AGN Central Engines

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

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

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

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

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

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

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

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

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

Plugging in for constants:

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

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

$\rightarrow$ Seyferts have SMBHs with masses $M_\bullet > 8 \times 10^4 M_\odot$

or

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

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

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

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)

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Accretion rate

For a black hole, the Schwarzschild radius is

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

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:

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

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

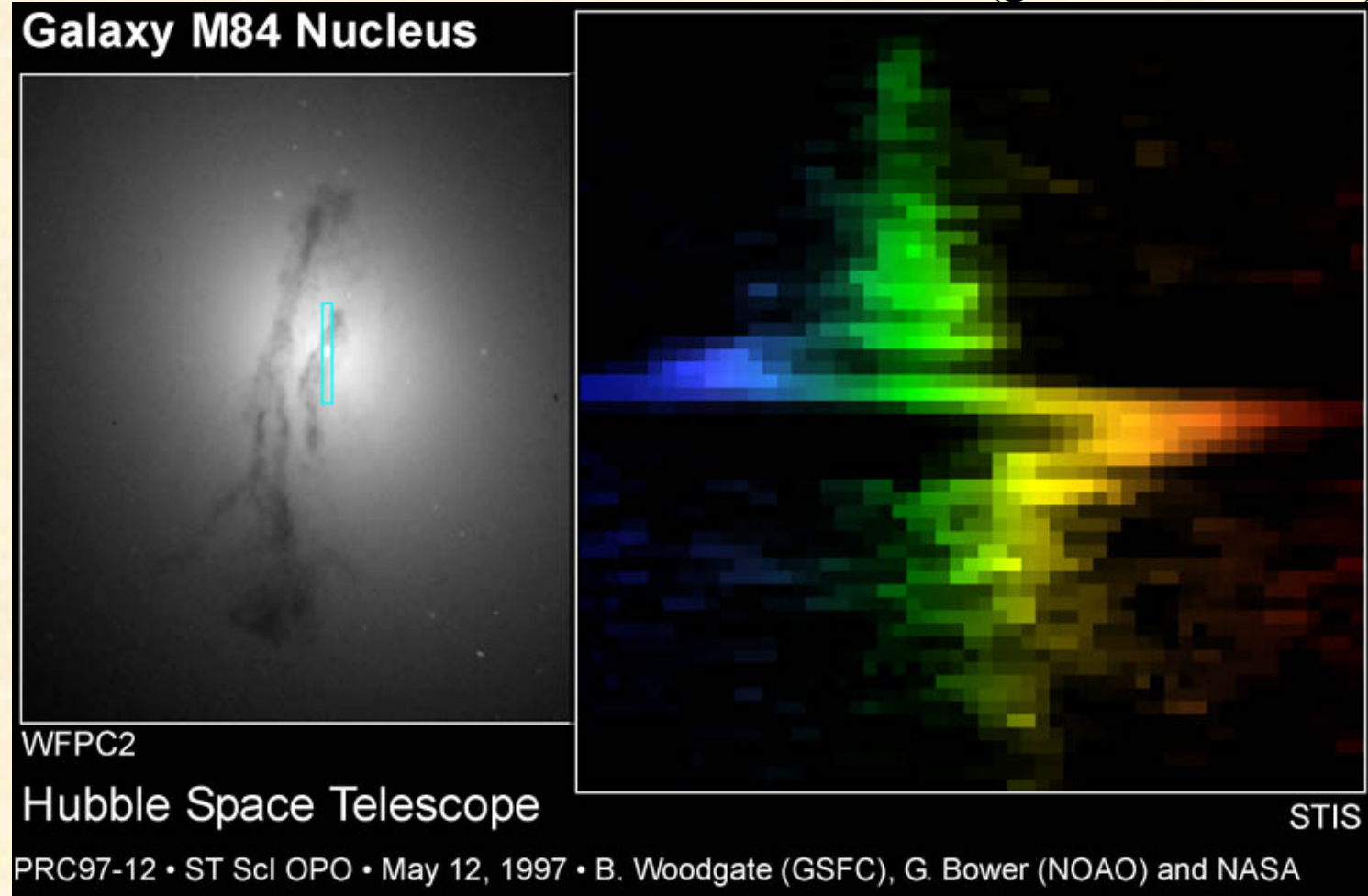So for a Seyfert galaxy: $\dot{M} \approx 0.02 \, M_\odot / yr \rightarrow$ not much fuel needed

Relative accretion rate: $\dfrac{\dot{M}}{M} \propto \dfrac{L}{L_E}$ (Eddington ratio)
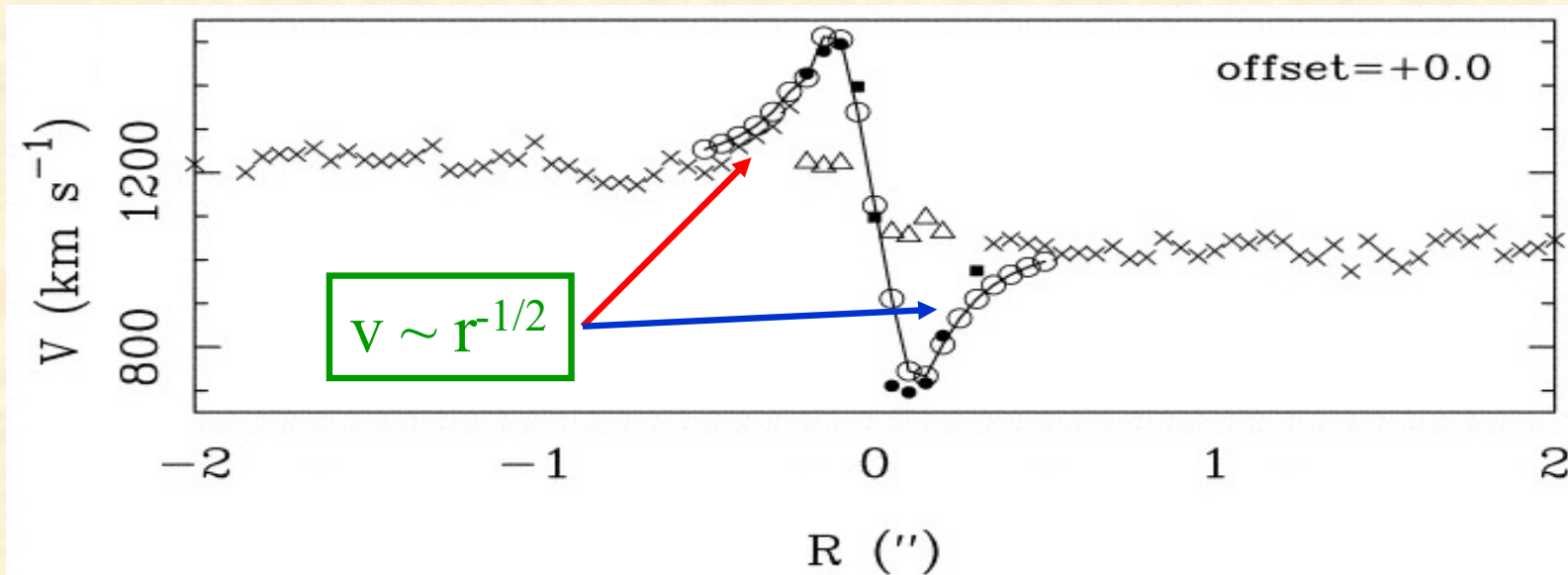
Measuring SMBH Masses in AGN
1) Gas Disk Dynamics

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

- slit placed along ionized disk (diameter = 82 pc)
- classic Keplerian rotation curve: $M_{\bullet} = 3 \times 10^9 \, M\odot$!
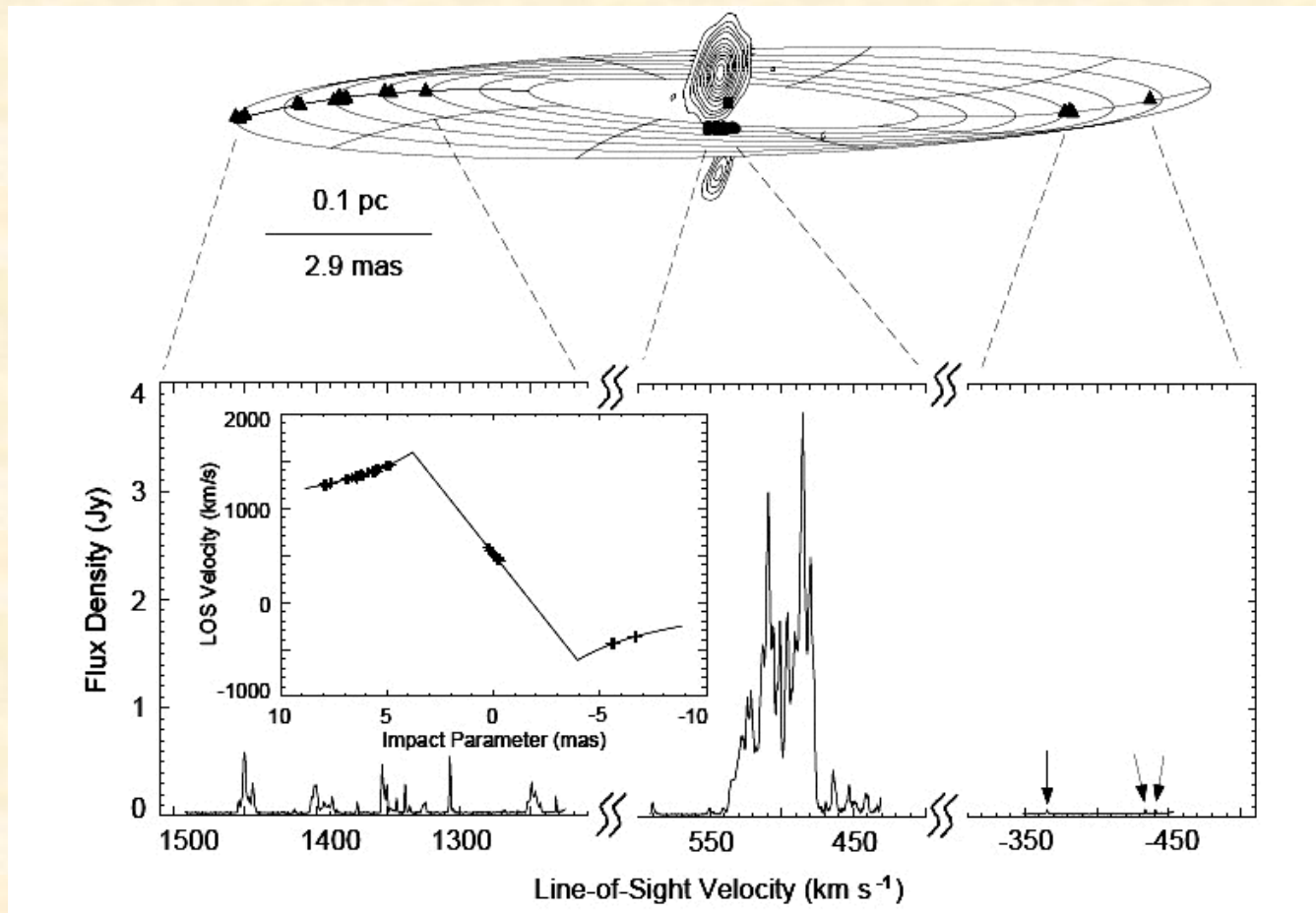
M84 Rotation Curve

$v \sim r^{-1/2}$

(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 black hole masses

- However, cold gas disks are now being used: CO observations with ALMA (Zhang+ 2025, MNRAS, 541, 2540).

  → still need to disentangle from molecular inflows/outflows

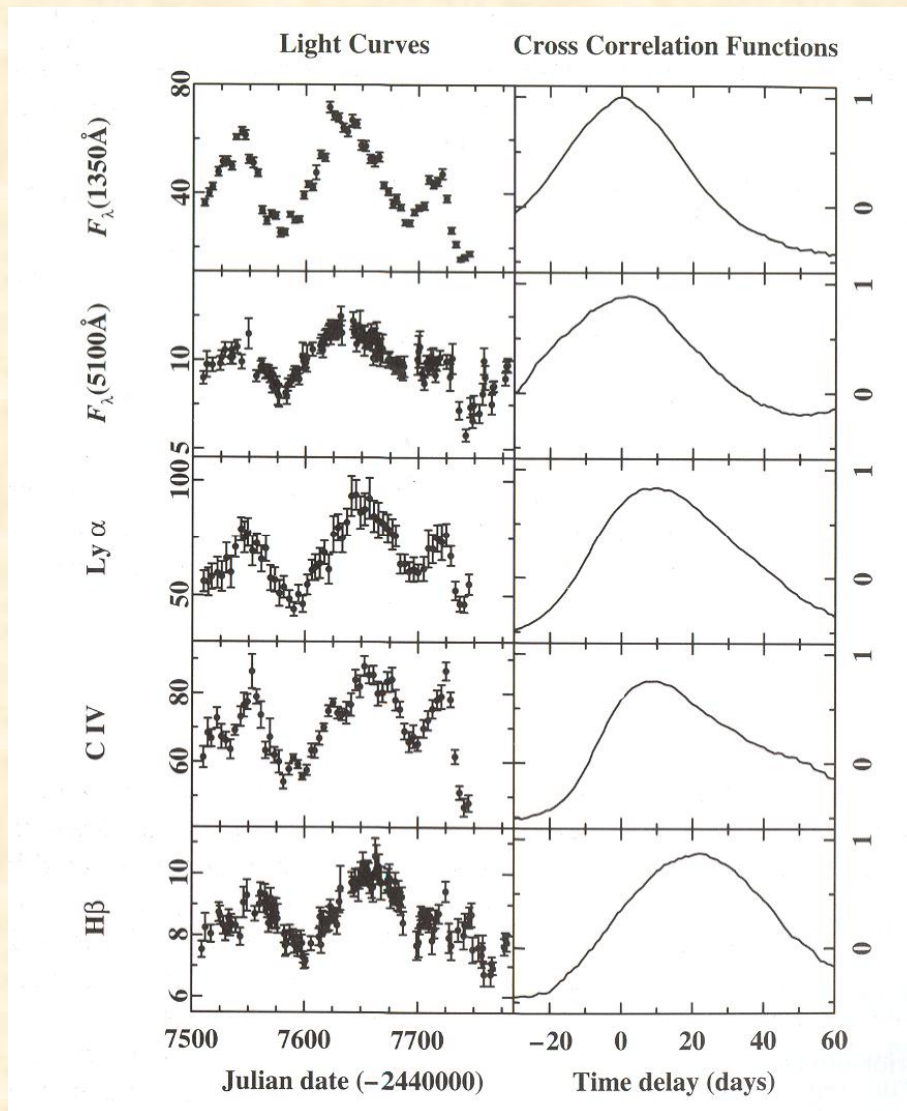# 2) H_2O Maser Disks (AGN) - NGC 4258 (LINER)

(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: $M_\bullet = 3.9 \times 10^7 \, M\odot$
  → Only works for nearly edge-on systems! (several dozen measured to date)

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

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

Light Curves — **Cross Correlation Functions**

$F_\lambda(1350\text{Å})$, $F_\lambda(5100\text{Å})$, Ly α, C IV, Hβ

Julian date (-2440000) — Time delay (days)

(Peterson, p. 86)

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

- 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
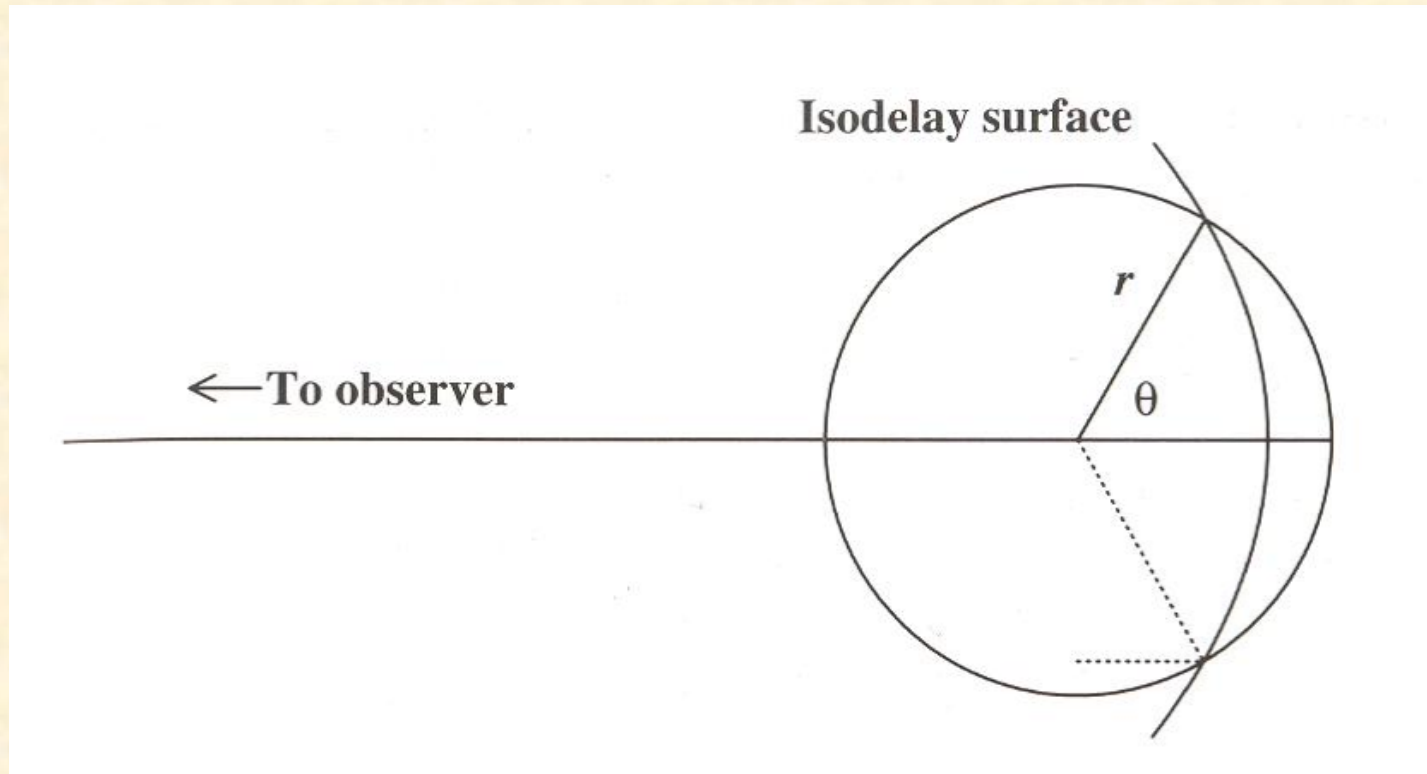
(Peterson, p. 83)

- 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:

$$\psi(\theta)d\theta = 2\pi\varepsilon r^2 \sin\theta \, d\theta \quad (\psi : \text{transfer function}, \varepsilon : \text{emissivity})$$

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

So the emission-line light curve looks like:

$$\psi(\tau) \, d\tau = \psi(\theta)\left|\frac{d\theta}{d\tau}\right|d\tau = 2\pi\varepsilon rc \, d\tau = \text{const. between } \tau = 0 \text{ and } 2r/c$$
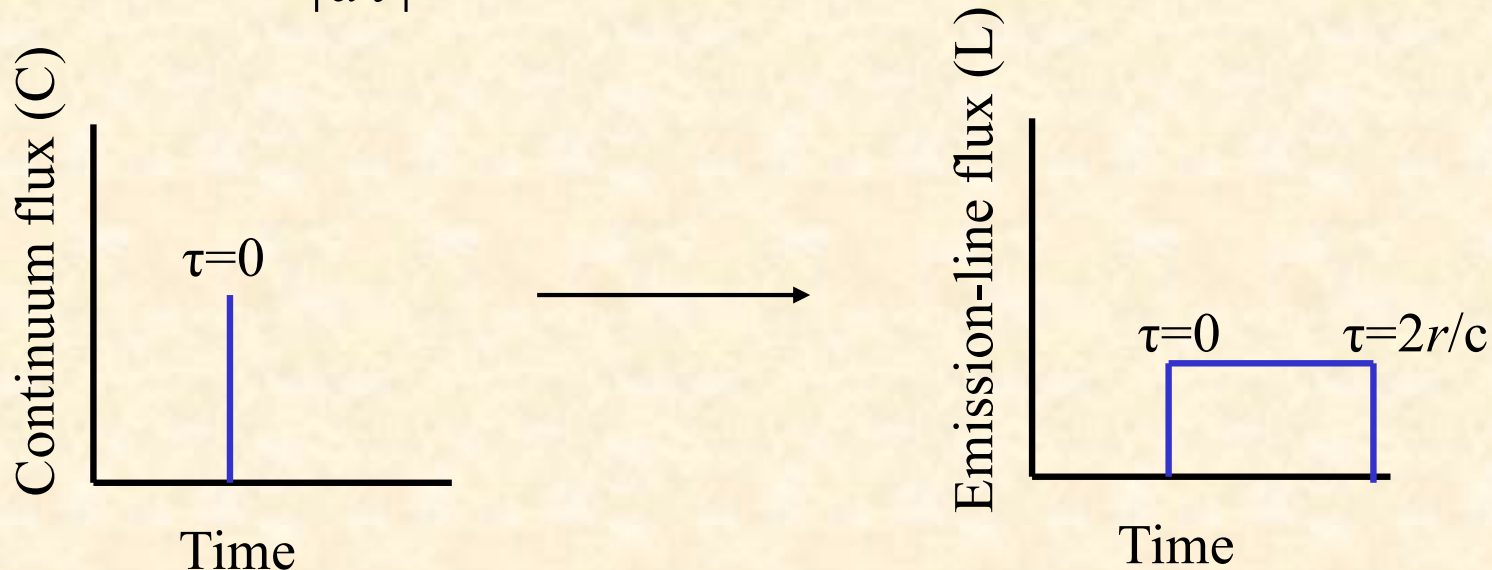
- CCF from above will give a box with centroid (lag) of $\boxed{\tau = r/c}$
- In general, $\Psi(\tau)$ gives the emission-line light curve for a δ-function continuum (Blandford & McKee 1982, ApJ, 255, 419)
- Observationally, the continuum is not a δ-function, so the emission-line light curve is a convolution of the continuum and transfer function:

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

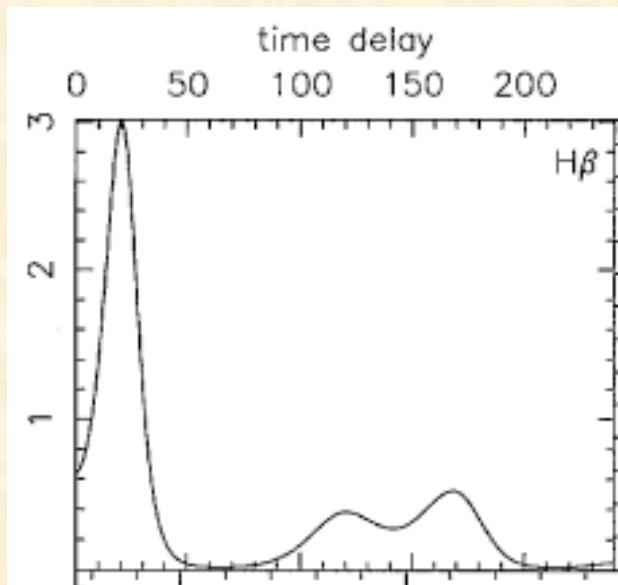Deconvolution requires high S/N spectra at high temporal resolution

Observationally, we usually settle for the CCF:

$$\text{CCF} = \int_{-\infty}^{\infty} L(\tau)\, C(t-\tau)\, d\tau \;\; \rightarrow \;\; \text{peak gives an average "lag"} \rightarrow \text{"radius"}$$
<div align="right">of BLR</div>

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

$$\text{CCF} = \int_{-\infty}^{\infty} \psi(\tau)\, \text{ACF}(t-\tau)\, d\tau \qquad \text{(ACF is for the continuum)}$$
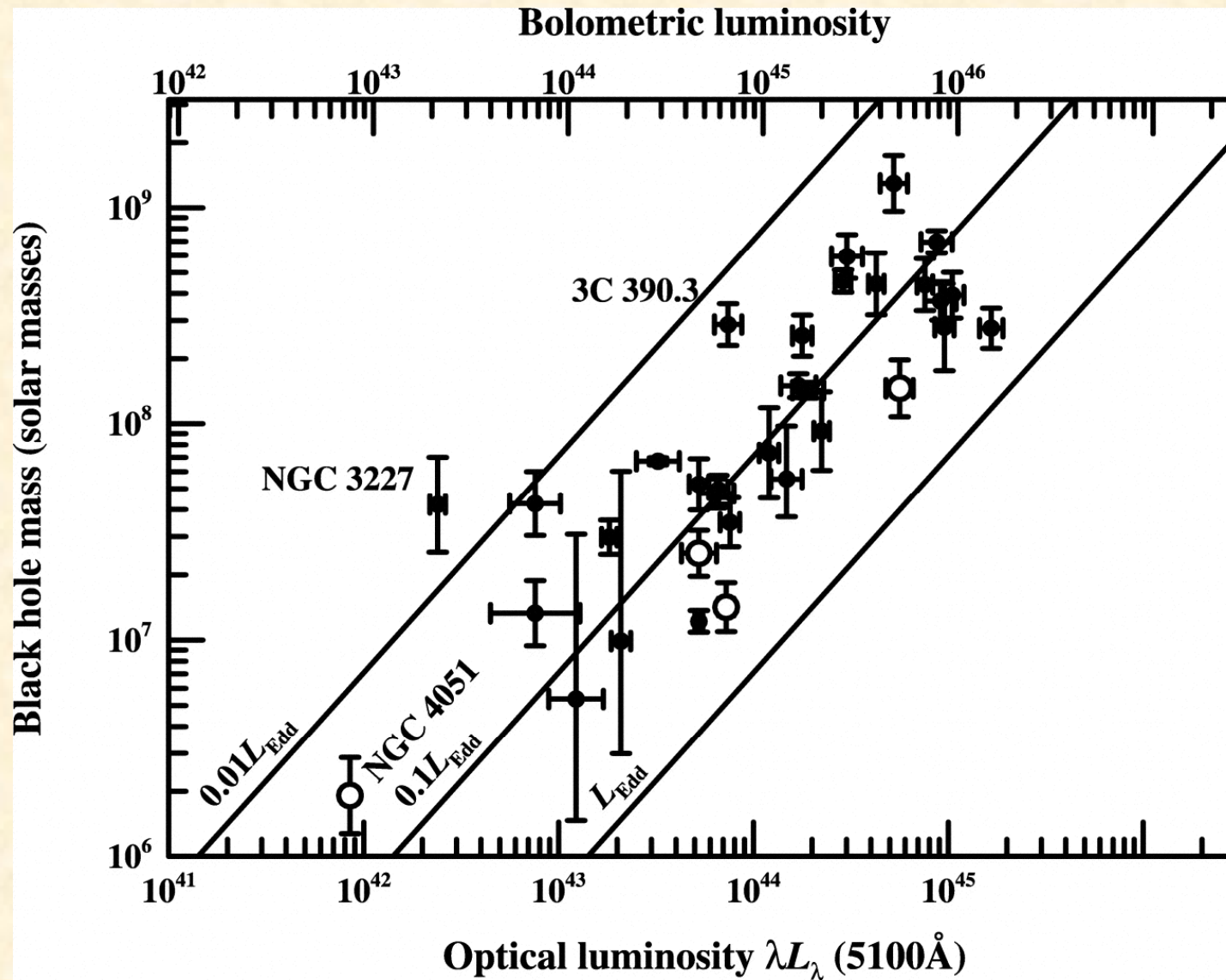
→ CCF gives a characteristic size, Ψ gives the geometry.

-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
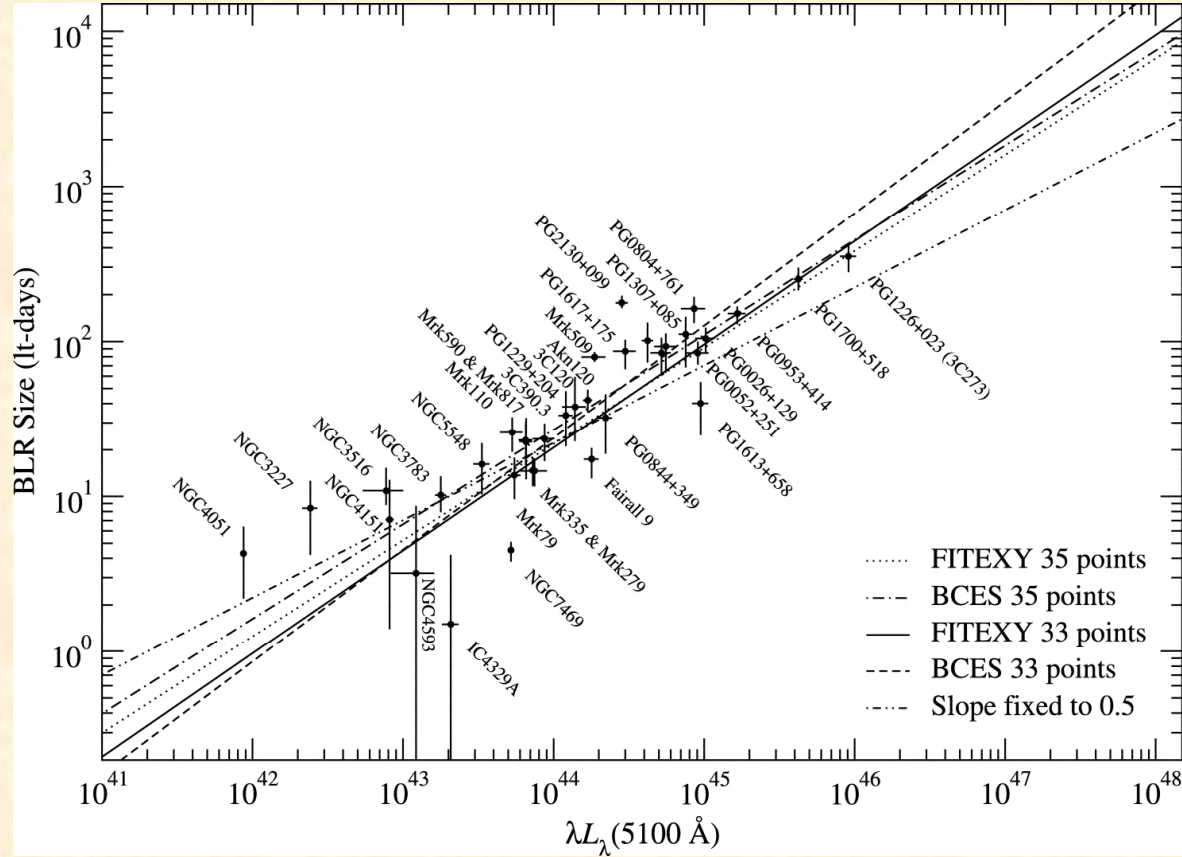 2) Optically thick gas in line of sight

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)

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

Summary: Measurements of SMBH Masses in AGN

- Direct Measurements:
  1) Ionized gas disks (only a few cases)
  2) Cold molecular disks (accuracy yet to be determined)
  3) H_2O maser disks (only a few cases)
  4) 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 $R_{BLR} \sim L_\lambda(5100\text{Å})^{0.5}$ (Kaspi et al. 2000)
     - mass from luminosity, widths of permitted lines (e.g., $H\beta$)
     - however, R-L relation has considerable scatter
  2) Mass from $M_\bullet - \sigma_*$ relation for bulges, ellipticals
     - same as for normal galaxies (to be continued)

Black Hole Spin

- Characterized by the spin parameter (a)

$$a = \frac{J}{M_\bullet \, c} \qquad (J = \text{angular momentum})$$

$a = 0$ (non-spinning BH, Schwarzschild metric)

to 1 (maximally spinning BH, Kerr metric)

- Innermost stable circular orbit (ISCO) – based on a test particle not exceeding the speed of light.

For $a = 0$: $r_{isco} = 6\dfrac{GM_\bullet}{c^2} = 6R_G$

For $a = 1$: $r_{isco} = \dfrac{GM_\bullet}{c^2} = R_G$ (prograde orbit, spin direction)

$r_{isco} = 9\dfrac{GM_\bullet}{c^2} = 9R_G$ (retrograde orbit)

- Inside the ISCO, a particle is dragged into the BH with no escape of energy (radiation).

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 $r = (\text{const.}) R_s$:

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

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

→ 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:

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

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) $\dfrac{c_s}{v_{rot}} << 1 \rightarrow$ 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:

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

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

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):

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

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

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

Contributions from larger radii $\rightarrow$ Spectrum peaks in the EUV

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

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

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 (e.g., from microlensing or continuum lags) 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 ($L/L_E \ll 0.01$), densities are low.
  - Radiative cooling is inefficient, heat is "advected" inward.
  - The radiative efficiency (η) is $\ll 0.1$
  - 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