AGN Central Engines

- Supermassive Black Holes (SMBHs)
- Masses and Accretion Rates
- SMBH Mass Determinations
- Accretion Disks

Supermassive Black Holes

- Need to generate $L > 10^{43}$ ergs/sec inside radius < 10 light days
- Fusion too inefficient (~ 0.7% of the mass converted to energy)
- Solution: SMBH + dissipative accretion disk
- Energy from gravitational infall, gas heated to high temperatures by collision in accretion disk

Eddington limit:

- Consider a proton-electron pair in an accreting gas composed of ionized hydrogen
- To avoid disruption of the accretion, the inward gravitational force must equal or exceed the outward radiation force
- The opacity of the gas is provided by the Thomson cross section σ_e (proton is linked to electron by electromagnetism)

$$P_{rad} = \frac{L}{4\pi r^2 c} \text{ (radiation pressure)}$$

$$F_{rad} = \sigma_e \frac{L}{4\pi r^2 c} \text{ (radiation force)}$$

$$F_{rad} \leq F_{grav} \quad \text{(for accretion to occur)}$$

$$\frac{\sigma_e L}{4\pi r^2 c} \leq \frac{GMm_p}{r^2}$$

$$\text{So: } L \leq \frac{4\pi Gcm_p}{\sigma_e} M \quad \text{(upper limit on luminosity)}$$

$$L_E \equiv \frac{4\pi Gcm_p}{\sigma_e} M \quad \text{is the Eddington luminosity}$$

$$M_E \equiv \frac{\sigma_e}{4\pi Gcm_p} L \quad \text{is the Eddington mass}$$

For a spherically accreting object: $L < L_E$, $M > M_E$

Plugging in for constants:

$M_E = 8 \text{ x } 10^5 L_{44} \ M_\odot$, where $L_{44} = L_{bol} / 10^{44} \text{ ergs s}^{-1}$

For a Seyfert galaxy, $L > 10^{43}$ ergs s^{-1}

→ Seyferts have SMBHs with masses $M_\bullet > 8 \text{ x } 10^4 M_\odot$

or

$L_E = 1.26 \text{ x } 10^{44} \ M_6$ ergs s^{-1}, where $M_6 = M_\bullet / 10^6 M_\odot$

The mass of the SMBH can be estimated directly from the distances (r) and motions (v) of the BLR clouds (if Keplerian):

$M \approx \frac{rv^2}{G}$ (r typically from reverberation mapping)

Typical Seyferts: $L \approx 10^{44}$ ergs s^{-1}; $M \approx 10^7 M_\odot \rightarrow L_E \approx 10^{45}$ ergs s^{-1}

So for Seyferts: $L/L_E \approx 0.1$ (range is actually ~0.01 to ~1.0)

Accretion rate

For a black hole, the Schwarzschild radius is

$$R_S = \frac{2GM}{c^2} \quad (\approx 10^{-3}\ M_7 \text{ light days } \approx\ 40\ M_7\ R_\odot)\ \ (R_S = 2R_g)$$

Energy released by a particle of mass falling to $\sim 5R_s$:

$$U = \frac{GMm}{5R_s} = \frac{GMm}{10GM/c^2} = 0.1mc^2$$

So: $\eta \approx 0.1$ (compared to 0.007 for fusion)

Rate at which energy is emitted:

$L = \eta \dot{M} c^2$ ($\dot{M}$ - mass accretion rate, η - efficiency)

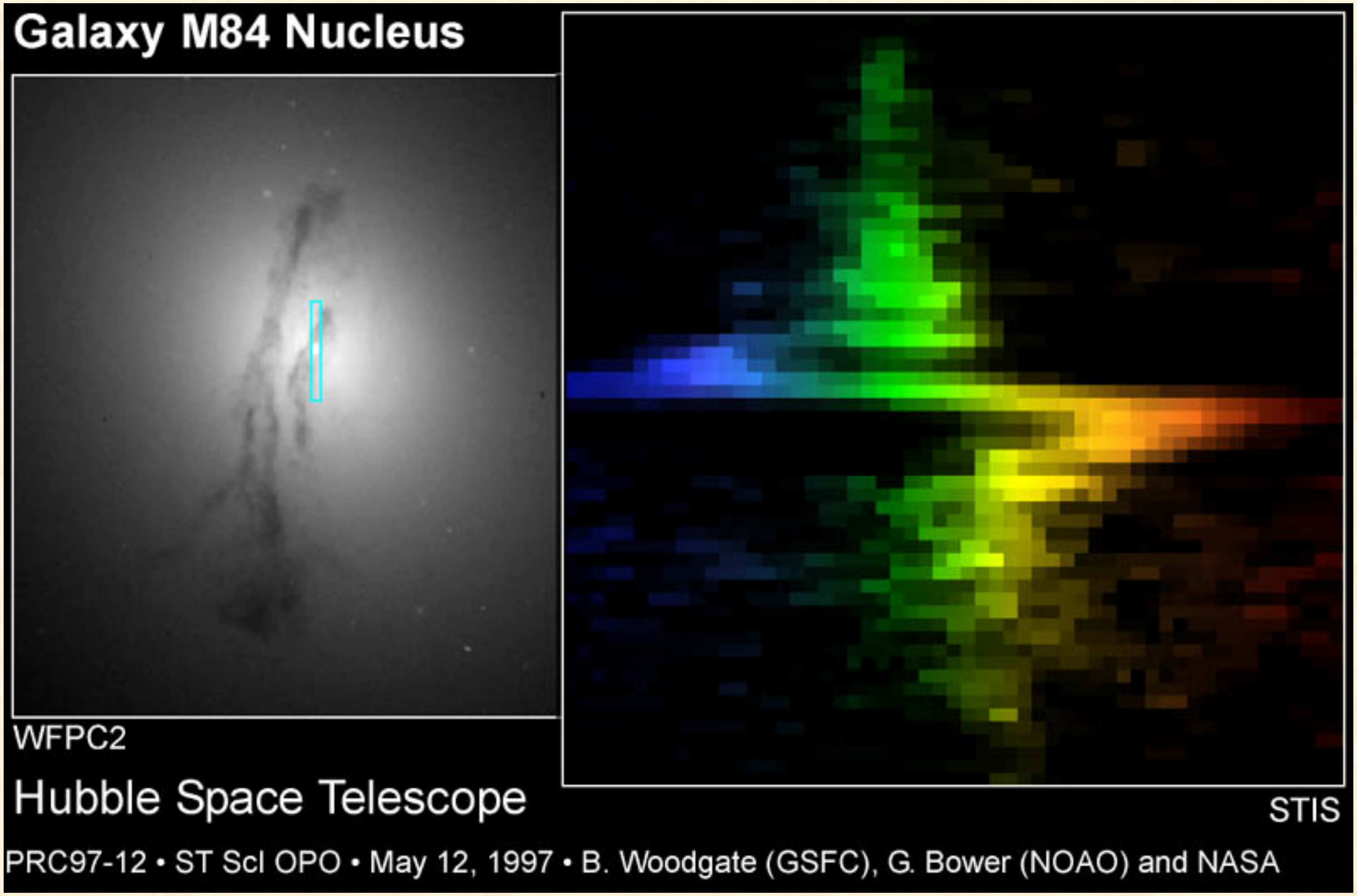
$$\dot{M} = \frac{L}{\eta c^2} \approx\ 1.8 \text{ x } 10^{-3} \frac{L_{44}}{\eta}\ \ M_\odot / \text{yr}$$

So for a Seyfert galaxy: $\dot{M} \approx 0.02\ M_\odot / \text{yr} \rightarrow$ not much fuel needed

Relative accretion rate: $\frac{\dot{M}}{M} \propto \frac{L}{L_E}$ (Eddington ratio)

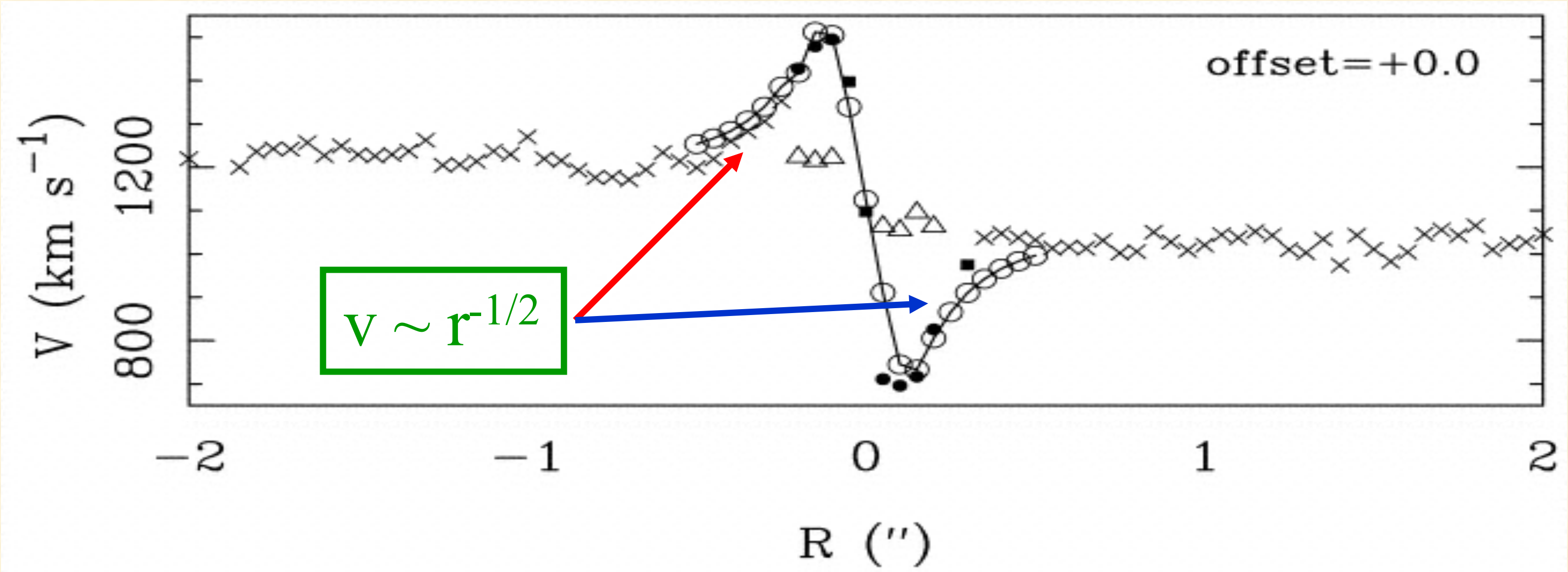
Measuring SMBH Masses
1) Ionized Disk Dynamics

STIS Obervations of Hα emission in M84 (giant E, LINER)



- slit placed along ionized disk (diameter = 82 pc)
- classic Keplerian rotation curve: $M_\bullet = 3 \times 10^9\ M_\odot$!

M84 Rotation Curve

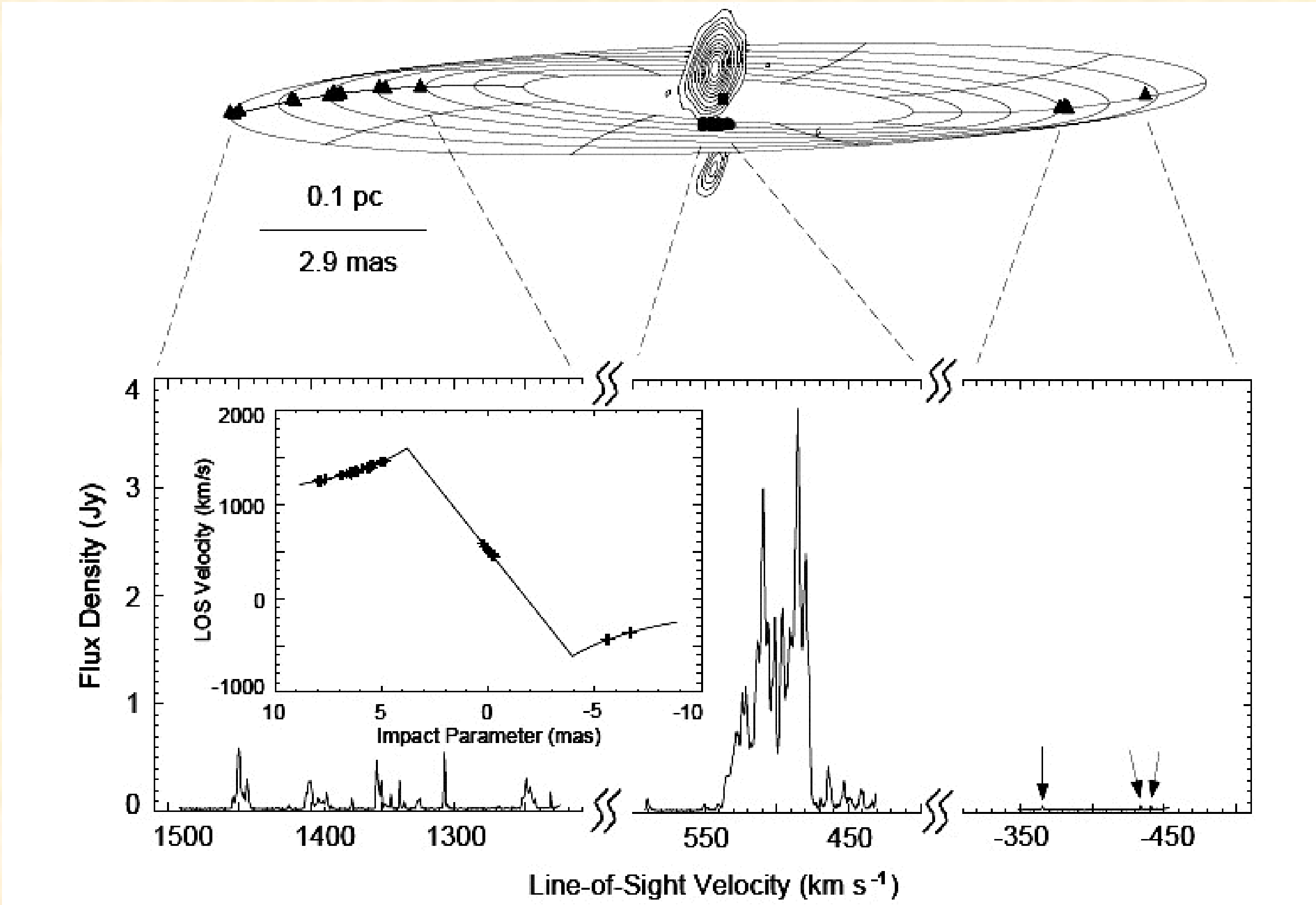


(Bower, G., et al. 1998, ApJ, 492, L111)

- Ionized gas disks in AGN are rare (seen in only a few percent of AGN)
- Most of the extended ionized gas in AGN (i.e., in the narrow-line region) is pushed outward by radiation pressure and/or winds

→ can't use in general to determine the black hole mass

2) H_2O Maser Disks (AGN) - NGC 4258 (LINER)

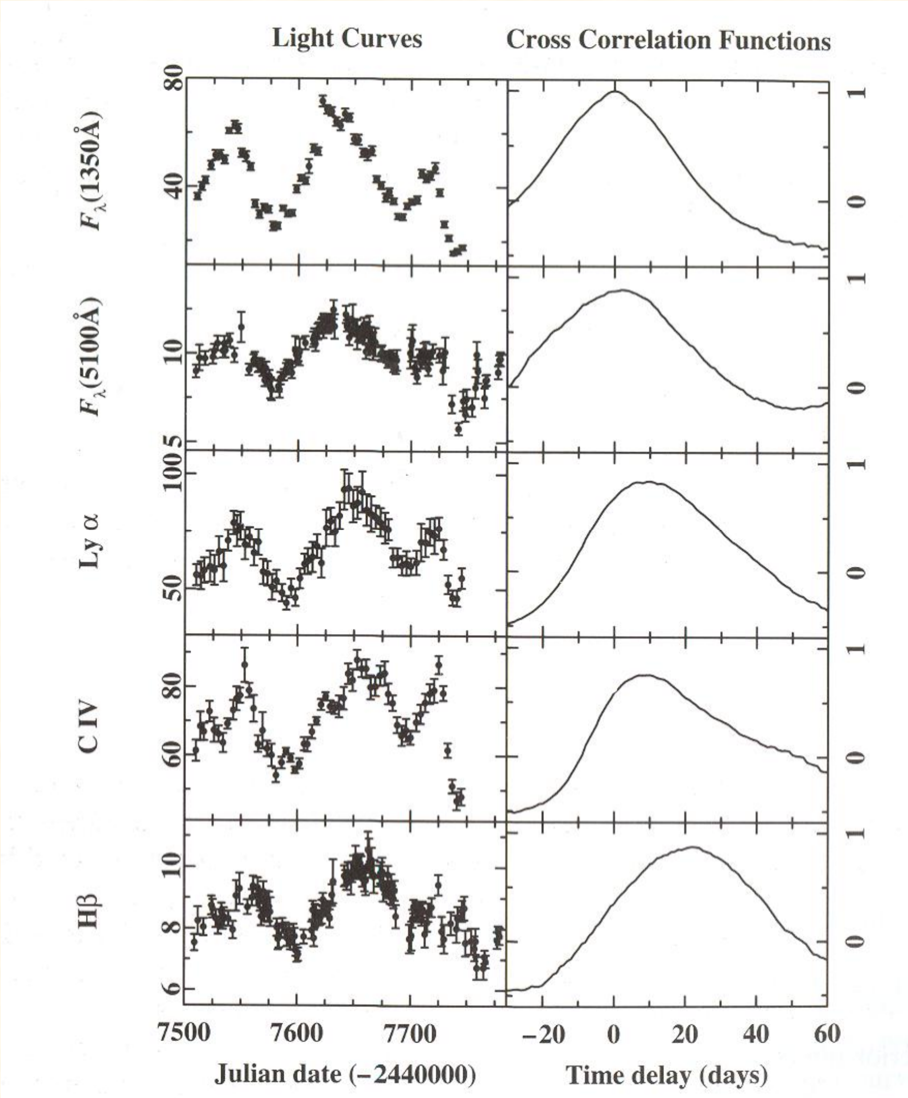


(Herrnstein, et al. 2005, ApJ, 629, 719)

- masers from dense, unresolved clumps of molecular gas, heated by X-rays
- high velocity masers are self-amplified, systemic masers amplify radio core
- Keplerian rotation curve for a warped disk: $M_\bullet = 4 \times 10^7 M_\odot$
  →Only works for nearly edge-on systems!

3) Reverberation Mapping (*IUE*/Optical Campaign on NGC 5548)

Light curves and cross-correlation functions (CCFs) relative to 1350 Å



(Peterson, p. 86)

- Emission-line light curves delayed relative to continuum variations.
- Lag due to light travel time effects, since recombination time is small: $\tau_{rec} = (n_e\alpha_B)^{-1} \approx 400$ sec for $n_e = 10^{10}$

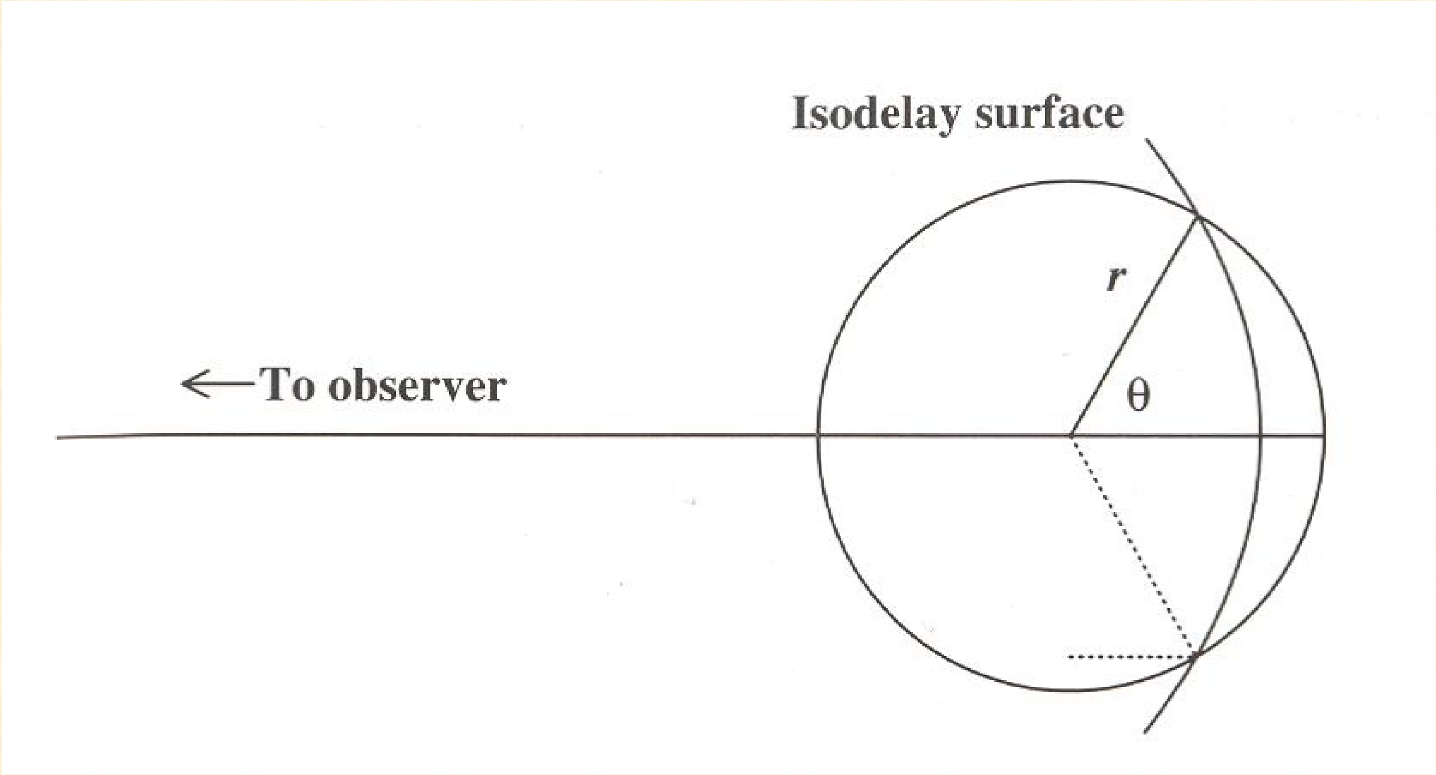
- Further evidence for photoionization
- Time lag gives approximate radius of BLR
- Low-ionization lines have longer lags →ionization stratification in BLR

Use to measure black hole mass!

$$M = f\frac{rv^2}{G}, \quad r = \text{BLR size} = c\tau_{lag}$$

v = width of line (e.g., FWHM)

Reverberation Mapping



(Peterson, p. 83)

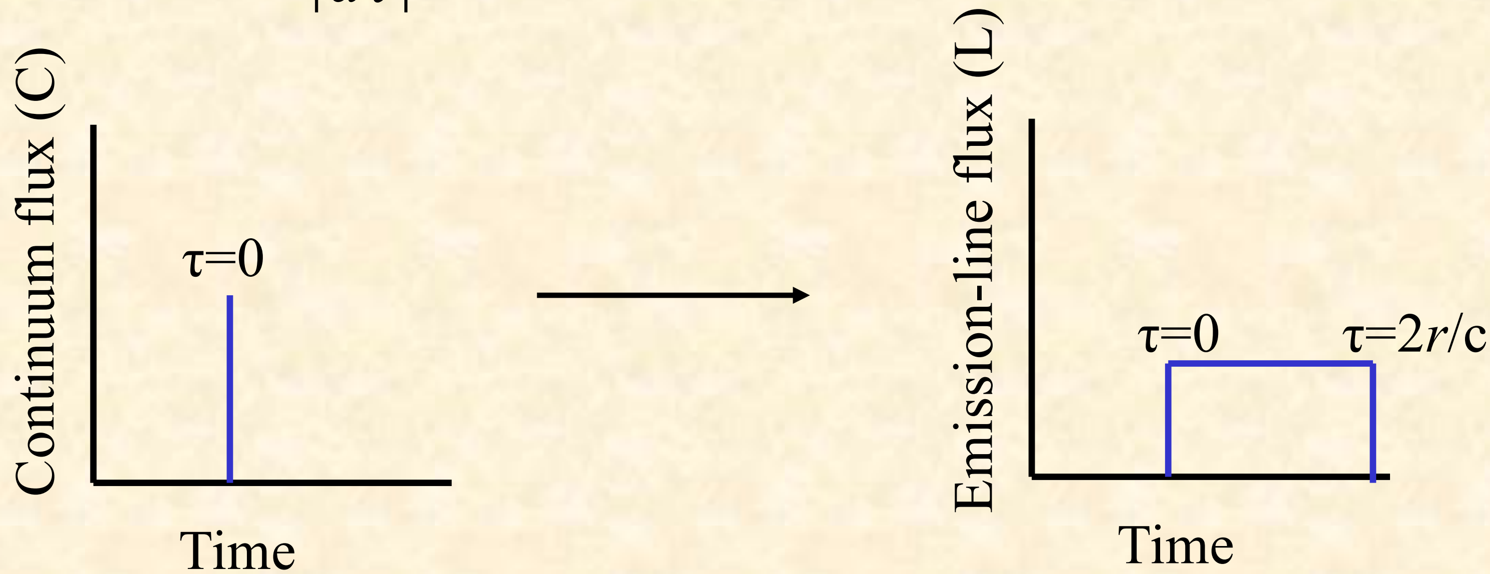
- Consider a δ-function continuum at $\tau = 0$, and a thin spherical shell BLR
- When the ionizing continuum reaches the shell, it responds instantaneously
- The observer sees isodelay surfaces at $\tau = (1 + \cos\theta)r/c$ → paraboloid
- Intersection with the shell gives an annulus with surface area $2\pi r^2 \sin\theta d\theta$
- If emissivity (ε) is same at all locations, the emission-line response is:

$\psi(\theta)d\theta = 2\pi\varepsilon r^2 \sin\theta \; d\theta$ (ψ : transfer function, ε : emissivity)

Since $\tau = \frac{(1+\cos\theta)r}{c}$, $d\tau = -\frac{r\sin\theta}{c} d\theta$

So the emission-line light curve looks like:

$$\psi(\tau)\, d\tau = \psi(\theta)\left|\frac{d\theta}{d\tau}\right| d\tau = 2\pi\varepsilon rc\; d\tau \;\; = \text{const. between } \tau = 0 \text{ and } 2r/c$$



- CCF from above will give a box with centroid (lag) of $\tau = r/c$
- In general, $\Psi(\tau)$ gives the emission-line light curve for a δ-function continuum (Blandford & McKee 1982, ApJ, 255, 419)
- Observationally, the continuum is not a δ-function, so the emission-line light curve is a convolution of the continuum and transfer function:

$$L(t) = \int_{-\infty}^{\infty} \psi(\tau)\, C(t-\tau)\, d\tau$$ (L = line flux, C = continuum flux)

Deconvolution requires high S/N spectra at high temporal resolution

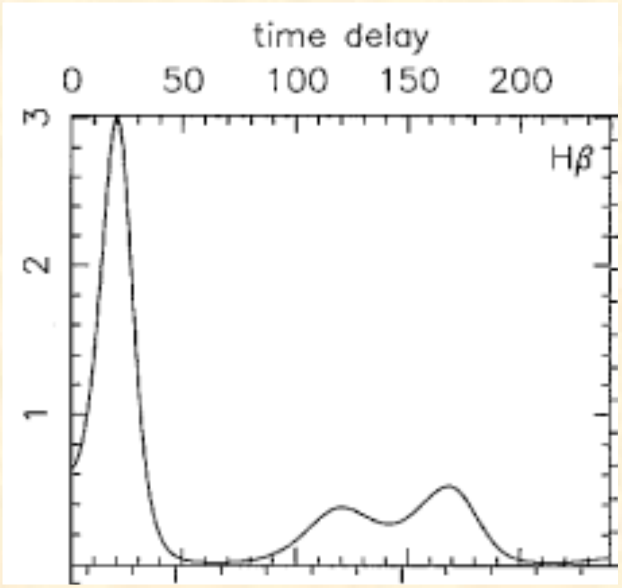
Observationally, we usually settle for the CCF:

$$\mathrm{CCF} = \int_{-\infty}^{\infty} L(\tau)\, C(t-\tau)\, d\tau$$ → peak gives an average "lag" → "radius" of BLR

"It can be shown that" (Peterson, p. 84):

$$\mathrm{CCF} = \int_{-\infty}^{\infty} \psi(\tau)\, \mathrm{ACF}(t-\tau)\, d\tau$$ (ACF is for the continuum)

→ CCF gives a characteristic size, Ψ gives the geometry.

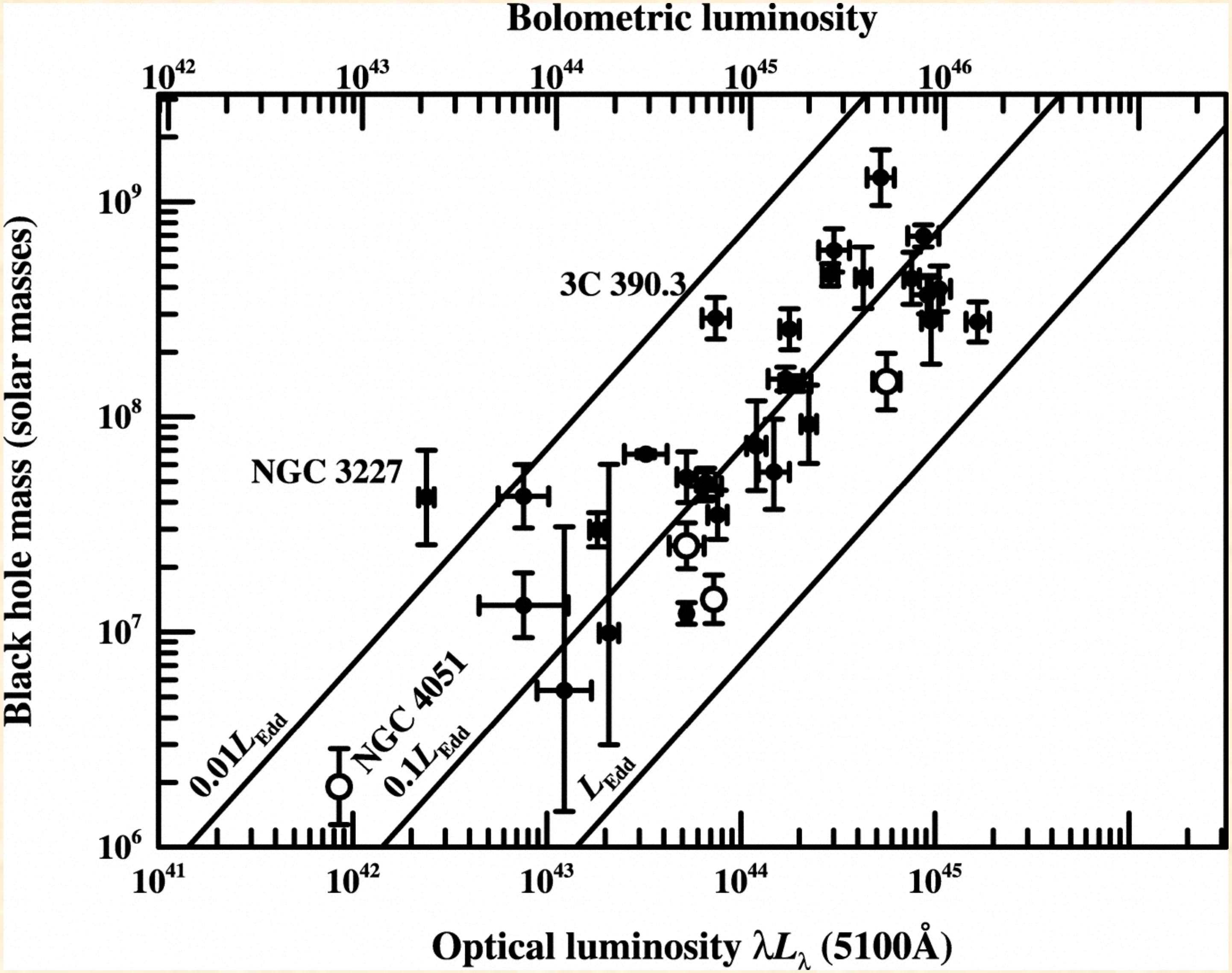


-Attempt to recover the transfer function for Hβ in NGC 5548 data set (Horne et al. 1991, ApJ, 367, L5)

- Lack of response at 0 time delay indicates
  1) Lack of gas in line of sight (disk?)
  or
  2) Optically thick gas in line of sight

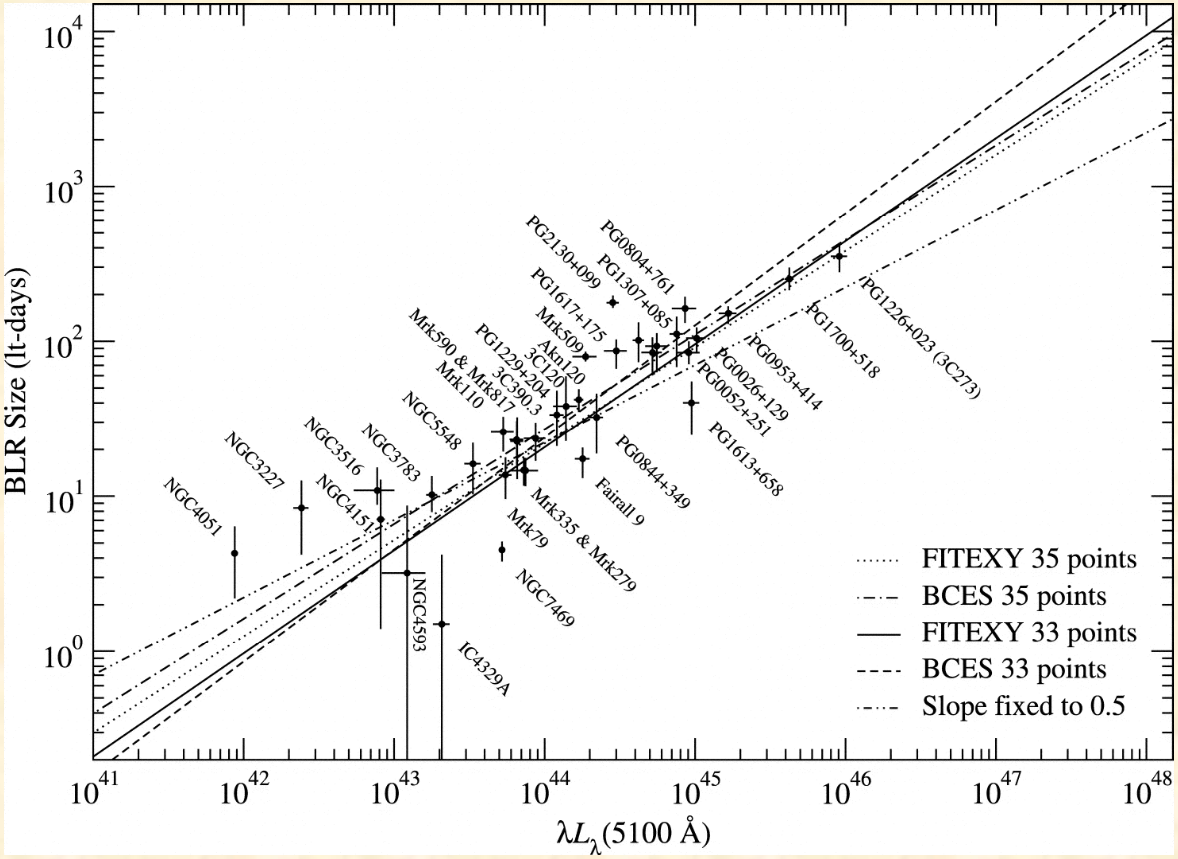
Mass Determinations

35 Reverberation-Mapped AGN



(Peterson et al., 2004, ApJ, 613, 682)

4) BLR Radius - Luminosity Relation



(Kaspi, et al. 2005, ApJ, 629, 61)

$r \propto L^{0.5}$ (Vestergaard & Peterson, 2006, ApJ, 641, 689; Bentz et al. 2013, ApJ, 767, 149)

$$\log M_{\bullet} = \log\left\{\left[\frac{\mathrm{FWHM(H\beta)}}{1000\ \mathrm{km\ s^{-1}}}\right]^{2}\left[\frac{\lambda L_{\lambda}(5100)}{10^{44}\,\mathrm{ergs\ s^{-1}}}\right]^{0.5}\right\} + (6.91 \pm 0.43)$$

Summary: Measurements of SMBH Masses in AGN

- Direct Measurements:
  1) Ionized gas disks (only a few cases)
  2) H_20 maser disks (only a few cases)
  3) Reverberation mapping (RM)
  - time delay between a change in the ionizing continuum and broad emission lines gives BLR size (r); FWHM of lines gives velocity (v)

- Indirect measurements (in order of decreasing quality):
  1) RM of 35 Seyfert galaxies gives $R_{BLR} \sim L_{\lambda}(5100Å)^{0.5}$ (Kaspi et al. 2000)
     - mass from luminosity, widths of permitted lines (e.g., Hβ)
     - however, R-L relation has considerable scatter
  2) Mass from $M_{\bullet}$- σ_{*} relation for bulges, ellipticals
     - same as for normal galaxies (to be continued)

Accretion Disks - Isothermal

Isothermal disk (naive): Virial theorem says that 1/2 of gravitational potential goes into heating the gas; the other 1/2 is radiated away

$$L = \frac{GM\dot{M}}{2r} = 2\pi r^2 \sigma T^4 \quad \rightarrow \quad T = \left(\frac{GM\dot{M}}{4\pi\sigma r^3} \right)^{1/4}$$

If the radiation is dominated by a disk with radius $r = (\text{const.})\, R_s$:

$$T \propto \left(\frac{M\dot{M}}{R_s^3} \right)^{1/4} \propto \left(\frac{M\dot{M}}{M^3} \right)^{1/4} \propto \left(\frac{\dot{M}}{M^2} \right)^{1/4} \propto \left(\frac{\frac{L}{L_E} M}{M^2} \right)^{1/4}$$

$$T \propto \left(\frac{L}{L_E} \right)^{1/4} M^{-1/4}$$

$\rightarrow$ temperature decreases with increasing mass: radiation peaks in the X-rays for stellar mass black holes, EUV for SMBHs

Thin (Alpha) Disk (Shakura & Sunyaev, 1973, A&A, 24, 337)

The height to radius ratio at any location in the disk is:

$$\frac{h}{r} \approx \frac{c_s}{\mathrm{v}_{rot}} \quad \text{(where } c_s = \text{ sound speed, } \mathrm{v}_{rot} = \text{ rotation velocity}$$

If the disk has a high density and viscosity (α) is efficient, then radiative cooling is high, the efficiency is high ($\eta \approx 0.1$), and T is low:

1) $\frac{c_s}{\mathrm{v}_{rot}} << 1 \rightarrow$ the disk is thin

2) The temperature at each annulus can be characterized by a black body:

A "proper" derivation for a viscous disk (see Krolik, p. 147 - 150) gives:

$$T(r) = \left\{ \frac{3GM\dot{M}}{8\pi\sigma \mathrm{r}^3} \left[1 - \left(\frac{r_{\min}}{r} \right)^{1/2} \right] \right\}^{1/4}, \text{ where } r_{\min} = \text{ last stable orbit}$$

For $r >> r_{\min}$ and $r_{\min} =$ (const.) R_s : $\quad T(r) \propto \left(\frac{M\dot{M}}{R_s{}^3} \right)^{1/4} \left(\frac{r}{R_s} \right)^{-3/4}$

As shown previously:

$$\left(\frac{M\dot{M}}{R_s^3}\right)^{1/4} \propto \left(\frac{L}{L_E}\right)^{1/4} M^{-1/4}$$

$$T(r) \propto \left(\frac{L}{L_E}\right)^{1/4} M^{-1/4} \left(\frac{r}{R_s}\right)^{-3/4} \quad \text{(for an annulus)}$$

Plugging in the constants (Peterson, p. 37):

$$T(r) = 6.3 \text{ x } 10^5 (L/L_E)^{1/4} M_8^{-1/4} \left(\frac{r}{R_s}\right)^{-3/4} K$$

For $L/L_E = 1$, $M_8 = 1$, and $r = 3R_s$: T = 276,000 K

Using Wien's law: $\lambda_{\text{peak}} = 2.898\text{x}10^7 / 276{,}000 \text{ K} = 105$ Å (= 0.12 keV)

Contributions from larger radii → Spectrum peaks in the EUV

If the optical radiation at 5000 Å is coming from the accretion disk:

$r \propto \lambda_{peak}{}^{4/3} = 184\ R_s = 2.1$ light days (at 1500 Å, $r = 0.4$ light days)

Limitations of the SS Model

- Doesn't explain hard X-rays (corona) or soft X-ray excess.
- Doesn't match the shape of the observed continuum in the optical/UV(superposition of blackbody spectra).
- Although observations of variability confirm decreasing temperature with radius, observed accretion disks are 2 – 3 times those predicted by the thin disk model.

→ Need accretion disk model that includes the effects of GR (including Kerr BHs) and magnetic fields (GRMHD), and generates winds/jets to dispose of angular momentum.

Other Types of Accretion Disks

- ADAFs (advection-dominated accretion flows):
  - At low accretion rates ($L/L_E << 0.01$), densities are low.
  - Radiative cooling is inefficient, heat is "advected" inward.
  - The radiative efficiency (η) is << 0.1
  - The temperature of the gas rises.

    → The central accretion disk puffs up to form an "ion torus".
  - Cooling is mainly bremsstrahlung → no EUV bump
- Super-Eddington ($L/L_E \geq 1$) accretion :
  - At high accretion rates, densities are high
  - Radiation is trapped in the vertical direction
  - Once again, heat is advected radially inward.

    → The disk puffs up into a "radiation torus", characterized by a single temperature (few x 10^4 K) → large EUV bump