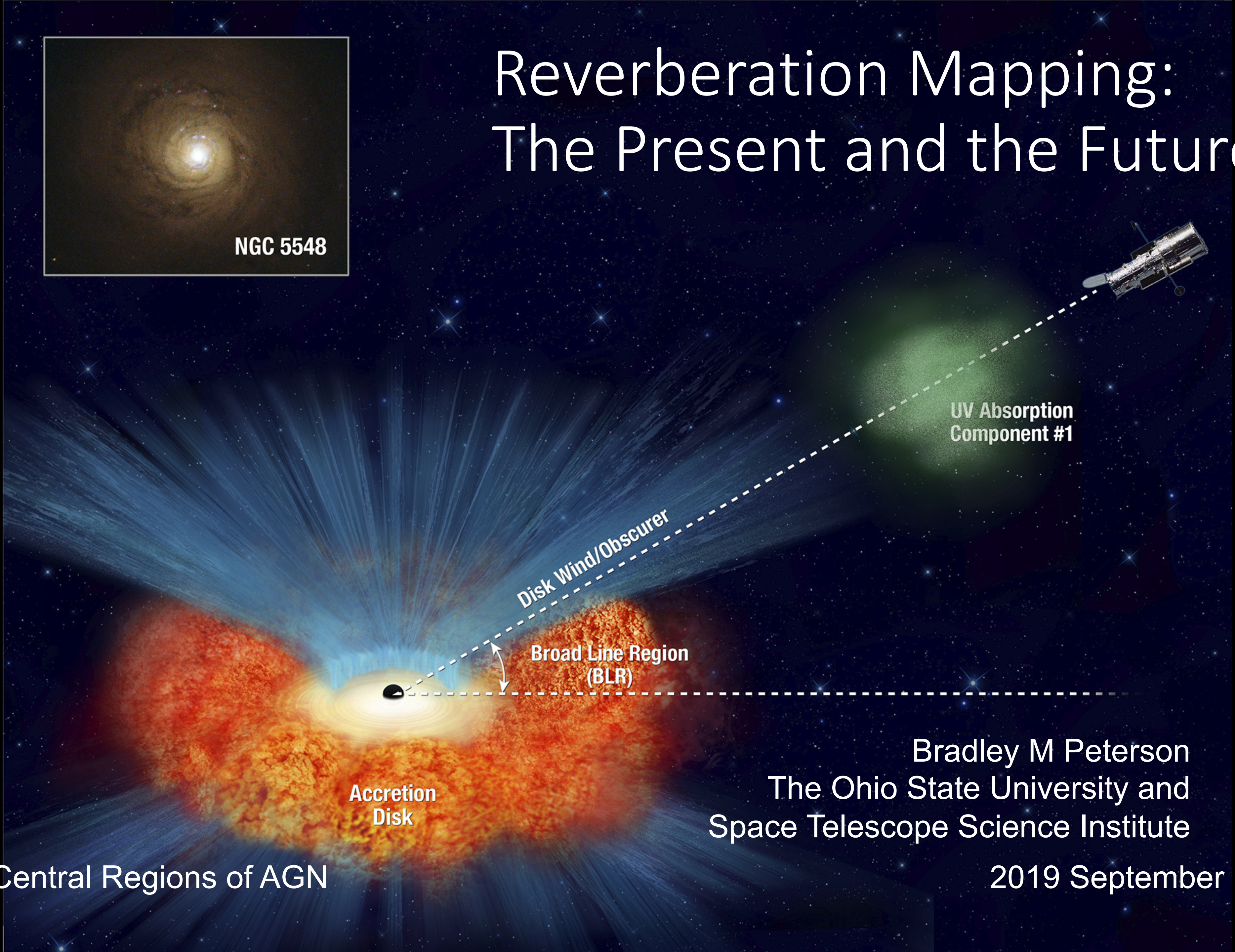
Reverberation Mapping: The Present and the Future



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Mapping the Central Regions of AGN

2019 September

Introduction

- My goal is to provide context for the many talks that we will hear over the next several days.
- While reverberation mapping is a centerpiece of this conference, it’s not an end in itself, simply a powerful tool for studying the structure of active nuclei.
- I will try to provide some historical background (very brief and highly selective [i.e., biased]) that I hope explains how we got where we are. I’ll defer some talk on the future till the end of the conference.

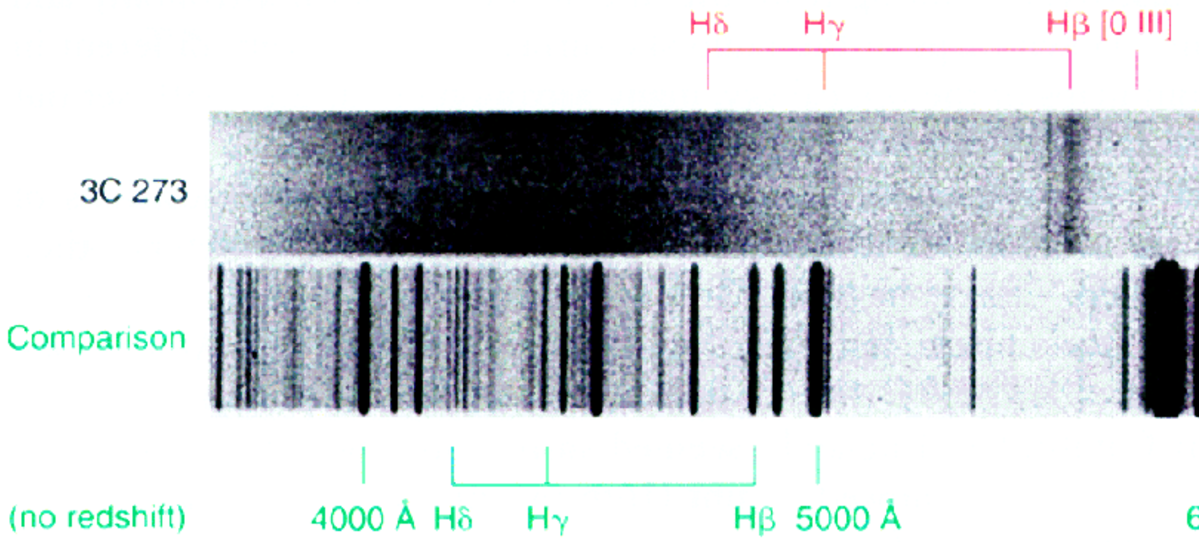
The Big Questions

- How does the black hole mass function evolve over cosmic time?
- How does the accretion process work and how is it related to outflows?
- Do AGN outflows play a role in galaxy evolution?
  - Do they quench (shut down) star formation?

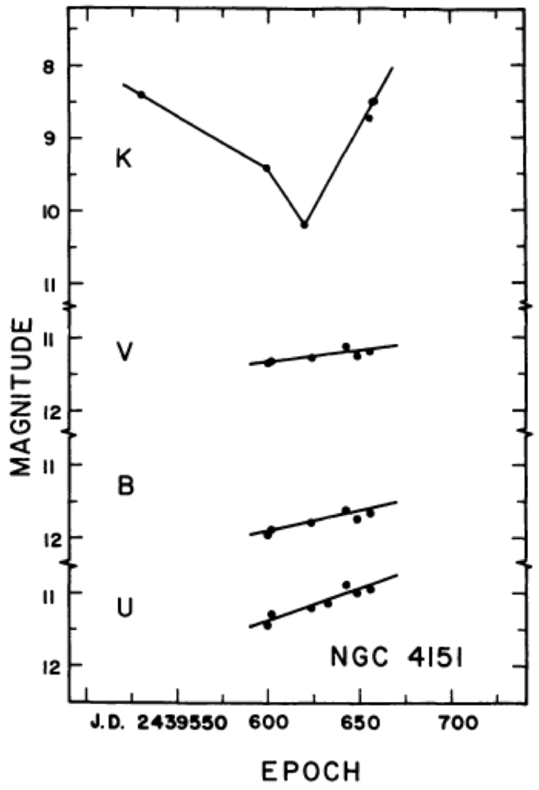
At this conference, we’ll be focusing most of our attention on smaller individual pieces of a much larger puzzle.

Pre-History

- Reverberation mapping (RM) theory was laid out by Bahcall, Kozlovsky, and Salpeter (1972, ApJ, 171, 467).
- No observational follow-up:
  - Technology wasn't up to it
- Little known about variability timescales or size of the BLR.
  - Mostly blazar variability was being studied, although Seyfert nuclei were known to vary



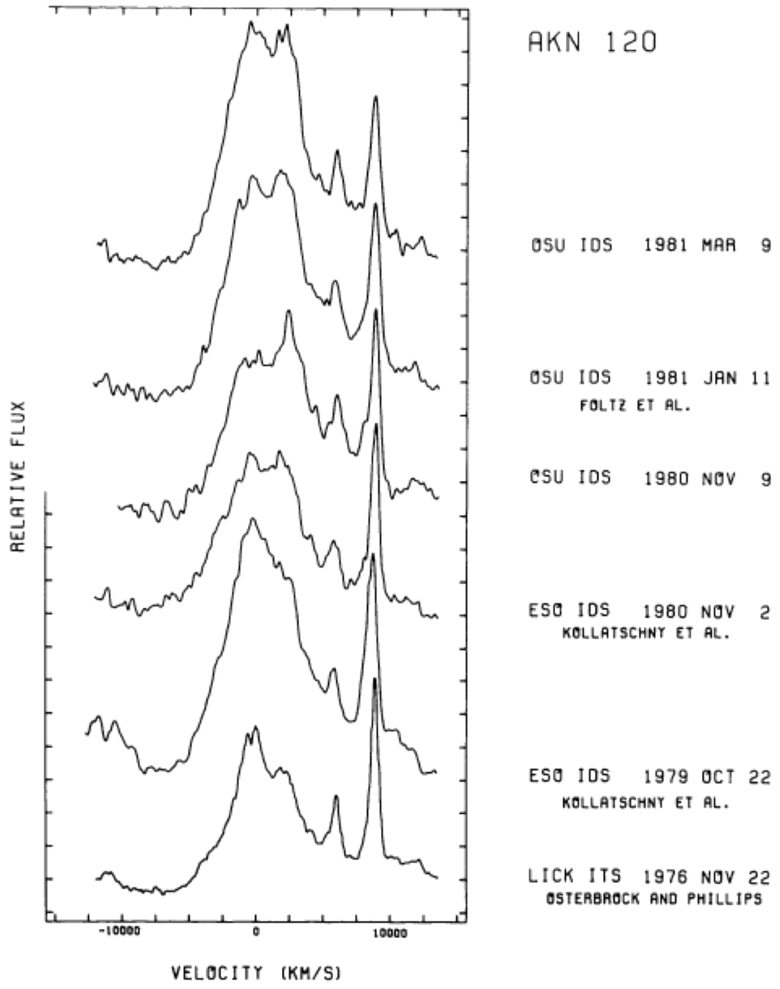
Schmidt's original spectrum



Fitch, Pacholczyk, & Weymann 1967

Early History

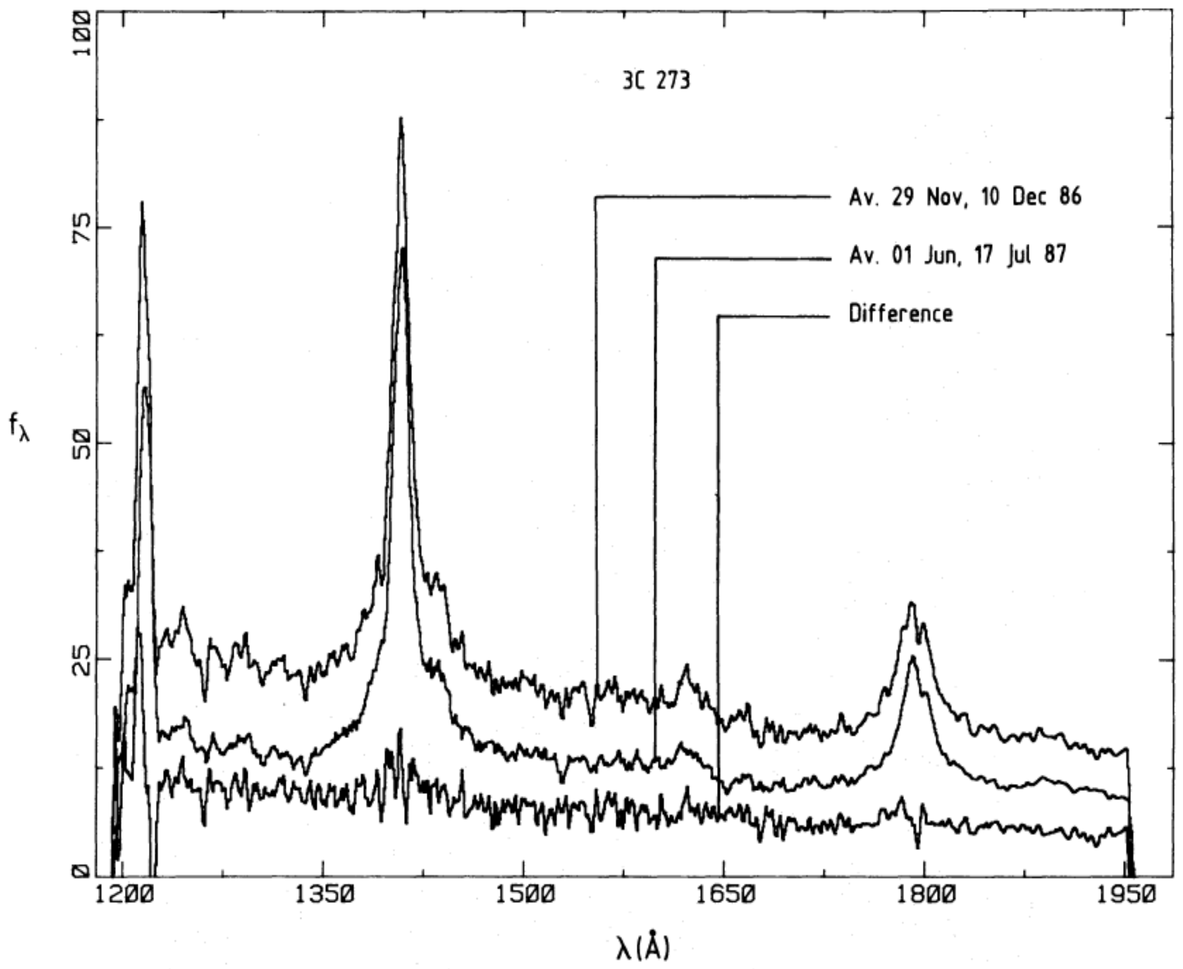
- Technological improvements in late 1970s and early 1980s led to initial discoveries of emission-line flux and profile variations
  - Sensitive, linear electronic detectors came into use.
    - CCDs were beginning to be used, but were not yet widespread



Capriotti, Foltz, Peterson 1982
Data from:
Foltz+ 1981
Kollatschny+ 1981
Schulz & Rafanelli 1981
Osterbrock & Phillips 1976

Early History

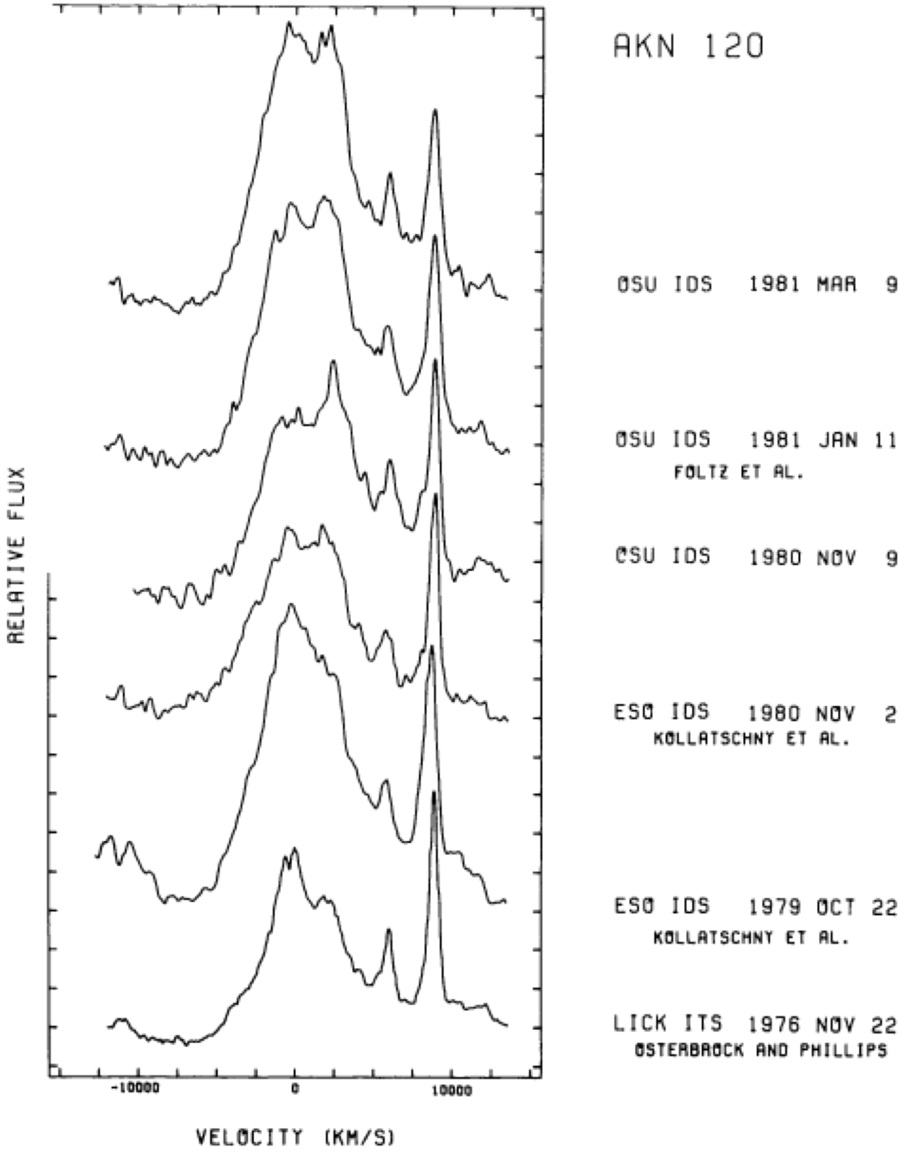
- The *International Ultraviolet Explorer* launched in 1978
  - Only a 45 cm telescope, but it opened up the rest-frame UV to spectroscopy.



Ulrich, Courvoisier, & Wamsteker 1988

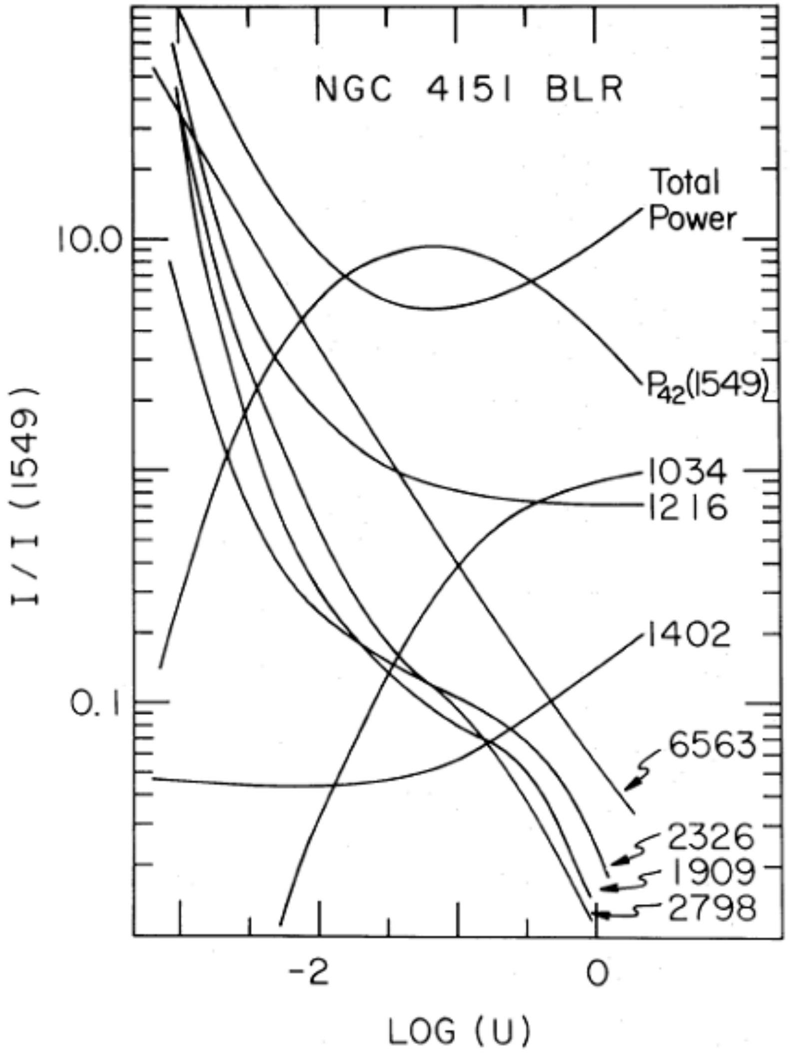
Early History

- Observed variability renewed interest in reverberation mapping.
- Numerous suggestions in the literature
- Most well-developed was Blandford & McKee (1982) who coined the term "reverberation mapping."
- Profile changes were thought to be reverberation effects.



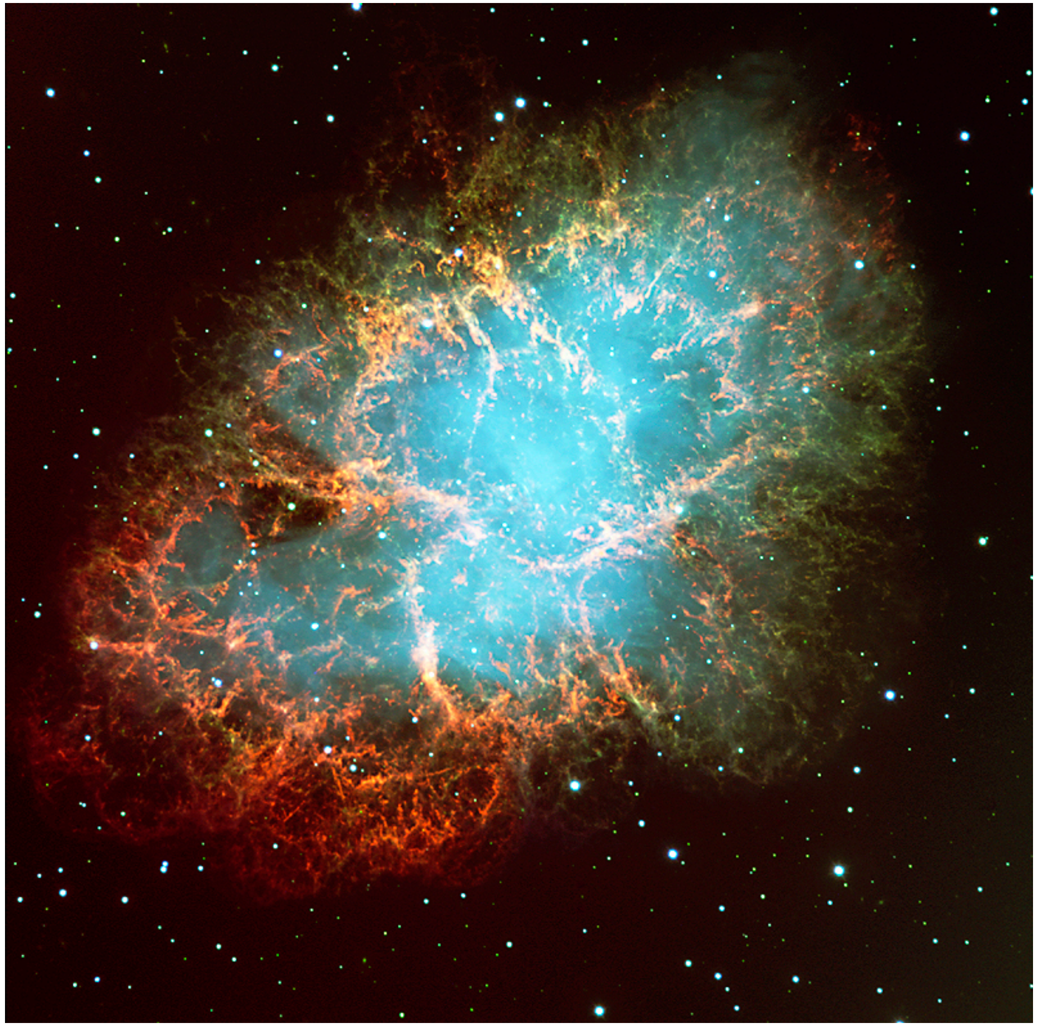
Landscape in mid-1980s

- While most AGN researchers believed that AGN hosted SMBHs, proof was lacking.
  - Eddington limit argues masses in excess of $10^6\ M_\odot$ are required.
  - Hard to explain hard X-ray emission any other way.
- Continuum variability timescales unknown.
- Whether or not different continuum bands varied together was unknown.
- BLR geometry unknown, and size estimates based on photoionization equilibrium models were incorrect.
  - Models predicted a BLR ~10× larger than reverberation measurements.



Ferland & Mushotzky 1982

What is the BLR?



Crab Nebula
with VLT

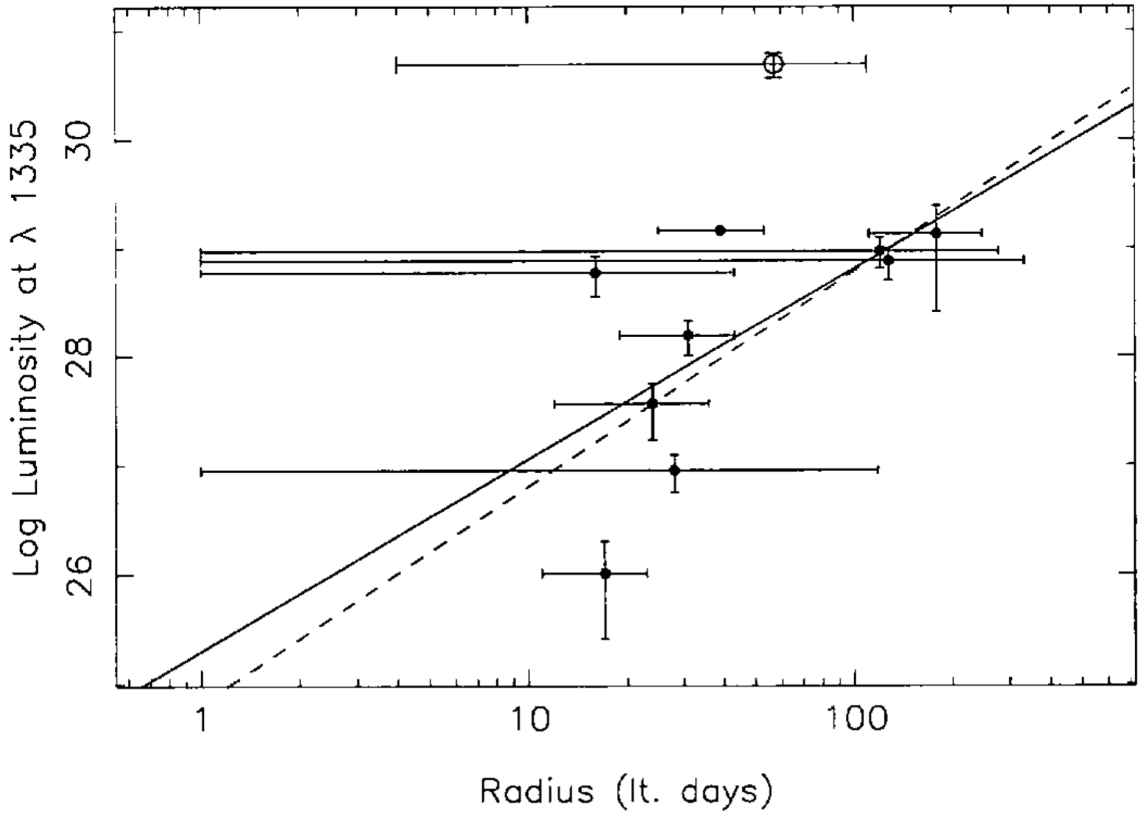
- First notions based on Galactic nebulae, especially the Crab
  - system of “clouds” or “filaments.”
- Merits:
  - Ballistic or radiation-pressure driven outflow $\Rightarrow$ logarithmic profiles

Photoionization prediction of $r - L$ relation

- Line flux ratios in AGNs seem to be independent of luminosity*, so U and n_H must be similar:

$$r = \left(\frac{Q_{ion}(H)}{4\pi n_H U} \right)^{1/2} \propto L^{1/2}$$

- This important result was anticipated.

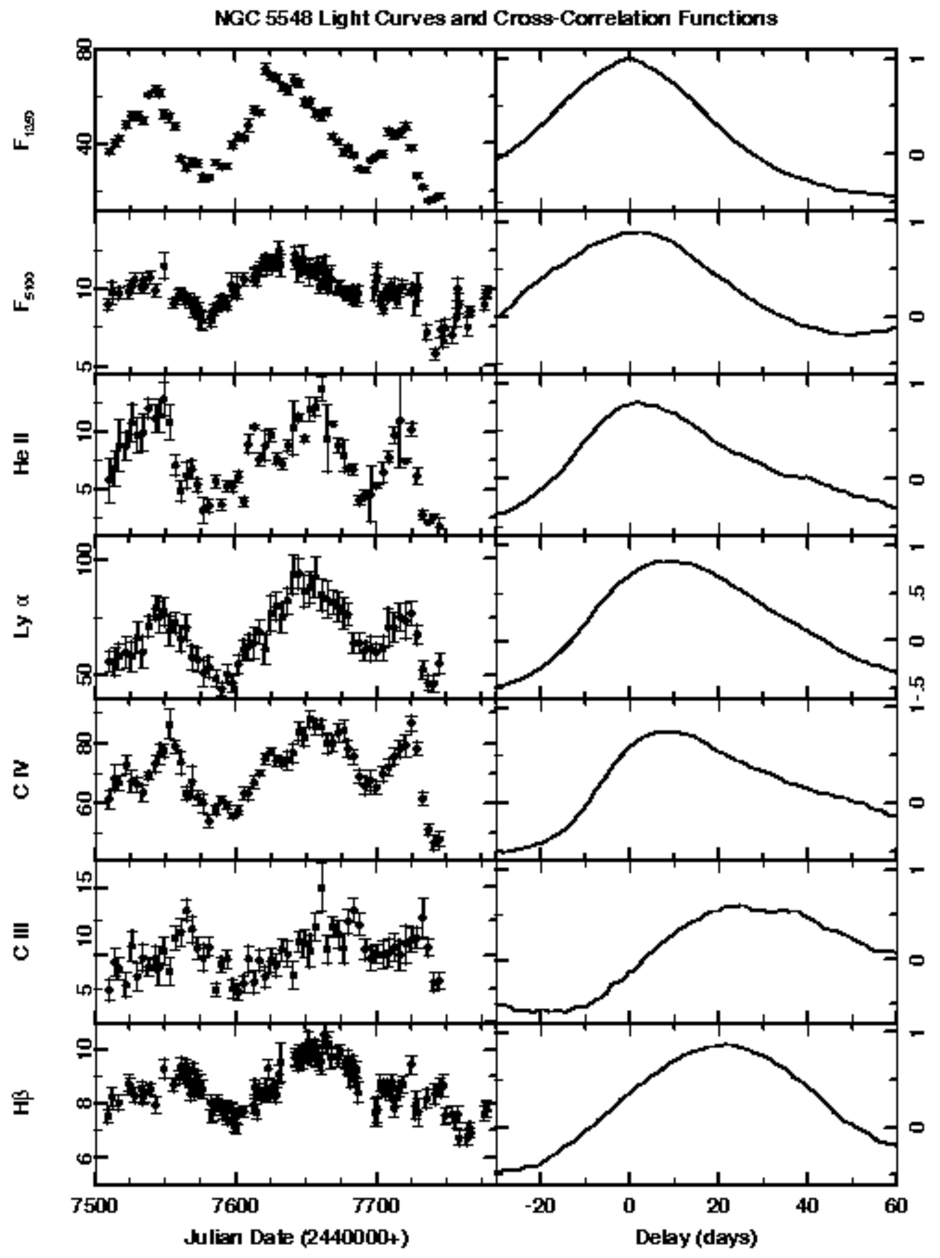


Koratkar & Gaskell 1991

* C IV 1549 is the important exception (Baldwin 1977)

Breakthrough!

- **The fundamental difficulty with RM is that it is resource-intensive.**
- Success was achieved when the RM community proposed *as a community* (The International AGN Watch) for a campaign with *IUE* and assorted ground-based telescopes in 1988-89.
- Major findings:
  - UV/optical continua varied similarly
  - Emission lines revealed ionization stratification
  - No strong evidence for purely radial motion
  - Later (combined with additional data): virial relationship between line width and lag



Data from Clavel et al. 1991 and Peterson et al. 1991

Virial Estimators

Source	Distance from central source
X-ray Kα	6-20 R_g
Broad-Line Region	400-10^4 R_g
Megamasers	8 x 10^4 R_g
Gas Dynamics	10^5 R_g
Stellar Dynamics	10^6 R_g

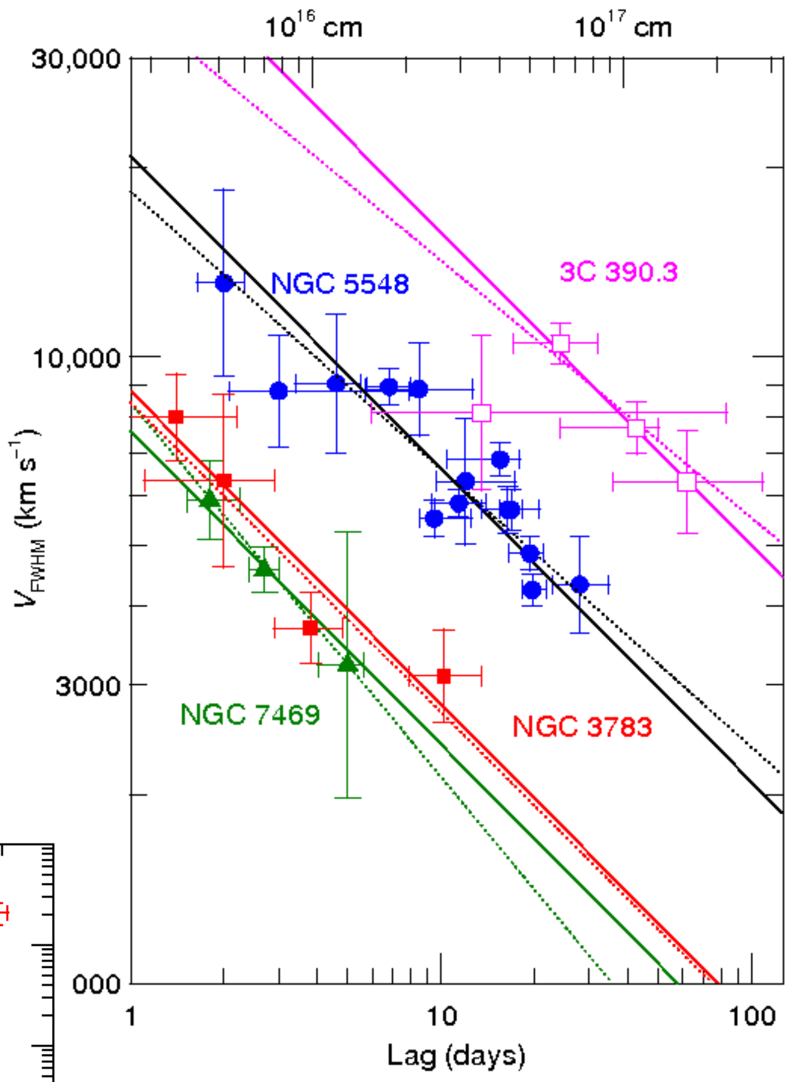
In units of the gravitational radius:

$$R_g = GM/c^2 = 1.5\times10^{13}\left(\frac{M}{10^8 M_\odot}\right)\mathrm{cm}$$

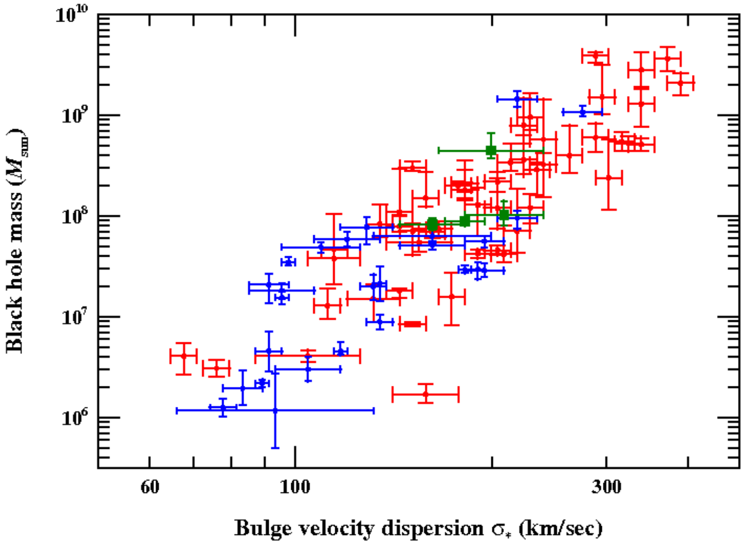
Mass estimates from the virial theorem:

$$M = f\,(r\,\Delta V^{2}/G)$$

where
r = scale length of region
ΔV = velocity dispersion
f = a factor of order unity, depends on details of geometry and kinematics.

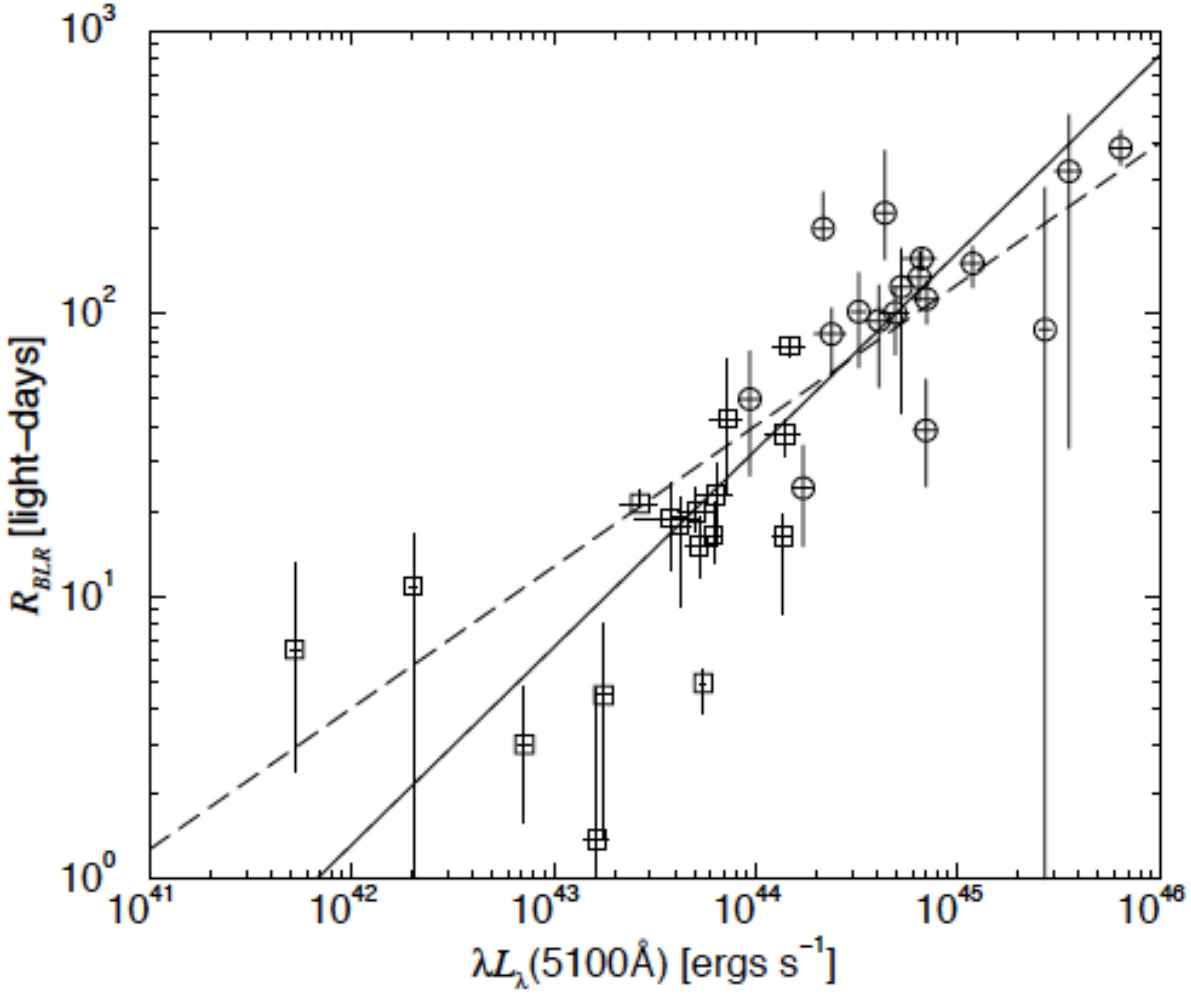


Peterson & Wandel 2000



Breakthrough!

- First unambiguous detection of the BLR radius—luminosity relation due to addition of 17 higher-luminosity PG quasars.
  - Extended to higher lags and luminosity
  - Explored a luminosity regime where the host-galaxy starlight contribution is minor.

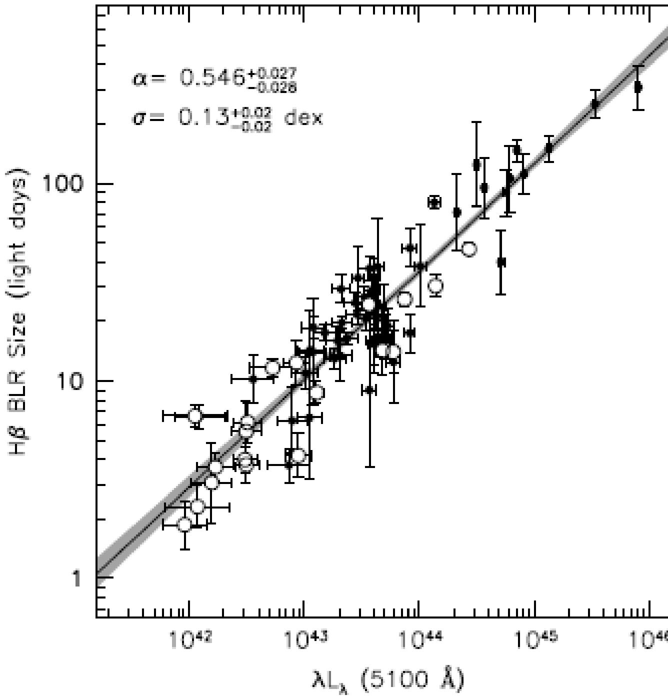


Kaspi et al. 2000

NGC 4051
z = 0.00234
log L_{opt} = 41.8

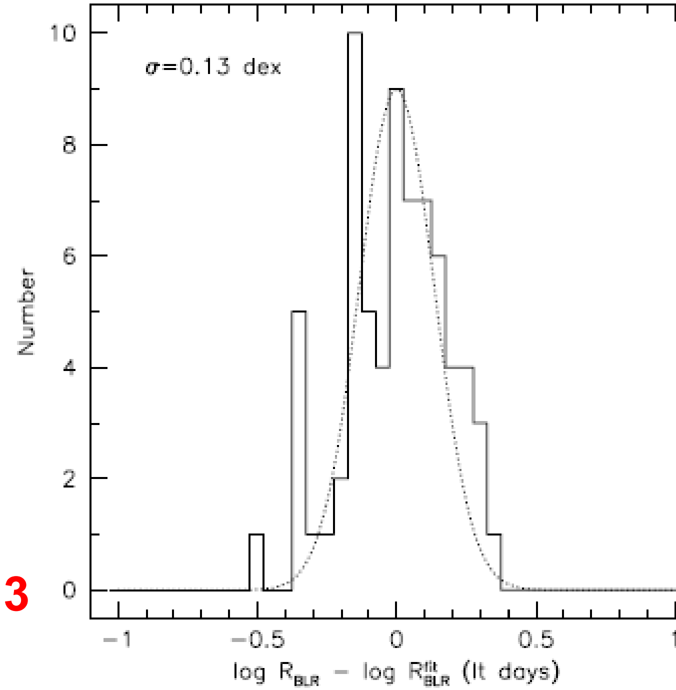
Mrk 79
z =0.0222
log L_{opt} = 43.7

PG 0953+414
z = 0.234
log L_{opt} = 45.1



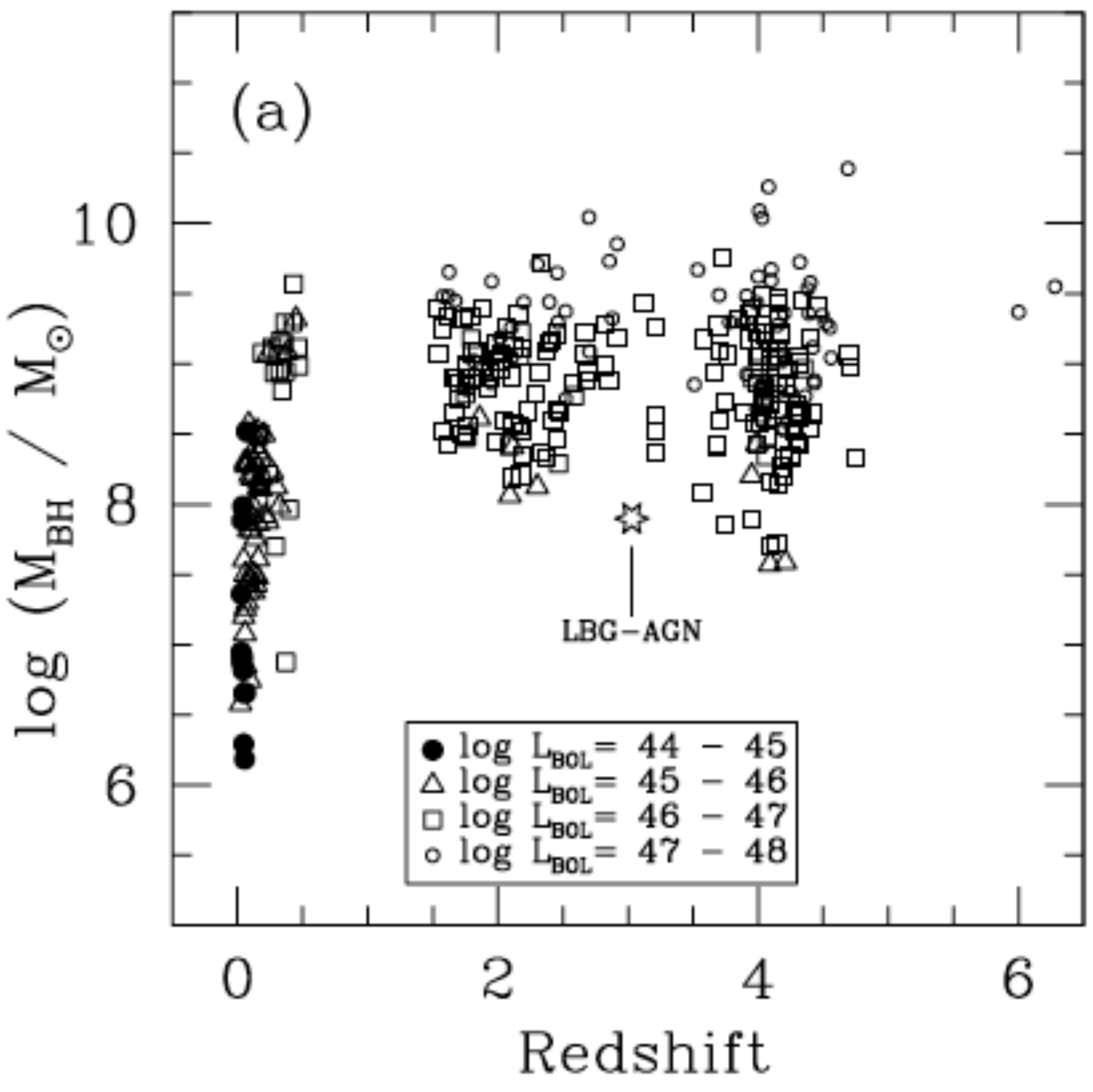
Getting the *R-L* slope right requires removing the host starlight contribution.

Bentz+ 2013



Masses of Quasars

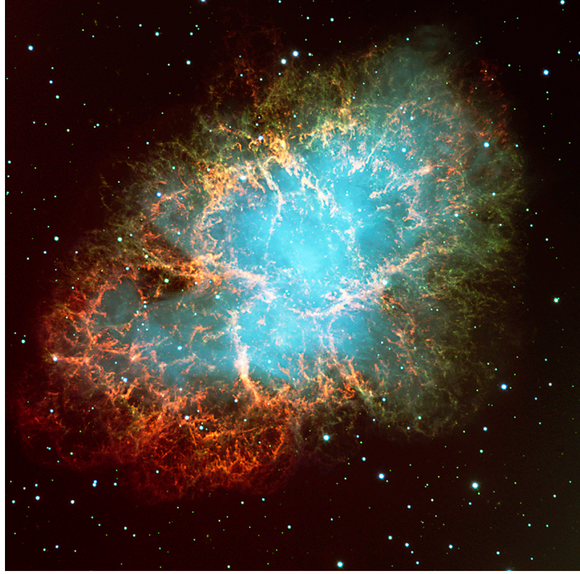
- With the *R*-*L* relation and a value for <*f*>, with a few assumptions, one can estimate quasar masses over cosmic time.

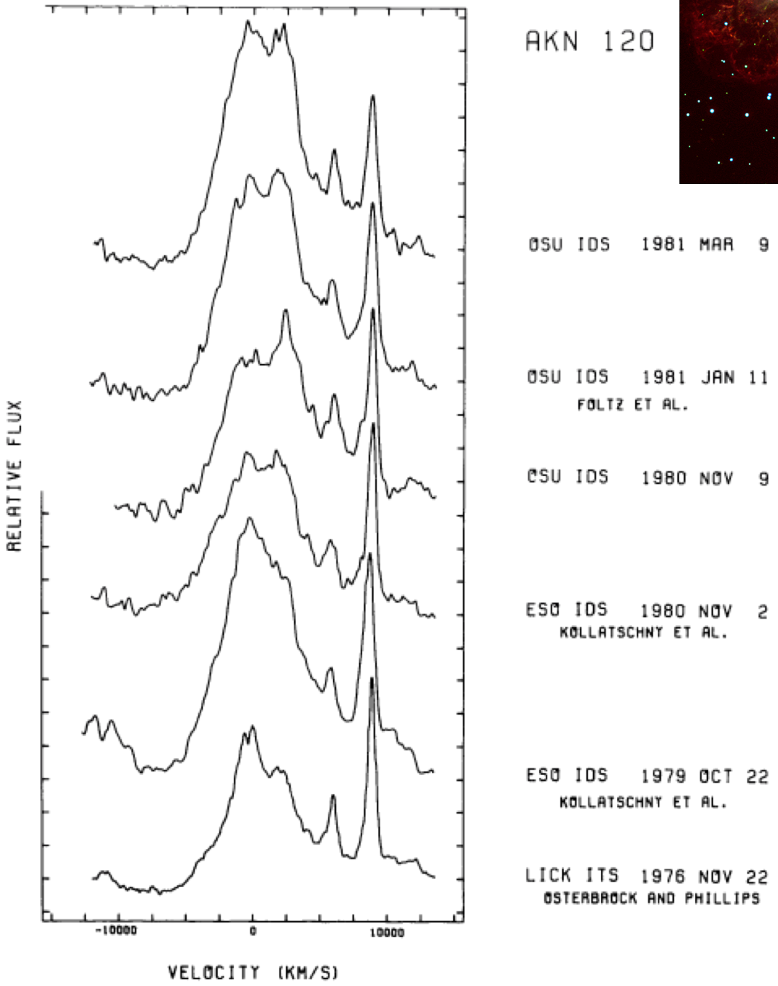


Vestergaard 2004

BLR geometry and kinematics

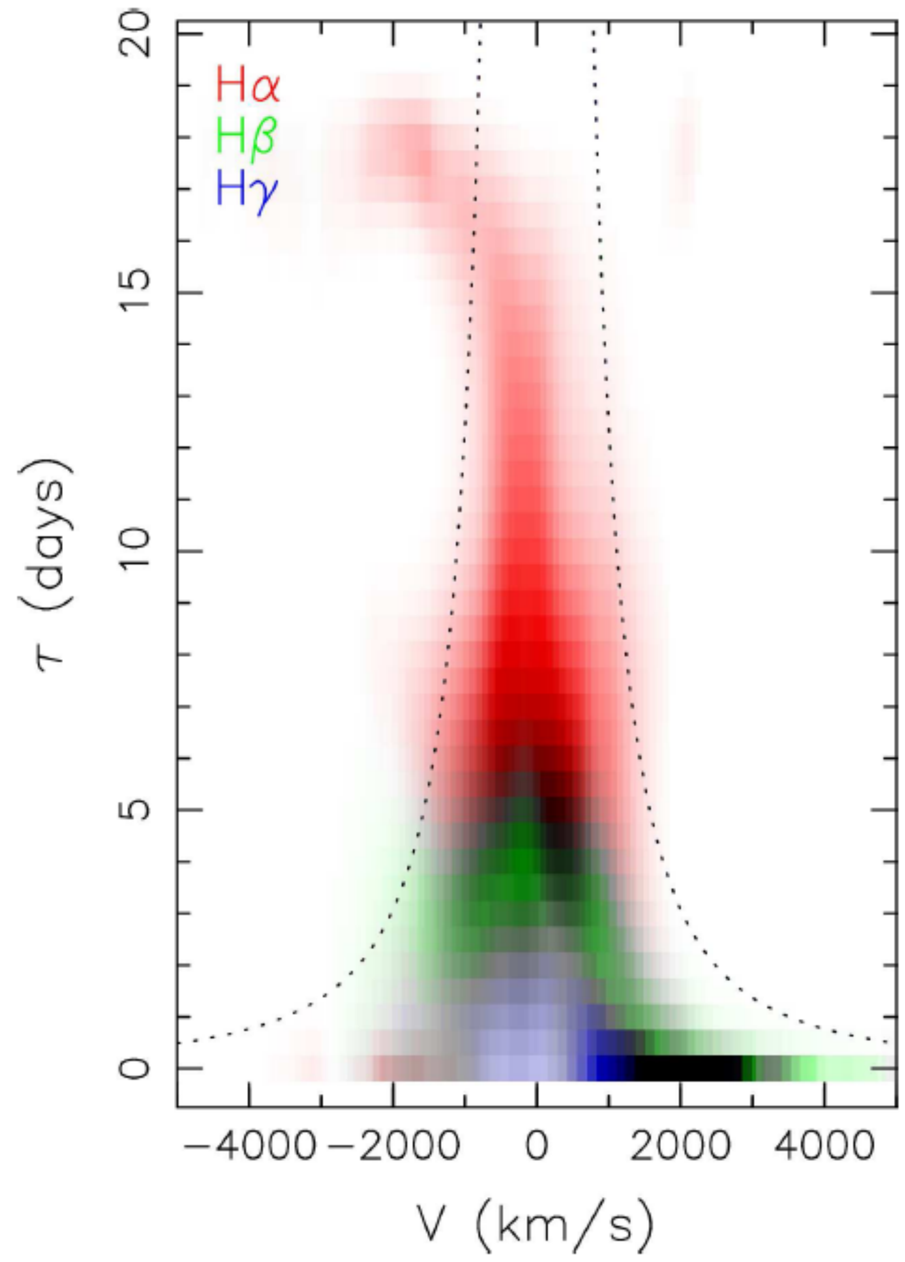
- Ability to measure SMBH masses made RM popular.
- Original goal of RM was to determine geometry and kinematics, which is more demanding.





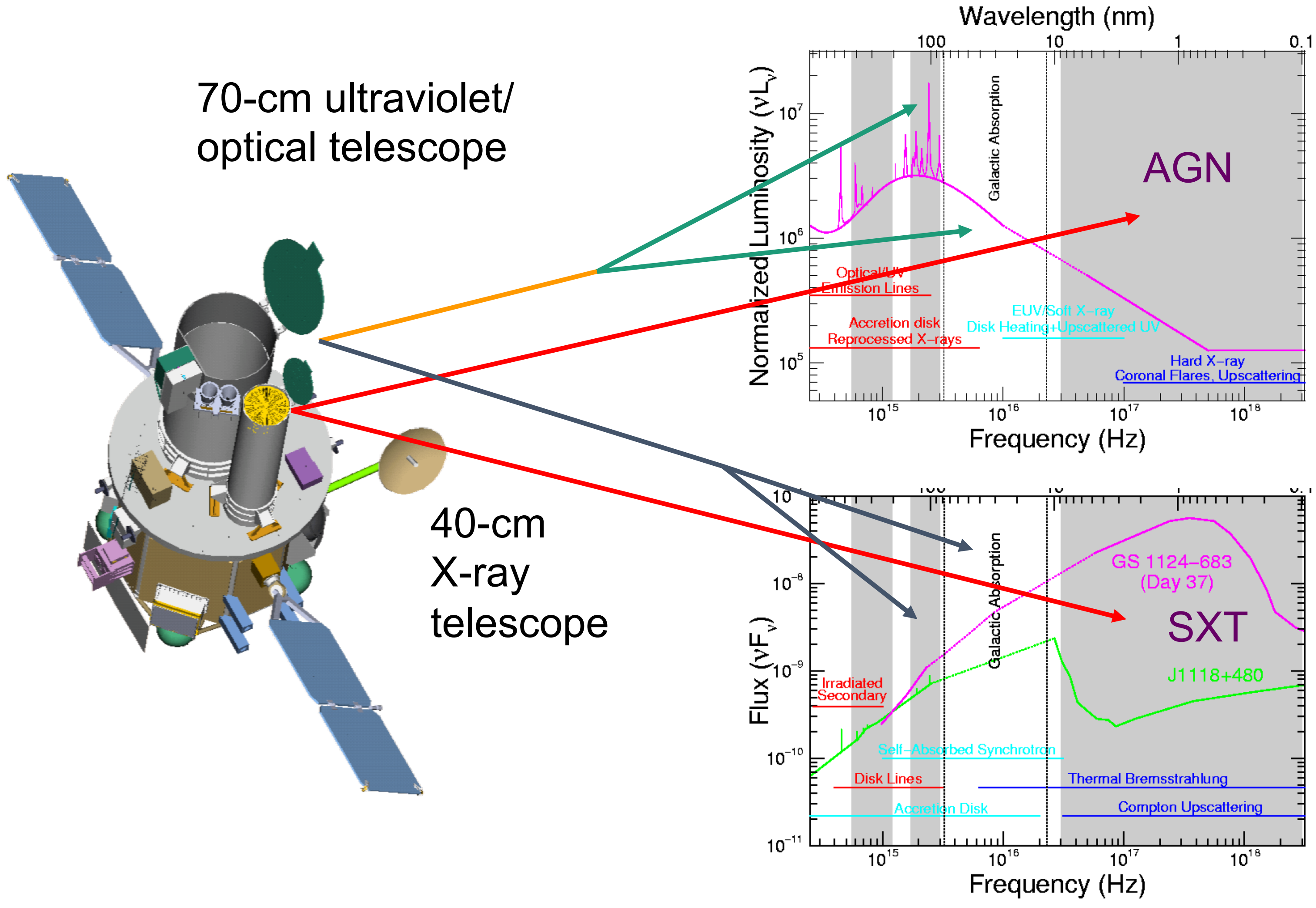
Breakthrough!

- About ten years ago, ground-based observations were producing the first velocity-delay maps.
  - There are still only about a dozen sources for which velocity-delay maps are available, but several more in the works by multiple groups.
  - Nearly all show evidence of some disk structure.
- But what about the high-ionization lines?



LAMP: PI, Barth – Bentz+ 2010

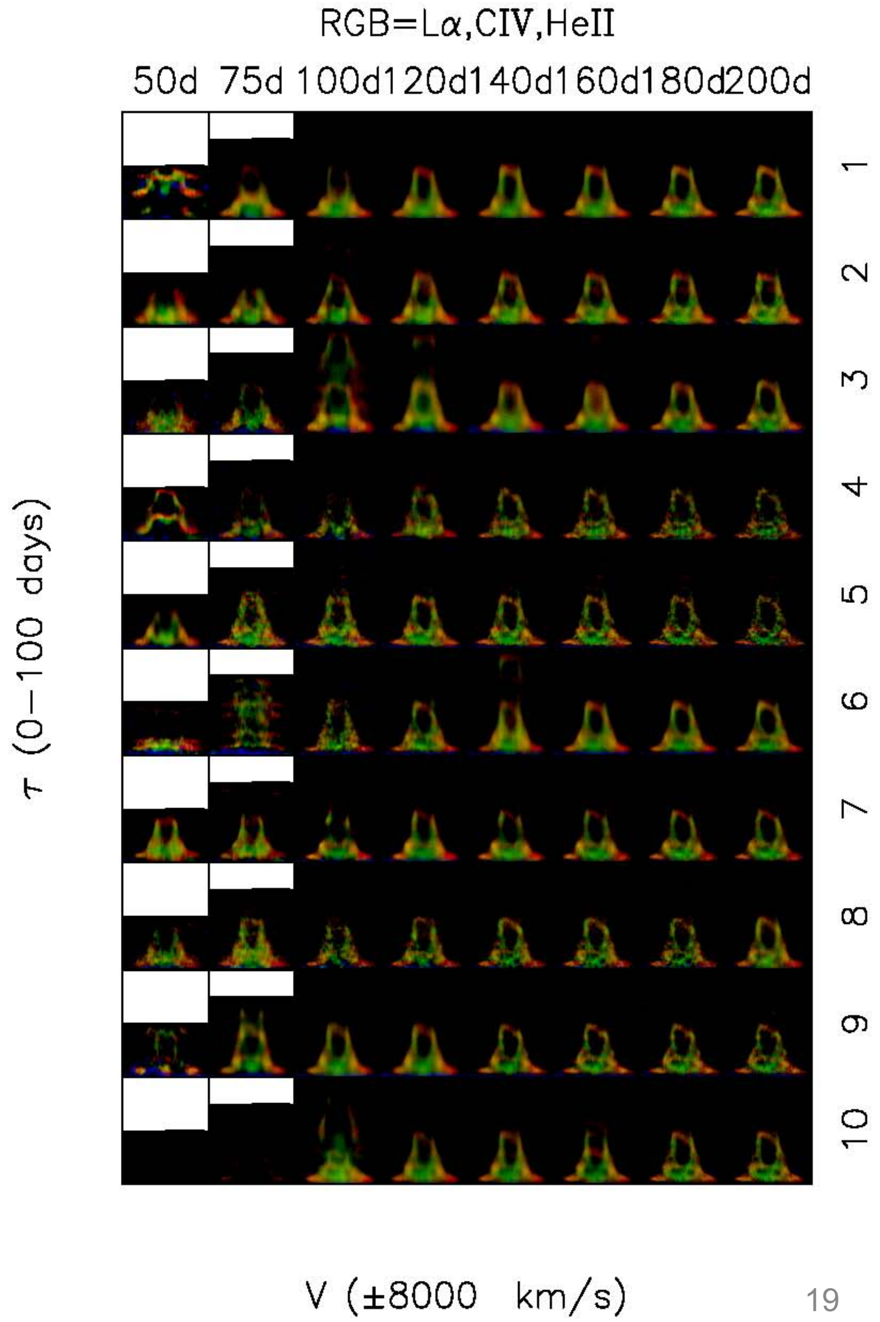
Kronos



- In 1998 and 2001, several of us proposed *Kronos* as a Medium Explorer satellite for NASA for RM and tomography of interacting binaries.
- While the *Kronos* proposal was unsuccessful, NASA awarded us funds for more detailed simulations to make our case.

RM simulations

- Horne et al. (2004) defined requirements for recovering velocity-delay maps. For bright Seyferts:
  - High sampling rate (~daily)
  - Long duration (months)
  - High S/N (~100/pixel)
  - Moderate spectral resolution
- *Kronos* simulations were easily adapted to *Hubble Space Telescope.*



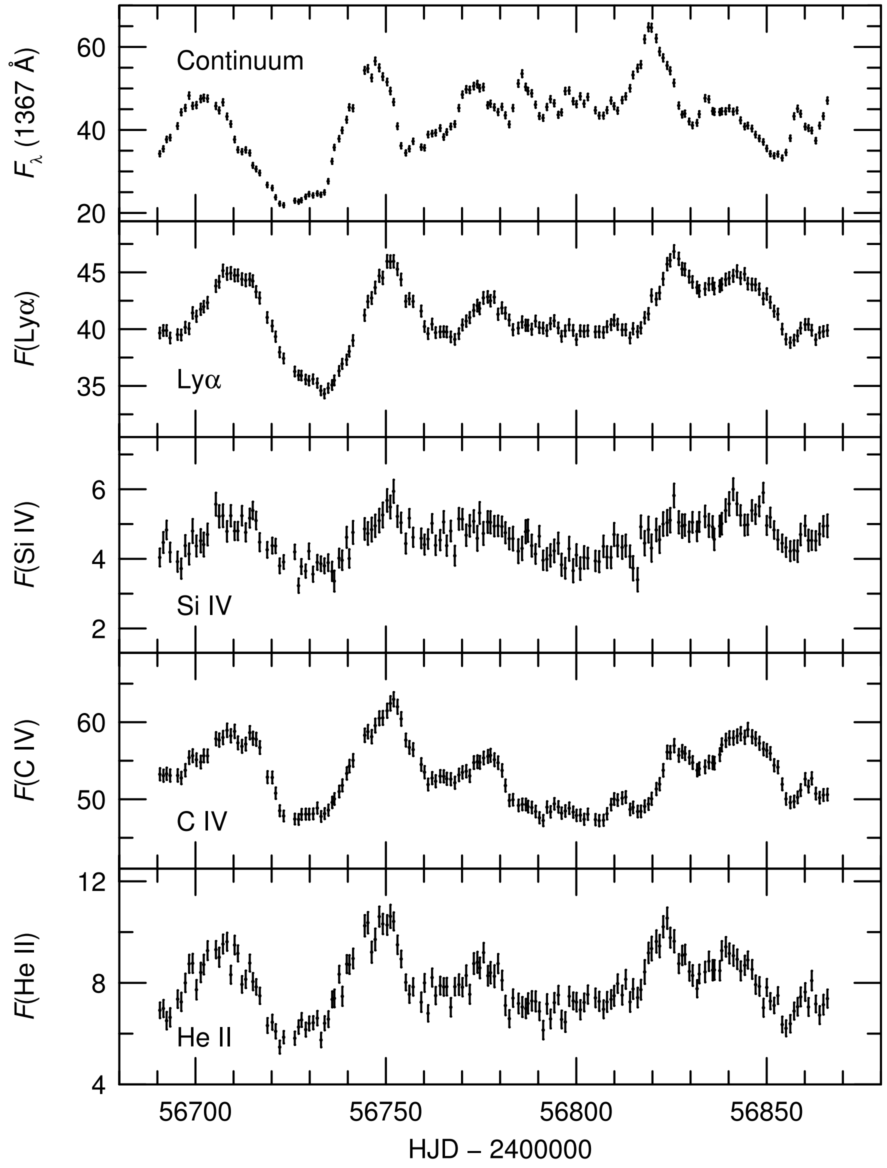
AGN Space Telescope and Optical Reverberation Mapping Program (AGN STORM)

- Anchored by daily *HST* COS observations of NGC 5548 (Cycle 21)
  - 2014 February 2 through July 27
  - 171/179 observations successful, single 2-day gap
  - Spectra cover 1153 −1796 Å (Lyα through He II 1640)
- Target selection:
  - Luminosity suited to daily cadence and one *HST* cycle
  - Obtain a high *S/N* COS spectrum in one orbit
  - Well-characterized, “reliably” variable source
  - Relatively weak absorption in resonance lines

AGN STORM
HST program

Mean lags relative to 1367 Å continuum

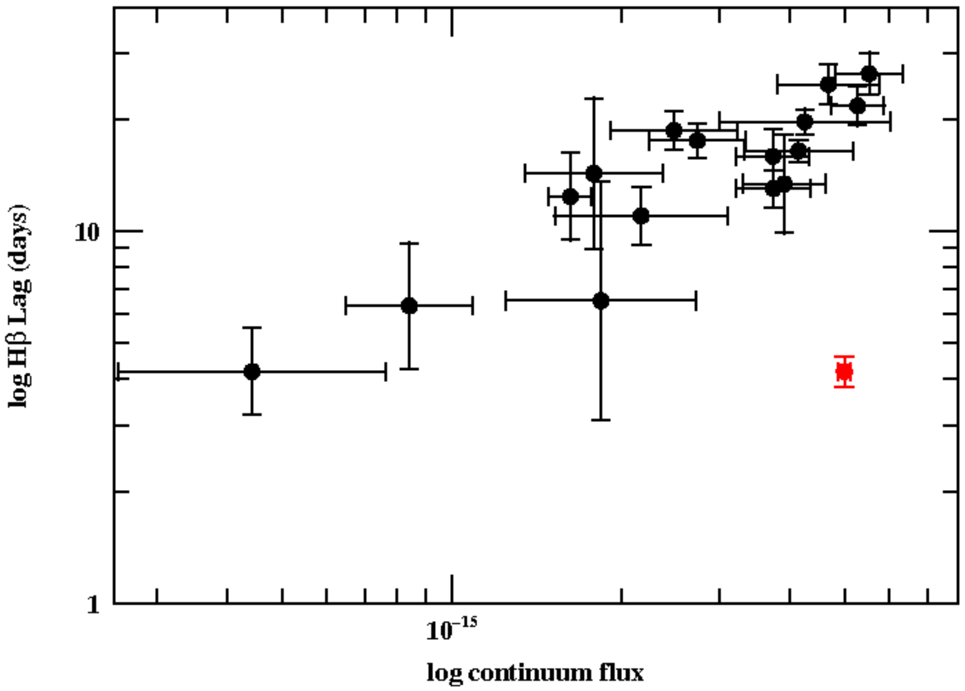
Ly α	6.19 ± 0.27 days
Si IV	5.44 ± 0.70 days
C IV	5.33 ± 0.46 days
He II	2.50 ± 0.33 days

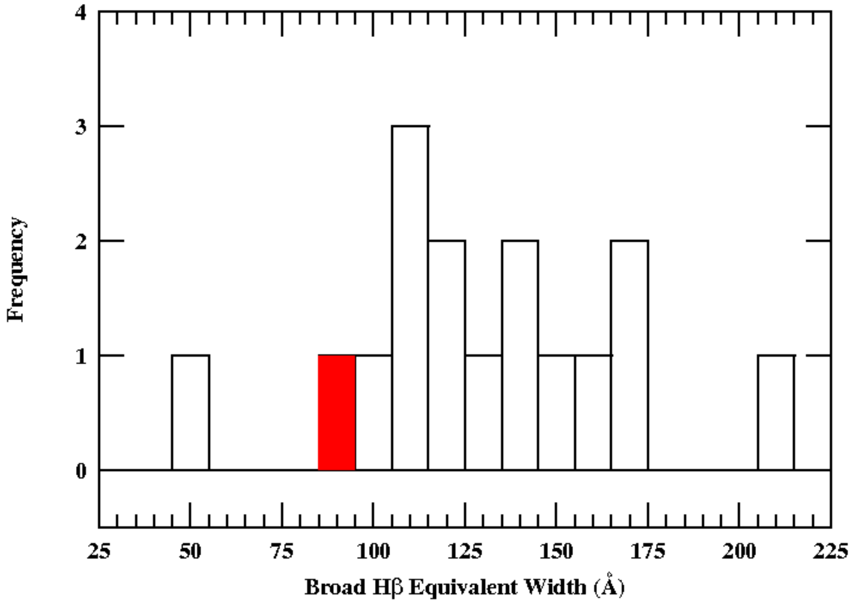


De Rosa+ 2015

Emission-Line Lags Much Smaller than Expected

- Given high luminosity in 2014, Hβ lag should be ~20 days.
- Measured lag ~6 days

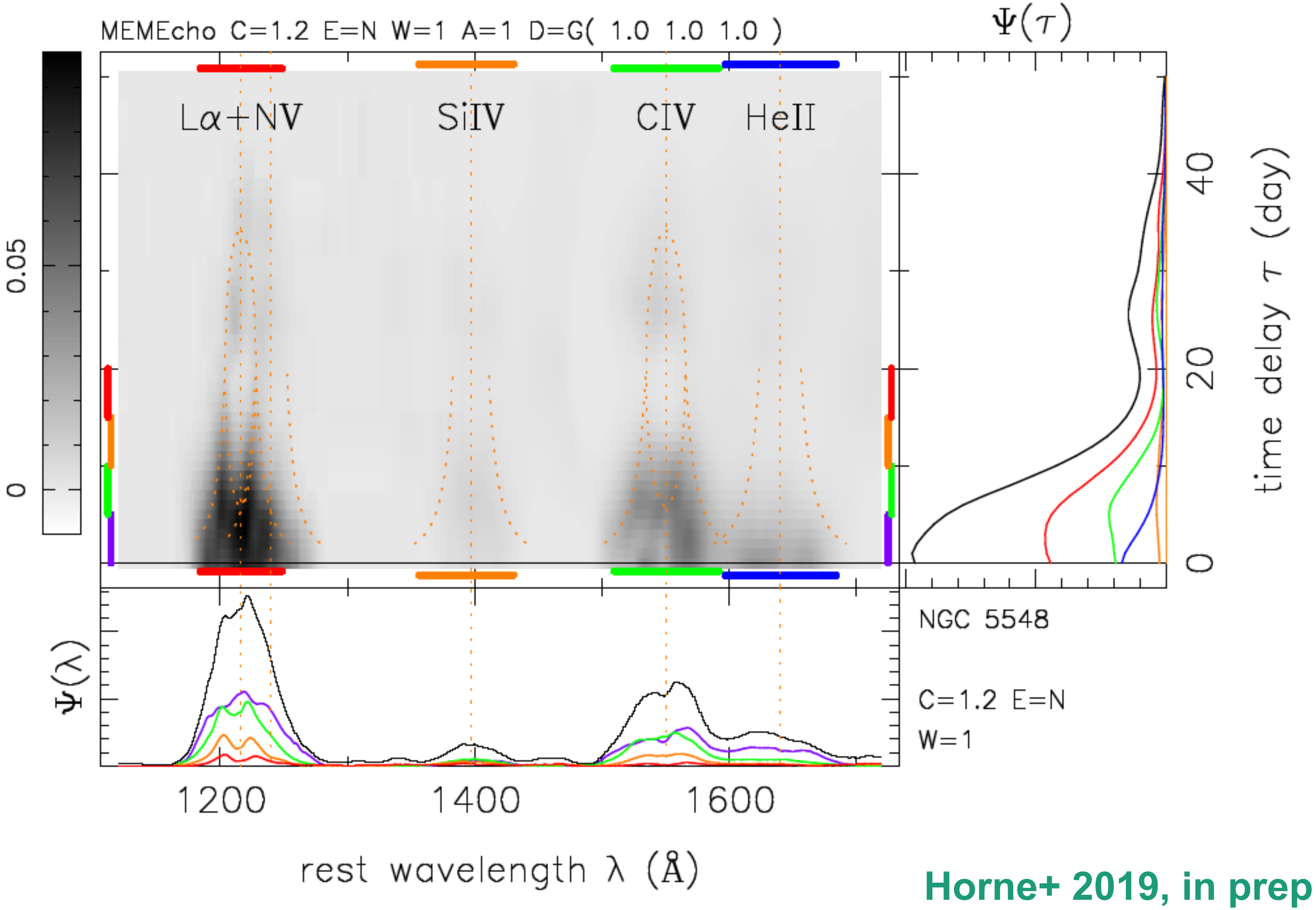




The equivalent width of Hβ (line to continuum ratio) is also low

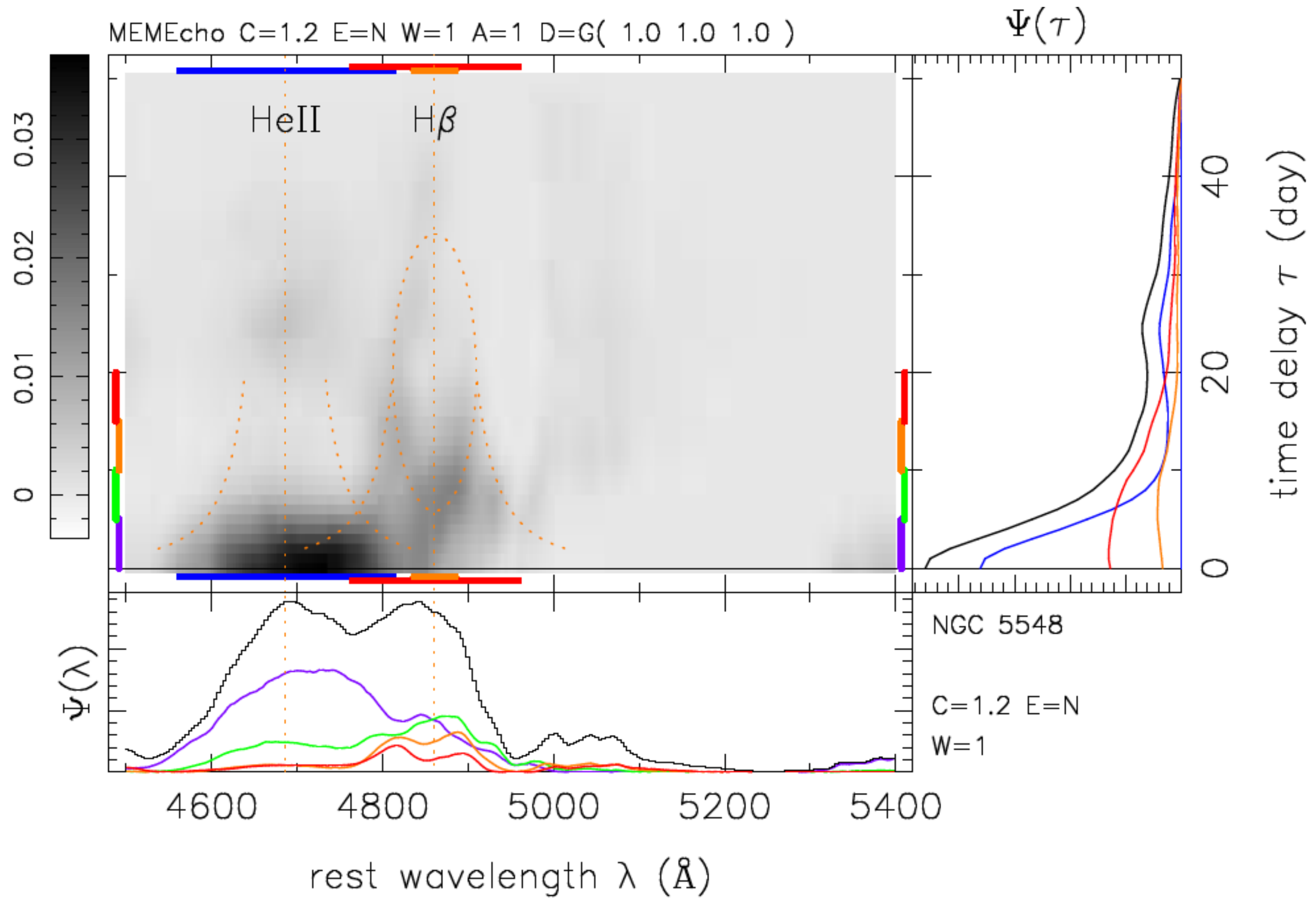
➔Is some BLR gas shielded?

UV Velocity-Delay Maps



Horne+ 2019, in prep

Optical Velocity-Delay Maps

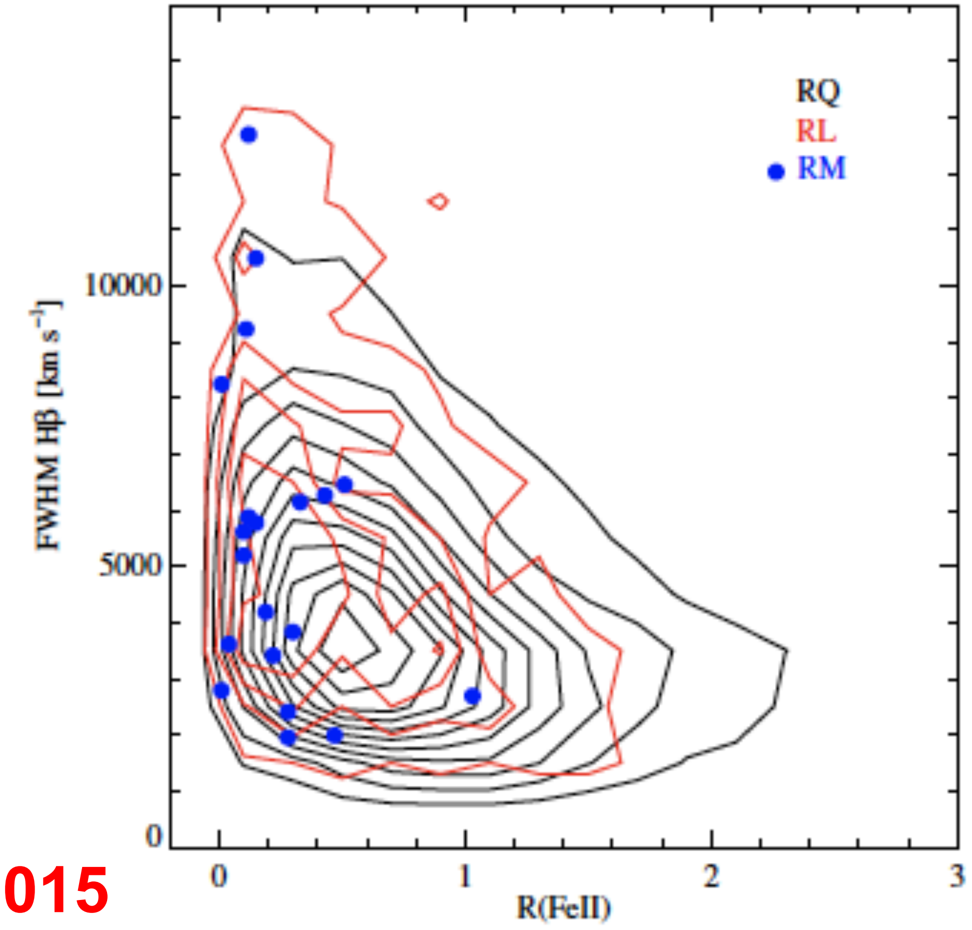


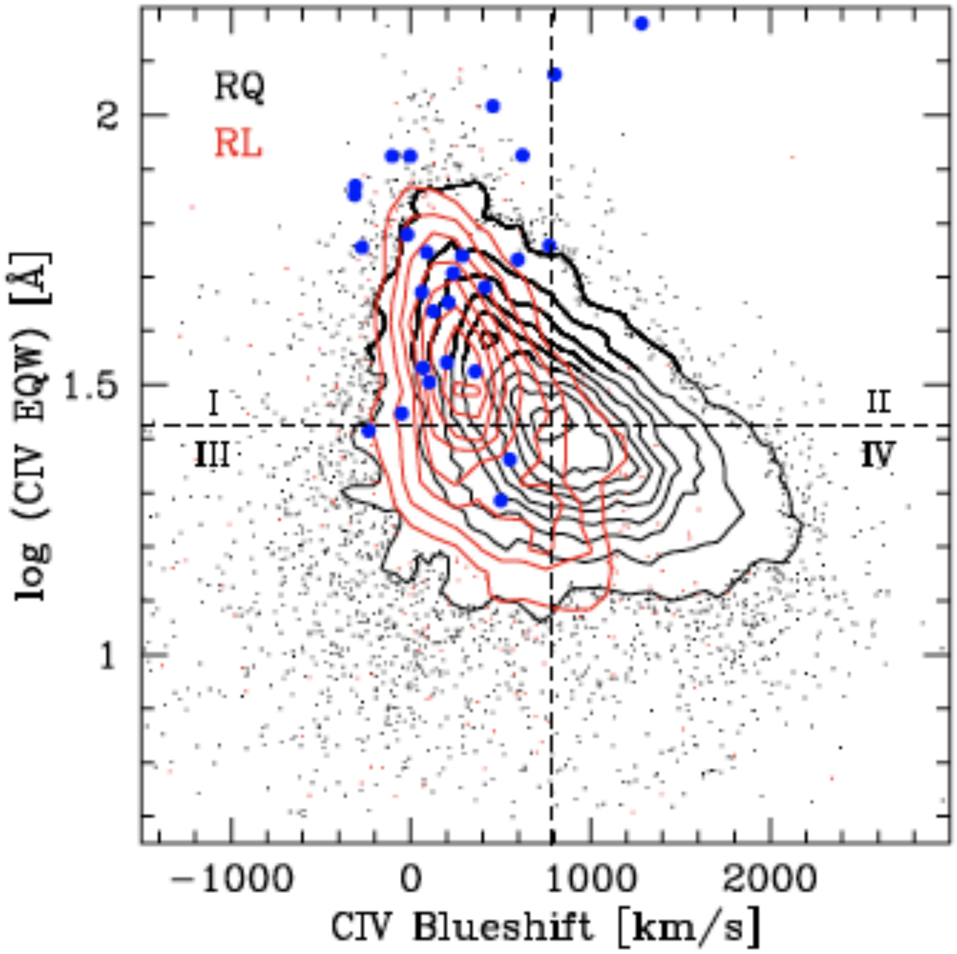
Horne+ 2019, in prep

The Current RM Database

- Published RM database has < 100 mass measurements, but only a dozen or so sources with kinematic information.
  - Misty Bentz maintains a useful website for AGN black hole masses: http://www.astro.gsu.edu/AGNmass
- Most RM results are for Hβ at low redshift.
- There are a number of important biases in the RM database.
- There are a number of RM programs (many talks here!) designed to probe a broader parameter space.

Bias in RM Samples





Shen+ 2015

RM quasars are lower luminosity and have weaker Fe II than typical

Origin of Biases

- **The fundamental difficulty with RM is that it is resource-intensive.**
- Most RM programs have been carried out on smaller telescopes where large allocations of time are feasible.
  - Selects apparently brighter, nearby, lower-luminosity AGNs
  - For lower luminosities, an RM campaign can succeed in a single observing season
- RM programs have necessarily been ”success oriented.”
  - Bright sources for high S/N spectra
  - Sources previously known to be variable (lower risk)

Expanding the RM database – Guilin talks

- High-luminosity quasars
- High Eddington ratio AGNs
- AGNs with outflows and/or disk winds
- AGNs at high redshift
- Changing-look AGNs

Current thrusts – Guilin talks

- More mass measurements, AGN demographics
  - “Industrial scale” RM (SDSS-RM and OzDES)
  - Lag detection/veracity, lag error estimation
- BLR geometry and kinematics
  - Data analysis and modeling
- Continuum RM (enabled by high cadence observations)
- Dust RM
- X-ray RM
- Complementary data and methods (e.g., microlensing)

RM is a powerful tool for probing unresolved/unresolvable sources by substituting time resolution for angular resolution.

Projected Size of BLR

$$\theta = r / D_A$$

Angular size of BLR of radius *r*

$$F = L / 4\pi D_L^2$$

Observed flux from BLR

$$D_A = D_L (1+z)^{-2}$$

Relationship between angular size distance and luminosity distance

$$r \propto L^{1/2}$$

BLR size-luminosity relation

$$\theta = r / D_A = \frac{r(1+z)^2}{D_L} \propto \frac{(1+z)^2 L^{1/2}}{D_L} \propto (1+z)^2 F^{1/2}$$

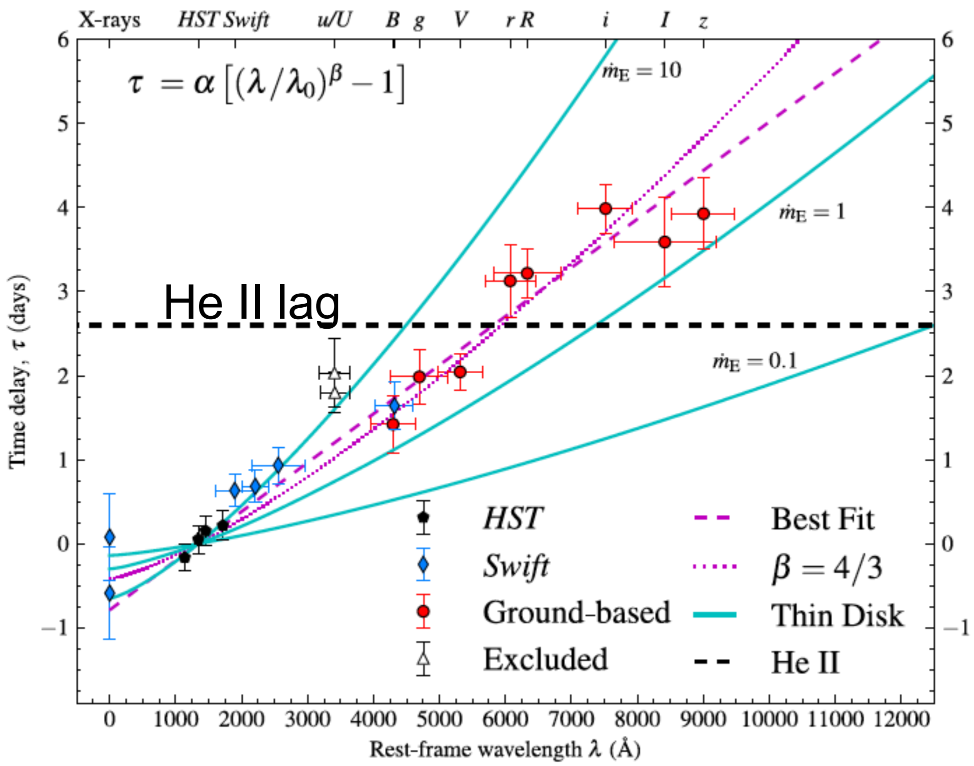
	3C 273	NGC 4151
D_A	550 Mpc	15 Mpc
z	0.15834	0.00332
θ	46 μarcsec	100 μarcsec

Revisiting the Simplifying Assumptions after AGN STORM

1) Central compact continuum source that is much smaller than the BLR
2) The filling factor of the BLR is so low that photons propagate freely at the speed of light.
3) There is a simple relationship between the observed continuum (often at optical wavelengths) and the unobserved ionizing continuum that drives the lines.
4) The most important timescale is the BLR light-crossing time $\tau_{LT} = r/c$.

Peterson 1993

Continuum Lag Spectrum



Fausnaugh+ 2016

- Assume delays are light-travel time (variations driven by irradiation of disk)
- Disk is ~3× larger than Shakura−Sunyaev model prediction (for Eddington ratio ~0.1)
- Best-fit slope is β = 0.99 ± 0.14 (dashed magenta)

Revisiting the Simplifying Assumptions

1) ~~Central compact continuum source that is much smaller than the BLR~~
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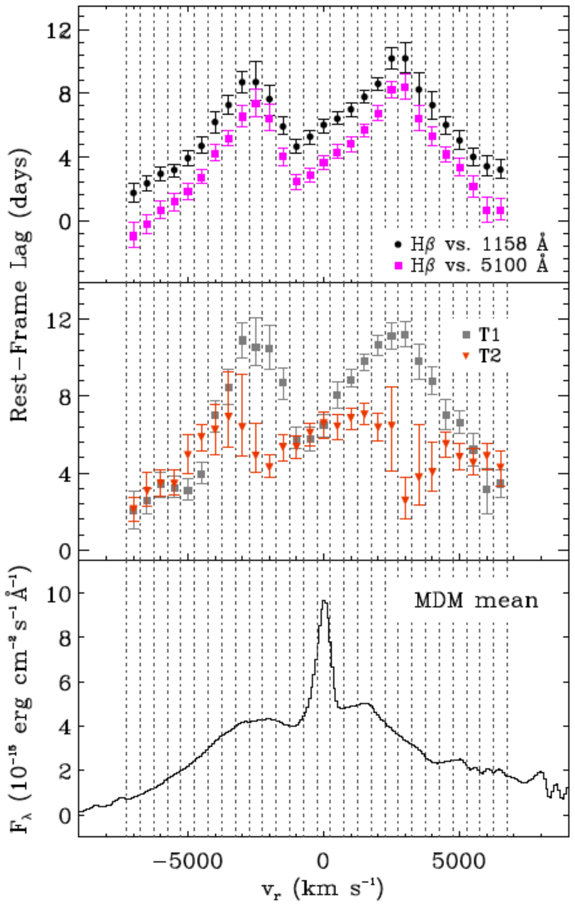
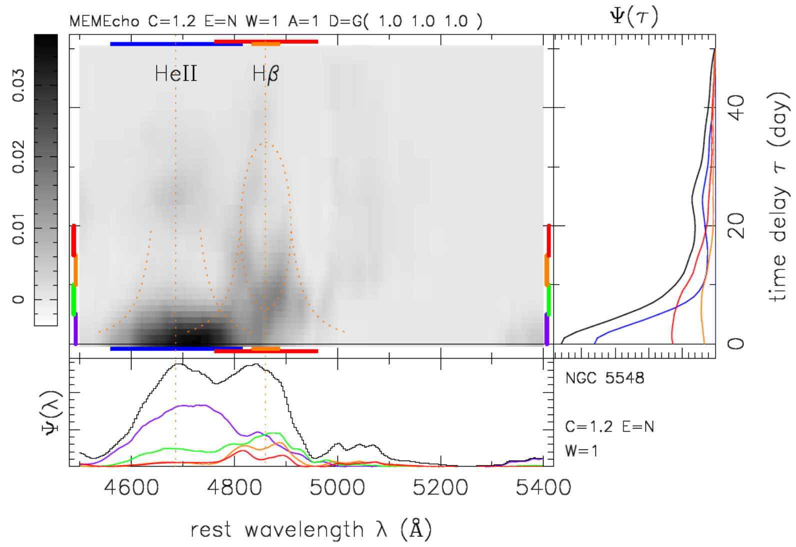
Peterson 1993

Weak Response of Far Side Implies Absorption Occurring with the BLR





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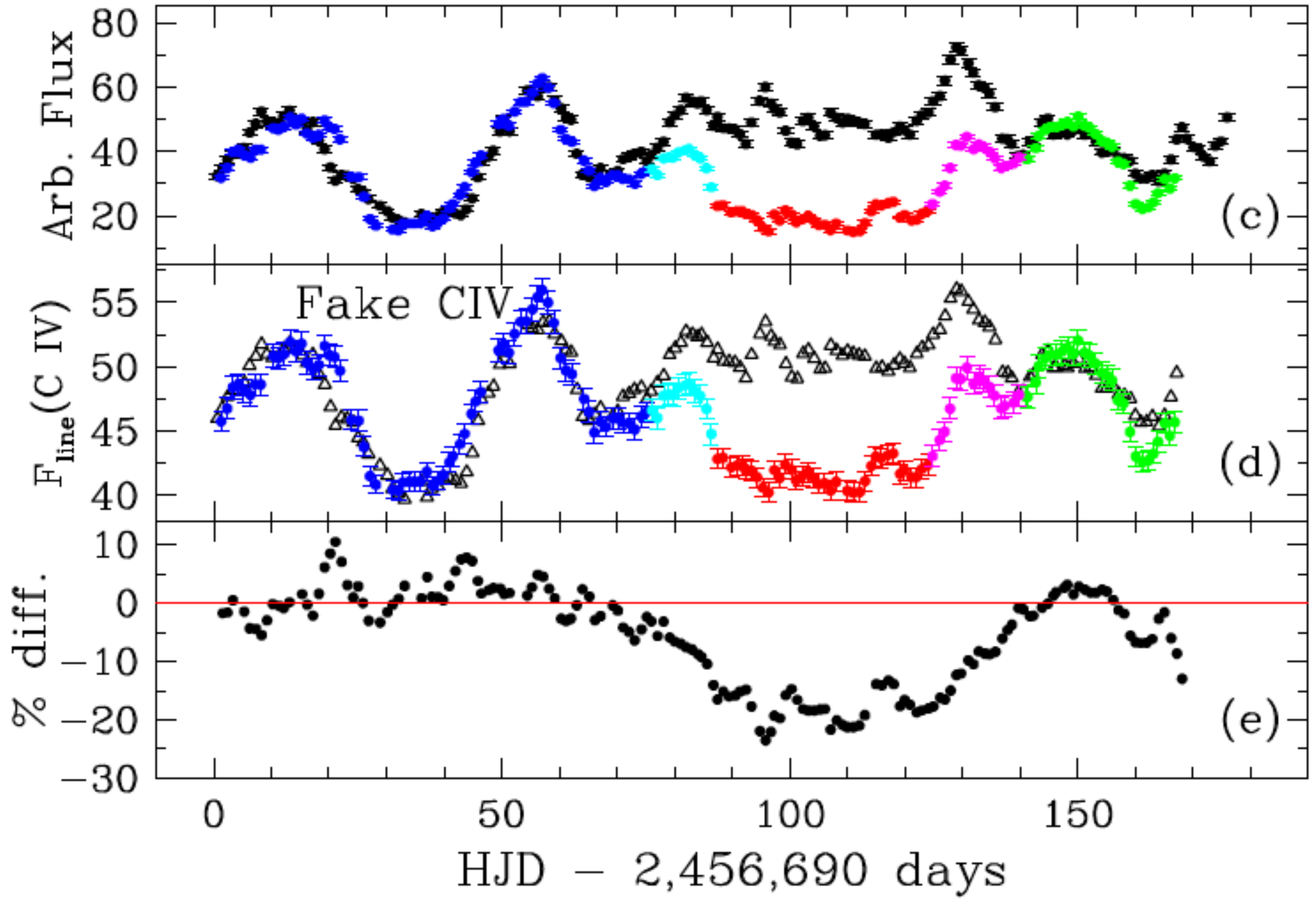
Peterson 1993

Line Responses "De-cohere"
60 Days into STORM Campaign



Goad+ 2016

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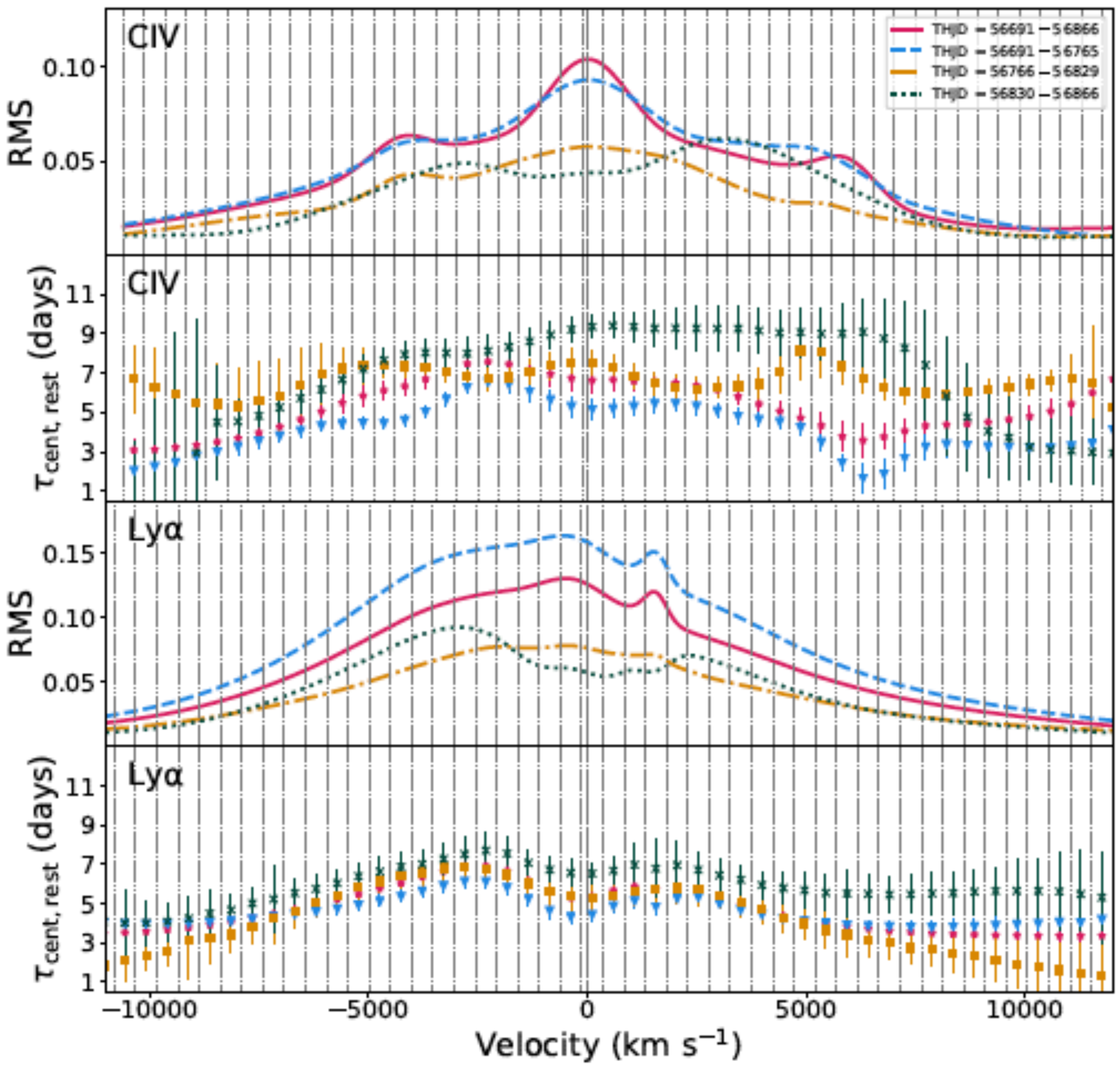
Peterson 1993

Lyα and CIV RMS profiles and lag spectra for different time intervals



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Peterson 1993

Take-away message

- Reverberation mapping works, but as we get better data, we find that AGNs are complex.
- We cannot analyze RM data using geometry only: photoionization physics and radiative transfer must be included.
- In at least some objects at some times, there are secular changes that complicate interpretation. Some changes are associated with variable absorption on BLR and sub-BLR scales (talk by Jerry Kriss).