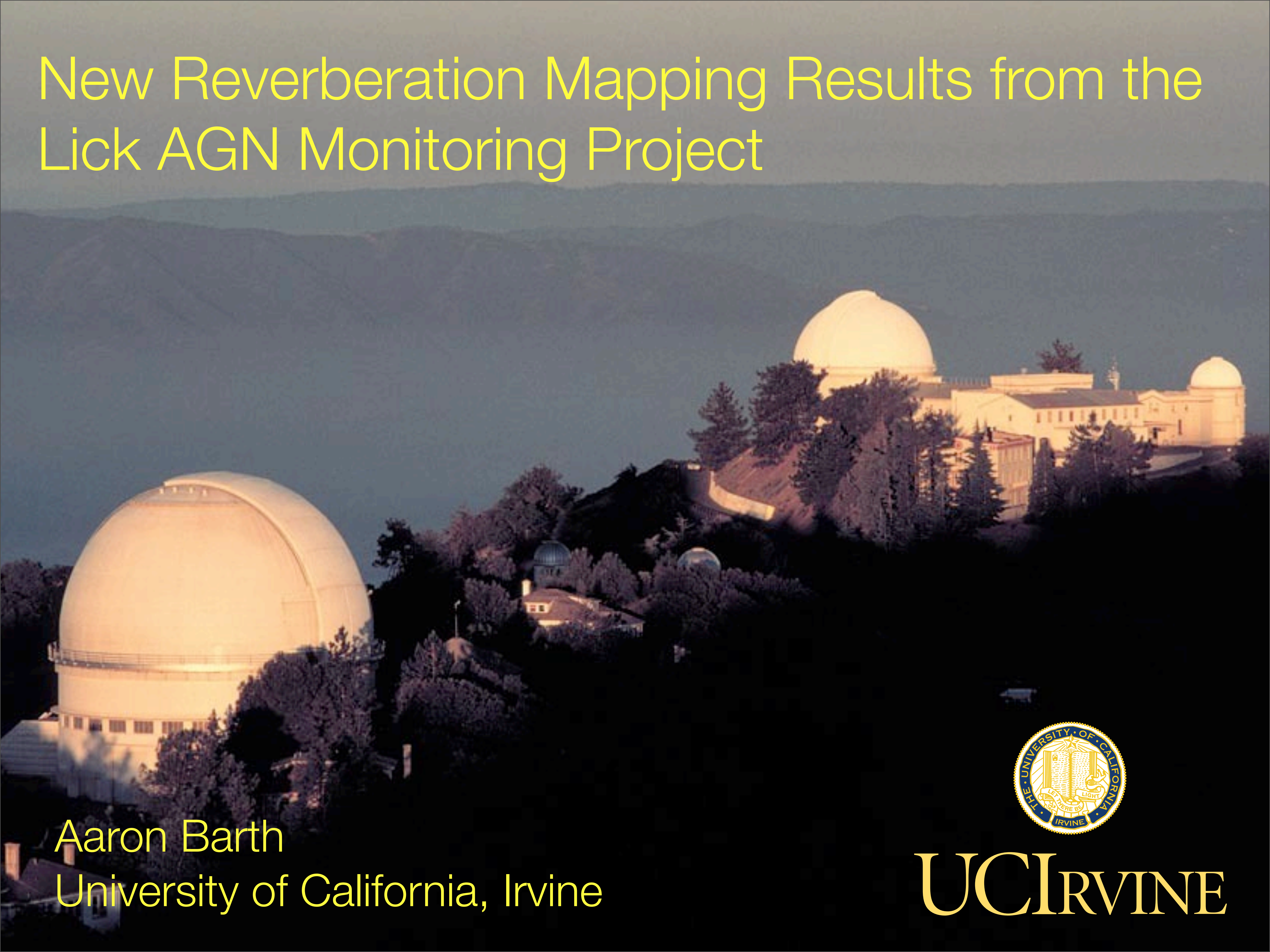
# New Reverberation Mapping Results from the Lick AGN Monitoring Project



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# The Team

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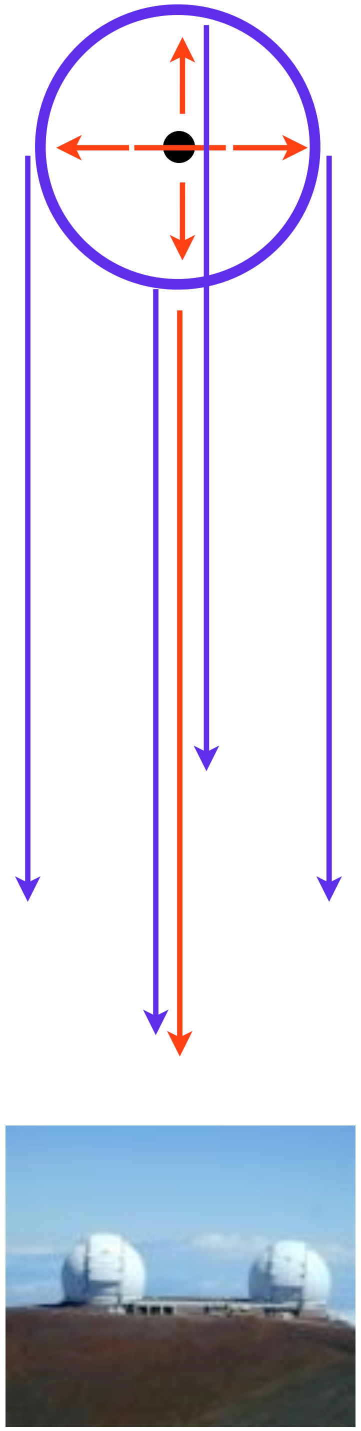
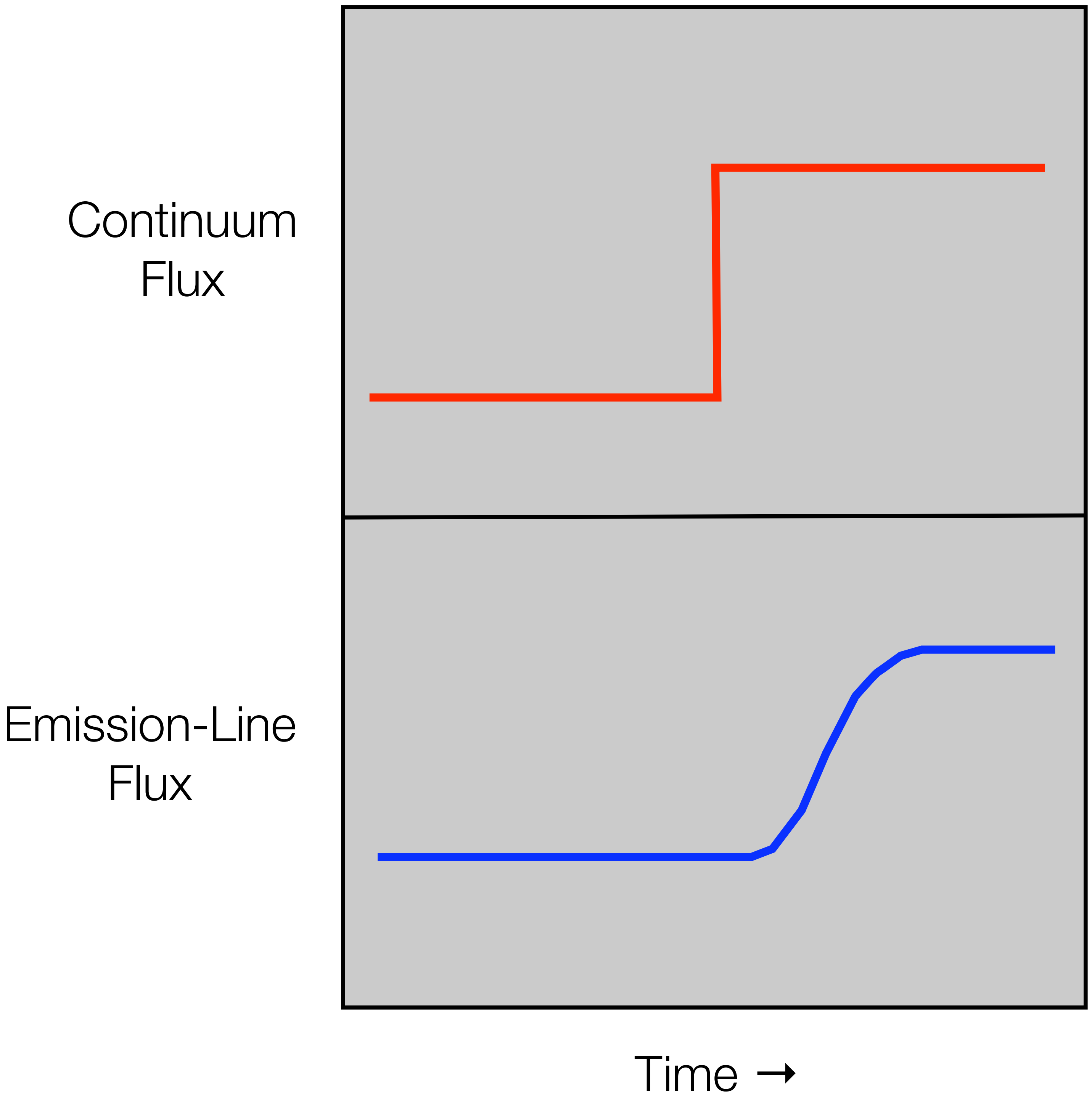
# Broad-line reverberation

Background:
Bahcall et al. 1972,
Blandford & McKee 1982,
Peterson 1993





# Black hole masses from reverberation

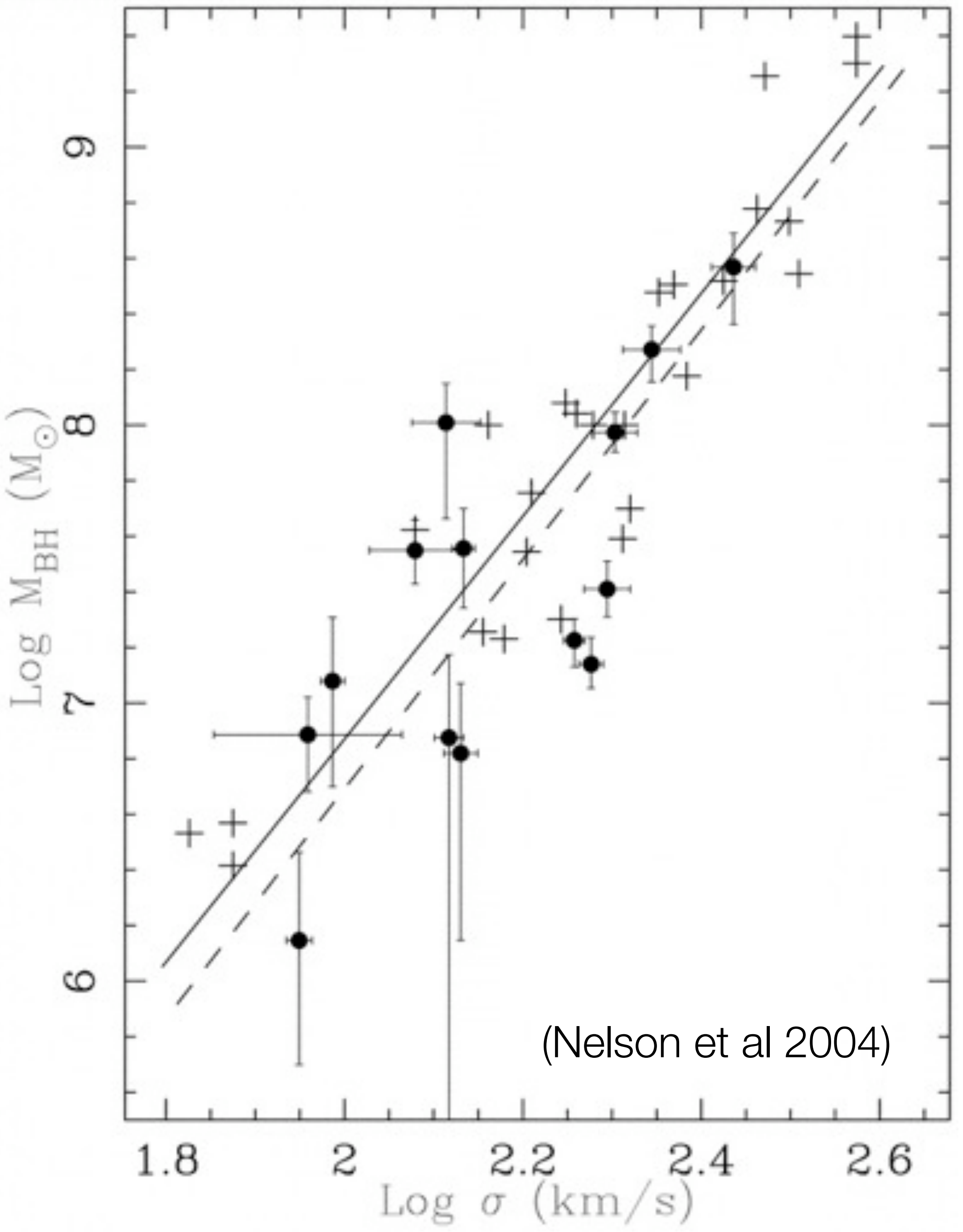
- If the broad-line kinematics are dominated by gravity, we can derive a virial estimate the central mass using the lag time Δt and the broad-line width:

$$M_{BH} = f\frac{rv^2}{G}$$

$$= f\frac{(c\Delta t)[\mathrm{FWHM}(\mathrm{H}\beta)]^2}{G}$$

- Hβ reverberation data available for ~35 low-redshift Seyferts & quasars (Kaspi et al. 2000; Peterson et al. 2004)

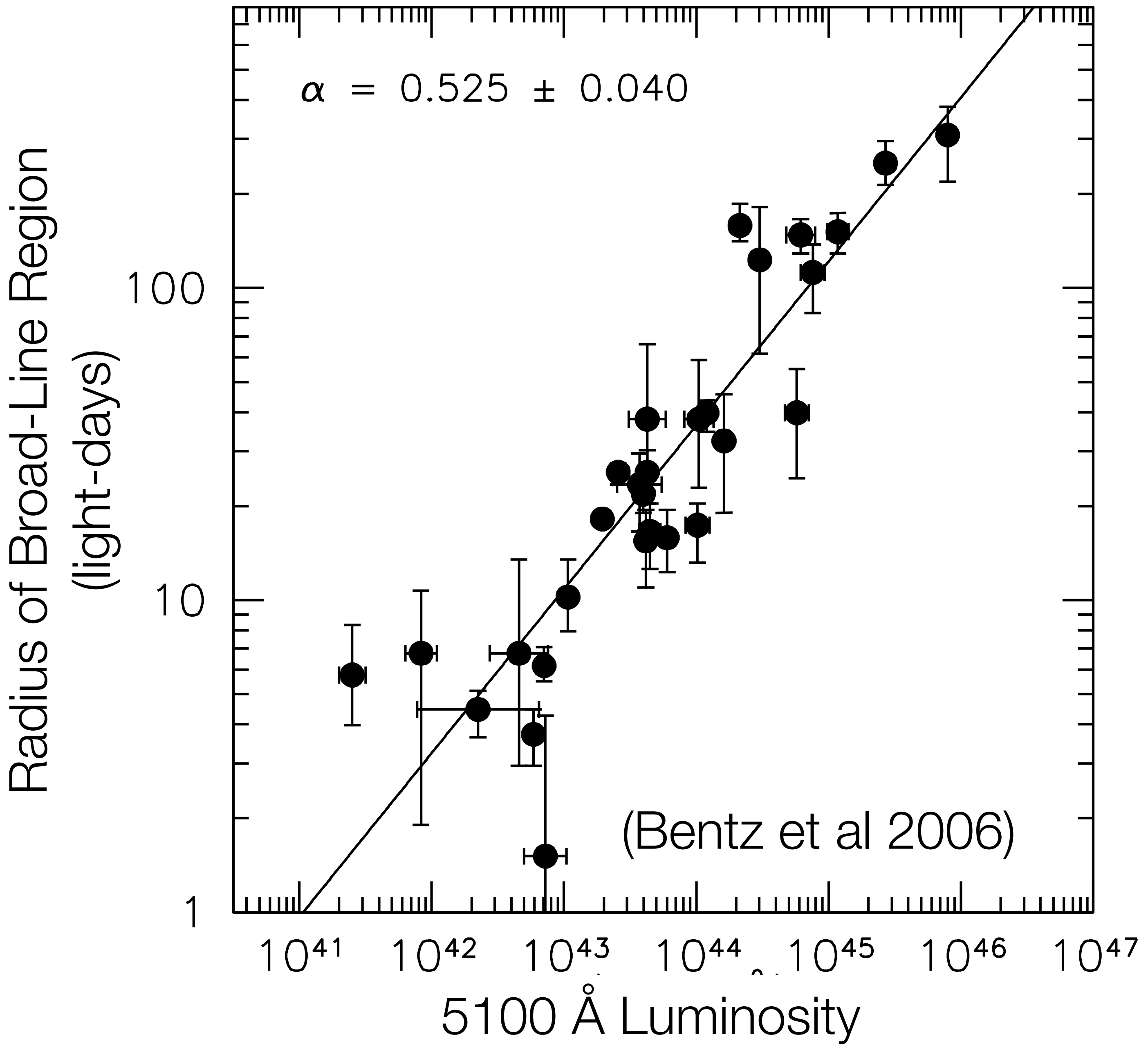
- Mass estimates from this technique are claimed to be accurate to typically a factor of ~3 (Onken et al 2004, Nelson et al 2004, Peterson et al 2004, Vestergaard et al 2006)



(Nelson et al 2004)

# The broad line region radius-luminosity relationship

- The broad-line region size is correlated with AGN continuum luminosity:

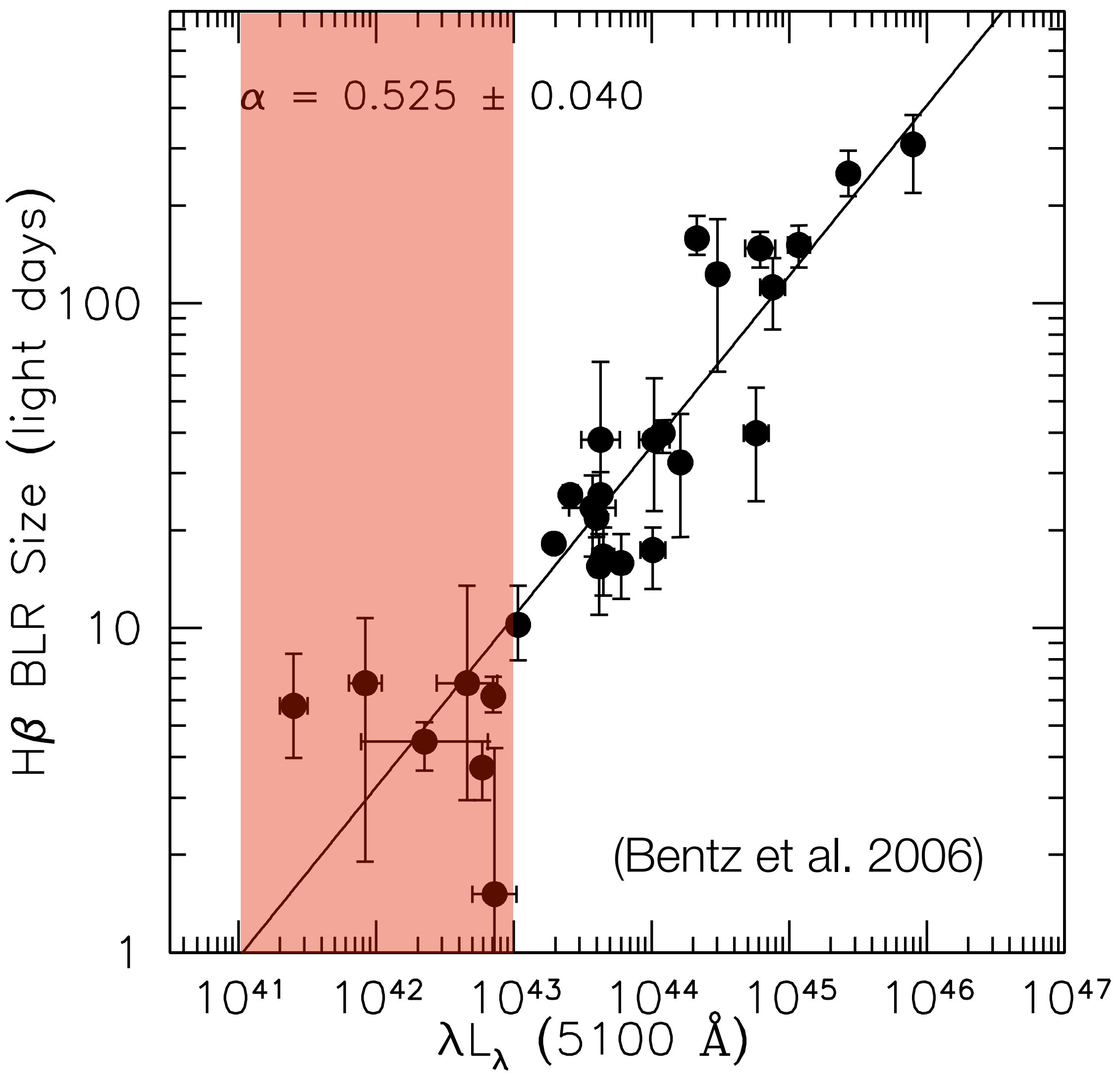


(Bentz et al 2006)

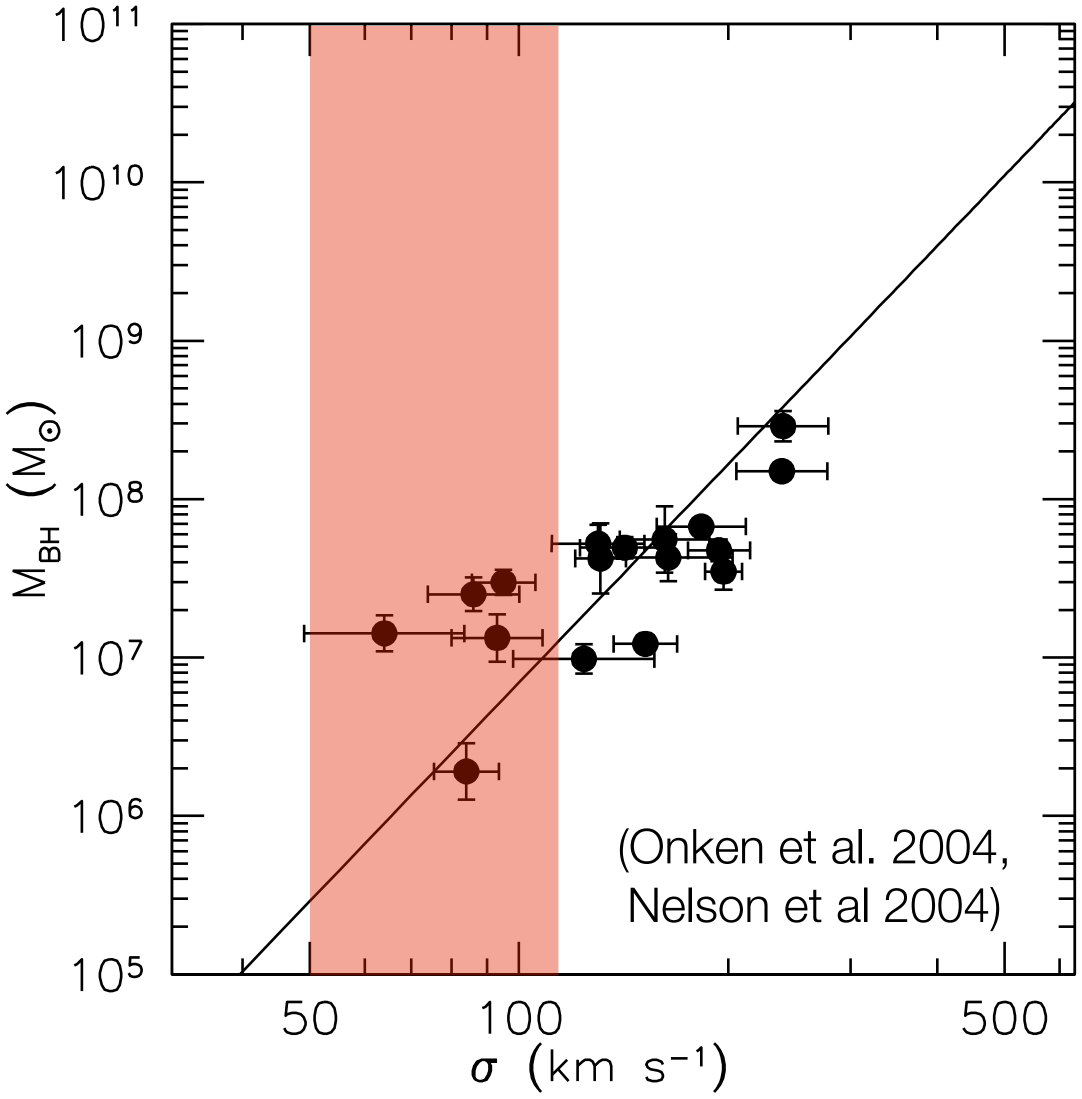
- This provides a quick way to estimate black hole masses in AGNs
- From a single spectrum, can measure both linewidth and continuum luminosity
- Use L to estimate r(BLR), then apply the virial relation to estimate M

(e.g., Laor 1998; Wandel et al. 1999; McLure & Dunlop 2001; Vestergaard 2002; Woo & Urry 2002; Shields et al. 2003; Netzer 2003, many others.... )

# Project Goals



(Bentz et al. 2006)

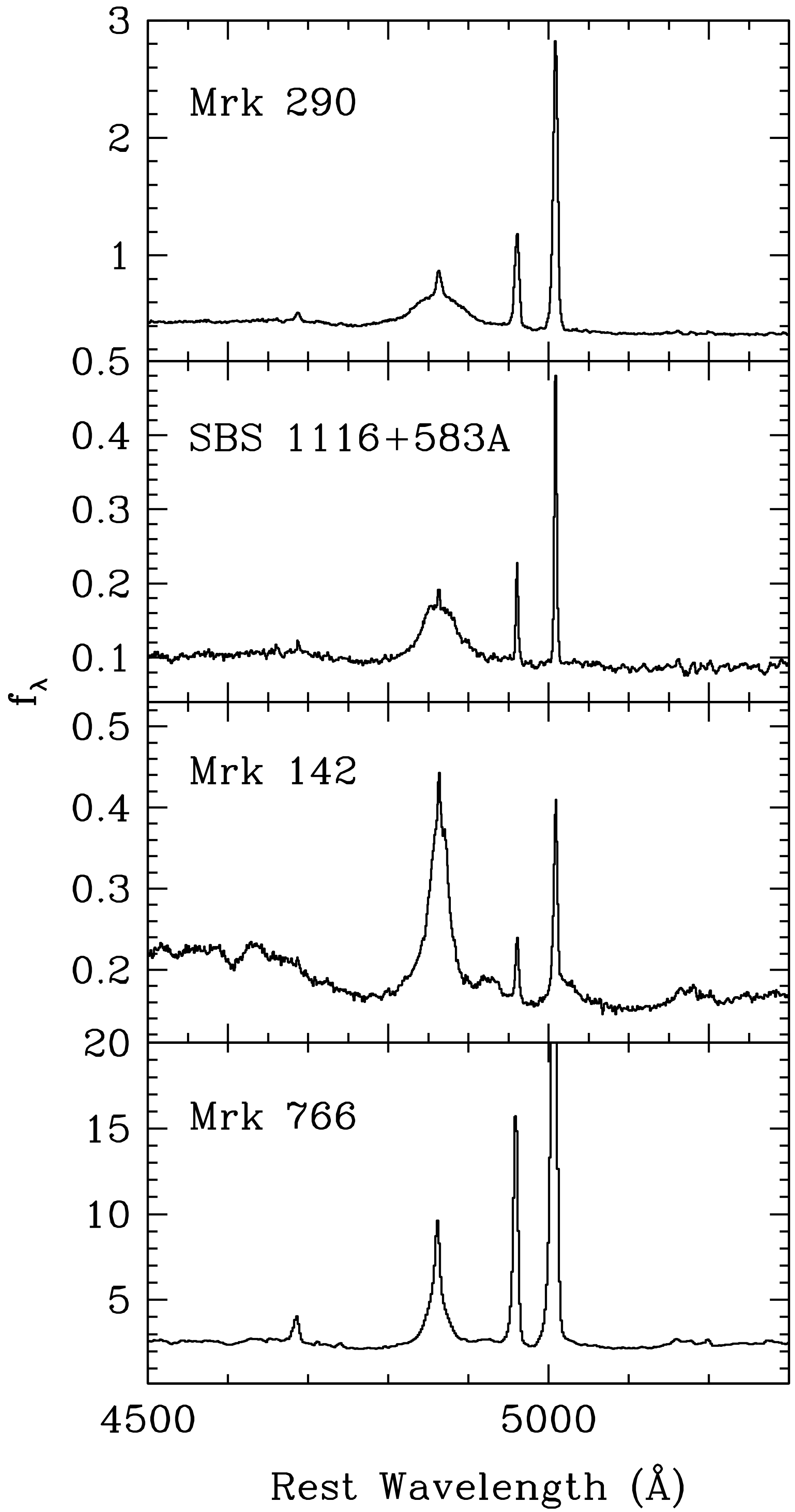


(Onken et al. 2004, Nelson et al 2004)

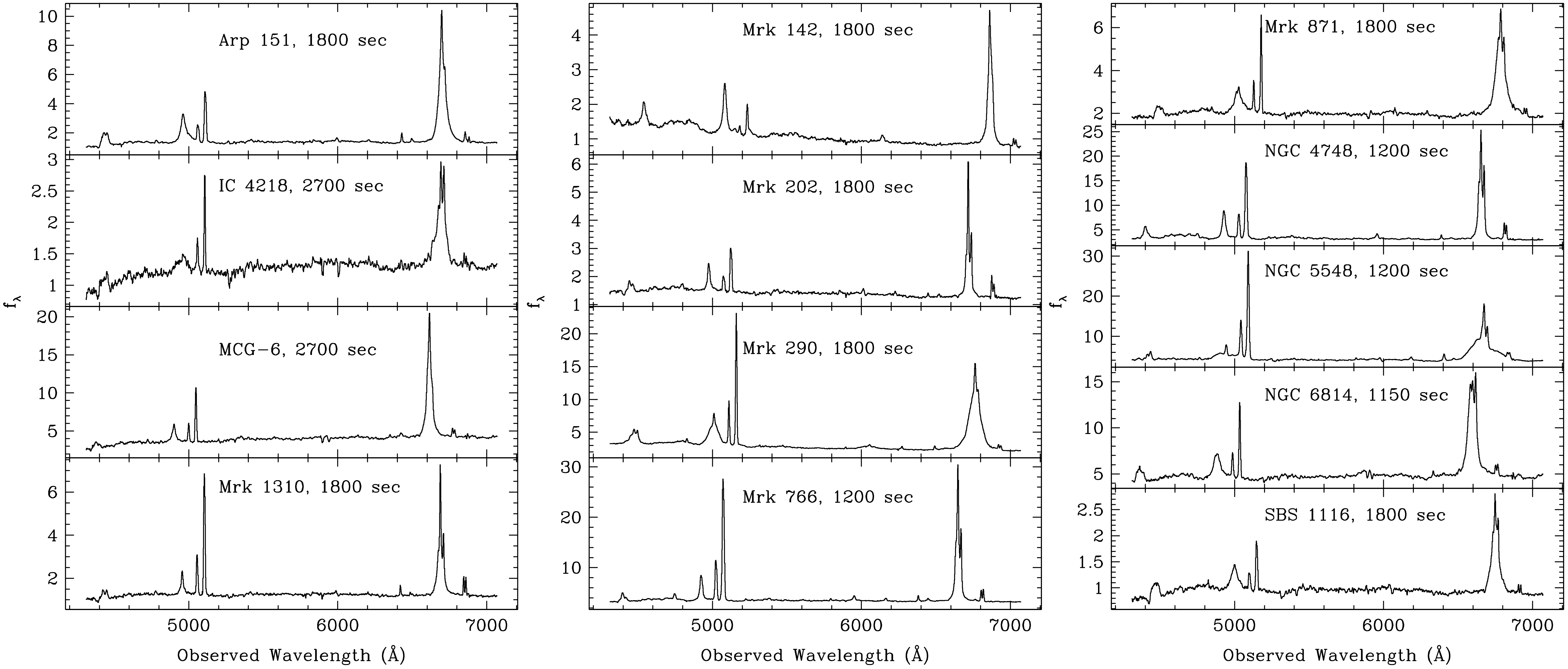
Overall goal: to improve the calibration of the AGN radius-luminosity relation and M-**σ** relation at low masses and low luminosities by measuring reverberation lags for more AGNs

# The Project

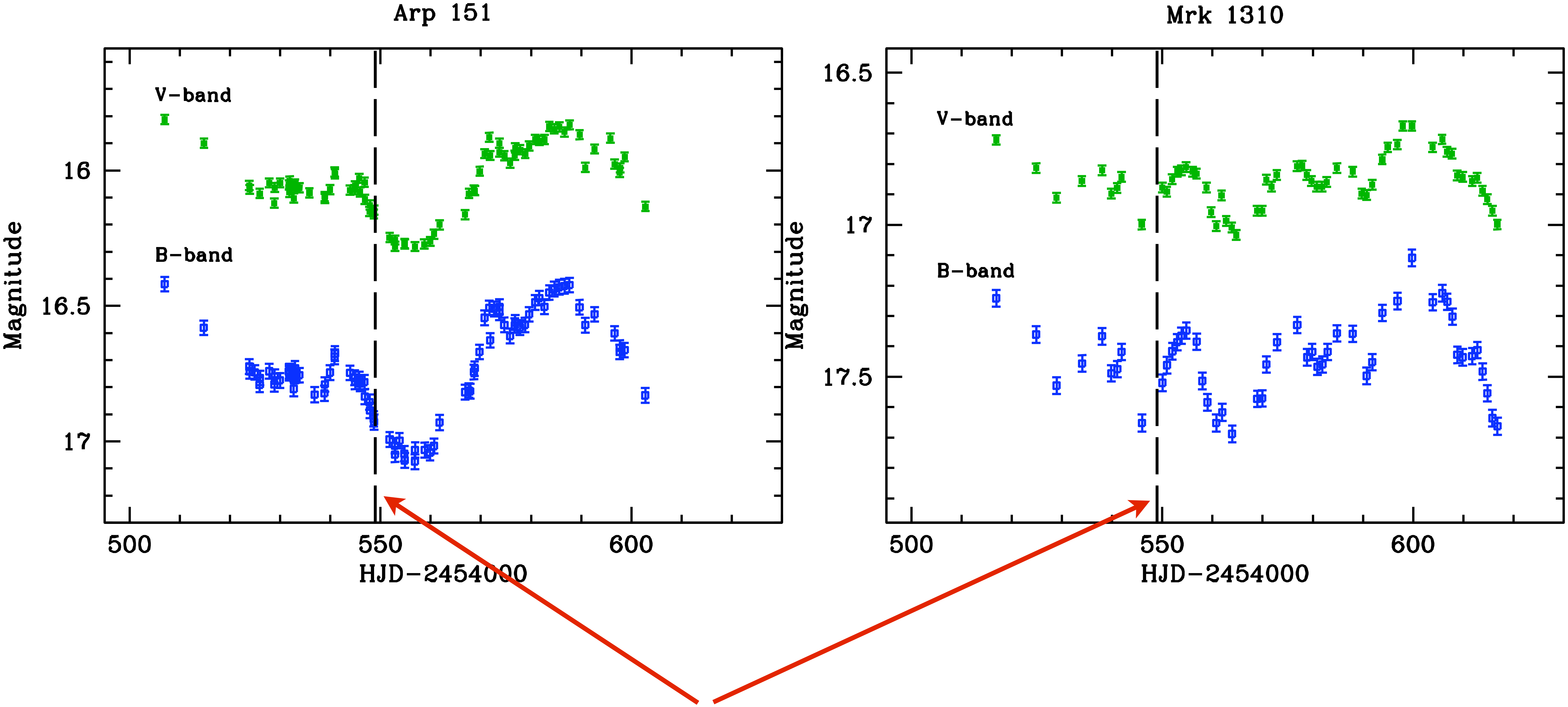
- Sample: 12 Seyfert galaxies having expected BH mass of $10^6$ - $3\times10^7$ $M_\odot$, and expected Hβ lag times of 3-10 days
  - plus one additional well-studied “control” object (NGC 5548)
- Need a *continuous* spectroscopic monitoring campaign to detect night-to-night variability
  - every object observed on every clear night
- 64 mostly consecutive nights on the Lick 3-m telescope allocated during March-May 2008
- Nightly photometric monitoring from 4 smaller telescopes: KAIT 0.8m, Tenagra 0.8m, Palomar 60-inch, and MAGNUM 2m



# The data: one night’s work at Lick



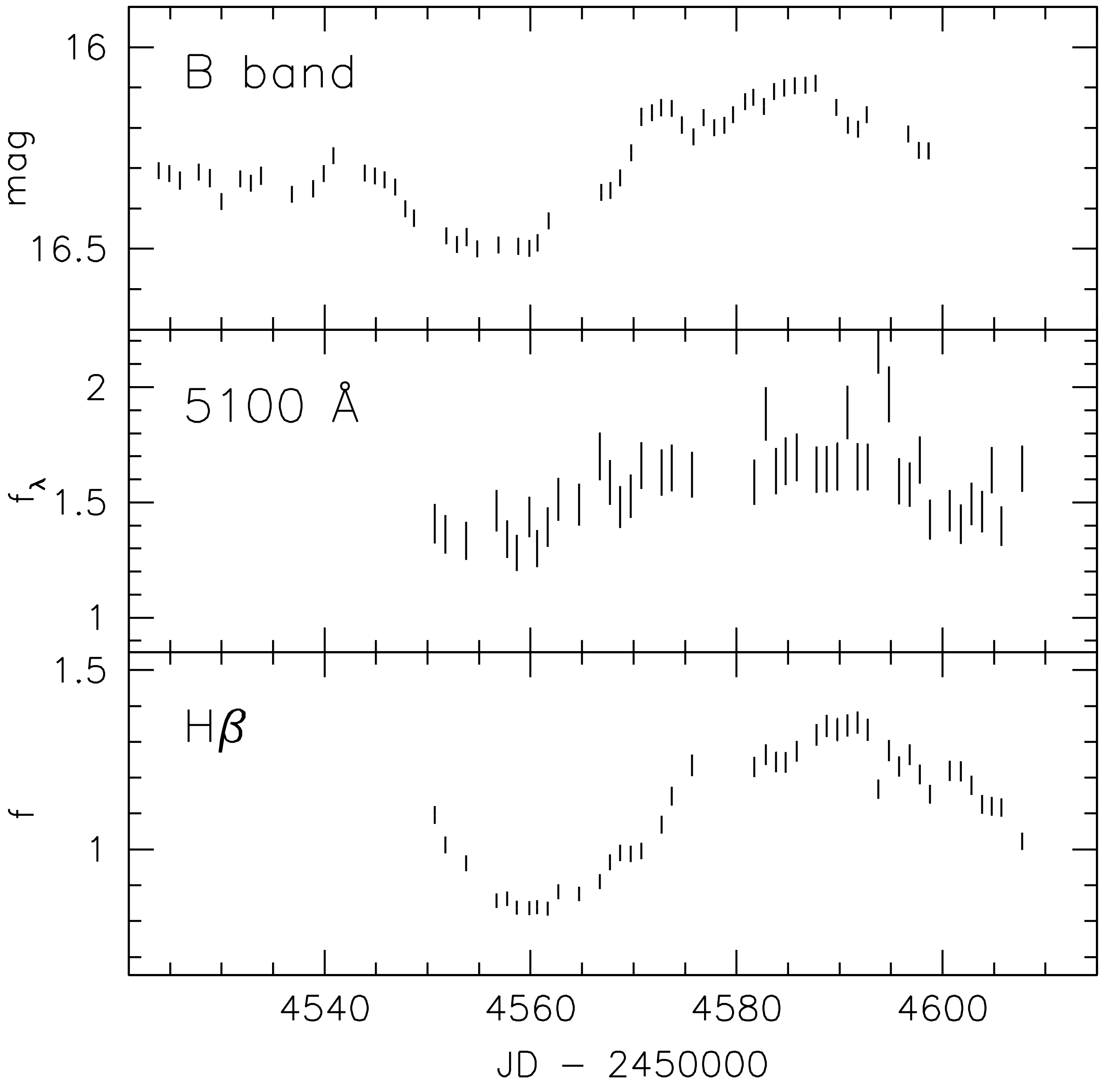
# Light curves from imaging data

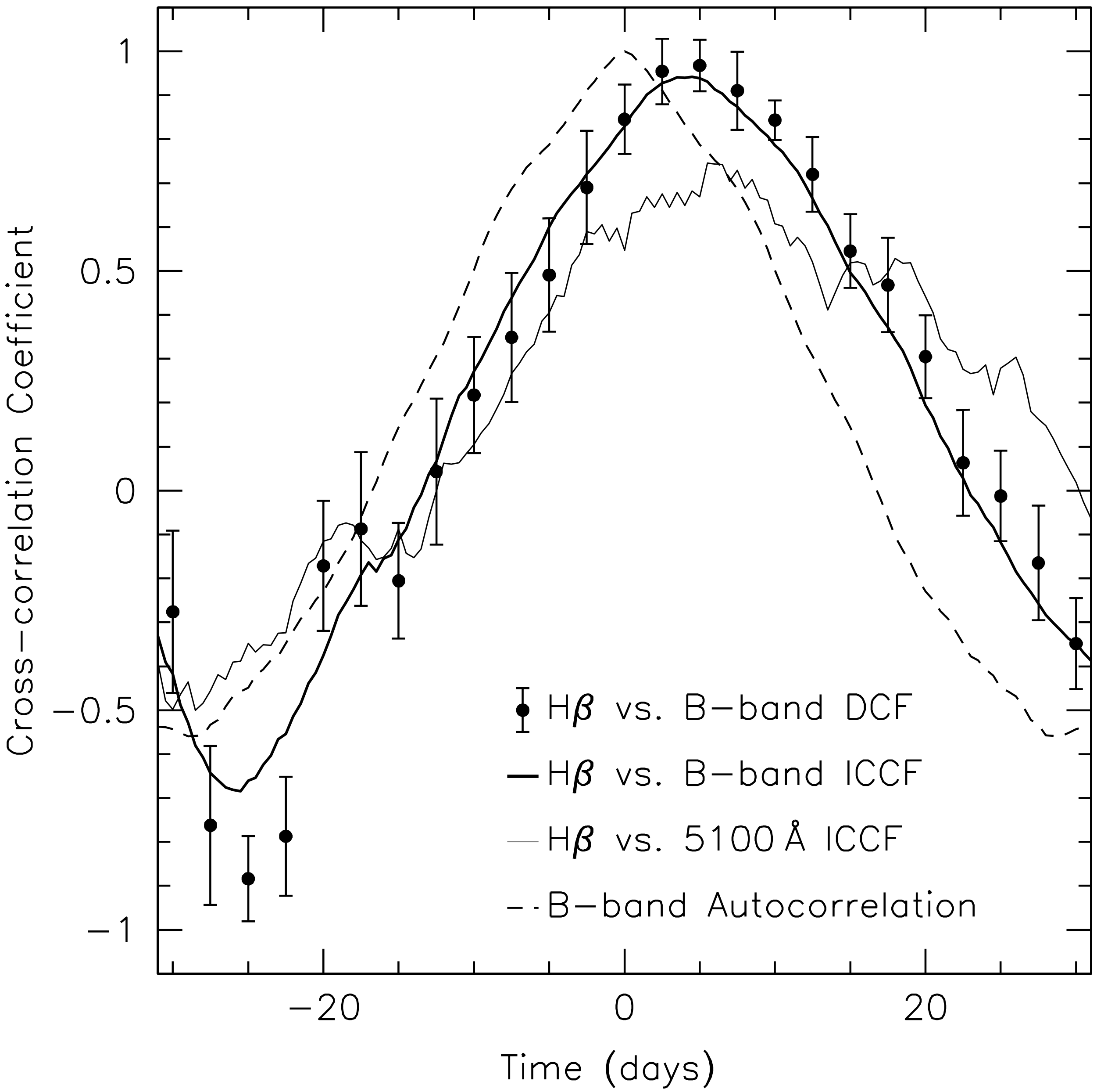


Spectroscopic monitoring started here

# Arp 151 results

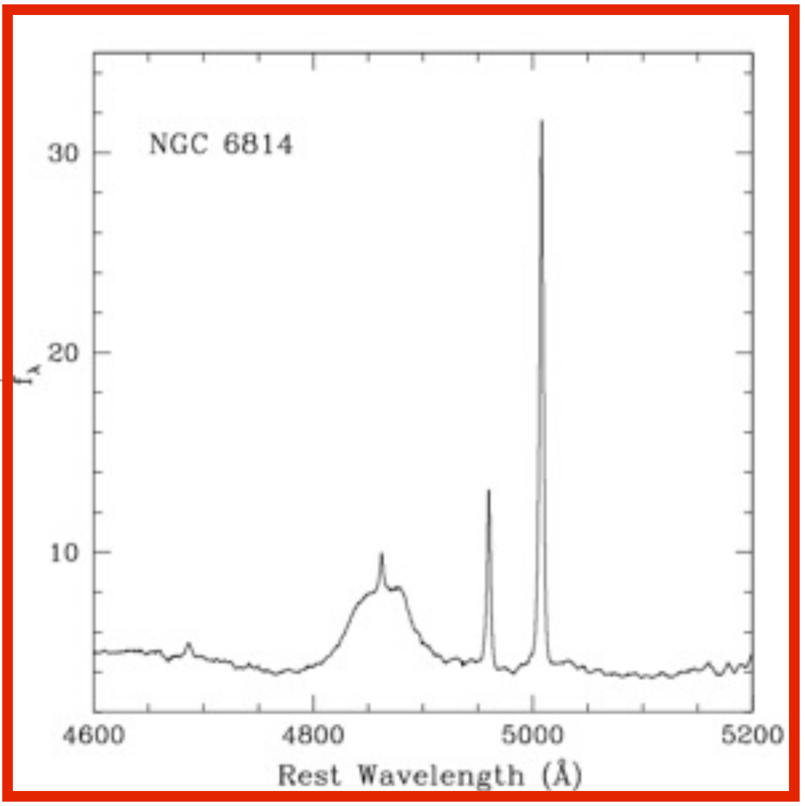
(Bentz, Walsh, Barth, et al, ApJL 2008)





Hβ lags the continuum by 4.3±0.7 days

# Velocity-resolved reverberation



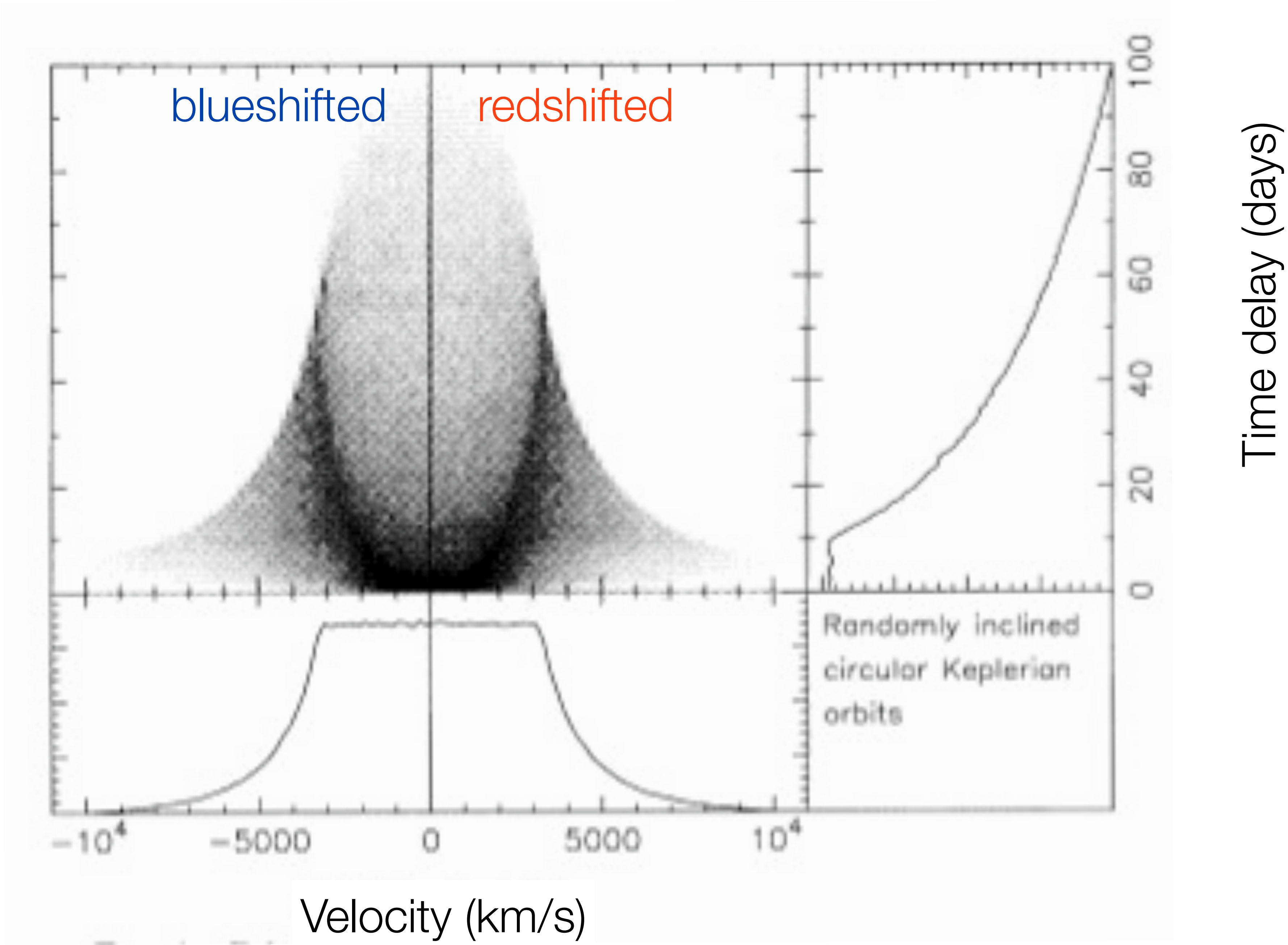
- The variability of the emission-line flux in response to the driving continuum variability is given by

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

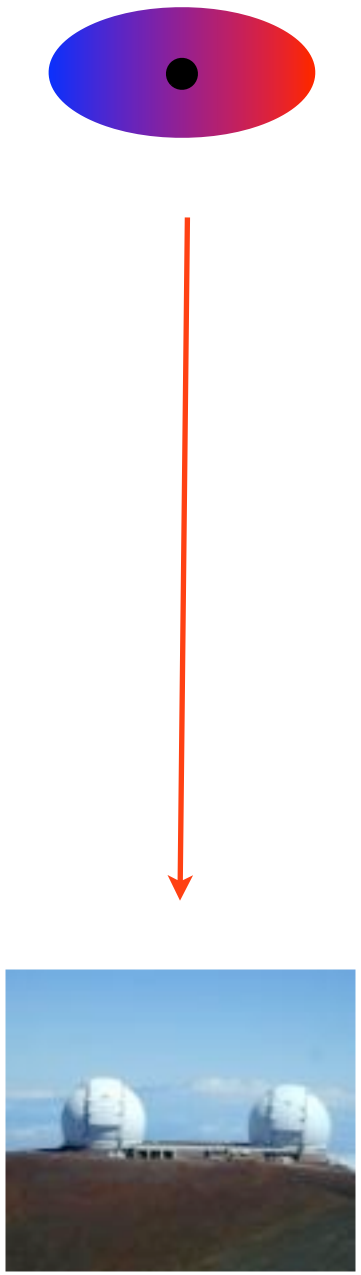
- C(t) is the continuum light curve
- L($V_r$, t) is the emission-line light curve as a function of line-of-sight velocity and time
- $\Psi$($V_r$, t) is the transfer function
    - it depends on the detailed geometry, kinematics, and emissivity distribution of the broad-line region

# Velocity-resolved reverberation

(figures from Welsh & Horne 1991)

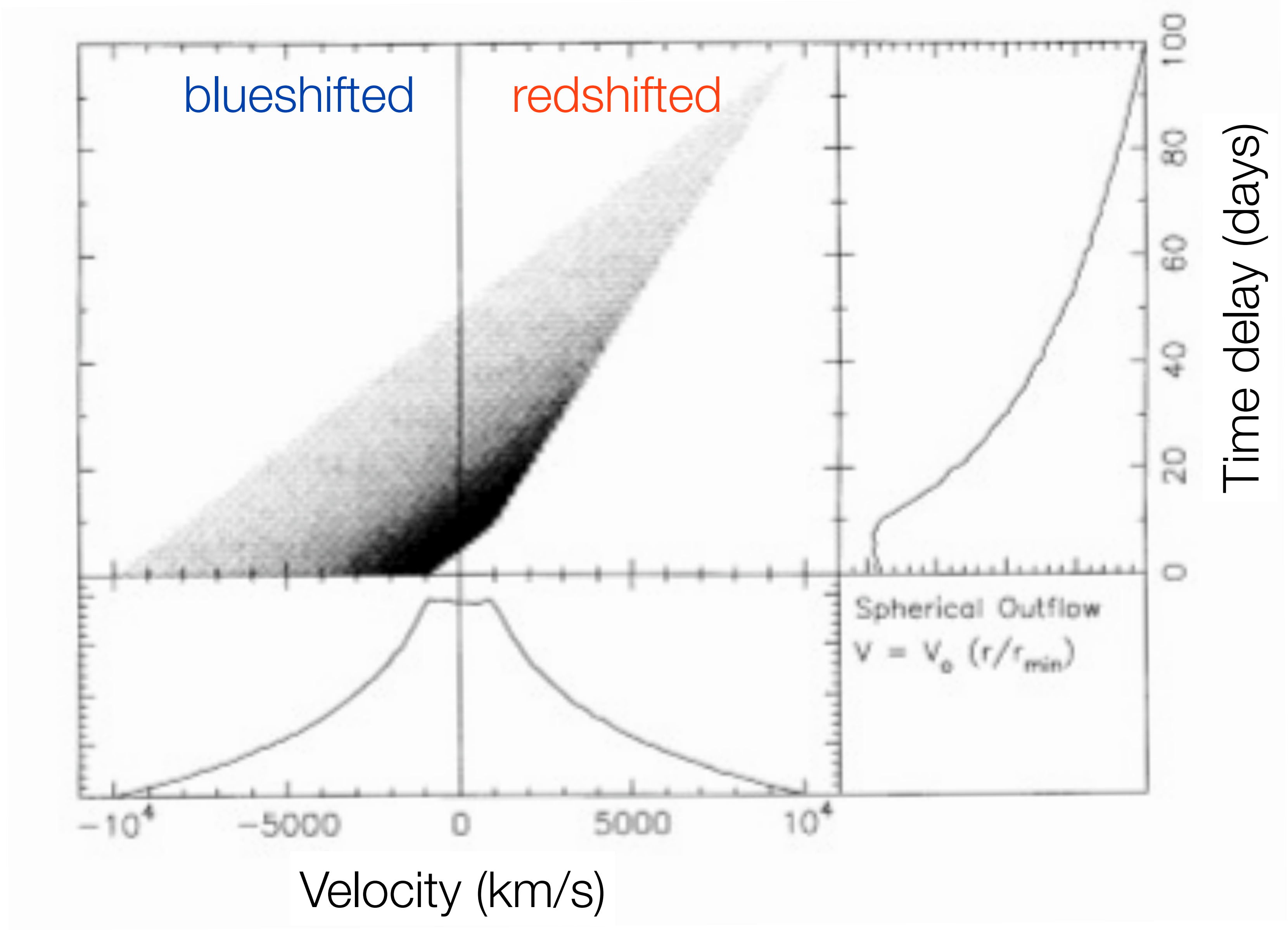


Rotating Keplerian disk

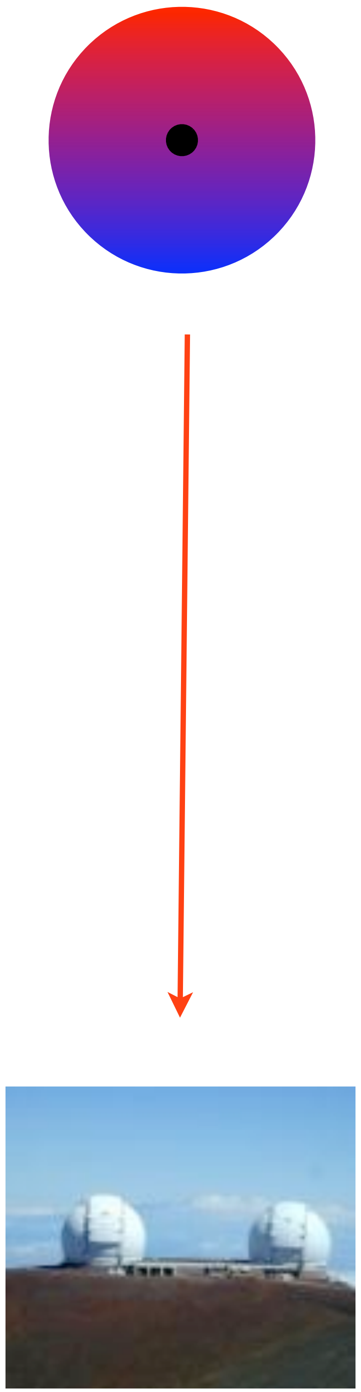


# Velocity-resolved reverberation

(figures from Welsh & Horne 1991)

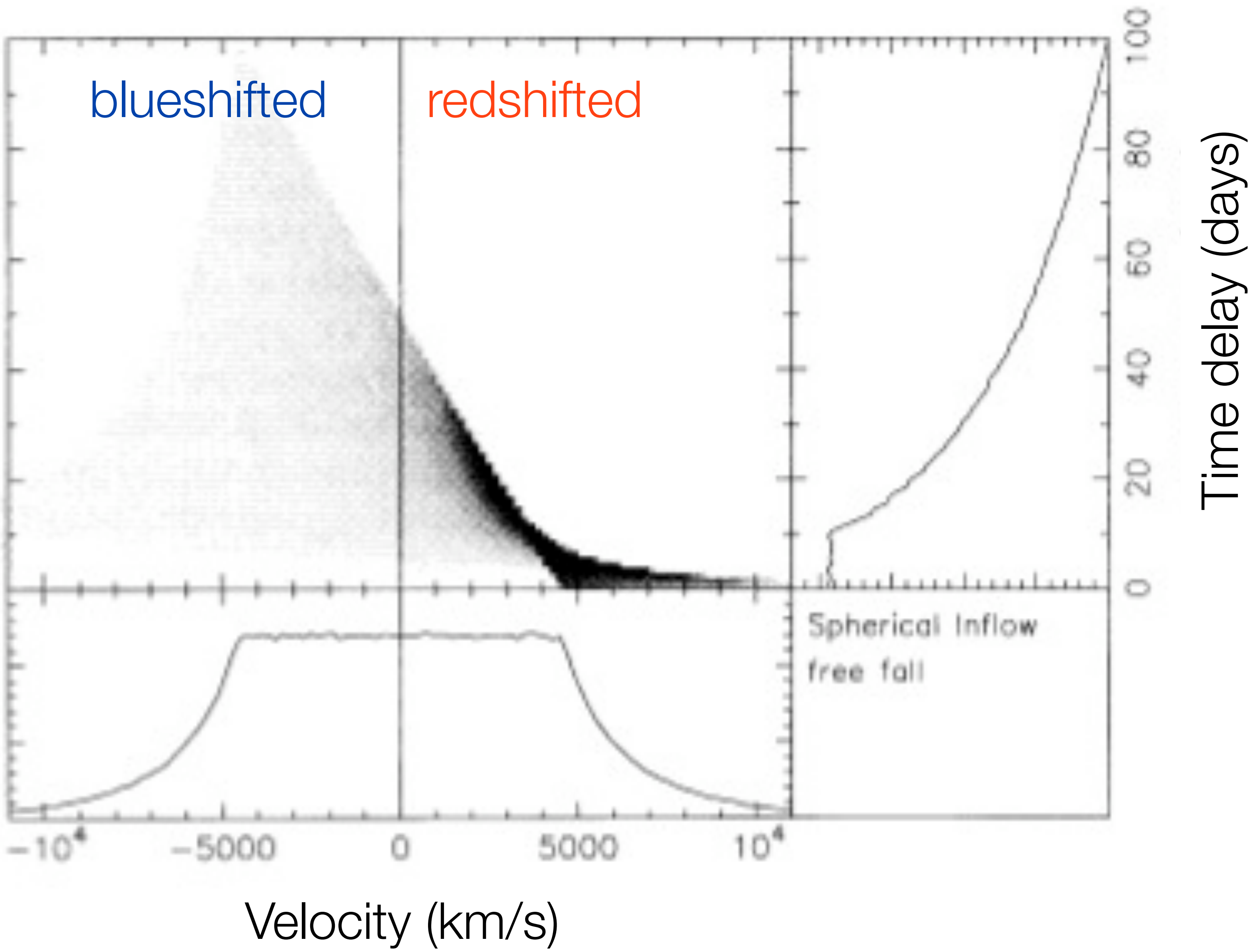


Outflow

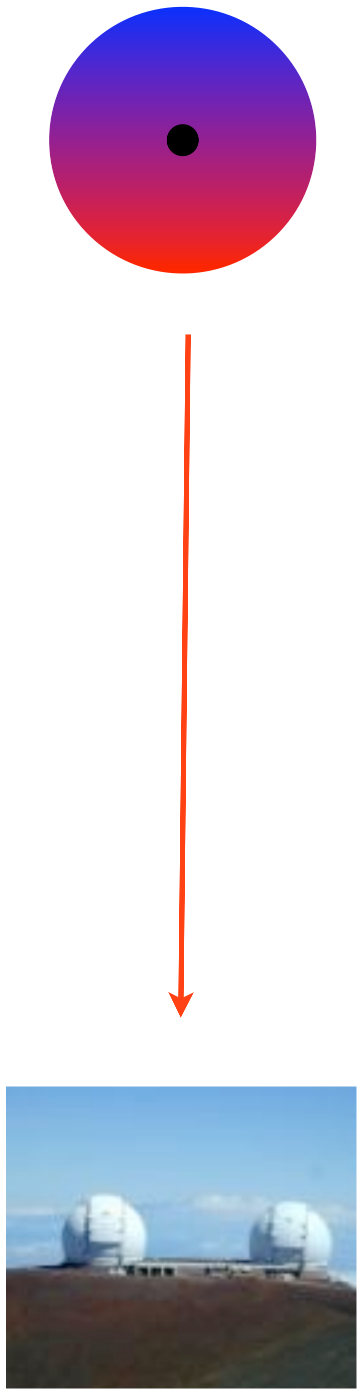


# Velocity-resolved reverberation

(figures from Welsh & Horne 1991)



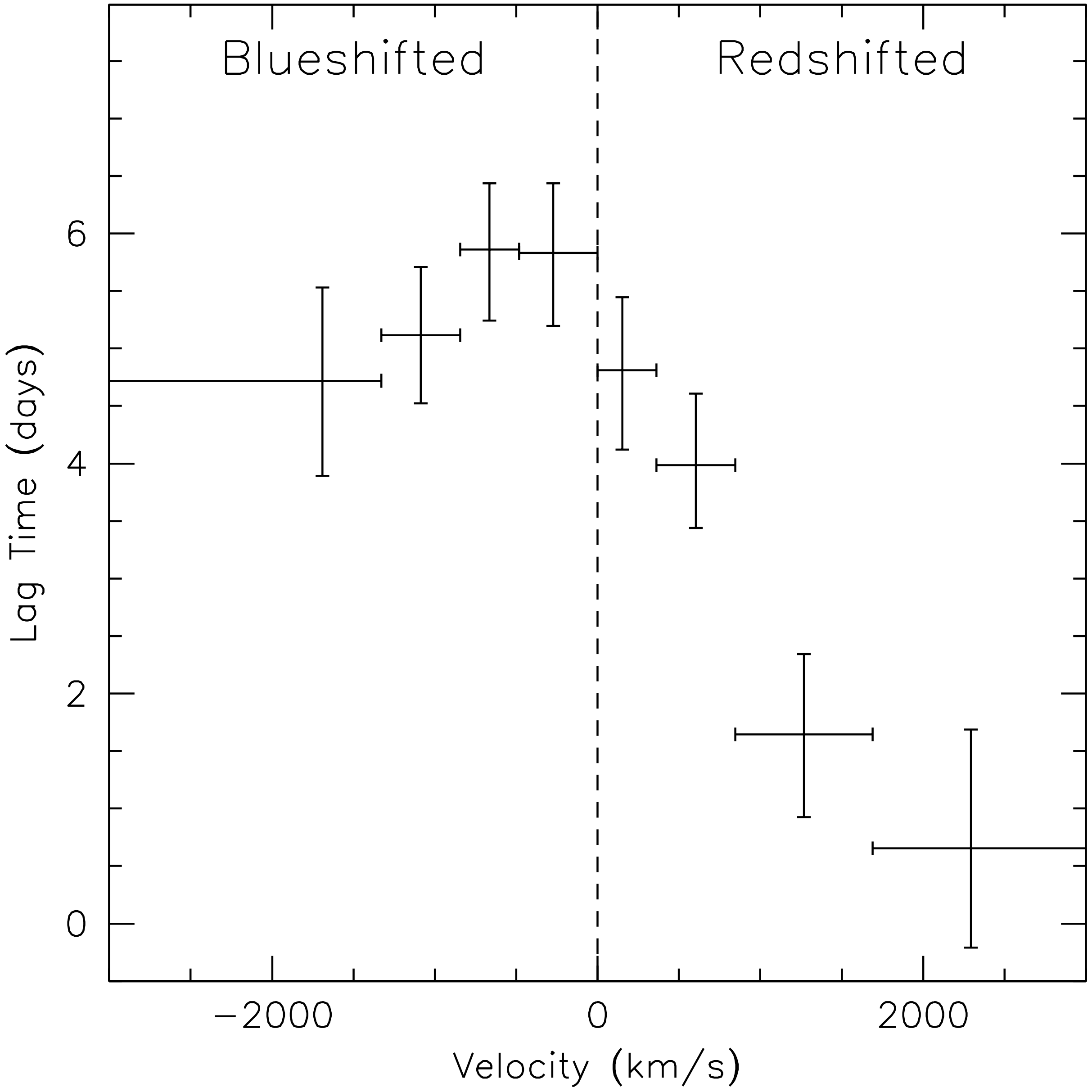
Infall



# Velocity-resolved reverberation in Arp 151

(Bentz, Walsh, Barth, et al, ApJL, 2008)

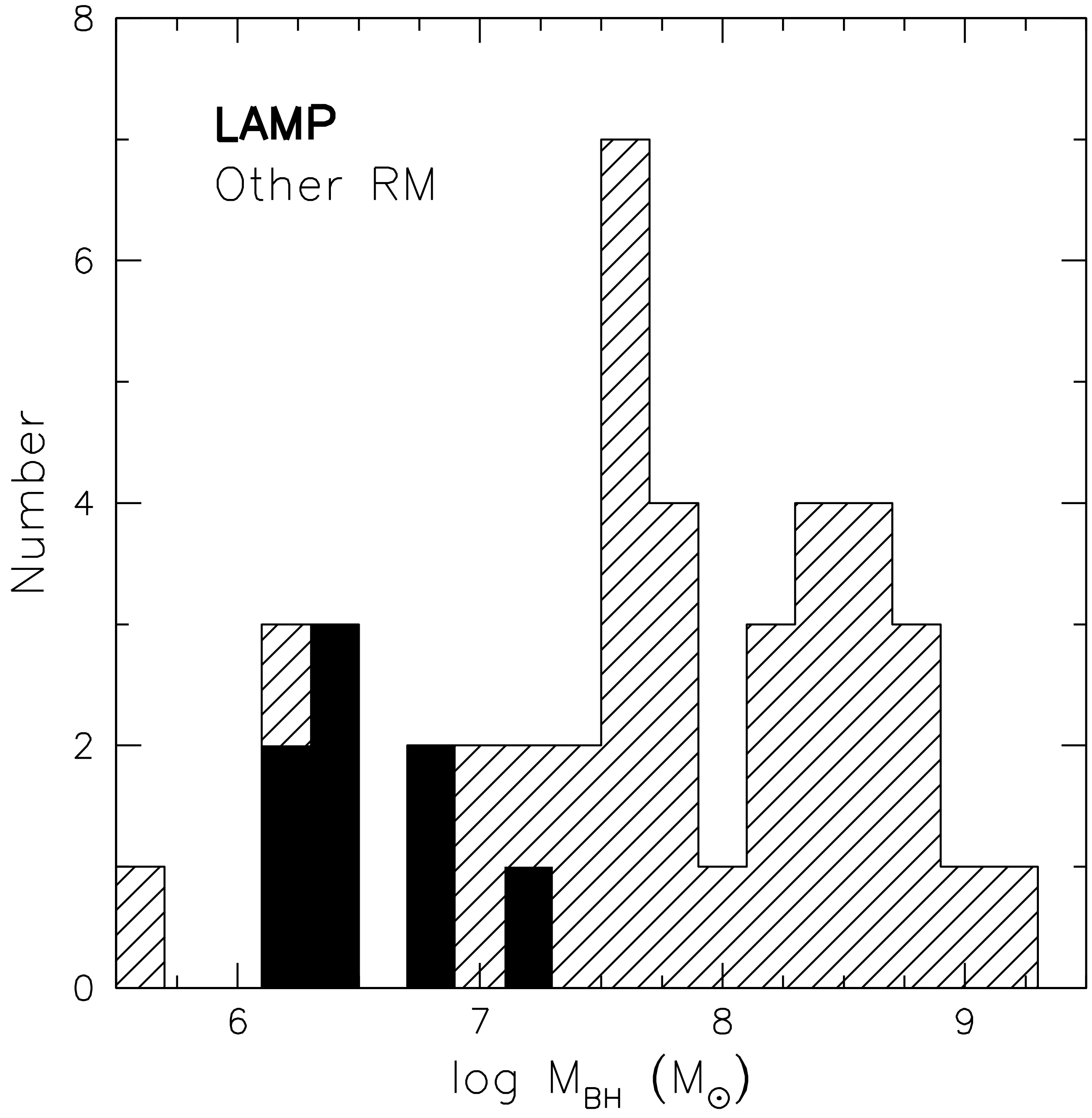
- Hβ lag measured as a function of velocity across the broad emission line
- Blue/red asymmetry indicates *inflowing* motions in the BLR



# Black hole masses

(Bentz et al, in prep.)

- Reverberation lags measured successfully for 9 out of 13 objects (including NGC 5548)
- Typical measurement uncertainty on the Hβ lag is ~20-25%



# Characteristic variability timescales

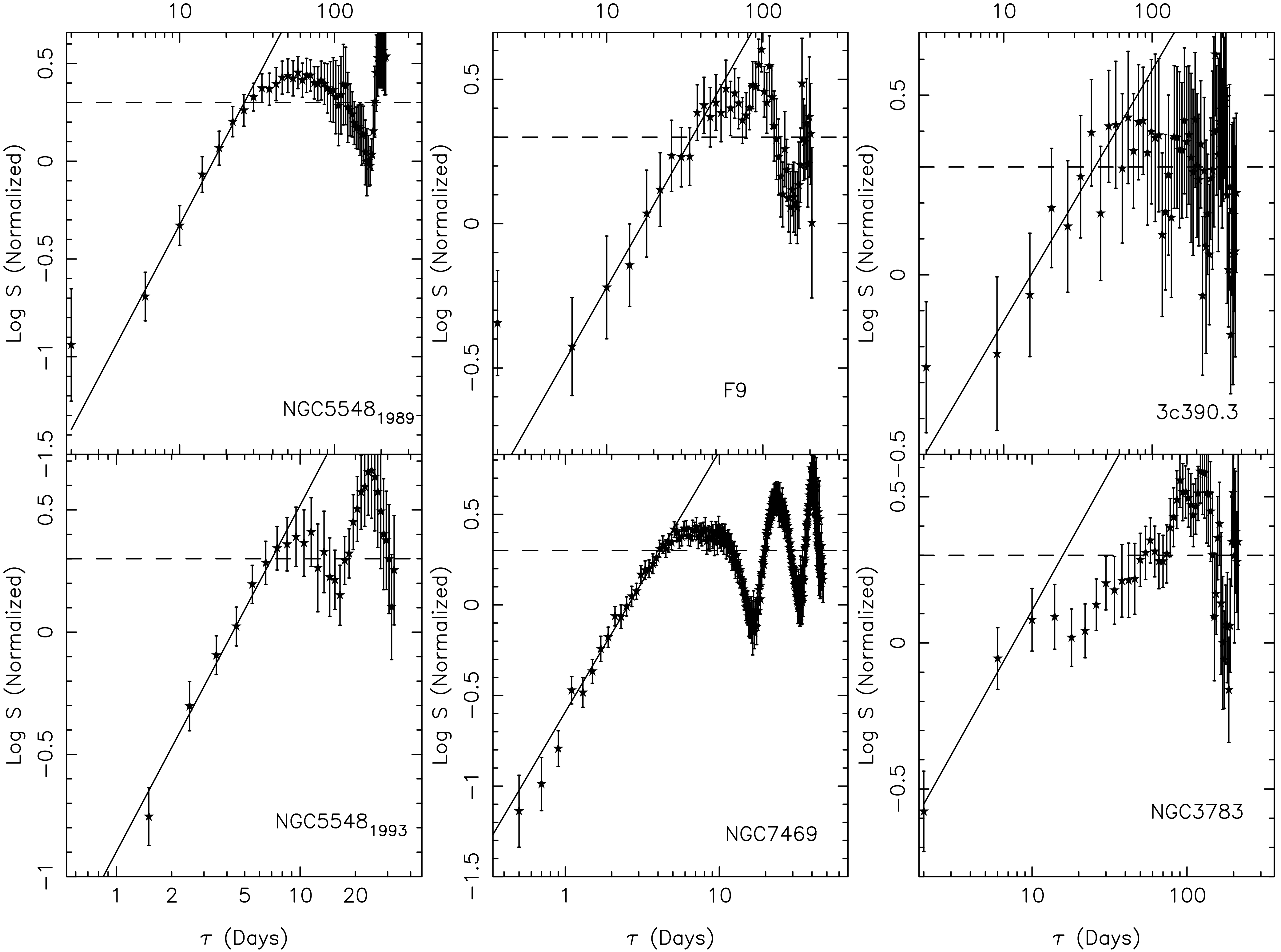
- For discretely-sampled time series, the variability can be characterized by a structure function (e.g., Cid Fernandes et al. 2000; Collier & Peterson 2001):

$$SF(\tau) = \frac{1}{N(\tau)} \sum [f(t_i) - f(t_j)]^2$$

where $\tau = t_j - t_i$

# Characteristic variability timescales

(Data from
Collier & Peterson 2001)



# Characteristic variability timescales

(Data from
Collier & Peterson 2001)

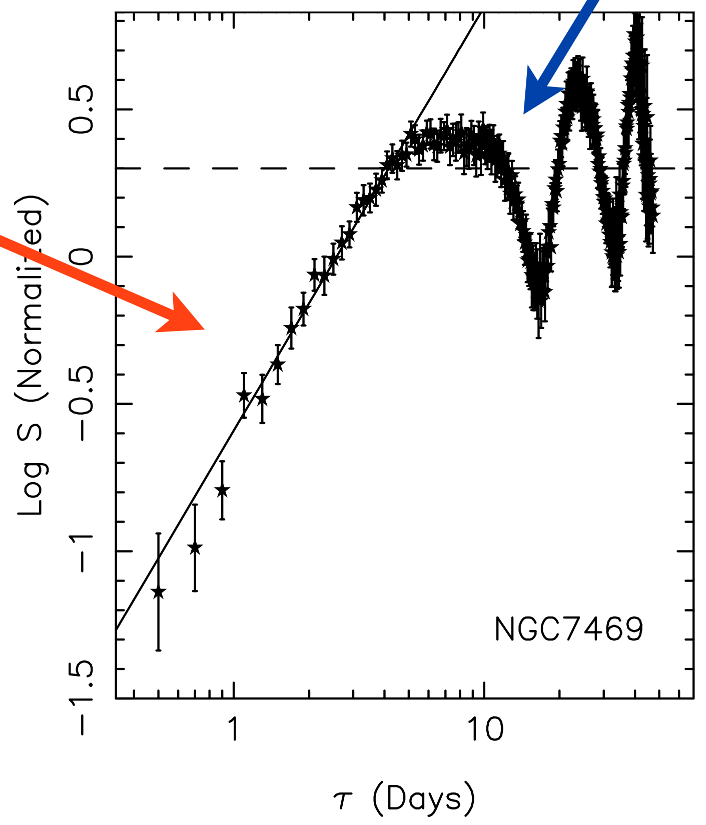
- SF is typically normalized by dividing by the light curve variance $\sigma^2$

Flat section:

For an infinite, stationary process, the light curve flattens out when variations are no longer correlated

Power-law section:

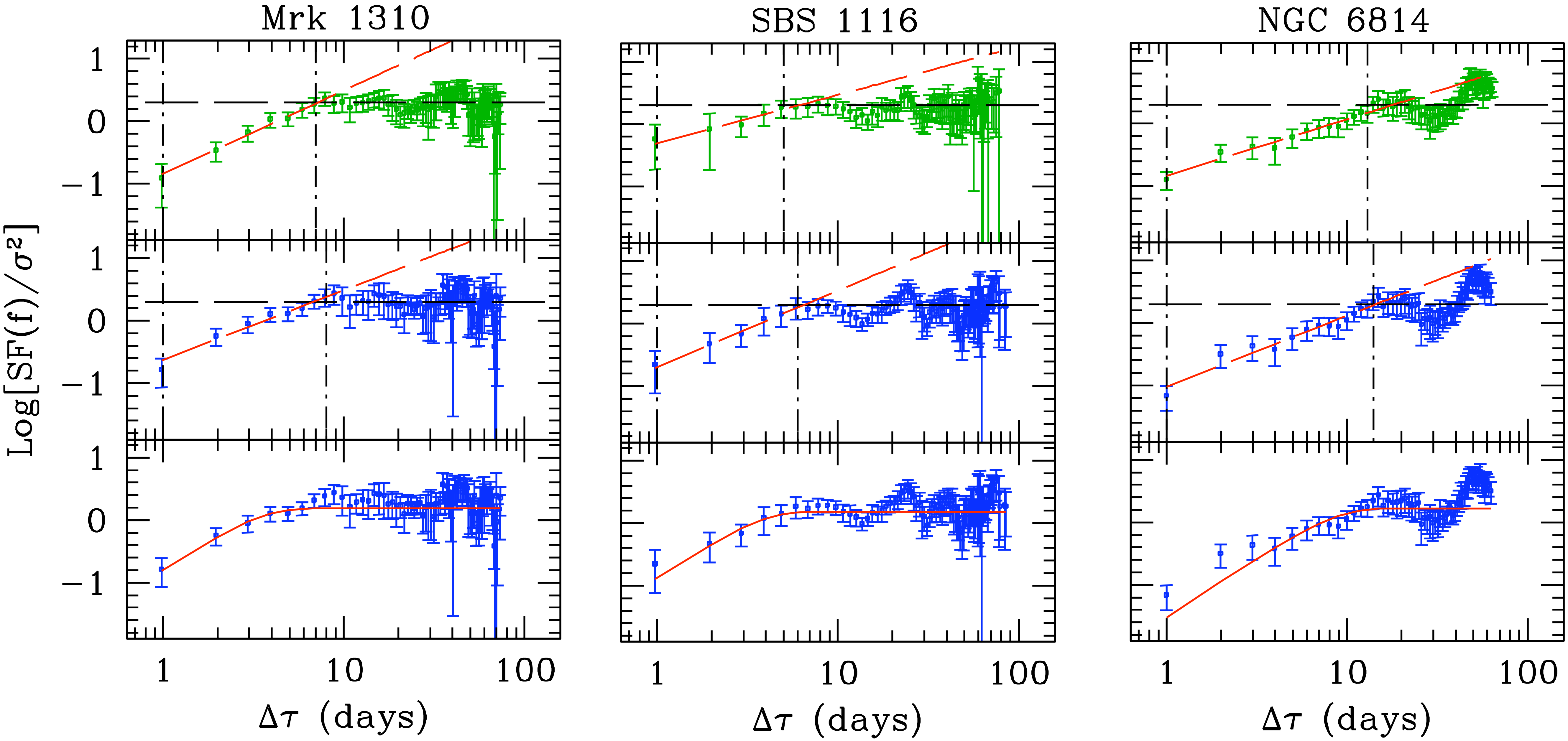
Shows the range of timescales over which variations are correlated



In the flat section, the structure function typically oscillates strongly due to the finite duration of the observed time series

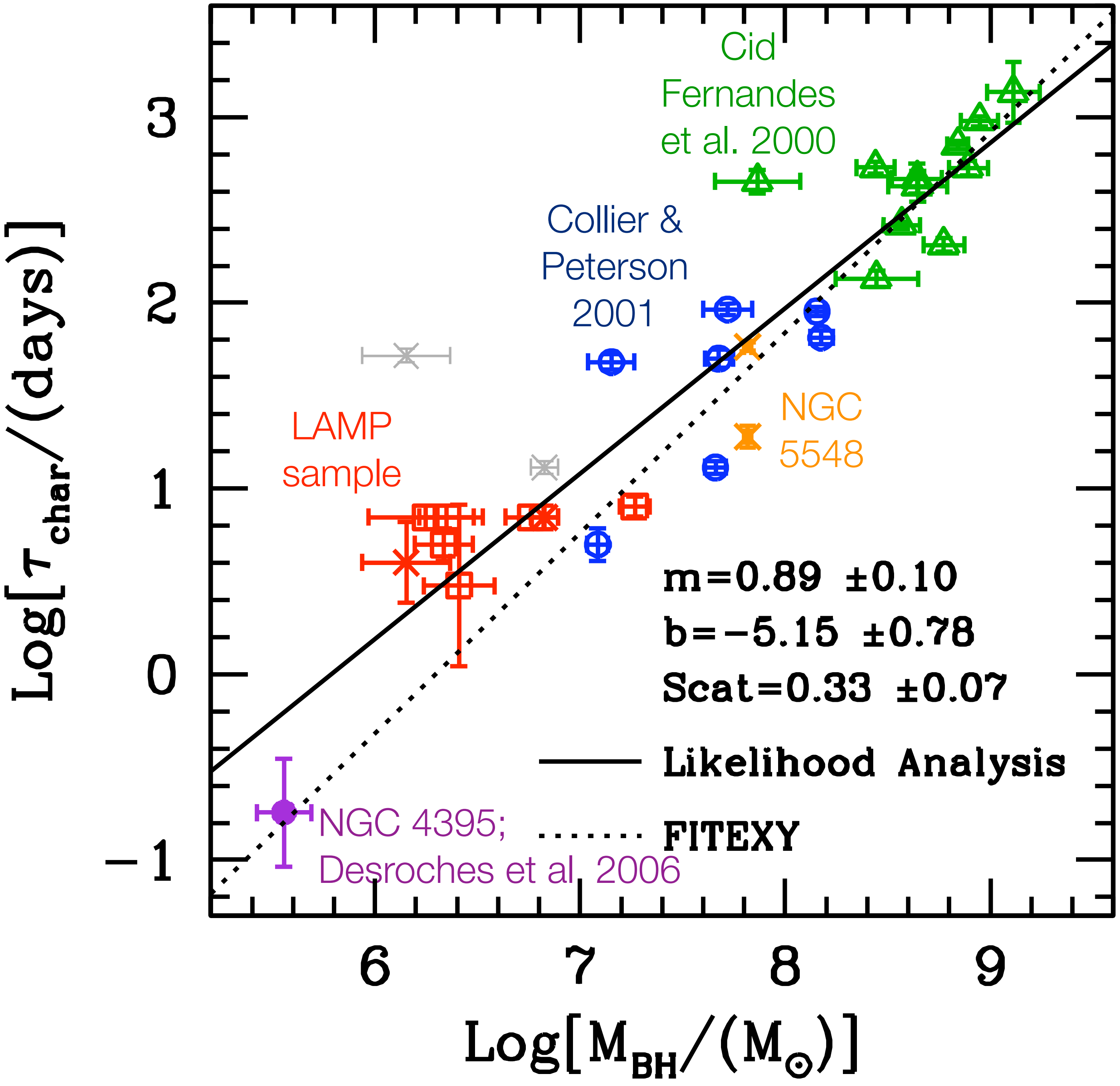
# LAMP Structure functions

(Walsh et al., in prep)



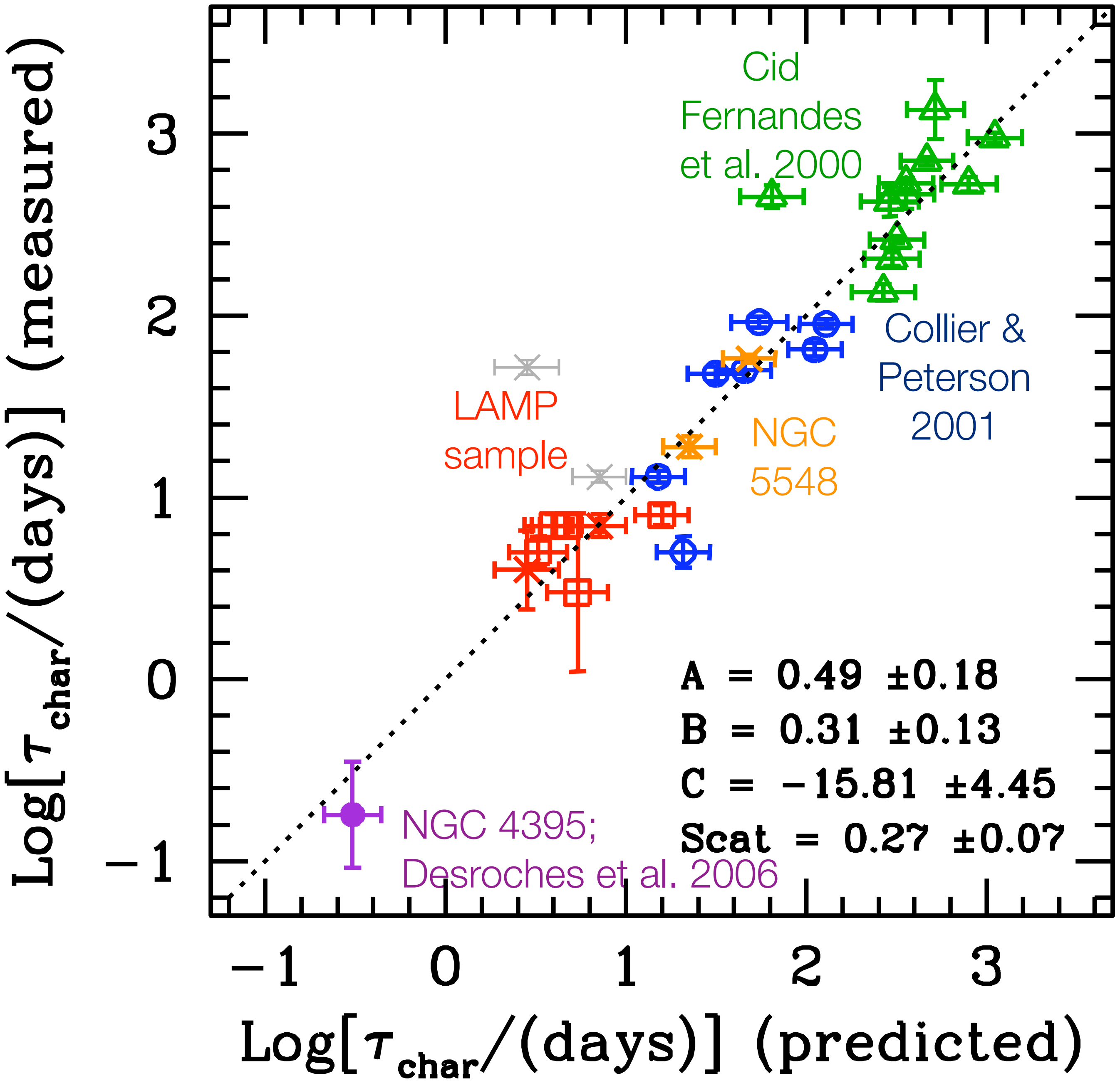
# Dependence of variability timescale on black hole mass

(Walsh et al., in prep)



# Variability timescale: relationship with $M_{BH}$ and L

(Walsh et al., in prep)



- Determine the combination of $\log(M_{BH})$ and $\log(L_{bol})$ that best predicts the characteristic timescale by minimizing the scatter
- Relationship holds over ~4 orders of magnitude in $M_{BH}$, including the dwarf AGN NGC 4395
- See also Kelly et al (2009) for related results from light-curve fitting

$$\log[\tau_{char}/\mathrm{days}] = A \log[M_{BH}/M_\odot] + B \log[L_{bol}/(\mathrm{erg\ s^{-1}})] + C$$

# Future work

- Reverberation lags for other lines: Hα, Hγ, He II
- Stellar velocity dispersions and the $M_{BH}$-$\sigma$ relation for the AGNs
- Cycle 17 Hubble project approved to image the entire sample
  - GALFIT modeling of HST images gives a clean measurement of the bulge starlight contamination of the AGN- use this to determine the BLR radius-luminosity relationship
  - $M_{BH}$ - $L_{bulge}$ relationship
- Modeling the velocity-resolved variability to constrain the BLR kinematics
- MAGNUM near-infrared light curves:  K-band reverberation
- Test which single-epoch recipes best reproduce the $M_{BH}$ determined from reverberation data

# Summary

- Reverberation mapping is fundamental for understanding the cosmic evolution of black hole masses
- LAMP has obtained 8 new reverberation lag measurements for local AGNs at low masses & luminosities
- Velocity-resolved variability shows a variety of kinematic states in BLRs
- Characteristic optical variability timescales in AGNs are well correlated with black hole mass and luminosity
  - With large multi-color variability surveys, these relationships can provide new clues to accretion disk structure
- Reverberation mapping remains an important niche for small to medium-sized telescopes