

This cume will ask about material discussed in the paper “Recalibration of the MBH σ_* Relation for AGN” by Batiste et al. I would read sections 1 and 2 to start to get thinking about the topic, but then just skim through the rest and refer to it as needed.

A 75 percent grade will guarantee a pass.

Gravitational constant $G = 6.67^{-8} \text{cm}^3 \text{gm}^{-1} \text{s}^{-2}$, mass of sun $M_{\text{sun}} = 2 \times 10^{33} \text{gm}$, speed of light $c = 3 \times 10^{10} \text{cm/s}$, $1 \text{pc} = 3.086 \times 10^{18} \text{cm}$

1. Early-type galaxies and observations

- (a) (5 points) Write an equation that provides a definition of stellar velocity dispersion (not an equation about how it might be related to other physical quantities, just a definition).

$$\sigma^2 = \int (v_{\text{los}} - \langle v_{\text{los}} \rangle)^2 F(v_{\text{los}}) dv$$

where $F(v_{\text{los}})$ is the fraction of stars at a given radial velocity. Alternatively, can formulate as a sum over stars.

- (b) (5 points) How would you measure a stellar velocity dispersion of an early-type galaxy, recognizing that absorption features observed in galaxies are generally blends of multiple lines?

Use a template stellar spectrum and determine how much it needs to be broadened to match observed galaxy spectrum.

- (c) (5 points) What are typical central velocity dispersions for luminous early-type galaxies?
100-300 km/sec

- (d) (5 points) What is r_e ? How would you measure it? Be specific.

R_e is the half-light radius. Generally measured by fitting a function (e.g., deVaucouleurs profile or Sersic profile) to observed surface brightness profile

- (e) (5 points) Knowing the velocity dispersion and r_e for an early type galaxy allows one to predict another global observable quantity of the galaxy. What is the relation called that allows you to do this, and what is the observable quantity you can predict?

Fundamental plane relation (alternatively, $D_n - \sigma$) allows you to predict luminosity or surface brightness (i.e., I_e).

- (f) (5 points) What is integral field spectroscopy? Describe how an integral field spectrograph might work (just the integral field part, not the details of the spectrograph part).

Integral field spectroscopy provide spatially resolved spectra over a contiguous 2D patch of the sky.

2. AGN

- (a) (5 points) Make a schematic sketch of what an AGN might look like, showing relative locations of black hole, accretion disk, broad line region and narrow line region

Central black hole surrounded by accretion disk, surrounded by broad line region, surrounded by narrow line region, with some obscuration in plane of accretion disk.

- (b) (5 points) What is meant by the unified model for AGN?

Different types of objects with central activity, e.g. Seyfert type I and II galaxies, quasars, etc., are the same type of object but observed from different viewing angle.

3. Black hole masses in quiescent galaxies

- (a) (5 points) The paper talks about measuring black hole (BH) masses in quiescent galaxies by modeling gas or stellar kinematics within the “gravitational sphere of influence” of the BH, i.e where the gravitational effect of the BH dominates. Give the expression for the radius of the sphere of influence in an early-type galaxy.

Sphere of influence is where velocity from central object is comparable to central velocity dispersion:

$$r = \frac{GM_{BH}}{\sigma_0^2}$$

- (b) (5 points) Apply the formula to calculate the physical size of the sphere of influence for a characteristic early-type galaxy. If your number seems off (or you have no idea of a formula), provide a guesstimate of what you think the physical size should be, with your reasoning.

In cgs units:

$$r = \frac{6.67e \times 10^{-8} 10^8 2 \times 10^{33}}{(250 \times 10^5)^2} \sim 10pc$$

- (c) (5 points) What is the angular size of the sphere of influence for an early type galaxy in the Virgo cluster, which has a mean radial velocity of ~ 1200 km/s? Again, if your number seems off, provide a guesstimate with your reasoning.

At 1200 km/s, $d \sim 17$ Mpc. At 17 Mpc, 10 pc is 0.12 arcsec.

- (d) (5 points) Describe an observational methodology that has been used to measure the central black hole mass in a quiescent galaxy.

4. Black hole masses in active galaxies

- (a) (10 points) Explain in your own words how reverberation mapping works. Draw a sketch to illustrate your explanation. Note that the key issue is how to determine R_{BLR} (see section 2.1).

AGN are variable in the inner regions. If this variability causes increased excitation in lines, the lines will respond some time later, depending on the location of the broad line region and the geometry. If you observe the time lag, you constrain the typical radius of the broad line region. Given the radius and the typical velocity of the region, you constrain the mass inside of it, i.e. the black hole mass.

- (b) (5 points) If a typical broad line width corresponds to a velocity of 3000 km/s, what is a typical value for R_{BLR} in a galaxy with $\sigma = 250$ km/s?

For $\sigma = 250$ km/s, $M_{BH} \sim 10^8$, $f \sim 5$:

$$VP = \frac{M_{BH}}{f} = \frac{V^2 R}{G}$$

$$R = \frac{GM_{BH}}{fV^2} \sim 0.01pc$$

