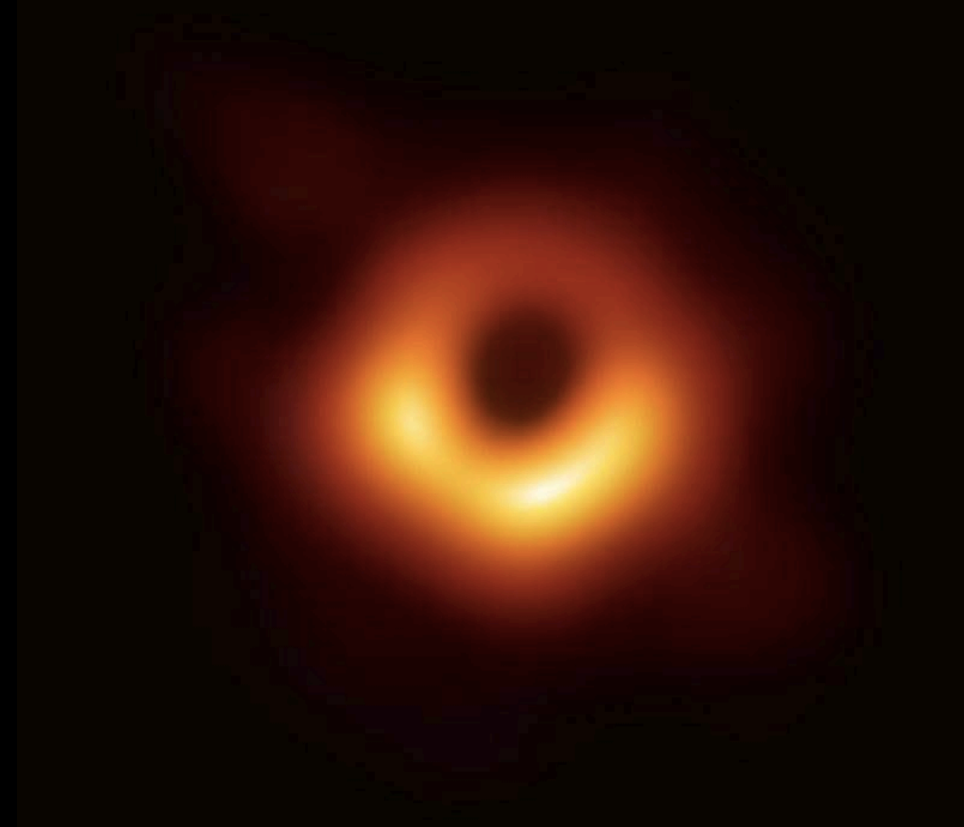
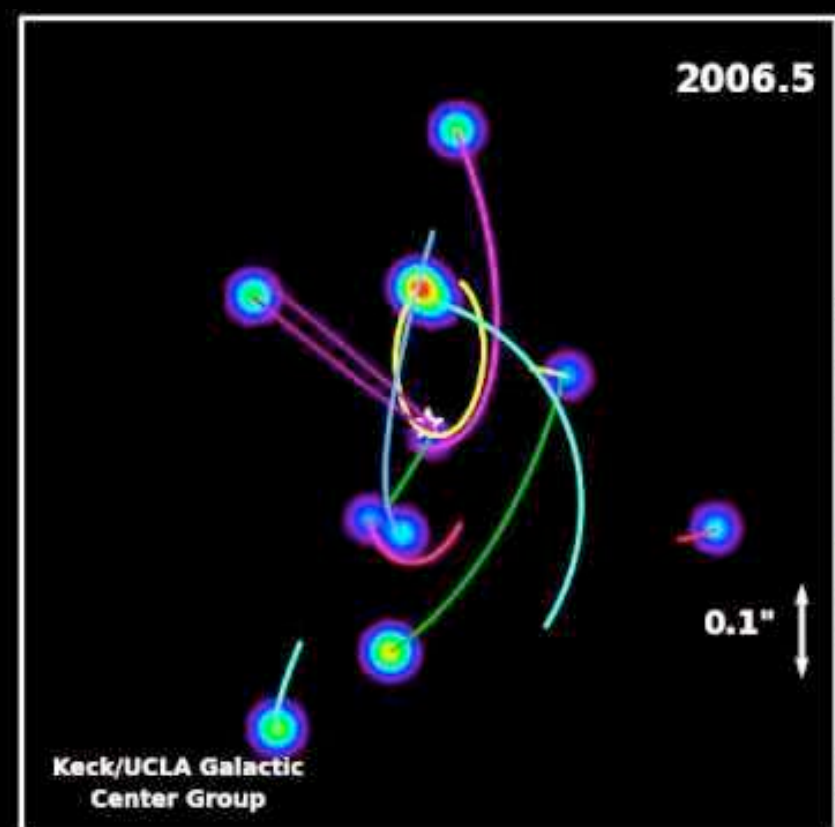


# Black Hole Masses in AGN

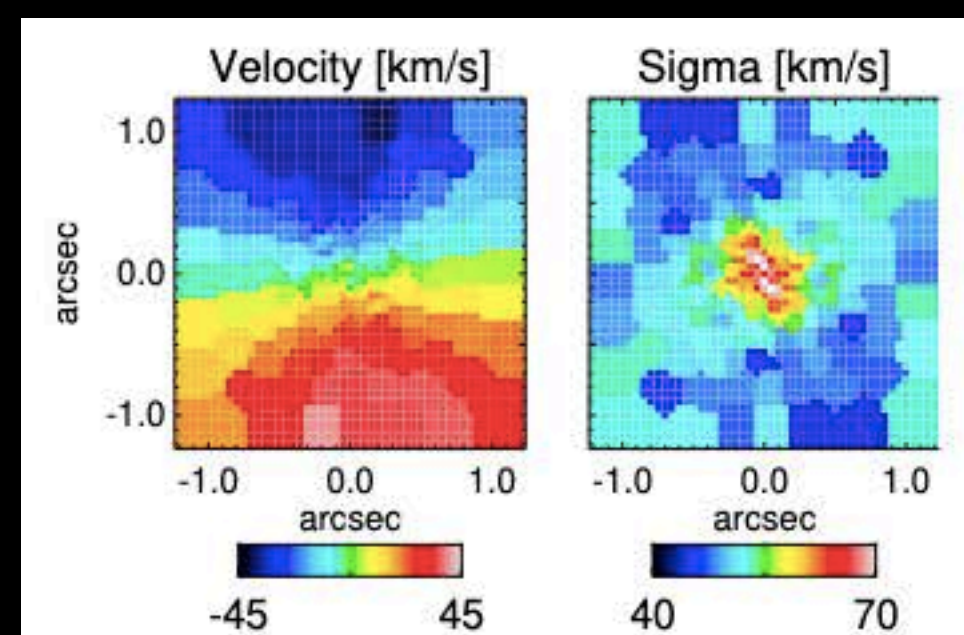
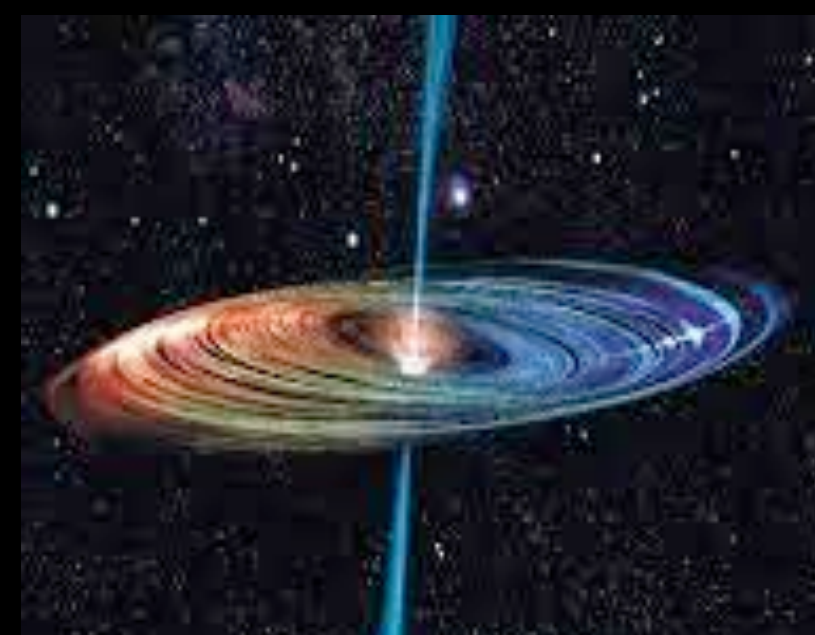


# Supermassive Black Holes at Cosmic Distances



Most  $M_{\text{BH}}$  methods rely on spatial resolution

Limited to  $D \lesssim 100$  Mpc

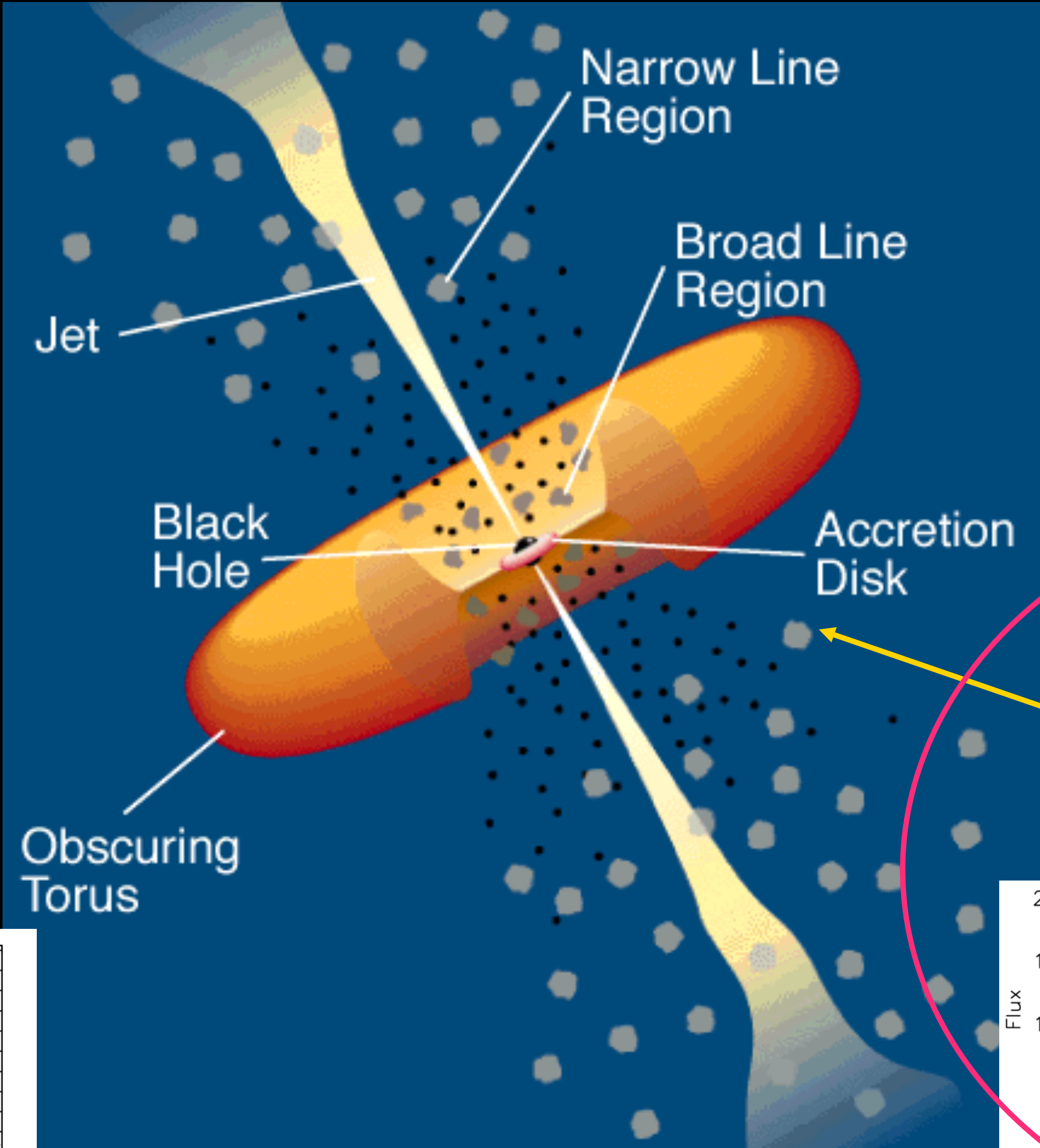


Conversion from angular to physical scales requires an accurate distance (not  $z$ )

At cosmic distances, AGN allow temporal resolution to replace spatial resolution  
(BONUS: avoids angular  $\rightarrow$  physical conversion)

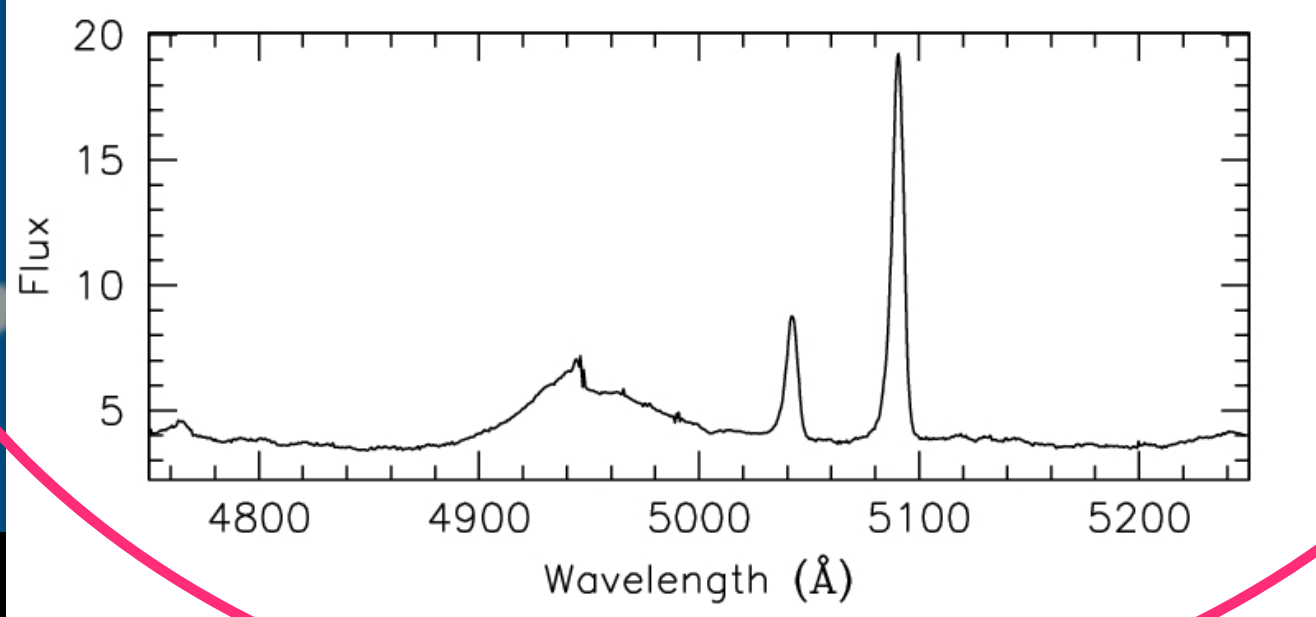
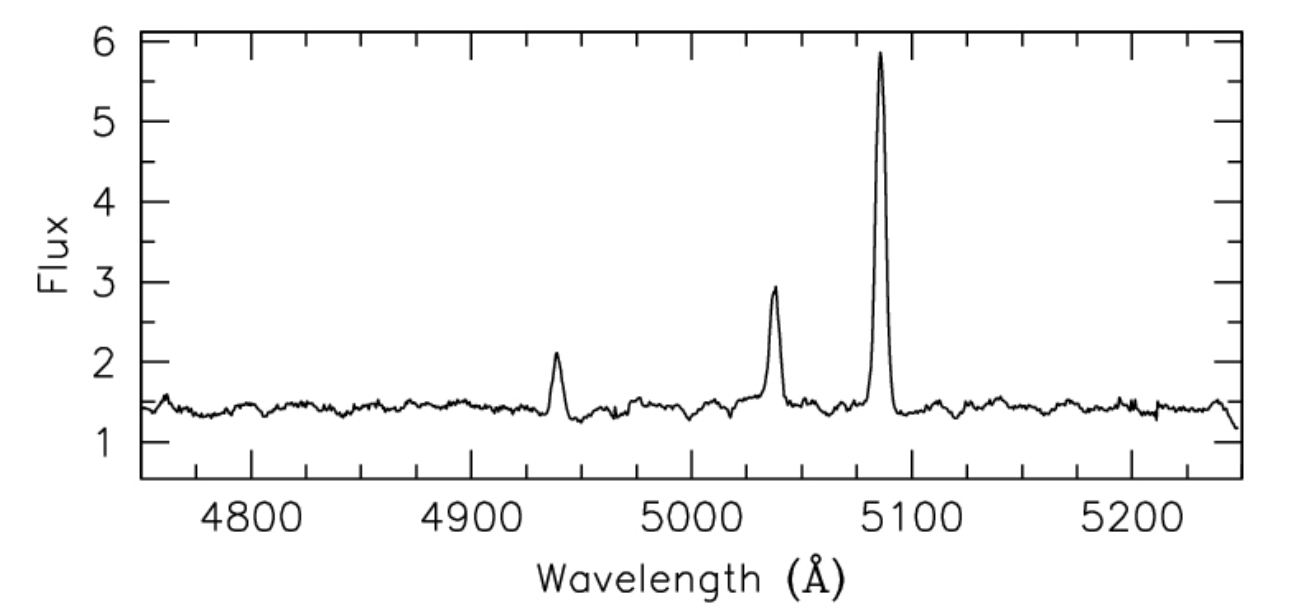
# AGN Anatomy

Blazars



Narrow-line AGN  
(Type 2)

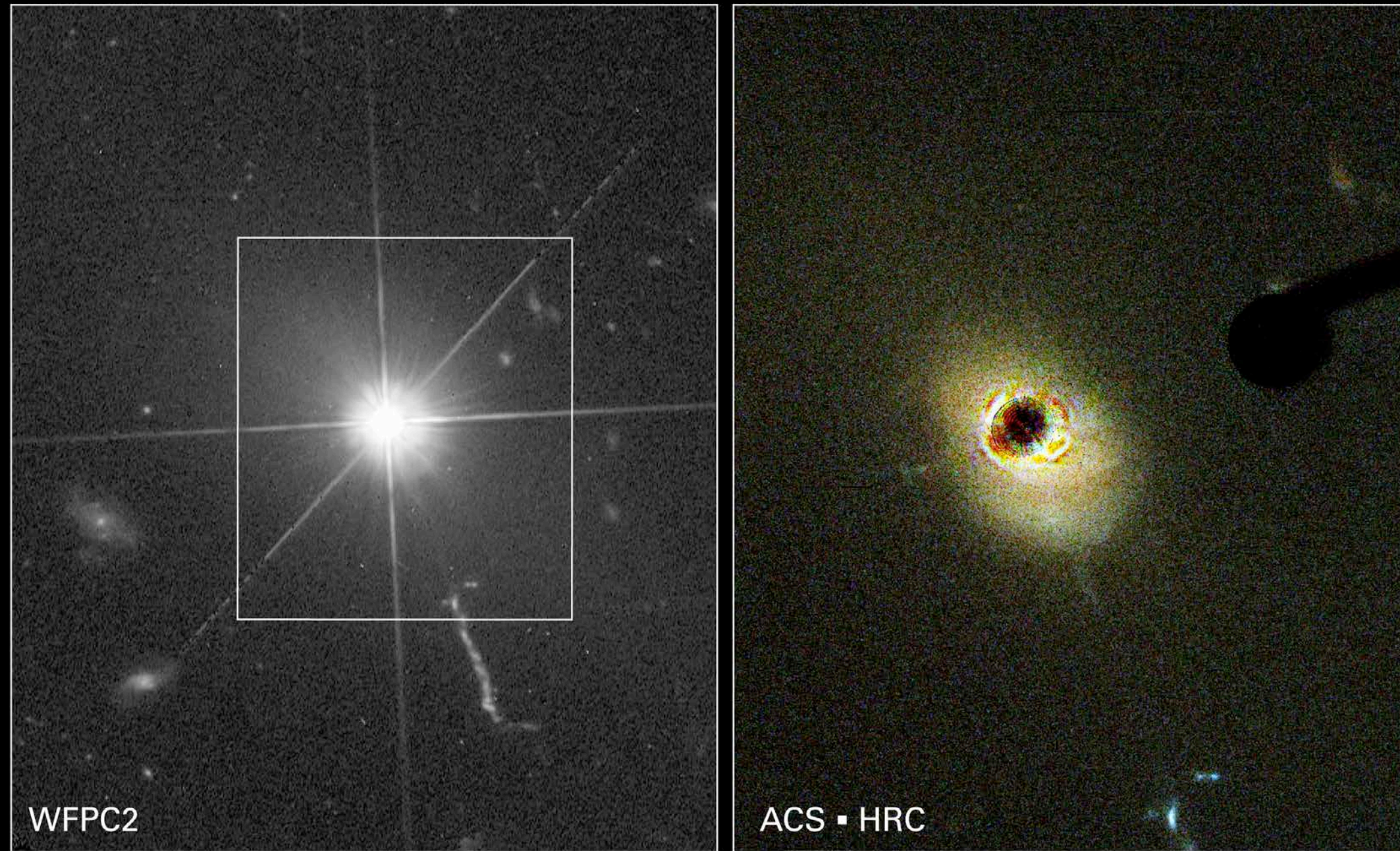
Broad-line AGN  
(Type 1)



# AGN are Luminous and Variable

May outshine their host galaxies

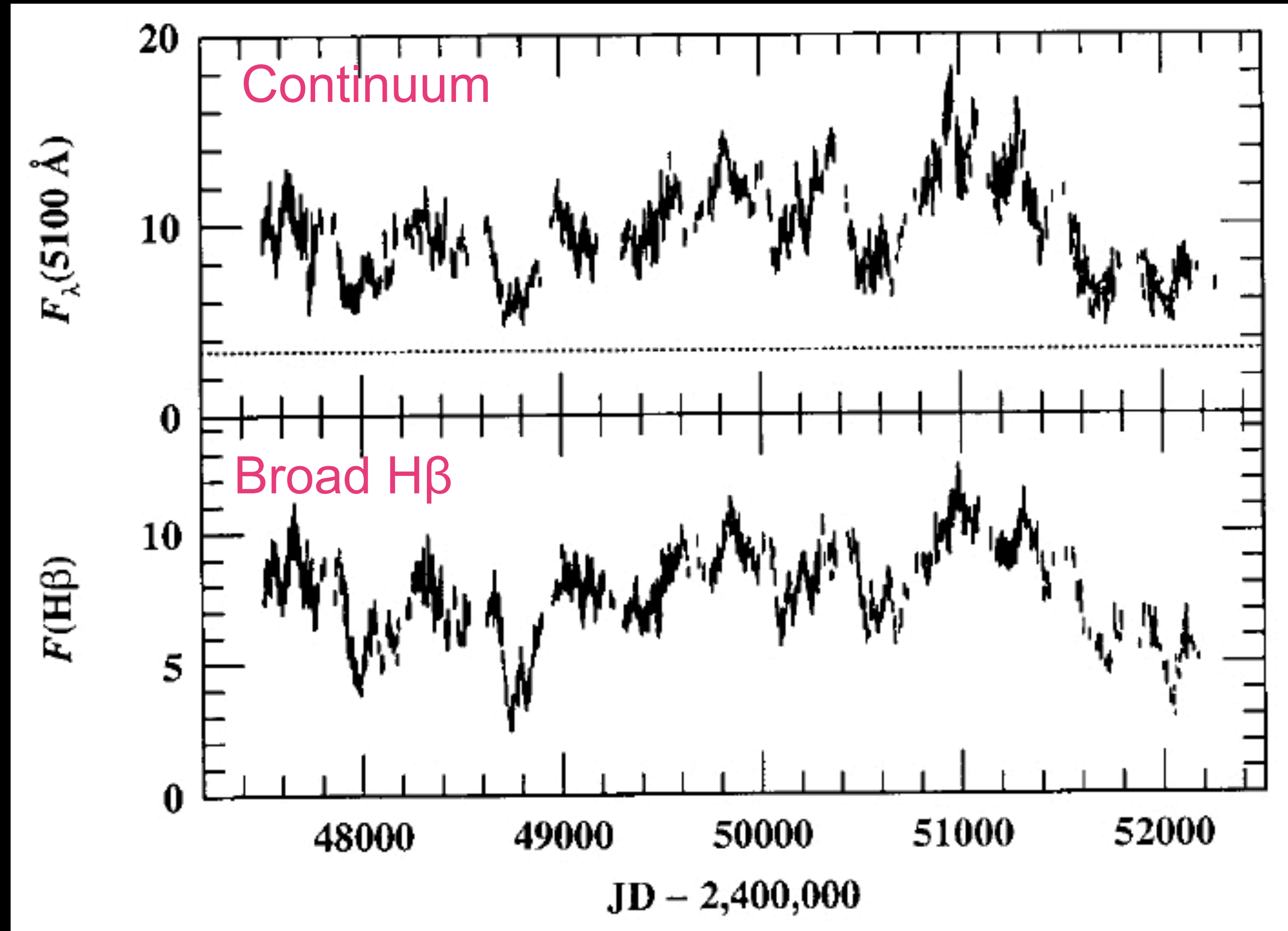
13 years of monitoring NGC 5548



Quasar 3C 273

Hubble Space Telescope • ACS HRC Coronagraph

NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA • STScI-PRC03-03

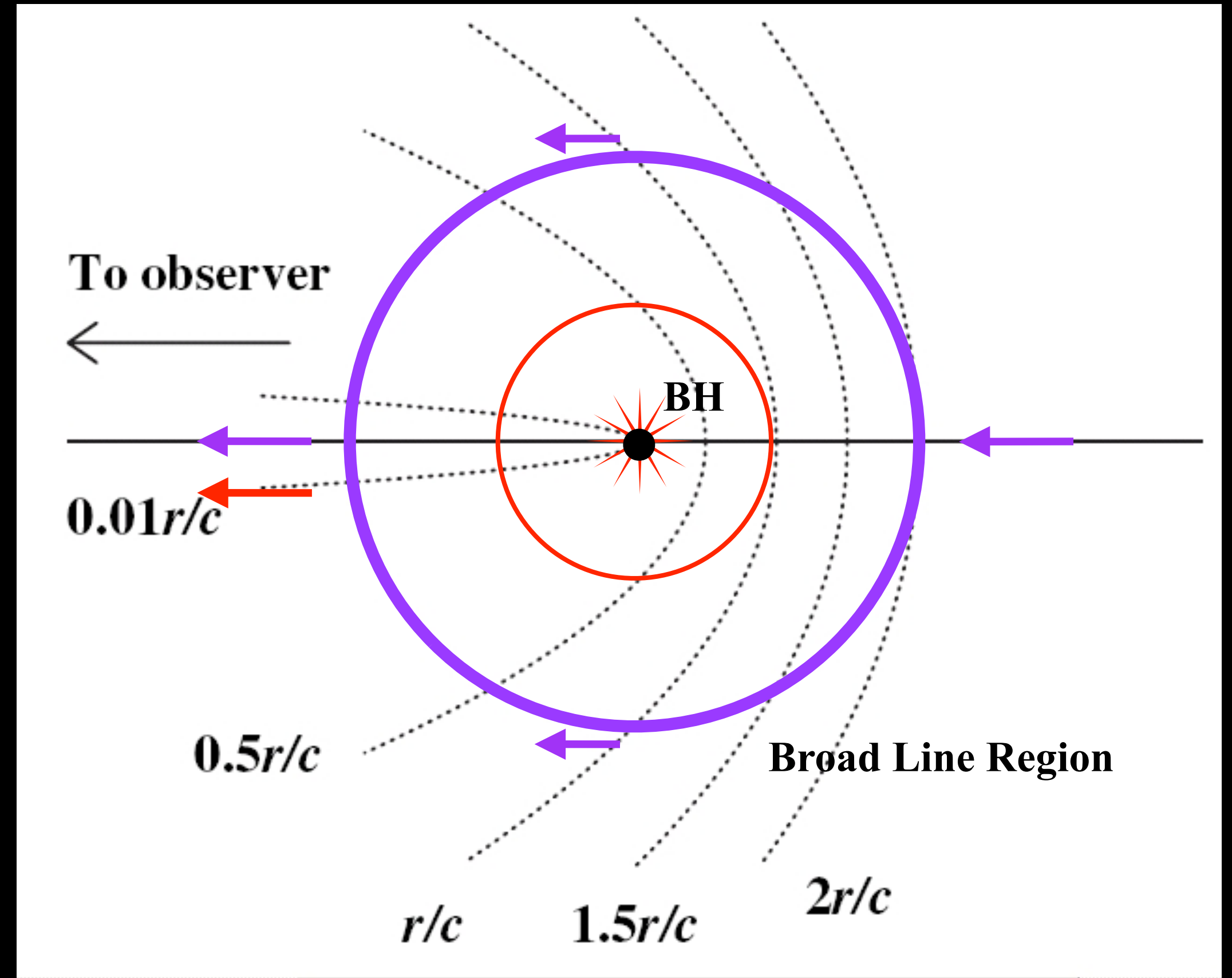
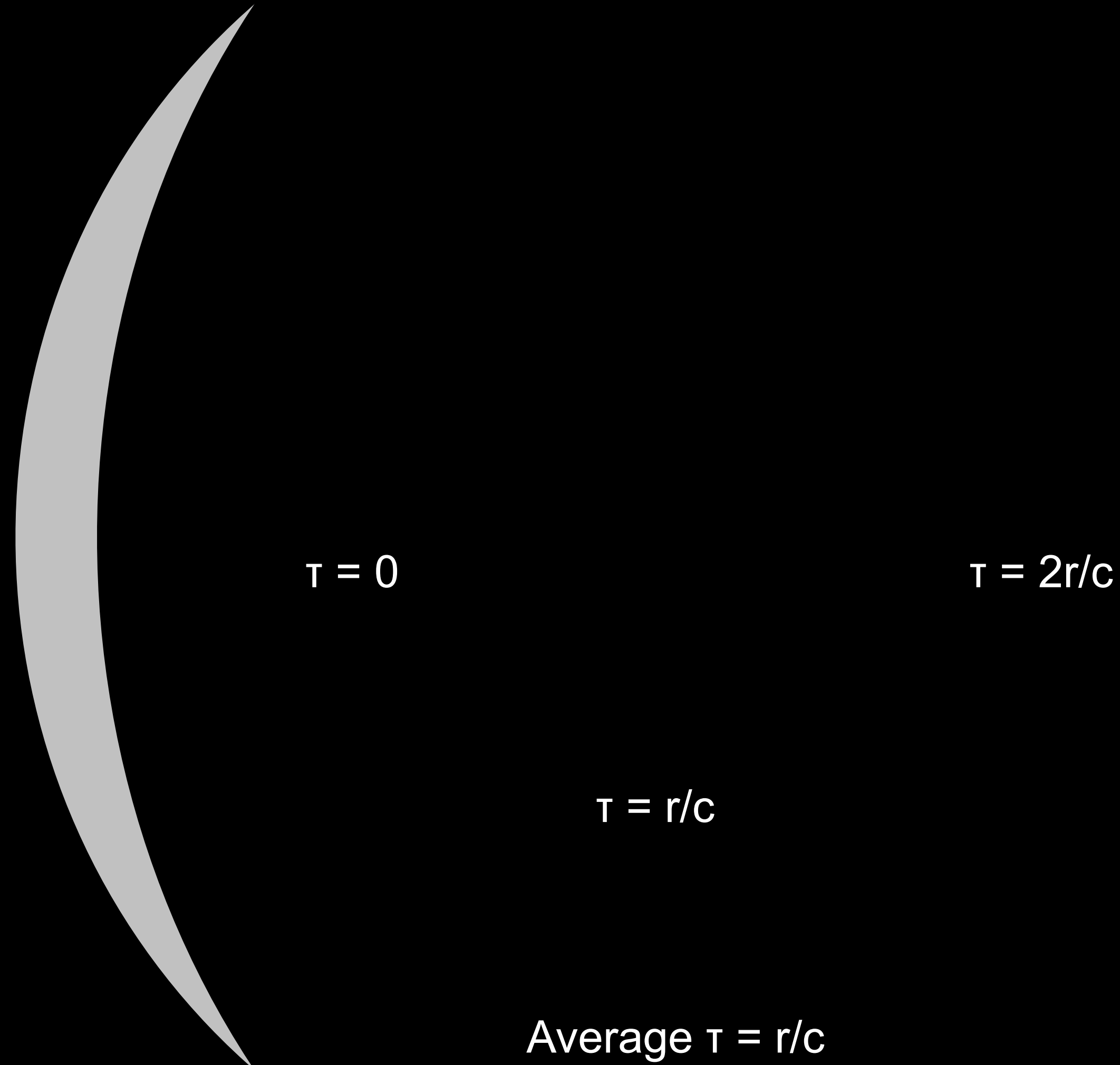


*Peterson et al. 2002*

# Measuring the BLR Radius

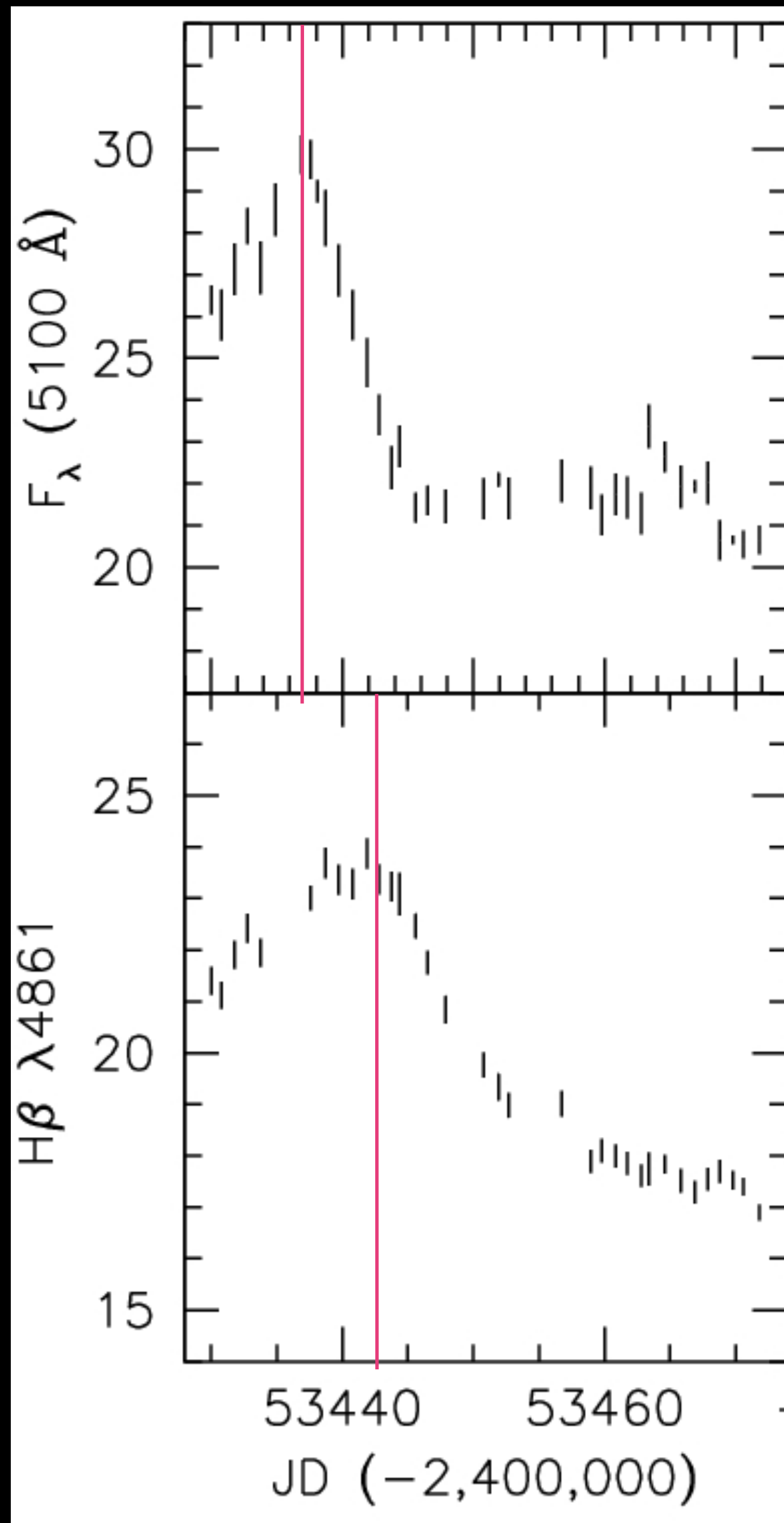
Telescope

AGN

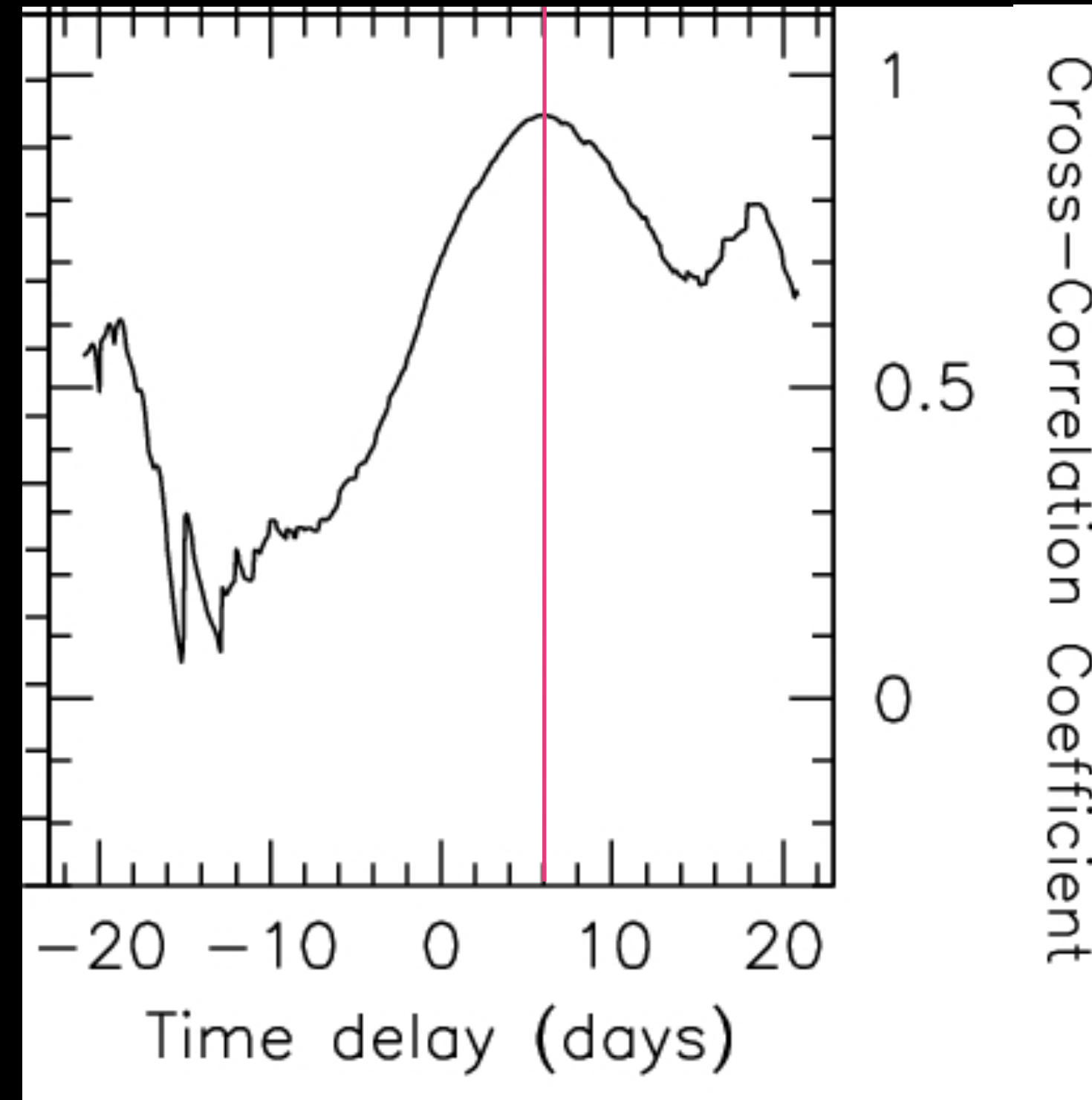


Red = continuum  
Purple = broad line

# Example Data – NGC 4151



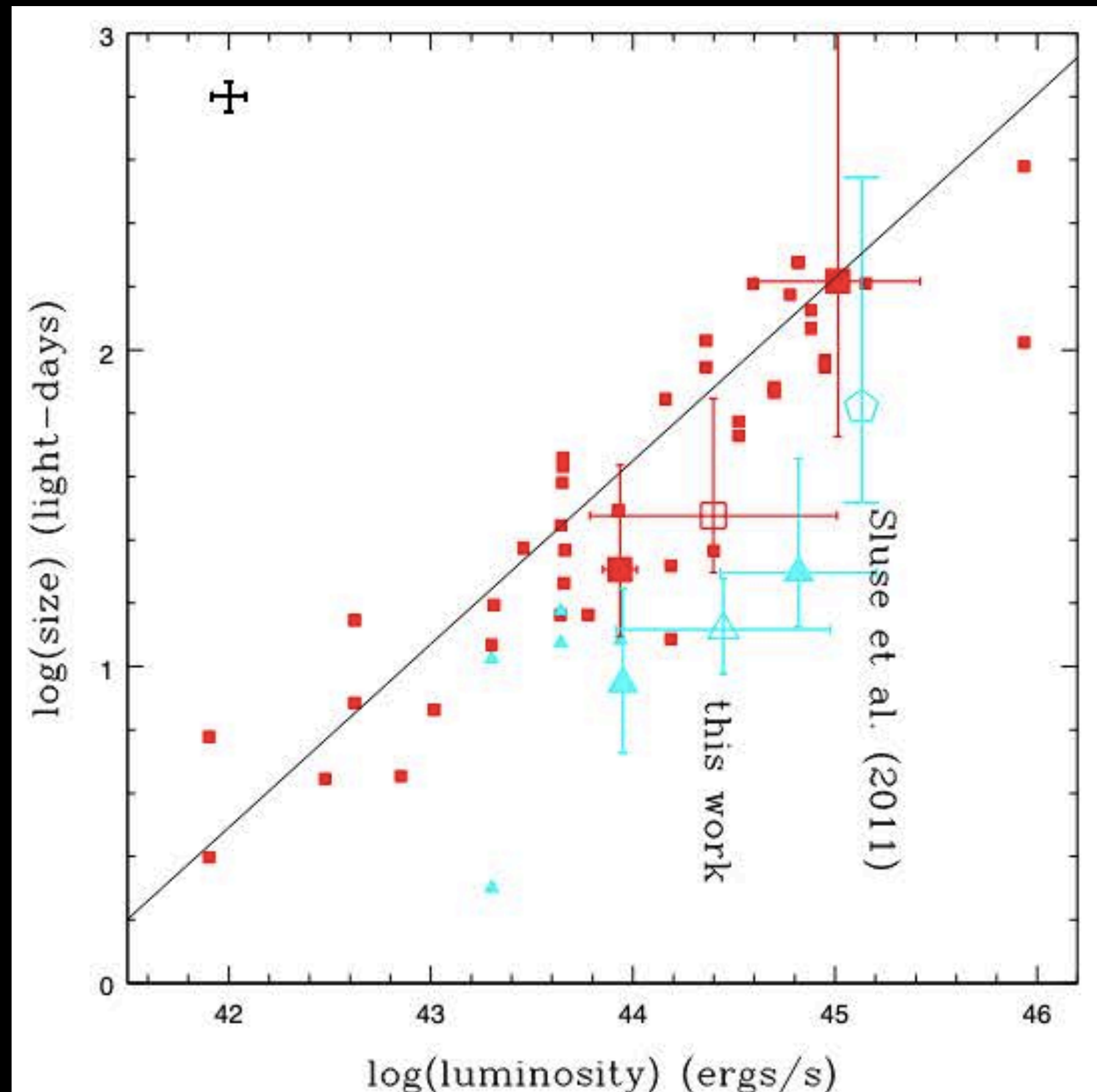
time lag between continuum variations  
and broad line response ~6 days



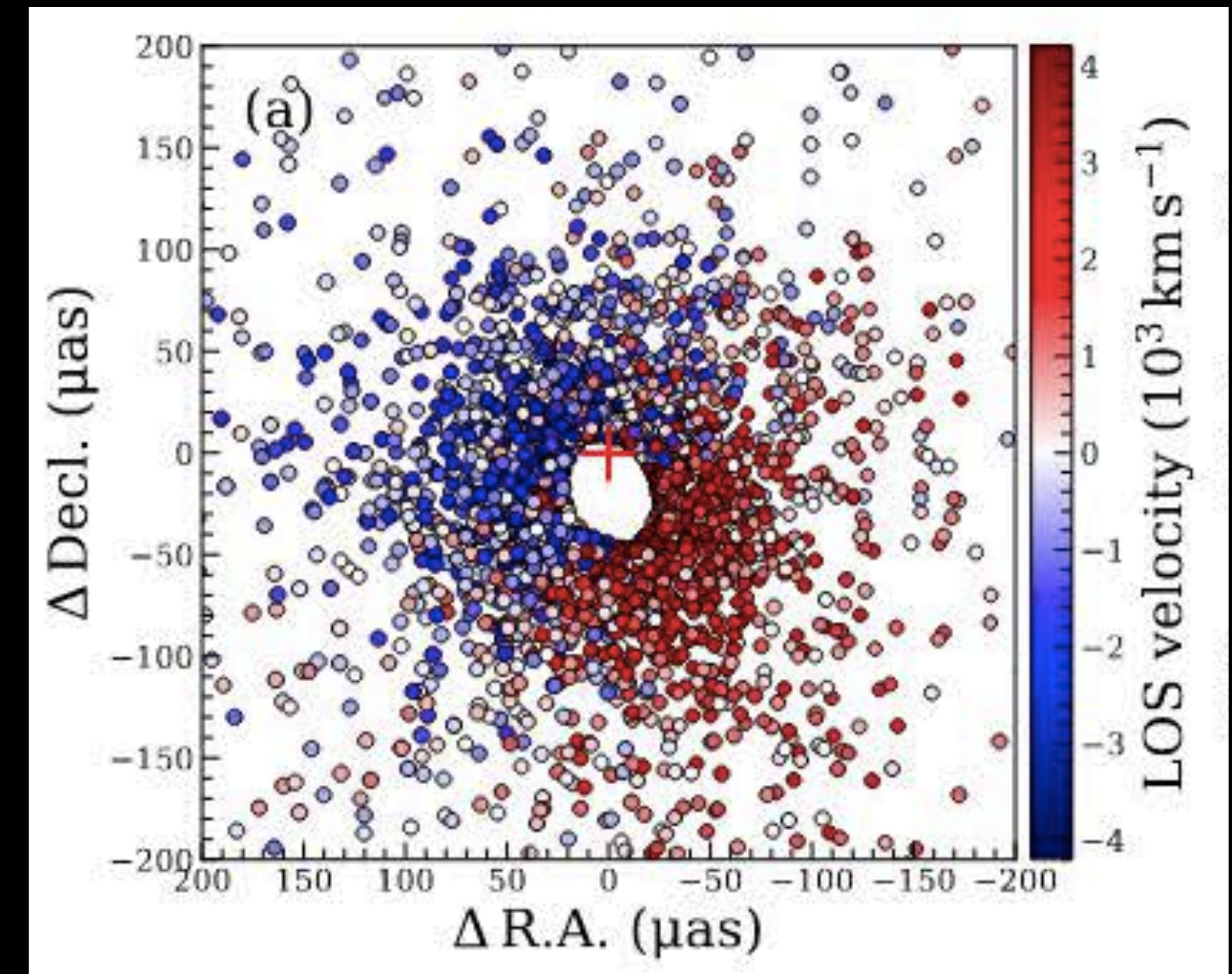
*Bentz et al. 2006*

# Comparing BLR Size Measurements

Microlensing and interferometry show good agreement with BLR sizes from RM



*Guerras et al. 2013*



*GRAVITY Collab. et al. 2021*

Complications:

- flux-weighted vs. responsivity-weighted measurements
- photoionization differences between emission lines

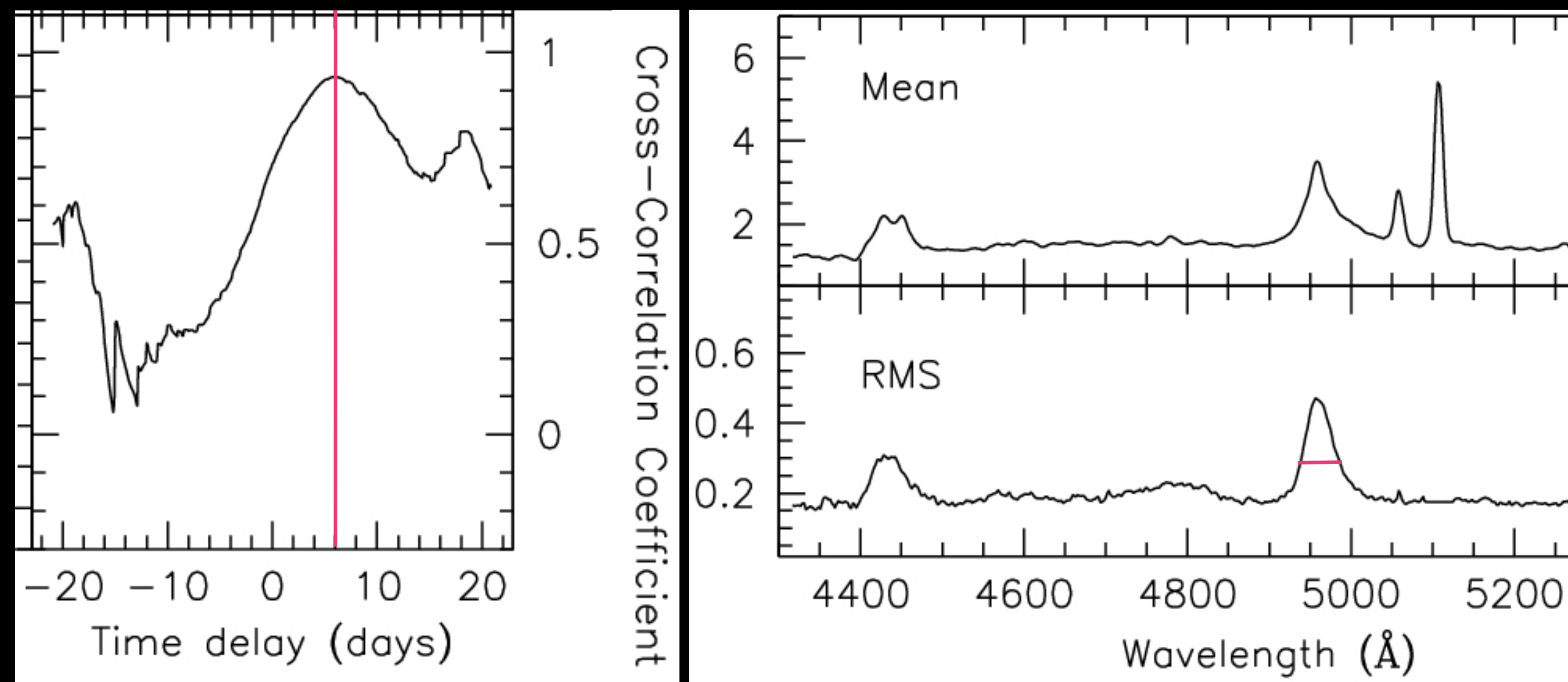
# Masses from Reverberation Mapping

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

$R$  from time delay

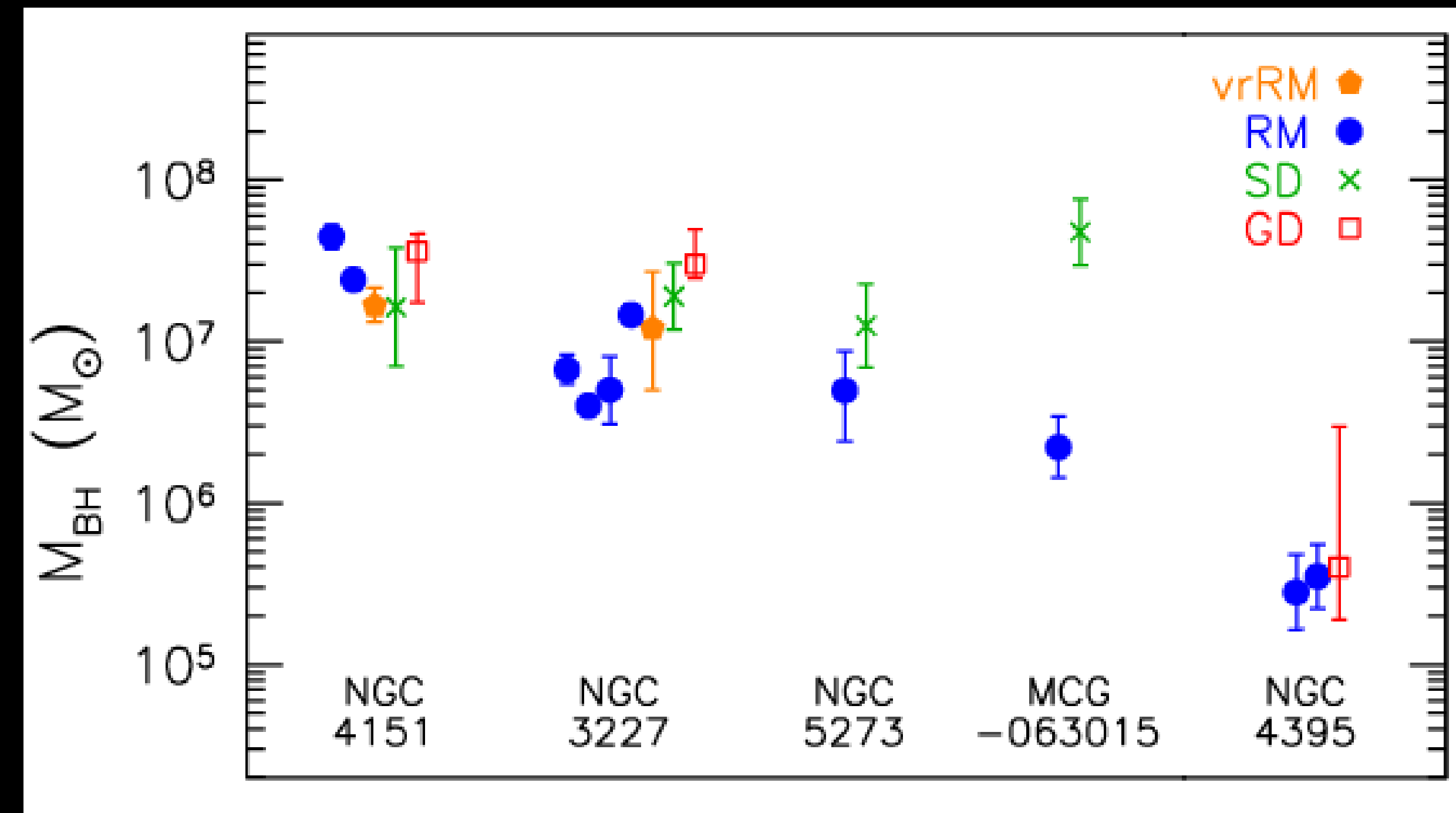
$V$  from width of line

$f$  depends on geometry & kinematics



masses derived for ~200 AGN

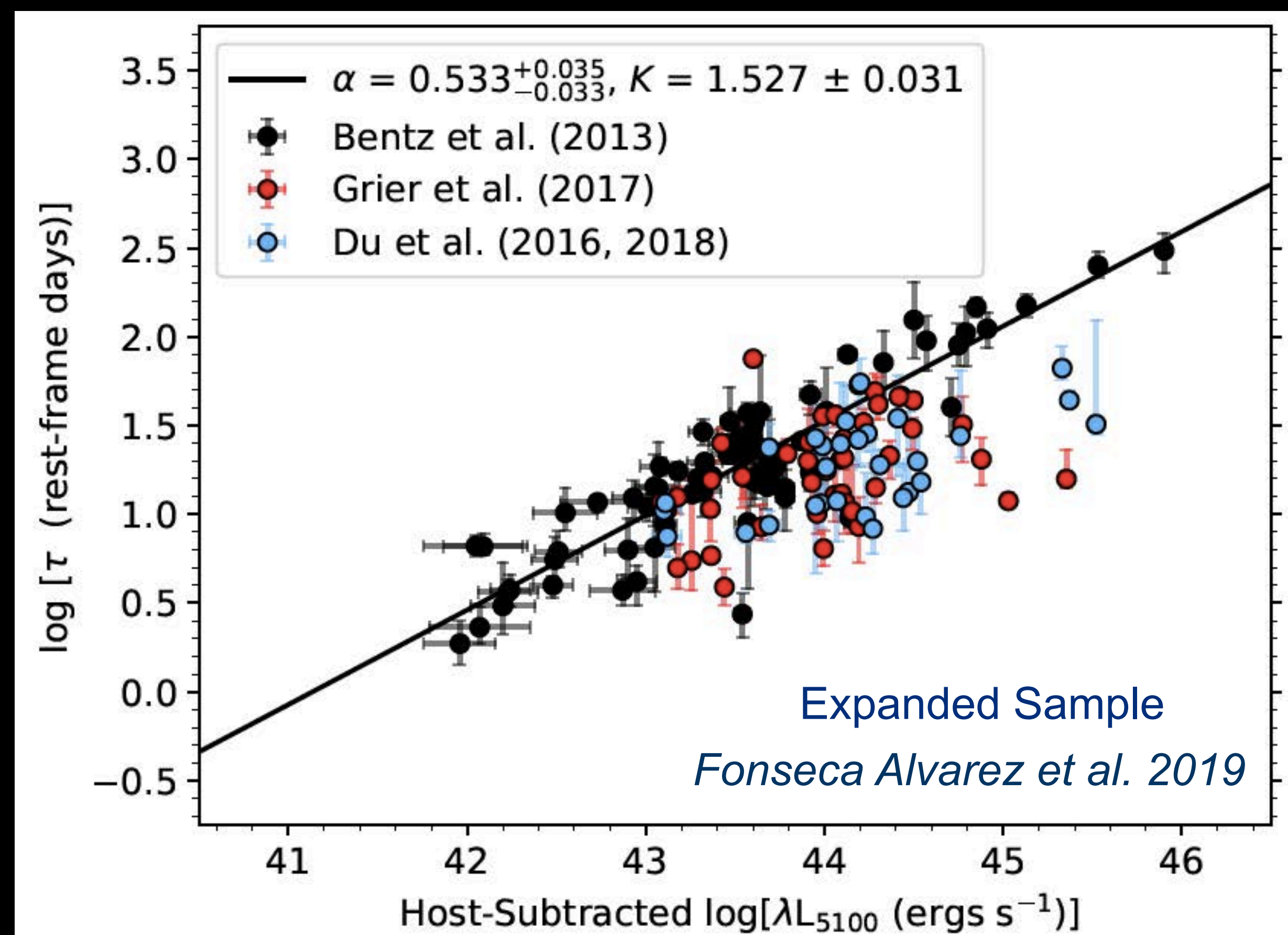
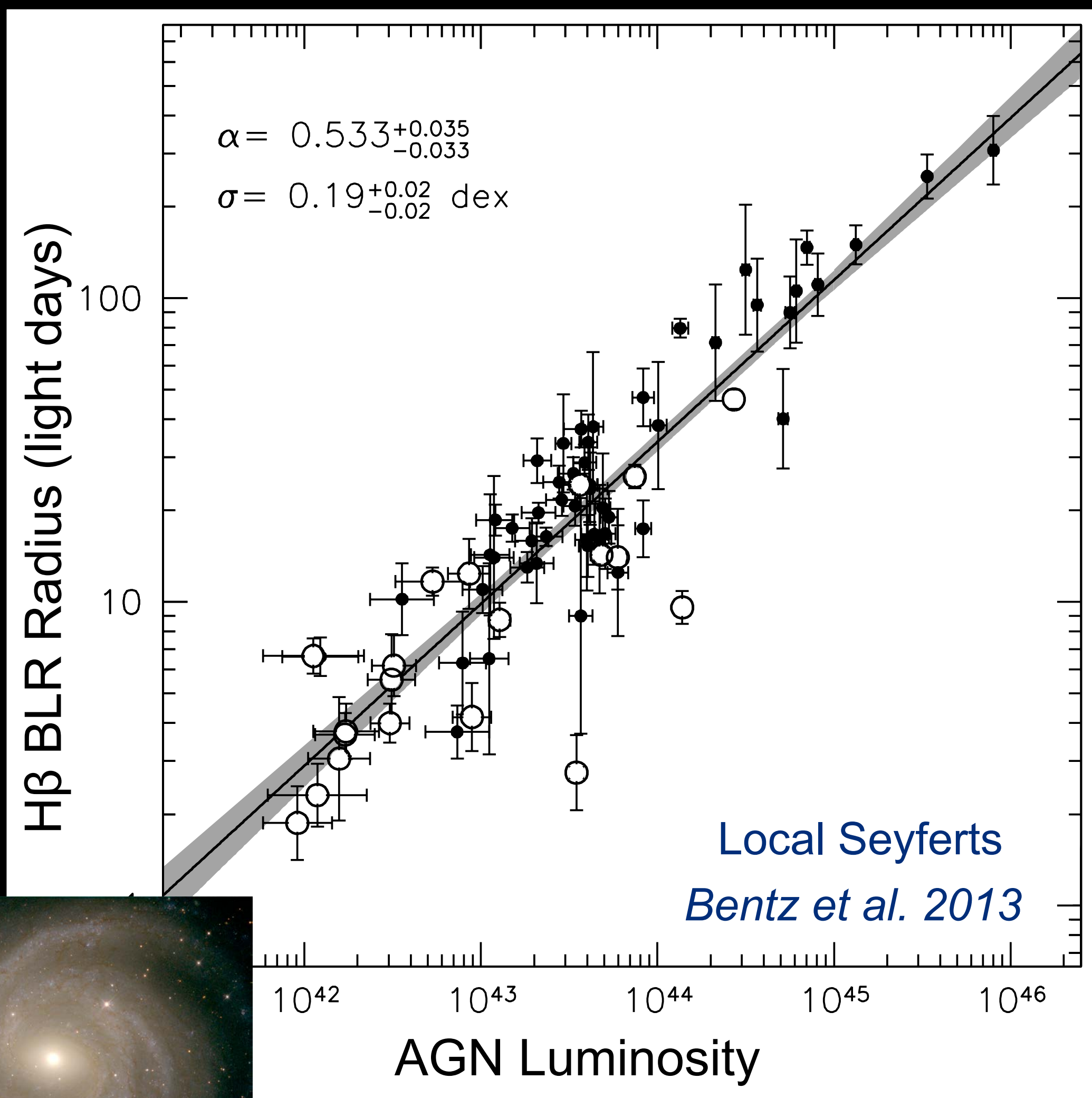
consistency with other  $M_{BH}$  techniques



SD: Roberts+ 2021, Merrell+ 2023, Das+ 2025  
more coming soon

# Radius - Luminosity Relationship

enables black hole mass estimates for large samples with one spectrum per object;  
"single epoch" masses



Complication: L or L<sub>edd</sub> dependence?

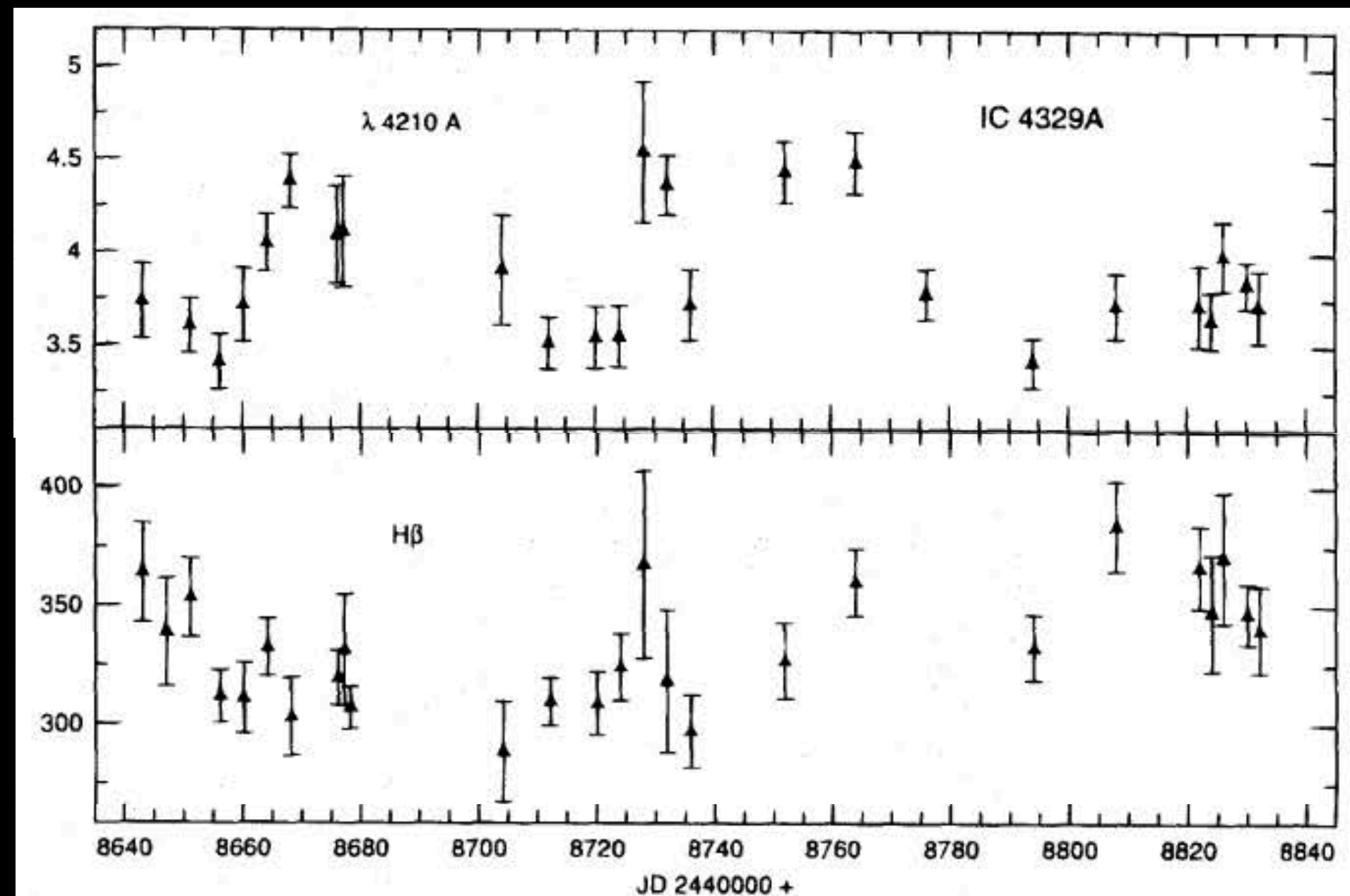
↑ corrected for galaxy starlight



# RM Challenges

1. Strong variability is not guaranteed
2. Variability is stochastic (non-repeating)
3. Requires dense time sampling and long time baselines while avoiding large gaps
4. Requires some amount of luck

*Winge et al. 1996*



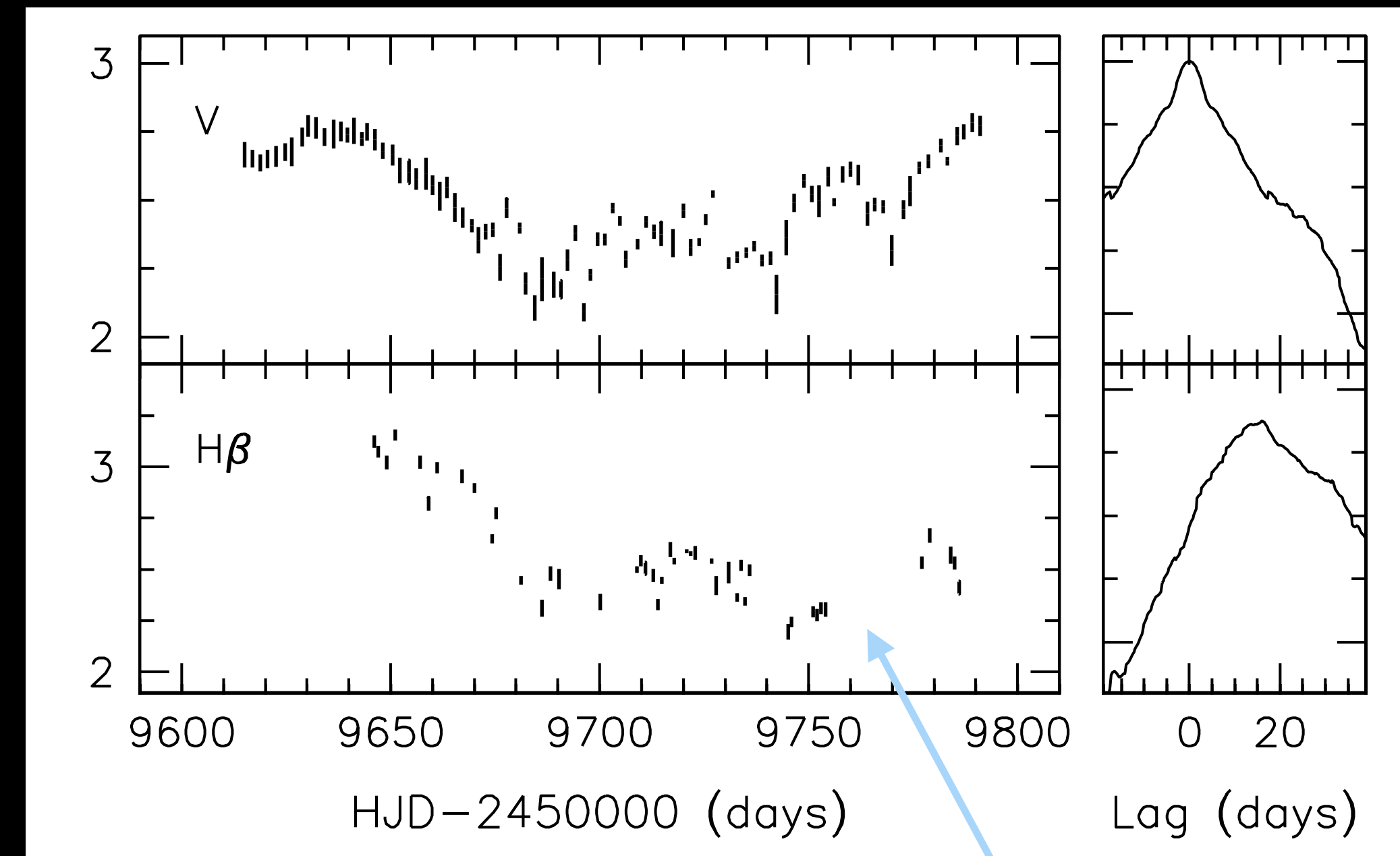
IC 4329A:

$$\overline{\Delta t} = 8d$$

vs.

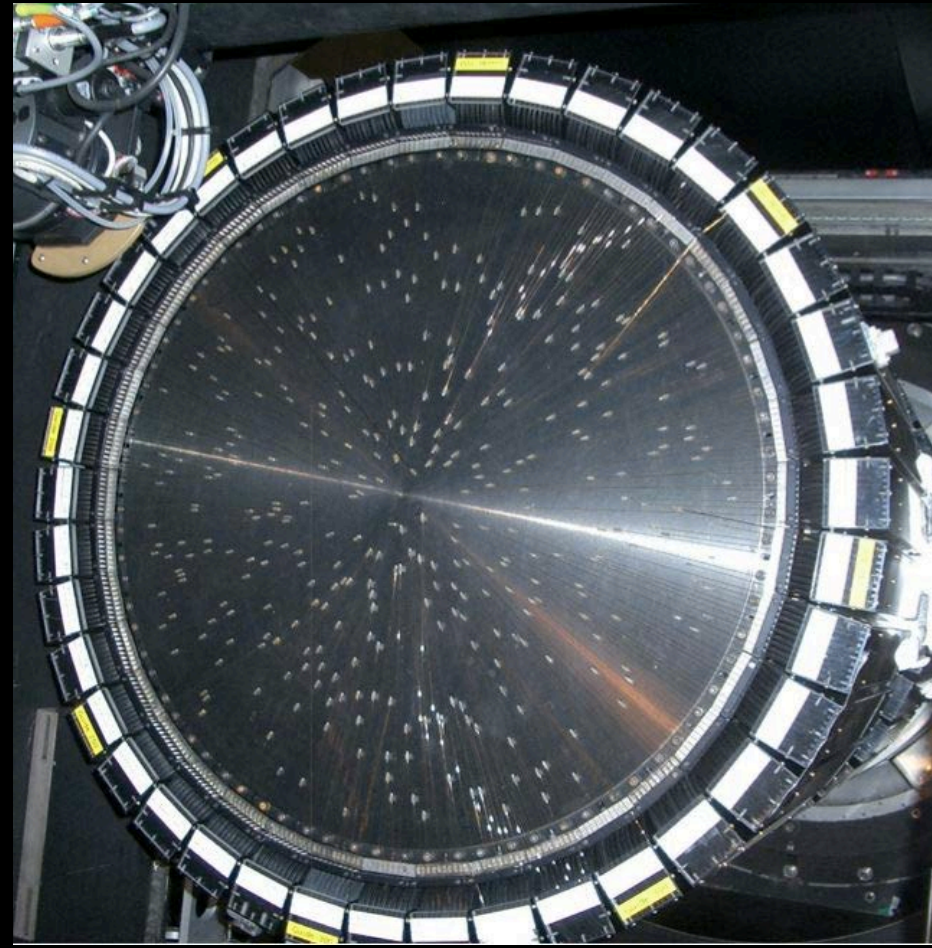
$$\overline{\Delta t} = 2d (V) \text{ and } 3d (H\beta)$$

*Bentz et al., 2023*



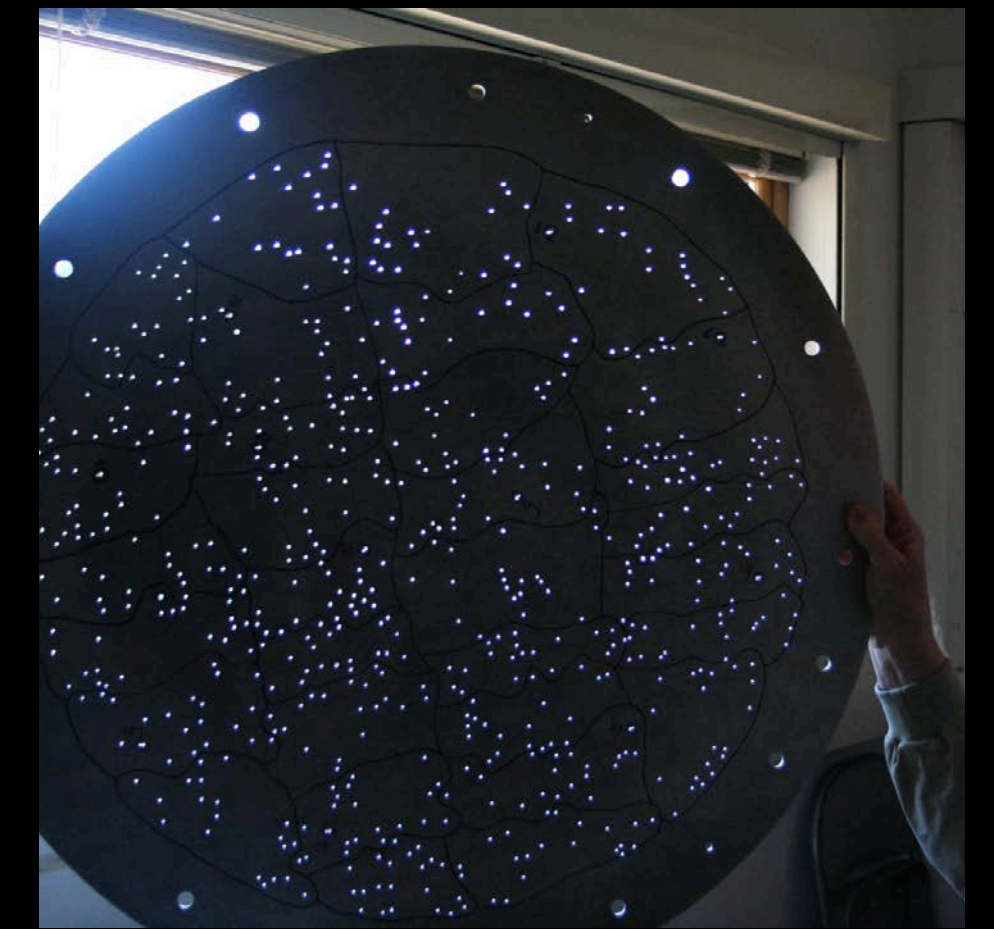
*Spectrograph broke*

# Using Luck to Your Advantage

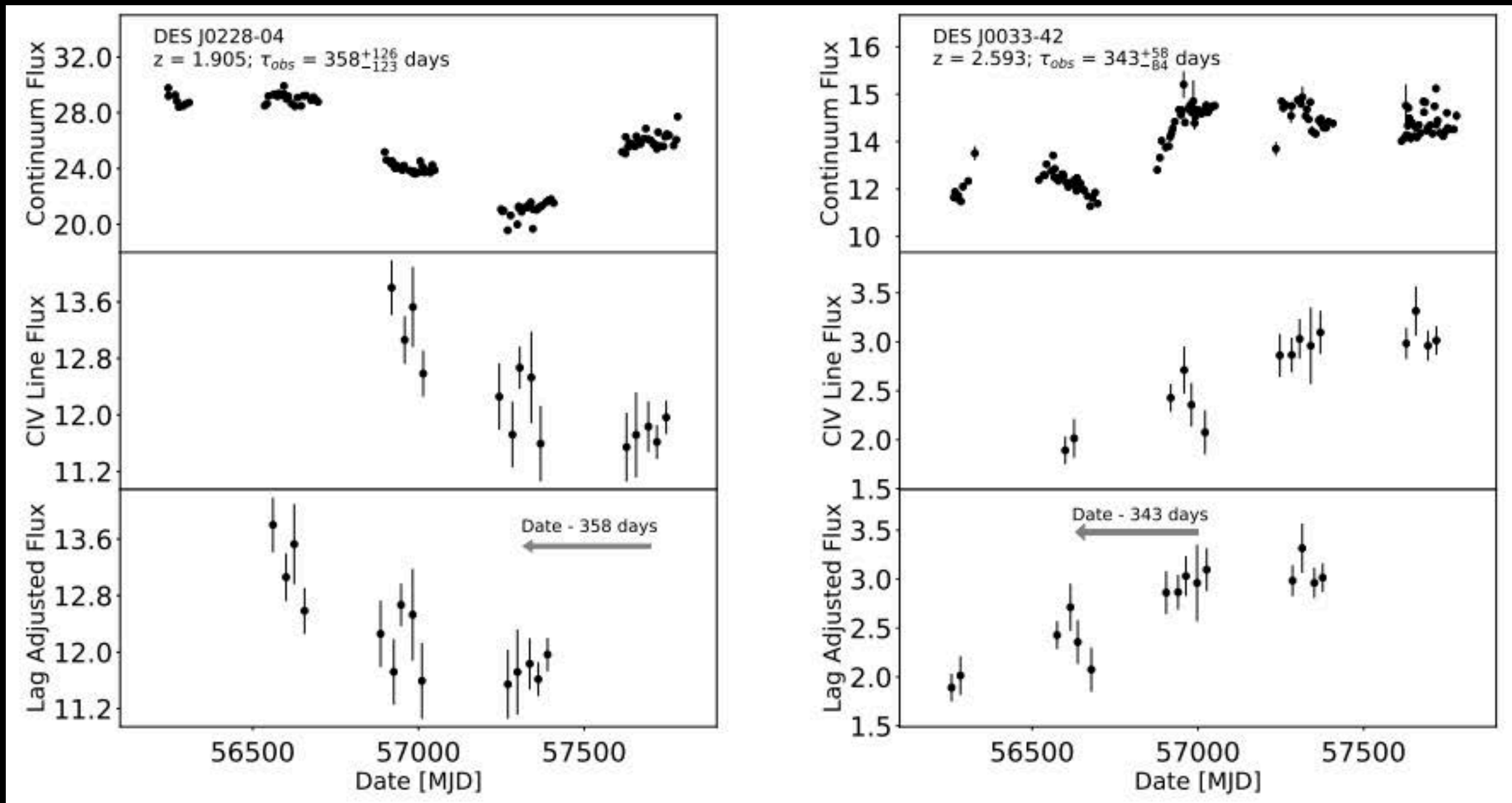


OzDES RM

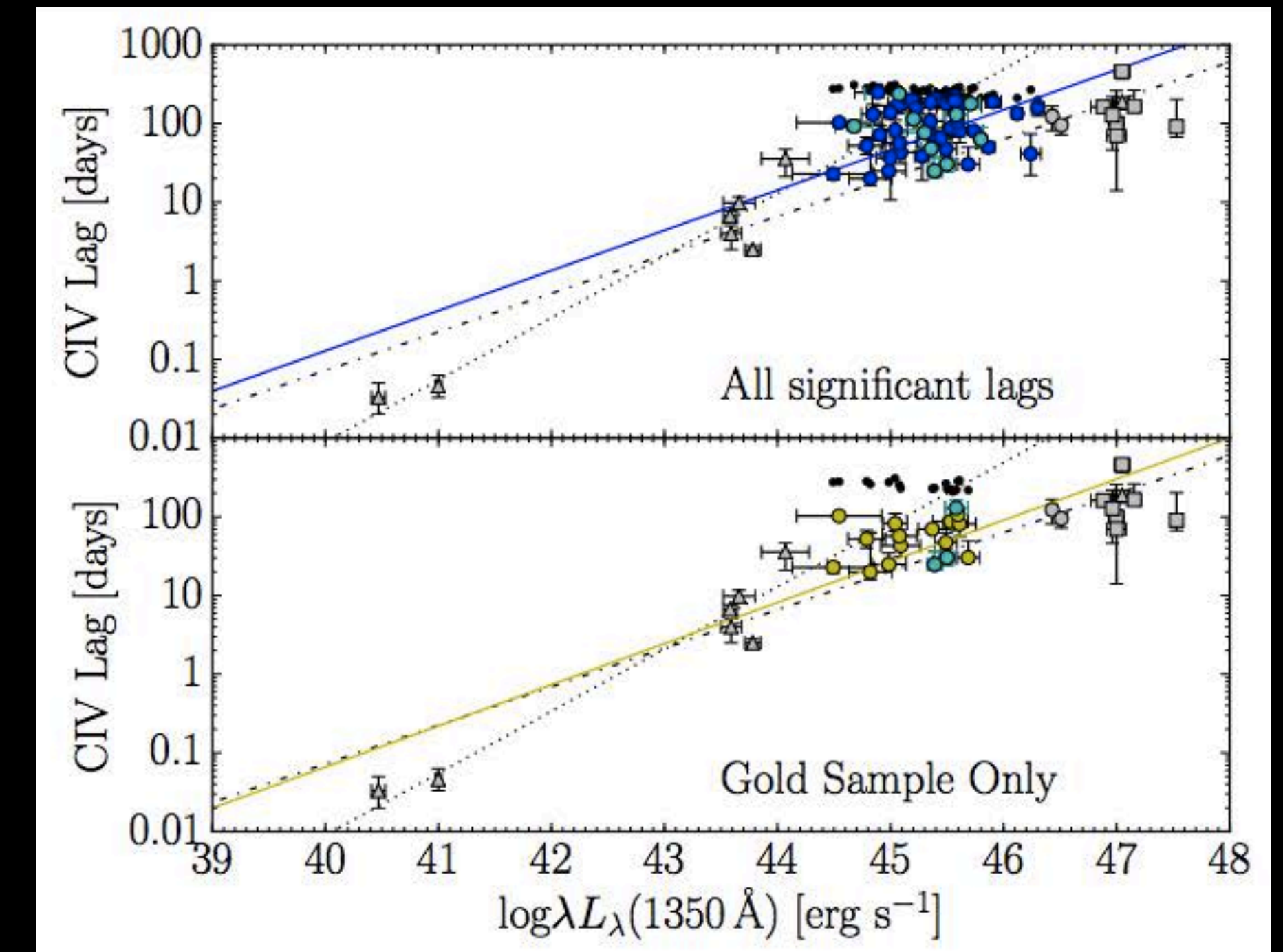
- Multiplexed reverberation mapping:
- probe more targets (some will be lucky)
- more representative AGN sample(?)
- additional emission lines



SDSS RM

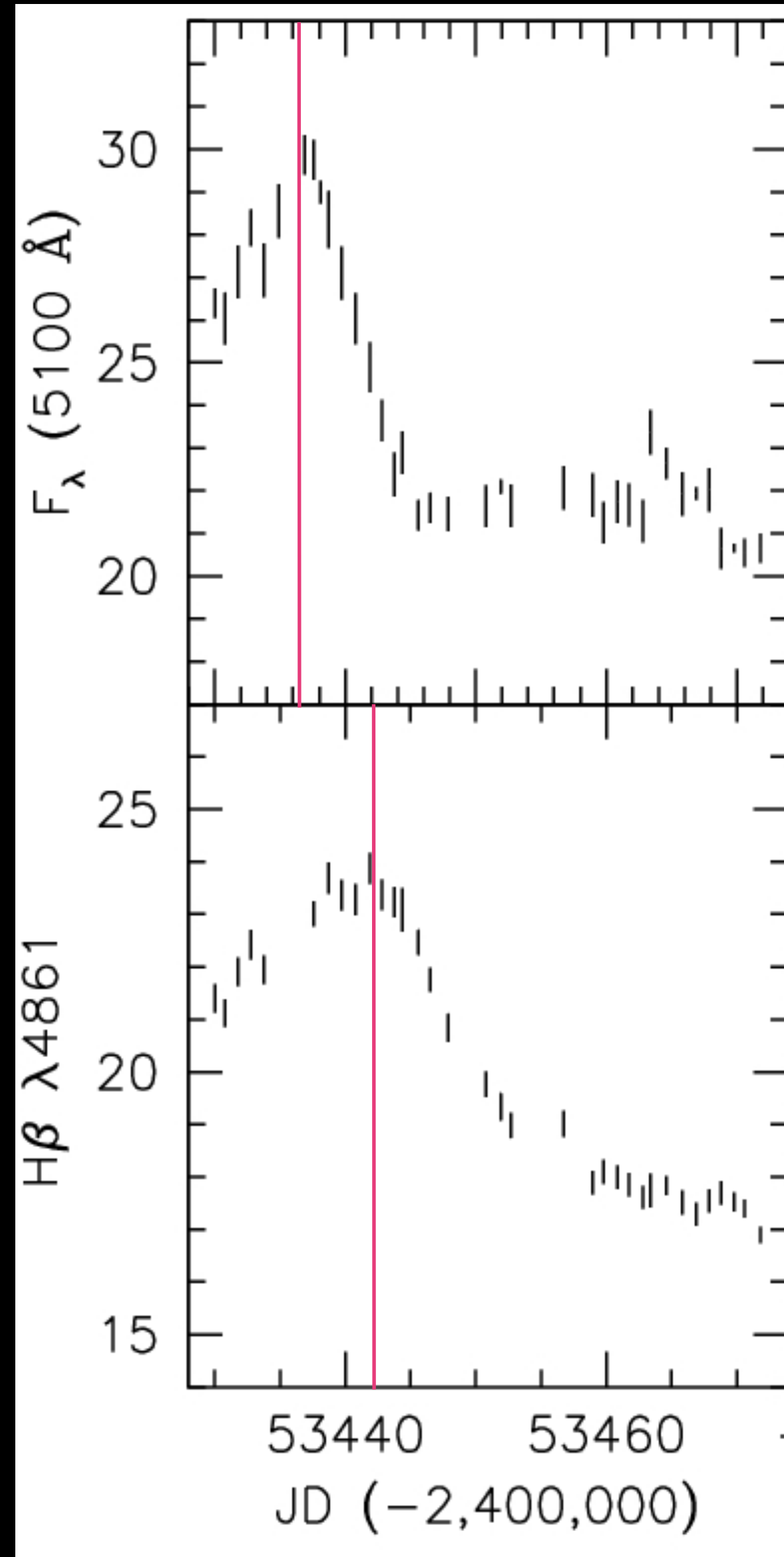


Hoormann et al. 2019



Grier et al. 2019

# Unraveling the Messy Details



$$\Delta L(\nu, t) = \int_0^{\infty} \Psi(\nu, \tau) \Delta C(t - \tau) d\tau$$

Observed Echo  
(emission line variations)

Response

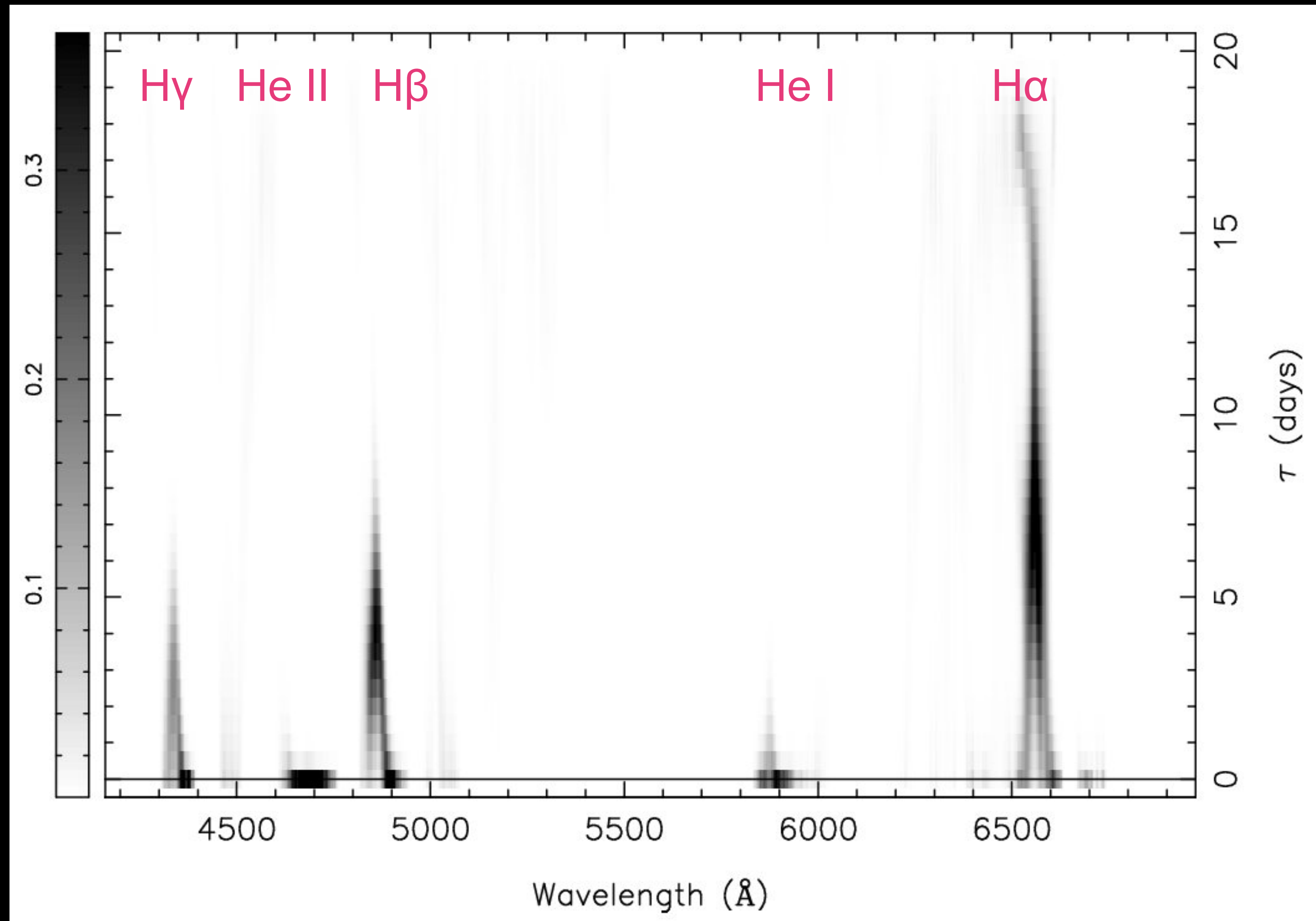
Event  
(continuum variations)

Deconvolution is needed!

Obstacles to overcome:

- Finite data length
- Irregular sampling
- Noisy data
- Sparse coverage

# Velocity-Delay Map



Balmer line  
differences caused  
by photoionization  
effects

# Simplified Velocity-Delay Map Examples

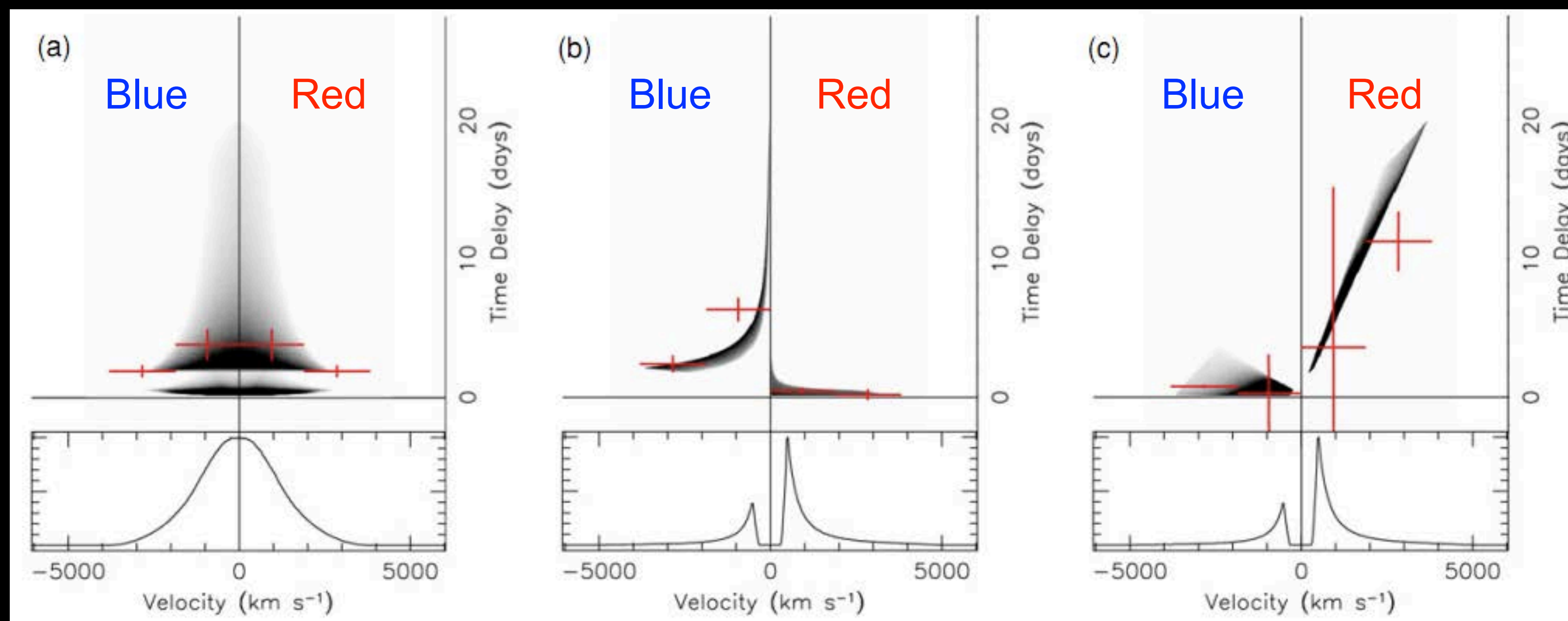
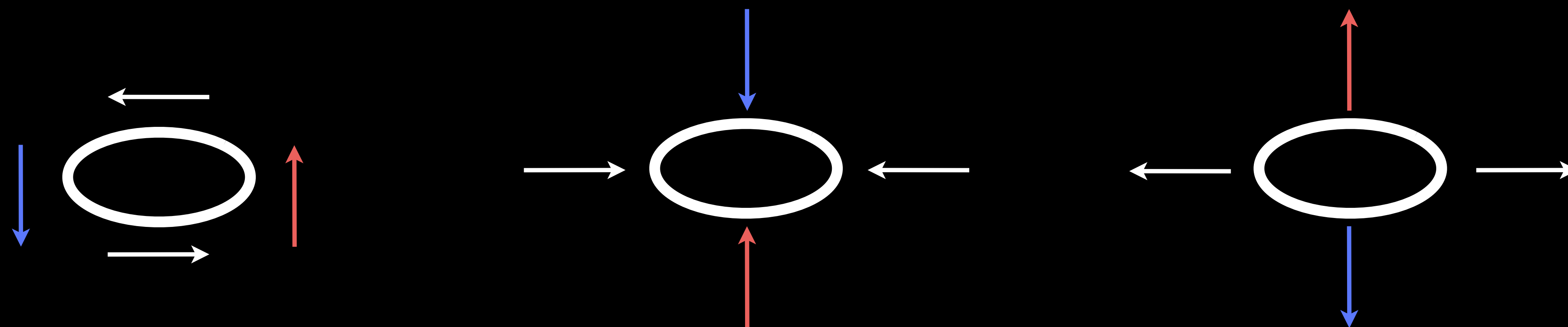
To Observer

Rotation

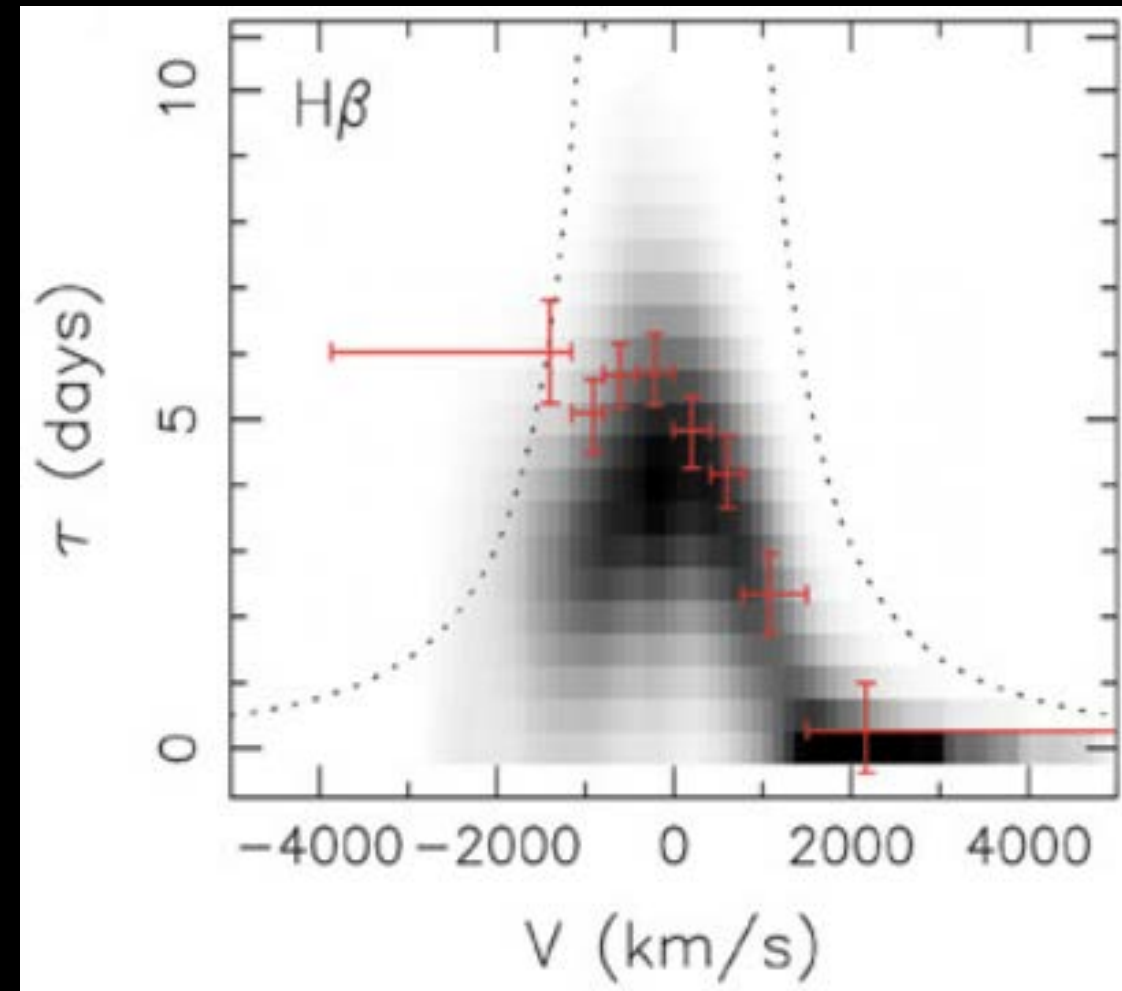
Infall

Outflow

Increasing Time Delay

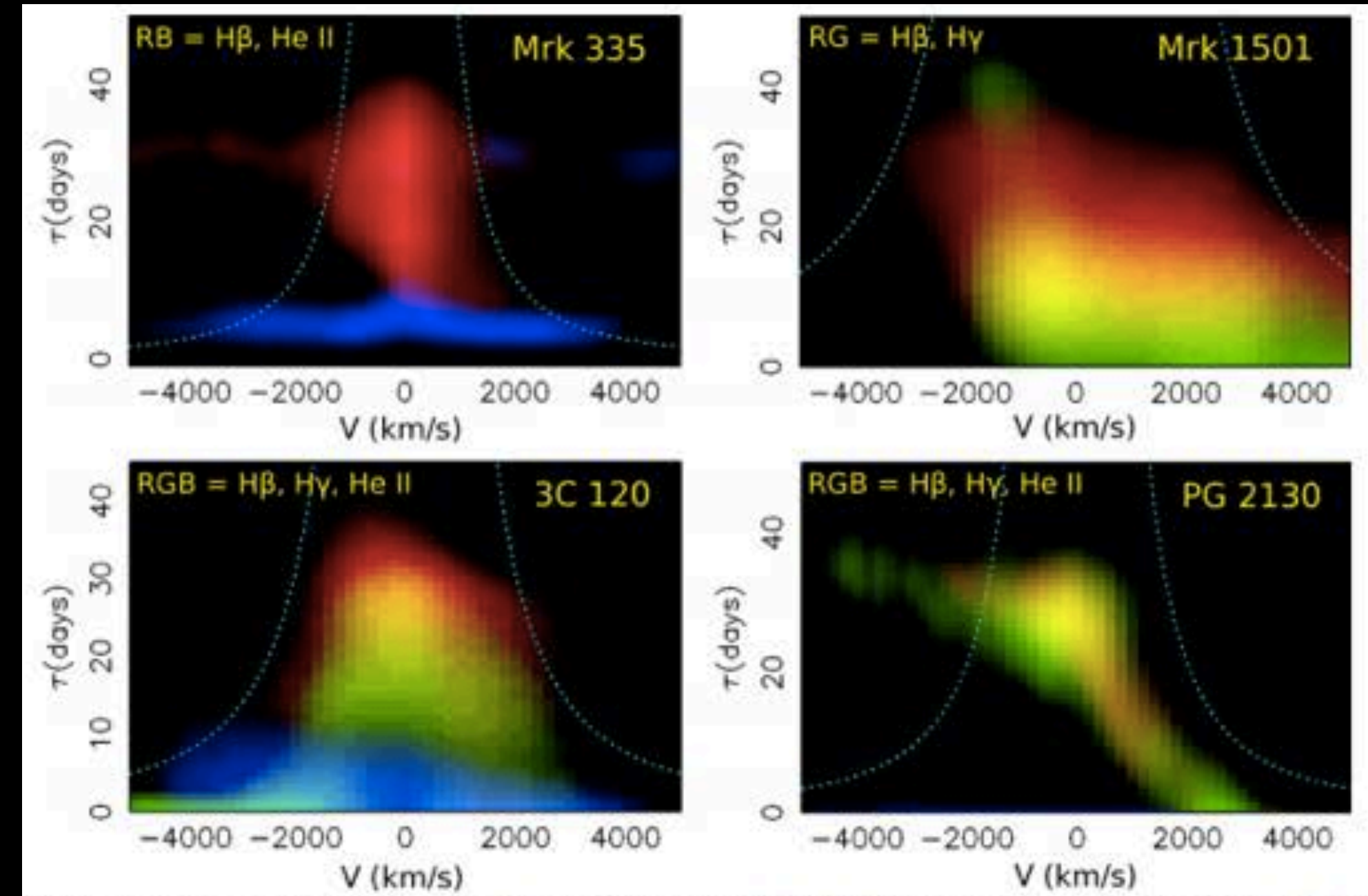


# Recovered Velocity-Delay Maps

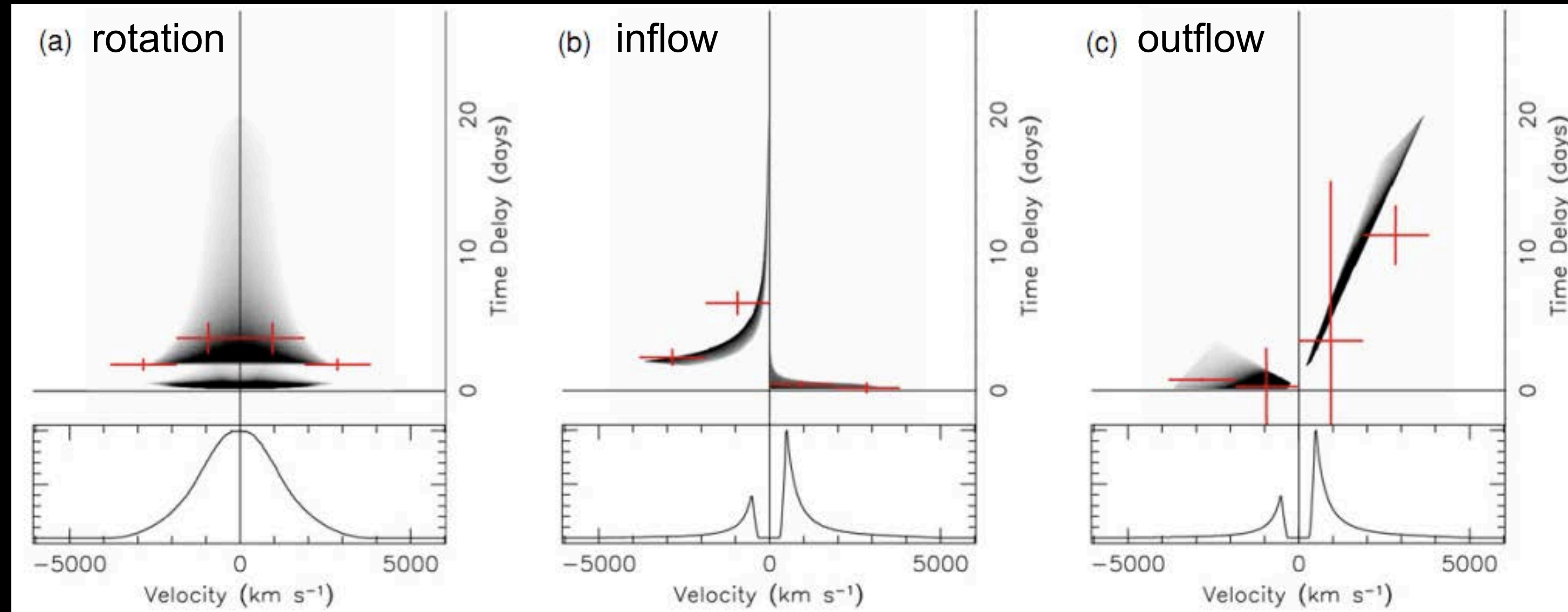


recovered velocity-delay  
map rules out outflow  
some evidence for inflow

*Bentz et al. 2010*



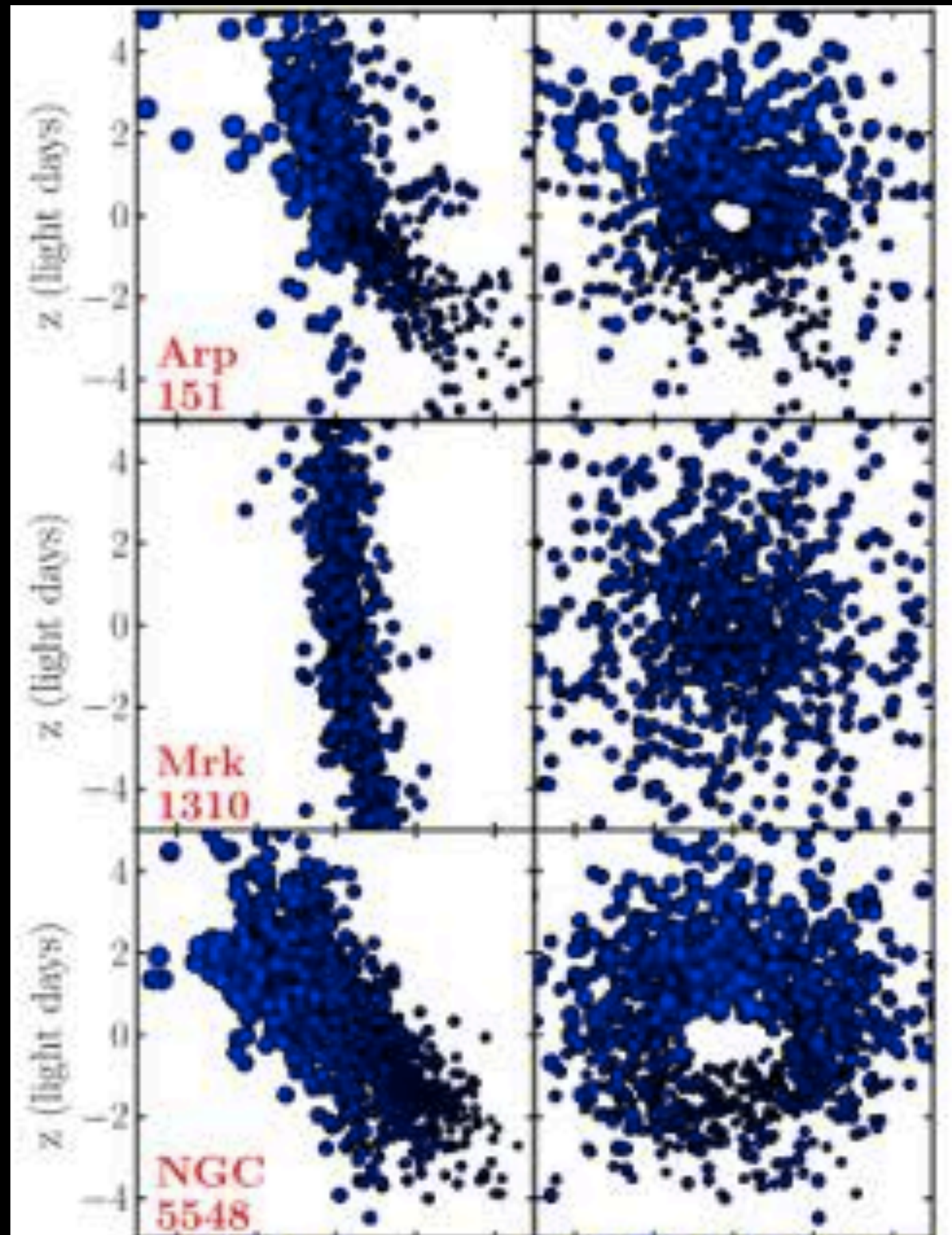
*Grier et al. 2013*



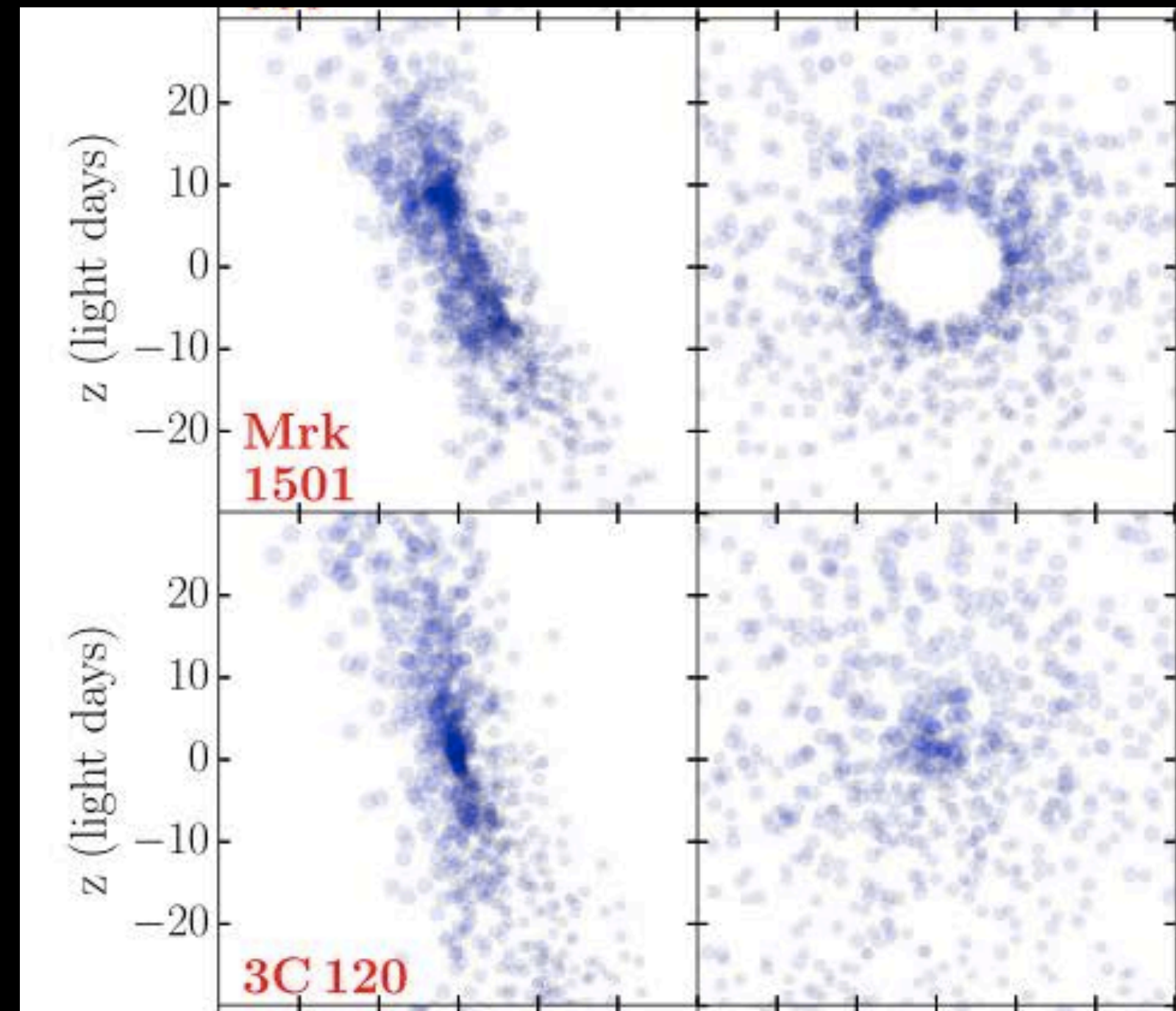
model-independent result,  
but requires interpretation

# Direct Modeling of RM Data

fits geometric & kinematic models directly to the lightcurves



Pancoast et al. 2014



Grier et al. 2017

Also: Williams et al. 2018, 2020  
Villafaña et al. 2022  
Bentz et al. 2021, 2022

~ 40 AGN modeled so far have:

- inclined, flattened BLR geometry
- significant scale height
- mostly rotation and/or infall

model dependent  
(big caveat: no photoionization physics included yet, code is in development)  
but results are straightforward to interpret

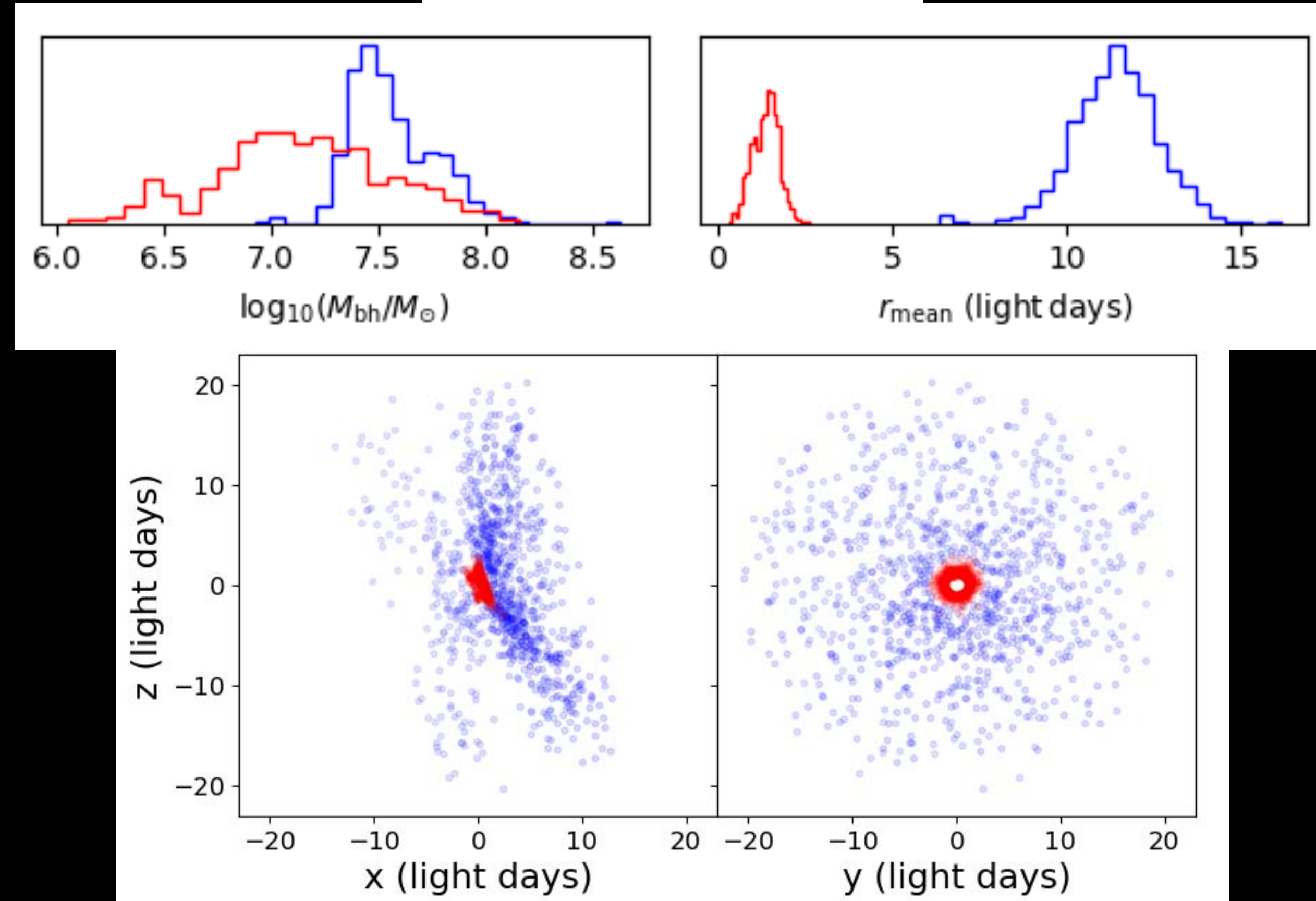
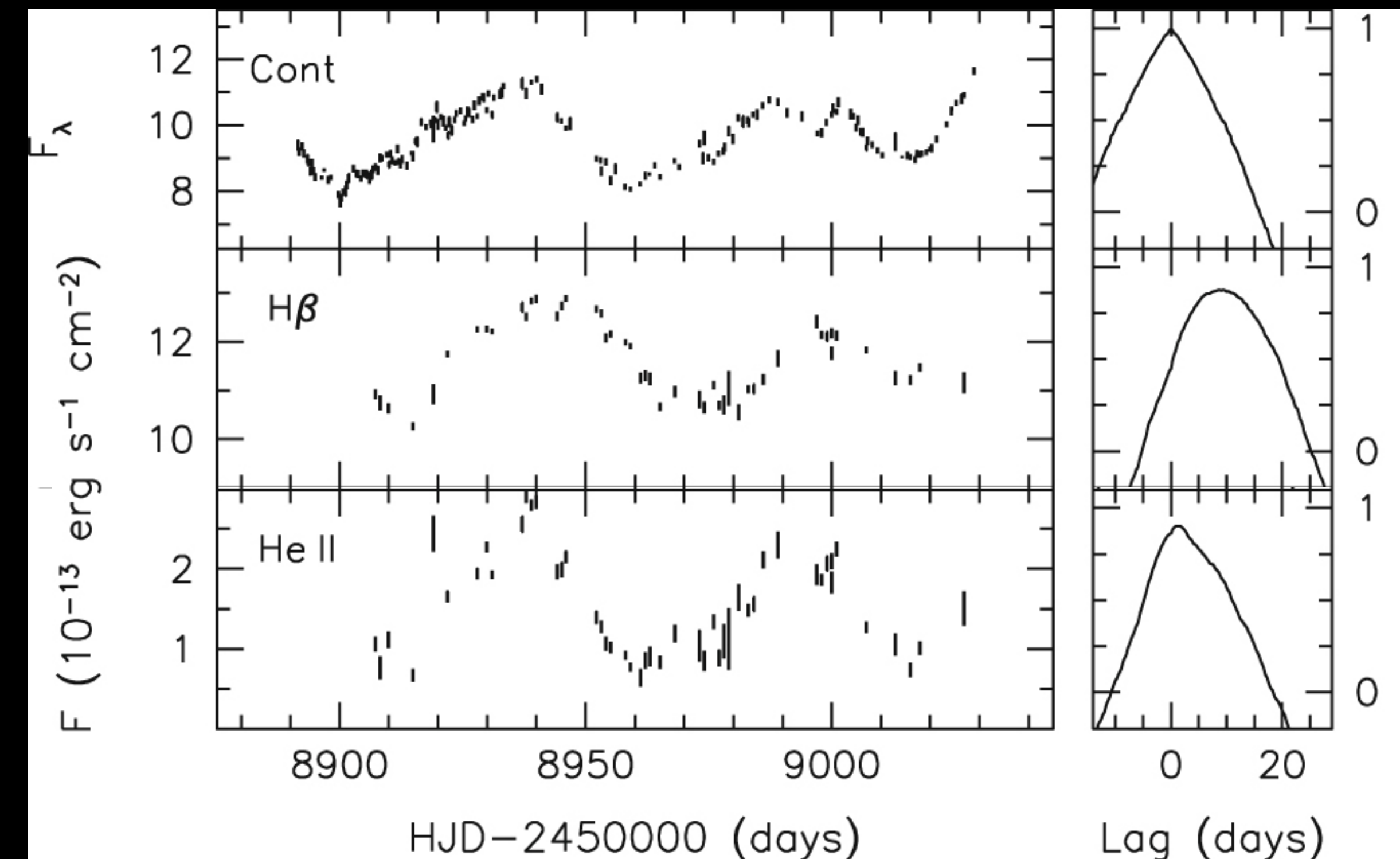
primary, direct  $M_{\text{BH}}$  !

# Direct Modeling of Multiple Emission Lines - NGC 3783

*Bentz et al. 2021a,b*

Hbeta

He II

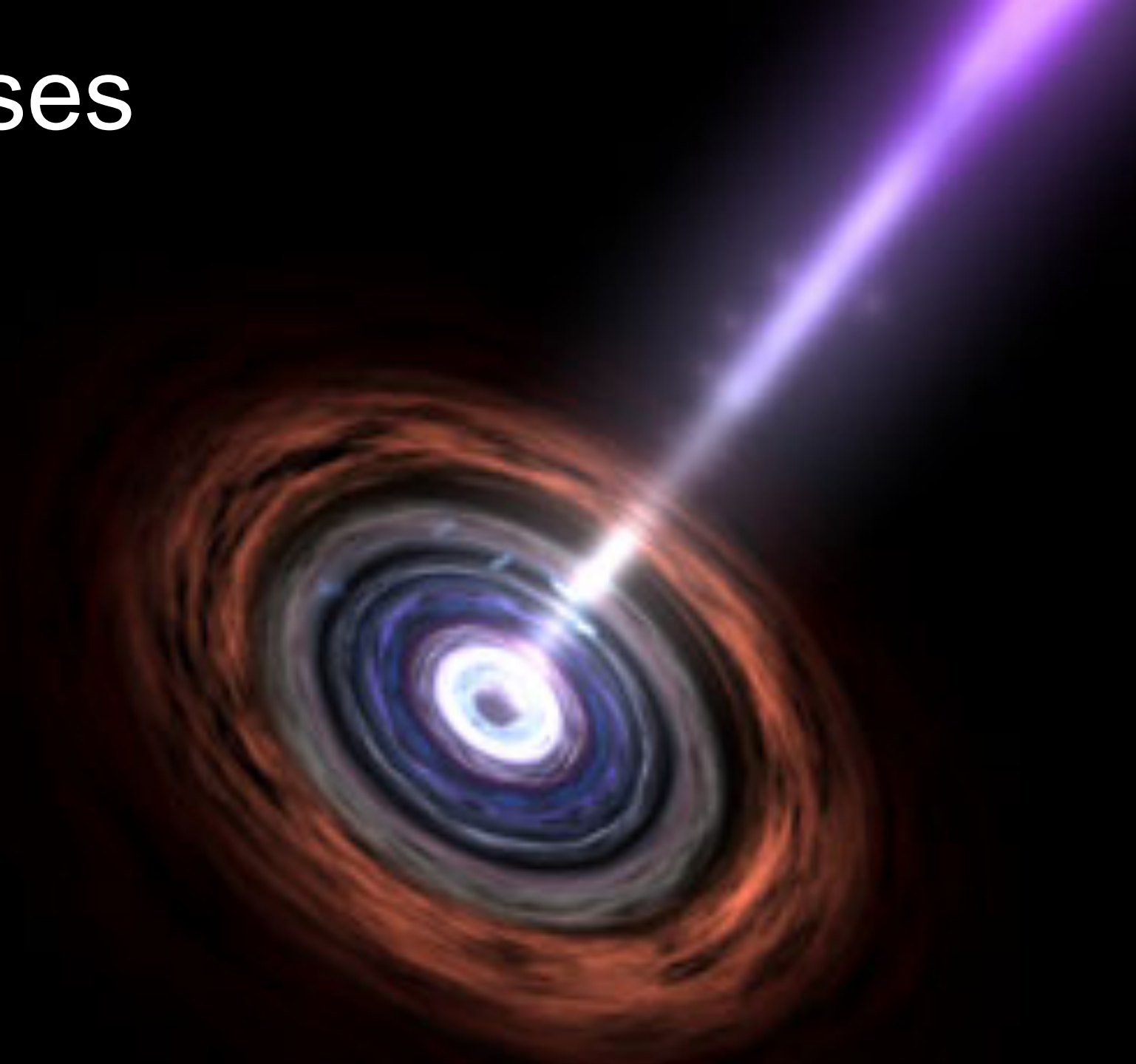


a few (2-3?) additional (potentially useful) data sets already exist...

# Complications for single-epoch masses

- spectrophotometric calibration
- low S/N spectra at high  $z$ 
  - absorption?
  - continuum placement and line width measurement
- R-L relationship
  - extrapolated from low  $z$ ?
  - same emission line?
  - accretion rate dependence?
- scale factor  $f$
- ionizing UV vs. non-ionizing continuum (applies to RM too)

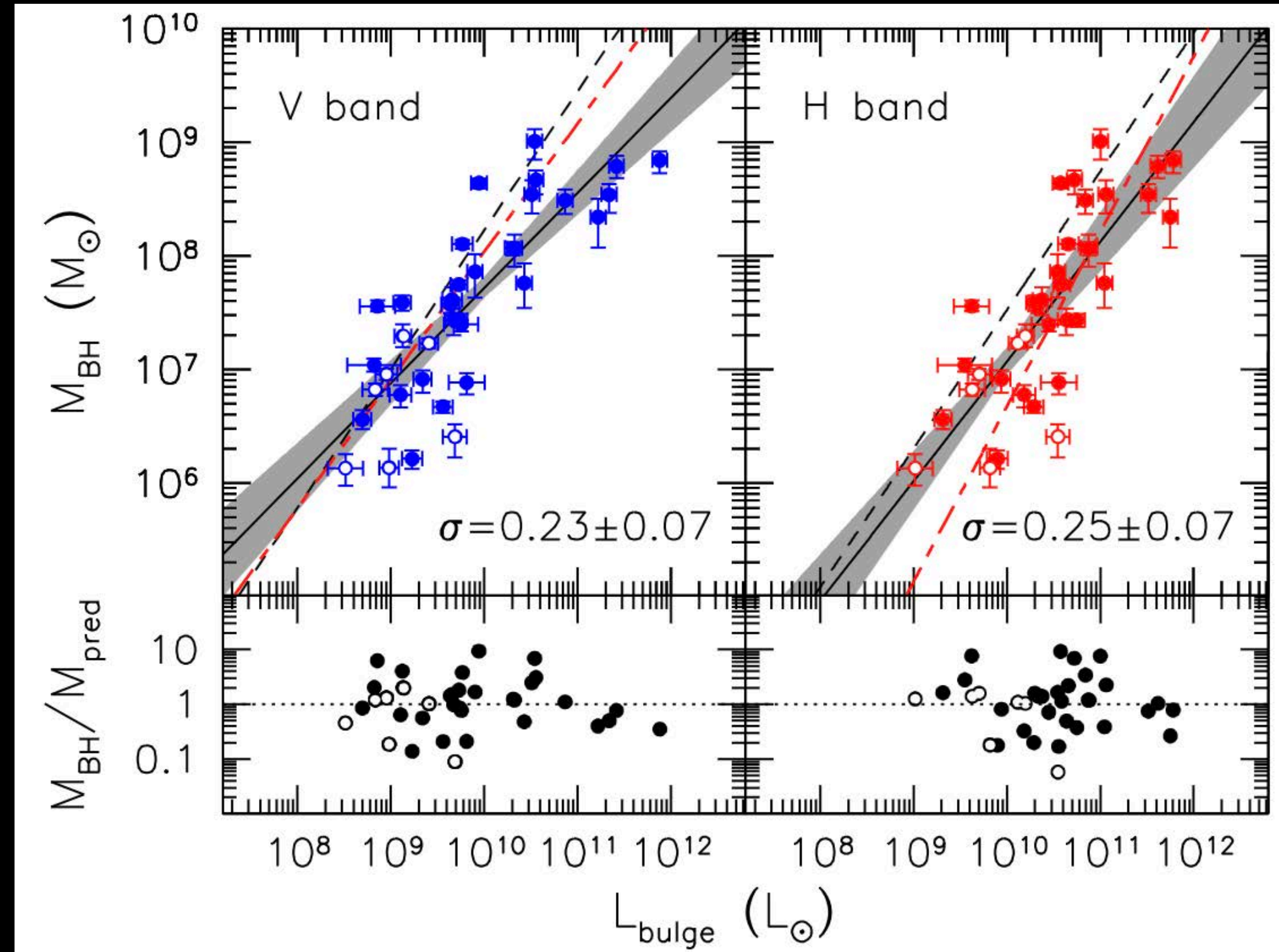
Reality: assume a factor of  $\sim 10$  uncertainty (could be more)



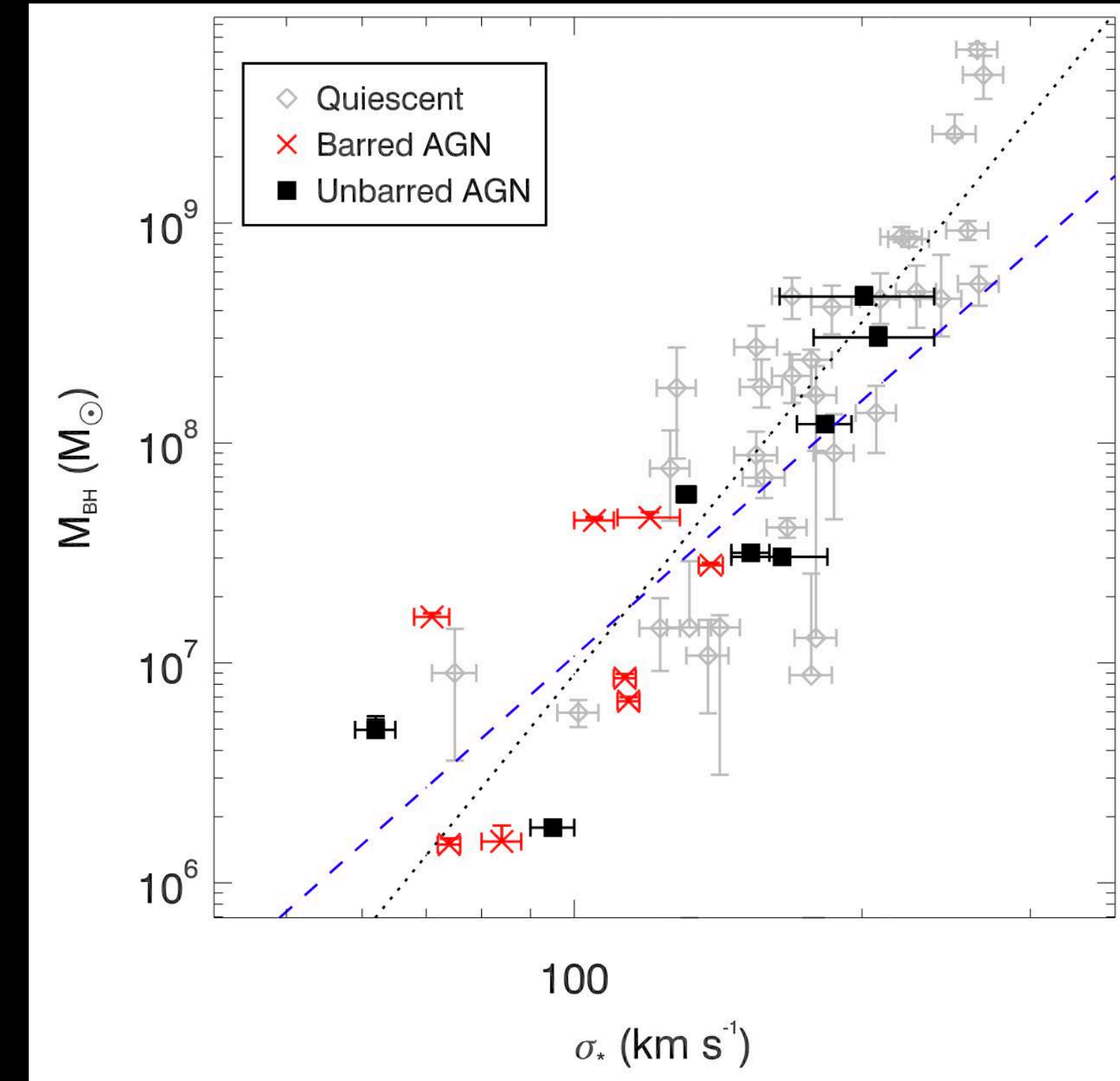
Recent RM review:  
Cackett, Bentz, & Kara 2021

 iScience

# Complications for host-galaxy scaling relationships



*Bentz et al. 2018*



*Batiste et al. 2017*

- requires high-resolution imaging (HST) to separate AGN and decompose galaxy components

- requires spatially resolved spectroscopy to constrain **bulge** velocity dispersion
- bars require extra caution

limited AGN sample

quiescent galaxy relations are dominated by early-type galaxies

Reality: assume a factor of  $\sim 10$  uncertainty (could be more)