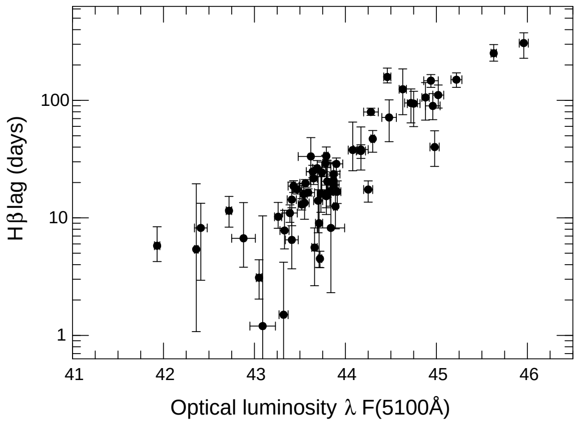
Reverberation Mapping

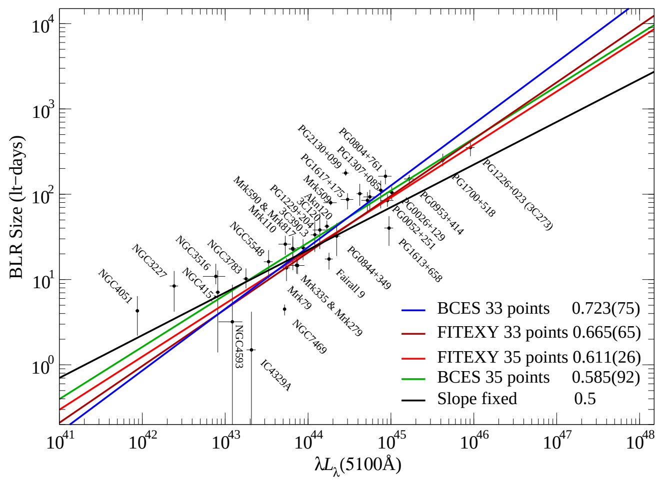


(Peterson, 2006, Fig. 6)

The photoionization parameter was $U \propto L/(D^2 n_e)$ (Eq. 7.20) so for U, n_e constant, we expect $D \propto L^{0.5}$. This is roughly what is observed!

$U =$ const. is expected since AGN spectra are all similar, so conditions in BLR are similar everywhere ("locally optimally emitting clouds").

Reverberation Mapping

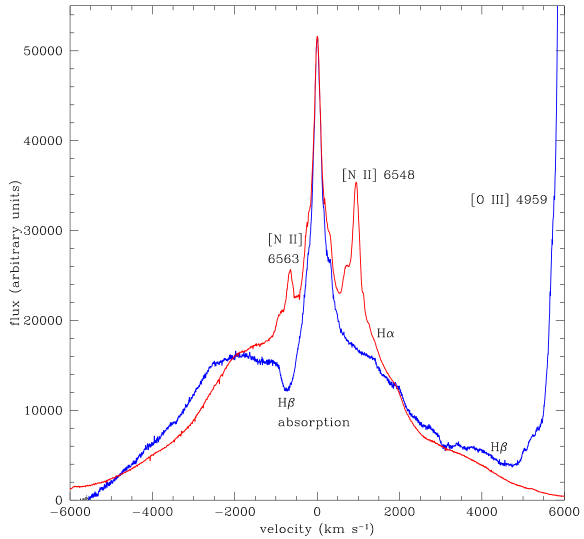


(Kaspi et al., 2005, Fig. 2)

In detail, things are more complicated, and slope is steeper than 0.5: $R \propto L^{0.67 \pm 0.05}$

$\Longrightarrow$ ionization parameter, density, and spectral shape depend somewhat on L.

What is the BLR?, I



NGC 4151 (Sy 1; Arav et al., 1998, Fig. 1)

Classical assumption: BLR is collection of cold clouds embedded in hot gas

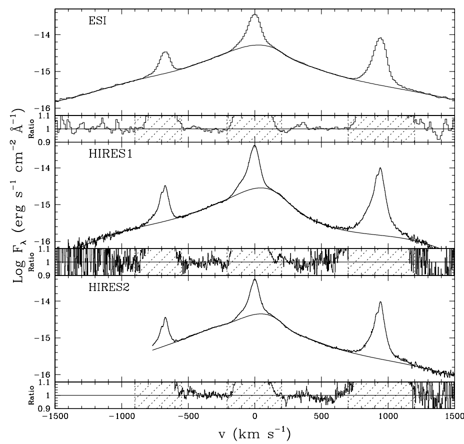
("two phase medium", Krolik, McKee & Tarter 1981)

$\Longrightarrow$ We expect to see evidence for emission from individual clouds.

Problem: BLR line profiles are *always* smooth!

$\Longrightarrow$ Does the BLR consist of *many* small clouds?

What is the BLR?, II



(NGC 4395 Laor et al., 2006)

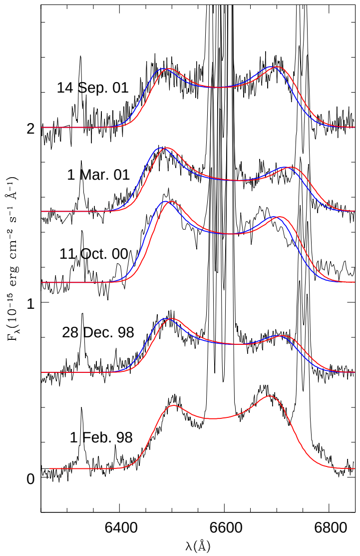
Observations show always smooth BLR profiles, even for lowest luminosity AGN such as NGC 4395 (the lowest luminosity Sy 1 known)

$\Longrightarrow$ this is only possible if there is a *very large* number of clouds such that it is better to speak about a "clumpy" gas.

For NGC 4151, Arav et al. (1998) find that there must be $\gtrsim 3 \times 10^7$ clouds, for NGC 4395, $> 10^5$ clouds are required (Laor et al., 2006). Since $R_{\text{BLR, 4395}} \sim 10^{14}$ cm from reverberation, $R_{\text{cloud, 4395}} \lesssim 10^{12}$ cm, i.e., much smaller than stars.

The BLR cannot consist of individual clouds, it rather is a smooth(ish) gas cloud surrounding the BH.

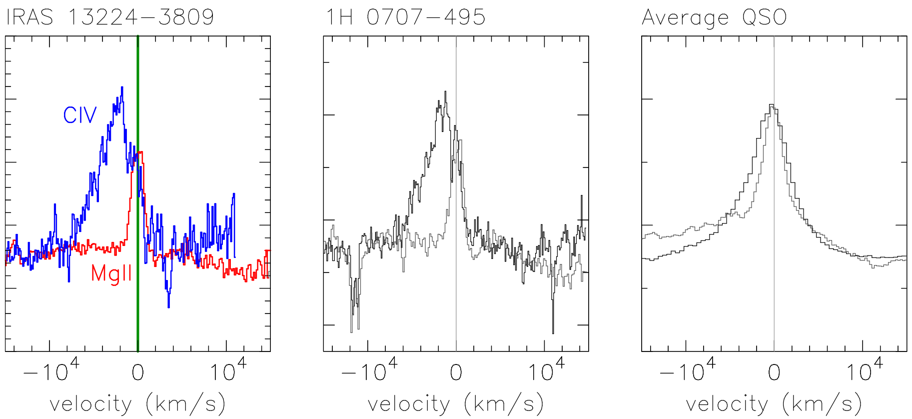
What is the BLR?, IV



In some AGN BLR profiles are double humped
⟹ is BLR the outer edge of accretion disk?

NGC 1097 (Sy1; Storchi-Bergmann et al., 2003, Fig. 8)

Winds



(Leighly & Moore, 2004)

While disk emission explains part of BLR emission, not all features can be explained: Sy 1 show asymmetric line profiles: Higher ionization lines are shifted bluewards ⟹ Outflow!

Winds

There are also findings that the line blueshift increases with AGN luminosity: evidence for radiatively driven outflows?

Is the BLR an accretion disk wind?

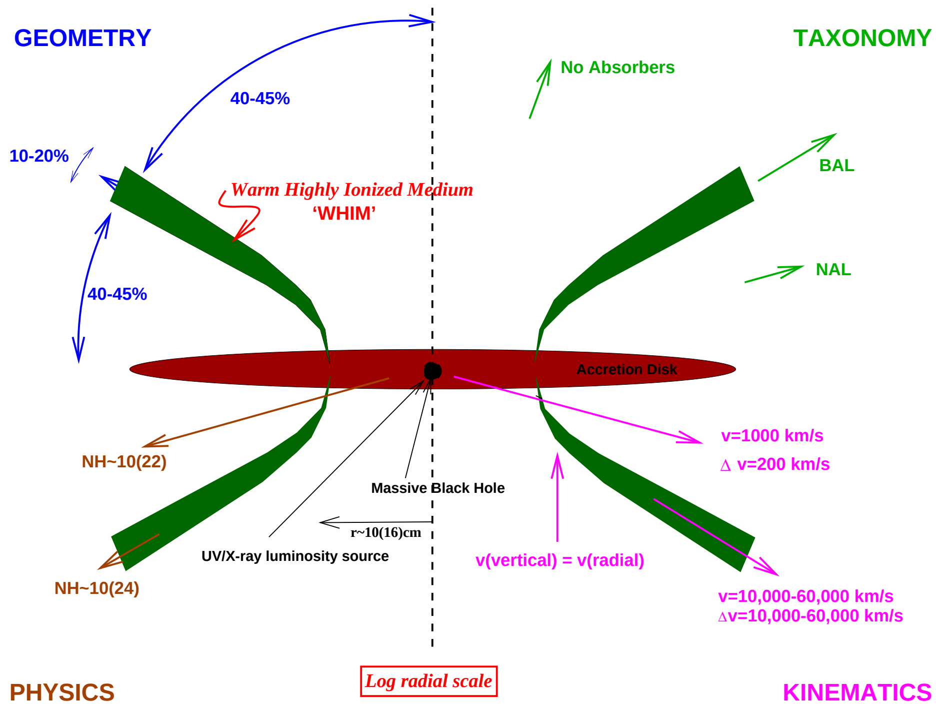
Driving mechanisms:

- Electromagnetic?

  related to jet?

- Radiatively driven?

  related to high AGN luminosity



BH Masses

Regardless of the detailed interpretation of the BLR, measurements of the BLR allow for a (statistical) determination of the mass of the Black Hole:

The virial theorem of mechanics states:

$$2T = \frac{1}{2}m\Delta V^2 = \eta \cdot G\frac{mM_{\mathrm{BH}}}{r_0} = U \tag{8.28}$$

where m mass of a test particle, r_0: characteristic BLR radius, ΔV: velocity dispersion, and η: geometry dependent factor.

Since r_0 and ΔV can be measured from reverberation mapping and the line width:

$$M_{\mathrm{BH}} = \frac{fr\Delta V^2}{G} \tag{8.29}$$

where f is a geometry dependent normalization factor, obtained from calibration measurements.

Note: For virial theorem to apply, motion of BLR must be dominated by gravity.

To derive the virial theorem, we look at a system of particles of mass m_i. The acceleration on particle i by all other particles is

$$\ddot{\mathbf{r}} = \sum_{j\neq i} \frac{Gm_j(\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{8.30}$$

...scalar product with $m_i\mathbf{r}_i$

$$m_i\mathbf{r}_i \cdot \ddot{\mathbf{r}}_i = \sum_{j\neq i} \frac{Gm_im_j\mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{8.31}$$

...since

$$\frac{1}{2}\frac{\mathrm{d}^2\mathbf{r}_i^2}{\mathrm{d}t^2} = \frac{\mathrm{d}}{\mathrm{d}t}(\dot{\mathbf{r}}_i \cdot \mathbf{r}_i) = \ddot{\mathbf{r}}_i \cdot \mathbf{r}_i + \dot{\mathbf{r}}_i \cdot \mathbf{r}_i \tag{8.32}$$

...therefore Eq. (8.31)

$$\frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}(m_i\mathbf{r}_i^2) - m_i\dot{\mathbf{r}}_i^{\,2} = \sum_{j\neq i} \frac{Gm_im_j\mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{8.33}$$

Summing over all particles in the system gives

$$\frac{1}{2}\sum_i \frac{\mathrm{d}^2}{\mathrm{d}t^2}(m_i\mathbf{r}_i^2) - \sum_i m_i\dot{\mathbf{r}}_i^{\,2} = \sum_i\sum_{j\neq i} \frac{Gm_im_j\mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|^3} \tag{8.34}$$

$$= \frac{1}{2}\left(\sum_i\sum_{j\neq i} Gm_im_j\frac{\mathbf{r}_i \cdot (\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_i - \mathbf{r}_j|^3} + \sum_j\sum_{i\neq j} Gm_jm_i\frac{\mathbf{r}_j \cdot (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_j - \mathbf{r}_i|^3}\right) \tag{8.35}$$

$$= \frac{1}{2}\left(\sum_i\sum_{j\neq i} Gm_im_j\frac{\mathbf{r}_i \cdot \mathbf{r}_j - \mathbf{r}_i^2}{|\mathbf{r}_i - \mathbf{r}_j|^3} + \sum_j\sum_{i\neq j} Gm_jm_i\frac{\mathbf{r}_j \cdot \mathbf{r}_i - \mathbf{r}_j^2}{|\mathbf{r}_j - \mathbf{r}_i|^3}\right) \tag{8.36}$$

$$= -\frac{1}{2}\sum_{\substack{i,j\\ i\neq j}} \frac{Gm_im_j}{|\mathbf{r}_i - \mathbf{r}_j|} \tag{8.37}$$

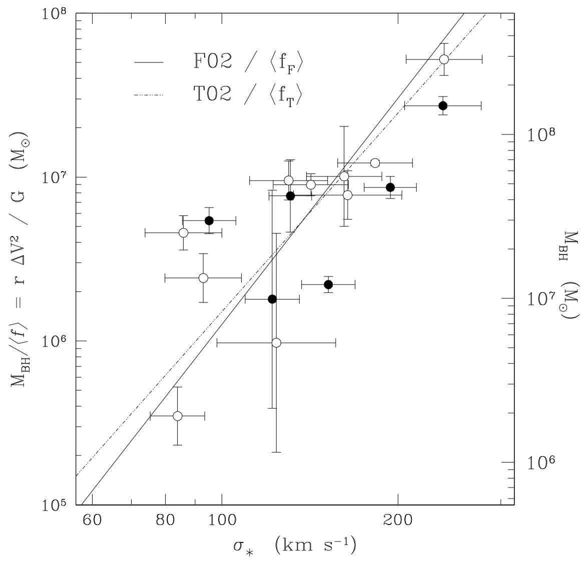
Thus, identifying the total kinetic energy, T, and the gravitational potential energy, U, gives

$$2T - U = \frac{1}{2}\frac{\mathrm{d}^2}{\mathrm{d}t^2}\sum_i m_i\mathbf{r}_i^2 = 0 \tag{8.38}$$

in statistical equilibrium.

Thus we find the virial theorem: $T = \frac{1}{2}|U|$

BH Masses

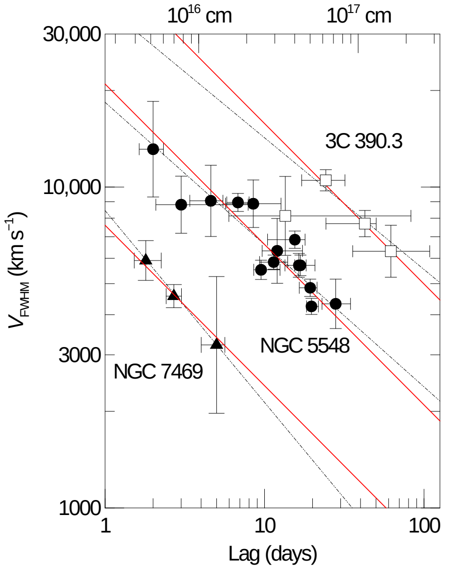


Onken et al. (2004): Calibration of reverberation mapping based on other AGN mass determinations (M–σ-relationship, see later):

$$f = 5.5 \pm 1.9$$

$\Longrightarrow$ Masses determined from reverberation mapping are exact to ~35%.

BH Masses



Since $M \propto r\Delta V^2$, for a single object (M = const.), we expect $r \propto \Delta V^{-1/2}$.

Observations: Line width versus lag scales as

$$\log V_{\rm rms} = a + b \log c\tau \qquad (8.39)$$

with $b = -1/2$, as expected!

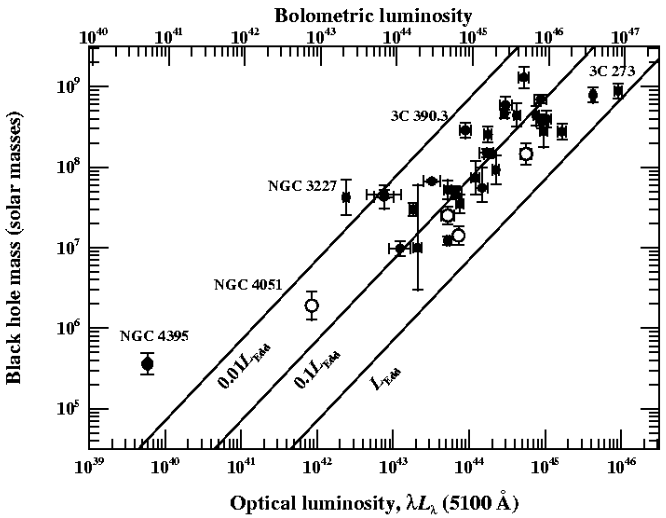
solid lines in the figure

Masses obtained from lag and V (Peterson & Wandel, 2000):

- NGC 7469: $8.4 \times 10^6\, M_\odot$
- NGC 5548: $5.9 \times 10^7\, M_\odot$
- 3C 390.3: $3.2 \times 10^8\, M_\odot$

(Peterson, 2001)

BH Masses



Until today: 36 AGN with reverberation measurements. Mass-luminosity relationship: typical efficiency for AGN accretion is 10%.

Peterson (2006; Xian AGN workshop)

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