Active galactic nuclei (AGNs): a brief observational tour

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Summary of lectures

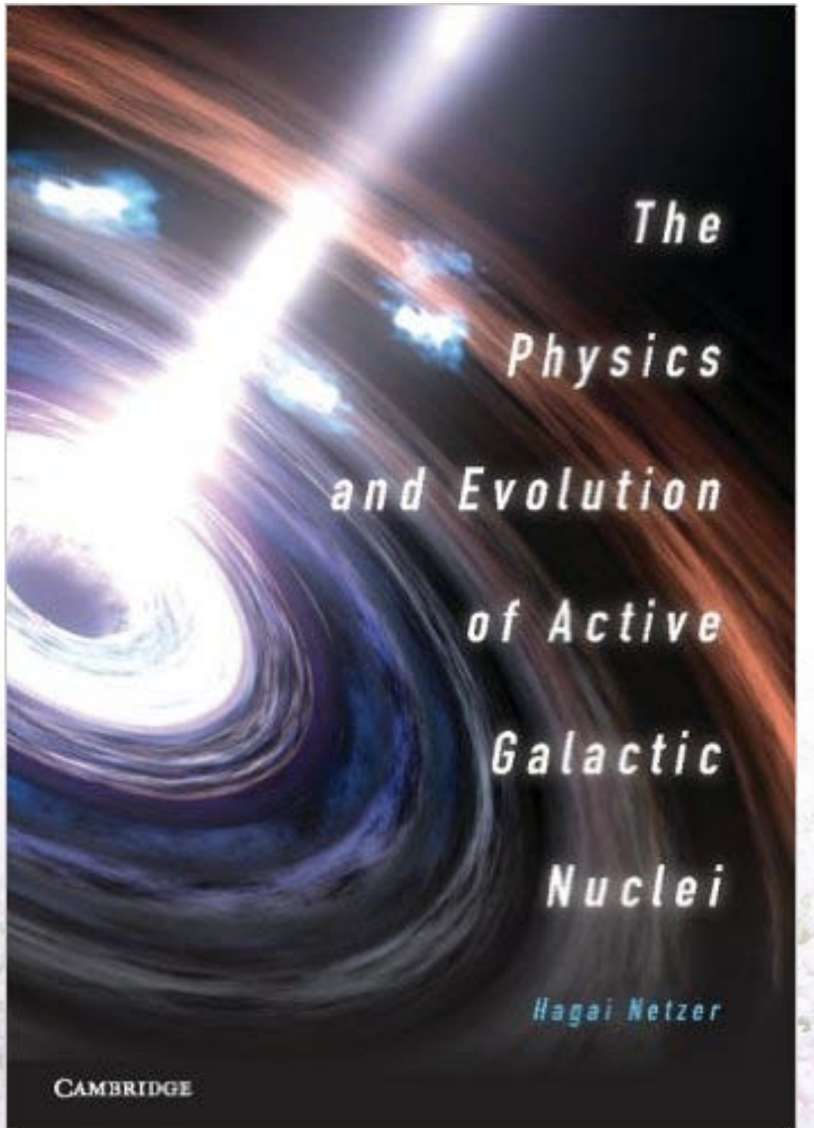
- Early history, AGN ABCs, finding AGNs, AGN terminology and unification
- Dissecting AGNs (I): black hole, accretion disk, broad line region
- Dissecting AGNs (II): torus, narrow line region, stars and starburst regions, jets
- Focused lecture: Lifting the veil of deeply buried supermassive black holes in the Universe

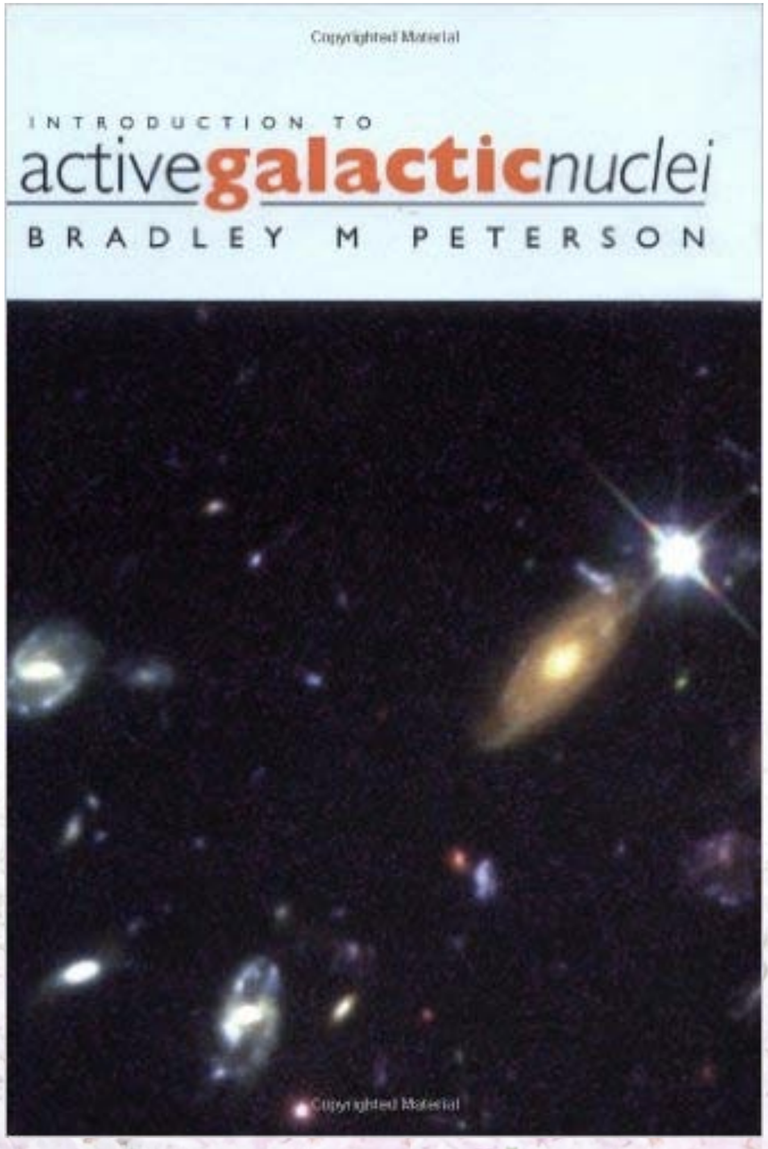
Many thanks to Prof. Niel Brandt (Penn State) and Prof. Feng Yuan (SHAO) for some of the slides!

Disclaimers

- Massive field: impossible to be complete
- Focus on the main ideas rather than every special case or exception
- Observation-oriented lectures
- Sometimes from personal point of view

Some reference books





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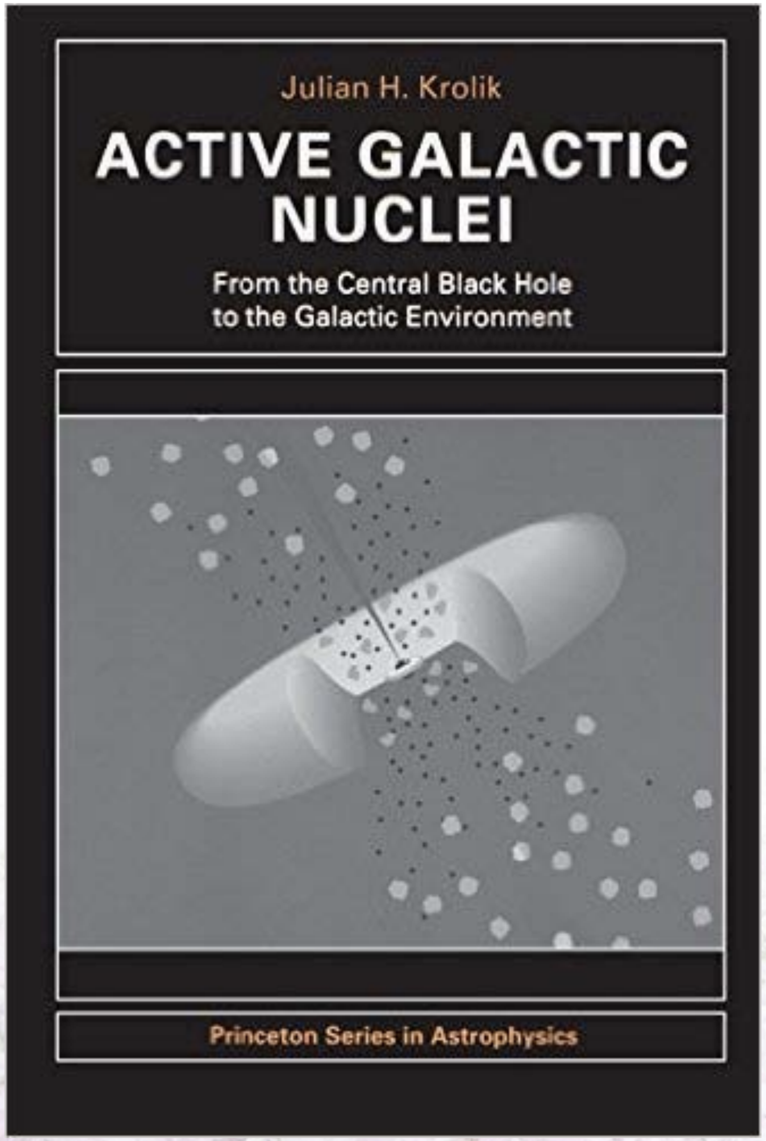

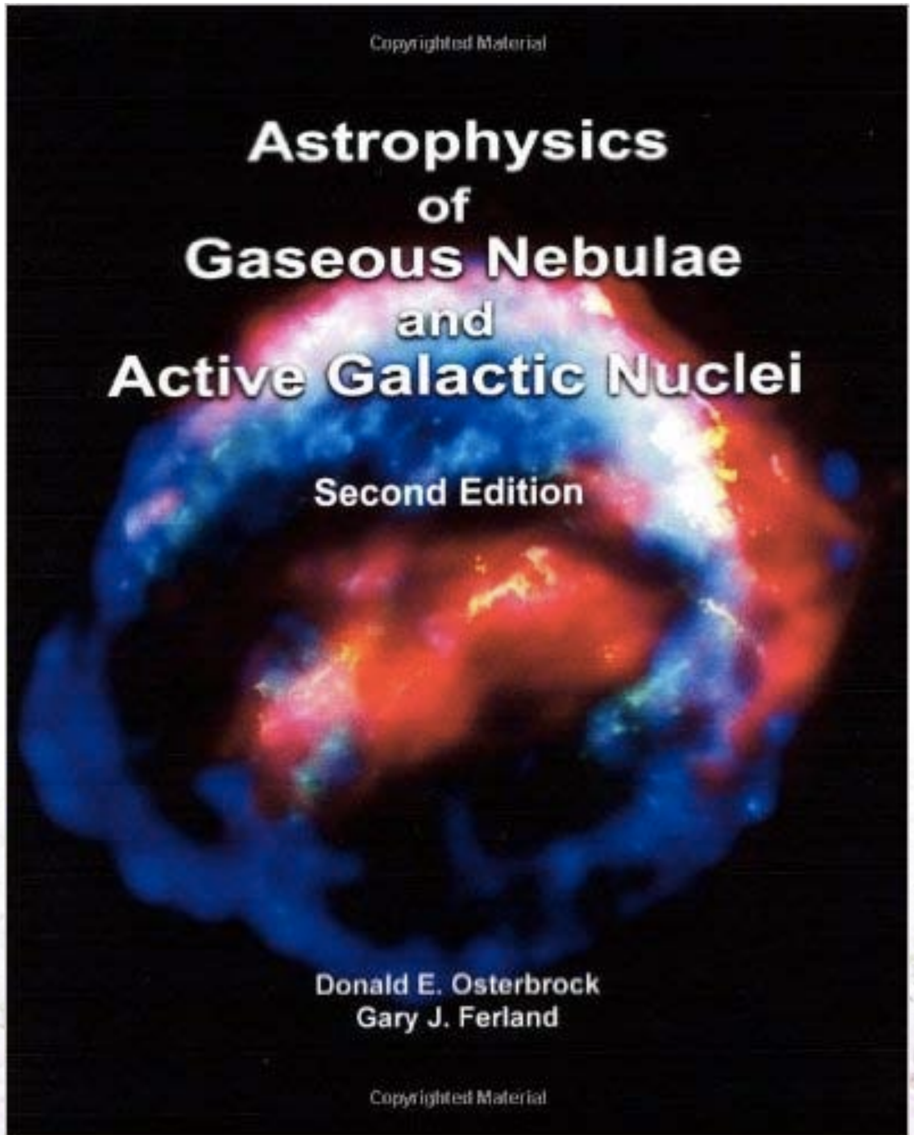

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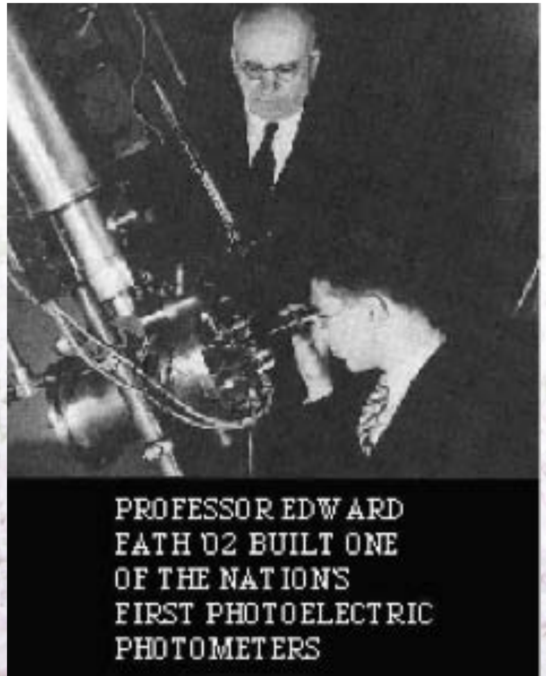
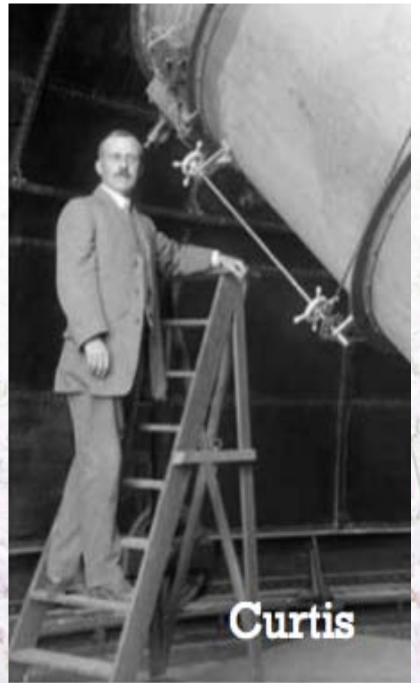
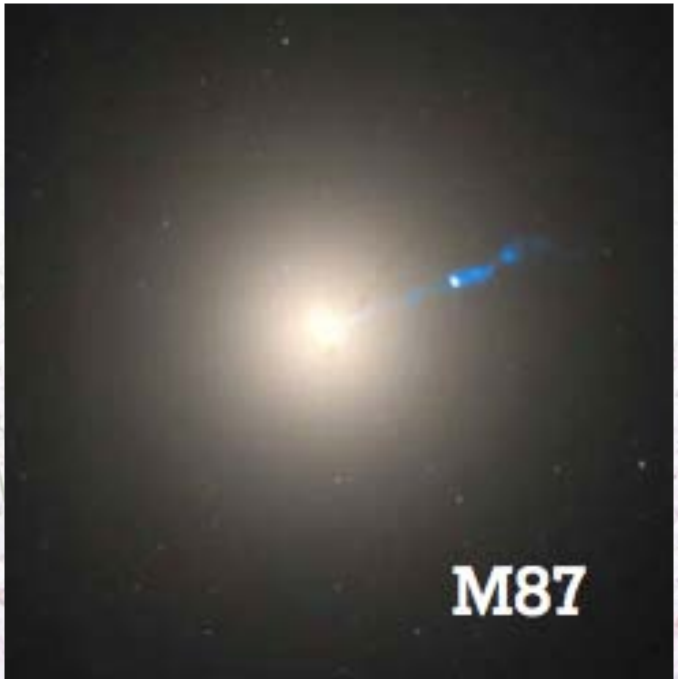
Early history

- Some early history of AGN studies:
  - 1908: Edward Fath notices strong emission lines from H, O, Ne in the nuclear spectrum of NGC 1068
  - 1915: General Relativity
  - 1916: Schwarzschild solution found, but not fully understood
  - 1917: Vesto Slipher obtains a higher quality spectrum of NGC 1068 and notes its emission lines are unusually broad
  - 1918: Herber Curtis notes in M87 a “curious straight ray … connected with the nucleus by a thin line of matter”







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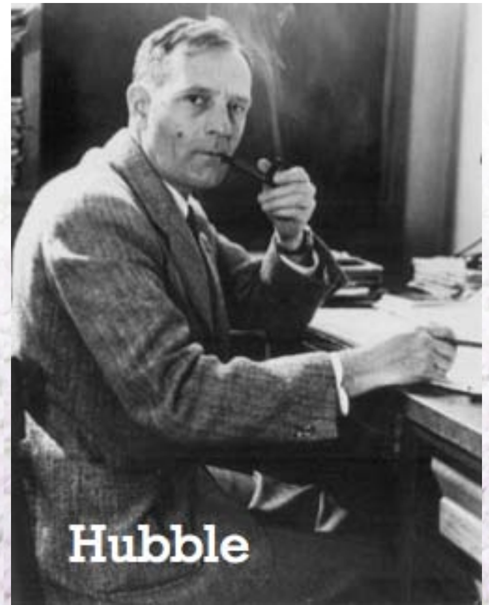
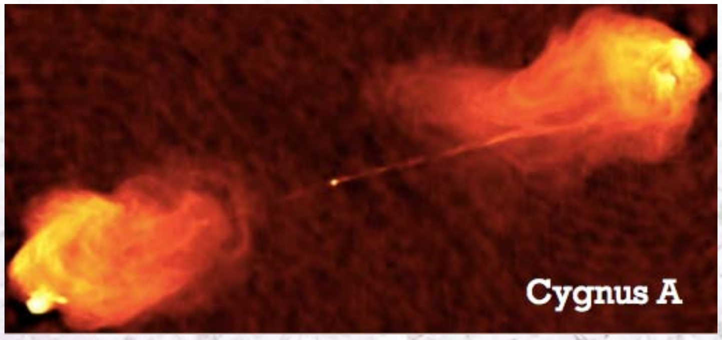
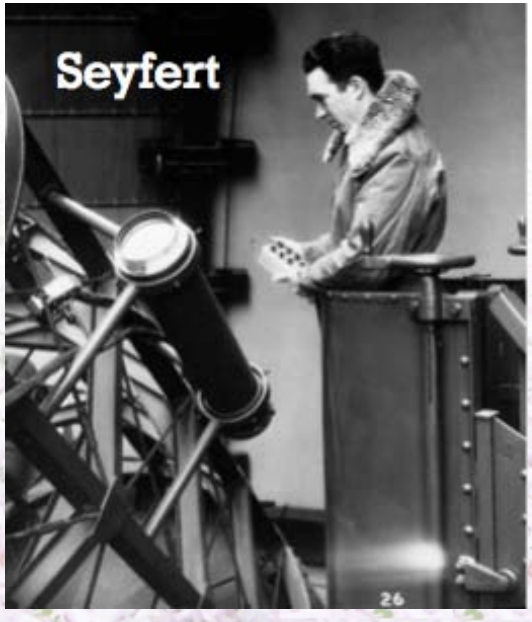
- Some early history of AGN studies:
  - 1924-1929: General realization that galaxies are extragalactic (led by Edwin Hubble)
  - 1926: Edwin Hubble notices the nuclear emission-line spectra of NGC 1068, NGC 4051, NGC 4151
  - 1939: Grote Reber discovers the radio source Cygnus A
  - 1943: Carl Seyfert shows that a fraction of galaxies have strong, broad emission lines and that these galaxies are especially luminous – now known as "Seyfert galaxies"







- Some early history of AGN studies:
  - 1954: Walter Baade and Rudolph Minkowski find the counterpart to Cygnus A at z=0.057
  - 1963: Maarten Schmidt discovers 3C273 to have z=0.158
  - 1964: Zeldovich & Novikov and Salpeter speculate about BHs powering QSOs
  - 1967: The term "black hole" comes into general use
  - 1968: Donald Lynden Bell notes that many galactic nuclei may contain "collapsed old quasars"
  - After: AGNs become a topic of widespread study
  - Now: AGN research - forefront of modern astrophysics

    exploding field - thousands of refereed papers per year (still growing)

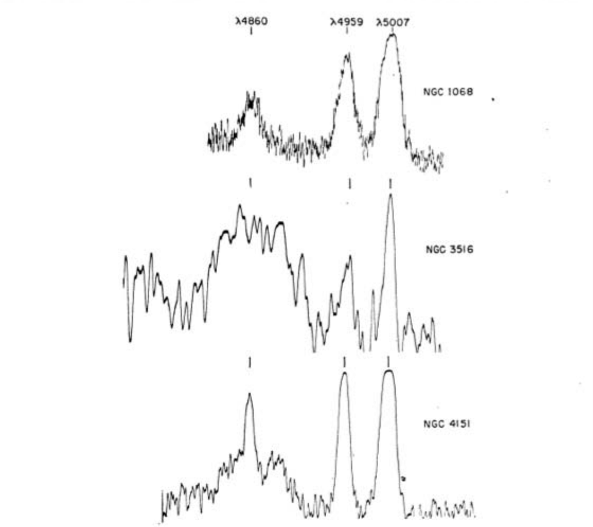
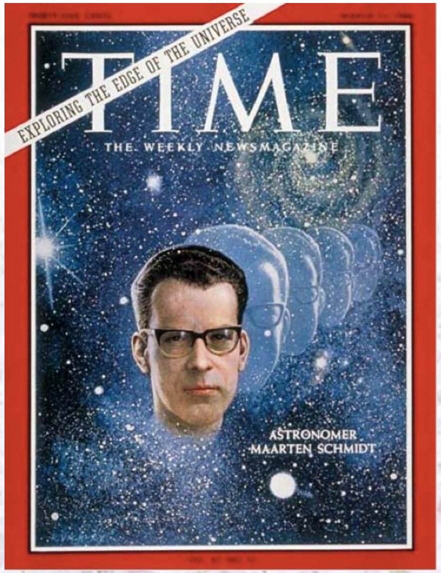


FIG. 1.—Microphotometer tracings of the emission lines λλ 4860 (Hβ), 4959 and 5007 [O III] in the nebulae NGC 1068, 3516, and 4151.



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AGN ABCs (I)

What are AGNs?

- What are active galaxies and active galactic nuclei (AGNs)?
  - vs. inactive (normal or regular) galaxies:
    presence of supermassive (SM) accreting black holes (BHs) in their centers
  - compact, luminous hearts of most if not all massive galaxies
  - excess emission across almost all wavelengths (and neutrino …)
  - ultimate energy source: accretion of mass onto SMBHs (~1e6-1e10 Msun)
    * gravitational energy → thermal & kinetic energy → radiation
  - many aspects: BHs, accretion disks, jets, dust, gas, interactions, environments, etc.

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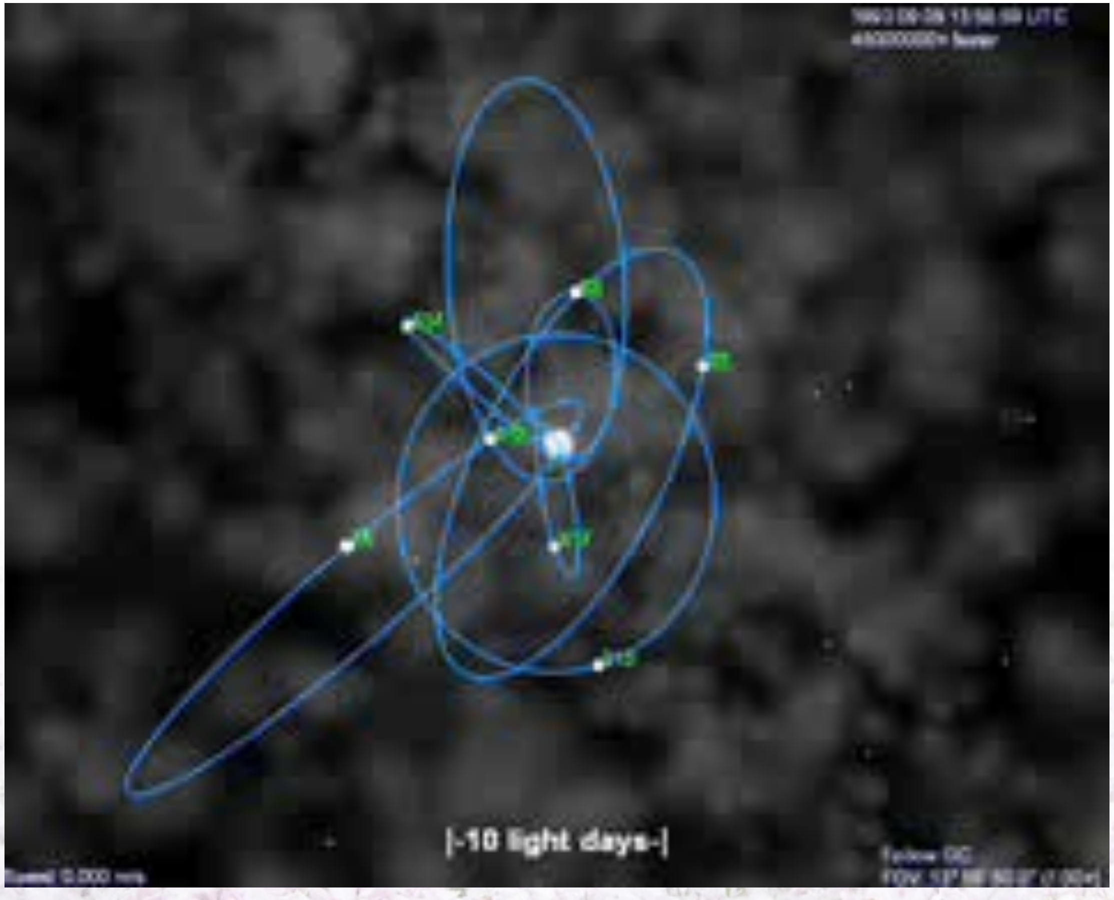
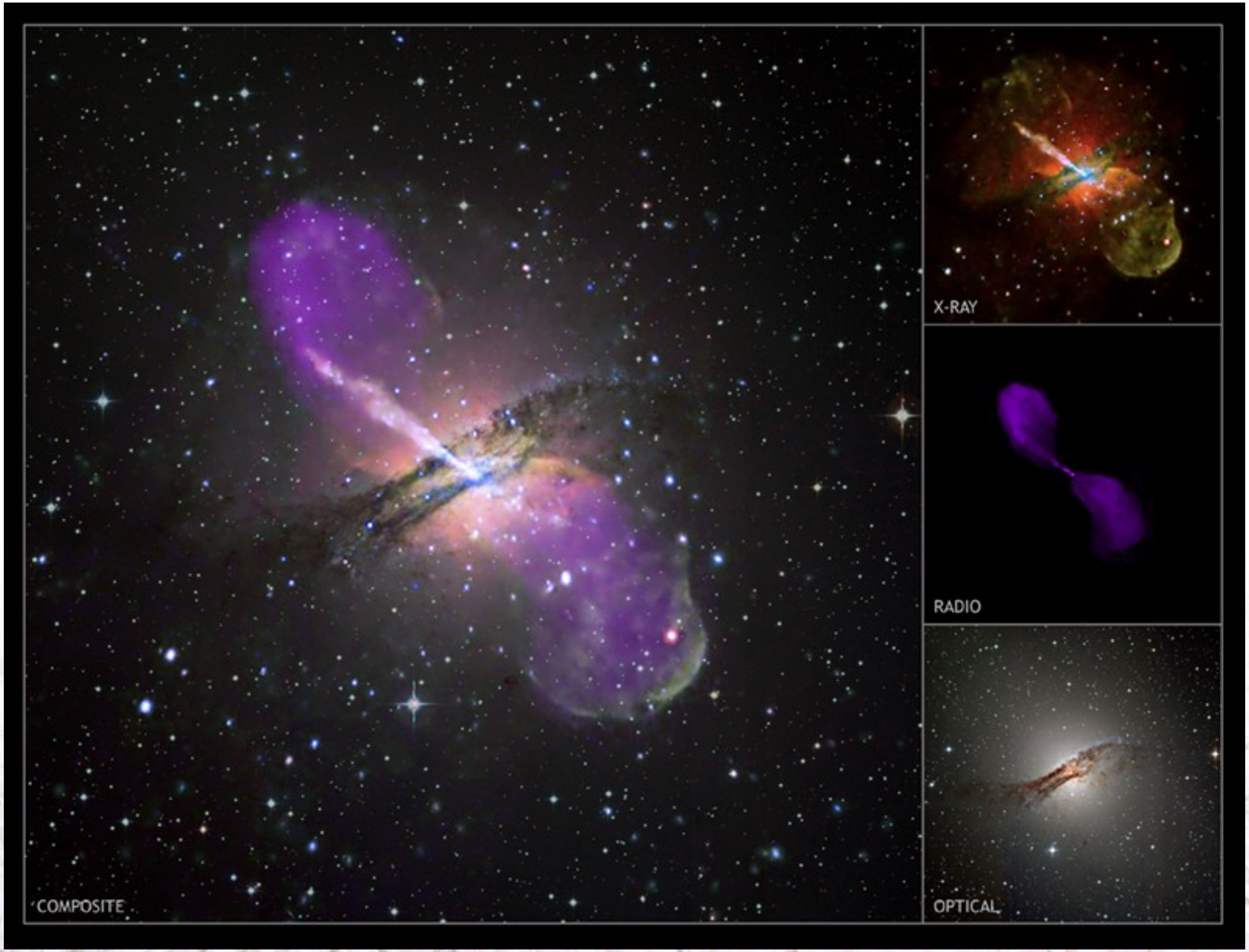
Best case: SMBH at the center of MW



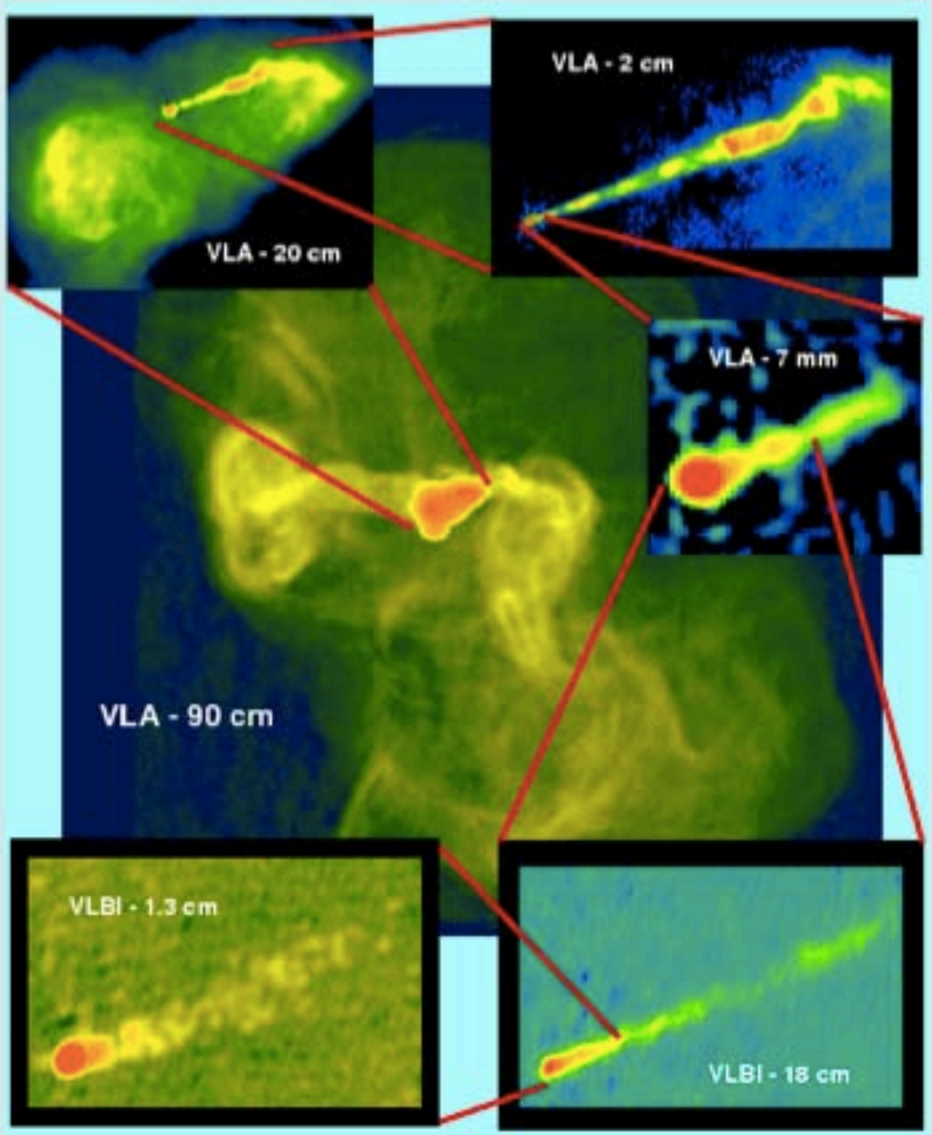
(MPE)

Active galaxy Centaurus A



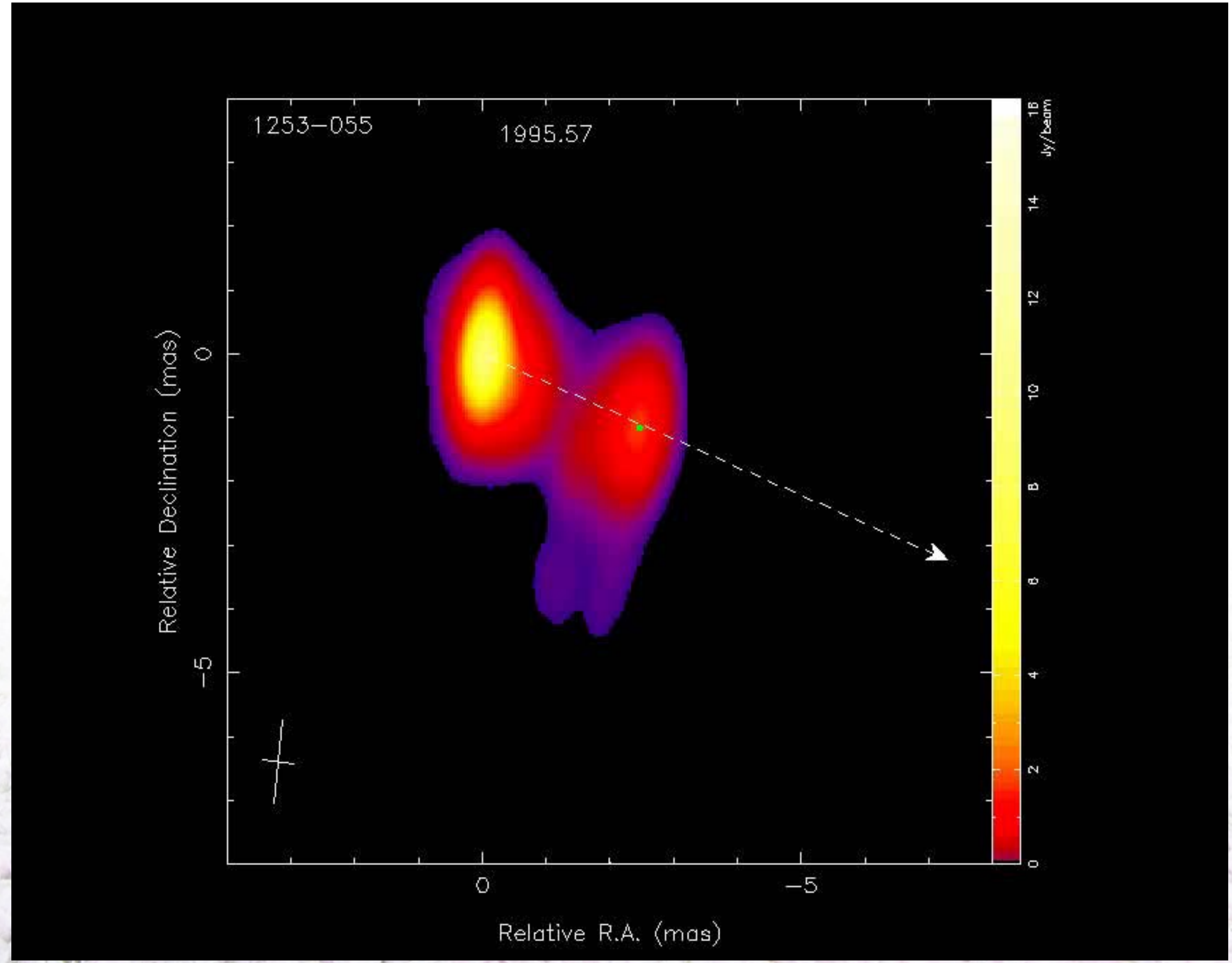
(NASA, CXC, R. Kraft et al.; NSF, VLA, M. Hardcastle et al.; ESO, M. Rejkuba et al.)

Launching of the M87 Jet



We can directly observe the M87 jet down to a few hundred R_S.

Quasar 3C 279



(Lister et al., MOJAVE project; http://www.physics.purdue.edu/MOJAVE)

Fly toward a SMBH

(CXC, A. Hobart)

Galaxy merger

(Animation: NASA/CXC/A. Hobart; Simulation: Josh Barnes/U. Hawaii, John Hibbard/NRAO)

AGN ABCs (II)

Normal vs. active galaxies

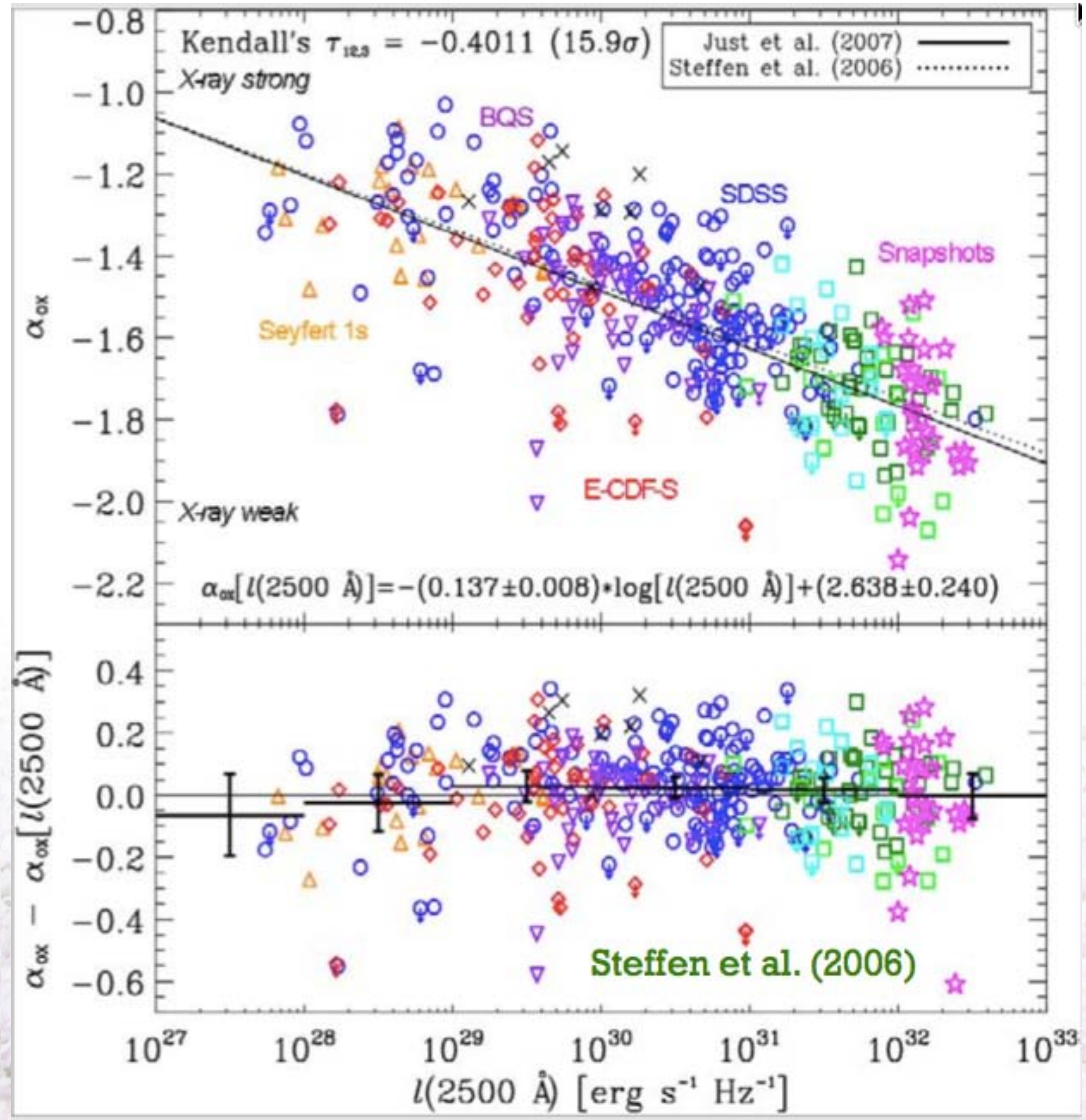
In the local universe:

~1/1e6 of massive galaxies contain luminous quasars (QSOs)

~5% are moderately luminous (Seyfert galaxies)

~30% show signs of low-level nuclear activity

Broad range of luminosities



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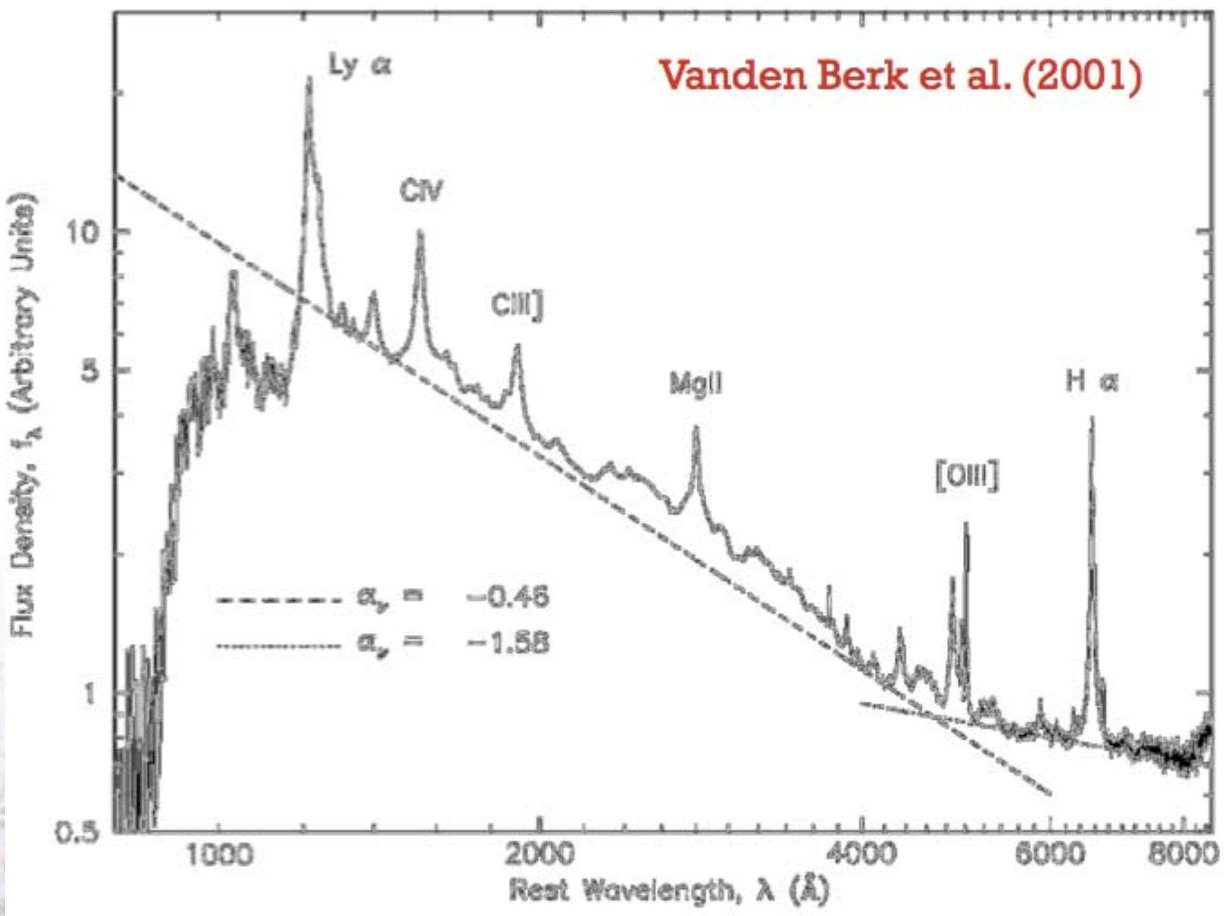
Strong and broad opt/UV emission lines



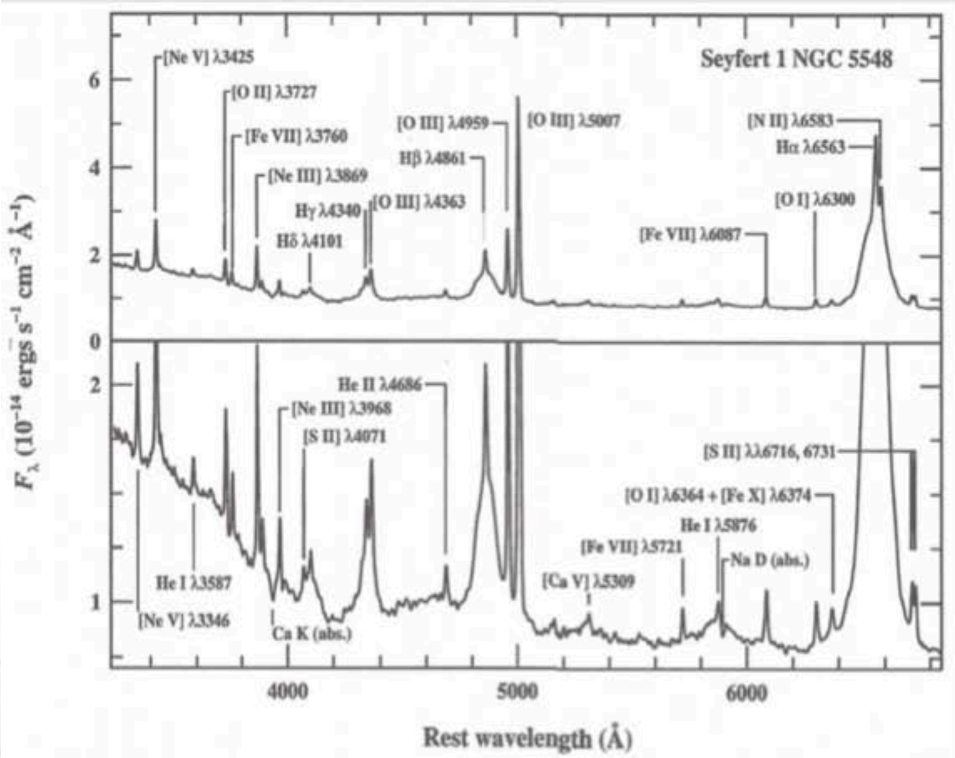
- indicate the presence of ionized nebular gas

- gas is photoionized by the brilliant central source

- line widths indicate high-speed motions (up to ~25000 km/s)

- abundances about solar or slightly supersolar

Example Type 1 AGN



Example Type 2 AGN

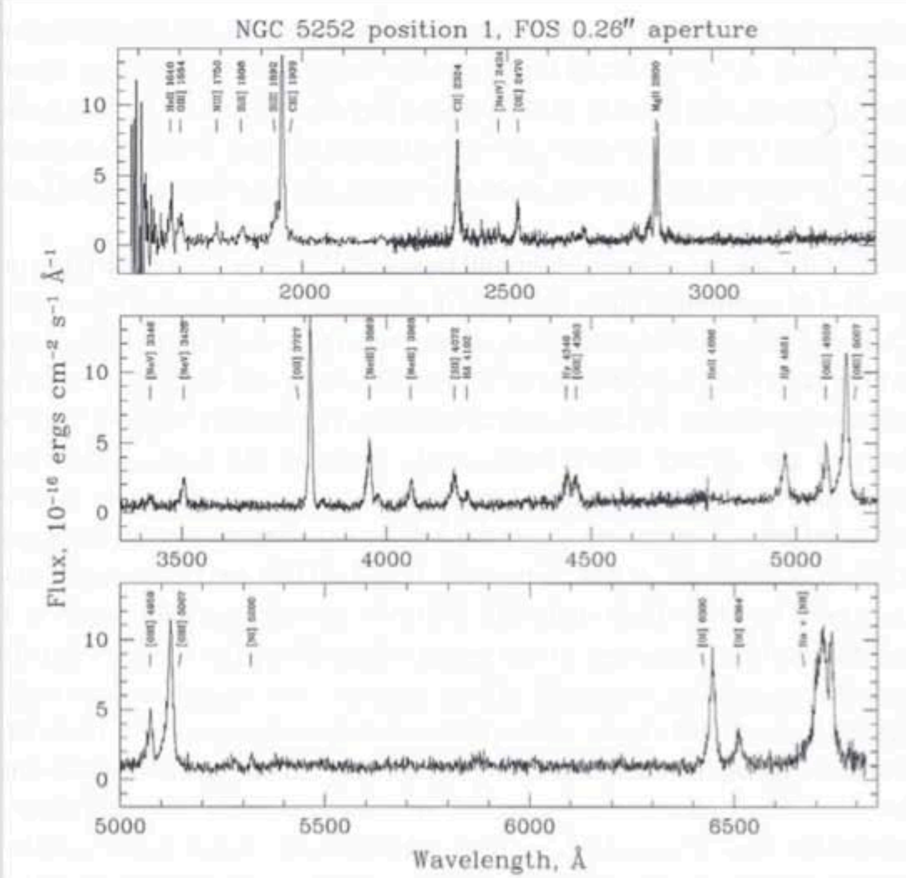
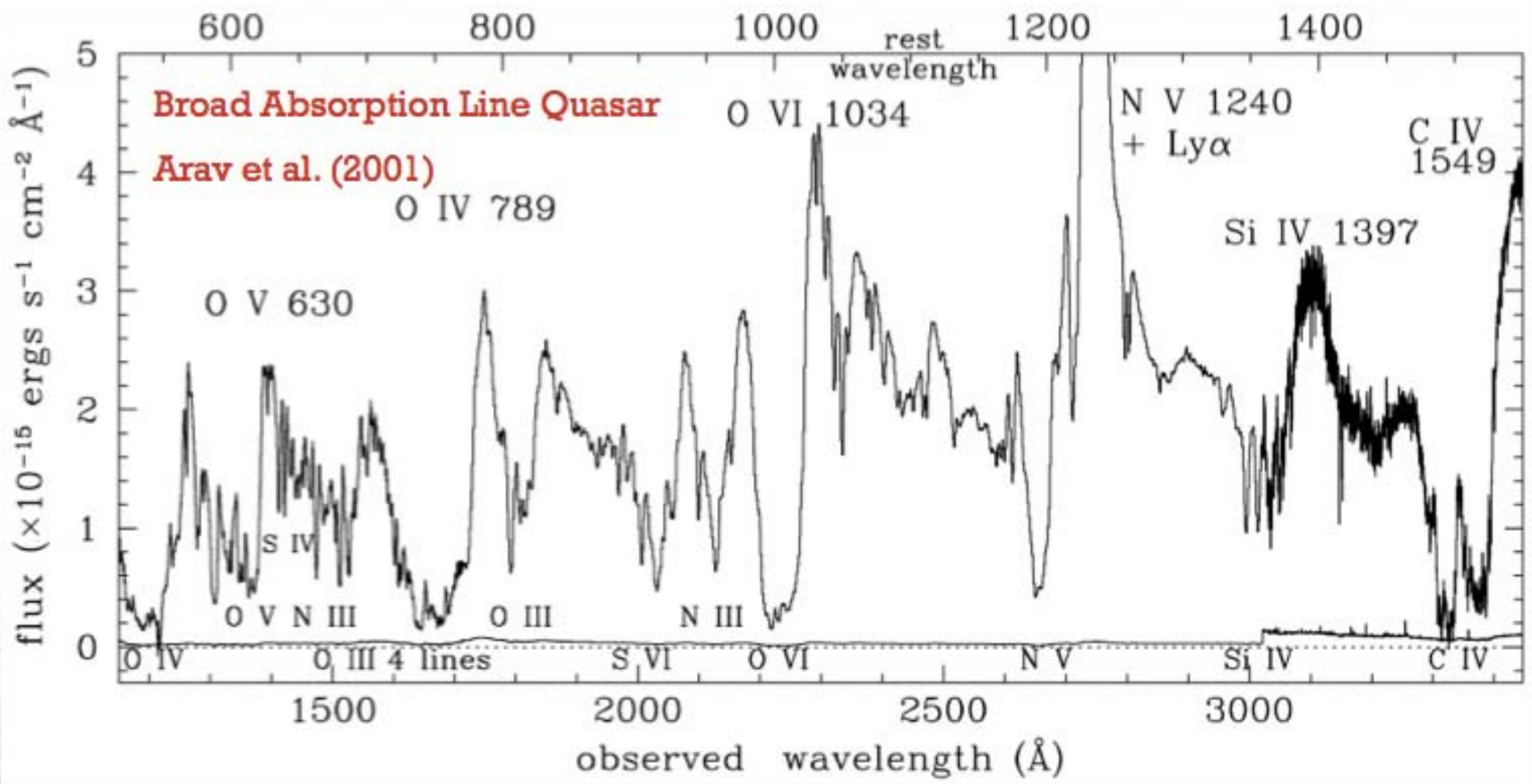


Figure 1.3. The spectrum of the low-luminosity, low-redshift type-II AGN NGC 5252 (courtesy of Zlatan Tsvetanov).

Peterson (1997)

Blueshifted absorption lines



In addition to emission lines, also often see blueshifted absorption lines.

Broadband emission

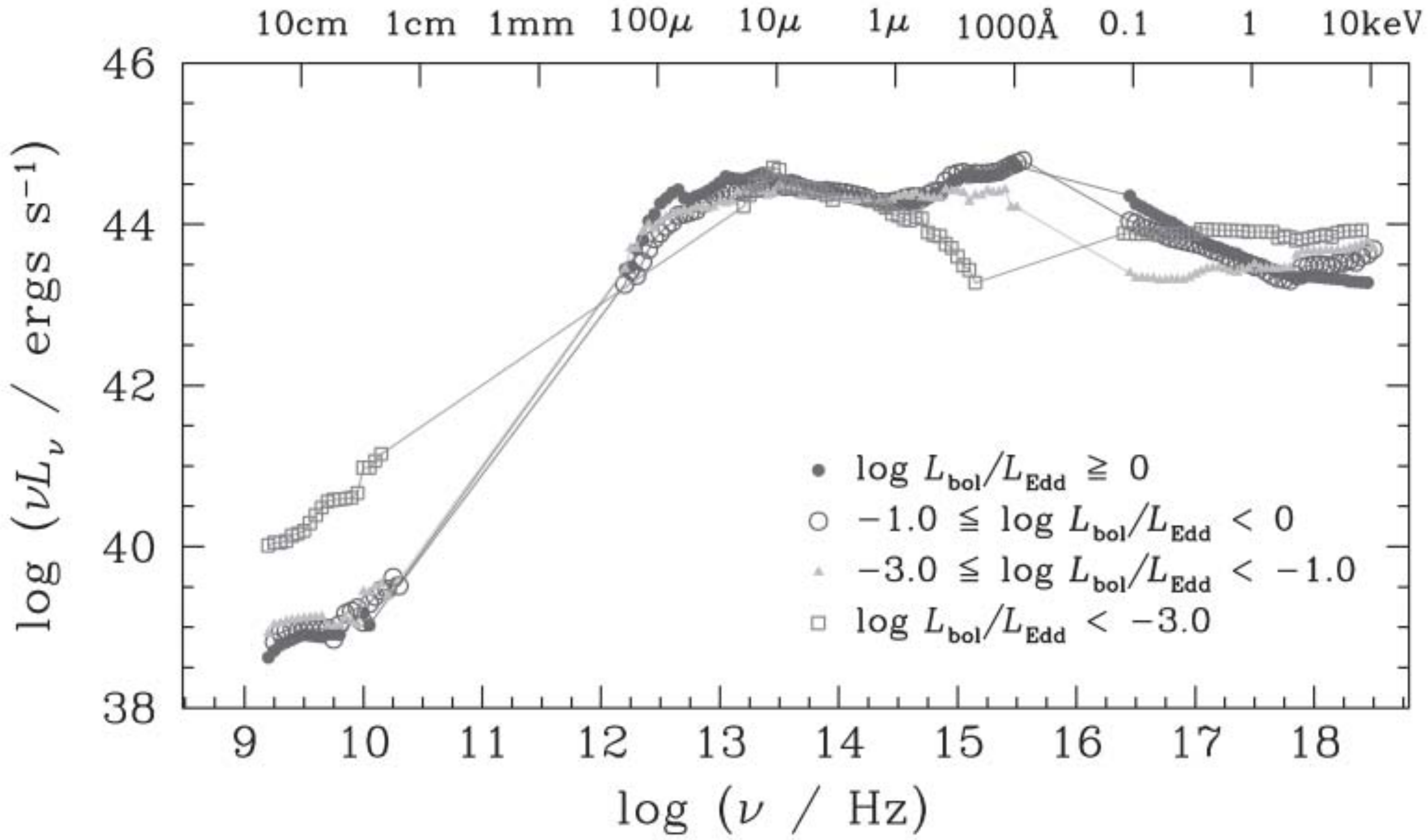


Figure 1.1. Broadband spectral energy distributions (SEDs) for various types of AGNs (from Ho, 2008; reproduced by permission of ARAA). The SEDs are normalized and do not reflect the very large range in intrinsic luminosity between different objects and different redshifts.

Broadband emission

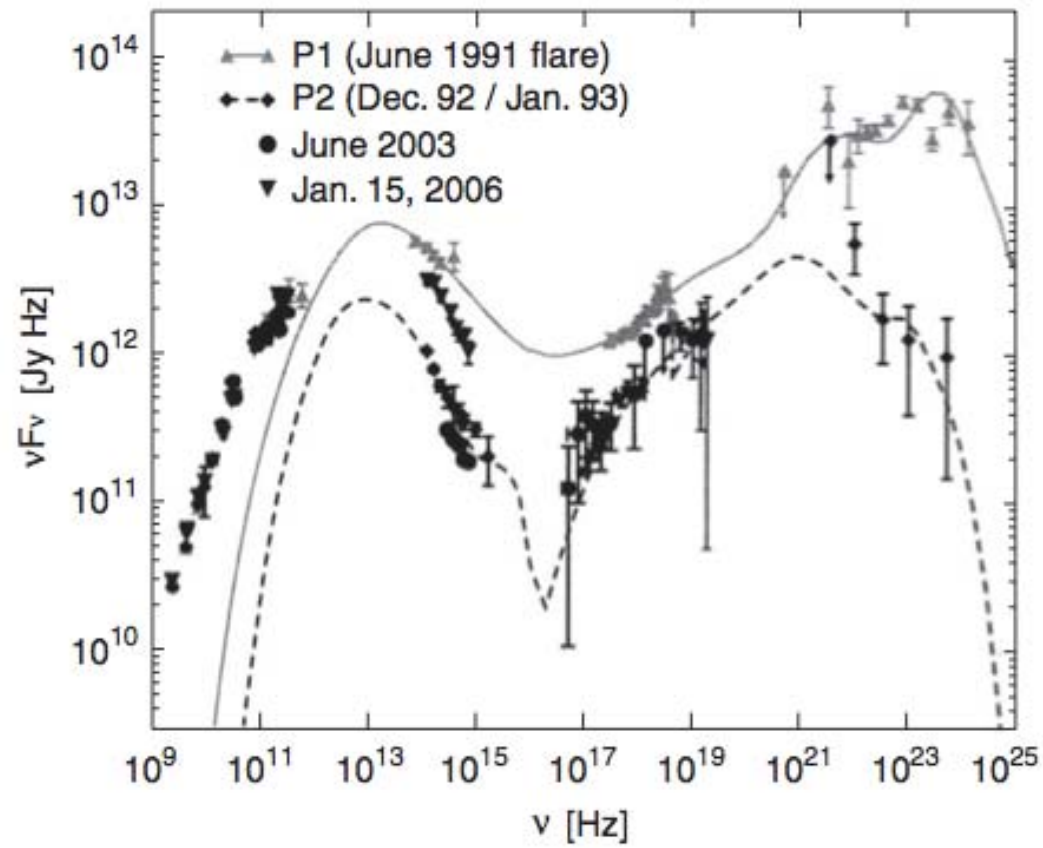
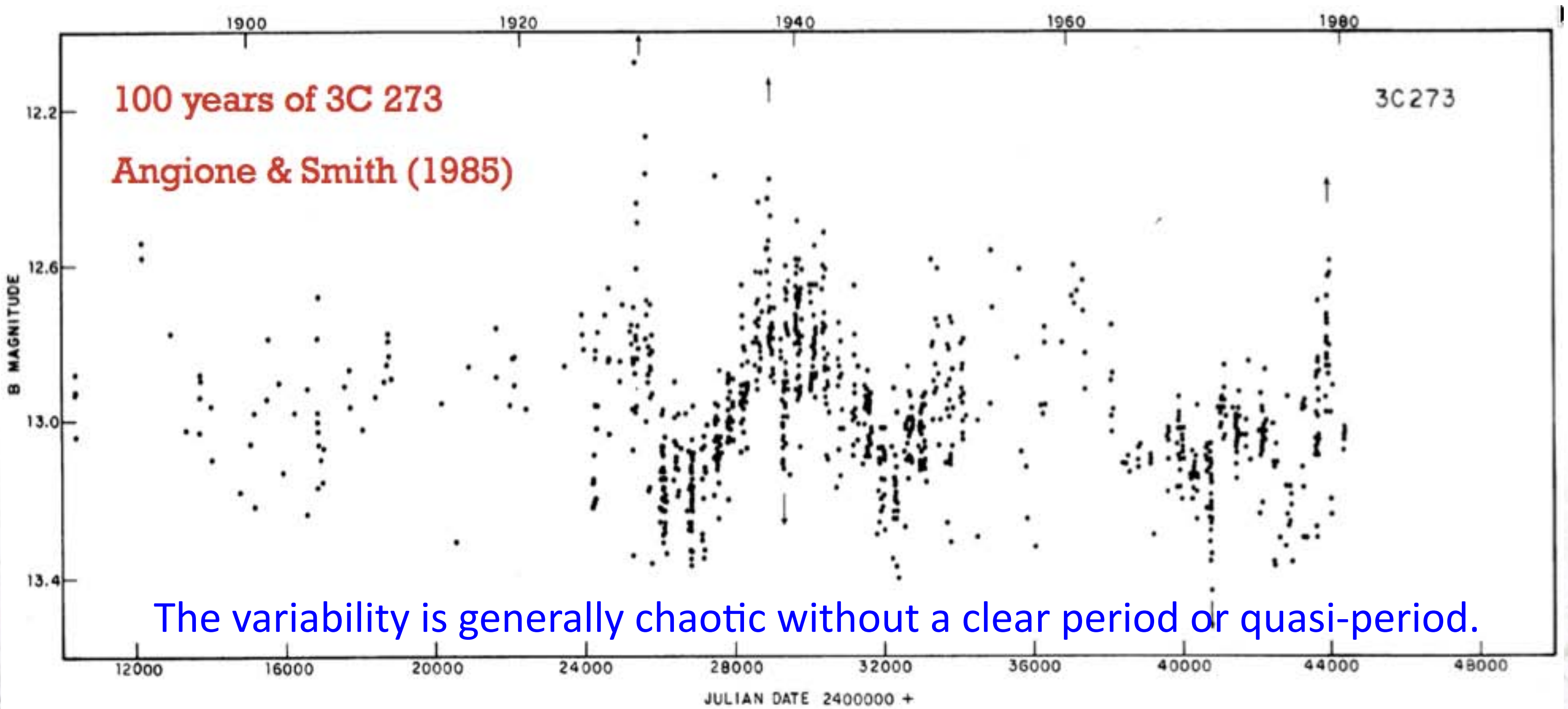


Figure 1.6. The multiepoch, multiwavelength spectrum of the blazar 3C 279 (from Bottcher et al., 2007; reproduced by permission of the AAS) showing the two characteristic peaks at low and high energies and the long-term variations of the source.

A defining feature of AGNs: variability



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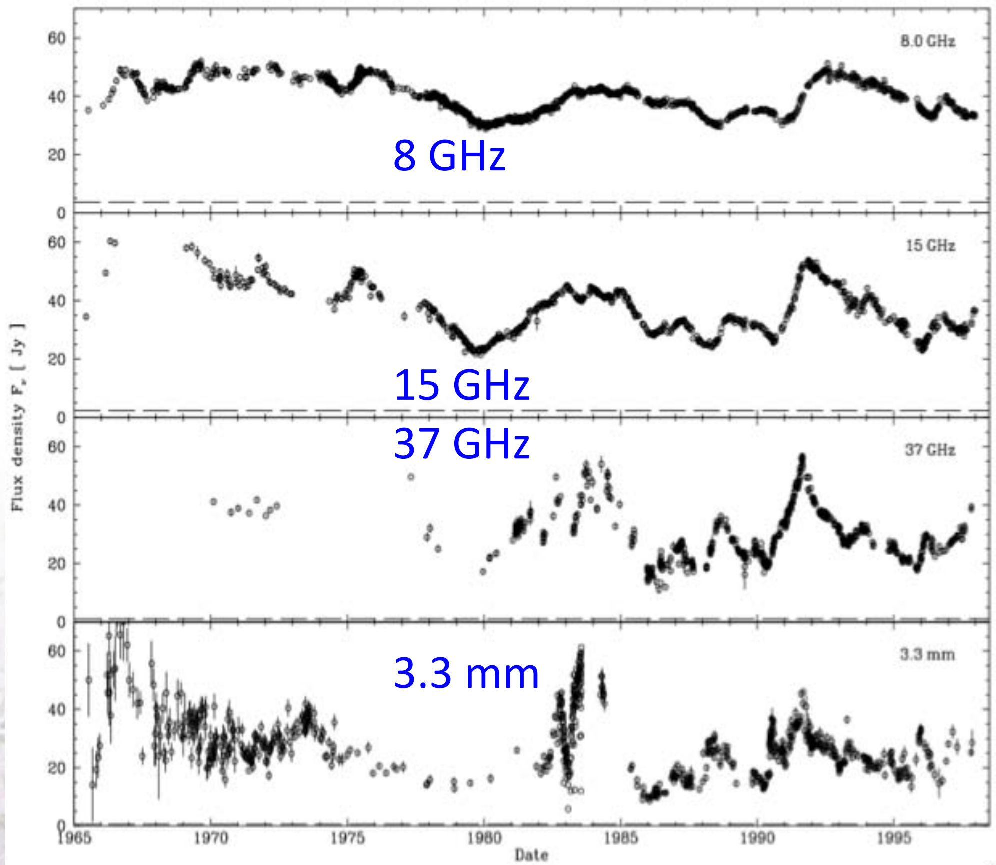
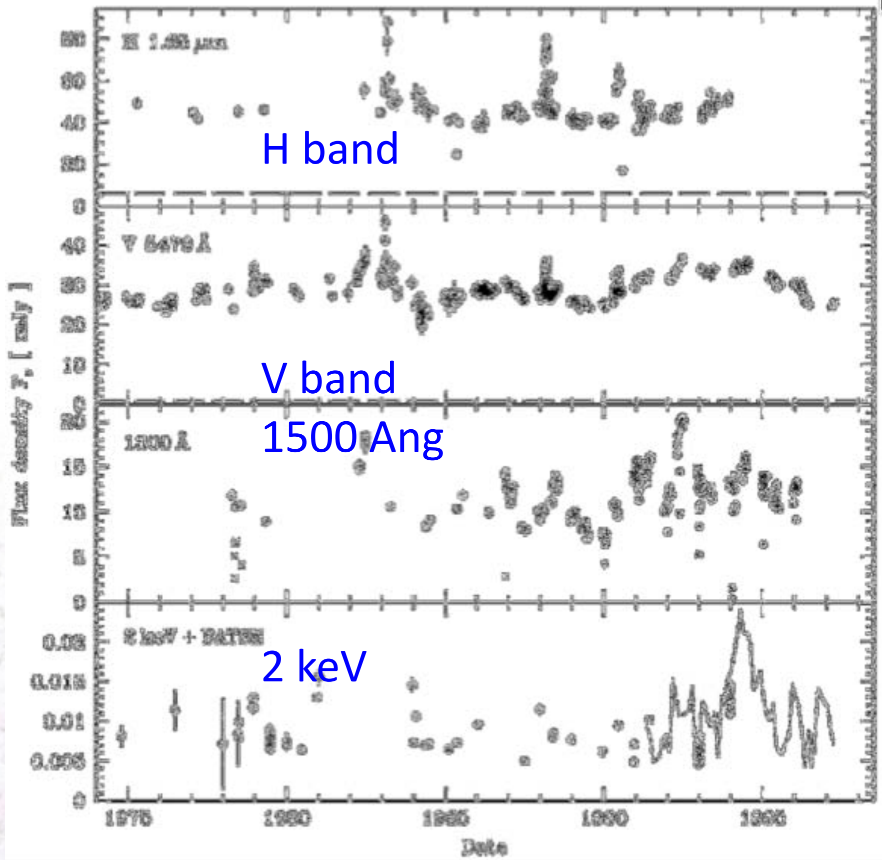
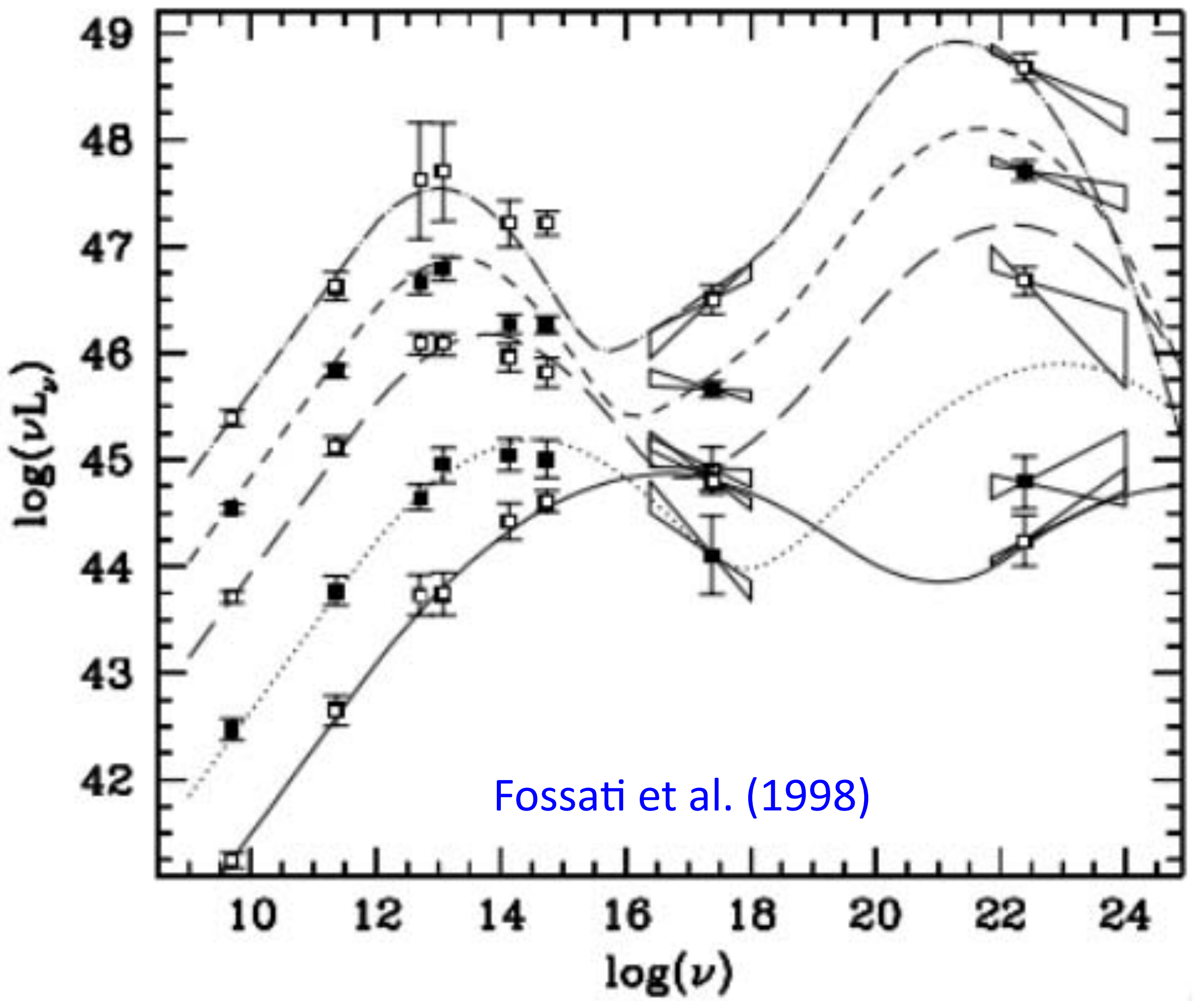
- Long-term variability of 3C 273 at many wavelengths (Turler et al. 1999):
  - variability in different bands is often correlated



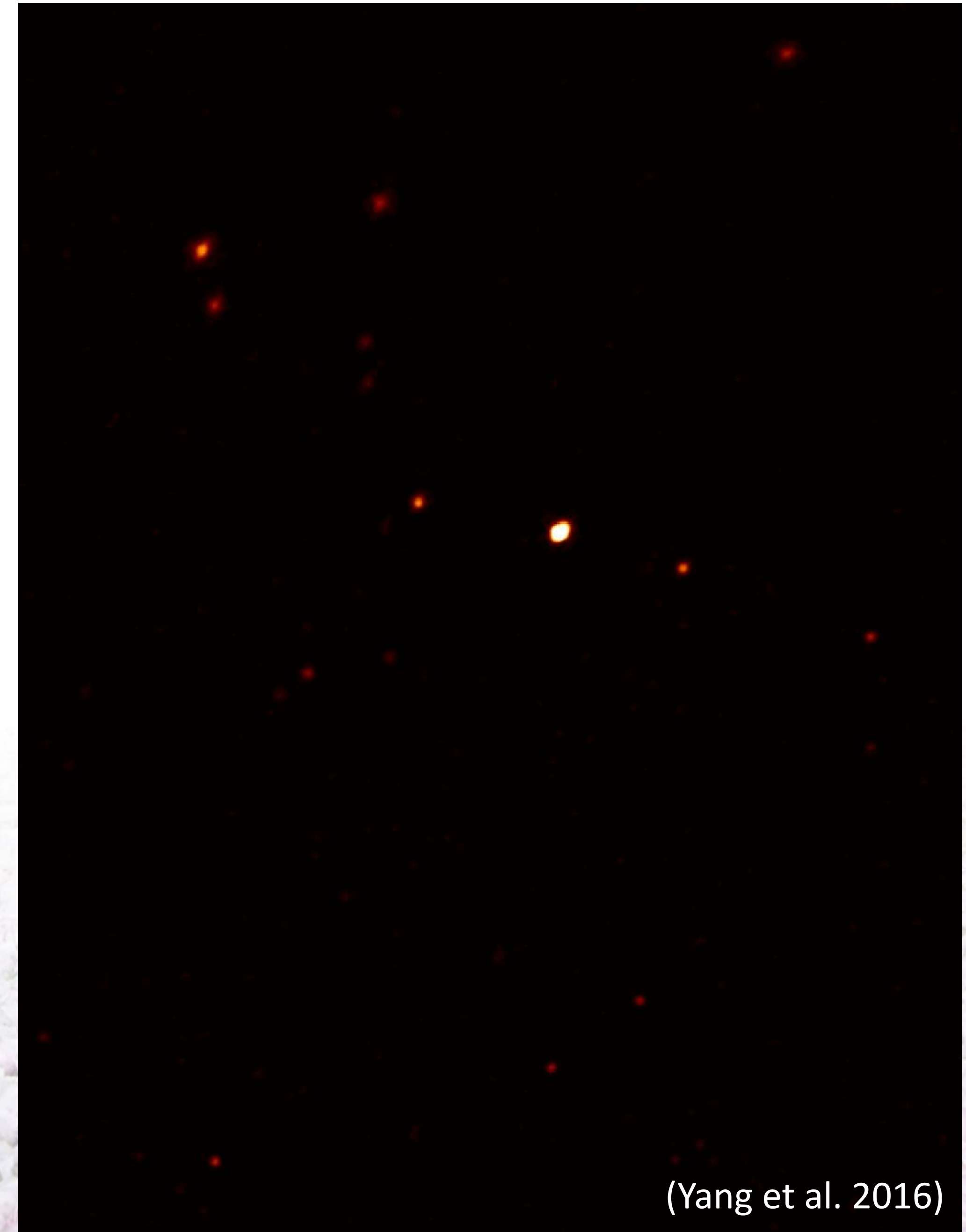




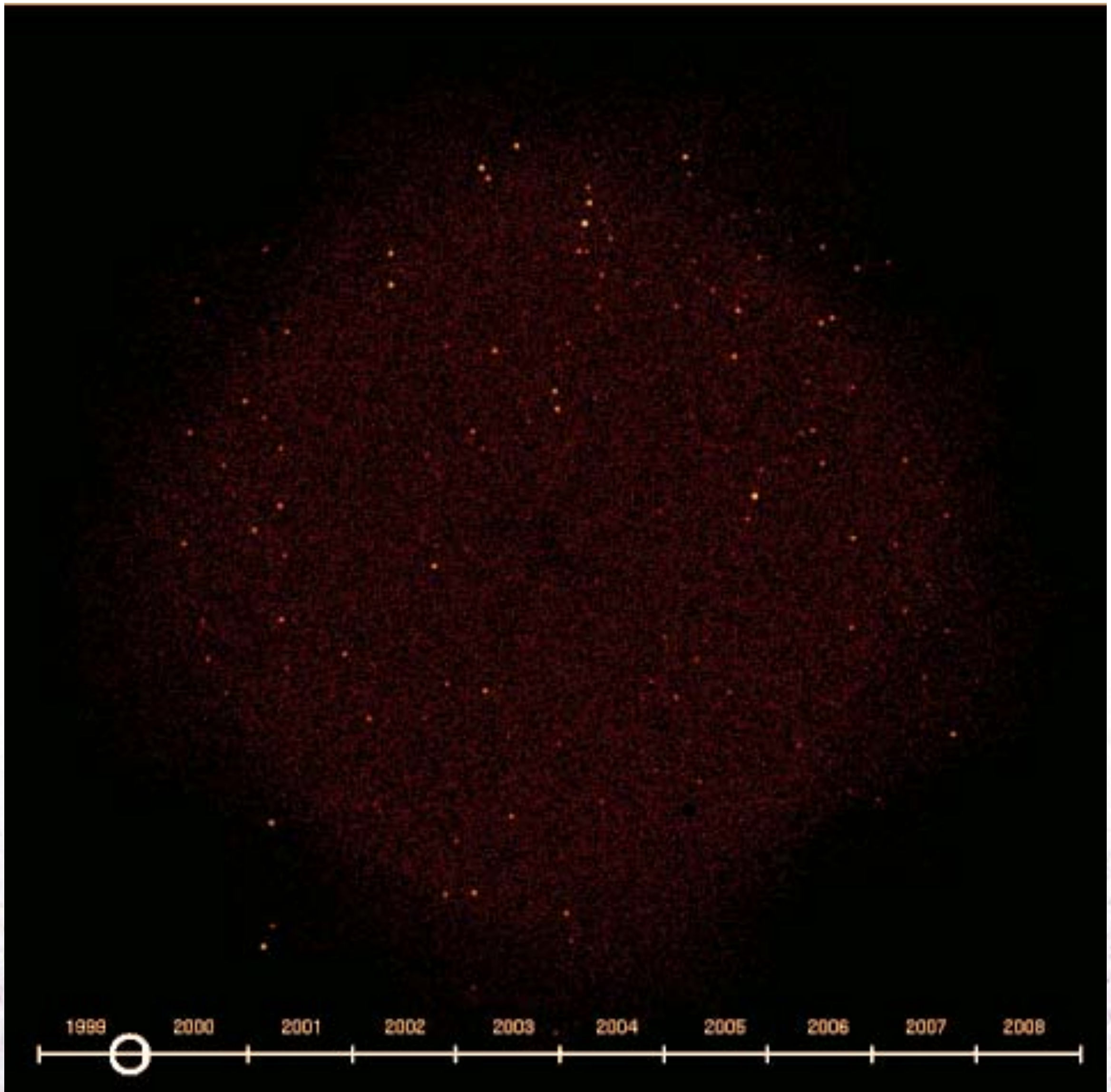
- correlated, very large energy band variations
- overall SED shape retained
- some bands more variable than others

Figure 1.3. Average SEDs for a large sample of blazars binned according to radio luminosity (from [11]). The overlaid curves are analytic approximations for the SEDs. Note that a photon with an energy of 1 TeV has a frequency of $\sim 2.4 \times 10^{26}$ Hz, which is slightly beyond the right border of the plot.

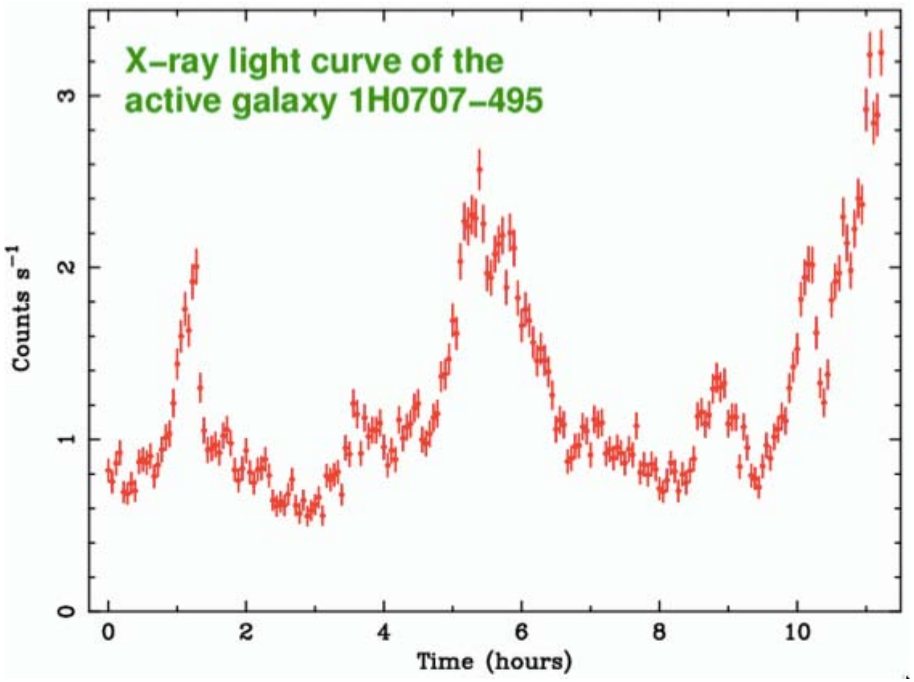
Variability of typical distant AGNs: CDF-S X-ray variability over 15 years (central)



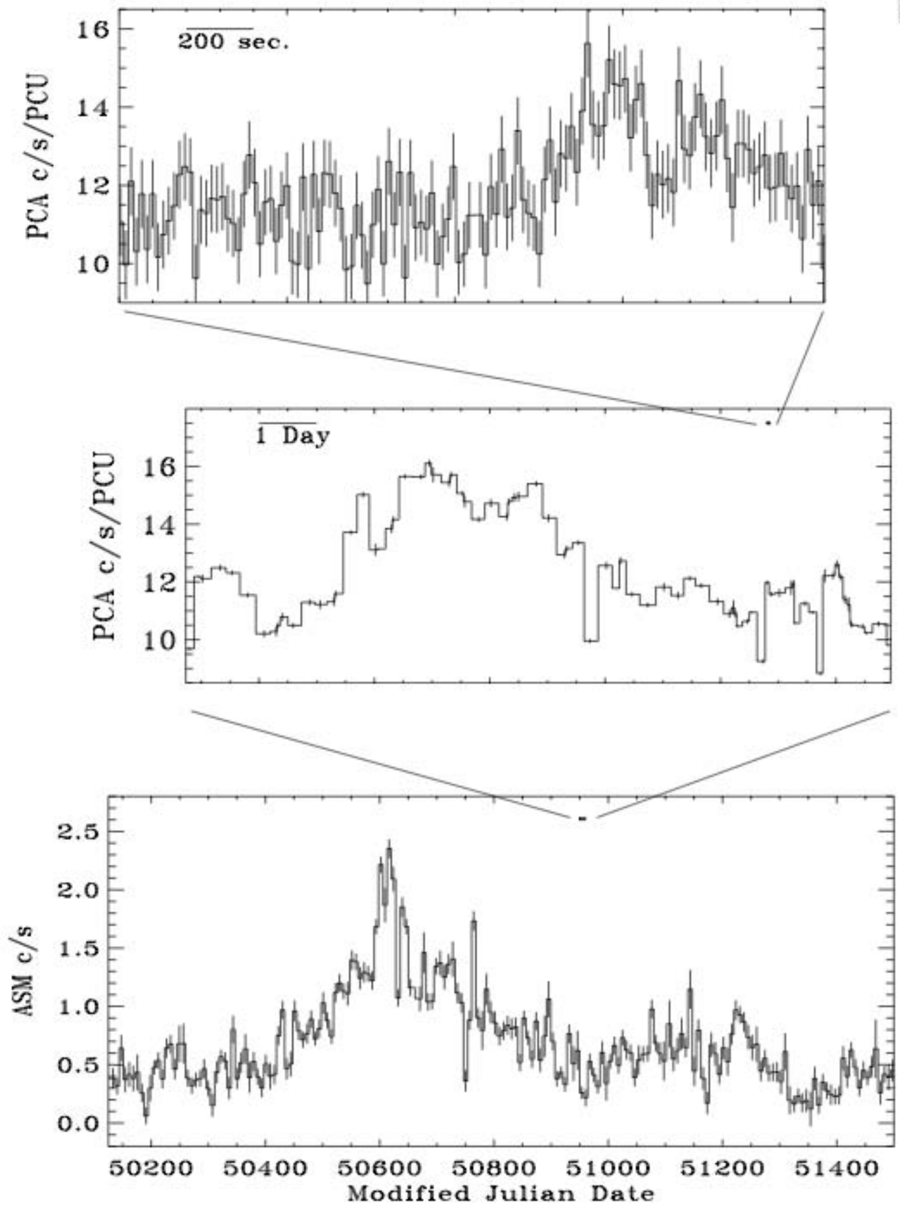
Variability of typical distant AGNs: CDF-S X-ray variability (full field)



(Young et al. 2011)



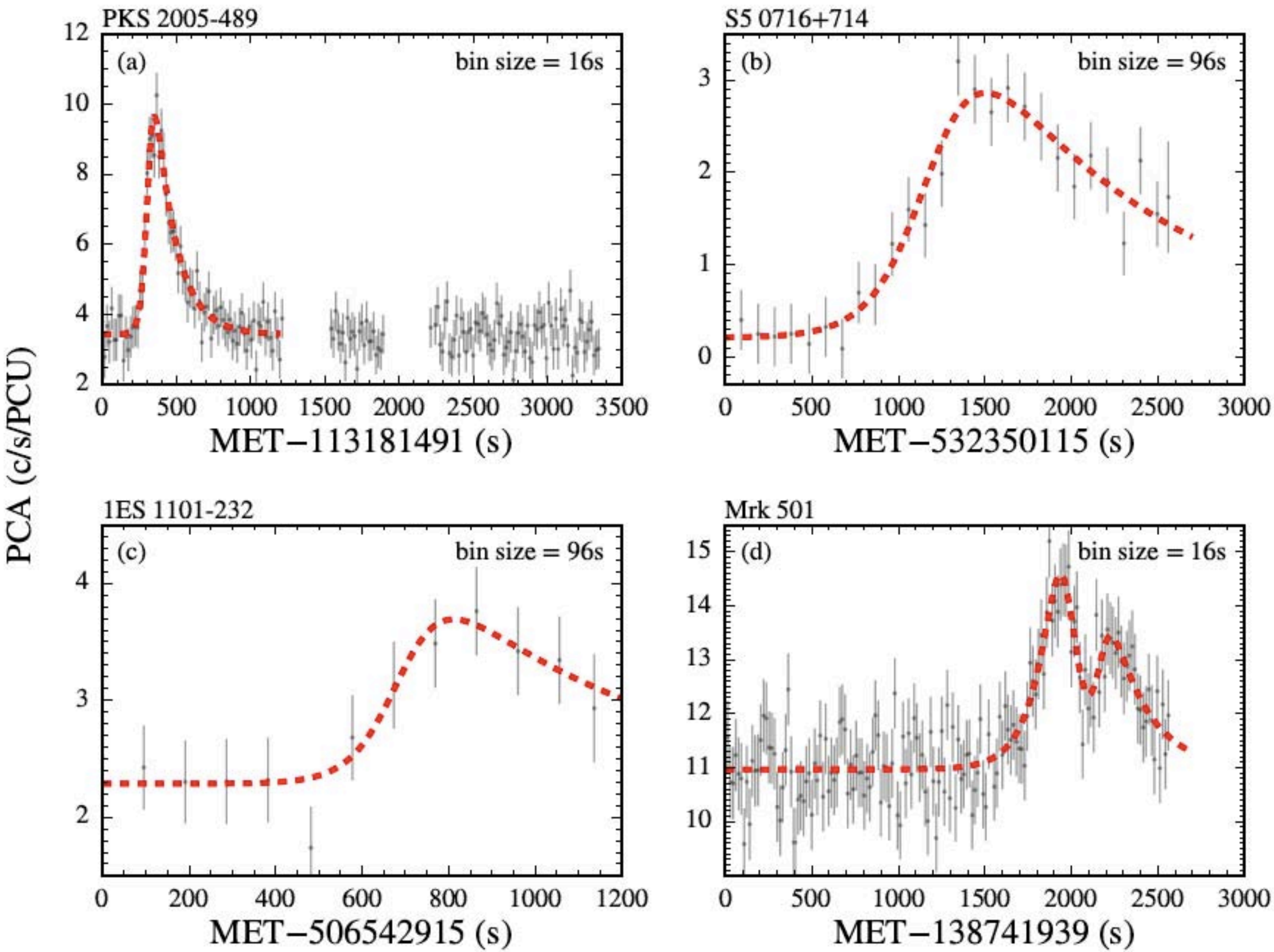
Scale-invariant variability in Mrk 501
(Xue & Cui 2005)



- Examples of rapid X-ray variability on timescales down to minutes:

  - broadly speaking, X-ray variability becomes larger amplitude and more rapid toward higher frequencies

  - X-ray variability often implies an emission-region size of light hours or less



Extremely fast X-ray flaring events of TeV blazars (Zhu, Xue et al. in prep.)

- Broad-emission-line variations are seen in all type I AGNs that have been monitored for long enough periods of time: thought to be direct result of UV continuum variations
- NIR (mostly K-band) variability is seen also in several nearby type I AGNs: interpreted as result of time-dep. heating of nuclear dust by the variable, primary source of radiation

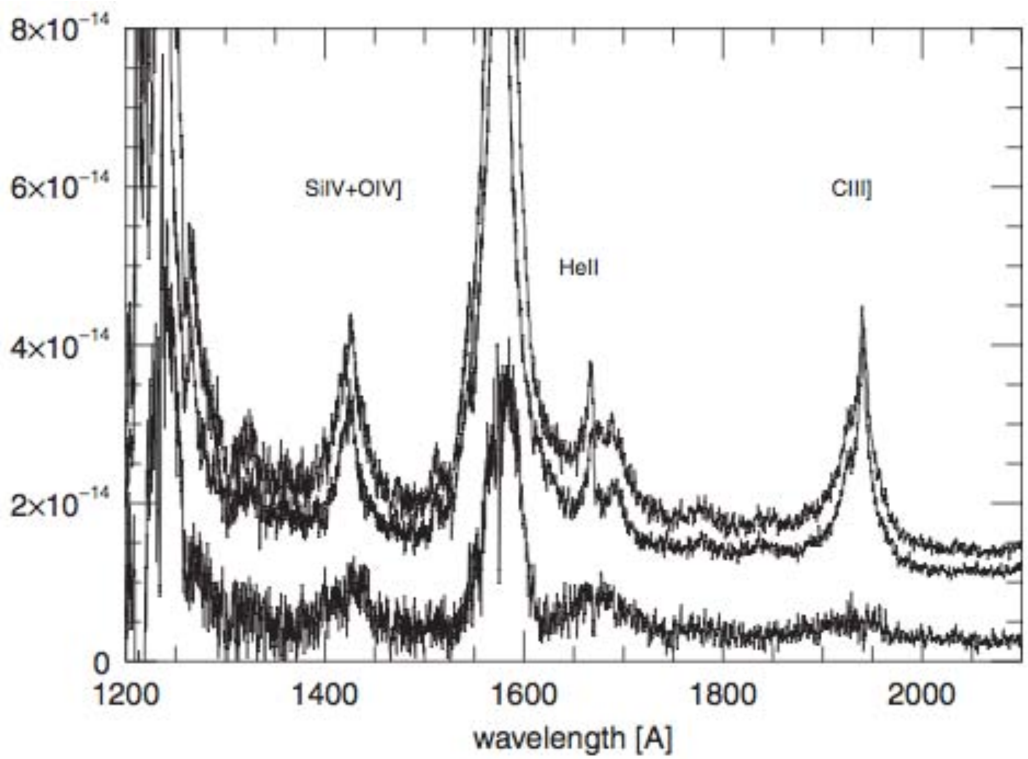


Figure 1.7. UV variability in the spectrum of NGC 5548. Two HST spectra taken 30 days apart are shown on the top, and their difference is shown on the bottom. The flux scale is in units of erg s^{-1} cm^{-2} $Å^{-1}$. The difference spectrum indicates both broad-emission-line and continuum variations.

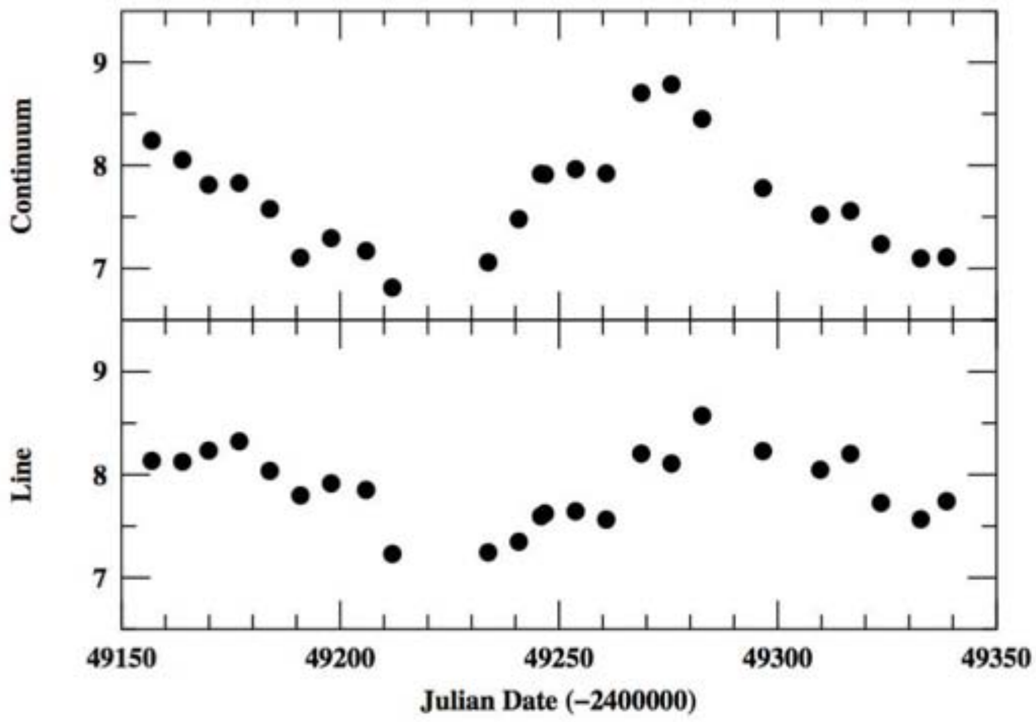


Figure 23. The Hβ emission-line and optical continuum fluxes for Mrk 335, as shown in Fig. 22, are plotted as a function of time. It is clear from the figure that the continuum and emission-line fluxes are well-correlated, and that the correlation can be improved by a linear shift in time of one time series relative to the other. The optimum linear correlation occurs by shifting the emission-line light curve backwards by 15.6 days.

- Broad emission line H_beta variability of Mrk 335 (Peterson 2001)

  - the broad emission lines also vary, generally following the continuum with a lag

  - reverberation mapping

AGN ABCs (III)

Observed Phenomena Needing Explanation

Broad range of luminosities, reaching very large values.

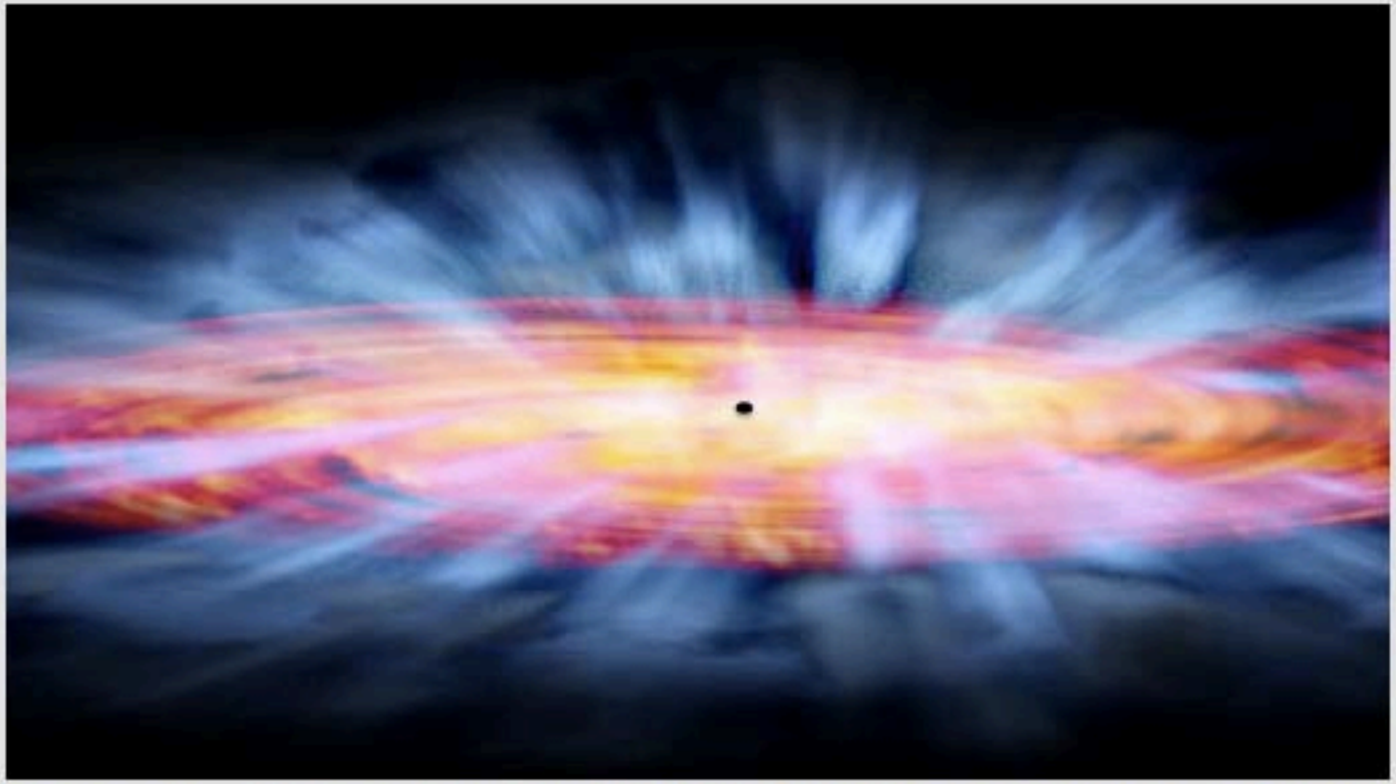
Strong and broad optical/UV emission lines.

Emission over a very broad band.

Variability.

Particle jets.

Black Hole + Accretion Disk Model



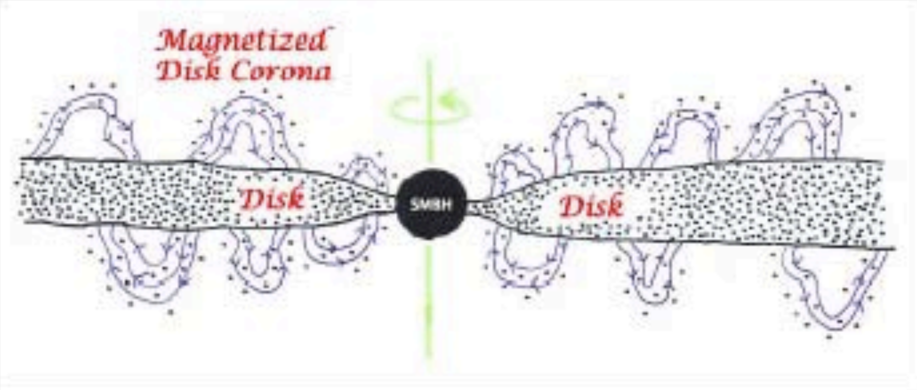
AGNs are accreting supermassive black holes (10^5-10^{10} $M_\odot$) radiating ~ 10^6-10^{15} $L_\odot$.

Accretion disk is multi-temperature, partly accounting for broad-band emission.

Optical/UV emission lines come from high-speed photoionized gas – disk, winds, clouds.

Origin of the X-ray Emission

~ Light-minutes scale



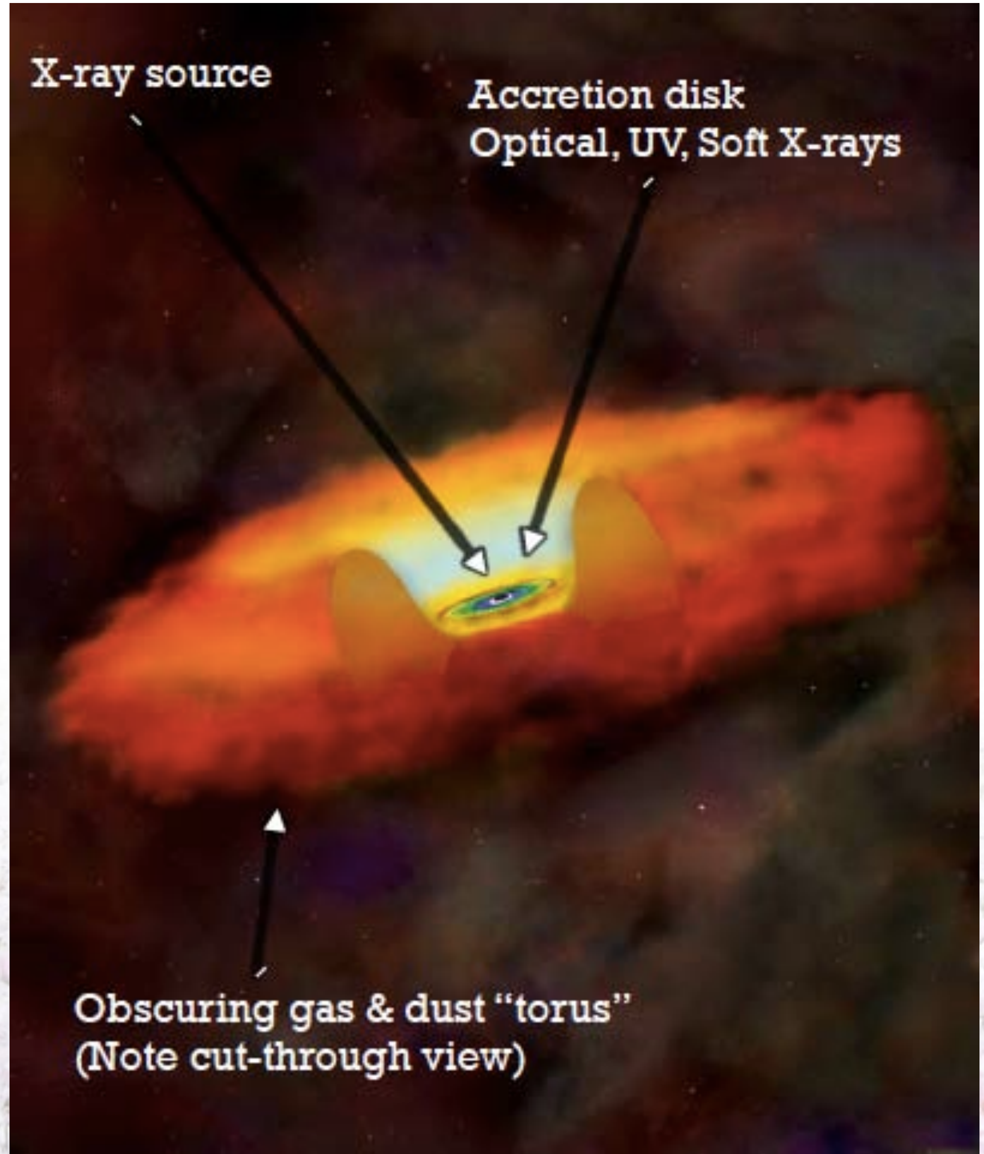
X-rays are not naturally produced by AGN disks; the disk is too cool.

Need to add an accretion disk "corona" with a temperature of ~ 150 keV.

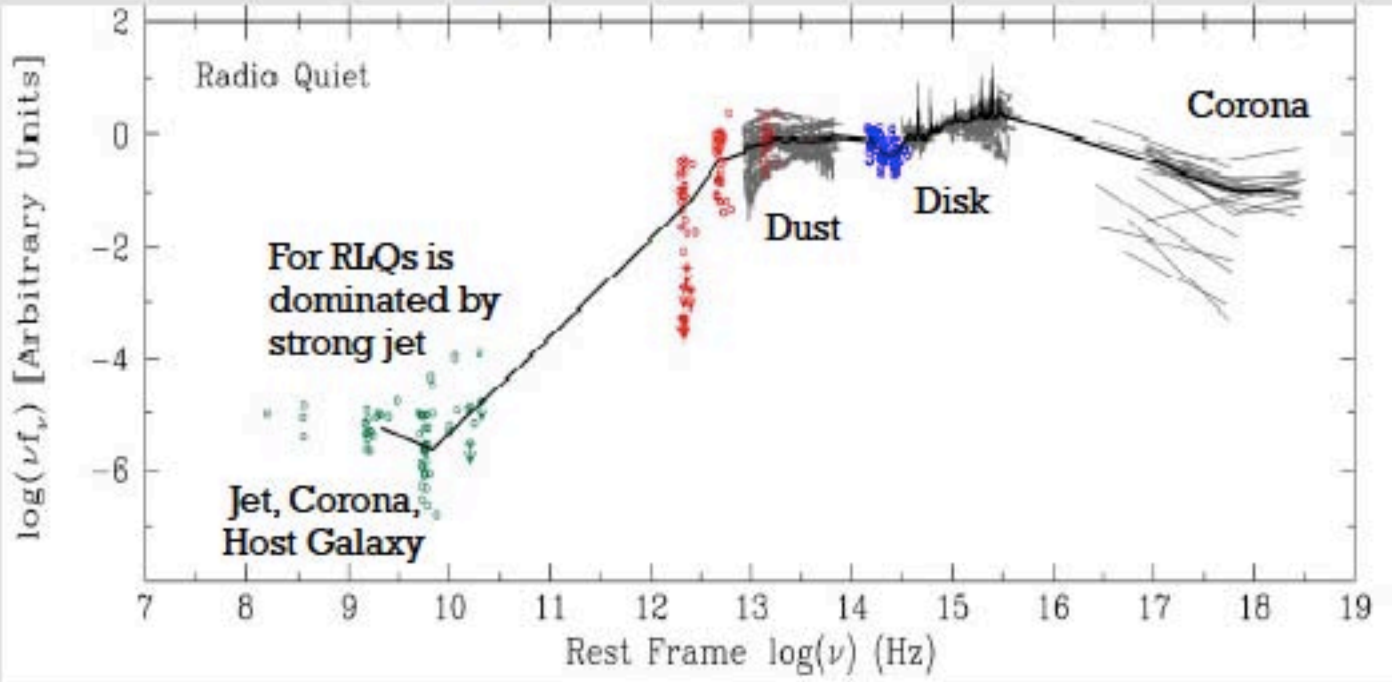
This makes X-rays by Compton scattering.

Perhaps low-energy X-rays from disk component.

Obscuration and radiation reprocessing



Explaining Emission Over a Very Broad Band



Shang et al. (2011)

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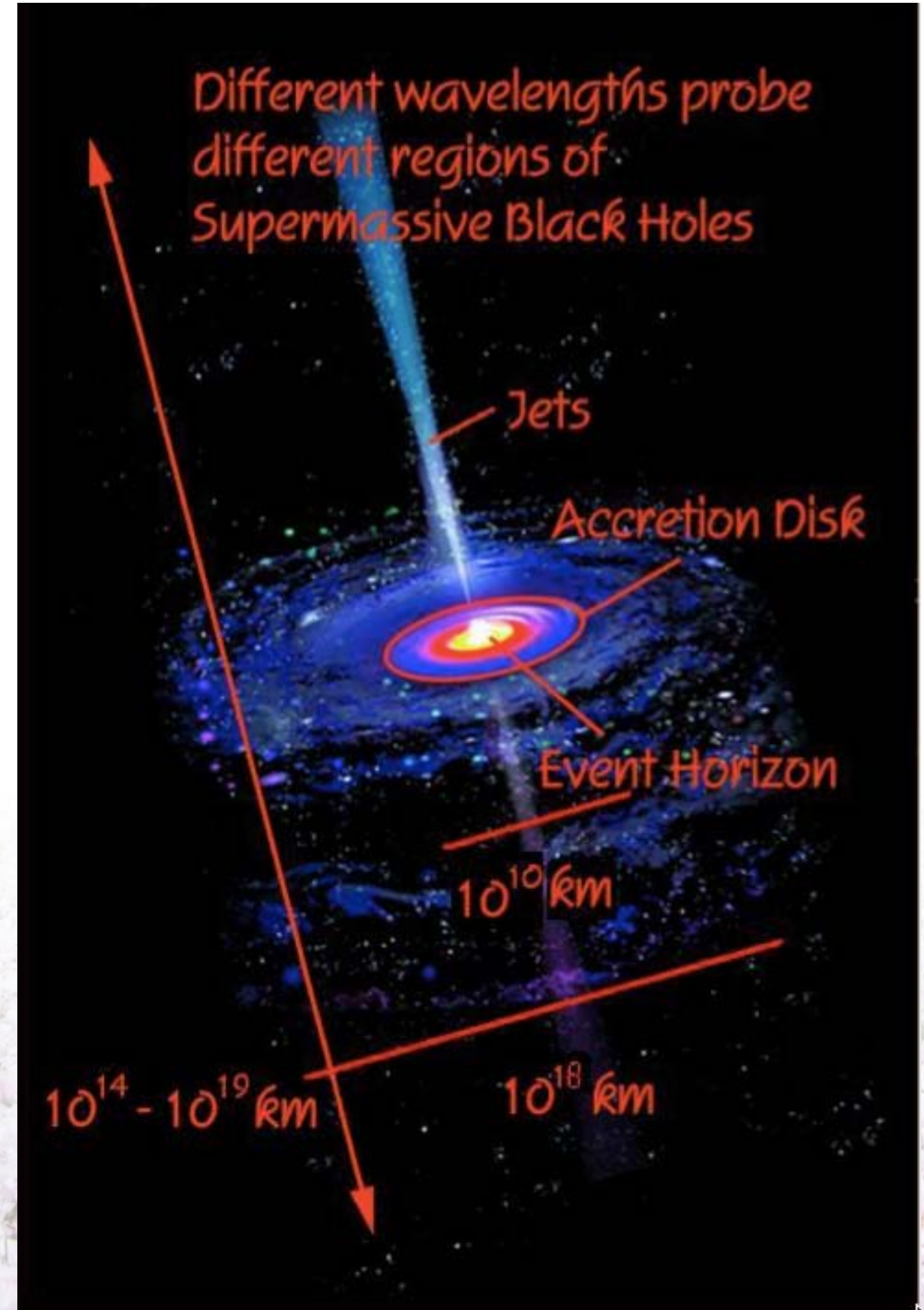


Different wavelengths probe different regions of Supermassive Black Holes
Jets
Accretion Disk
Event Horizon
10^10 km
10^14 - 10^19 km
10^18 km

Explaining Variability

The accretion disk is expected to have about the correct size to explain the observed variability timescales.

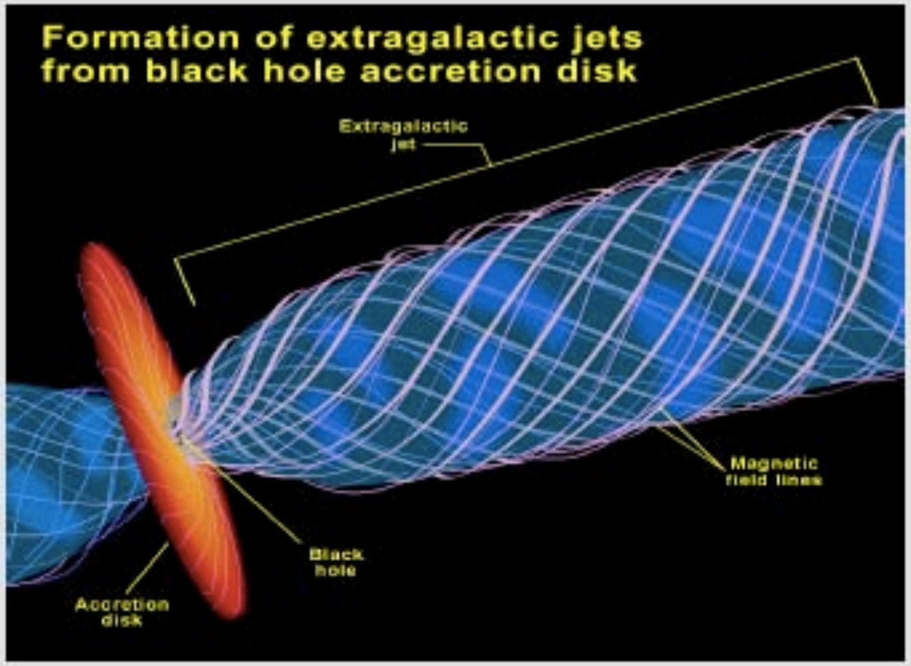
But, at a fundamental level, the physical origin of the variations remains poorly understood.

MHD simulations of accretion disks indicate several possible causes of variability: local random variations in dissipation, nonaxisymmetric structures, global precession of tilted flows, etc.

A deeper understanding will require proper simulation of both dynamics (good progress) and thermodynamics (slow progress).

Also can have variable accretion rates, variable obscuration, microlensing.

Explaining Particle Jets



Have relativistic motions, magnetic fields, stable "gyroscope".

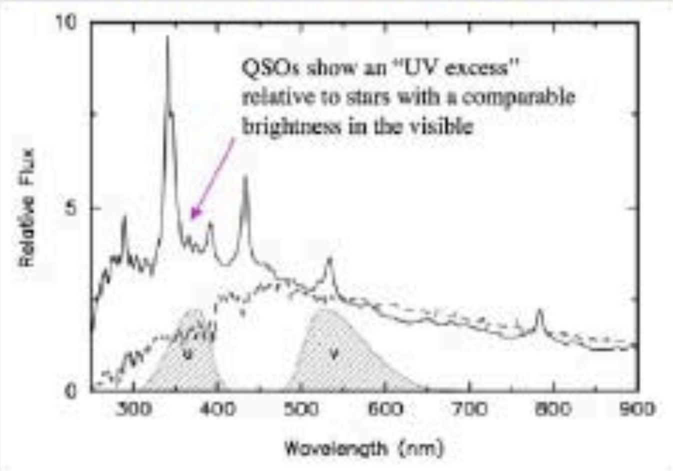
Finding AGNs

Discovering AGNs

- Various methods available, some almost as old as the subject itself
- All methods have limitations and selection effects
- Though some are more effective and give purer samples than others
- For a complete census, apply as many methods as possible enabling cross-check
- Most recent methods: largest number of new src. and most uniform samples
- Our current census appears sufficient to answer many key AGN questions
- Below introduce some of the most important techniques

Optical/UV Colors

Look for Point Sources Brighter in UV Than Normal Stars – Works to $z \sim 2$-2.5

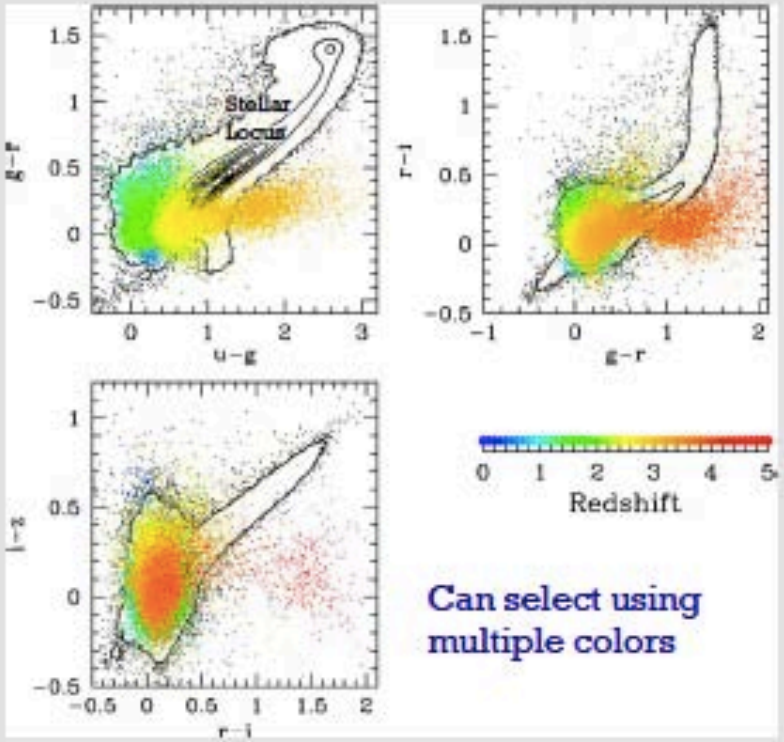


These methods work best for unobscured quasars; e.g., reddening causes trouble.

Furthermore, at lower AGN luminosities, host-galaxy light becomes problematic.

Can also use objective prism surveys.

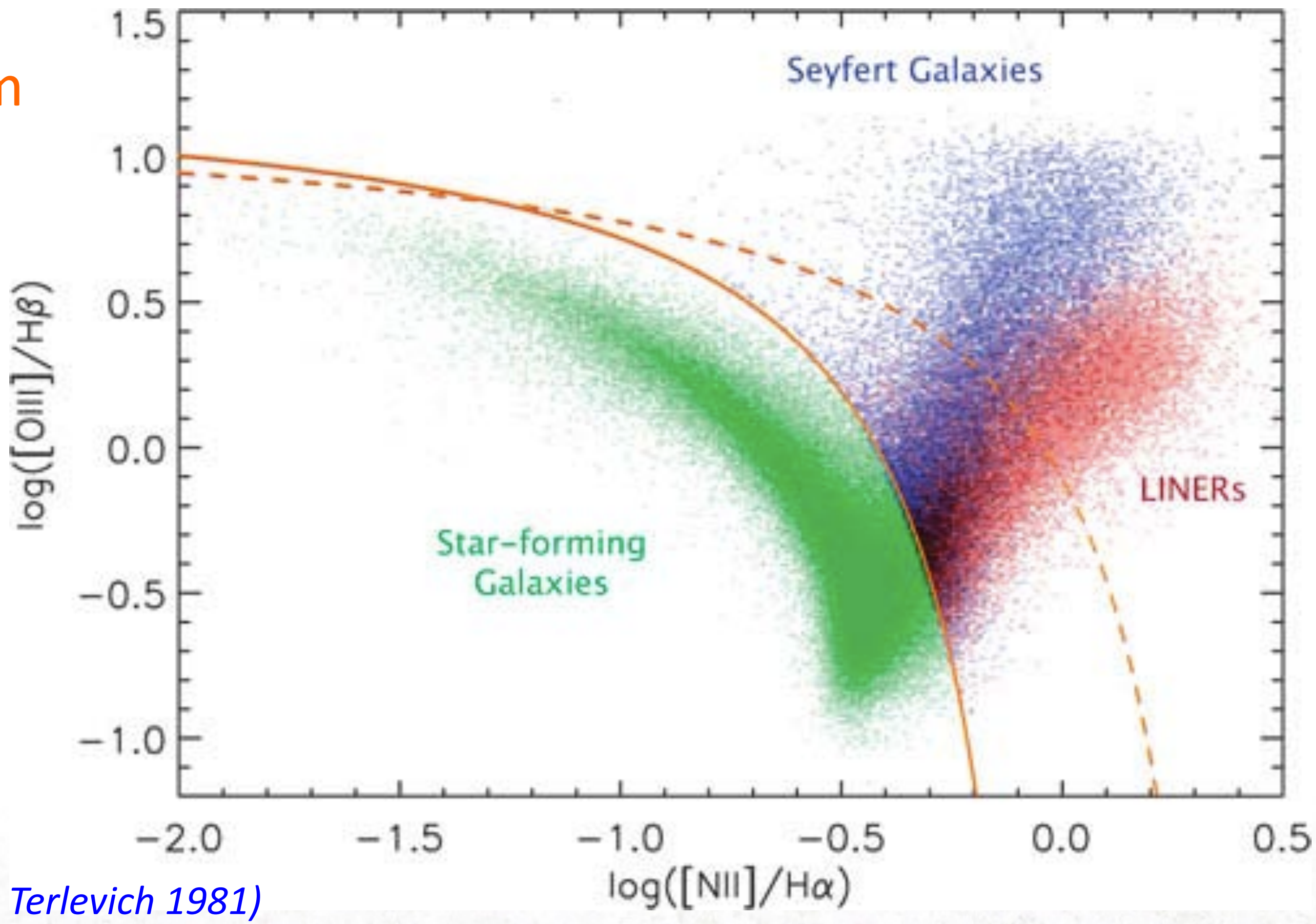
At Higher Redshifts, Absorption by the IGM Makes Quasars Very Red in Blue Part of Spectrum



Can select using multiple colors

Schneider et al. (2010)

BPT diagram



(Baldwin, Phillips & Terlevich 1981)

Figure 6.1. The spread of emission-line galaxies from the SDSS on one diagnostic diagram that uses four strong optical emission lines, Hα, Hβ, [O III] λ5007, and [N II] λ6584, to distinguish galaxies that are dominated by ionization from young stars (green points) from those that are ionized by a typical AGN SED (blue points for high-ionization AGNs and red points for low-ionization AGNs). The AGN and SF groups are well separated, but the division between the two AGN groups is less clear. The curves indicate empirical (solid) and theoretical (dashed) dividing lines between AGNs and star-forming galaxies (courtesy of B. Groves).

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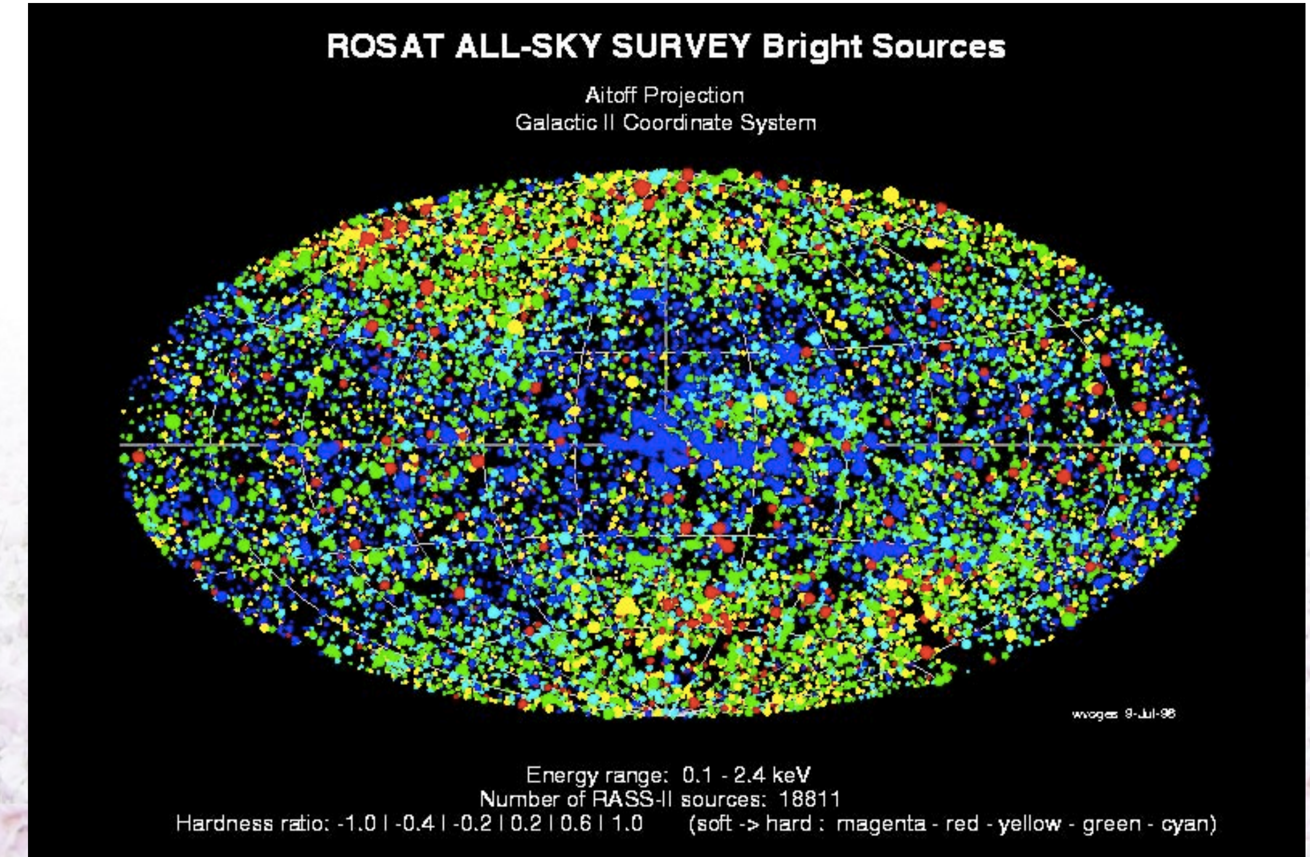
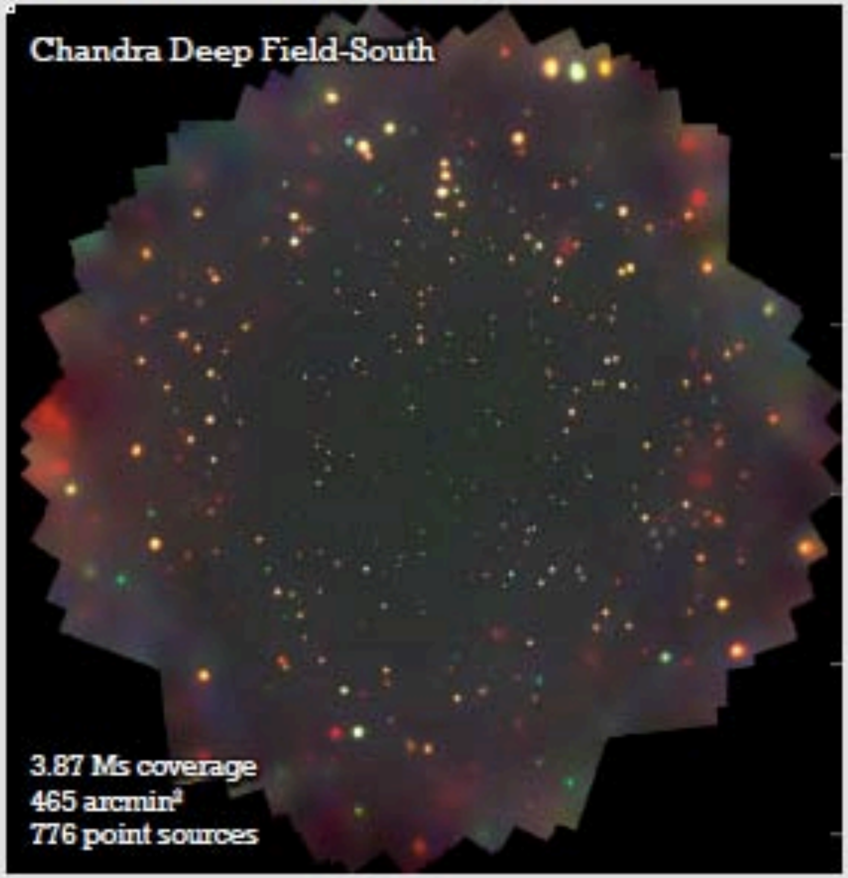
X-ray surveys for AGNs

- Almost all AGNs are strong X-ray emitters: can use deep X-ray surveys
- An early example: ROSAT all-sky survey; soft X-ray
  - sensitive deep X-ray surveys tend to pick bright soft X-ray src with strong 0.5-2 keV emission
  - type II AGNs with N_H >= 1e22 cm^{-2}: more difficult to detect



X-ray Surveys for AGNs



Xue et al. (2011)

X-ray emission nearly universal from AGNs.

X-rays have reduced absorption bias compared to optical/UV, especially for high-energy X-rays.

X-rays maximize contrast between black-hole vs. host-galaxy light.

Can find obscured AGNs and lower luminosity AGNs than in optical/UV.

Now are a wide variety of X-ray surveys, ranging from shallow all-sky to deep pencil-beam.

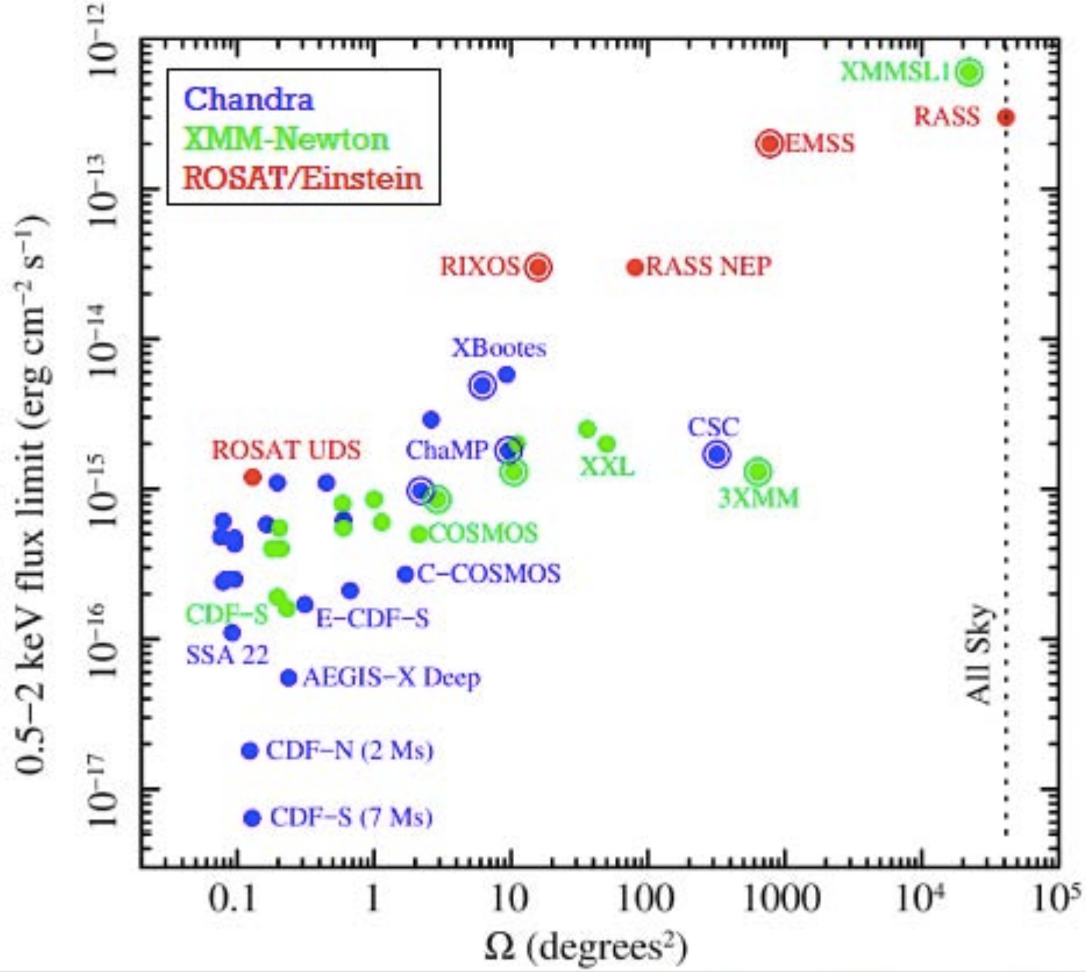
X-ray survey discovery space

- Recent (since 1999) deep surveys: conducted with Chandra and XMM-Newton

  - Chandra surveys: extremely deep because of superb angular resolution (<1”)

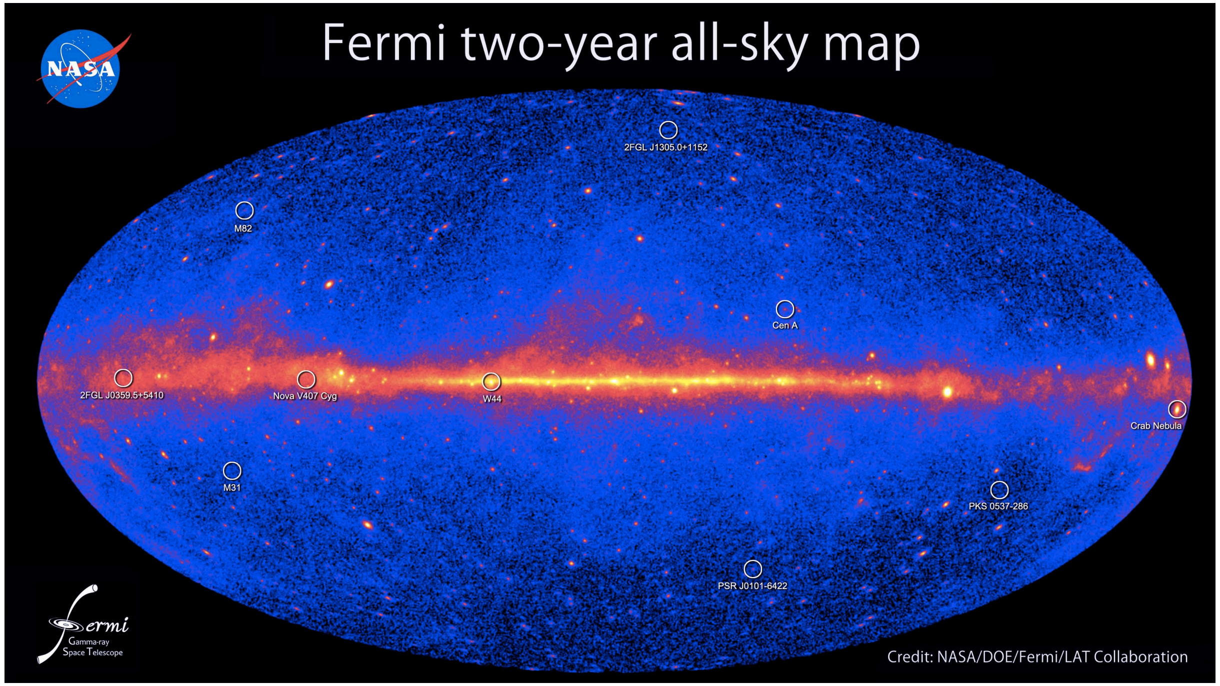
  - both Chandra and XMM: * can observe at higher energies (~10 keV)

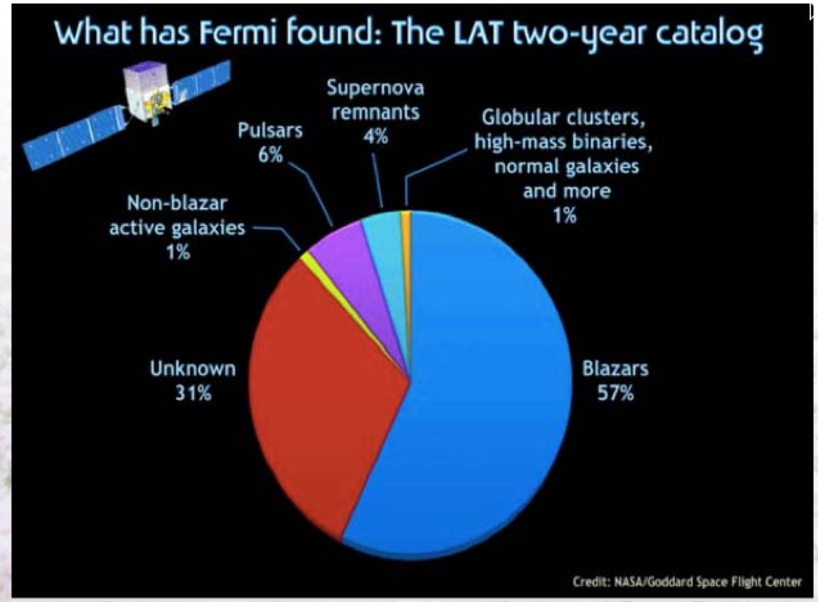
    * have only covered a small fraction of the sky



Updated from Brandt & Alexander (2015)

Gamma-ray surveys for AGNs: mostly blazars





Infrared Selection of AGNs

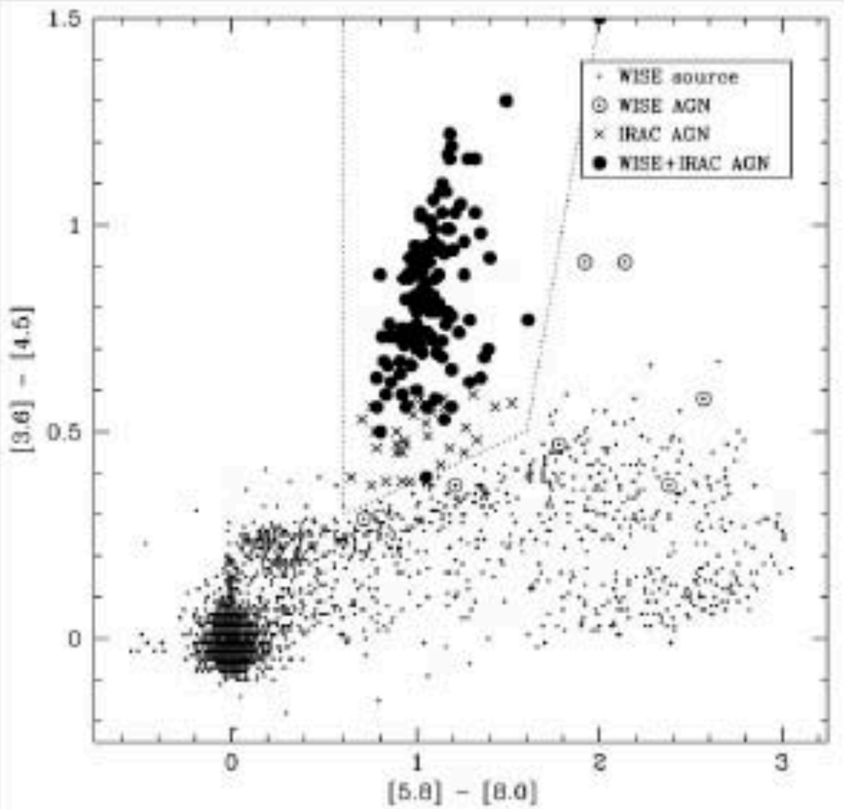


Figure 4. IRAC color–color diagram of *WISE*-selected sources in the COSMOS field. We only plot sources with S/N $\geq$ 10 in $W1$ and $W2$, and we require [3.6] > 11 to avoid saturated stars. Sources with $W1 - W2 \geq 0.8$ are indicated with larger circles; filled circles indicate sources that were also identified as AGNs using the Stern et al. (2005) mid-infrared color criteria. Sources identified as AGNs using *Spitzer* criteria but not using the *WISE* criterion are indicated with $\times$'s.

Stern et al. (2012)

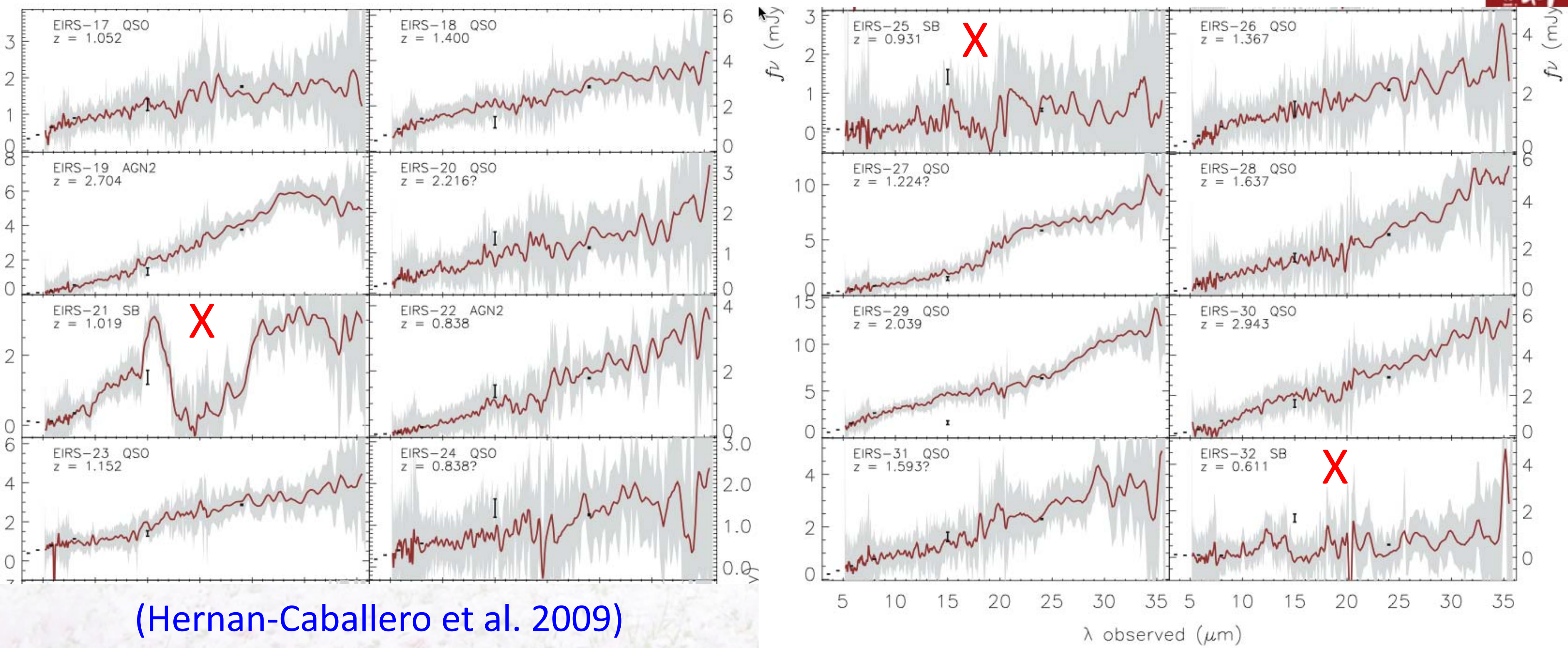
Several methods have been developed for the effective selection of AGNs in sensitive infrared data.

Often are seeing infrared power-law emission or "waste heat" from the AGN re-emitted by warm dust.

These are also relatively resistant against obscuration effects. They sometimes even find AGNs missed in X-ray surveys.

At lower AGN luminosities, such surveys suffer substantial contamination from star-forming galaxies.

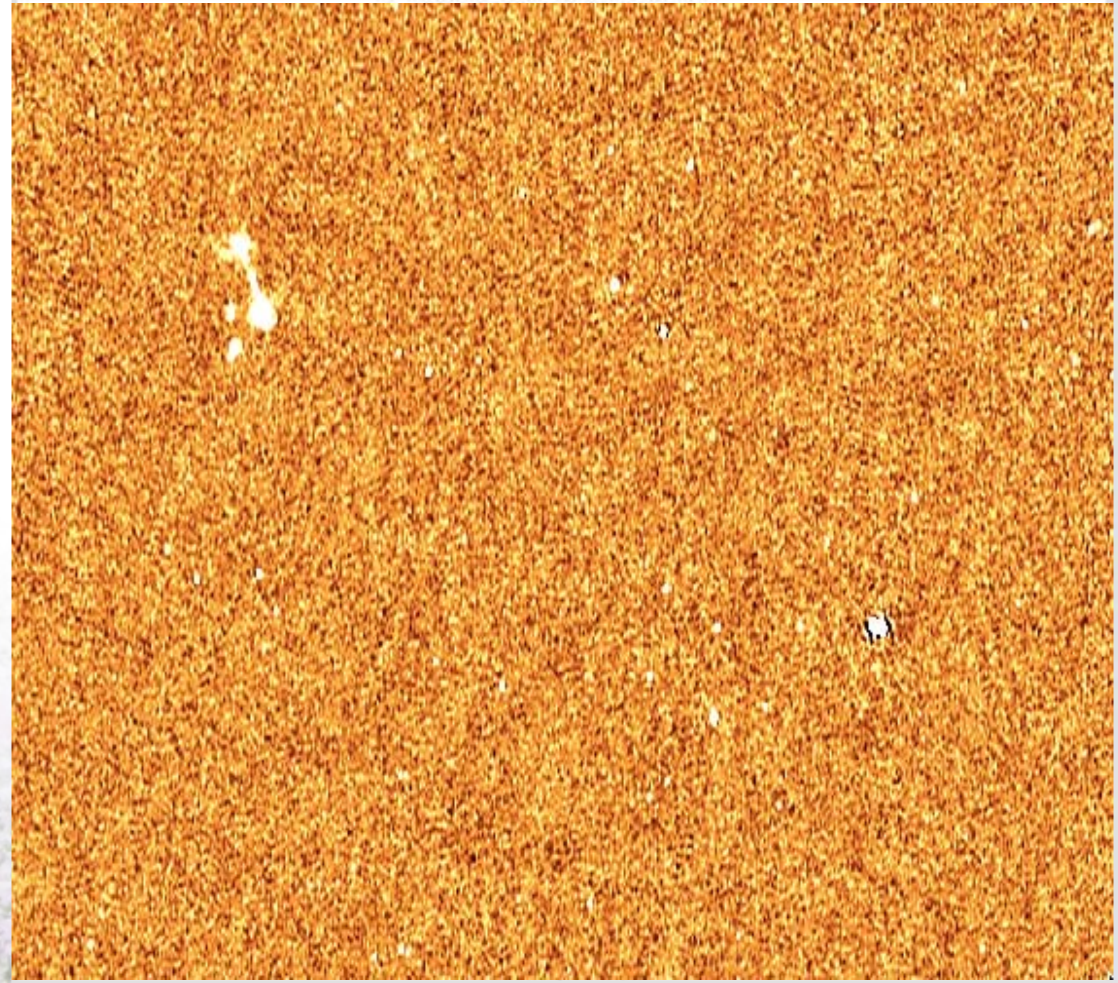
- AGNs: powerlaw IR spectra



(Hernan-Caballero et al. 2009)

Figure 3. Observed IRS spectra for the ELAIS-IRS sources. The shaded area represents the 1σ uncertainty in f_ν, while the solid line represents the smoothed spectrum after a Gaussian filter with a FWHM of three resolution elements has been applied. The error bars mark the flux density measured in the IRAC (3.6, 4.5, 5.8 and 8 μm) and MIPS (24 μm) bands from SWIRE and ISOCAM (15 μm) from ELAIS. The IR classification obtained in Section 5.2 is indicated as QSO (AGN1), AGN2 or SB. A question mark besides the redshift estimate indicates that the measurement is unreliable.

Radio Surveys for AGNs



(A cutout of the VLA 1.4 GHz E-CDF-S radio image; Miller et al. 2013)

Many of the first quasars were found via radio selection (3C).

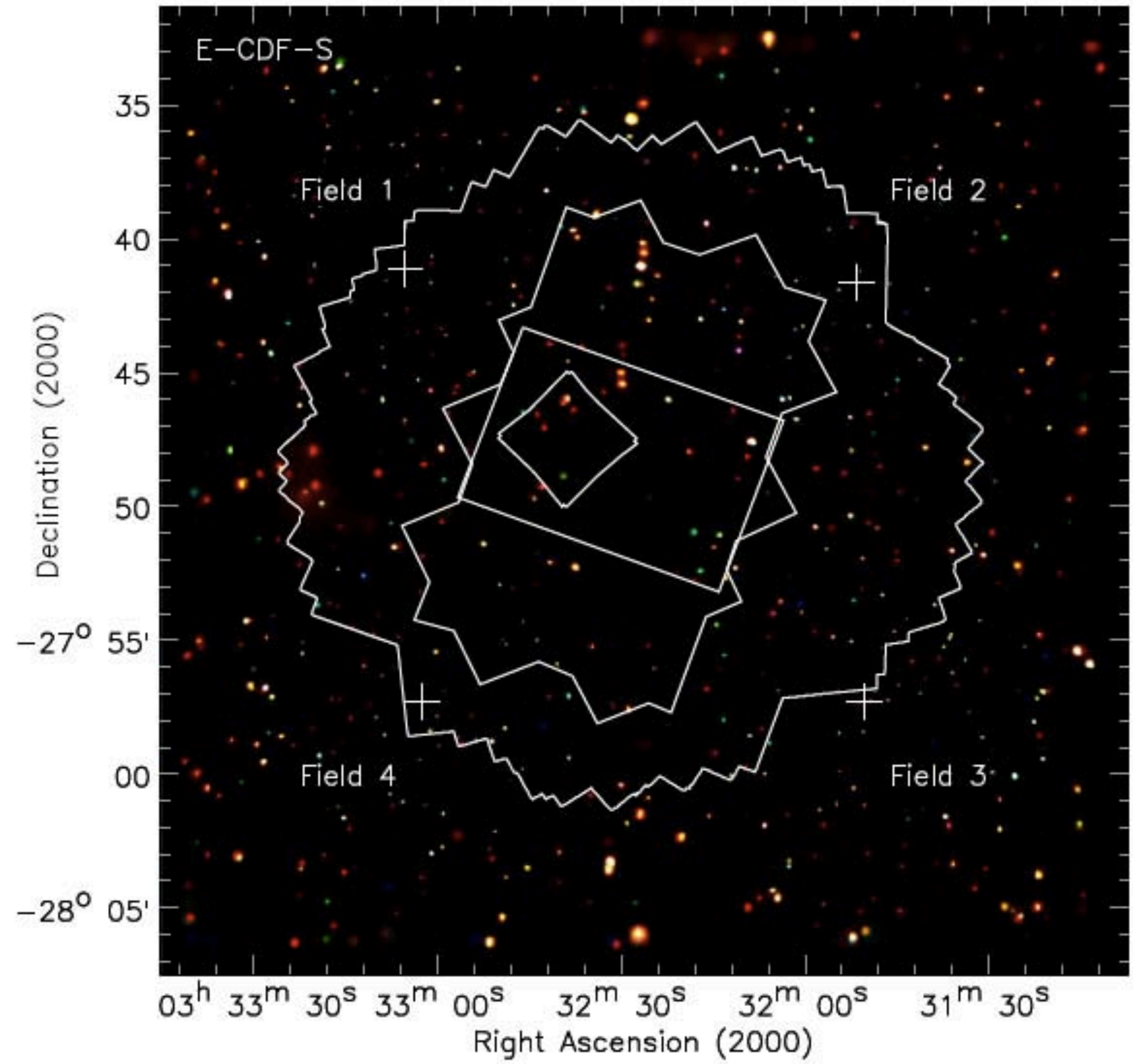
About 10% of AGNs are radio-loud sources.

Sensitive radio surveys can detect many radio-quiet AGNs too.

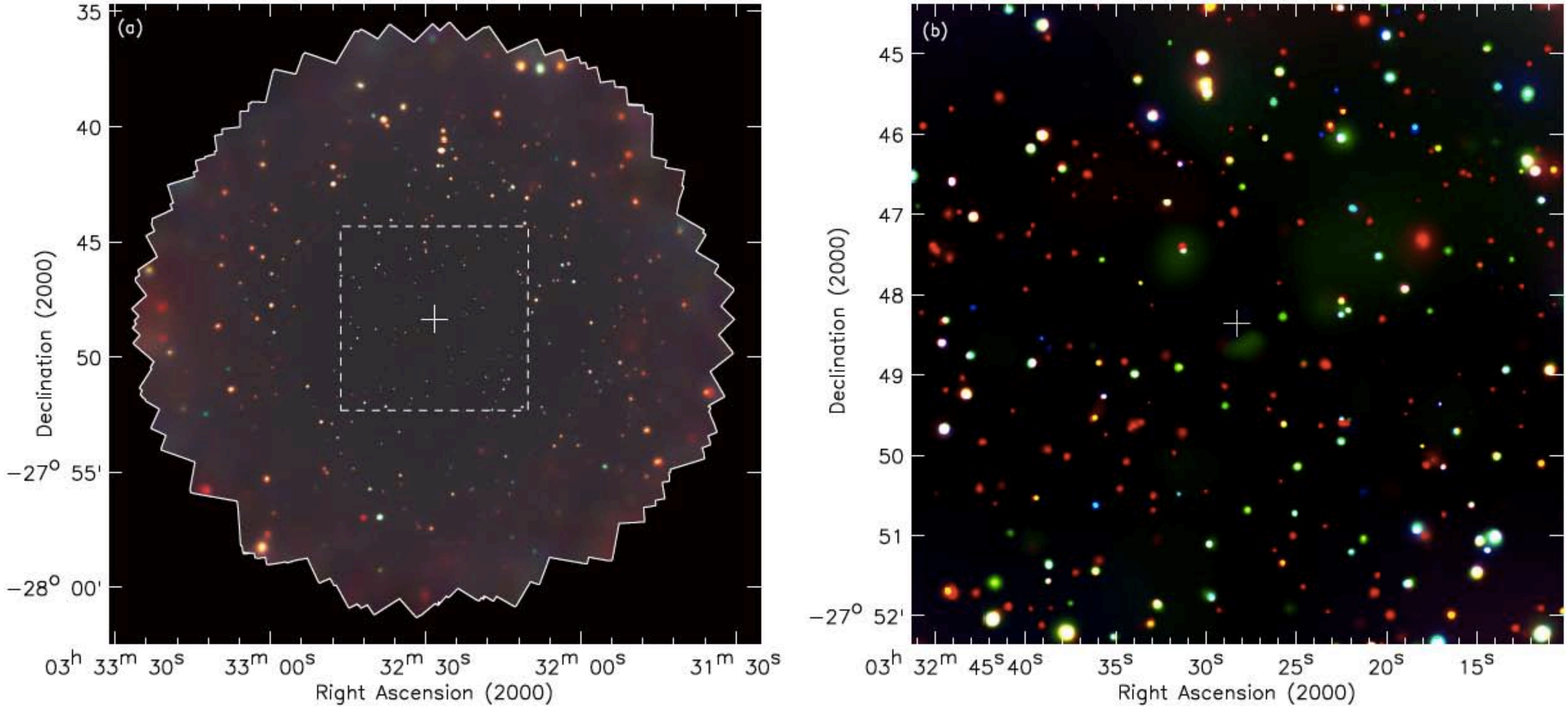
Stars are usually very weak radio sources, so little stellar contamination.

Generally good radio positions allow efficient follow-up studies.

Often quite incomplete, owing to radio-quietness of many AGNs.



(250 ks Chandra E-CDF-S X-ray false−color image; Xue et al. 2016; cf. the radio one)



We classified AGNs from the detected X-ray sources by selecting sources having X-ray and/or multiwavelength properties significantly different from those of typical normal galaxies. Besides AGNs and Galactic stars, the other X-ray sources are considered to be normal galaxies, although it is possible that some of these galaxies host low-luminosity and/or heavily obscured AGNs where the AGN signatures are not evident based on our selection criteria; some of these missed AGNs could be identified by other means such as X-ray variability

(CDF-S: Xue, Luo, Brandt et al. 2011; Luo, Brandt, Xue et al. 2017)

We classified an X-ray source as an AGN if it satisfies one of the following six criteria: (1) $L_{X,int} \geq 3 \times 10^{42}$ erg s^{-1} (luminous X-ray sources), (2) $\Gamma_{eff} \leq 1.0$ (hard X-ray sources),[42] (3) X-ray-to-optical flux ratio of $\log(f_X/f_R) > -1$, where f_X is, in order of priority, the full-band, soft-band, or hard-band detected flux, and f_R is the R-band flux, (4) spectroscopically classified as AGNs, (5) X-ray-to-radio luminosity ratio of $L_{X,int}/L_{1.4GHz} \geq 2.4 \times 10^{18}$, (6) X-ray-to-NIR flux ratio of $\log(f_X/f_{Ks}) > -1.2$. The first five criteria were described in

As more data become available,
more selection criteria can be applied.

(CDF-S: Xue, Luo, Brandt et al. 2011; Luo, Brandt, Xue et al. 2017)

AGN terminology and unification

Examples of AGN Names (No Ordering Implied)

Seyfert 1 galaxy

BAL Quasar

Radio Loud Quasar

FR I

Radio-Quiet Quasar

Blazar

Broad Line Radio galaxy

OVVs

Seyfert 2 galaxy

Narrow-Line Radio Galaxy

LLAGN

FR II

Narrow-Line Seyfert 1

LINER

BL Lac Object

Type 2 Quasar

Weak Line Quasars

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Key Classification Variables

Strength of Radio Emission

- Radio-Loud Quasar vs. Radio-Quiet Quasar

Optical/UV Emission-Line Properties

- Seyfert 1 galaxy vs. Seyfert 2 galaxy
- Type 1 Quasar vs. Type 2 Quasar
- Broad Line vs. Narrow Line Radio Galaxy
- Also intermediate Seyfert types, Narrow-Line Seyfert 1, BL Lac, Weak-Line Quasar

Also Variability and UV Absorption-Line Properties

Luminosity is also often used in classifications for largely historical reasons; usually not so fundamental (e.g., Seyferts are just low-luminosity quasars).

AGN zoo: 3 dimensional classification: optical spectral type, radio properties, and L

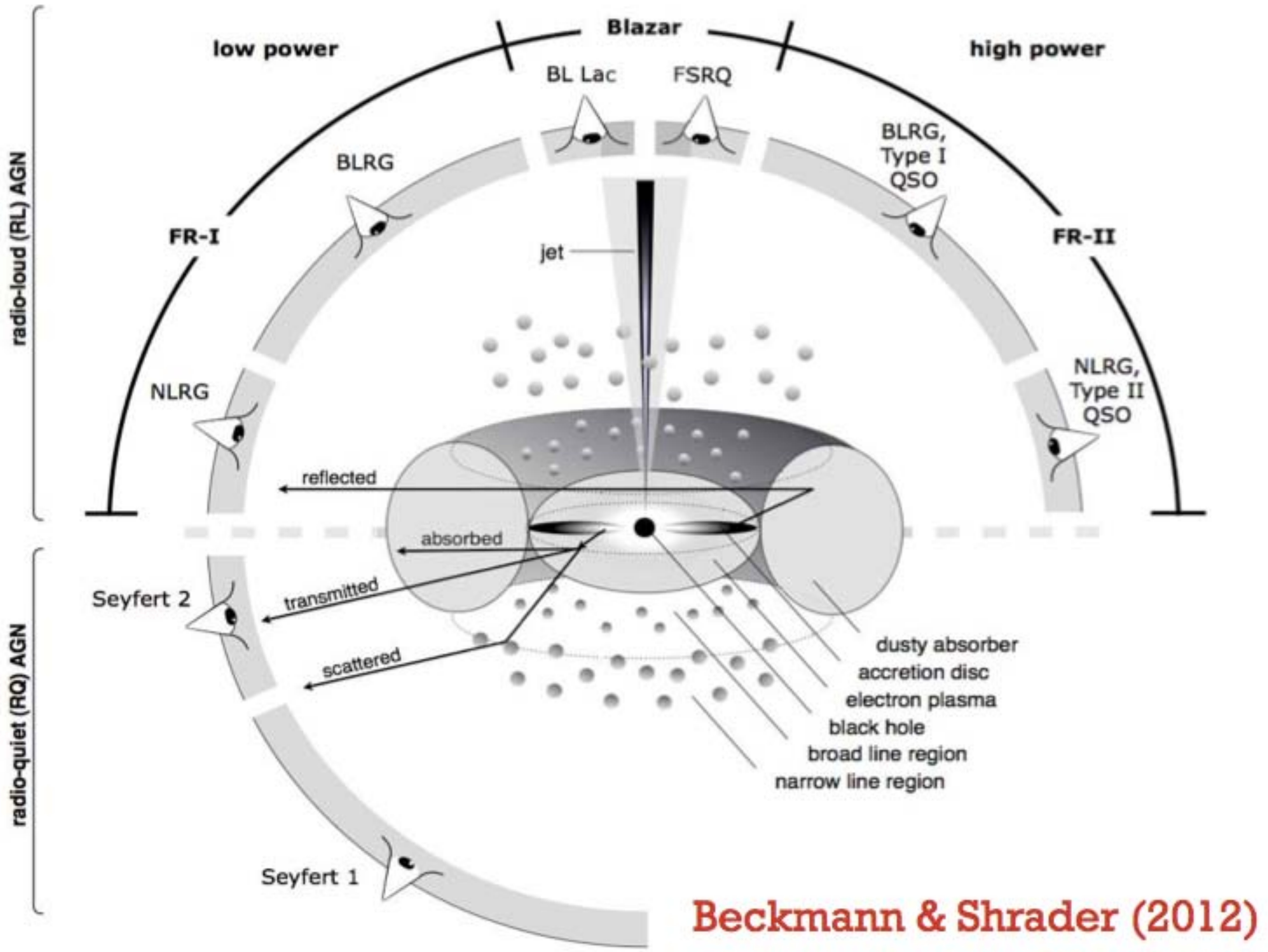
Name	Optical spectral type?	Radio Loud?	Luminosity?
Seyferts	1, 1.2, 1.5, 1.8, 1.9, 2.0	No	Moderate
Quasars	1, 2	No	High
LINERS or low-luminosity AGN	1, 2	Yes and No	Low
Broad-line Radio Galaxies (BLRGs)	1	Yes	Moderate
Narrow-line Radio Galaxies (NLRGs)	2	Yes	Moderate
Radio-loud quasars	1, 2	Yes	High
FRIs	1	Yes	Low
FRIIs	1, 2	Yes	Low-High
Blazars	0!!!	Yes	Low-High

Radio sub types

Beast	Pointlike	Broad-band	Broad Lines	Narrow Lines	Radio	Variable	Polarized
Radio-loud quasars	Yes	Yes	Yes	Yes	Yes	Some	Some
Radio-quiet quasars	Yes	Yes	Yes	Yes	Weak	Weak	Weak
Broad line radio galaxies (FR2 only)	Yes	Yes	Yes	Yes	Yes	Weak	Weak
Narrow line radio galaxies (FR1 and FR2)	No	No	No	Yes	Yes	No	No
OVV quasars	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BL Lac objects	Yes	Yes	No	No	Yes	Yes	Yes
Seyferts type 1	Yes	Yes	Yes	Yes	Weak	Some	Weak
Seyferts type 2	No	Yes	No	Yes	Weak	No	Some
LINERs	No	No	No	Yes	No	No	No

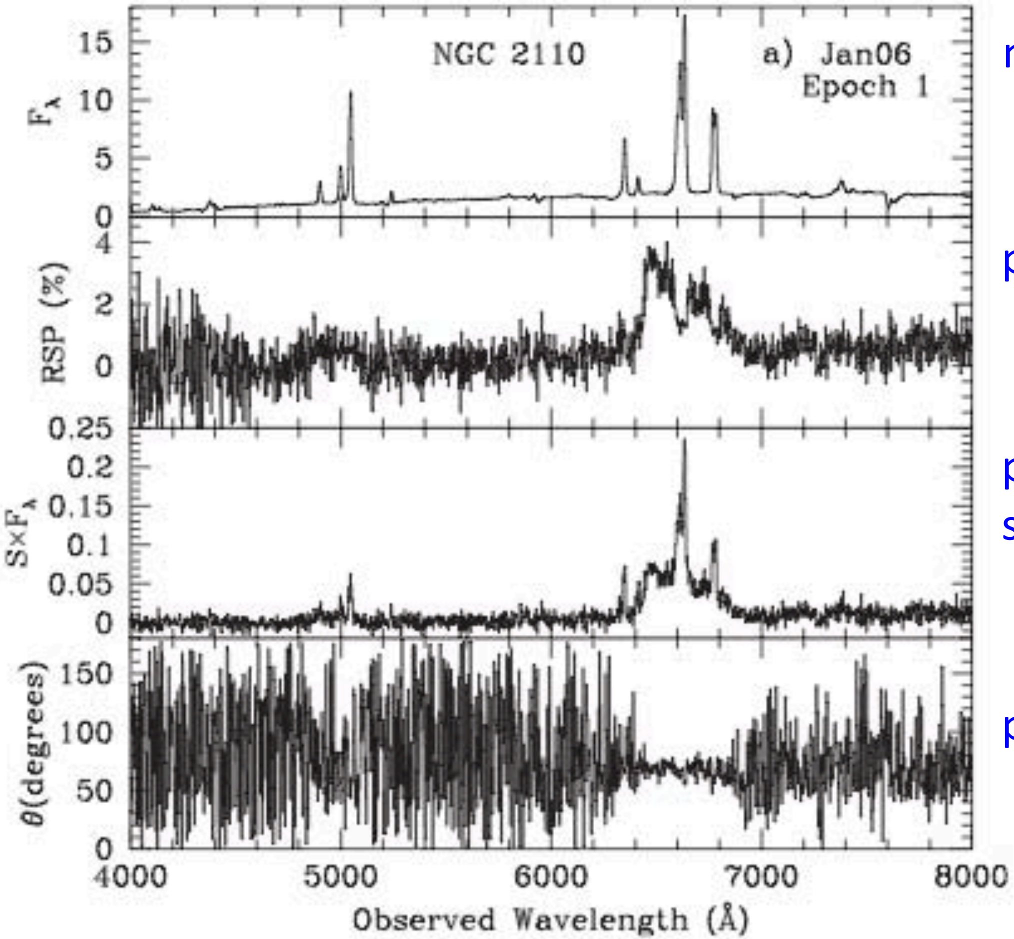
The AGN bestiary (Krolik 1999)

Orientation-based unification model for AGNs



Beckmann & Shrader (2012)

Unification evidence (1)



normal type II spectrum

percentage polarization P

polarized light:
spectrum*P

polarization angle

Figure 6.2. Spectropolarimetry of the type-II source NGC 2110 (from Tran, 2010; reproduced by permission of the AAS). The top panel shows the "normal" spectrum of a typical type-II AGN with strong narrow emission lines. The central panel shows the percentage polarization, and the bottom panel is the polarized light obtained only by multiplying the two upper panels by each other at every wavelength. The bottom panel is the angle of polarization. The polarized light shows a typical type-I spectrum with a broad, double-peak Hα line confirming the presence of a continuum source, and broad emission lines, behind the obscuring material.

X-rays and the Unified Model

Additional evidence for the unified model comes from studies of X-ray absorption and iron K line emission in Type 2 AGNs.

The X-ray opacity of gas is strongly energy dependent, and high-energy X-rays can in many cases pierce through the torus.

This enables the column density through the torus to be estimated, with values of 10^{22}-10^{24} cm^{-2} often being found.

Some Type 2 AGNs have very large column densities that cannot be pierced even with high-energy X-rays – these are called "Compton-thick" AGNs.

Additional evidence for the unified model comes from the very high EWs of iron K line emission in some Type 2 AGNs. The large EW arises when the direct continuum is blocked but the torus and/or mirror are able to produce iron K lines.

Distributions of intrinsic photon index and N_H

(Liu et al. 2017: 7Ms CDF-S results)

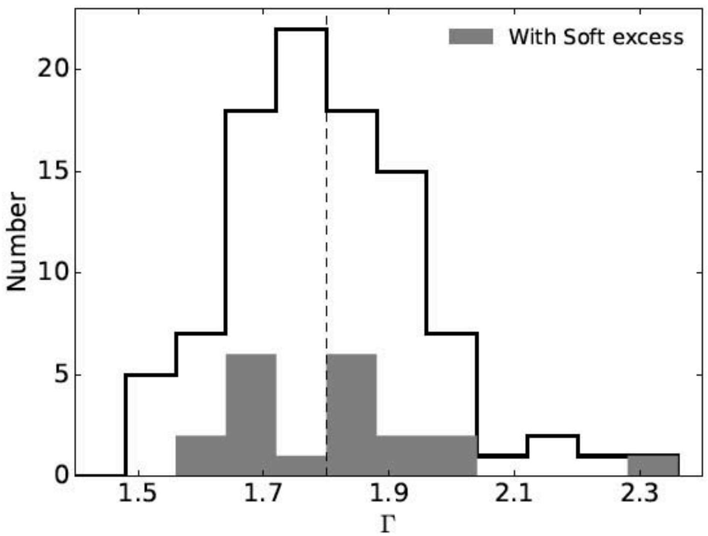


Figure 4. The distribution of best-fit Γ for the 97 sources for which we are able to measure the power-law slope. The vertical line shows the median value of this distribution (Γ = 1.8). The shaded part corresponds to the sources which have soft excess component detected.

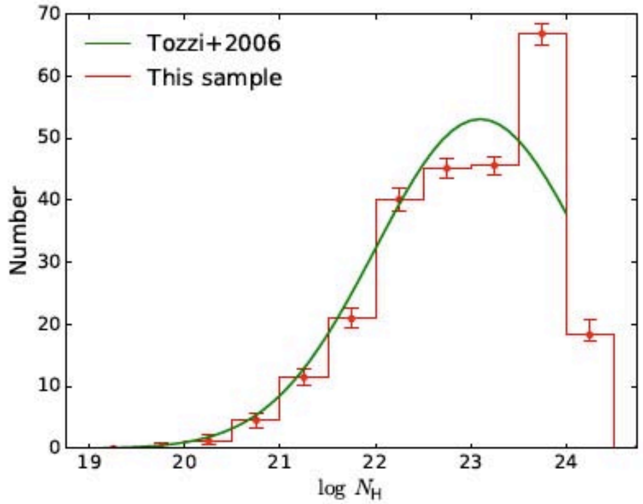
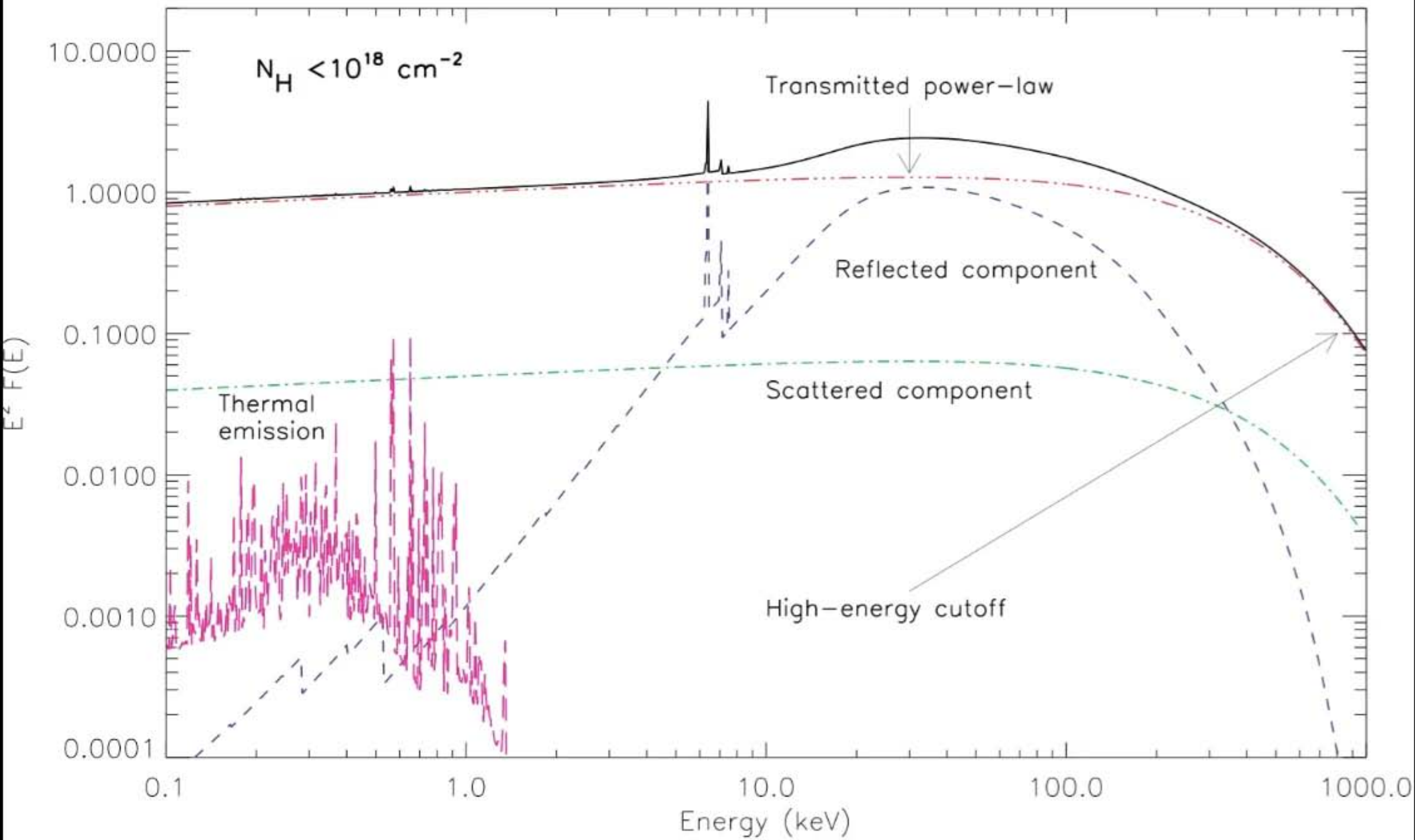


Figure 25. Intrinsic N_H distribution of our whole sample, summing up the intrinsic N_H distributions in the four redshift bins as shown in Figure 24. The green line which is derived from the 1Ms CDFS by Tozzi et al. (2006), is a log-normal distribution centered at 23.1 with a σ=1.1 and normalized to the integration of the distribution of this work between 19 and 24.



(http://www.isdc.unige.ch/~ricci/Website/AGN_in_the_X-ray_band_files/AGN_xrayspec.mov)

Unification evidence (4)

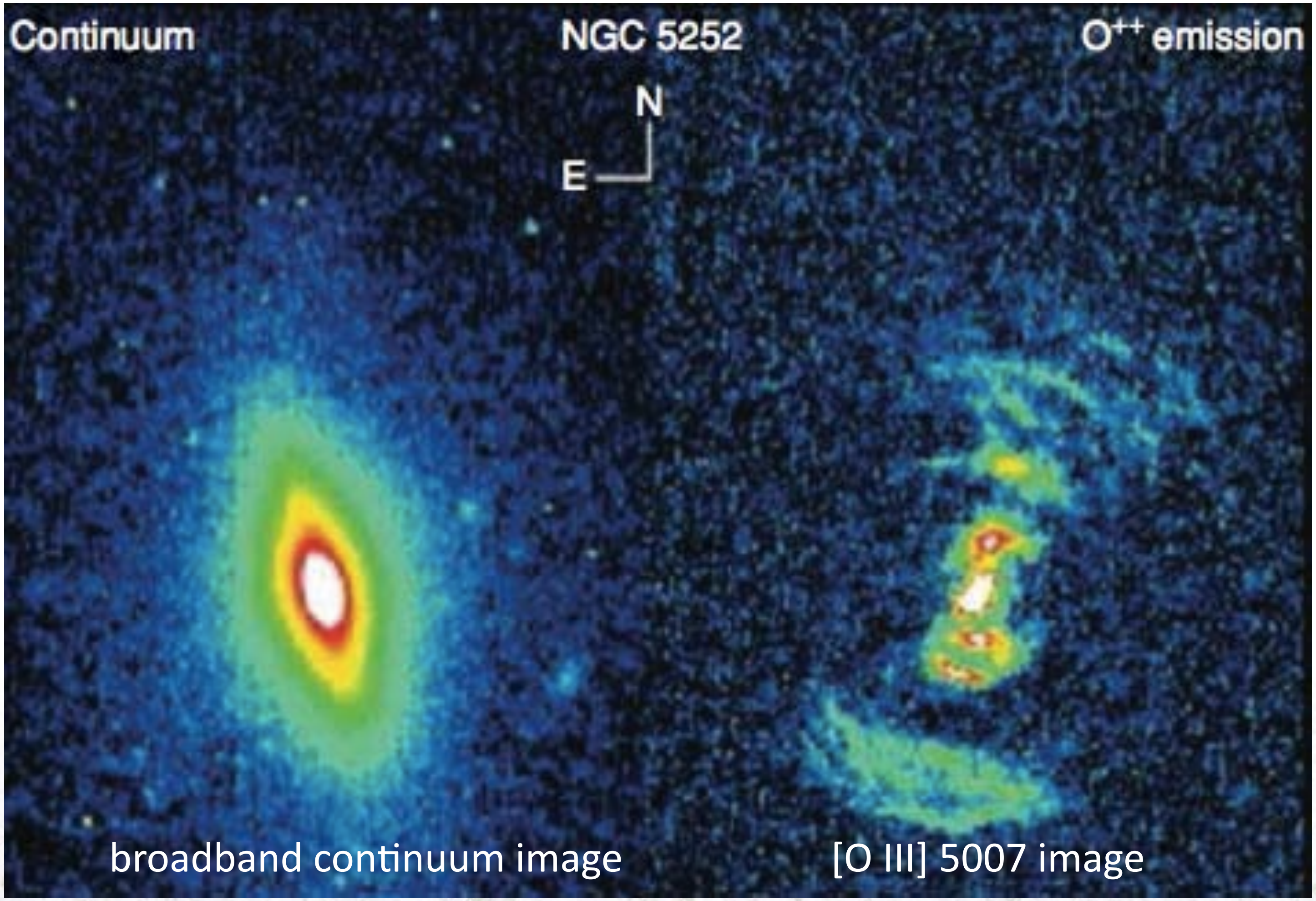


Figure 6.4. Optical images of the type-II AGN NGC 5252. (left) Broadband continuum image. (right) [O III] λ5007 image showing the central double-cone structure of ionized gas (courtesy of C. Tadhunter). (See color plate)

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The Circinus galaxy (Marconi et al. 1994)

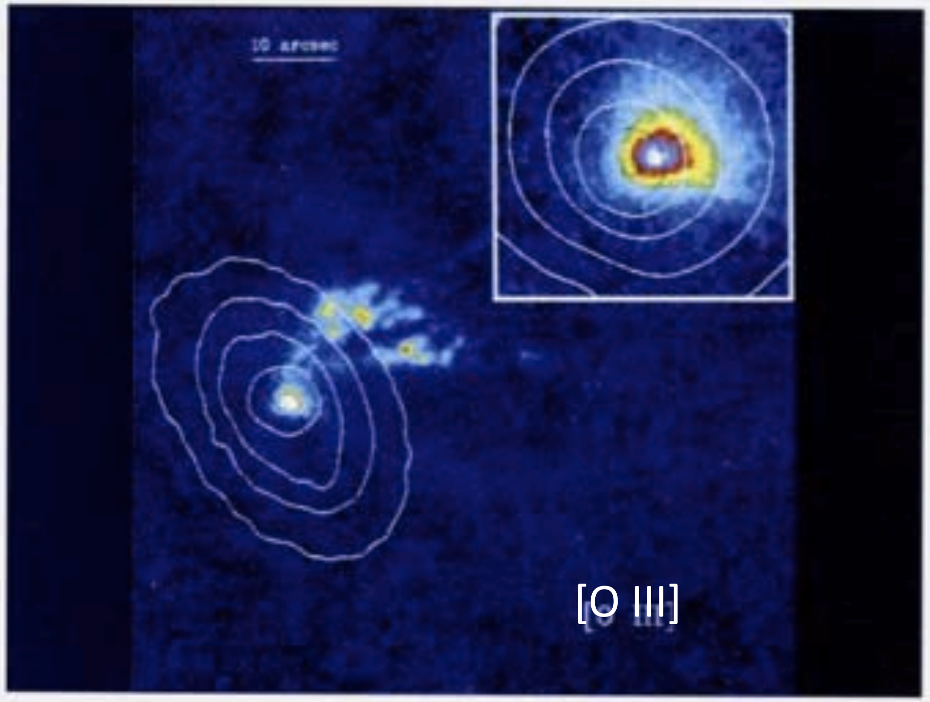


Figure 3: *Same as Figure 1 but in the [OIII] line. Note the clear cone-shaped structure and the displacement between the line and K' continuum peaks.*

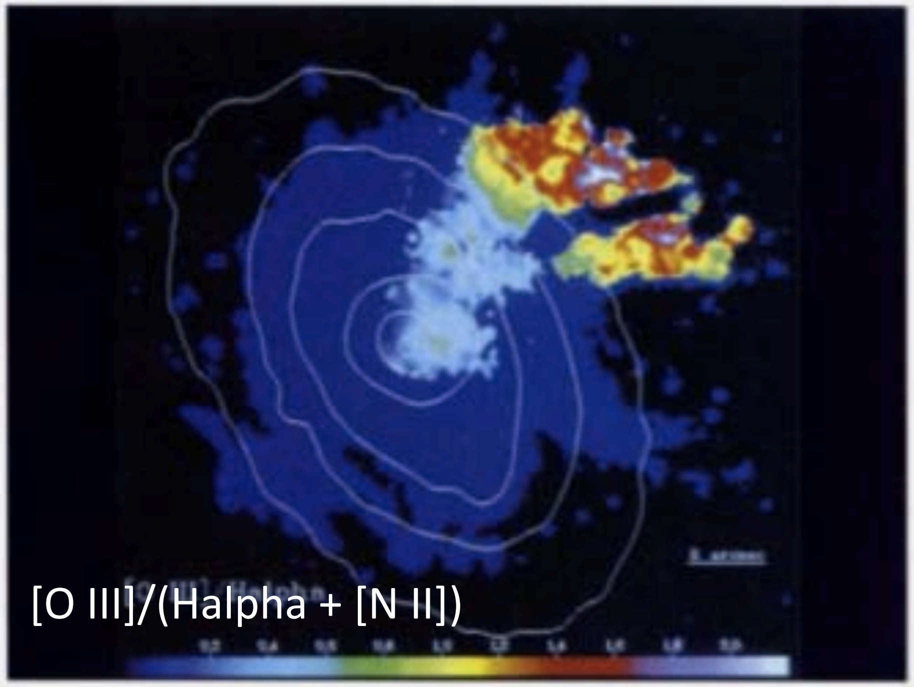
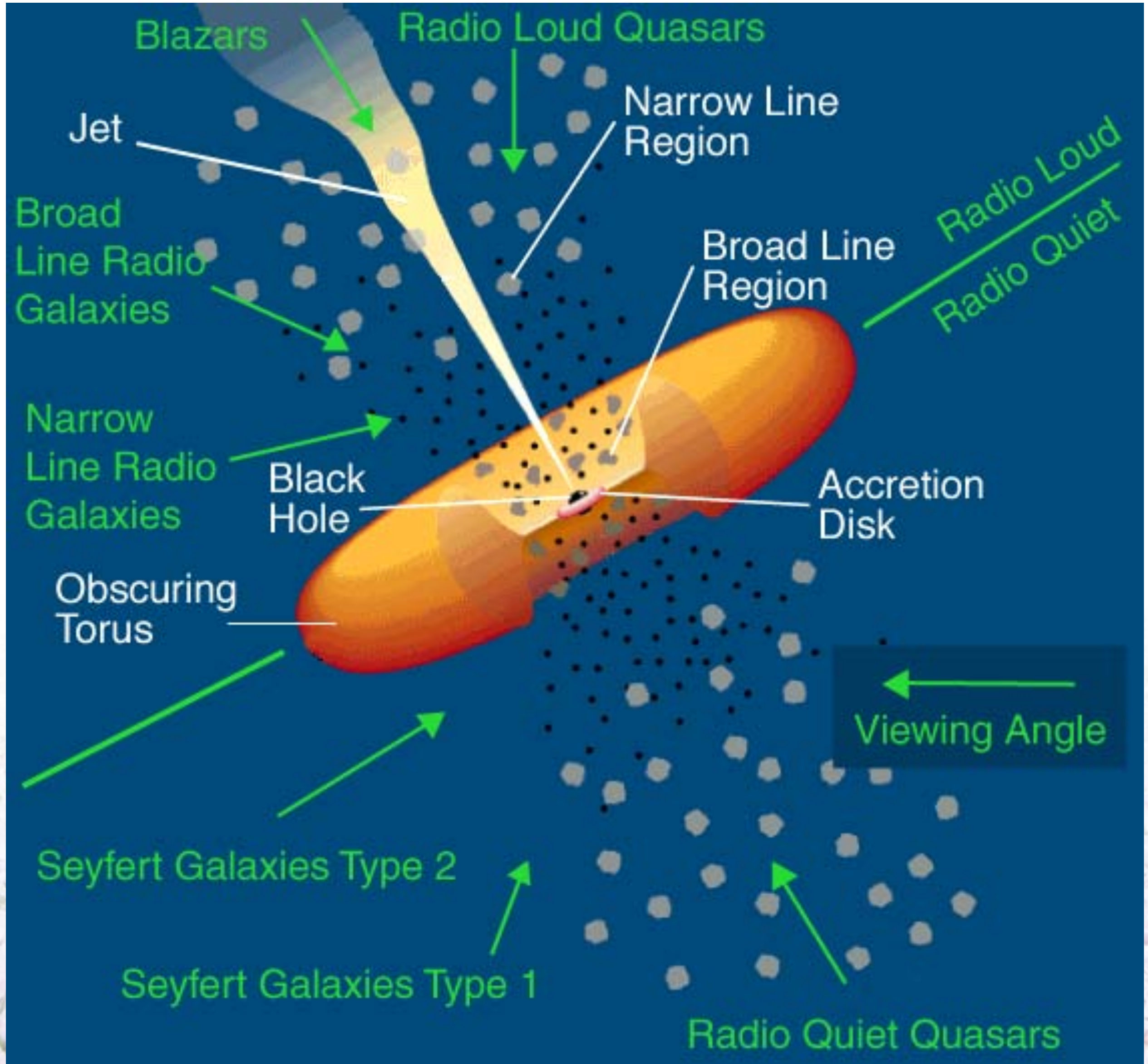


Figure 6: *[OIII]/(Hα+[NII]) showing the ionization structure of the cone. The uniform dark blue region is where Hα+[NII] but not [OIII] was detected at more than 10σ.*

Orientation-based unified models for AGNs



(NASA)

The end