Reverberation Mapping of the Broad-Line Region in AGNs

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Brera Lectures

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Topics to be Covered

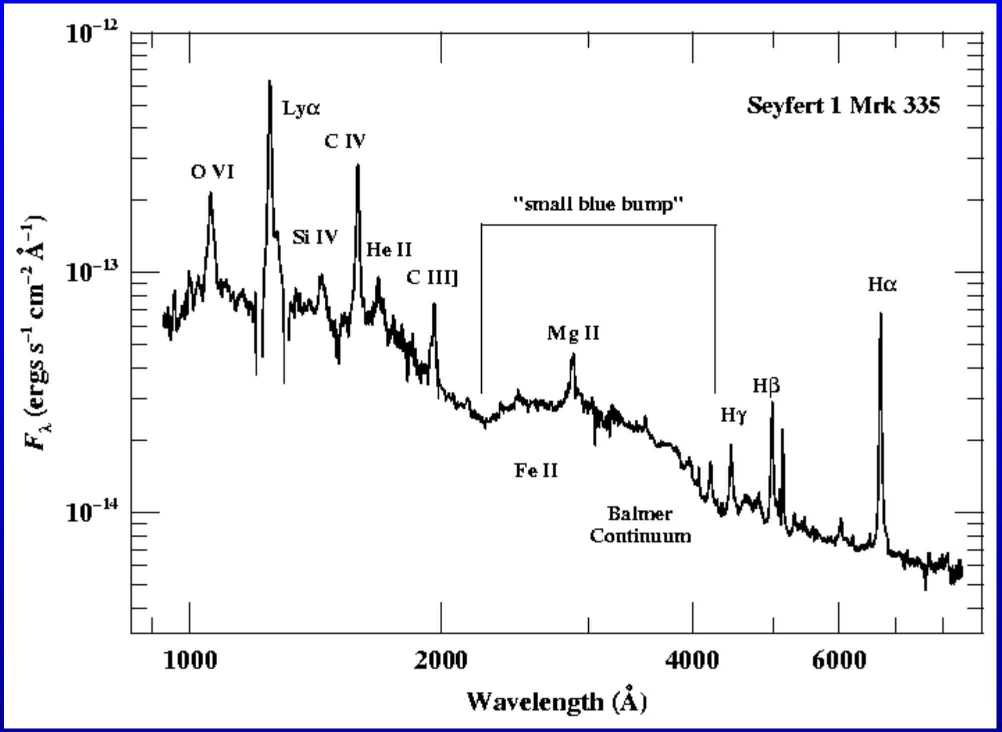
- *Lecture 1:* AGN properties and taxonomy, fundamental physics of AGNs, AGN structure, AGN luminosity function and its evolution
- *Lecture 2:* The broad-line region, emission-line variability, reverberation mapping principles, practice, and results, AGN outflows and disk-wind models, the radius–luminosity relationship
- *Lecture 3:* Role of black holes, direct/indirect measurement of AGN black hole masses, relationships between BH mass and AGN/host properties, limiting uncertainties and systematics

The Broad-Line Region (BLR)

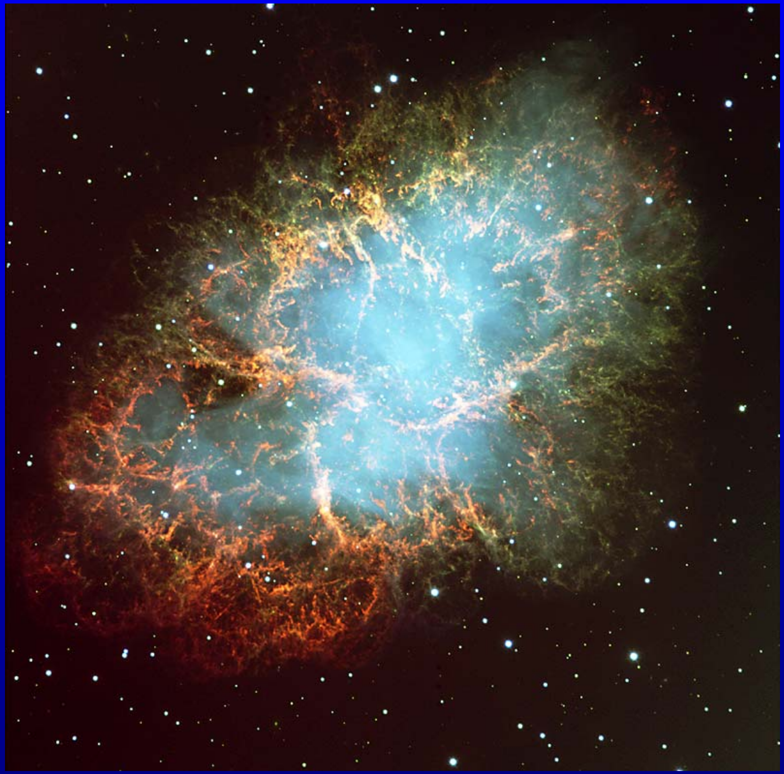
- Why focus on the BLR?
  - It is the gas closest to the central source, and it would be surprising if it is not involved in fueling the central black hole.
  - Central black hole apparently dominates kinematics, enabling measurement of black hole mass (Lecture 3).
- Difficulty: its angular size is only a few tens of microarcseconds, even in nearby AGNs.

Some Simple Inferences

- Temperature of gas is ~10^4 K
  - Thermal width ~10 km s^{-1}
- Density is high, by nebular standards ($n_e \geq 10^9$ cm^{-3})
  - Efficient emitter, can be low mass
- Line widths FWHM 1000 – 25,000 km/sec ⇒ Gas moves supersonically



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
  - Virial models implied very large masses
    - Early photoionization models overpredicted size of BLR (to be shown)

What is the BLR?

Flaw in the argument: emissivity per cloud is not proportional to cloud volume, but $N_c R_c^2 R_{Stromgren}$ Number and size not independently constrained.

Crab Nebula with VLT

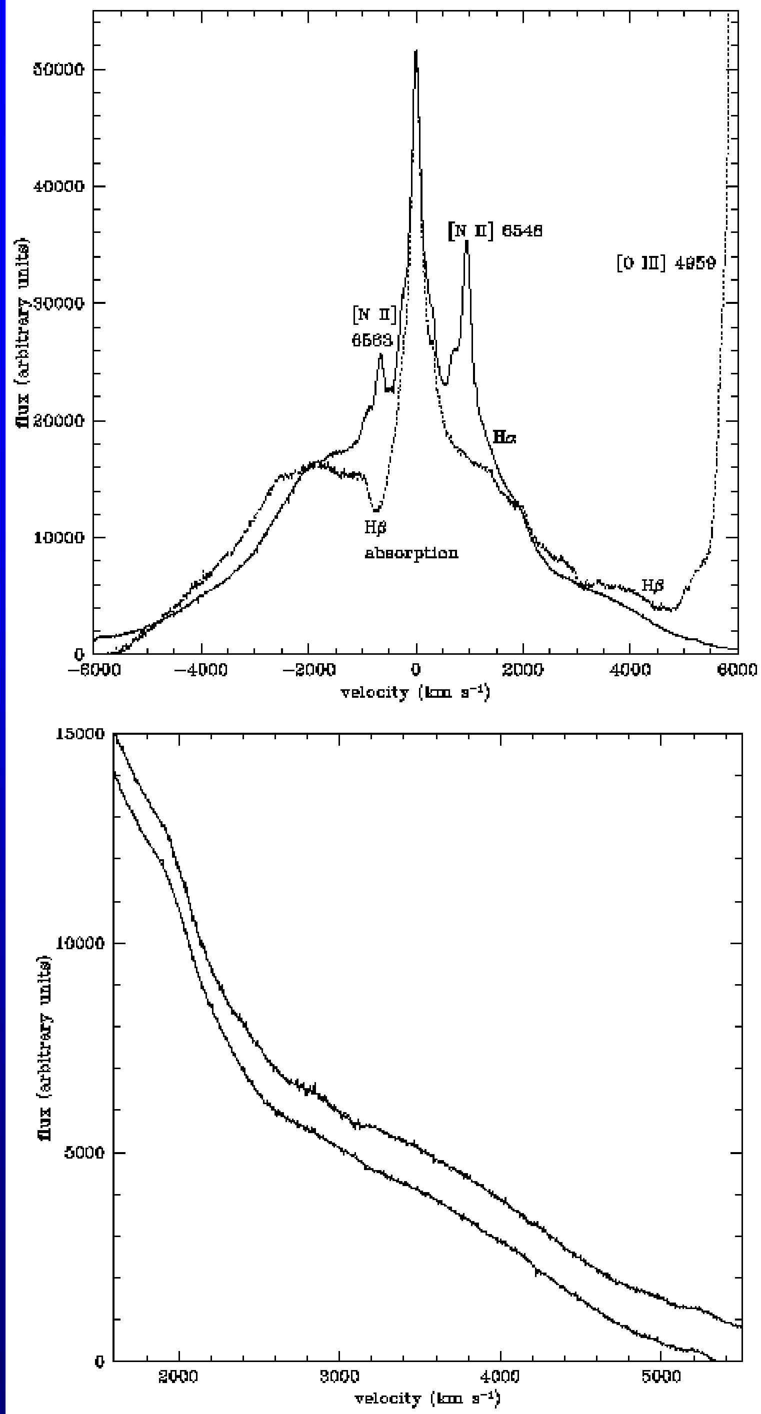
- Number of clouds N_c of radius R_c:
  - Covering factor $\propto N_c R_c^2$
  - Line luminosity $\propto N_c R_c^3$
  - Combine these to find large number ($N_c > 10^8$) of small ($R_c \approx 10^{13}$ cm) clouds.
  - Combine size and density ($n_H \approx 10^{10}$ cm^{-3}), to get column density ($N_H \approx 10^{23}$ cm^{-2}), compatible with X-ray absorption.
  - Minimum mass of line-emitting material $\sim 1 M_\odot$.

Large Number of Clouds?

- If clouds emit at thermal width (10 km/sec), then there must be a very large number of them to account for lack of small-scale structure in line profiles.

NGC 4151

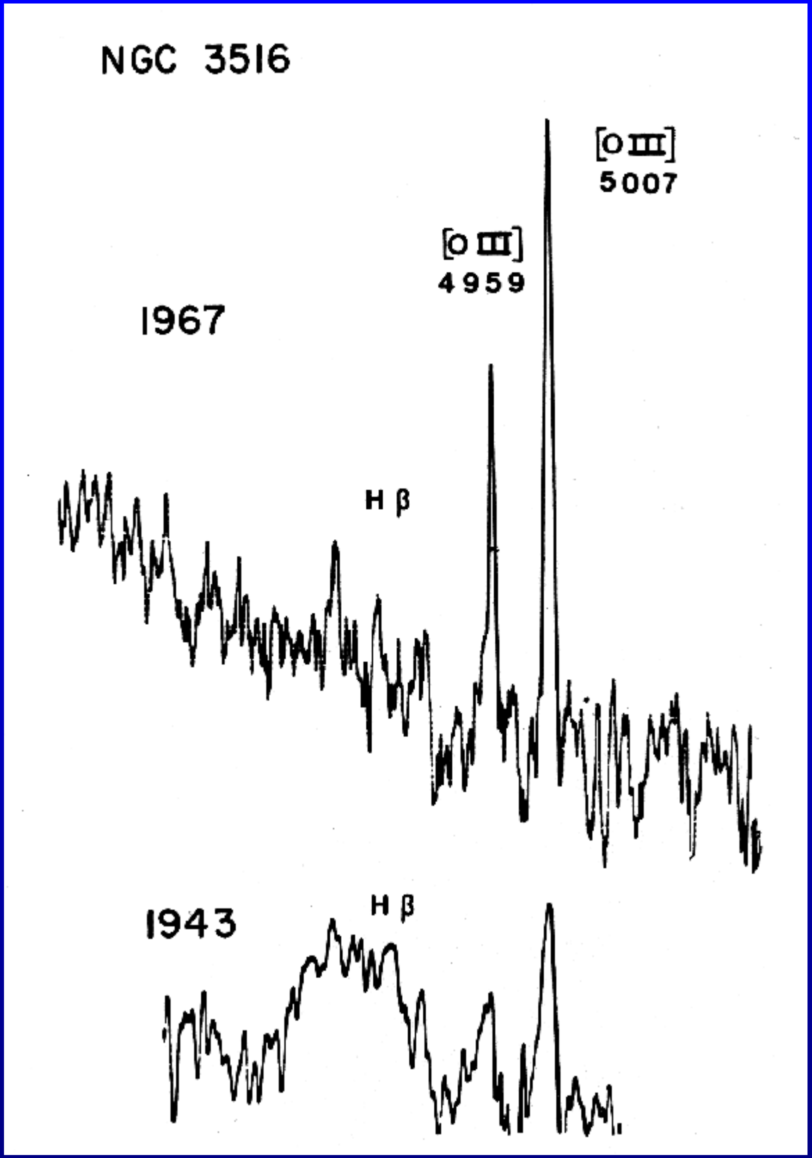
Arav et al. (1998)



Emission-Line Variability

- First reported by Andrillat & Souffrin based on photographic spectra of NGC 3516
- Subsequent reports were scattered, and seemed to be widely regarded as "curiosities".

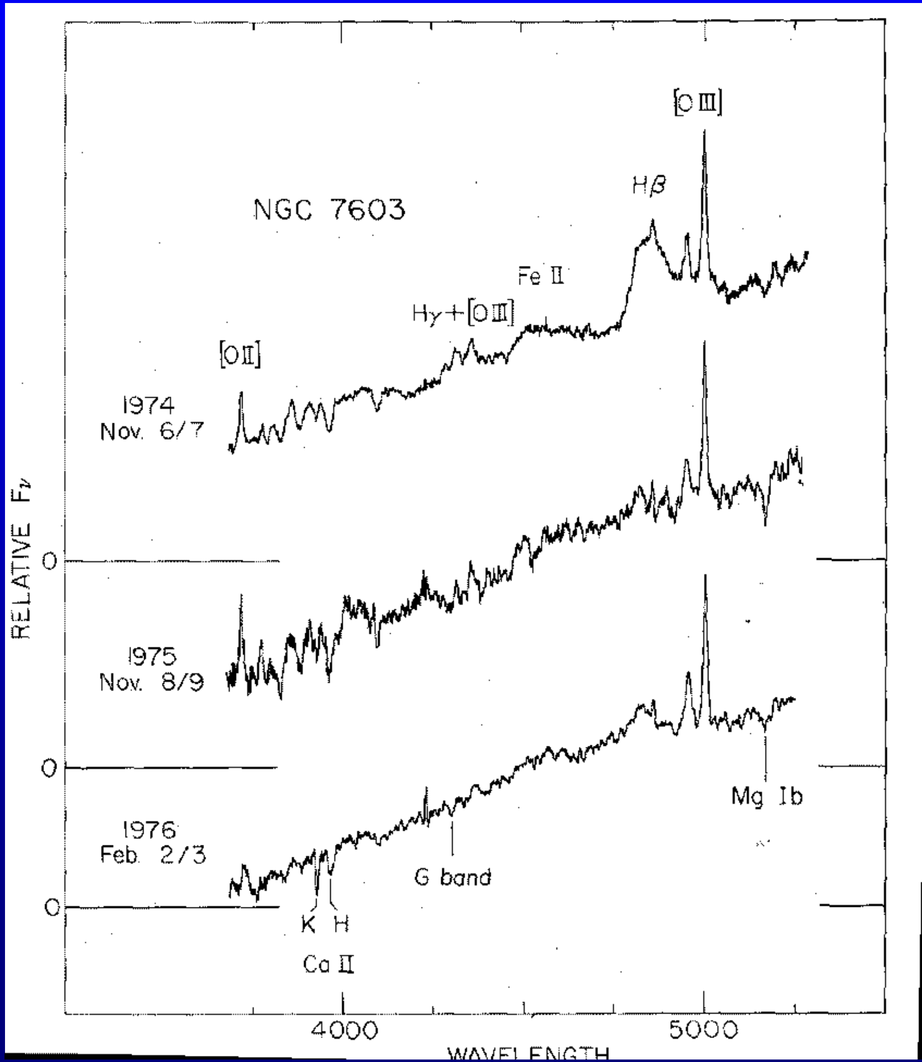
Tohline and Osterbrock (1976)
Phillips (1978)



Andrillat & Souffrin 1968

Emission-Line Variability

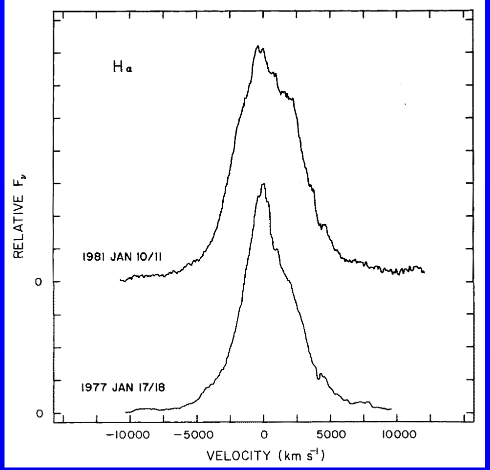
- Only very large changes could be detected photographically or with intensified television-type scanners (e.g., Image Dissector Scanners).
- Changes that were observed were often dramatic and reported as Seyferts changing “type” as broad components appeared or disappeared.



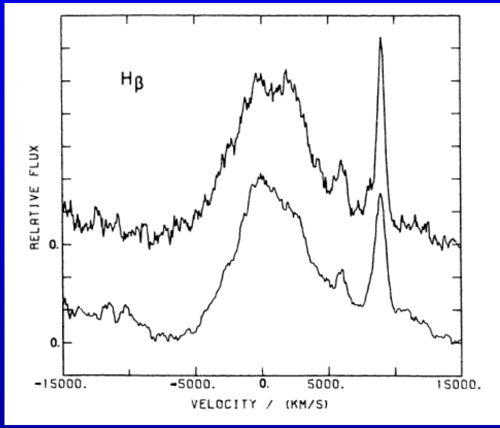
Tohline & Osterbrock 1976

Emission-Line Profile Variability

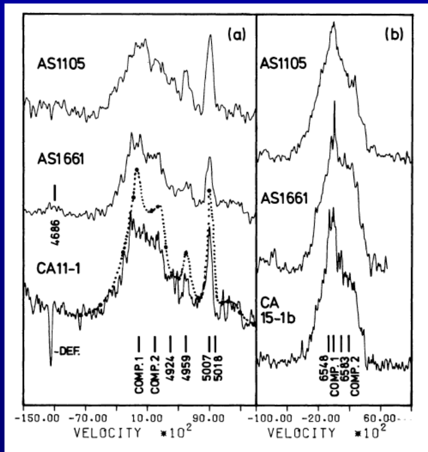
- Variability of broad emission-line profiles was detected in the early 1980s.
- This was originally thought to point to an ordered velocity field and propagation of excitation inhomogeneties.
- Led to development of reverberation mapping (seminal paper by Blandford & McKee 1982).



Foltz et al. 1981



Kollatschny et al. 1981



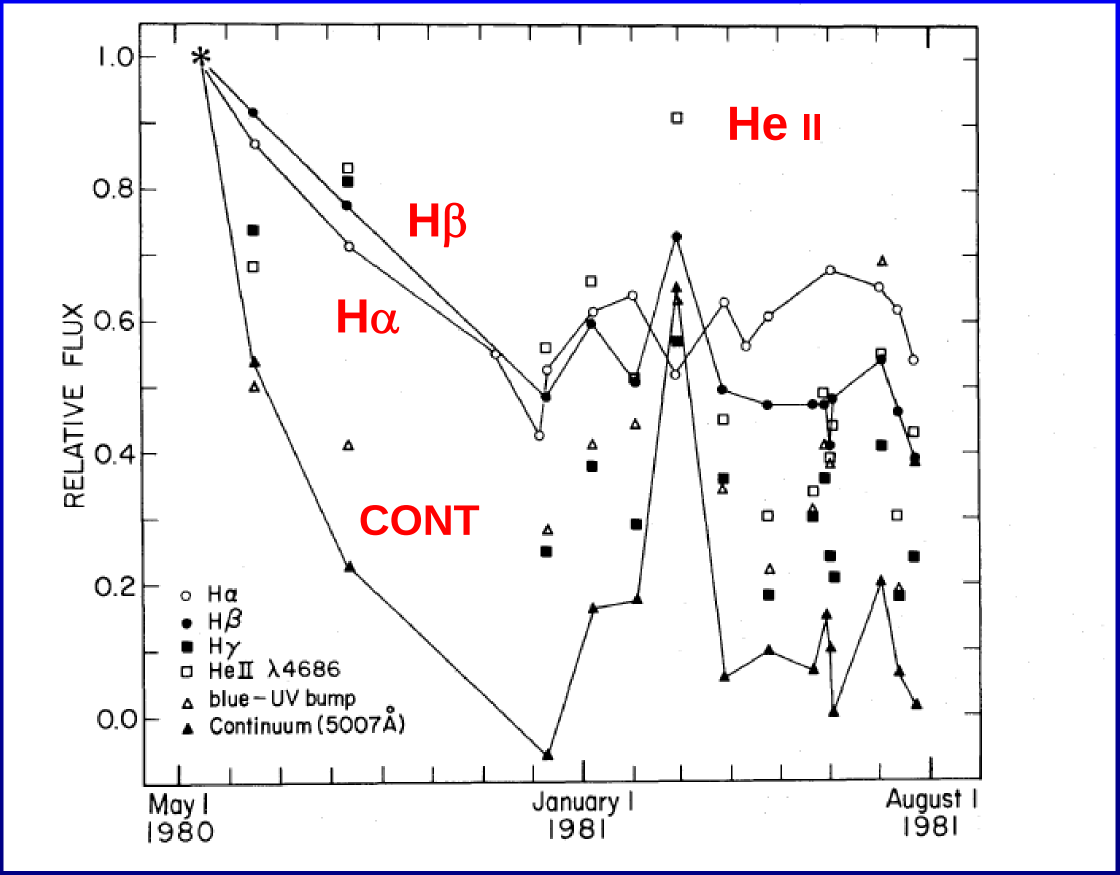
Schulz & Rafanelli 1981

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

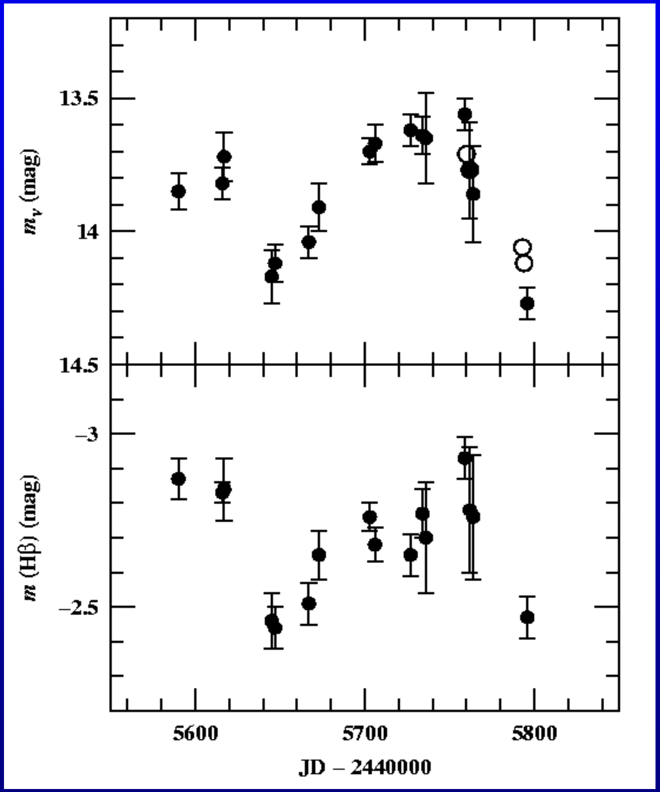
- NGC 4151: Monitored at Lick Observatory by Antonucci and Cohen in 1980 and 1981
  - short time scale response of Balmer lines (<1 month)
  - higher amplitude variability of higher-order Balmer lines and He II λ4686



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

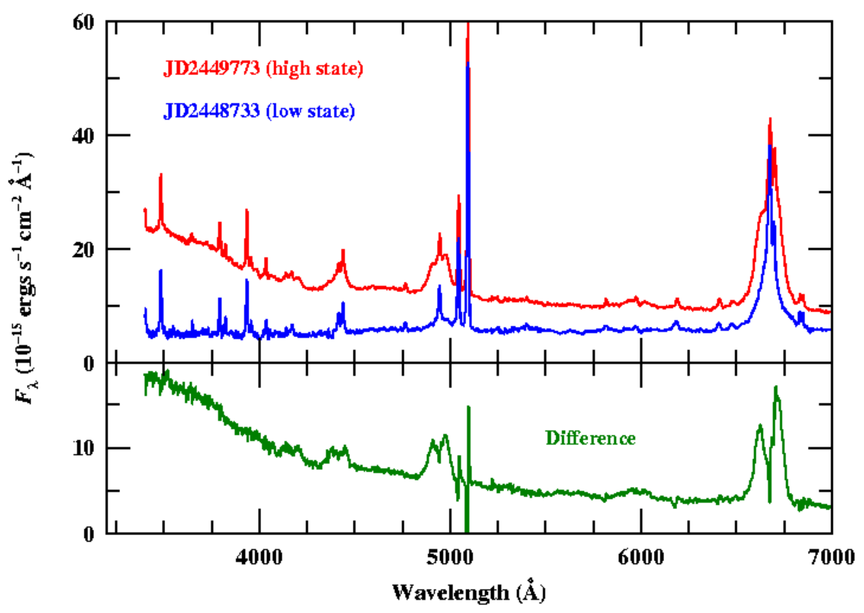
30 Years of NGC 5548

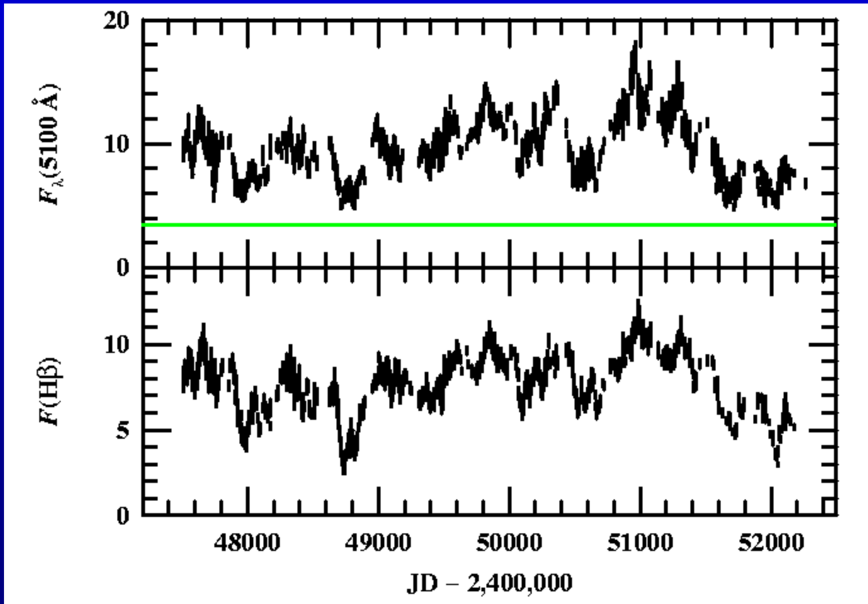
Hβ & Continuum Variability
1972–2002

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

Broad-Line Flux and Profile Variability

- Emission-line fluxes vary with the continuum, but with a short time delay.
- Inferences:
  - Gas is photoionized and optically thick
  - Line-emitting region is fairly small



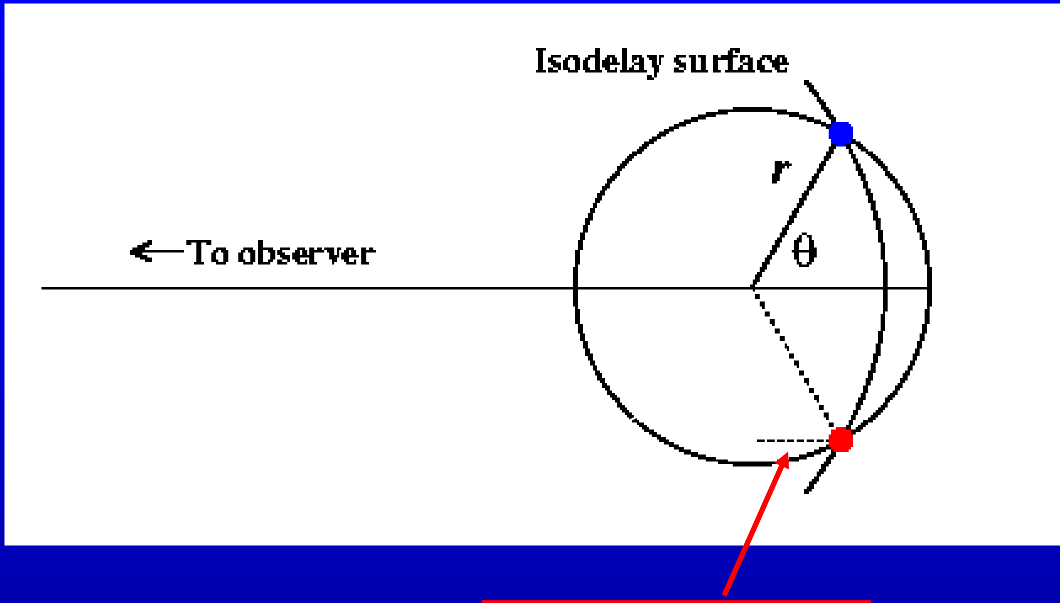


Reverberation Mapping Assumptions

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 $\tau_{dyn} = R/\Delta V$, so $\tau_{dyn}/\tau_{LT} = c/\Delta V \approx 100$.
   - Recombination time is $\tau_{rec} \approx (\alpha_B\, n_e)^{-1} \approx 400\ s^{-1}$ for a density of $10^{10}\ cm^{-3}$.
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 $\tau = (1 + \cos\theta) r / c$



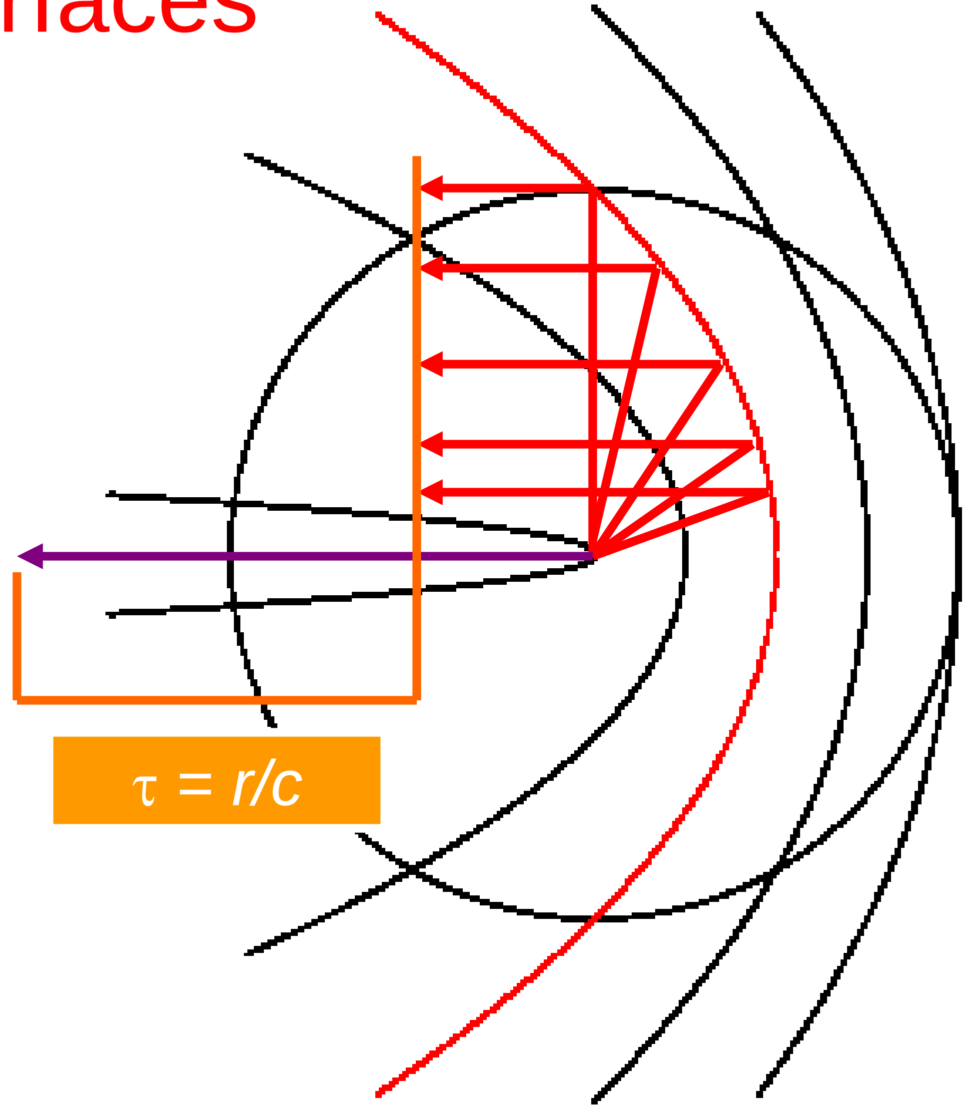
$\tau = r \cos\theta / c$

The isodelay surface is a parabola:

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

“Isodelay Surfaces”

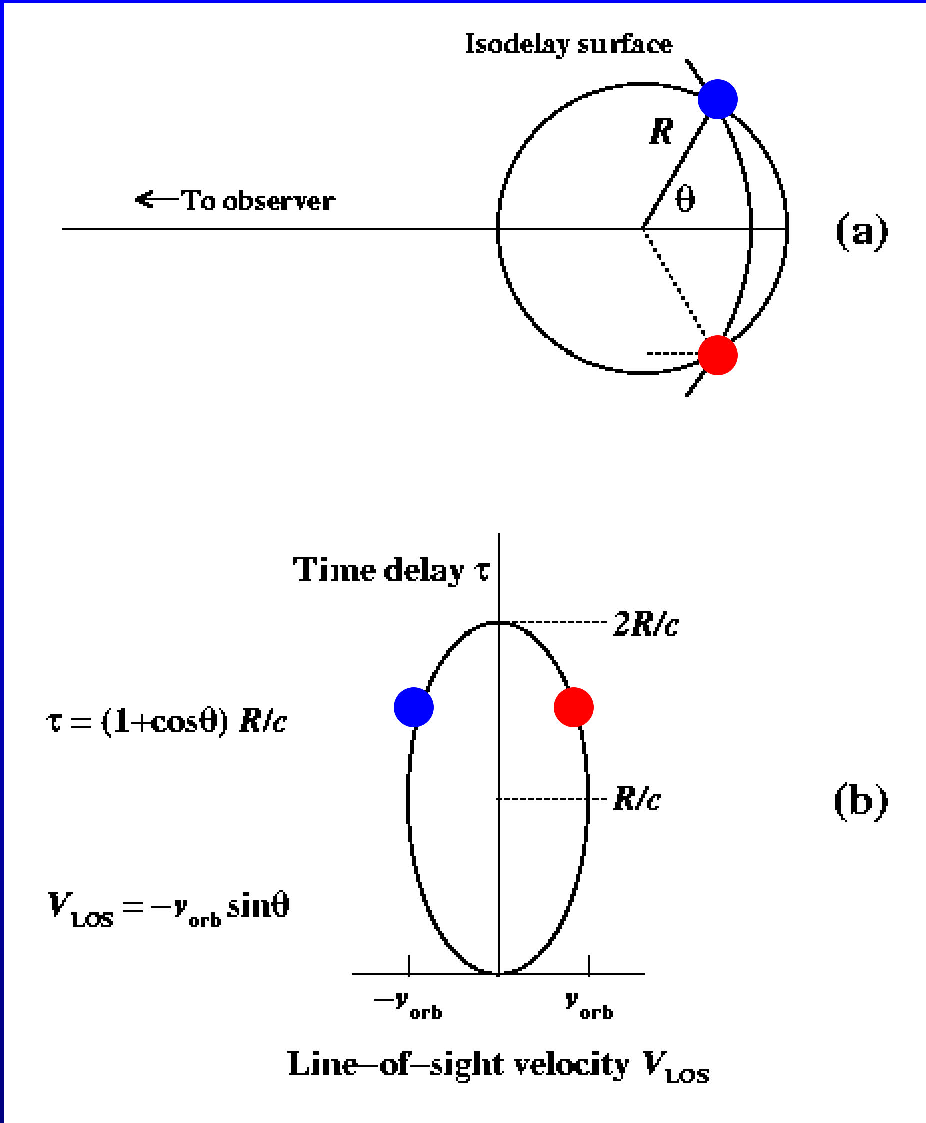
All points on an “isodelay surface” have the same extra light-travel time to the observer, relative to photons from the continuum source.



τ = *r*/*c*

Velocity-Delay Map for an Edge-On Ring

- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V_{LOS} = \pm V_{orb} \sin\theta$.
- 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)

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

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

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

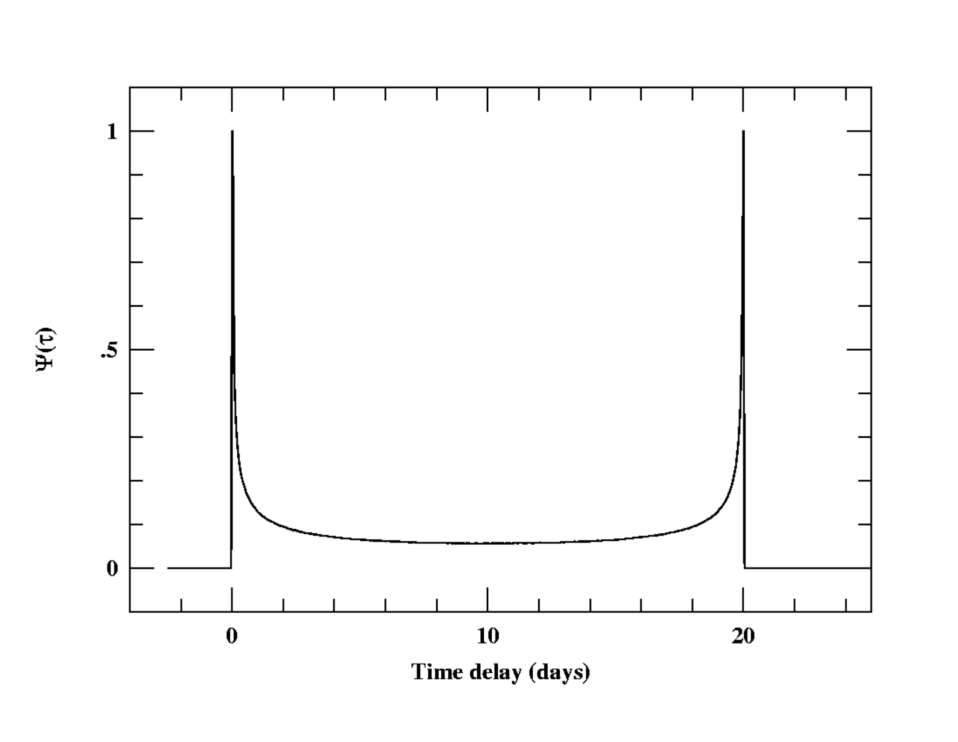
Do some algebra

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

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)

$$\Psi(V_{\rm LOS})\; dV_{\rm LOS} = \Psi(\theta)\frac{d\theta}{dV_{\rm LOS}}\; dV_{\rm LOS}$$

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

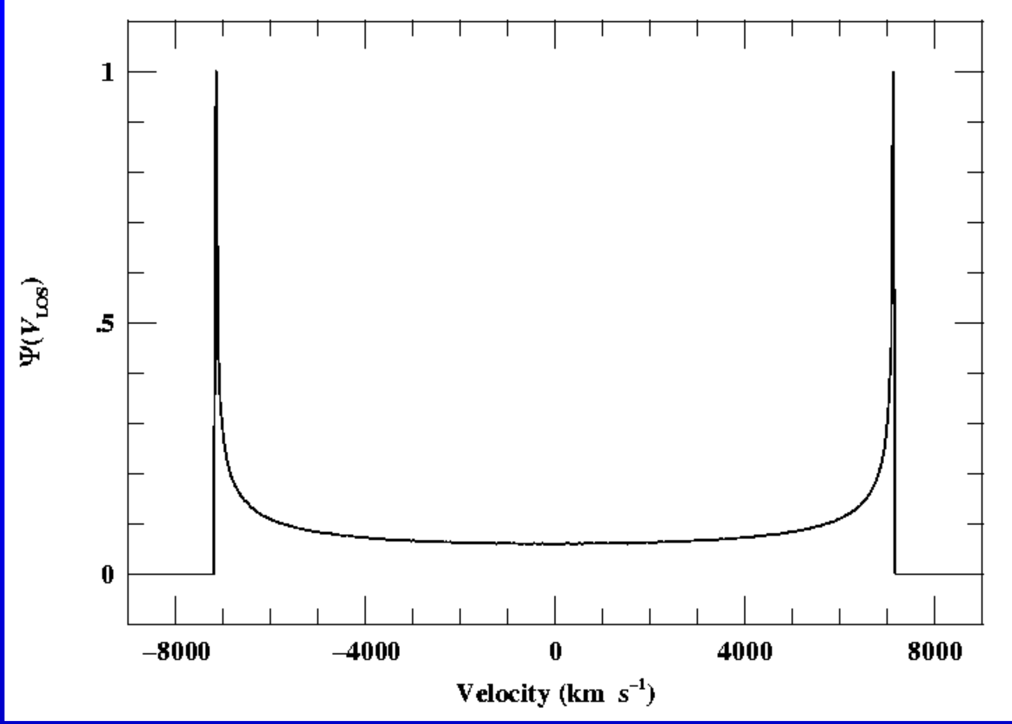
$$\frac{dV_{\rm LOS}}{d\theta} = -V_{\rm orb} \cos\theta$$

Do some algebra again

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

Line Profile for a Ring

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

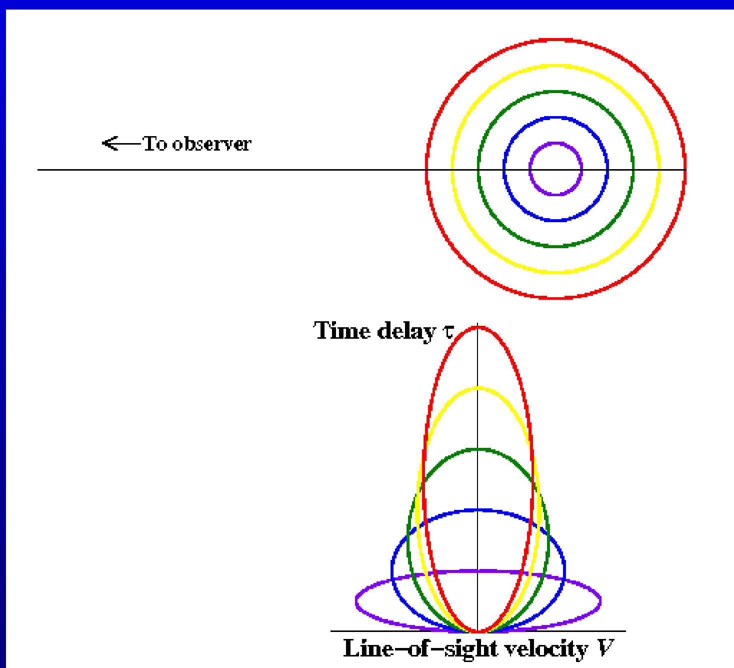


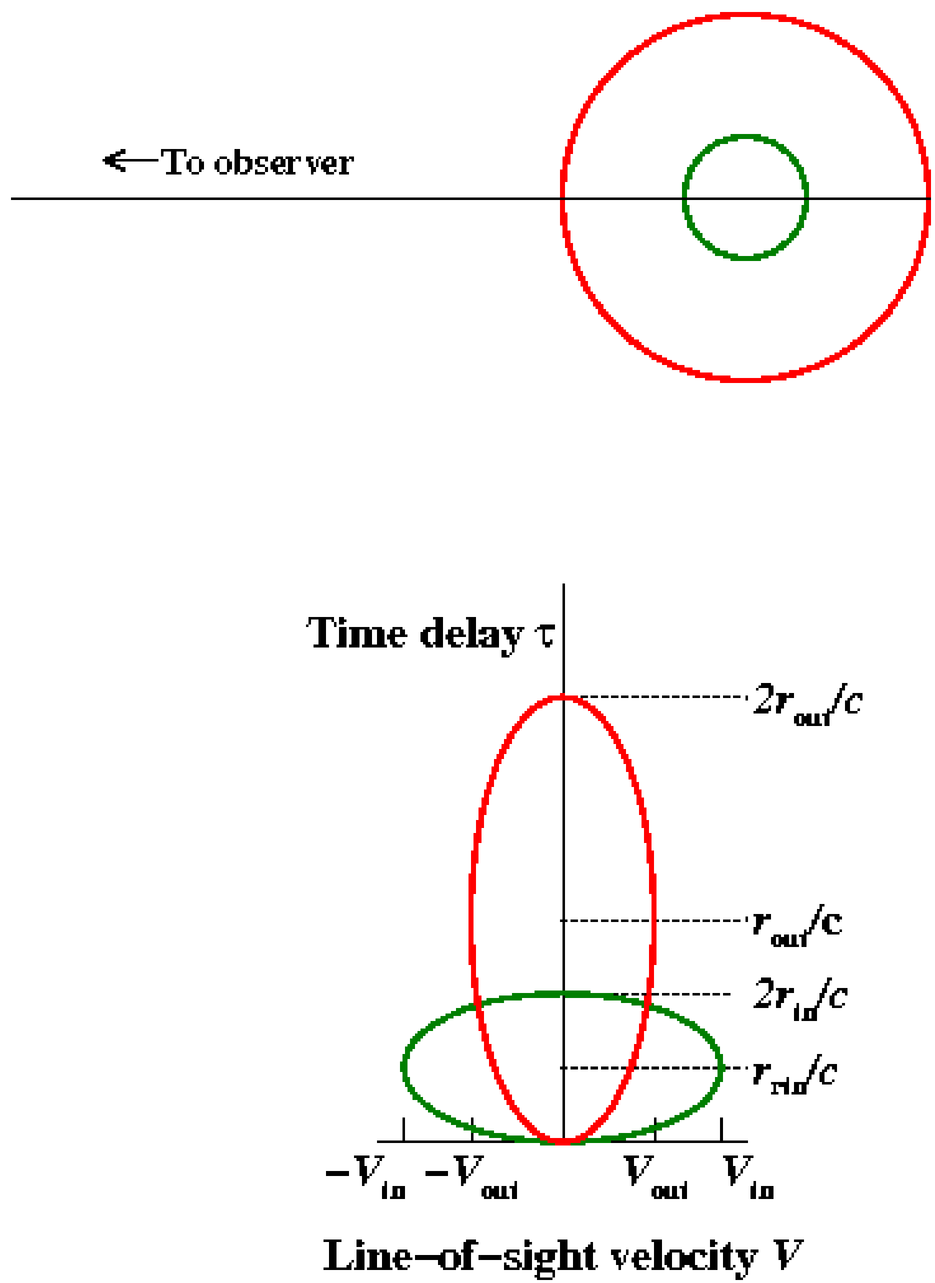
$$\sigma_{line} = \left(\langle V_{LOS}^2 \rangle - \langle V_{LOS} \rangle^2 \right)^{1/2} = \left[\frac{\int_{-V_{orb}}^{V_{orb}} V_{LOS}^2 \Psi(V_{LOS})\, dV_{LOS}}{\int_{-V_{orb}}^{V_{orb}} \Psi(V_{LOS})\, dV_{LOS}} - \left(\frac{\int_{-V_{orb}}^{V_{orb}} V_{LOS} \Psi(V_{LOS})\, dV_{LOS}}{\int_{-V_{orb}}^{V_{orb}}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

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.





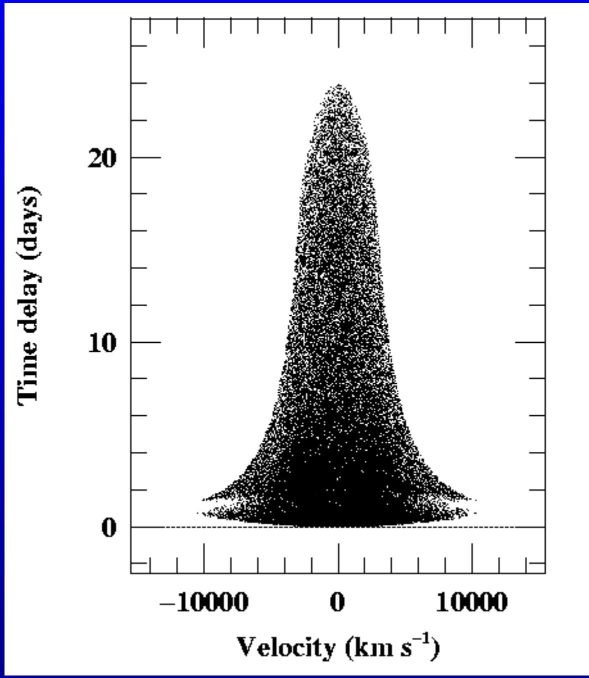
Observed Response of an Emission Line

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

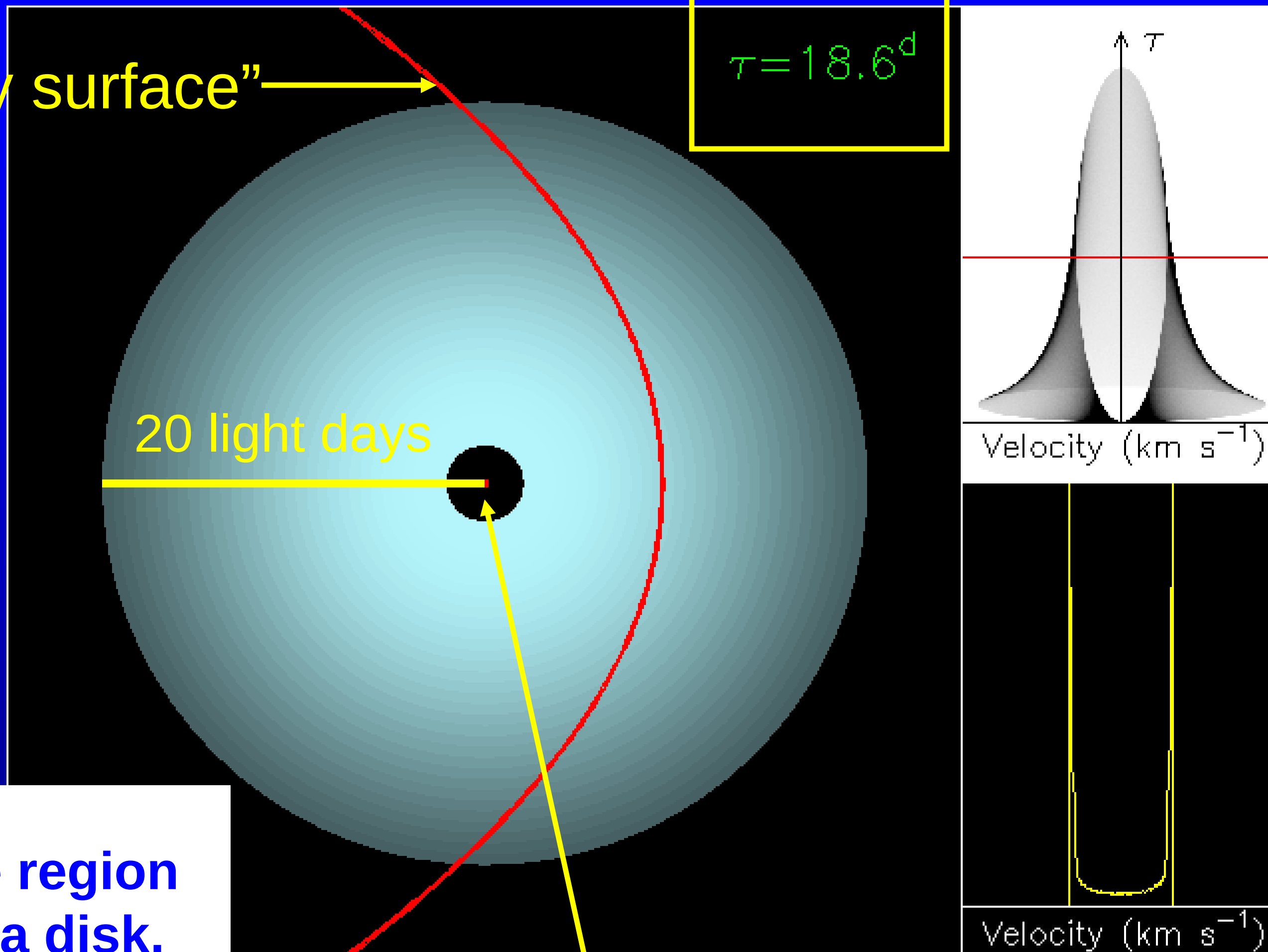
Velocity-delay map is observed line response to a δ-function outburst



Simple velocity-delay map

Time after continuum outburst

"Isodelay surface"

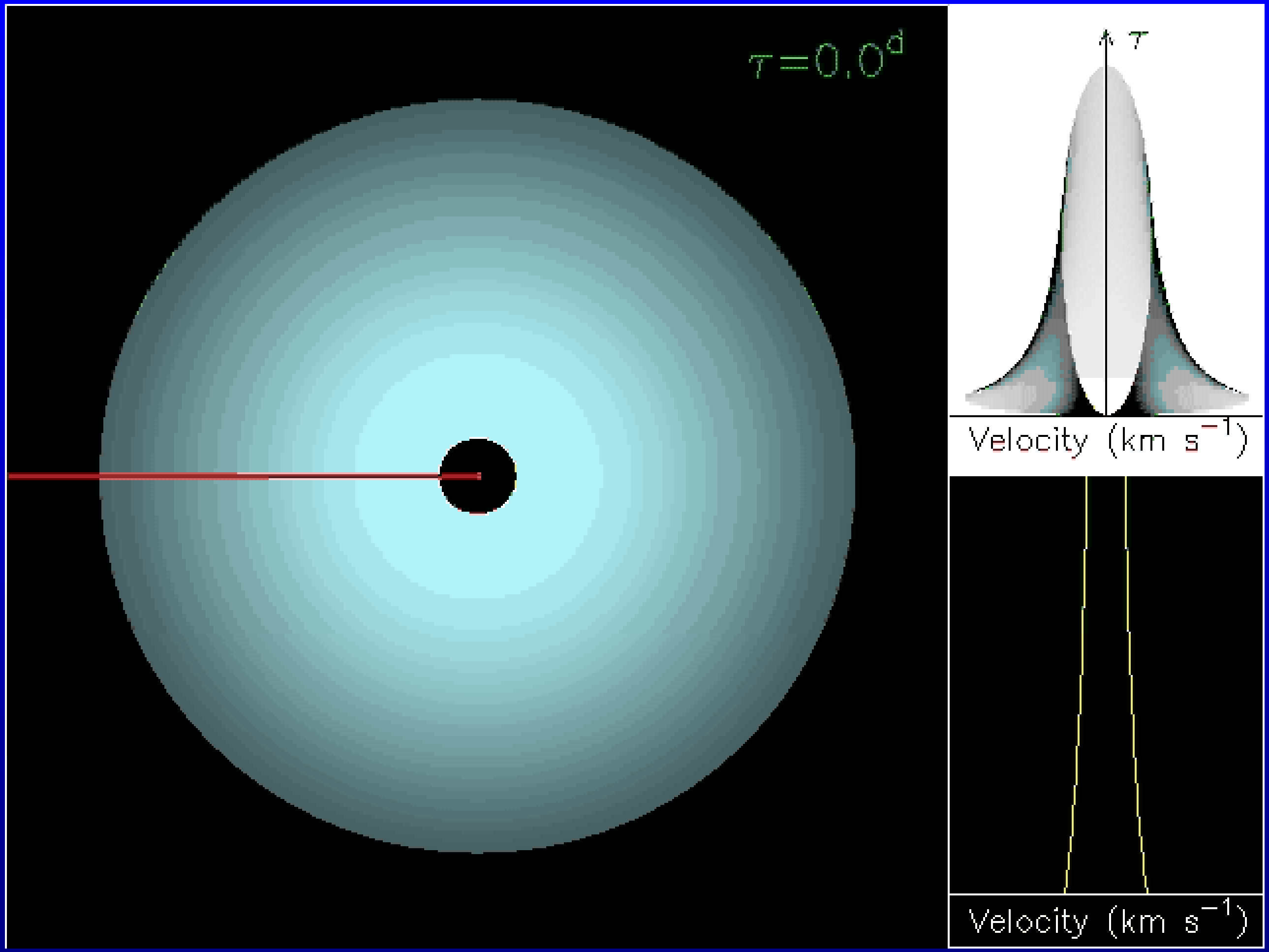


Time delay

Broad-line region as a disk, 2–20 light days

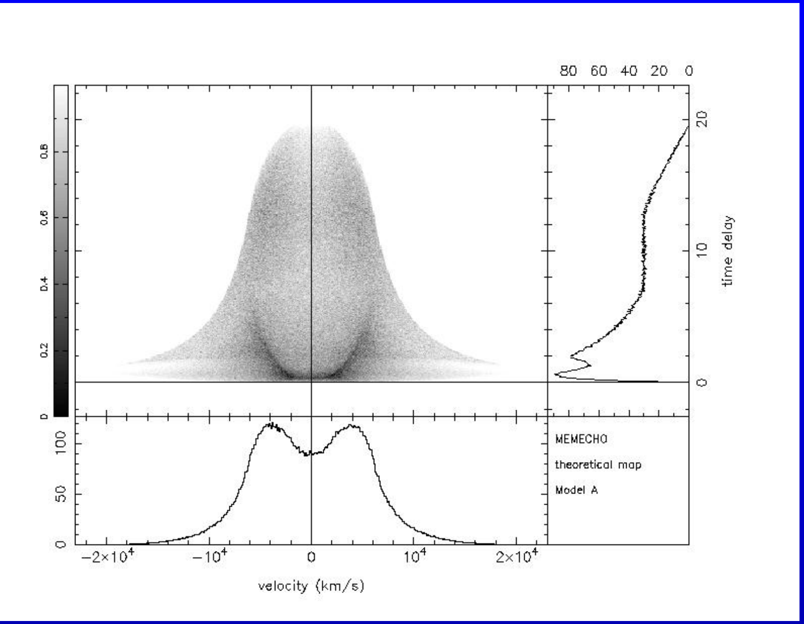
Black hole/accretion disk

Line profile at current time delay

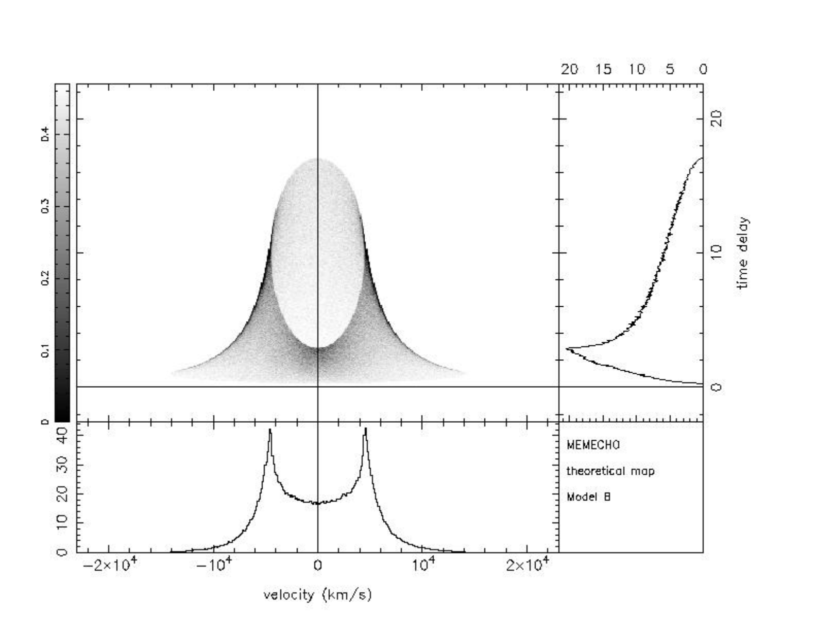


τ=0.0d
τ
Velocity (km s−1)
Velocity (km s−1)

Two Simple Velocity-Delay Maps



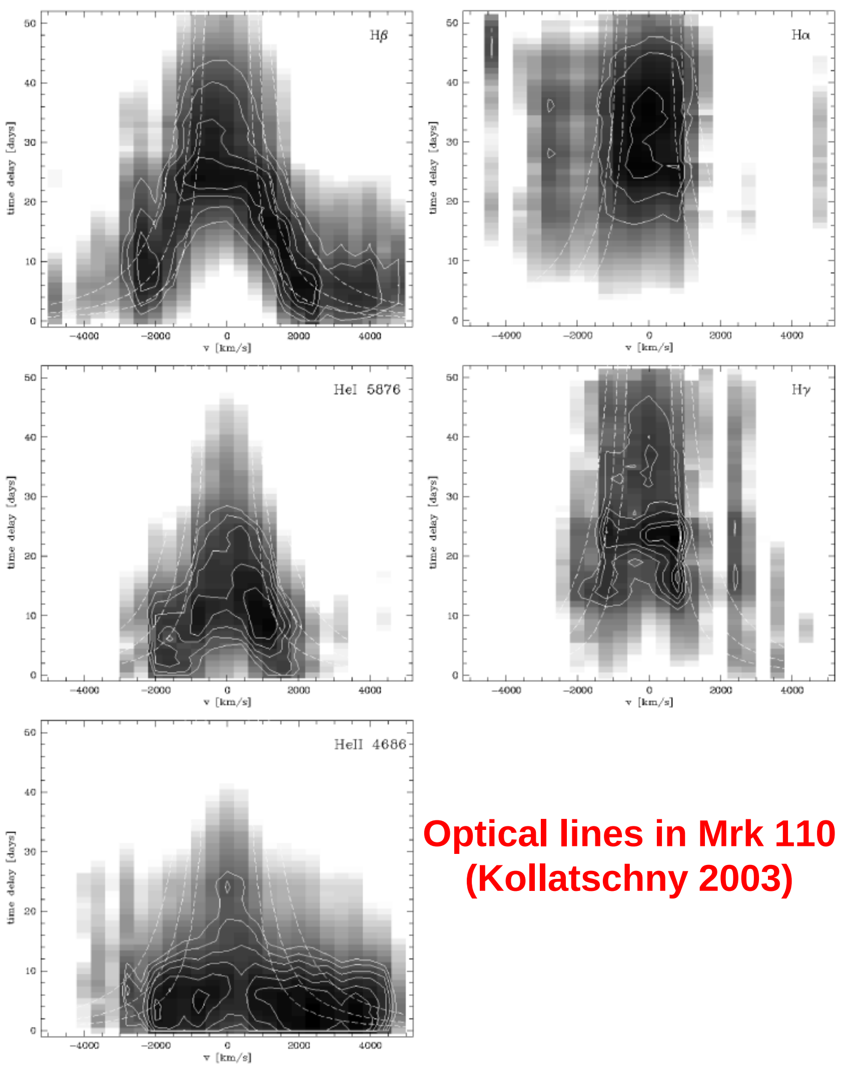
Inclined Keplerian disk



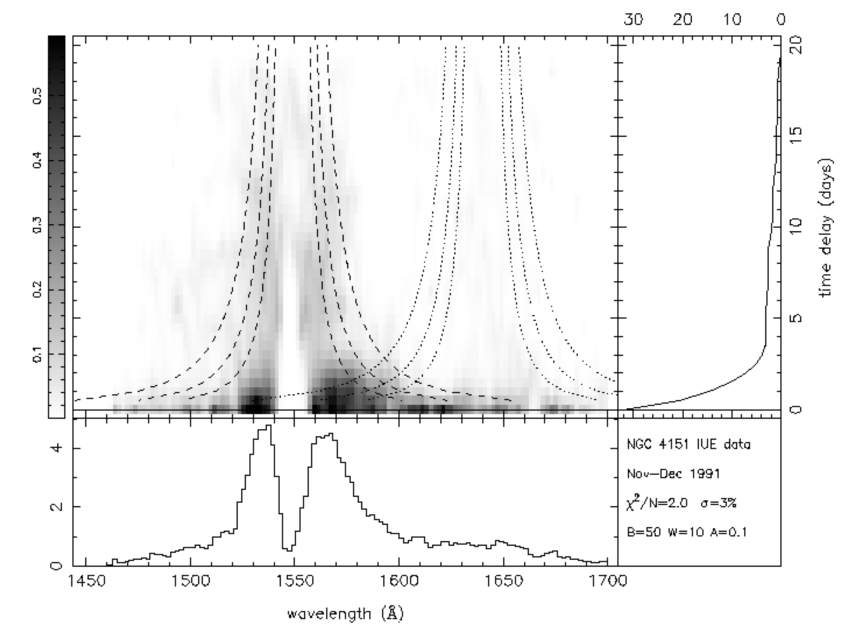
Randomly inclined circular Keplerian orbits

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

Recovering Velocity-Delay Maps from Real Data



Optical lines in Mrk 110 (Kollatschny 2003)



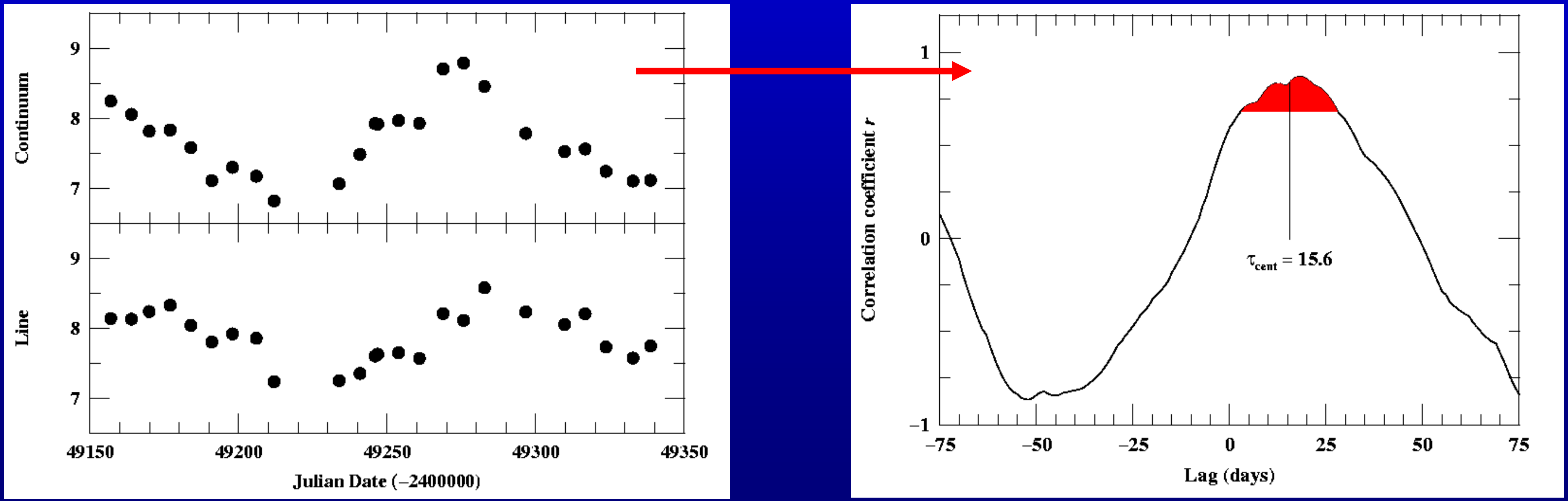
C IV and He II in NGC 4151 (Ulrich & Horne 1996)

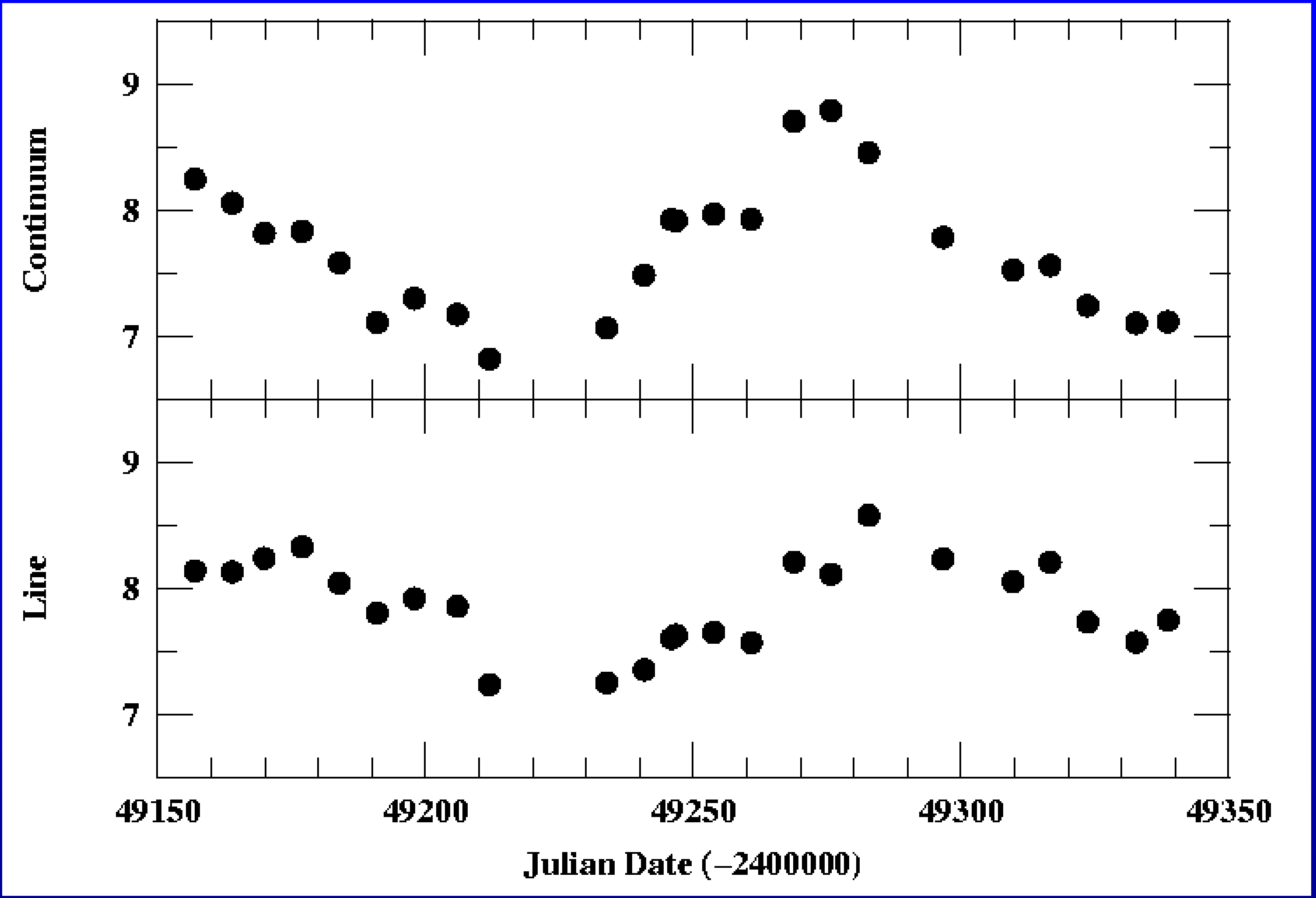
- Until recently, velocity-delay maps have been noisy and ambiguous
- In no case has recovery of the velocity-delay map been a design goal for an experiment (as executed)!

Emission-Line Lags

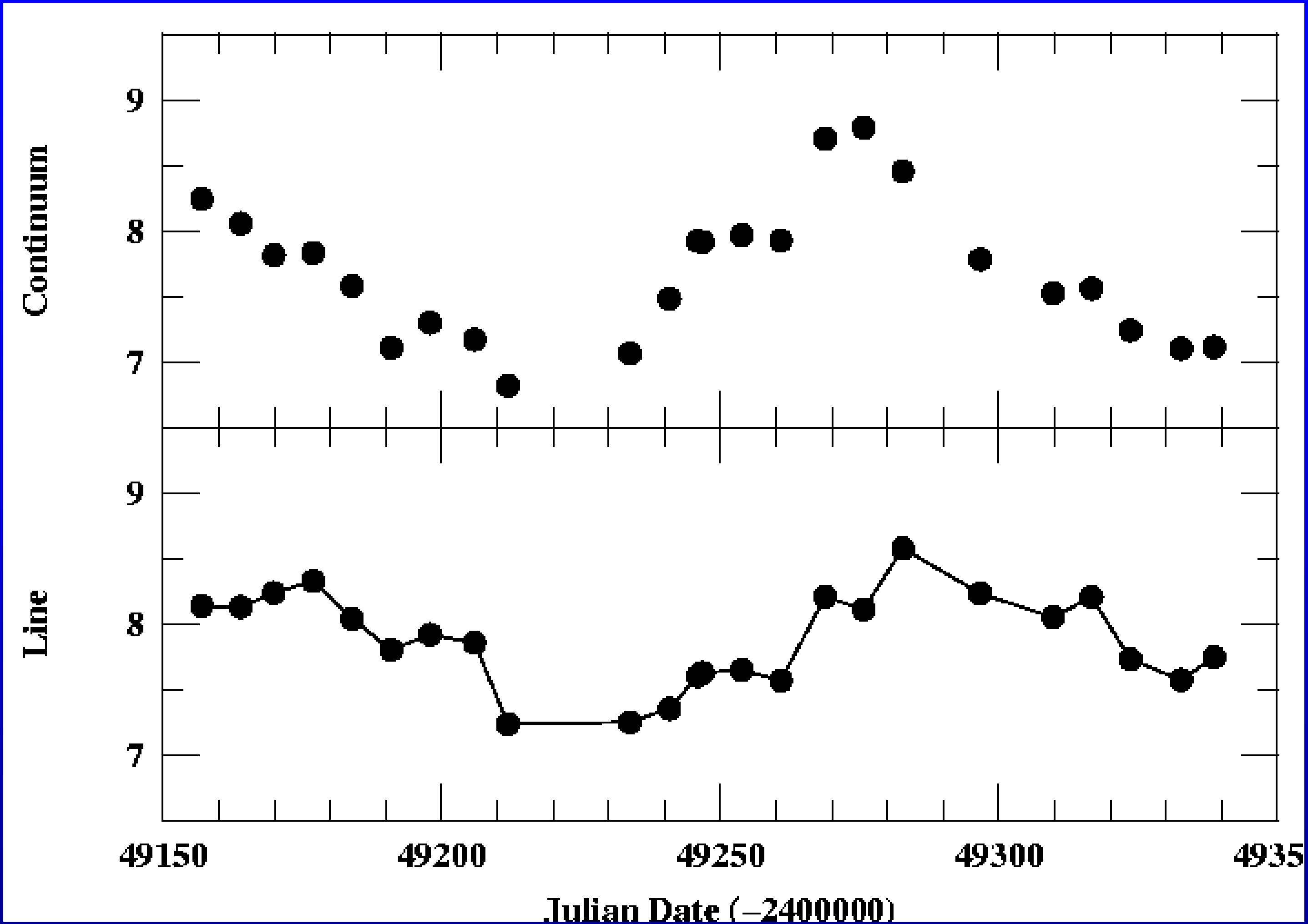
- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the “lag” (mean response time):

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

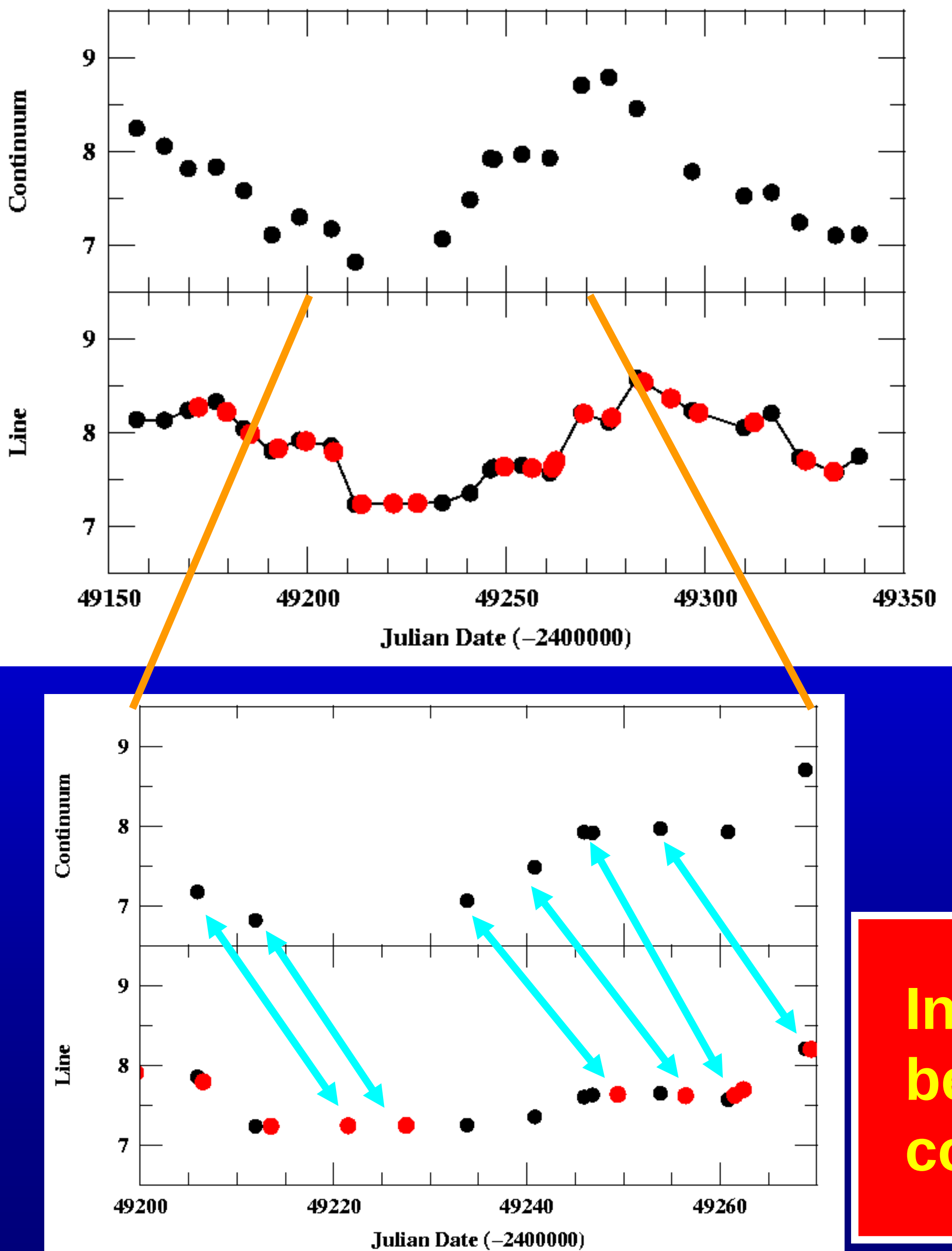




Determine the shift or “lag” between these two series that maximizes the linear correlation coefficient.
Data on Mrk 335.



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.

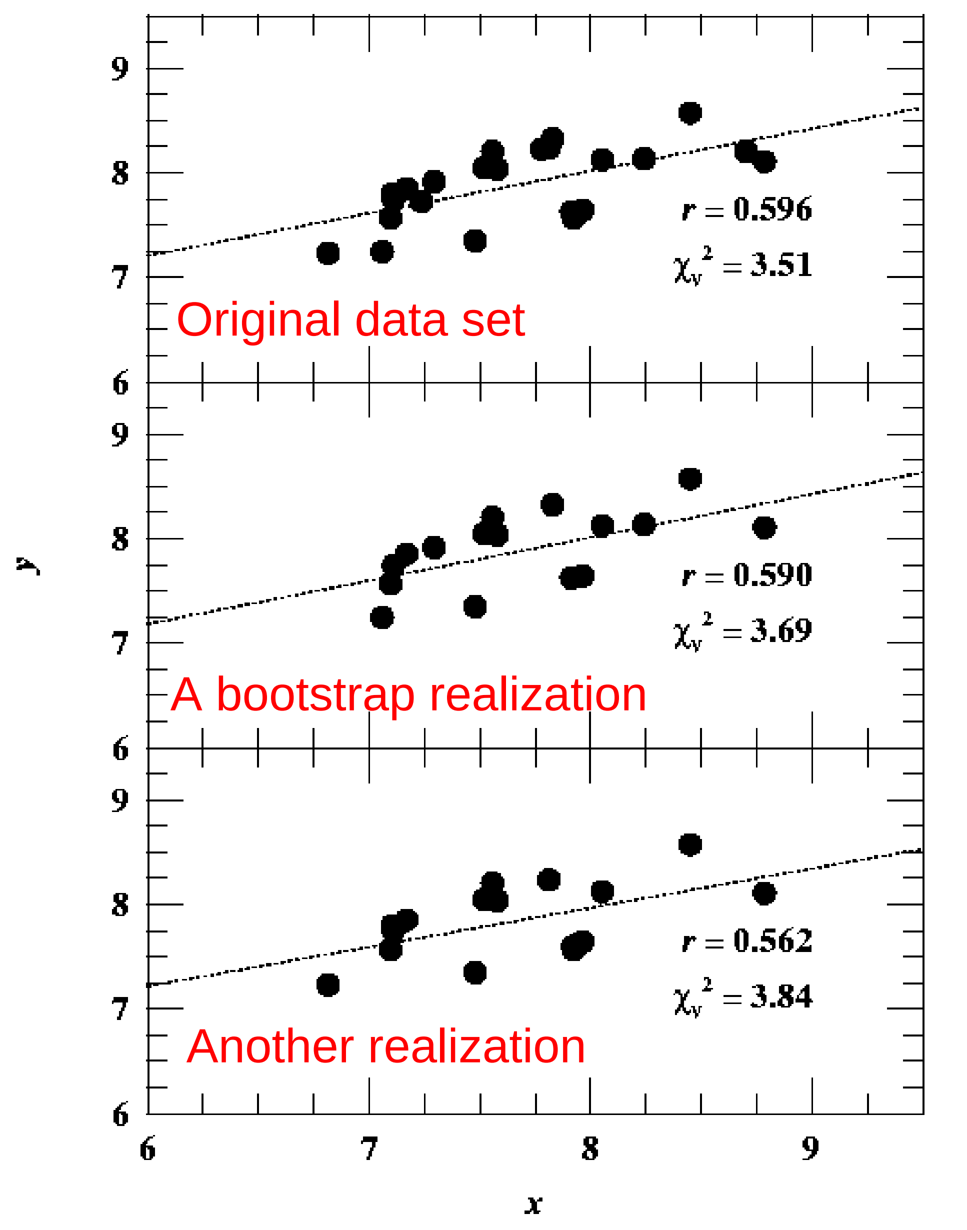
Interpolated line points lag behind corresponding continuum points by 16 days.

Uncertainties in Cross-Correlation Lags

- At present, the most commonly used method is a model-independent Monte-Carlo method called “FR/RSS”:
  - FR: Flux redistribution
    - accounts for the effects of uncertainties in flux measurement
  - RSS: Random subset selection
    - accounts for effects of sampling in time

Bootstrap Method

- RSS is based on a computationally intensive method for evaluating significance of linear correlation known as the "bootstrap method".
- Bootstrap method:
  - for *N* real data points, select at random *N* points without regard to whether or not they have been previously selected.
  - Determine *r* for this subset
  - Repeat many times to obtain a distribution in the value of *r*. From this distribution, compute the mean and standard deviation for *r*.

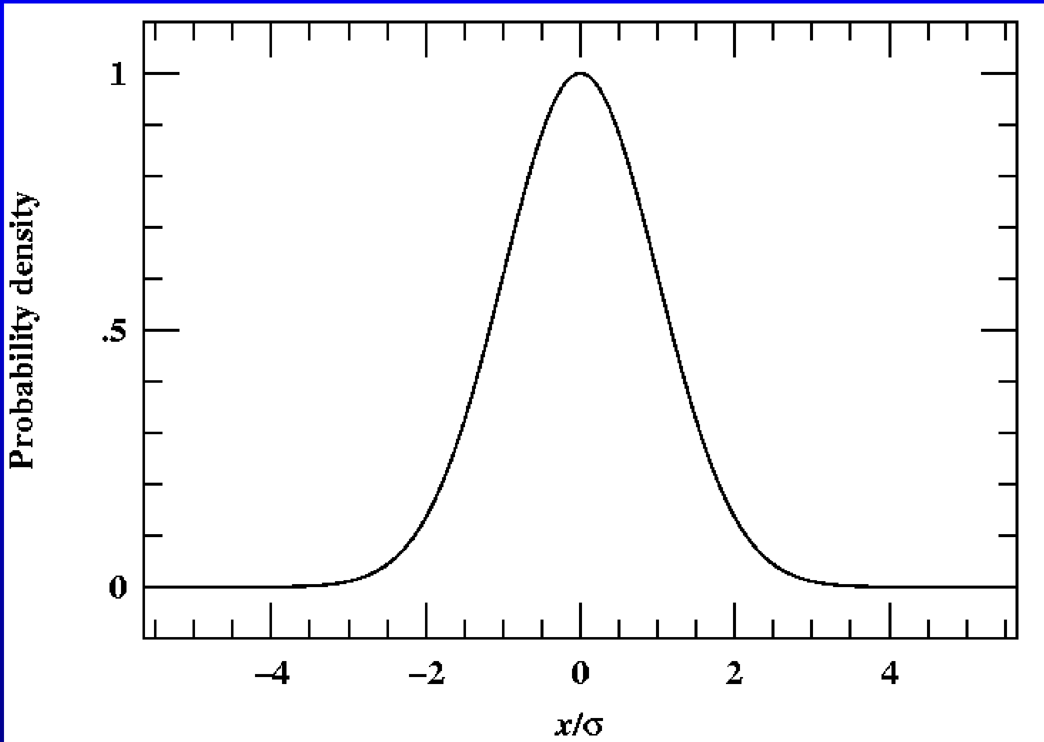


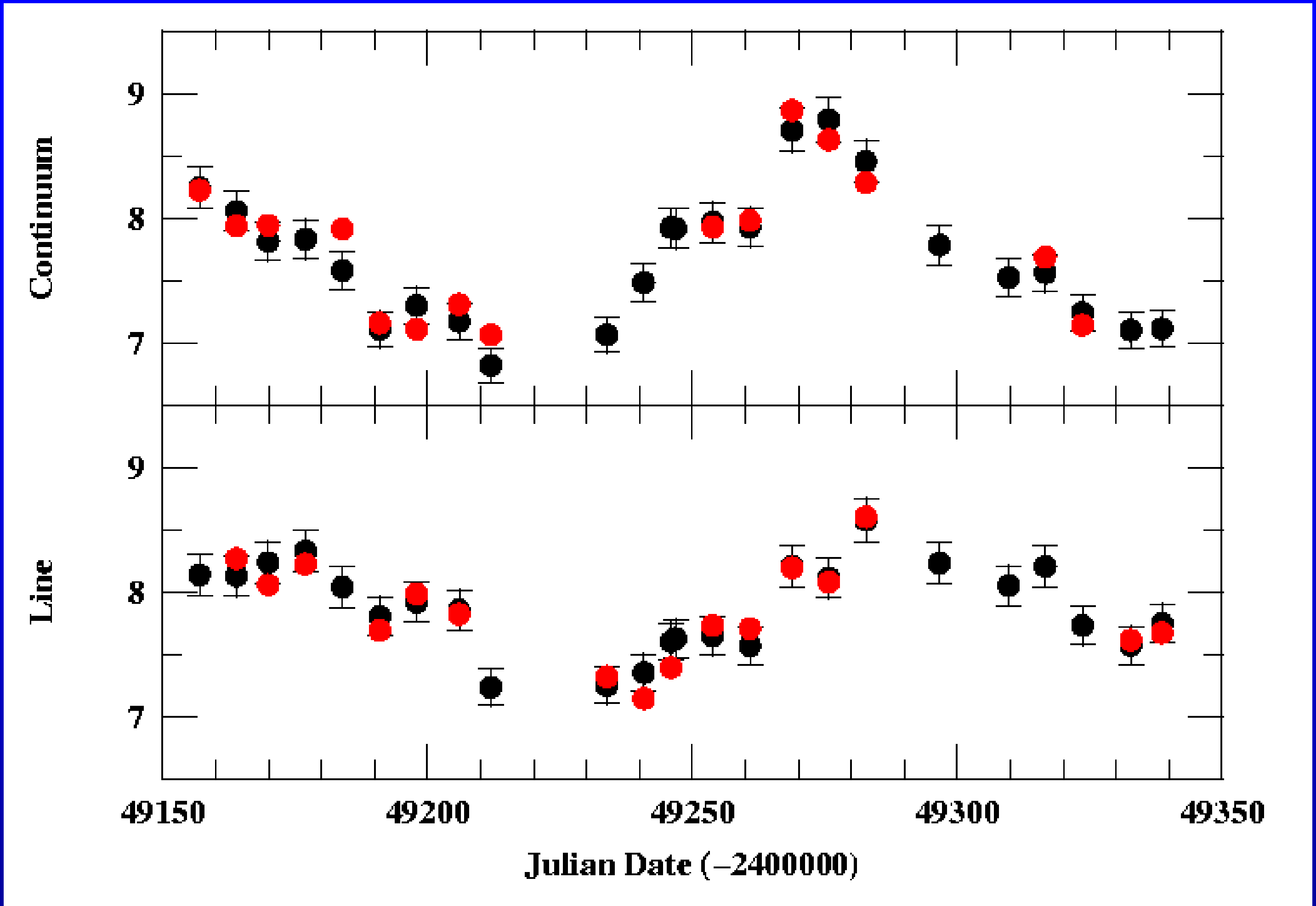
Random Subset Selection

- How do you deal with redundant selections in a time series, where order matters? Either:
  - Ignore redundant selections
    - Each realization has typically 1/*e* fewer points than the original (origin of the name RSS).
    - Numerical experiments show that this then gives a conservative error on the lag (the real uncertainty may be somewhat smaller).
  - Weight each datum according to number of times selected
    - Philosophically closer to original bootstrap.

Flux Redistribution

- Assume that flux uncertainties are Gaussian distributed about measured value, with uncertainty σ.
- Take each measured flux value and alter it by a random Gaussian deviate.
- Decrease σ by factor $n^{1/2}$, where n is the number of times the point is selected.

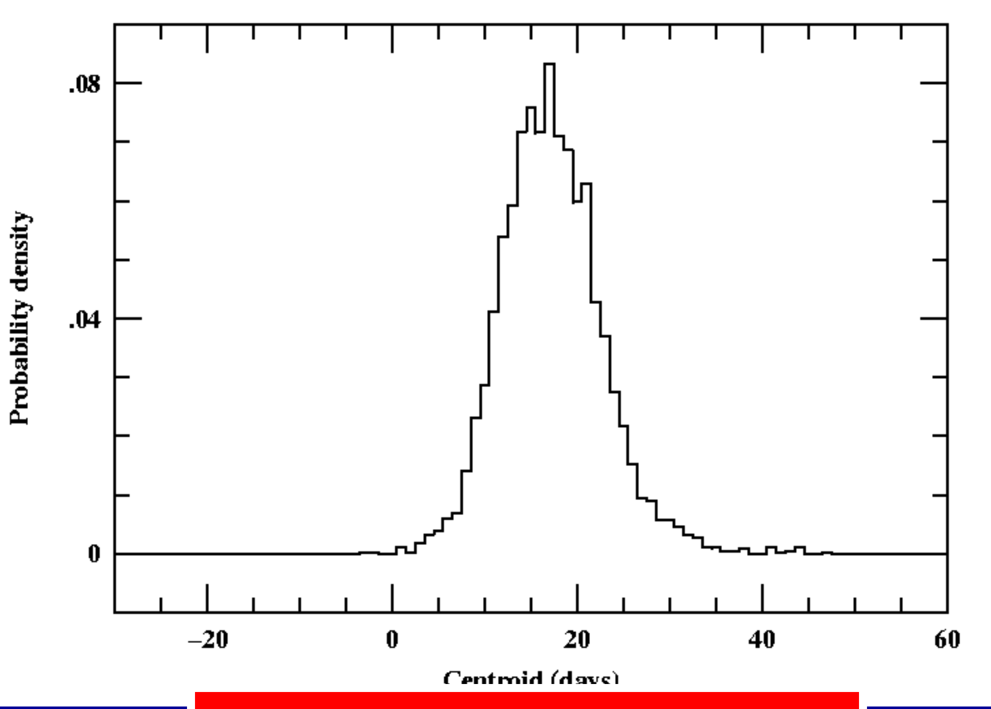




A single FR/RSS realization. Red points are selected at random from among the real (black) points, redundant points are discarded, and surviving points redistributed in flux using random Gaussian deviates scaled by the quoted uncertainty for each point. The realization shown here gives τ_{cent} = 17.9 days (value for original data is 15.6 days)

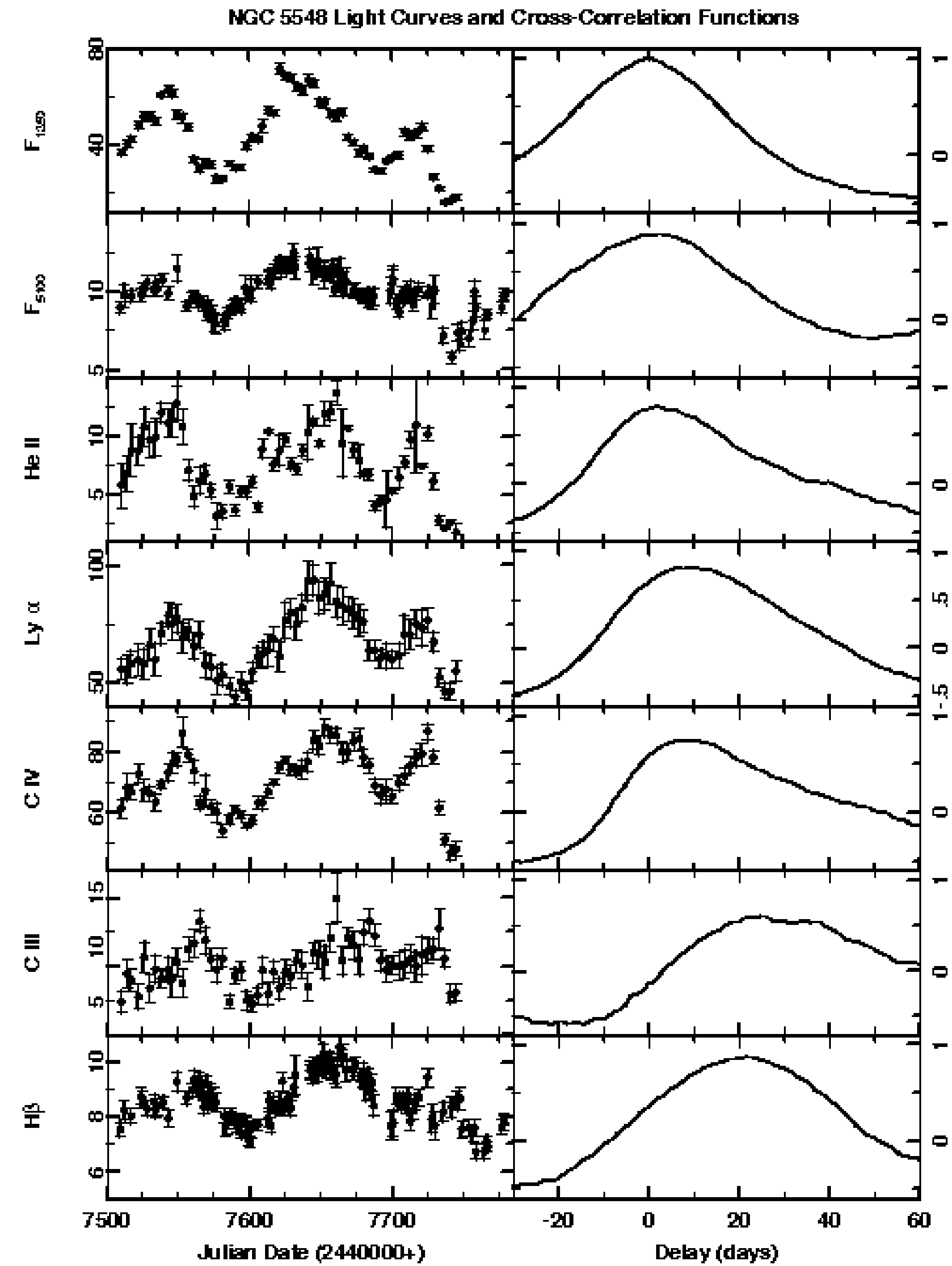
Cross-Correlation Centroid Distribution

- Many FR/RSS realizations are used to build up the "cross-correlation centroid distribution" (CCCD).
- The rms width of this distribution (which can be non-Gaussian) can be used as an estimate of the lag.



Mrk 335 FR/RSS result:

$$\tau_{\rm cent} = 15.6^{+7.2}_{-3.1}\ \text{days}$$



Reverberation Mapping Results

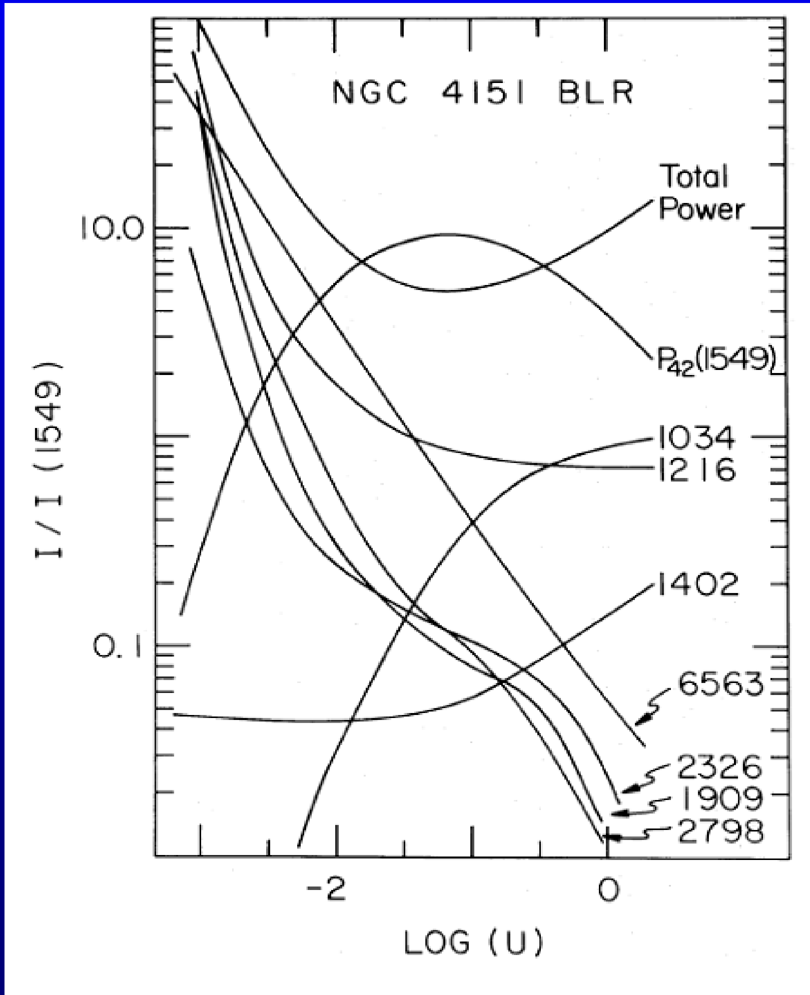
- Reverberation lags have been measured for ~45 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

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)

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

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

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 Scaling with Luminosity

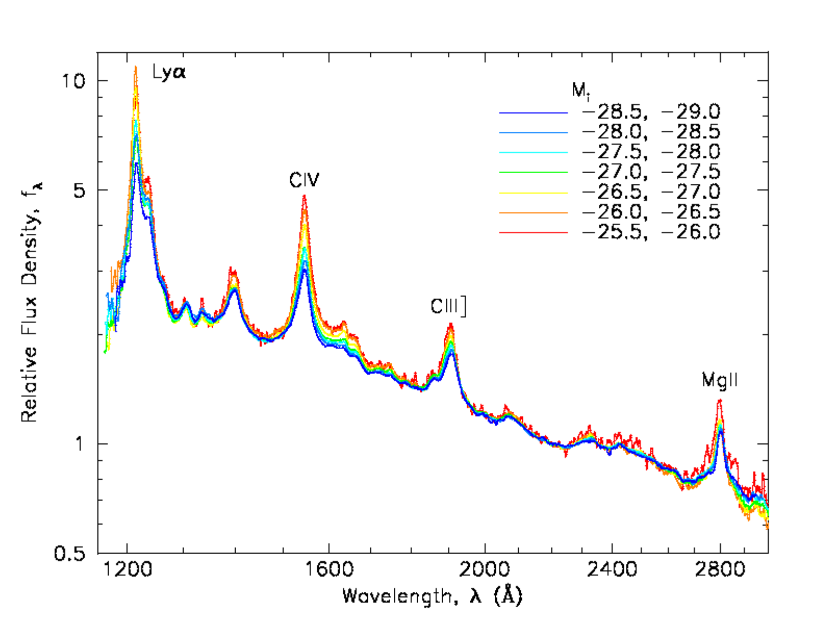
- To first order, AGN spectra look the same:

$$U = \frac{Q(\mathrm{H})}{4\pi r^2 n_{\mathrm{H}} c} \propto \frac{L}{n_{\mathrm{H}} r^2}$$

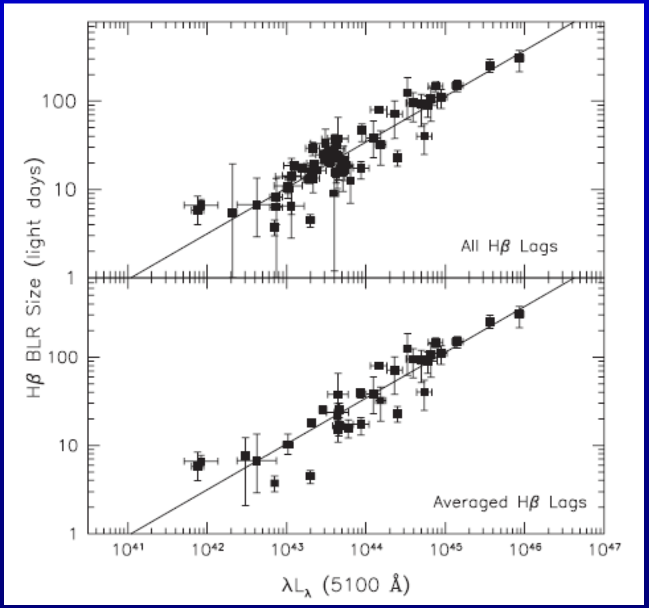
$\Rightarrow$ Same ionization parameter

$\Rightarrow$ Same density

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



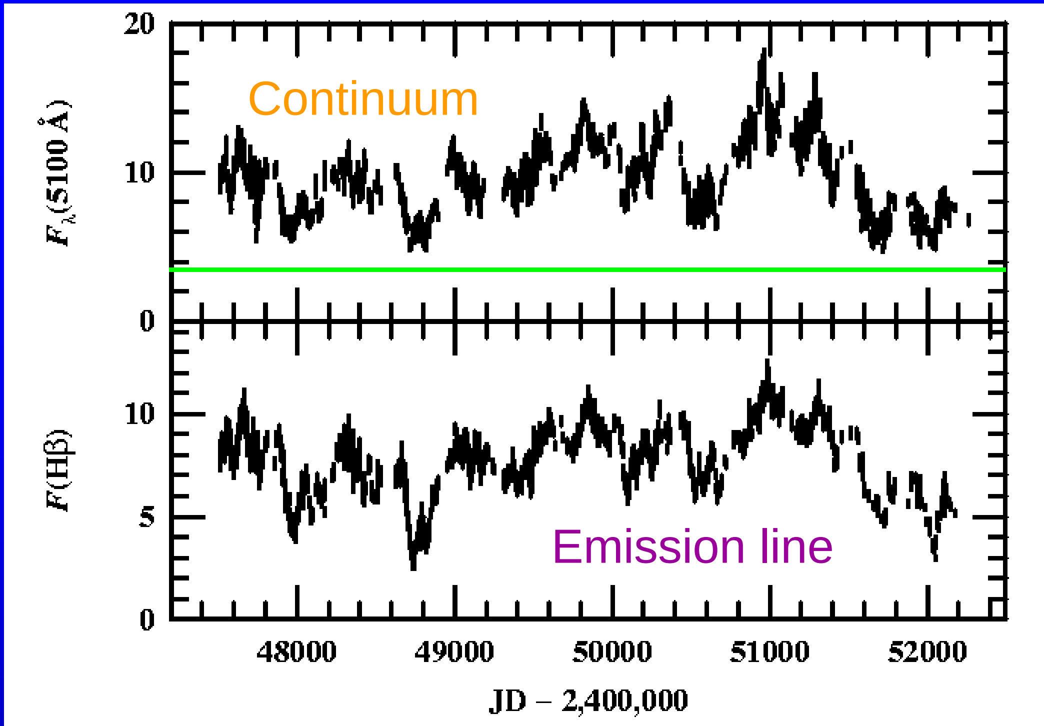
SDSS composites. Vanden Berk et al. (2004)

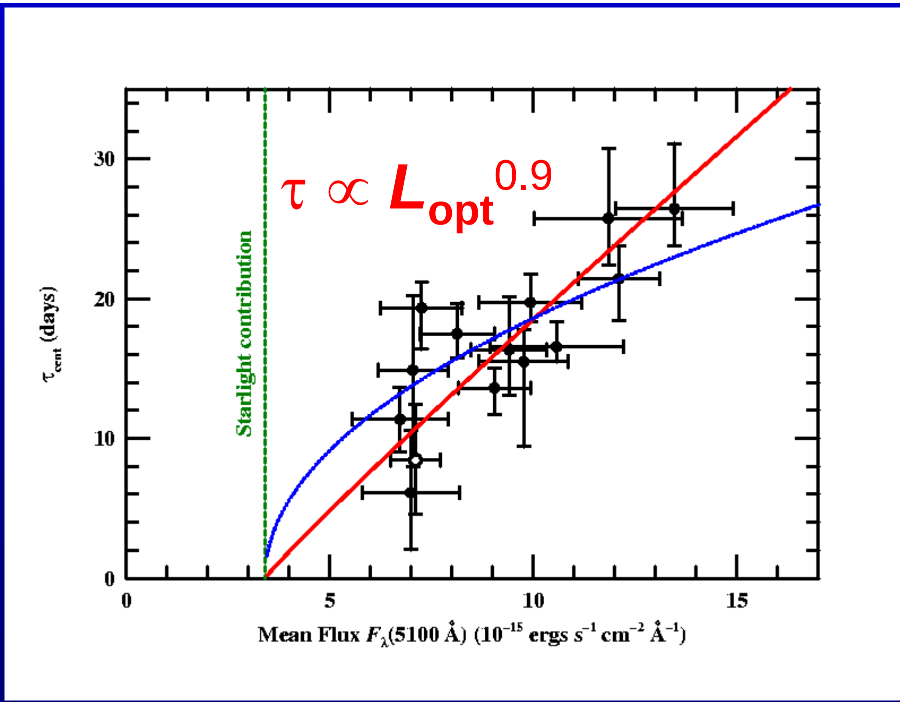


Bentz et al. (2009)

BLR Size vs. Luminosity

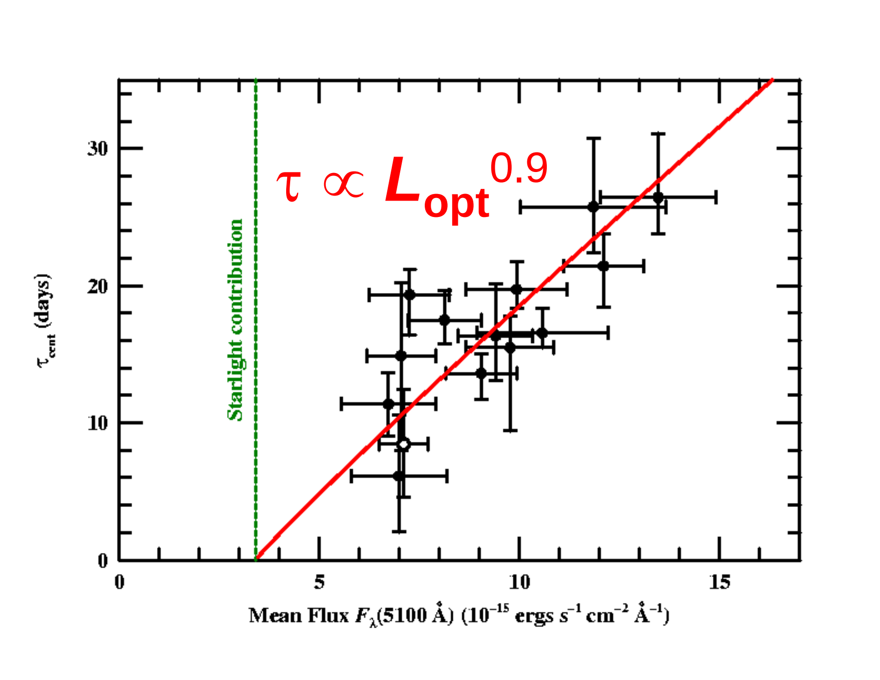
- Should the same relationship should hold as a single object varies in luminosity?
- The Hβ response in NGC 5548 has been measured for ~16 individual observing seasons.
  - Measured lags range from 6 to 26 days
  - Best fit is $\tau \propto L_{opt}^{0.9}$

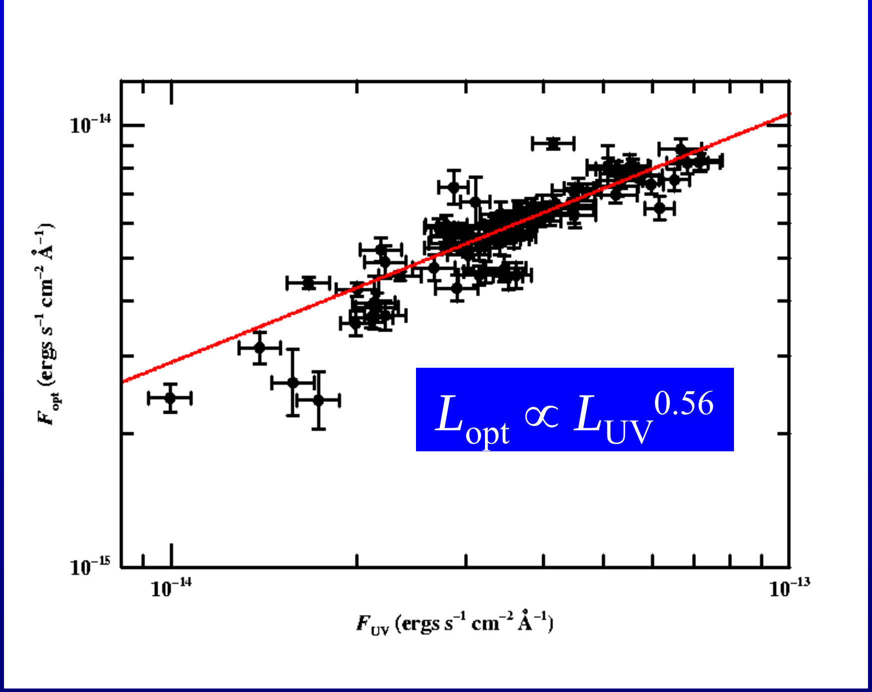




BLR Size vs. Luminosity

- However, UV varies with higher amplitude than than optical!





$\tau \propto L_{opt}^{0.9} \propto (L_{UV}^{0.56})^{0.9} \propto L_{UV}^{0.5}$

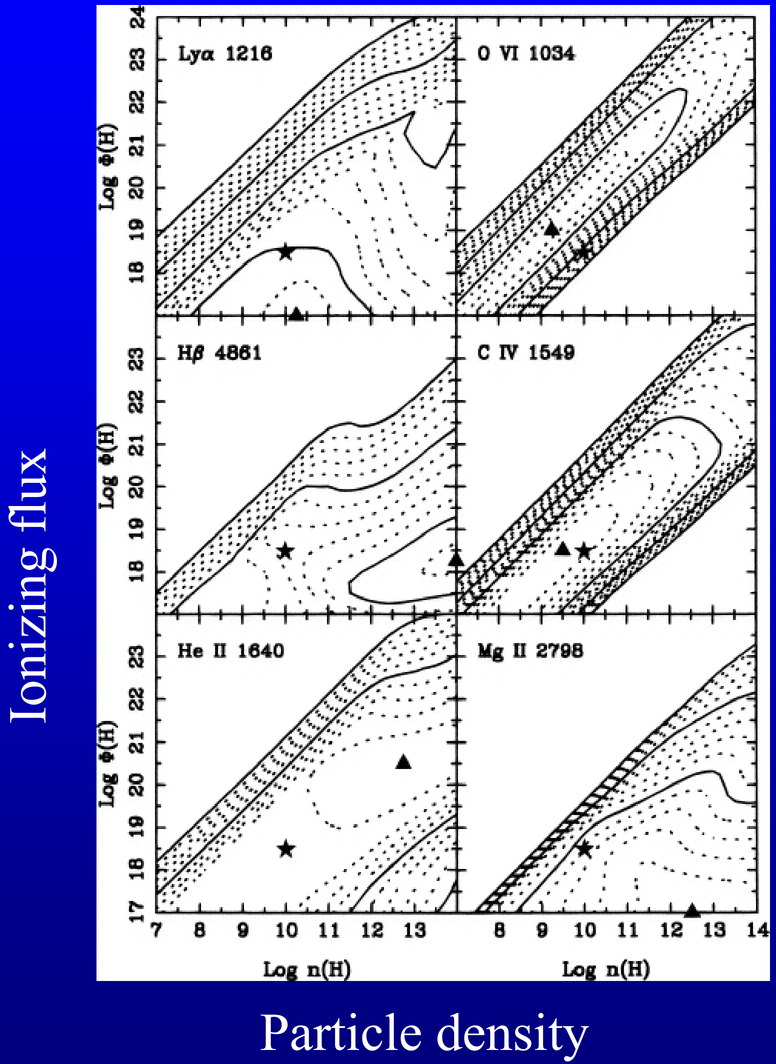
Again surprisingly consistent with the naïve prediction!

What Fine-Tunes the BLR?

- Why are the ionization parameter and electron density the same for all AGNs?
- How does the BLR know precisely where to be?
- *Answer:* gas is everywhere in the nuclear regions. We see emission lines emitted under optimal conditions.

Locally optimally-emitting cloud (LOC) model

- “Clouds” of various density are distributed throughout the nuclear region.
- Emission in a particular line comes predominantly from clouds with optimal conditions for that line.



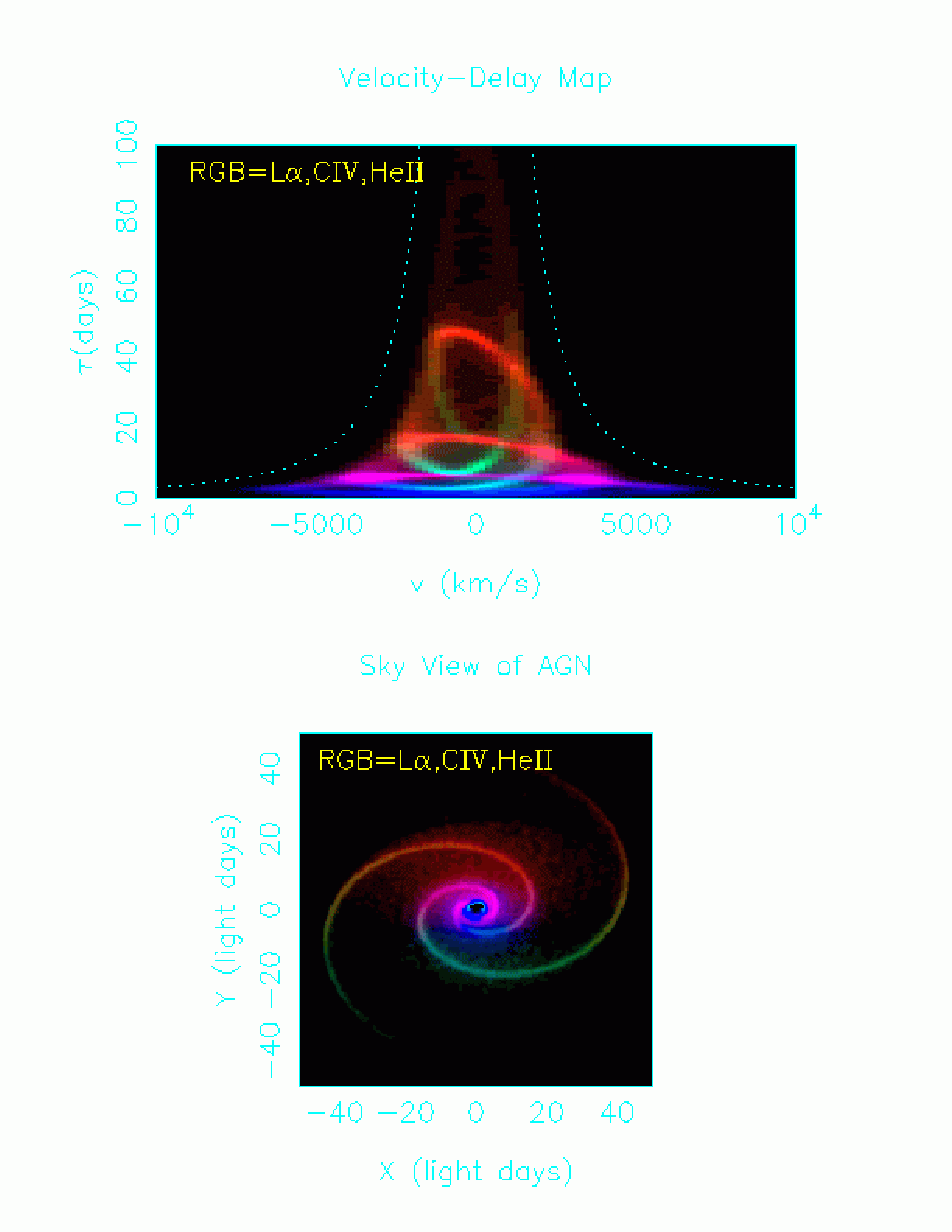
Korista et al. (1997)

Mass of the BLR

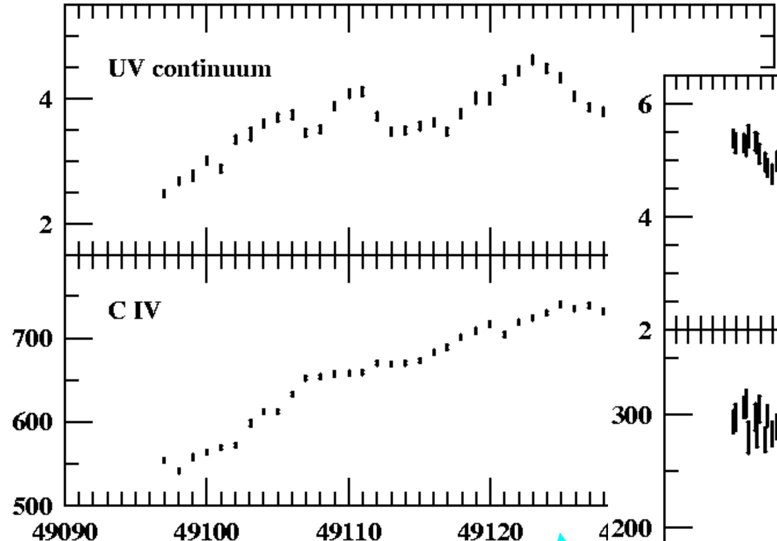
- Reverberation mapping + LOC model suggest that there is a large amount of mass in the BLR, most not emitting very efficiently.
- Baldwin et al. (2003) estimate total mass of BLR at 10^4 – 10^5 $M_\odot$
  - Compare to naïve estimate of ~$1M_\odot$ at the beginning of this lecture.

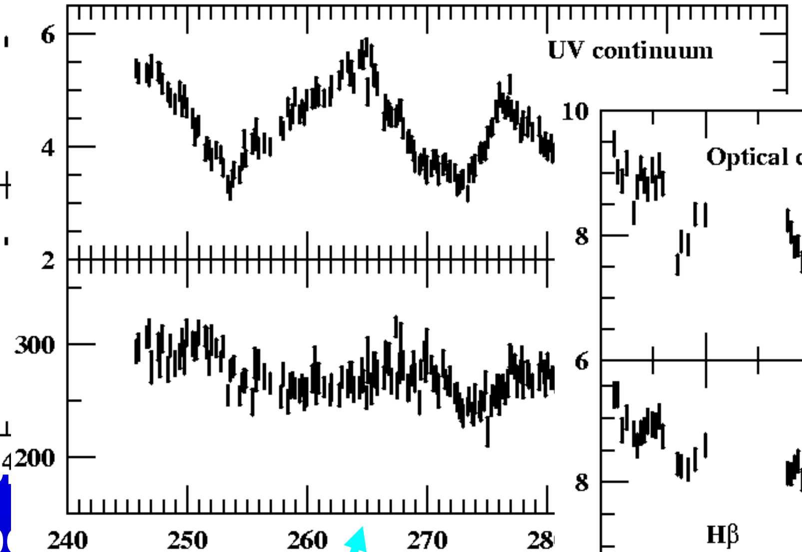
Next Crucial Step

- Obtain a high-fidelity velocity-delay map for at least *one line* in *one AGN.*
  - Even one success would constitute “proof of concept”.

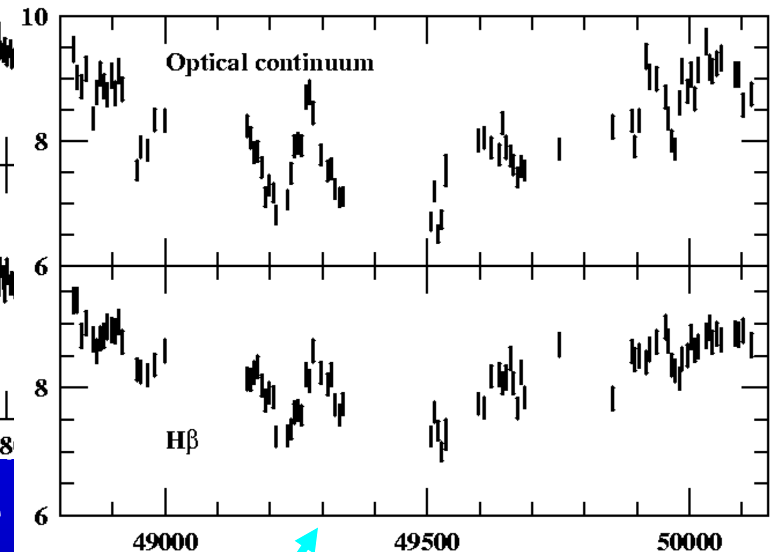


BLR with a spiral wave and its velocity-delay map in three emission lines (Horne et al. 2004)





BLR

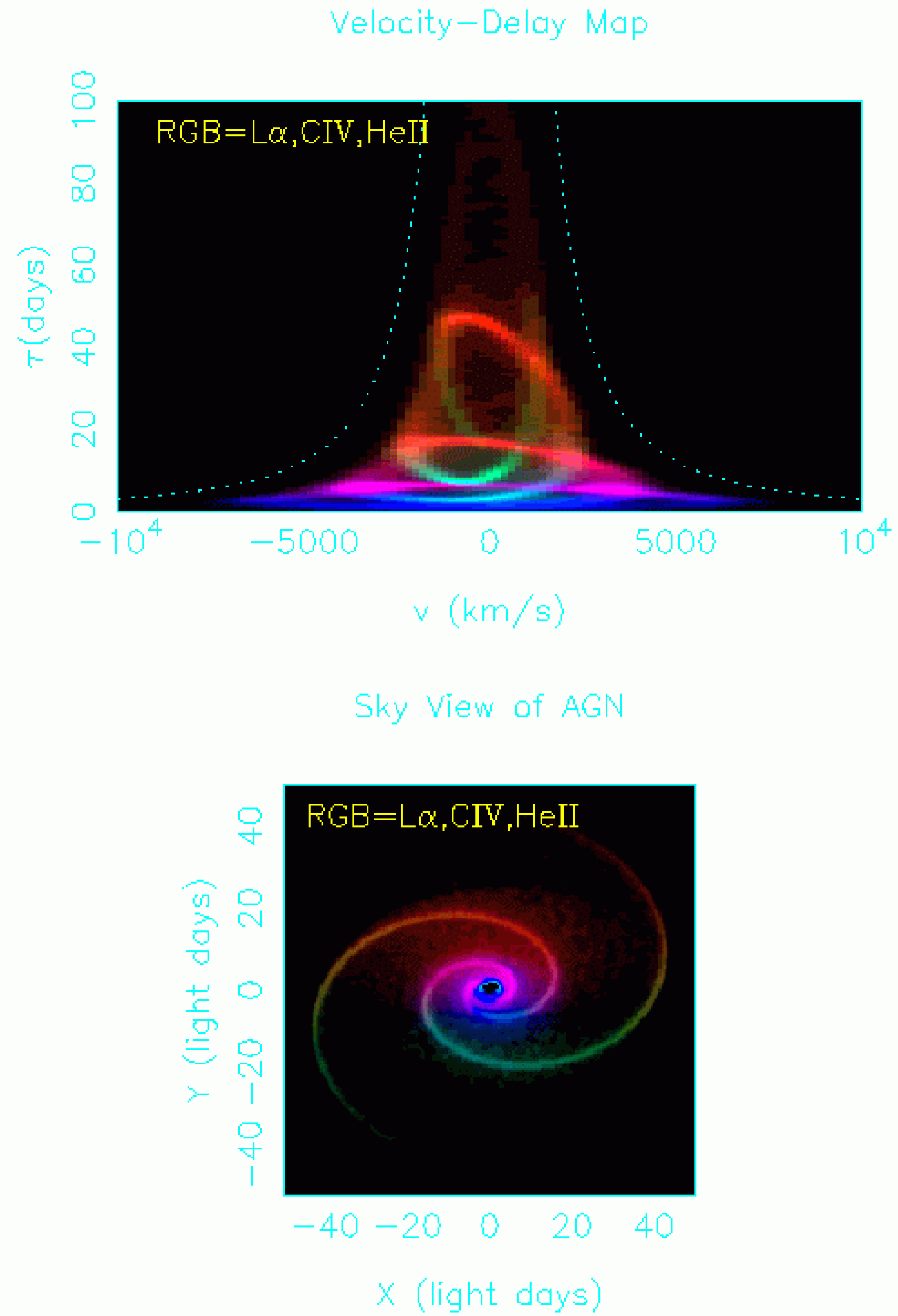


– Moderate sp

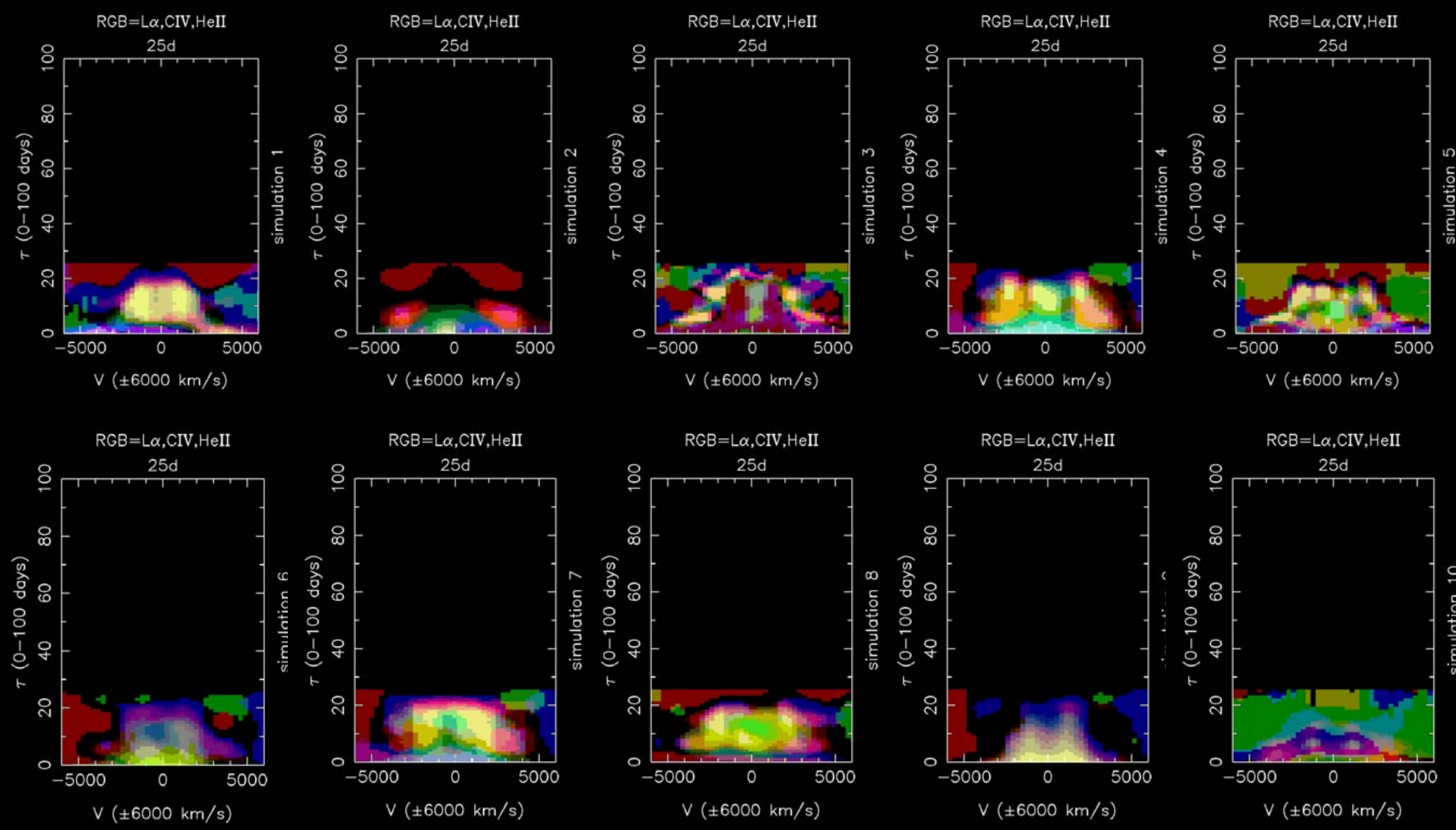
– High homogeneity and signal-to-noise

Program	AGN Watch NGC 5548			AGN Watch NGC 4151		AGN Watch NGC 7469		AGN Watch (other)		OSU	CTIO/OSU	LAG	Wise 1988	Wise/SO PG
	IUE 89	HST 93	Opt	IUE	Opt	IUE	Opt	IUE	Opt	Opt	Opt	Opt	Opt	Opt
No. Sources	1	1	1	1	1	1	1	3	5	8	2	5	3	15
Time Resolution	yellow	green	yellow	green	yellow	green	yellow	yellow	yellow	red	red	red	red	red
Duration	green	yellow	green	yellow	green	green	green	green	green	green	green	green	green	green
Spectral Resolution	green	green	green	green	yellow	green	green	green	green	green	green	green	red	yellow
Homogeneity	green	green	yellow	green	yellow	green	yellow	green	yellow	green	green	red	green	green
Signal/Noise Ratio	red	green	yellow	red	yellow	yellow	yellow	red	yellow	yellow	red	red	red	yellow

A program to obtain a velocity-delay map is not much more difficult than what has been done already!


Velocity−Delay Map
RGB=Lα,CIV,HeII
τ (days)
0
20
40
60
80
100
−10^4
−5000
0
5000
10^4
v (km/s)
Sky View of AGN
RGB=Lα,CIV,HeII
Y (light days)
−40
−20
0
20
40
X (light days)

10 Simulations Based on *HST*/STIS Performance



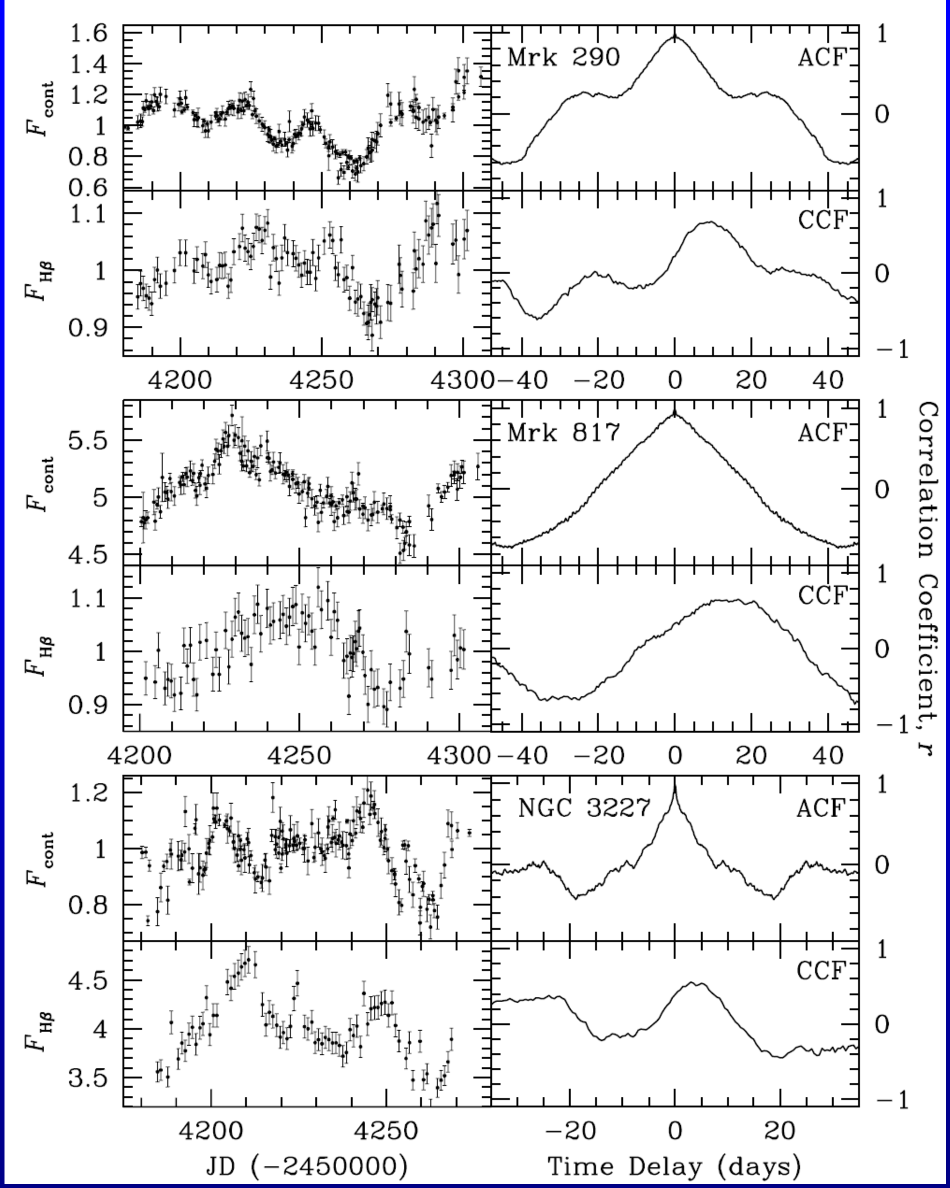
Each step increases the experiment duration by 25 days

Some Important Points

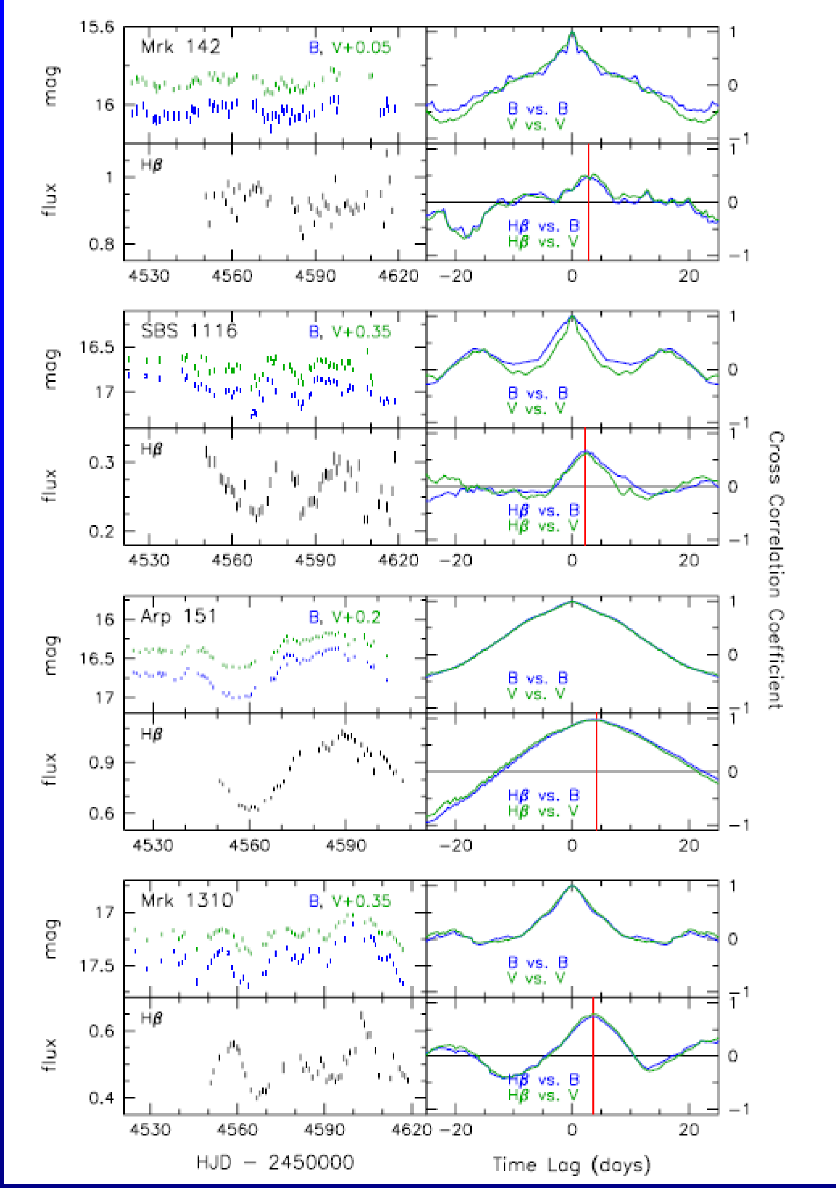
- For NGC 5548, all experiments succeed within 200 days
  - With some luck, success can be achieved in as little as ~60 days (rare) or ~150 days (common)
- Results are robust against occasional random data losses
  - Nominal S/C and instrument safings have been built into the simulations with no adverse effect
- What if the velocity-delay map is a “mess”?
  - You’ve still learned something important about the BLR structure and/or continuum source.
  - It probably won’t be a mess since long-term monitoring shows persistent features that imply there is some order or symmetry.

Recent Major Reverberation Campaigns

- Ohio State – MDM/CrAO and partners:
  - 2005 (43 nights): NGC 4151, NGC 4593, NGC 5548
  - 2007 (86 nights): NGC 3227, NGC 3516, NGC 4051, NGC 5548, Mrk 290, Mrk 817
  - 2010 (124 nights): in progress
- Lick AGN Monitoring Program (LAMP)
  - 2008 (64 nights): 8 low-luminosity AGNs (notably Arp 151), NGC 5548



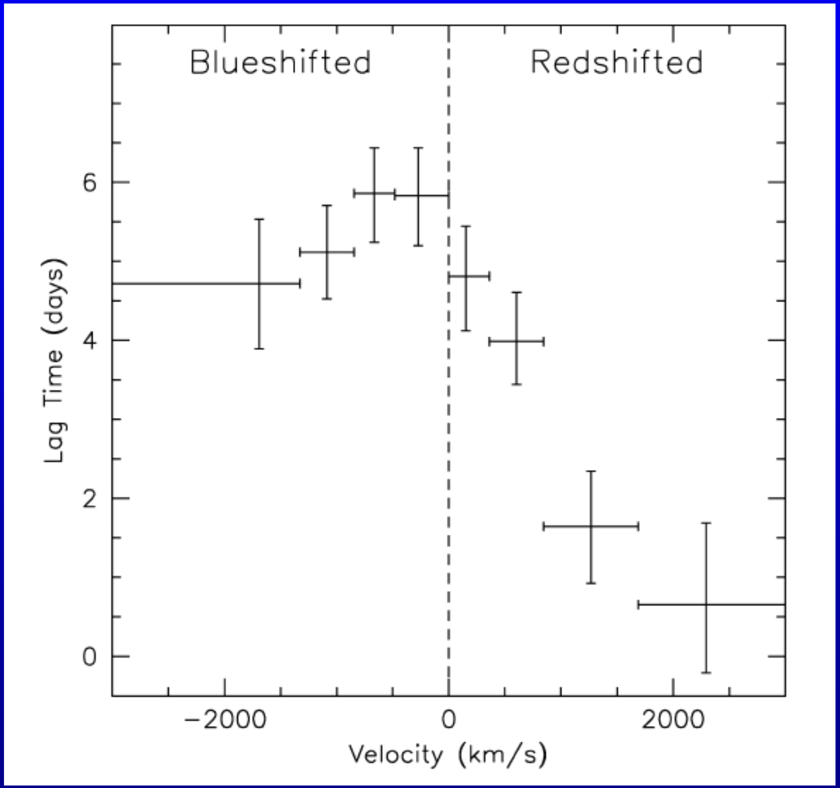
Ohio State



LAMP

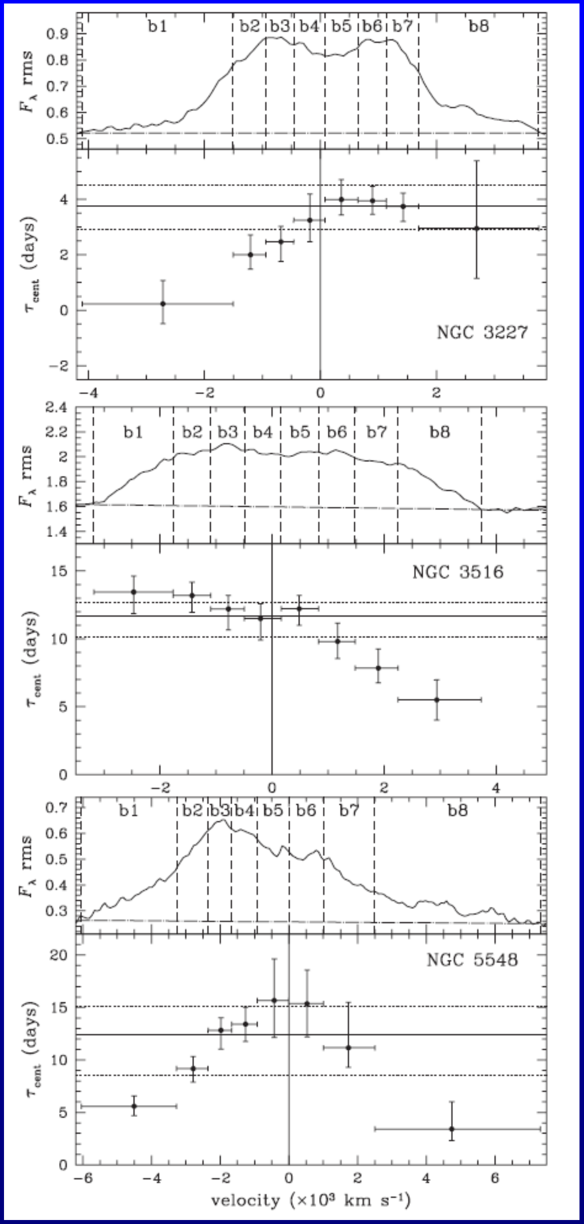
Velocity-Dependent Lags

- Arp 151: First statistically significant detection of lags varying with LOS velocity.
- Redshifted gas has smaller lags, closer to observer ⇒ infall!



Bentz et al. 2008

Diverse kinematic signatures in Hβ response



Blueshifted gas responds earlier ⇒ outflow

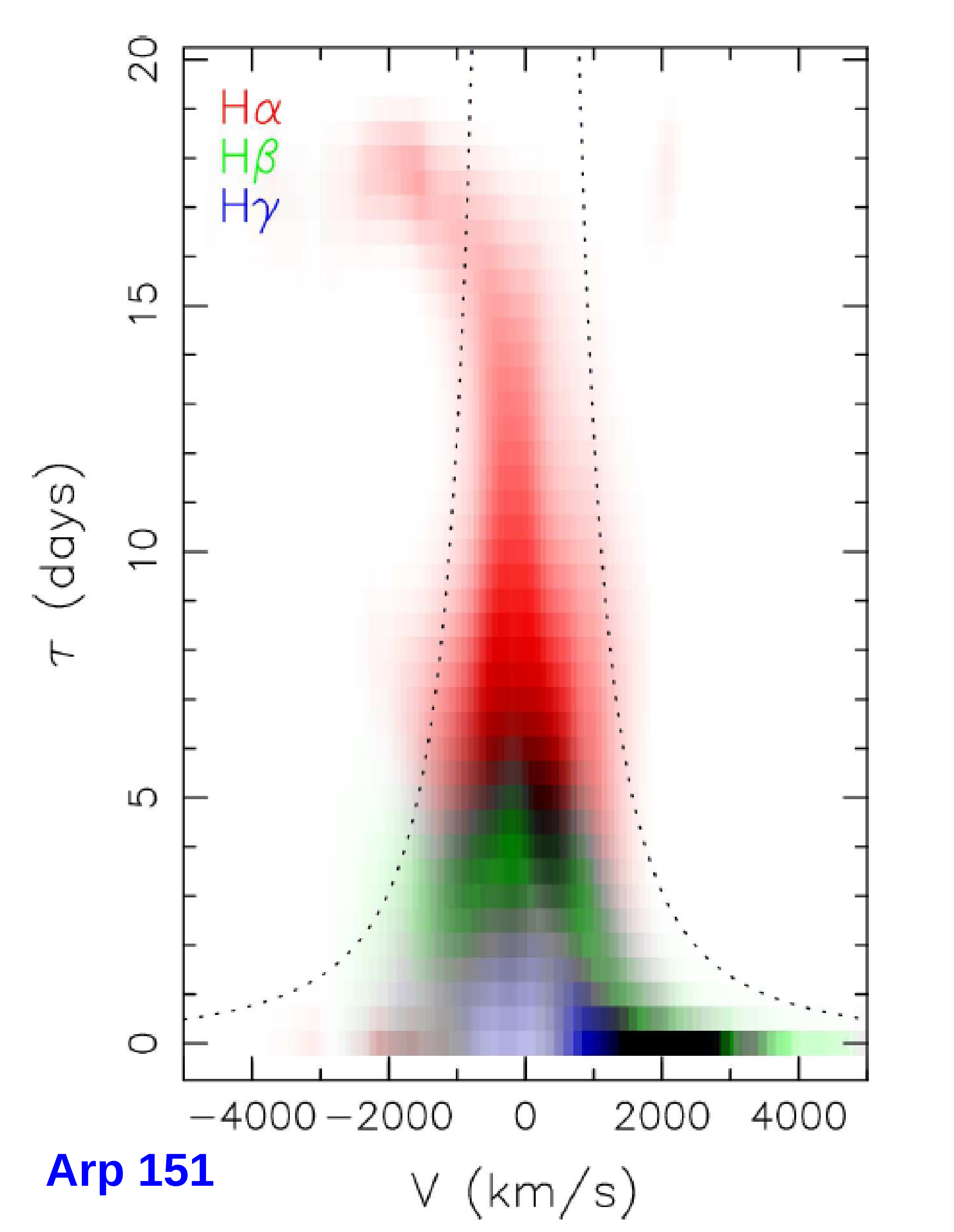
Redshifted gas responds earlier ⇒ infall

Highest velocity gas responds first ⇒ virial motion

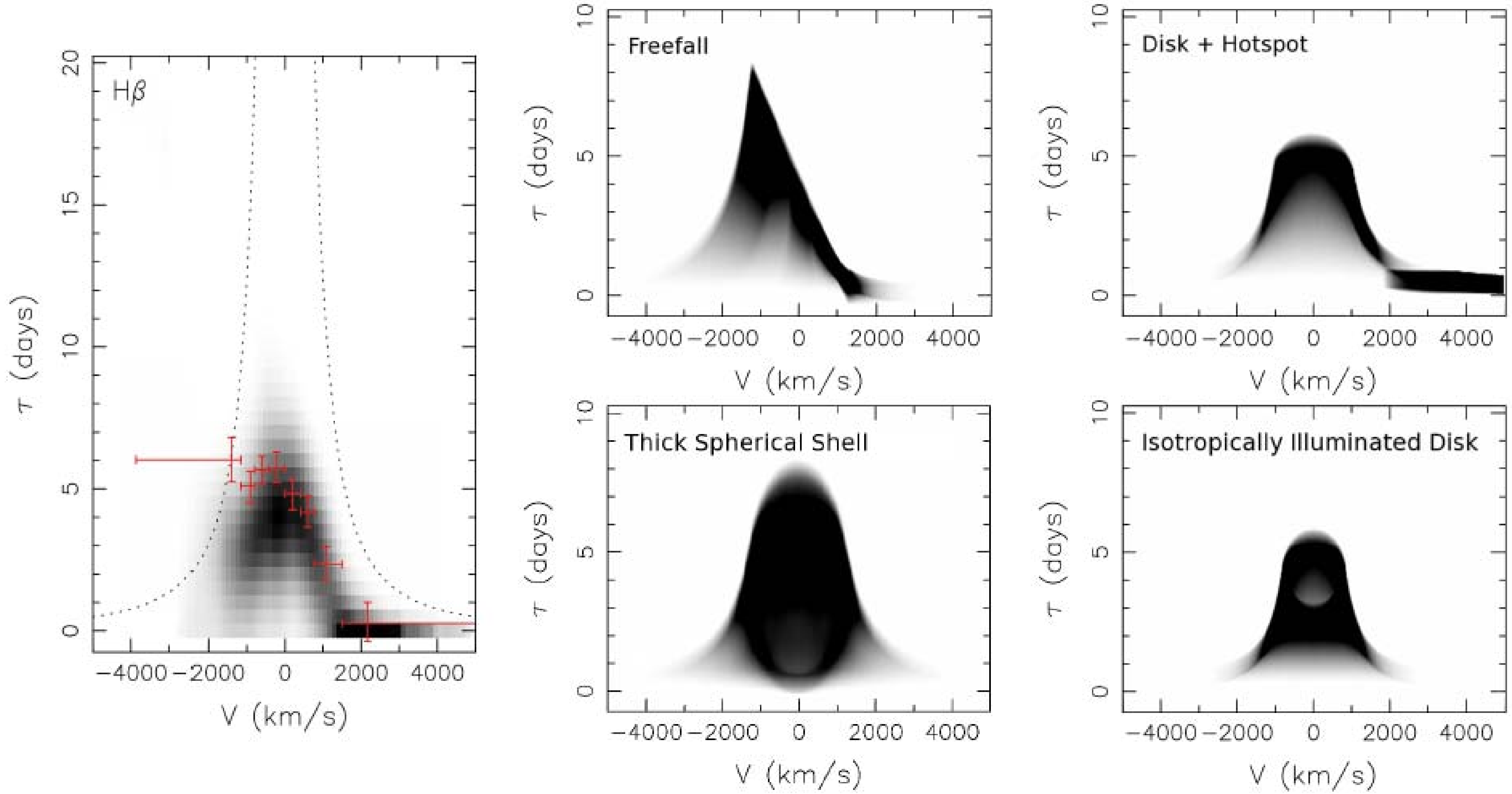
Denney et al. (2010)

Recent Velocity-Delay Maps

- Velocity-delay maps from these campaigns are beginning to show believable structure.



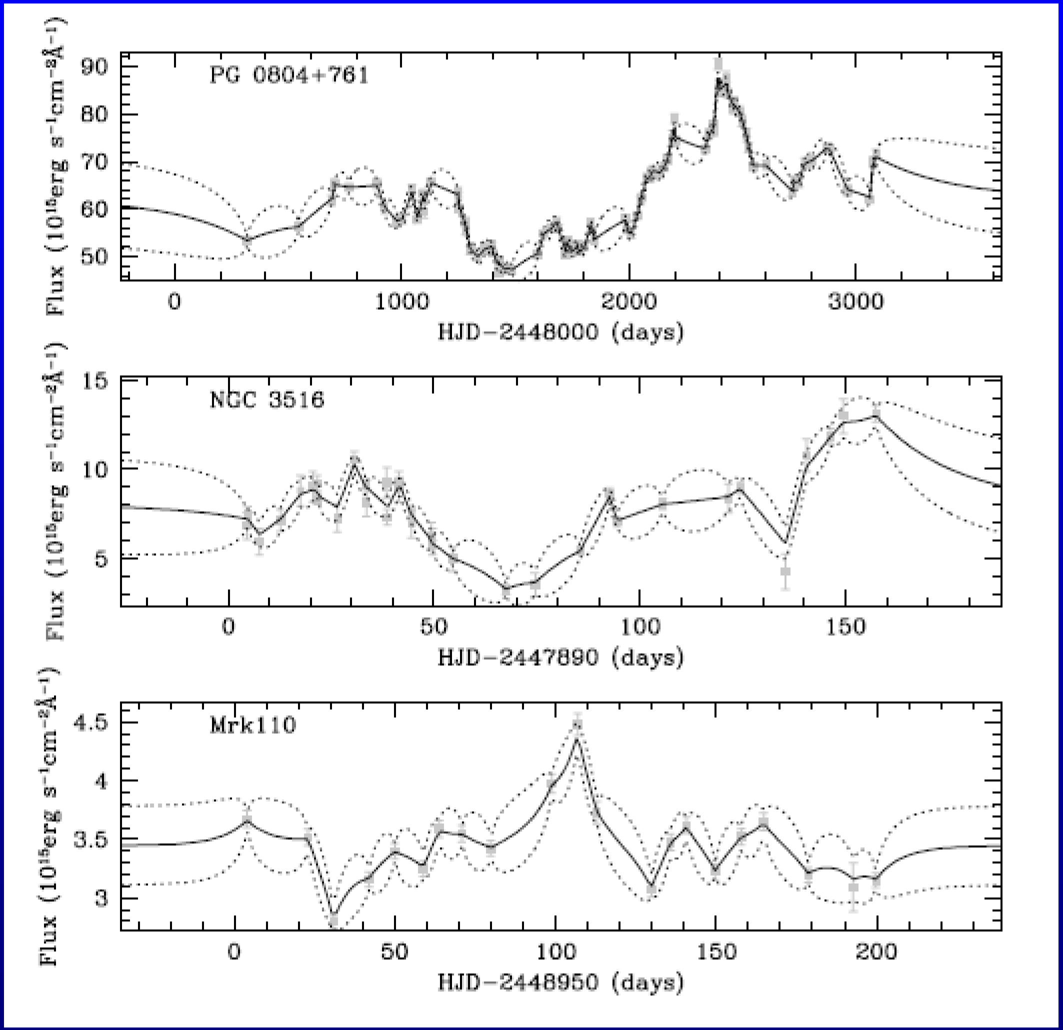
LAMP: Bentz et al. 2010



LAMP results from Bentz et al. 2010

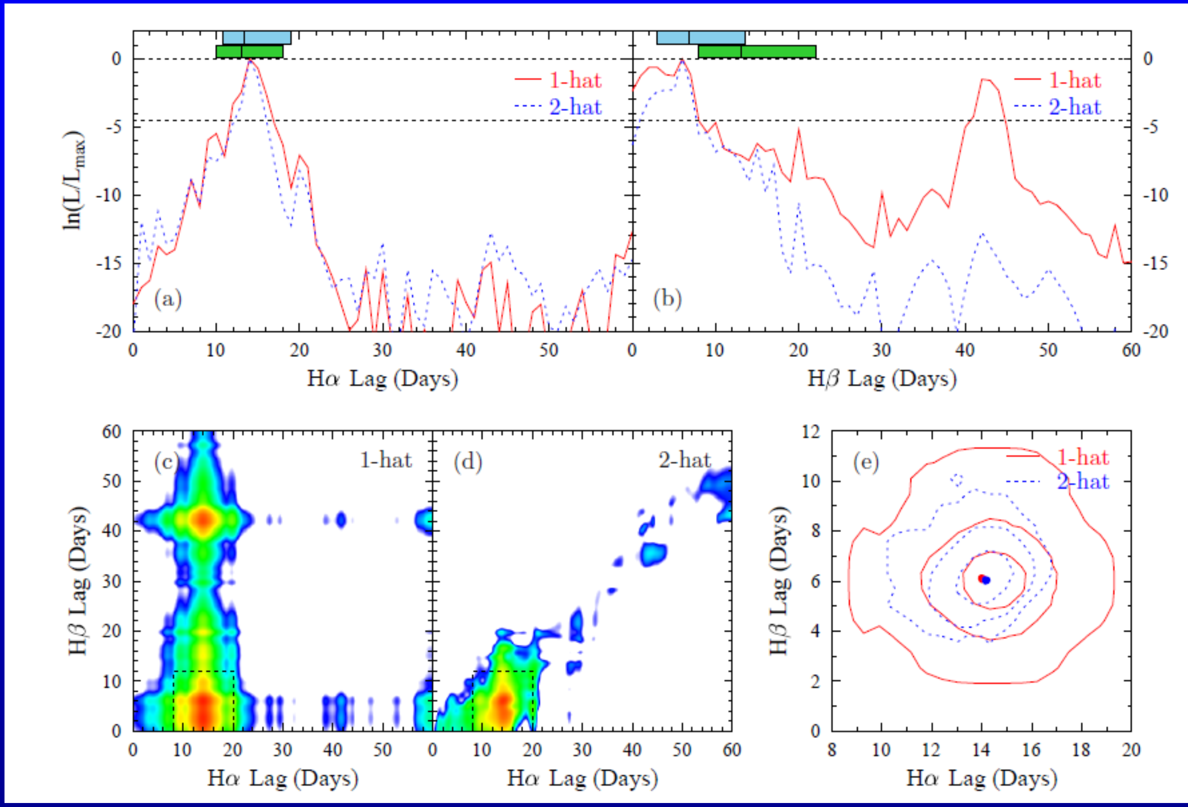
A New Reverberation Methodology

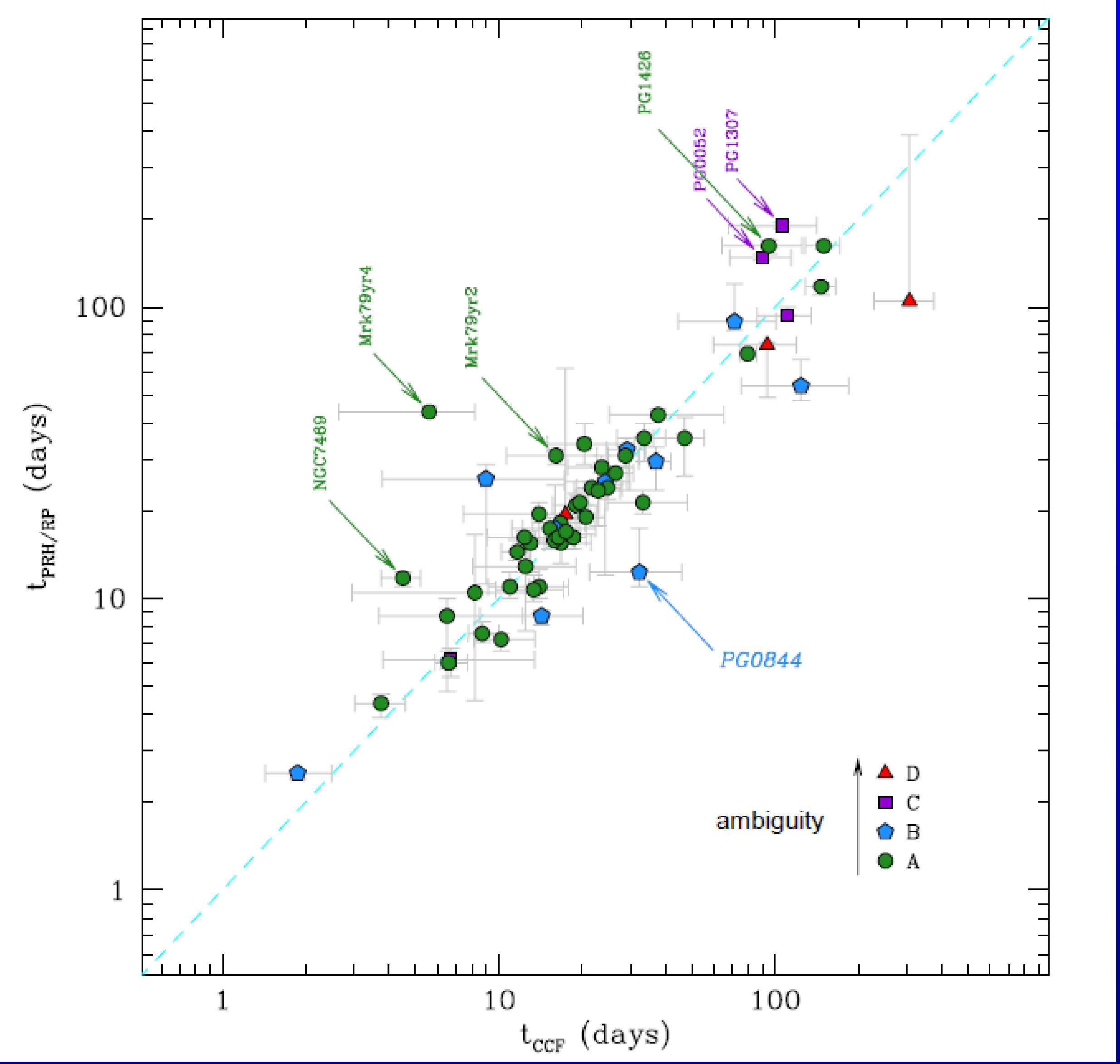
- Statistical modeling of light curves can be used to fill in gaps with all plausible flux values.
  - Based on statistical process modeling
    - **Press, Rybicki, & Hewitt (1992)**
    - **Rybicki & Press (1992)**
    - **Rybicki & Kleyna (1994)**
  - "Stochastic Process Estimation for AGN Reverberation" (SPEAR)
- A likelihood estimator can be used to identify the most probable lags.



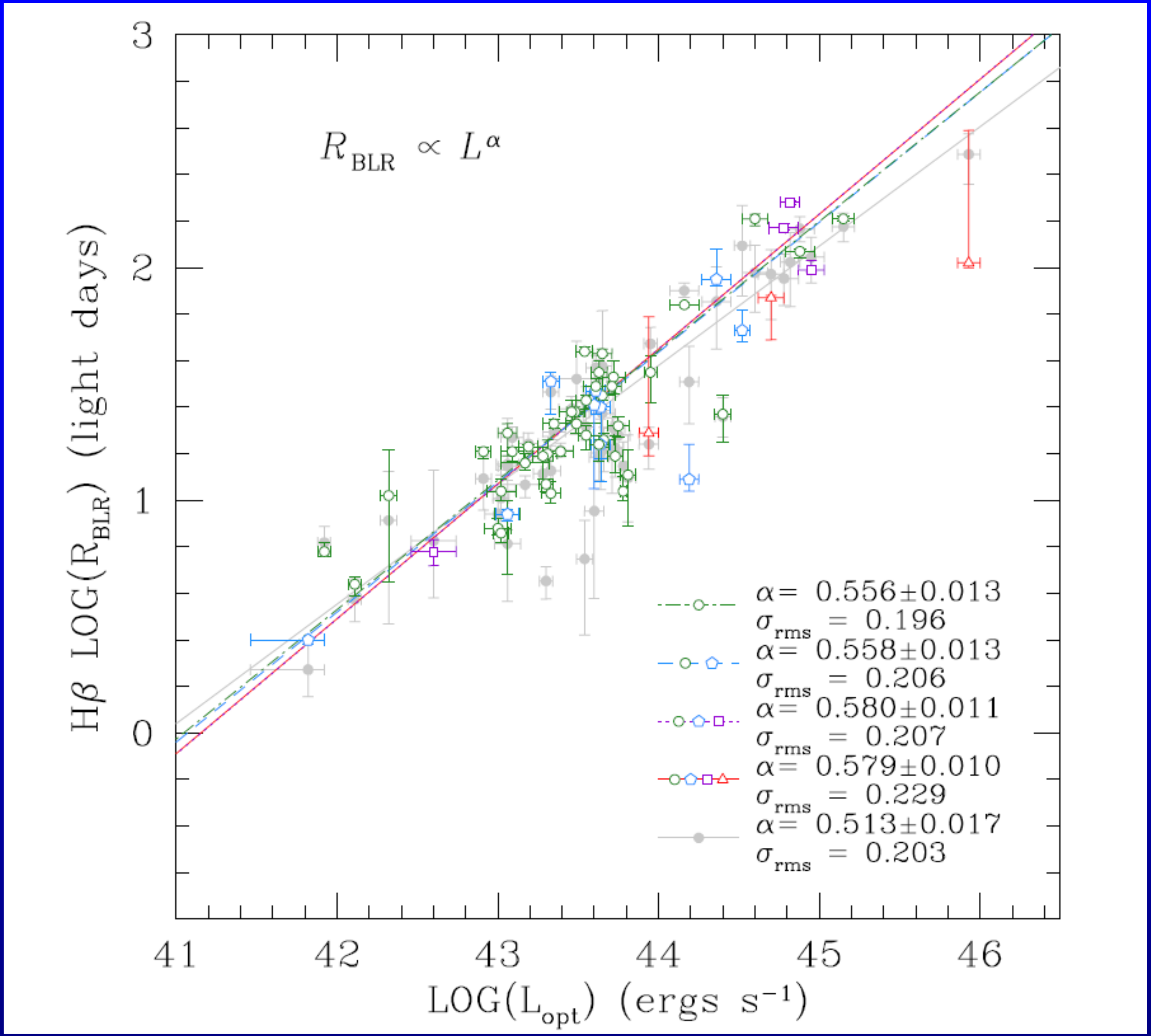
Zu, Kochanek, & Peterson 2011

- Uncertainties are computed self-consistently and included in the model.
- Trends, correlated errors are dealt with naturally.
- Can simultaneously fit multiple lines (which effectively backfill gaps in the time series).





Results are in good agreement with results from CCF and formal errors are somewhat smaller.



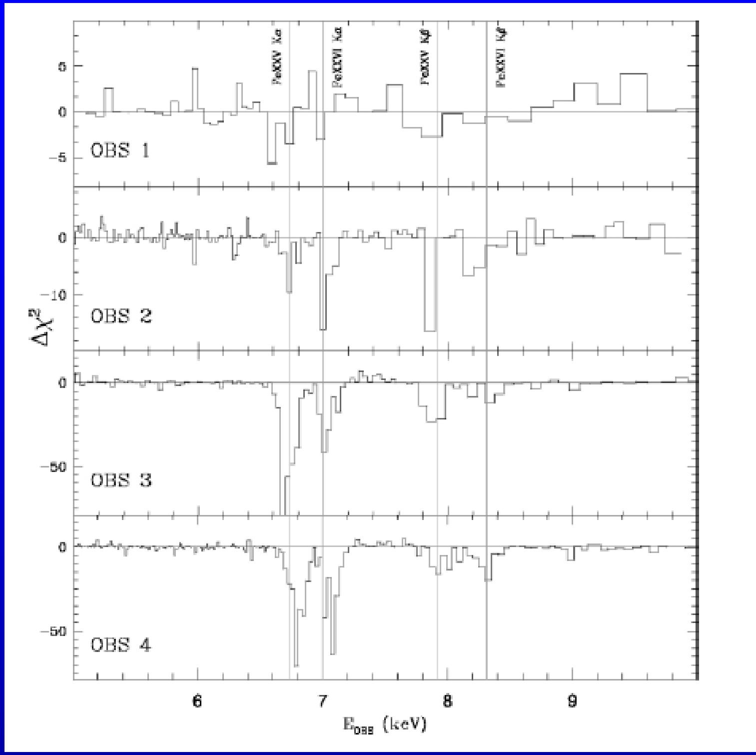
$R_{BLR} \propto L^{\alpha}$
Hβ LOG(R_{BLR}) (light days)
LOG(L_{opt}) (ergs s^{-1})
3
2
1
0
41
42
43
44
45
46
$\alpha = 0.556 \pm 0.013$
$\sigma_{rms} = 0.196$
$\alpha = 0.558 \pm 0.013$
$\sigma_{rms} = 0.206$
$\alpha = 0.580 \pm 0.011$
$\sigma_{rms} = 0.207$
$\alpha = 0.579 \pm 0.010$
$\sigma_{rms} = 0.229$
$\alpha = 0.513 \pm 0.017$
$\sigma_{rms} = 0.203$

What Else Have We Learned About the BLR?

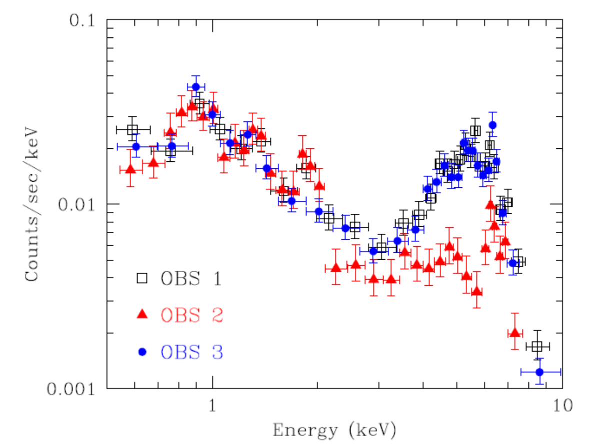
- Reverberation results suggest a disk-like structure and (probably) inflow.
- Additional information can be gleaned from the absorption spectra of AGNs.

Highly Variable X-Ray Absorption

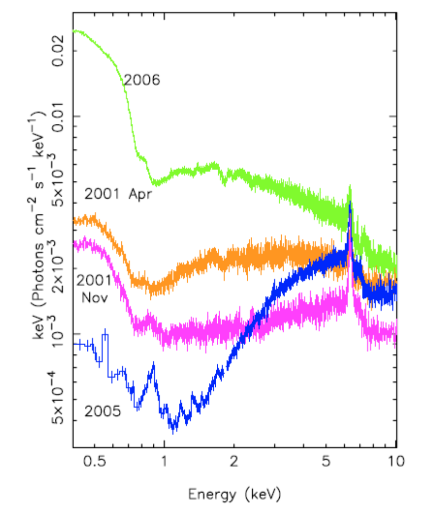
- Changes in absorption columns (~10^{23} cm^{-2}) on timescales of ~ 1 day or less.
  - Implied columns, transverse velocities, distance from central source point to BLR.



Risaliti et al. 2005



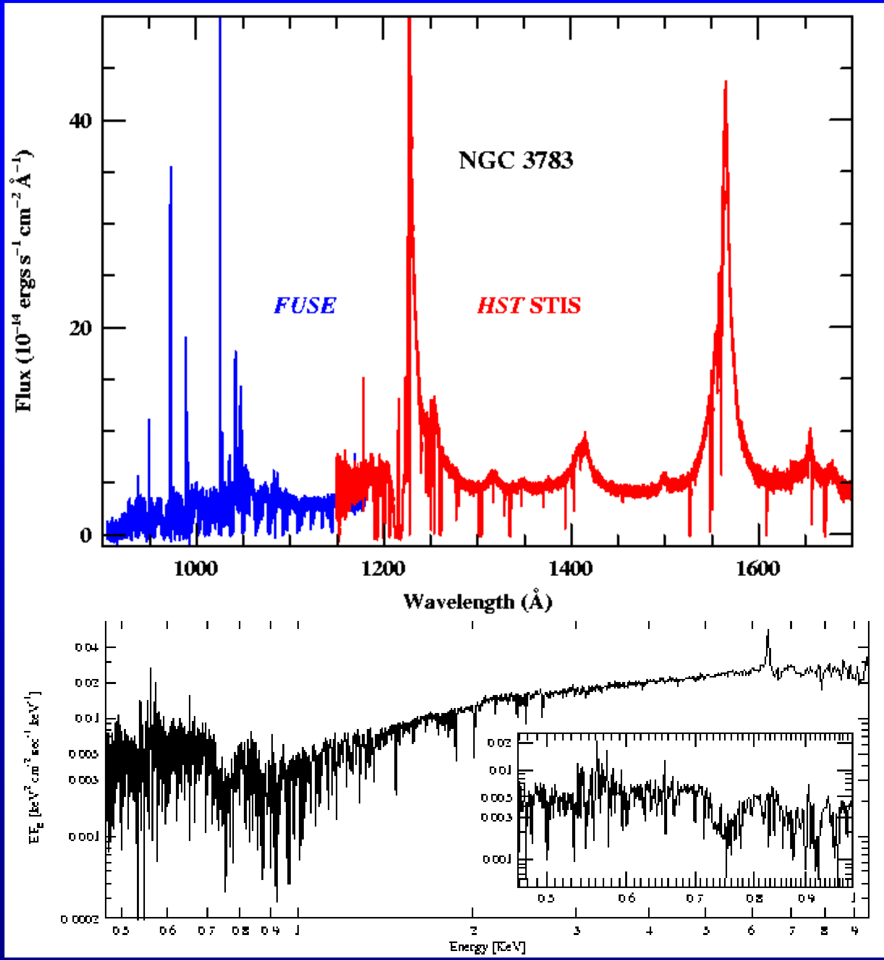
Risaliti 2007

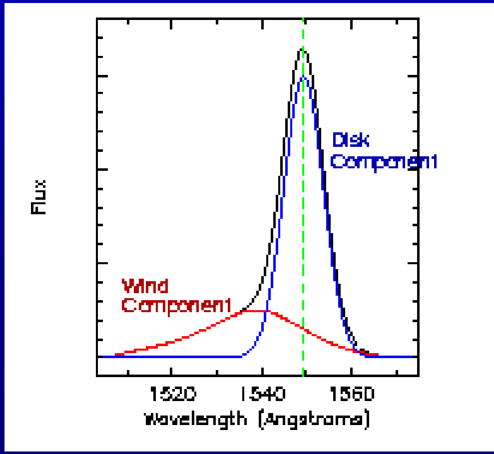


Turner et al. 2008

The Nature of the BLR

- Evidence for outflows
  - Blueshifted absorption features are common Clear blueward asymmetries in some cases



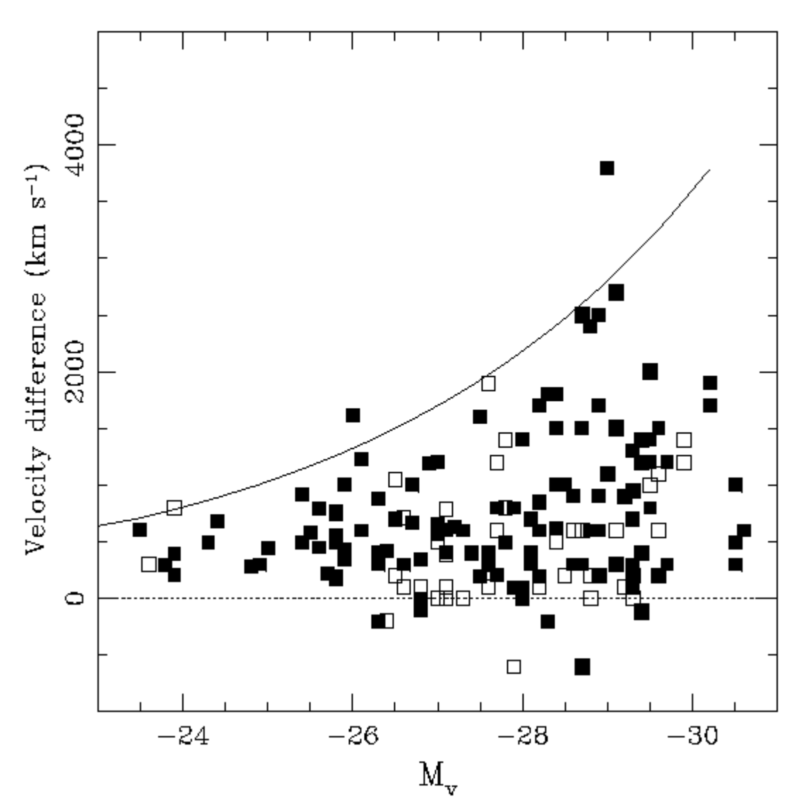


Leighly (2001)

Chandra: Kaspi et al. (2002)
HST: Crenshaw et al. (2002)
FUSE: Gabel et al. (2002)

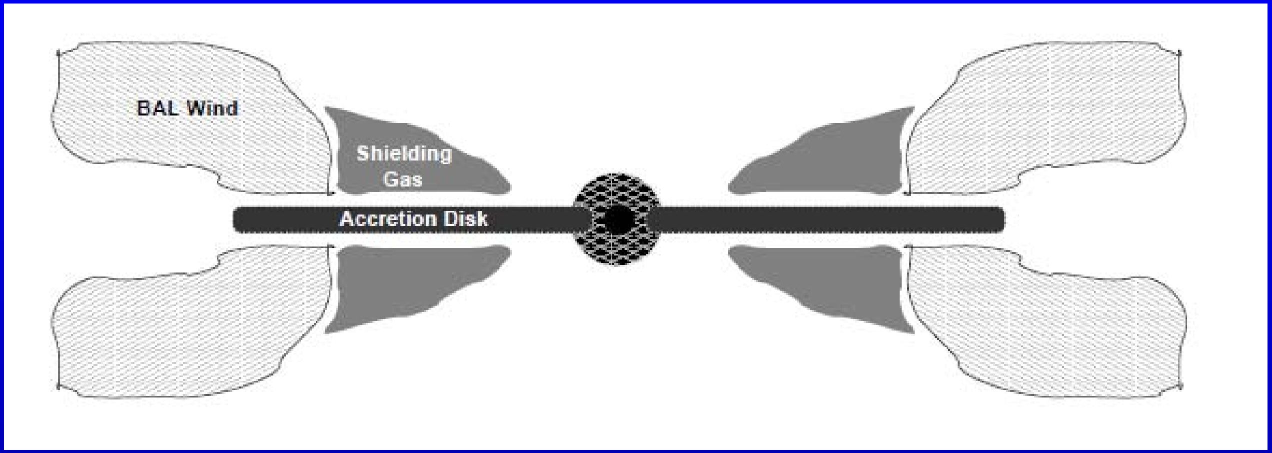
Evidence for Outflows in AGNs

- Peaks of high ionization lines are blueshifted relative to systemic.
- Maximum blueshift increases with luminosity.



Espey (1997)

A Disk-Wind Concept



Gallagher et al. 2004

Wind could be hydromagnetically or radiation-pressure driven

- Theory: Murray & Chiang, Proga, Blandford & Payne
- Phenomenology: Elvis, S. Gallagher, Vestergaard

Summary of Key Points

1) Reverberation mapping provides a unique probe of the inner structure of AGNs.
2) Broad-line region size has been measured directly in ~45 AGNs.
3) In cases where multiple lines are measured, the BLR shows ionization stratification.
4) We are on the verge of recovery of high-fidelity velocity-delay maps.
5) There is a tight correlation between BLR size and AGN luminosity.
6) Circumstantial evidence most consistent with a disk-wind model for BLR. *There is still no self-consistent model of the BLR.*