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

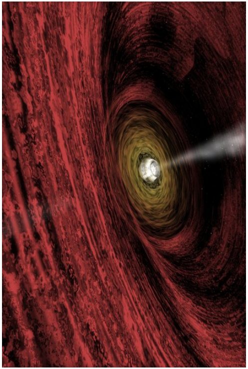
Giorgio Calderone – INAF OATs

Accreting super massive black holes ($M \sim 10^6 \div 10^{10} M_\odot$)

Black hole "size"

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

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



Accretion luminosity

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

Eddington luminosity ($F_{\mathrm{rad}} = F_{\mathrm{grav}}$)

$$L_{\mathrm{Edd}} = \frac{4\pi G c m_{\mathrm{p}}}{\sigma_{\mathrm{T}}} M \sim 1.3 \times 10^{46} \left(\frac{M}{10^8 M_\odot}\right) \mathrm{erg\ s}^{-1}$$

Eddington ratio

$$\epsilon \sim 5\eta \left(\frac{\dot{M}}{M_\odot \mathrm{yr}^{-1}}\right) \left(\frac{M}{10^8 M_\odot}\right)^{-1}$$

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]:

$$\Phi_{\text{stars}} \sim \Phi_{\text{BH}} \qquad \Rightarrow \qquad \sigma_*^2 = \frac{GM}{R_{\text{SOI}}}$$

- Typical values:

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

$$\theta_{\text{SOI}} \sim 0.1'' \left(\frac{M}{10^8 M_\odot}\right) \left(\frac{200\text{km s}^{-1}}{\sigma_*}\right)^2 \left(\frac{D}{20\text{Mpc}}\right) \Rightarrow \textit{requires high spatial resolution}$$

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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):
  - $M - \sigma_*$, $M - L_{\rm bulge}$, $M - C$, etc.;
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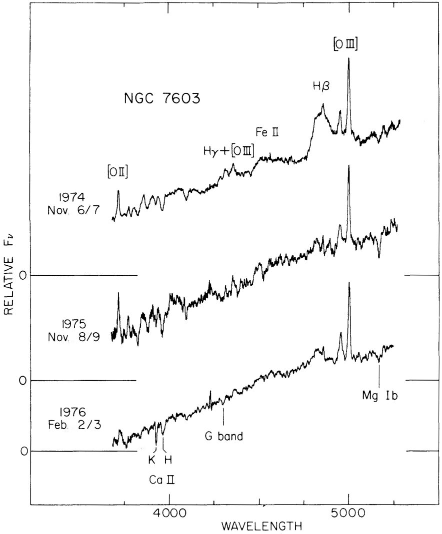
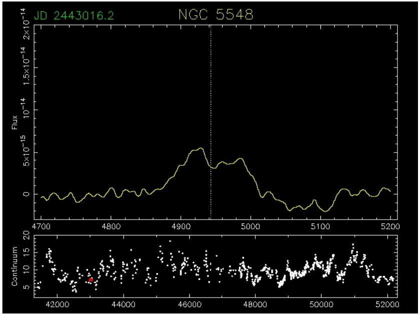
Emission line variability

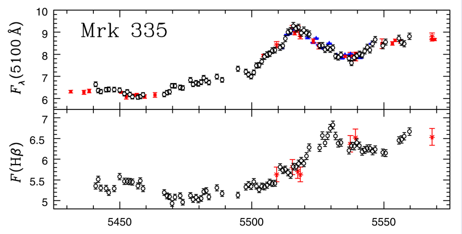


Tohline & Osterbrock 1976



Play movie online

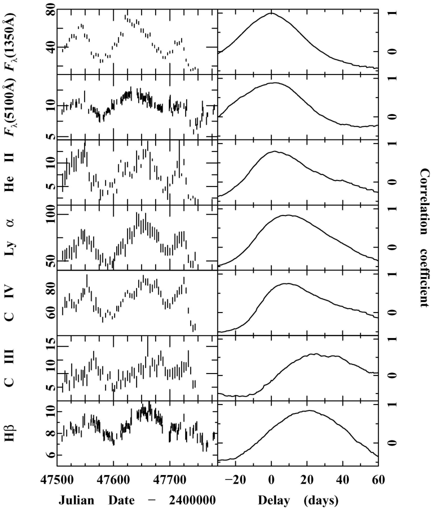
Reverberation mapping



Grier+2012

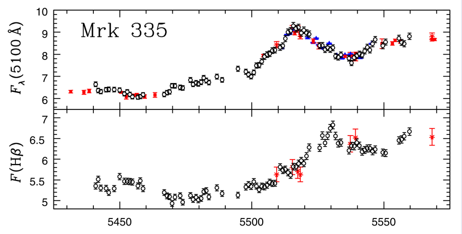
- line variations correlates with the continuum ones, with time delays of $\sim$10–100 days;
- different lines respond at different times (stratified BLR);
- correlation plots show “narrow peaks”, i.e. line emitting region is rather small;
- $\Rightarrow$ use time lags as a proxy for BLR distance:

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



Peterson 2002

Reverberation mapping



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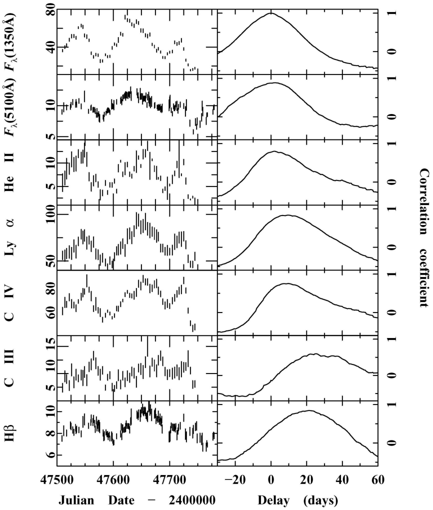

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Reverberation mapping + virial motion

- line widths ⇒ BLR clouds speed;
- line variability ⇒ BLR distance from BH;
- **virial motion** assumption:

$$M \propto \frac{R_{\rm BLR}\, V^2}{G} \quad \text{(virial product)}$$

- Consistency check:

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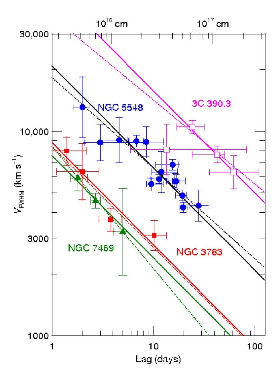

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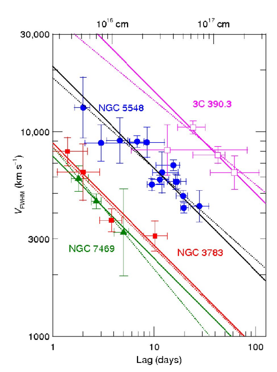
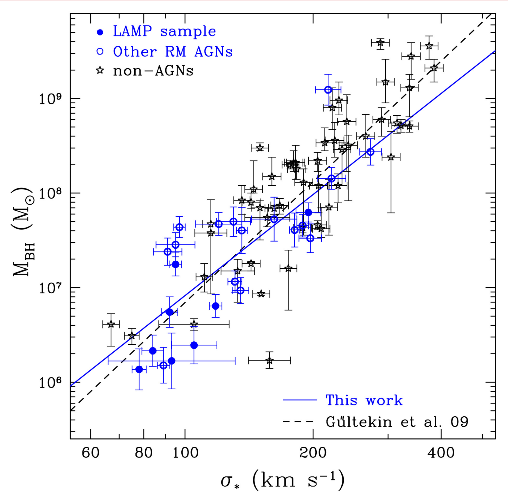


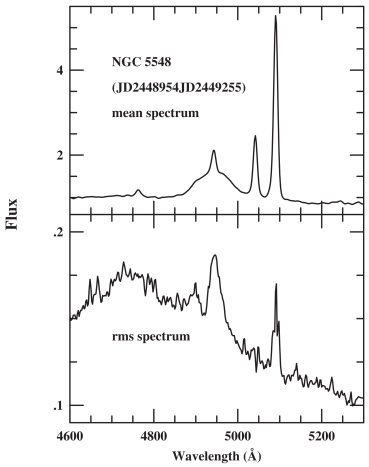
Calibration required!



Woo+2010

Reverberation mapping: estimate line width

Use RMS spectrum



Peterson 2004

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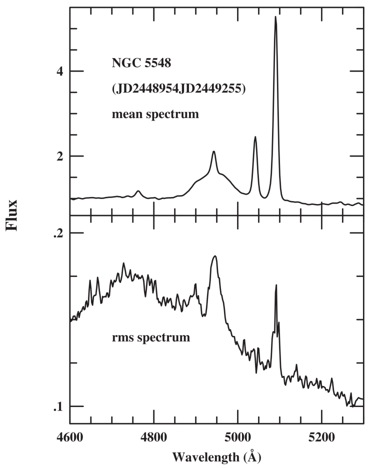

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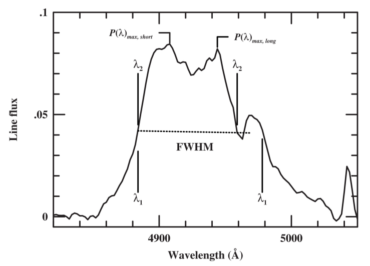
Estimate FWHM...



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...or line dispersion

$$\sigma_{\rm line}^2(\lambda) = \langle \lambda^2 \rangle - \lambda_0^2 = \left[\int \lambda^2 P(\lambda) d\lambda \Big/ \int P(\lambda) d\lambda \right] - \lambda_0^2$$

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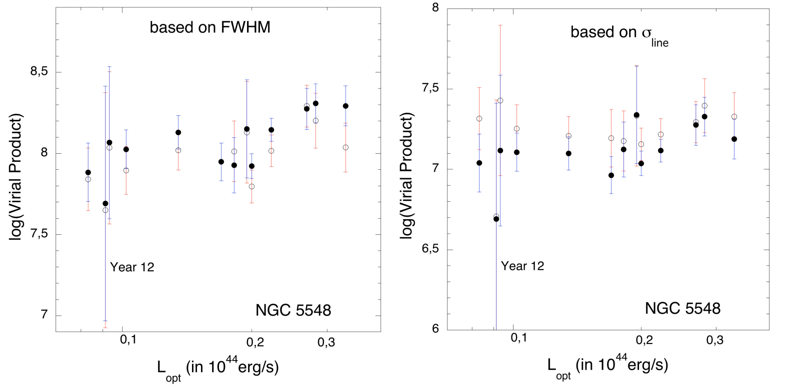

Collin+2016

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

Mass estimate

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

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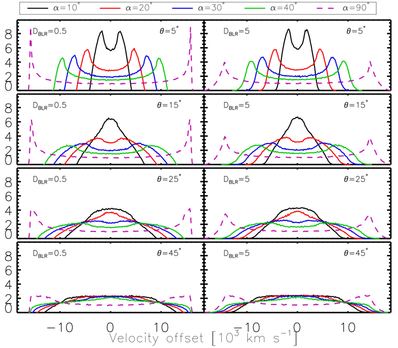
Convert: line widths $\rightarrow V$

We still lack a model for the line profile!



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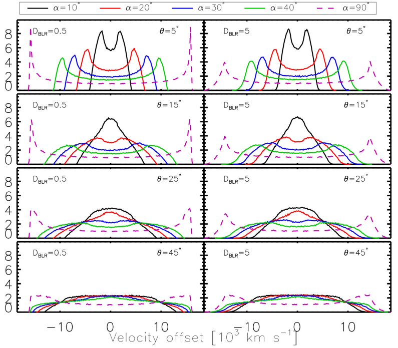

BLR geometry and inclination

- 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 ~ 0.4 dex;

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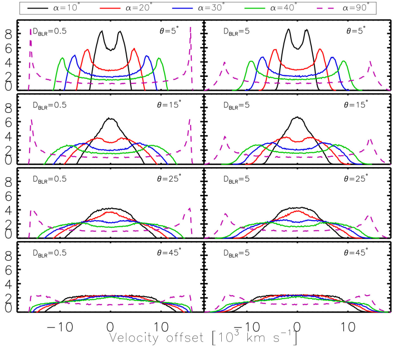

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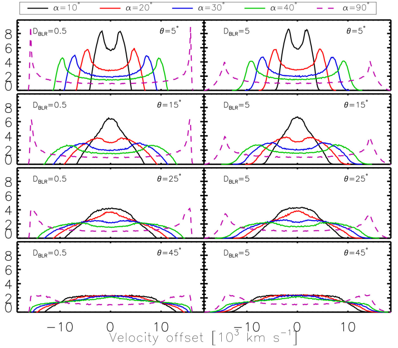

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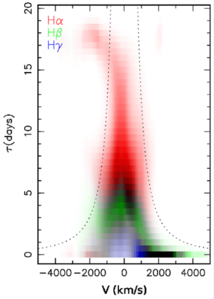
Velocity–delay maps (2D RM)

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



Bentz+2010, Pancoast+2012

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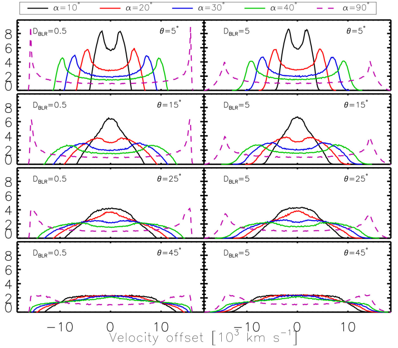

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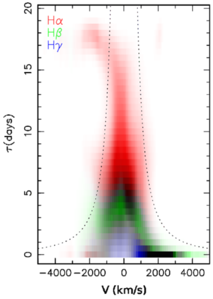

Bentz+2010, Pancoast+2012

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:

$$U = \frac{\text{ionizing photons}}{\text{recombinations}} \propto \frac{L_{\text{ion}}}{R^2 n_e}$$

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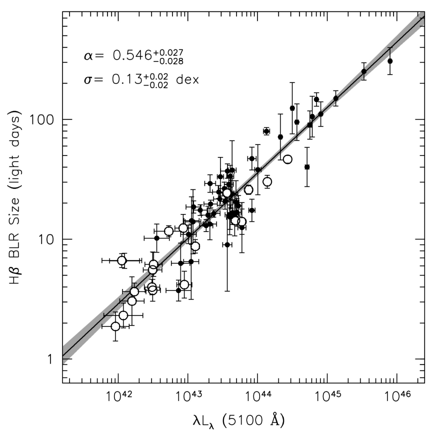
$R - L$ (Kaspi) relation



Bentz+2013

Reverberation mapping mass estimation method

Summary

- $\sim$ 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–σ;
- 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

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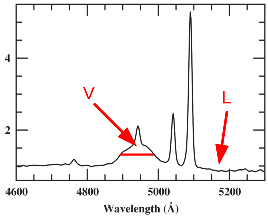
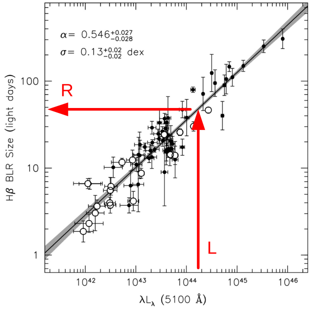
$$M = {\color{red} f}\,\frac{R_{\mathrm{BLR}}\,V^2}{G}$$





Single epoch virial method

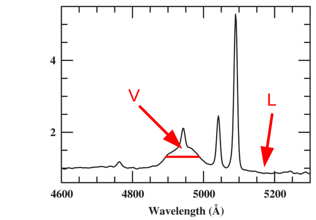
Mass estimate

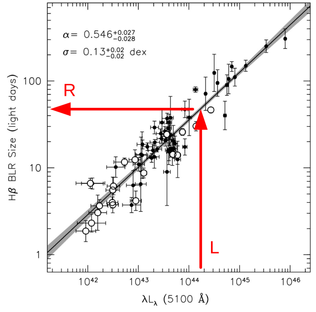
$$M = f\frac{R_{\rm BLR}V^2}{G}$$

$$\log\frac{M_{\rm vir}}{M_\odot} = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\ {\rm erg\ s^{-1}}}\right) + c\log\left(\frac{\rm FWHM}{\rm km\ s^{-1}}\right)$$

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

- Hβ, (Bentz+2009): a=0.83, b=0.519, c=2;
- MgII (Shen+2011): a=0.74, b=0.62, c=2;
- CIV (Vestergaard+2006): a=0.66, b=0.53, c=2;





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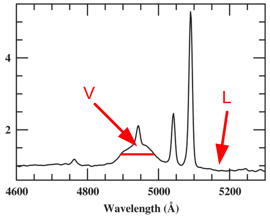
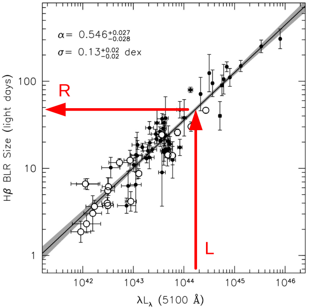
Recent values (Woo+2015, 2018):

- Hβ, (Woo+2015): a=0.47, b=0.533, c=2;
- MgII (Woo+2018): a=1.51, b=0.83, c=1.82, (add.unc. $\sim$ 0.2 dex);





Single epoch virial method: issues

- is f unique for all AGNs ?;
- radiation pressure (Marconi, 2008, Chiaberge 2010):

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

- λL_λ 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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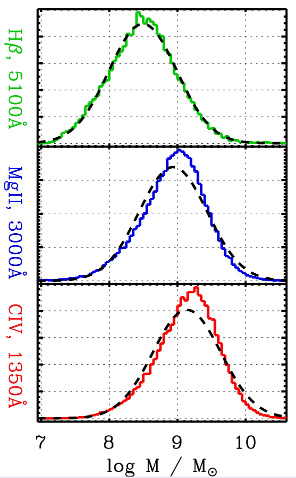


Single epoch virial method

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

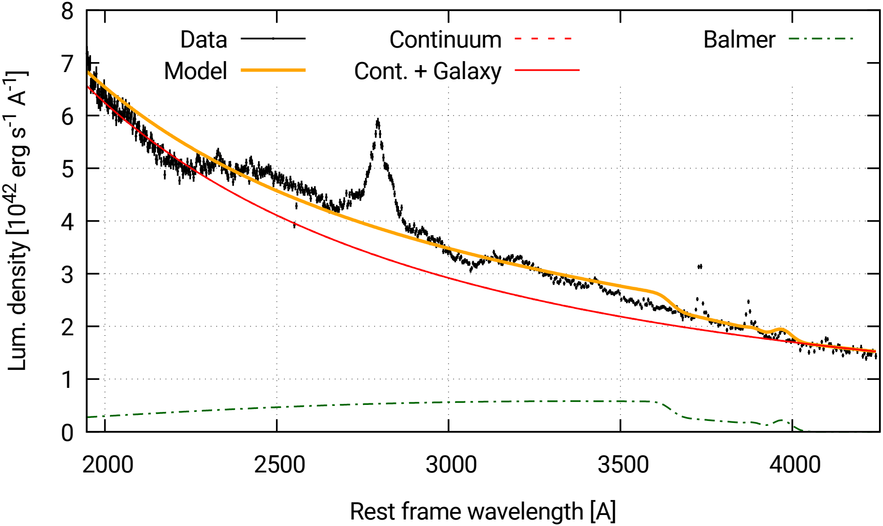
QSFit (empirical) recipe:

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): Polletta et al. 2007, ApJ, 663, 81
- Emission lines: Gaussian profile
- Iron UV template: Vestergaard and Wilkes 2001, ApJS, 134, 1V
- Iron optical template: Veron-Cetty, Joly and Veron 2004, A&A, 417, 515

Line	Wl [Å]	Type	Line	Wl [Å]	Type
Si IV	1399.8	B	[O III]	4960.295	N
C IV	1549.48	B	[O III]	5008.240	N
C III]	1908.734	B	He I	5877.30	B
Mg II	2799.117	B	[N II]	6549.86	N
[Ne VI]	3426.85	N	Hα	6564.61	B
[O II]	3729.875	N			N
[Ne III]	3869.81	N	[N II]	6585.27	N
Hδ	4102.89	B	[Si II]	6718.29	N
Hγ	4341.68	B	[Si II]	6732.67	N
Hβ	4862.68	B			
		N			

Example: high–Z



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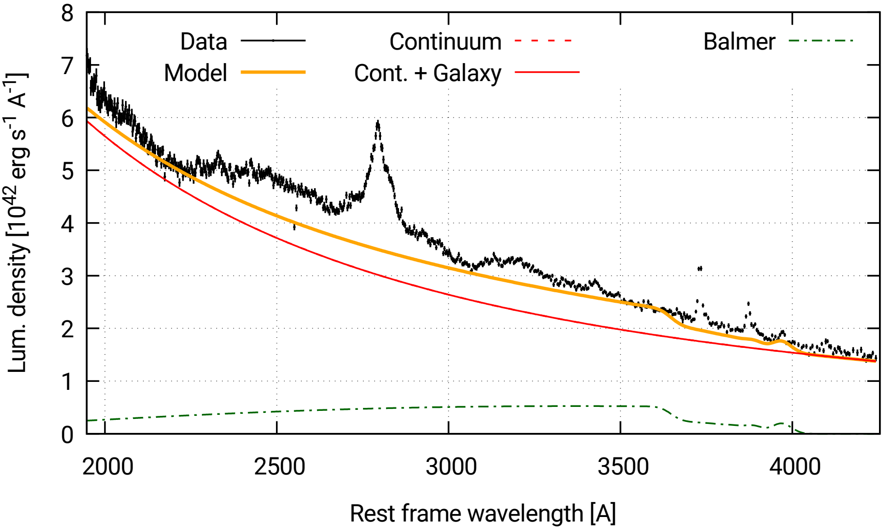

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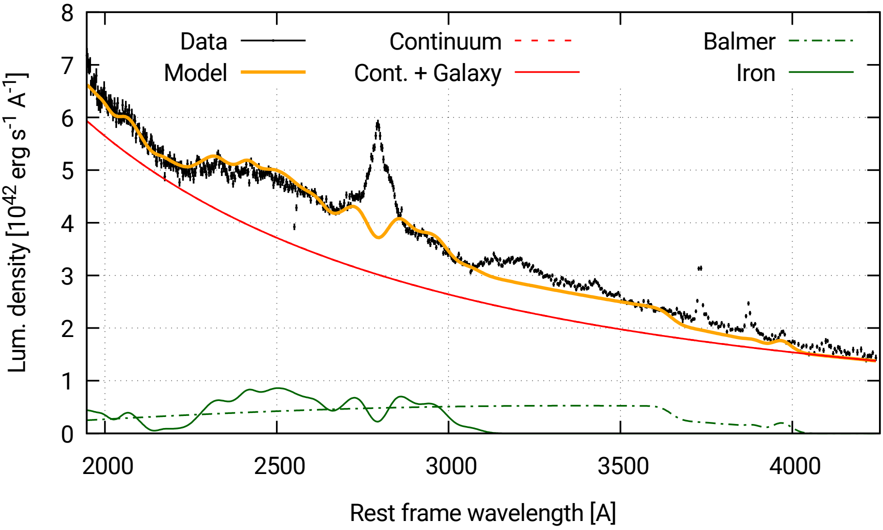

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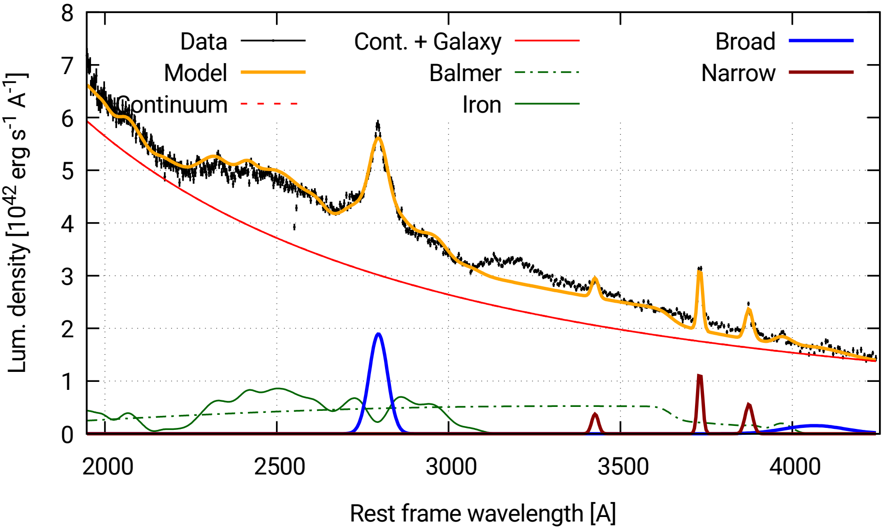
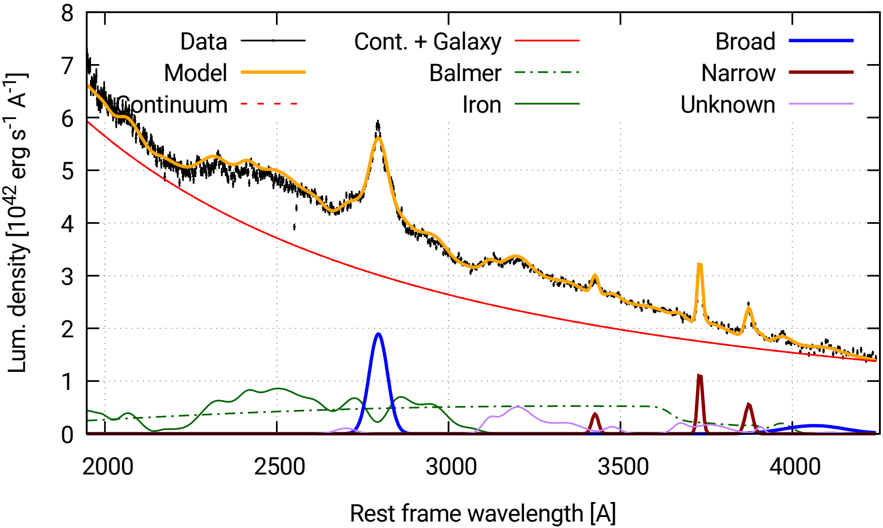
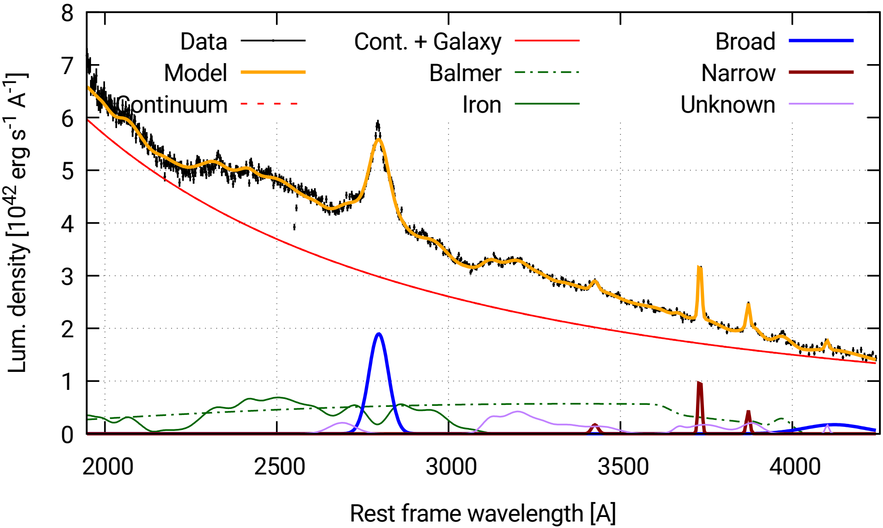


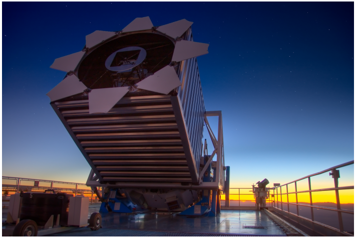

Data
Model
Continuum
Cont. + Galaxy
Balmer
Iron
Broad
Narrow
Unknown
Lum. density [10^42 erg s^-1 A^-1]
Rest frame wavelength [A]
0
1
2
3
4
5
6
7
8
2000
2500
3000
3500
4000

Example: high–Z



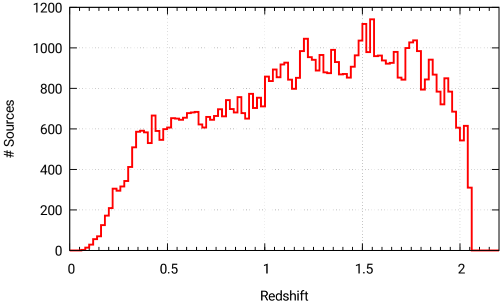
New quasar spectral catalog: *The QSFit catalog*

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



The QSFit catalog

- 71,251 sources;
- QSFit input (SDSS): $\sim$ 18 GB;
- QSFit output (results, plots, logs): $\sim$ 35 GB, FITS: $\sim$ 85 MB;
- $\chi^2_{\rm red} \sim 1.09$;
- Analysis time (12 CPU INAF–Bo): $\sim$ 24 hours;
- Elapsed time/source $\sim$ 7 s;



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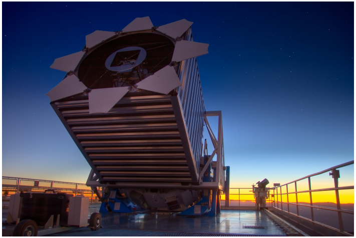

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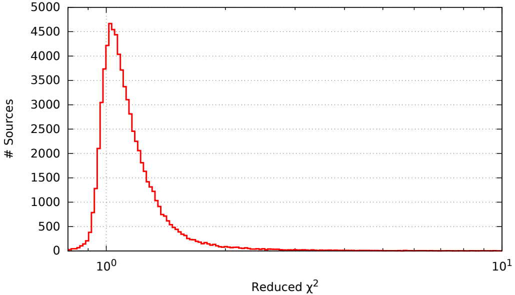

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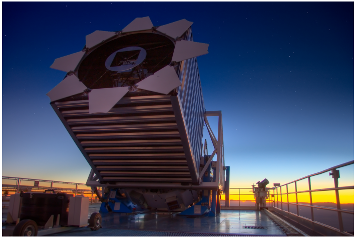

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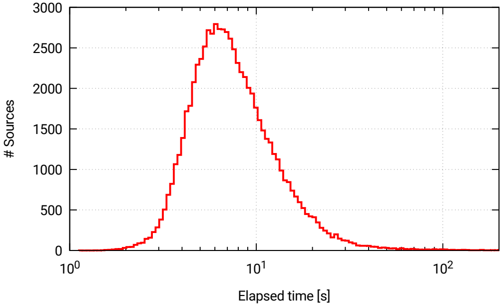

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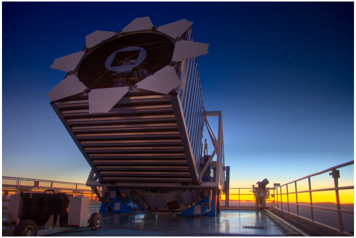

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The whole analysis is easily replicable:

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

The QSFit website: `http://qsfit.inaf.it/`

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 ($n \geq 7$);
- 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

The paper was published on **MNRAS, 72, 4, 4051-4080 (2017)**. Preprint available from **arXiv**.

If you make use of the catalog or the code, please unknowledge 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/`

About « Who we are » Composite spectra

Catalogue of spectral properties of Type 1 AGN (observed with SDSS DR10)

Version 1.2

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

The QSFit catalog (ver. 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:

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- 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.

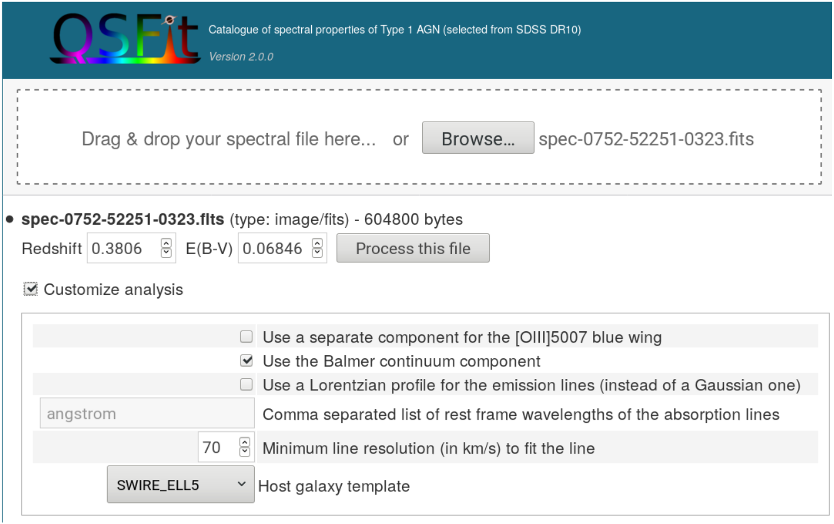
The catalog is available as a **FITS table**. We also provide an **enlarged version** of the catalog where we added, for each source, the quantities reported in the Shen et al. 2011 catalog, to allow an easy comparison of the estimates in both catalogs.

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.

Select by: Plate-MJD-Fiber SDSS name Redshift Coords

289 - 51990 - 234 Submit Reset

Coming soon: online analysis



Accretion disk spectrum modeling

- accreting matter produce a characteristic spectrum
- compare predicted spectrum with SED
- $\Rightarrow$ 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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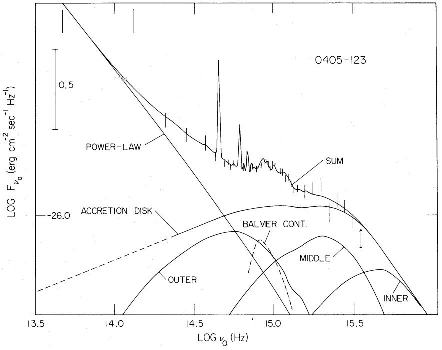

Malkan 1983

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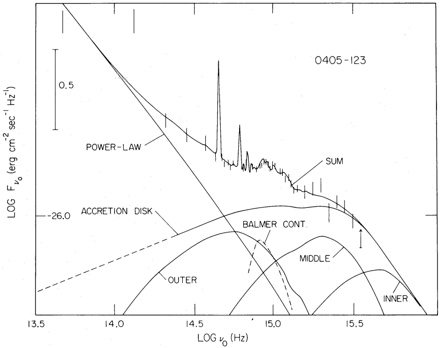

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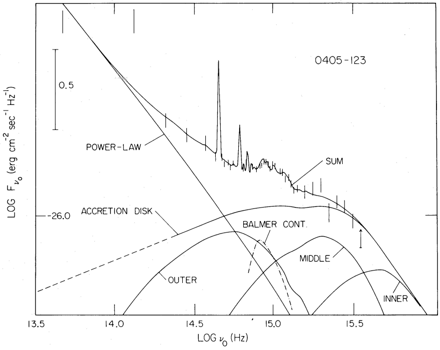
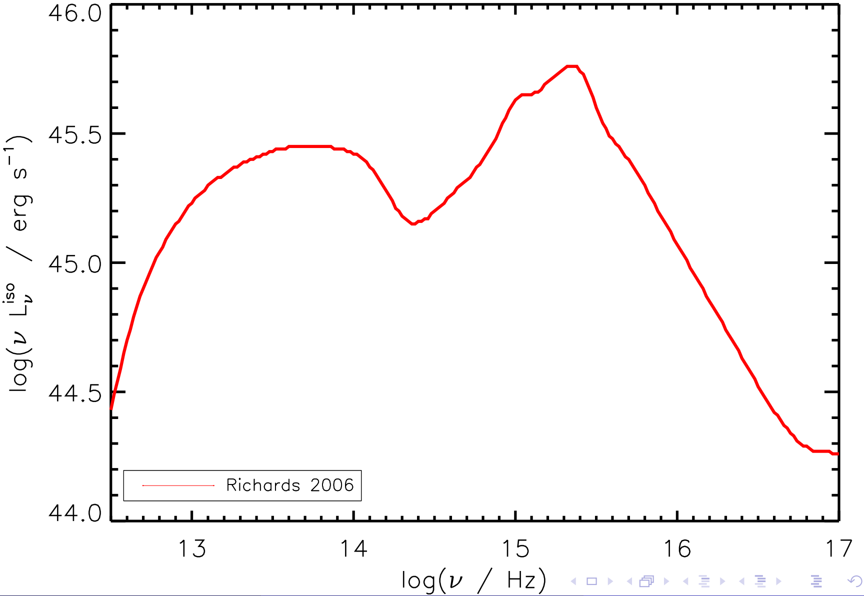
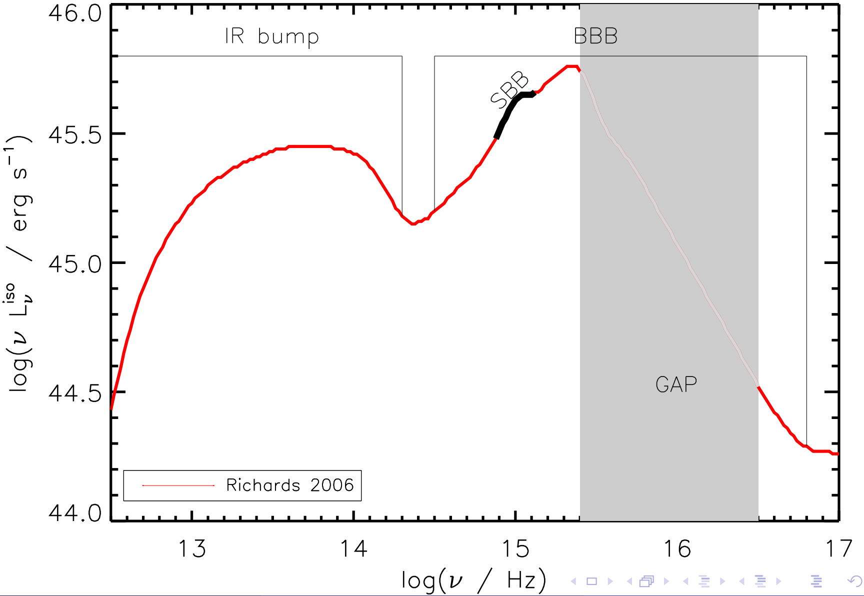


Malkan 1983

Composite SED of AGN (Richards et al. 2006)



BBB ↔ AD connection



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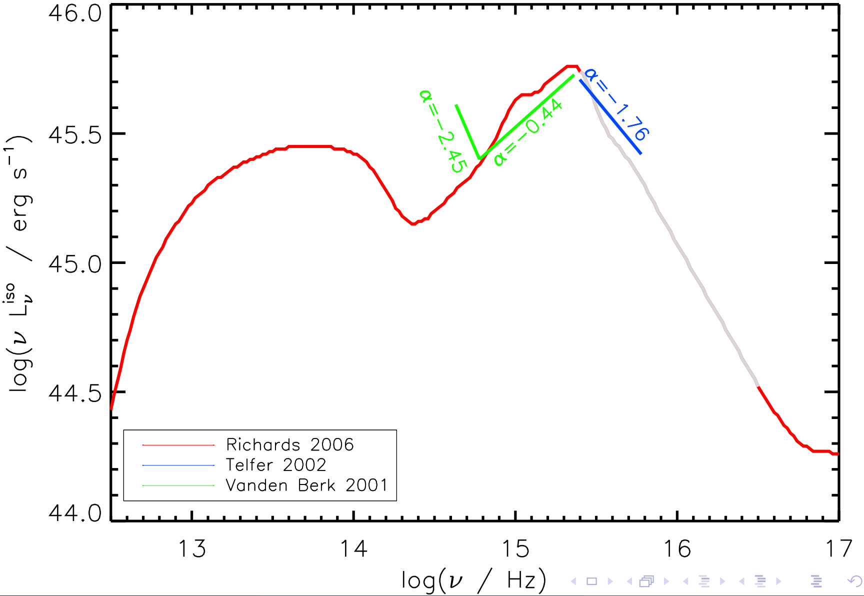
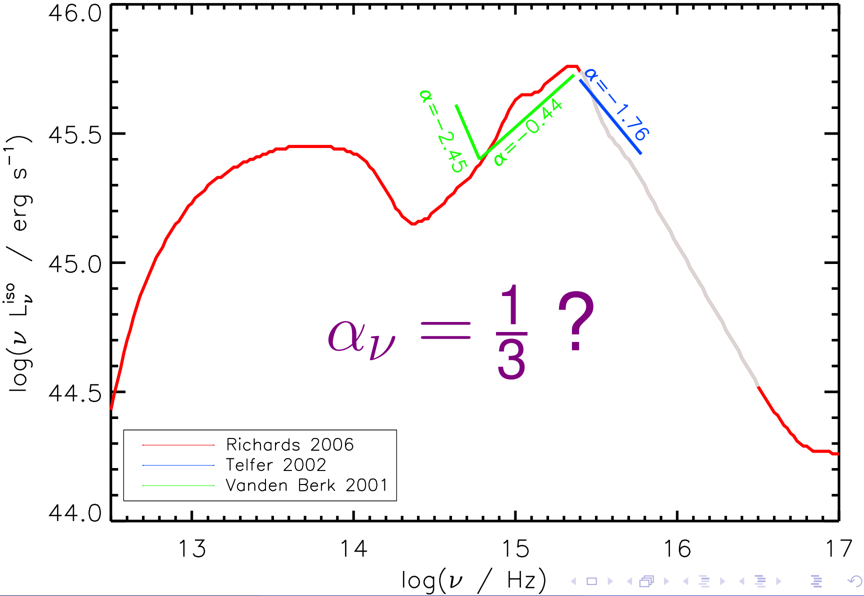
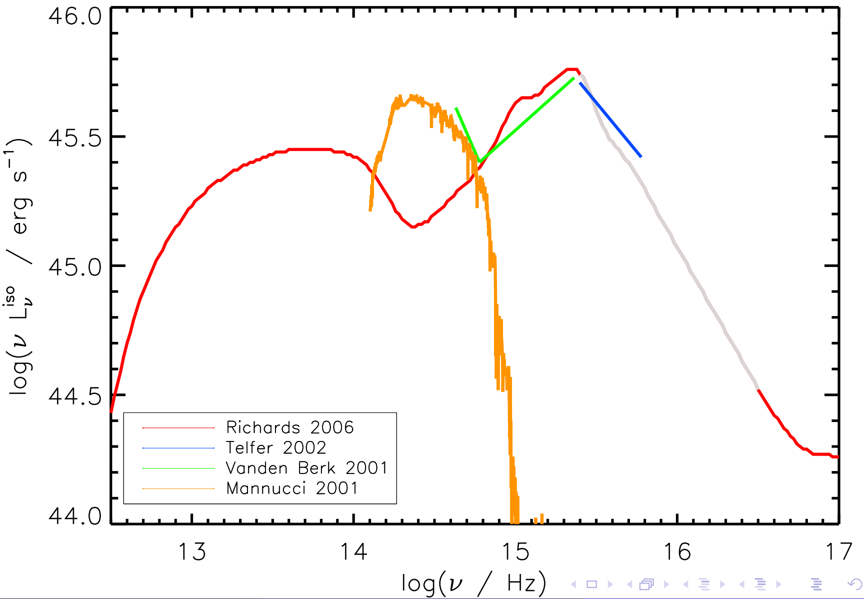




$$\alpha_\nu = \frac{1}{3}\ ?$$

BBB ↔ AD connection



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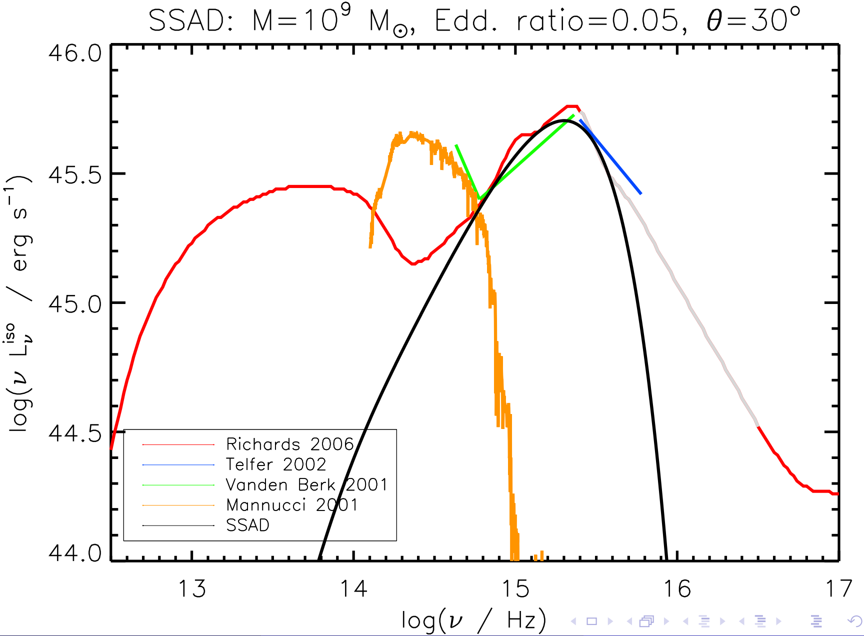

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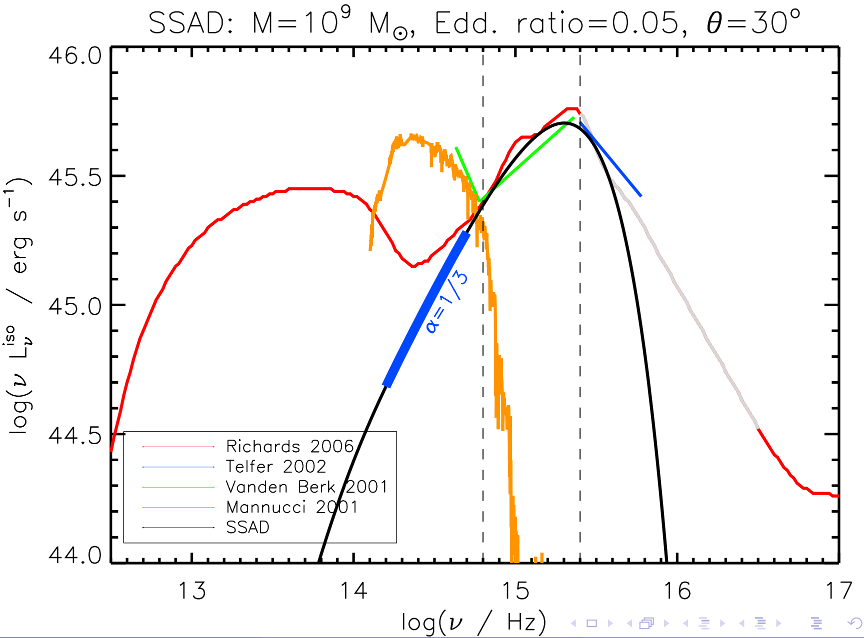

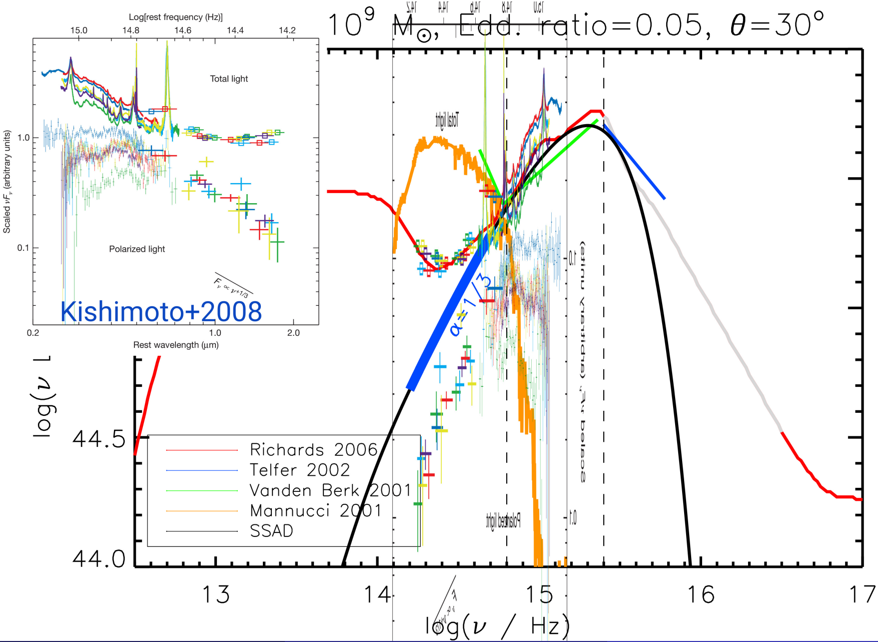
Log[rest frequency (Hz)]
15.0
14.8
14.6
14.4
14.2
Total light
1.0
0.1
Scaled νF_ν (arbitrary units)
Polarized light
$F_\nu \propto \nu^{+1/3}$
Kishimoto+2008
0.2
1.0
2.0
Rest wavelength (μm)
10^9 $M_\odot$, Edd. ratio=0.05, θ=30°
$\alpha = 1/3$
log(ν L
44.5
44.0
Richards 2006
Telfer 2002
Vanden Berk 2001
Mannucci 2001
SSAD
13
14
15
16
17
log(ν / Hz)

Accretion disk spectrum modeling

AD model parameters

- disk extension: $R_{\rm in}$, $R_{\rm out}$
- disk inclination: $\cos(\theta)$
- black hole mass: M;
- disk luminosity: $L_{\rm d}$.

- spectra are self–similar in log–log plots;
- scaling relations:

$$\begin{aligned} \nu_{\rm p} &\propto M^{-1/2} L_{\rm d}^{1/4} \\ \nu_{\rm p} L_{\nu_{\rm p}} &\propto L_{\rm d} \end{aligned}$$

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(GR corrections → Samuele's talk)

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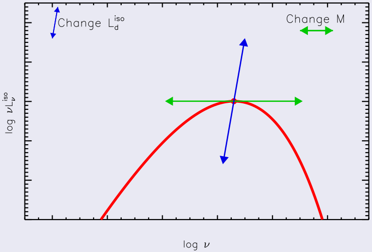

AD model parameters

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(GR corrections → Samuele's talk)

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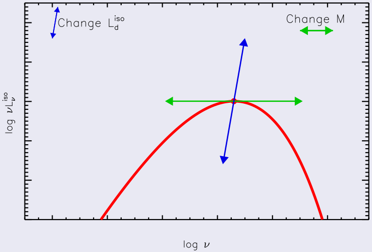

Accretion disk spectrum modeling

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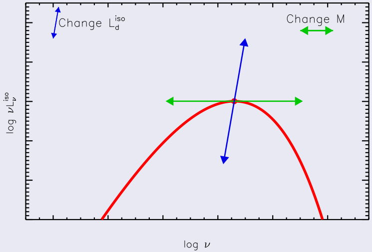

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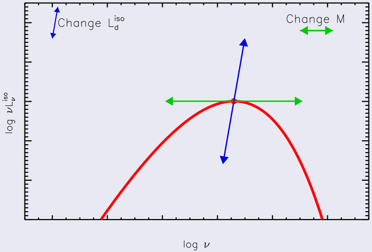

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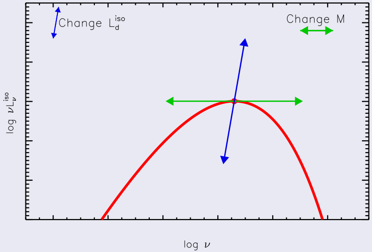

The method is thoroughly discussed in Calderone+2013.
Accuracy: < 0.7 dex (worst case).

 preliminary!

Method:

- Use IR data to estimate synchrotron contamination, optical/UV data to constrain the peak;
- Assume radiative efficiency $\eta \sim 10\%$;
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Disk modeling on a RL–NLS1 sample **preliminary!**

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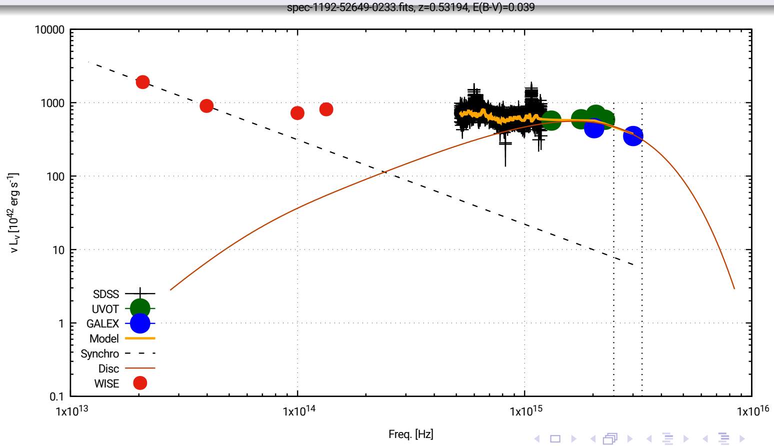
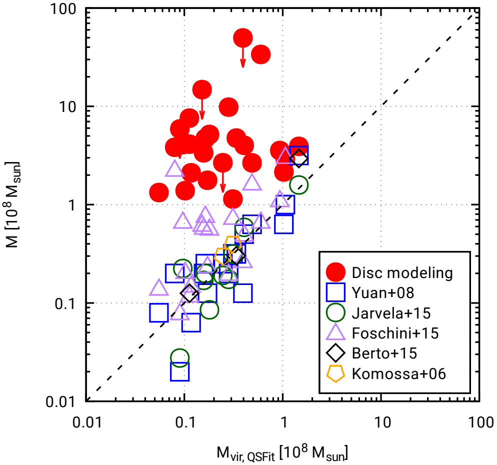
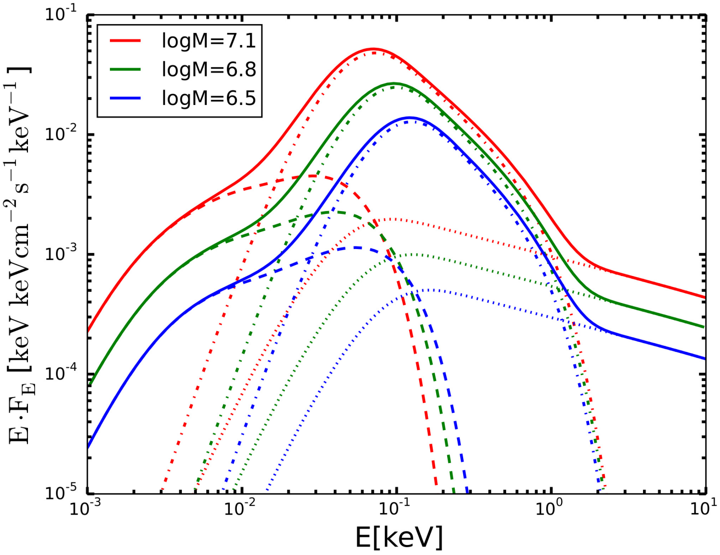


Incompatible with single epoch virial estimates!



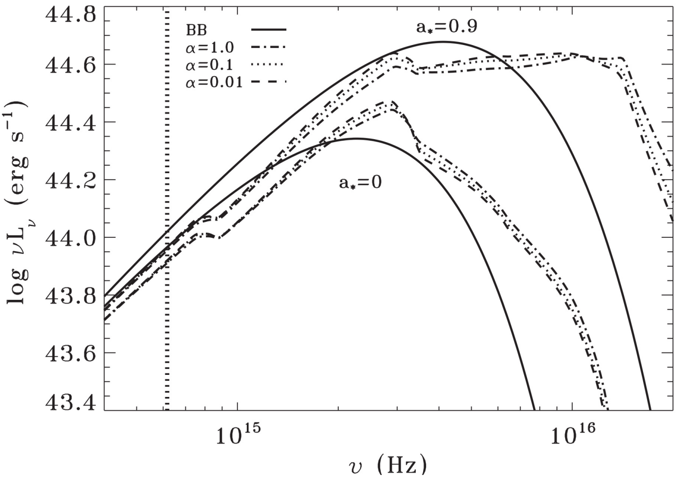
Calderone, D'Ammando, Sbarrato, in prep.

Accretion disk modeling



OPTXAGN, Done+2012

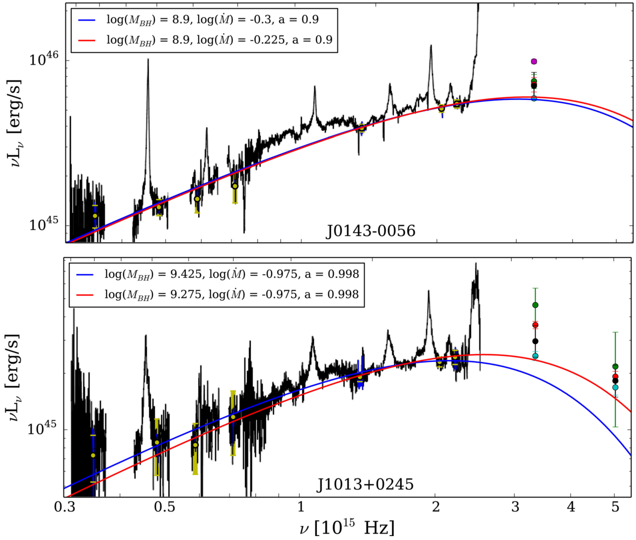
Accretion disk modeling



DISK+TLUSTY, Hubeny+2000

Davis+2011 uses virial $M_{\rm BH}$ **AND** disk modeling to constrain the spin!

Accretion disk modeling



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

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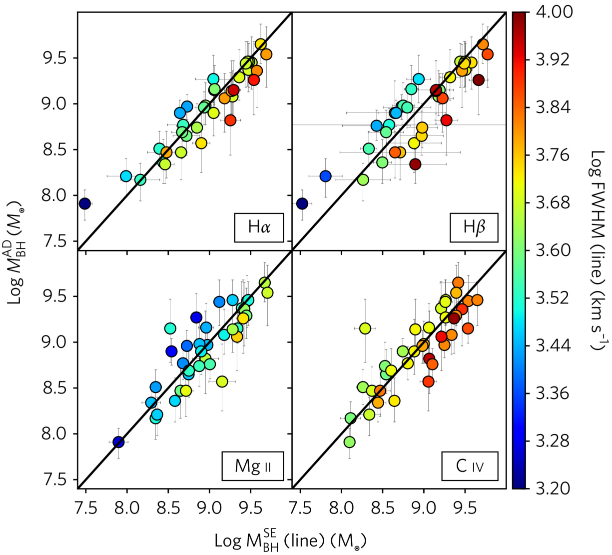
arguments include the lack of the expected relationships of spectral energy distributions with mass and luminosity[7,8], both at single epochs and in difference-spectra (high

Accretion disk modeling



Mejía-Restrepo+2018, Nature Astronomy

Summary

- **Estimating $M_{\rm BH}$ 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!**