The Central Black Hole and Relationships with the Host Galaxy

Bradley M. Peterson
The Ohio State University

"Active Galactic Nuclei at the Highest Angular Resolution"

August 2007

Topics to be Covered

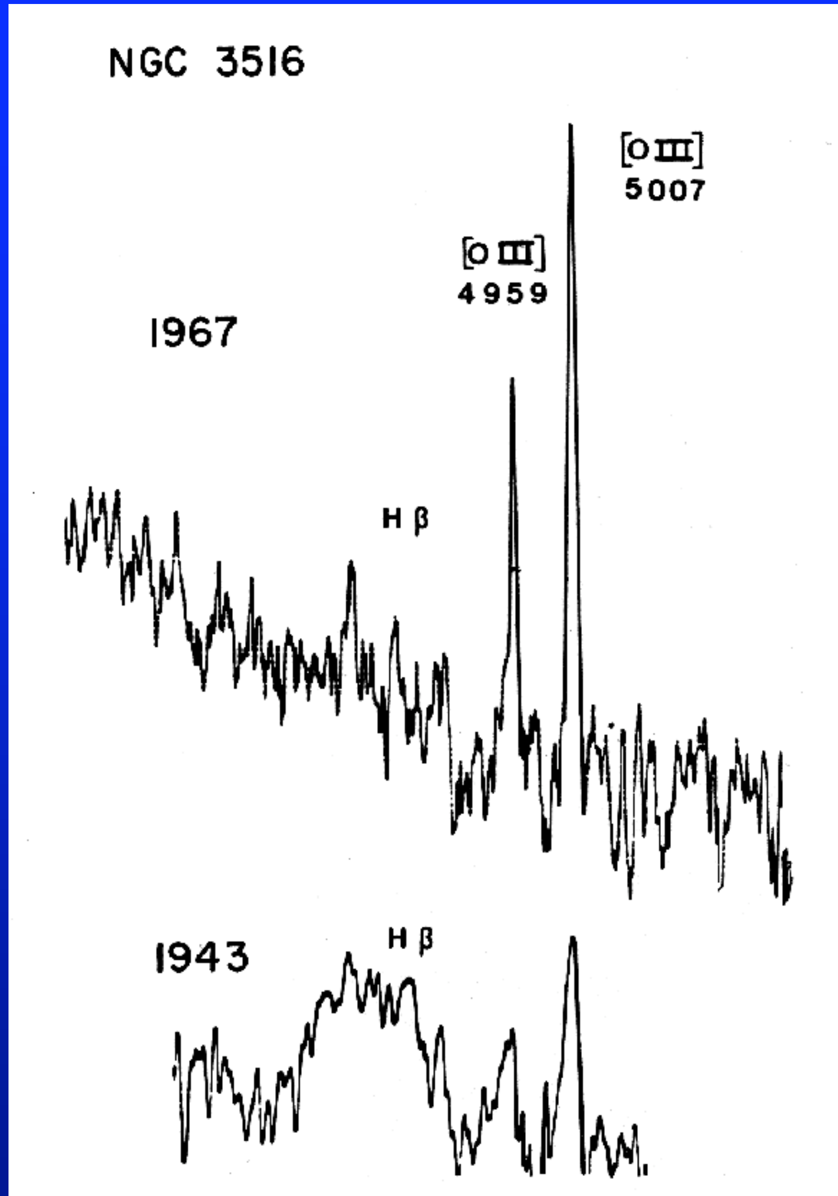
- *Lecture 1:* AGN fundamentals, evidence for supermassive black holes, AGN continuum variability
- *Lecture 2:* Emission-line variability, reverberation mapping, the radius–luminosity relationship
- *Lecture 3:* AGN black hole masses, comparisons between methods, relationships between BH mass and AGN/host properties, requirements for velocity–delay maps, the nature of NLS1s

Lecture 2

- Emission-line variability
- Reverberation mapping
  - Principles
  - Practice
  - Results
- The BLR radius–luminosity relationship

Emission-Line Variability

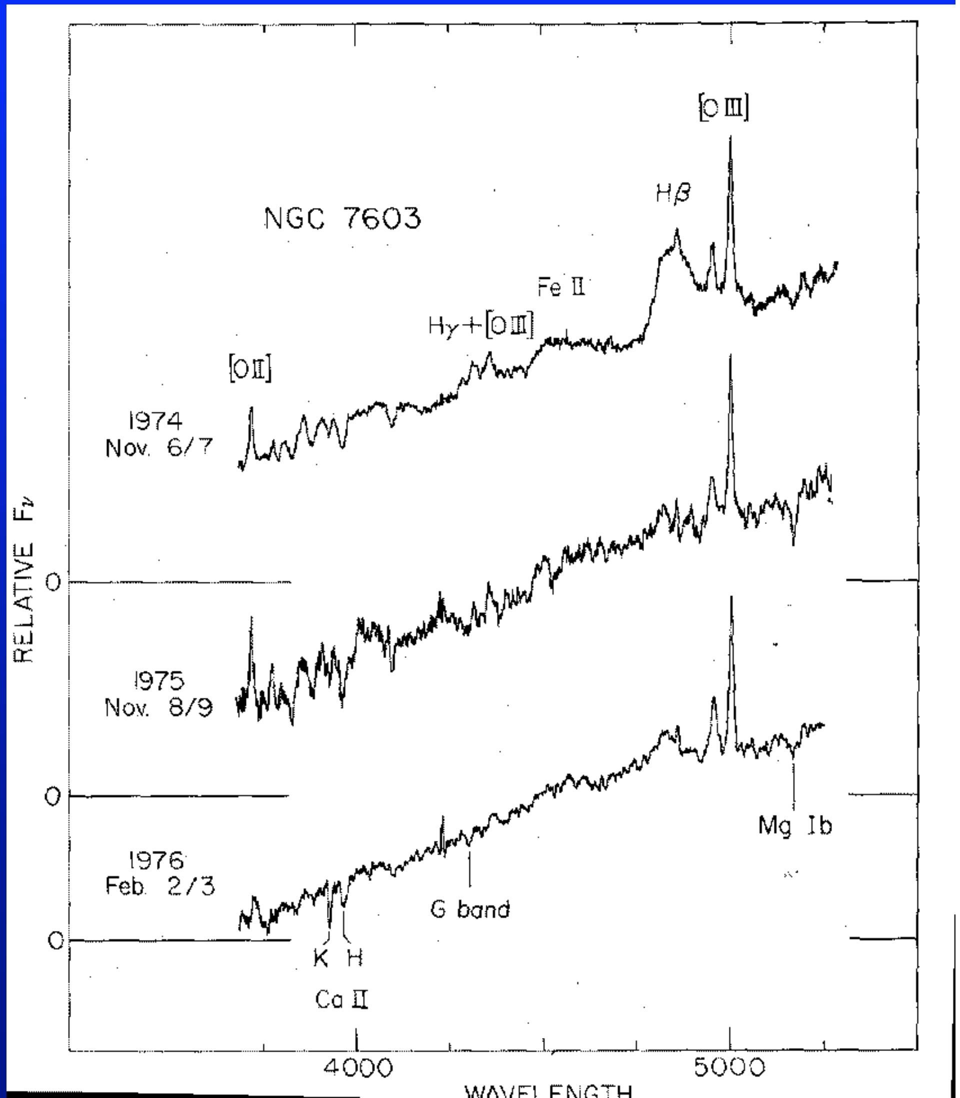
- First detected reported by Andrillat & Souffrin (1968)
  - Based on photographic spectra of NGC 3516
- Subsequent reports were scattered, and seemed to be widely regarded as “curiosities”.
  - Tohline and Osterbrock (1976); Phillips (1978)



Andrillat & Souffrin 1968

Emission-Line Variability

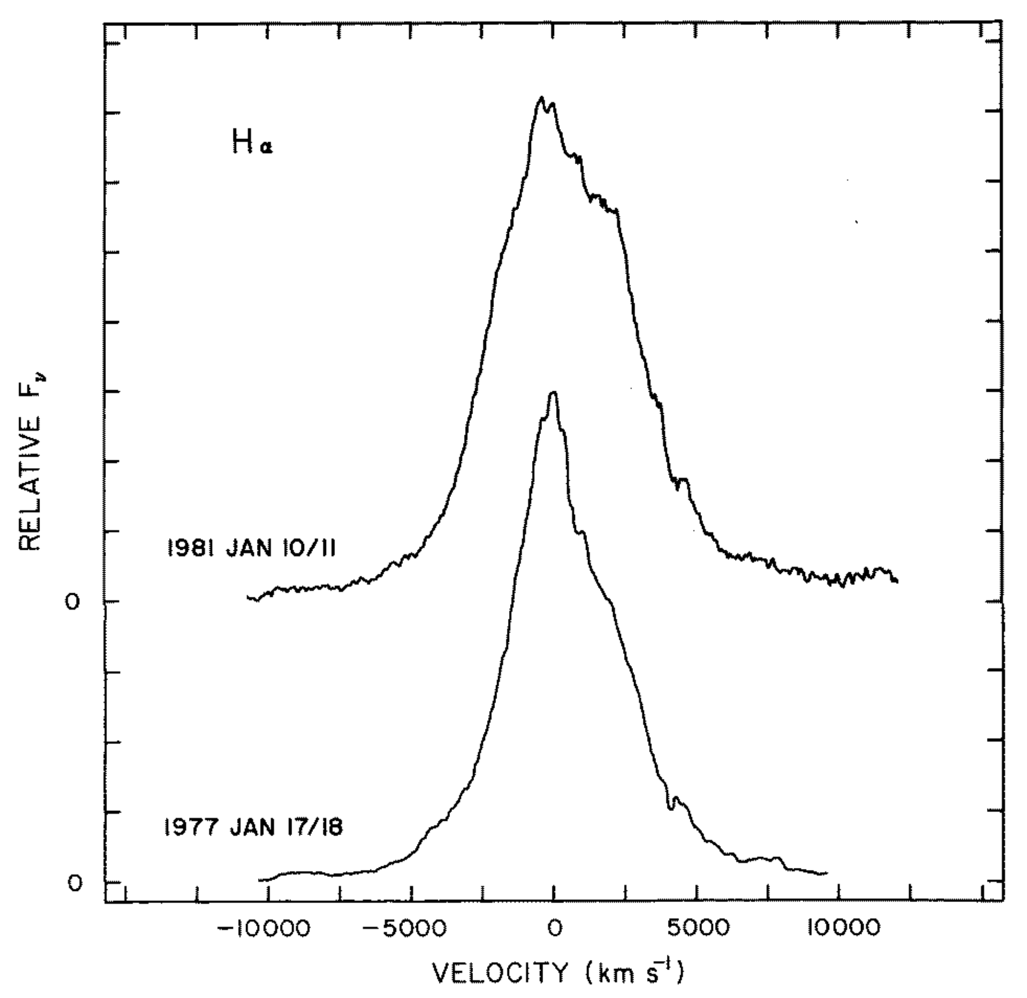
- Only very large changes could be detected photographically or with intensified television-type scanners (e.g., Image Dissector Scanners).
- Changes that were observed were often dramatic and reported as Seyferts changing “type” as broad components appeared or disappeared.



Tohline & Osterbrock 1976

Emission-Line Profile Variability

- Variability of broad emission-line profiles was detected in the early 1980s.
- This was originally thought to point to an ordered velocity field and propagation of excitation inhomogenieties.
- Led to development of reverberation mapping (seminal paper by Blandford & McKee 1982).



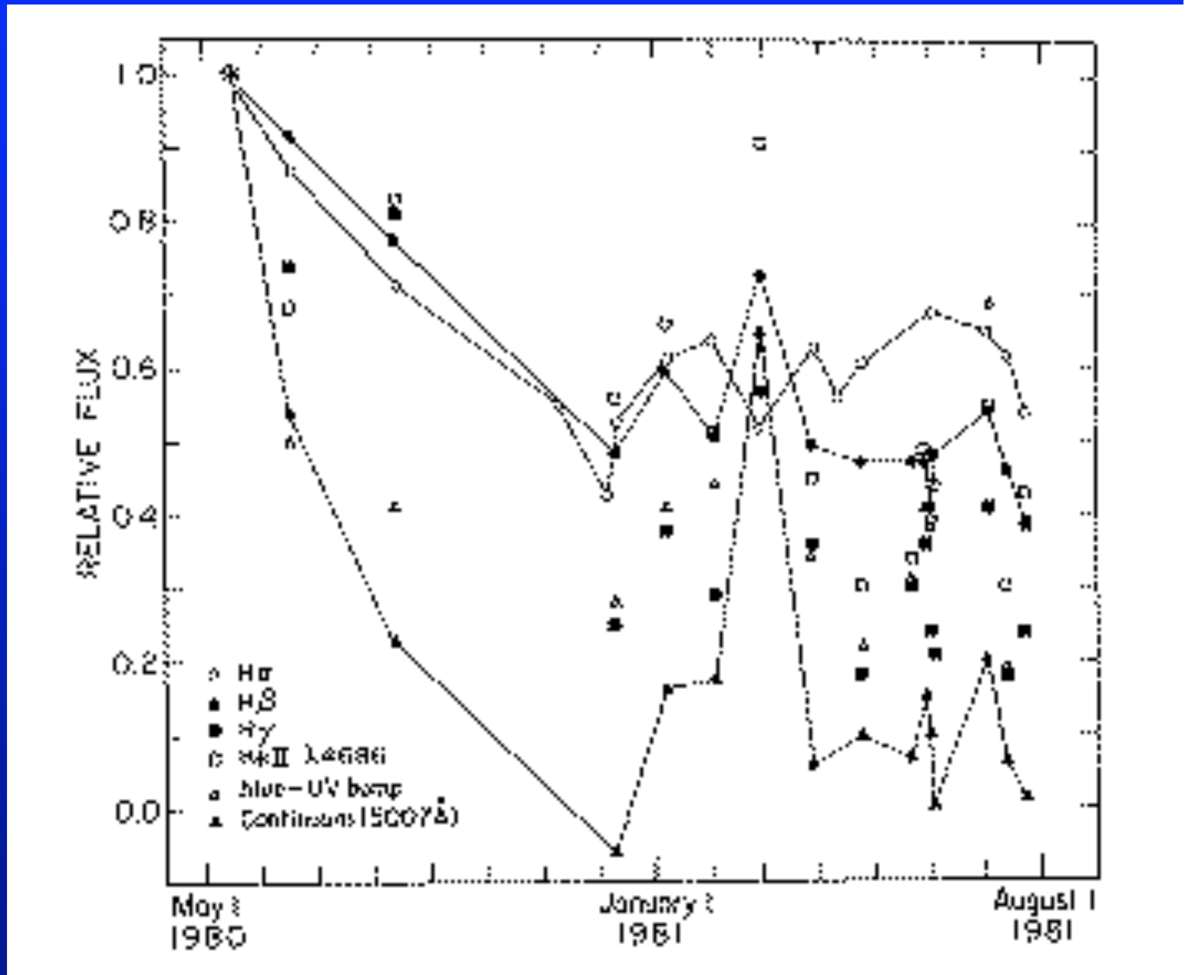
Foltz et al. 1981

First Monitoring Programs

- Made possible by existence of *International Ultraviolet Explorer* and proliferation of linear electronic detectors on moderate-size (1–2m) ground-based telescopes
- NGC 4151: UV monitoring by a European consortium (led by M.V. Penston and M.-H. Ulrich).
  - Typical sampling interval of 2–3 months.
  - Several major results:
    - close correspondence of UV/optical continuum variations
    - line fluxes correlated with continuum, but different lines respond in different ways (amplitude and time scale)
    - complicated relationship between UV and X-ray
    - variable absorption lines

First Monitoring Programs

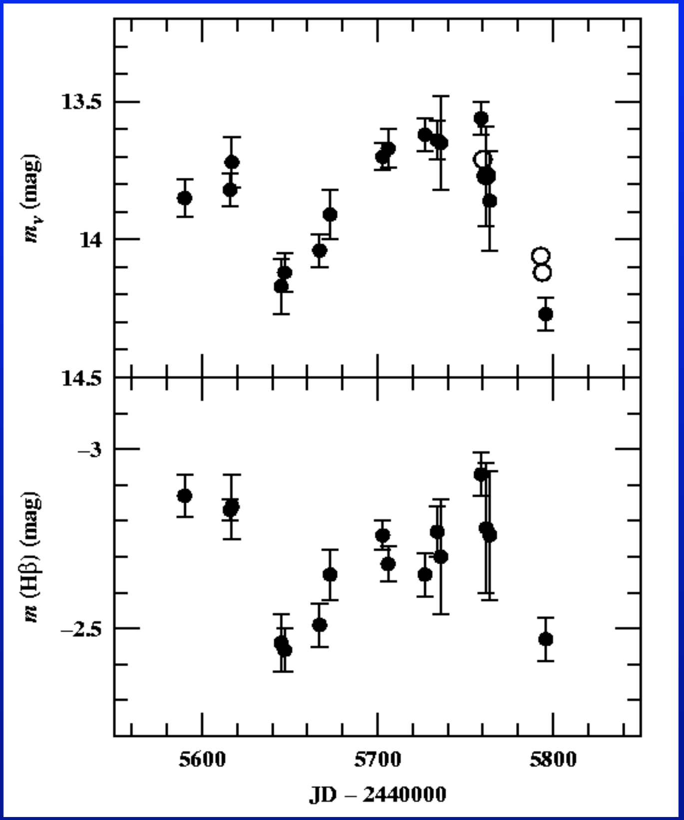
- NGC 4151: Monitored at Lick Observatory by Antonucci and Cohen in 1980 and 1981
  - short time scale response of Balmer lines (<1 month)
  - higher amplitude variability of higher-order Balmer lines and He II λ4686



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

30 Years of NGC 5548

Hβ & Continuum Variability
1972–2002

Sergei Sergeev (CrAO)
Richard Pogge (OSU)
Bradley Peterson (OSU)

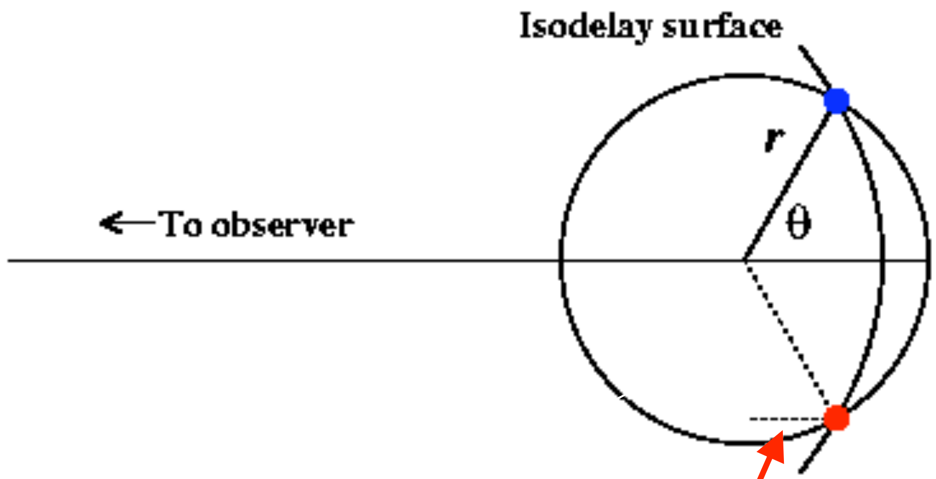
THE OHIO STATE UNIVERSITY

Reverberation Mapping Assumptions

1) The continuum originates in a point source
2) The most important timescale is the BLR light-crossing time $\tau_{LT} = R/c$.
   - Dynamical time is $\tau_{dyn} = R/\text{FWHM}$, so $\tau_{dyn}/\tau_{LT} = c/\text{FWHM} \approx 100$.
   - Recombination time is $\tau_{rec} \approx (\alpha_B\, n_e)^{-1} \approx 400\ \text{s}^{-1}$ for a density of $10^{10}\ \text{cm}^{-3}$.
3) There is a simple, though not necessarily linear, relationship between the observable UV/optical continuum and the ionizing continuum

Reverberation Mapping Concepts: Response of an Edge-On Ring

- Suppose line-emitting clouds are on a circular orbit around the central source.
- Compared to the signal from the central source, the signal from anywhere on the ring is delayed by light-travel time.
- Time delay at position (r, θ) is $\tau = (1 + \cos\theta)r / c$



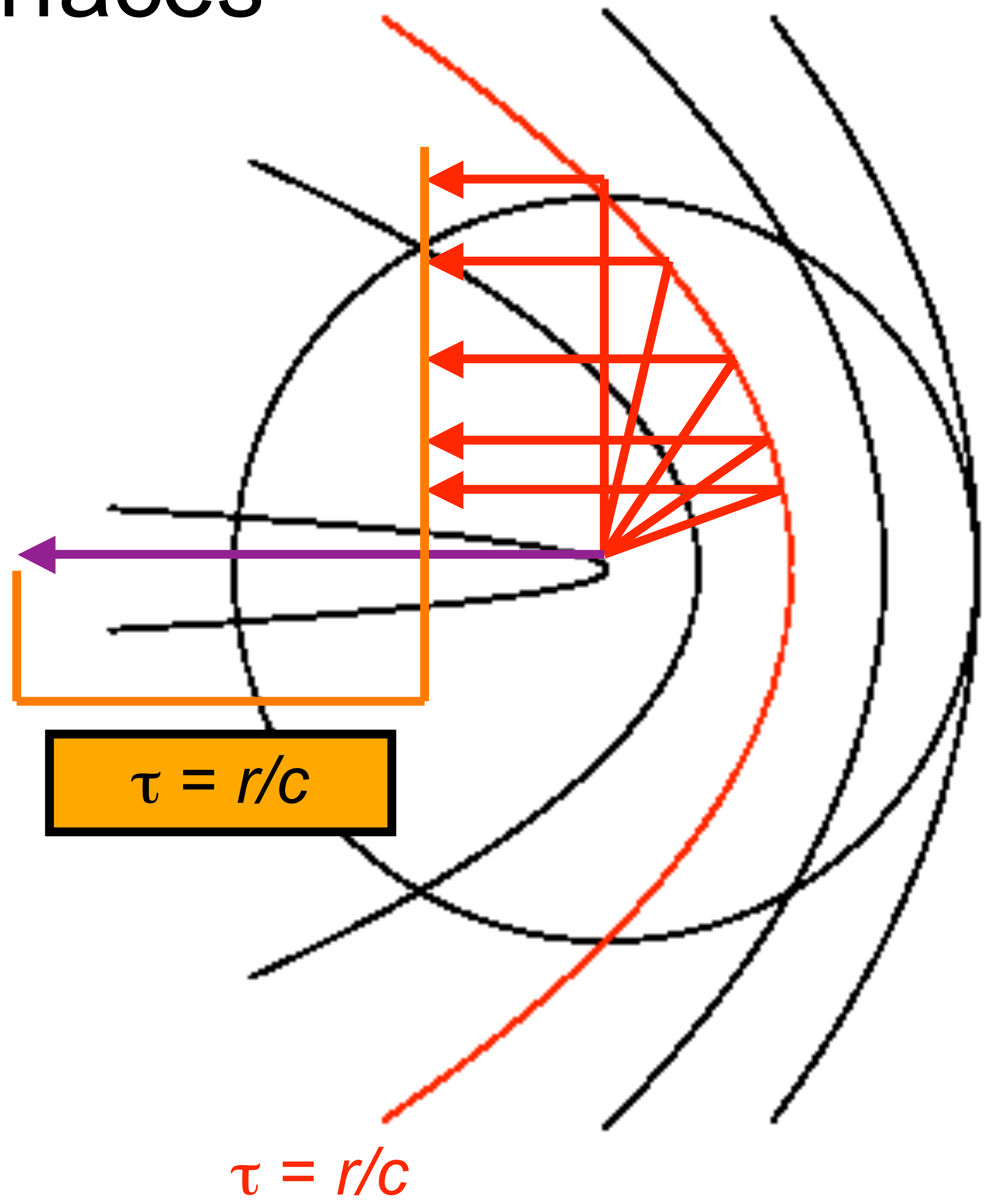
$\tau = r \cos\theta / c$

The isodelay surface is a parabola:

$$r = \frac{c\,\tau}{1+\cos\theta}$$

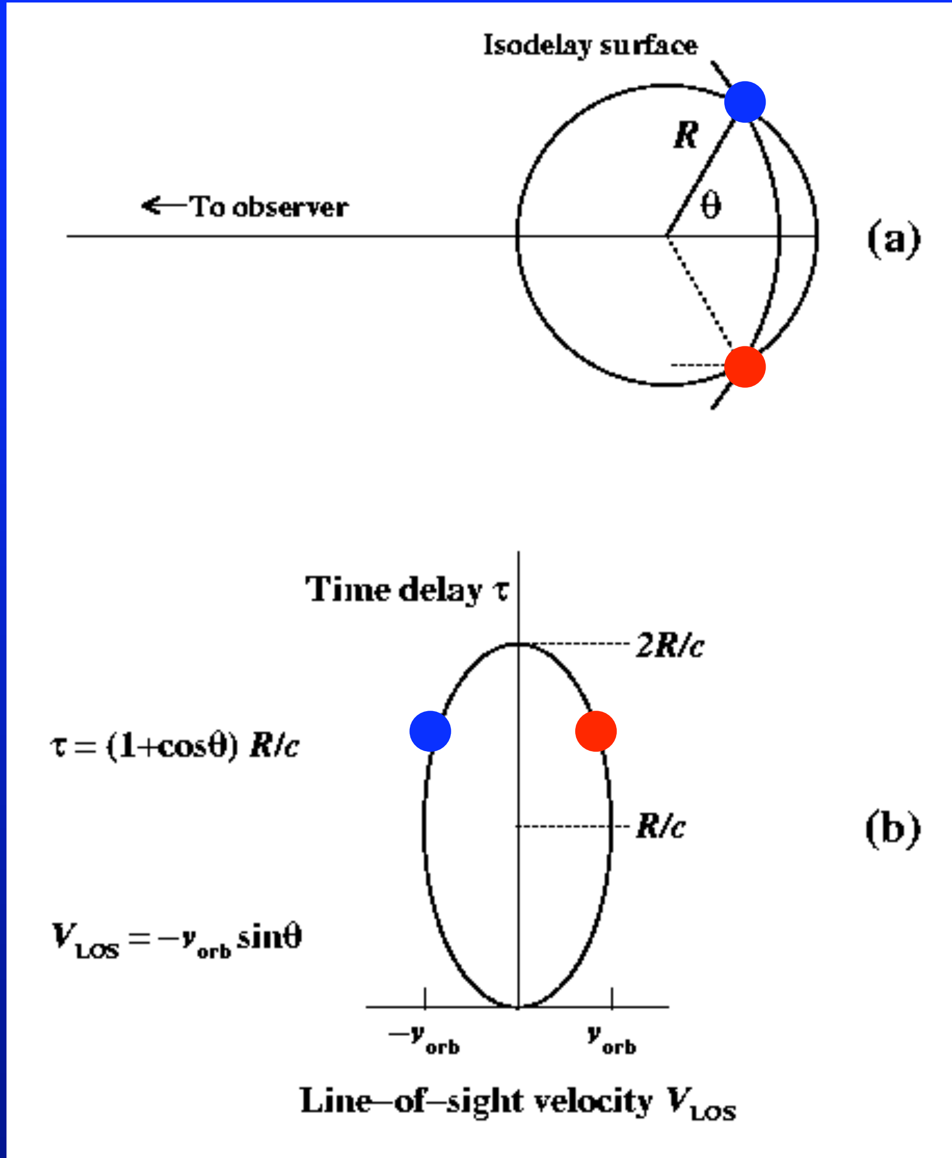
“Isodelay Surfaces”

All points on an “isodelay surface” have the same extra light-travel time to the observer, relative to photons from the continuum source.



Velocity-Delay Map for an Edge-On Ring

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



Projection in Time Delay

Assume isotropy

$$\Psi(\theta) = \varepsilon$$

Transform to time-delay (observable)

$$\Psi(\tau)\ d\tau = \Psi(\theta)\frac{d\theta}{d\tau}\ d\tau$$

$$\tau = (1+\cos\theta)R/c$$

$$\frac{d\tau}{d\theta} = -\frac{R}{c}\sin\theta$$

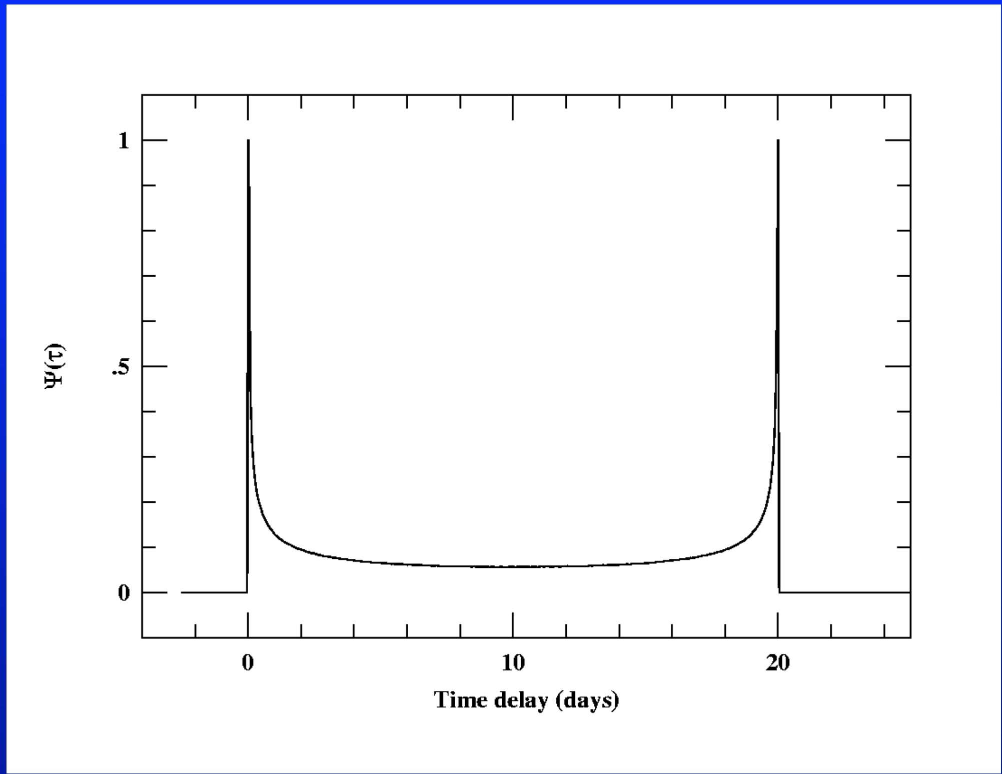
Do some algebra

$$\Psi(\tau)\ d\tau = \frac{\varepsilon}{R(2c\tau/R)^{1/2}(1-c\tau/2R)^{1/2}}\ d\tau$$

Delay Map for a Ring

Symmetry, or some calculus, will show that:

$$\langle \tau \rangle = \frac{\int_0^\infty \tau \, \Psi(\tau) \, d\tau}{\int_0^\infty \Psi(\tau) \, d\tau} = \frac{R}{c}$$



Projection in Line-of-Sight Velocity

Assume isotropy $\Psi(\theta) = \varepsilon$

Transform to LOS velocity (observable)

$$\Psi(V_{\mathrm{LOS}})\, dV_{\mathrm{LOS}} = \Psi(\theta) \frac{d\theta}{dV_{\mathrm{LOS}}}\, dV_{\mathrm{LOS}}$$

$$V_{\mathrm{LOS}} = -V_{\mathrm{orb}} \sin\theta$$

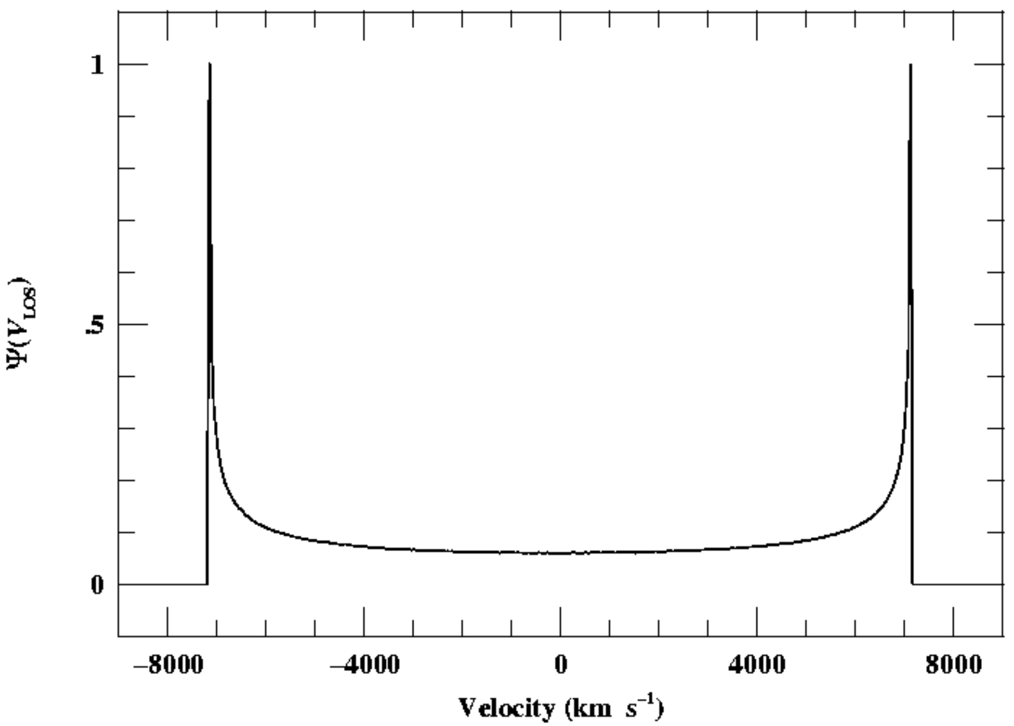
$$\frac{dV_{\mathrm{LOS}}}{d\theta} = -V_{\mathrm{orb}} \cos\theta$$

Do some algebra again

$$\Psi(V_{\mathrm{LOS}})\, dV_{\mathrm{LOS}} = \frac{\varepsilon}{V_{\mathrm{orb}}(1-(V_{\mathrm{LOS}}/V_{\mathrm{orb}})^2)^{1/2}}\, dV_{\mathrm{LOS}}$$

Line Profile for a Ring

- Characterize line width
  - FWHM = $2V_{orb}$
  - σ_{line}

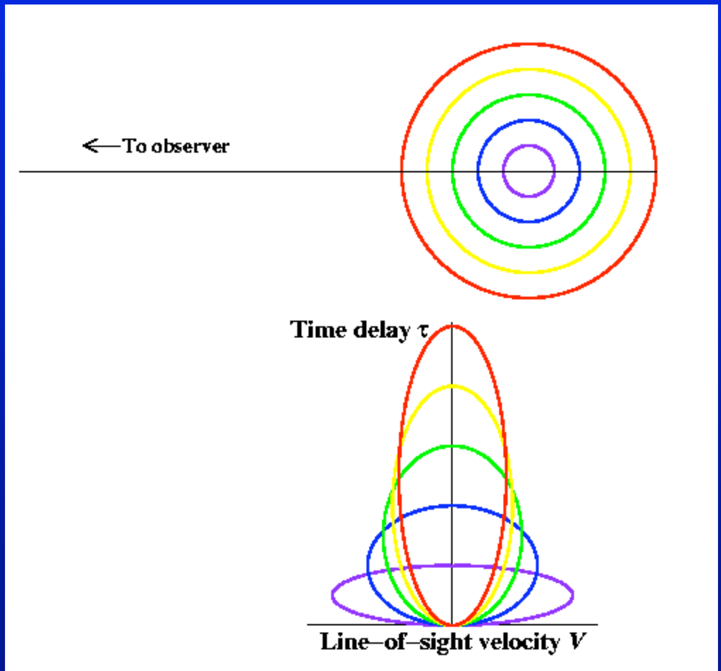


$$\sigma_{\rm line} = \left(\langle V_{\rm LOS}^2 \rangle - \langle V_{\rm LOS} \rangle^2\right)^{1/2} = \left[\frac{\int_{-V_{\rm orb}}^{V_{\rm orb}} V_{\rm LOS}^2 \Psi(V_{\rm LOS})\, dV_{\rm LOS}}{\int_{-V_{\rm orb}}^{V_{\rm orb}} \Psi(V_{\rm LOS})\, dV_{\rm LOS}} \right]^{1/2} = \left(\frac{V_{\rm orb}}{2}\right)^{1/2}$$

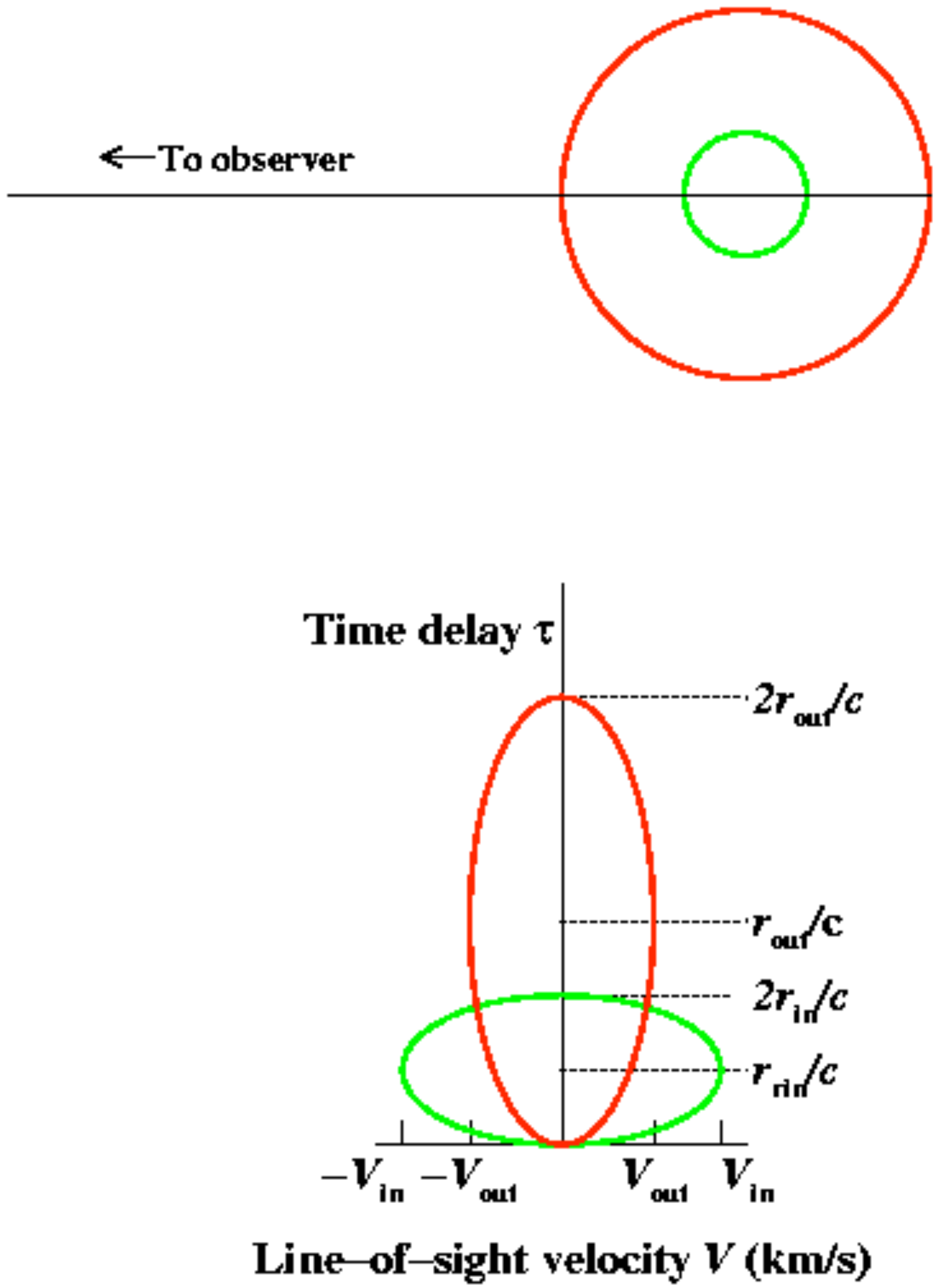
For a ring, FWHM/σ_{line} = $2 \times 2^{1/2}$ = 2.83

Thick Geometries

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



A multiple-ring system



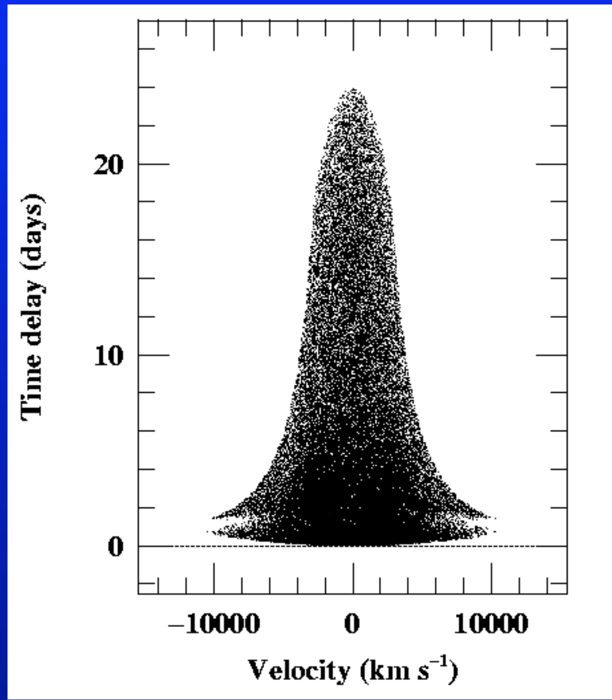
Observed Response of an Emission Line

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

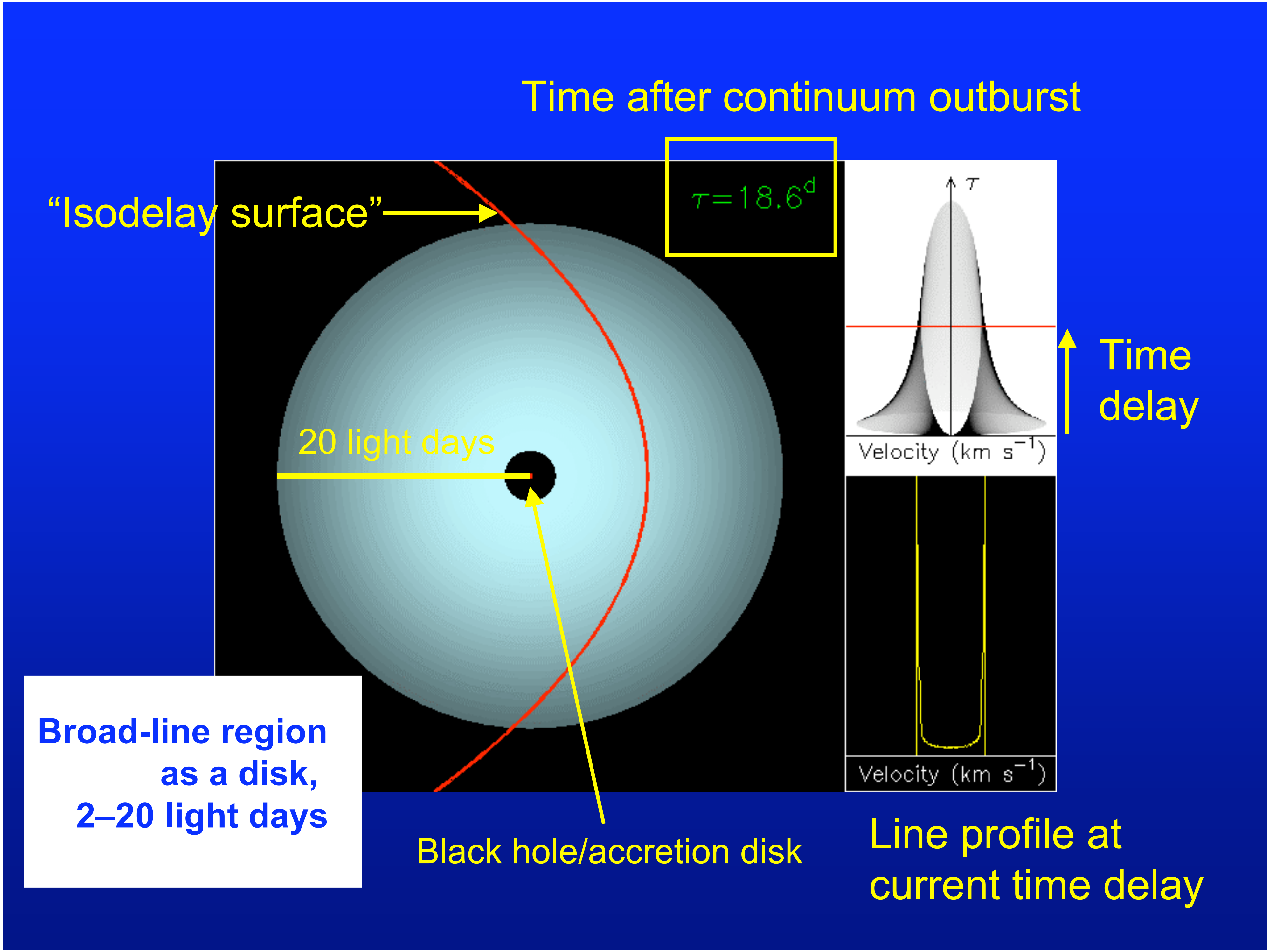
$$L(V,t) = \int_{-\infty}^{\infty} \Psi(V,\tau)\, C(t-\tau)\, d\tau$$

Emission-line light curve — "Velocity-Delay Map" — Continuum Light Curve

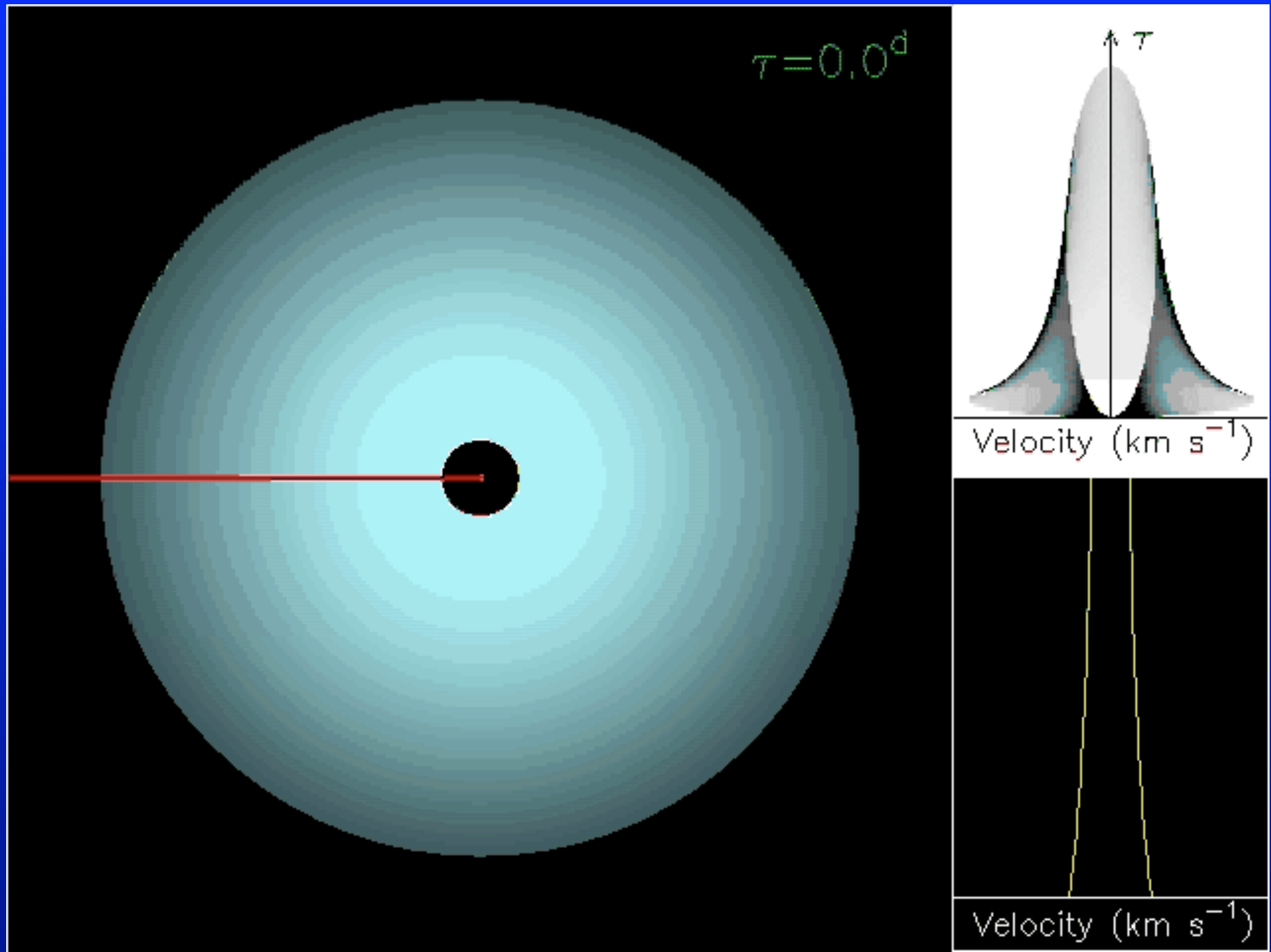
Velocity-delay map is observed line response to a δ-function outburst



Simple velocity-delay map

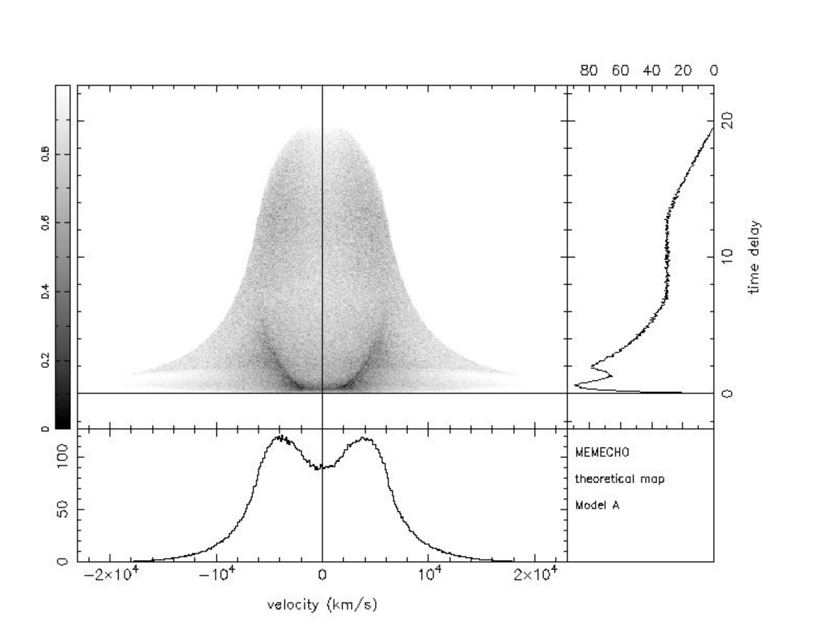


Time after continuum outburst
"Isodelay surface"
τ=18.6d
20 light days
Velocity (km s−1)
Time delay
Velocity (km s−1)
Broad-line region as a disk, 2–20 light days
Black hole/accretion disk
Line profile at current time delay

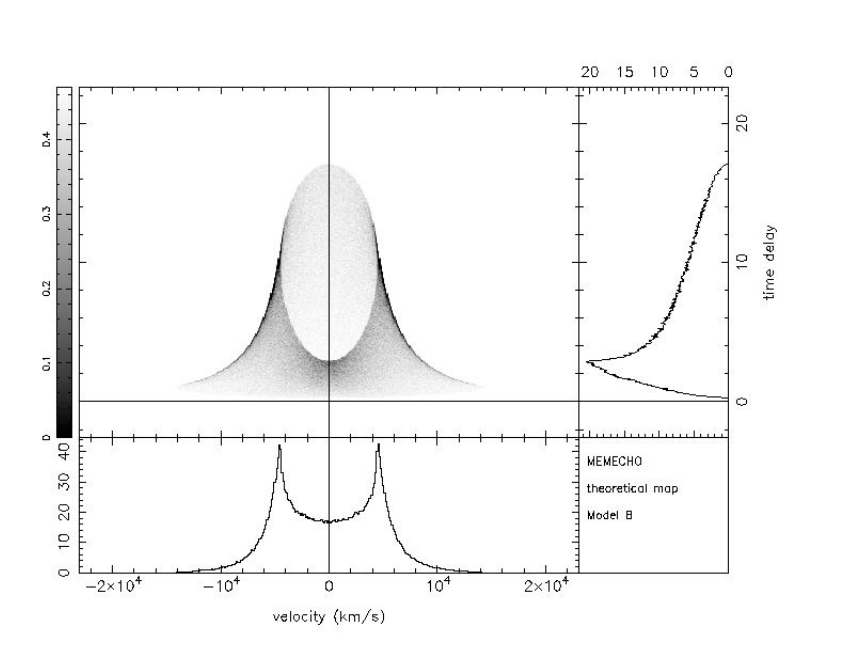


τ=0.0d
τ
Velocity (km s−1)
Velocity (km s−1)

Two Simple Velocity-Delay Maps



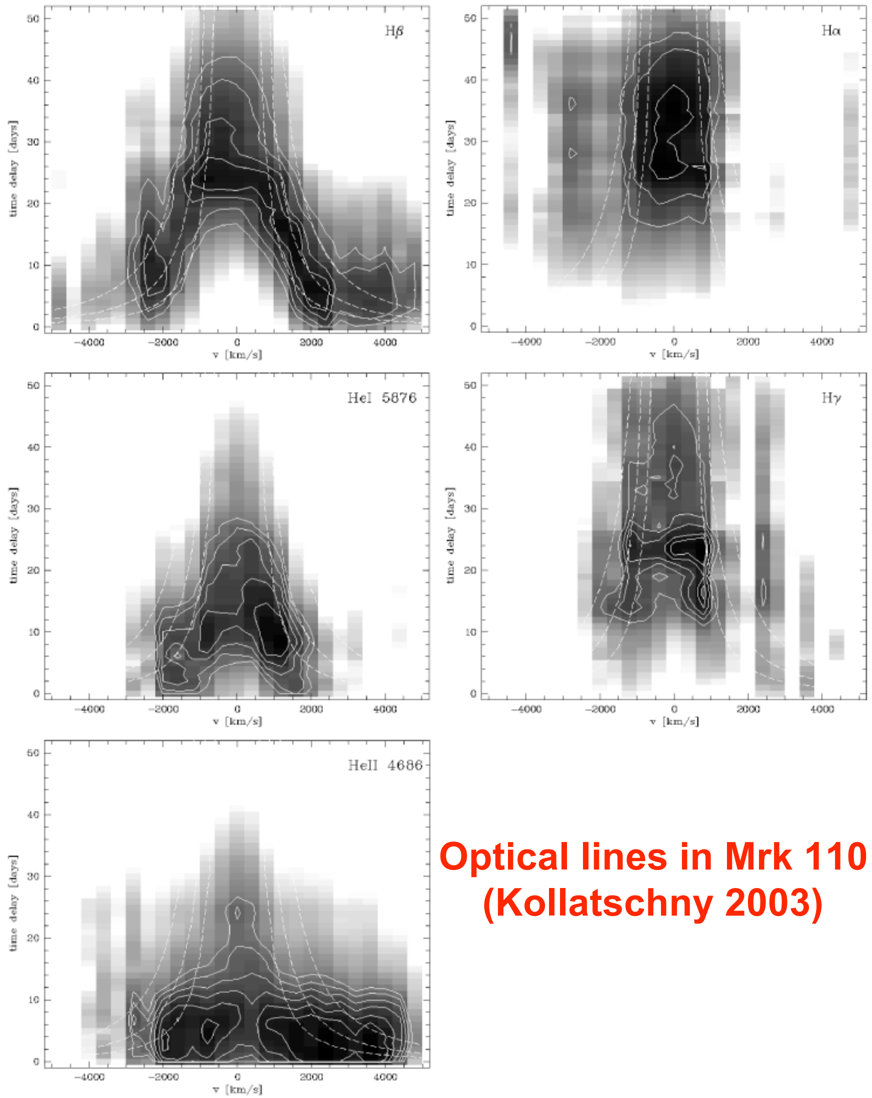
Inclined Keplerian
disk



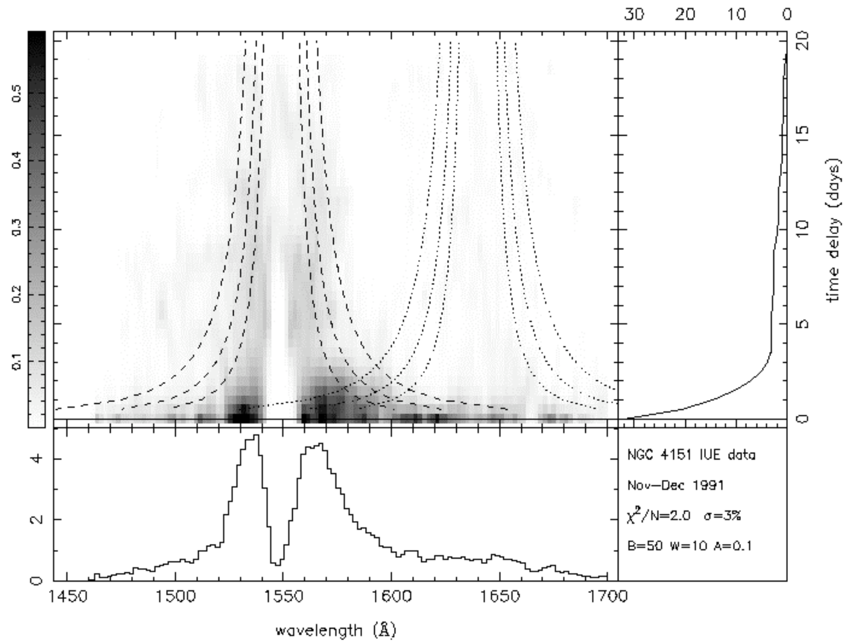
Randomly inclined
circular Keplerian orbits

The profiles and velocity-delay maps are superficially similar, but can be distinguished from one other and from other forms.

Recovering Velocity-Delay Maps from Real Data



Optical lines in Mrk 110 (Kollatschny 2003)



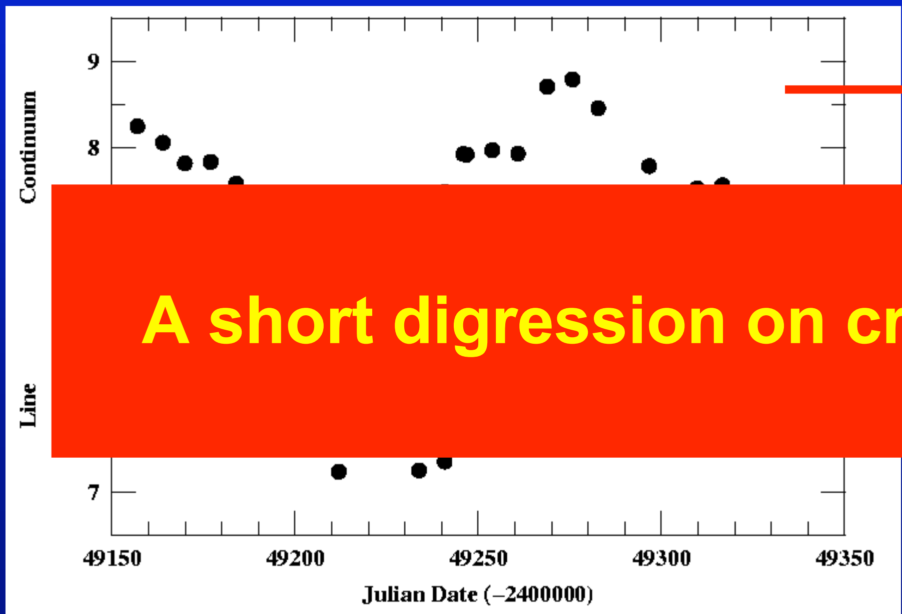
C IV and He II in NGC 4151 (Ulrich & Horne 1996)

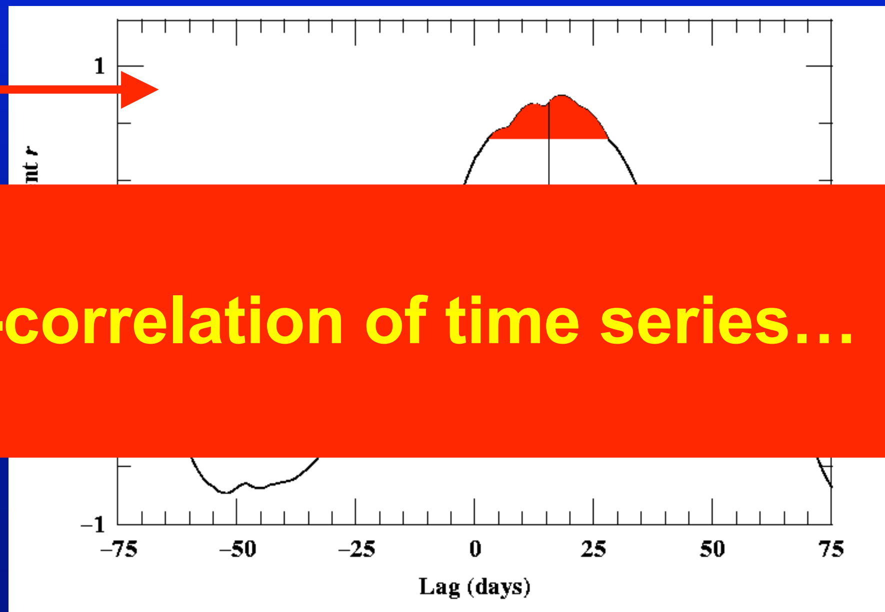
- Existing velocity-delay maps are noisy and ambiguous
- In no case has recovery of the velocity-delay map been a design goal for an experiment!

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):

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



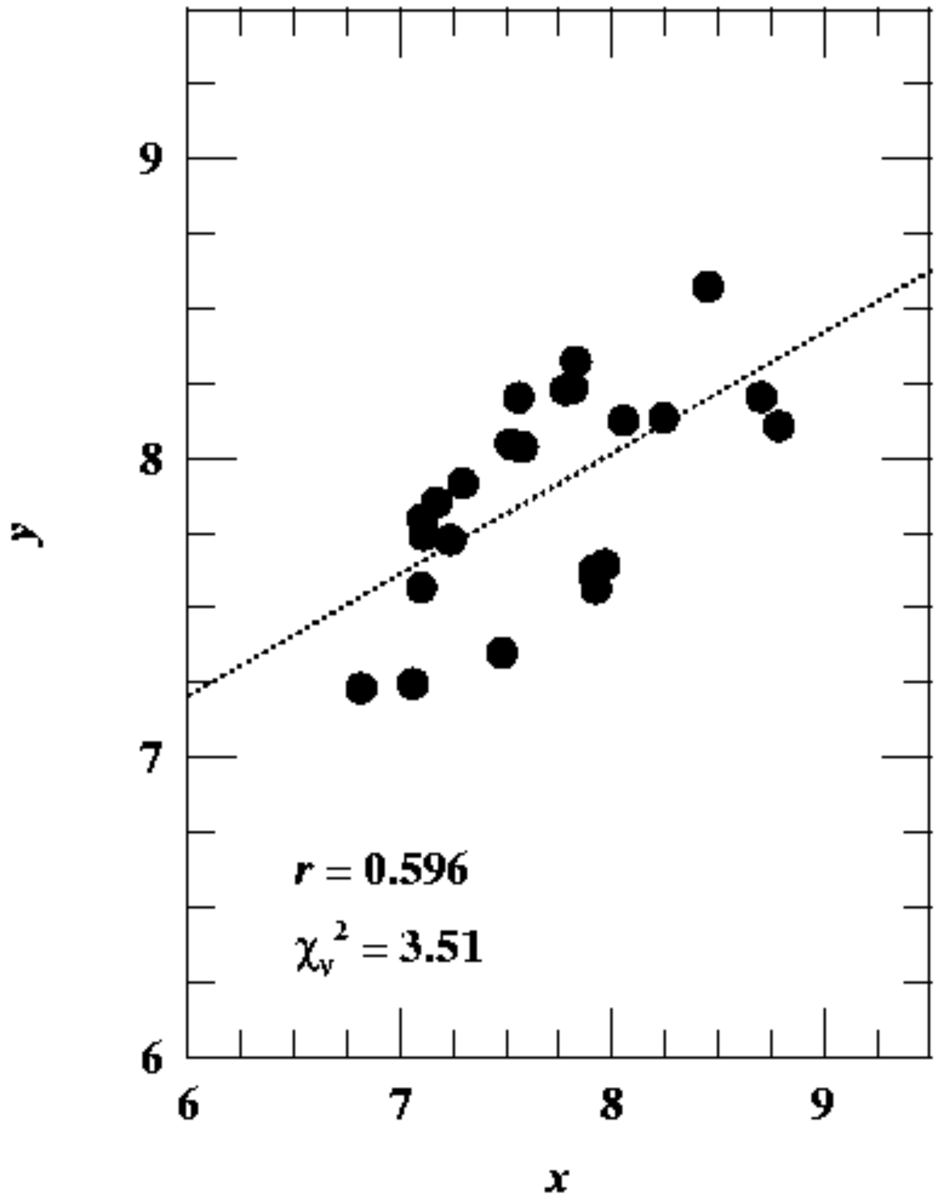


A short digression on cross-correlation of time series…

Linear Correlation

- Degree to which two parameters are ***linearly*** correlated can be expressed in terms of the linear correlation coefficient:

$$r = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\left(\sqrt{\sum_i (x_i - \overline{x})^2}\right)\left(\sqrt{\sum_i (y_i - \overline{y})^2}\right)}$$



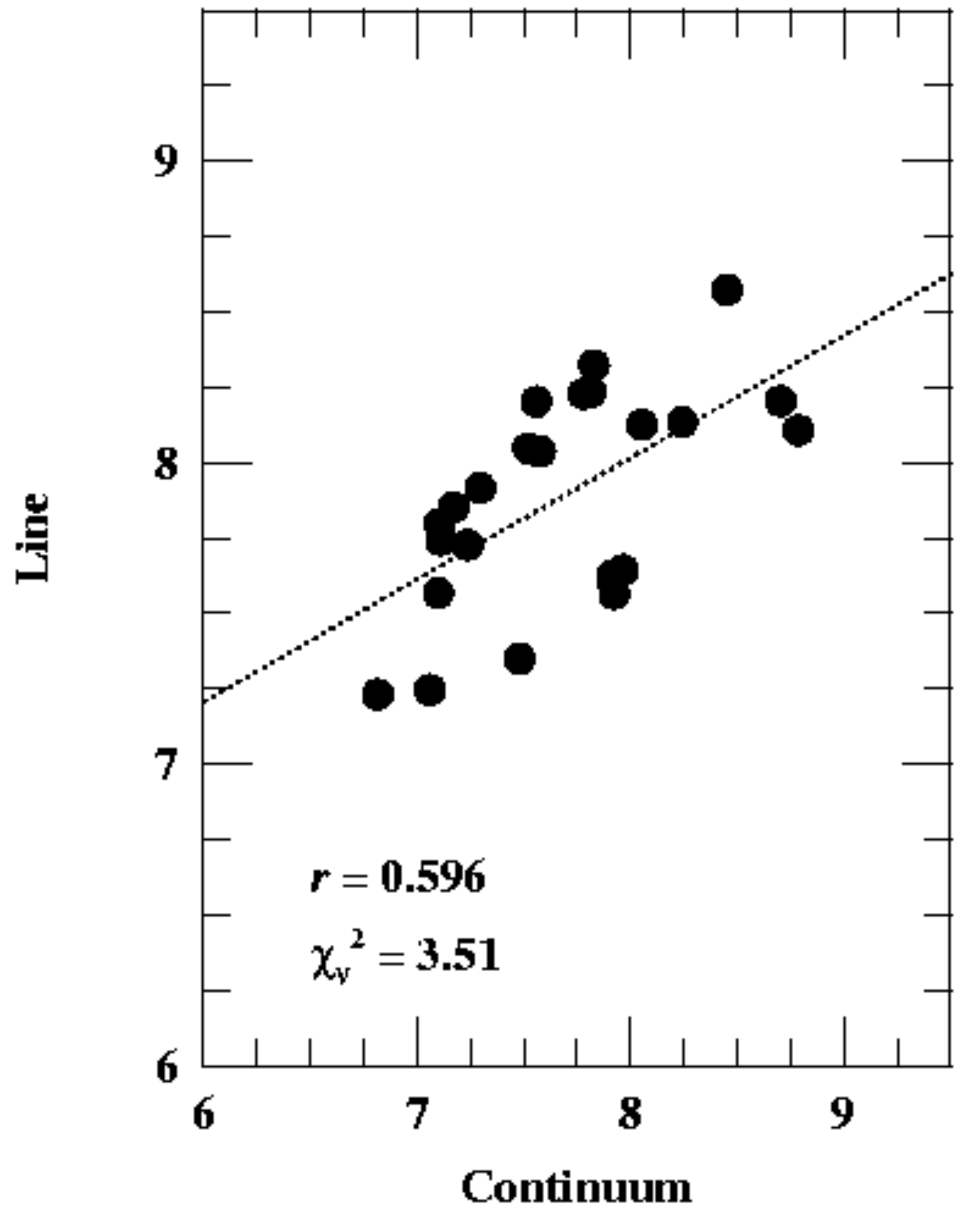
r **= 1: perfect correlation**

r **= 0: no correlation**

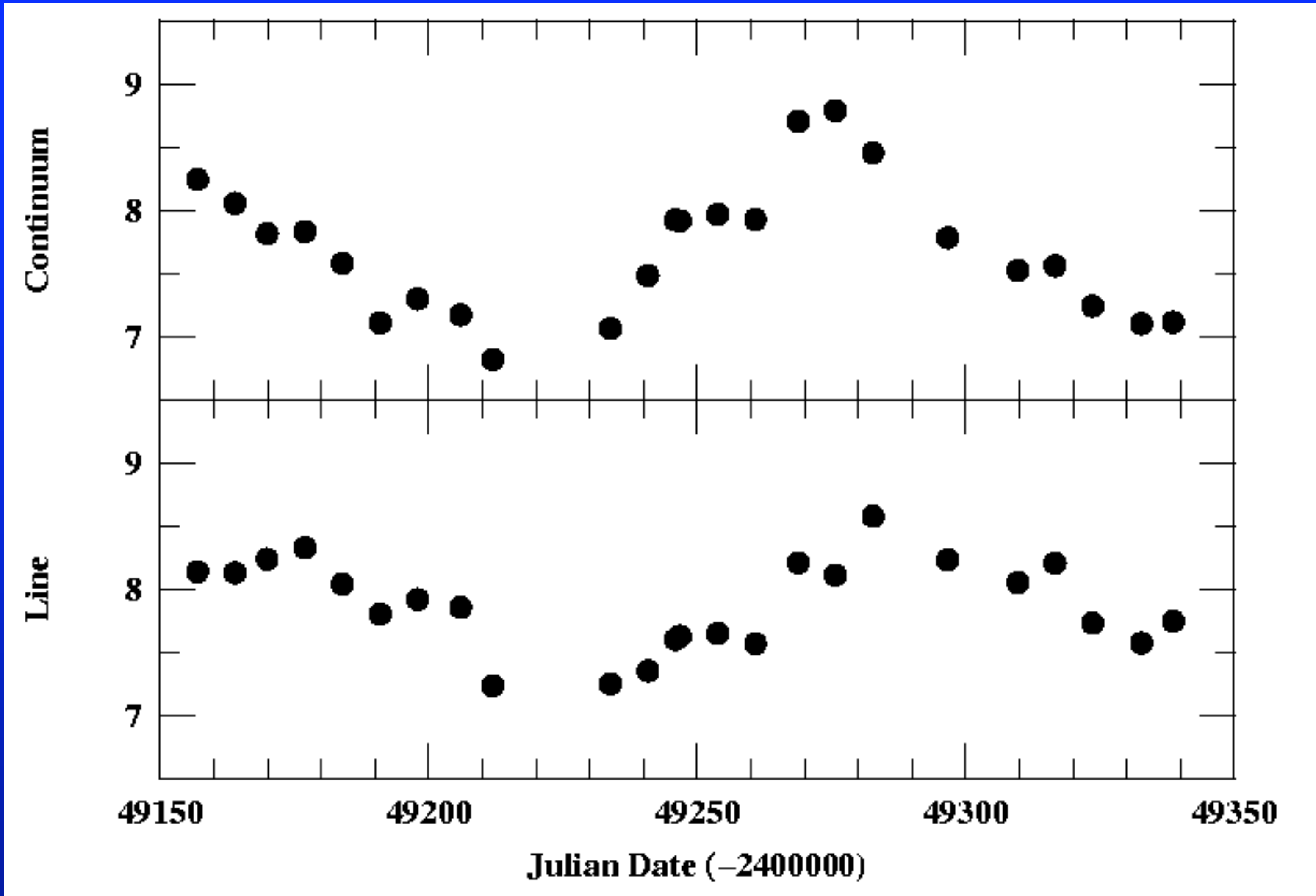
r **= –1: perfect anticorrelation**

Correlation Between Time-Varying Parameters

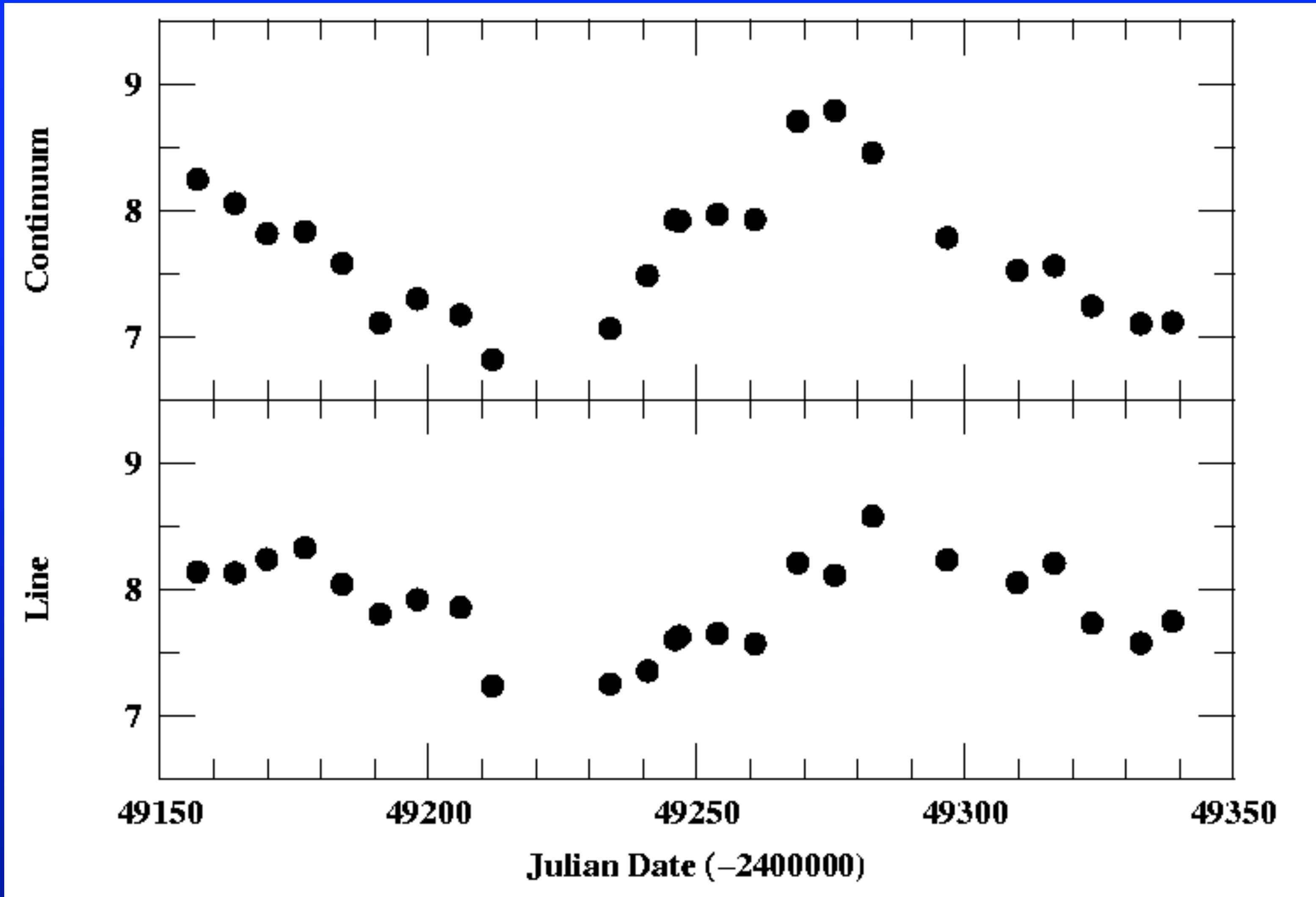
- In fact, the data shown in the example are continuum and Hβ fluxes in a variable Seyfert 1 galaxy, Mrk 335.
  - $x = C(t)$
  - $y = L(t)$
- The continuum and emission-line fluxes are highly correlated.



Mrk 335 data consists of 24 points average spacing of 7.9 days.

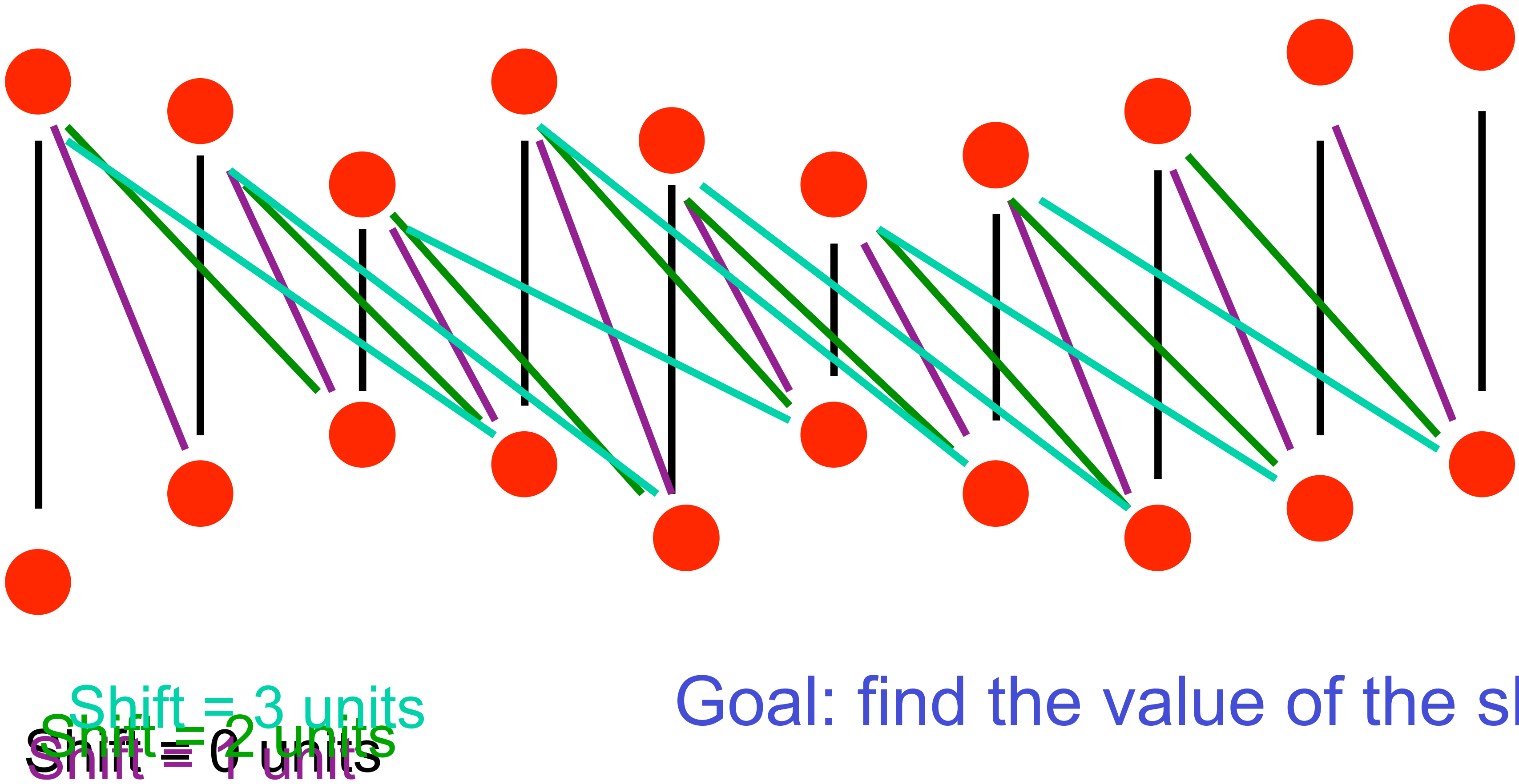


The same data plotted as a function of time.
We see that the correlation is good, but in fact would be even better if we shifted them in time.

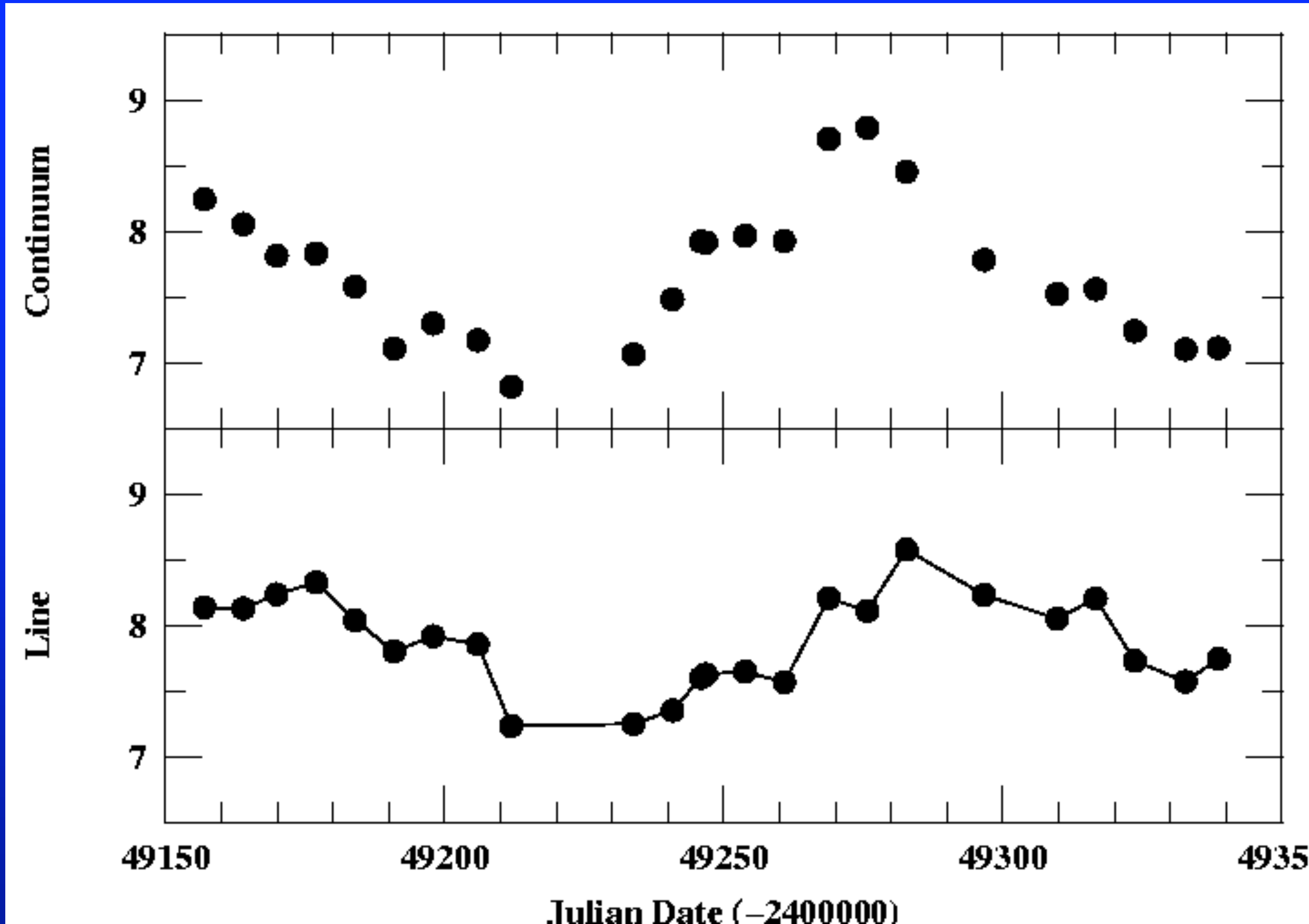


Instead of letting $x = C(t)$ and $y = L(t)$, improve the correlation by letting $x = C(t)$ and $y = L(t + \tau)$, where τ is the time-shift or "lag"

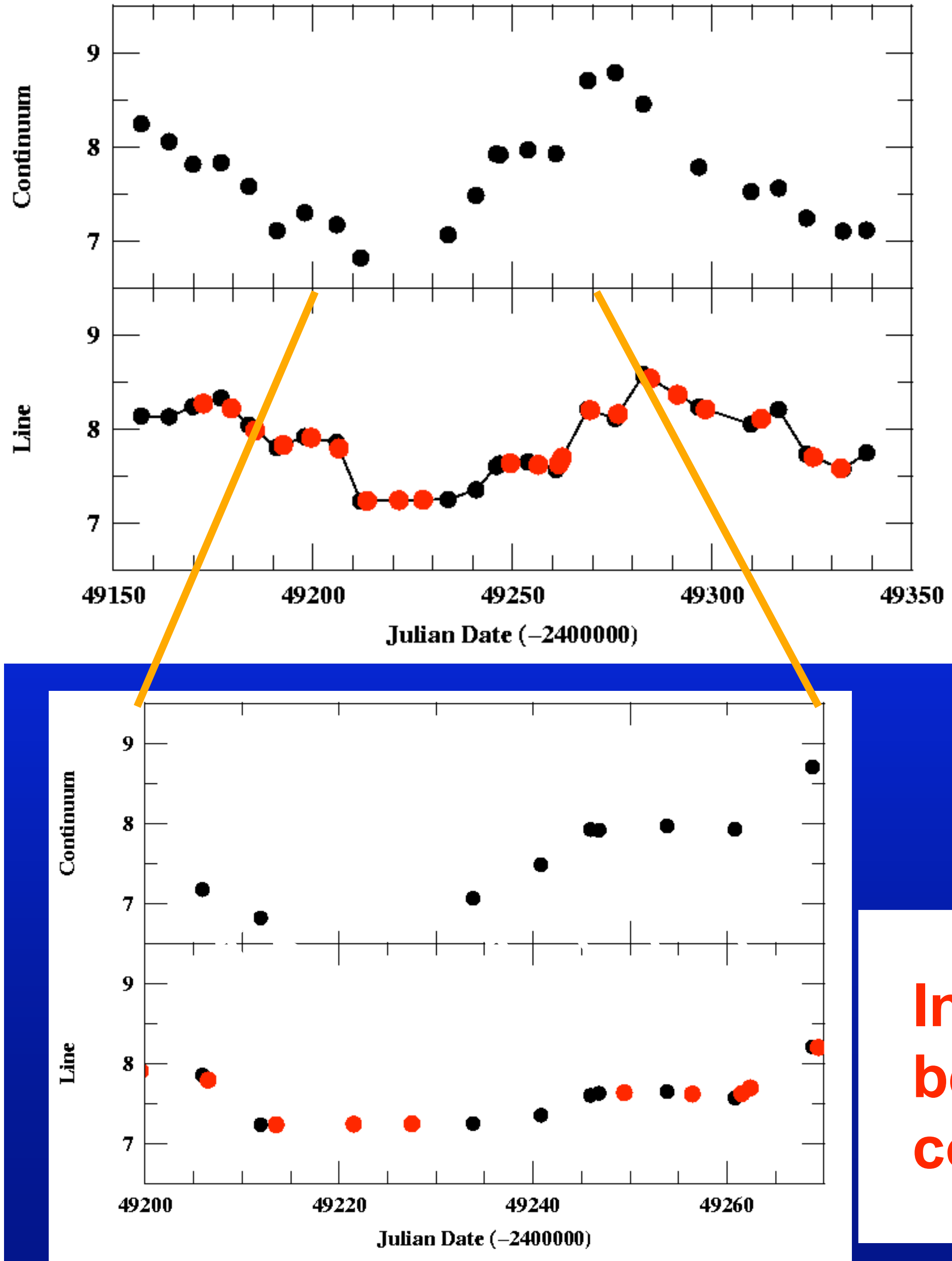
Cross-correlating evenly spaced data is trivial



Goal: find the value of the shift that maximizes the correlation coefficient.



Practical problem: in general, data are not evenly spaced. One solution is to interpolate between real data points.

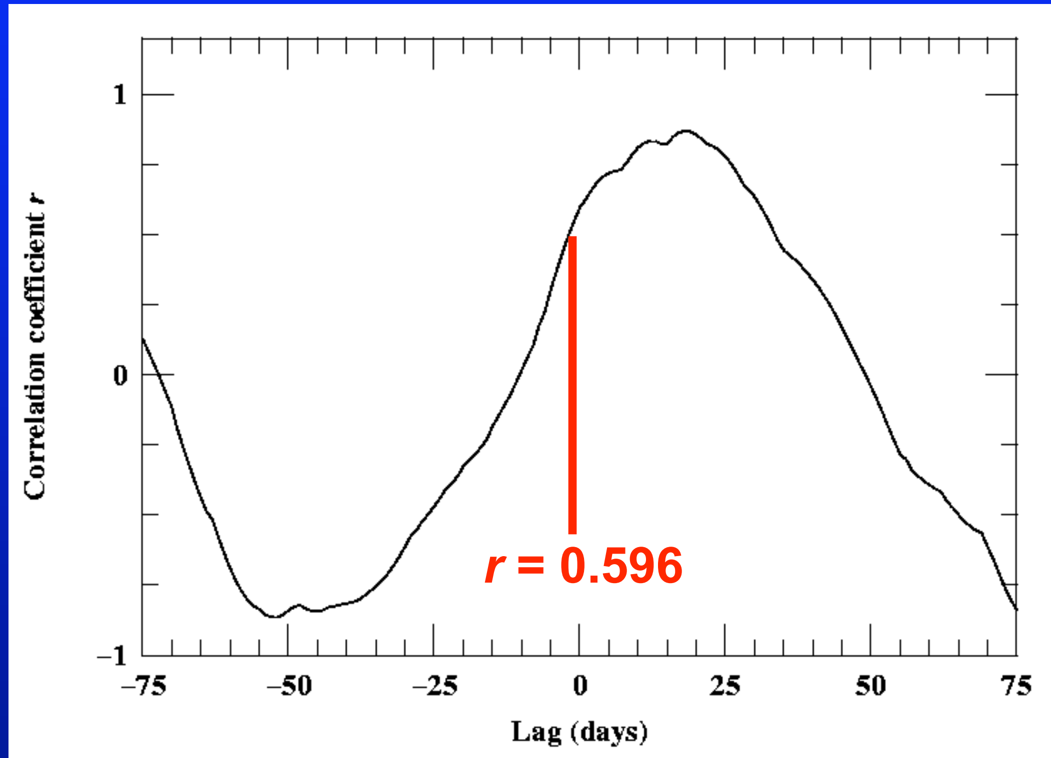


Each real datum $C(t)$ in one time series is matched with an interpolated value $L(t + \tau)$ in the other time series and the linear correlation coefficient is computed for all possible values of the lag τ.

Interpolated line points lag behind corresponding continuum points by 16 days.

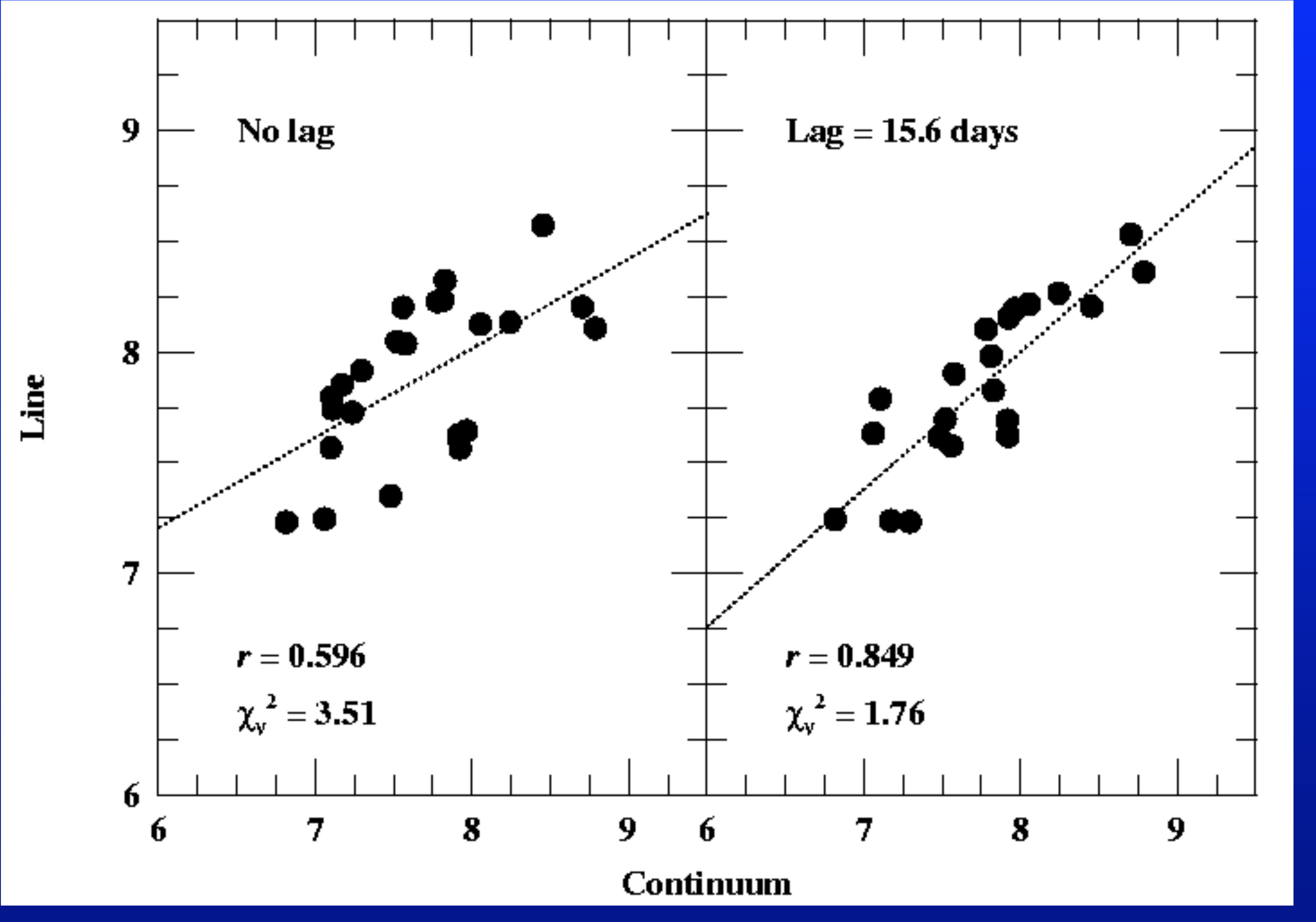
Cross-Correlation Function

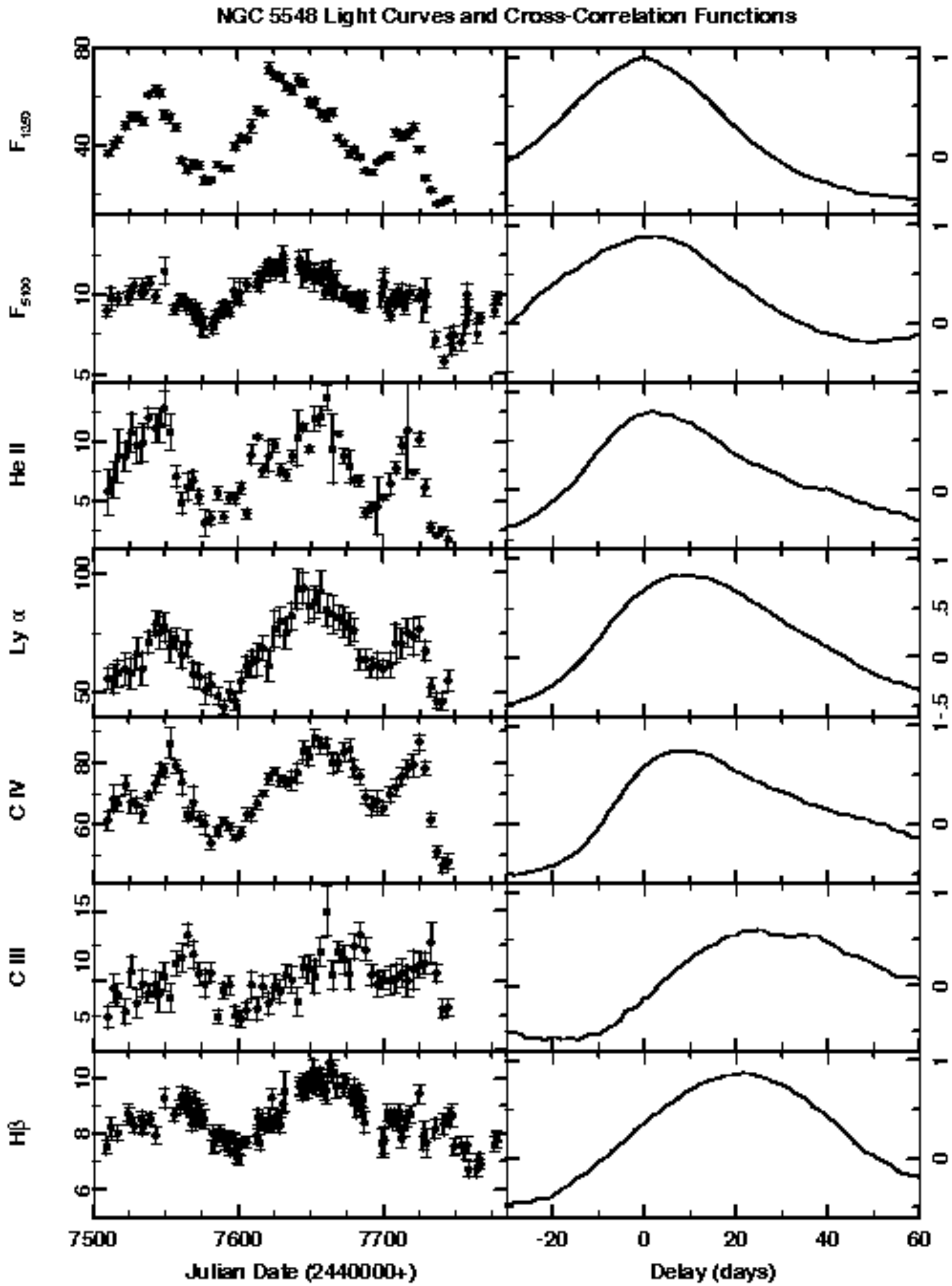
- Linear correlation coefficient as a function of time lag is the “cross-correlation function” (CCF).
- The formal definition of the CCF as a continuous function is the convolution integral:



$$\mathrm{CCF}(\tau) = \int_{-\infty}^{+\infty} L(t)\, C(t-\tau)\, dt$$

The Time-Shift Improves the Linear Correlation





Reverberation Mapping Results

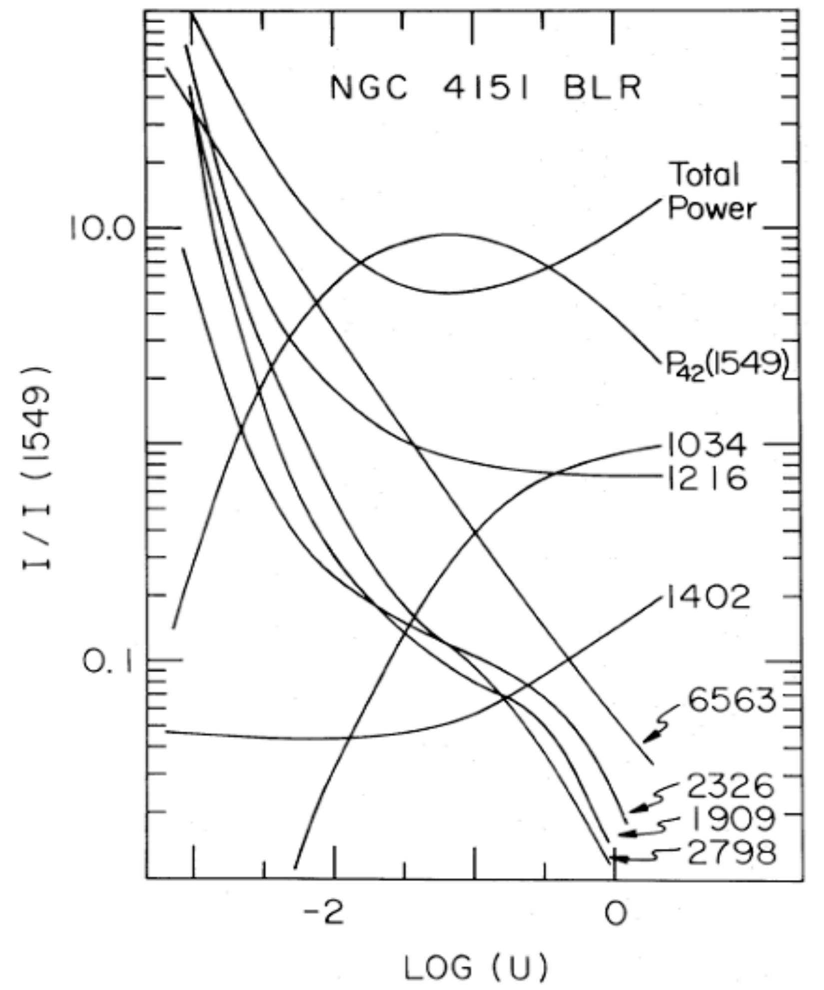
- Reverberation lags have been measured for 36 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

NGC 5548 - 1989

Feature	F_{var}	Lag (days)
UV cont	0.321	…
Opt. Cont	0.117	$0.6^{+1.5}_{-1.5}$
He II λ1640	0.344	$3.8^{+1.7}_{-1.8}$
N V λ1240	0.441	$4.6^{+3.2}_{-2.7}$
He II λ4686	0.052	$7.8^{+3.2}_{-3.0}$
C IV λ1549	0.136	$9.8^{+1.9}_{-1.5}$
Lyα λ1215	0.169	$10.5^{+2.1}_{-1.9}$
Si IV λ1400	0.185	$12.3^{+3.4}_{-3.0}$
Hβ λ4861	0.091	$19.7^{+1.5}_{-1.5}$
C III] λ1909	0.130	$27.9^{+5.5}_{-5.3}$

Photoionization Modeling of the BLR (circa 1982)

- Single-cloud model:
  - Assume that C IV λ1549 and C III] λ1909 arise in same zone
  - Implies $n_e = 3 \times 10^9$ cm^{-3}
  - Line flux ratios then yield $U \approx 10^{-2}$



Ferland & Mushotzky (1982)

Predicting the Size of the BLR (for NGC 5548)

$$Q_{\mathrm{ion}}(H) = \int_{\nu_{\mathrm{ion}}}^{\infty} \frac{L_\nu}{h\nu}\, d\nu \approx 1.4 \times 10^{54} \text{ photons s}^{-1}$$

$$r = \left(\frac{Q_{\mathrm{ion}}(H)}{4\pi c n_{\mathrm{H}} U} \right)^{1/2} \approx 3.3 \times 10^{17}\,\mathrm{cm} \approx 130\,\text{light days}$$

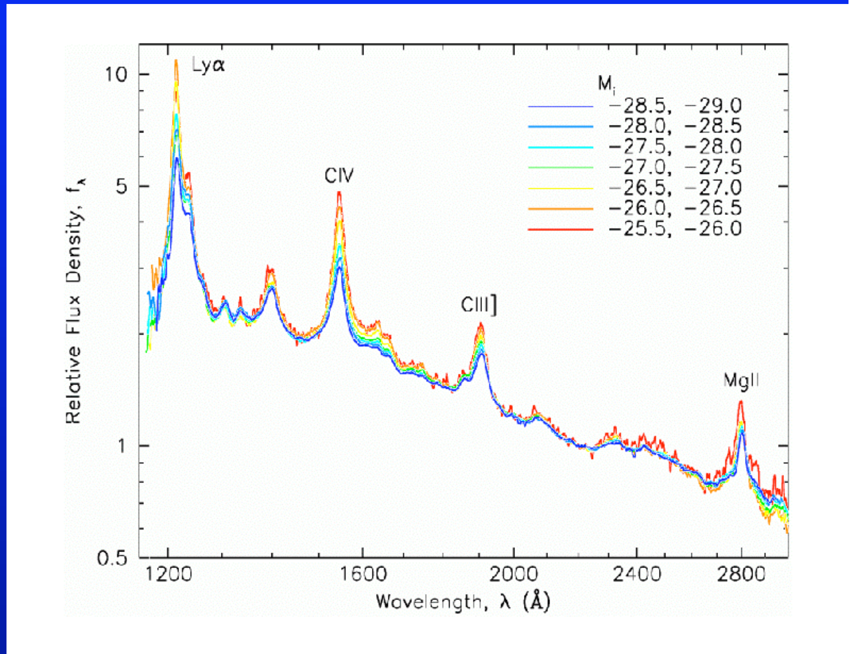
This is an order of magnitude larger than observed!

A Stratified BLR

- C IV and C III] are primarily produced at different radii.
- Density in C IV emitting region is about 10^{11} cm^{-3}

BLR Radius-Luminosity Relationship

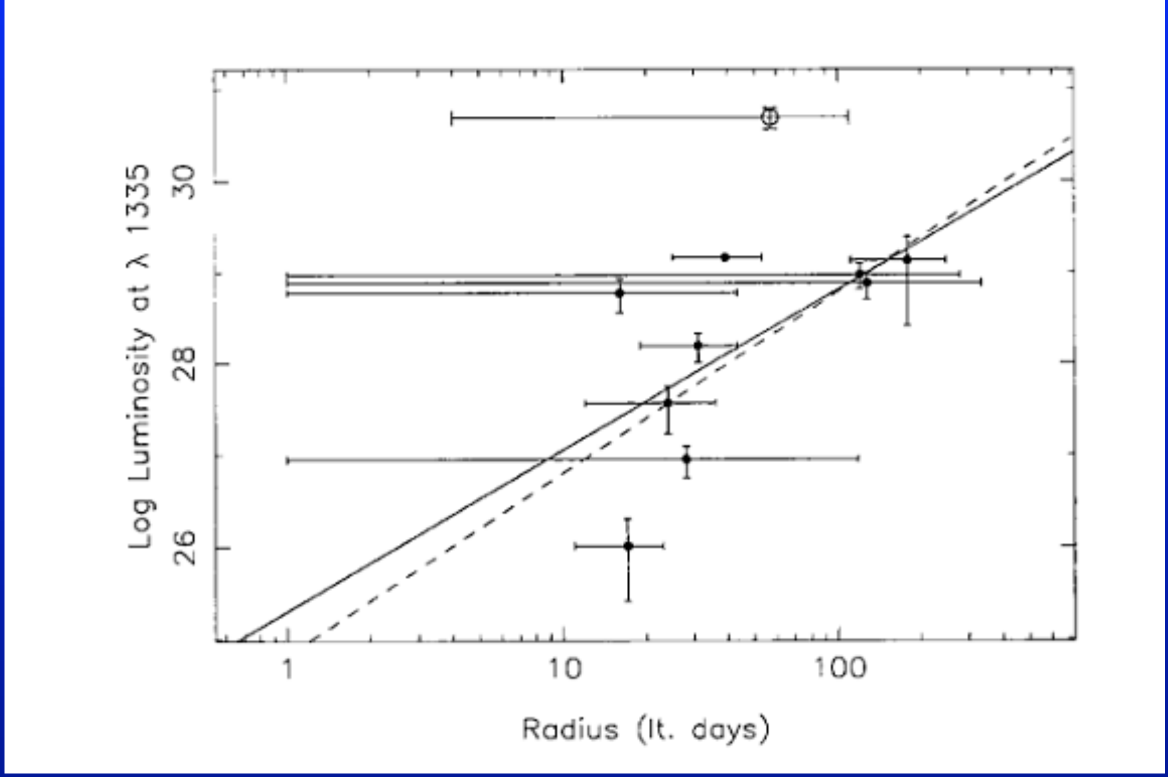
- Similarity of AGN spectra over wide range of luminosity suggests that physical conditions in the BLR are similar.
  - *U*, and n_e are the same



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

BLR Radius-Luminosity Relationship

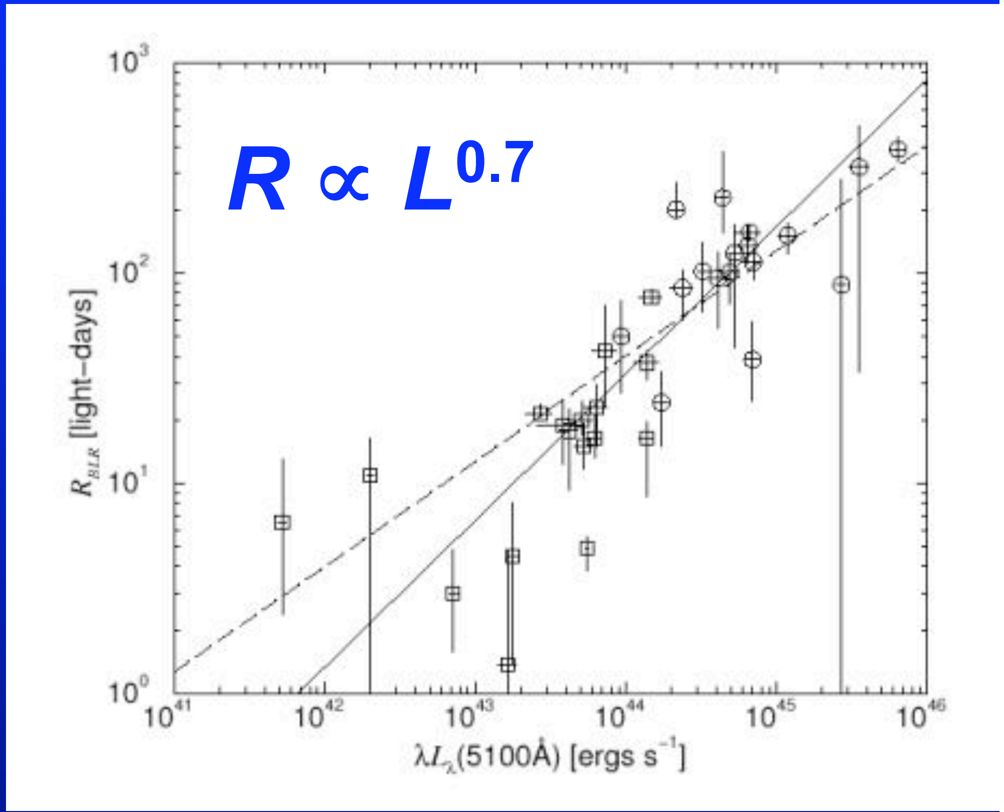
- *R* ∝ *L*^{½} relationship was anticipated long before it was well-measured.



Koratkar & Gaskell 1991

BLR Radius-Luminosity Relationship

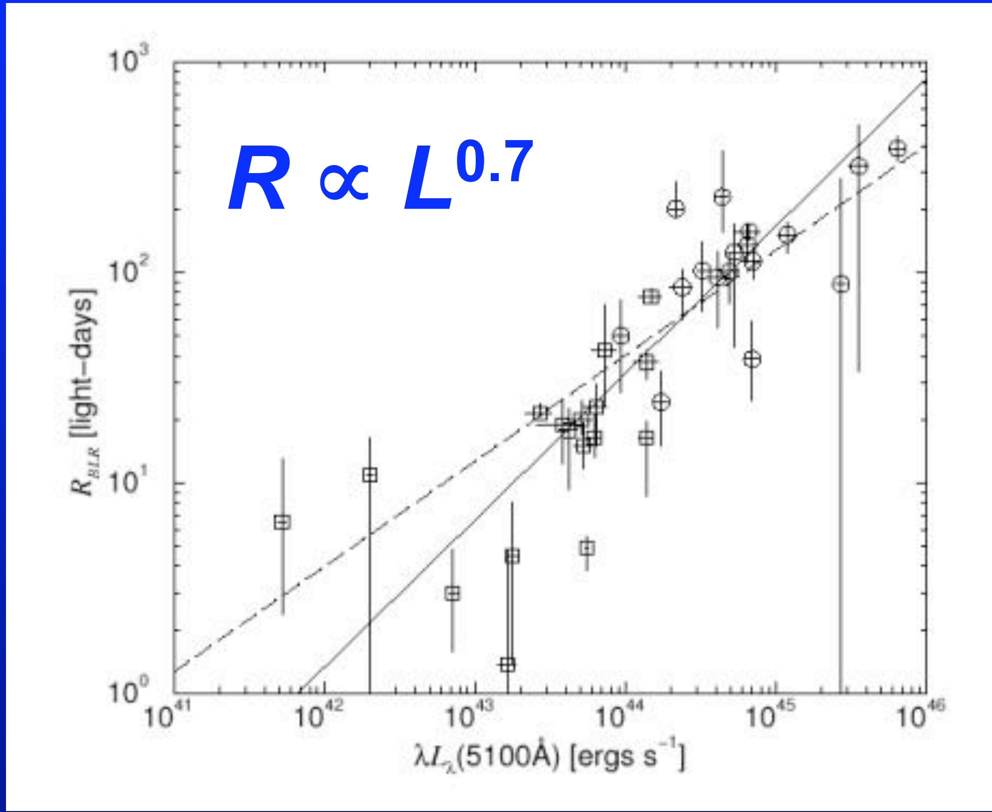
- Kaspi et al. (2000) succeeded in observationally defining the *R*-*L* relationship
  - Increased luminosity range using PG quasars
  - PG quasars are bright compared to their hosts



Kaspi et al. 2000

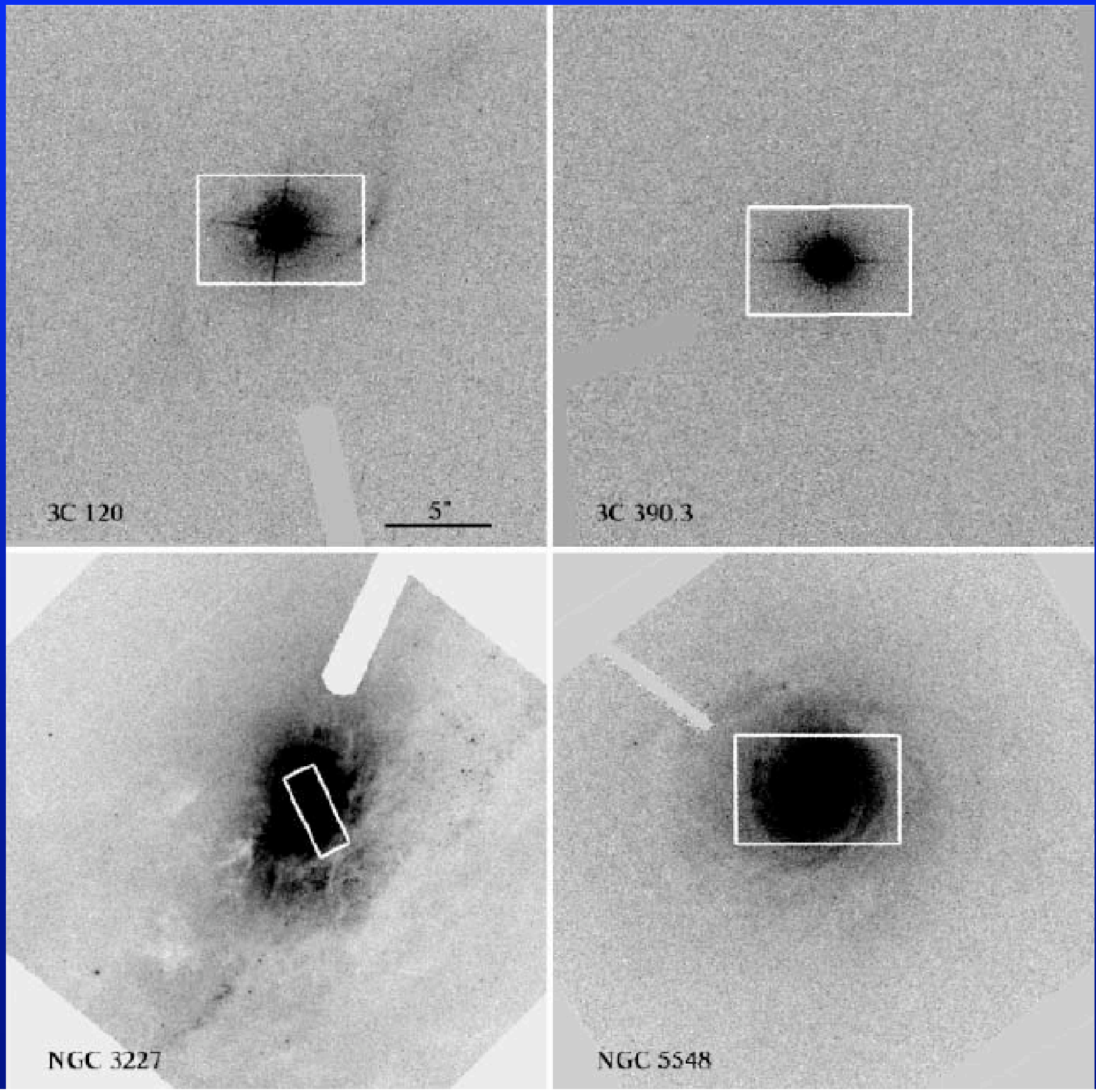
BLR Radius-Luminosity Relationship

- Problems:
  - Some lag measurements were in error
  - Starlight contamination of host galaxies was not taken into account
    - Large apertures for spectrophotometric accuracy
    - Aperture varied among experiments and groups

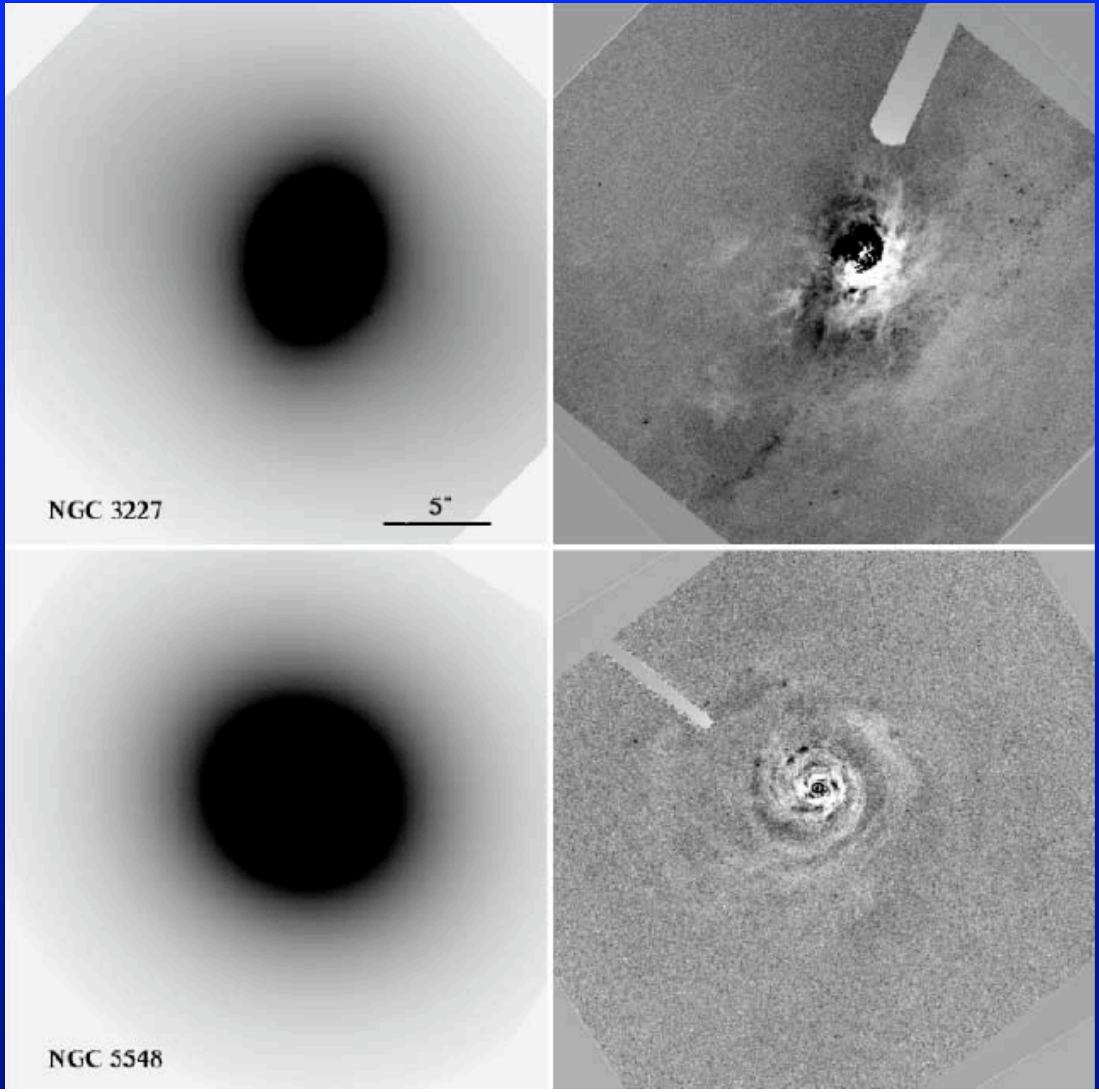


Kaspi et al. 2000

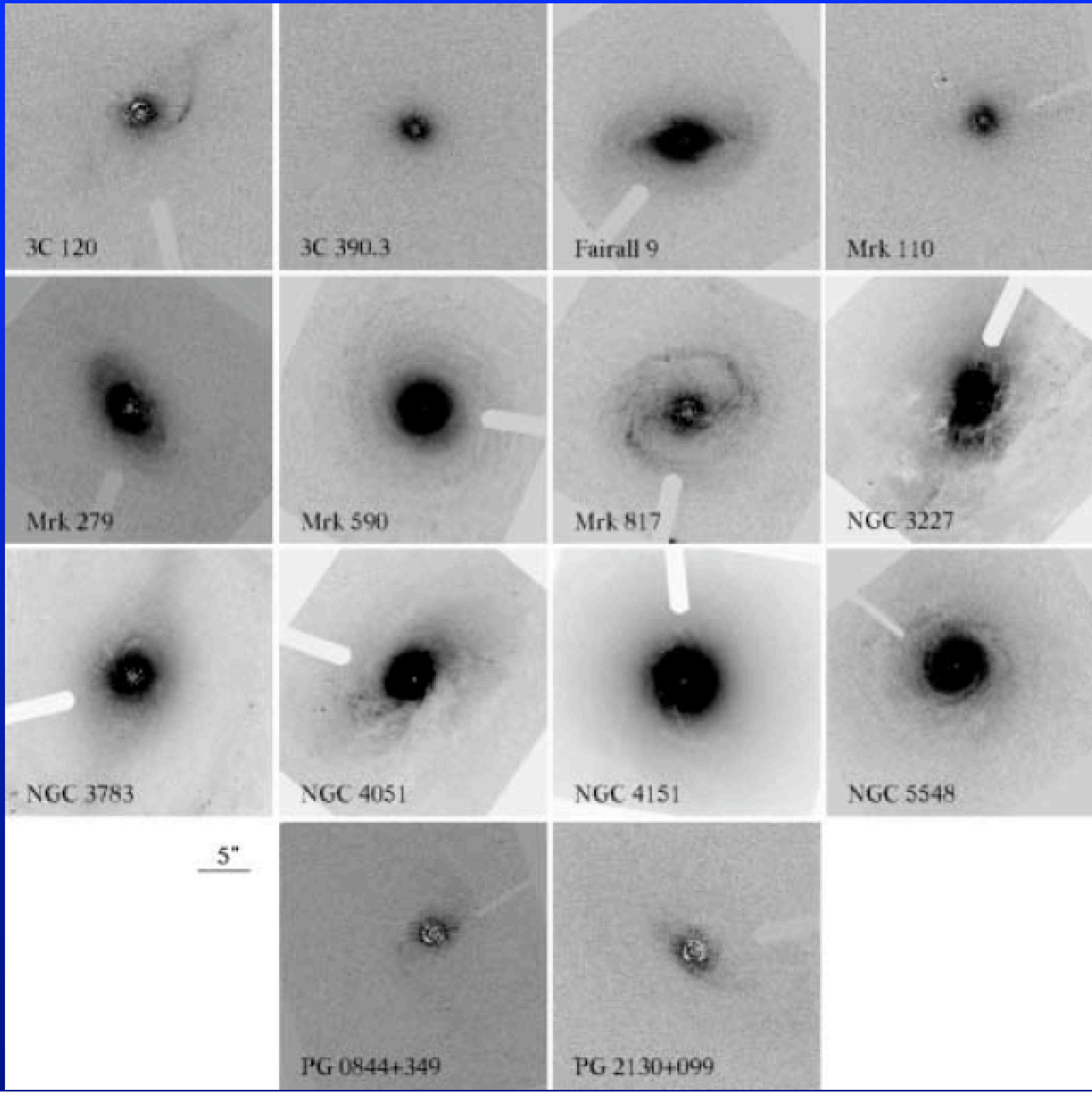
Typical Aperture Geometries for Reverberation-Mapped AGNs



ACS HRC images and model residuals

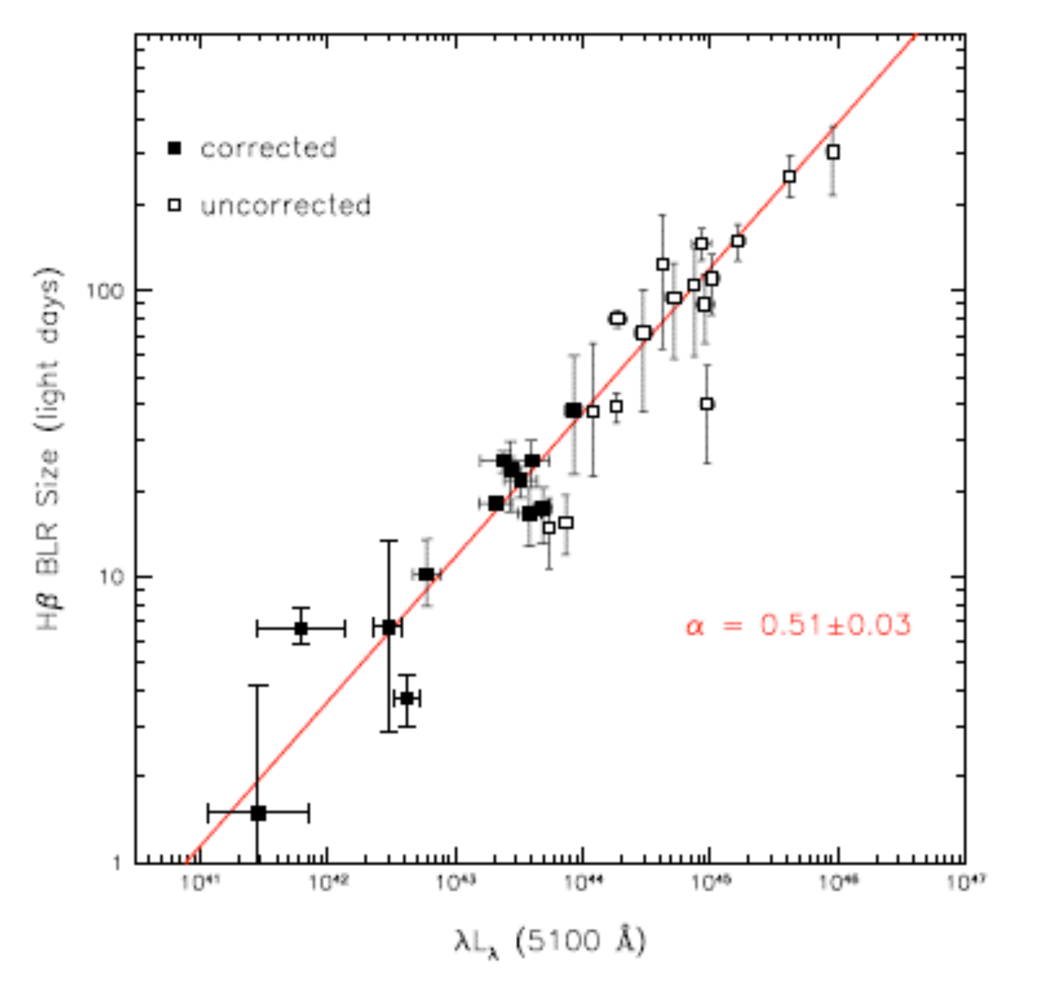


Host Galaxies with AGNs Removed



BLR Radius-Luminosity Relationship

- Improved *R-L* relationship
  - Host galaxy starlight removed
  - Improved masses for NGC 4593 and NGC 4151
- Slope now consistent with $R \propto L^{1/2}$
- This is an important result we'll return to later.



Bentz et al. 2006