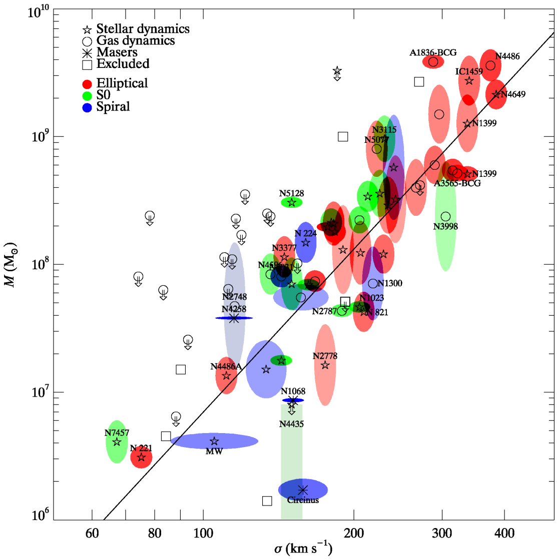
Active Galactic Nuclei

- Outline of this lecture
  - The M-sigma relation, & black hole masses
  - The basic properties of AGN
  - Broad vs narrow line AGN: The Unified Model
  - Radio-quiet vs radio-loud AGN: Jets
  - The X-ray properties of AGN

I : Supermassive black holes

The ubiquity of SMBHs in galaxies

- Every “major” galaxy possesses a supermassive black hole (SMBH)
- Mass of SMBH related to properties of host galaxy
  - Well correlated to velocity dispersion of bulge stars
  - This is famous M_{BH}-σ relationship
  - Implies connection between growth of galaxy and SMBH
  - More about this in Richard Mushotzky’s lecture…
- How do we measure the mass of a SMBH?



Gultekin et al. (2009)

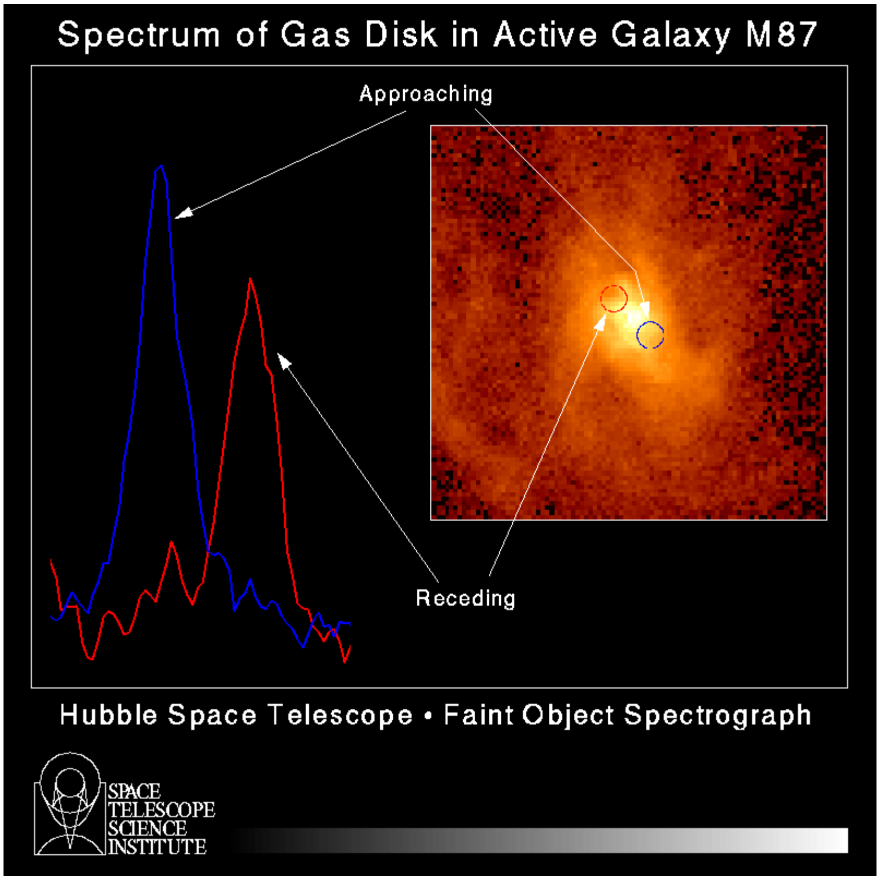
I : Supermassive black holes

Measuring the mass of a SMBH

- **Definition** : The sphere of influence of a SMBH is the region of the galaxy in which the SMBH dominates the gravitational forces.
  - If velocity dispersion of stars in galactic bulge is σ_*, then sphere of influence R_{BH} is given by

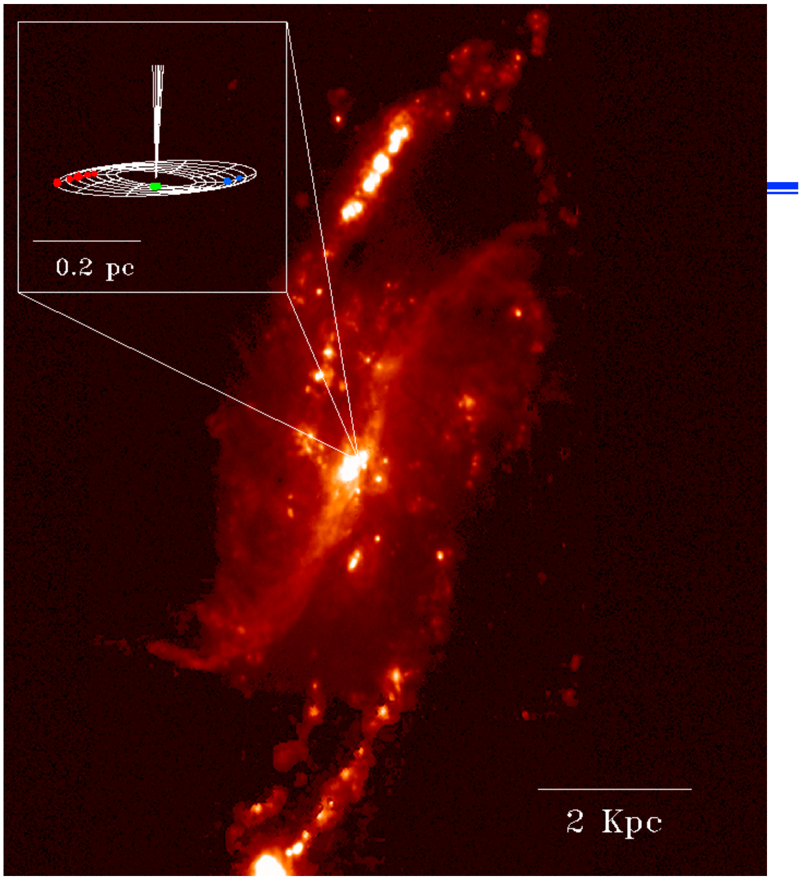
$$\frac{GM_{BH}}{R_{BH}^2} = \frac{\sigma_*^2}{R_{BH}} \quad \Rightarrow \quad R_{BH} = \frac{GM_{BH}}{\sigma_*^2}$$

- Direct mass indicators involve analyzing dynamics within RBH
  - **Special cases**… can find and study rotating gas disks within sphere of influence. Trace out Keplerian rotation curve and so find mass. E.g. ionized gas disk in M87; maser disk in NGC4258.
  - **Another special case**, our Galactic Center… can trace the proper motion of individual stars close to the black hole, reconstruct their orbit and hence determine the mass of the SMBH
  - **More generally** : use 2-d surface brightness and velocity dispersion data to construct best-fitting mass distribution ➔ M_{BH}



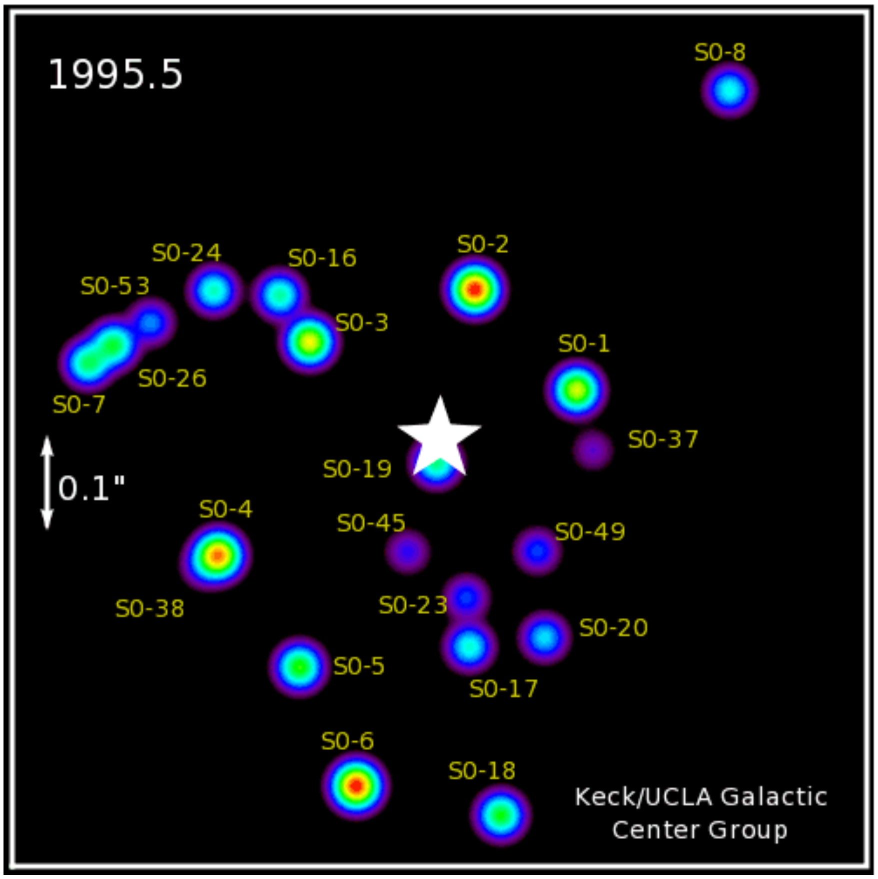
M87 (HST)
$M=3x10^9M_{sun}$
(Harms et al.1995)

Recently revised to $M{\sim}6x10^9M_{sun}$
(Gebhardt et al. 2009)



NGC4258
Maser disk
$M=3.5x10^{7}M_{sun}$

(Miyoshi et al. 1995)



Keck/UCLA Galactic
Center Group

Direct view of
stars orbiting
in potential of
SMBH

$M=4x10^{6}M_{sun}$

I : Supermassive black holes

The energetics of SMBHs

- Let's get a feel for tremendous energetics associated with SMBHs (assuming a 10% efficiency)
- Consider the M87 black hole ($M=6\times10^9 M_{sun}$)

$$L_{Edd} = 1.4\times10^{38}\left(\frac{M}{M_\odot}\right)\,\mathrm{erg\,s^{-1}} = 8.4\times10^{47}\,\mathrm{erg\,s^{-1}}$$

$$E = \eta M c^2 \approx 1\times10^{63}\,\mathrm{erg\,s^{-1}}$$

$$\frac{E}{L_{\mathrm{Edd}}} = 41\,\mathrm{Myr}$$

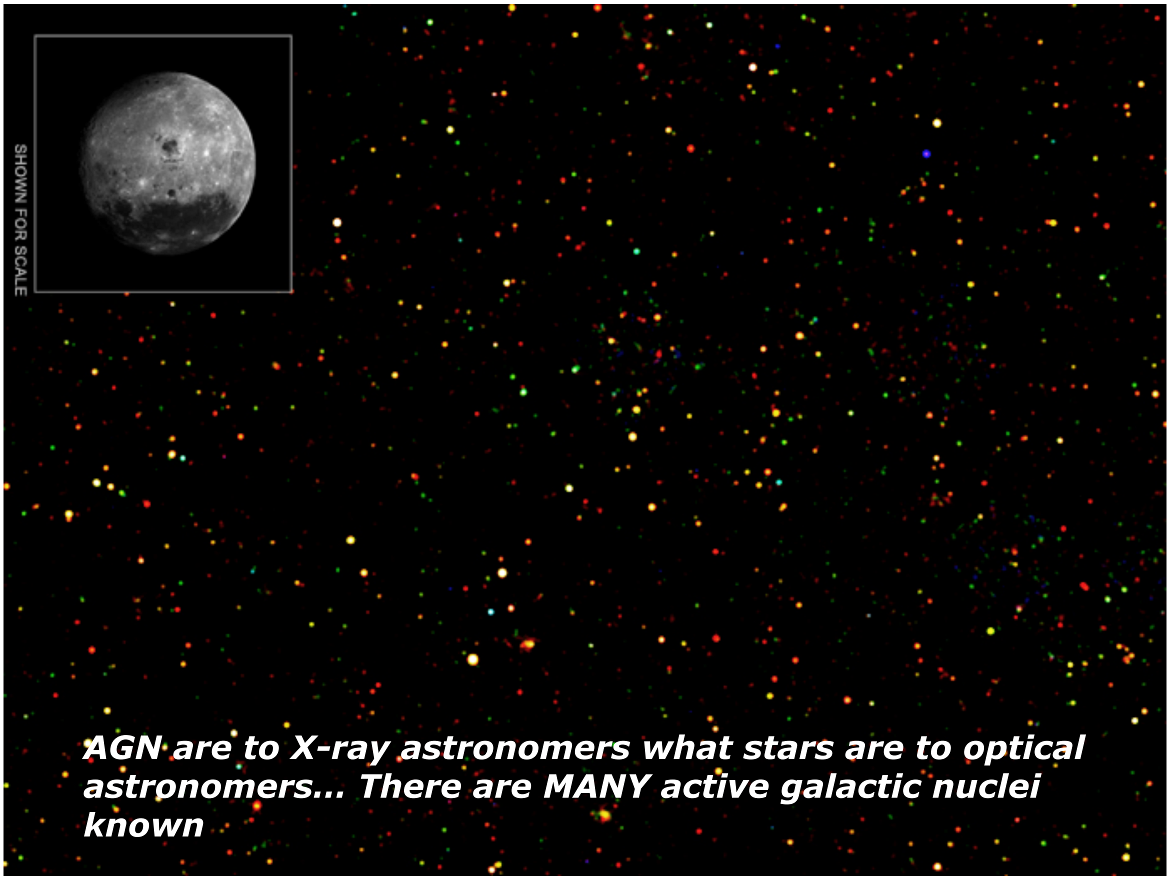
(characteristic time for which a SMBH of a given mass could have been radiating at the Eddington limit)

- For comparison, the binding energy of the baryonic matter in the galaxy is approximately

$$E_{\mathrm{bind}} \sim \frac{G M_B M_{\mathrm{DM}}}{R_{\mathrm{gal}}} \sim 10^{62}\,\mathrm{erg\,s^{-1}}$$

$$(M_B \sim 10^{12} M_\odot, M_{\mathrm{DM}} \sim 10^{13} M_\odot, R_{\mathrm{gal}} \sim 10\,\mathrm{kpc})$$

Let's go hunting for live monsters!



AGN are to X-ray astronomers what stars are to optical astronomers… There are MANY active galactic nuclei known

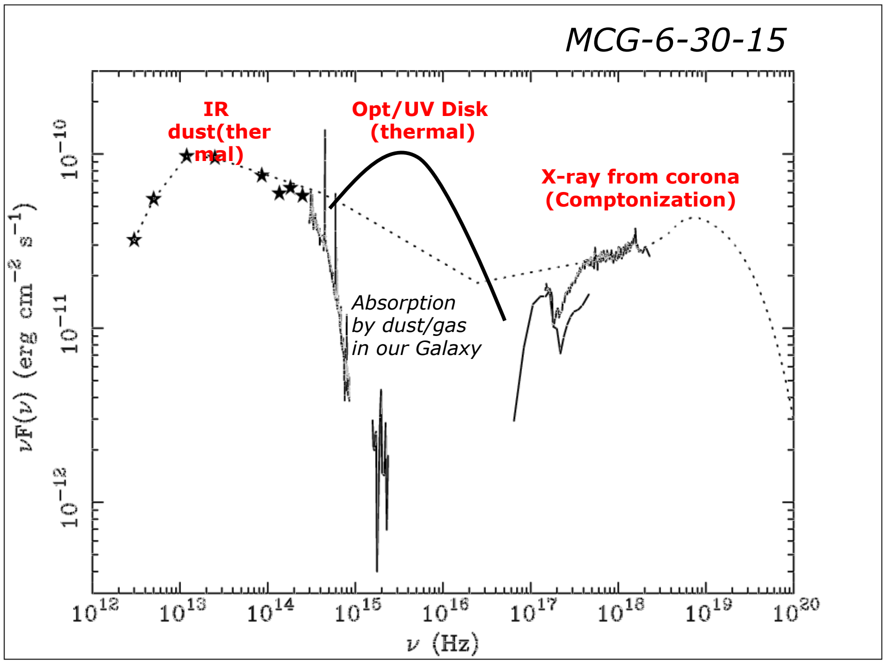
II : Broadband spectrum

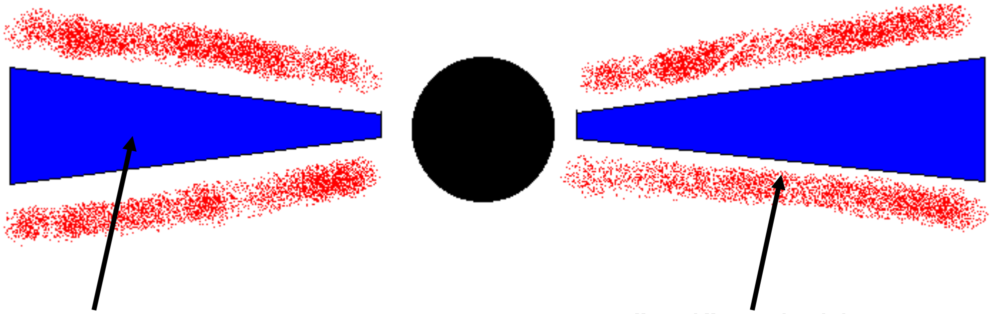
- AGN emit over a VERY broad range of wavelengths

- Typical components
  - Radio power-law (synchrotron radiation from jets)
  - Sub-mm/IR bump (thermal emission from heated dust)
  - Optical/UV bump (thermal emission from accretion disk)
  - X-ray power-law (Comptonization from disk corona)

- In addition, some AGN show very high-energy emission (Comptonization in relativistic jet)

II : Broadband spectrum

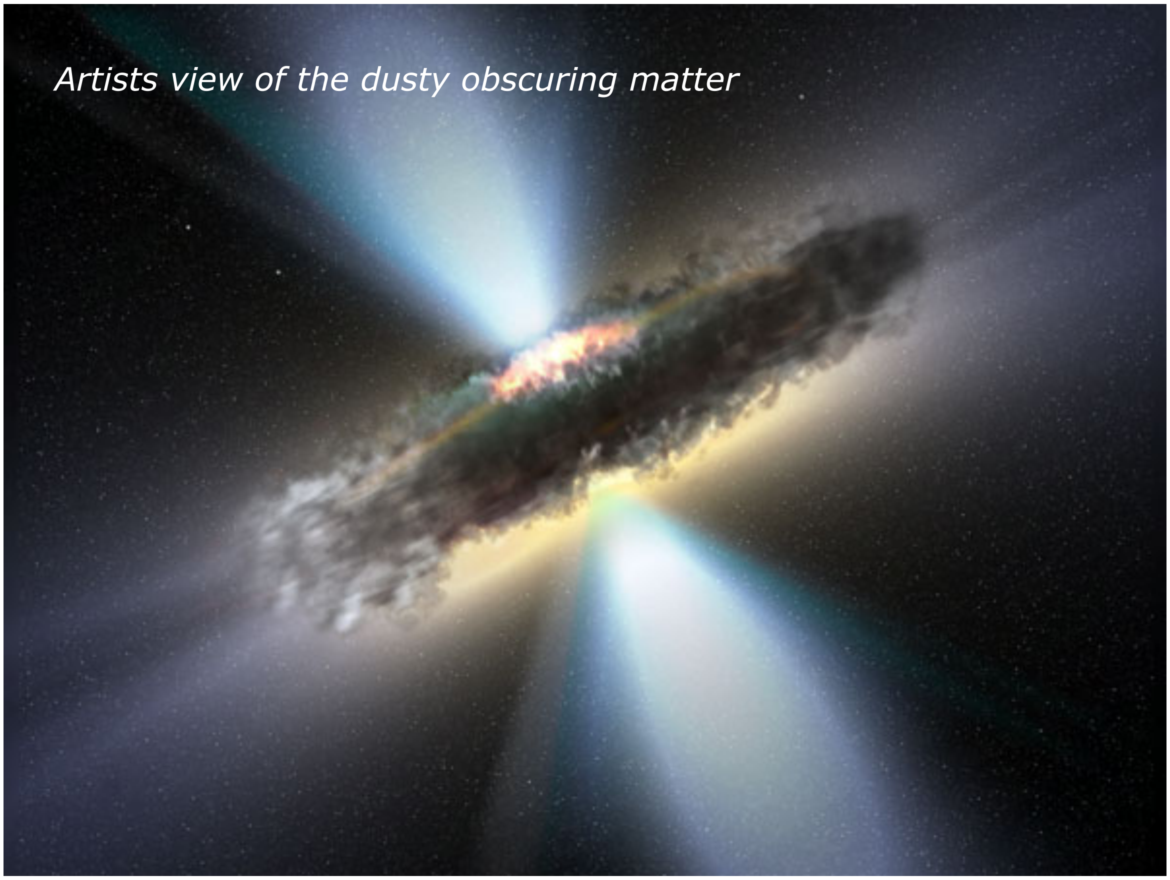




Optically-thick part of the accretion disk emits thermal spectrum… black body radiation with

$$T = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_{\rm SB}}\right)^{1/4}$$

X-ray "tail" probably comes from a hot corona that sandwiches the disk… inverse Compton scattering of thermal disk emission by electrons with T~10^{9}K



II : Broad-band spectrum

Constraints on accretion efficiency

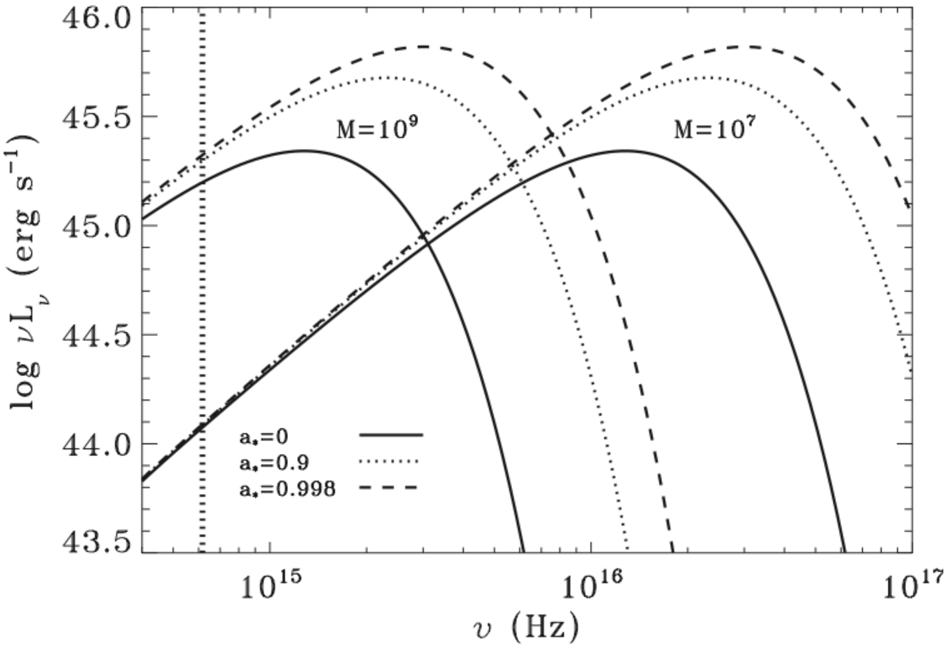
- Reminder : radiative-efficiency of an accretion flow is defined by

$$L = \eta \dot{M} c^2$$

- Can determine accretion efficiency in following way (Davis & Laor 2010)…
  - Use M-sigma or some other method to determine SMBH **mass**
  - Compare optical/UV spectrum with thermal disk models to determine **accretion rate**
  - Integrate over broad-band spectrum to determine bolometric **(total) luminosity**

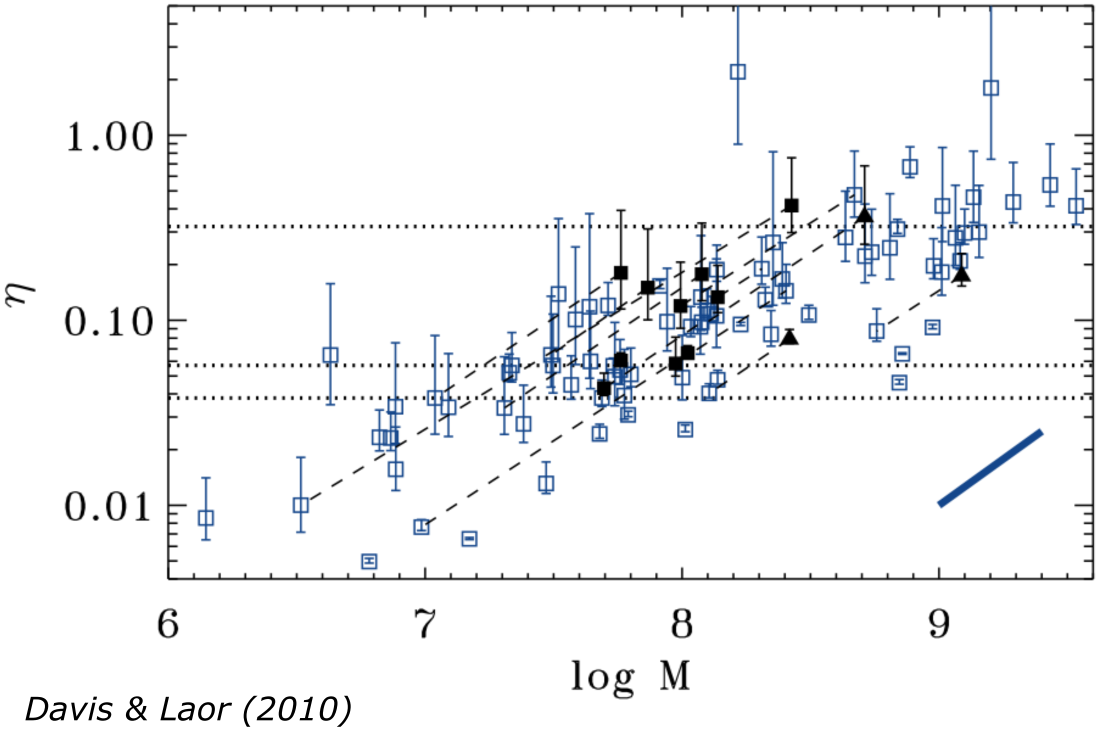
- For radiatively-efficient disks, the efficiency can be used to estimate the black hole spin

Theoretical models of the thermal emission from an AGN accretion disk…
for illustration, all curves assume accretion rate of 1 Msun/yr



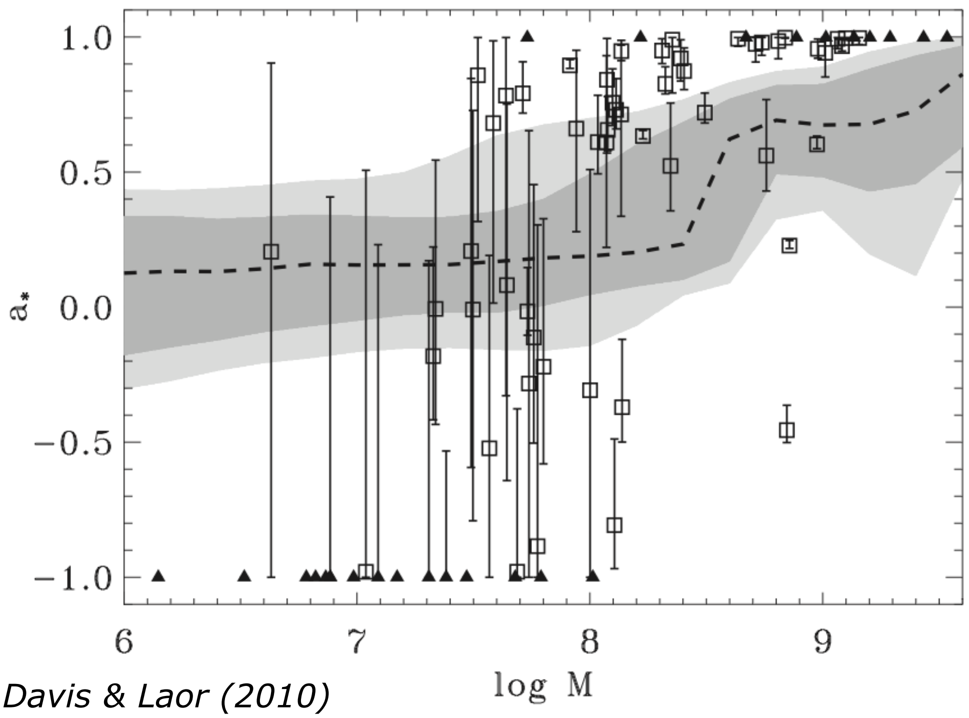
Davis & Laor (2010)

Efficiency inferred from comparing thermal disk emission and bolometric luminosity



Davis & Laor (2010)

Spin inferred from efficiency



Davis & Laor (2010)

III : AGN Unification

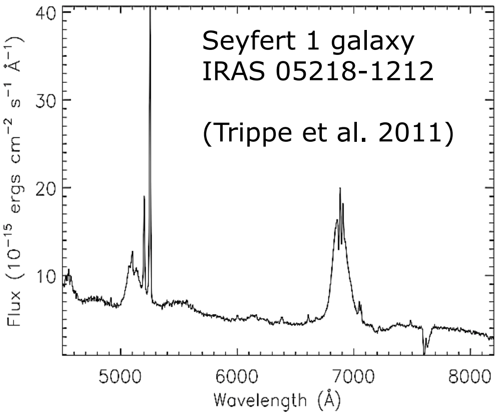
General comments

- AGN are diverse… they have a vast range of properties
- In general, there are three "axes" to consider…
- Luminosity
  - Range from <10^{40} erg/s to ~10^{48} erg/s
  - Fundamental parameter controlling this is **mass accretion rate**
  - Powerful objects called quasars (historically, AGN found before galaxy)
- Level of obscuration
  - In some objects, can see all of the way down to the SMBH
  - In other objects, view at some wavelengths is blocked by column of obscuring material (some objects are blocked at all wavelengths)
  - 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 these powerful jets (often possess weak jets)
  - Fundamental parameter controlling jet production **unknown** **(maybe black hole spin; or magnetic field configuration)**

III : AGN Unification

Broad line (type-1) objects

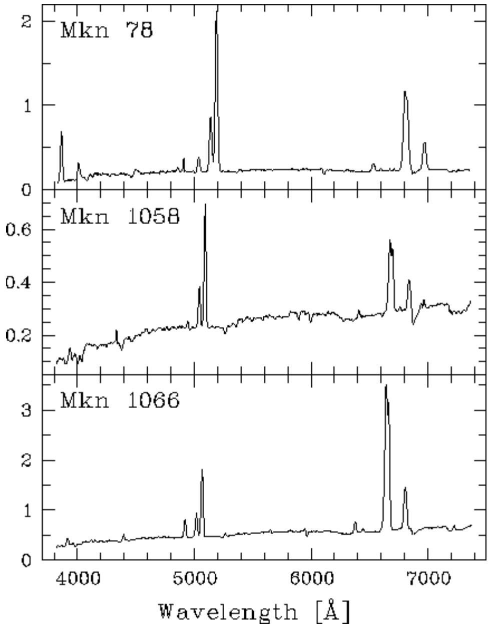
- Blue optical/UV continuum
- Broad optical/UV lines
  - Emission lines from permitted (not forbidden) transitions
  - Photoionized matter $n>10^9$cm^{-3}
  - FWHM~2000-20000 km/s
  - BLR - an accretion disk wind
- Narrow optical/UV lines
  - Emission lines from both permitted and forbidden transitions
  - FWHM~500km/s
  - Spatially resolved 0.1-1kpc
  - NLR - AGN-driven wind + photoionized galactic material
- **Overall spectrum reveals unabsorbed/unreddened nucleus**

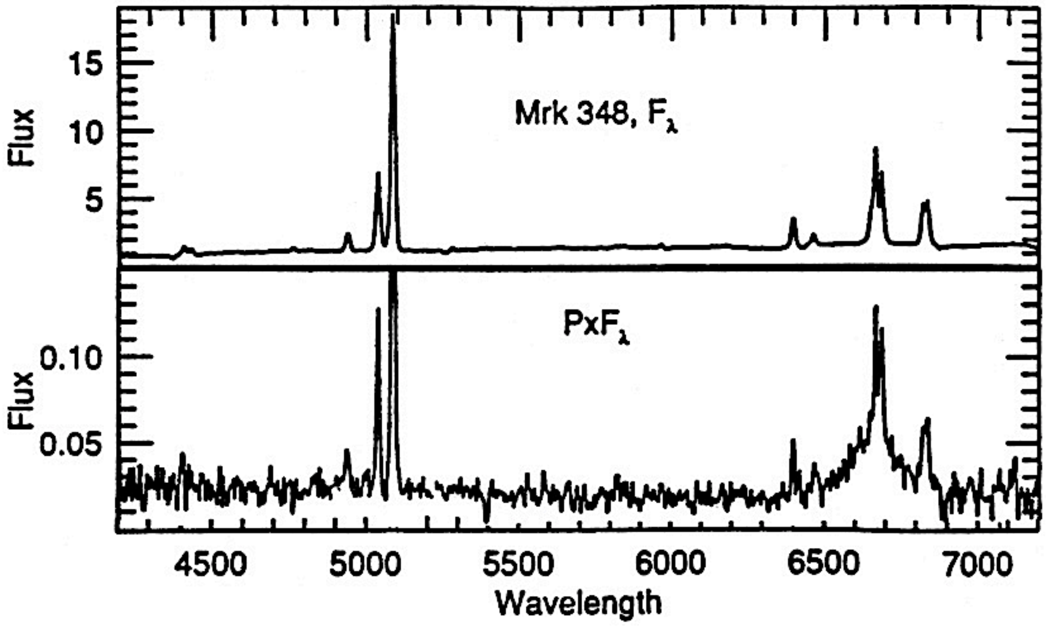


III : AGN Unification

Narrow line (type-2) objects

- Reddened Optical/UV continuum
- Emission line spectrum
  - "Full light" spectrum only shows narrow optical/UV lines
  - Broad optical/UV lines seen in polarized light… shows that there is a hidden broad line region seen in scattered light (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 wavelengths

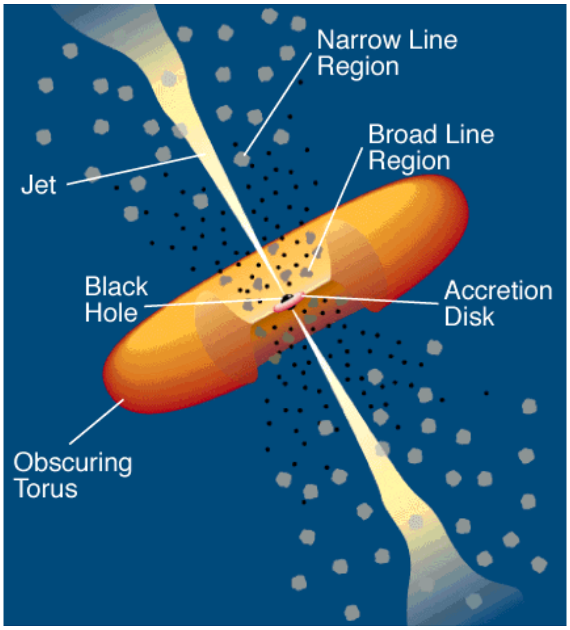




III : AGN Unification

The Unified Model of AGN

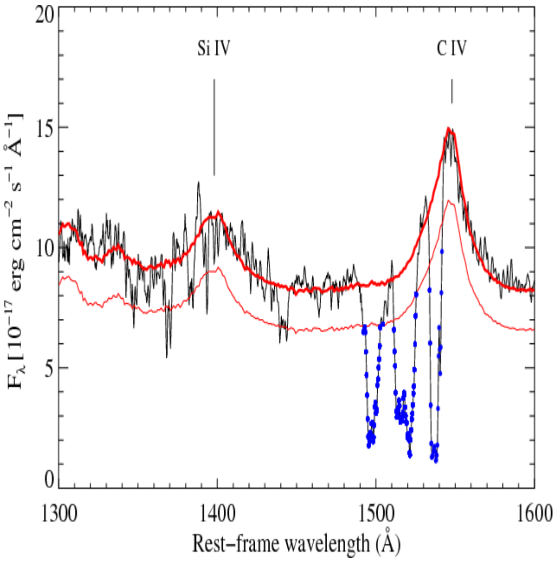
- Assumption of the "strict" Unified Model
  - There is one "fundamental" geometry for any AGN
  - An obscuring structure lies between the BLR and NLR (torus, warped disk, wind)
  - Differences between AGN types reflect different viewing orientations
- Reasonably deviations from strict unification:
  - Column density & opening angle of the obscurer may be luminosity dependent
  - Very low-luminosity AGN seem to lack any broad line region



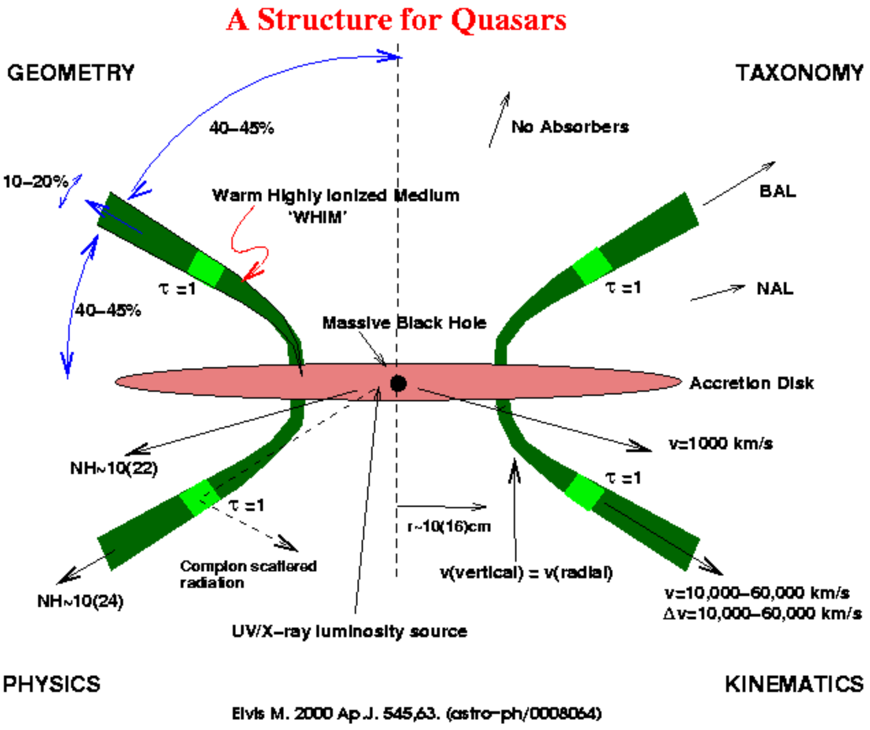
III : AGN Unification

Two interesting and unusual classes

- Narrow Line Seyfert 1 nuclei
  - Possess unusually narrow broad optical/UV lines (<2000km/s)
  - Tend to possess…
    - Strong soft X-ray excesses
    - Steep X-ray continuum
    - Strong [FeII] line emission
    - Rapid variability
  - Current paradigm is that they are low-mass SMBH accreting close to the Eddington limit
- Broad Absorption Line (BAL) QSOs
  - Display strong, broad absorption troughs in their optical/UV spectrum (upto 5000-60,000km/s)
  - Implies powerful, fast winds
  - Compromises about 10% of powerful AGN
  - Most AGN may have such flows… but need to be corrected oriented



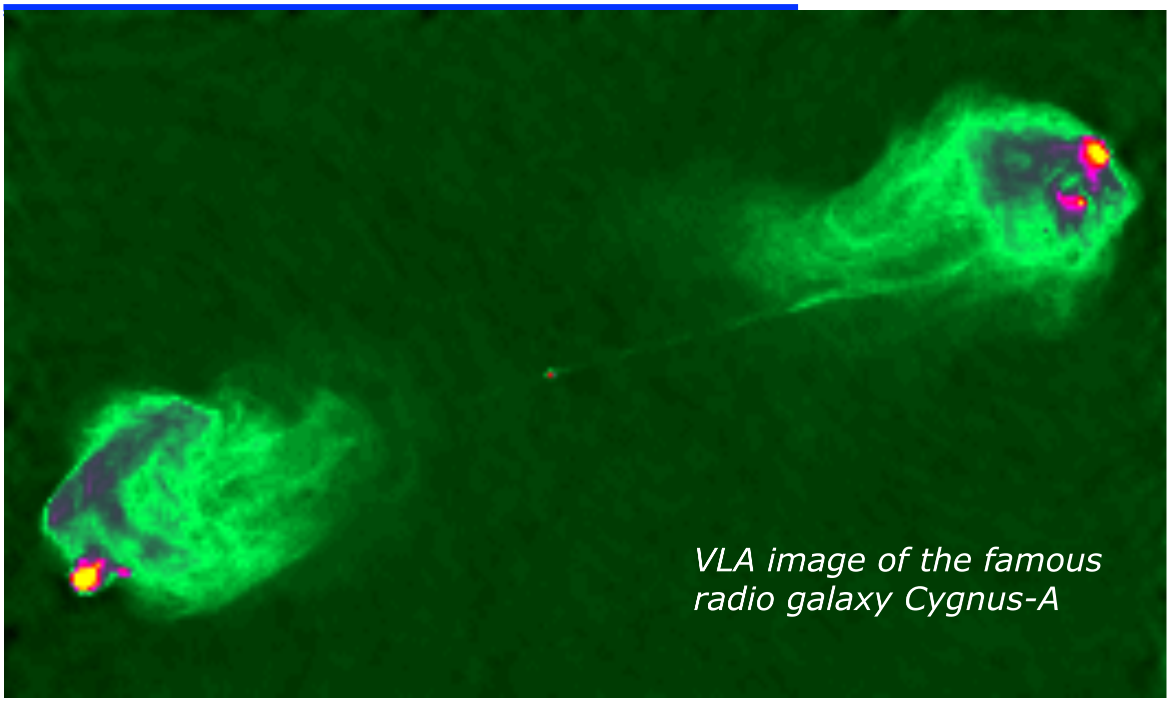
SDSS BALQSO (Noterdaeme et al. 2009)



Elvis M. 2000 Ap.J. 545,63. (astro-ph/0008064)

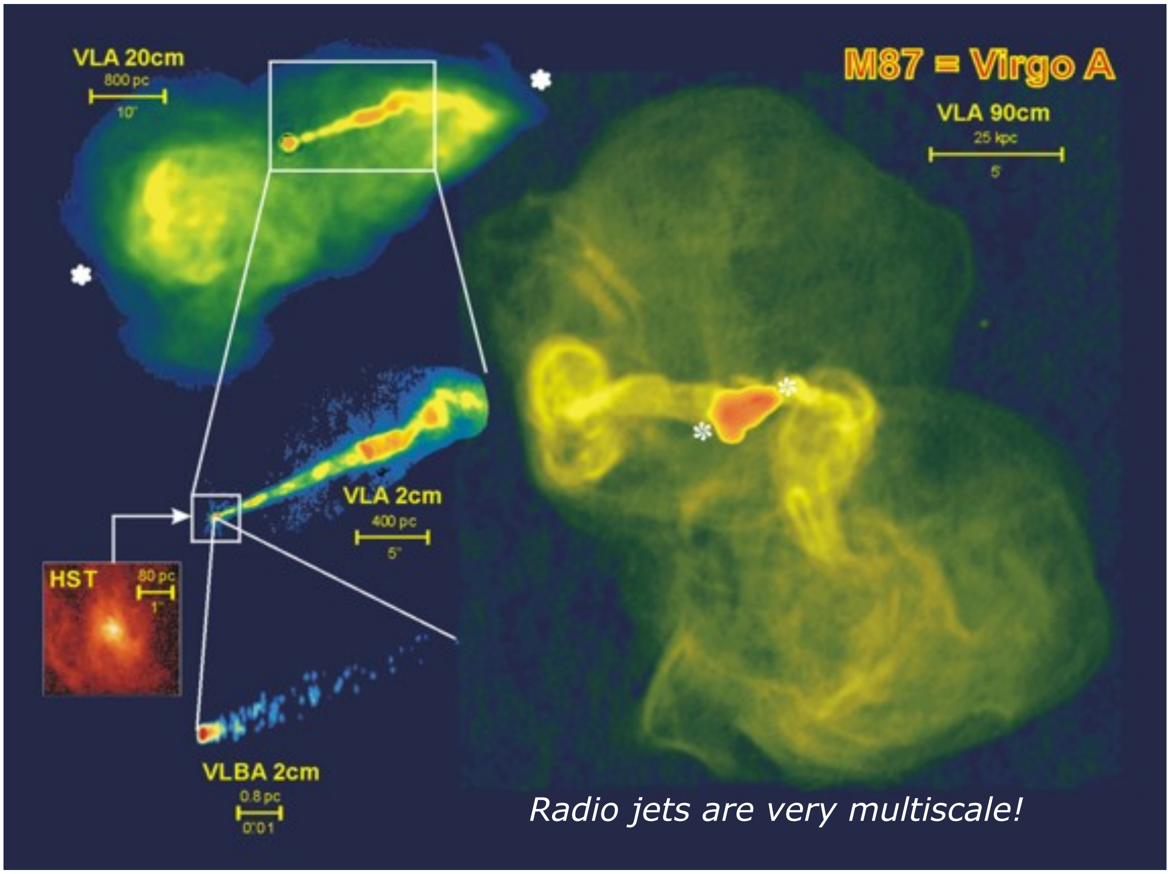
III : AGN Unification

The Radio-loud/Radio-quiet dichotomy

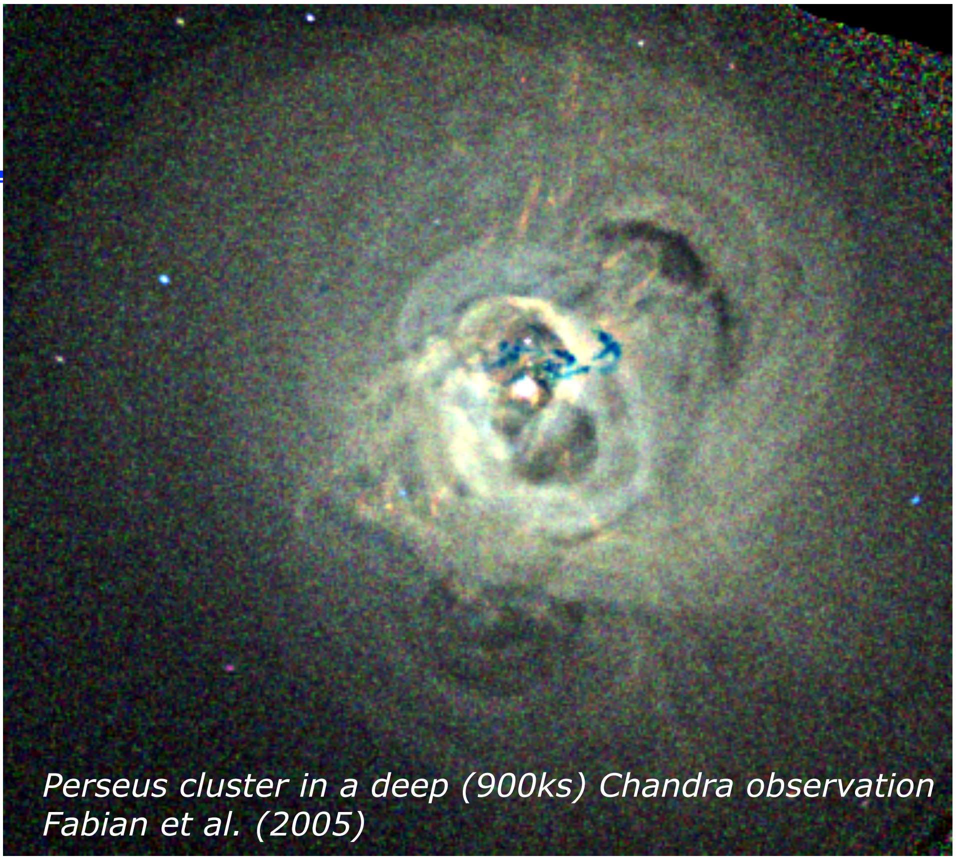


VLA image of the famous radio galaxy Cygnus-A

Composite VLA/optical/Chandra image of the radio galaxy Centaurus-A



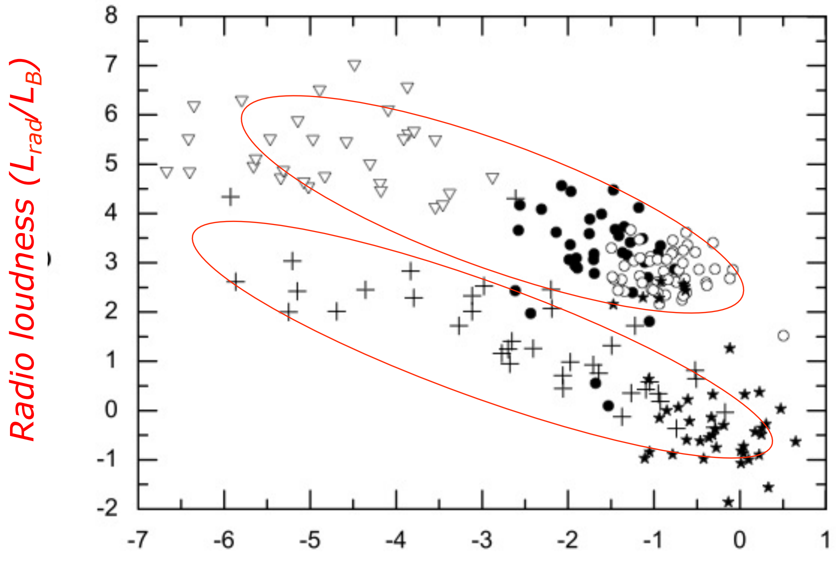
Radio jets are very multiscale!



Perseus cluster in a deep (900ks) Chandra observation Fabian et al. (2005)

III : AGN Unification

The Radio-loud/Radio-quiet dichotomy

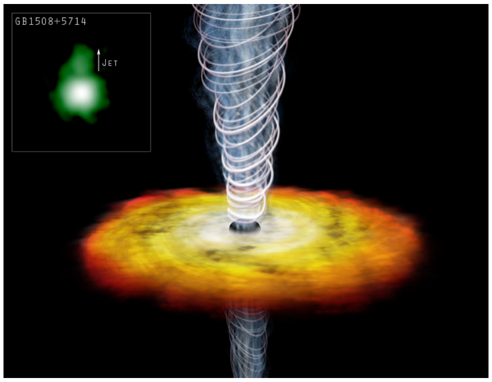


Sikora et al. (2007)

III : AGN Unification

The Radio-loud/Radio-quiet dichotomy

- Origin of the radio-loud/ radio-quiet dichotomy is very mysterious
- What we know…
  - Radio-loud AGN are only found in elliptical galaxies with massive BHs ($M > 10^8 M_{sun}$)
  - Radio-quiet AGN can be found in spirals and ellipticals
- Possible factors at play…
  - Black hole spin
  - Retrograde/prograde spin
  - Magnetic flux threading disk
  - Circumnuclear environment



IV : X-ray properties of AGN

Origin of the X-rays

- Where do the X-rays come from?
- **Can it just be the accretion disk? Generally, no!!!**
  - Assuming a radiatively-efficient disk emitting as a black body, its easy to show that the temperature at given radius is

$$T = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_{\rm SB}}\right)^{1/4}$$

  - Now, the radius of the inner disk scales with BH mass, $r \propto M$
  - Also, for a given Eddington fraction, accretion rate scales with mass, $\dot{M} \propto M$
  - Thus, we have…

$$\boxed{T \propto M^{-1/4}}$$

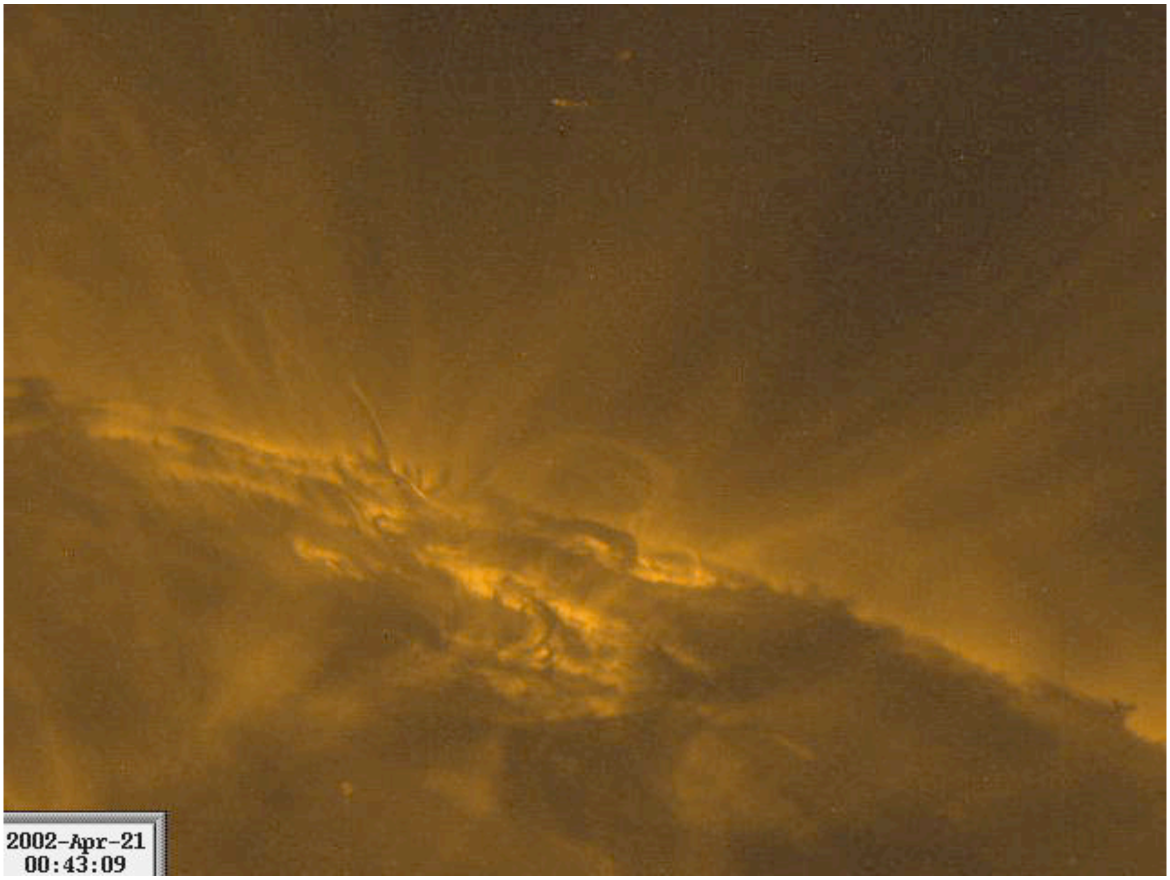
  - **More massive black holes have lower characteristic disk temperatures!**
  - Typical inner disk temperature for AGN disks is T~10^5—10^6K

IV : X-ray properties of AGN

Origin of the X-rays

- **So… where DO the X-ray come from?**

- Three possible origins…
  - Accretion disk corona
    - Basic physics : Compton upscattering of thermal disk photons by hot coronal e^-
    - Characteristics : Γ~2 power-law with "thermal" cutoff at kT~50-200keV
    - Relevant for luminous RQ-AGN and misaligned RL-AGN
  - Jet
    - Basic physics : Synchrotron emission OR Compton upscattering
    - Seed photons for Comptonization from either synchrotron emission or ambient
    - Characteristics : Double-bump spectra… synchrotron bump & Comptonization bump
    - Relevant for RL-AGN
  - Body of a hot, optically-thin accretion disk
    - Basic physics : Compton upscattering of synchrotron photons by hot e- in disk
    - Thus, only relevant for radiatively-inefficient disks in low-luminosity AGN
    - Characteristics : still strongly debated…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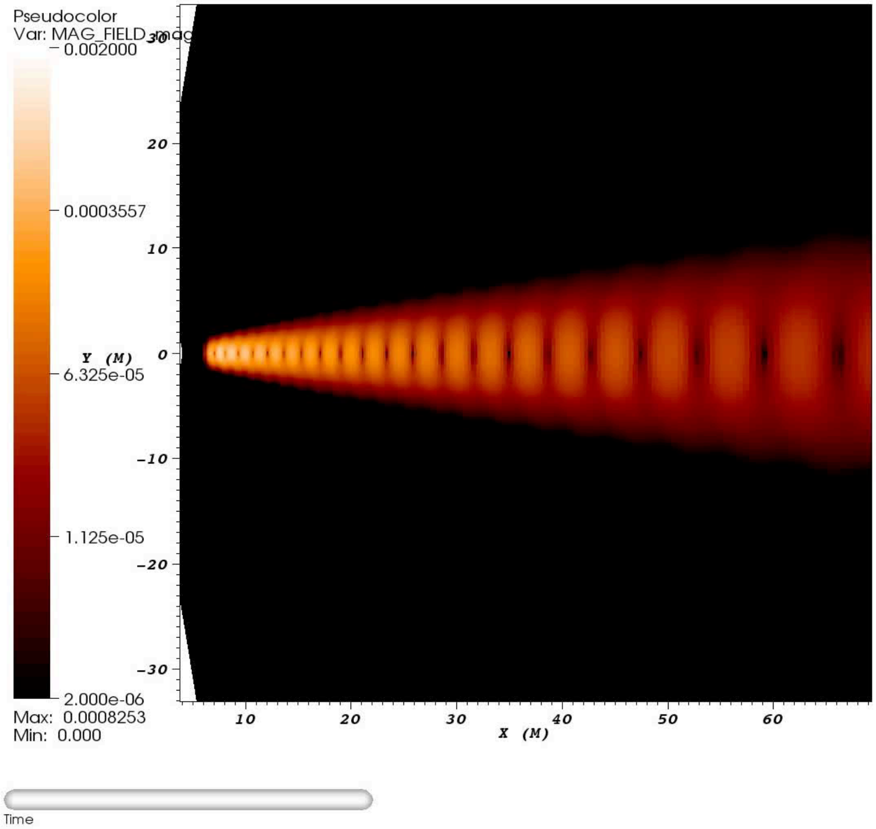
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Y (M)
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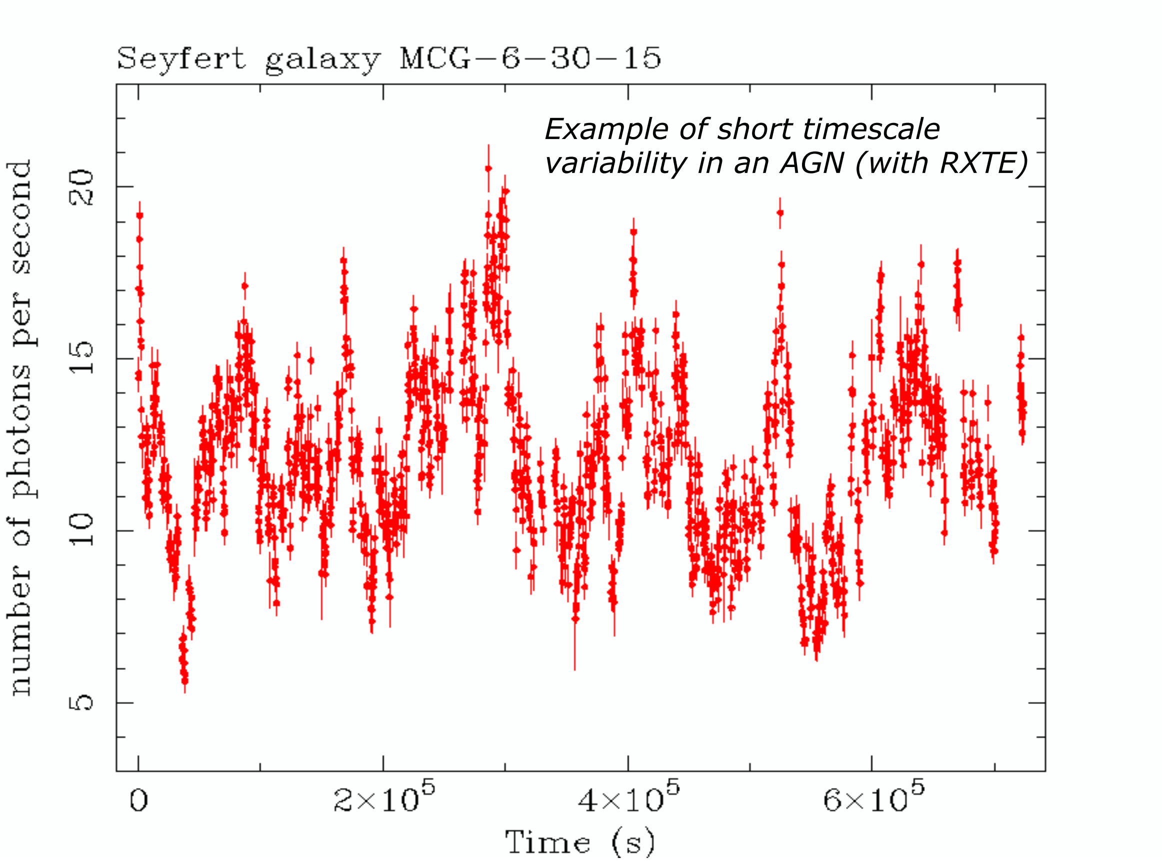
60
X (M)
Time

IV : X-ray properties of AGN

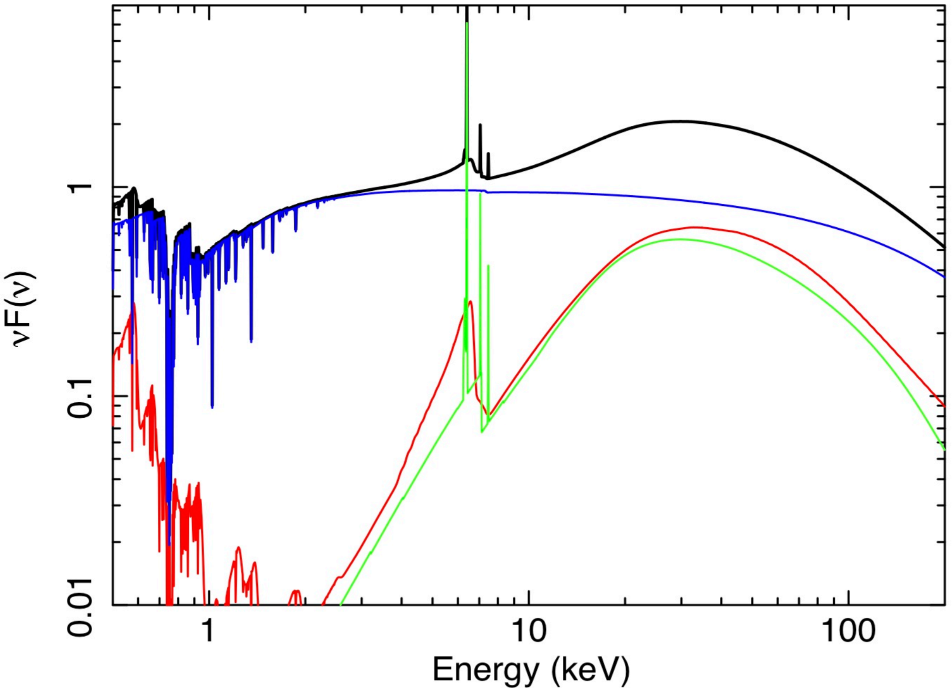
RQ- and disk-dominated RL-AGN

- Let’s review basic characteristics
- X-ray luminosity is strongly variable
  - Short timescales (< few days for typical Seyfert)
    - X-rays leads (drives) optical variability
    - Suggests that variability is due to intrinsic instabilities in disk corona, and some component of optical emission is driven by X-ray irradiation
  - Long timescales (> few days for typical Seyfert)
    - Optical variability leads X-ray variability
    - Suggests that variability is driven by changes in overall accretion rate, and with the optical emitting region experiencing accretion “pulses” before the (closer) X-ray emitting regions
- X-ray spectra display standard components
  - Primary X-ray continuum (Γ~2 powerlaw with cuttoff at 50—300 keV)
  - Absorption (cold and photoionized gas along line-of-sight)
  - X-ray reflection from distant gas (torus of the unified scheme)
  - X-ray reflection from the inner accretion disk (strongly broadened)
  - Soft excess (origin unknown... maybe luke-warm Comptonization, or X-ray reflection from ionized accretion disk)

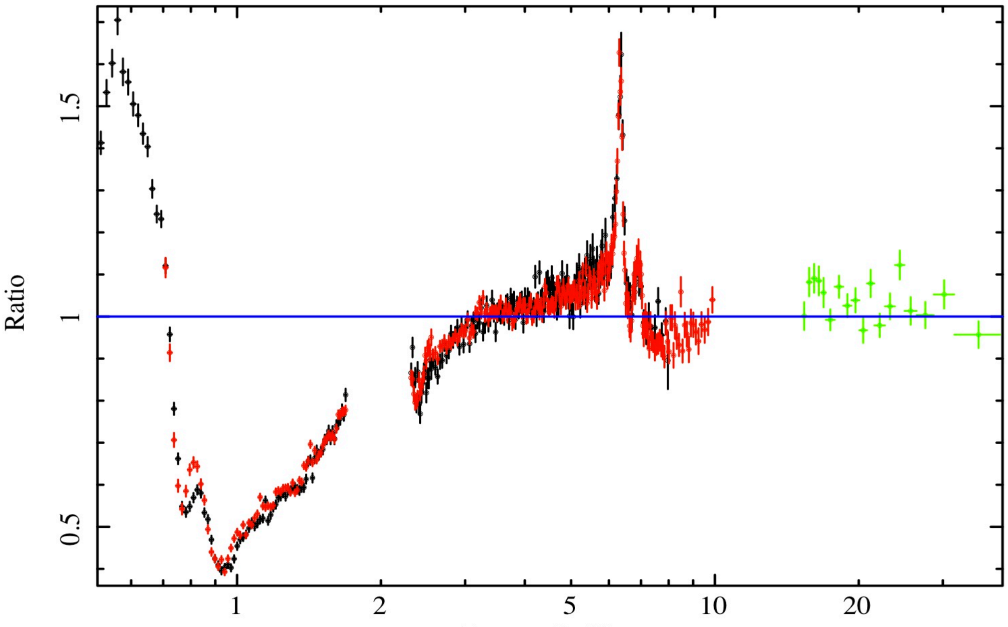


Example of short timescale variability in an AGN (with RXTE)

The multi-component X-ray spectrum of a typical RQ-AGN

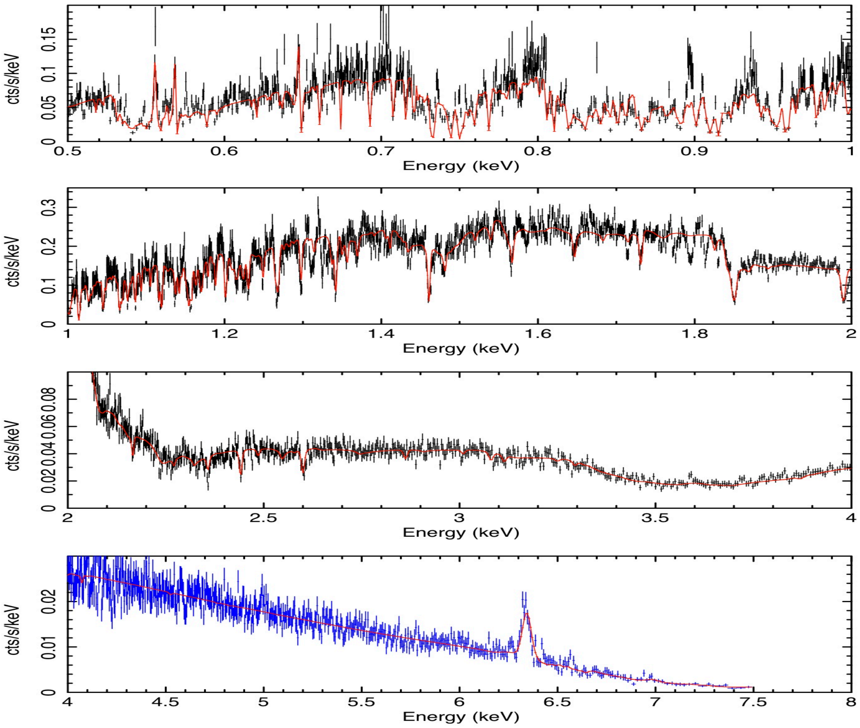


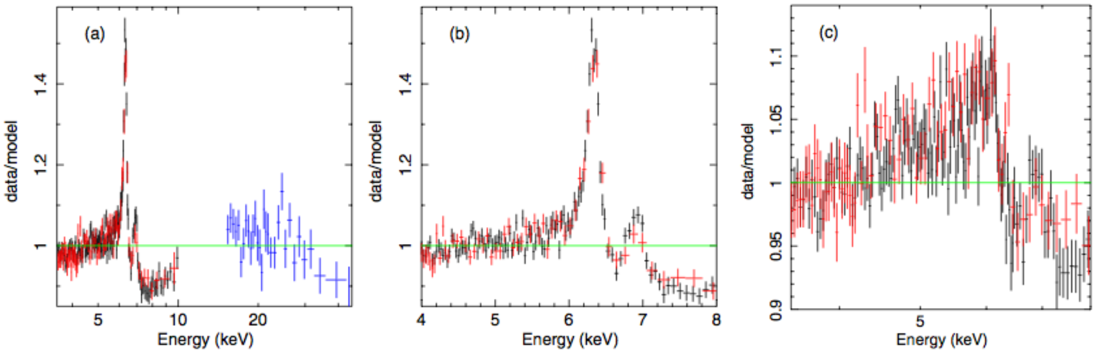
Example of a typical RQ AGN
Seyfert 1.5 nucleus in NGC3783 (Suzaku 200ks)



Brenneman, Reynolds, Nowak et al. (2011)
Reis, Fabian, Reynolds et al., ApJ, submitted

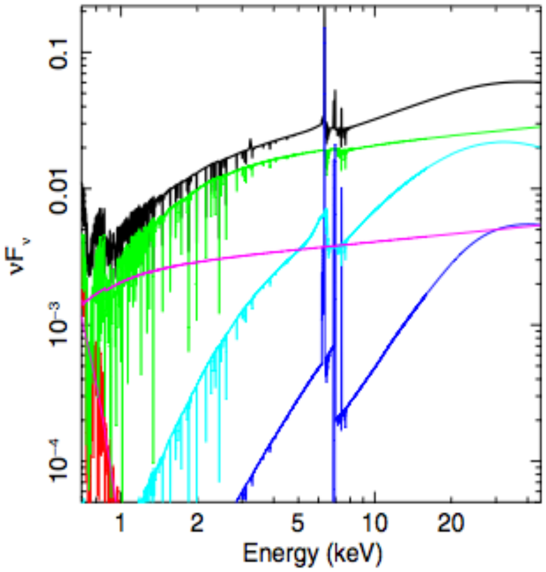
900ks Chandra/HETG (e.g. see Krongold et al. 2003, Netzer et al. 2003)

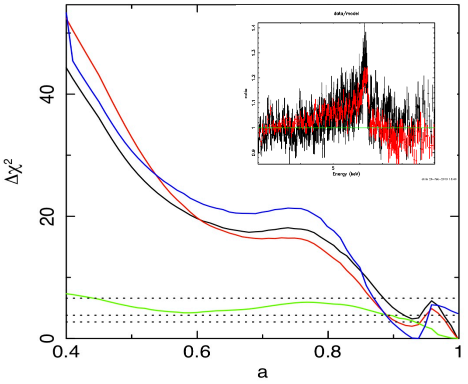




Brenneman, Reynolds, Nowak et al. (2011)
Reis, Fabian, Reynolds et al., ApJ, submitted

Require high spin (a>0.90 at 90% CL). This includes all uncertainties associated with ionized absorption, irradiation profile of inner disk, iron abundance, and treatment of PIN background.

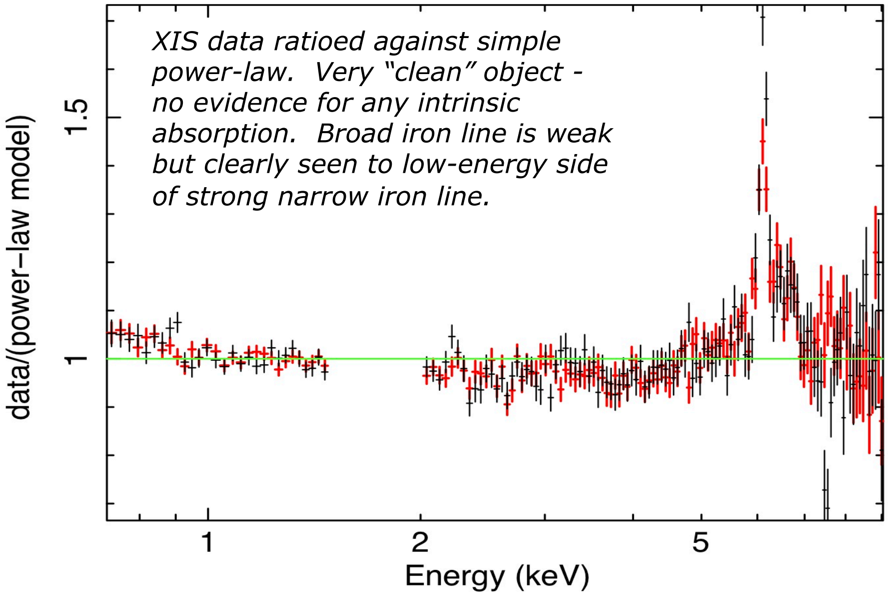




Brenneman, Reynolds, Nowak et al. (2011)
Reis, Fabian, Reynolds et al., ApJ, submitted

Example of a “bare” Seyfert nucleus – no warm absorber

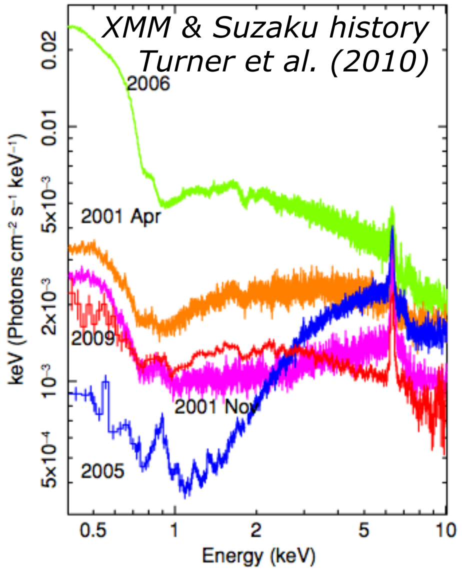
Powerful Seyfert/QSO Fairall 9 (Suzaku 250ks)

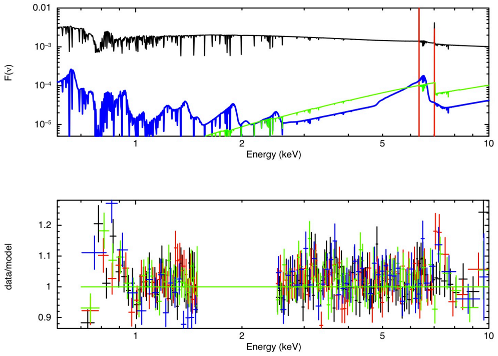


XIS data ratioed against simple power-law. Very “clean” object - no evidence for any intrinsic absorption. Broad iron line is weak but clearly seen to low-energy side of strong narrow iron line.

Example of object with complex/variable absorption

Seyfert 1 nucleus in NGC3516 (Suzaku 250ks)


XMM & Suzaku history
Turner et al. (2010)

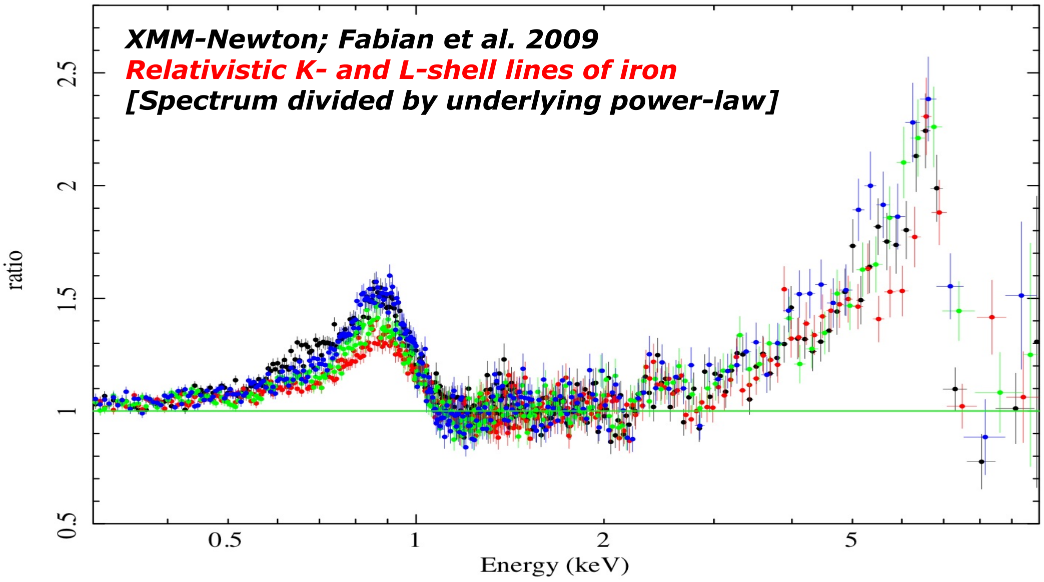


Suzaku data consistent with presence of reflection from inner disk… but poor constraints on properties of disk or spin

Example of object with complex soft spectrum

Narrow-line Seyfert 1 nucleus 1H0707-495

This object shows reverberation effect


XMM-Newton; Fabian et al. 2009

Relativistic K- and L-shell lines of iron

[Spectrum divided by underlying power-law]

Summary

- SMBHs are found in essentially every galaxy
- AGN are the “actively growing” SMBHs

- Observed AGN have a wide diversity of properties
- Real differences…
  - Differences in luminosity (accretion rate; spin)
  - Presence/absence of jet (reason unknown)
- Apparent differences…
  - Inclination and obscuration effects
- X-rays provide powerful probe
  - Originate from the inner disk, where most energy is released
  - Can penetrate substantial columns of obscuring matter
  - Give detailed probe of inner accretion disk and SMBH