= 5.0).

To run QSFit you should download and unzip the package from Github, then change to the directory where you unpacked the source code and start an IDL session. There is no need to change the IDL PATH system variable, QSFit provide a simple way to compile all the required procedures: simply call compile at the IDL prompt.

The QSFit package already comes with a SDSS DR-10 FITS file to test the code. The commands to run the analysis
The QSFit website: [http://qsfit.inaf.it/](http://qsfit.inaf.it/)

Version 1.2

The QSFit reference paper is accepted for publication in MNRAS. See the arXiv preprint.

The QSFit catalog (var. 1.2) is a collection of spectral properties of 71,251 Type 1 Active Galactic Nuclei (AGN), obtained by the SDSS-DR10 survey.

The QSFit catalog was compiled using the QSFit software package, specifically designed to automatically perform spectral analysis of AGN at optical/UV wavelengths, in a simple, replicable and shareable way.

The catalog provides estimates of:

- AGN continuum luminosities and slopes at several rest frame wavelengths;
- host galaxy luminosities (for sources with $z < 0.8$);
- luminosities, widths and velocity offsets of 20 individual emission lines (Hα, Hβ, MgII, [OIII], CIV, etc.), and luminosity of the blended Balmer lines ($n > 7$);
- luminosities of iron blended lines at optical and UV wavelengths;
- luminosity of the Balmer continuum;
- several "quality flags" to assess the reliability of the results.

The catalog is available as a FITS table. We also provide an enlarged version of the catalog where we added, for each source, the quantities reported in the Shen et al. 2011 catalog, to allow an easy comparison of the estimates in both catalogs.

You can browse the catalog using the search form below. The available search criteria are: the SDSS plate/MJD/fiber; the SDSS name; a redshift interval; and coordinates circle.

For each source we provide the interactive plot of best fitting model and residuals, the QSFit and Shen+11 estimates, several images of the source (using AladinLite), the SDSS FITS file of the spectra used for the analysis and the QSFit outputs, namely the log file, the gnuplot files and the IDL binary file where all the relevant info are stored.
Coming soon: online analysis

QSEFit
Catalogue of spectral properties of Type 1 AGN (selected from SDSS DR10)
Version 2.0.0

Drag & drop your spectral file here... or Browse... spec-0752-52251-0323.fits

- spec-0752-52251-0323.fits (type: image/fits) - 604800 bytes
  Redshift 0.3806  E(B-V) 0.06846
  Process this file

Customize analysis

- Use a separate component for the [OIII]5007 blue wing
- Use the Balmer continuum component
- Use a Lorentzian profile for the emission lines (instead of a Gaussian one)

angstrom
Comma separated list of rest frame wavelengths of the absorption lines

Minimum line resolution (in km/s) to fit the line

SWIRE_ELL5
Host galaxy template
Accretion disk spectrum modeling

- Accreting matter produce a characteristic spectrum
- Compare predicted spectrum with SED
  \[ \Rightarrow \text{infer } M, \dot{M} \]

Shakura & Sunyaev (1973) model

- Simple model
- Simple relationships between \( M, \dot{M} \) and observational properties
- Historically, this has been the first SMBH mass estimation method
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![Graph showing accretion disk spectrum modeling](image)
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Malkan 1983
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\[ \alpha_{\nu} = \frac{1}{3} \ ? \]
SSAD: $M=10^9 \ M_\odot$, Edd. ratio=0.05, $\theta=30^\circ$
BBB ↔ AD connection

Kishimoto+2008

$10^9 \, M_\odot, \text{ Edd. ratio}=0.05, \, \theta=30^\circ$
Accretion disk spectrum modeling

AD model parameters

- **disk extension**: $R_{\text{in}}, R_{\text{out}}$
- **disk inclination**: $\cos(\theta)$
- black hole mass: $M$
- disk luminosity: $L_d$

- spectra are self–similar in log–log plots;
- scaling relations:
  \[
  \nu_p \propto M^{-1/2} L_d^{1/4} \\
  \nu_p L_{\nu_p} \propto L_d
  \]
- If we locate the peak $\rightarrow M, L_d$;
- otherwise use line luminosities as proxy $\rightarrow L_{\text{ion}} \rightarrow L_d$;
- **note**: $M_{\text{estimate}} \propto \eta$

Total luminosity given by:

\[
L_d = \eta \dot{M} c^2 = L_{\text{iso}} d^2 \cos(\theta)
\]

(GR corrections $\rightarrow$ Samuele's talk)

The method is thoroughly discussed in Calderone+2013.

Accuracy: $< 0.7$ dex (worst case).
Accretion disk spectrum modeling

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(Gravitational correction → Samuele’s talk)

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(Graph corrections $\rightarrow$ Samuele’s talk)

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Method:

- Use IR data to estimate synchrotron contamination, optical/UV data to constrain the peak;
- Assume radiative efficiency $\eta \sim 10\%$;
- Uncertainties: $\sim 0.7$ dex (conservative);
- For 25/31 RL-NLS1 sources we obtained a good fit;
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Disk modeling on a RL–NLS1 sample

**Method:**

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![Graph showing the relationship between frequency and luminosity](image_url)
Incompatible with single epoch virial estimates!

![Graph showing comparison of different methods for estimating galaxy masses]

Calderone, D’Ammando, Sbarrato, in prep.
Accretion disk modeling

![Graph showing accretion disk modeling](image)

- logM=7.1
- logM=6.8
- logM=6.5

E \cdot F_E \ [keV \ keVcm^{-2} s^{-1} keV^{-1}]

E[keV]

OPTXAGN, Done+2012
Davis+2011 uses virial $M_{BH}$ AND disk modeling to constrain the spin!
Accretion disk modeling

\[ \nu L_\nu \] [erg/s]

\[ \nu [10^{15} \text{ Hz}] \]

\[ \log(M_{BH}) = 8.9, \log(\dot{M}) = -0.3, a = 0.9 \]

\[ \log(M_{BH}) = 8.9, \log(\dot{M}) = -0.225, a = 0.9 \]

\[ \log(M_{BH}) = 9.425, \log(\dot{M}) = -0.975, a = 0.998 \]

\[ \log(M_{BH}) = 9.275, \log(\dot{M}) = -0.975, a = 0.998 \]

J0143-0056

J1013+0245

Capellupo+2016
Quasar viscosity crisis

Recent observations of extreme variability in active galactic nuclei have pushed standard viscous accretion disk models over the edge. I suggest either that some kind of non-local physics dominates accretion disks, or that the optical output we see comes entirely from reprocessing a central source.

Andy Lawrence

Old news on quasar viscosity

To the Editor — Much of the active galactic nuclei and quasar community has been fixated on a particular model for the energetically dominant ‘Big Blue Bump’ component of the spectral energy distribution for the past 40 years\(^1\)\(^2\), despite the fact that the model is qualitatively incorrect. It’s a ‘quasi-static’ model, meaning arguments include the lack of the expected relationships of spectral energy distributions with mass and luminosity\(^7\)\(^8\), both at single epochs and in difference-spectra (high...
Estimating $M_{BH}$ for nearby “little beast” may be easy, but the vast majority are fierce, elusive beasts!

- Even worse: different methods apply to different sources (Type I/II, low/high $z$, high low contrast wrt host galaxy;
- ...except for the **single epoch virial** methods, which can be applied to all Type I AGN, but may suffer from serious biases;
- Accretion disk modeling method may be a viable alternative, it already provided encouraging results, but further theoretical work is required;
- In general, obtaining an accuracy below $\sim 0.4$ dex is **challenging!**