Active Galactic Nuclei at the Half-Century Mark

Bradley M. Peterson
The Ohio State University

UFRGS Lectures

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Topics to be Covered

- *Lecture 1:* AGN properties and taxonomy, fundamental physics of AGNs, AGN structure
- *Lecture 2:* The broad-line region, emission-line variability, reverberation mapping principles, practice, and results, the radius–luminosity relationship, AGN outflows and disk-wind models
- *Lecture 3:* AGN luminosity function and its evolution, role of black holes, direct/indirect measurement of AGN black hole masses, relationships between BH mass and AGN/host properties, “industrial scale” reverberation mapping

A Caveat: “Buyer Beware”

- The AGN phenomenon is complicated.
- Any attempt to cover it in a few lectures will be biased.
- In these lectures, I will try to focus on very fundamental properties, black hole masses in particular.

“Active Galactic Nuclei (AGN)”

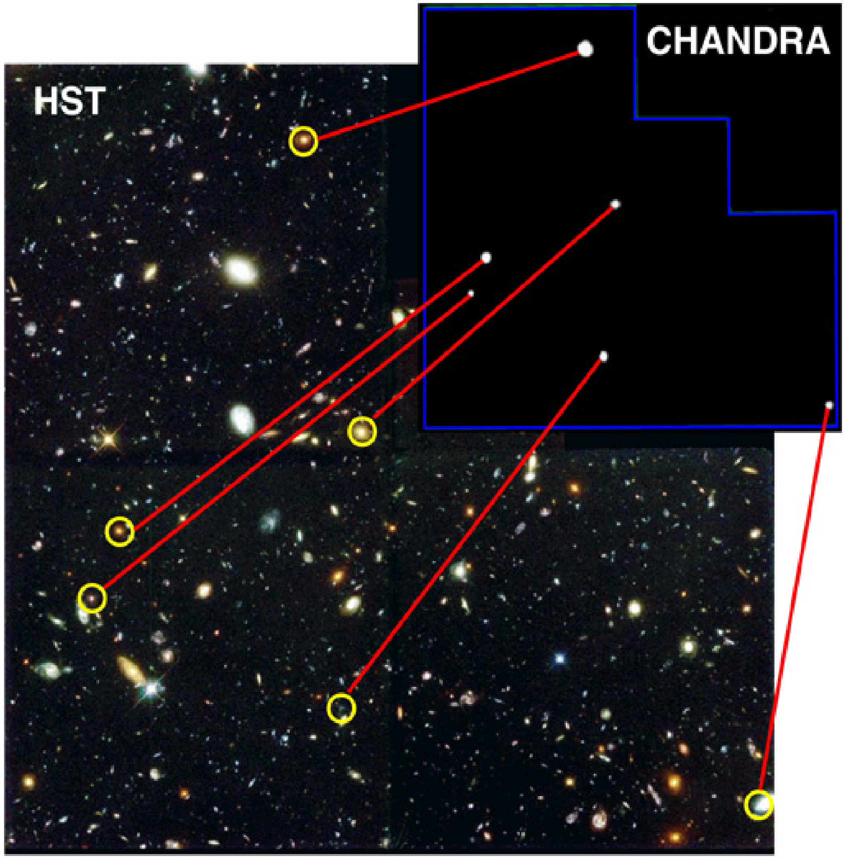
- The phrase “active nucleus” was originally used by V.A. Ambartsumian in 1968
  - “the violent motions of gaseous clouds, considerable excess radiation in the ultraviolet, relatively rapid changes in brightness, expulsions of jets and condensations” ***Ambartsumian 1970***
- First use in paper title: 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”
    University of British Columbia

“Active Galactic Nuclei (AGN)”

- “Activity” was usually taken to mean “radio source”, although sometimes also meant “starburst”
- 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.”

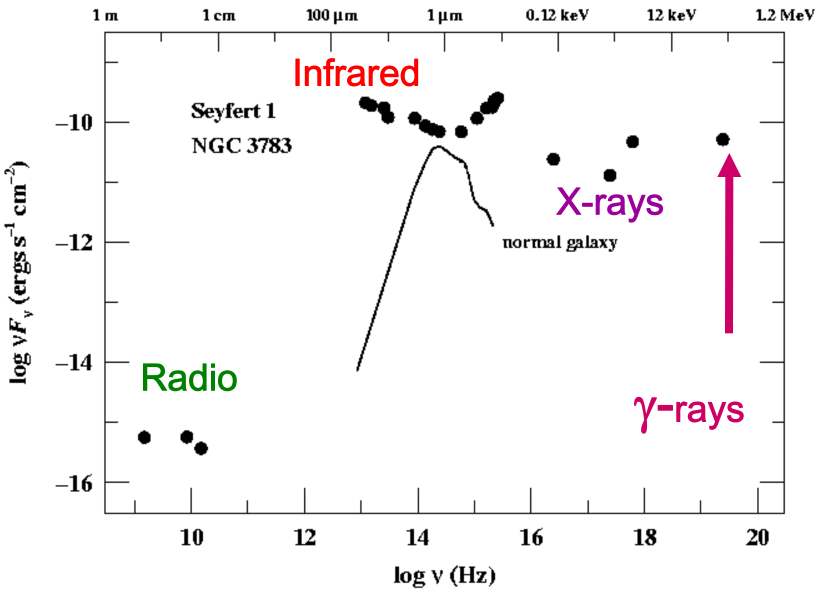
Properties of AGNs

- Strong X-ray emission



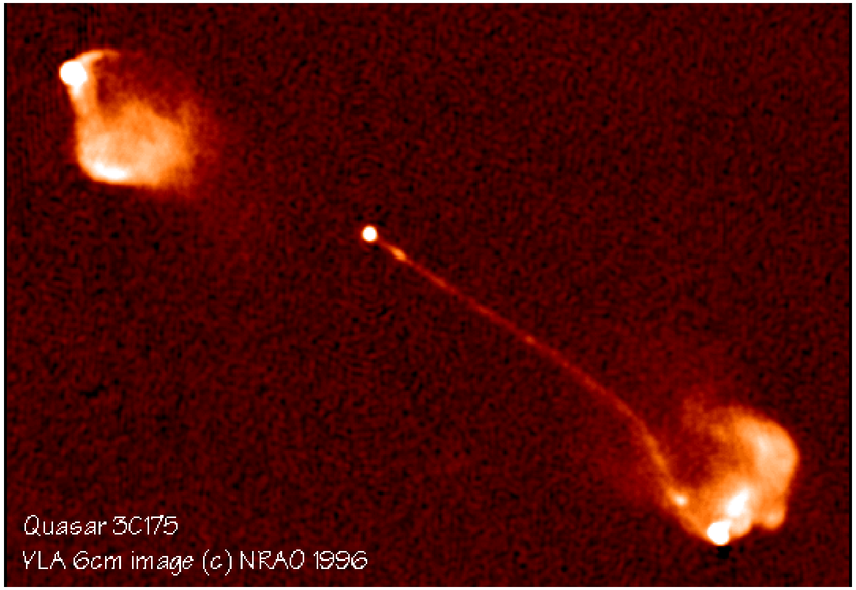
Properties of AGNs

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



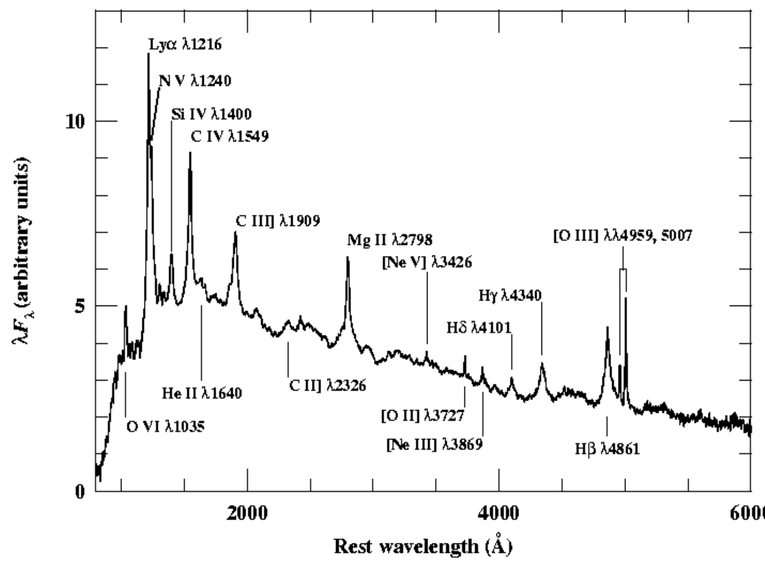
Properties of AGNs

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



Properties of AGNs

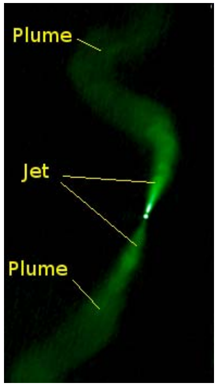
- Strong X-ray emission
- Non-stellar ultraviolet/optical continuum emission
- Relatively strong radio emission
- UV through IR spectrum dominated by strong, broad emission lines.

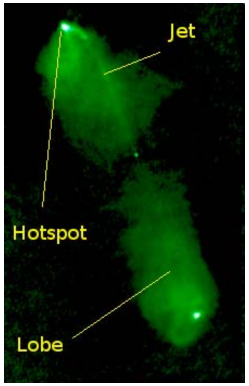


Not every AGN shares all of these characteristics.

AGN Classification

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





			Radio galaxies	
Object	Quasars	Seyferts	FR I	FR II
Luminosity	High	Low	Low	High
Accretion rate	High	High	Low	Low

LINERs are somewhat problematic in this classification.

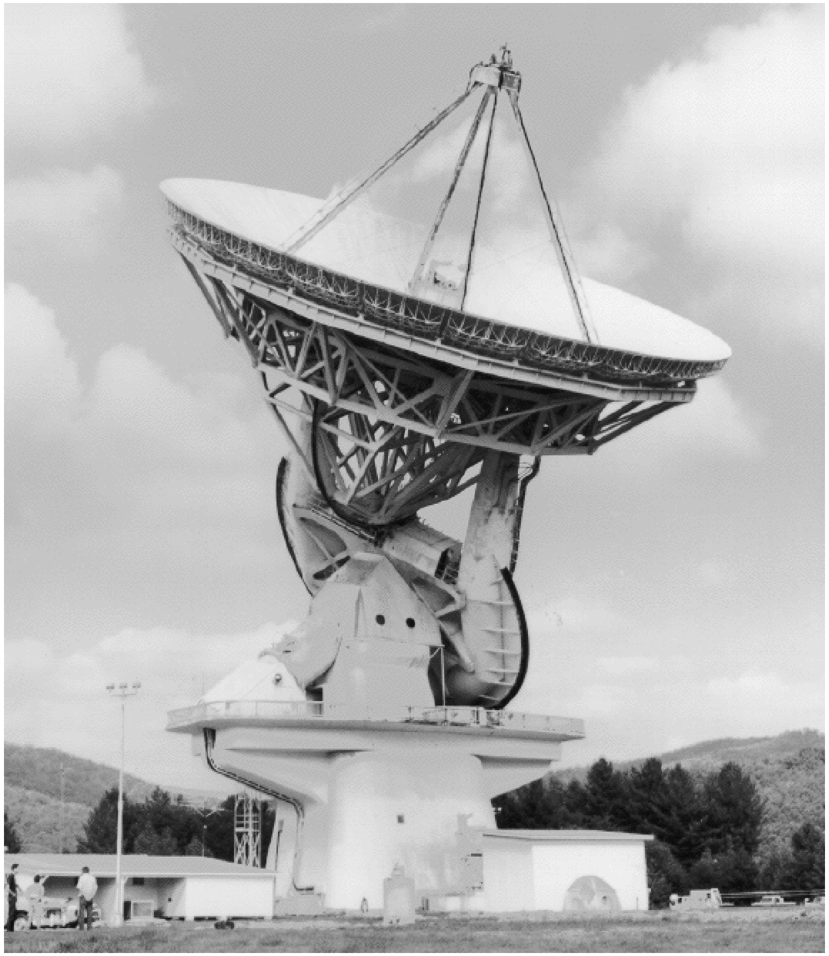
Seyfert Galaxies

- 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



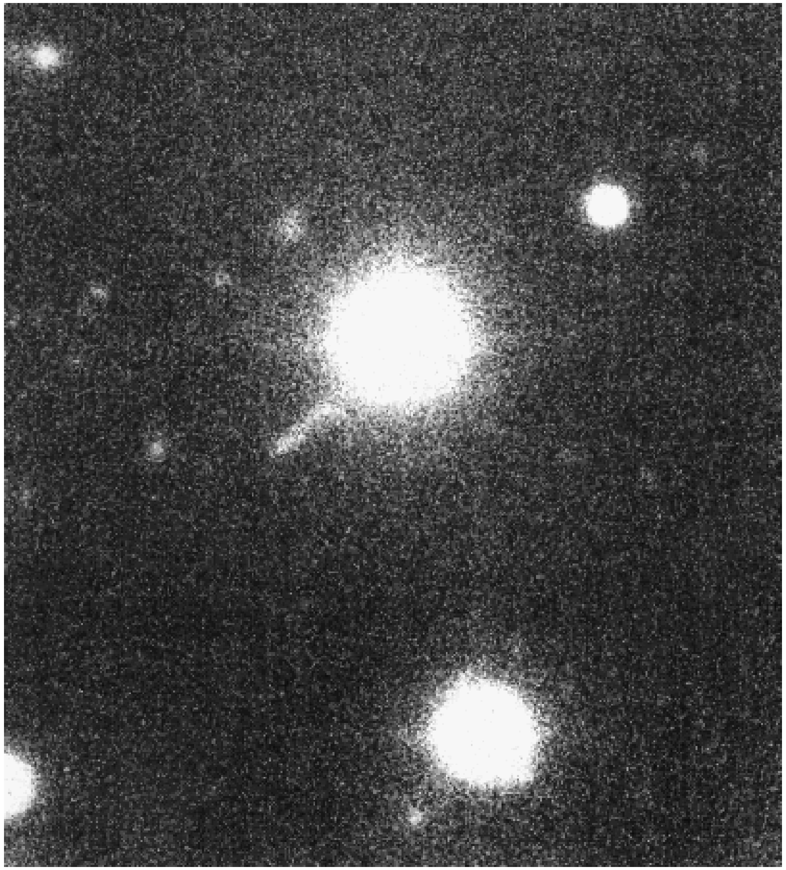
Radio Galaxies

- 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, 3C 273

Optical Studies of Quasi-Stellar Radio Sources

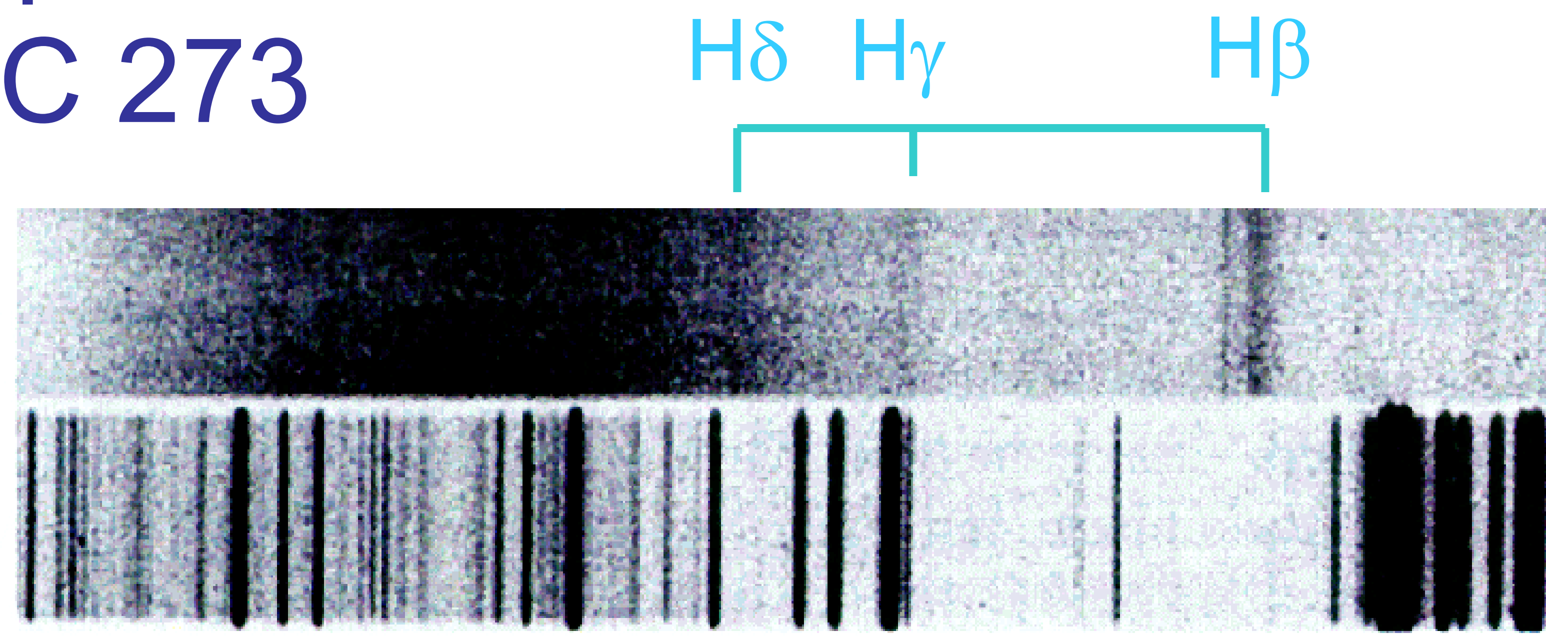
- Optical observations of these sources were made with the Hale 5-m telescope on Mt. Palomar.
- Early spectra were confusing. In 1963, Maarten Schmidt identified features as redshifted emission lines.

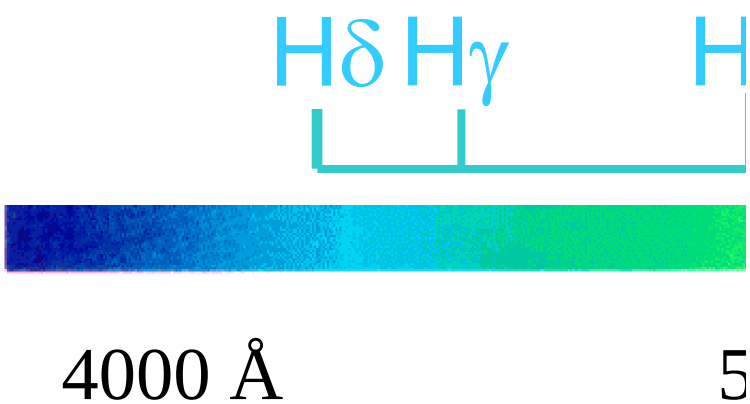
Maarten Schmidt (left) and Allan Sandage

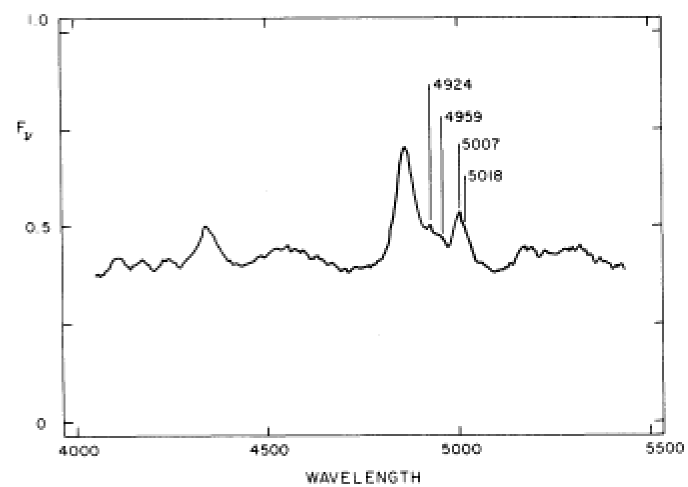
First Spectrum of 3C 273

3C 273

Comparison





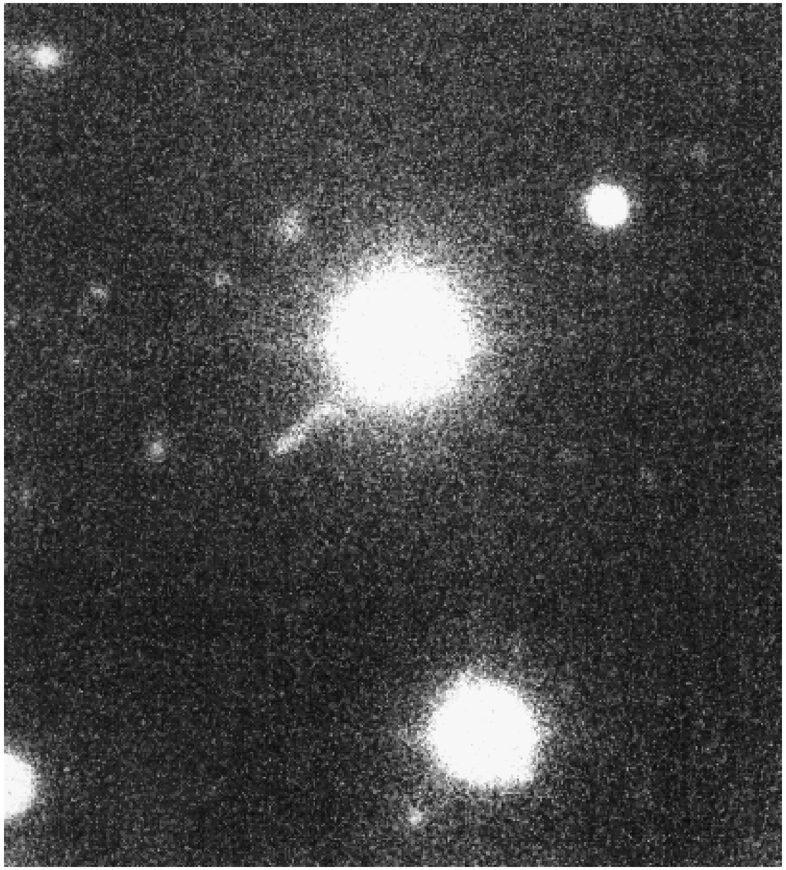


Quasi-Stellar Sources

- 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

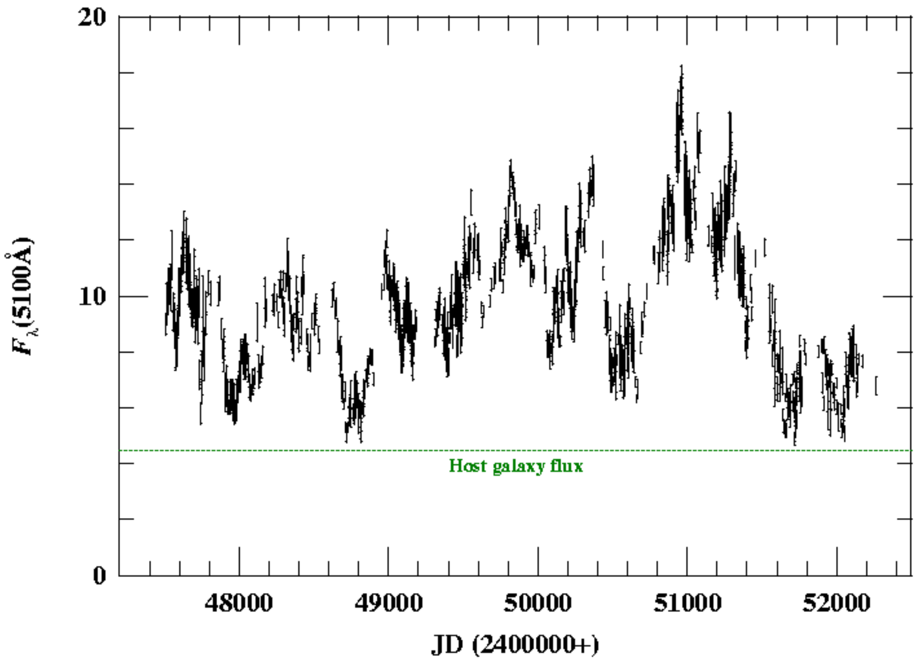
The Brightest Objects in the Universe

- 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

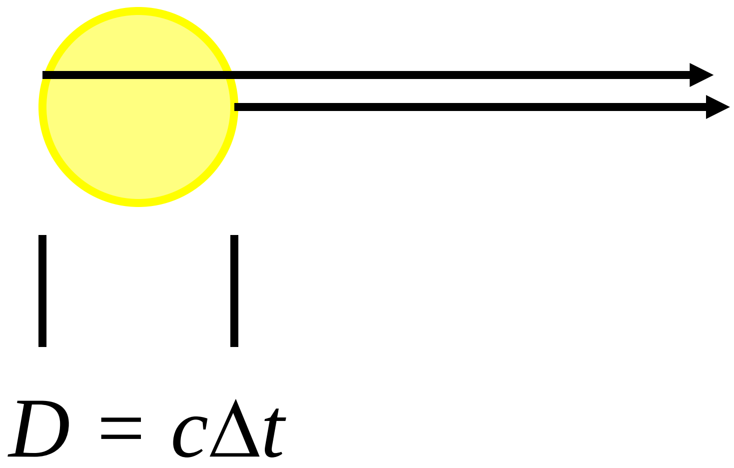
And Now Another Surprise...

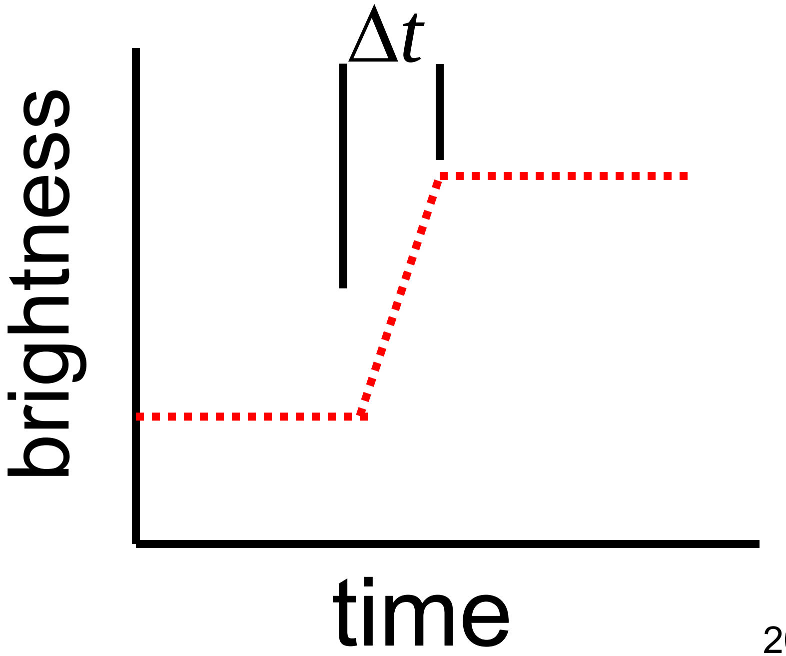
- Shortly after their discovery, quasars were found to be highly variable in brightness.
- Rapid variability implies that the emitting source must be very small.



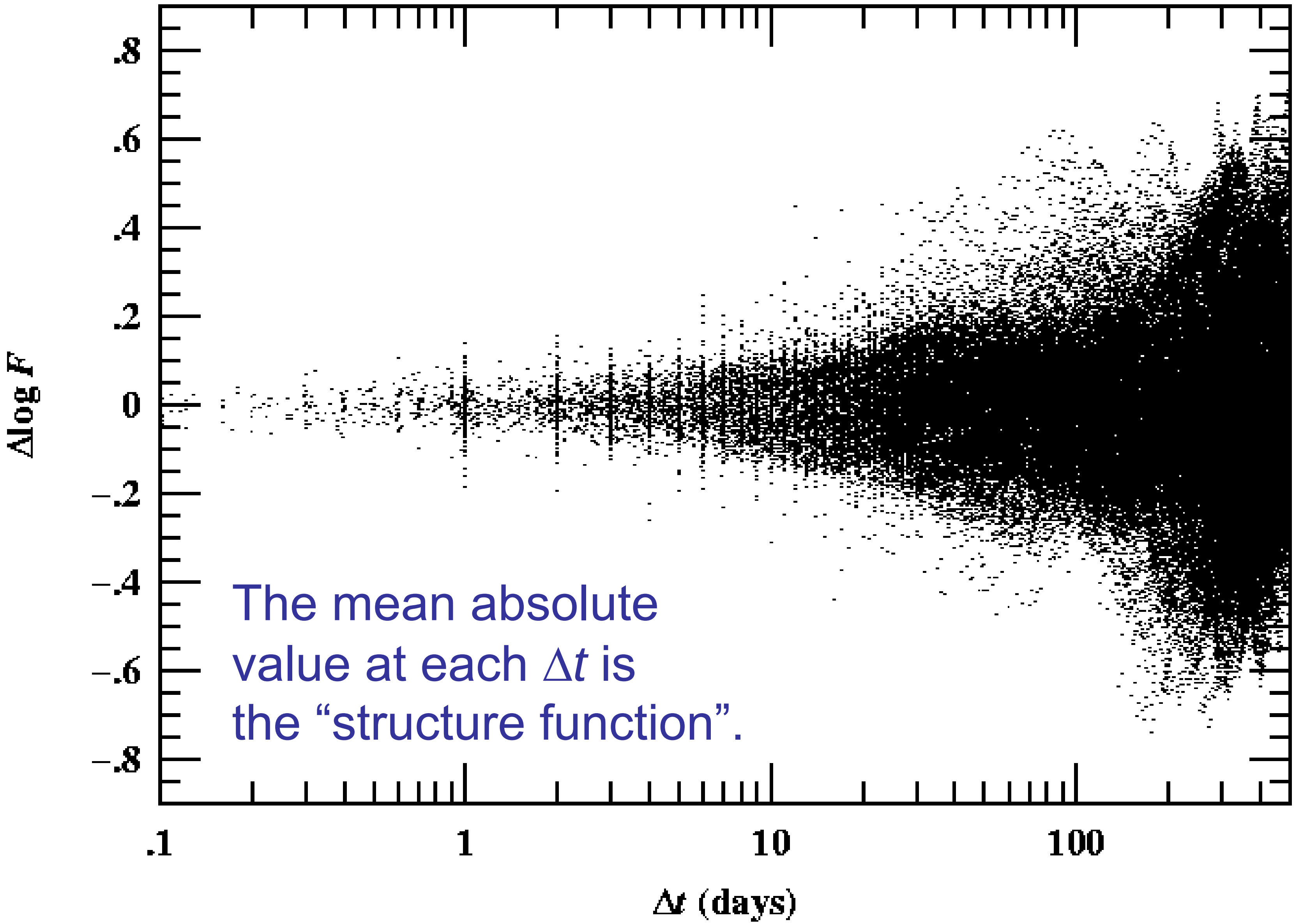
Source "Coherence"

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





Amplitude of Optical Variability



The mean absolute value at each Δ*t* is the "structure function".

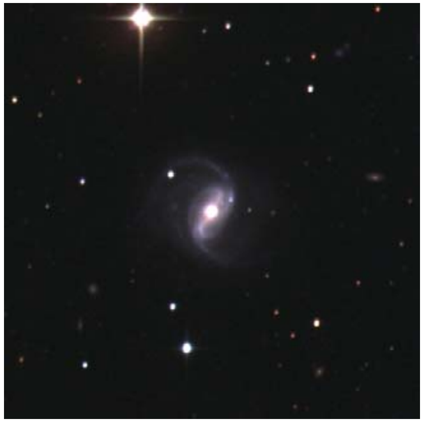
Sizes of Quasars

- 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
$z = 0.00234$
$\log L_{opt} = 41.2$

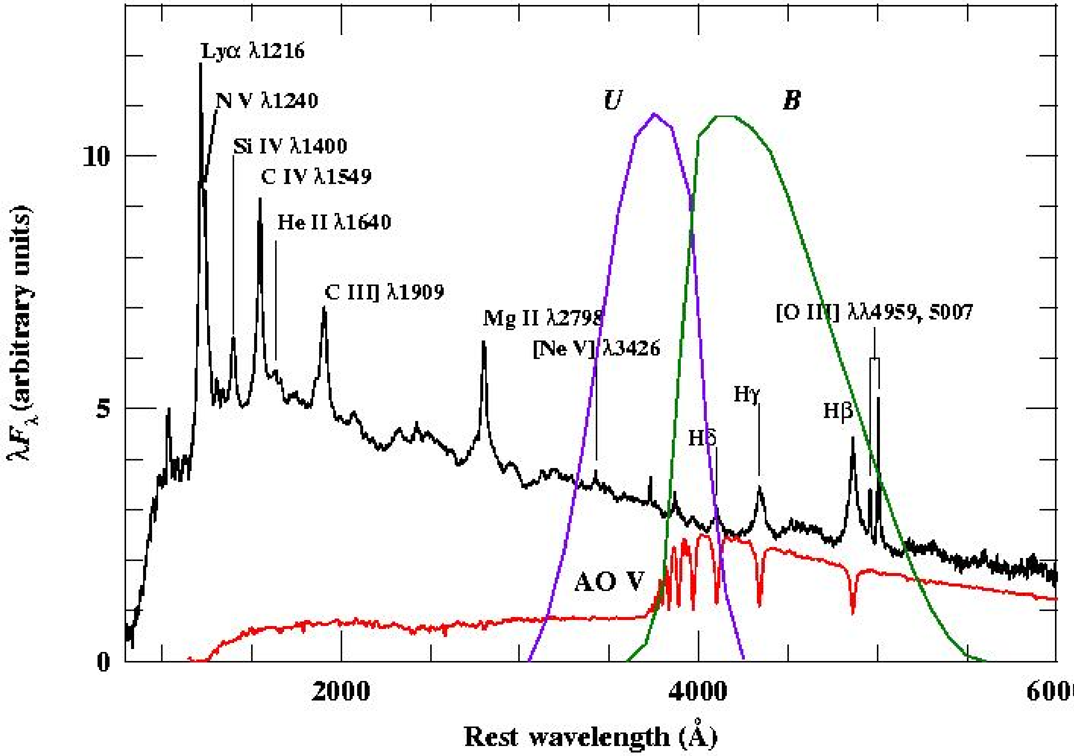


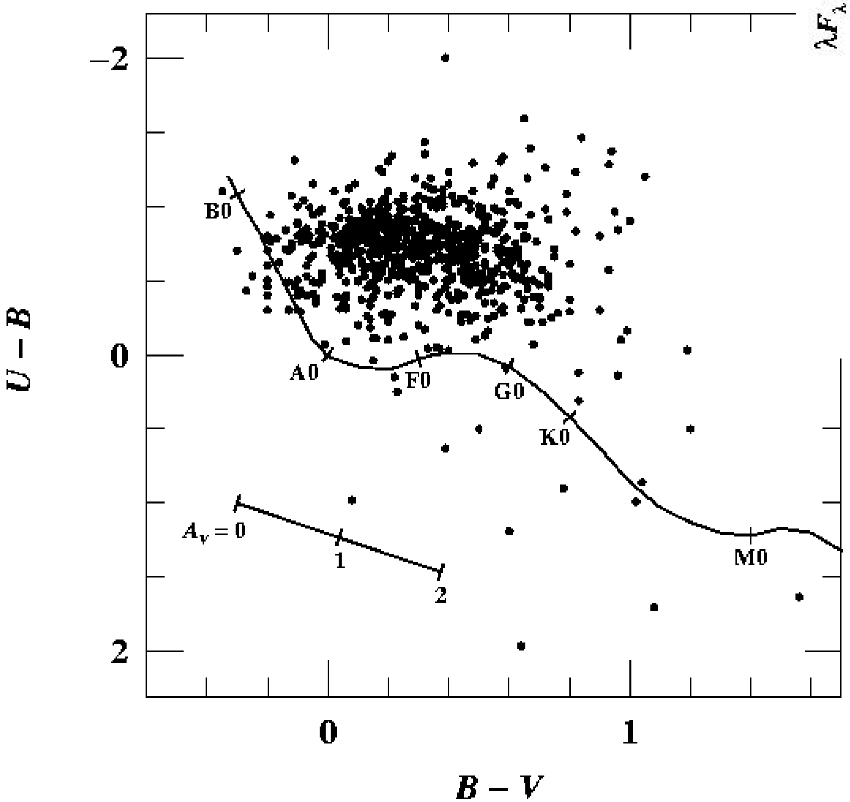
Mrk 79
$z = 0.0222$
$\log L_{opt} = 43.7$

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

Finding Quasars

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

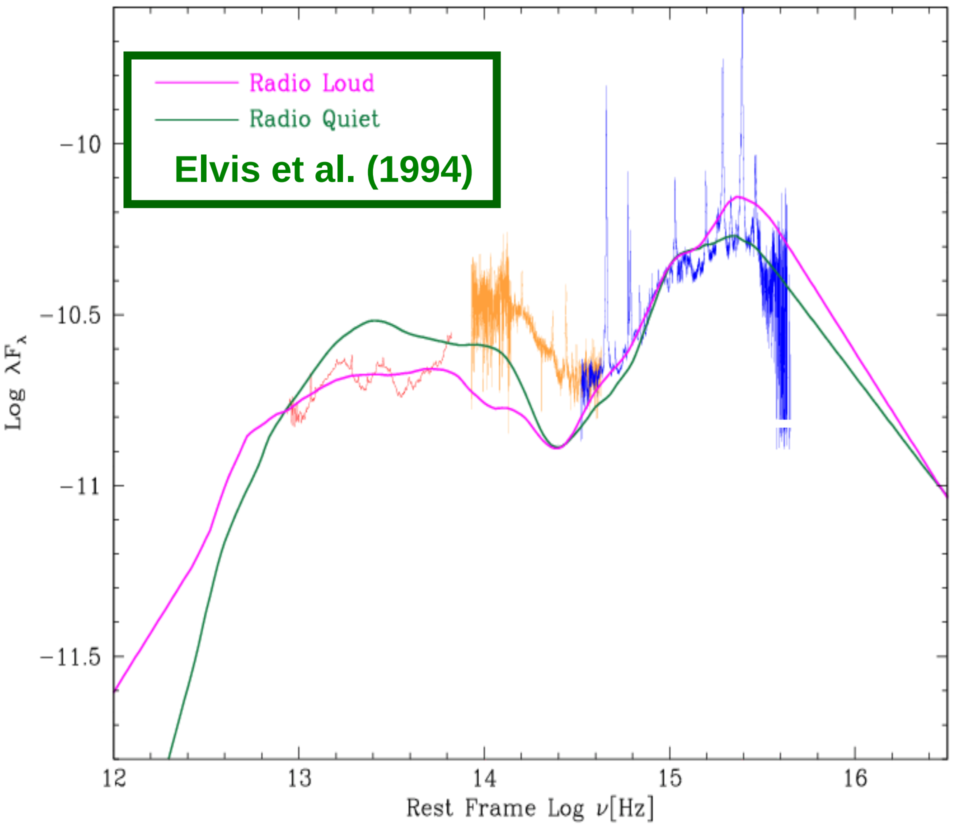




Optical color selection allows us to bypass the difficult radio identification by using "UV excess".

Quasi-Stellar Objects

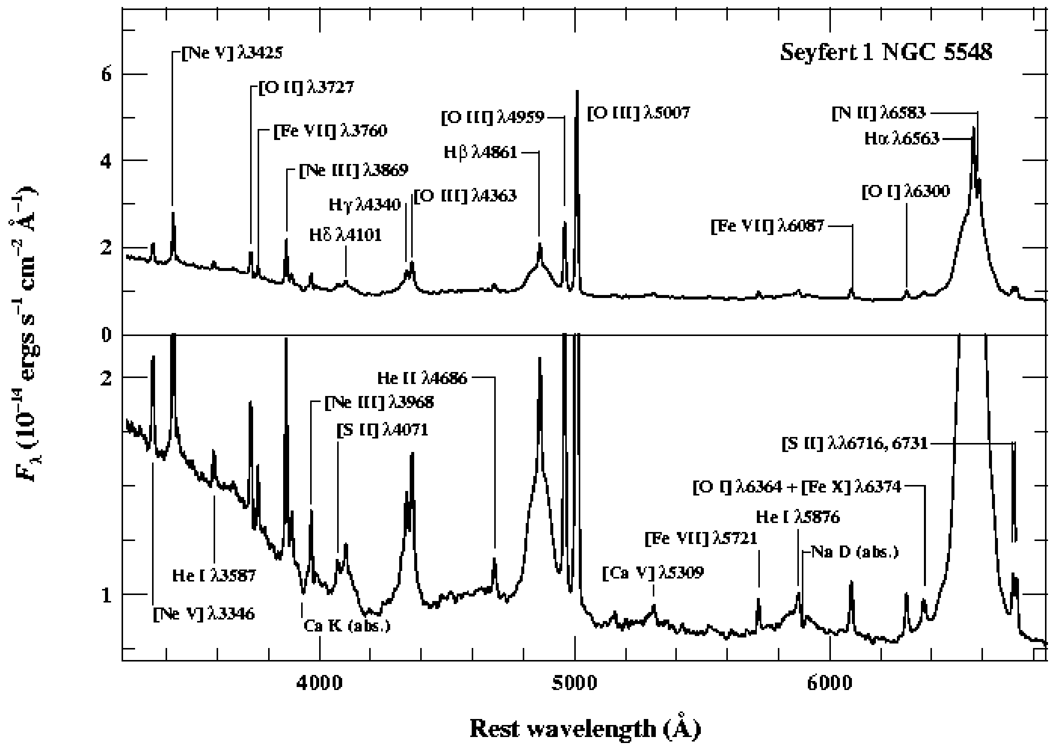
- Most of these blue star-like sources are like the radio-selected quasars, but are ***radio-quiet***.
- These became generically known as "***quasi-stellar objects***", or ***QSOs***.



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

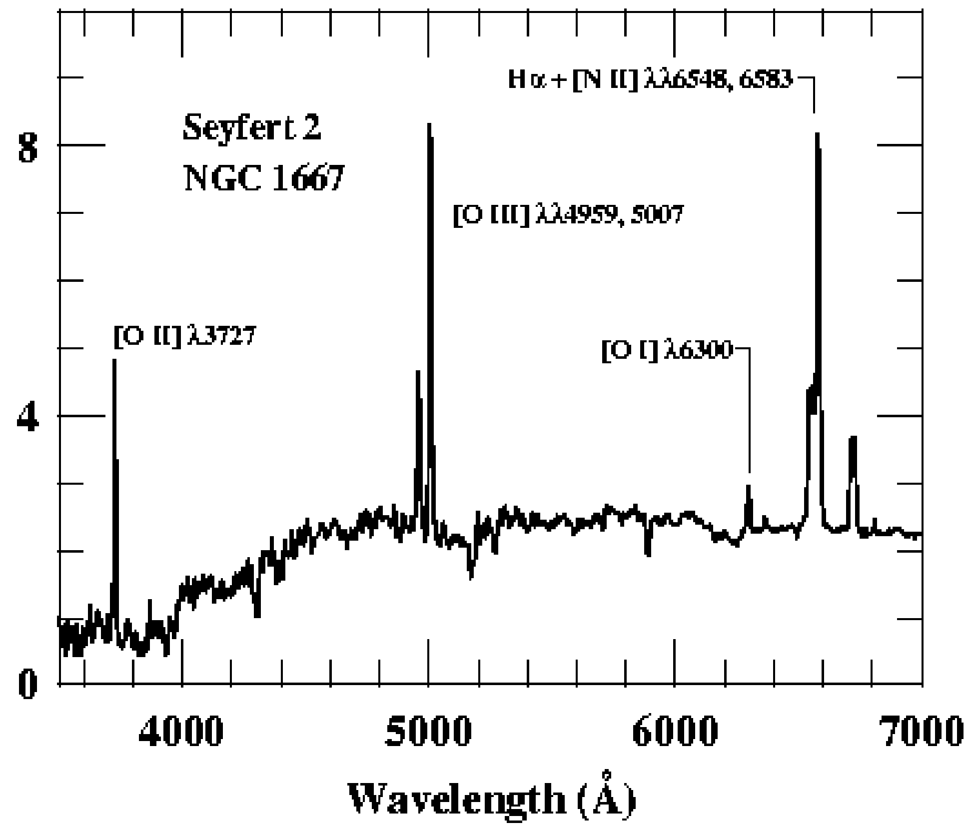
AGN Taxonomy

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



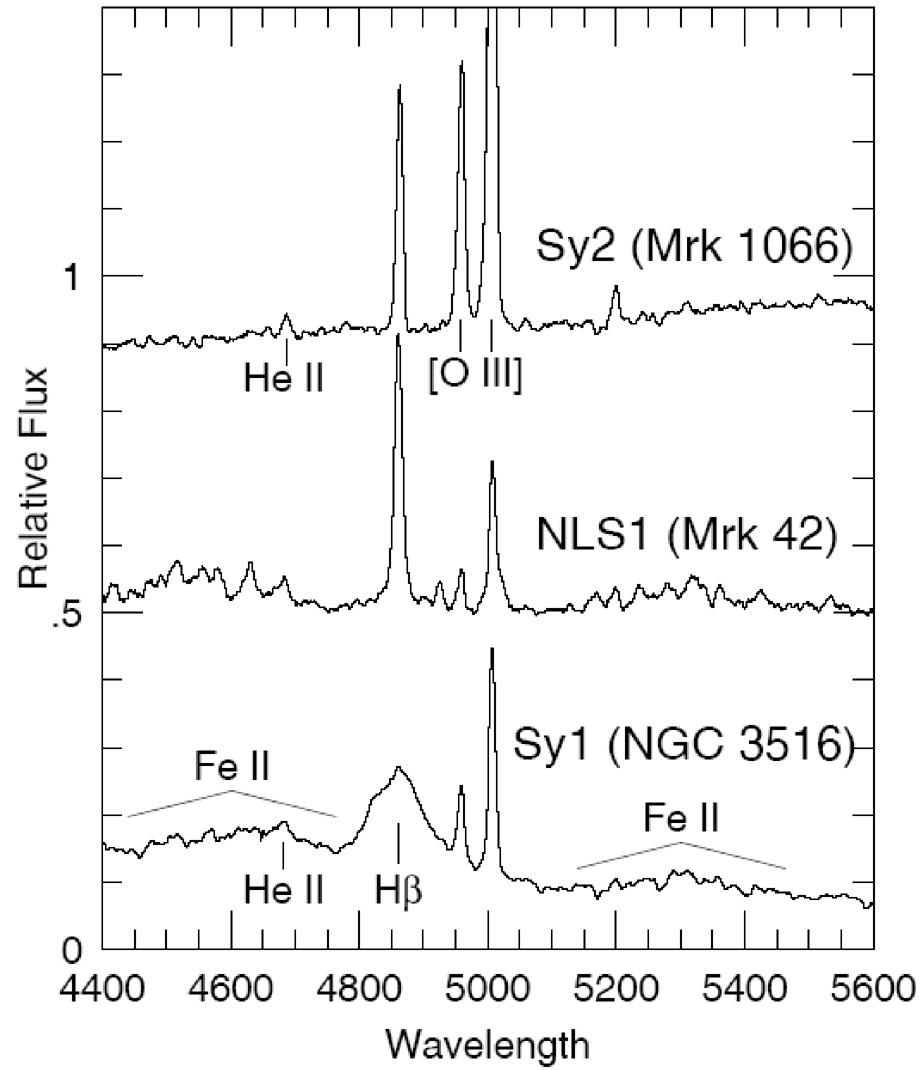
AGN Taxonomy

- 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

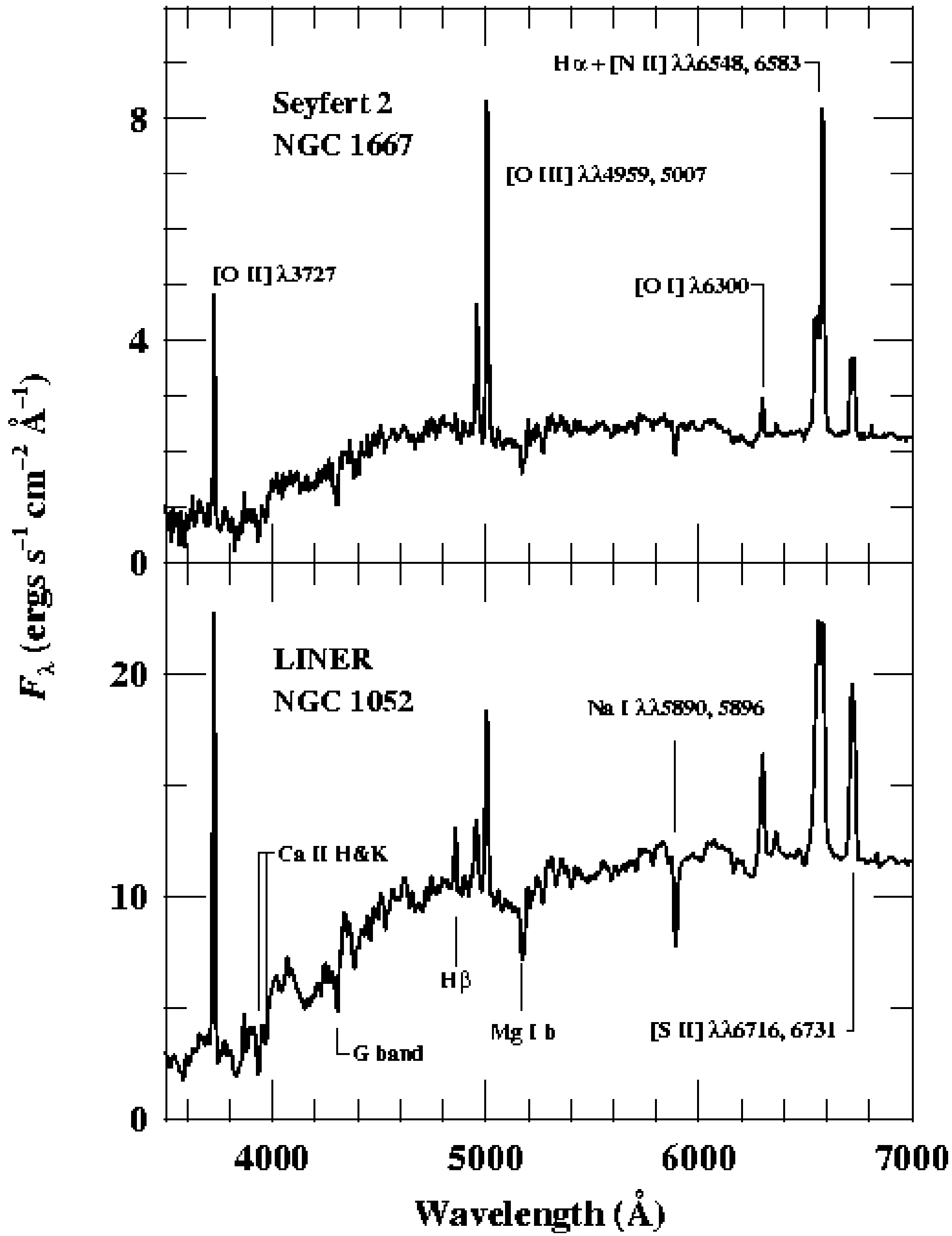
- Narrow-line Seyfert 1 (***NLS1***) galaxies are true broad-line objects, but with an especially narrow broad component, FWHM < 2000 km s^{-1}



Osterbrock & Pogge 1985

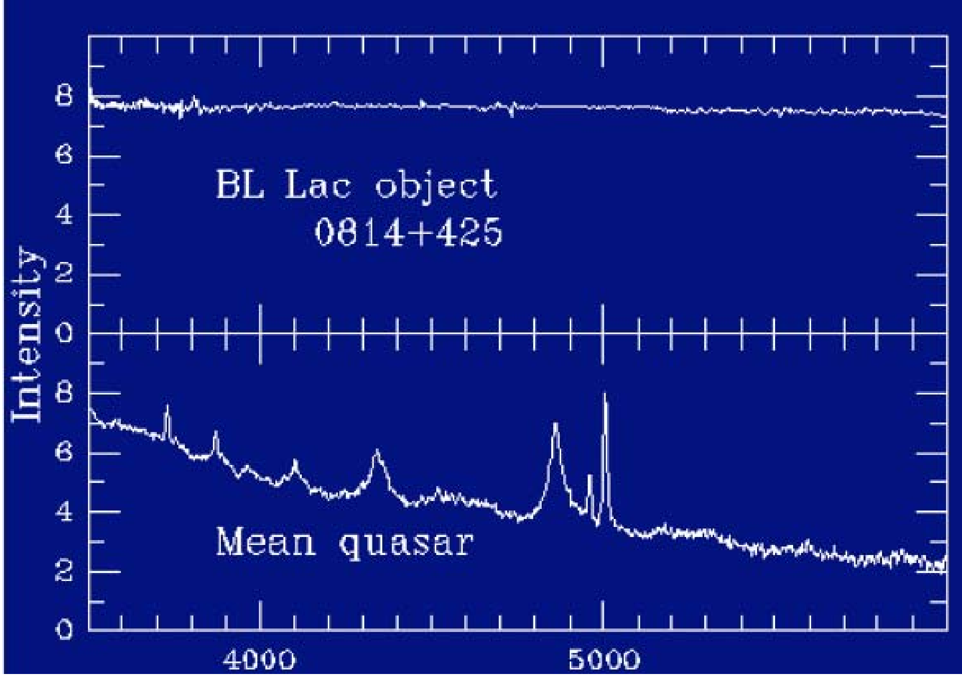
AGN Taxonomy

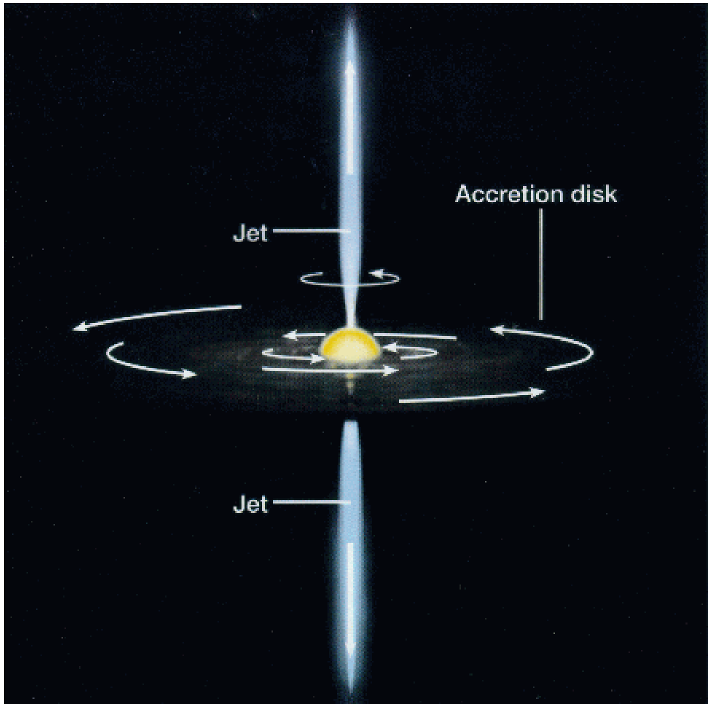
- Heckman (1980) identified a class of Low-Ionization Nuclear Emission Region (***LINER***) galaxies.
  - Lower ionization level lines are stronger than in Sy 2



AGN Taxonomy

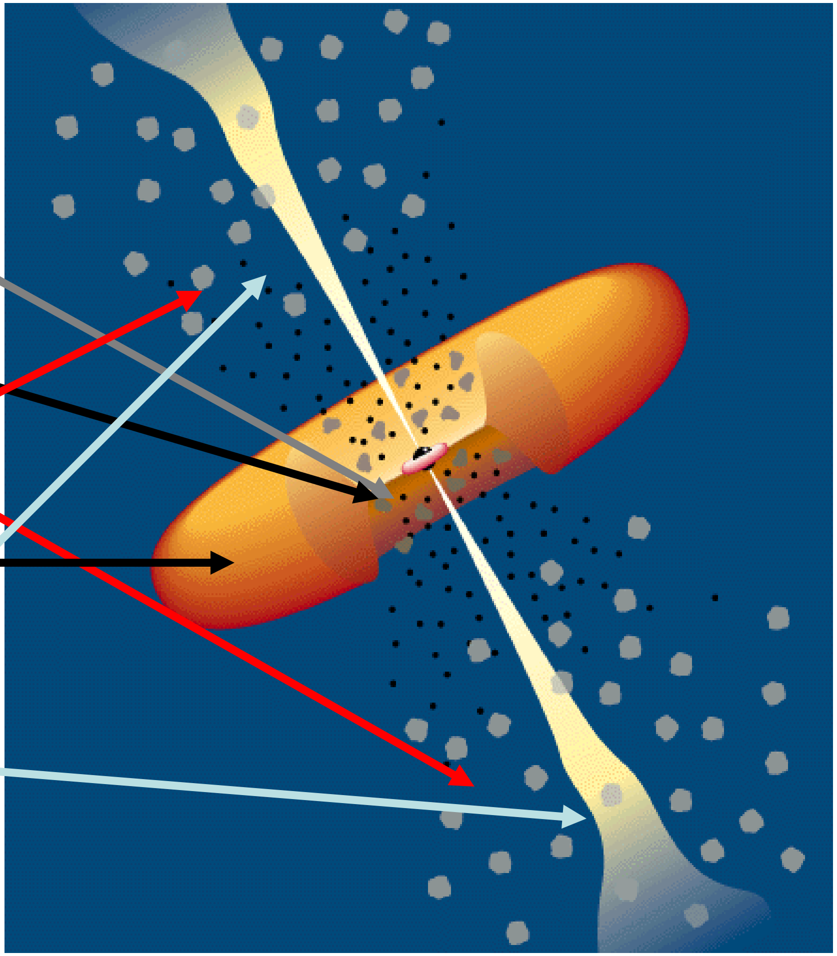
- ***BL Lac objects*** share many quasar properties (blue, variable, radio sources), but have no emission or absorption lines.
  - Appear to be quasars observed along the jet axis
  - Are often subsumed into a larger class called ***blazars.***





AGN Paradigm circa 1995

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



Urry & Padovani 1995

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

Key insights: Salpeter 1964; Zel'dovich & Novikov 1964; Lynden-Bell 1969

- 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

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

$$L < \frac{4\pi Gcm}{\sigma_e} M \approx 1.26\times 10^{38} \left(\frac{M}{M_\odot}\right) \mathrm{ergs\ \ s^{-1}}$$

"The Eddington Limit"

- Potential energy of infalling mass m is converted to radiant energy with some efficiency η so $E = \eta m c^2$
- 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:

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

- Thus the efficiency of accretion $\eta \approx 0.1$

Compare to hydrogen fusion 4H $\rightarrow$ He with $\eta = 0.007$

Eddington Rate

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

$$\dot{M}_{\mathrm{Edd}} = \frac{L_{\mathrm{Edd}}}{\eta c^2} = \frac{1.47\times10^{17}}{\eta}\left(\frac{M_{\mathrm{BH}}}{M_{\odot}}\right)\mathrm{gm\ s^{-1}}$$

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

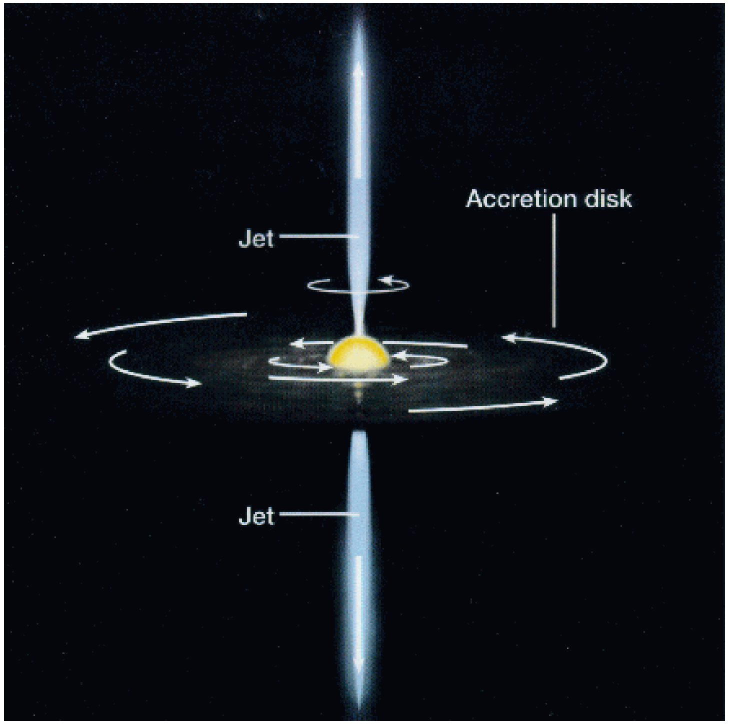
$$\dot{m} \equiv \lambda = \dot{M} \big/ \dot{M}_{\mathrm{Edd}}$$

Accretion Disks

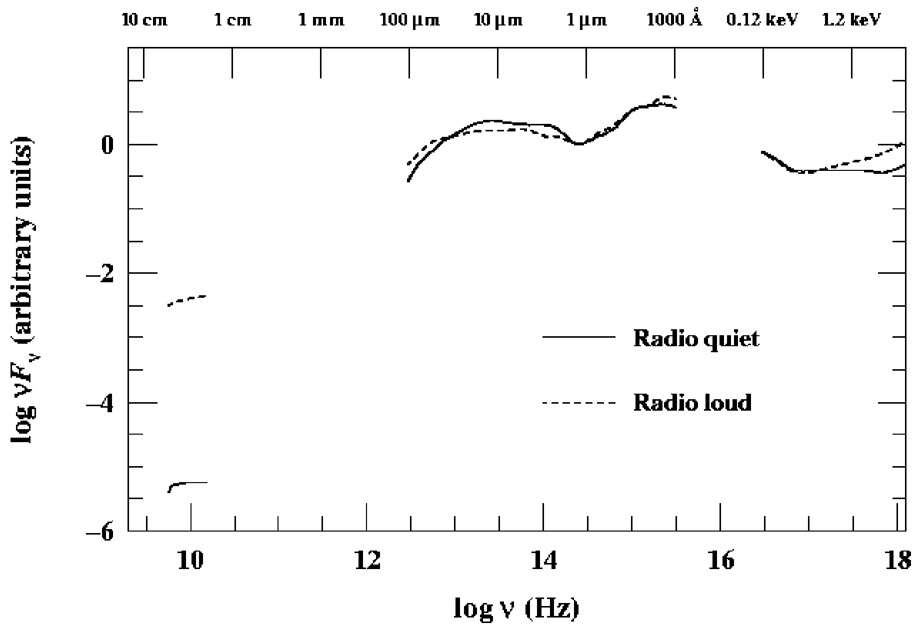
- Angular momentum of infalling material will lead to formation of an accretion disk.

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

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



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

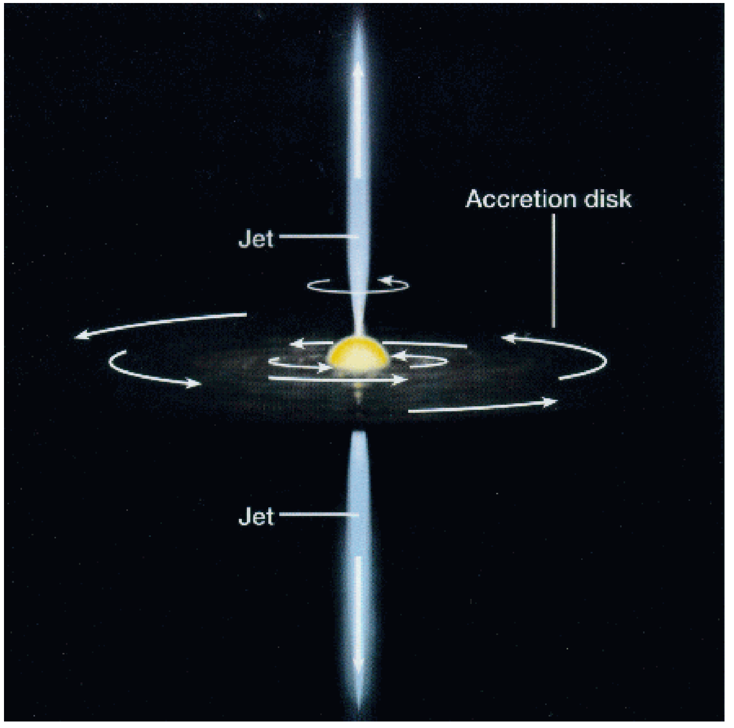


Assuming that QSO SED peak at 1000 Å represents accretion disk, Wien's law tells us $T \approx 5\times10^5$ K.

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

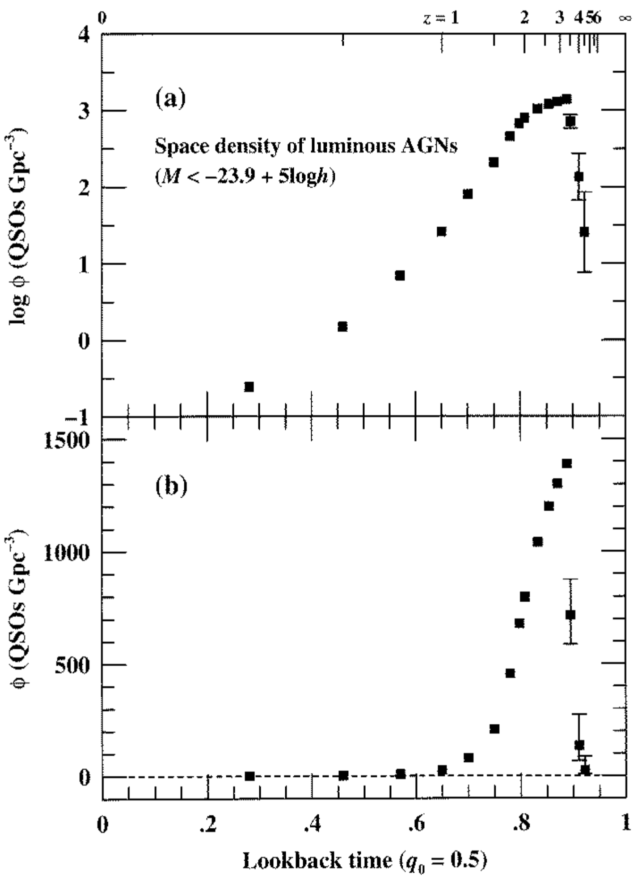
Other Quasar Properties

- Quasars as radio sources
  - High spin, conservation of B field leads to jet formation
  - Jets are common, but apparently not mandatory
- Quasars as X-ray sources
  - *All* highly accreting objects are X-ray sources
  - Hard X-rays (~ 10 keV) are the surest identifier of an active nucleus

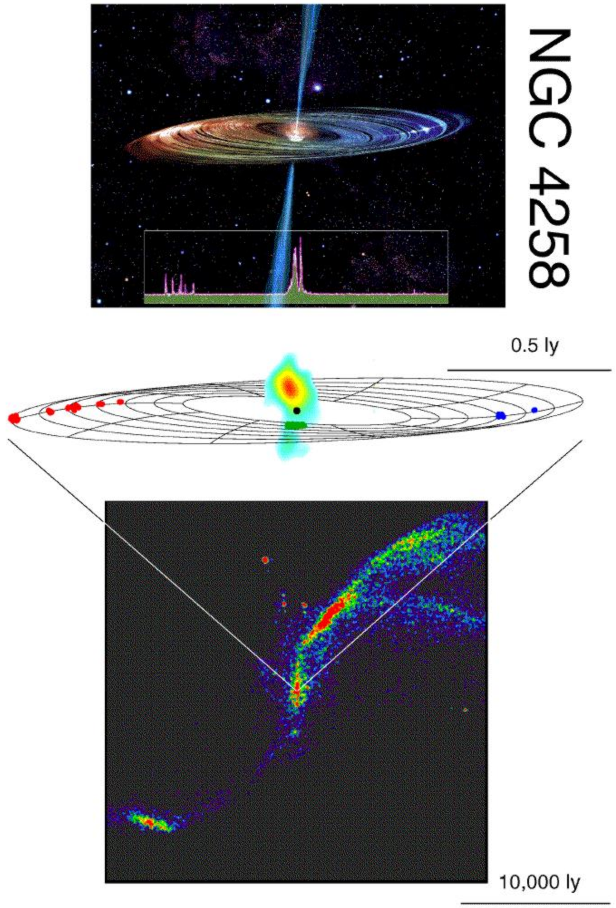


Even Quiescent Galaxies Should Harbor Black Holes

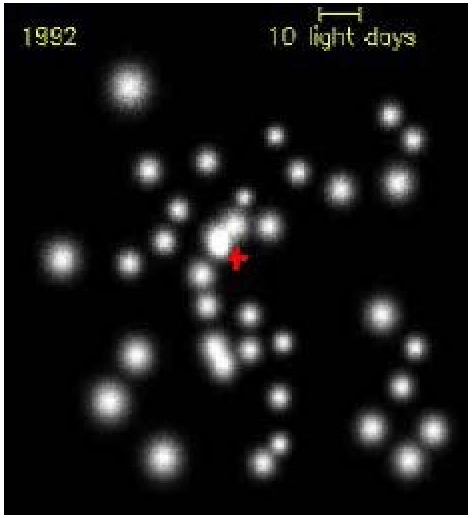
- The comoving space density of quasars was much higher in the past ($z \sim 2 - 3$); where are they now?
- Integrated flux density of quasars reveals the integrated accretion history of black holes. **(Soltan 1982)**



Evidence for Supermassive Black Holes



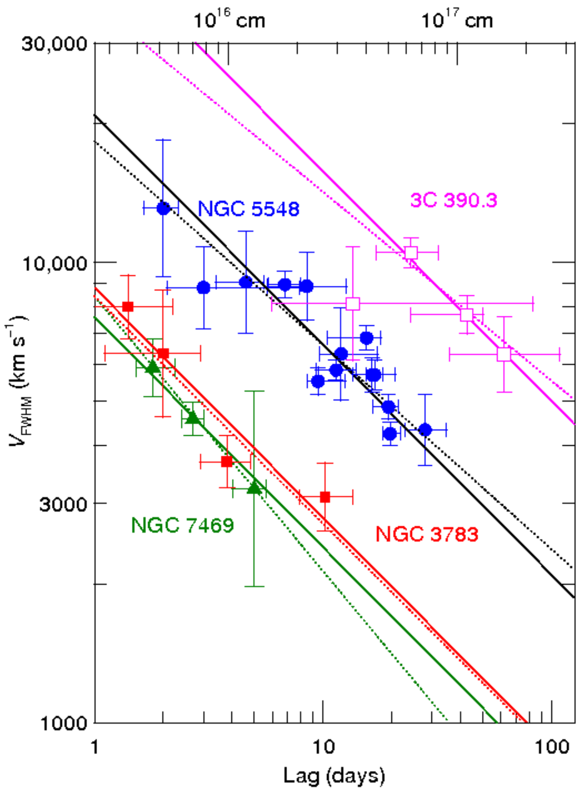
- Milky Way: Stars orbit a black hole of $2.6 \times 10^6 M_\odot$.



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

Evidence for Supermassive Black Holes

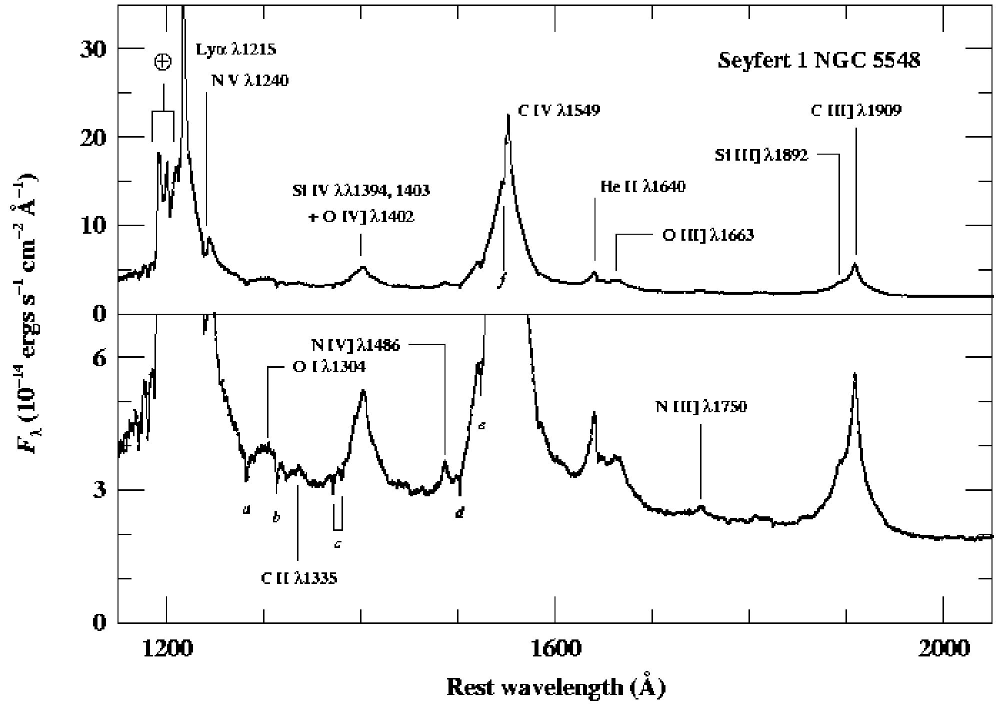
- In the case of AGNs, reverberation mapping of the broad emission lines can be used to measure black hole masses.
  - Later elaboration

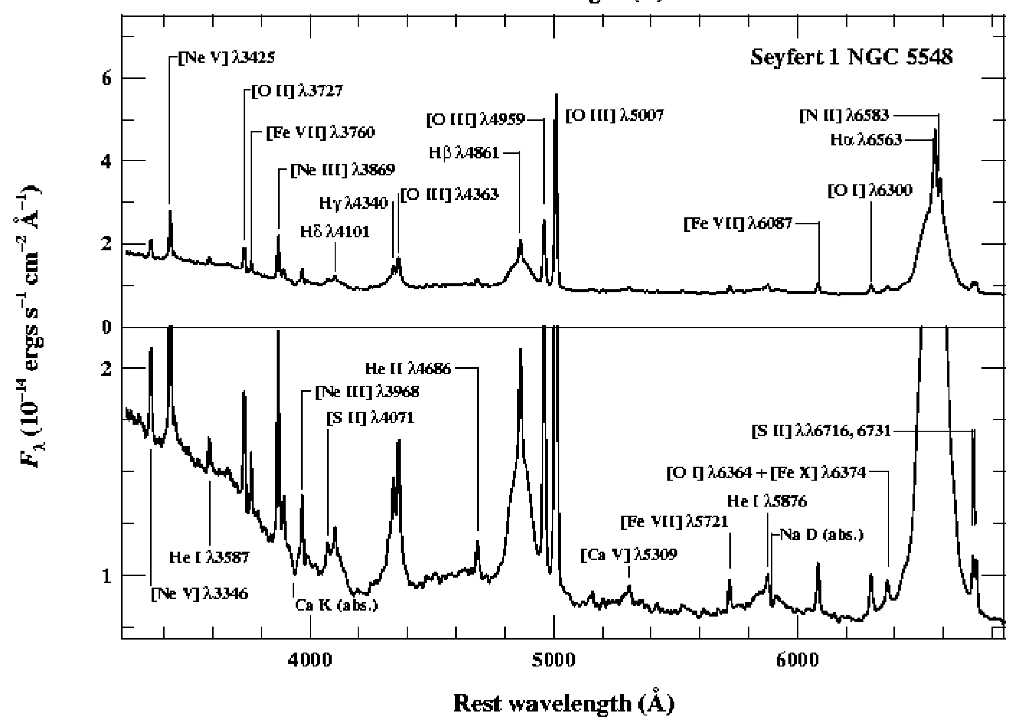


$$M_{BH} \propto \frac{\Delta V^2 R}{G} \Rightarrow \Delta V \propto R^{-1/2}$$

The Broad-Line Region

- UV, optical, and IR permitted lines have broad components
  - $1000 \leq \text{FWHM} \leq 25{,}000\ \text{km s}^{-1}$
  - Spectra are typical of photoionized gases at $T \approx 10^4$ K
  - Absence of forbidden lines implies high density
    - C III] $\lambda 1909 \Rightarrow n_e < 10^{10}\ \text{cm}^{-3}$





Photoionization Equilibrium Modeling

- Tool of long standing in AGNs

  Davidson & Netzer 1979

- Simple photoionization models are characterized by:

1) Shape of the ionizing continuum
2) Elemental abundances
3) Particle density
4) An ionization parameter U that is proportional to ratio of ionization rate to recombination rate

The (Dimensionless) Ionization Parameter *U*

Rate at which H-ionizing photons are emitted by source.

$$Q_{\rm ion}(H) = \int_{\nu_{\rm ion}}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$$

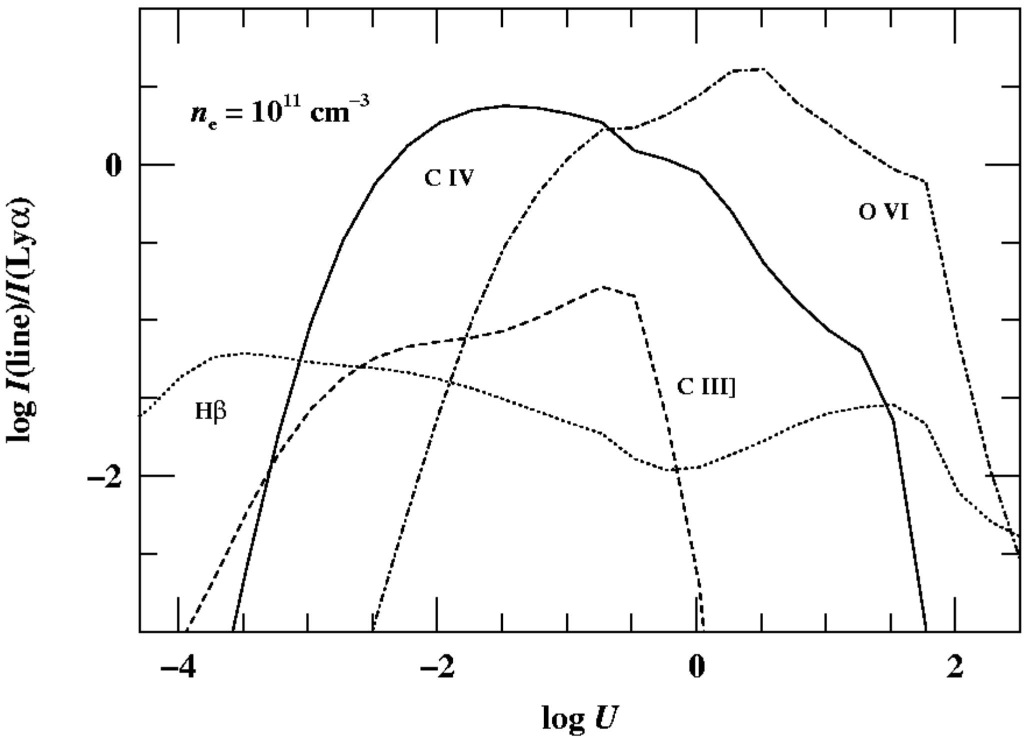
Ratio of ionizing photon density at distance r from source to particle density.

$$U = \frac{Q_{\rm ion}(H)}{4\pi r^2 c n_{\rm H}}$$

Davidson 1972

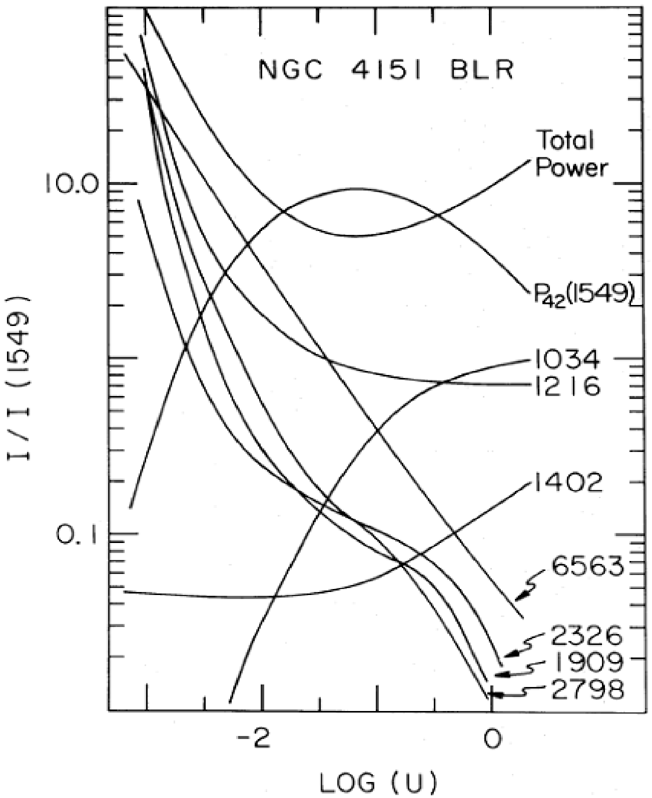
A Simple Model

- Assumptions:
  - AGN-like continuum
  - Solar abundances
  - Fixed density 10^{11} cm^{-3}
  - Maximum column density
- Output product:
  - Predicted flux ratios as a function of *U*
- Conclusion:
  - Best fit to AGN spectrum is $U \approx 10^{-2}$



Photoionization Model of the BLR in NGC 4151

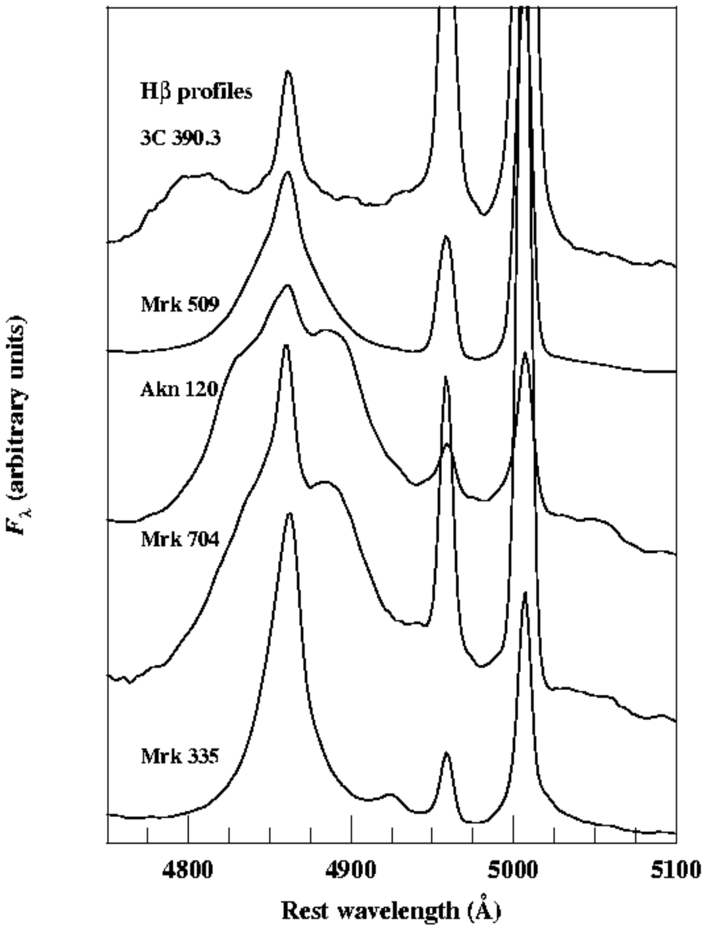
- Limitations:
  - Single-cloud model cannot simultaneously fit low and high-ionization lines.
  - Energy budget problem: line luminosities require more than 100% of the continuum energy



Ferland & Mushotzky 1982

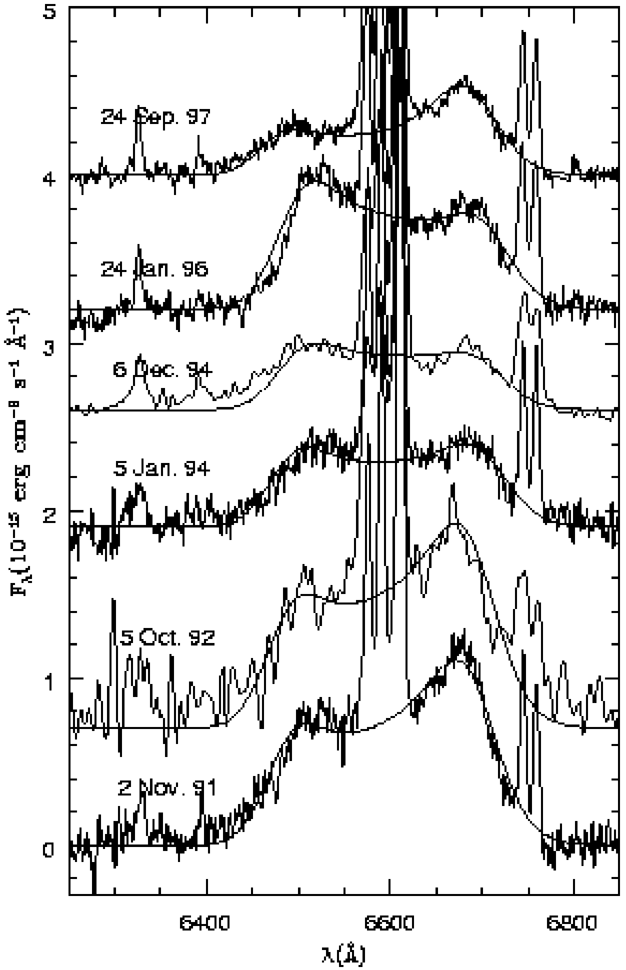
Broad-Line Profiles

- For the most part, broad-line profiles tell us little about kinematics.



Double-Peaked Emission Lines

- A relatively small subset of AGNs have double-peaked profiles that are characteristic of rotation.
  - Tendency to appear in low accretion-rate objects
  - Disks are not simple; non-axisymmetric.
  - Sometimes also seen in difference or rms spectra.

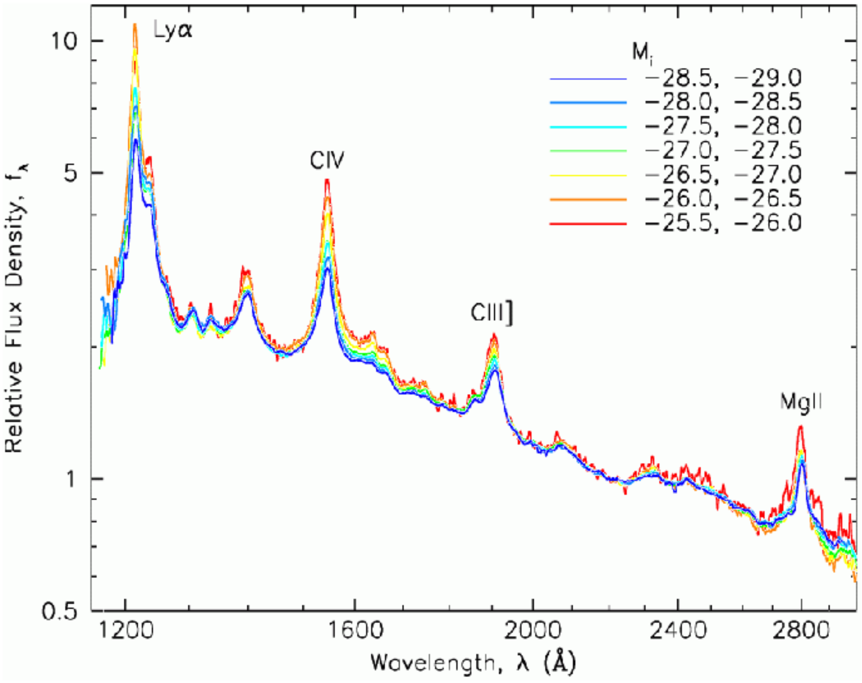


NGC 1097

Storchi-Bergmann et al. 2003

Luminosity Effects

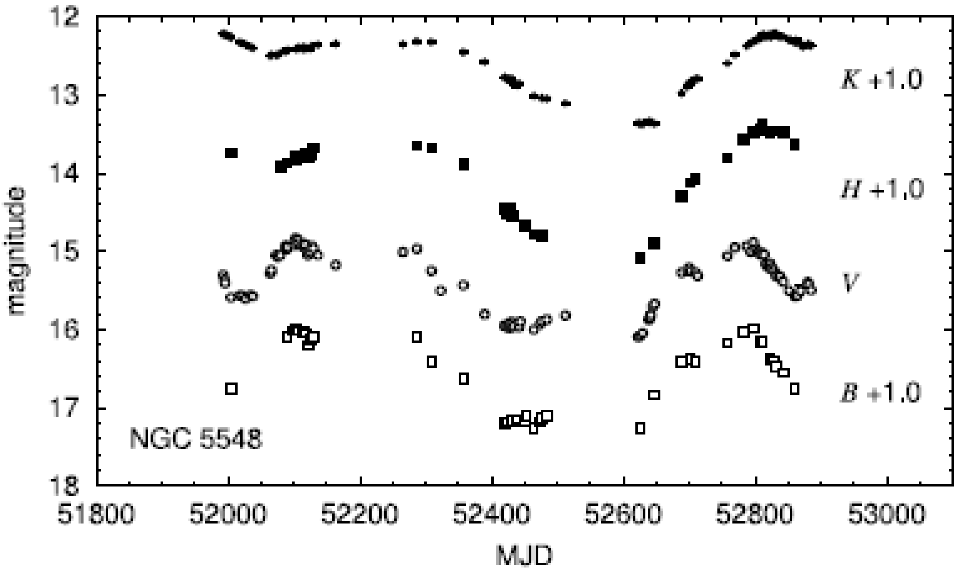
- Average line spectra of AGNs are amazingly similar over a wide range of luminosity.
- Exception: Baldwin Effect
  - Relative to continuum, C IV λ1549 is weaker in more luminous objects
  - Origin unknown



SDSS composites, by luminosity
Vanden Berk et al. (2004)

Dust Reverberation

- Near-IR continuum variations follow those of the UV/optical with a time-delay:
  - Time delays are longer than broad-lines
  - Time delays consistent with dust sublimation radius:

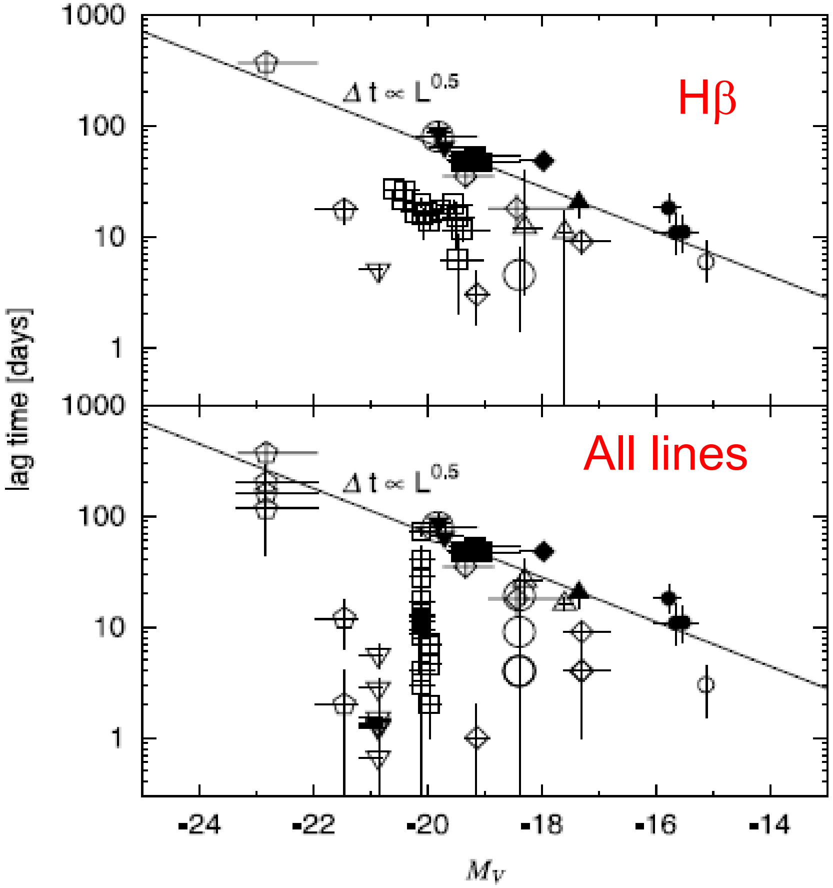


Suganuma et al. 2006

$$r_{\rm sub} = 1.3 \left(\frac{L_{\rm UV}}{10^{46}\ \rm ergs\ s^{-1}} \right)^{1/2} \left(\frac{T_{\rm sub}}{1500\,\rm K} \right)^{-2.8} \rm pc$$

Dust Reverberation

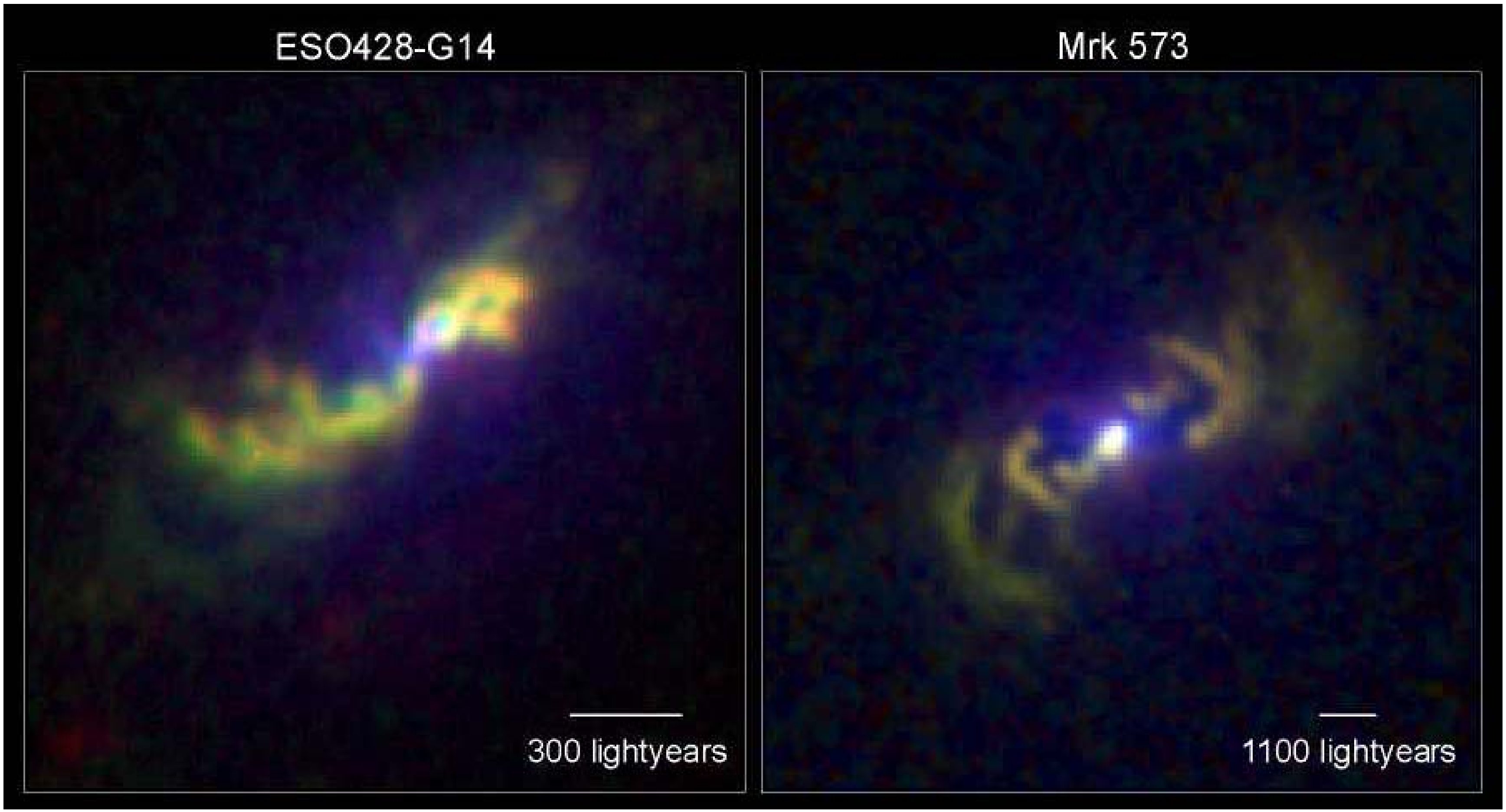
- IR continuum is due to reprocessed UV/optical emission at the closest point to the AGN that dust can survive.
- This probably occurs at the inner edge of the obscuring torus.
- All emission lines are inside r_{sub}: the BLR ends where dust first appears.



Suganuma et al. 2006

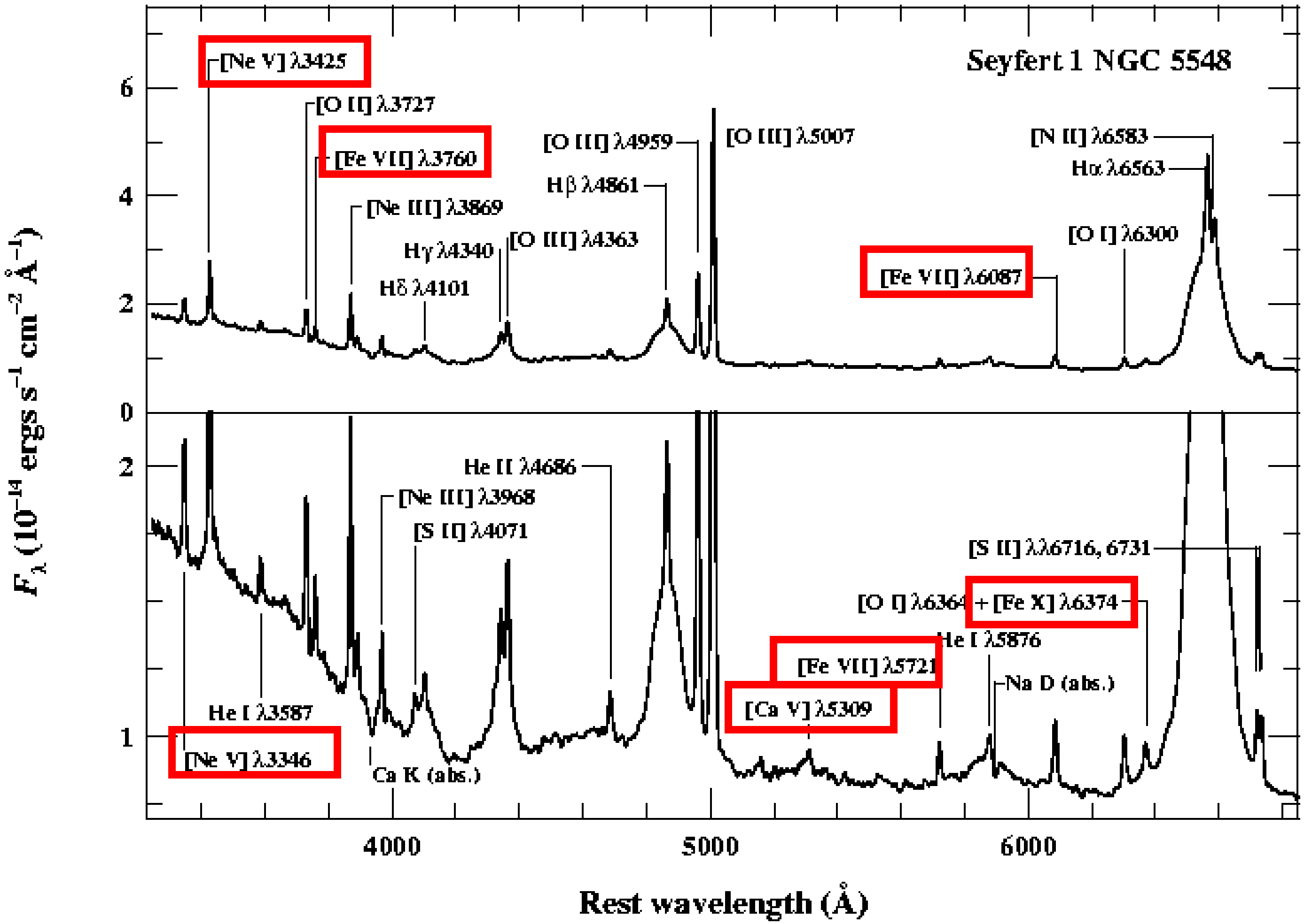
The Narrow-Line Region

- 200 < FWHM < 1000 km s^{-1}
- Partially resolvable in nearby AGNs
- In form of "ionization cones"



Falcke, Wilson, & Simpson 1998

NLR Spectra characterized by very high ionization lines

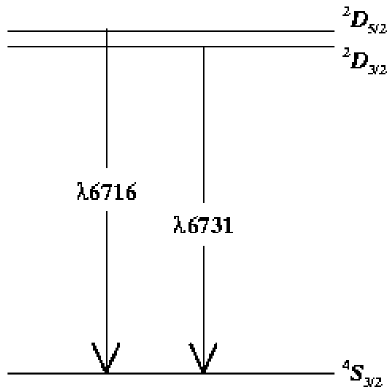


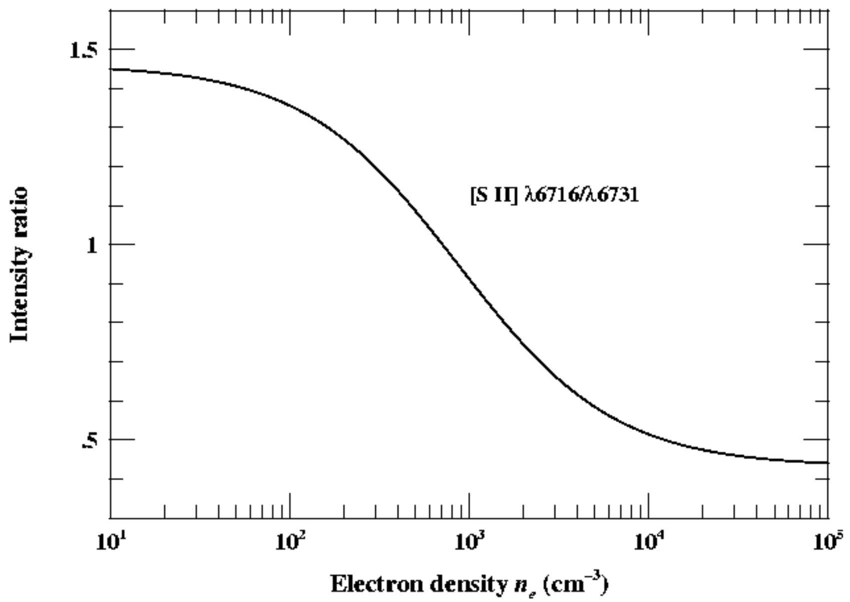
Photoionization Modeling

- Advantages relative to BLR:
  - Kinematics less ambiguous
  - Can use forbidden-line temperature and density diagnostics
  - Forbidden lines are not self-absorbed
- Disadvantage relative to BLR:
  - Dust!

Measuring Density

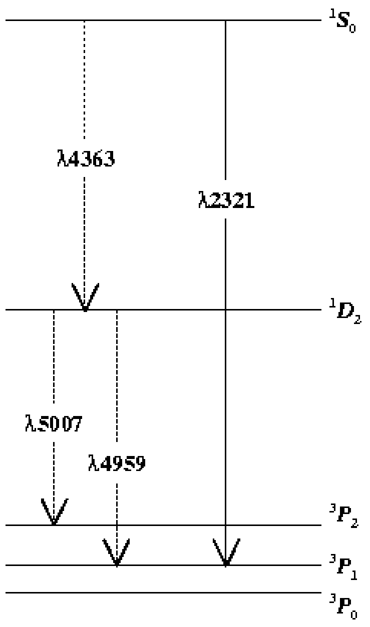
- Low density: radiative de-excitation, emissivity $\propto n_e^2$
- High density: collisional de-excitation competes, so emissivity $\propto n_e$
- Cross-over point occurs at critical density n_{crit} where radiation de-excitation rate = collisional de-excitation rate
  - n_{crit}([S II] λ6716) = 1.5×10^3 cm^{-3}
  - n_{crit}([S II] λ6731) = 3.9×10^3 cm^{-3}

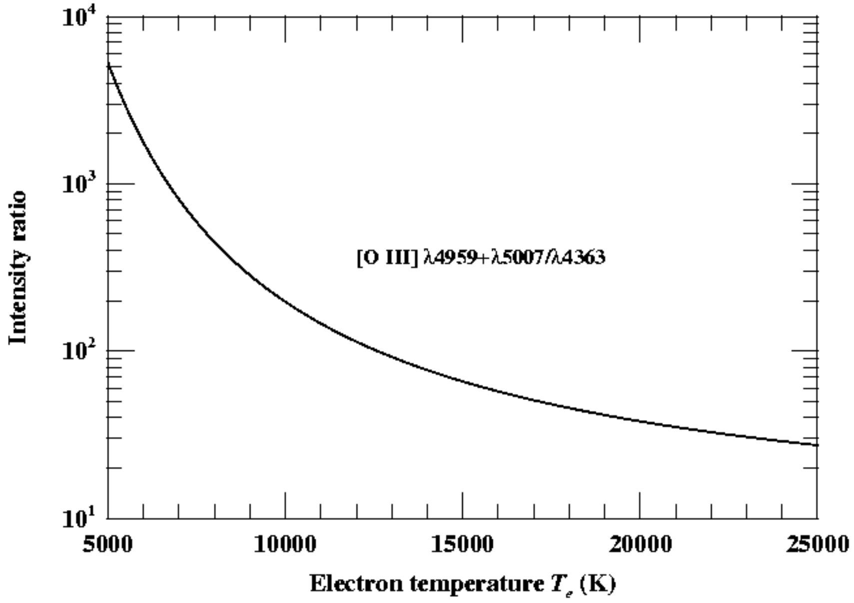




Measuring Temperature

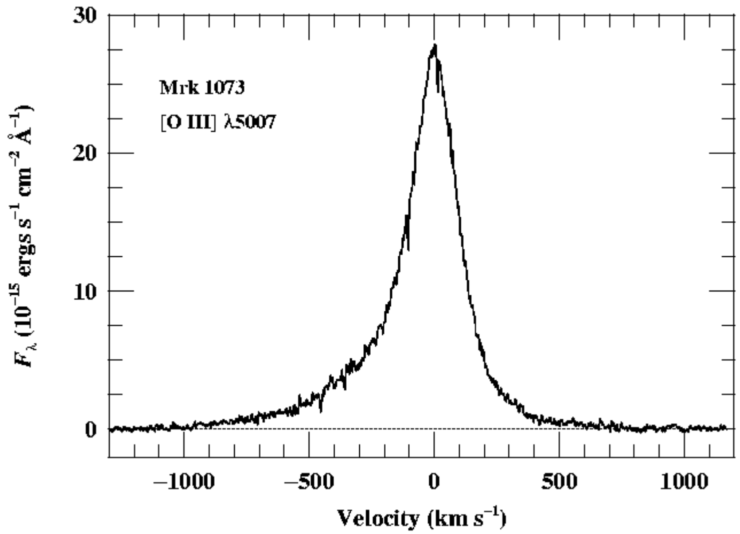
- As temperature increases, [O III] λ4363 increases in strength relative to [O III] λλ4959, 5007 because of increasing collisional excitation of $^1S_0$ level.

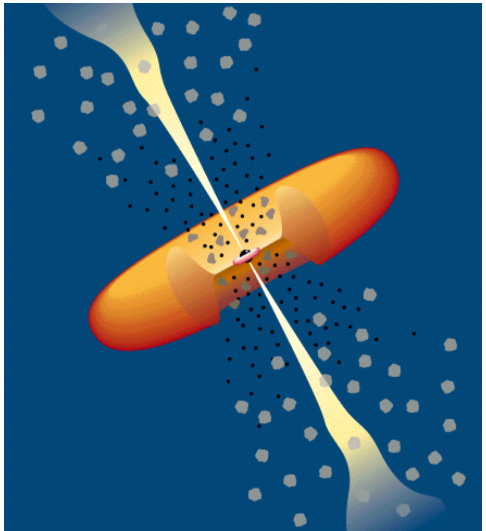




Narrow-Line Profiles

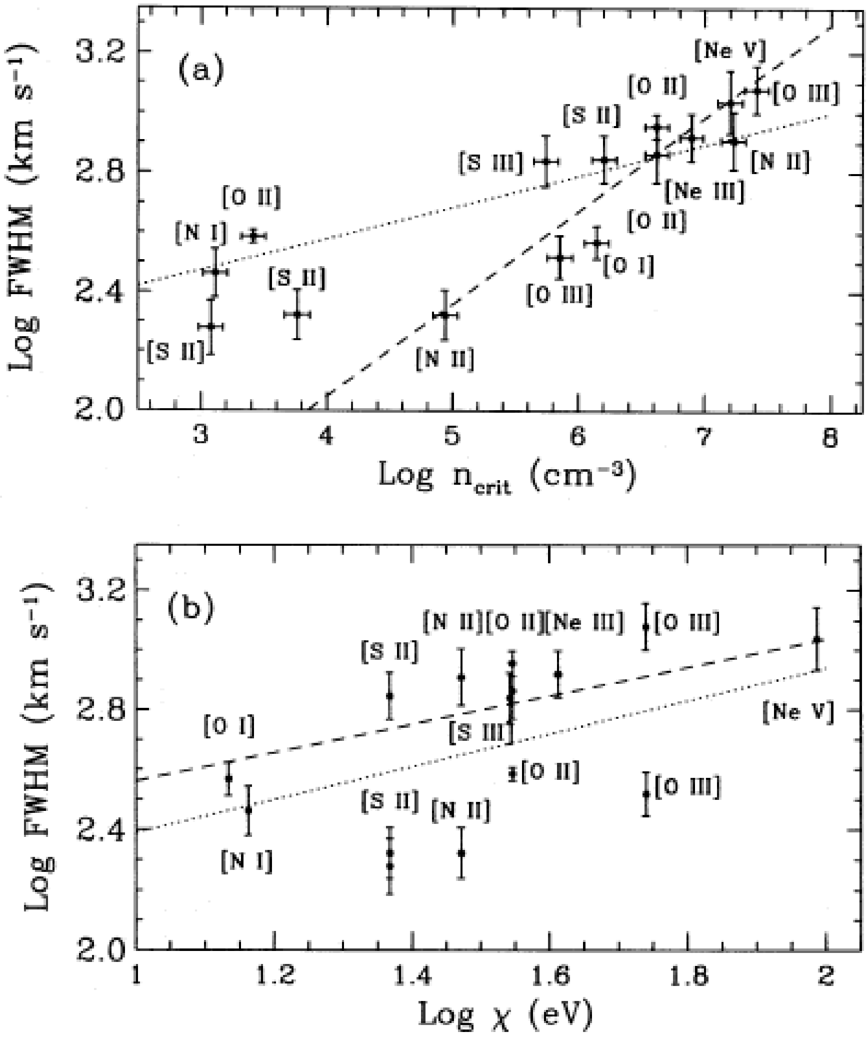
- Typically blueward asymmetric, indicating outflow and obscuration of far (redward) side.





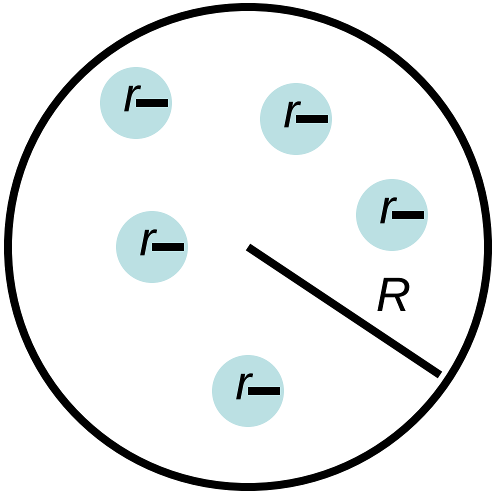
Narrow Line Widths

- Correlate with:
  - Critical density
    - Gas near n_{crit} emits most efficiently
  - Excitation potential
- Interpretation:
  - Consistent with higher densities and higher excitation closer to accretion disk, in deeper gravitational potential



Size of the Narrow-Line Region

$$j(\mathrm{H}\beta) = n_e^2 \alpha_{eff}(\mathrm{H}\beta) \frac{h\nu}{4\pi} \text{ ergs s}^{-1}\text{cm}^{-3}\text{ster}^{-1}$$



For N_c clouds, total emitting volume is $N_c \times 4\pi r^3/3$

Define filling factor ε such that $\varepsilon 4\pi R^3/3 = N_c 4\pi r^3/3$

$$L(\mathrm{H}\beta) = \iint j(\mathrm{H}\beta)\, d\Omega\, dV = \frac{4\pi\varepsilon n_e^2}{3} 1.24\times10^{-25} R^3 \text{ ergs s}^{-1}$$

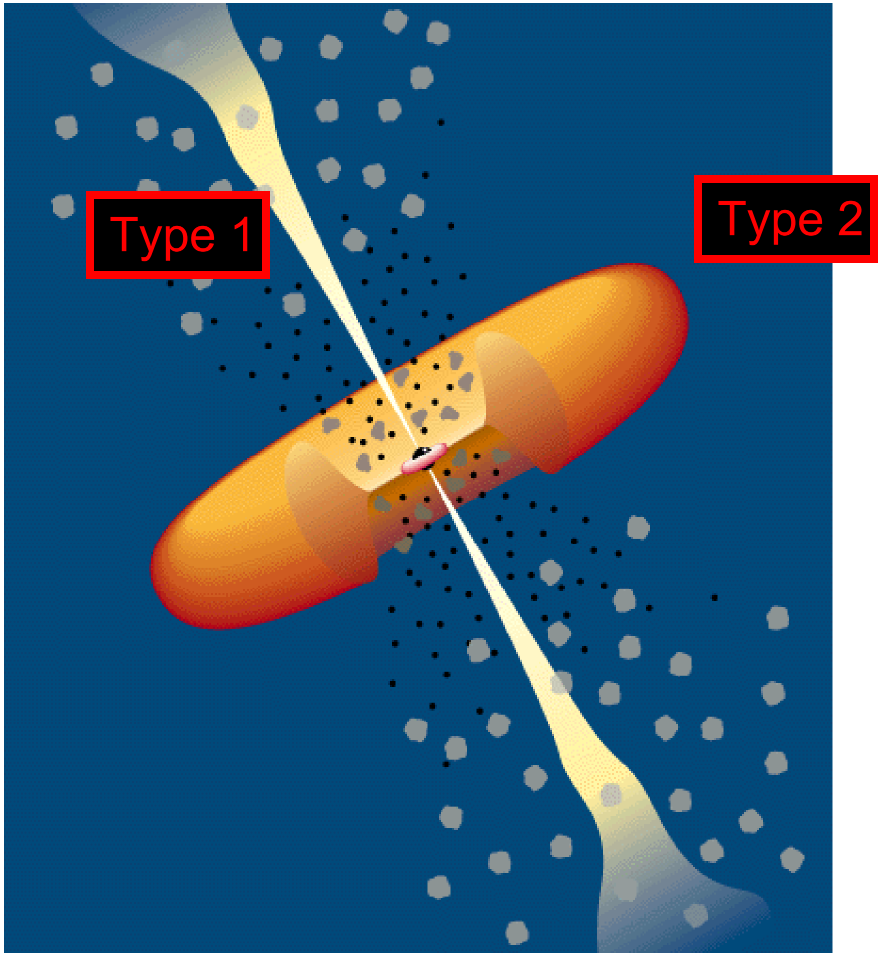
For $L(\mathrm{H}\beta) = 10^{41}$ ergs s^{-1}, $n_e = 10^3$ cm^{-3}, we get $R = 20\ \varepsilon^{1/3}$ pc. Typically, R ≈ 100 pc, so $\varepsilon \approx 0.01$.

Mass of the Narrow-Line Region

$$M_{\mathrm{NLR}} = \frac{4\pi}{3} \varepsilon R^3 n_{\mathrm{e}} m_p \approx 10^6 M_\odot$$

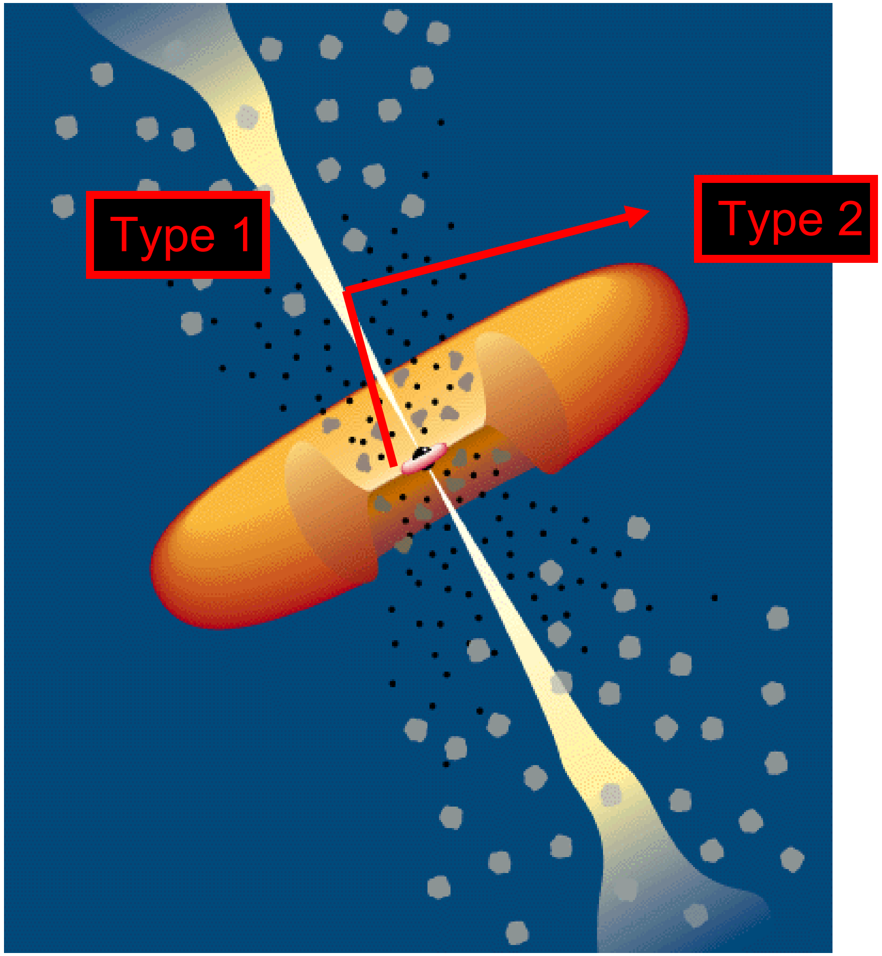
The "Obscuring Torus"

- The answer to the question: "why don't Seyfert 2s have broad lines?"
- Osterbrock (1978) suggested this since a simple absorbing medium would:
  - Redden the continuum
  - Completely obscure the continuum as well as the BLR



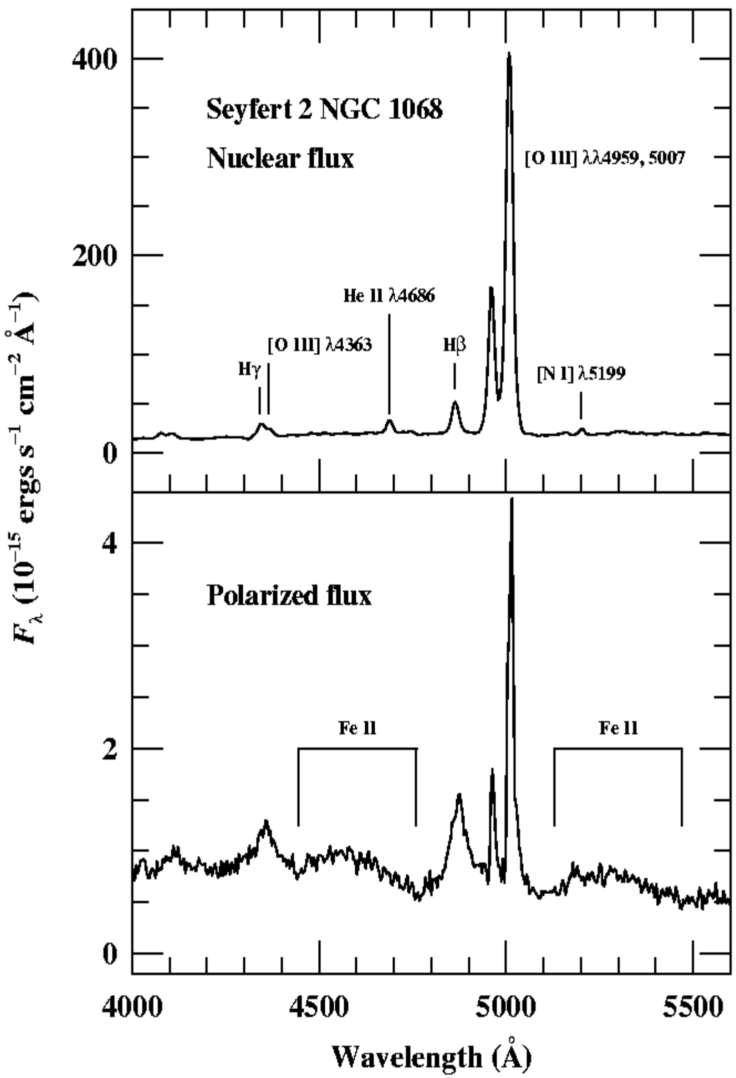
The "Obscuring Torus"

- The key to making this work is scattering by material in the throat of the torus.
  - Prediction: scattering introduces polarization, with E vector perpendicular to axis



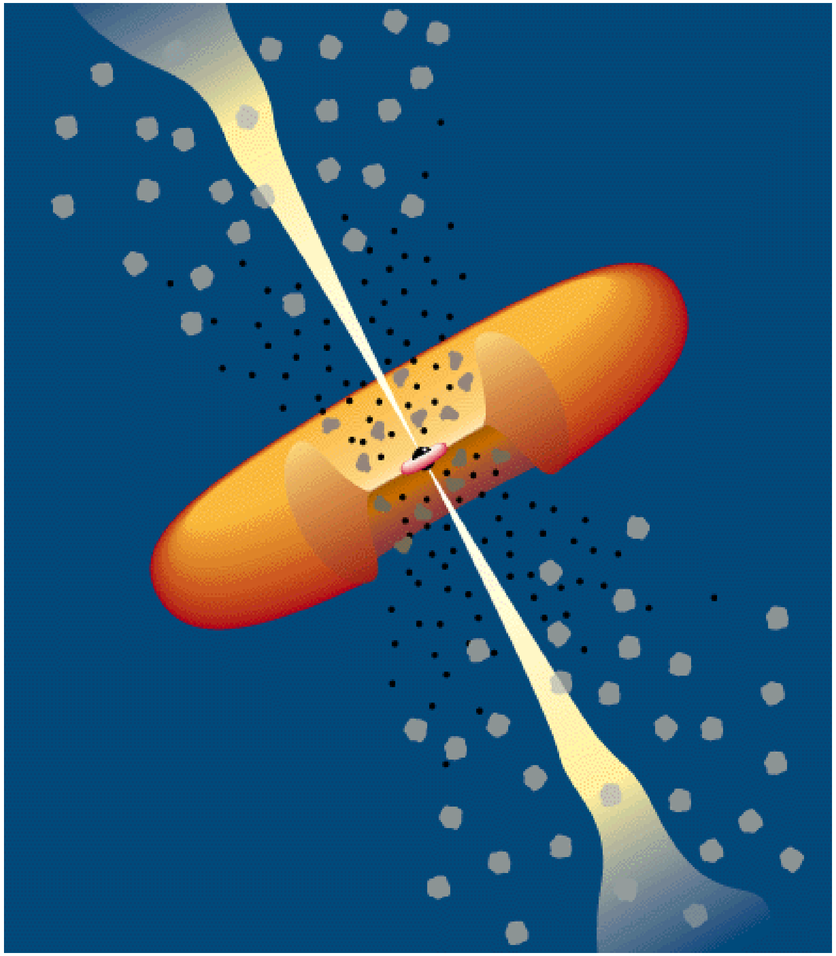
Spectropolarimetry of Seyfert 2 Galaxies

- Spectropolarimetry of the nuclei of Type 2 Seyferts shows Type 1 spectra in polarized light, as predicted.

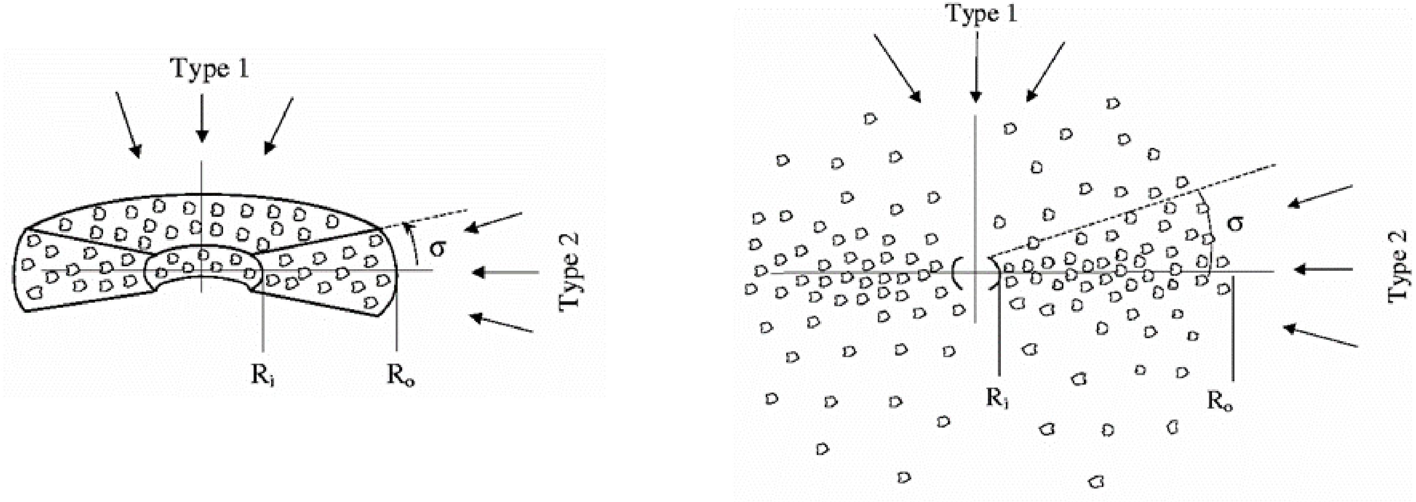


Unification Issues and the NLR

- Problems with the torus:
  - Theoretical size much larger than IR cores of nearby AGN
  - Models are unstable



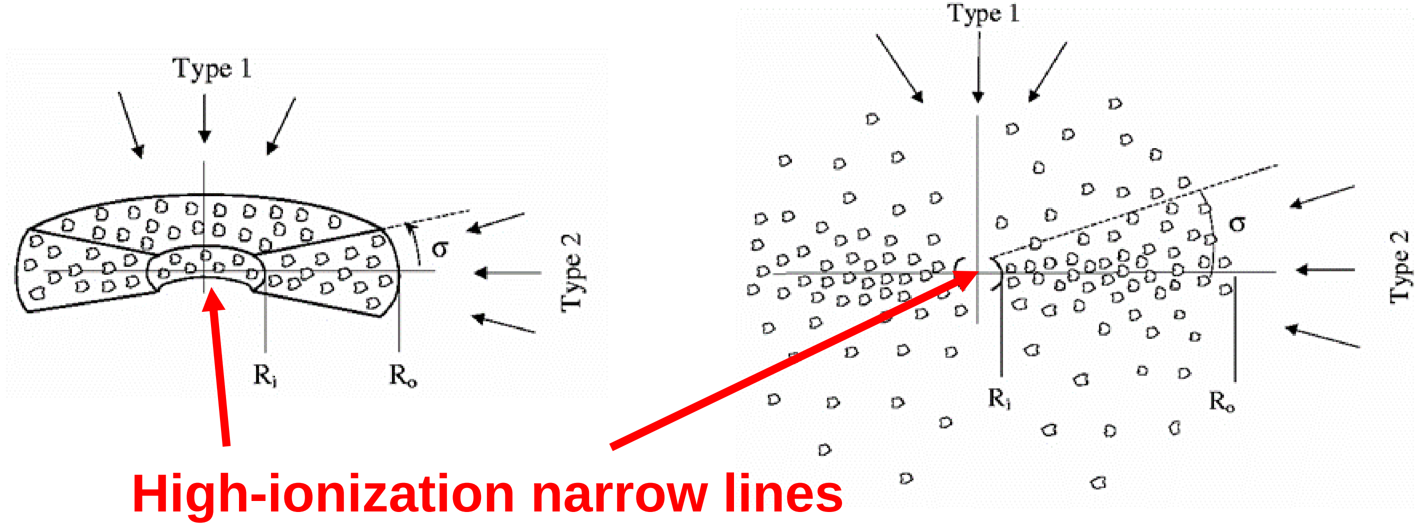
Unification Issues and the NLR



Elitzur 2006

- Solution: replace "doughnut" with system of small, dusty clouds
  - Increase emitting area
  - Better reproduces spectrum
  - Increases emitting area, smaller system
  - Can explain changes of AGN type

Unification Issues and the NLR



Elitzur 2006

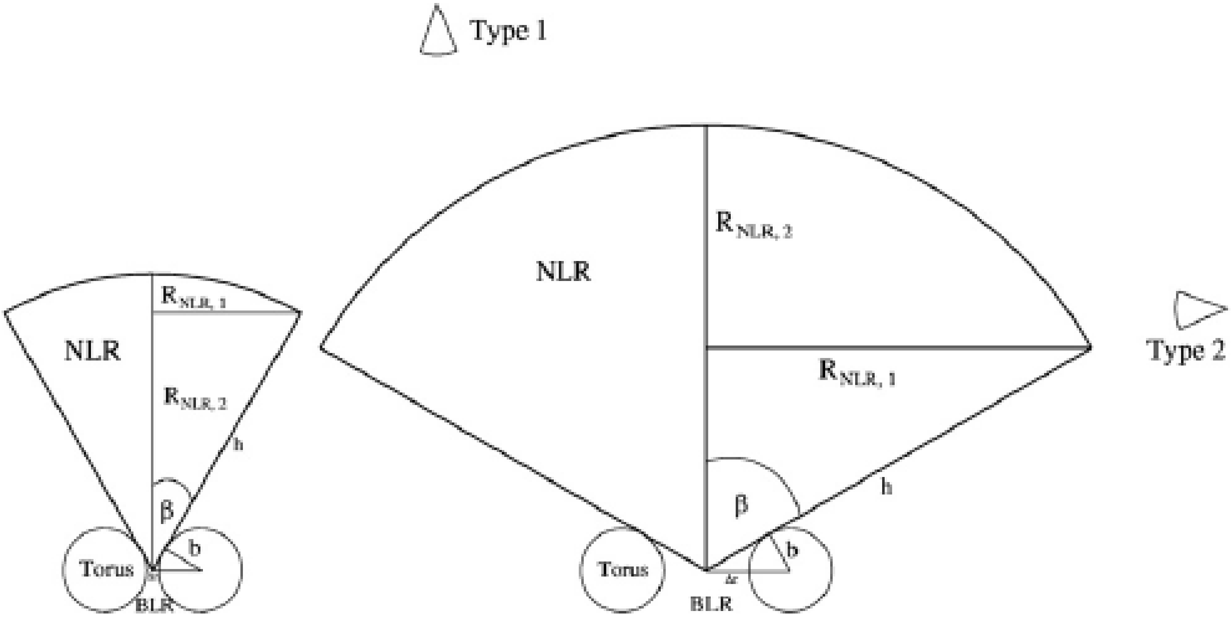
- A naïve expectation is that the narrow-line spectra of Sy 1 and Sy 2 are the same.
- Type 1 objects have stronger high-ionization lines.
- These are probably formed in the “throat” of the torus.

Unification Issues and the NLR

- At low luminosity, Type 2 AGNs outnumber Type 1 AGNs by 3:1
- High luminosity Type 2s (“Type 2 quasars) are exceedingly rare.
- Can be explained by a “receding torus”.
  - Model below can explain apparent difference in how the projected size of the NLR scales differently in Type 1 and Type 2 objects.

Type 1: $r \propto L^{0.44}$

Type 2: $r \propto L^{0.29}$



Bennert et al. 2006

Summary of Key Points

- Apparently all massive galaxies have supermassive black holes at their centers.
- Black holes accreting mass are "active galactic nuclei".
- A broad range of AGN phenomena are attributable to differences in inclination, luminosity, and Eddington accretion rate.