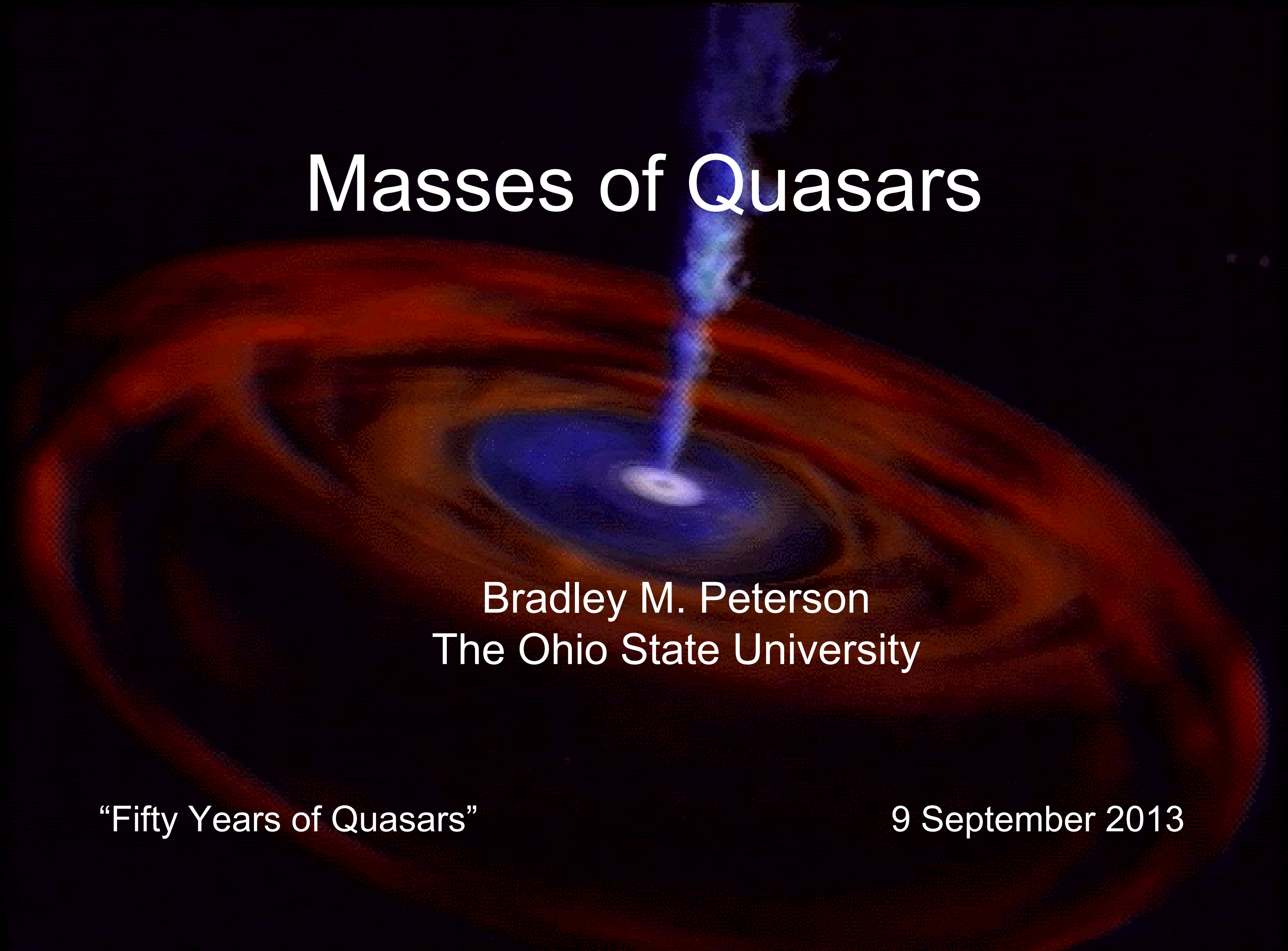


Masses of Quasars

Bradley M. Peterson
The Ohio State University

"Fifty Years of Quasars"

9 September 2013

Measuring Central Black-Hole Masses: Direct vs. Indirect Methods

- *Direct methods:* based on dynamics of gas or stars accelerated by the central black hole.
  - Stellar dynamics, gas dynamics, reverberation mapping
- *Indirect methods:* based on observables correlated with the mass of the central black hole.
  - M_{BH}–σ_* and M_{BH}–L_{bulge} relationships, fundamental plane, AGN scaling relationships (R_{BLR}–L)

Primary and Secondary Methods

- Depends on model-dependent assumptions required.
- Fewer assumptions, little model dependence:
  - Proper motions/radial velocities of stars and megamasers (Sgr A*, NGC 4258)
- More assumptions, more model dependence:
  - Stellar dynamics, gas dynamics, reverberation mapping
    - Since the reverberation mass scale currently depends on other "primary direct" methods for a zero point, it is currently technically a "secondary method" though it is a "direct method."
    - It will soon become a primary method.

Early Mass Estimates: The Eddington Limit

$$\frac{L\sigma_e}{4\pi r^2 c} < \frac{GMm}{r^2}$$

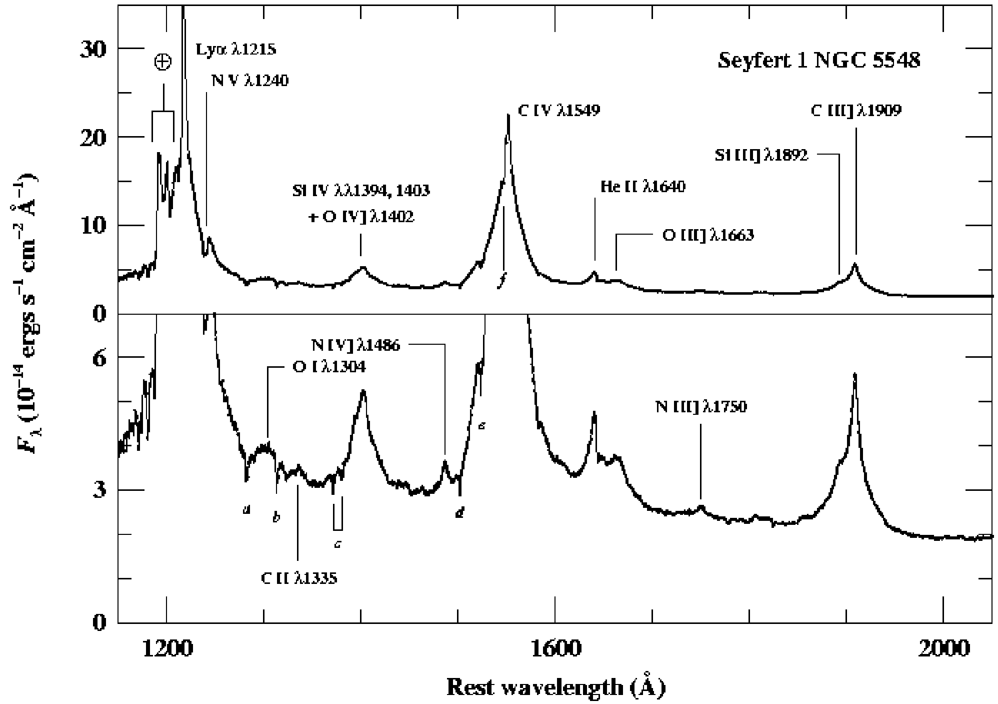
$$L < \frac{4\pi Gcm}{\sigma_e} M \approx 1.26 \times 10^{38} \left(\frac{M}{M_\odot} \right) \text{ergs s}^{-1}$$

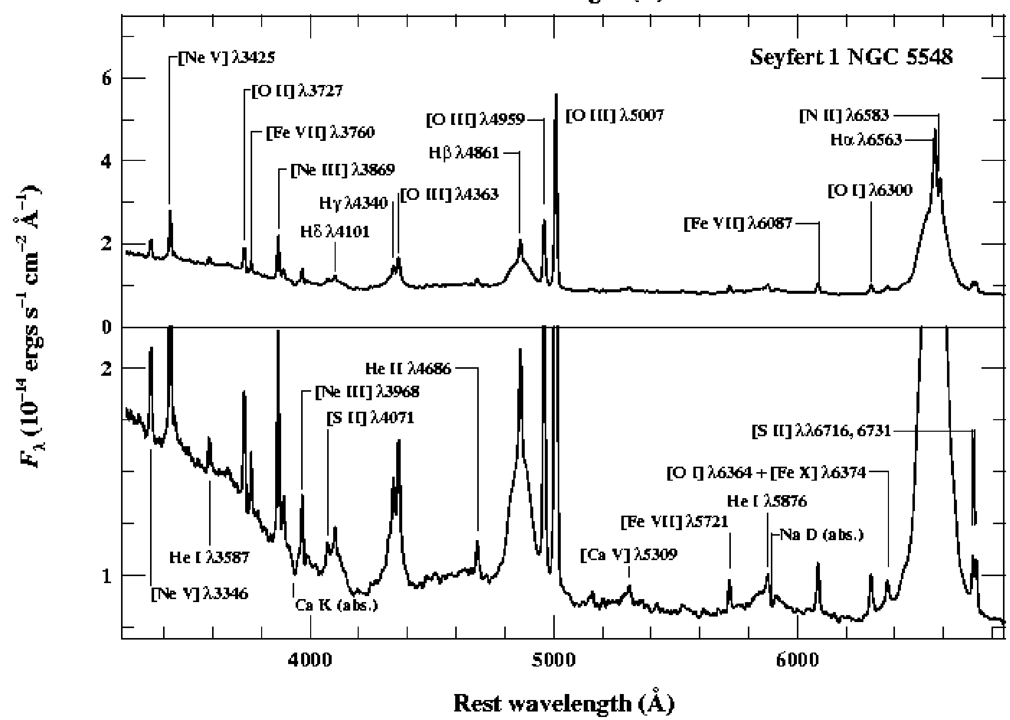
- Outward radiation pressure cannot exceed gravity.

$$L \sim 10^{45} \text{ erg s}^{-1} \Rightarrow M > 10^7 M_\odot$$

The Broad-Line Region

- $1000 \leq \text{FWHM} \leq 25{,}000$ km s^{-1} $\Rightarrow$ motion in deep potential?
  - $M \sim r\,\Delta V^{2}/G$
- Spectra $\Rightarrow$ Photoionized gas at $T \approx 10^4$ K
- Absence of forbidden lines implies high density
  - But C III] λ1909 $\Rightarrow$ $n_e < 10^{10}$ cm^{-3}





The (Dimensionless) Ionization Parameter *U*

Rate at which H-ionizing photons are emitted by source.

$$Q_{\rm ion}(H) = \int_{\nu_{\rm ion}}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$$

Ratio of ionizing photon density at distance *r* from source to particle density.

$$U = \frac{Q_{\rm ion}(H)}{4\pi r^2 c n_{\rm H}}$$

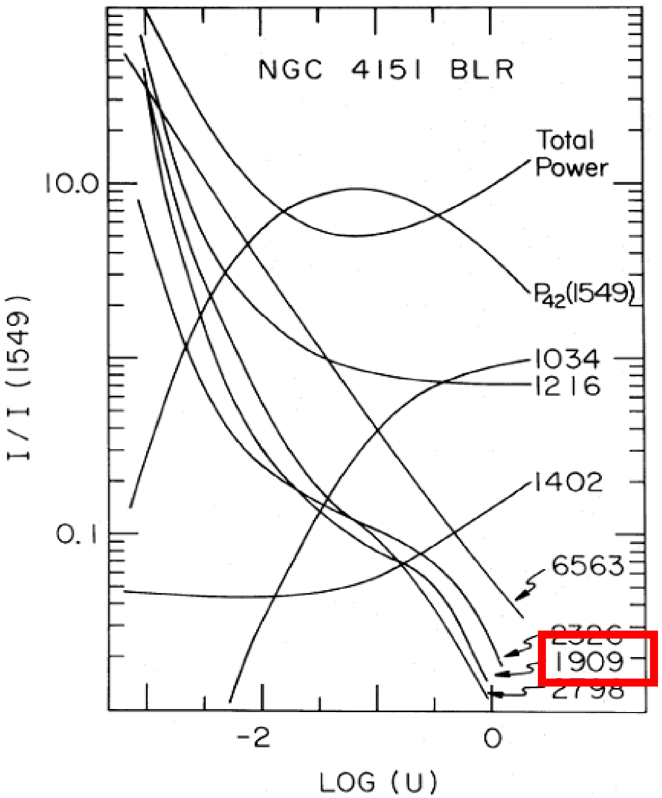
Aside:

$$r = \left[\frac{Q_{\rm ion}}{4\pi U c n_{\rm H}}\right]^{1/2} \propto L^{1/2}$$

Davidson 1972

Photoionization Model of the BLR in NGC 4151

- Single-cloud model cannot simultaneously fit low and high-ionization lines.
- Energy budget problem: line luminosities require more than 100% of the continuum energy.
- Single-cloud models predict size of BLR of order light year in bright Seyfert galaxies.

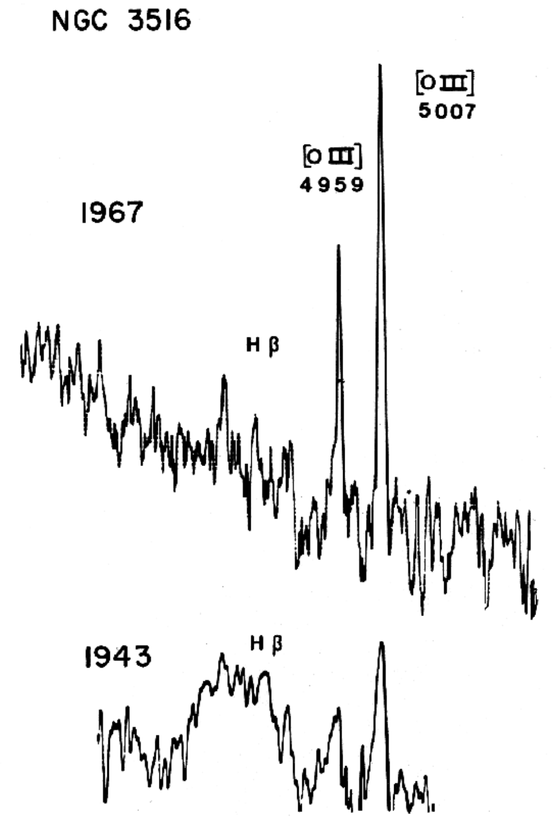


Ferland & Mushotzky 1982

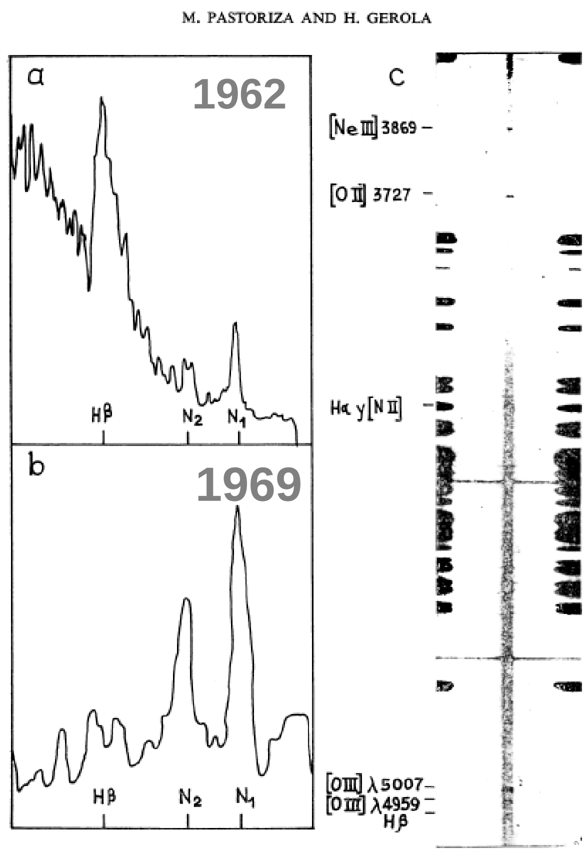
Emission-Line Variability in Seyfert 1s

- First detected reported by Andrillat & Souffrin (1968) in NGC 3516
- Second case (NGC 1566) found by Pastoriza & Gerola (1970)

Photographic spectra reveal only extreme changes.



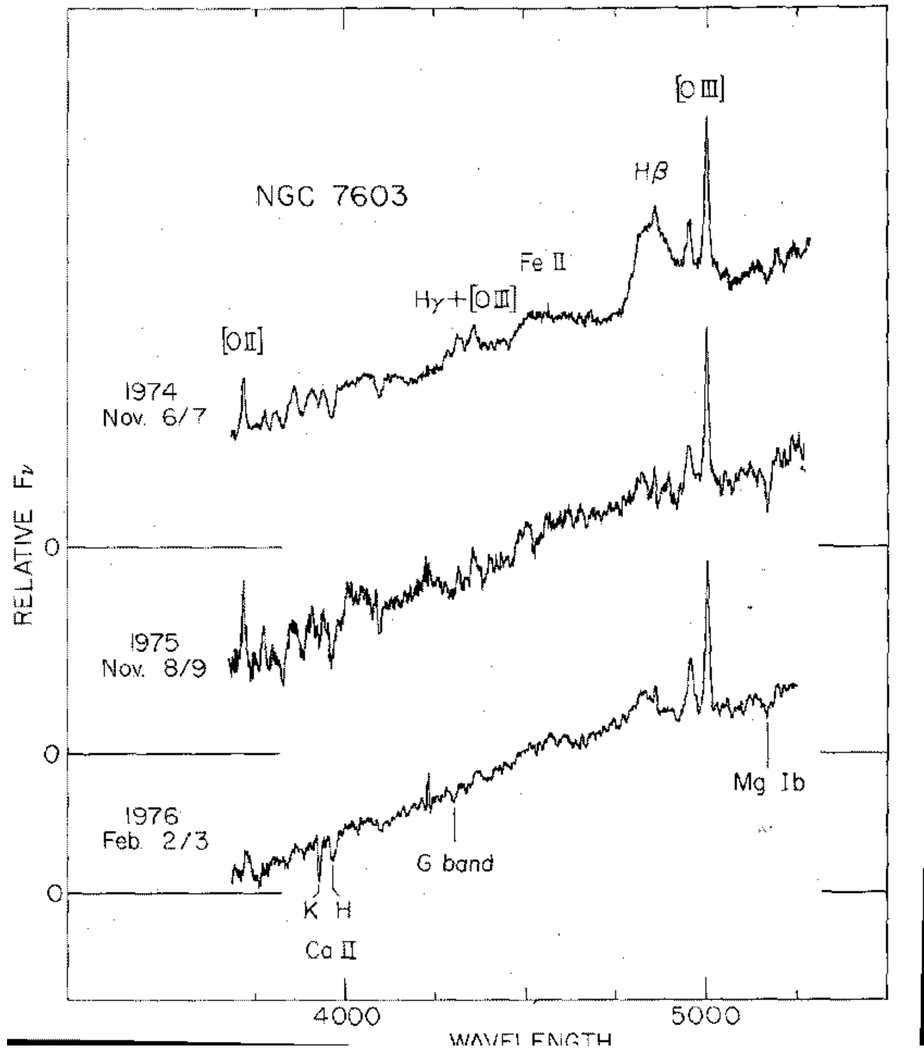
Andrillat & Souffrin 1968



Pastoriza & Gerola 1970

Emission-Line Variability

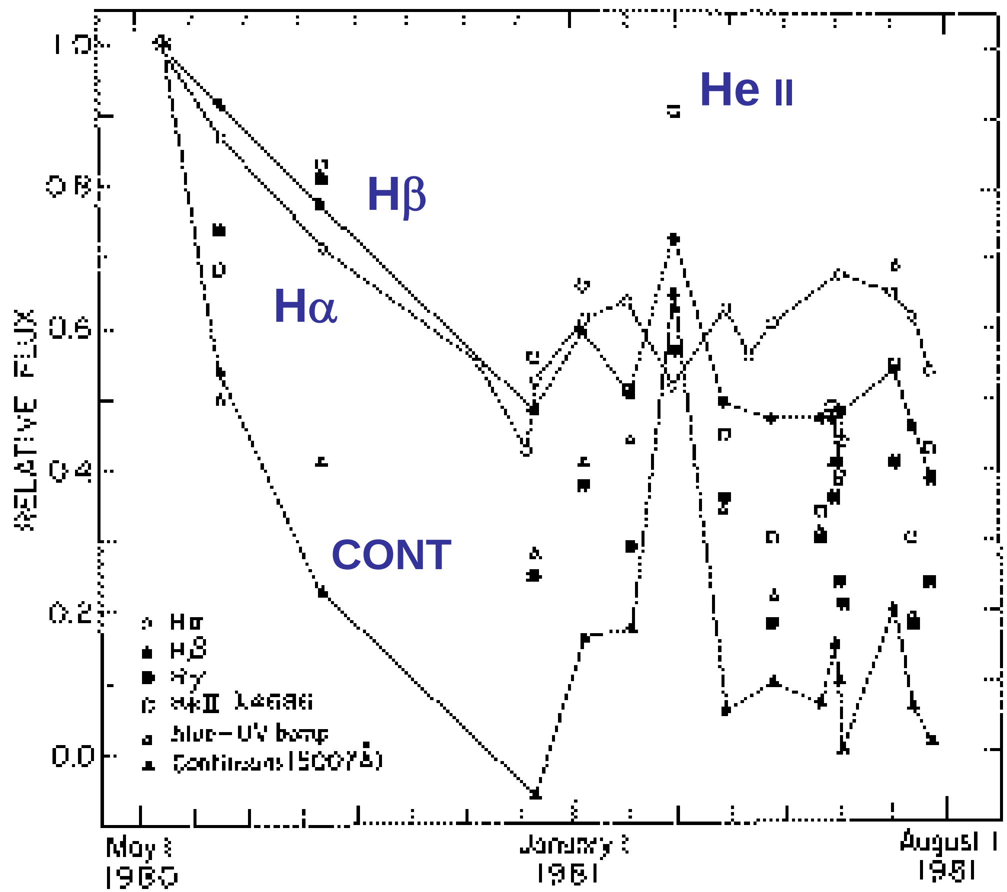
- Only very large changes could be detected photographically or with intensified television-type scanners (e.g., Image Dissector Scanners).
- Changes that were observed were often dramatic and reported as Seyferts "changing type" as broad components appeared or disappeared.



Tohline & Osterbrock 1976

First Monitoring Programs

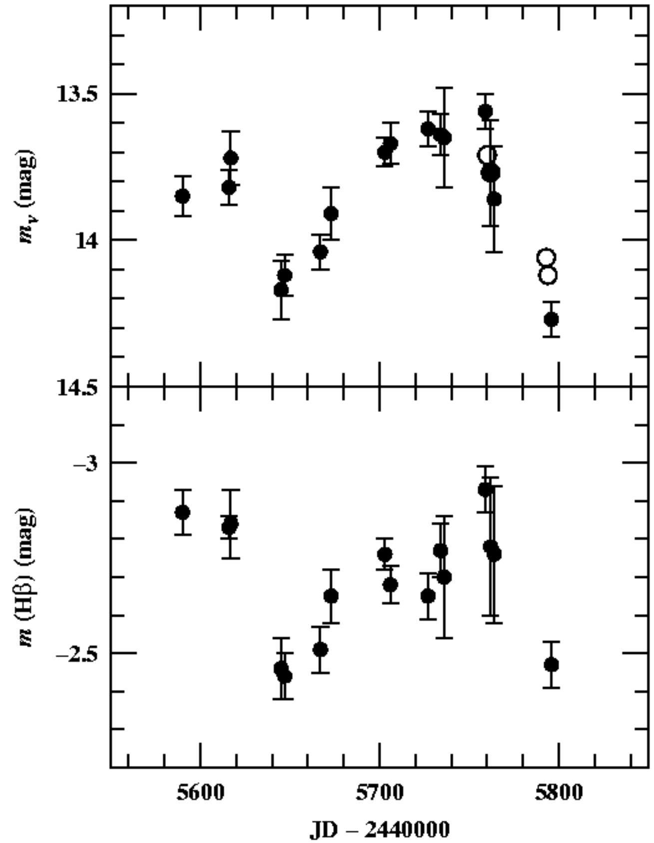
- NGC 4151: Monitored at Lick Observatory by Antonucci and Cohen in 1980-81
  - short time scale response of Balmer lines (<1 month)
  - higher amplitude variability of higher-order Balmer lines and He II λ4686



Antonucci & Cohen 1983

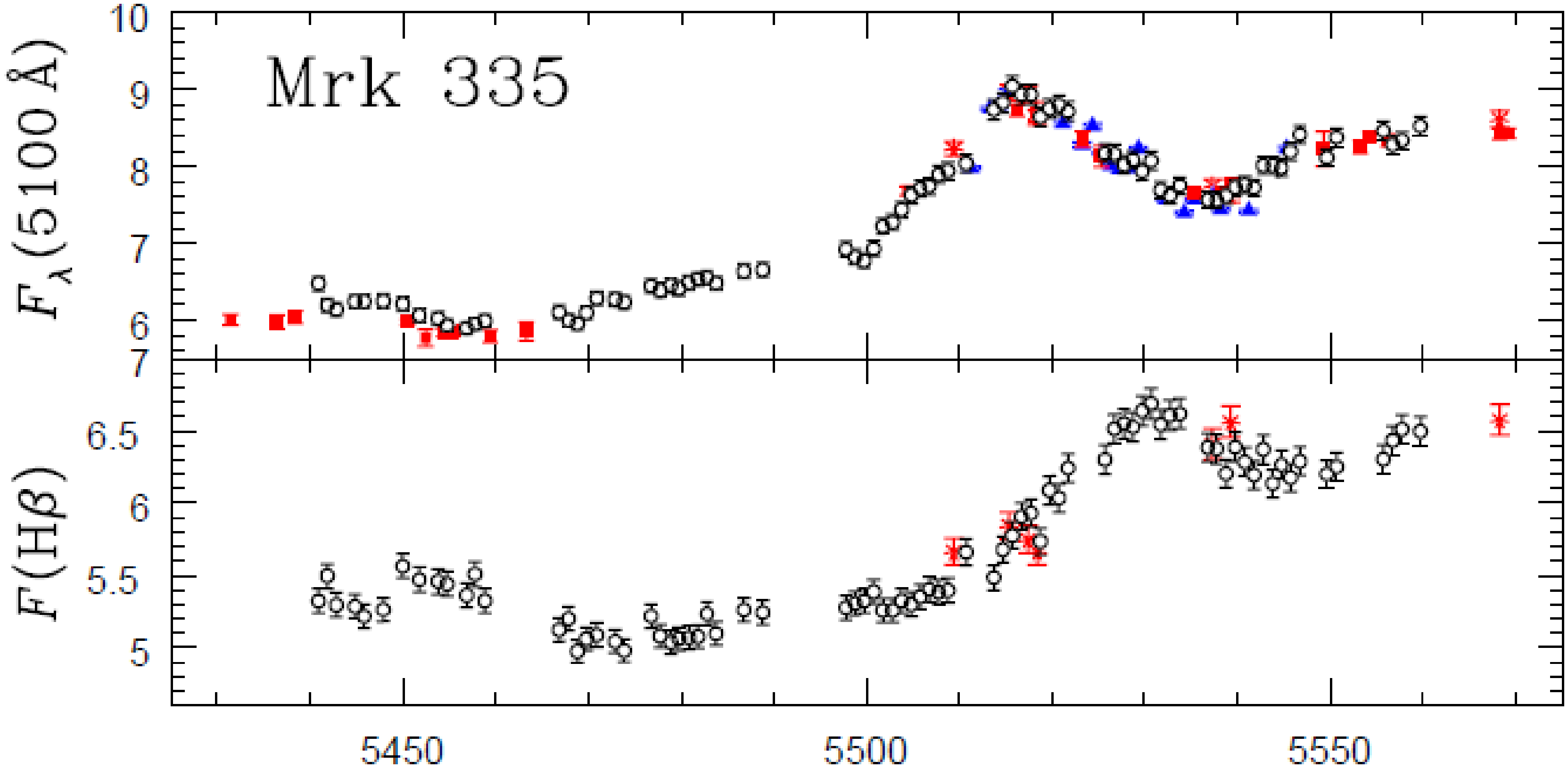
First Monitoring Programs

- Akn 120:
  - Monitored in optical by Peterson et al. (1983; 1985).
    - Hβ response time suggested BLR less than 1 light month across
    - Suggested serious problem with existing estimates of sizes of broad-line region
  - Higher luminosity source, so monthly sampling provided more critical challenge to BLR models



Data from Peterson et al. 1985

Reverberation Mapping

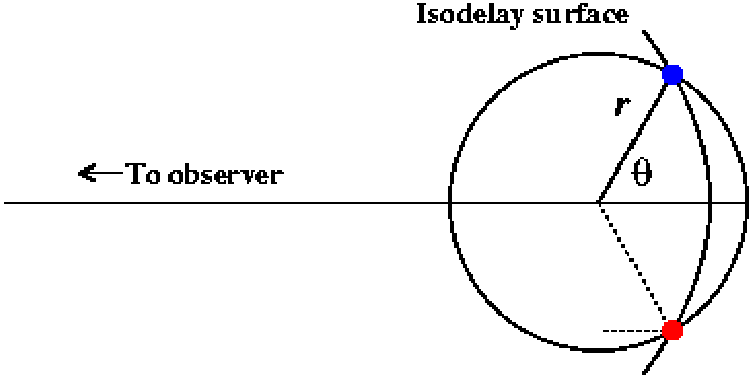


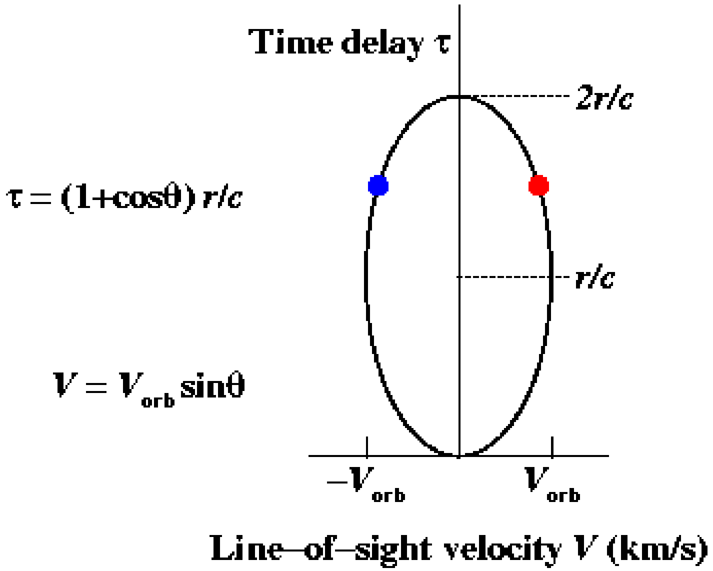
Emission line variations follow those in continuum with a small time delay (14 days here) due to light-travel time across the line emitting region.

Grier+ 2012, ApJ, 744, L4

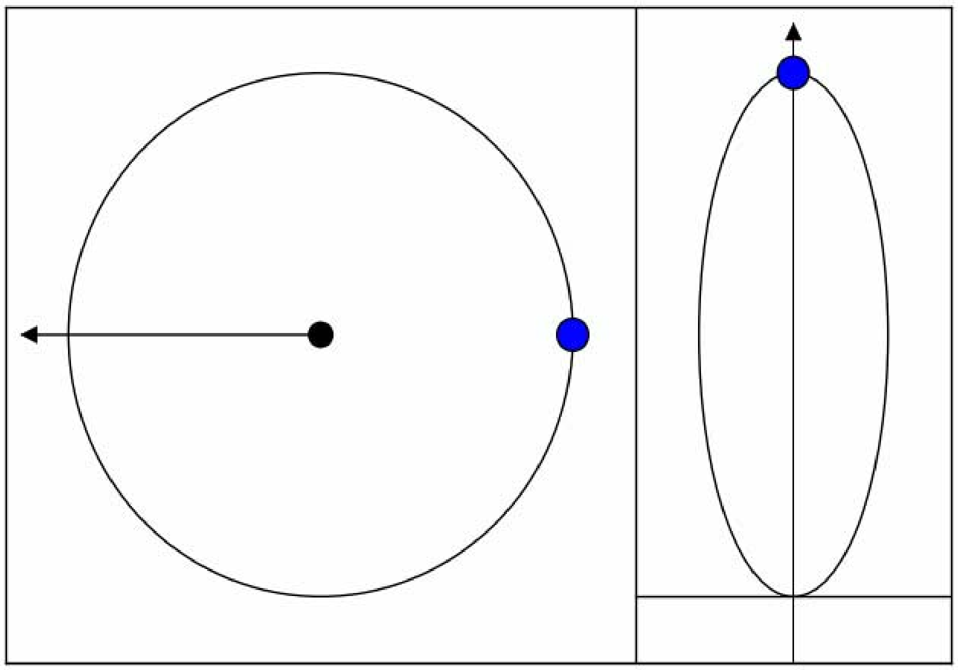
Velocity-Delay Map for an Edge-On Ring

- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V = \pm V_{\mathrm{orb}} \sin\theta$.
- Response time is $\tau = (1 + \cos\theta)r/c$
- Circular orbit projects to an ellipse in the (V, τ) plane.



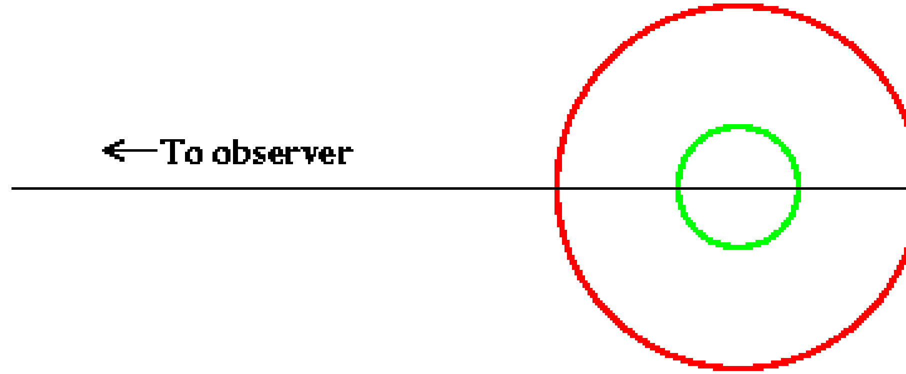


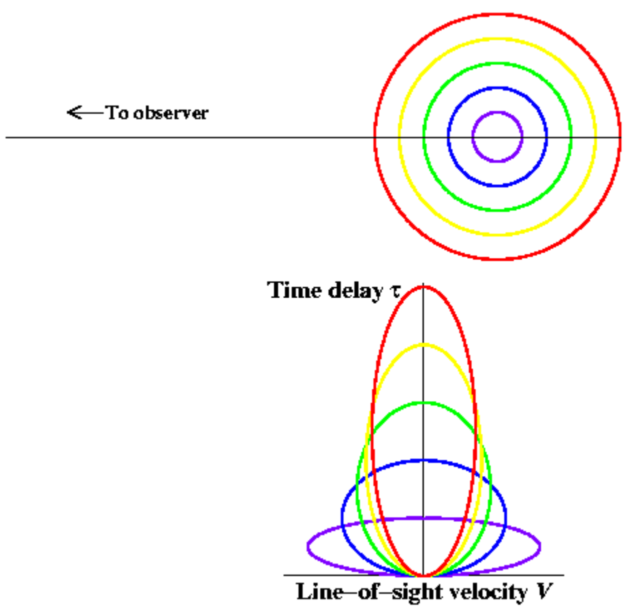
Velocity-Delay Map



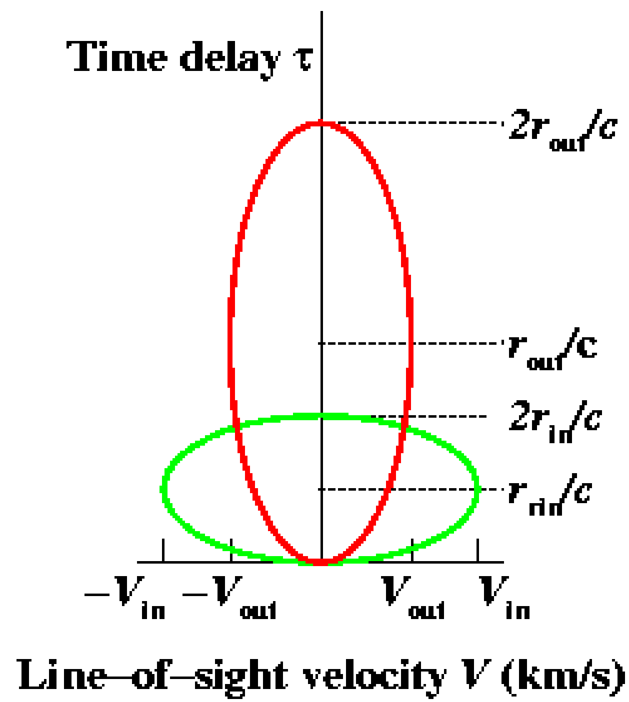
Thick Geometries

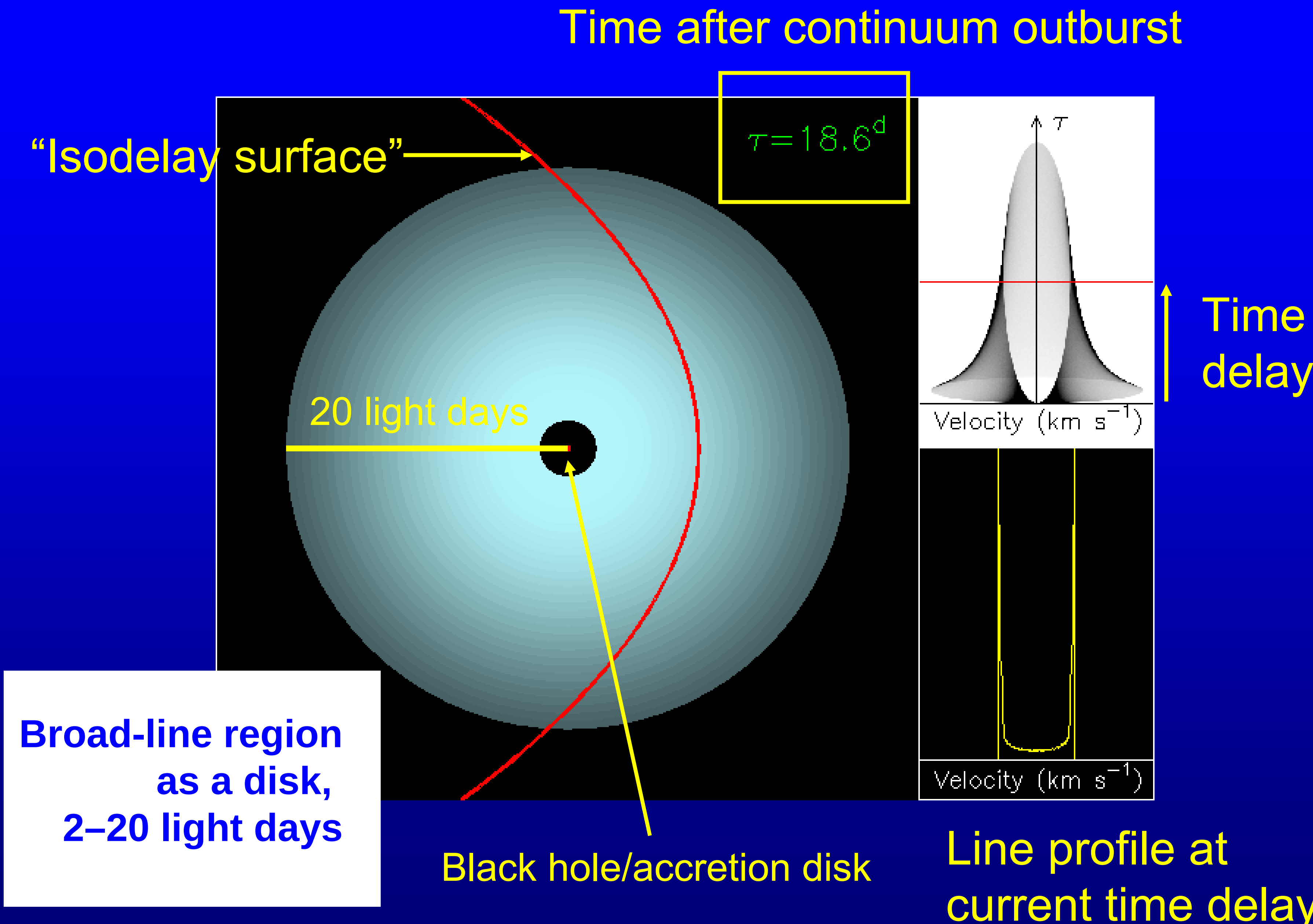
- Generalization to a disk or thick shell is trivial.
- General result is illustrated with simple two ring system.





A multiple-ring system





Time after continuum outburst
$\tau = 18.6^d$
"Isodelay surface"
20 light days
τ
Velocity (km s^{-1})
Velocity (km s^{-1})
Time delay
Broad-line region as a disk, 2–20 light days
Black hole/accretion disk
Line profile at current time delay

Reverberation Response of an Emission Line to a Variable Continuum

The relationship between the continuum and emission can be taken to be:

$$L(V,t) = \int \Psi(V,\tau)\, C(t-\tau)\, d\tau$$

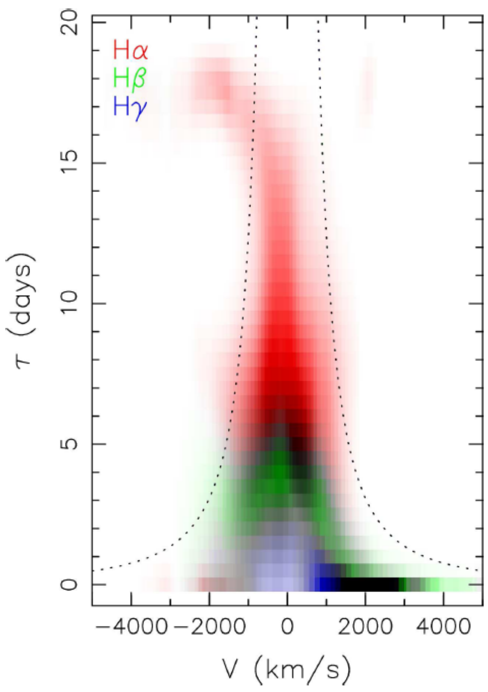
Velocity-resolved emission-line light curve

"Velocity-delay map"

Continuum light curve

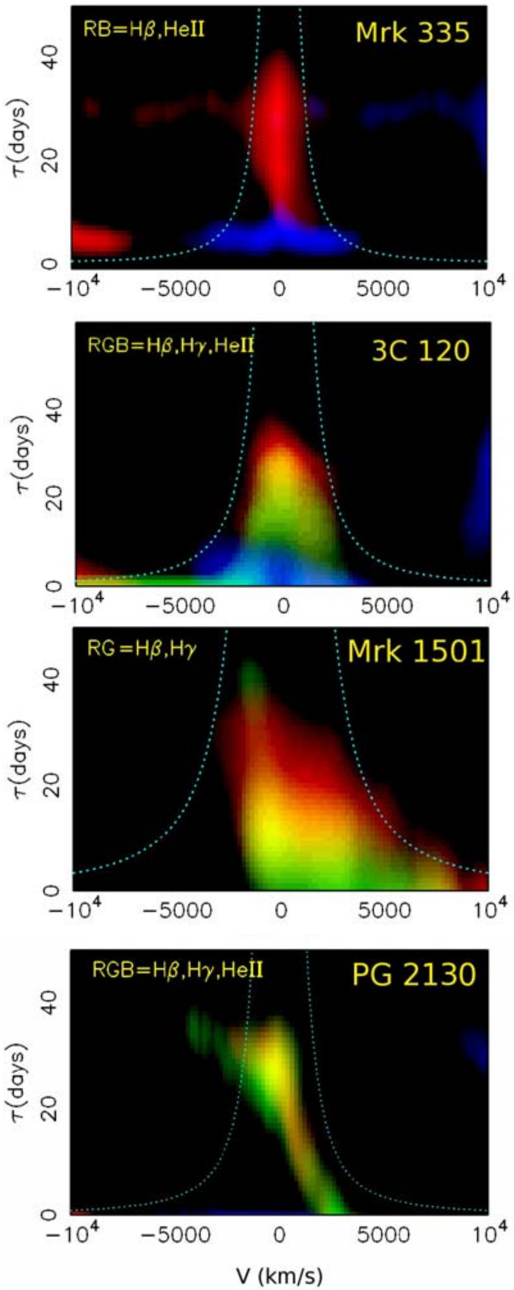
Velocity-delay map is observed line response to a δ-function outburst

Required time sampling, duration, and *S/N* makes velocity-delay map recovery very difficult.

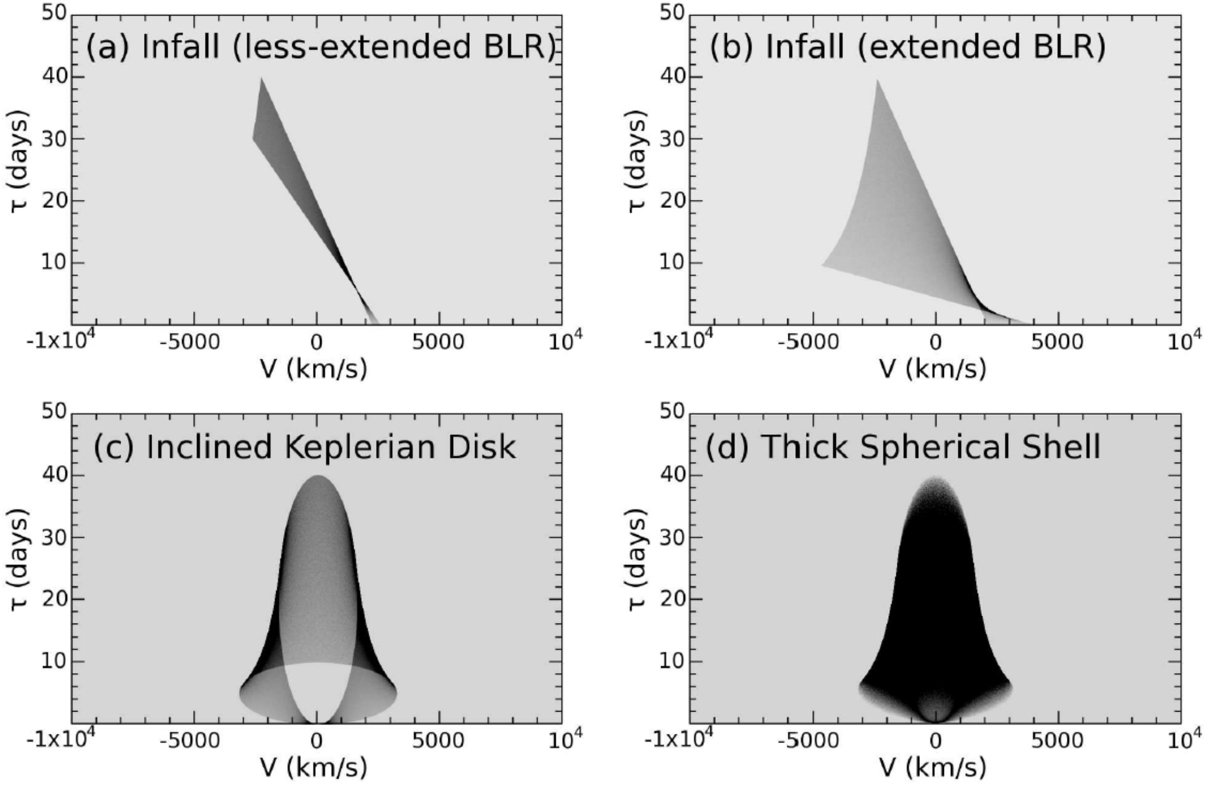


Arp 151

LAMP: Bentz+ 2010

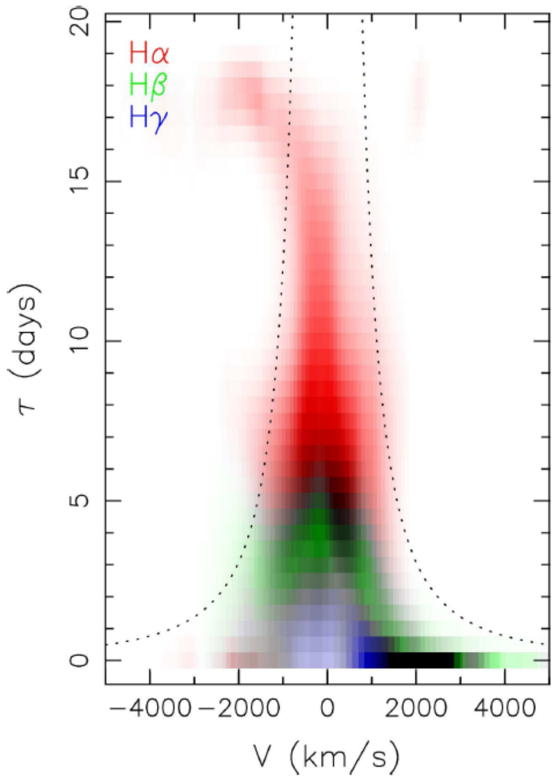


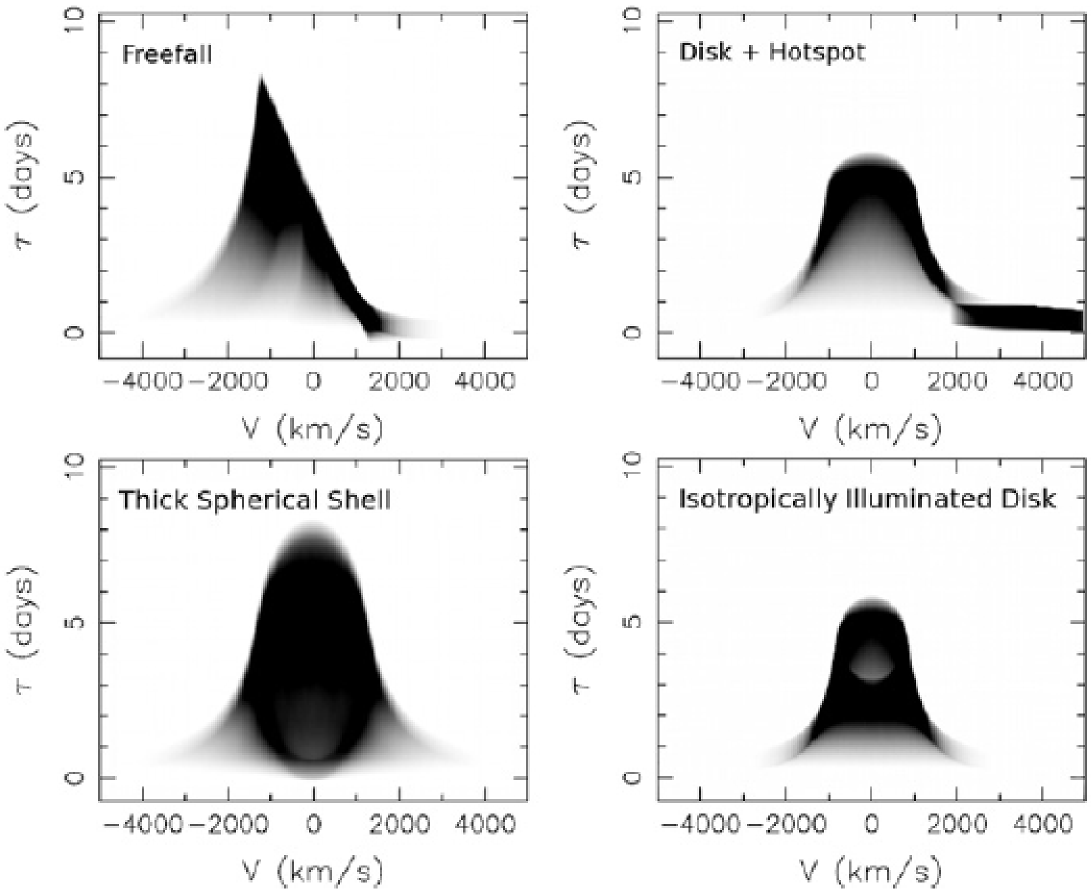
Toy Models



Grier+ 2013, ApJ, 764:47

A Complex Multicomponent Broad-Line Region?





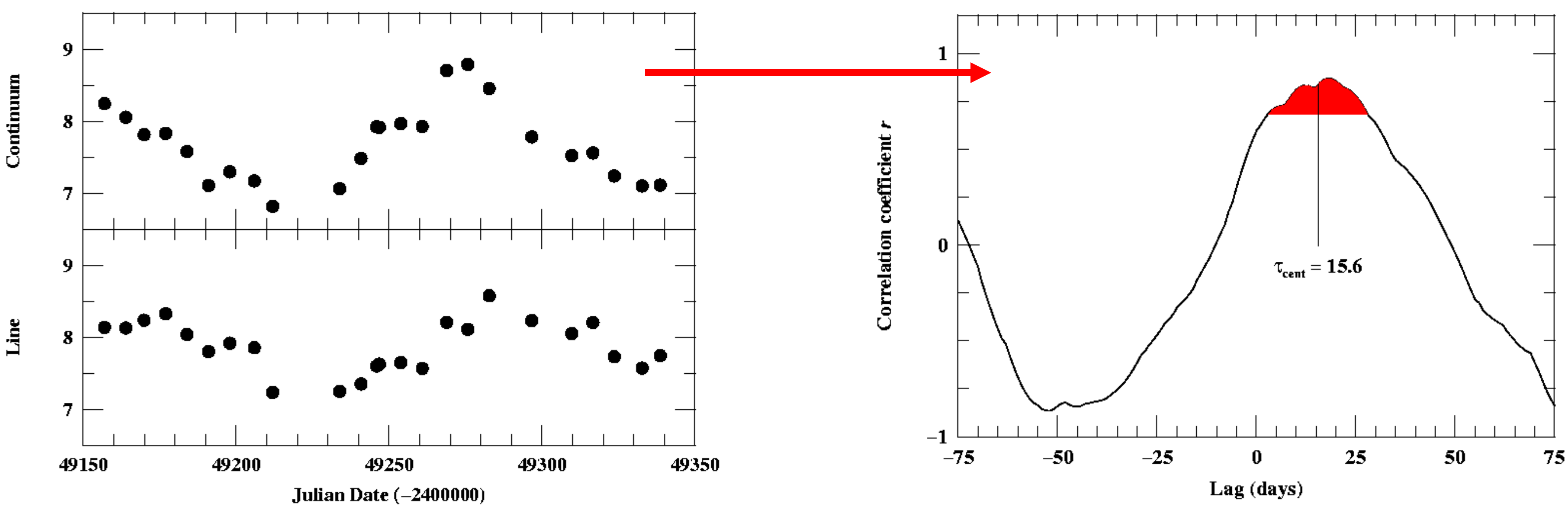
Arp 151

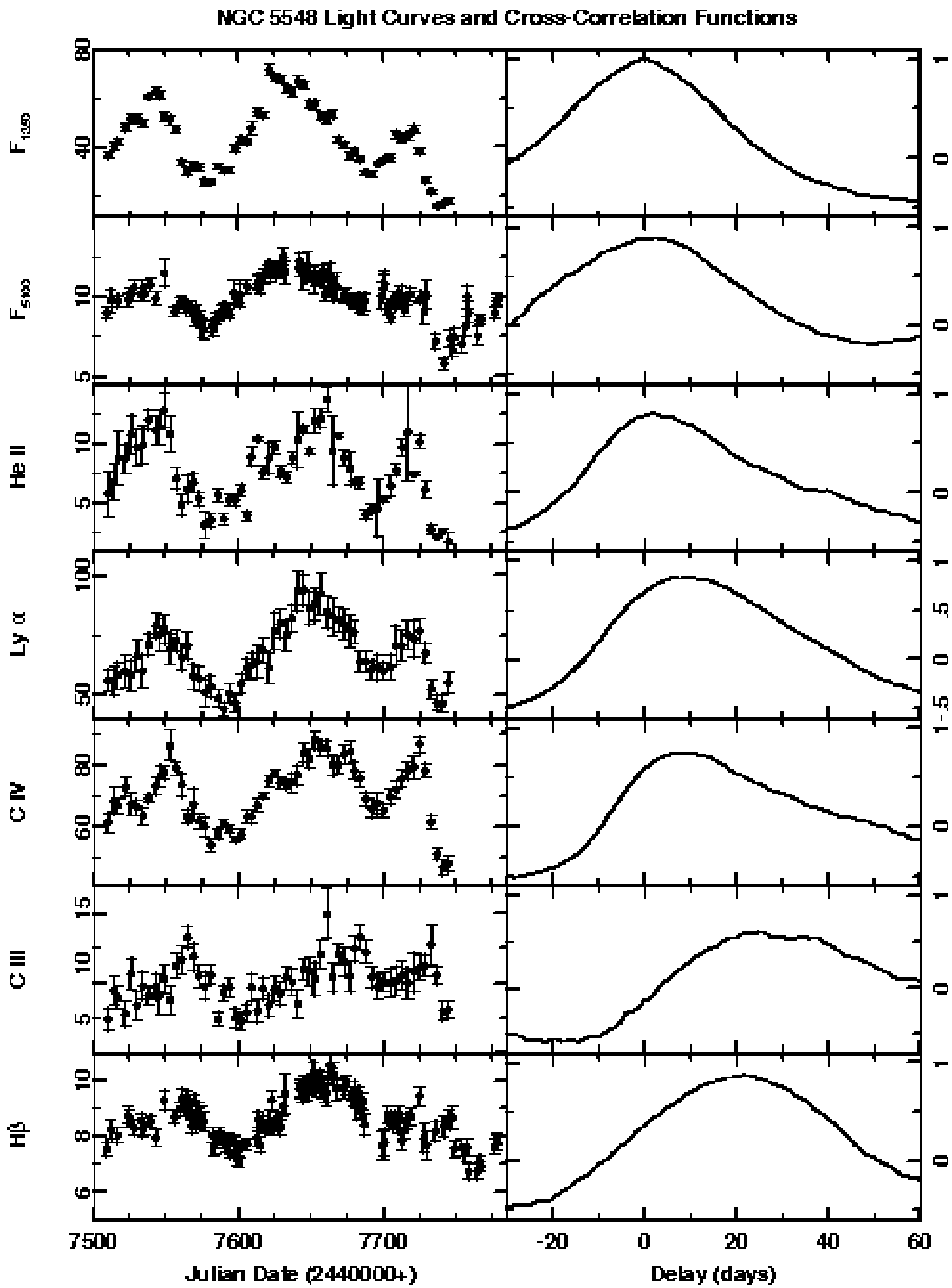
LAMP: Bentz+ 2010

Emission-Line Lags

- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the “lag” (mean response time):

$$\mathrm{CCF}(\tau) = \int \Psi(\tau')\ \mathrm{ACF}(\tau - \tau')\, d\tau'$$

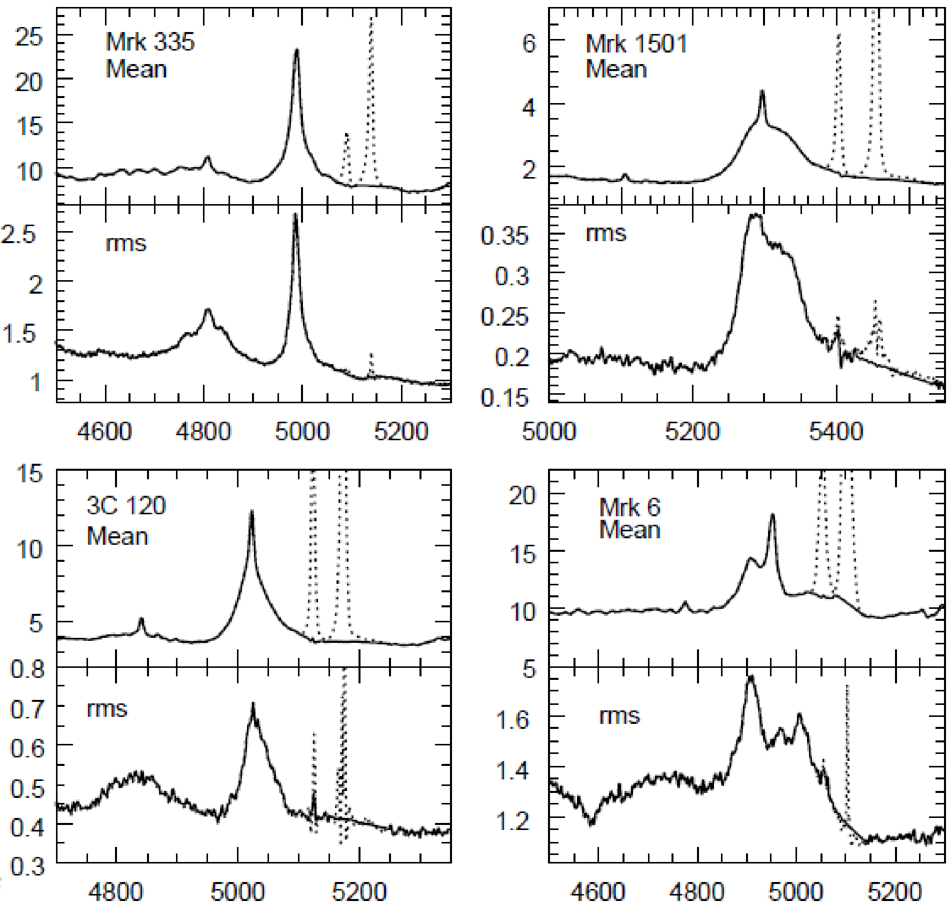




Reverberation Mapping Results

- Reverberation lags have been measured for ~50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

Measuring the Emission-Line Widths

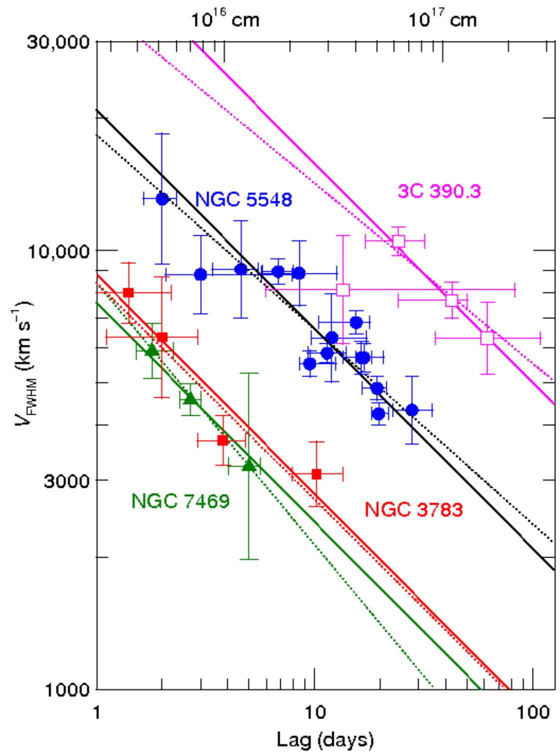


Grier+ 2012, ApJ, 755:60

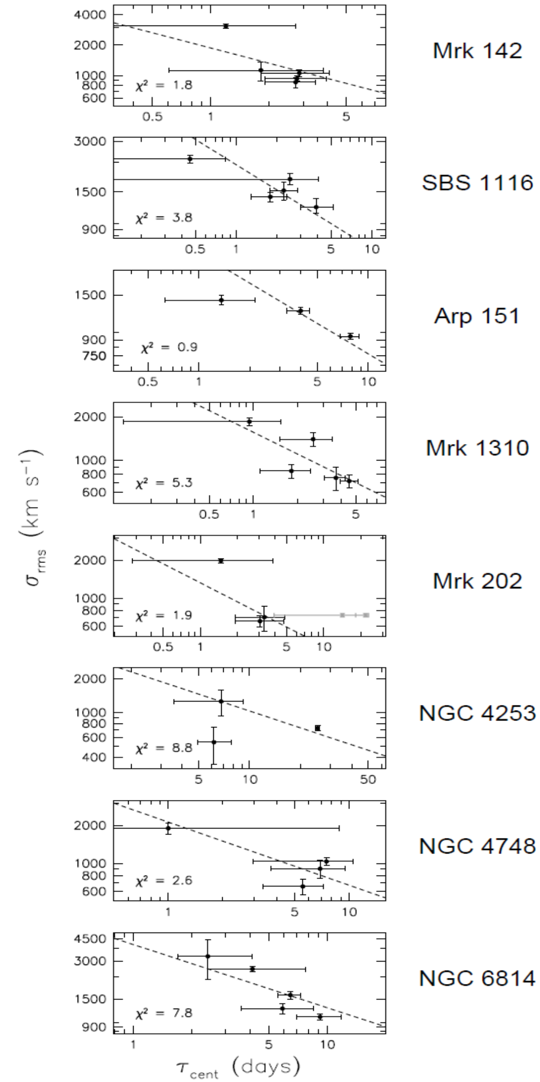
- We preferentially measure line widths in the rms residual spectrum.
  - Constant features disappear, less blending.
  - Captures the velocity dispersion of the gas that is responding to continuum variations.

A Virialized BLR

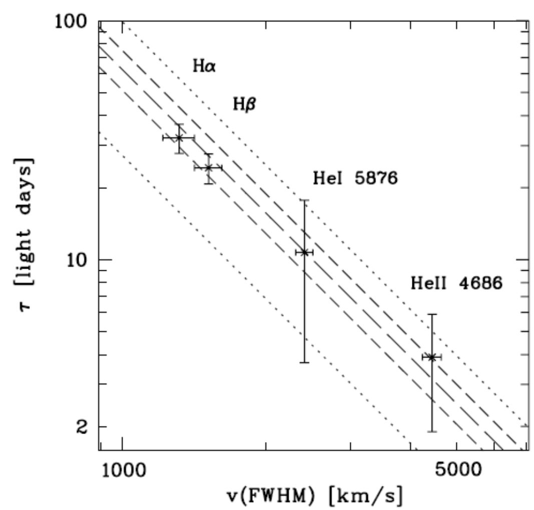
- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.
  - Caveat: radiation pressure!



Peterson & Wandel 2002



Bentz+ 2009



Kollatschny 2003

Reverberation-Based Masses

"Virial Product" (units of mass)

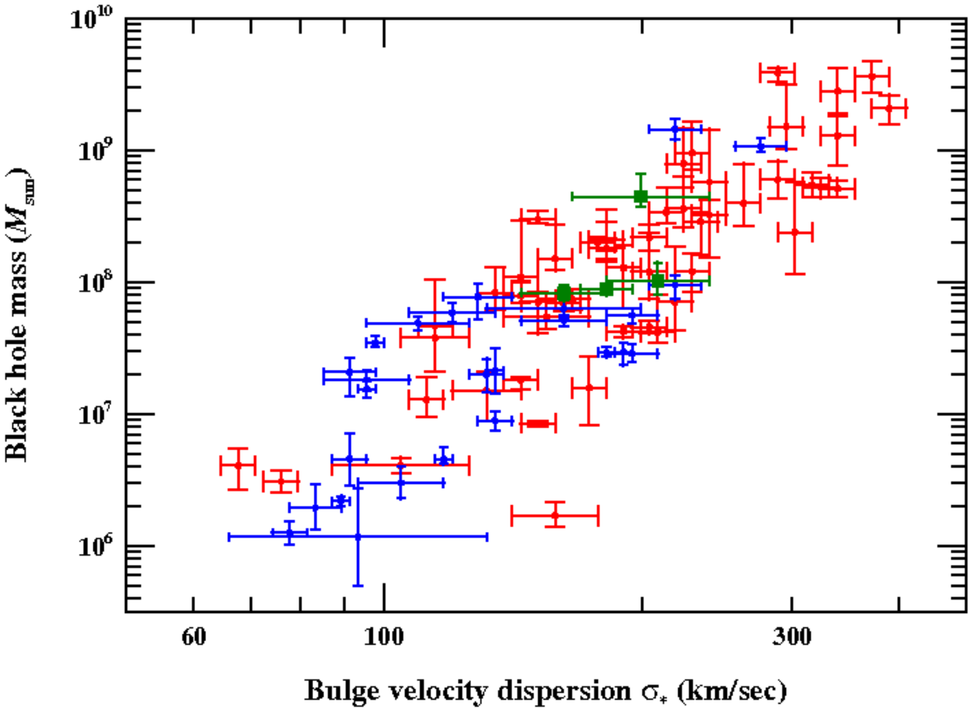
$$M_{\mathrm{BH}} = f \left[\underline{r\, \Delta V^2} / G \right]$$

Observables:
r = BLR radius (reverberation)
ΔV = Emission-line width

Set by geometry and inclination
(subsumes everything we don't know)

If we have independent measures of M_{BH}, we can compute an ensemble average $\langle f \rangle$

The AGN M_{BH}–σ_* Relationship



- AGN
- AGN, new *H*-band σ_*
- Quiescent galaxy

Grier+ 2013, ApJ, 773:90

- Assume zero point of most recent quiescent galaxy calibration.

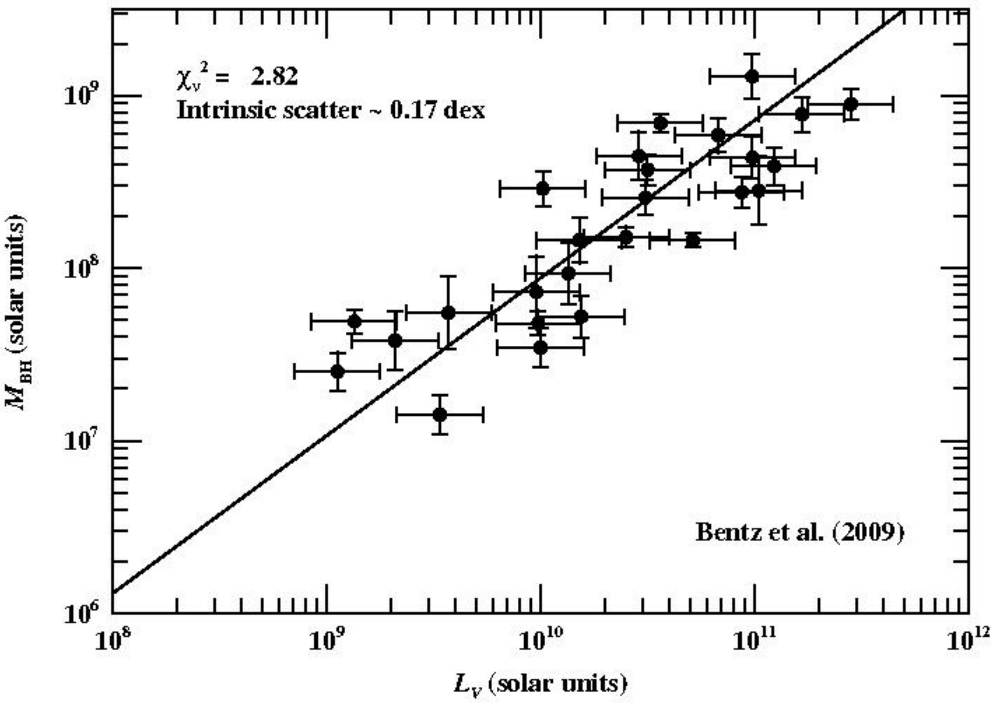
  $\langle f \rangle = 4.19 \pm 1.08$

- Maximum likelihood places an upper limit on intrinsic scatter

  $\Delta \log M_{BH} \sim 0.40$ dex.

  – Consistent with quiescent galaxies.

The AGN M_{BH}–L_{bulge} Relationship



- Line shows best-fit to quiescent galaxies
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta\log M_{BH} \sim 0.17$ dex.
  - Smaller than quiescent galaxies ($\Delta\log M_{BH} \sim 0.38$ dex).

Black Hole Mass Measurements (units of $10^6 M_\odot$)

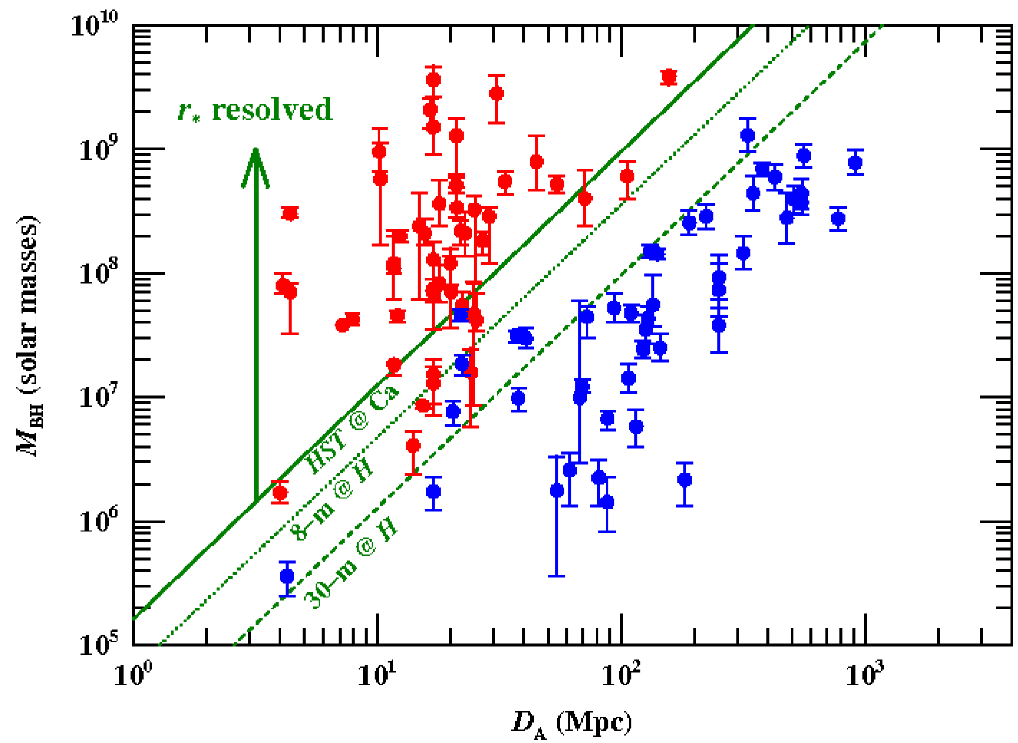
Galaxy	NGC 4258	NGC 3227	NGC 4151
Direct methods:			
Megamasers	38.2 ± 0.1	N/A	N/A
Stellar dynamics	33 ± 2	7–20	47^{+11}_{-14}†
Gas dynamics	25 – 260	20^{+10}_{-4}	$30^{+7.5}_{-22}$
Reverberation	N/A	7.63 ± 1.7	46 ± 5
Quoted uncertainties are statistical only, not systematic.			

References: see Peterson (2010) [arXiv:1001.3675]

† Onken et al., in preparation

Masses of Black Holes in Quasars

- Stellar and gas dynamics requires higher angular resolution to proceed further.
  - Even a 30-m telescope will not vastly expand the number of AGNs with a resolvable r_*.
- Reverberation is the future path for direct AGN black hole masses.
  - Trade time resolution for angular resolution.
  - Downside: resource intensive.



- Quiescent galaxies
- RM AGNs

Masses of Black Holes in Quasars

- Stellar and gas dynamics requires higher angular resolution to proceed further.
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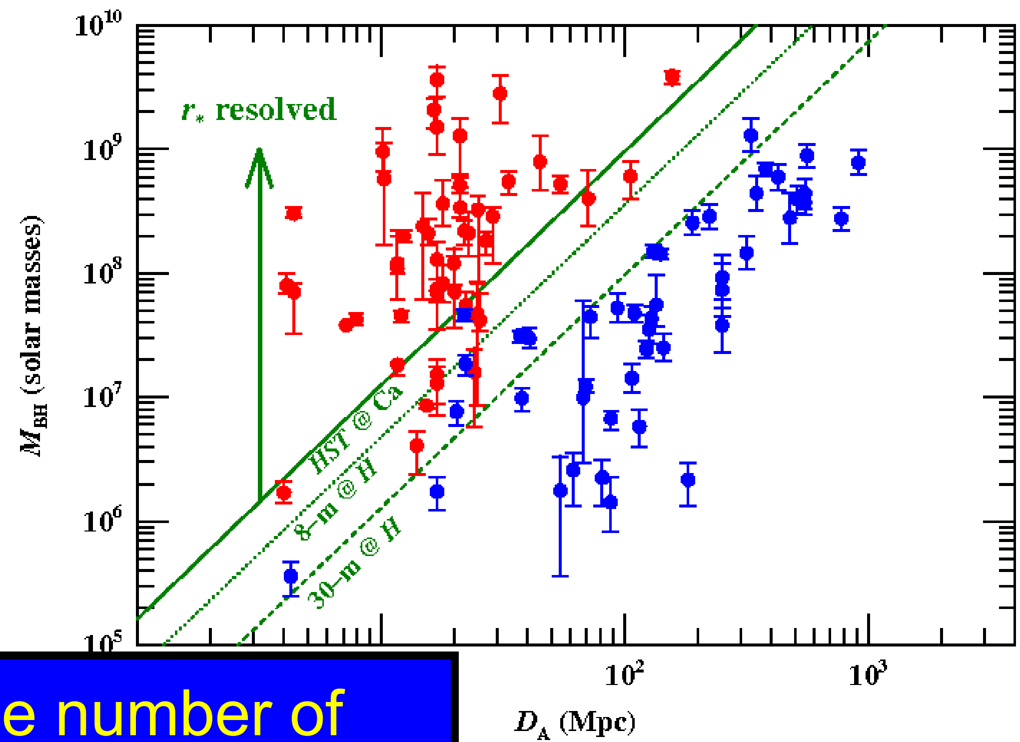


uiescent galaxies

M AGNs

To significantly increase number of measured masses, we need to go to secondary methods.



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

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

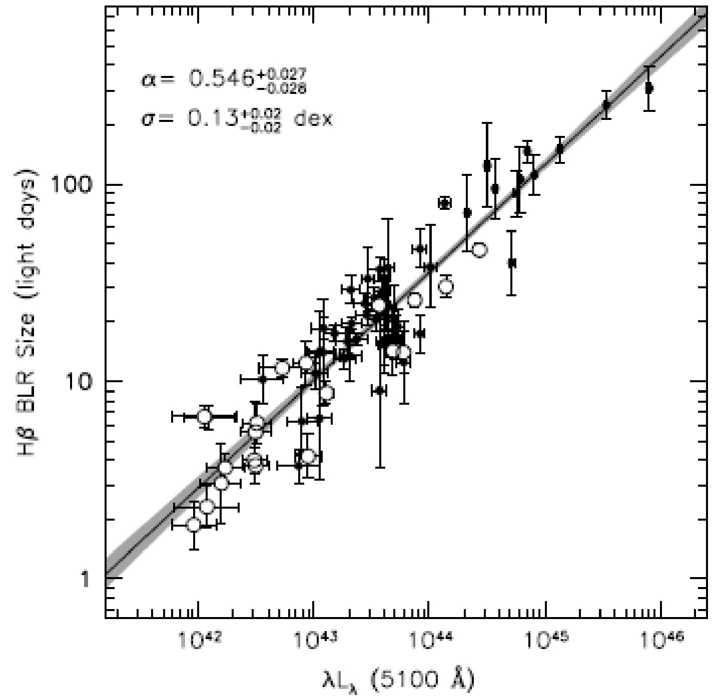
PG 0953+414
$z = 0.234$
$\log L_{opt} = 45.1$

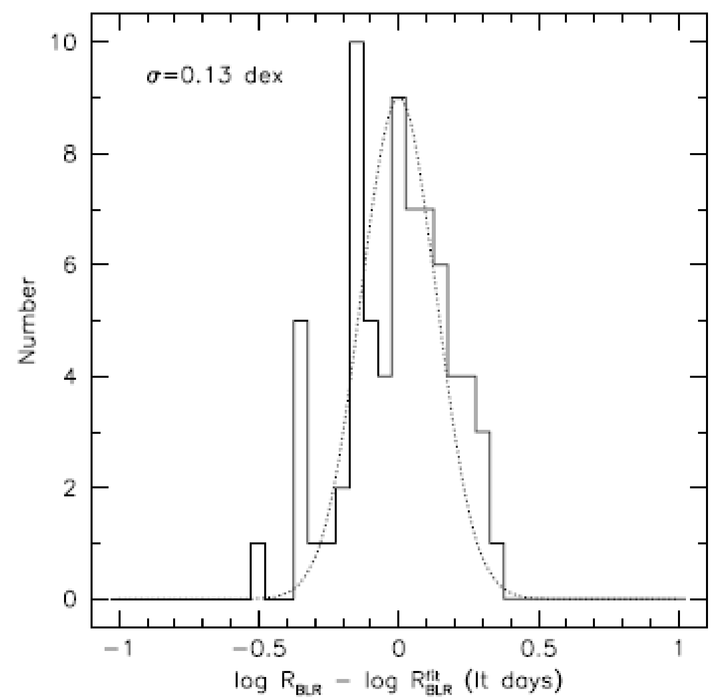
Reverberation experiments use large spectrograph apertures for accurate spectrophotometry.
This results in significant starlight contribution to the measured optical luminosity.

MDM images courtesy of M. Bentz

The *R–L* Relation

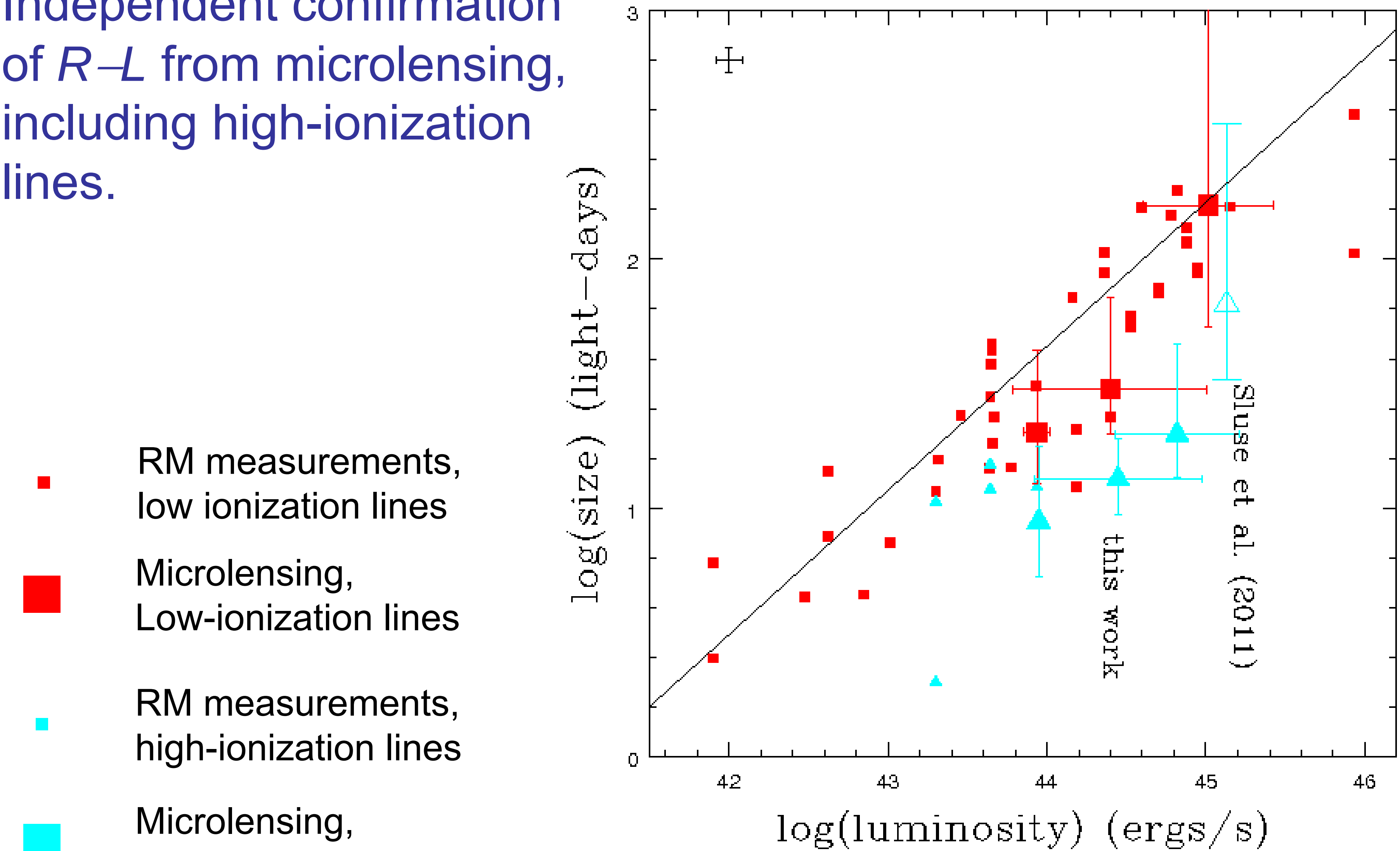
- Empirical slope ~0.55 ± 0.03
- Intrinsic scatter ~0.13 dex
- Typical error bars on best reverberation data ~0.09 dex
- Conclusion: for Hβ over the calibrated range ($41.5 \leq \log L_{5100}$ (ergs s^{-1}) ≤ 45 at $z \approx 0$), *R-L* is nearly as effective as reverberation.





Bentz+ 2013

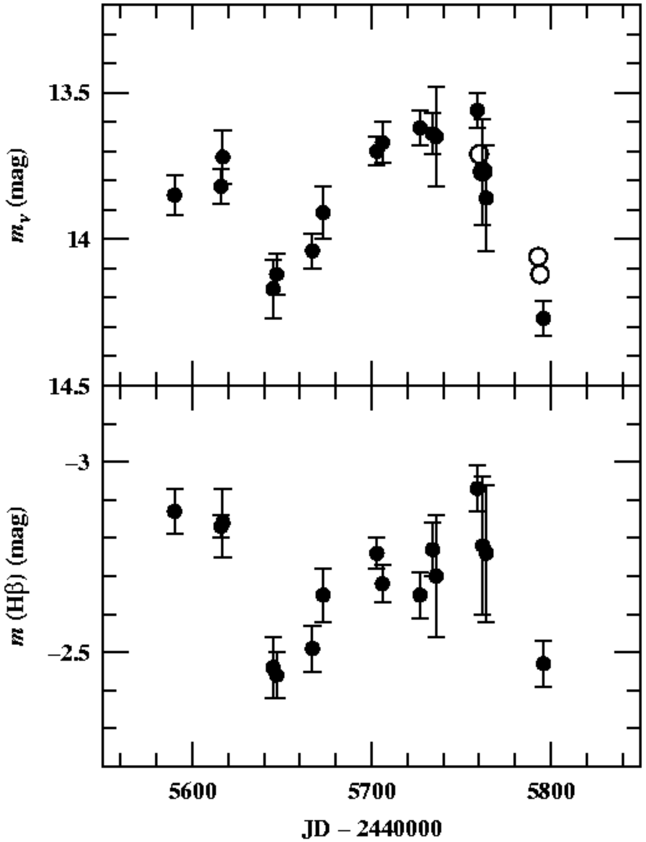
Independent confirmation of R–L from microlensing, including high-ionization lines.



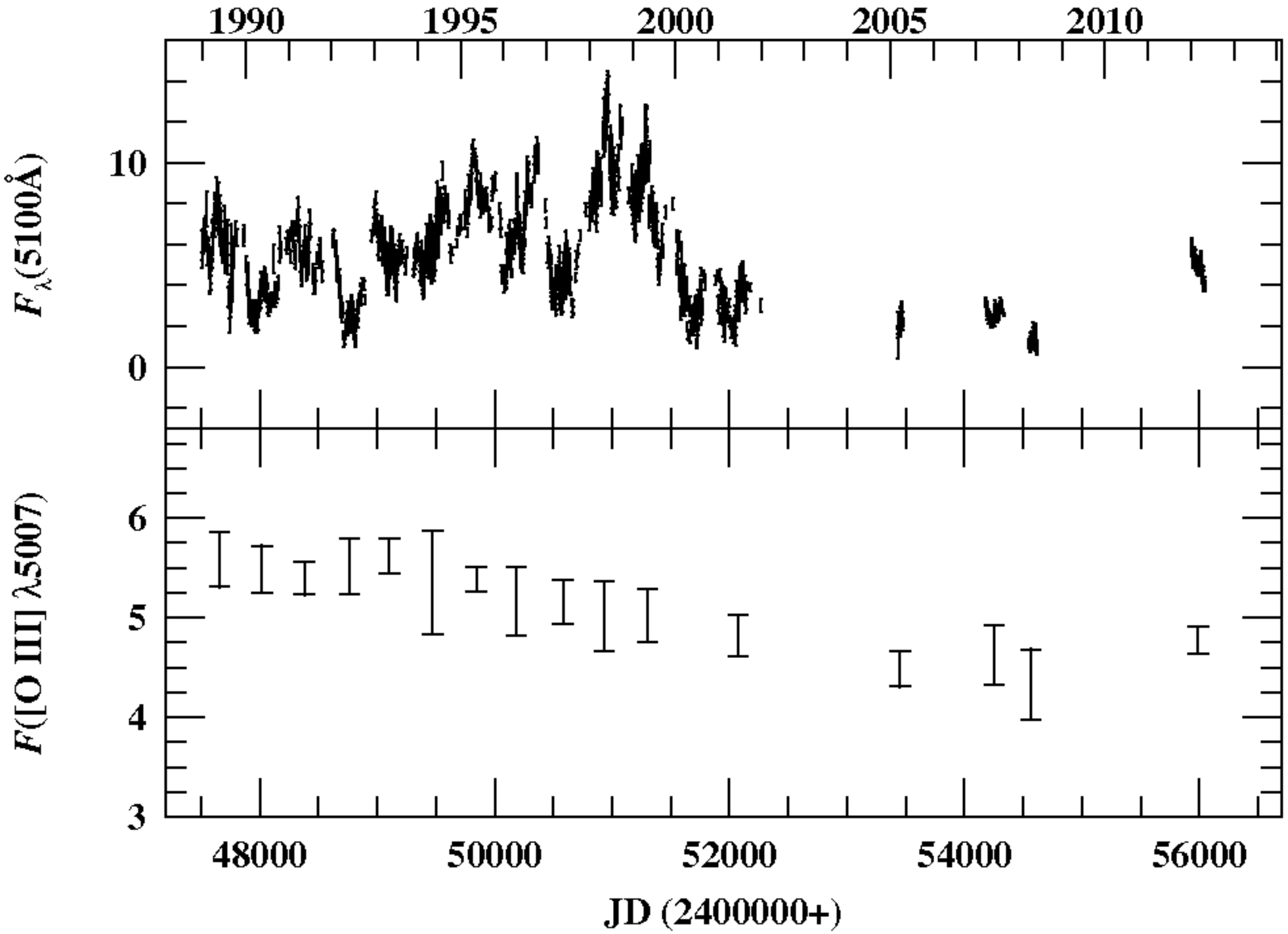
Guerras, Kochanek + 2013

And now for something completely different.

It's…



Narrow Emission-Line Variability in NGC 5548



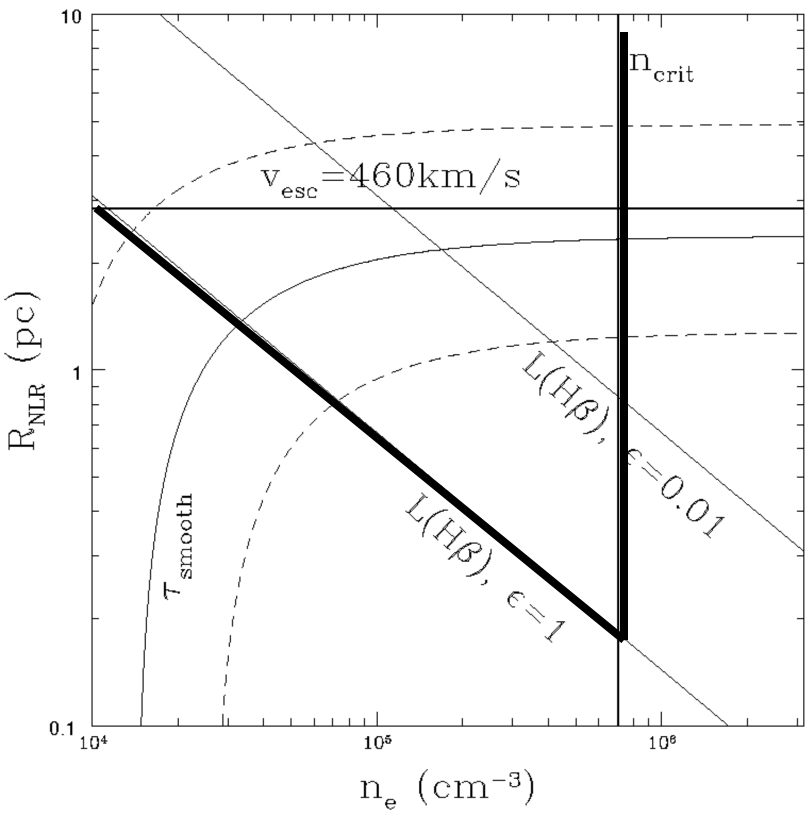
Peterson+, on astro-ph today

Narrow Emission-Line Variability in NGC 5548

$$\tau_{\rm smooth} = \left(\frac{2R_{\rm NLR}}{c}\right) + \left(\frac{1}{n_e \alpha_B}\right)$$

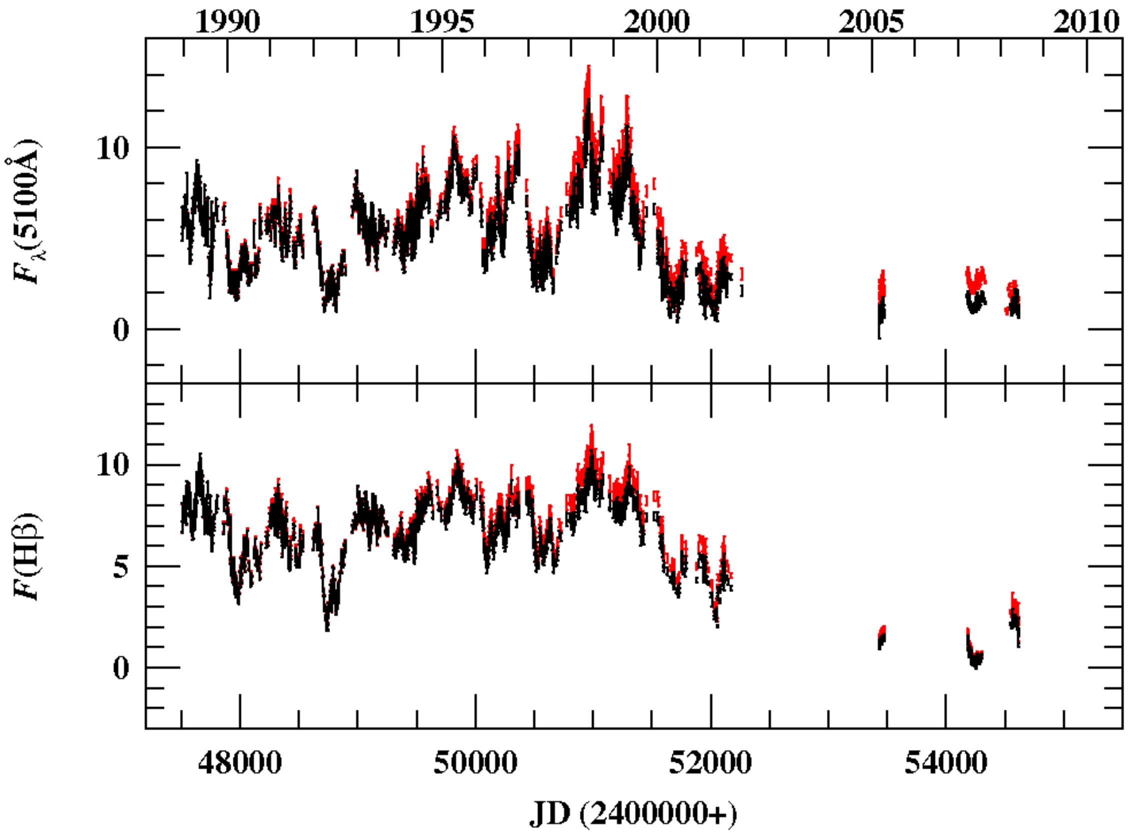
Light-travel time | Recombination timescale

- Size of narrow-line region constrained to 1-3 pc
- Density ~ 10^5 cm^{-3}
- Second credible detection of [O III] variability (3C 390.3 by Zheng+ 1995), but first to measure $R_{\rm NLR}$



Peterson+, on astro-ph today

Narrow Emission-Line Variability in NGC 5548



Requires recalibration of long-term light curves, but doesn't affect any reverberation results to date.

Peterson+, on astro-ph today

To Conclude

- Reverberation mapping has reached a level of maturity:
  - BH masses becoming increasingly reliable, typically 0.3-0.4 dex over a range of more than 3 orders of magnitude
  - Beginning to probe BLR structure/kinematics
    - All maps so far show evidence for infall in the Balmer lines
  - We are preparing a new UV RM program (180 orbits) for execution in Cycle 21 with HST. Goal: first high-fidelity UV velocity-delay maps.
  - Techniques that can be applied on “industrial scales” are under development.