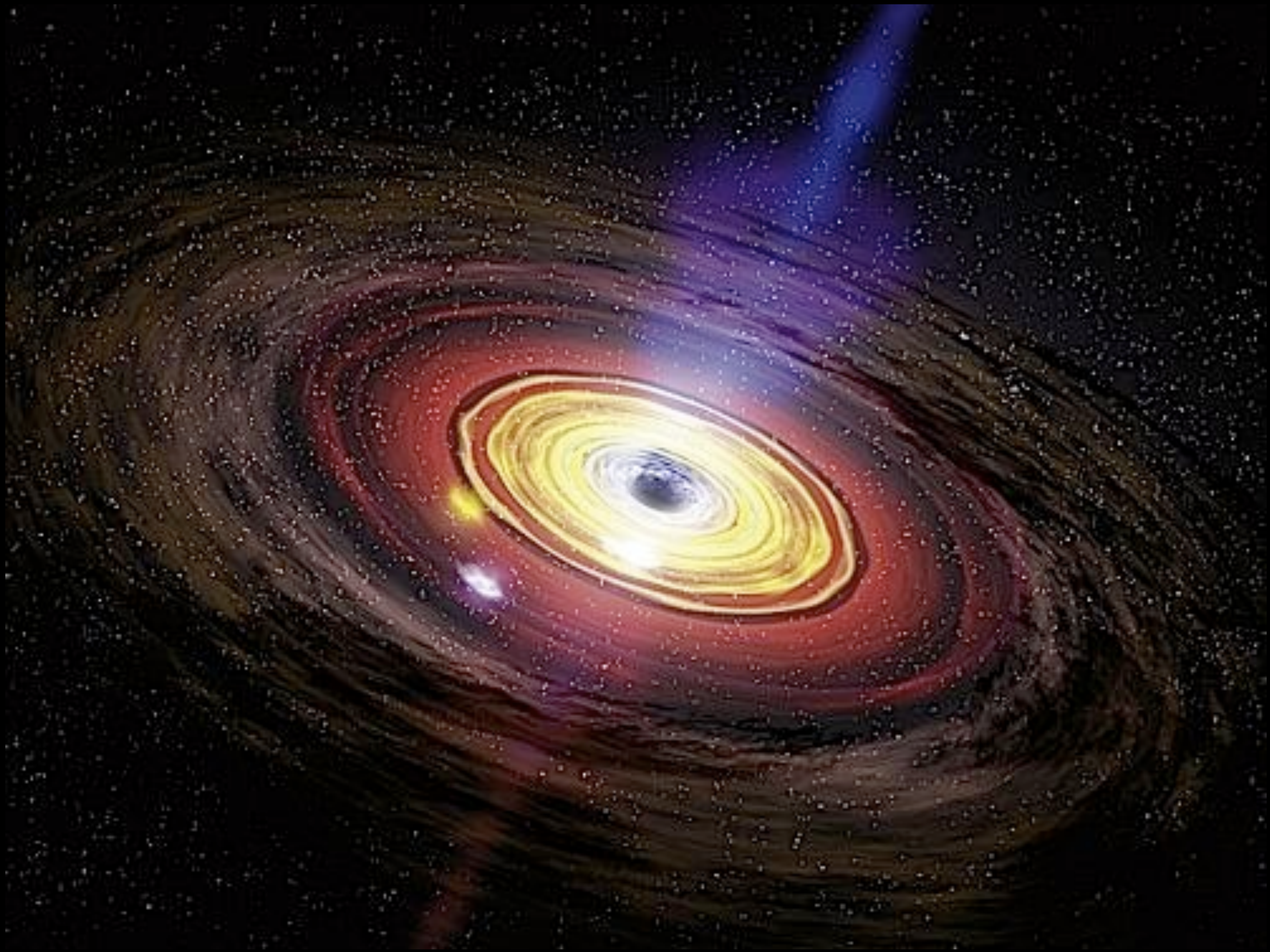
Methods of Measuring Black Hole Masses: Reverberation Mapping



Misty C. Bentz
Georgia State University

Monday, September 12, 2011

Black Hole Masses in AGNs

Dynamical methods generally not feasible in AGNs

- AGNs rare = distant, poor spatial resolution
- AGNs are bright, outshine the "test particles"

Use variability instead → Reverberation mapping

- relies on time resolution instead of spatial resolution

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

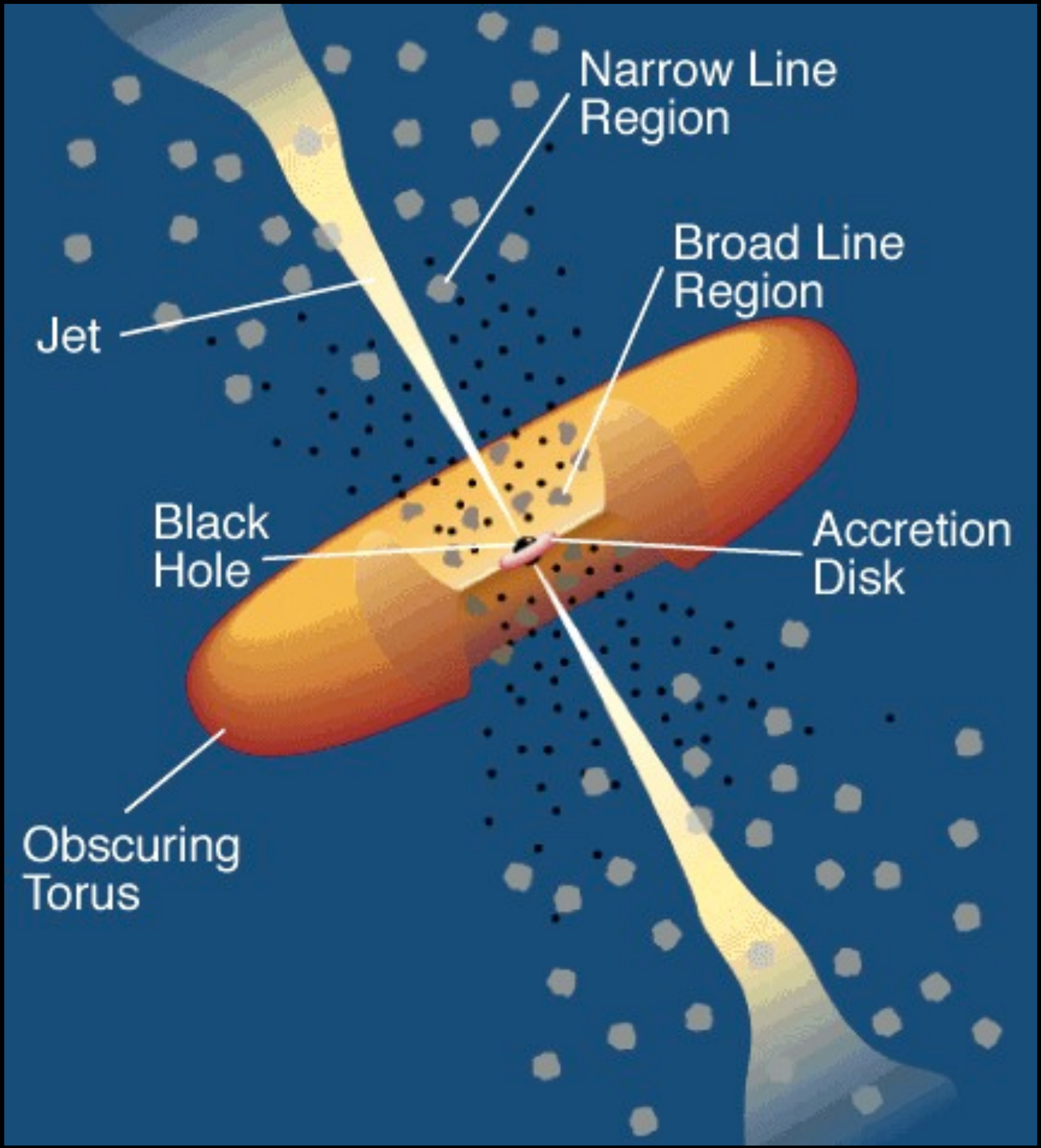
R – size of emission region
V – velocity of gas in that region
f – order unity scale factor

RM Assumptions:

1. R (continuum emission region) << R (BLR)
2. time delays arise from light travel time effects
3. optical continuum has simple relationship to ionizing continuum

RM <u>does not</u> assume any specific models

AGN Unified Model



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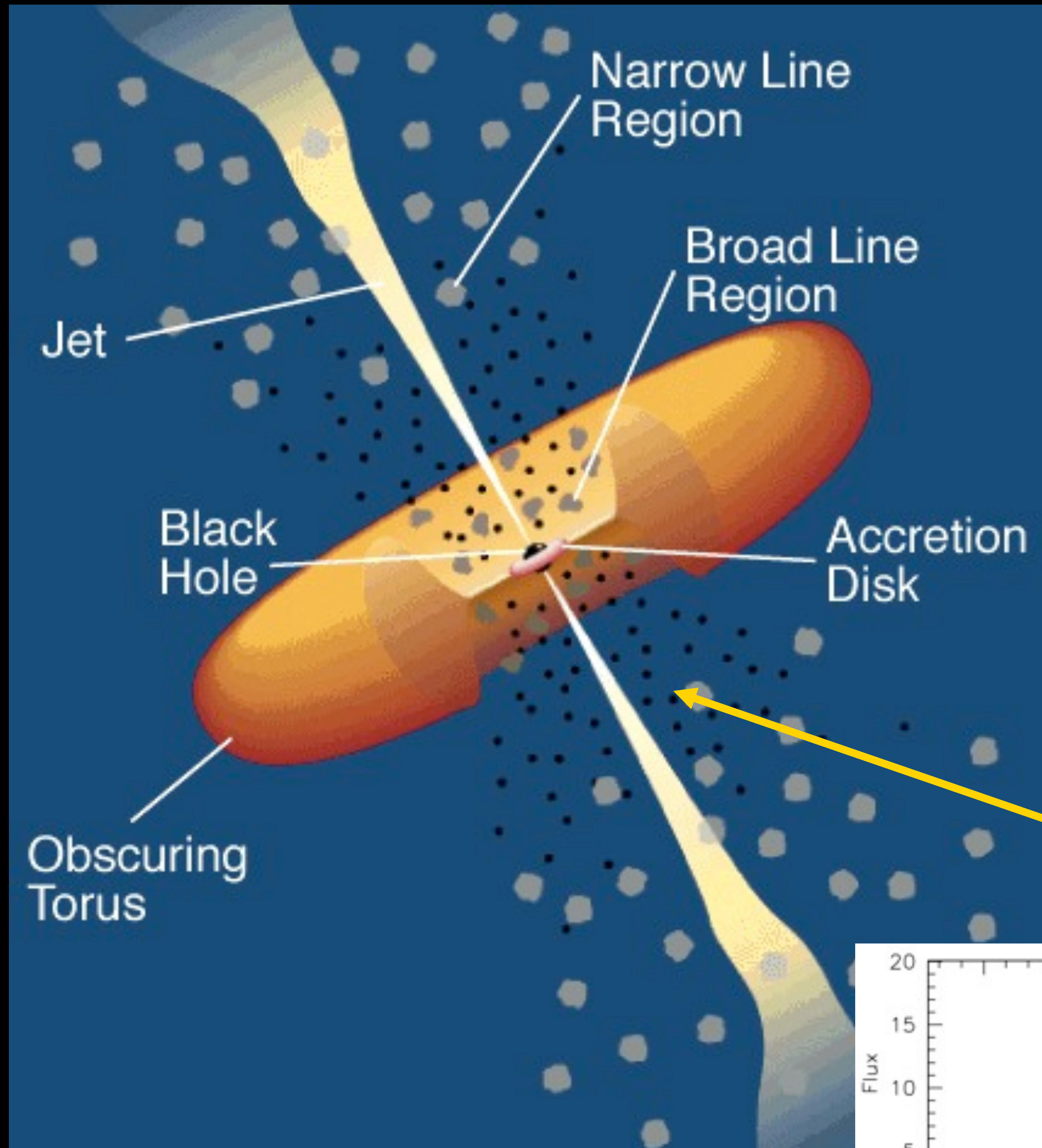
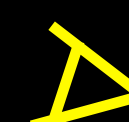
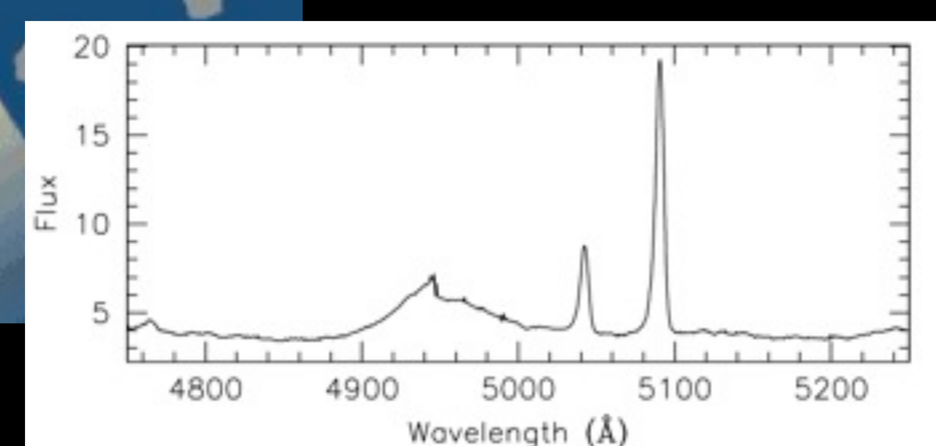
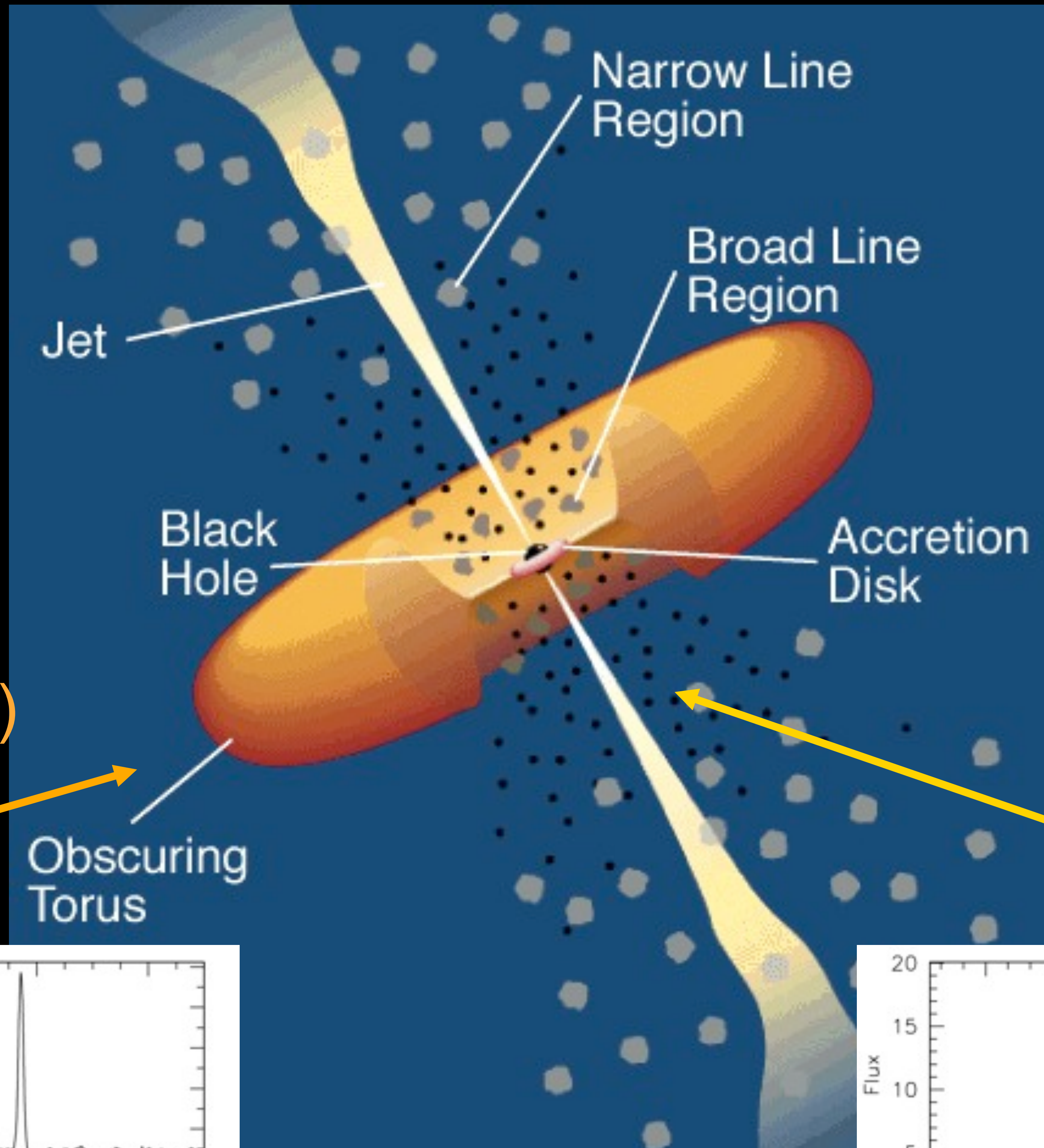


Broad-line
AGNs (Type 1)



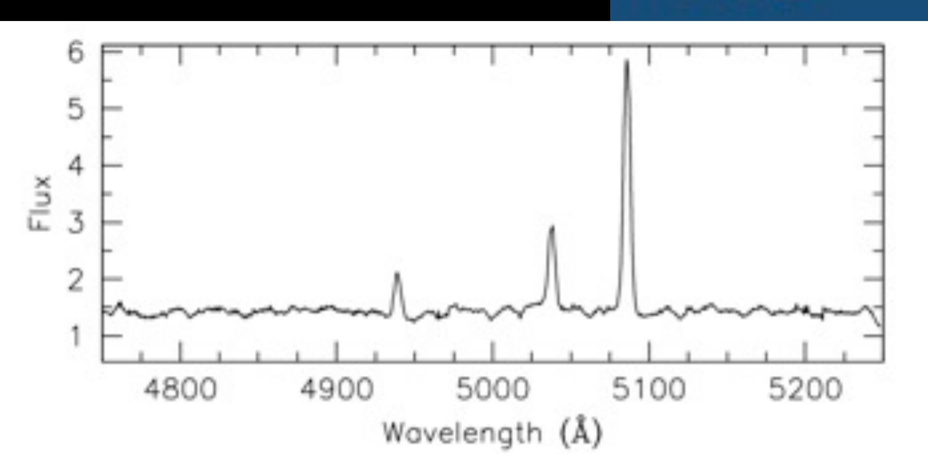


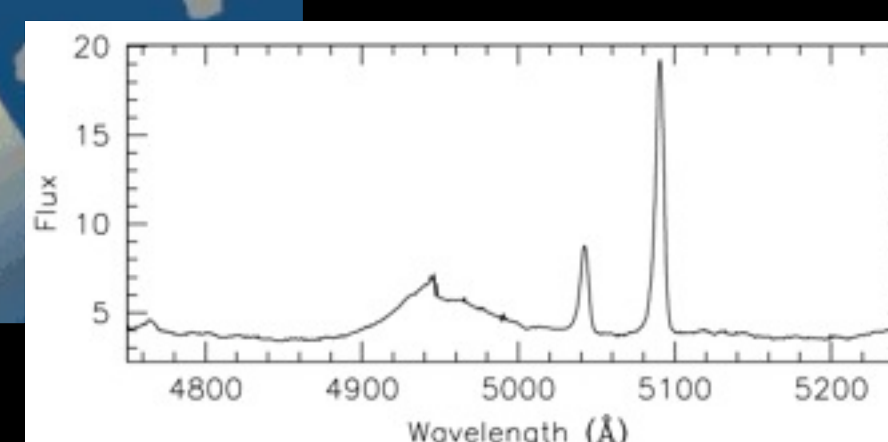
AGN Unified Model



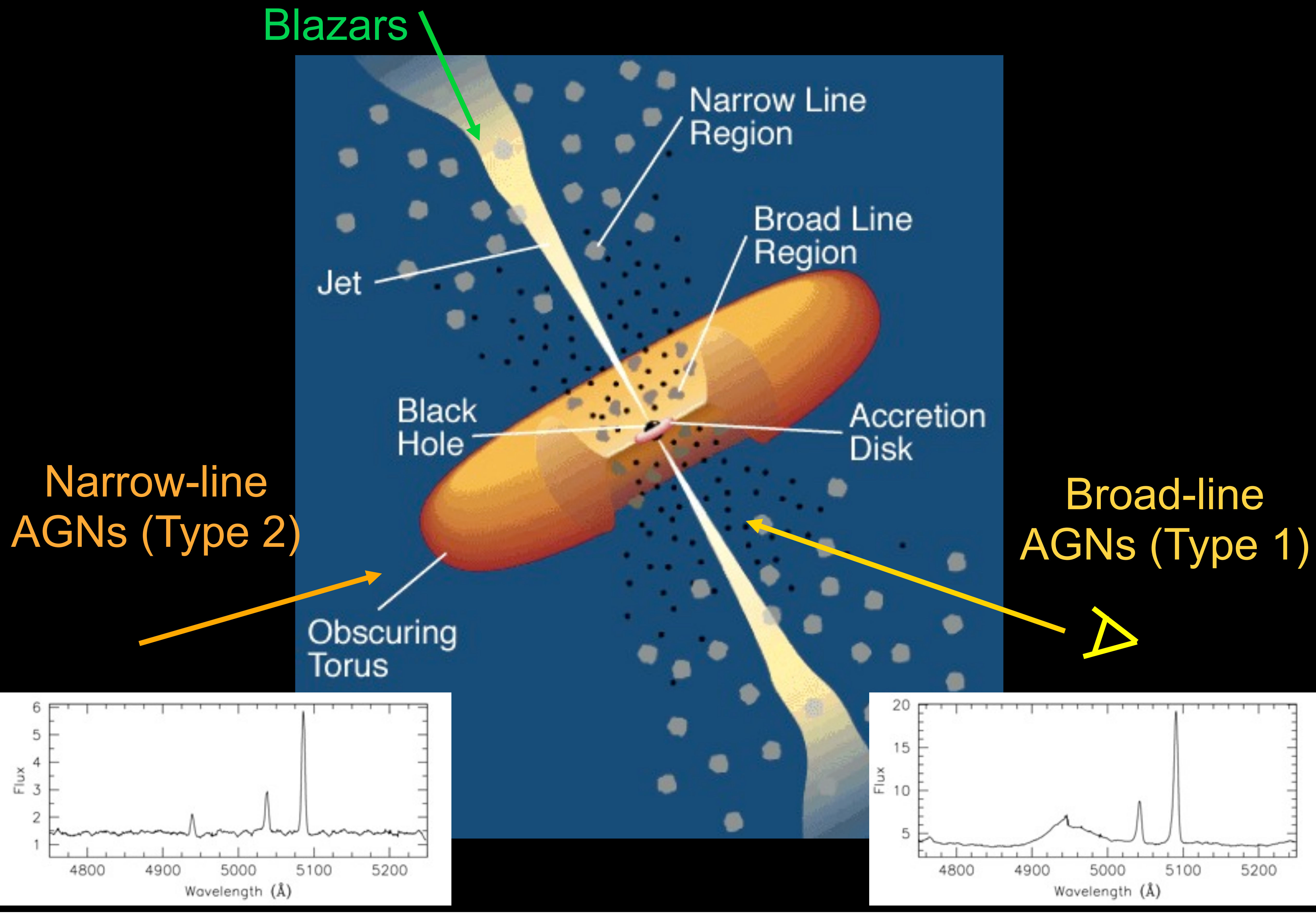
Narrow-line
AGNs (Type 2)

Broad-line
AGNs (Type 1)

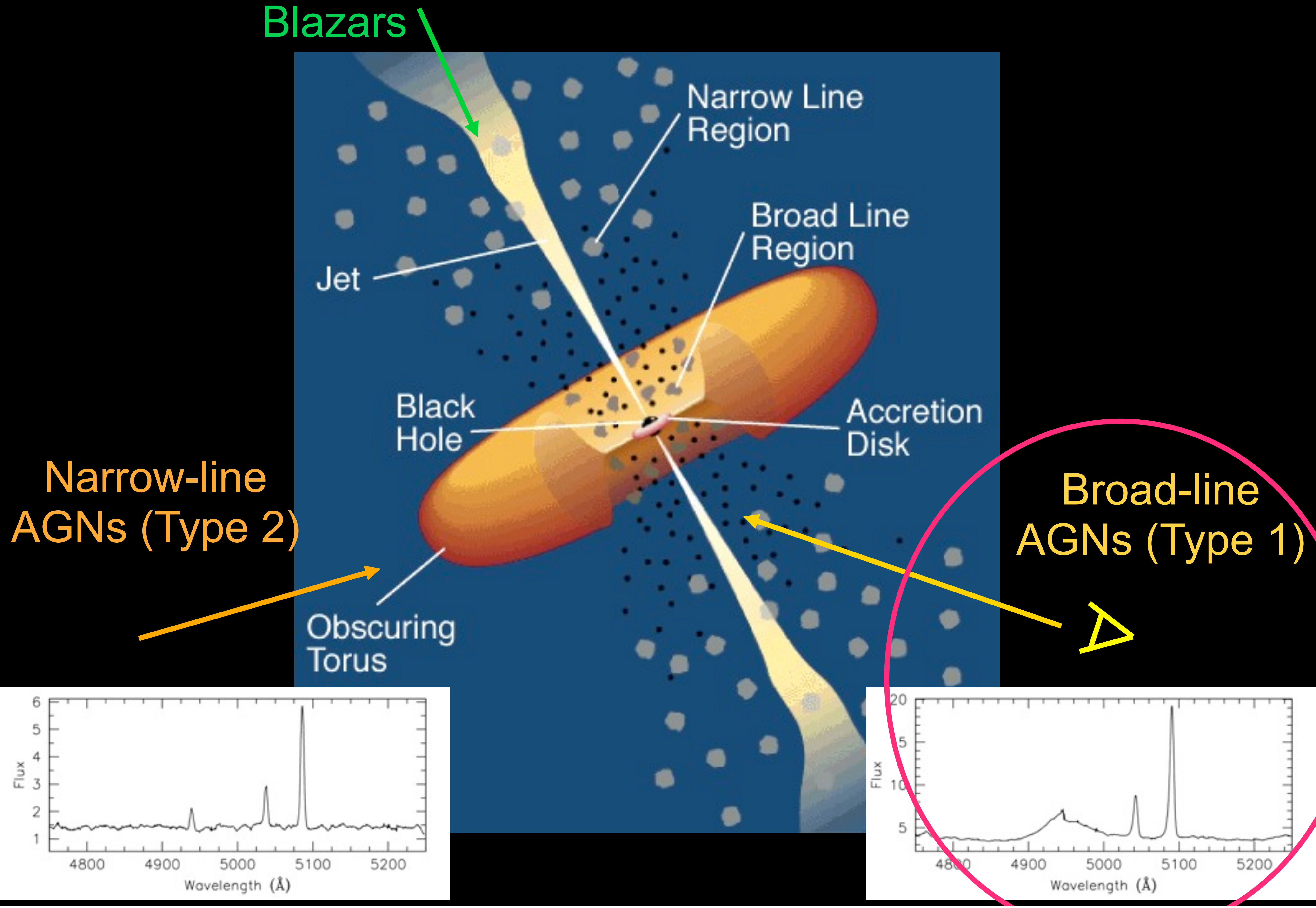




AGN Unified Model

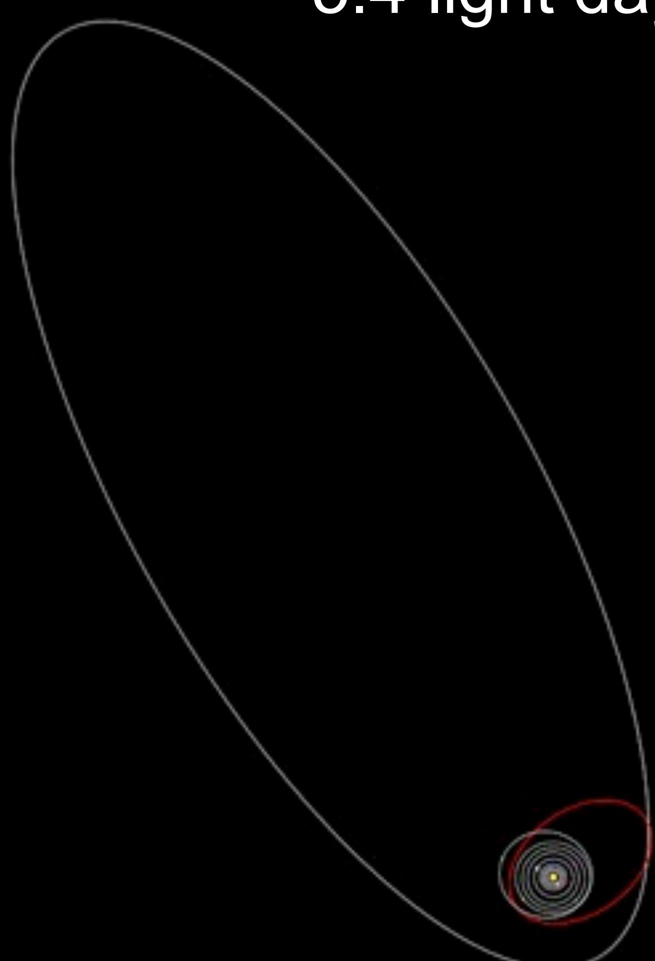


AGN Unified Model



AGN Scales or Why It’s Hard to Study the BLR in Detail

Orbit of Sedna
aphelion = 928AU
= 5.4 light days



Inner Solar System

AGN Scales or Why It's Hard to Study the BLR in Detail

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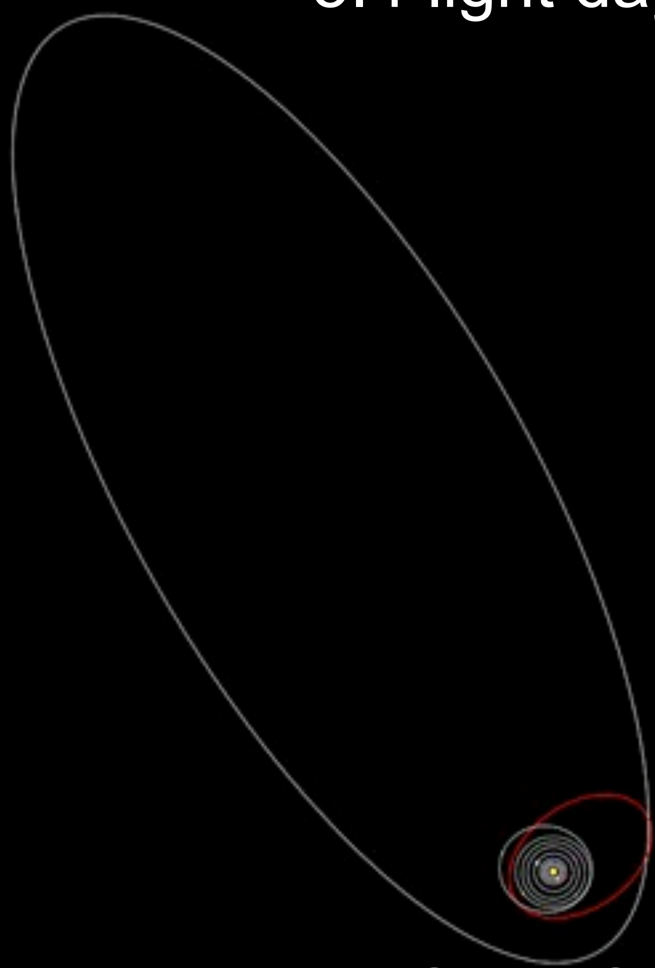


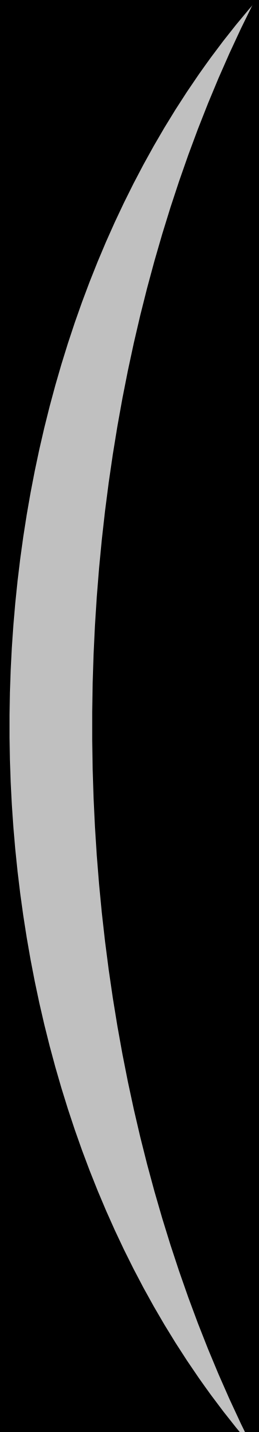
Inner Solar System

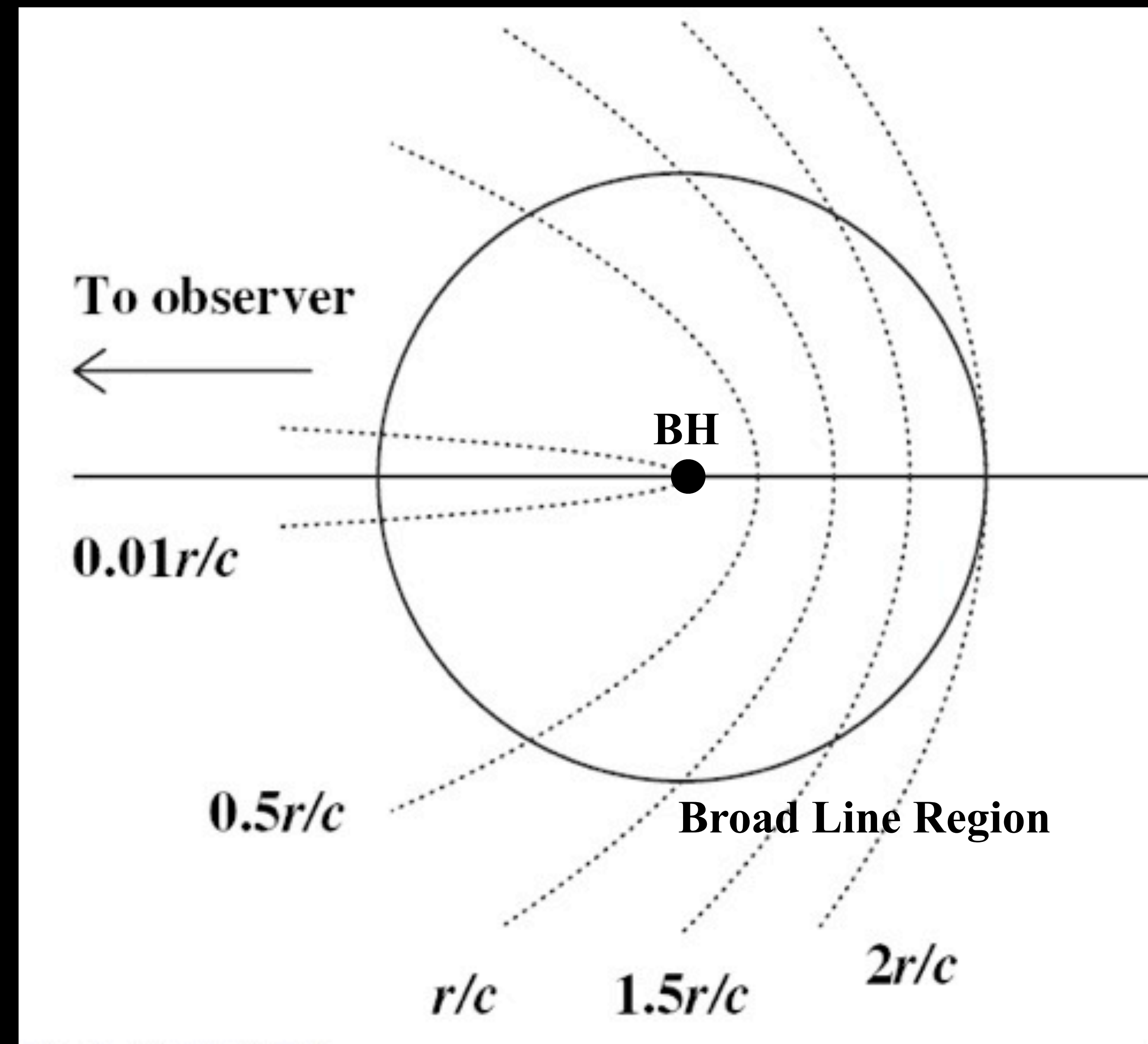
Embedded in the center of a galaxy
~40Mpc away (z~0.01)

Measuring the BLR Radius -- RM Cartoon

Telescope

AGN

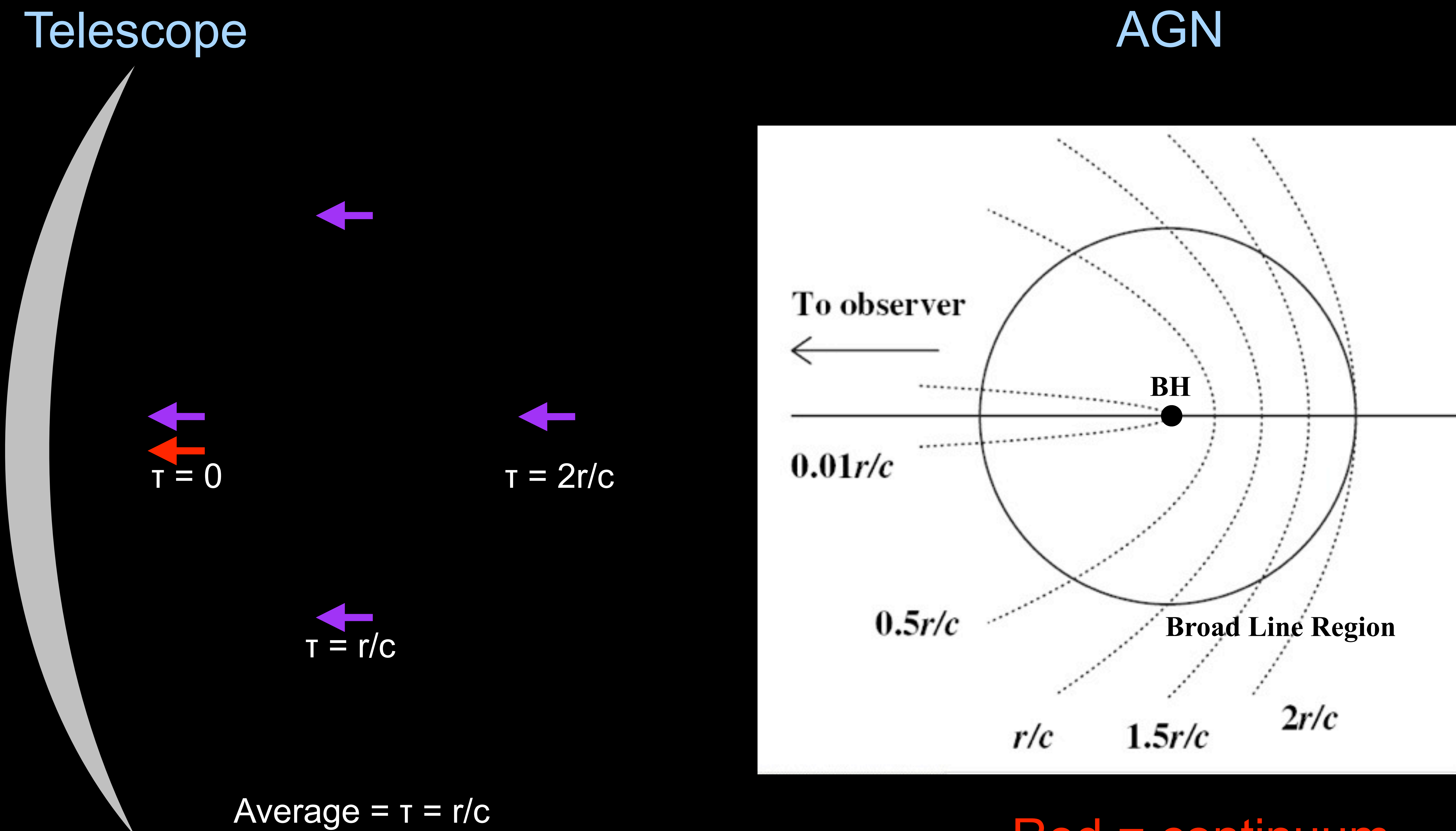




Red = continuum

Purple = broad line

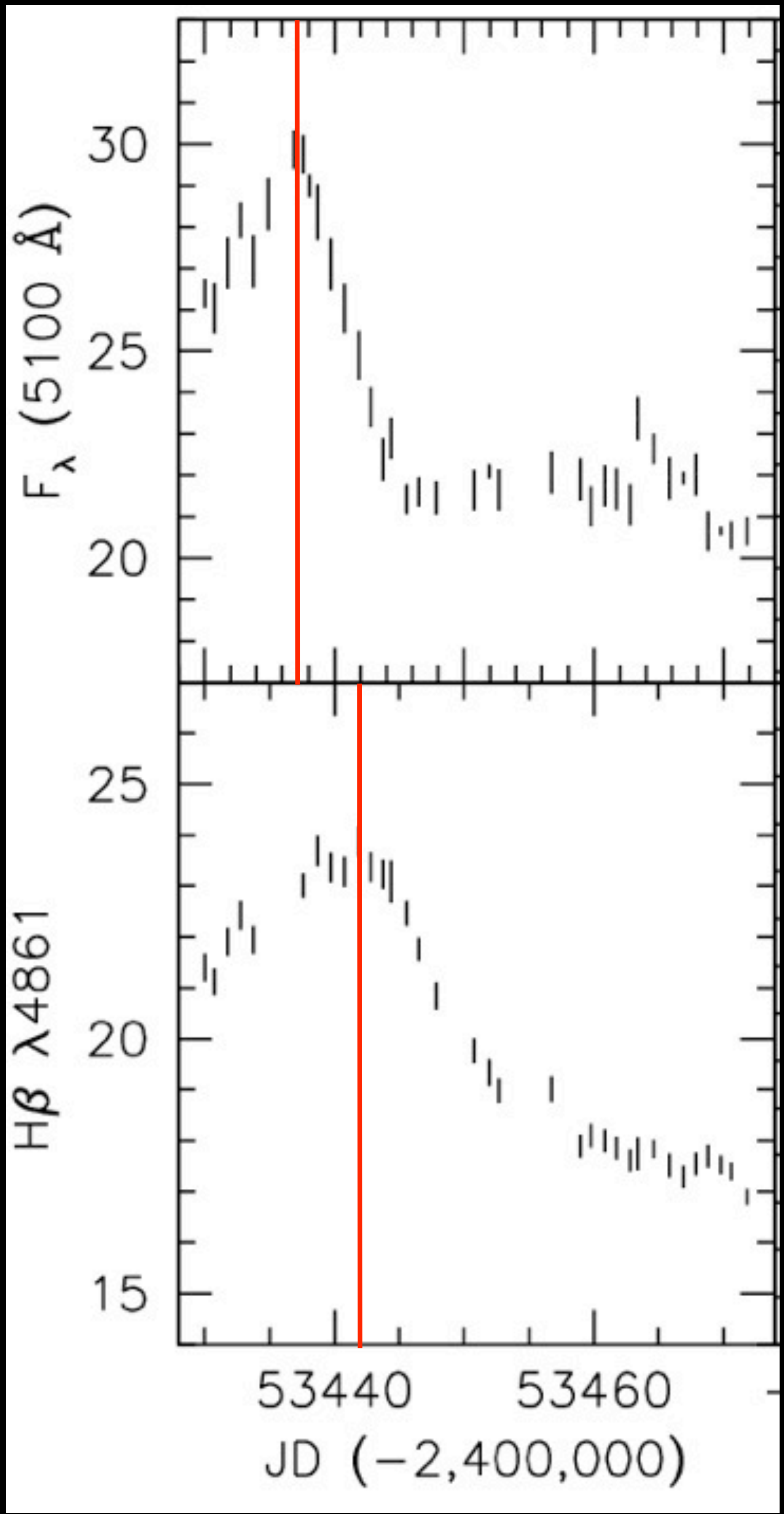
Measuring the BLR Radius -- RM Cartoon



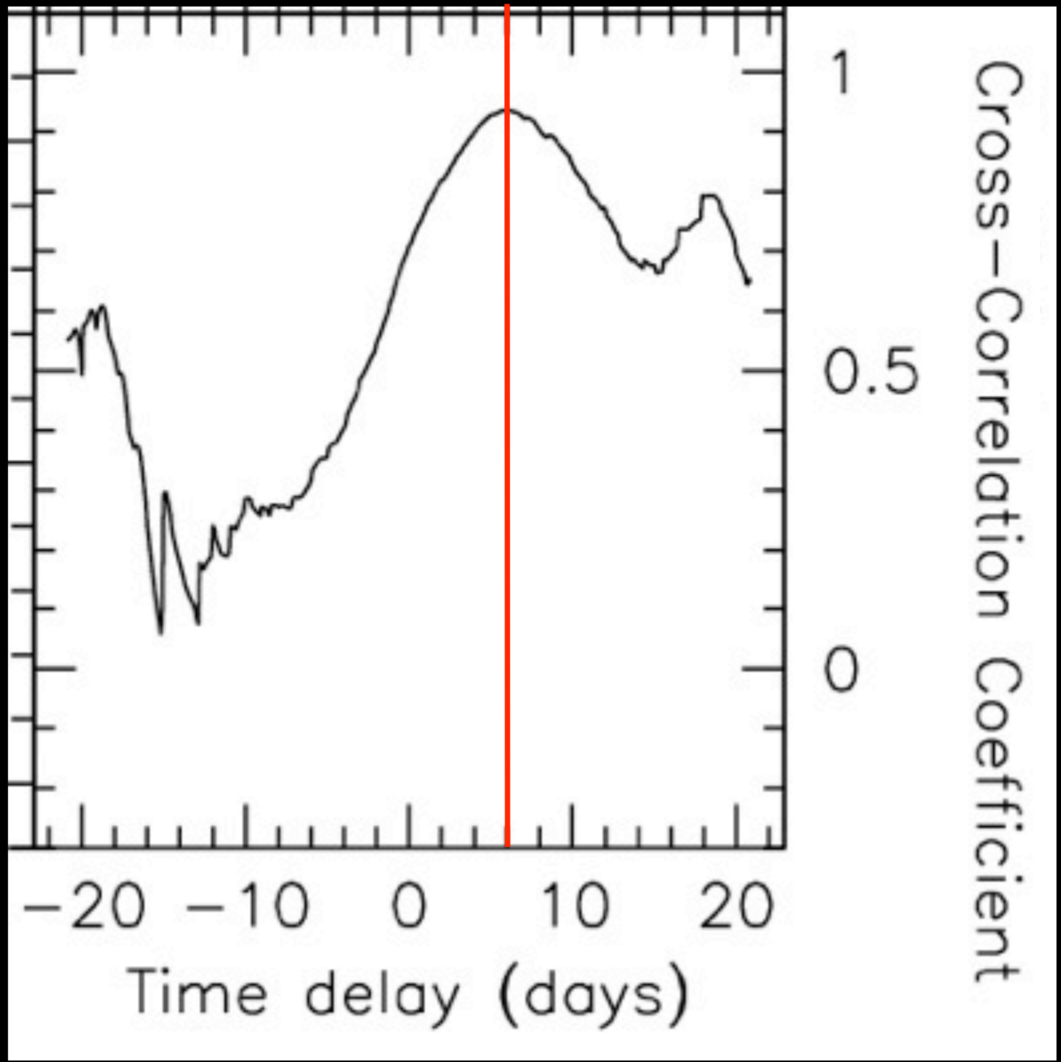
Red = continuum

Purple = broad line

Example Data – NGC 4151

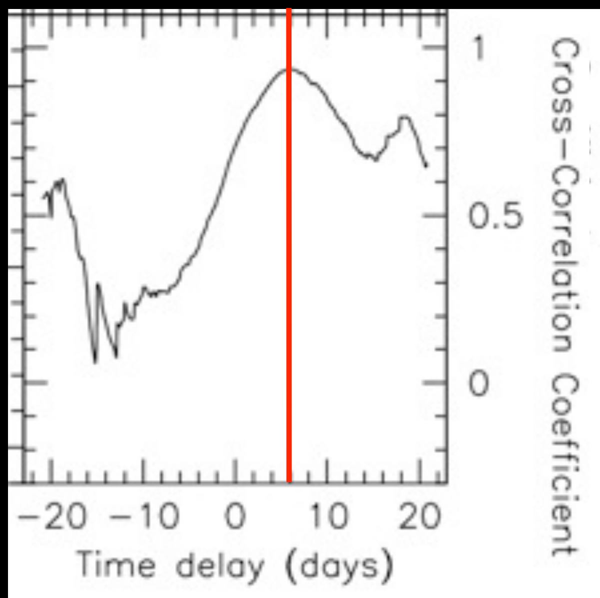


Cross-correlation → time delay of broad line response to continuum variations



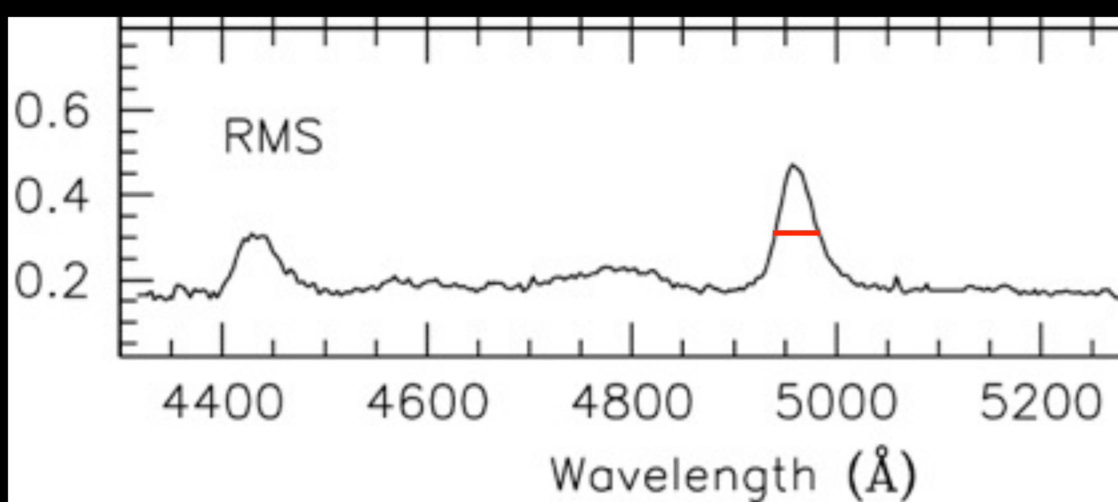
Bentz et al. 2006, ApJ, 651, 775

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



Time delay ($c\tau$) → average BLR radius R

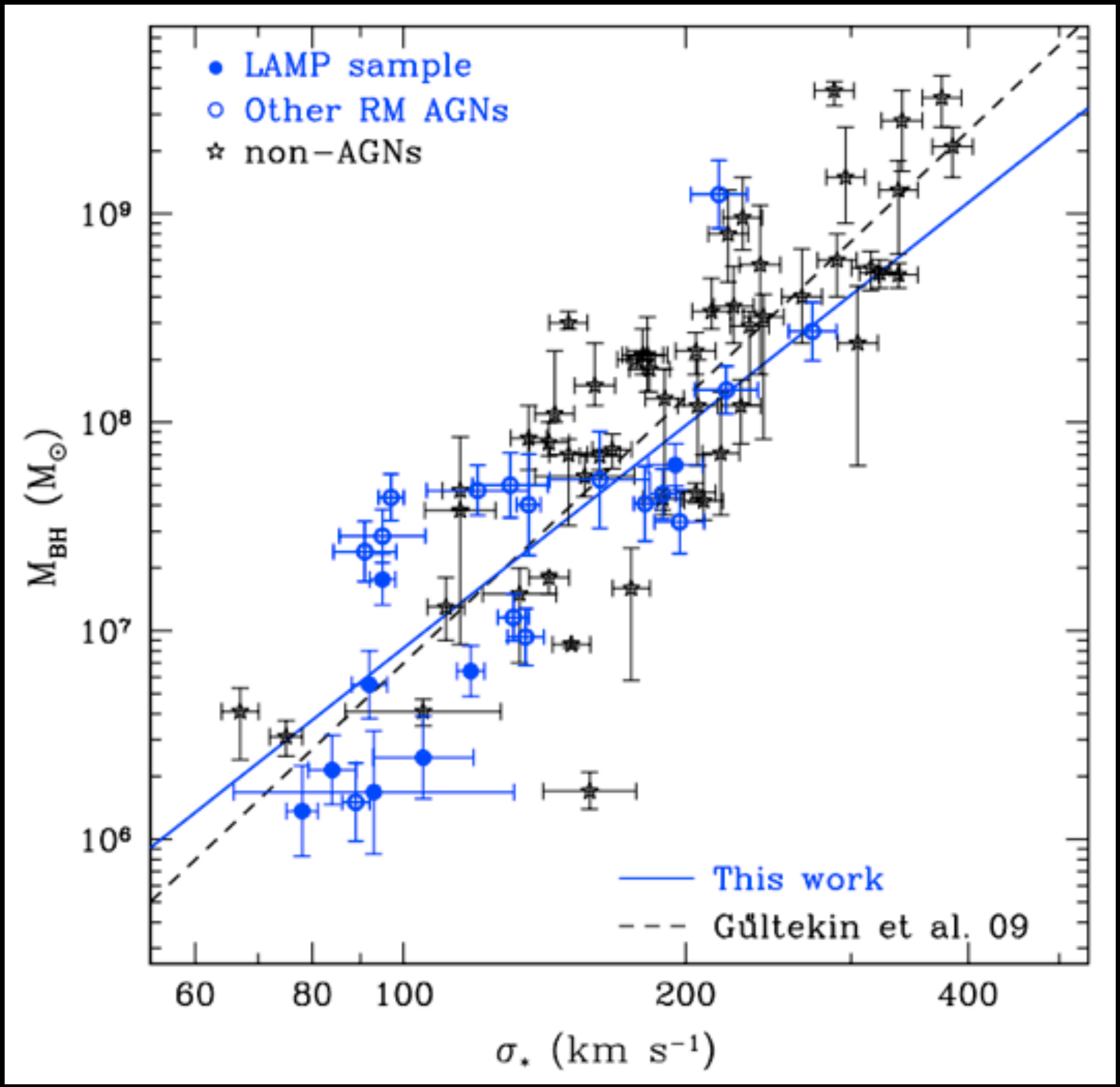
measured for ~50 AGNs



width of variable line emission → line-of-sight BLR gas velocity (V)

f includes BLR physical details (e.g., inclination, geometry, kinematics)

The Fudge Factor *f*



Woo et al. 2010

Assume M_{BH} - σ relationship is same for AGNs and quiescent galaxies

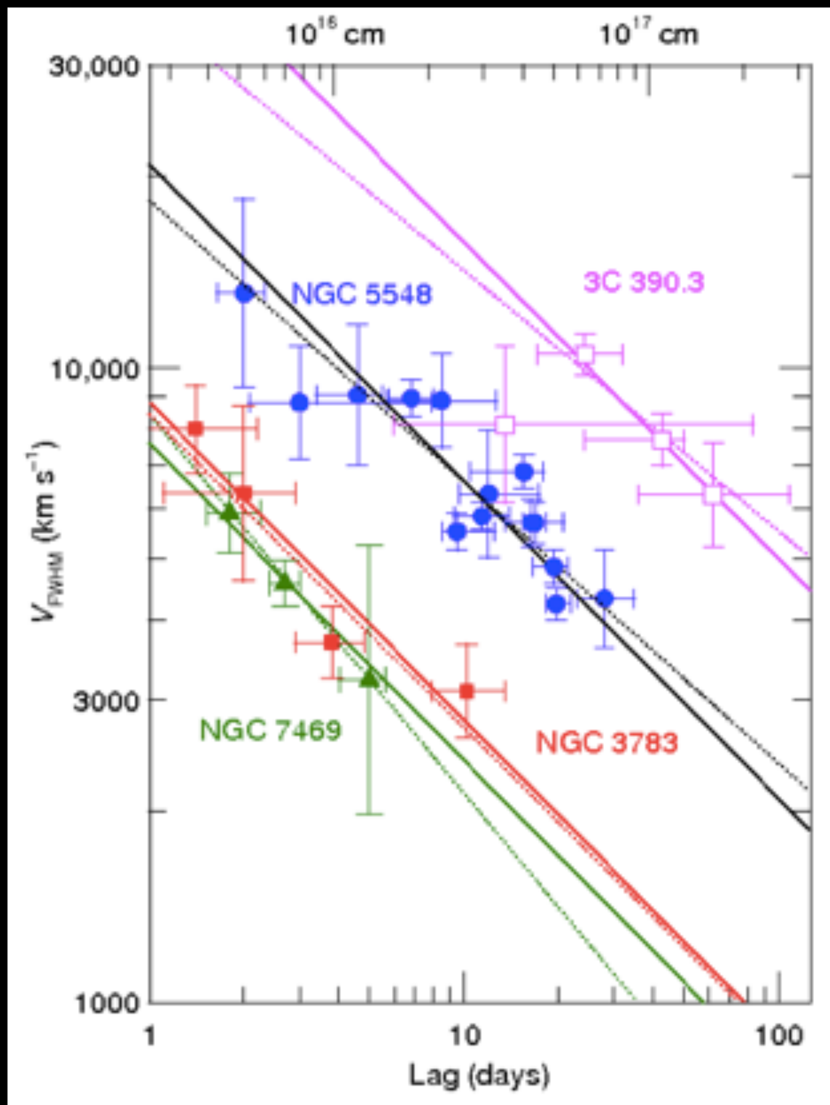
population average:

<f> = 5.2 +/- 1.1

σ difficult to measure for high-L AGNs (*z > 0.1)*

Morphological biases in σ measurements?

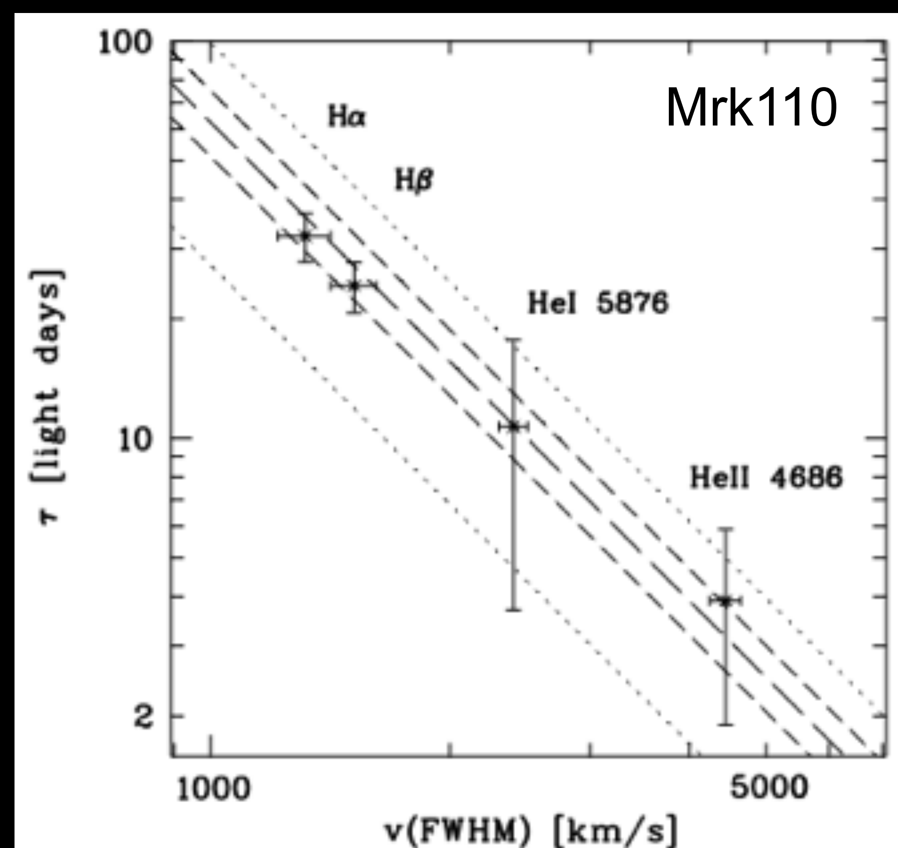
Virial Behavior in the BLR



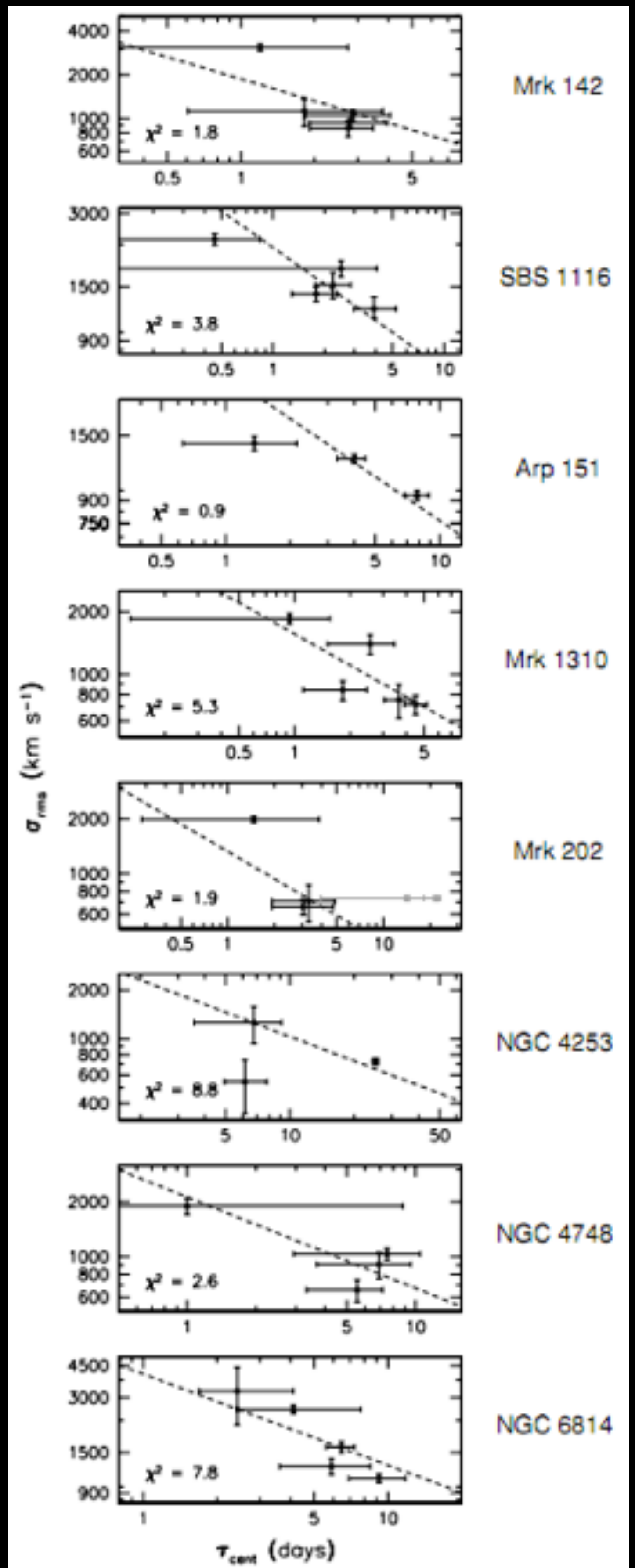
Peterson & Wandel 2002

$V \propto T^{-1/2}$

where measurements exist for multiple emission lines

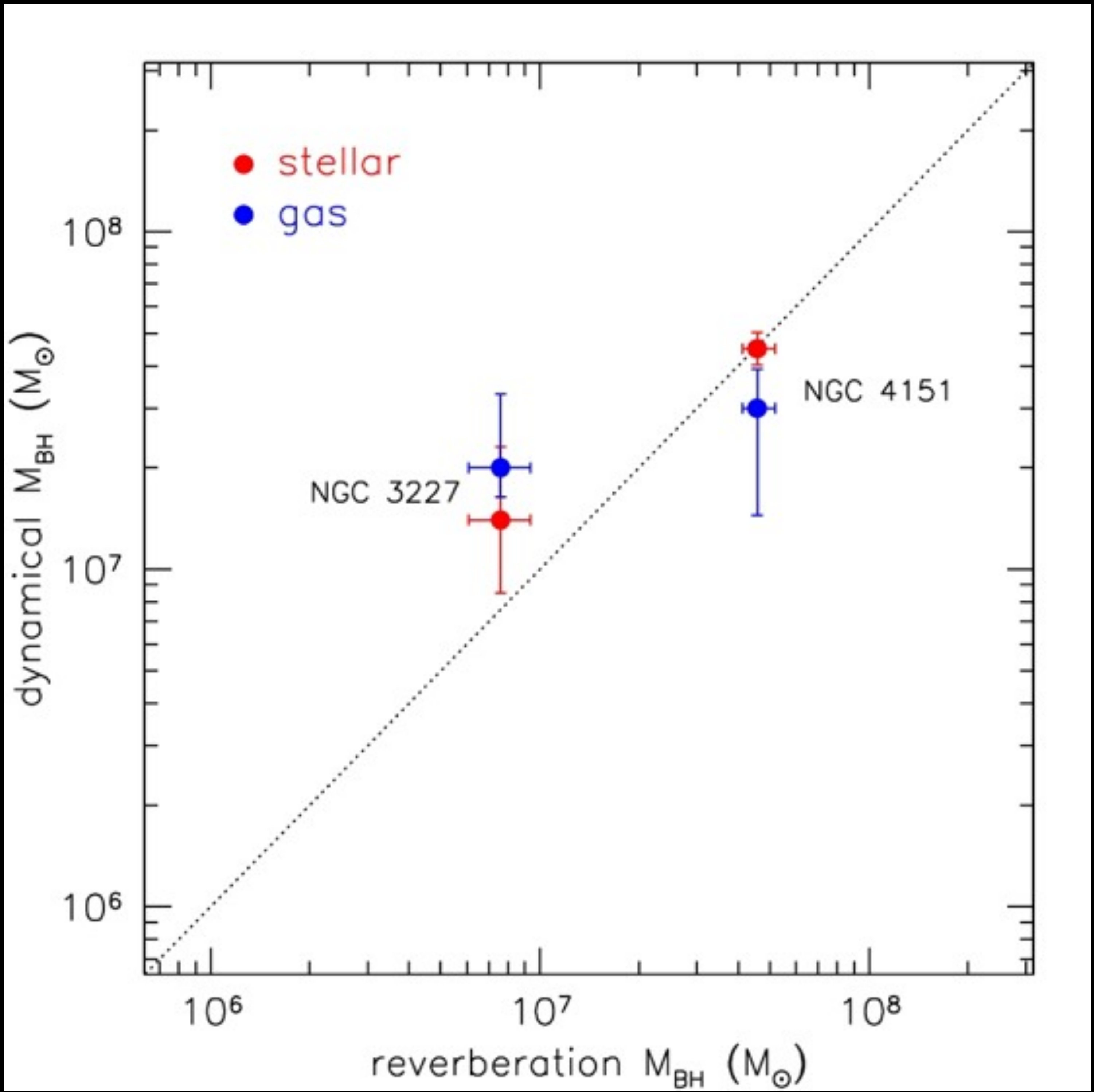


Kollatschny 2003



Bentz et al. 2010

Consistency with Dynamical Masses



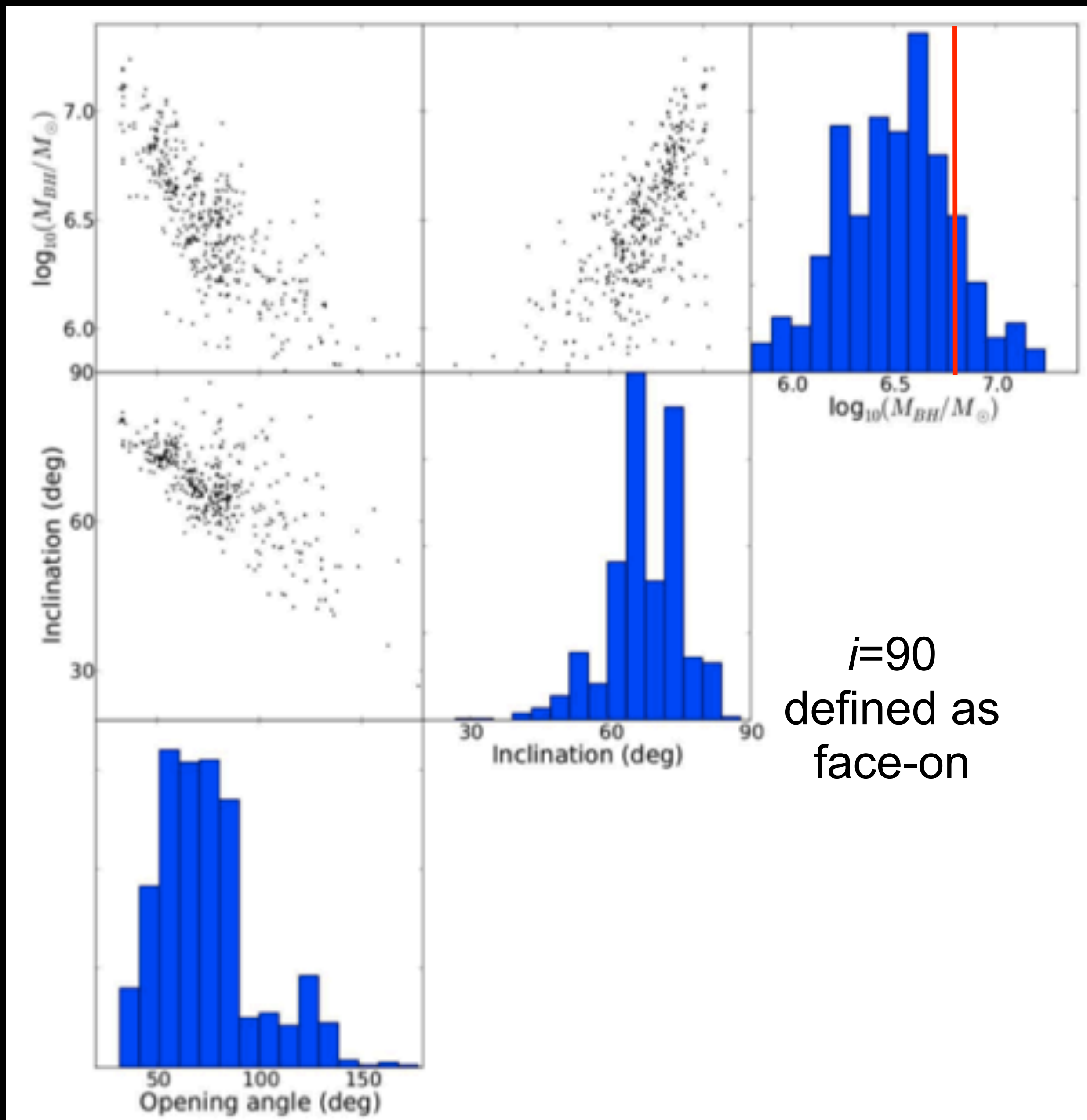
Davies et al. 2006, Onken et al. 2007, Hicks & Malkan 2008

Stellar and gas dynamical measurements for 2 AGNs with RM masses

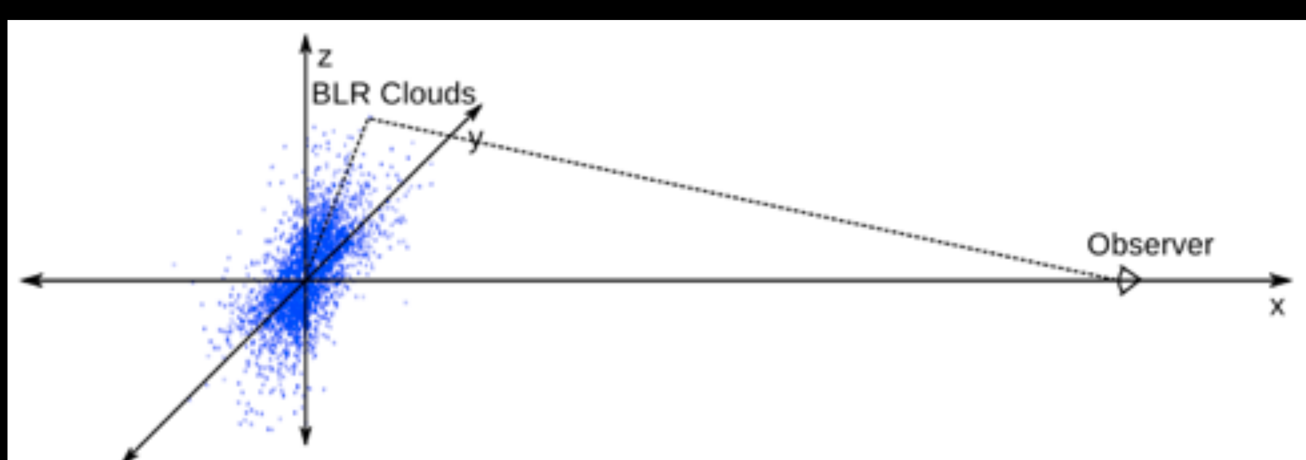
Dynamical and RM masses are generally consistent for NGC 4151 and NGC 3227

More direct comparisons are needed, limited by AGN distances

Bayesian Modeling of RM Data



Brewer et al. 2011



Fits RM datasets with plausible BLR models

Simple RM:

log M_{BH} = 6.82 +/- 0.07

(Bentz et al. 2009)

vs.

Bayesian modeling:

log M_{BH} = 6.51 +/- 0.28

(Brewer et al. 2011)

Models are still simplistic

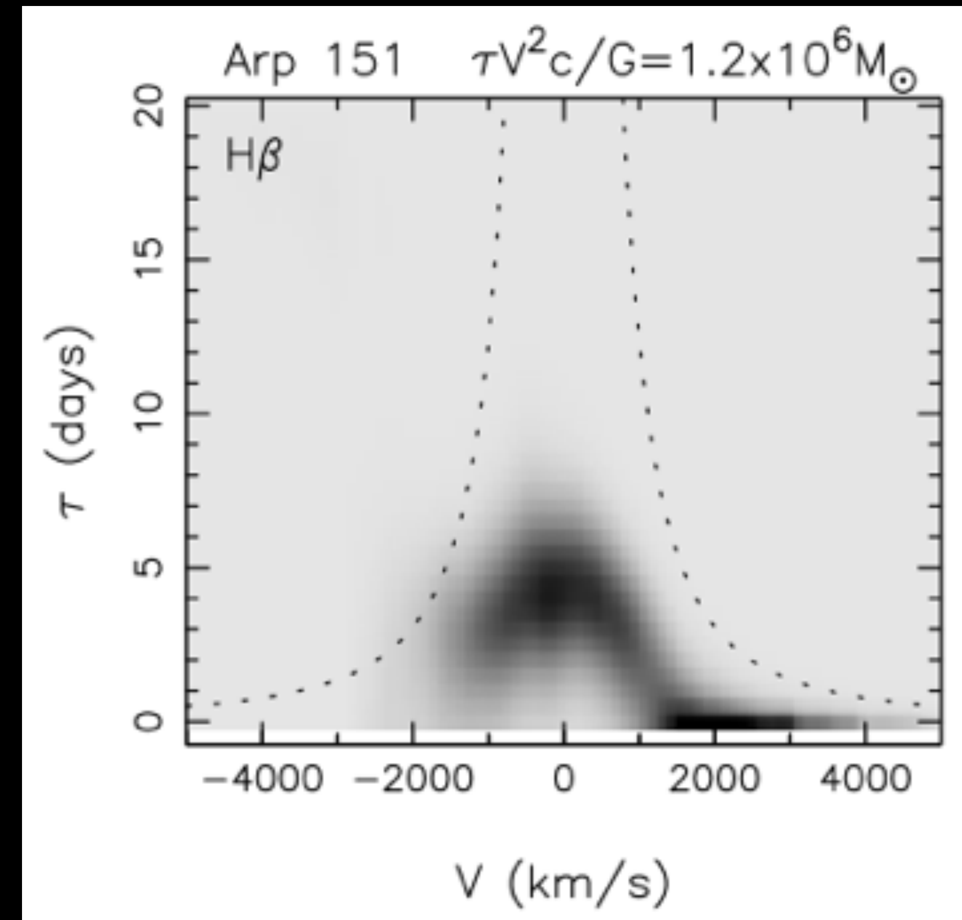
Need to study more objects

Echo Mapping - BLR Transfer Function

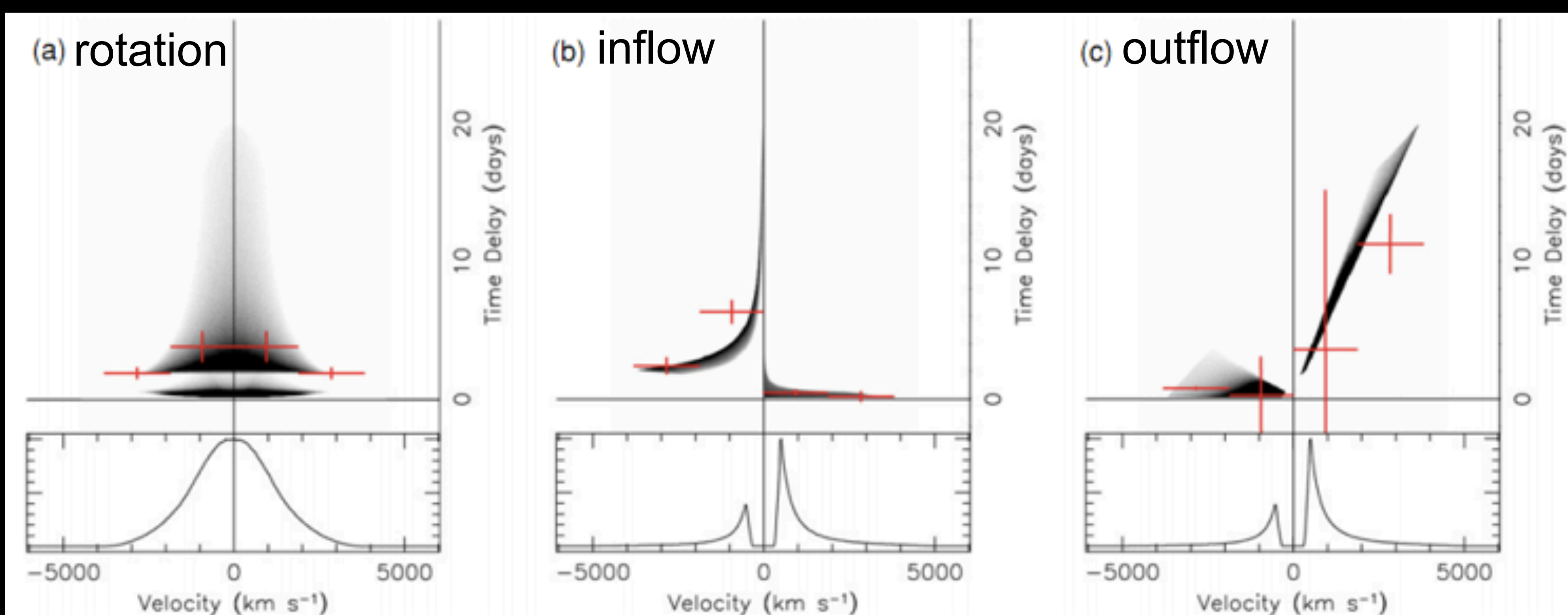
$$\Delta L(v,t) = \int_0^\infty \Psi(v,\tau)\,\Delta C(t-\tau)\,d\tau$$

recovered transfer function rules out outflow

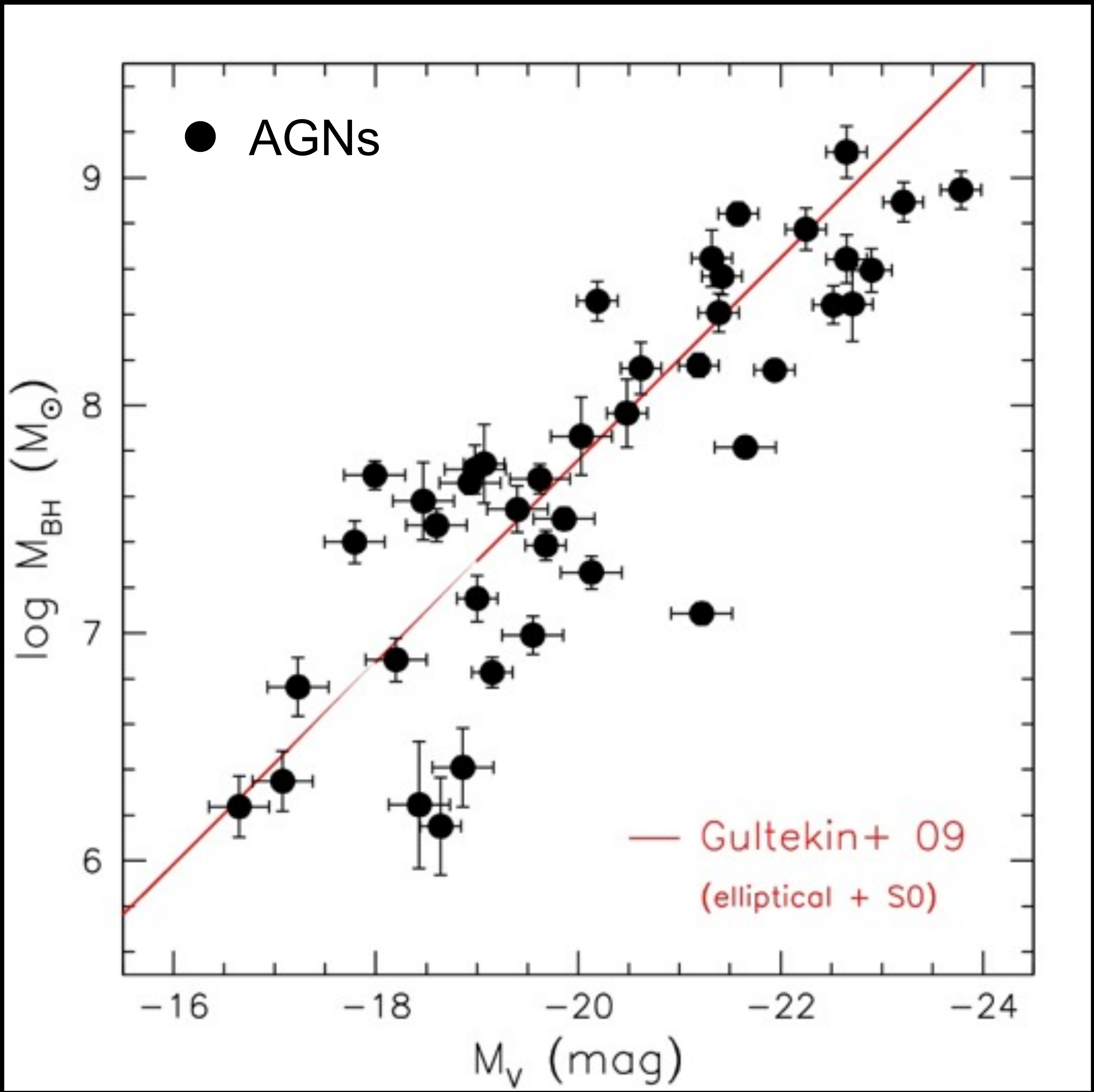
possible evidence for inflow



Bentz et al. 2010



M-L relationship



Bentz et al. 2011, in prep

AGN L_{bulge} from 2-D decomposition of optical HST images

AGN M-L relationship

and

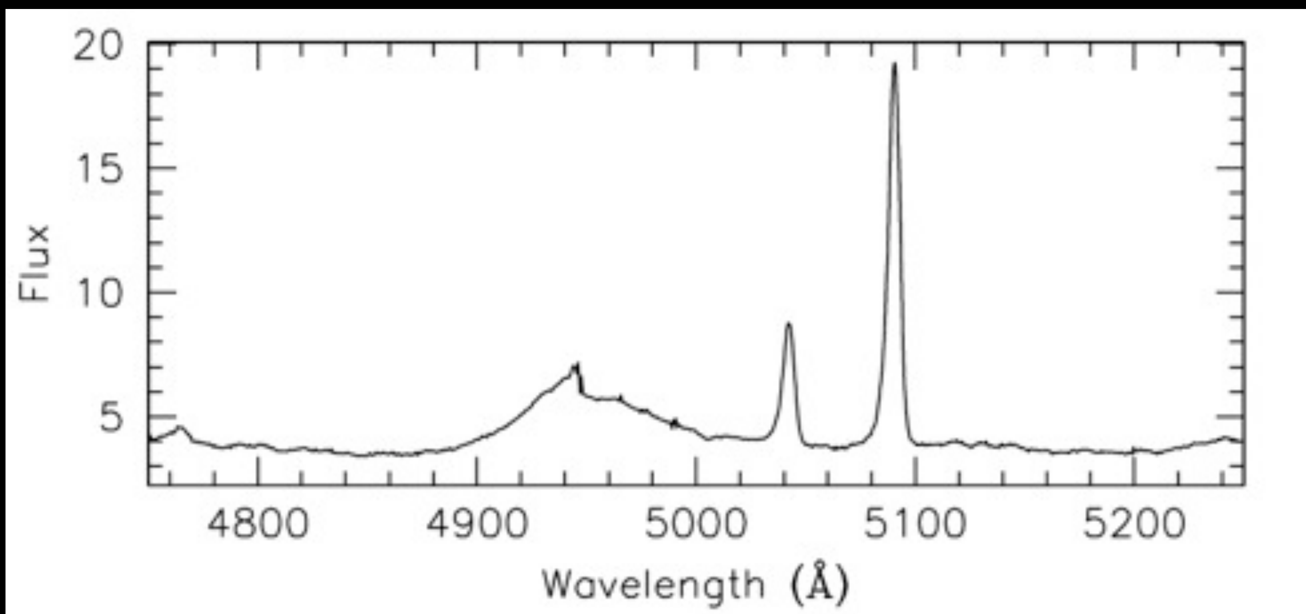
M-L relationship for only early type quiescent galaxies

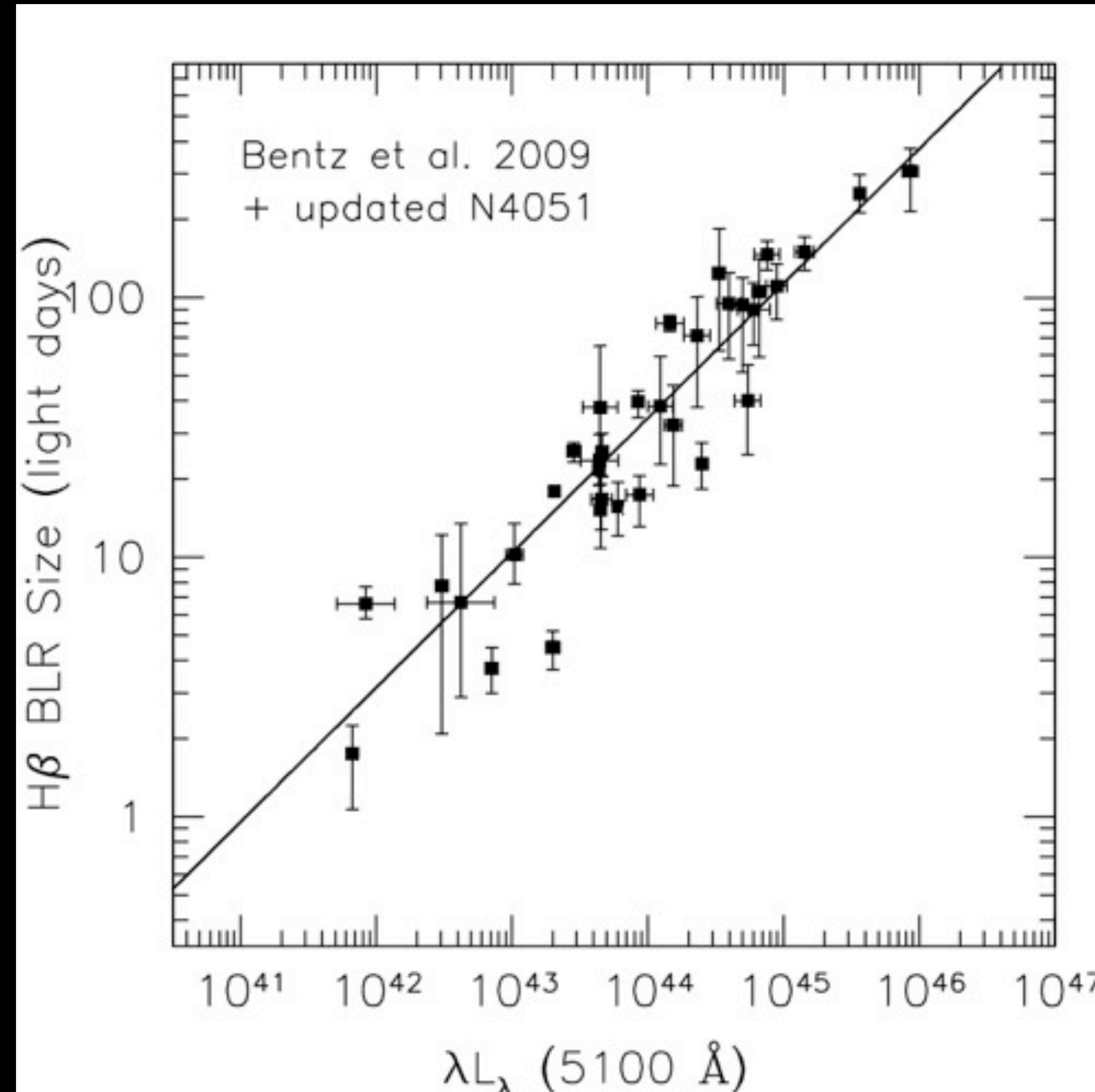
are consistent

Needs to be studied in NIR to minimize dust

Single Epoch M_{BH} Estimates

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

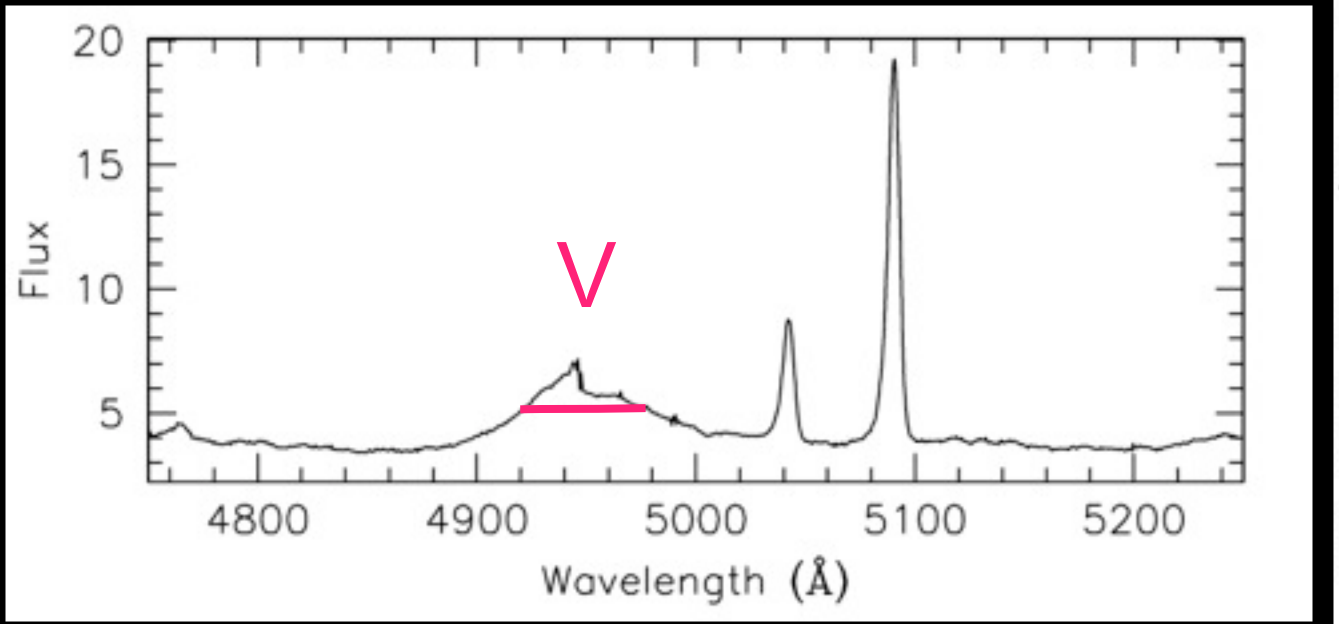


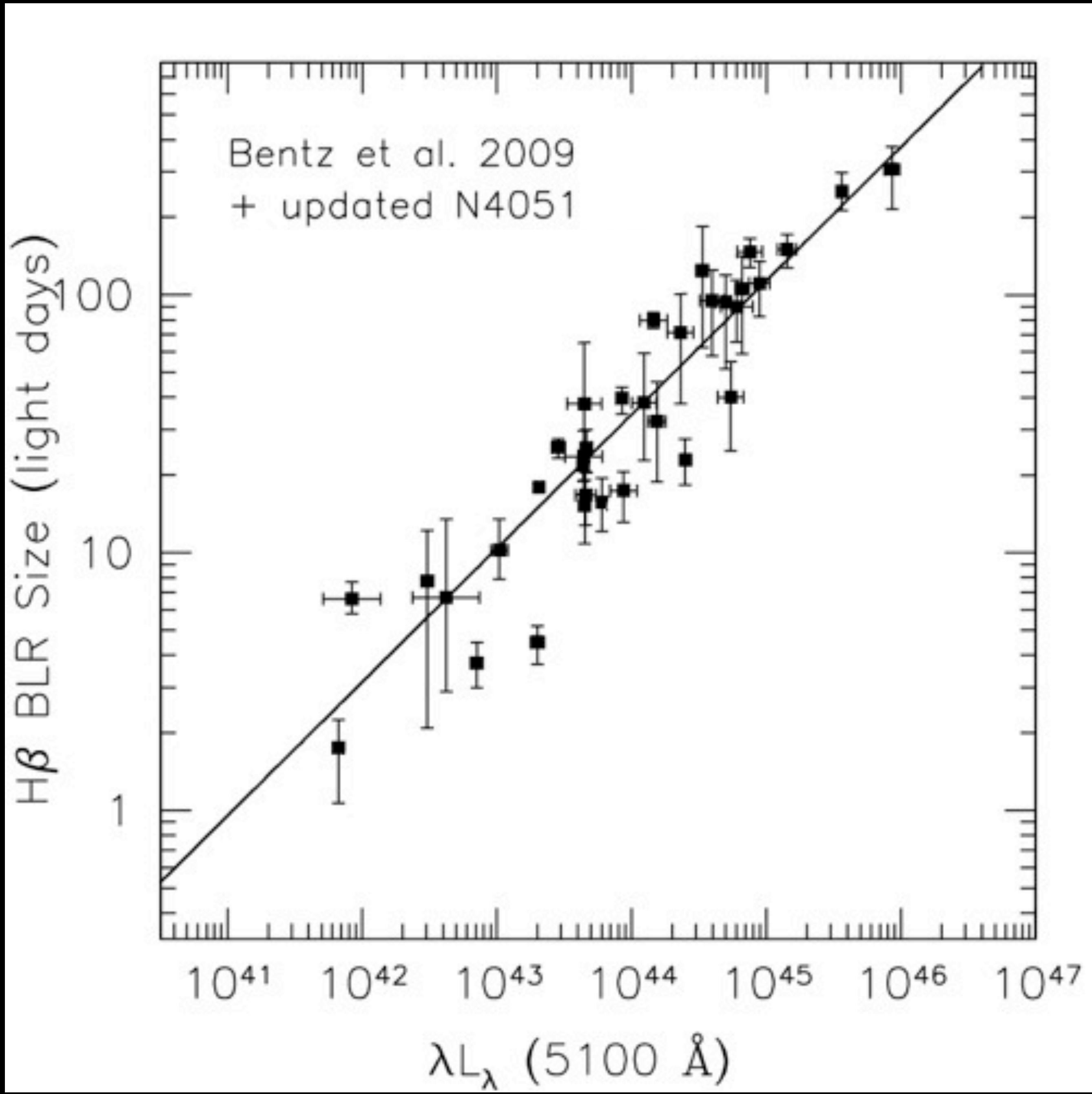


R – *L* relationship yields black hole mass with one spectrum and two measurements:

Single Epoch M_{BH} Estimates

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



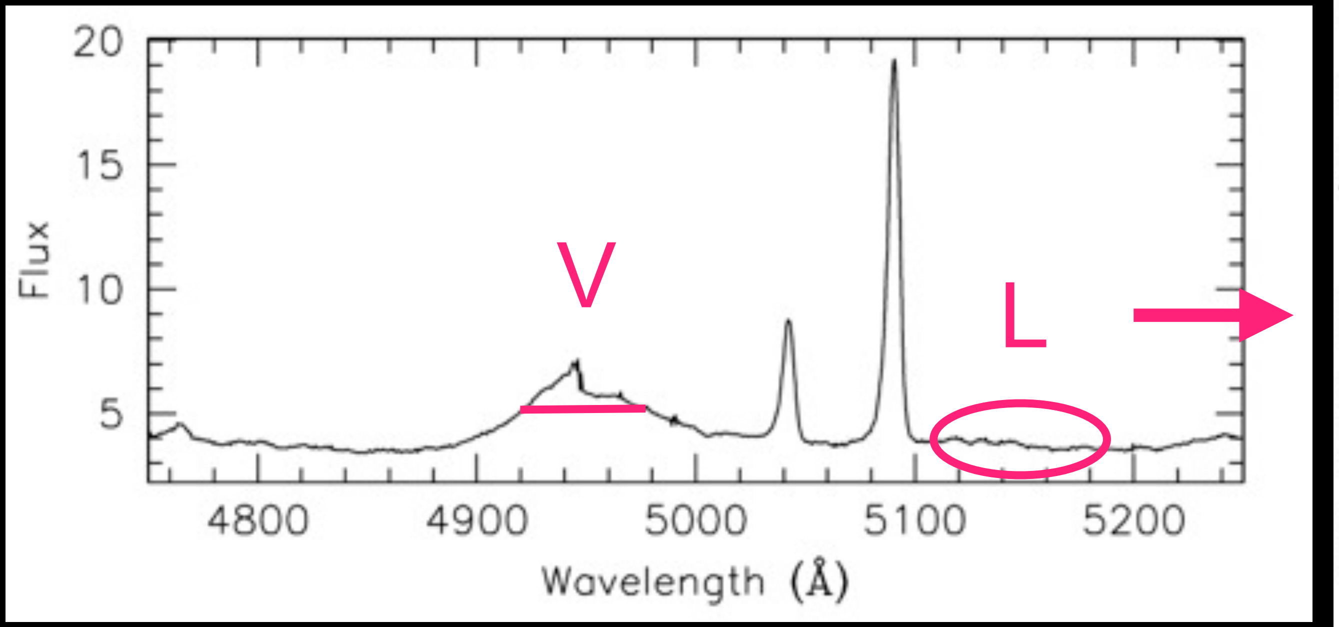


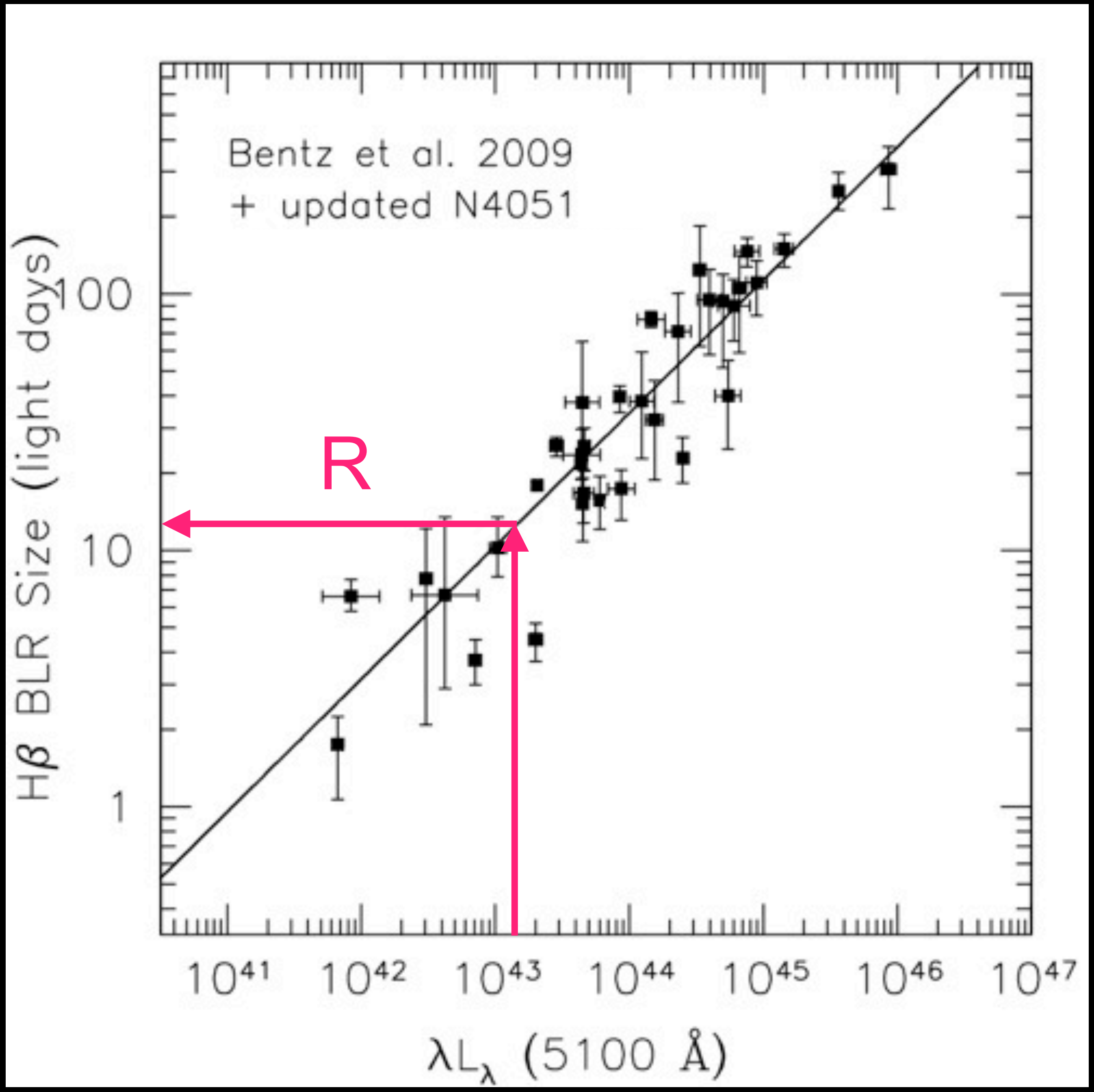
R – L relationship yields black hole mass with one spectrum and two measurements:

1. emission line width (*V*)

Single Epoch M_{BH} Estimates

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





R – *L* relationship yields black hole mass with one spectrum and two measurements:

1. emission line width (*V*)
2. AGN *L* → proxy for *R*

Single Epoch M_{BH} Estimates

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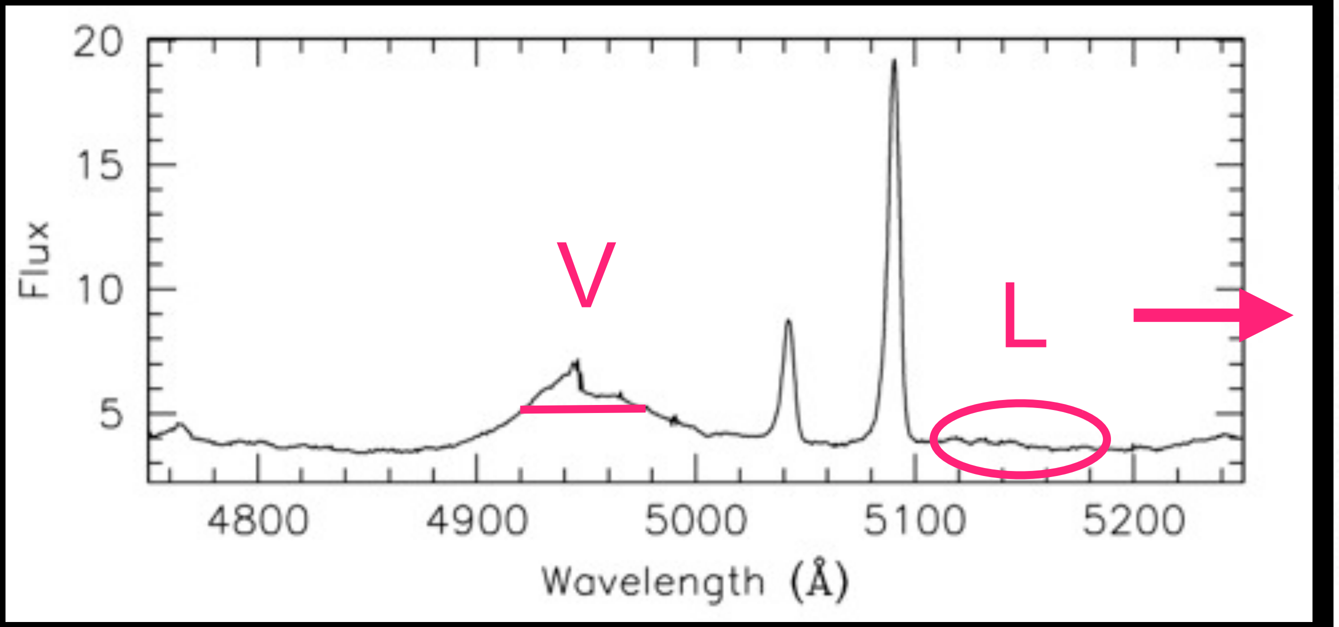
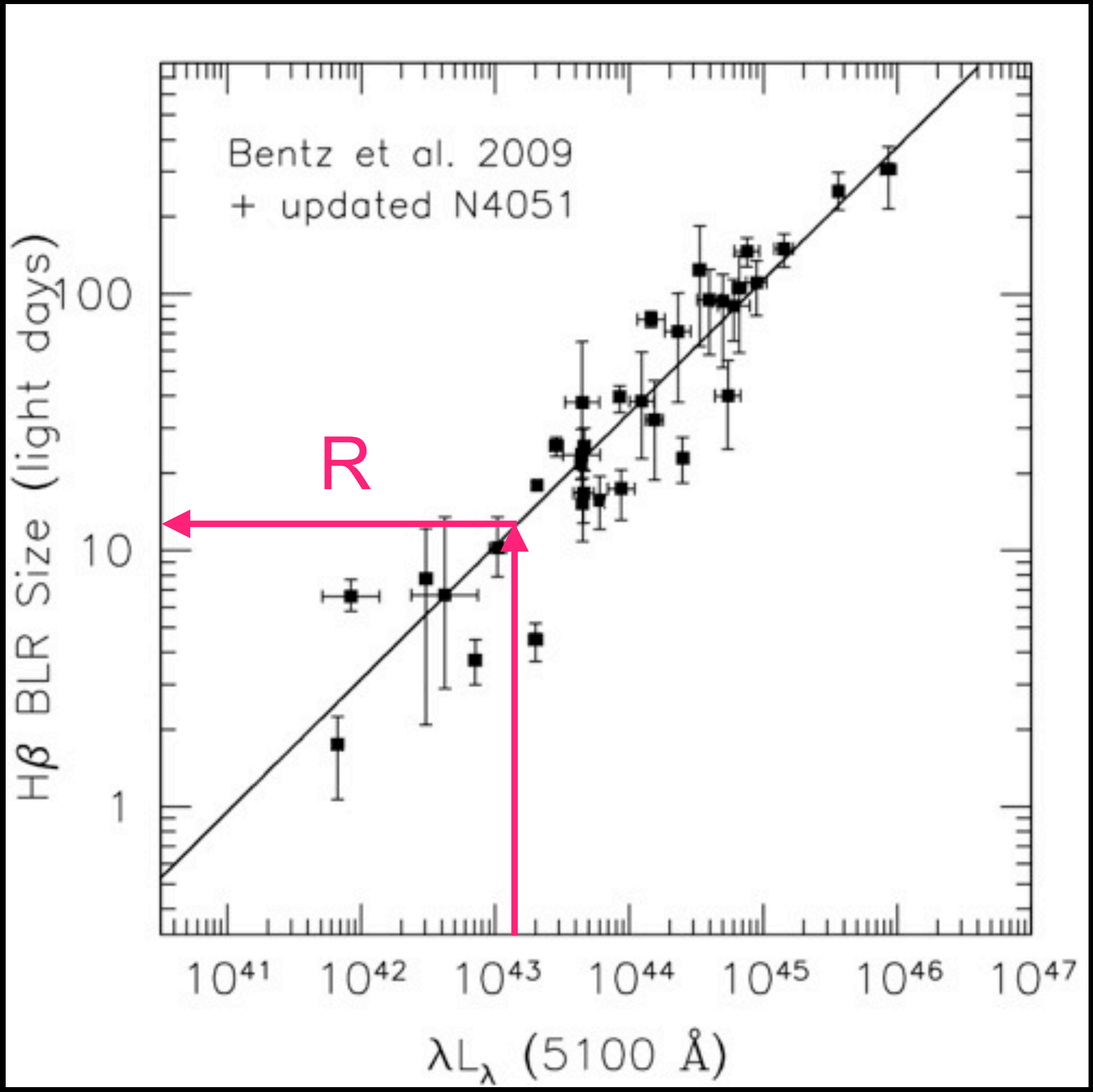




R – L relationship yields black hole mass with one spectrum and two measurements:

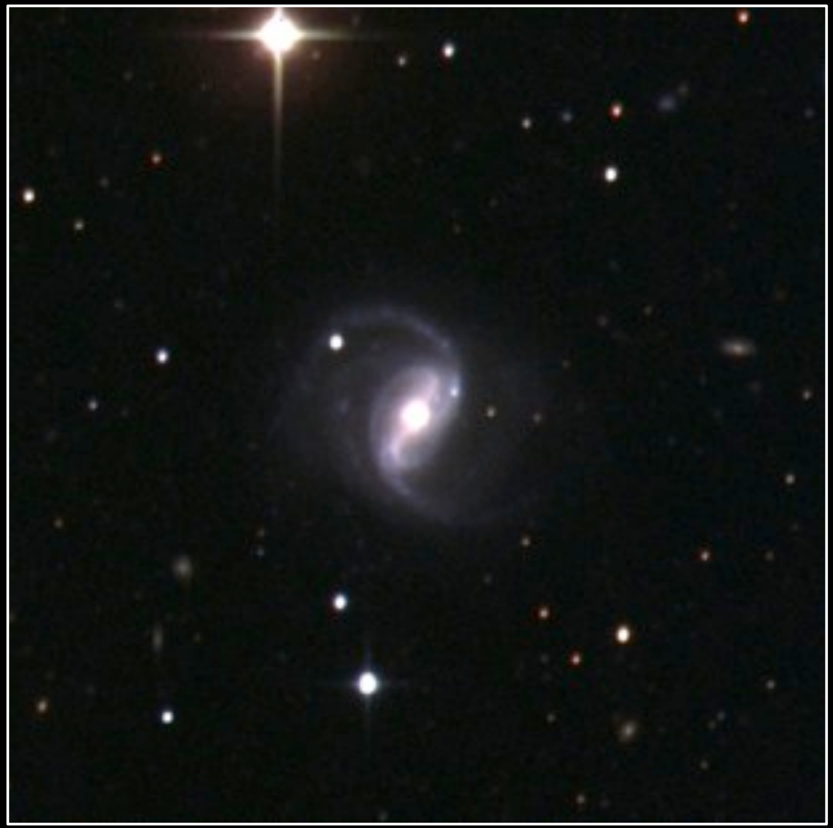
1. emission line width (*V*)
2. AGN *L* → proxy for *R*

ALL mass estimates for AGNs using emission lines are based on the local observed R – L relationship for Hβ

AGN Luminosities – Host Galaxy Starlight

5’ x 5’ images

NGC 4051
z = 0.00234



Mrk 79
z =0.0222

PG 0953+414
z = 0.234

Large slit (i.e. 4”x10”) used to minimize aperture effects
→ strong starlight contamination at low z

Updates to RM Database

MDM 2007

Denney et al. 2010

Hβ Results Summary:

1 new object
3 replacements
2 additions

LAMP 2008

Bentz et al. 2009

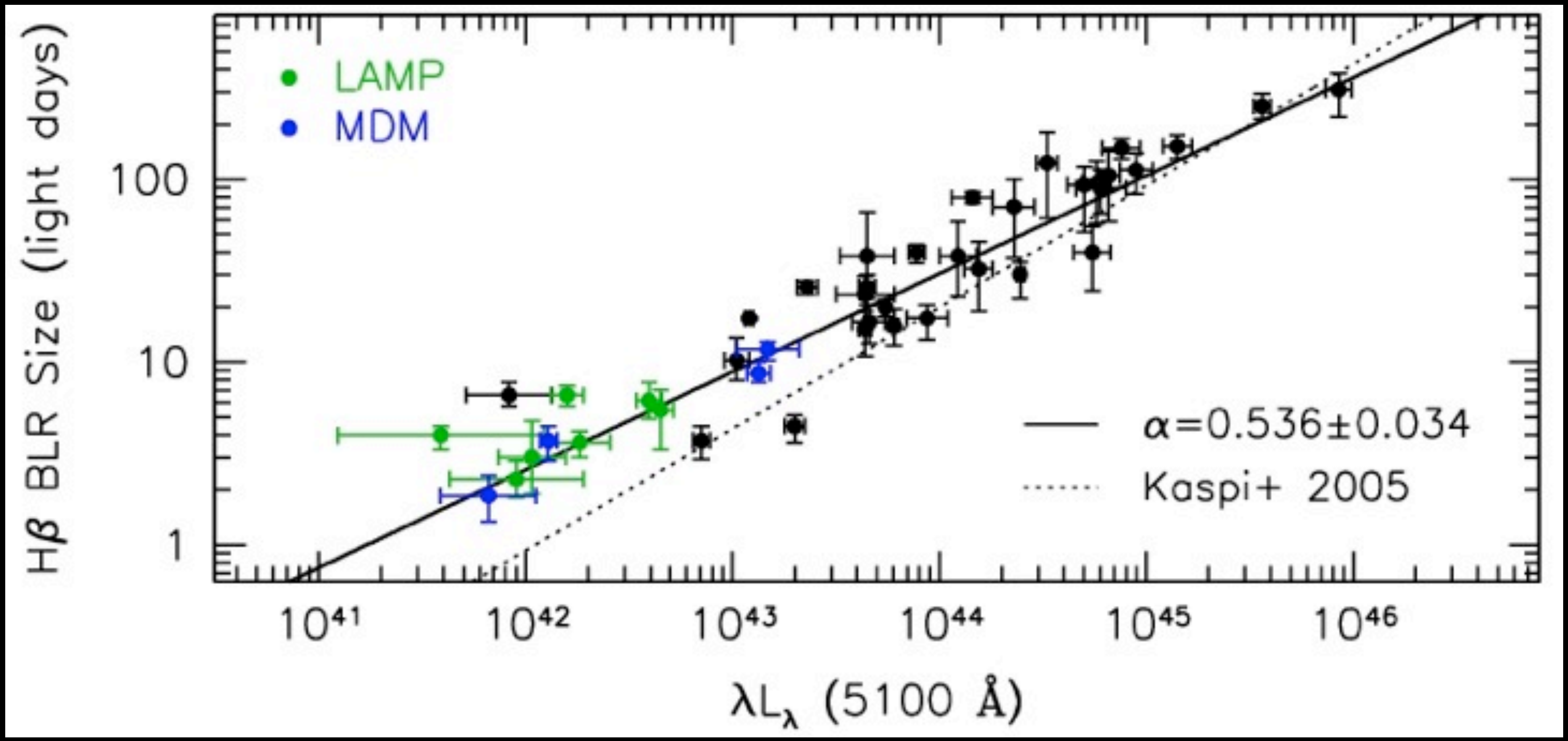
Hβ Results Summary:

7 new objects
1 addition

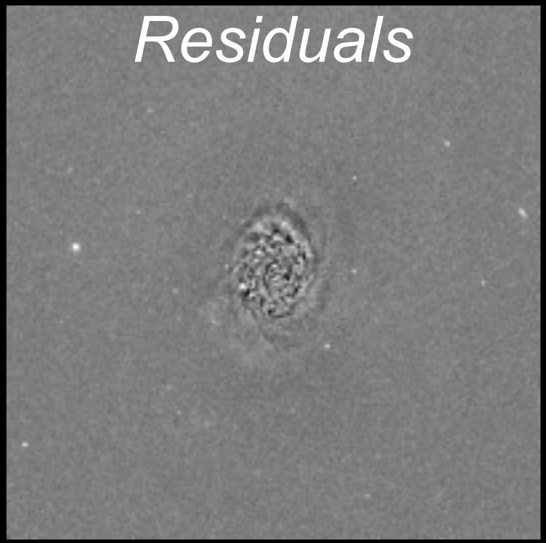
HST Cycle 17 WFC3
Imaging Campaign

Updated Radius - Luminosity Relationship: Preliminary Version

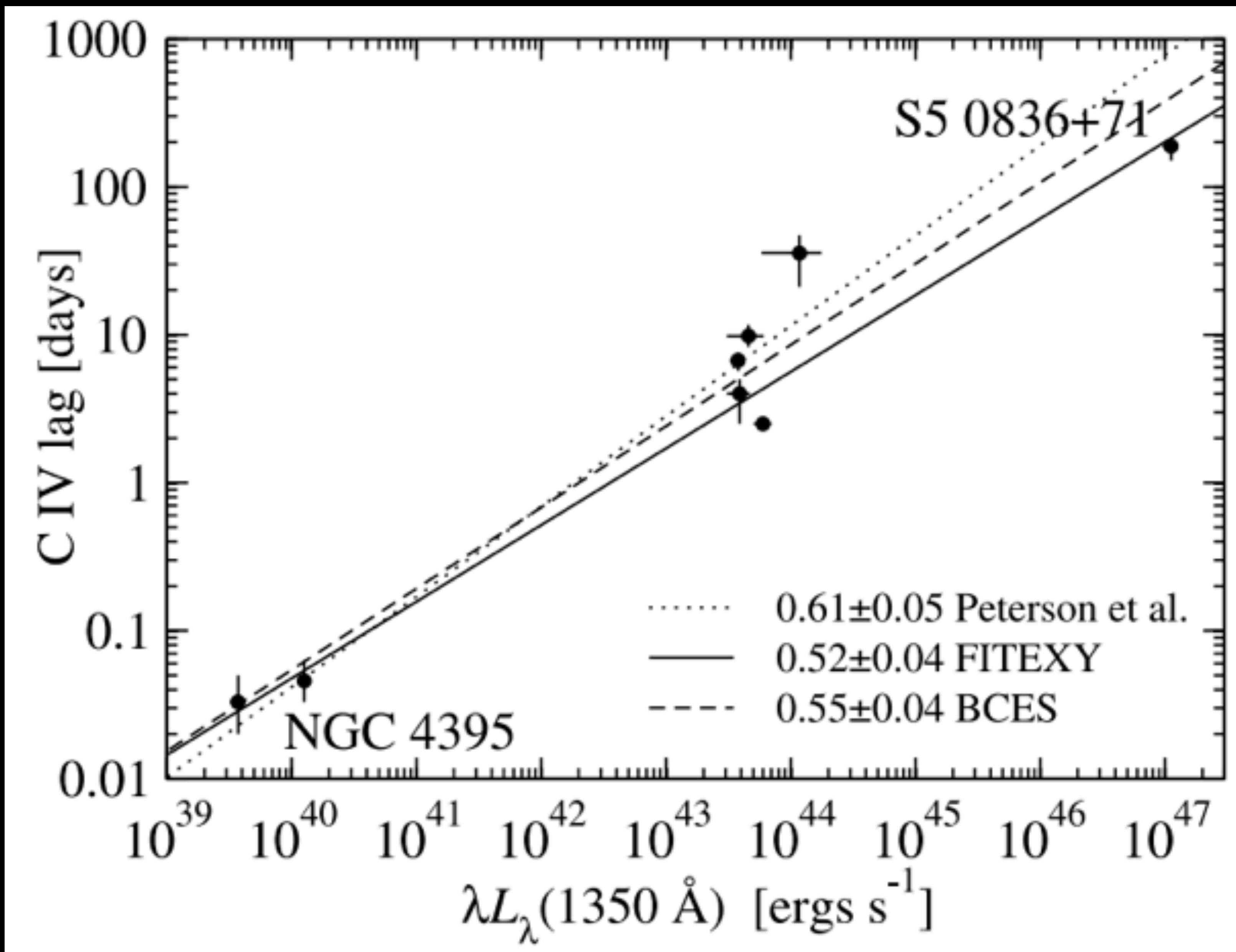
New and replacement measurements in color



Bentz et al. 2011, in prep



CIV R-L Relationship



Kaspi et al. 2007

Slope of CIV R-L
is consistent
with slope of Hβ R-L

Only 7 AGNs,
and 5 have similar
luminosities

Not enough MgII
measurements for
R-L relationship

Summary

- Reverberation mapping substitutes time resolution for spatial resolution and probes the gravity of the BH

- RM masses consistent with dynamics and with Bayesian modeling

- We are just beginning to acquire data that could soon allow direct constraints on the detailed physics of the BLR gas

- The R-L relationship provides a convenient method for estimating M_{BH} in any broad-lined AGN

Some Big Questions:

1. What is the origin of the BLR?

2. What systematic errors are inherent in AGN black hole masses?

3. What (if any) is the role of radiation pressure in the BLR?

4. What is the range of physical characteristics (and *f* values) among BLRs?

5. What are the differences between the optical BLR and the UV BLR (e.g. kinematics or wind launching)?

6. What (if any) are the physical differences between low-z and high-z AGNs?