The Central Black Hole and Relationships with the Host Galaxy

Bradley M. Peterson
The Ohio State University

"Active Galactic Nuclei at the
Highest Angular Resolution"

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Lecture 1

- AGN fundamentals
  - – Basic observations, taxonomy
  - – Arguments for black holes as the "central engine"
    - Accretion and the Eddington limit
- Evidence for supermassive black holes
- AGN continuum variability

“Active Galactic Nuclei (AGN)”

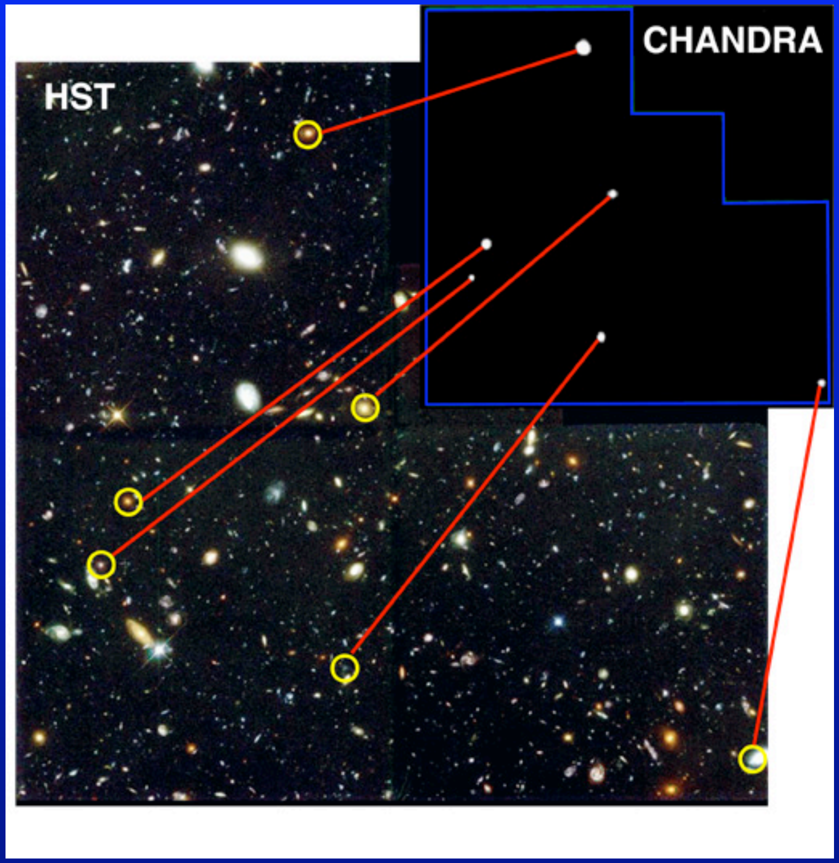
- The phrase “active nuclei” was originally used by V.A. Ambartsumian in 1968
  - “the violent motions of gaseous clouds, considerable excess radiation in the ultraviolet, relatively rapid changes in brightness, expulsions of jets and condensations” ***Ambartsumian 1970***
- First use in paper title: Dan Weedman (1974)
  - “nuclei that contain extensive star formation or luminous non-thermal sources” ***BAAS, 6, 441***
- First use in PhD dissertation title: Jean Eilek (1975)
  - “Cosmic Ray Acceleration of Gas in Active Galactic Nuclei”

“Active Galactic Nuclei (AGN)”

- “Activity” was usually taken to mean “radio source”
- Came to be used to encompass “Seyfert galaxies” and “quasars”
  - “…energetic phenomena in the nuclei, or central regions, of galaxies which cannot be attributed clearly and directly to stars.” **(Peterson 1997, *An Introduction to Active Galactic Nuclei*)**
- Modern definition: “Active nuclei are those that emit radiation that is fundamentally powered by accretion onto supermassive (> $10^6\ M_\odot$) black holes.”

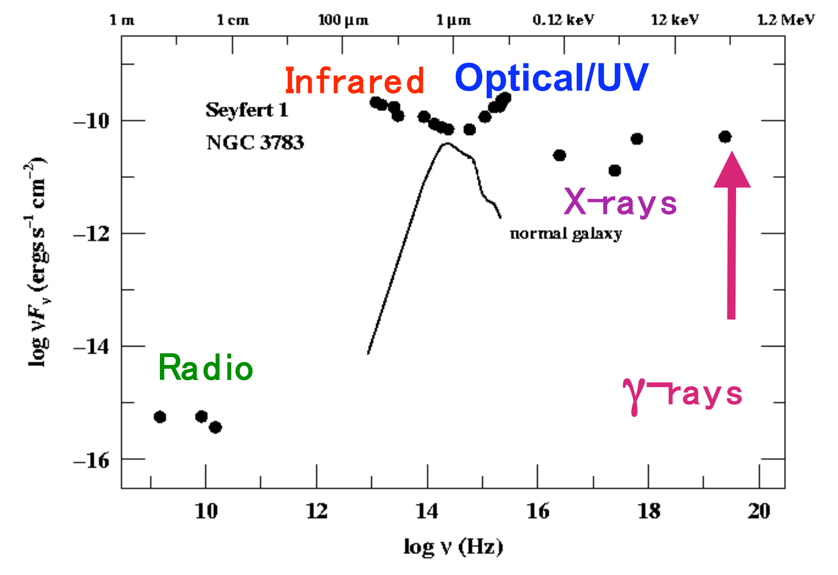
Properties of AGNs

- Strong X-ray emission



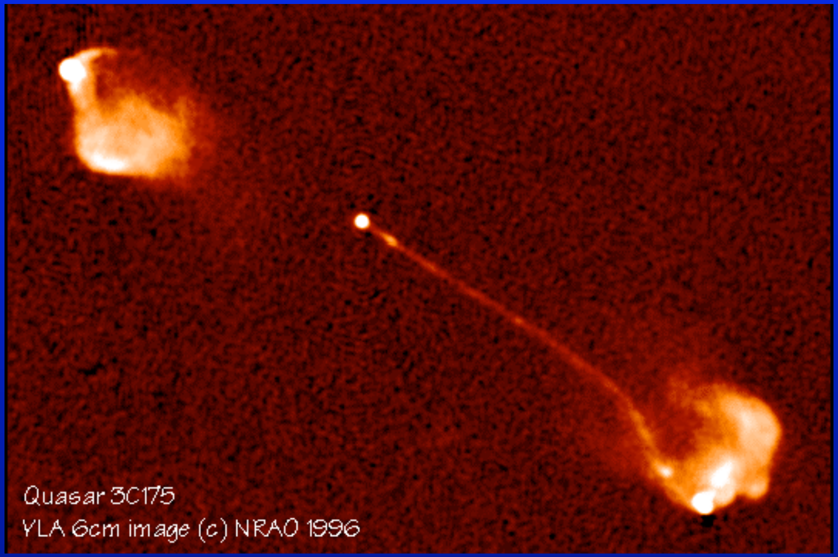
Properties of AGNs

- Strong X-ray emission
- Non-stellar ultraviolet/optical continuum emission



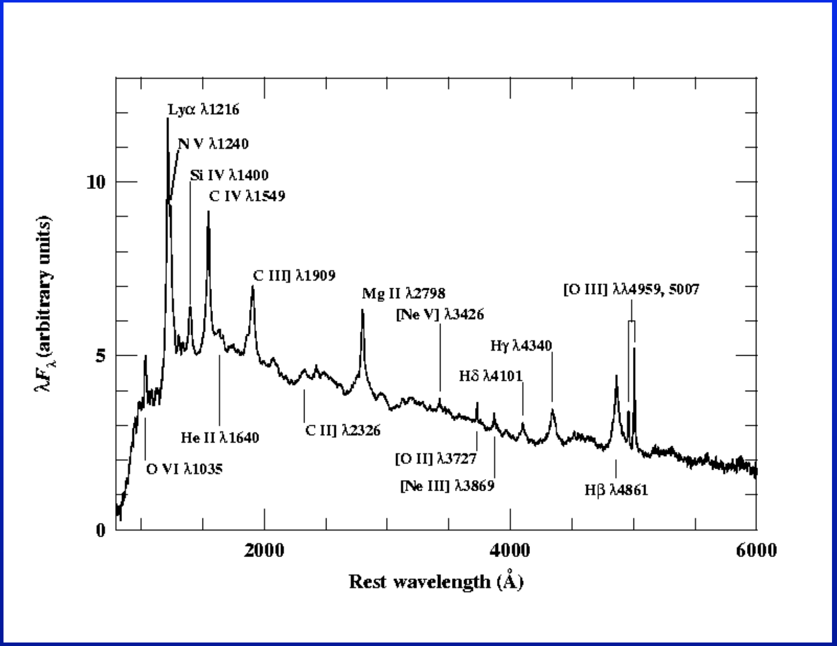
Properties of AGNs

- Strong X-ray emission
- Non-stellar ultraviolet/optical continuum emission
- Relatively strong radio emission



Properties of AGNs

- Strong X-ray emission
- Non-stellar ultraviolet/optical continuum emission
- Relatively strong radio emission
- UV through IR spectrum dominated by strong, broad emission lines.



Not every AGN shares all of these characteristics.

AGN Classification

- There are three major classes of AGNs:
  - Seyfert galaxies
  - Quasars
  - Radio galaxies

Seyfert Galaxies

- Spiral galaxies with high surface brightness cores
  - Spectrum of core shows strong, broad emission lines

NGC 4151

Quasars

- “Quasar” is short for “quasi-stellar radio source”.
  - Discovered in 1960s as radio sources.
  - Radio astronomy was an outgrowth of radar technology developed in the Second World War

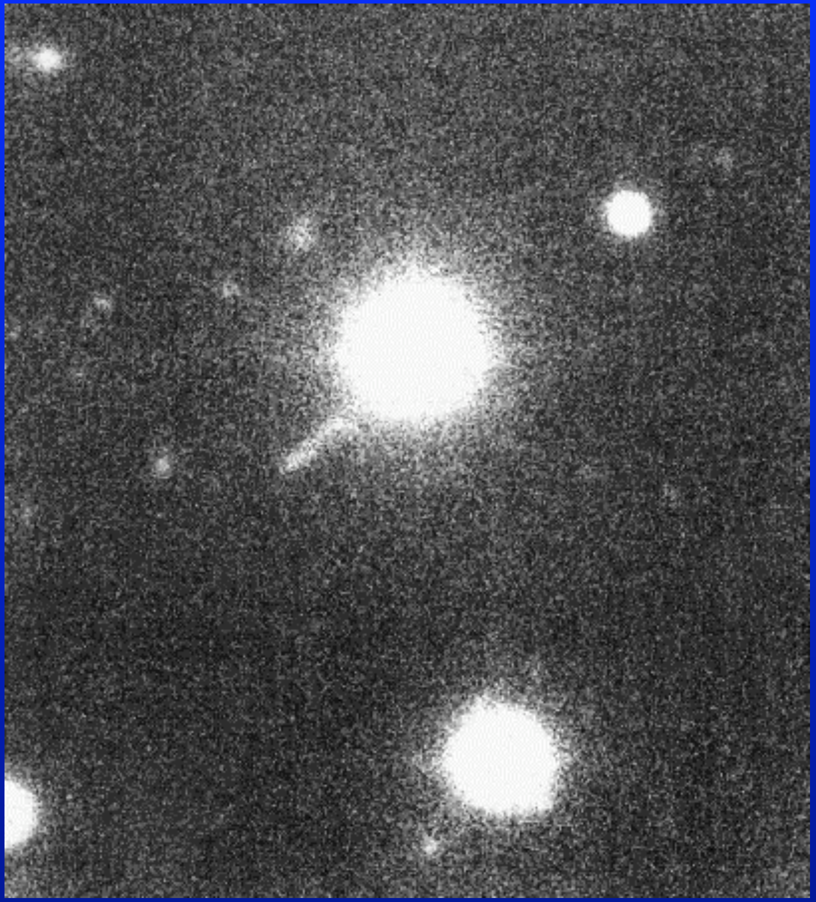
Radio Galaxies

- Most radio sources were found to be associated with galaxies.
- However, some of the radio sources were high Galactic latitude (out of the Galactic plane) star-like sources.

The radio galaxy Centarus A

Quasars

- These “radio stars” had a somewhat “fuzzy” appearance.
- Some radio stars had linear features like “jets”.
- These unusual sources were thus “quasi-stellar radio sources”.



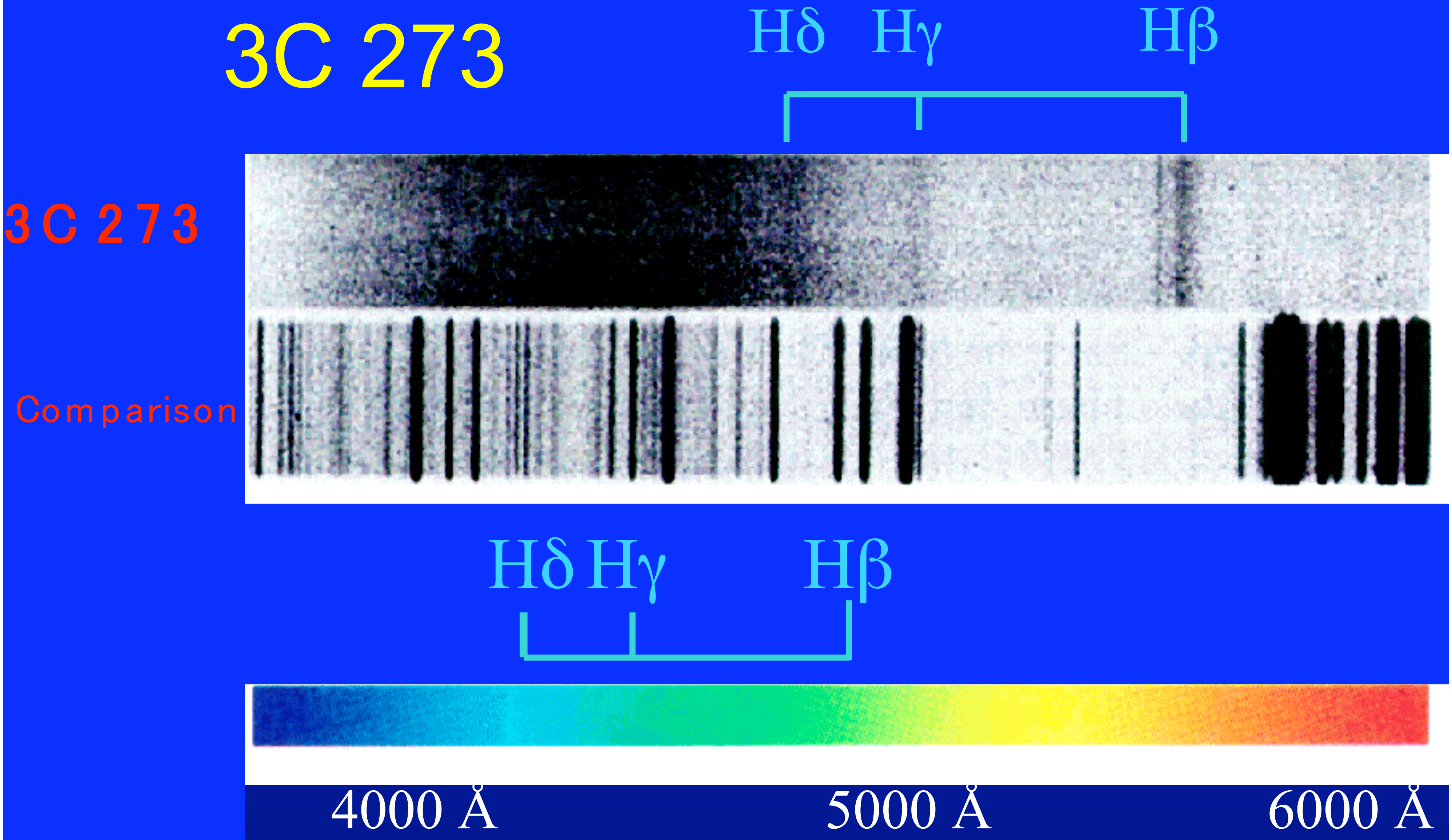
The brightest (still!) quasi-stellar source, 3C273

Optical Studies of Quasi-Stellar Radio Sources

- Optical observations of these sources were made with the Hale 5-m telescope on Mt. Palomar.
- Early spectra were confusing. In 1963, Maarten Schmidt identified features as redshifted emission lines.

Maarten Schmidt (left) and
Allan Sandage

First Spectrum of 3C 273

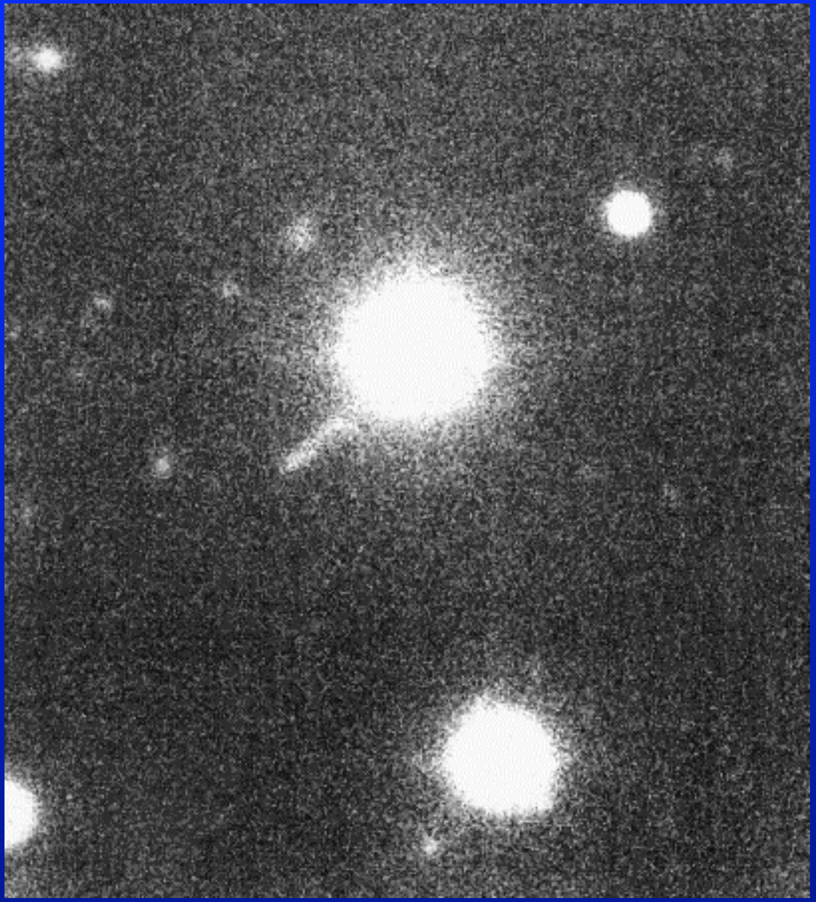


Quasi-Stellar Sources

- The spectral lines in 3C 273 are highly redshifted:

$$z = \frac{\Delta\lambda}{\lambda} = 0.158$$

- This is comparable to the most distant clusters of galaxies known in 1963.



3C 273

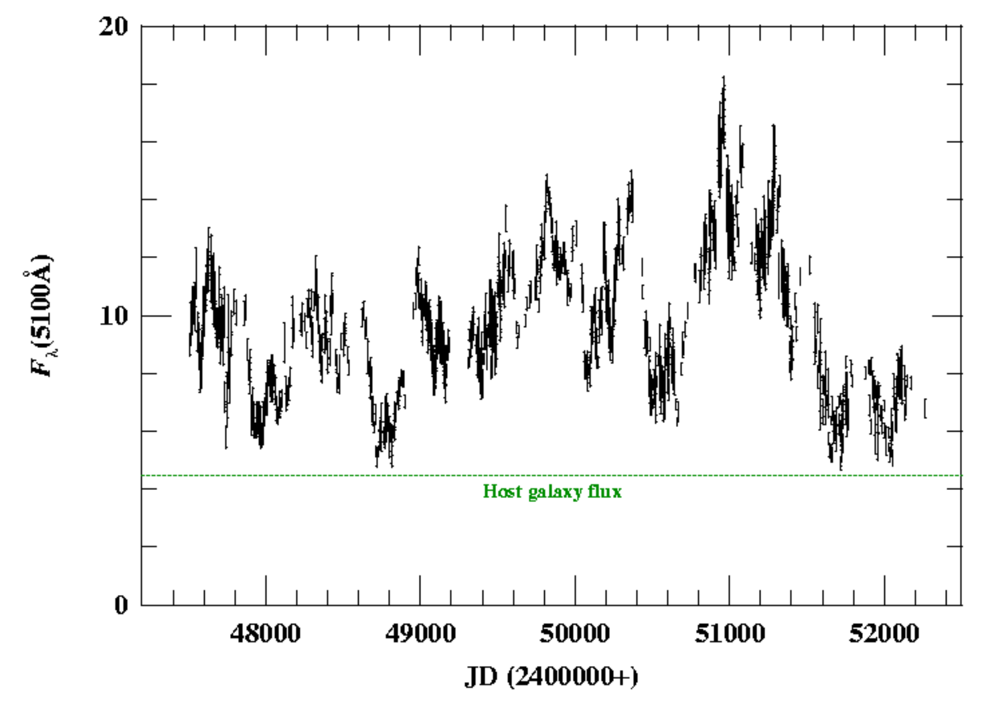
The Brightest Objects in the Universe

- For 3C 273, the large redshift implies:
  - $D \approx 680$ Mpc
  - 3C 273 is about 100 times brighter than giant galaxies like the Milky Way or M 31.

The Andromeda Galaxy M 31

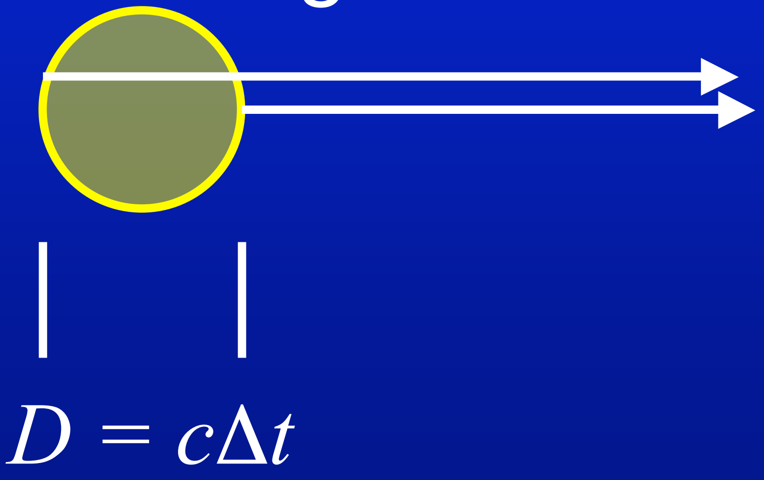
And Now Another Surprise...

- Shortly after their discovery, quasars were found to be highly variable in brightness.
- Rapid variability implies that the emitting source mus be very small.

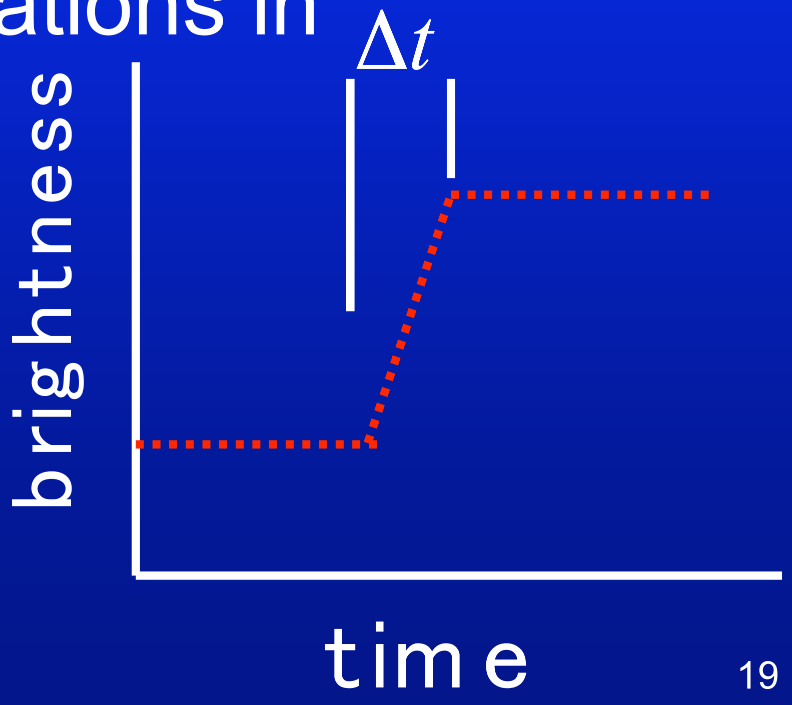


Source “Coherence”

- A variable source must be smaller than the light-travel time associated with significant variations in brightness.

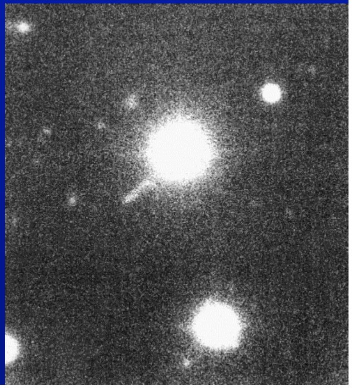


$$D = c\Delta t$$



Sizes of Quasars

- Variability on time scales as short as one day implies sources that are less than one light day in size.
- A volume the size of our Solar System produces the light of a nearly a trillion (10^{12}) stars!
- This ushered in a two-decade controversy about the nature of quasars redshifts.
  - Weedman's premise: this wouldn’t have happened had not the original Seyferts and original quasars been such extreme members of their respective classes



Seyferts and Quasars

- Modern view:
  - Seyferts are lower-luminosity AGNs
  - Quasars are higher-luminosity AGNs
- View in the 1960s:
  - Seyferts are relatively local spiral galaxies with rather abnormally bright cores
  - Quasars are mostly unresolved, high redshift, highly luminous, variable, non-stellar radio sources

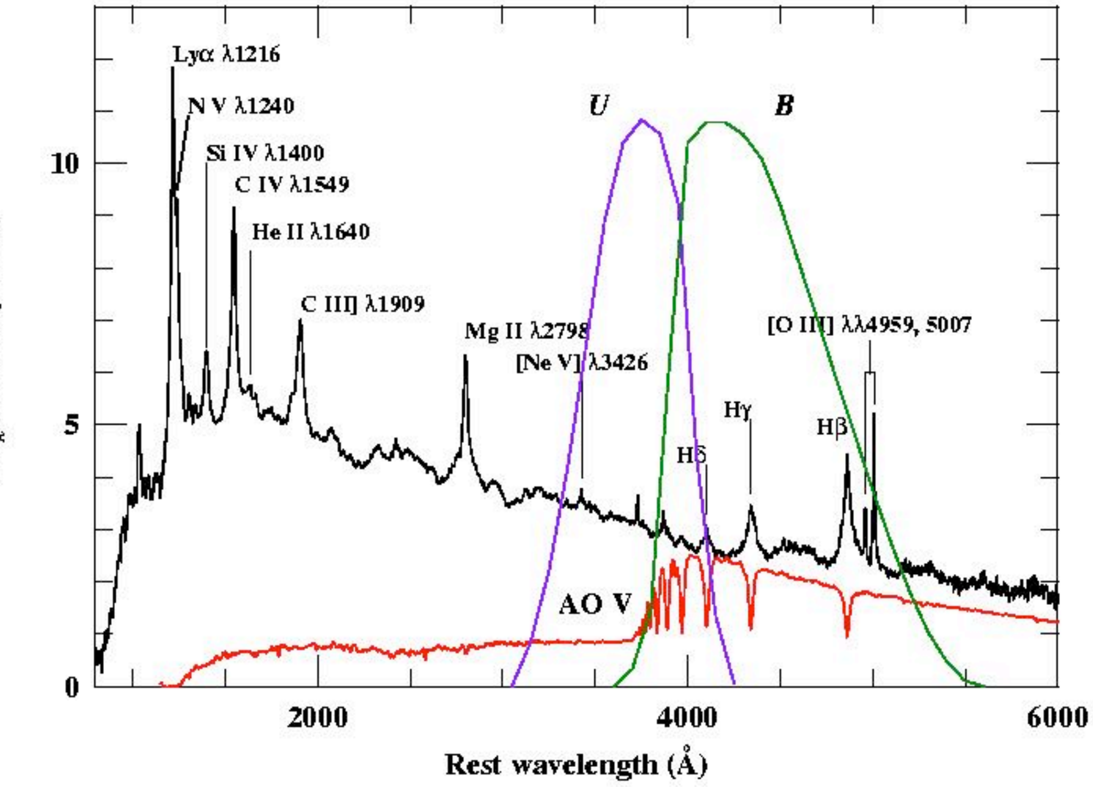
NGC 4051
$z = 0.00234$
$\log L_{\mathrm{opt}} = 41.2$

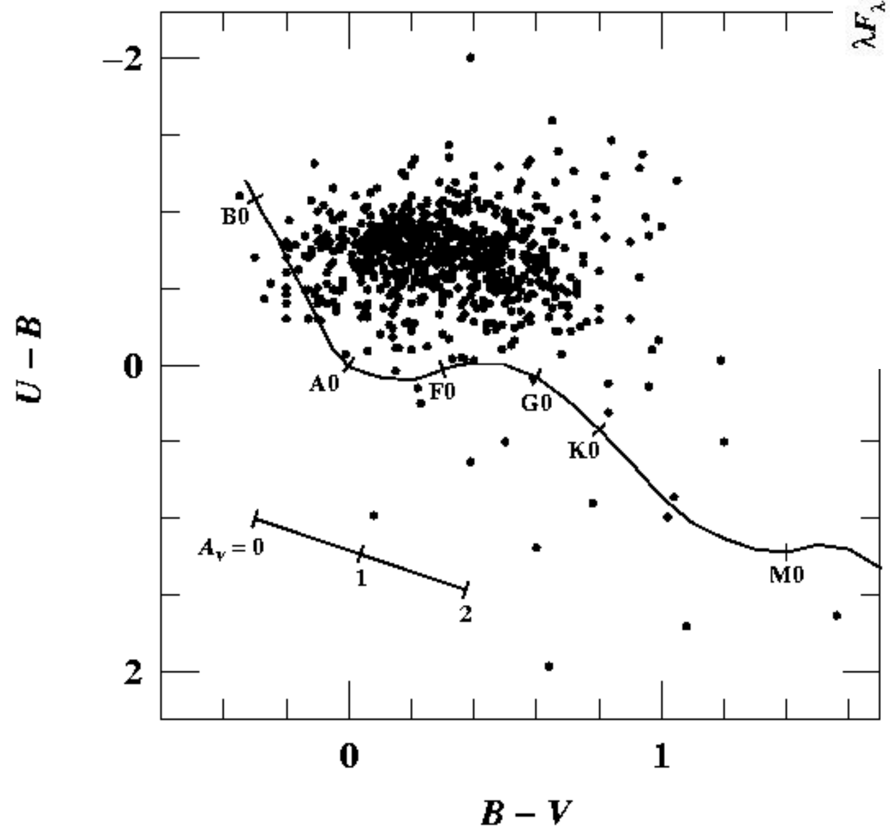
Mrk 335
$z = 0.0256$
$\log L_{\mathrm{opt}} = 43.8$

PG 0953+414
$z = 0.234$
$\log L_{\mathrm{opt}} = 45.1$

Finding Quasars

- That quasars are very blue compared to stars was recognized early.

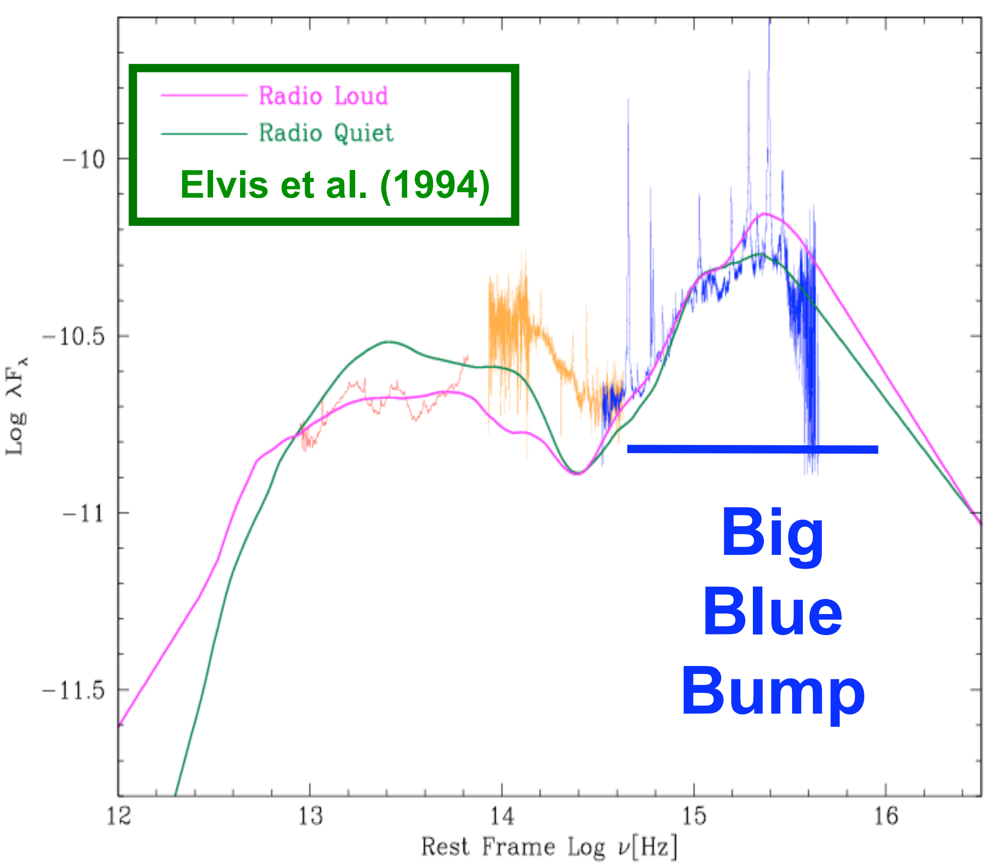




Optical color selection allows us to bypass the difficult radio identification by using “UV excess”.

Quasi-Stellar Objects

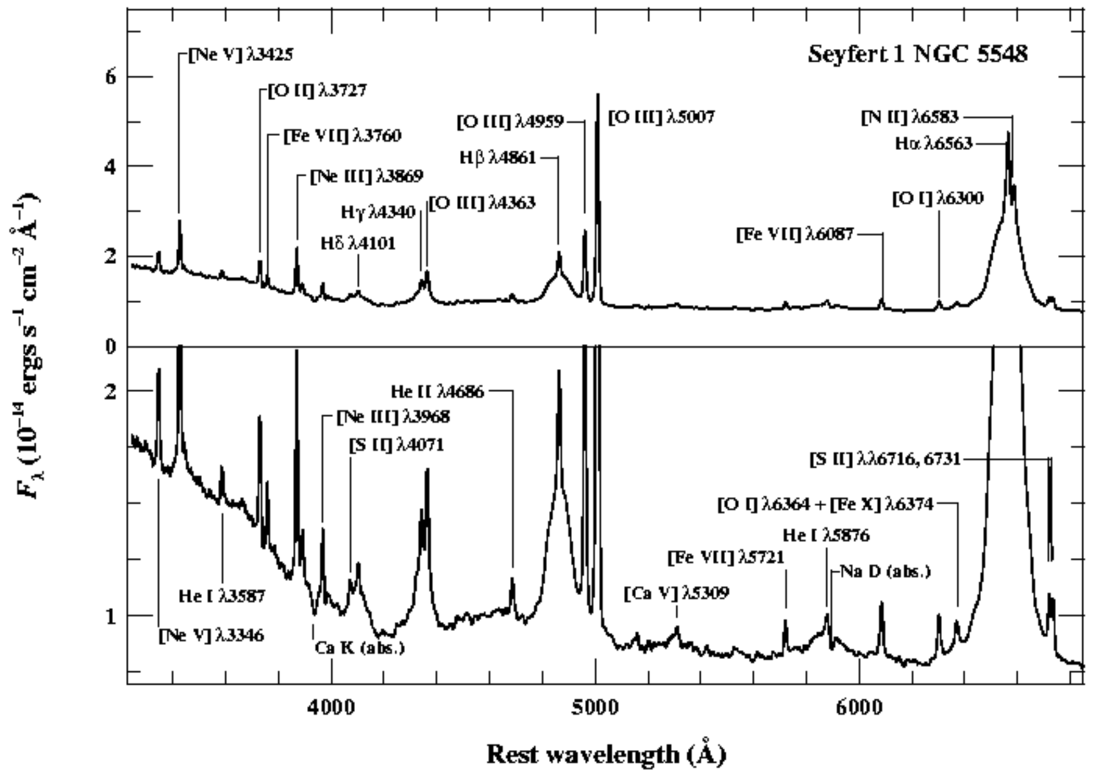
- Most of these blue star-like sources are like the radio-selected quasars, but are ***radio-quiet*.**
- These became generically known as “***quasi-stellar objects***”, or ***QSOs***.



***Spitzer*-era mean SED from Shang et al. (2006)**

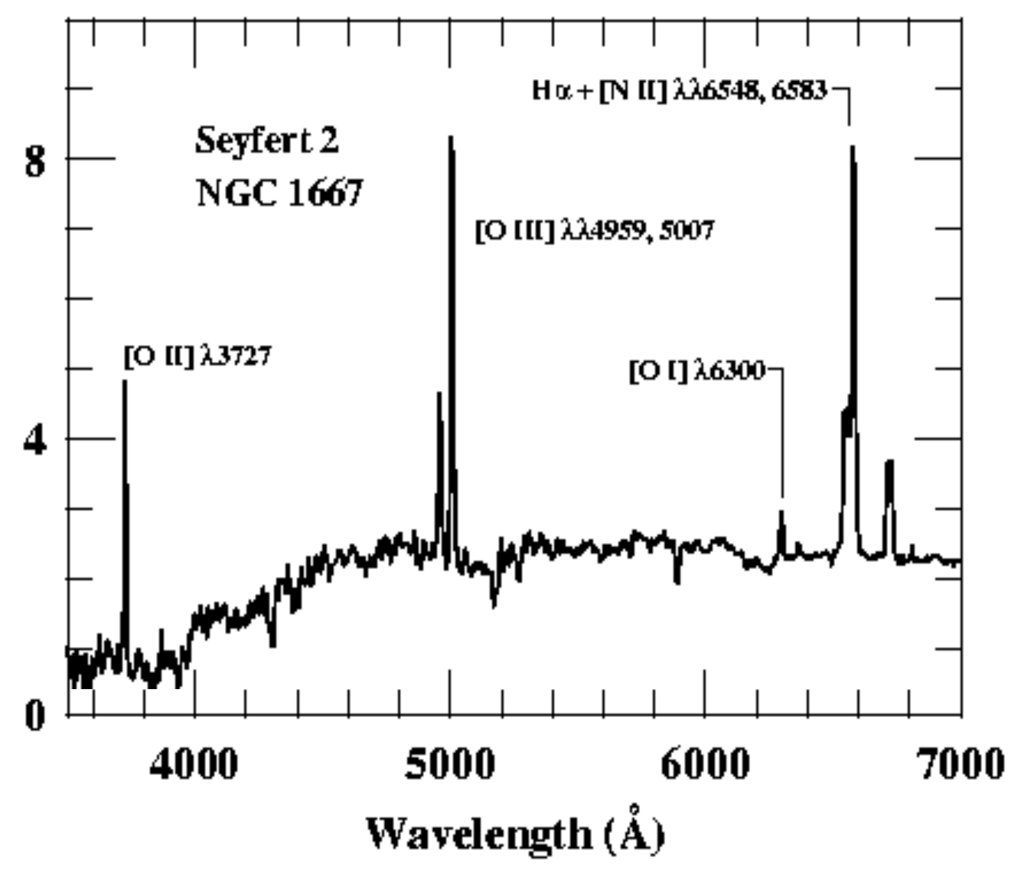
AGN Taxonomy

- Khachikian and Weedman (1974) found that Seyfert galaxies could be separated into two spectroscopic classes.
  - Type 1 Seyferts have broad and narrow lines



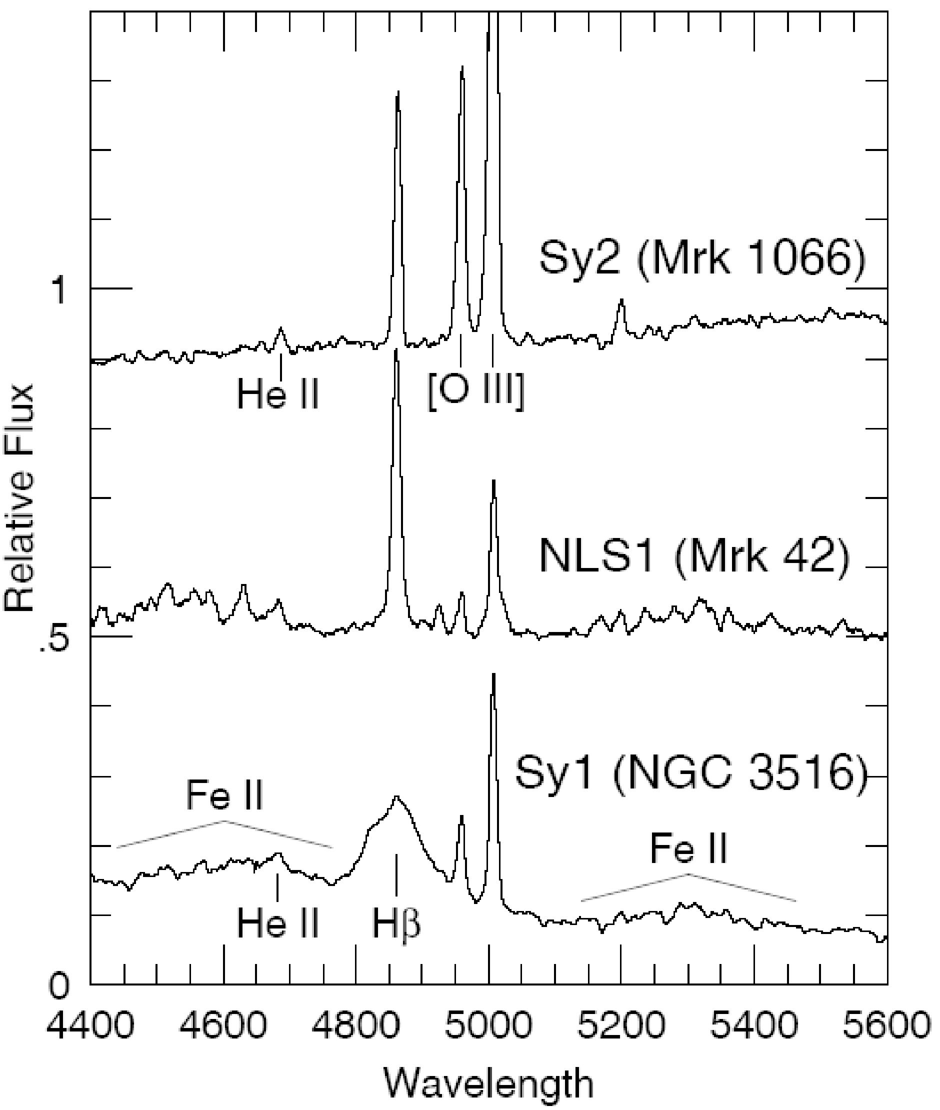
AGN Taxonomy

- Khachikian and Weedman (1974) found that Seyfert galaxies could be separated into two spectroscopic classes.
  - – Type 1 Seyferts have broad and narrow lines
  - – Type 2 Seyferts have only narrow lines



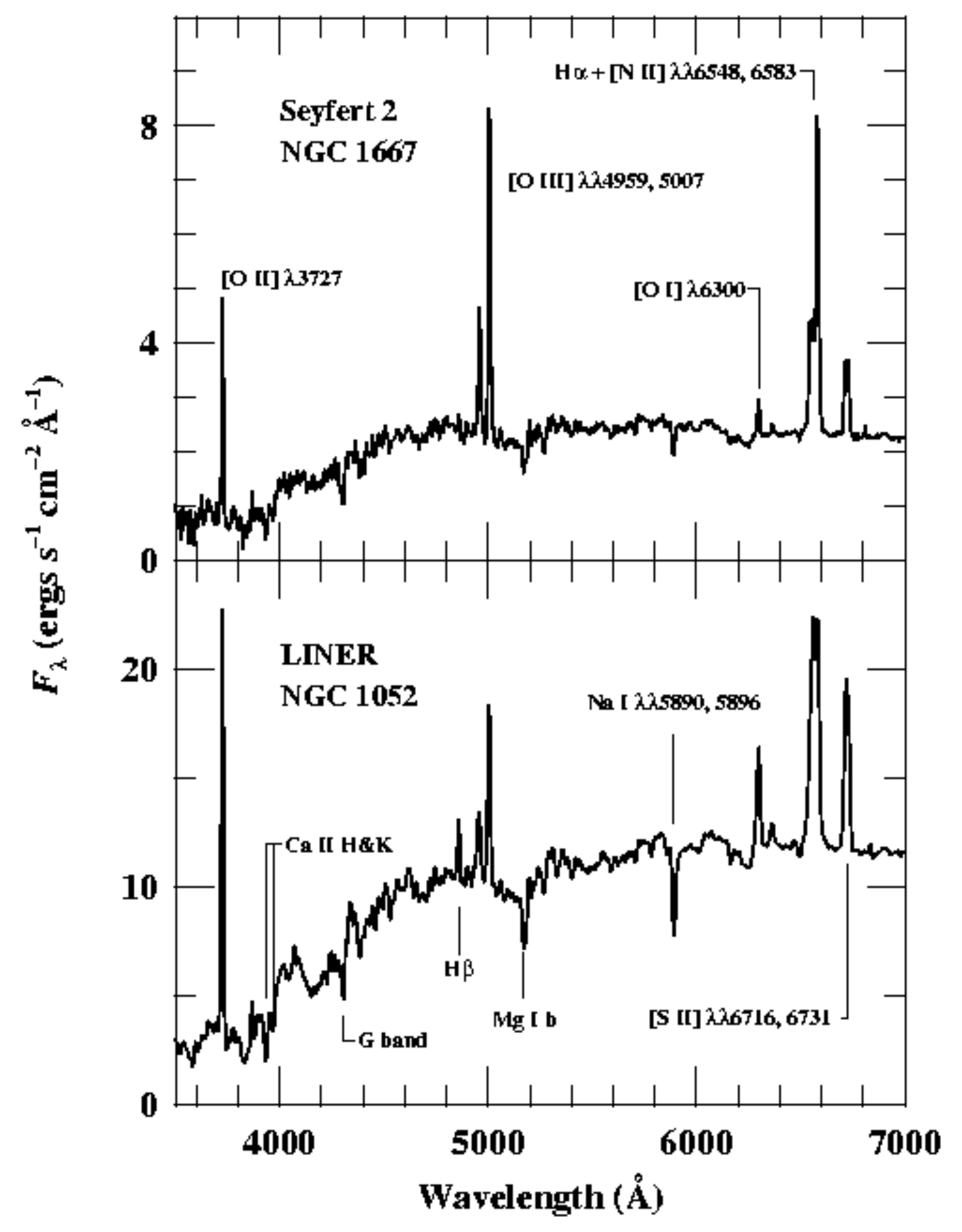
AGN Taxonomy

- Narrow-line Seyfert 1 (***NLS1***) galaxies are true broad-line objects, but with an especially narrow broad component, FWHM < 2000 km s^{-1}



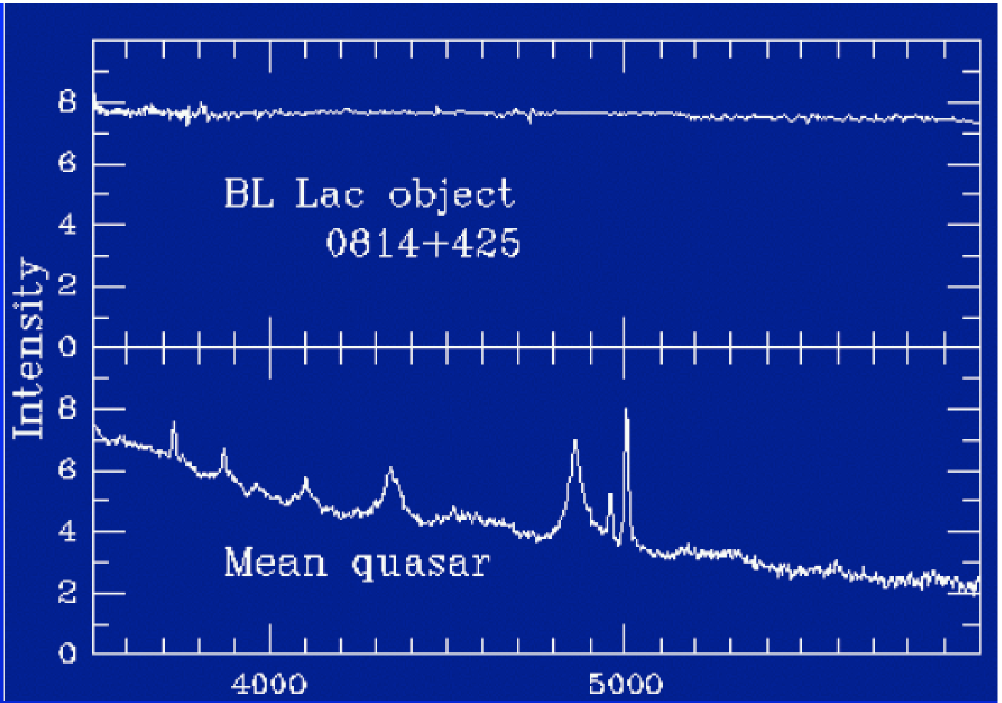
AGN Taxonomy

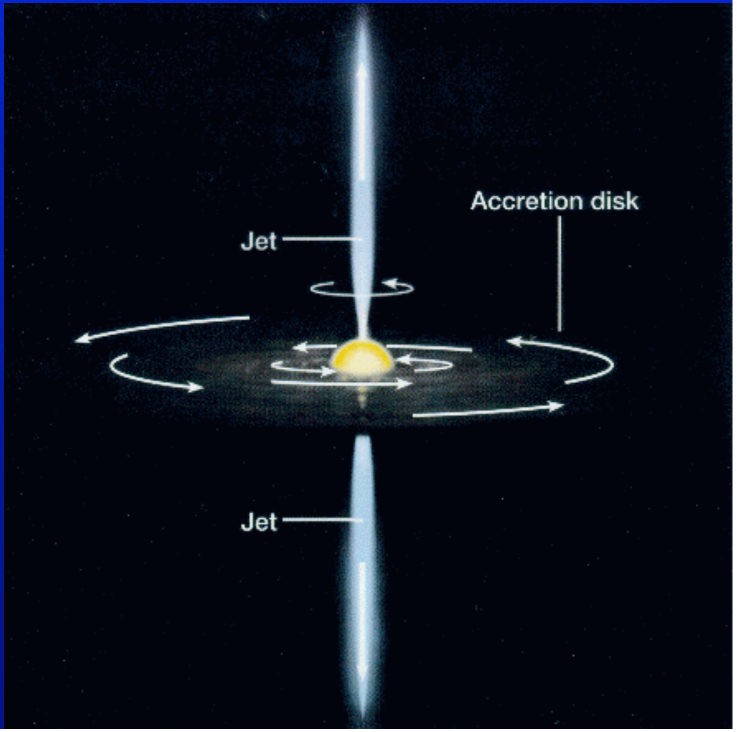
- Heckman (1980) identified a class of Low-Ionization Nuclear Emission Region (***LINER***) galaxies.
  - Lower ionization level lines are stronger than in Sy 2



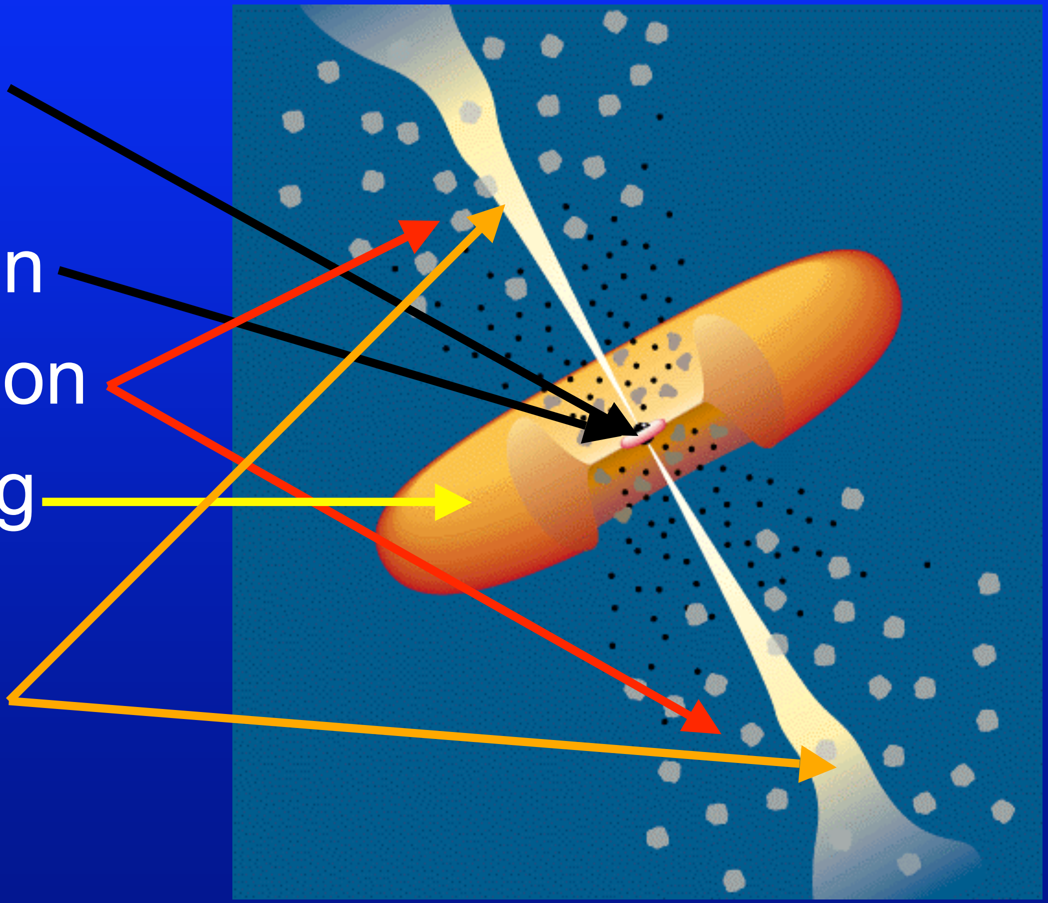
AGN Taxonomy

- ***BL Lac objects*** share many quasar properties (blue, variable, radio sources), but have no emission or absorption lines.
  - Appear to be quasars observed along the jet axis
  - Are often subsumed into a larger class called ***blazars.***





Current AGN Paradigm



- Black hole plus accretion disk
- Broad-line region
- Narrow-line region
- Dusty “obscuring torus”
- Jets (optional?)

Driving Force in AGNs

- Simple arguments suggest AGNs are powered by supermassive black holes
  - Eddington limit requires $M \geq 10^6 M_\odot$ for moderately luminous Seyfert galaxy with $L \approx 10^{44}$ ergs s^{-1}
  - Requirement is that self-gravity exceeds radiation pressure

- Energy flux

$$F = \frac{L}{4\pi r^2}$$

- Momentum flux

$$P_{\mathrm{rad}} = \frac{F}{c} = \frac{L}{4\pi r^2 c}$$

- Force due to radiation

$$F_{\mathrm{rad}} = P_{\mathrm{rad}}\sigma_e = \frac{L\sigma_e}{4\pi r^2 c}$$

- This must be less than gravity

$$\frac{L\sigma_e}{4\pi r^2 c} < \frac{GMm}{r^2}$$

$$L < \frac{4\pi Gcm}{\sigma_e} \approx 1.26\times10^{38}\left(\frac{M}{M_{\odot}}\right)\mathrm{ergs\ \ s^{-1}}$$

“The Eddington Limit”

- Simple arguments suggest AGNs are powered by supermassive black holes
  - Potential energy of infalling mass is converted to radiant energy with some efficiency η so $E = \eta mc^2$
  - Potential energy is $U = GM_{\mathrm{BH}}m/r$
  - Energy dissipated at ~10 R_g where $R_g = GM_{\mathrm{BH}}/c^2$ (to be shown)
  - Available energy:

$$U = \frac{GM_{\mathrm{BH}}m}{10R_g} = 0.1\frac{GM_{\mathrm{BH}}m}{GM_{\mathrm{BH}}/c^2} = 0.1mc^2$$

  - Thus $\eta \approx 0.1$

Eddington Rate

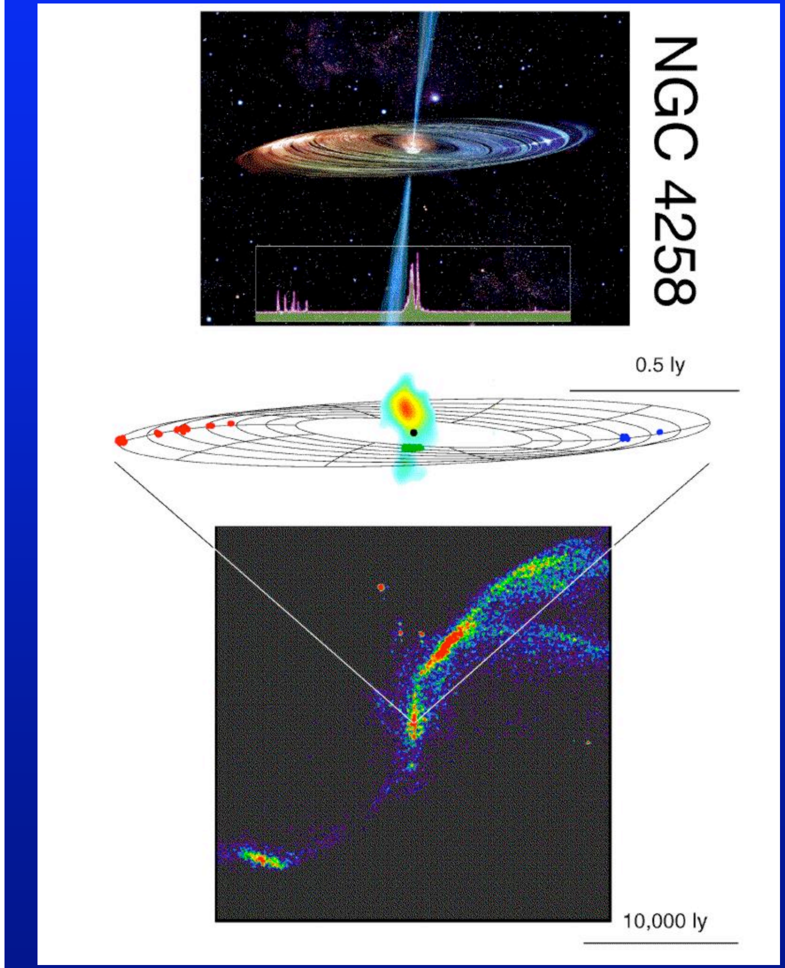
- Accretion rate necessary to attain Eddington luminosity is the maximum possible

$$\dot{M}_{\mathrm{Edd}} = \frac{L_{\mathrm{Edd}}}{\eta c^2} = \frac{1.47\times 10^{17}}{\eta}\left(\frac{M_{\mathrm{BH}}}{M_{\odot}}\right)\mathrm{gm\ s^{-1}}$$

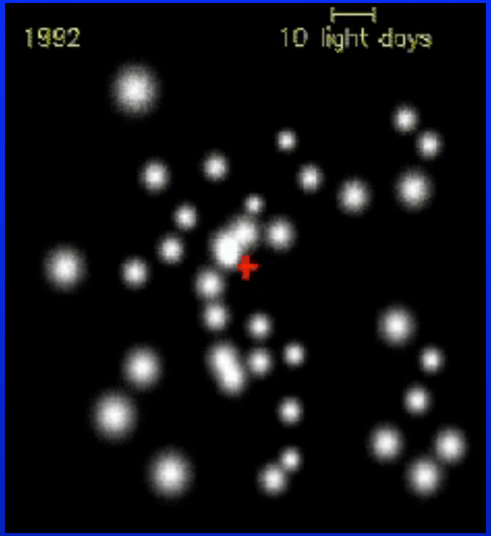
- Eddington rate is ratio of actual accretion rate to maximum possible

$$\dot{m} = \dot{M}\Big/\dot{M}_{\mathrm{Edd}}$$

Evidence for Supermassive Black Holes



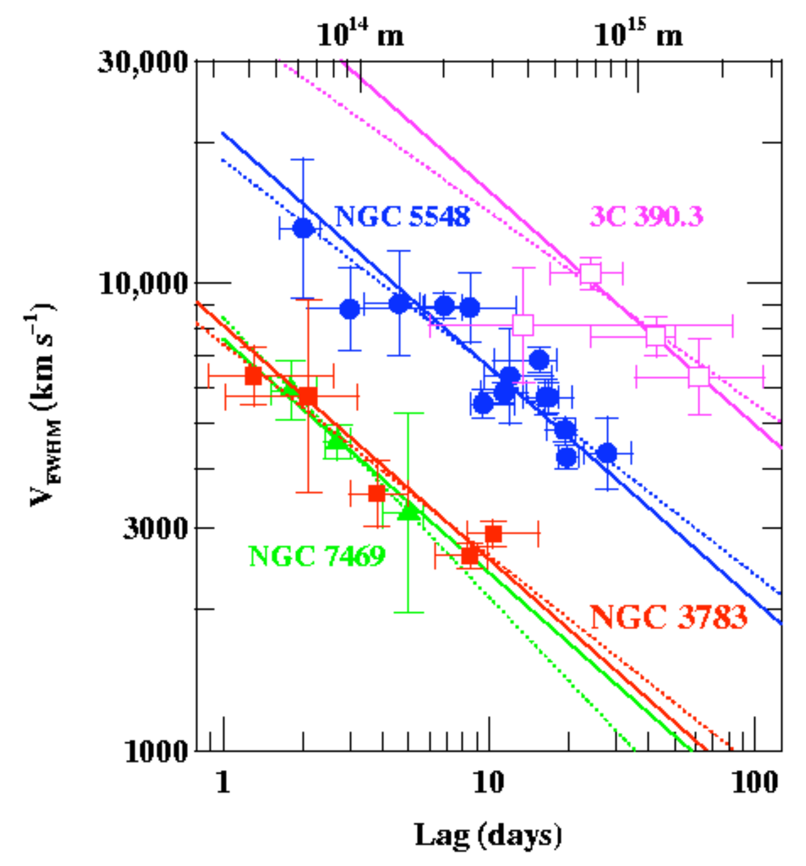
- Milky Way: Stars orbit a black hole of $2.6 \times 10^6 M_\odot$.



- NGC 4258: H_2O megamaser radial velocities and proper motions give a mass $4 \times 10^7 M_\odot$.

Evidence for Supermassive Black Holes

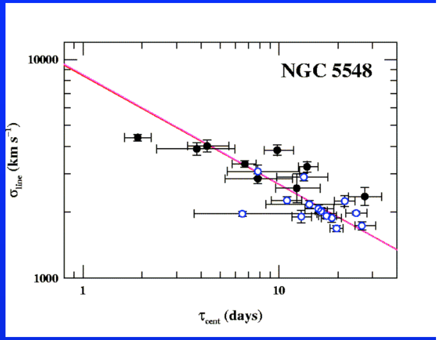
- In the case of AGNs, reverberation mapping of the broad emission lines can be used to measure black hole masses.
  - Later elaboration



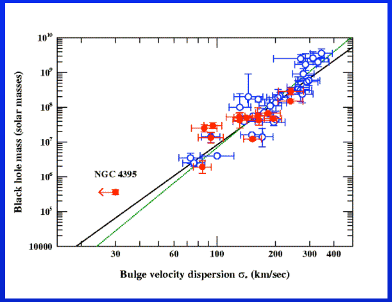
$$M_{\mathrm{BH}} \propto \frac{\Delta V^2 R}{G} \Rightarrow \Delta V \propto R^{-1/2}$$

Evidence That Reverberation-Based Masses Are Reliable

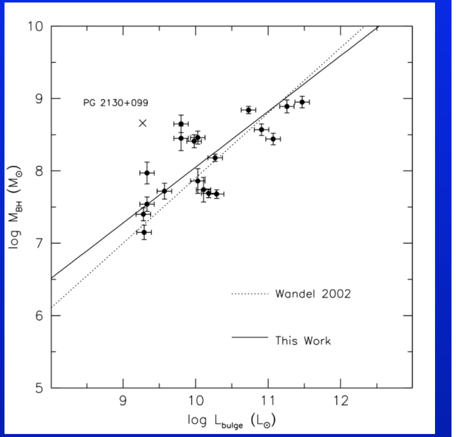
1. Virial relationship for emission-line lags (BLR radius) and line widths



2. $M_{\rm BH} - \sigma_*$ relationship

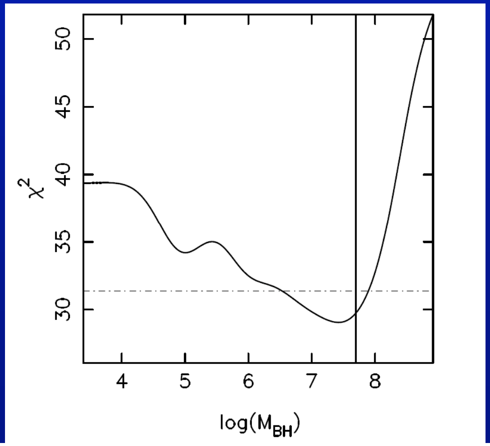


3. $M_{\rm BH} - L_{\rm bulge}$ relationship



4. Direct comparisons with other methods:

  - Stellar dynamical masses
    In the cases of
    NGC 3227
    and NGC 4151

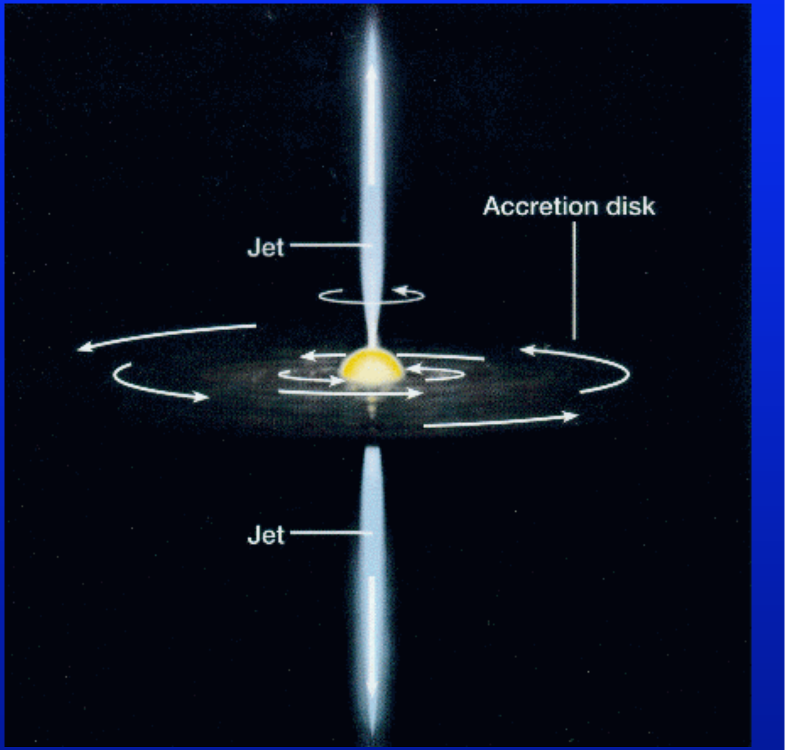


Accretion Disks

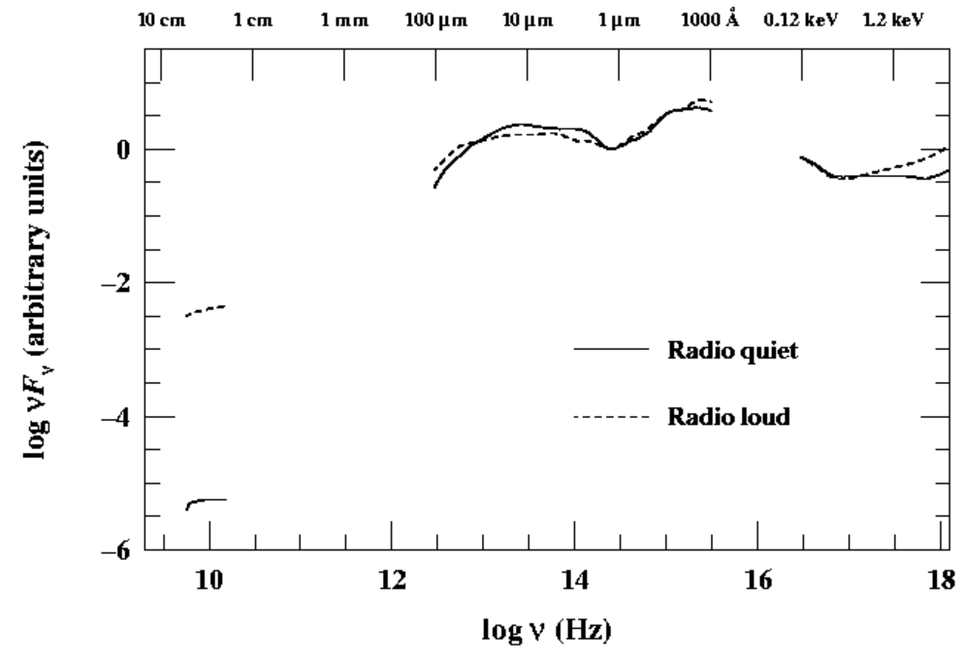
- Angular momentum of infalling material will lead to formation of an accretion disk.

$$L = \frac{GM_{\mathrm{BH}}\dot{M}}{2r} = 2\pi r^2 \sigma T^4$$

$$T(r) = \left(\frac{GM_{\mathrm{BH}}\dot{M}}{4\pi\sigma r^3} \right)^{1/4}$$



$$T(r) \approx 3.7\times10^{5}\,\dot{m}^{1/4}\left(\frac{M_{BH}}{10^{8}M_{\odot}}\right)^{-1/4}\left(\frac{r}{R_{\mathrm{g}}}\right)^{-3/4}\ \mathrm{K}$$



Assuming that QSO SED peak at 1000 Å represents accretion disk, Wien's law tells us $T \approx 5\times10^{5}$ K.

For $M_{\mathrm{BH}} = 10^{8}\ M_{\odot}$, $R \approx 14\ R_{\mathrm{g}}$.

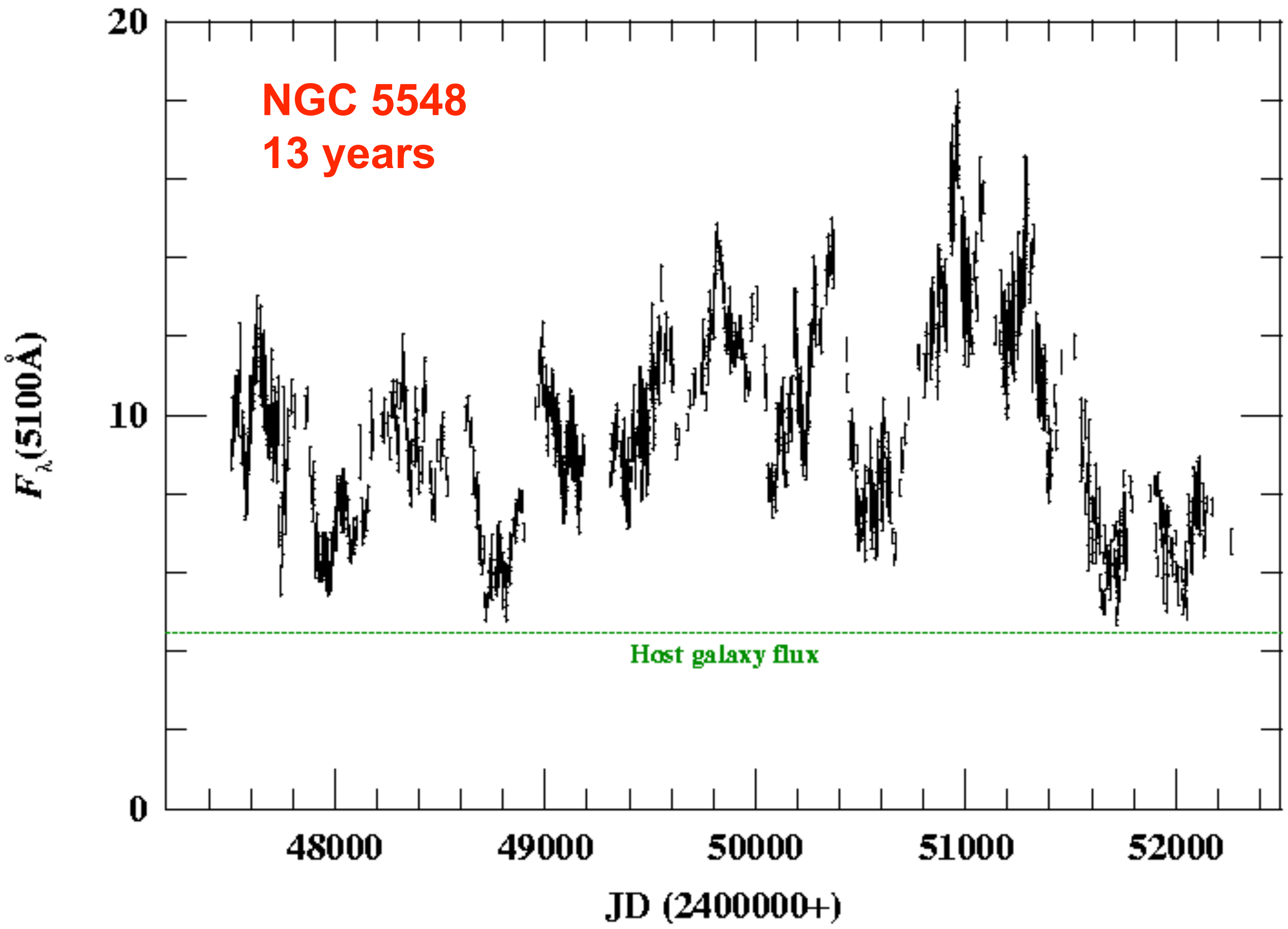
Optical Continuum Variability

- One of the first recognized properties of quasars (Mathews & Sandage 1963; Smith &Hoffleit 1963).
- Established that significant variations in brightness (~ 0.1 mag) could occur on time scales as short as days
  - Implies size of emitting region must be of order light days (1 light day = 2.6×10^{15} cm).

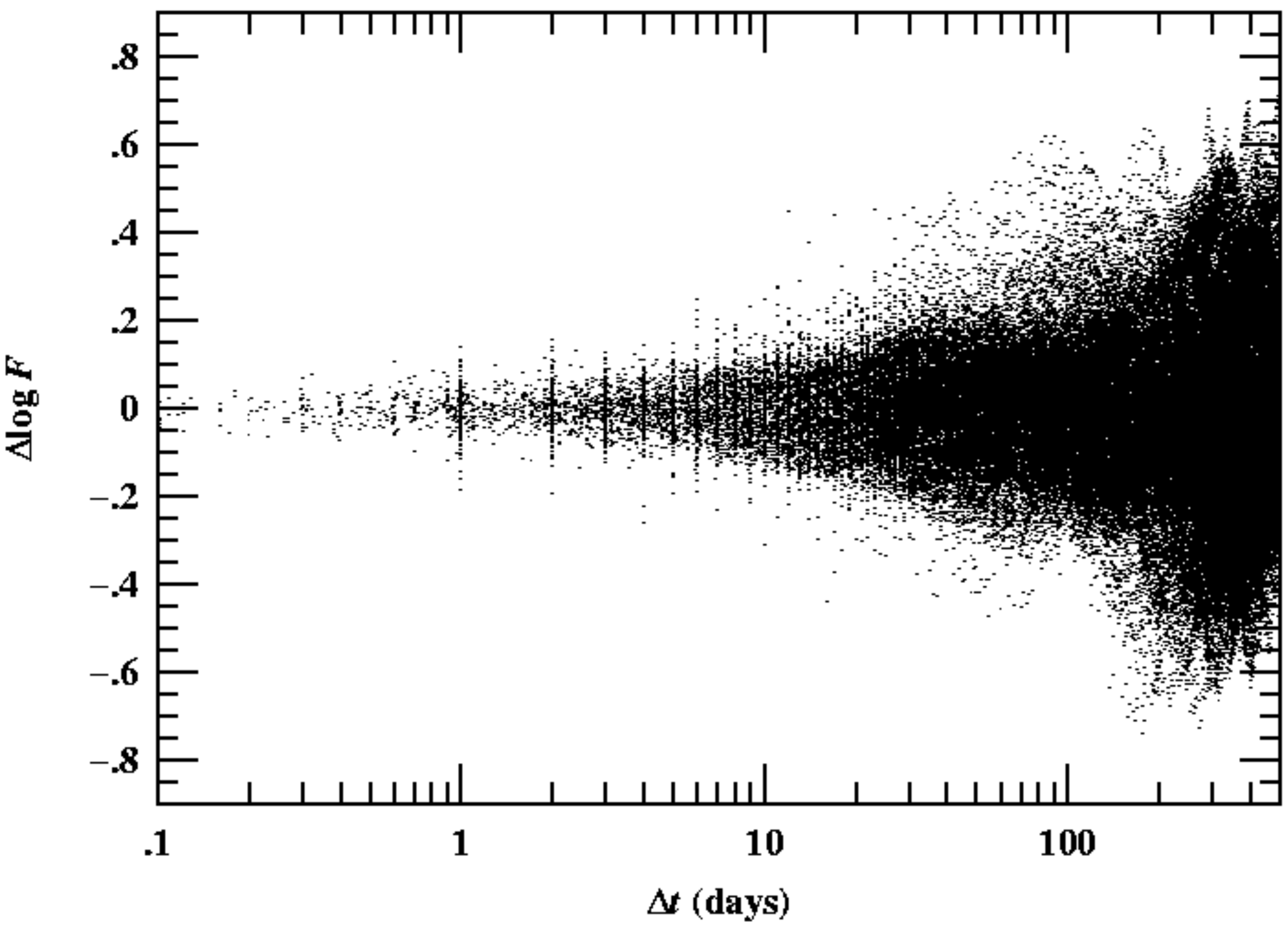
Quasar Variability

- Quasars were found to be variable at all wavelengths.
  - Variations appeared to be aperiodic
- Variability in Seyfert galaxies was not reported until 1967, and was less dramatic.
- Most of the quasars that were monitored are now known to be the jet-dominated sources known as “blazars”: BL Lac objects and optically violent variables (OVVs).
- Original conclusions about AGN sizes proved to be generally correct, however.

Optical Variability



Amplitude of Optical Variability



Characterizing Variability

- Common parameter to characterize variability is the “excess variance”:

$$F_{\mathrm{var}} = \frac{(\sigma^2 - \Delta^2)^{1/2}}{\langle f \rangle}$$

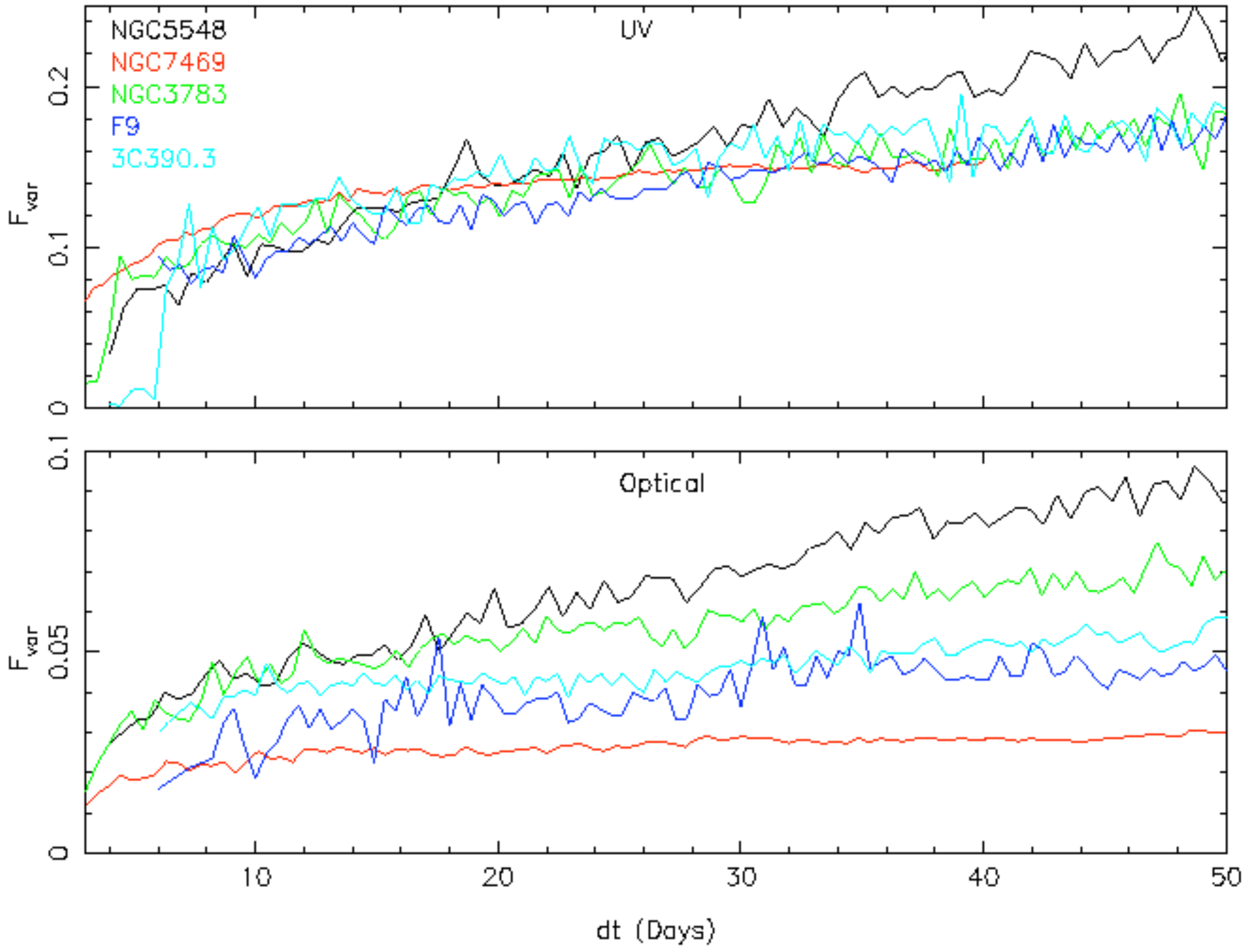
Where: $\langle f \rangle = \frac{1}{N}\sum_{i=1}^{N} f_i$ (Mean flux)

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(f_i - \langle f \rangle)^2$$ (Measured variance of flux)

$$\Delta^2 = \frac{1}{N}\sum_{i=1}^{N}\Delta_i^2$$ (Mean square uncertainty of fluxes)

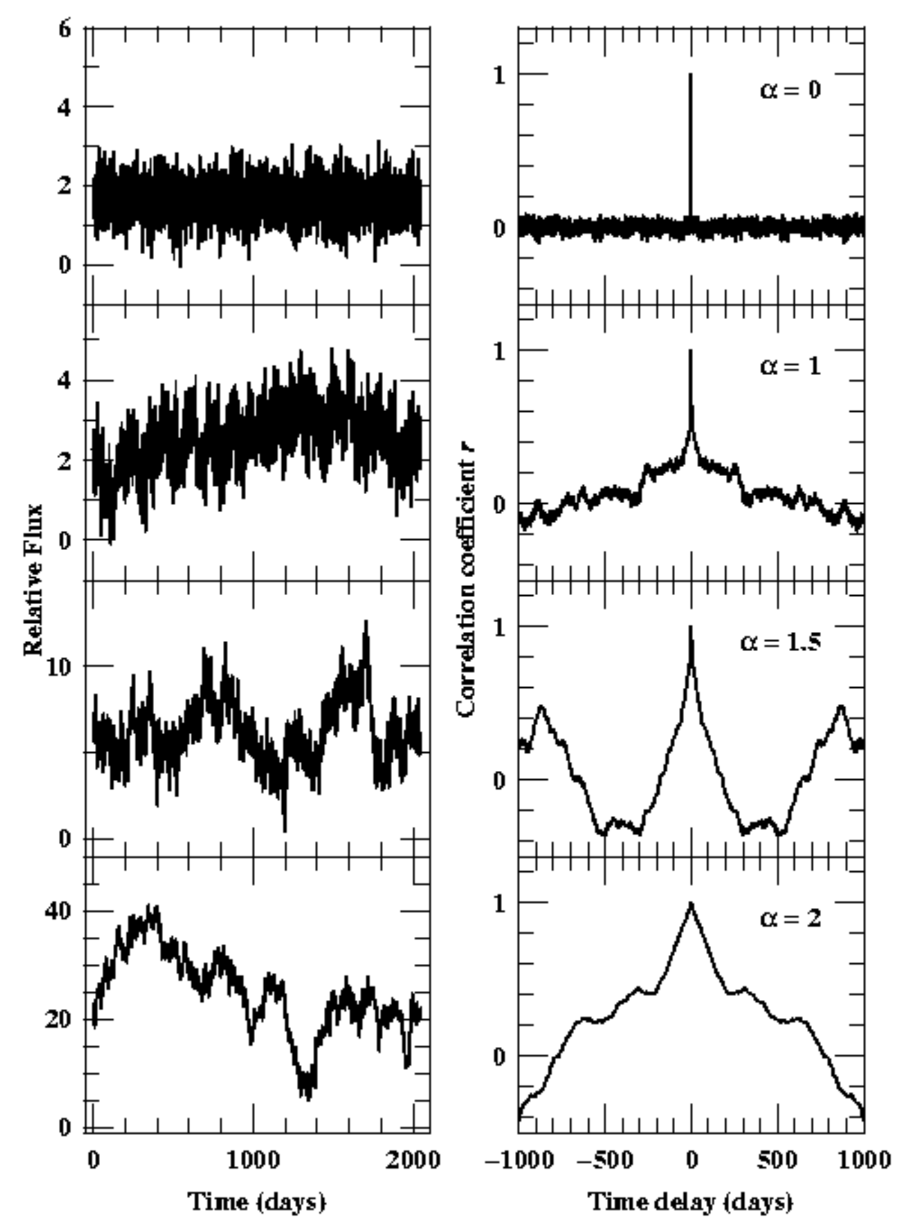
This accounts for the contribution to the scatter in the fluxes due to random errors.

Observed F_{var} vs. Δt for Well-Studied AGNs



Power-Density Spectra

- A useful way to characterize variability is in terms of the "power density spectrum (PDS)" $P(f) = f^{-\alpha}$
  - Product of Fourier transform of light curve and its complex conjugate.
- Observed variations can be characterized by $1 \leq \alpha \leq 2.5$



Cause of Variations

- Actual reason for variability is unknown, but thought to be due to accretion instability
- Variations of the form $1/f^{\alpha}$ can be explained by magnetohydrodynamic instabilities (disconnection events) within the disk (Kawaguchi et al. 1999).
- Other proposed mechanisms:
  - variable accretion rate
  - in special cases:
    - obscuration
    - microlensing

Physical Time Scales for AGN Accretion Disks

- Light-travel time across X-ray emitting region.

$$t_{\mathrm{crossing}} = 0.005\ M_7 (R/10R_{\mathrm{g}})\ \mathrm{days}$$

- Orbital period in X-ray emitting region.

$$t_{\mathrm{orbital}} = 0.12\ M_7 (R/10R_{\mathrm{g}})^{3/2} \mathrm{days}$$

- Time for thermal instabilities to develop.

$$t_{\mathrm{thermal}} = 1.9\ (\alpha/0.01)^{-1} M_7 (R/10R_{\mathrm{g}})^{3/2}\ \mathrm{days}$$

Physical Time Scales for AGN Accretion Disks

- Sound-crossing time.

$$t_{\mathrm{sound}} = 12(R/100H)M_7(R/R_{\mathrm{g}})^{3/2}\ \mathrm{days}$$

- Time for variations in accretion rate to propagate through disk.

$$t_{\mathrm{drift}} = 19{,}000(R/H)^2(\alpha/0.01)^{-1}M_7(R/10R_{\mathrm{g}})^{3/2}\ \mathrm{days}$$