The Properties of AGN

Eddington Limit and Growth Rate

- Is there a limit on accretion?- Eddington limit- maximum rate a black hole can grow
- Derived by balancing radiation pressure against gravity
- Assumption is that the relevant cross section for radiation pressure is the Compton cross section

- If the accreting material is exposed to the radiation it is producing it receives a force due to radiation pressure

Eddington Limit

Radiation pressure is (Flux/c)xσ (σ is the relevant cross section)

The Thompson cross section is the minimum cross section and thus since the flux is $L/(4\pi r^2)$; L is the luminosity the radiation pressure is $\mathbf{L\sigma_T/4\pi r^2 c}$; (σ_T is the Thompson cross section (6.6×10^{-25} cm^2)

The gravitational force on the proton is $\mathbf{Gm_p M_{BH}/R^2}$
m_p is the mass of the proton) and $\mathbf{M_{BH}}$ is the mass of the accretor
equating the two
$[L\sigma_T/4\pi r^2 c]=[\,Gm_p M_{BH}/r^2]$

Gives the Eddington limit

$L_{Edd}=4\pi M_{BH} G m_p c/\sigma_T = 1.3\times10^{38} M_{sun}$ erg/sec $=\lambda$

Frank, King & Raine, "Accretion Power in Astrophysics",

Eddington Limit and Growth Rate

- Balance the accretion rate onto the BH against the Eddington limit (λ)
- $dM_{BH}/dt=L_{acc}/\eta c^2<4\pi G m_p M/\eta c\sigma_t$
- solution is $M=M_o e^{t/\tau}$
- where $\tau=\eta c\sigma_t/4\pi G m_p$ ~5×10^7yrs where the efficiency of converting mass to energy η~0.1 and $\lambda=1$
- If supermassive black holes grow primarily by accretion then the

integral of the accretion rate across cosmic time should be equal to their present mass. (Soltan 1982 MNRAS.200..115)-

- Integrating the bolometric luminosity function -compare this to the present day mass of black holes integrated over all objects.
- $L_{bol}=\eta(dM_{acc}/dt)c^2= \eta(M_{BH}/dt)c^2/(1-\eta)$
- dM_{acc}/dt=accretion rate
- dM_{BH}/dt= BH growth rate

$$\rho_{\mathrm{BH,acc}}(z) = \int_z^\infty \frac{dt}{dz'}dz' \int_0^\infty \frac{(1-\epsilon)L_i\kappa_i}{\epsilon c^2}\phi(L_i,z)dL_i$$

Limits to Growth

Eddington implies limit on *growth rate of mass*: since

$$\dot{M} = \frac{L_{acc}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}$$

we must have

$$M \leq M_0 e^{t/\tau}$$

where

$$\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5\times10^7\, yr$$

is the *Salpeter timescale*

η is the efficiency of converting
matter into energy
σ_T is the Thompson cross section

'Soltan' Argument

- If supermassive black holes grow primarily by accretion then the integral of the accretion rate across cosmic time should be equal to their present mass.
- Integrating the bolometric luminosity function and assuming a conversion factor, ε, from mass to energy one can compare this to the present day mass of black holes integrated over all objects

$L_{bol}=\varepsilon(dm_{acc}/dt)c^2=\varepsilon(dm_{BH}/dt)c^2(1-\varepsilon)$

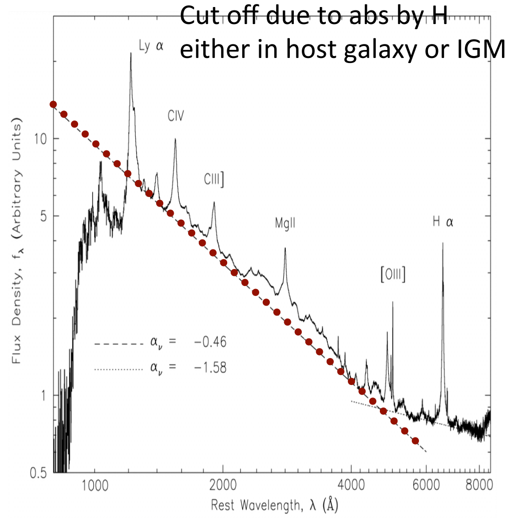
- dm_{acc}/dt=accretion rate
- dm_{BH}/dt= BH growth rate

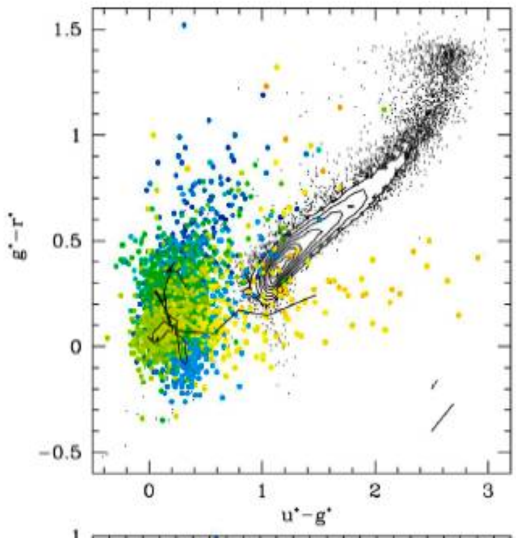
The higher the conversion factor for converting energy to mass the smaller the predicted BH mass at a given redshift is for a fixed observed luminosity

ε derived this way is independent of the cosmological model
At z=0 the observed BH mass density is ~$4\times10^{-5}\, M_\odot/Mpc^3$
Utilizing the best estimate of evolution of luminosity vs redshift this gives ε=0.06, marginally consistent with a non-spinning BH

Optical Properties of AGN

- **Strong lines** of hydrogen, carbon, oxygen from highly ionized species ….



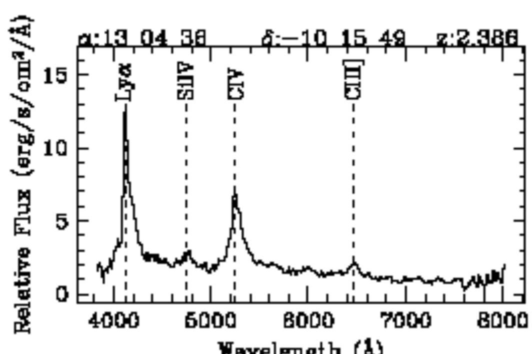


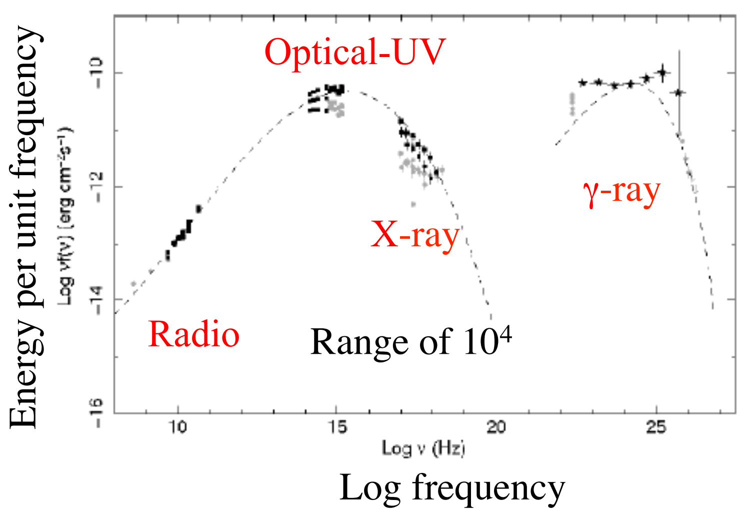
Unusual optical colors
(Richards et al SDSS)- quasars in color, stars are black

UV-Optical Continuum is thought to arise via thermal emission in an accretion disk

Broad Band Properties of AGN

- **Broad band continuum- very different from stars or galaxies**
- **Strong UV lines not seen in stars**
- Can be very variable



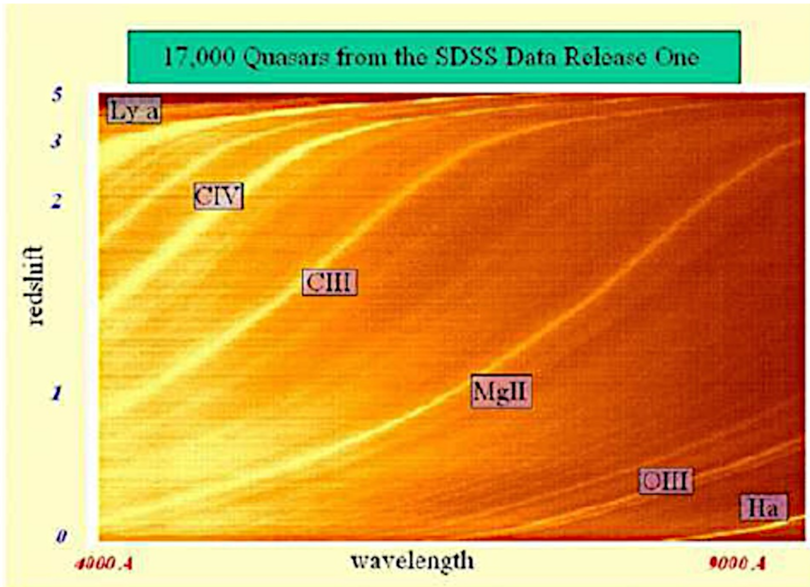


Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

A large fraction of the total observed energy appears in the **γ-ray** band (due to relativistic beaming)

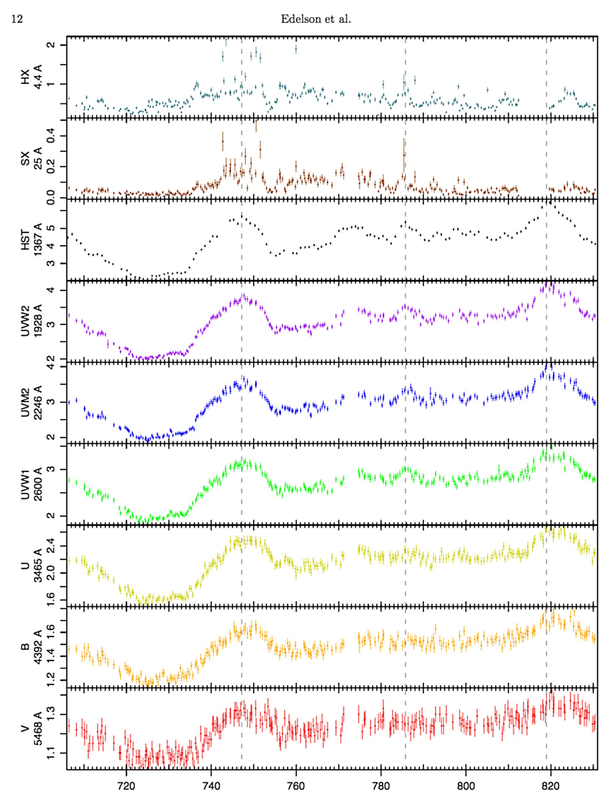
AGN Optical Spectra Across Cosmic Time

- There is very little evolution in the optical spectra of AGN out to z~5 (Fan 2009)



Rapid High Amplitude Variability

- Strong variability is often detected in the radio, optical,UV and x-ray (NGC5548 Edelson et al 2015 1501.05951.pdf



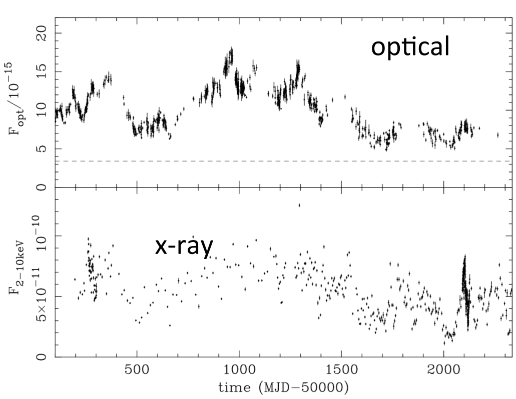
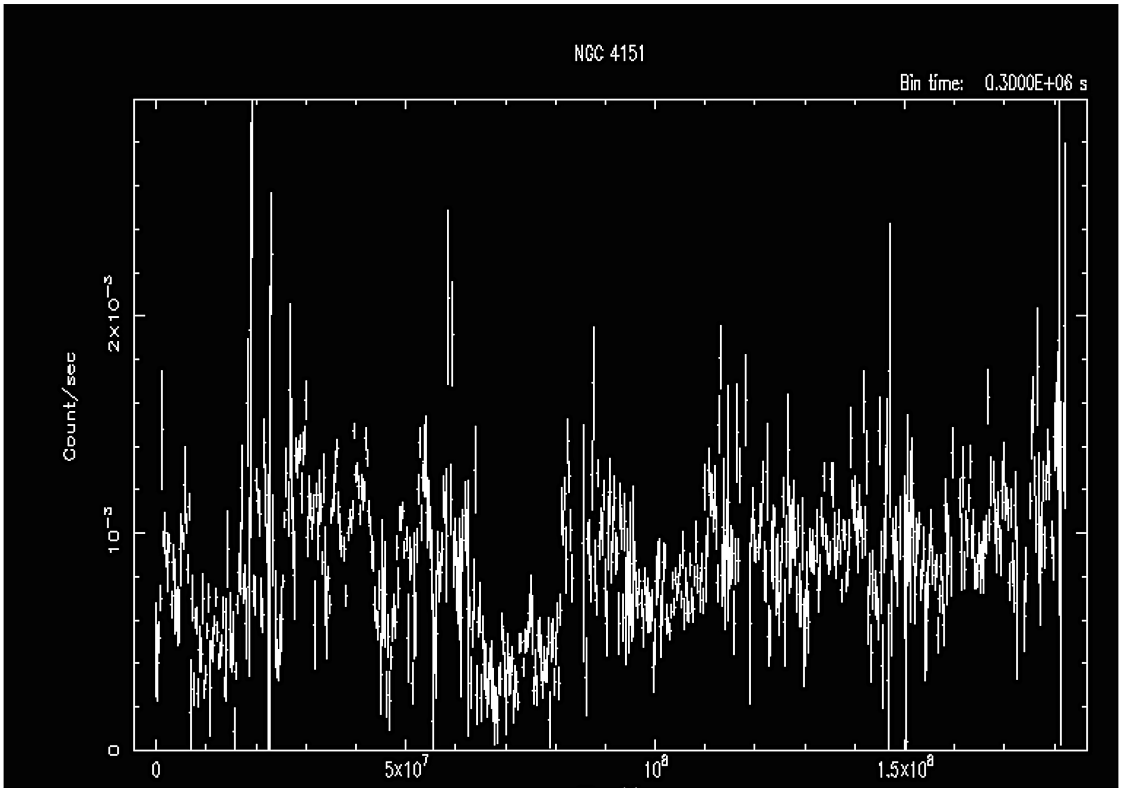
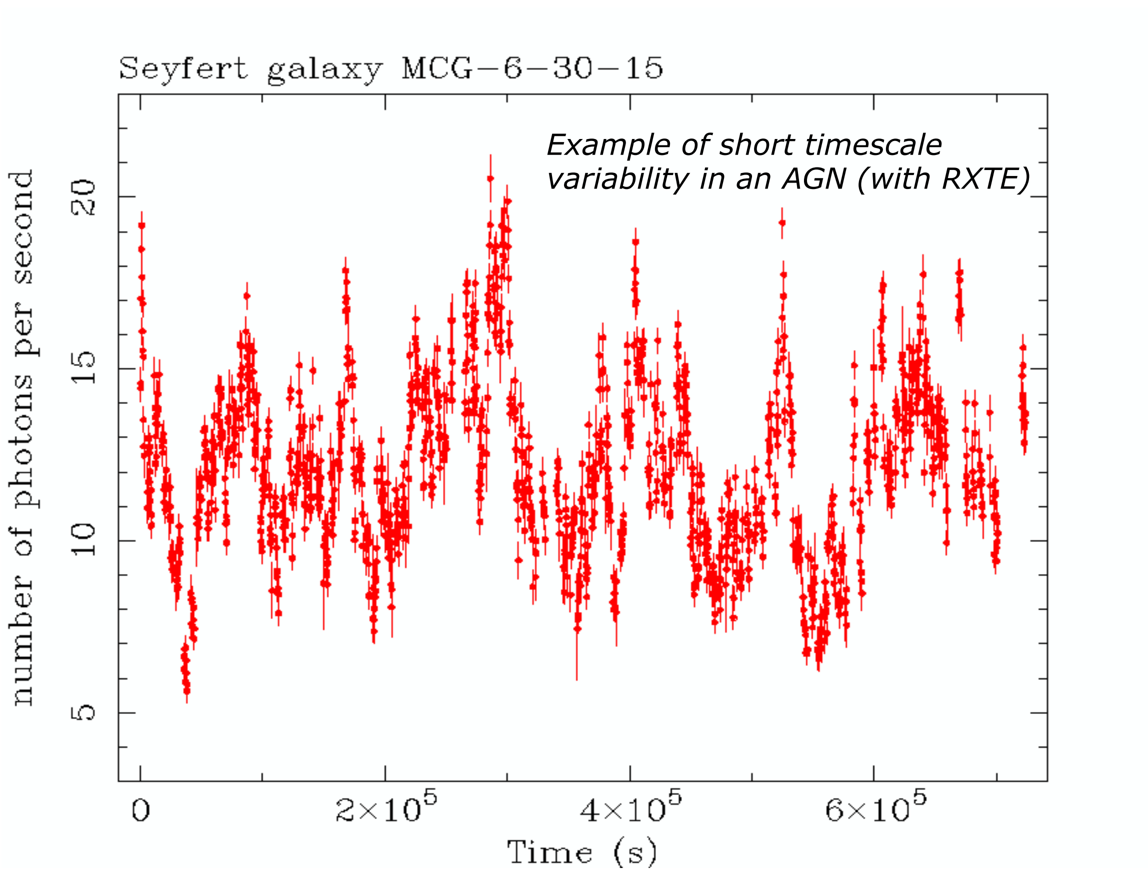


Fig. 1.— Long-term optical 5100Å (top) and X-ray 2-10 keV (bottom) light curves of

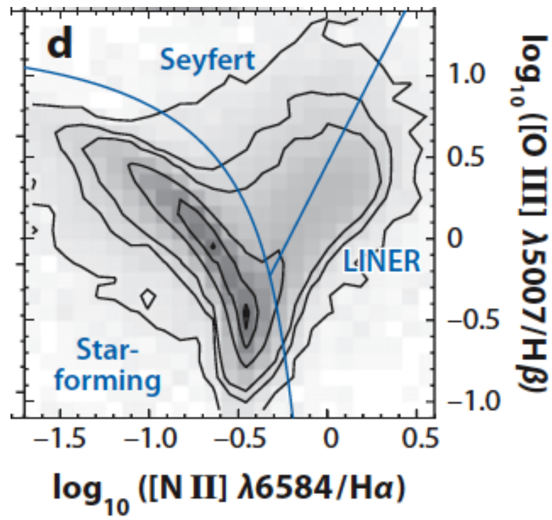
6 years of NGC4151 in Hard X-rays





Optical Emission Lines

- Remember that star forming galaxies also can have strong emission lines
- *AGN emission line ratios are different*- indicating ionization by a different type of source ('harder' spectrum- more energy at shorter wavelengths than stars)

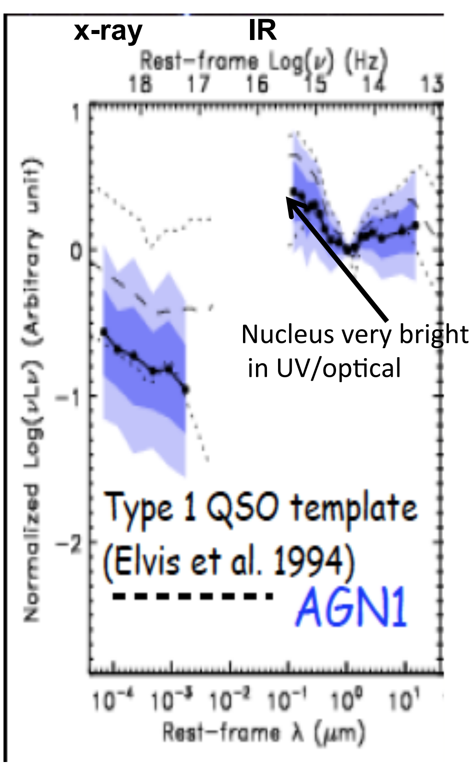


line ratio plot NII/Hα compared to OIII/Hβ−

AGN lie in a particular part of this diagram

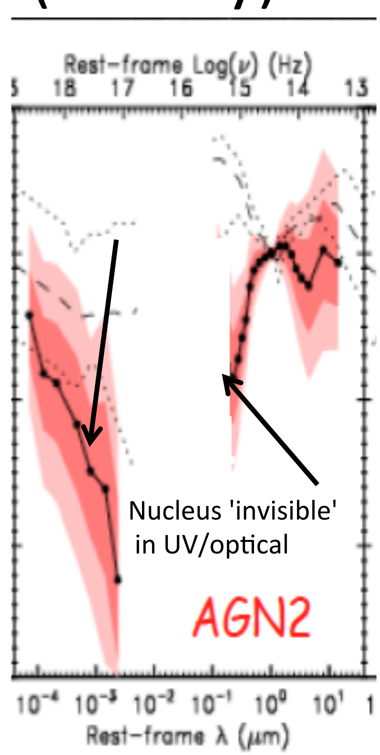
Darkness of plot is log of the number of objects inside the contour

Broad Band Continuum (IR-Xray)



X-rays reduced by absorption by cold gas

Optical UV absorbed by dust

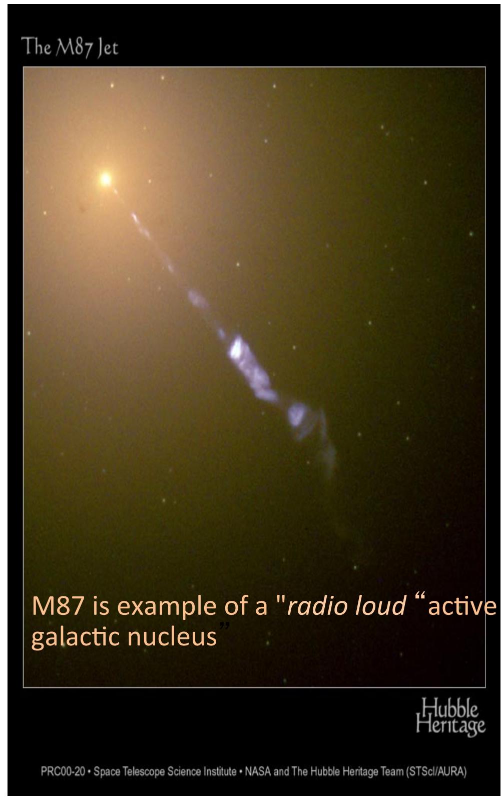


Active Galactic Nuclei

- Material flows (accretes) into black hole
- Energy released by accretion of matter powers energetic phenomena

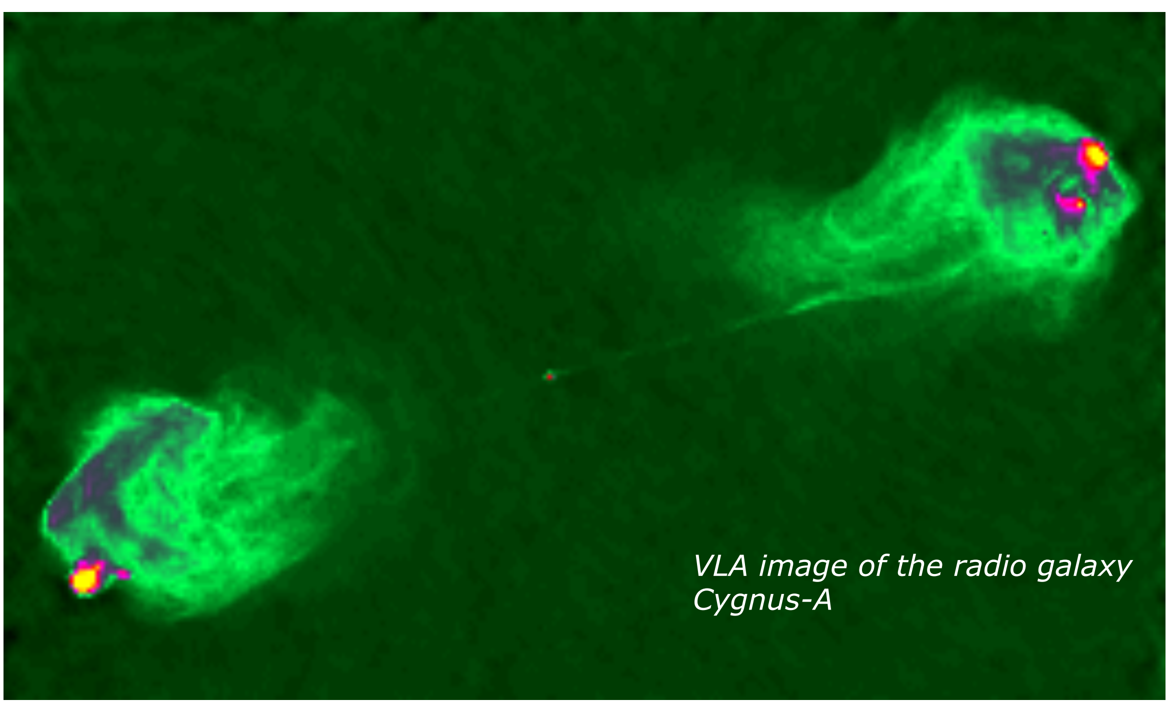
- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor ($1/\sqrt{1-v^2/c^2}$)of >6
  - Can be very energetic (particle luminosity)
  - in radio to x-ray band jet radiation is primarily synchrotron (see text)- in gamma-ray it is inverse Compton
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole

12/6/17

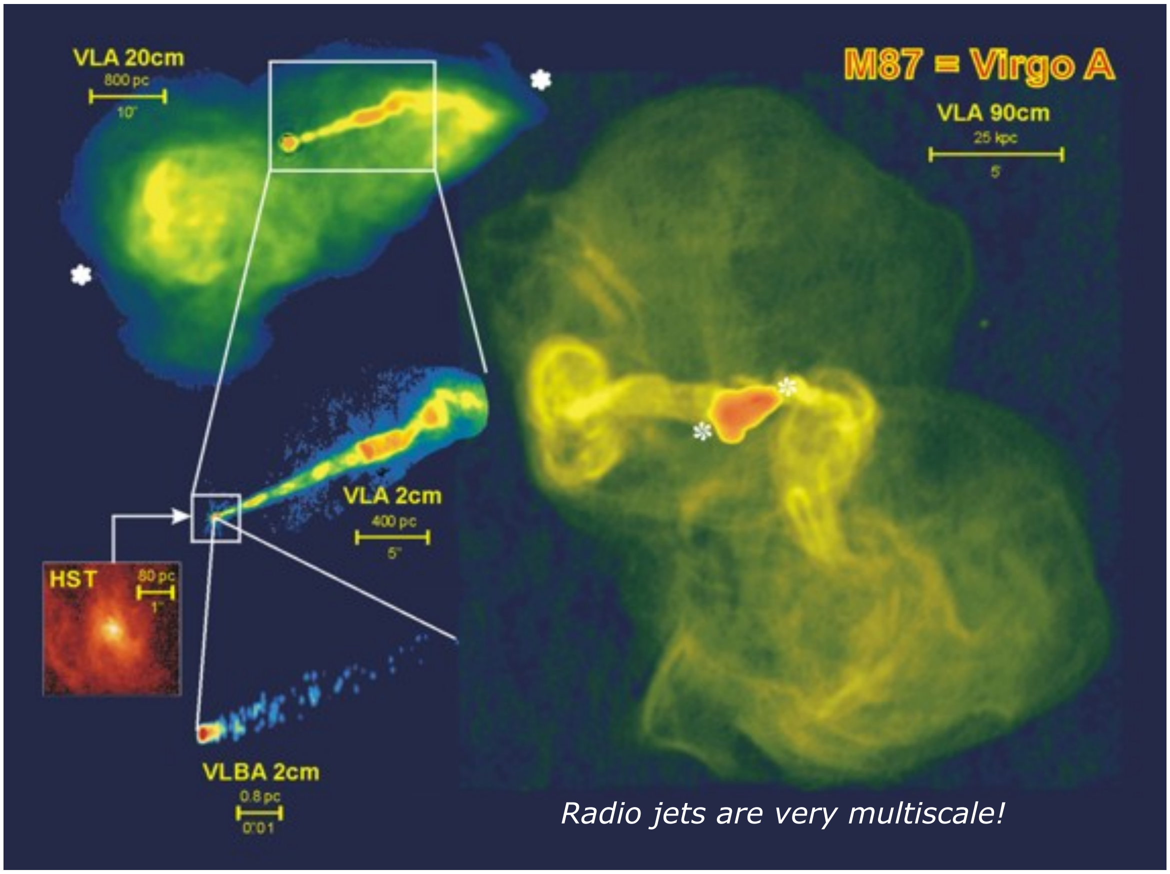


M87 is example of a "*radio loud* "active galactic nucleus"

AGN 'Types' The Radio-loud/Radio-quiet dichotomy

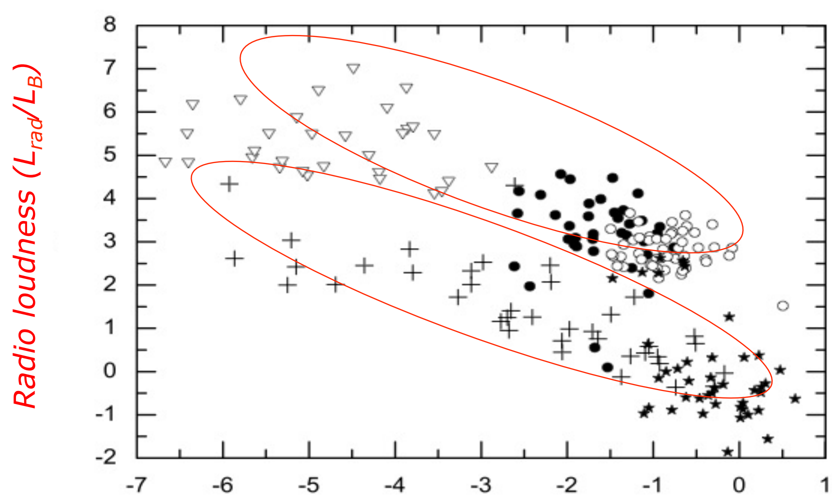


VLA image of the radio galaxy Cygnus-A



The Radio-loud/Radio-quiet dichotomy

Define relative importance of radio emission by ratio of
radio luminosity L_{rad} to optical luminosity L_B- *8 order of magnitude range*

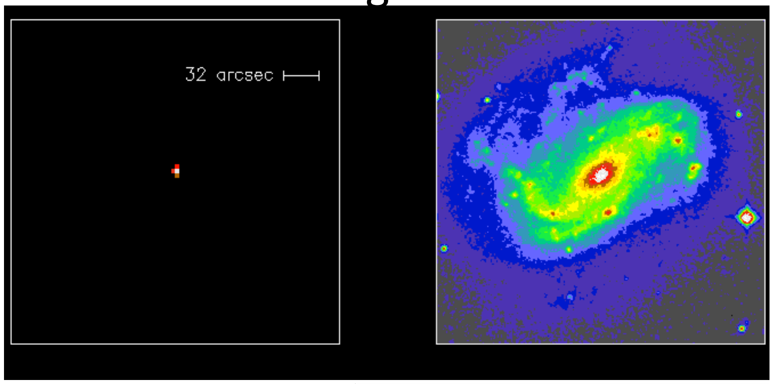


Sikora et al. (2007) *Accretion rate (Eddington Units)*

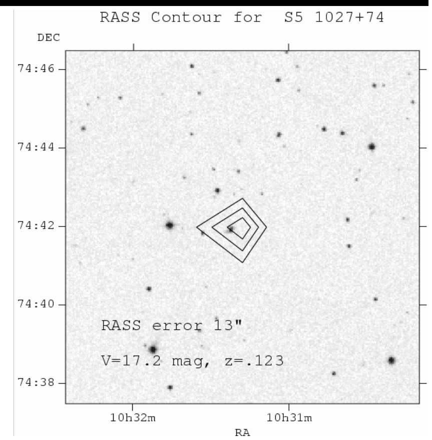
X-ray Selection of Active galaxies

- X-ray and optical image of a nearby AGN NGC4051-
- Note the very high contrast in the x-ray image
- Find x-ray AGN via
  - luminous* pointlike x-ray source in nucleus of galaxy
  - hard x-ray spectrum
  - frequently variable

* Find lots of AGN 'hidden' at other wavelengths

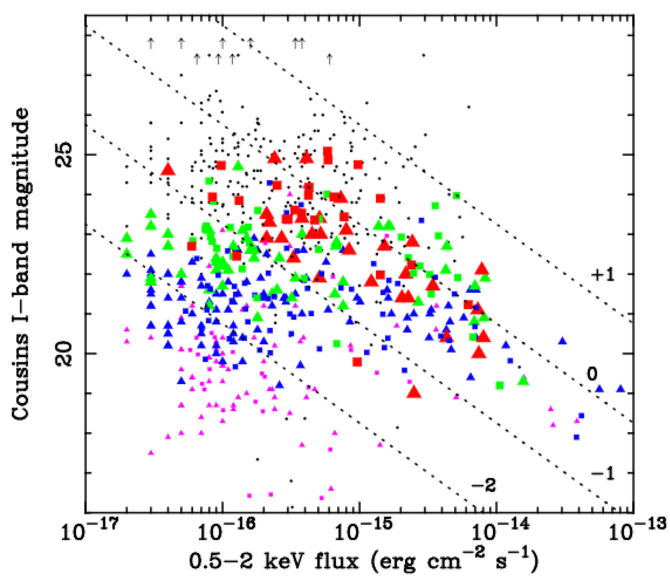


Rosat x-ray all sky survey image overlaid on sky survey image



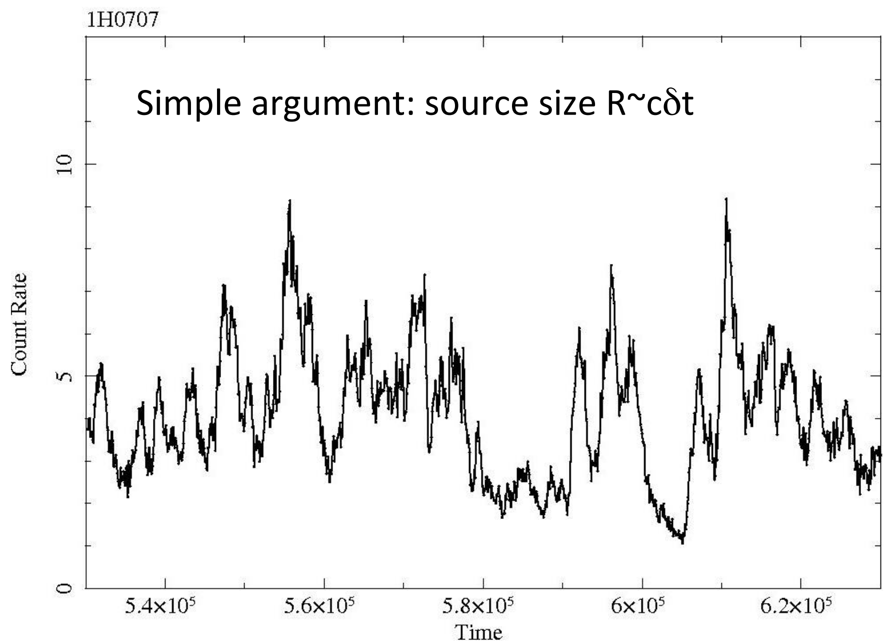
X-ray Selection of AGN

- Comparison of x-ray luminosity of AGN vs the total galaxy luminosity in a 'blind' x-ray survey
- AGN have log L(x)~L(opt)



Hasinger and Brandt ARAA 2005
color code is which observation the data were obtained from

Rapid variability in AGN
Source luminosity ~5x10^43 ergs/sec



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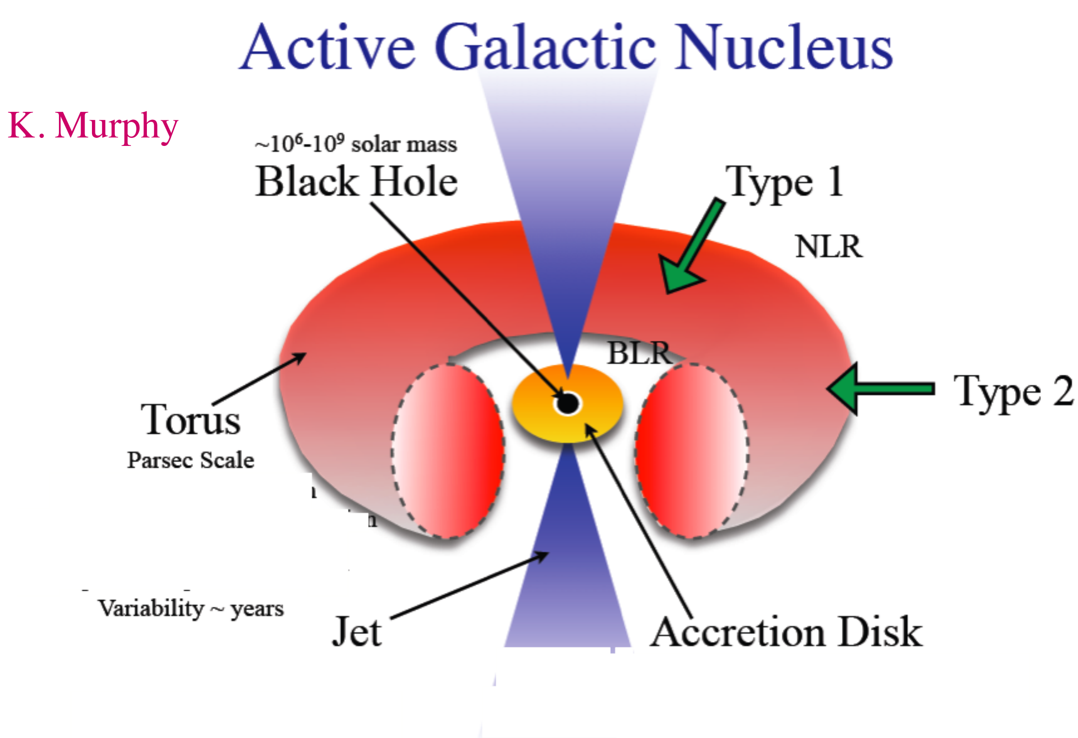
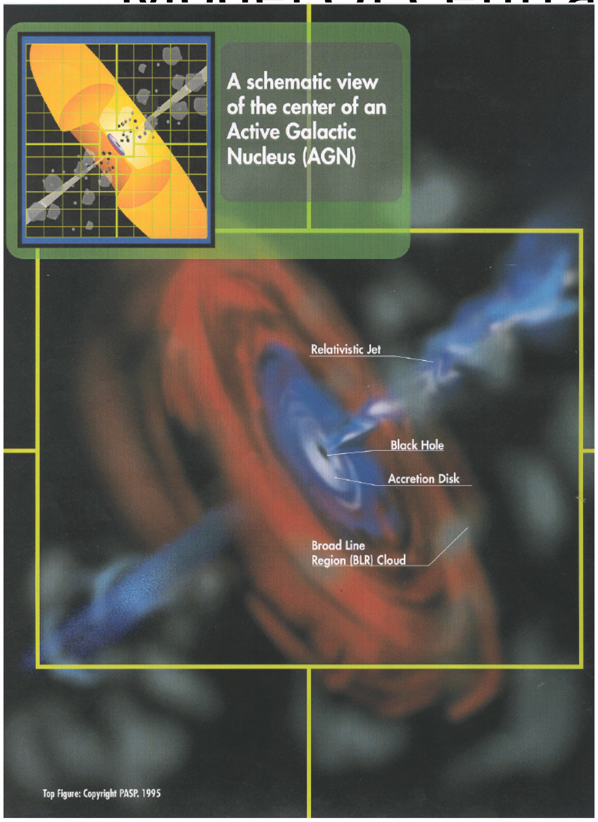
- www.courseevalum.umd.edu
- Why?
  - For the benefit of your peers
  - Because your comments count and we use it to improve our teaching and/or redesign the course
  - Because your opinion is used to evaluate our performance
- Don't put it off till Dec 11th!

Broad Range of Properties

- Luminosity
  - Range from $<10^{40}$ erg/s to $\sim 10^{48}$ erg/s
  - Fundamental parameters controlling L are **mass and mass accretion rate**
  - Most Powerful objects (quasars)- AGN totally outshines host galaxy
- Level of obscuration- how much material is in our line of sight
  - In some objects, can see all of the way down to the SMBH (type I)
  - In other objects, view at some wavelengths is blocked by obscuring material (some objects are blocked at all wavelengths)- type II
  - Level of obscuration connected to **viewing inclination**
- Presence of powerful relativistic (radio) jets
  - Radio-loud AGN : generate powerful jets, seen principally via synchrotron radiation in the radio band
  - Radio-quiet AGN : lack **powerful** jets (often possess weak jets)
  - Fundamental parameter controlling jet production **unknown** **(maybe black hole spin; or magnetic field configuration)**



Model Of Central Region of AGN



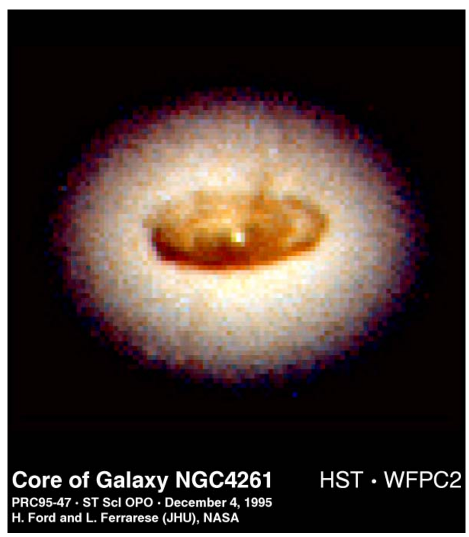
Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

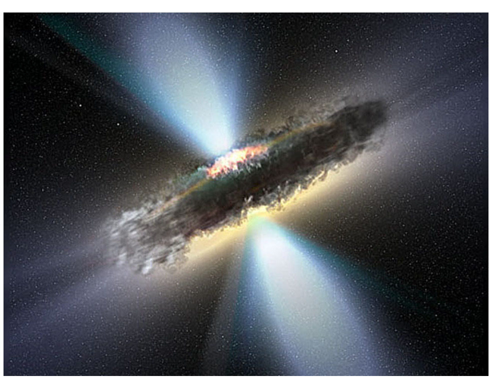
R_s= Schwarschild radius=$2GM/c^2$

$R_s=1.4\times10^{13}M_8$cm; $R_s/c \sim 500M_8$ sec

The Dark Side of AGN

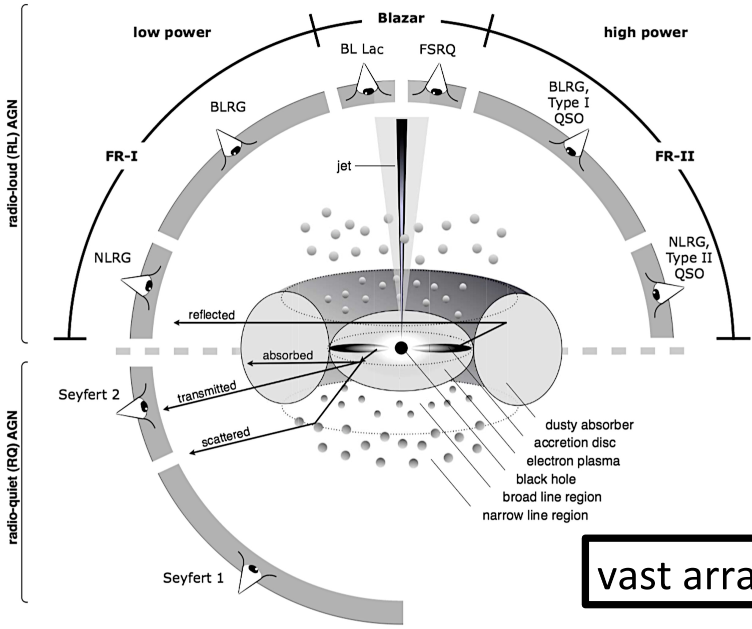
- ***Many AGN are obscured***- obscuring material is of several types
  - Located in the ISM of the host galaxy
  - A wind associated with the AGN
  - Perhaps a 'obscuring torus'
  - Etc
  - Lack of uniform sample not sensitive to absorption or emission from this structure has limited knowledge of true distribution of properties





physical conditions in obscuring regions are not the same from object to object - can be complex with large and unpredictable effects on the spectrum

The Overall Picture (Beckman and Shrader 2013)

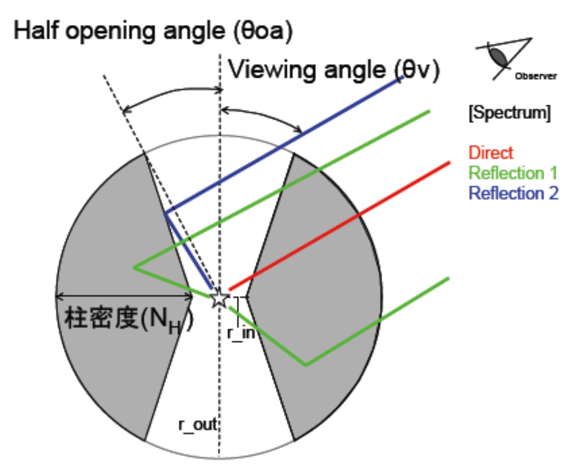


vast array of names

1: Schematic representation of our understanding of the AGN phenomenon in the unified scheme
: type of object we see depends on the viewing angle, whether or not the AGN produces a significant
sion, and how powerful the central engine is. Note that radio loud objects are generally thought to

AGN Zoo

- In a simple unification scenario broad-lined (Type 1) AGN are viewed face-on
- narrow-lined (Type 2) AGN
  - the broad emission line region (BELR) the soft X-rays and much of the optical/UV emission from the Accretion Disk are hidden by the dust



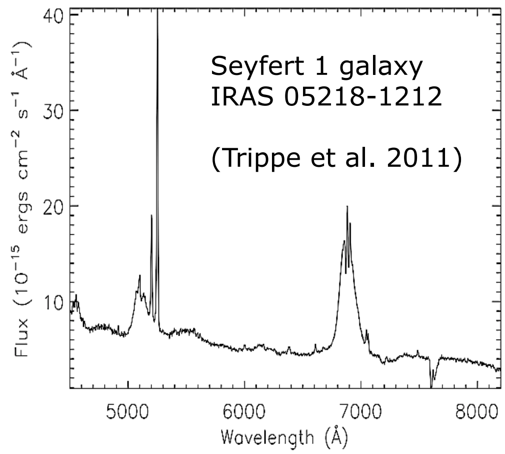
- However there are other complications like jets and a range in the geometry
- 'Radio loud' objects- e.g. with strong jets and/or luminous extended radio emission lie ONLY in elliptical galaxies!

Radio Loudness	Optical Emission Line Properties		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG { FR I / FR II	BLRG SSRQ FSRQ	Blazars { BL Lacs / (FSRQ)
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.

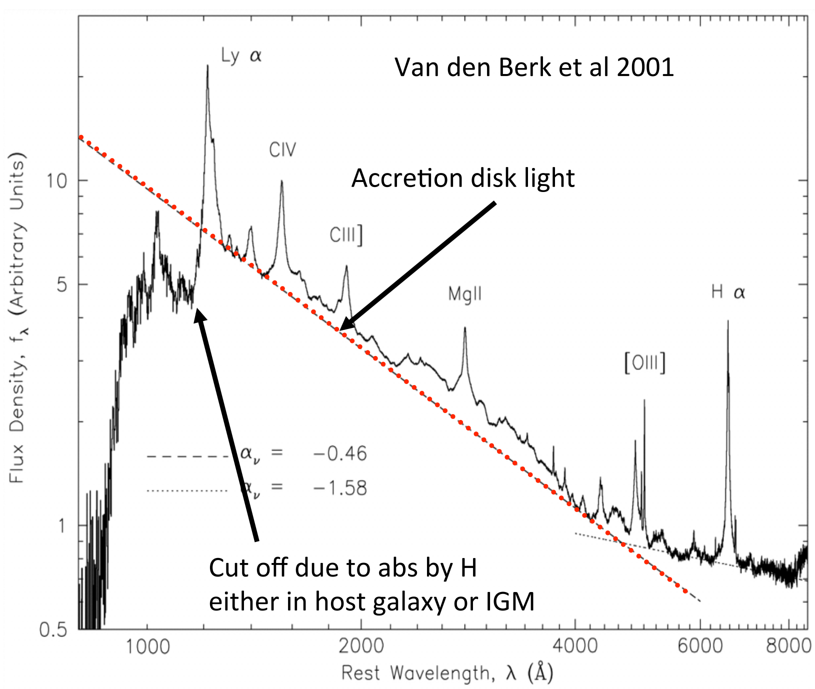
AGN Types
Broad line (type-1) objects

- 'Blue' optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9 cm^{-3}$
  - FWHM~2000-20,000 km/s
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Spatially resolved 0.1-1kpc



Hβ, [OIII], [NII],Hα

- AGN (type I) optical and UV spectra consist of a 'feature less continuum' with strong 'broad' lines superimposed
- Typical velocity widths (σ, the Gaussian dispersion) are ~2000-5000km/sec
- The broad range of ionization is due to the 'photoionzation' of the gas- the gas is **not** in collisional equilibrium
- At short wavelengths the continuum is thought to be due to the accretion disk



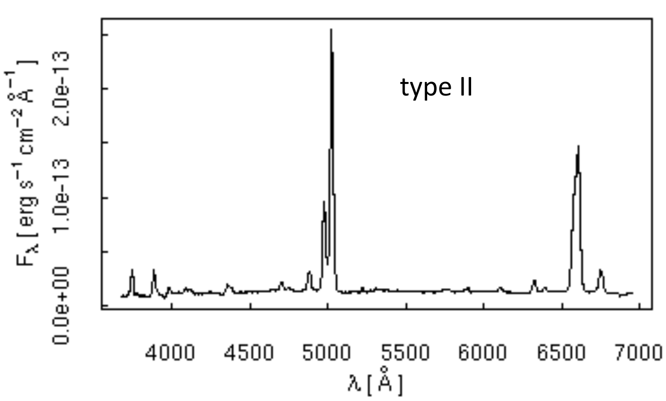
Origin of λ>4000Å continuum not known

AGN Types
Narrow line (type-2) objects

- Reddened Optical/UV continuum
- Optical Emission line spectrum
  - "Full light" spectrum only shows narrow (~500km/sec) optical/UV lines
  - Broad optical/UV lines seen in *polarized* light… shows that there is a hidden broad line region seen via scattering (Antonucci & Miller 1985)
- **X-ray spectrum usually reveals highly absorbed nucleus ($N_H > 10^{22} cm^{-2}$)**
- Intermediate type objects (type-1.2, 1.5, 1.8, 1.9) have obscurers which become transparent at sufficiently long/short wavelengths

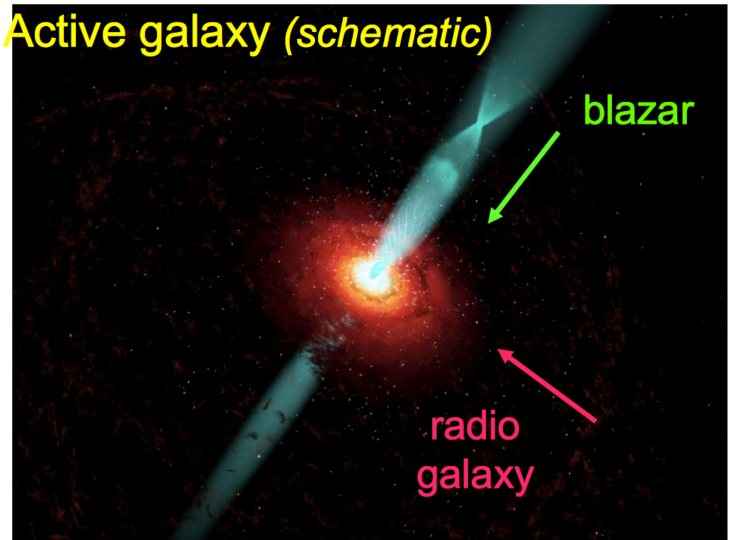
Objects without a Strong Continuum-e.g type II

- type II do not have broad lines and have a weak or absent 'non-stellar' continuum
- Depending on the type of survey and luminosity range ~50% of all AGN are of type II
- Have high line of sight column densities in the x-ray (>3x10^{22} atms/cm^2)



AGN types Blazar

- Thought to be due to emission from jet in our line of sight
- Can be very luminous
- Two types
  - Bl Lacs- Featureless (no lines) broad band continuum radio-gamma rays
  - FSRQs (flat spectrum radio quasars) have strong optical lines – very high luminosity



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Radio Loudness	Names and Properties		No Lines
Radio quiet (weak or no jet)	Type II (narrow forbidden lines) Seyfert 2	Type I (broad permitted lines) Seyfert 1 QSO	
Radio Loud (strong jet)- **ONLY in ELLIPTICAL Galaxies**	FR I NLRG FR II	BLRG	Bl Lac Blazars FSRQ
X-ray Properties	Highly Absorbed- strong narrow Fe K line, strong low E emission lines	Not absorbed- or ionized absorber often broad Fe K line- low energy spectrum with absorption lines	Featureless continuum- highly variable γ-ray sources

table 27-2 Properties of Active Galactic Nuclei (AGNs)

Object	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	Luminosity (watts)	Luminosity (Milky Way Galaxy = 1)
Blazar	Elliptical	Strong	Weak (compared to synchrotron emission)	10^{38} to 10^{42}	10 to 10^5
Radio-loud quasar	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^5
Radio galaxy	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^5
Seyfert 1	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Seyfert 2	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

- Some of different classes of AGN are truly different 'beasts' - (e.g. radio loud vs radio quiet) ***but***
- Much of the apparent differences are due to geometry/inclination effects- this is called the Unified Model for AGN (e.g. type I vs Type I radio quiet objects, blazars - radio loud objects observed down the jet)
- The ingredients are: the black hole, accretion disk, the jet, some orbiting dense clouds of gas close in (the broad line region), plus a dusty torus that surrounds the inner disk, some less dense clouds of gas further out (the narrow line region) (adapted from T. Treu)