The Monsters of the Universe:

Reverberation Mapping and Supermassive Black Hole Masses in Distant Quasars

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August 29, 2019

Image credit: Nahks Tr’Ehnl

Outline

- Introduction to supermassive black holes, active galaxies, and reverberation mapping (RM)

- Reverberation Mapping Approaches
  - “Traditional” Reverberation Mapping Campaigns
  - “Large-Scale, Multi-Object” Campaigns

- The SDSS-Reverberation Mapping Project:
  - Project Design and Goals
  - Recent Results

- Future Prospects in Reverberation Mapping

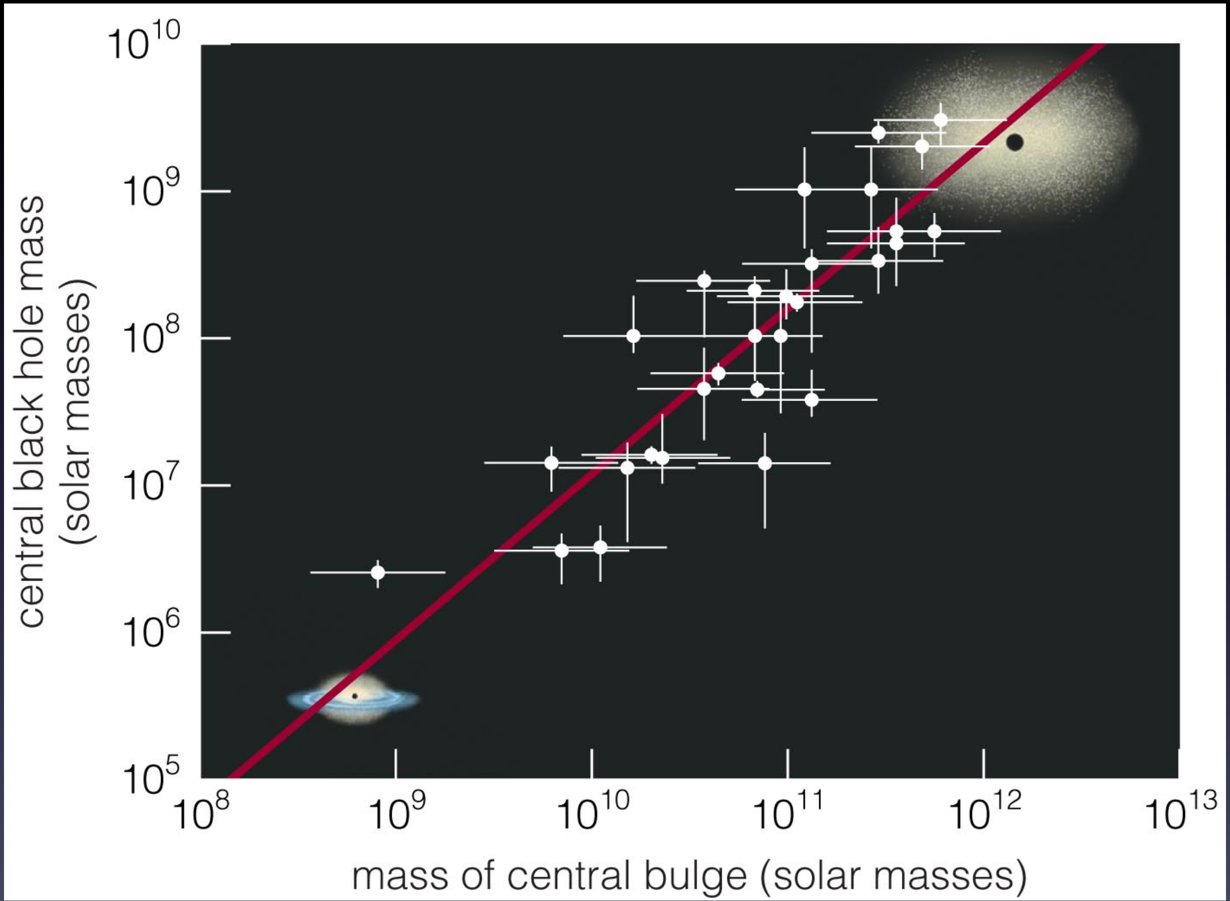
Supermassive Black Holes (SMBHs)

- SMBH mass: Hundreds of thousands to billions of solar masses
- Exist at the centers of all massive galaxies
- Powerhouses behind active galactic nuclei/quasars

Largest BH ever found: NGC 4889b

SMBH simulation from the movie "Interstellar"

Why do we care about SMBHs? Galaxy Evolution!



The mass of a galaxy's central black hole is closely related to the mass of its bulge.

But how does the black hole know how massive the galaxy is?

How do we measure SMBH masses?

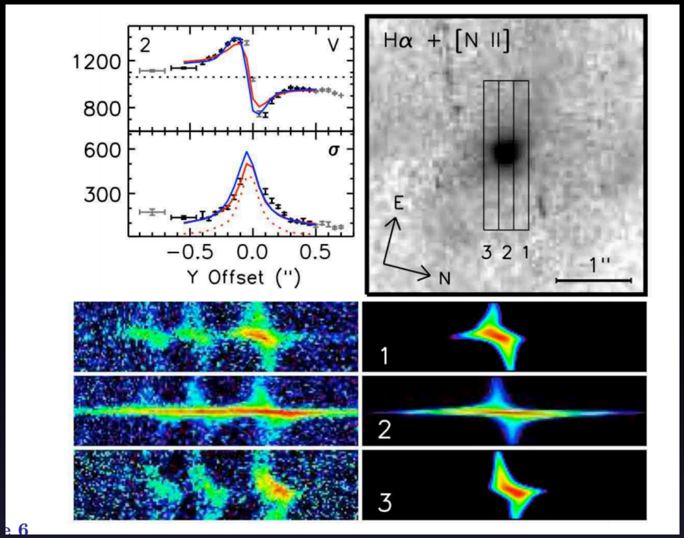
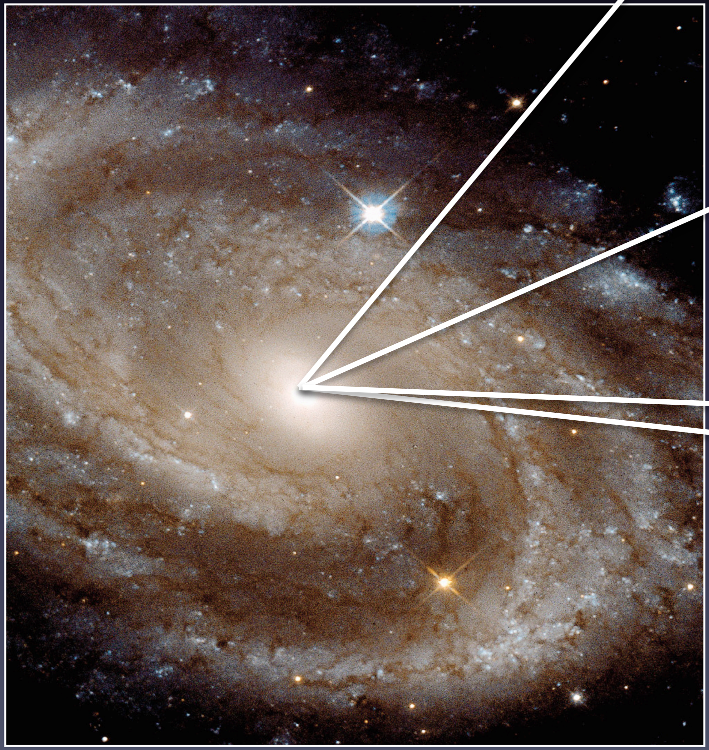


Image credit: Kormendy & Ho (2013)

- In nearby galaxies: We can measure the motion/rotation of stars and ionized gas at the center of the galaxy
- In far away galaxies, we can't make these observations, so we look at Active Galactic Nuclei

Active Galactic Nuclei



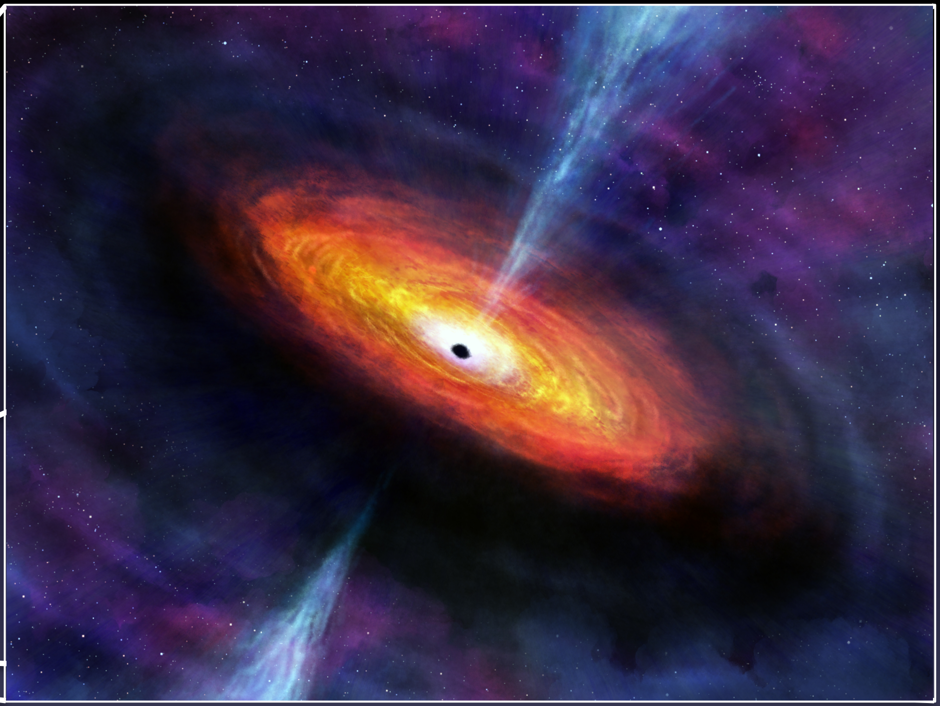
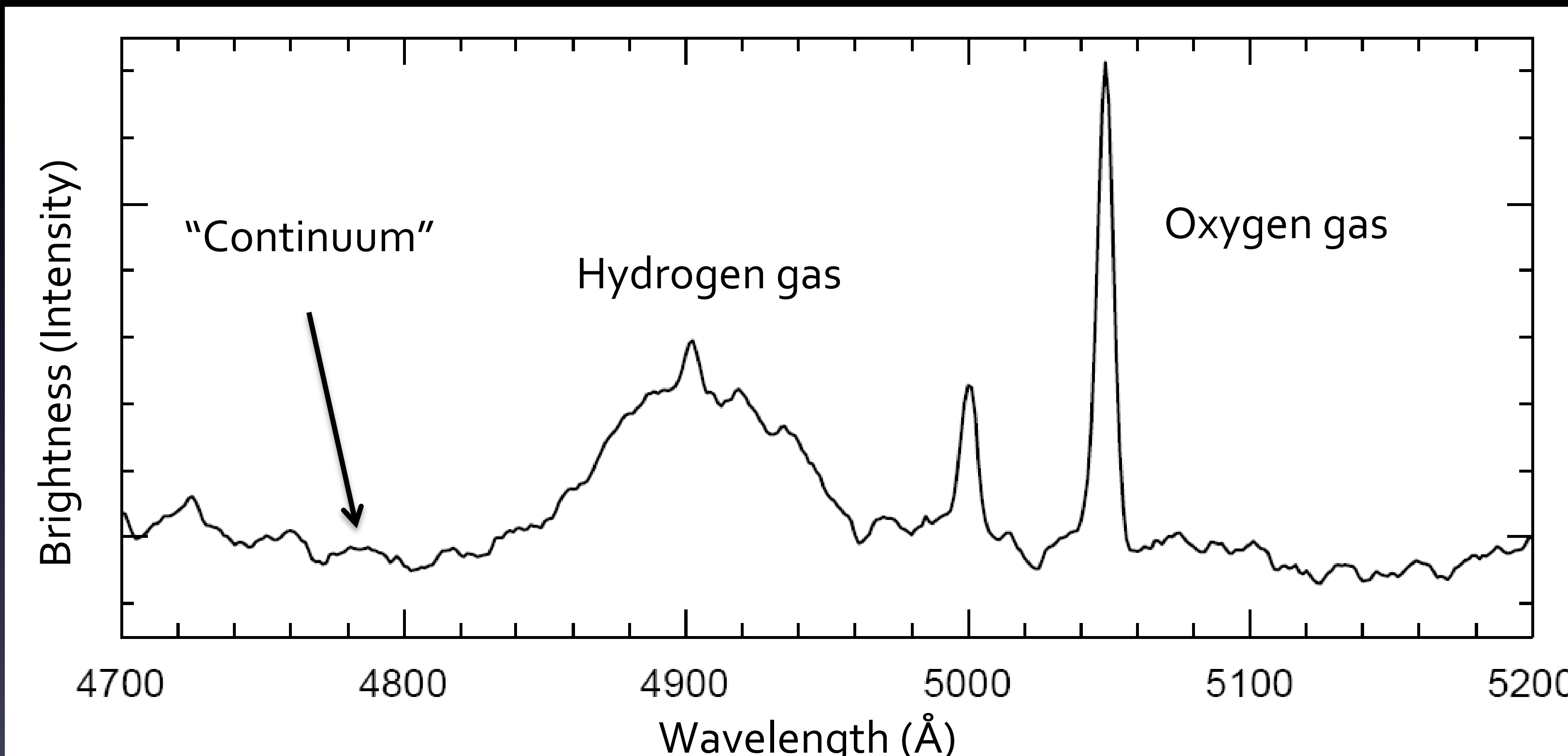
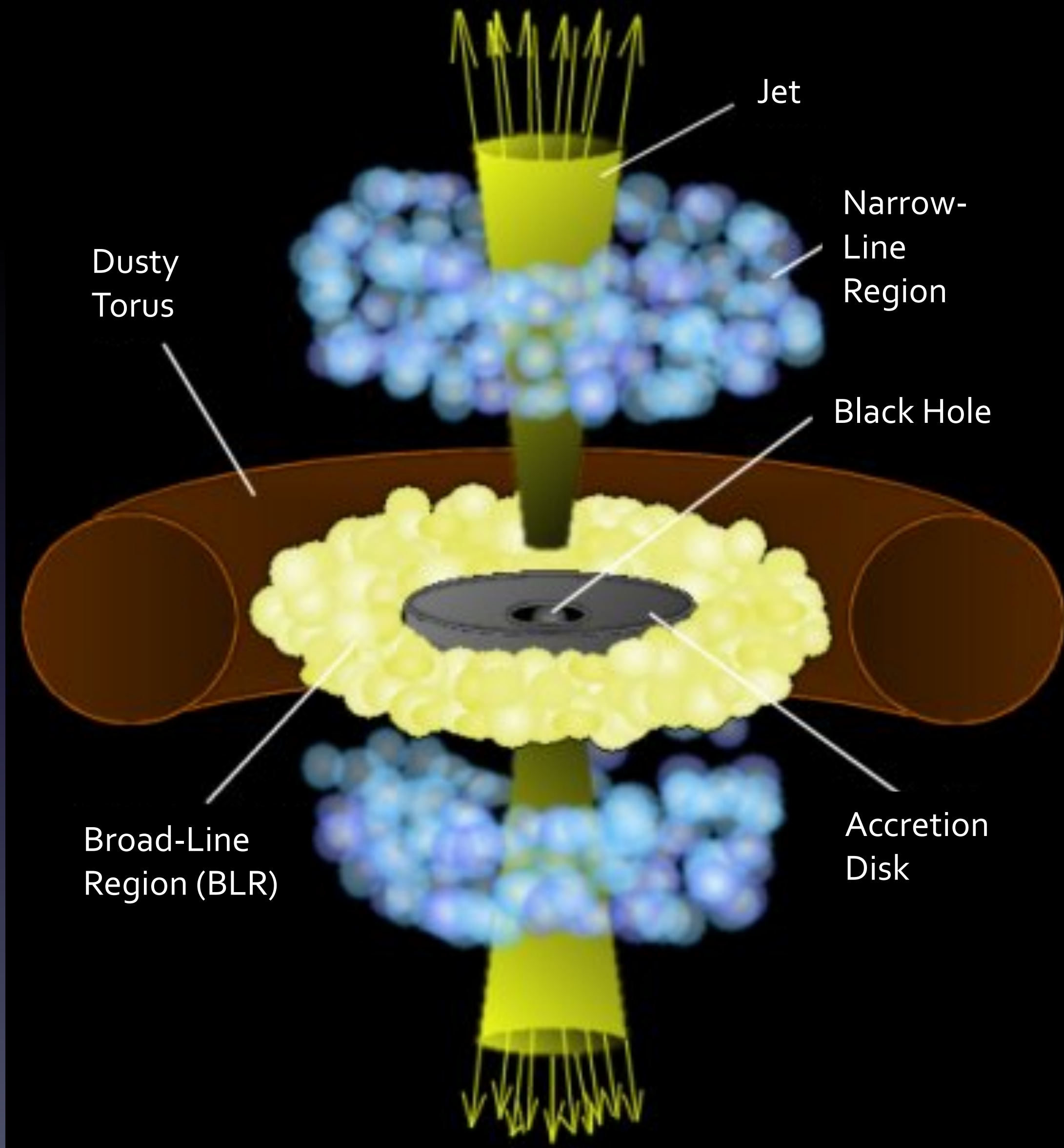


Image credit: Nahks Tr'Ehnl

Type 1 Active Galaxy Spectra



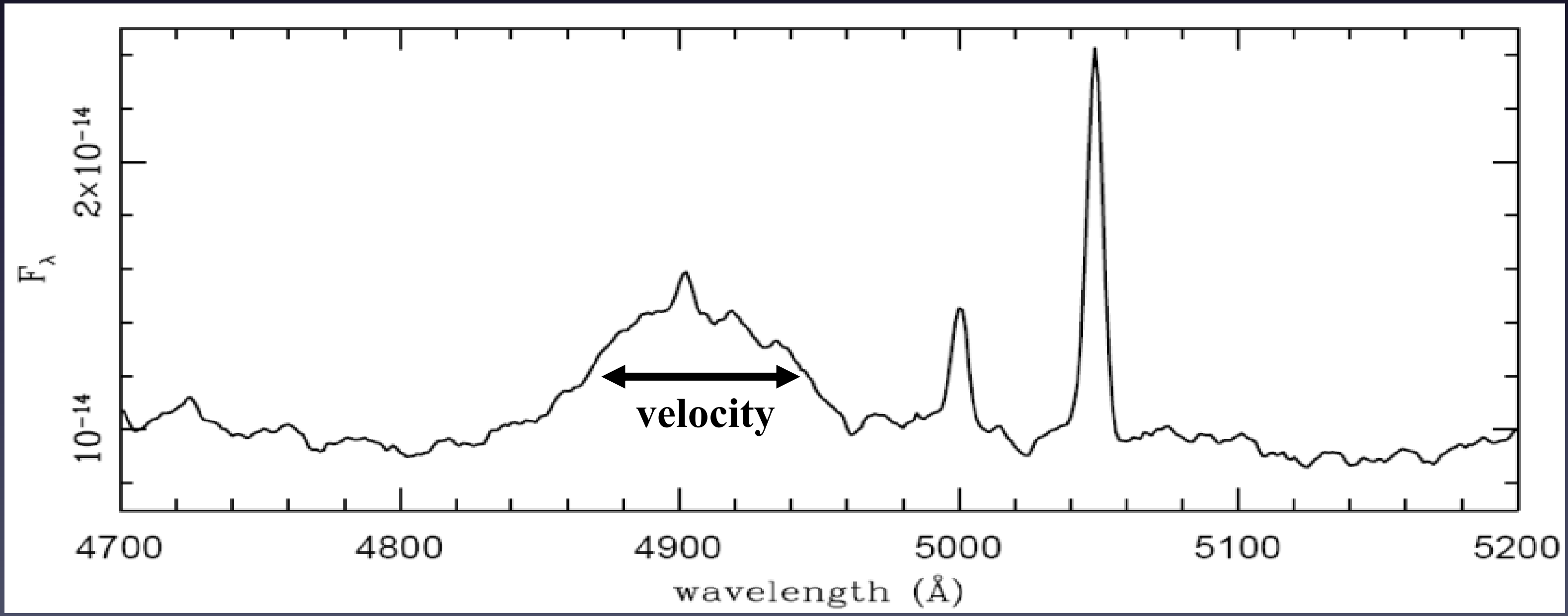
Active Galaxy Inner Structure



$$M_{\mathrm{BH}} = \frac{f R_{\mathrm{BLR}} \Delta V^2}{G}$$

Measuring M_{BH}: Velocities

$$M_{\rm BH} = \frac{f R_{\rm BLR} \Delta V^2}{G}$$



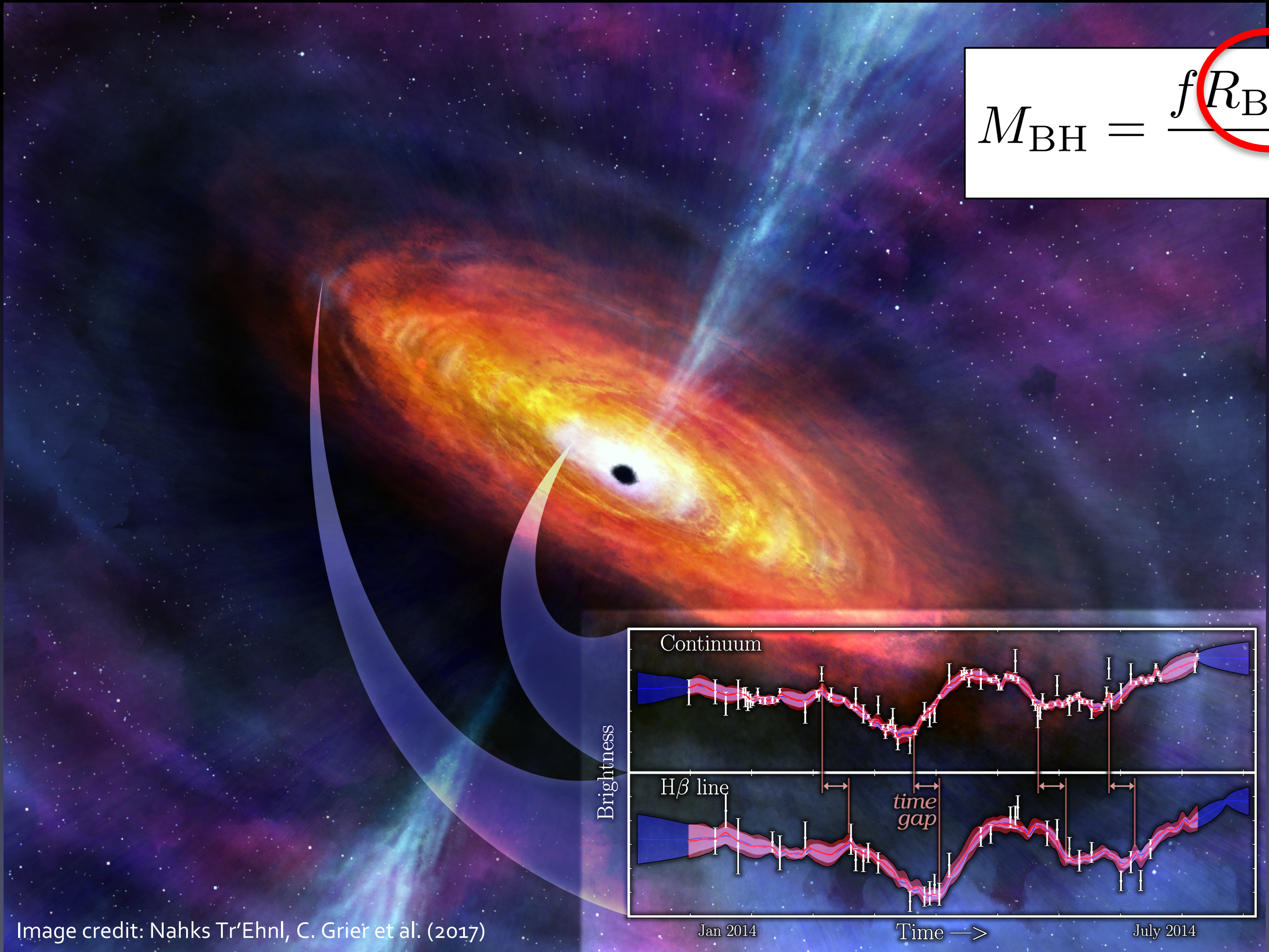
Measuring M_{BH}: BLR Radius

$$M_{\mathrm{BH}} = \frac{f R_{\mathrm{BLR}} \Delta V^2}{G}$$

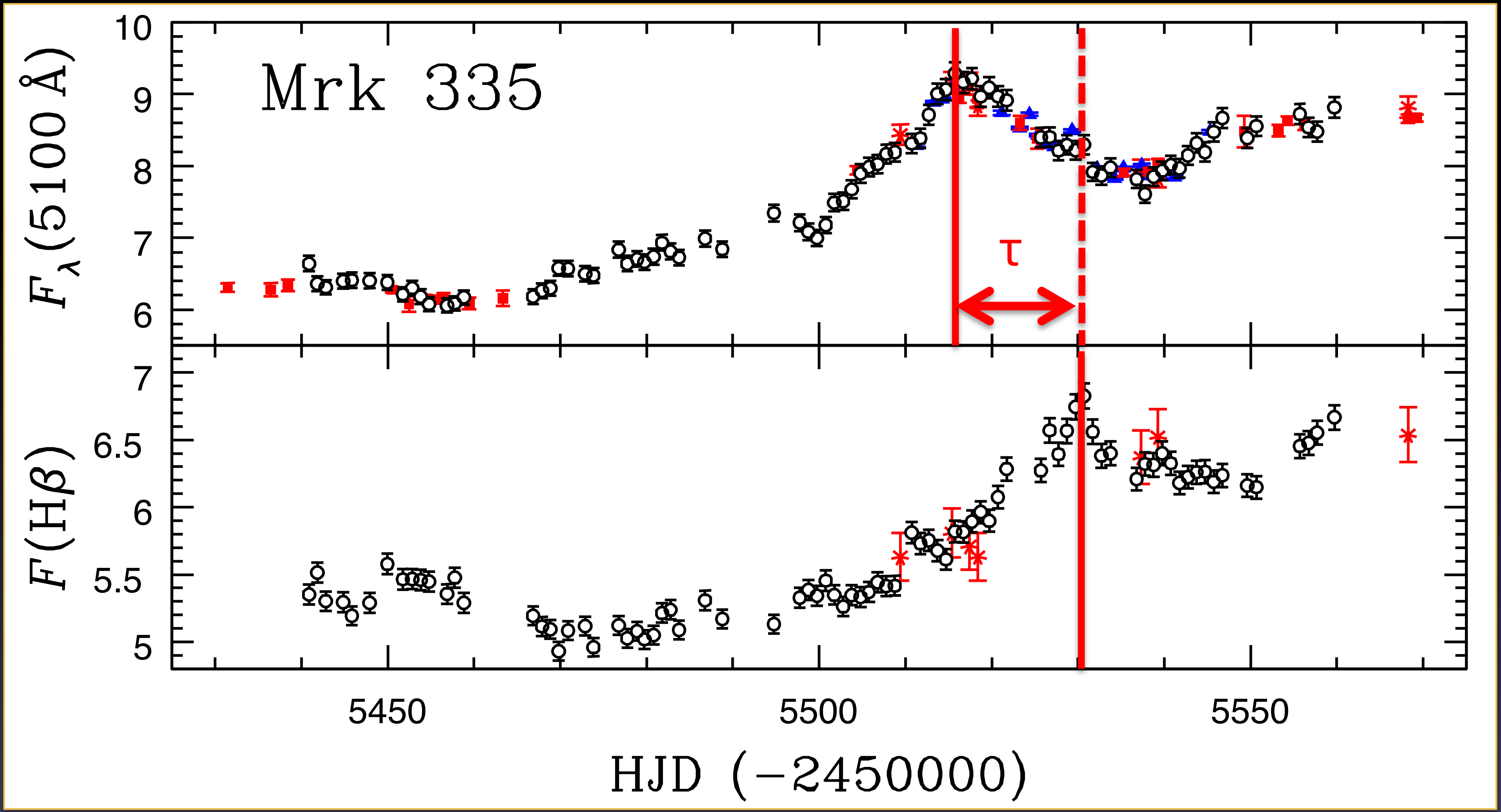
How do we measure R (or *f*, for that matter) if we can't resolve the broad line region?

Measuring R_{BLR} with Reverberation Mapping (RM)

$$M_{\rm BH} = \frac{f R_{\rm BLR} \Delta V^2}{G}$$



Reverberation Mapping Data



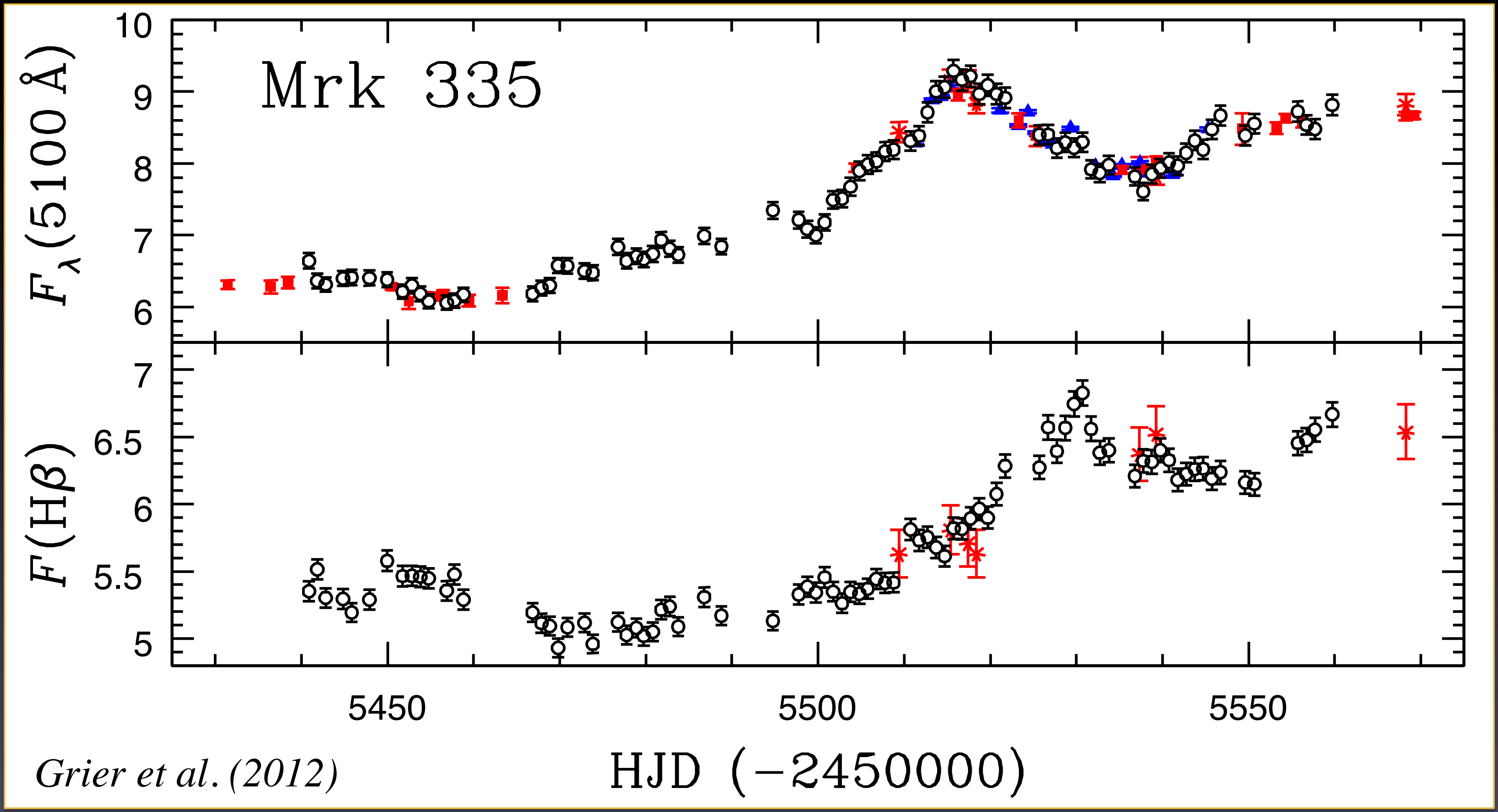
$R_{BLR} = c\tau$

$$M_{\rm BH} = \frac{f R_{\rm BLR} \Delta V^2}{G}$$

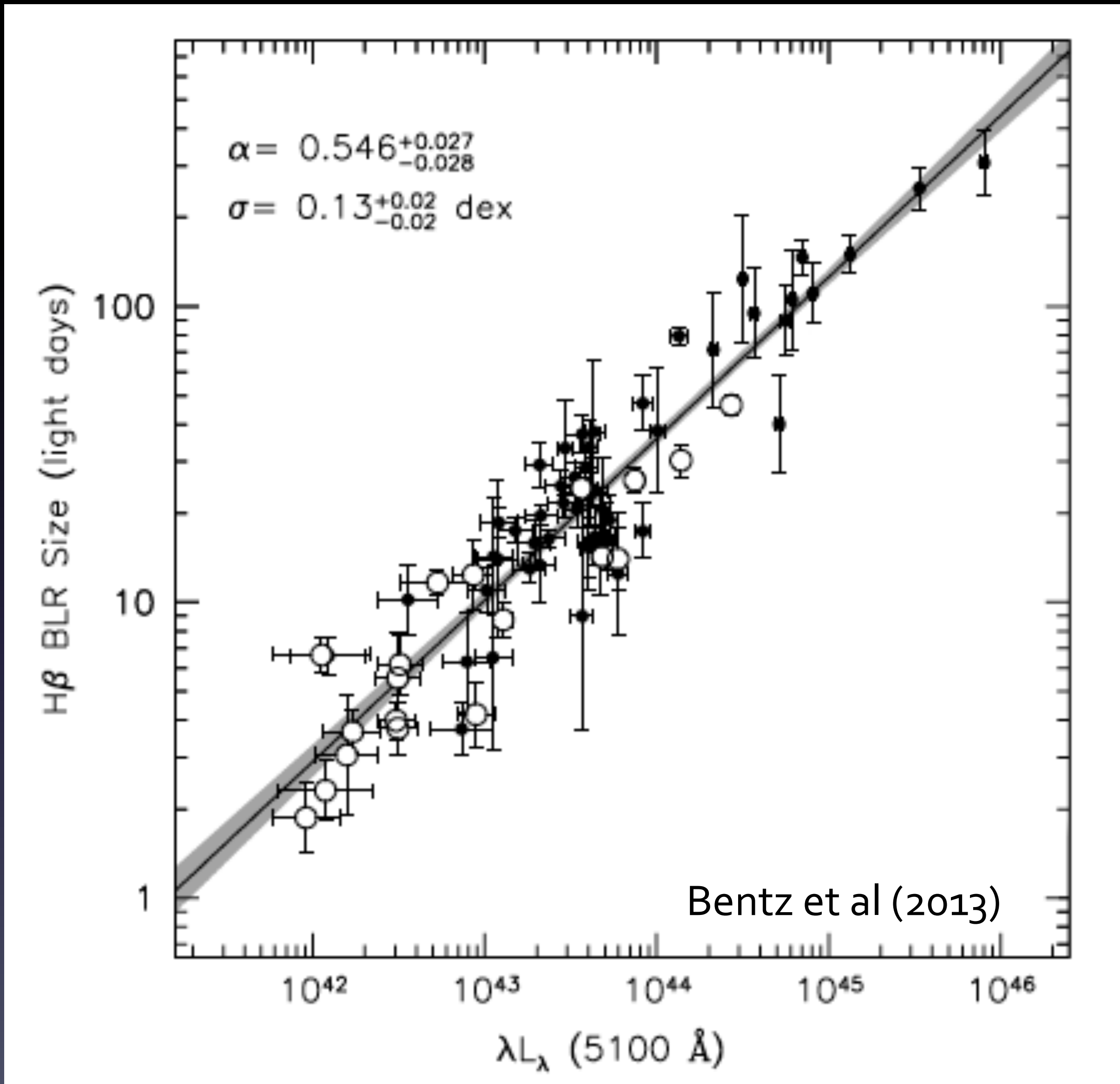
Reverberation Mapping In Practice:
Observational Requirements

1. Relatively high S/N spectra
2. Flux measurements accurate to a few percent
3. Program lasting ideally at least 3 times the longest time scale of interest
4. High time sampling relative to expected time lag

One single RM measurement is observationally EXPENSIVE!



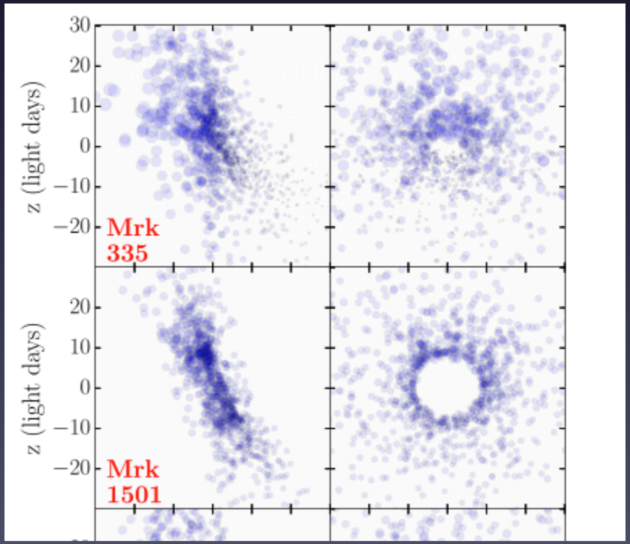
The *R-L* Relation



Allows us to make M_{BH} estimates in AGN using a single spectrum!

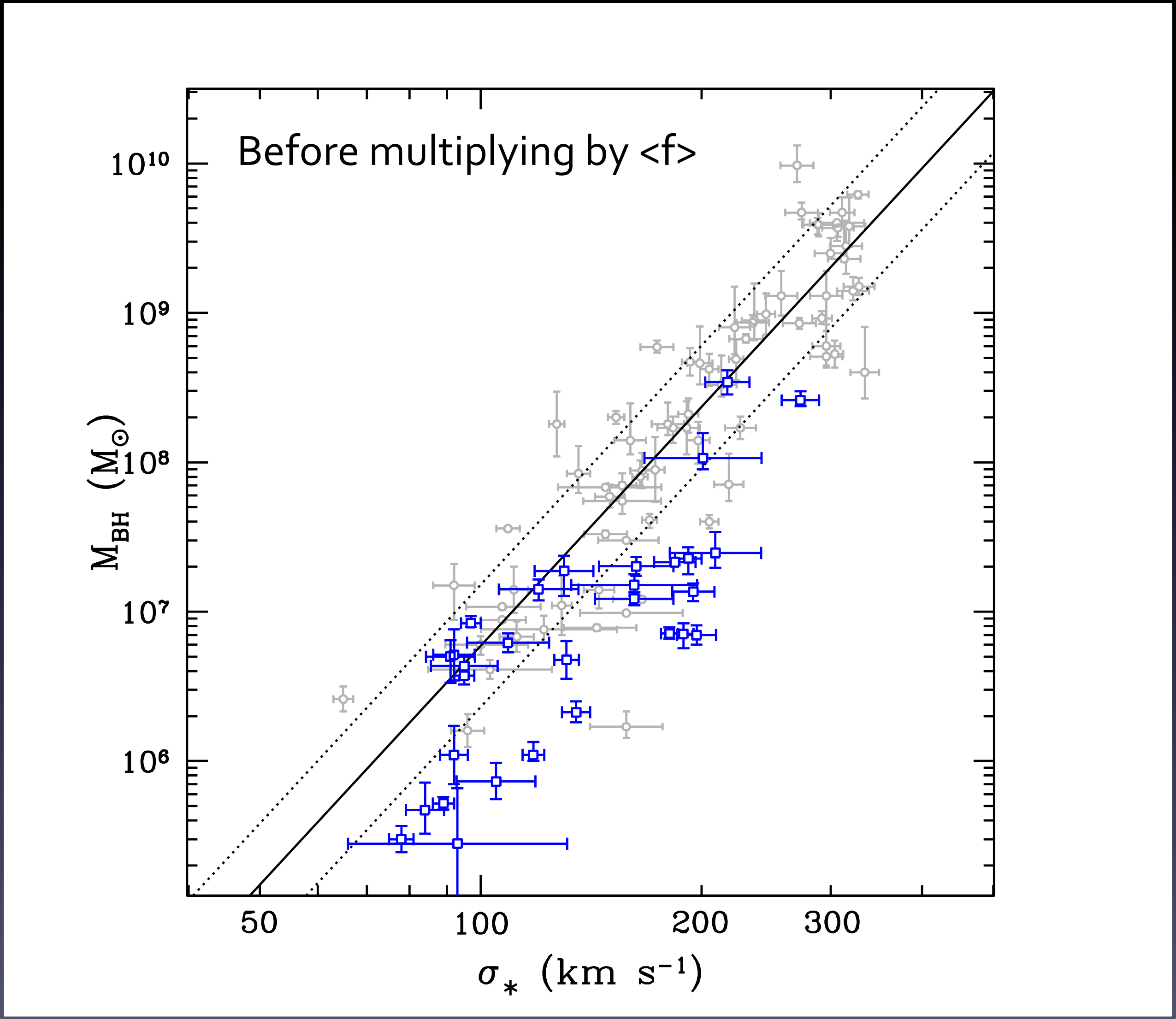
Measuring M_{BH}: the factor f

$$M_{\mathrm{BH}} = \frac{f R_{\mathrm{BLR}} \Delta V^2}{G}$$

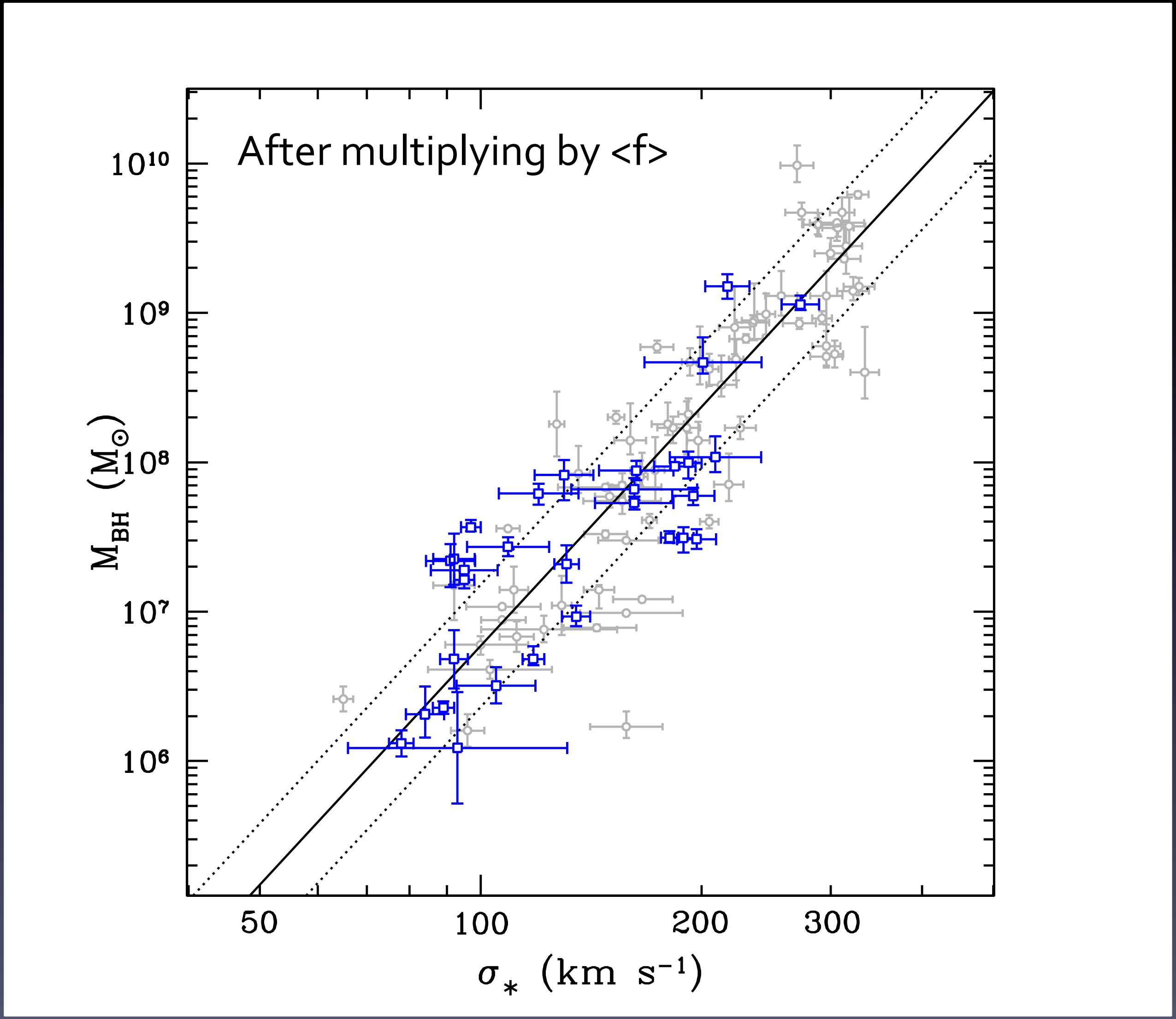


The factor f depends on the geometry, orientation, and kinematics of the BLR.

Using the M_{BH}-σ_* relation to calculate *f*

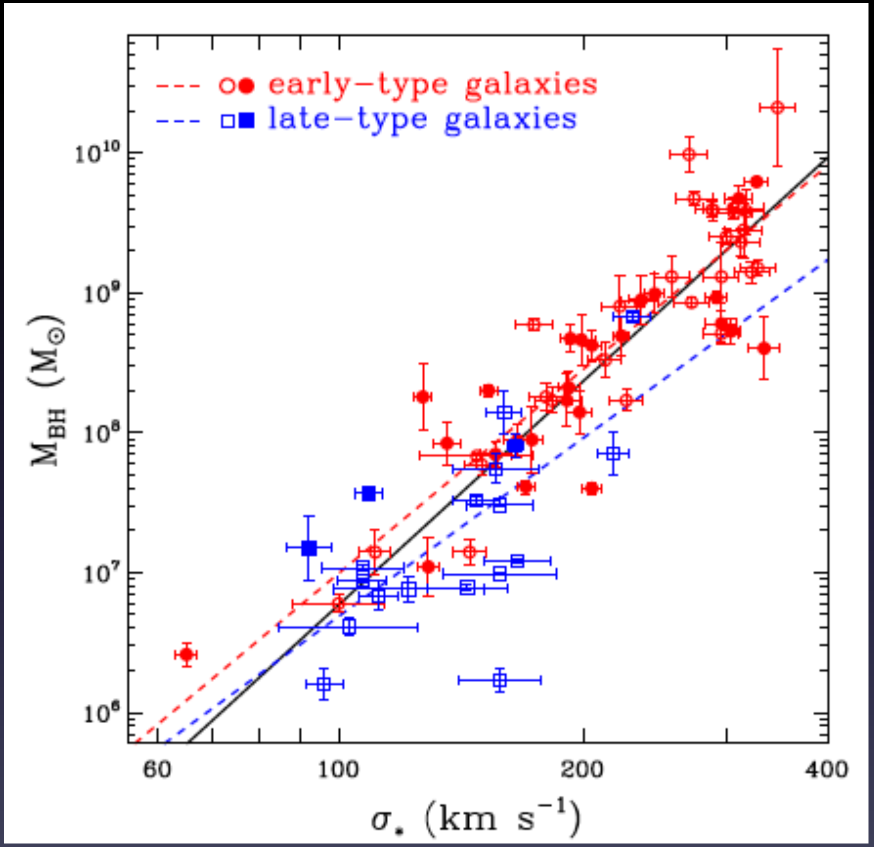


Using the M_{BH}-σ_* relation to calculate *f*



The problems with this...

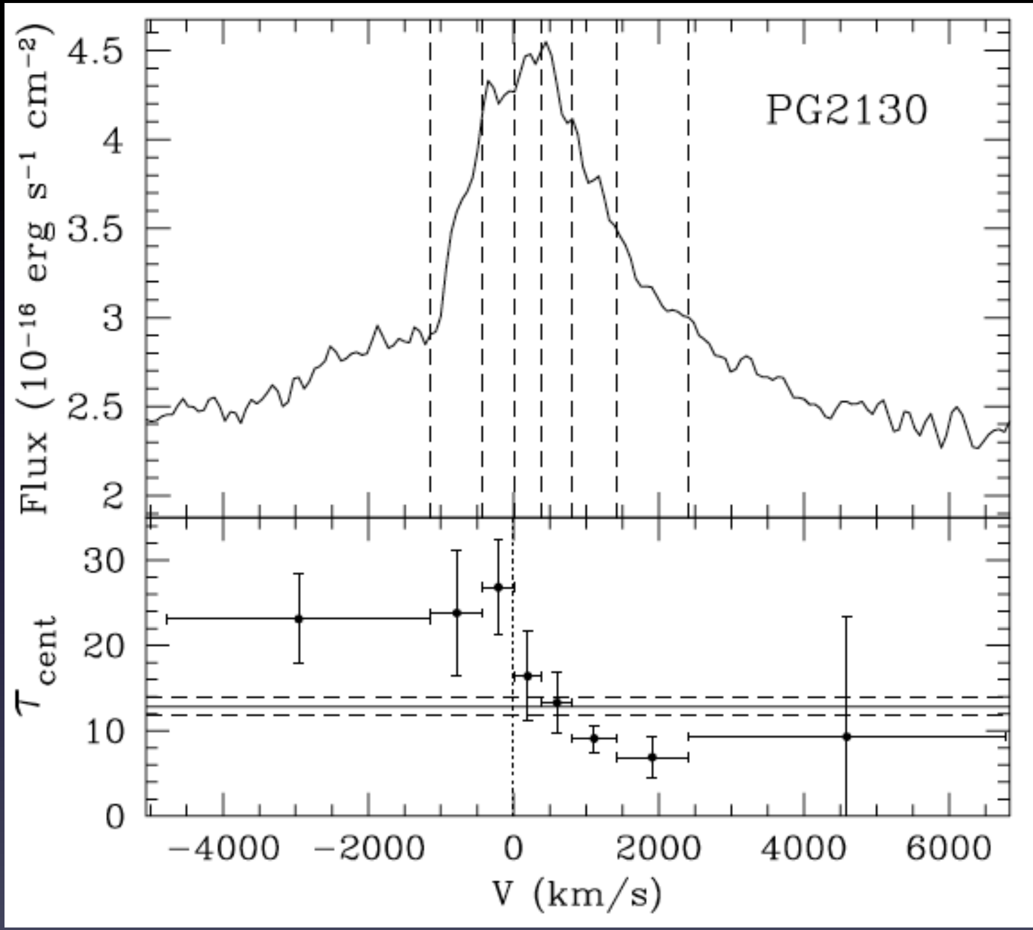
- We cannot directly observe the conditions within the BLR... and each AGN has a different *f* factor
- The M-σ_* relation might not be universal



From Woo et al. (2013)

Velocity-Resolved RM

Different lags at different gas velocities tell us more about the structure of the BLR.

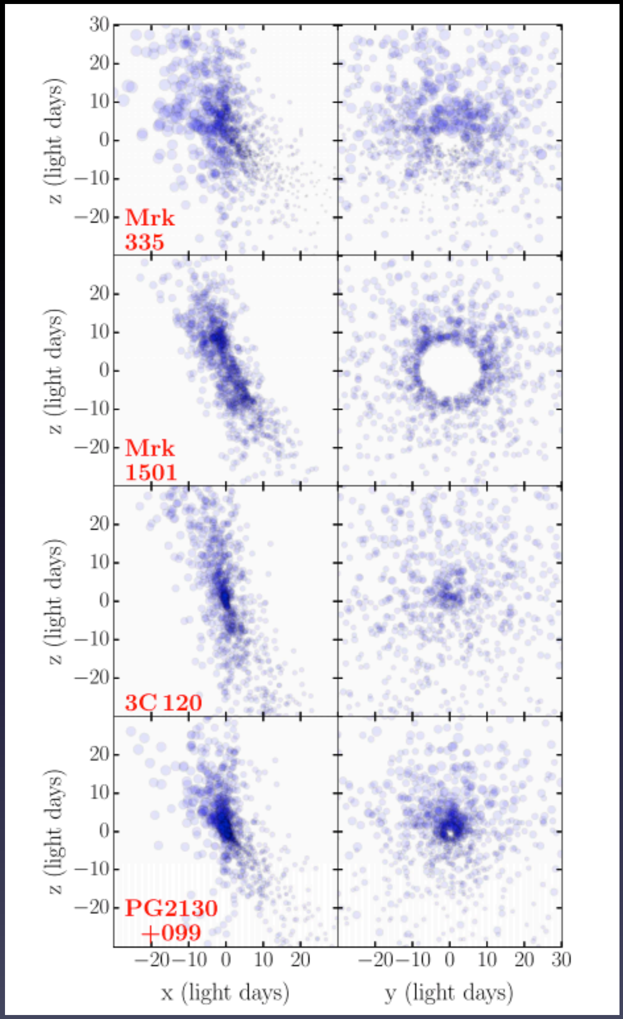


From Grier et al. (2013)

Velocity-Resolved RM

With really high-quality data, we can produce models of BLR geometry and kinematics.

$$M_{\mathrm{BH}} = \frac{f R_{\mathrm{BLR}} \Delta V^2}{G}$$



From Grier et al. (2017)

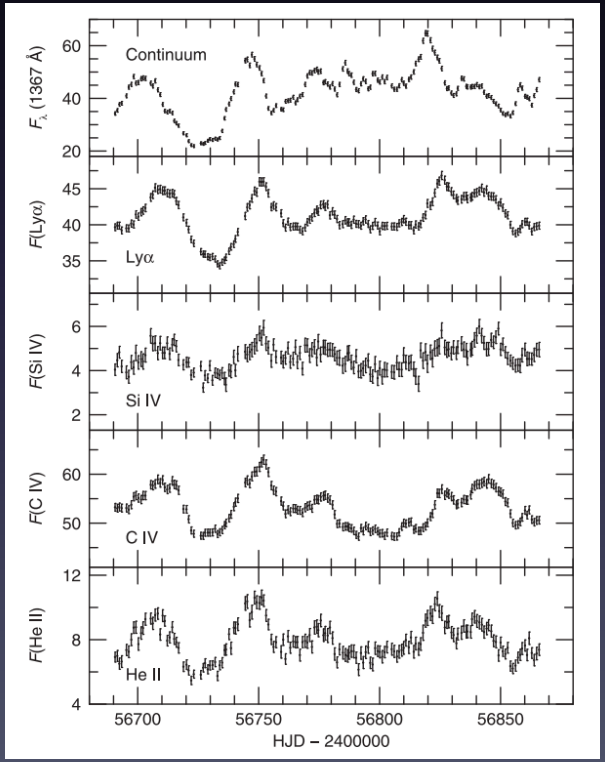
“Traditional” RM Campaigns

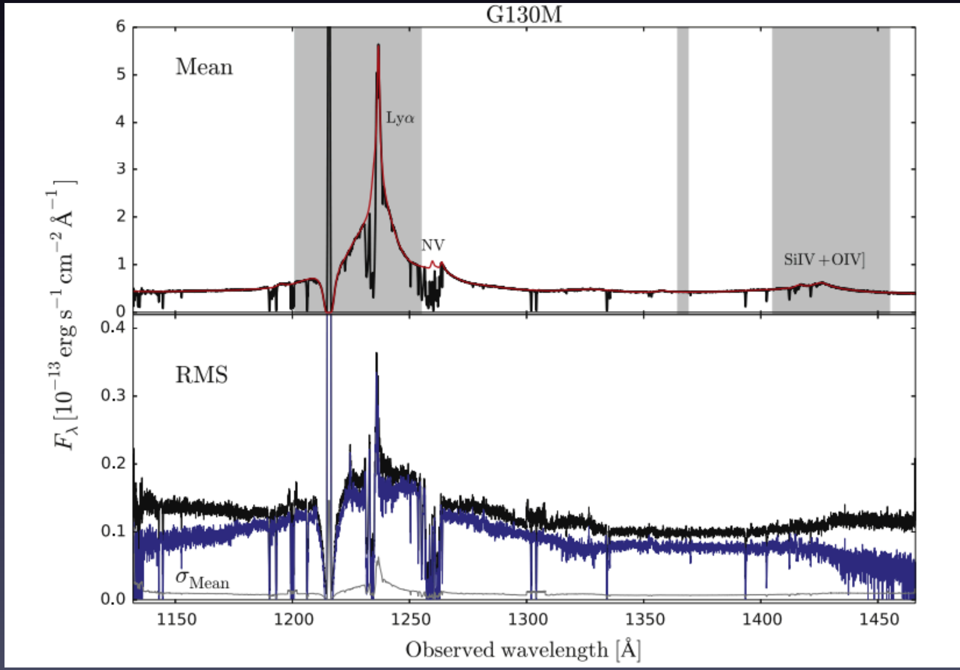
Examples:

1. The AGN STORM Project (PI: Brad Peterson, OSU) – NGC 5548
2. The SEAMBH project (Du et al., Wang et al.)
3. The Lick AGN Monitoring Project
4. The AGN 2005/2007/2010/2012/2014 projects led by OSU

Main Goals:

1: Obtain velocity-resolved reverberation mapping results
2: Observe relationships between ionizing continuum at various wavelengths
3: Measure properties of accretion disks
4: Model the BLR in great detail.



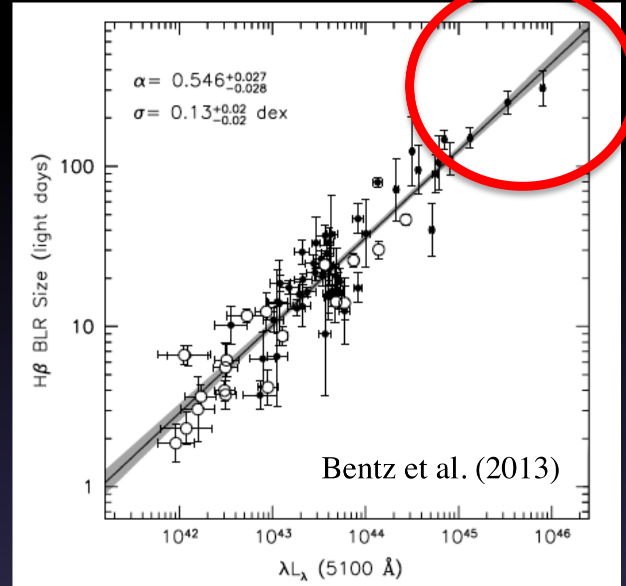


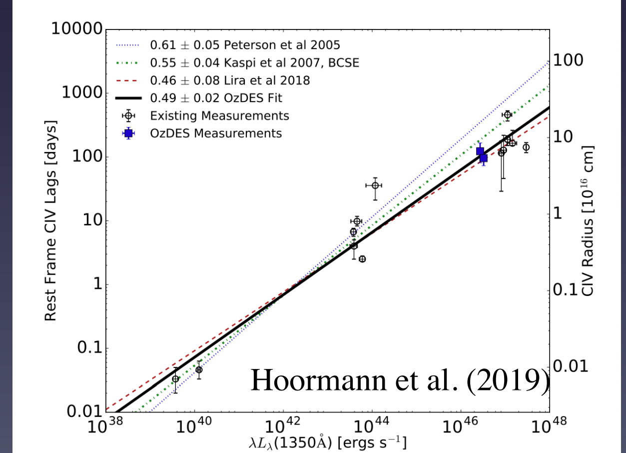
De Rosa et al. (2015)

“Large-Scale, Multi-Object Campaigns”

Main goals:

1. Measure MBH in large uniform sample of quasars
2. Push out to higher redshifts and higher luminosities
3. Obtain results for emission lines like CIV and Mg II, which haven’t been done extensively.
4. Look for evolution in galaxy—BH relationships like M-σ





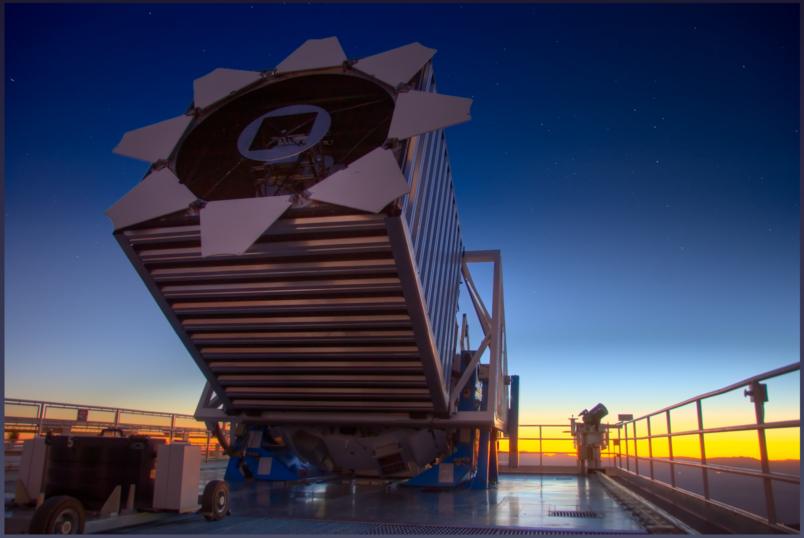
“Large-Scale, Multi-Object Campaigns”

Examples:

1. The Sloan Digital Sky Survey Reverberation Mapping Project (SDSS-RM)
   850 Quasars, began in 2014
   Using the SDSS telescope and photometry from CFHT and Bok
   To be discussed next!

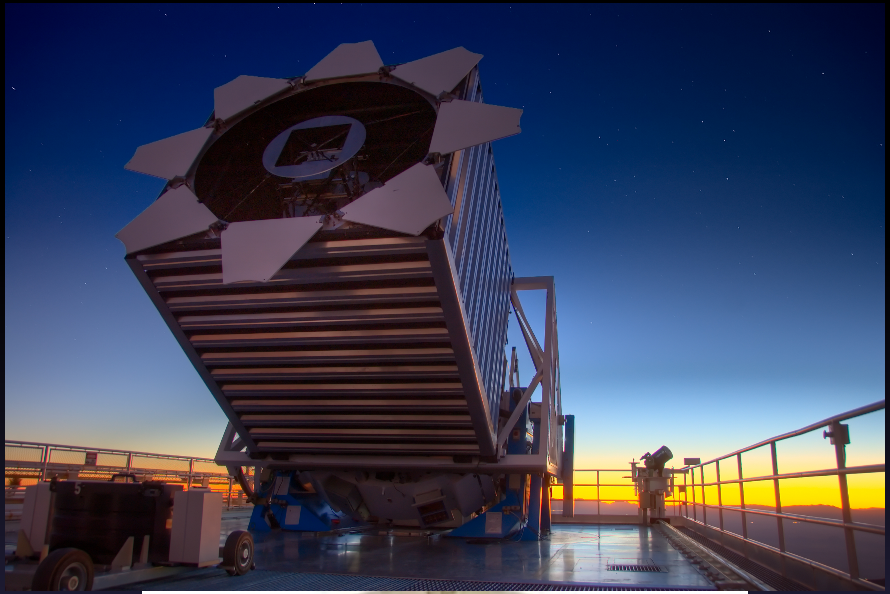
2. OzDES
   ~1000 quasars, began in 2015
   Using the Anglo-Australian Telescope and Dark Energy Survey photometry.

The Sloan Digital Sky Survey Reverberation Mapping Project (SDSS-RM)



SDSS-RM in a nutshell

- Motivation: expanding the RM AGN sample in both size and luminosity range
- 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
- Dense photometric light curves (~2-4 day cadence) since 2010 (PanSTARRS 1 + SDSS-RM imaging)
- Multiwavelength follow-up (XMM, Spitzer, HST)



SDSS-RM Observational Stats

SDSS-RM Data

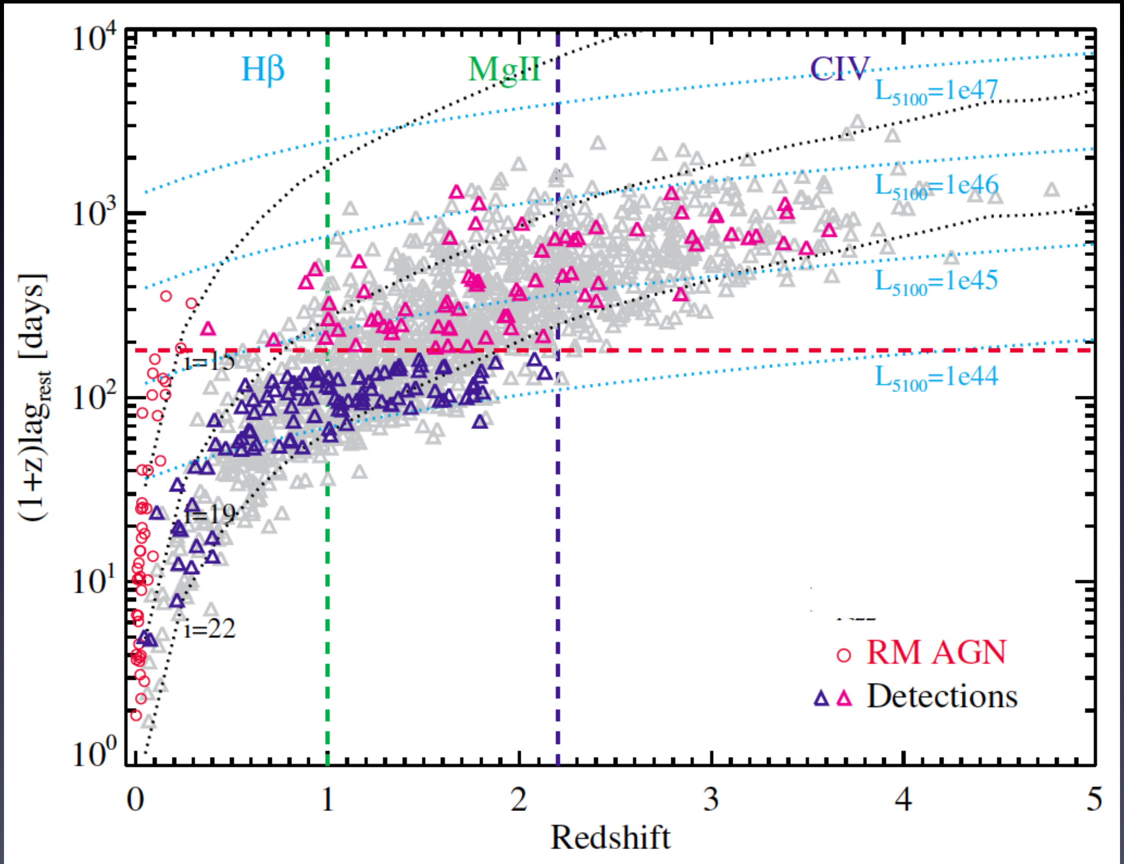
- **Spectroscopy:**
  - BOSS spectroscopy in SDSS-III: 2014 (32 epochs in Jan-July)
  - eBOSS spectroscopy in SDSS-IV: 2015-2019 (~10-12 epochs/year)
  - We have obtained a total of 86 spectral epochs over 6 years of observing so far.
  - Continuing to obtain SDSS spectra in 2020.

- **Imaging:**
  - PanSTARRS1 Medium-Deep field imaging light curves: 2010-2013 (~300 epochs each in *grizy*)
  - Dedicated SDSS-RM imaging light curves (CFHT; 2014-2016), Bok (2014-2020) (~Hundreds of epochs each in *g* and *i* bands)

SDSS-V (begins in 2020) will execute a dedicated RM program called the Black Hole Mapper. SDSS-RM is the pathfinder/test program for this upcoming one. Planning is underway.

Major Goals/Aims of SDSS-RM

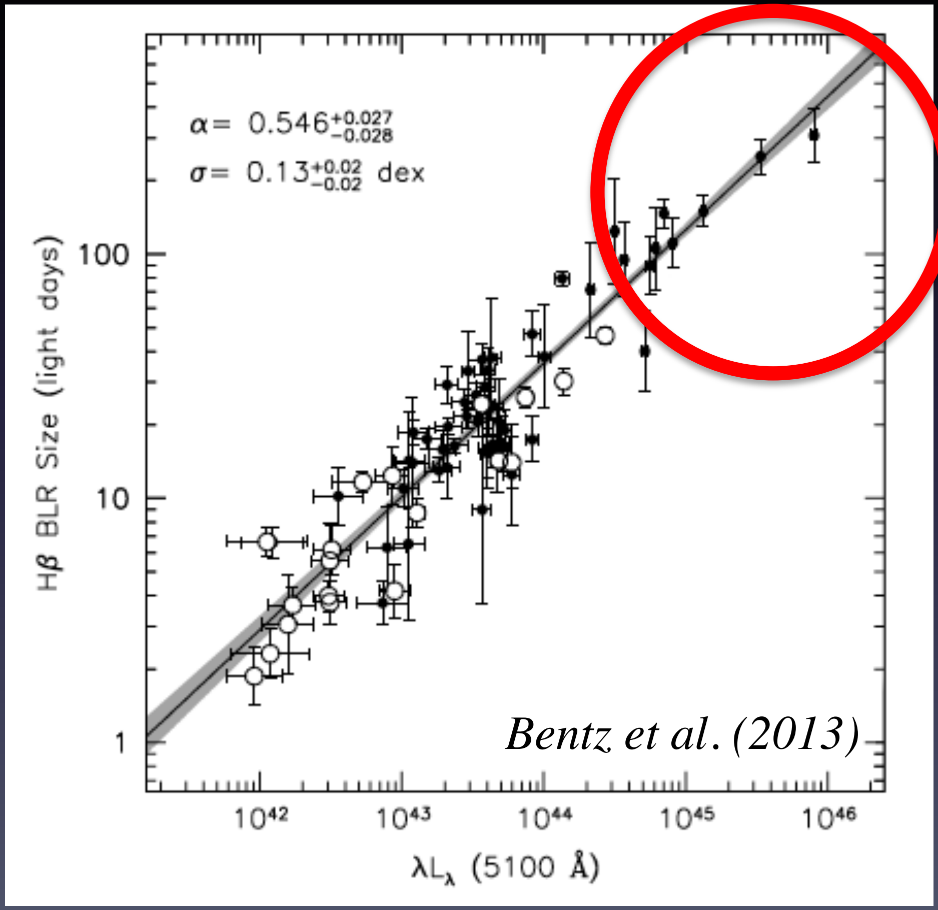
1. Measure M_{BH} with reverberation mapping for ~100 quasars at larger distances than ever before



Shen et al. (2015, ApJS, 216, 4)

Major Goals/Aims of SDSS-RM

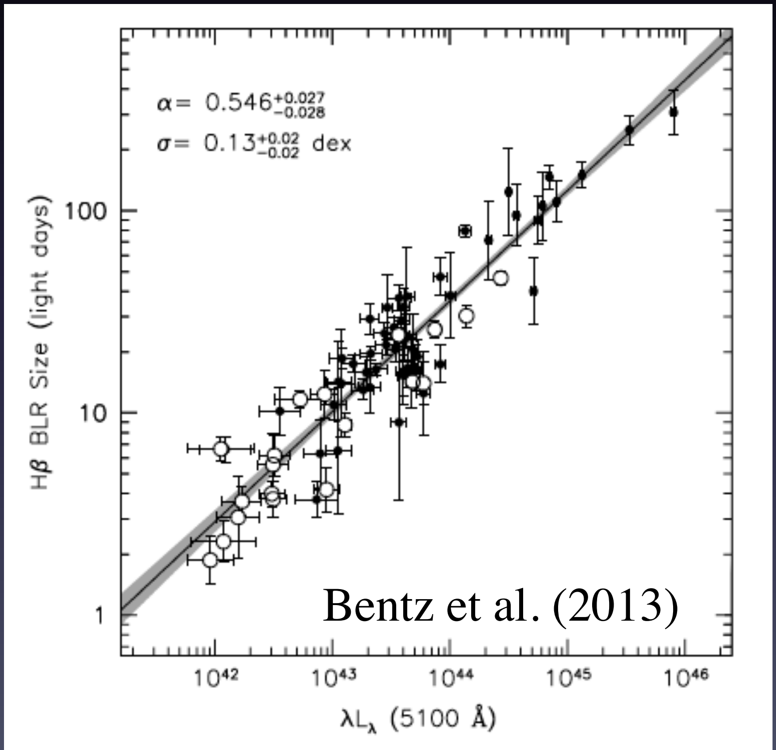
2. Fill out the AGN parameter space that is not well covered by the previous RM sample



Major Goals/Aims of SDSS-RM

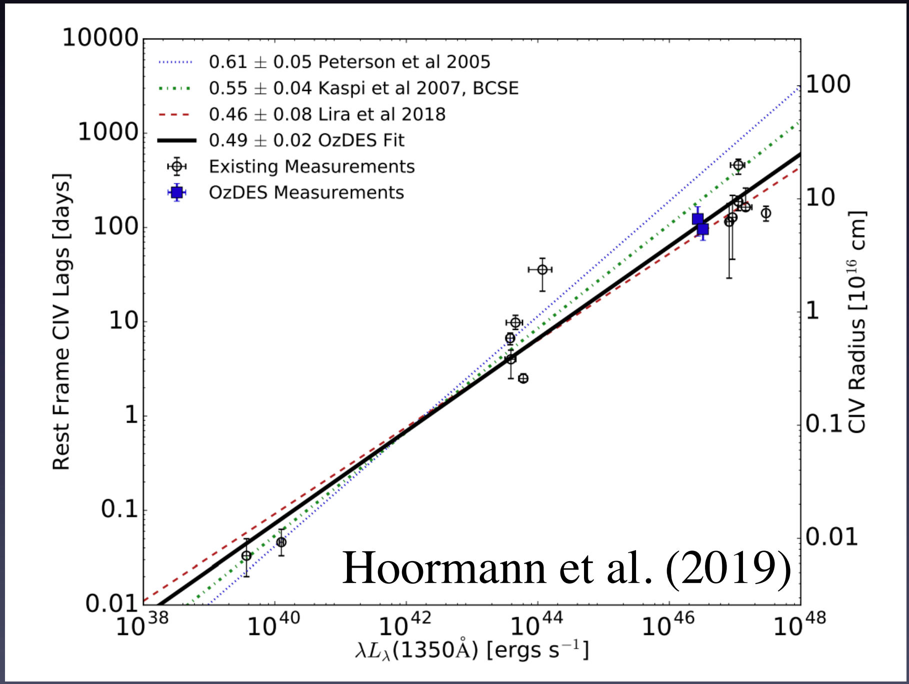
3. Obtain R—L relations for different emission lines which are currently not well-calibrated

Hbeta R-L relation



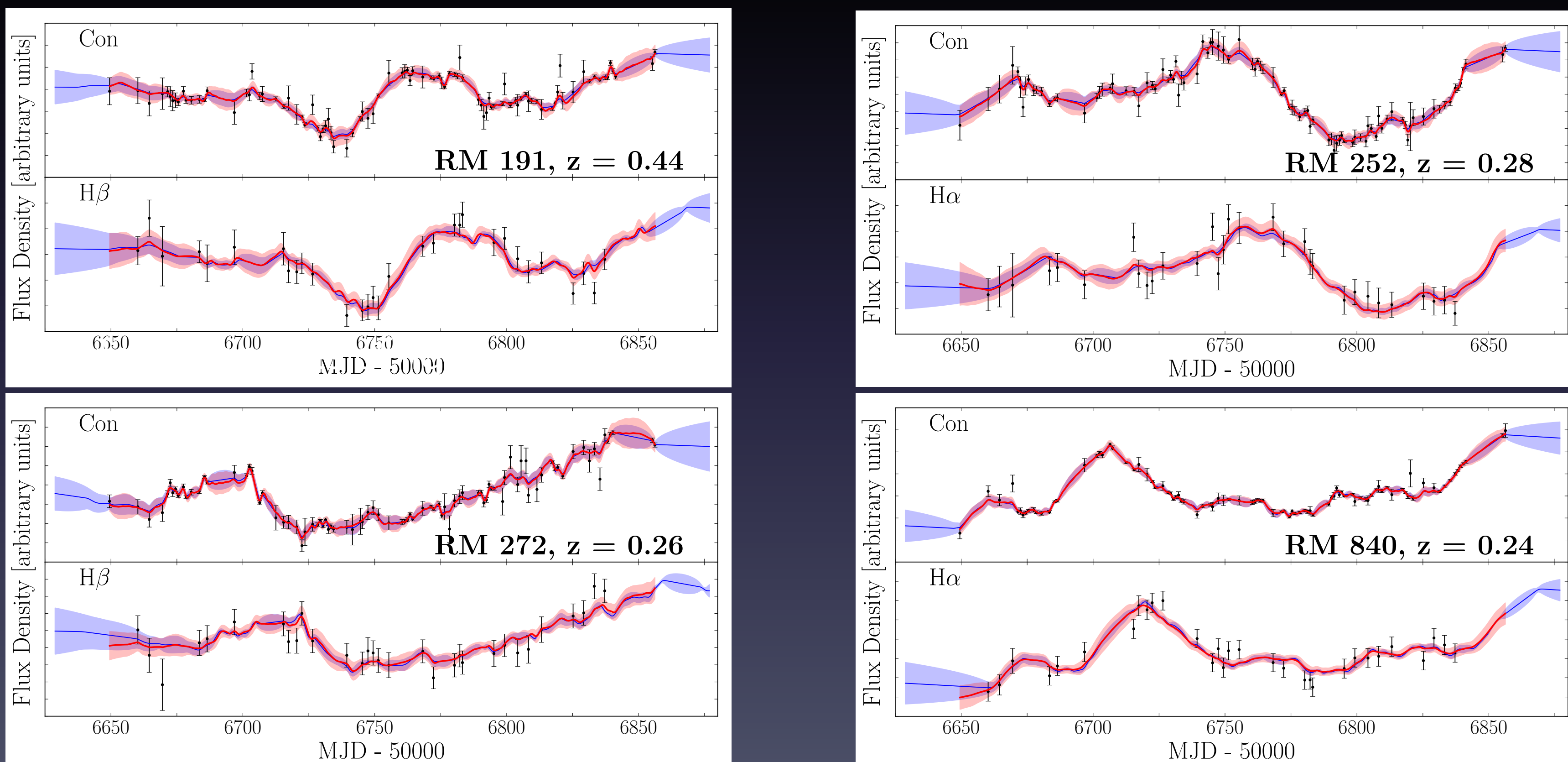
Vs.

CIV R-L relation



SDSS-RM results

- The first large batch of Main Science (RM) Results: Grier et al. (2017, ApJ, 851, 21)
- Reverberation Mapping time lags + M_{BH} measurements for 44 quasars using Hβ and Hα emission lines --- increases the sample by 2/3



Grier et al. (2017)

SDSS-RM results (and some press!)

How massive is supermassive? Astronomers measure more black holes, farther away

January 10, 2018

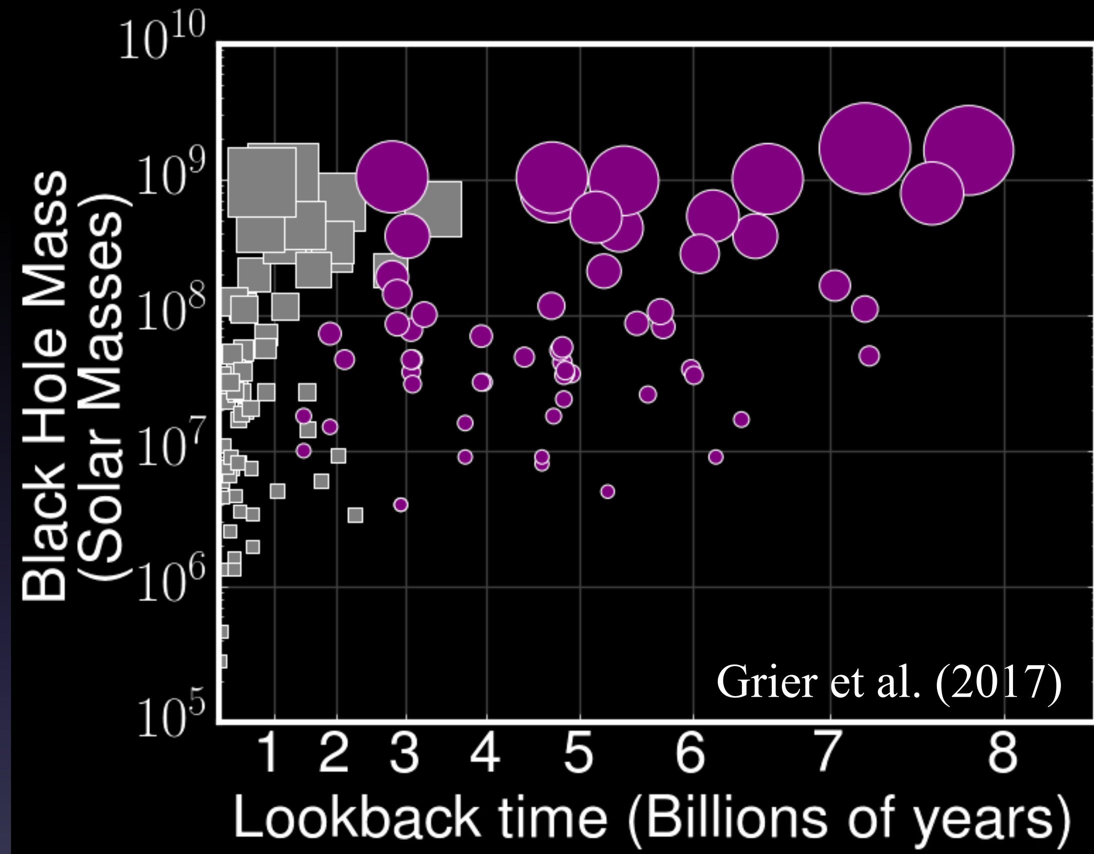
UNIVERSITY PARK, Pa. — A team of astronomers from the Sloan Digital Sky Survey (SDSS), including several Penn State scientists, announced new measurements of the masses of a large sample of supermassive black holes far beyond the local universe.

The results, being presented at the American Astronomical Society (AAS) meeting in National Harbor, Maryland, and published in the Astrophysical Journal, represent a major step forward in our ability to measure supermassive black hole masses in large numbers of distant quasars and galaxies.

"This is the first time that we have directly measured masses for so many supermassive black holes so far away," said Catherine Grier, a postdoctoral fellow at Penn State and the lead author of this work. "These new measurements, and future measurements like them, will provide vital information for people studying how galaxies grow and evolve throughout cosmic time."

Supermassive black holes are found in the centers of nearly every large galaxy, including those in the farthest reaches of the universe. Their gravitational pull is so great that nearby dust and gas is inexorably drawn in. The infalling material heats up to such high temperatures that it glows brightly enough to be seen all the way across the universe, forming bright disks of hot gas known as quasars. By studying quasars, scientists learn not only about supermassive black holes, but also about the distant galaxies that they live in. But to do all of this requires measurements of the properties of the supermassive black holes, most importantly th[e] masses.

news.psu.edu

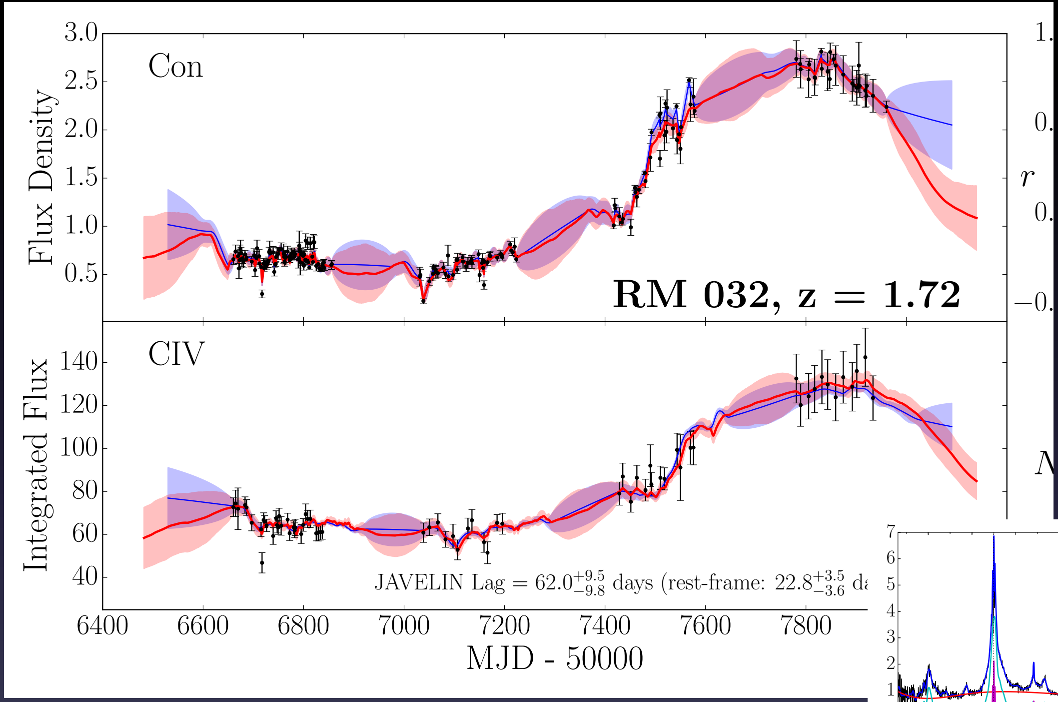


SPACE.com NEWS TECH SPACEFLIGHT SCIENCE & ASTRONOMY SEARCH FOR LIFE SKYWATCHIN[G]

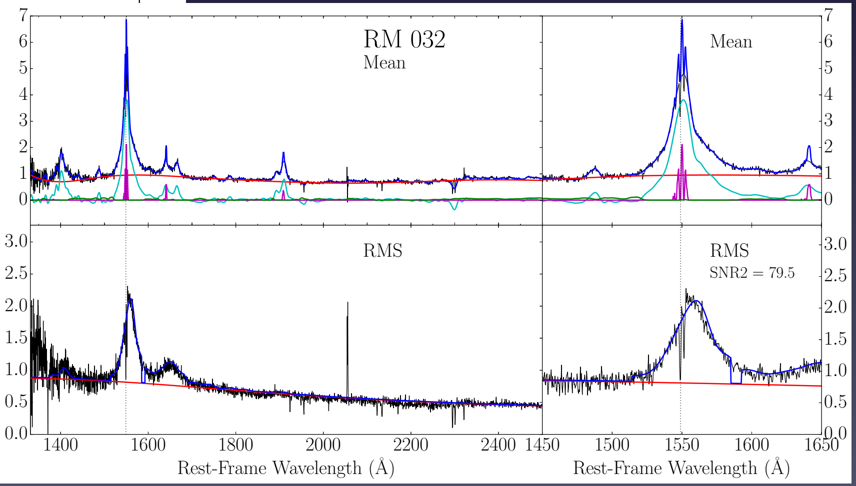
How Astronomers Are Measuring Monster Black Hole Masses Faster Than Ever Before

By Nola Taylor Redd, Space.com Contributor | January 11, 2018 07:15am ET

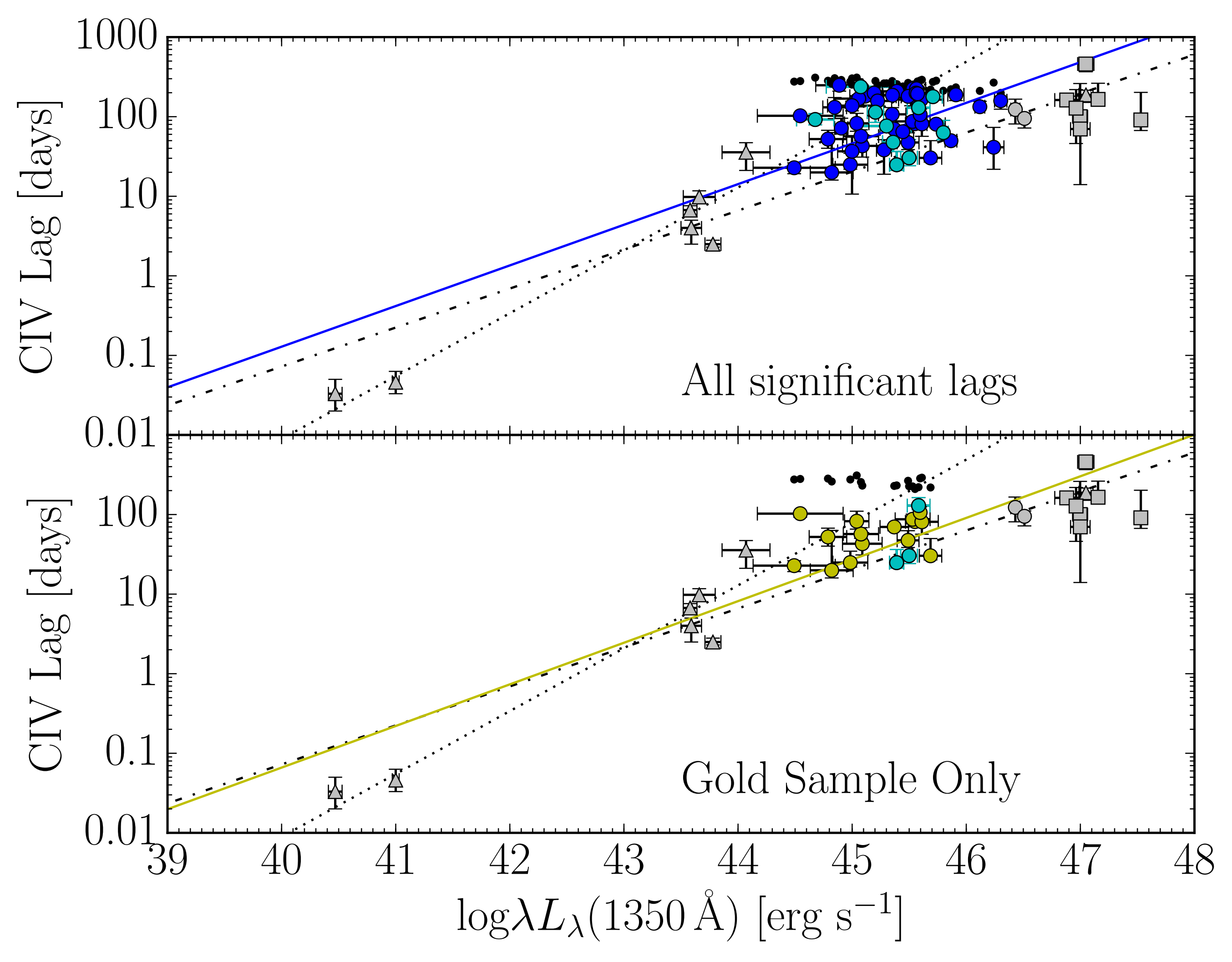
Recent work: Four Years of Data and the CIV Line



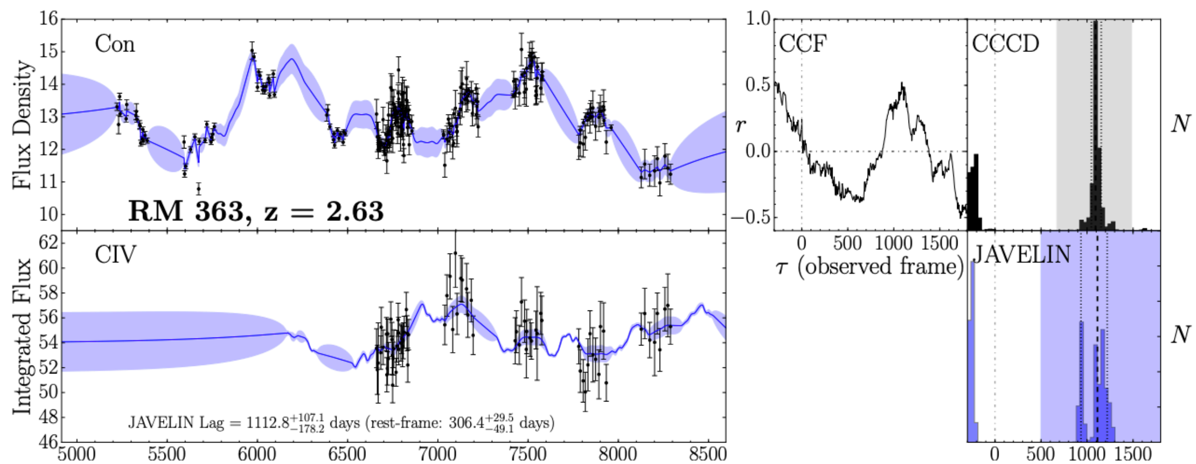
Lags measured in 52 quasars using the CIV emission line



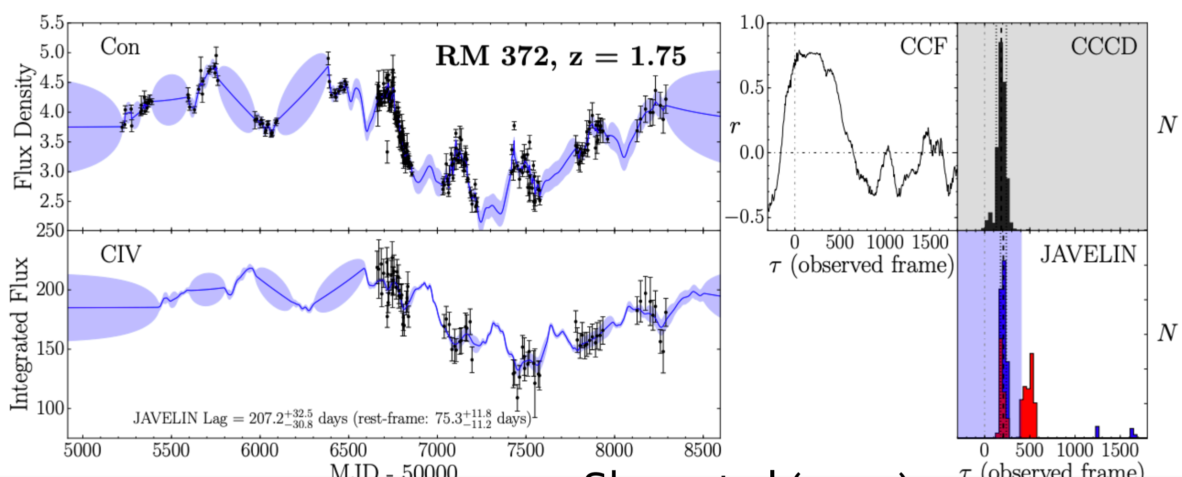
The CIV R-L Relationship



Longer Time Baseline = More Lags



Shen et al (2019)

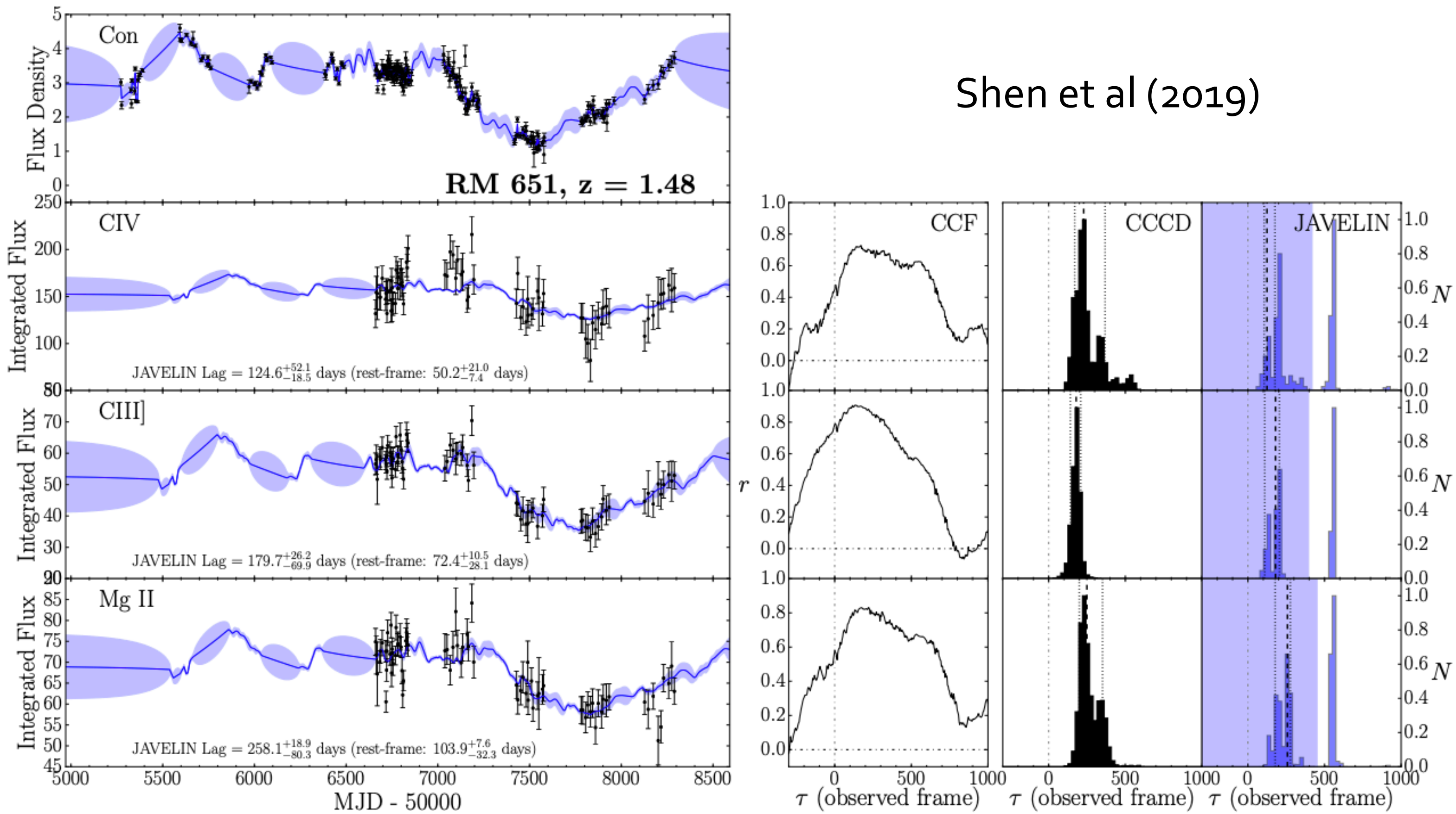


Shen et al (2019)

Grier et al. (2019) includes only 4 years of monitoring

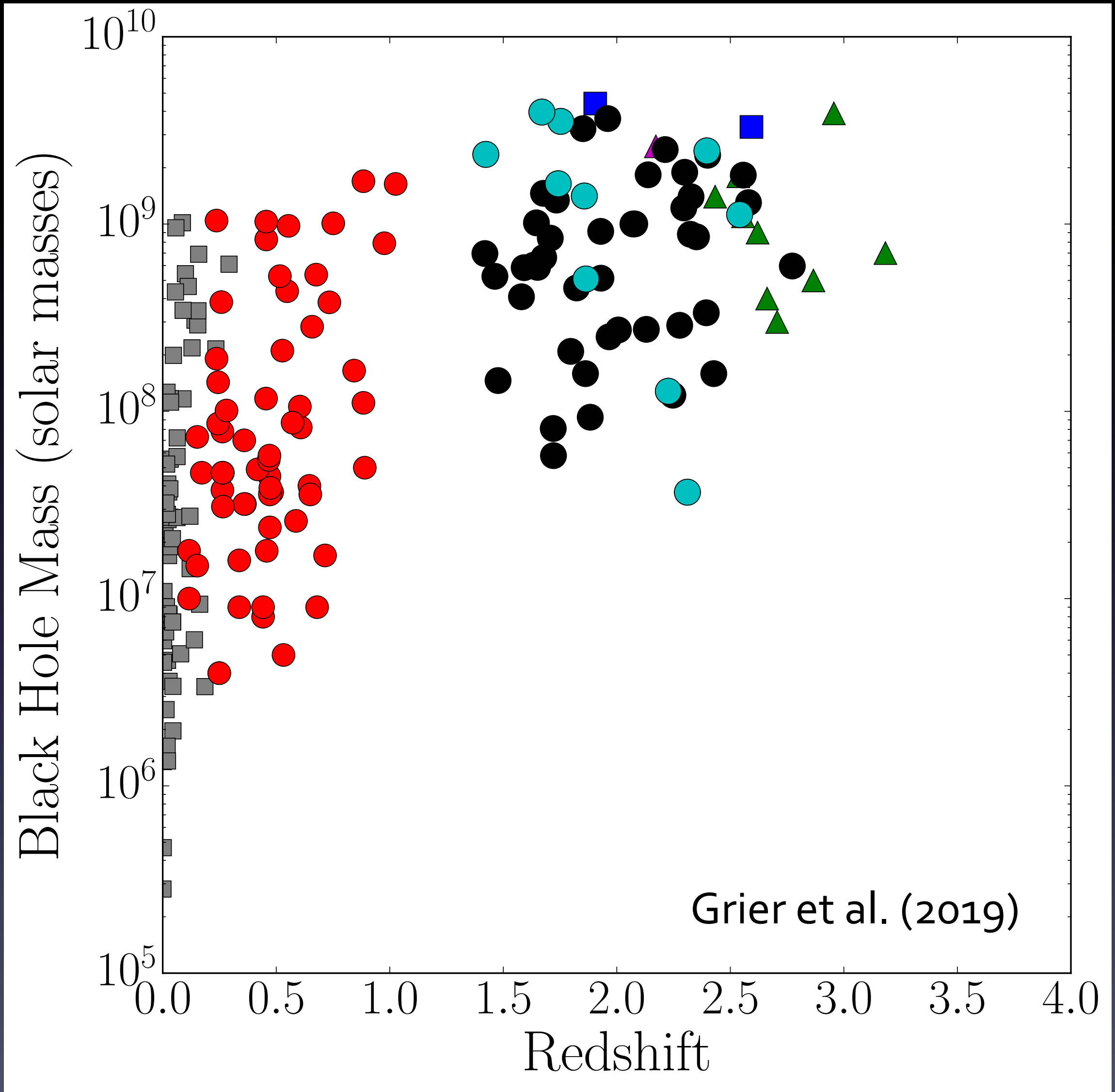
Shen et al (2019) includes 9 years!

With SDSS-RM, we can explore many different emission lines.



Shen et al (2019)

RM Black Hole Mass Measurements



Gray = Pre-SDSS-RM (using Hβ; Bentz & Katz 2015)

Red = SDSS-RM Hβ (Grier et al. 2017)

Black and Cyan = SDSS-RM CIV (Grier et al. 2017)

Blue/green = Other CIV (Lira et al. 2018, Kaspi et al. 2005, etc)

SDSS-RM has contributed RM measurements in 99 sources so far, more than doubling the size of the RM-measured sample!

Other Science from SDSS-RM

- 18 journal papers have been published using SDSS-RM data so far

- Only seven of them cover Reverberation Mapping science!
  - The other papers (including a technical paper and a sample-characterization paper) include discussions of:
    - Host galaxy properties and scaling relations
    - Broad Absorption Line Variability
    - Emission-line variability
    - Emission-line properties (velocity shifts, etc)

- 3 more papers have been submitted, and several more in-progress.

What's Next?

- We are entering our final year of data collection; we will then combine all 10+ years of monitoring (including photometry and spectroscopy) and search for more lags with the full, final dataset
  - Longer Hβ lags
  - Mg II lags
  - Additional, longer CIV lags
  - Lags of other species (CIII], etc)

- There is so much we can do with a dataset of high-cadence spectra of 850 quasars!
  - Ancillary science studies: Extreme/unique objects, absorption-line studies, emission-line properties, host galaxy studies, the list goes on…

- Multi-Object RM is becoming popular: Upcoming programs such as SDSS-V, 4MOST, PFS, DESI, and LSST will enable future quasar monitoring studies

Stay tuned for many more results over the next years!

Thank you!