Starburst Galaxies

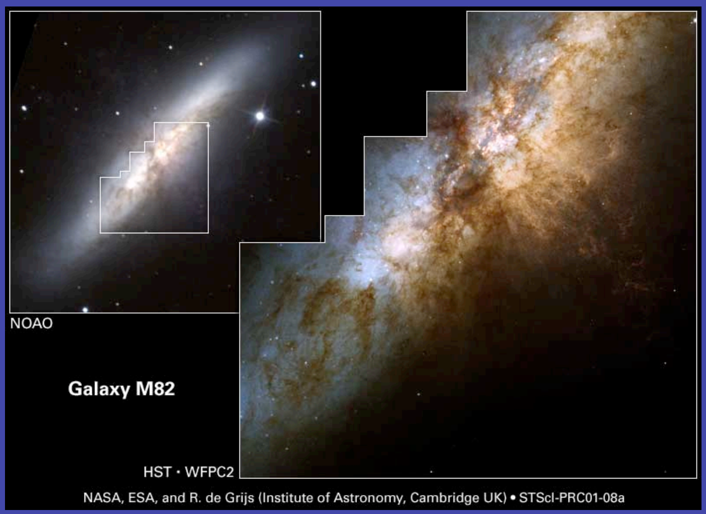
SBG: Galaxy experiencing intense, short lived period of star formation

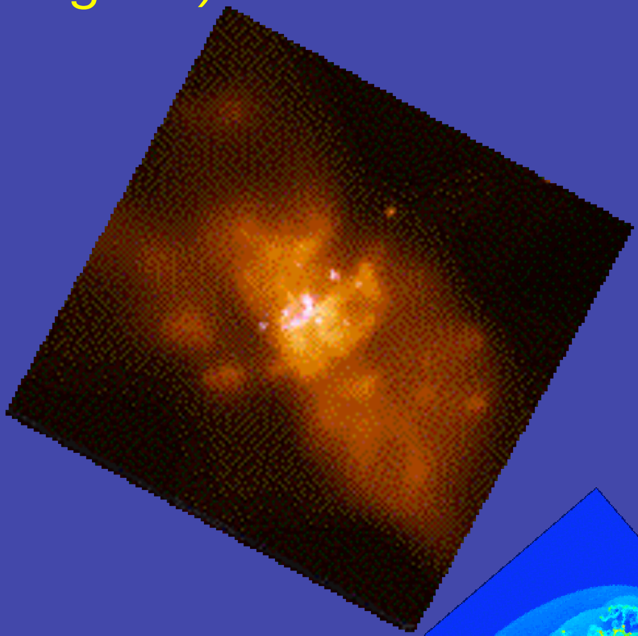
SFR 10-100x greater than normal

Intense IR sources

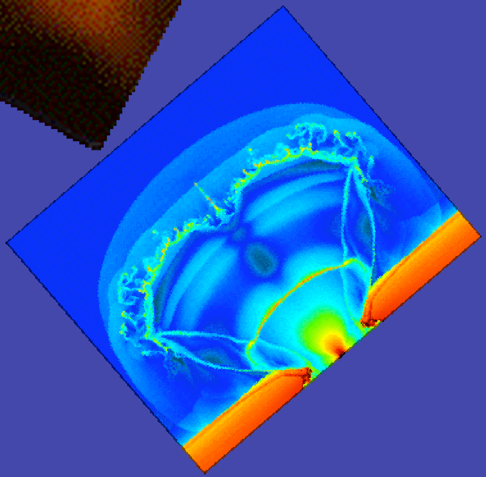
M82: Canonical Starburst

M82 is an irregular galaxy (a “disk” irregular) which has SFR~10 SFR_{MW}.





Rapid SF produces lots of SNe which can blow a hole through the galaxy, and feed the IGM.



LIRGS

LIRGs: Luminous Infrared Galaxies; emit up to 90% of their bolometric luminosity ($L_{bol} \sim 10^{11}\ L_{O}$) in the IR. Most found in interacting/merging galaxies which are rich in molecular gas.

LIRGs either

- starburst galaxies where the starbursts occur in dense molecular clouds which heats dust which re-radiates the stellar flux in the IR
- or possibly a newly formed AGN which is swallowing lots of molecular gas, producing high IR luminosity
- ULIRGs: can have as much luminosity as a low-luminosity AGN

Wolf-Rayet Galaxies

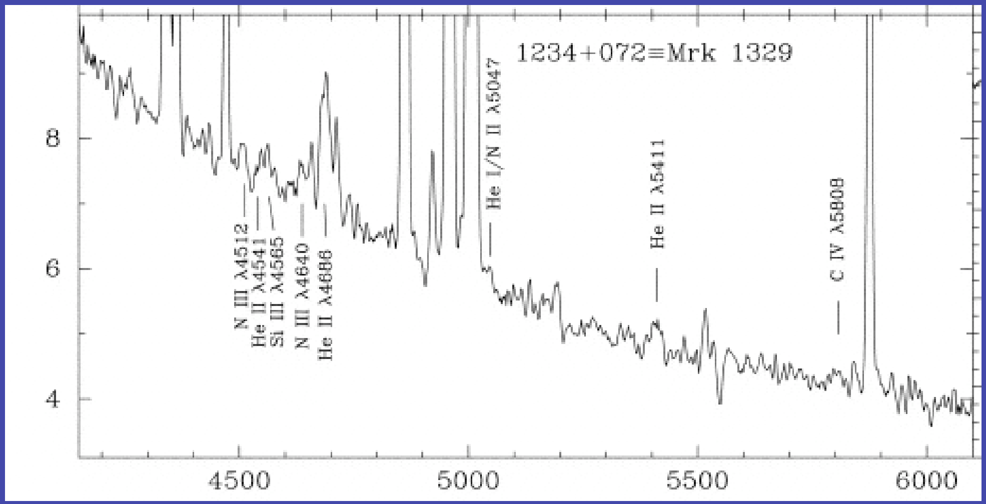
Wolf-Rayet (WR) galaxies have integrated spectra which show direct signatures from Wolf-Rayet stars (evolved very massive stars), most commonly a broad HeII 4686 feature originating in the stellar winds of these stars. (Schaerer et al. 1999, Astronomy & Astrophysics Supplement Series, 1999, **136**, 35-52)

Large variety of galaxy types (SBs, Irrs, blue compact dwarf ellipticals, etc)

About 137 known

Help constrain starburst process in starburst galaxies

Mass-loss process at different redshifts, metallicities



Guseva & Izotov 2000, ApJ 531, 776

Active Galaxies

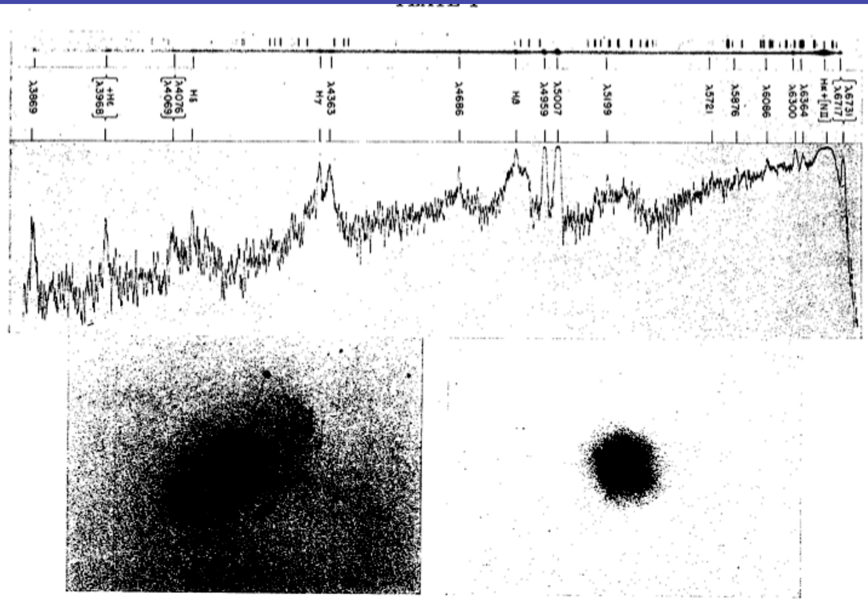
Active Galaxies are those which have bolometric luminosities which are orders of magnitudes larger than “normal” galaxies

Activity usually/often confined to a small region (nucleus) near the center of the galaxy

Often exceptionally bright at very high energies (X-rays, gamma-rays) and very low energies (radio)

Seyferts

1st type of active galaxy was identified in 1943 by Carl Seyfert



NGC 4151

Spectrum, microphotometer tracing, and direct photographs. The spectrum is an enlargement from a 325^{m} exposure taken with the one-prism Cassegrain spectrograph and 10-inch camera at the 60-inch reflector. The photographs (enlargements from a plate taken with the 100-inch reflector) show the weak, amorphous arms on the left and the semistellar nucleus on the right.

This class (Seyfert galaxies) have bright nuclei which dominates the optical emission; emission lines from highly ionized species; deeper observations show that they are spiral galaxies

About 2% of spirals are Seyferts

Type I: Broad emission lines ($\Delta\lambda/\lambda \sim 1000$ km/s)

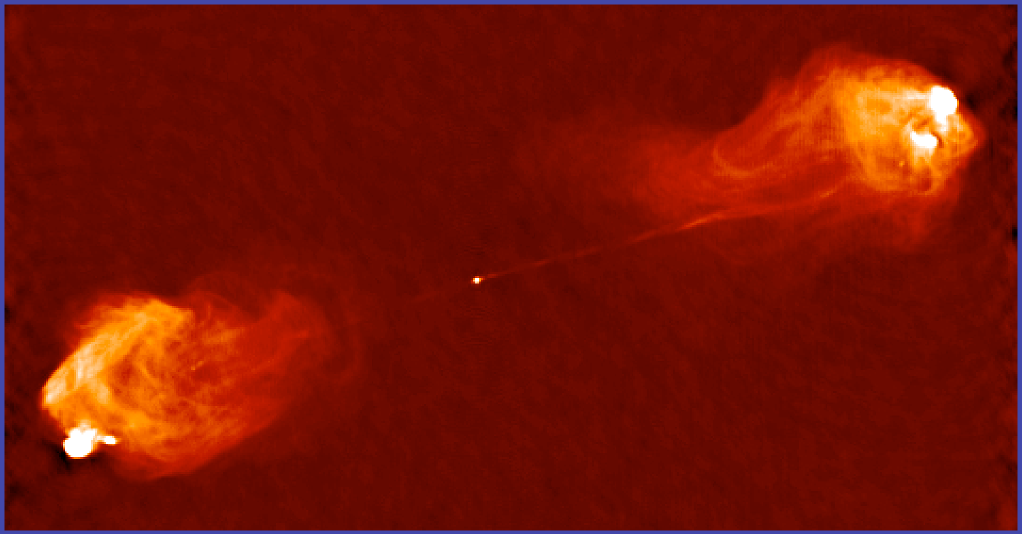
Type II: Narrow emission lines ($\Delta\lambda/\lambda \sim 100$ km/s)

Radio Galaxies

Radio surveys at Cambridge in the 1960's found strong radio emission; sources often resolved into oppositely directed lobes.

Sometimes there might be a central pointlike object between the lobes

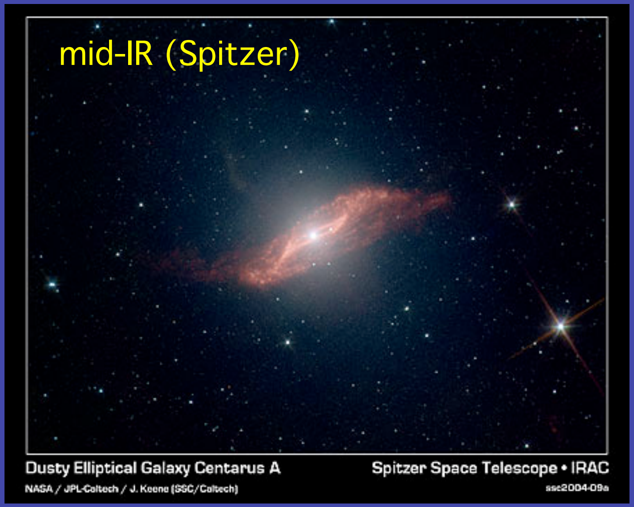
Followup observations show that jets come from a central elliptical galaxy

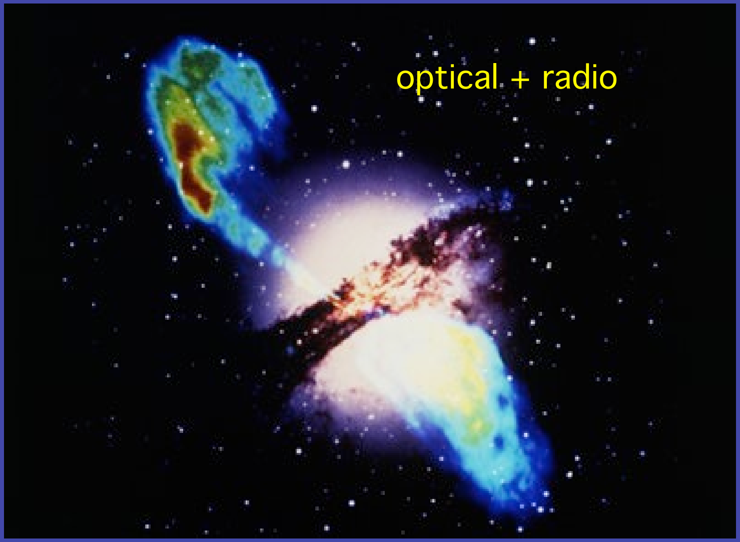


Cygnus A: 6cm radio
(Ward, M. J., Blanco, P. R., Wilson, A. S. & Nishida, M. Ap.J.382, 115.)

Example: Cen A

Centaurus A is one of the best studied radio galaxies, with a peculiar "dusty elliptical" counterpart





Quasars

Quasar: “quasi-stellar radio object” (coined by H. Y. Chiu). Detected as unresolved point sources in early radio catalogs in the 60’s. Strong, unusual emission lines

1963: Maarten Schmidt realized that the emission lines in 3c273 where ordinary H lines at high redshift (z=0.158)

Cosmological (how to explain large luminosities?) or nearby (how to explain large velocities?)

Blazars

Some quasars show extreme variability. These are called Blazars.

Blazar characteristics: high observed luminosity, very rapid variations, high polarization (when compared with non-blazar quasars), and the apparent *superluminal motions* detected along the first few parsecs of the jets (in most blazars).

Blazars are divided into 2 classes:

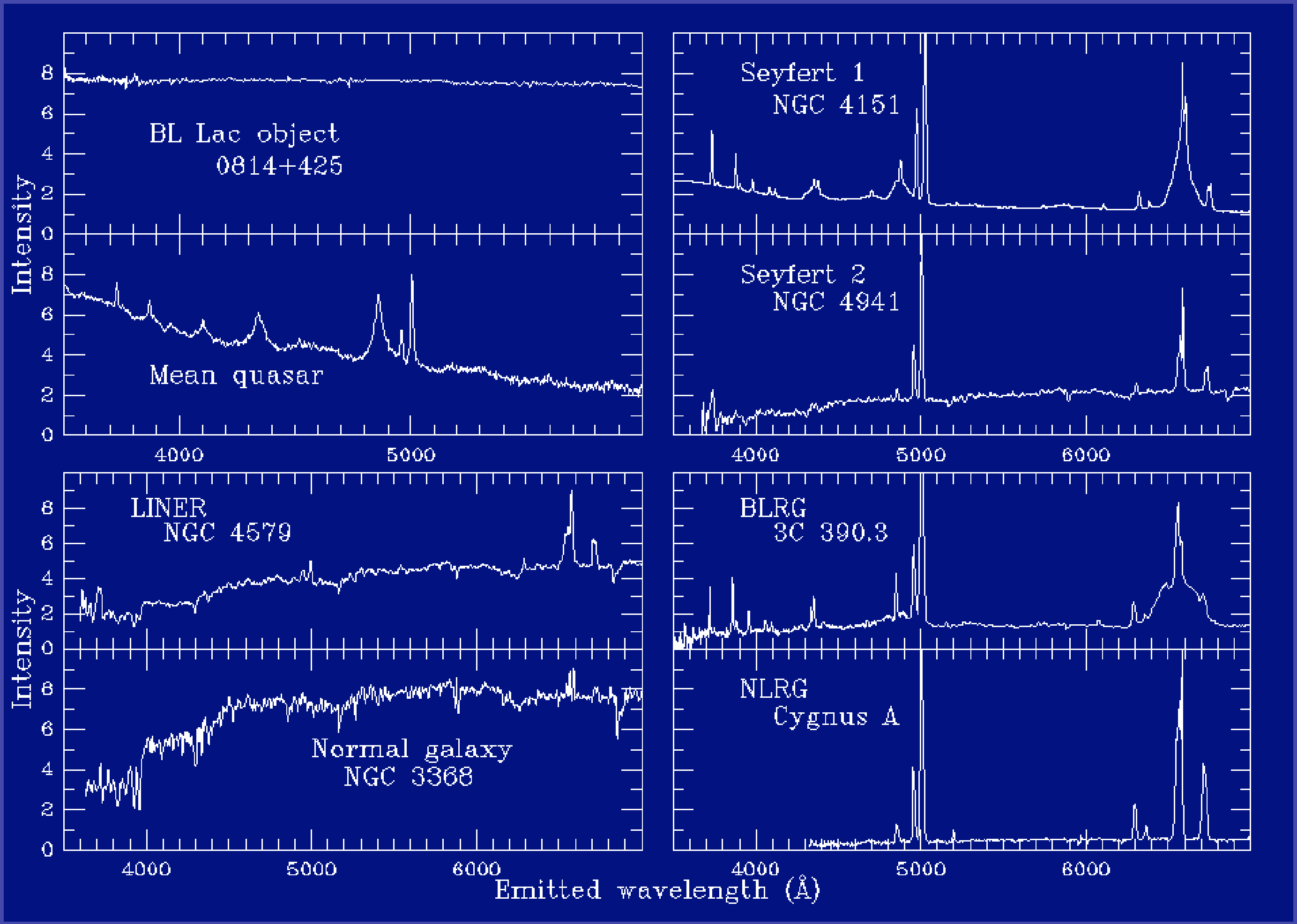
- Optically Violently Variable (OVV) quasars
- BL Lac Objects: radio-loud AGN which lack emission and absorption lines

Liners

Liners: galaxies which show some evidence of activity (point-like nuclei, strong emission lines) but the emission from the nucleus is not as dominant

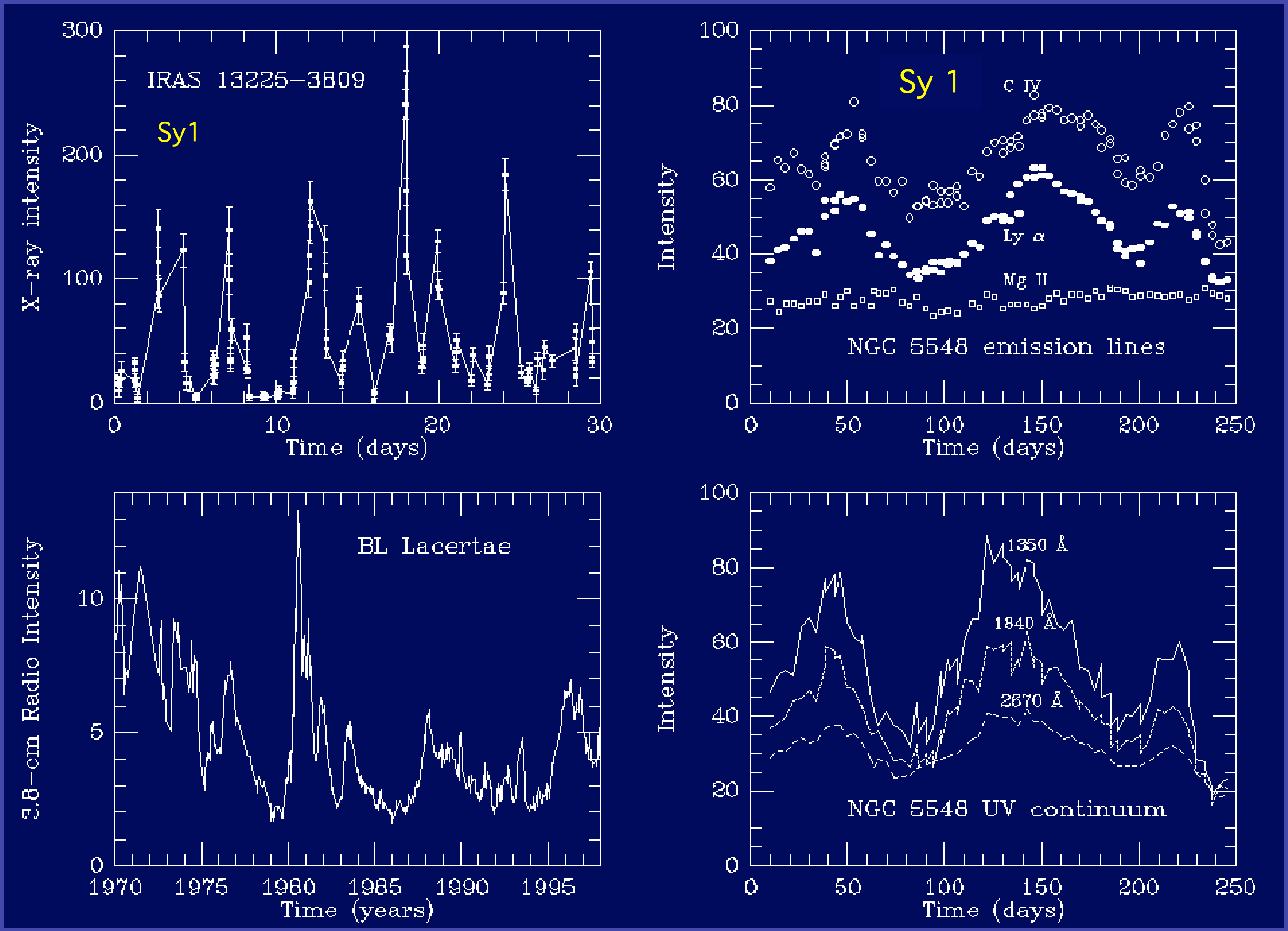
sometimes called LLAGN (Low-luminosity AGN)

Spectra Comparison

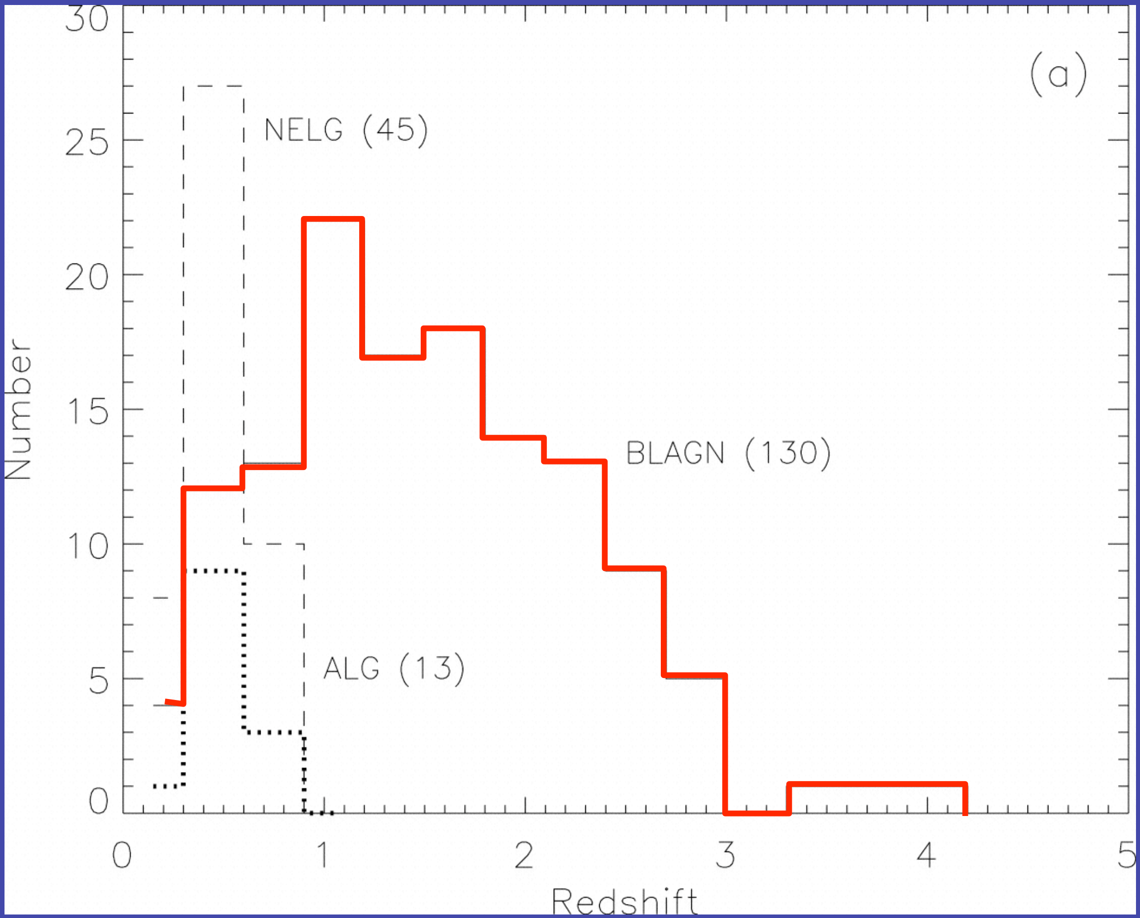


http://www.astr.ua.edu/keel/agn/spectra.html

Timing Comparison



Redshift Distribution



Distribution of X-ray selected active (BLAGN, NELG) and normal (ALG) galaxies vs. redshift from selected Chandra fields

Silverman et al. 2005 ApJ 618, 123

Taxonomy

806 URRY AND PADOVANI

TABLE 1
AGN Taxonomy

Optical Emission Line Properties

Radio Loudness		Type 2 (Narrow Line)	Type 1 (Broad Line)	Type 0 (Unusual)
	Radio-quiet:	Sy 2	Sy 1	
		NELG		
		IR Quasar?	QSO	BAL QSO?
	Radio-loud:	NLRG { FR I	BLRG	Blazars { BL Lac Objects
		FR II	SSRQ	(FSRQ)
			FSRQ	

Black Hole Spin? (↓)

Decreasing angle to line of sight (→)

BLRG: broad-line radio galaxy; SSRQ: steep-spectrum radio quasars; FSRQ: flat spectrum radio quasars; NELG: narrow emission-line galaxy; NLRG: narrow-line radio galaxy; BAL QSO: broad-absorption line qso

Jets

Radio galaxies eject large jets of material. Usually there is a jet on either side of the galaxy.

Jets can also be seen at other wavelengths (optical, X-ray) but are most prominent in the radio.

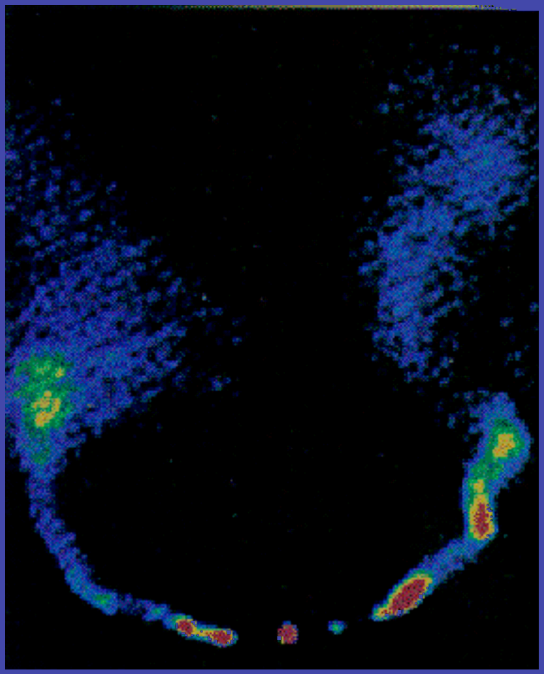
Emission in radio is non-thermal, highly polarized: synchrotron emission (no spectral line diagnostics)

Lengths: 100 kpc - Mpc

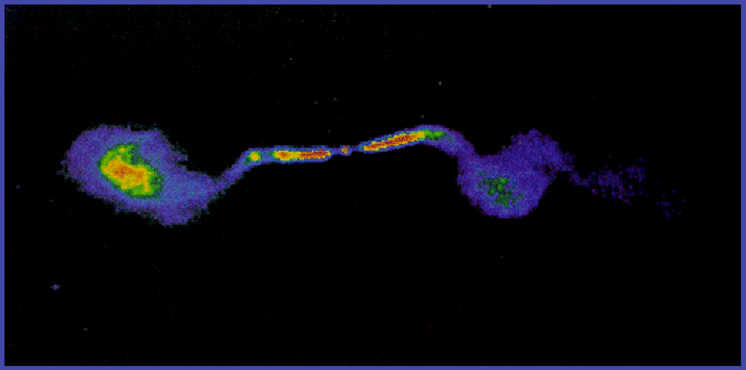
Fanaroff & Riley type I: weaker, 1st half of jet brightest in radio

FRII: stronger, double-lobed, most of emission from the lobes

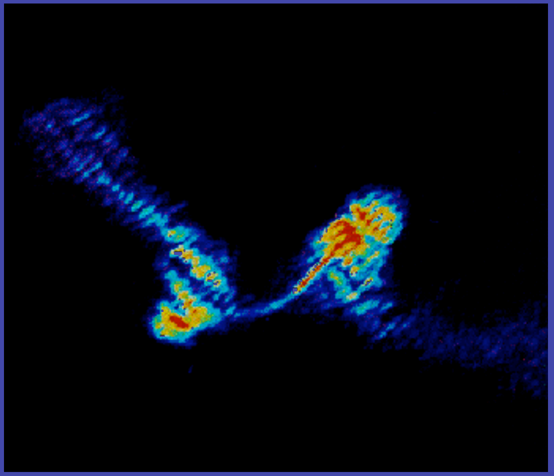
Jet Morphologies



NGC 1265: Wide Angle tail (from motion through IGM?)



3C449: mirror symmetry (host galaxy in orbit around companion?)



NGC 326: kinked jet (precession?)

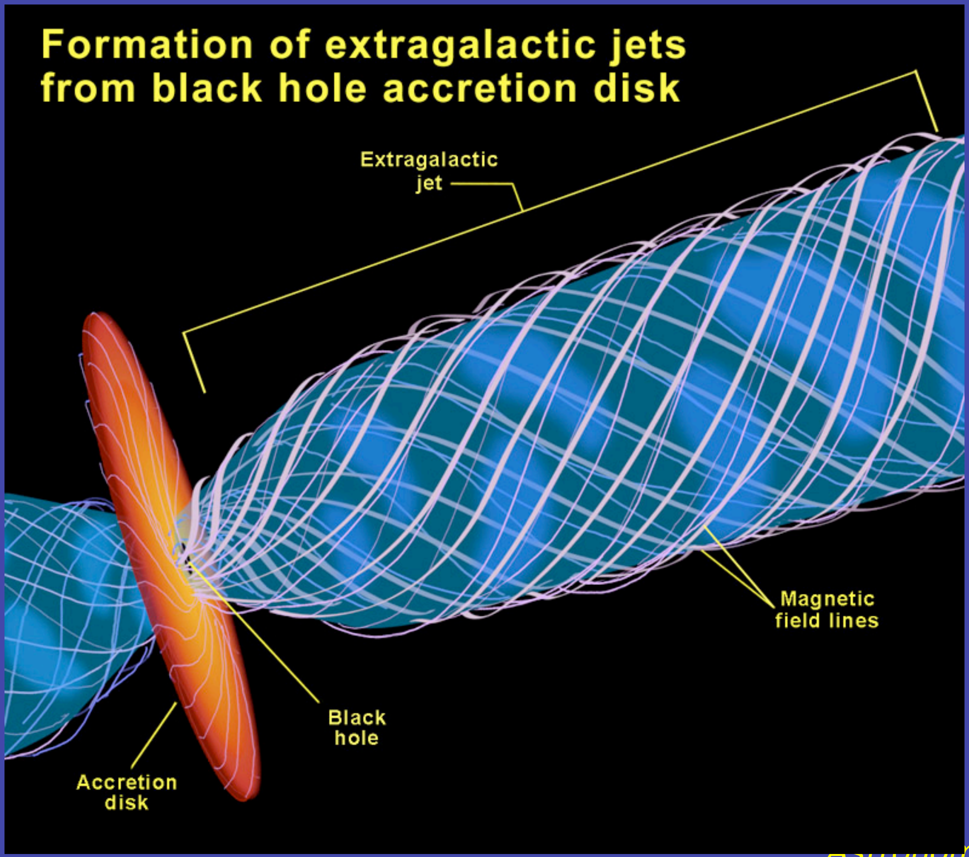
http://cosmos.astroscu.unam.mx/~sergio/phdthesis/phdlatex2html/

(Begelman & Rees, 1996)

Formation of Jets

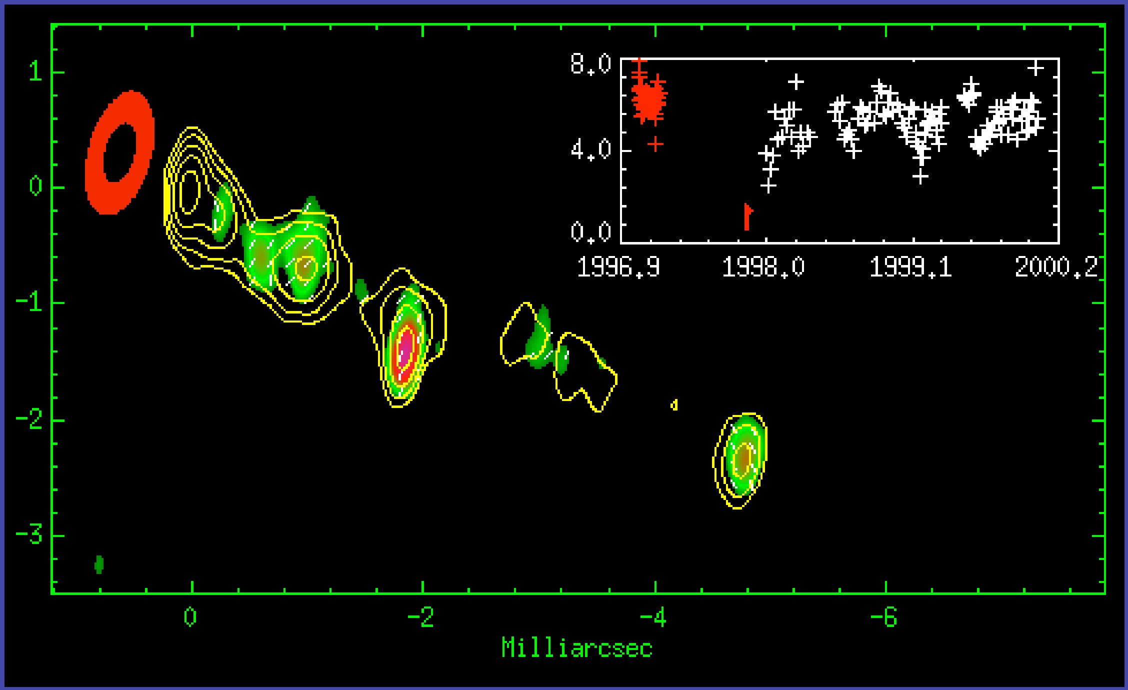
Jet collimation over a Mpc is difficult.

Probably magnetic field near the black hole confines outflow of matter



Behavior of Jets

Very Long Base Array (VLBA) radio observations along with RXTE X-ray observation of the radio galaxy 3c120 show correlated X-ray, radio behavior



contours: radio
inset: RXTE X-ray
green: radio polarization
red/black disk: black hole accretion disk

shortly after the central X-ray source (red) decreases, the inner radio emission increases.

see Marscher et al., http://www.bu.edu/blazars/3c120.html

3c120 & Old Faithful

The inner accretion disk gets swallowed by the black hole;

when this happens, the outer part of the accretion disk gets ejected

Similar phenomena to "Old Faithful" X-ray nova

Relativistic Effects in Jets

A source of radiation moving with velocity $\beta = v/c$ at an angle θ to the line of sight will have an apparent transverse velocity

$$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$

.

$\beta_{app} > 1$ for high β and low θ

A jet moving towards us is Doppler-boosted and looks brighter; if

$$S(\nu) = S_{em}(\nu) D^{(2+\alpha)}$$

where

$$D = \left(\frac{1}{\sqrt{1-\beta^2}} \frac{1}{1 - \beta\cos\theta}\right)$$

is the Doppler boosting factor and the observed frequency ν is related to the intrinsic frequency ν' by

$$\nu = \nu' D.$$

Central Engines

The active galactic nuclei

- very high luminosities ($L \sim 10^{14}\ L_0$ vs. 10^{11-12} for normal galaxy)
- very small ($c\delta t <$ light year)
- very high energies (up to TeV)

Phenomena suggestive of a black hole

By balancing gravity and radiation pressure force on electrons, the mass necessary is

$$M \geq \frac{2r_e^2 L}{3Gm_H c}$$

$$M \geq 7.8 \times 10^8 (L/10^{47}) M_\odot$$

Unified Model

AGNs believed to consist of

- supermassive black hole in the active nucleus
- accretion disk around the BH
- obscuring dust torus around the BH/accretion disk
- relativistic jets emanating from the center of the disk

Matter falls onto the BH releasing gravitational energy

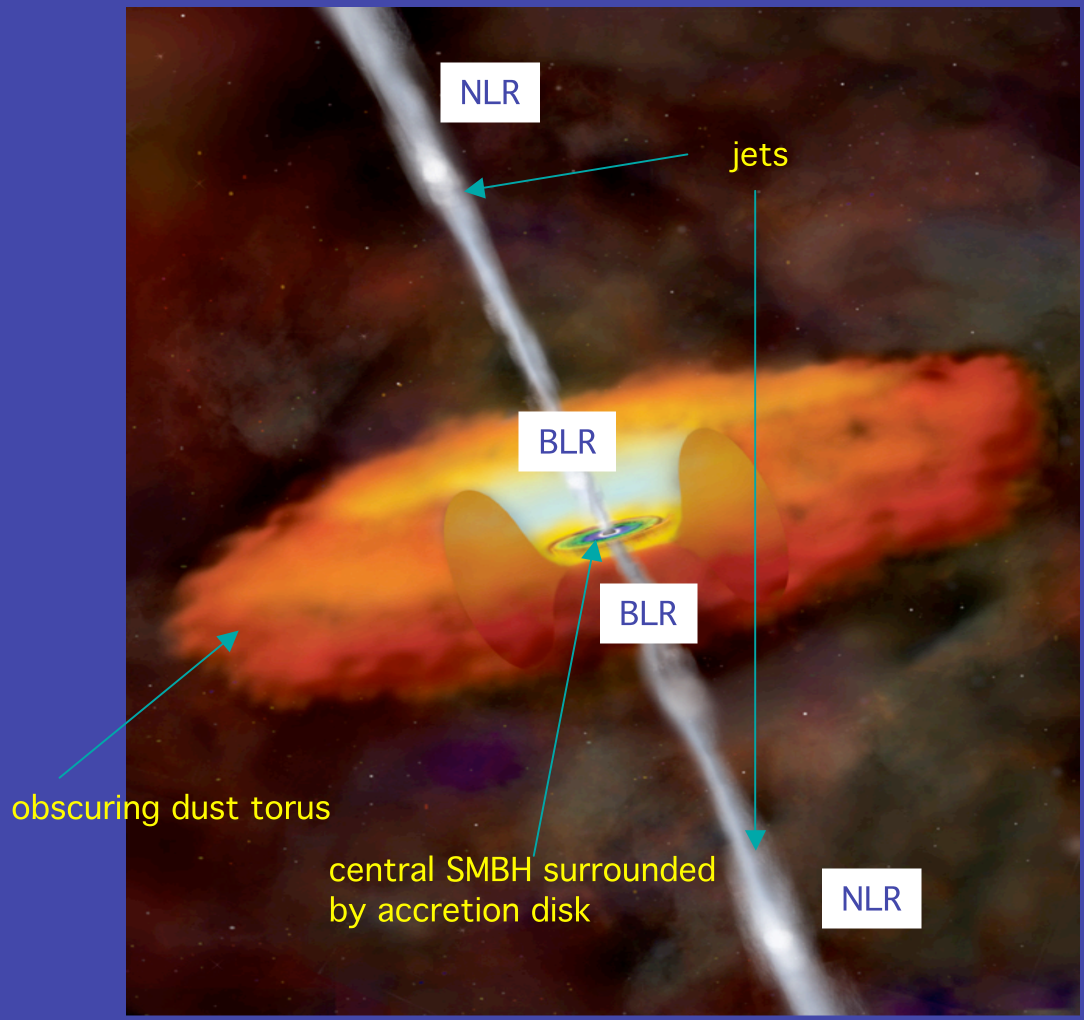
Accretion disk produces UV+soft X

hot electrons above the disk may produce hard X & gamma-rays via inverse Compton scattering

Broad optical, UV emission lines produced in broad-line clouds near the disk/torus

slow moving clouds above the disk/torus produce narrow emission lines

Schematic



The central engine which powers all active galaxies: SMBH+accretion disk + jet + broad-line and narrow line clouds

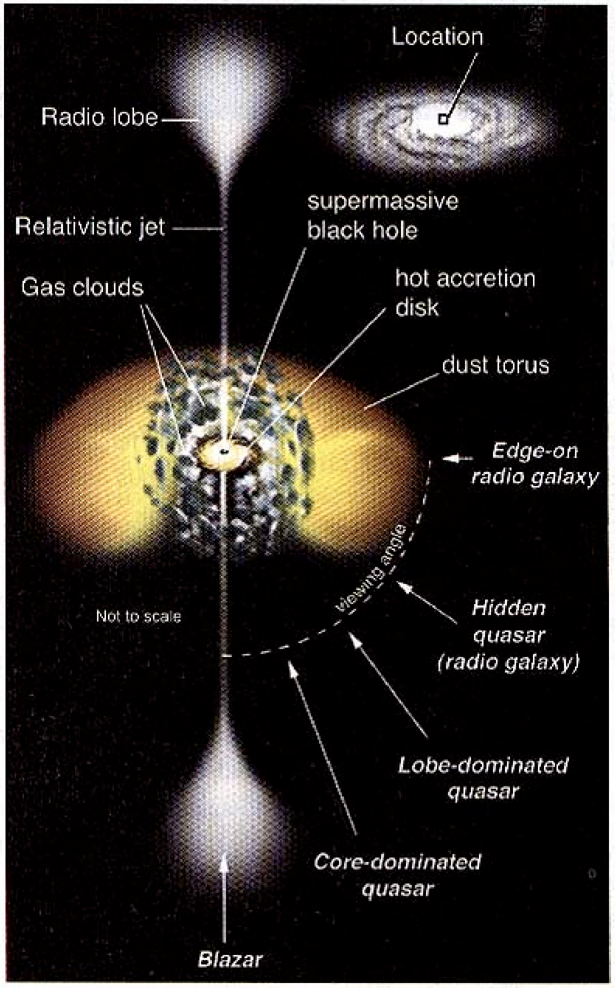
Broad-line clouds: high velocity dispersion, near SMBH

Narrow-line clouds: low velocity dispersion ("cold") far from SMBH

Geometric Phenomenology

AGN types depend on:

- rate at which black hole accretes (low: Liners; high: Quasars, radio galaxies)
- orientation of the axis of the torus/disk to the line of sight: (near 0°: quasars; near 90°: radio galaxies
- SMBH spin
- magnetic field strength, orientation

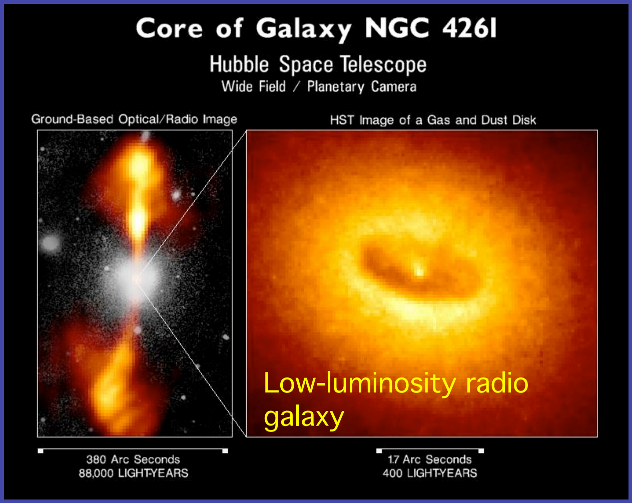


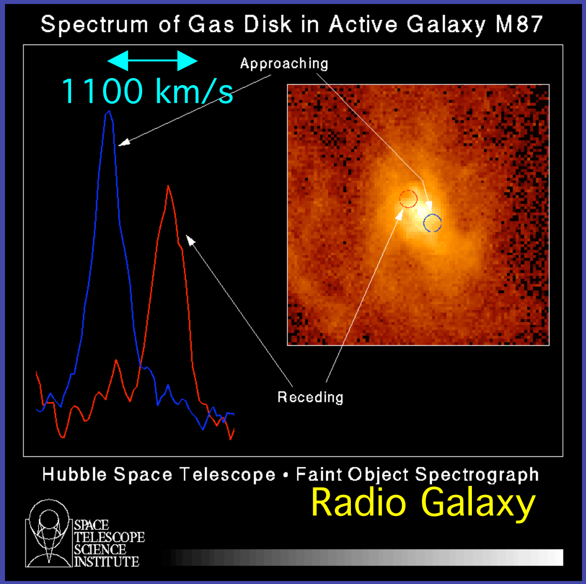
Slanted story. Seemingly diverse astronomical objects may be different views of galactic cores.

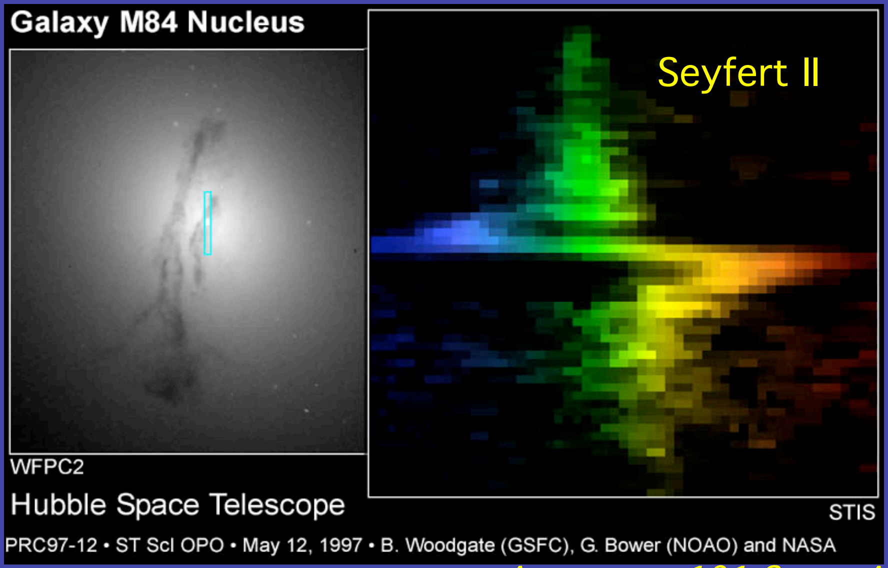
15 June 2001 issue of *Science*

Imaging the Nuclei

High spatial resolution images and spectra show large velocity variations, unresolved central sources, and disk like structures at the centers of some active galaxies







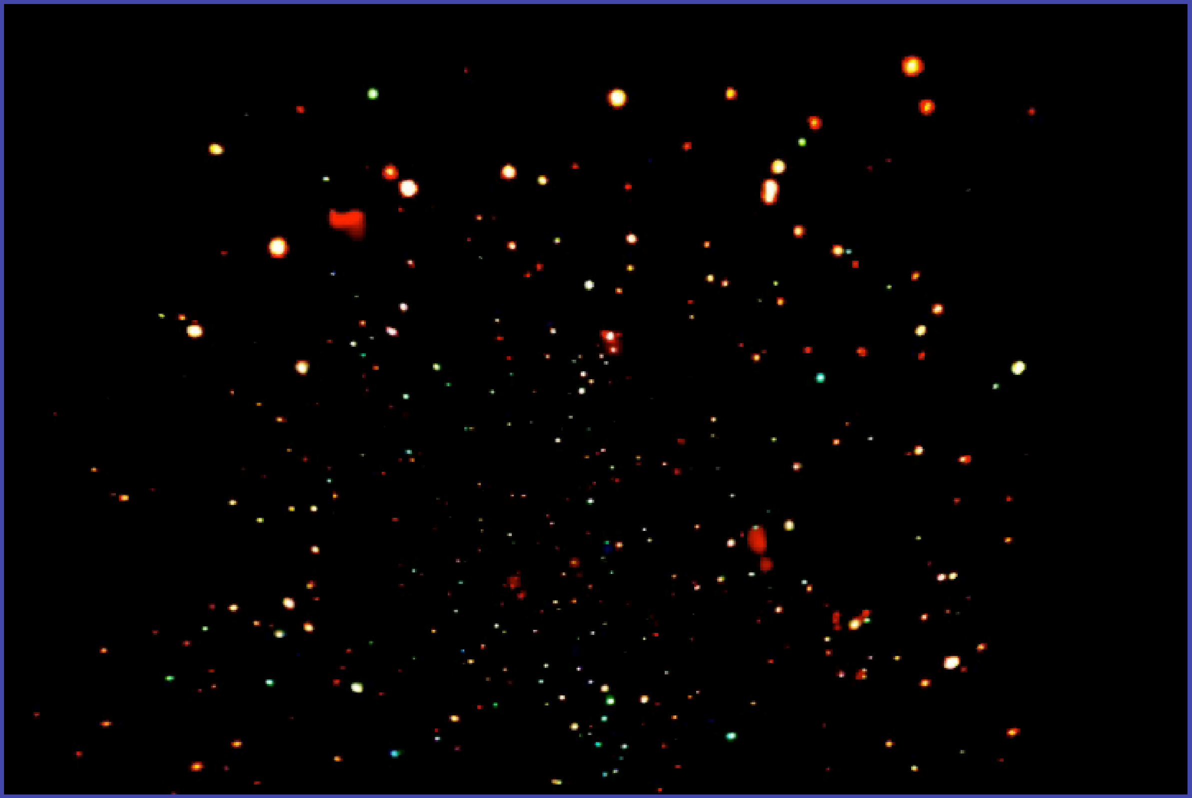
AGN-Starburst connection

Concentrated nuclear starburst (cf. the Arches, Quintuplet clusters in the MW) might help form/feed SMBH:

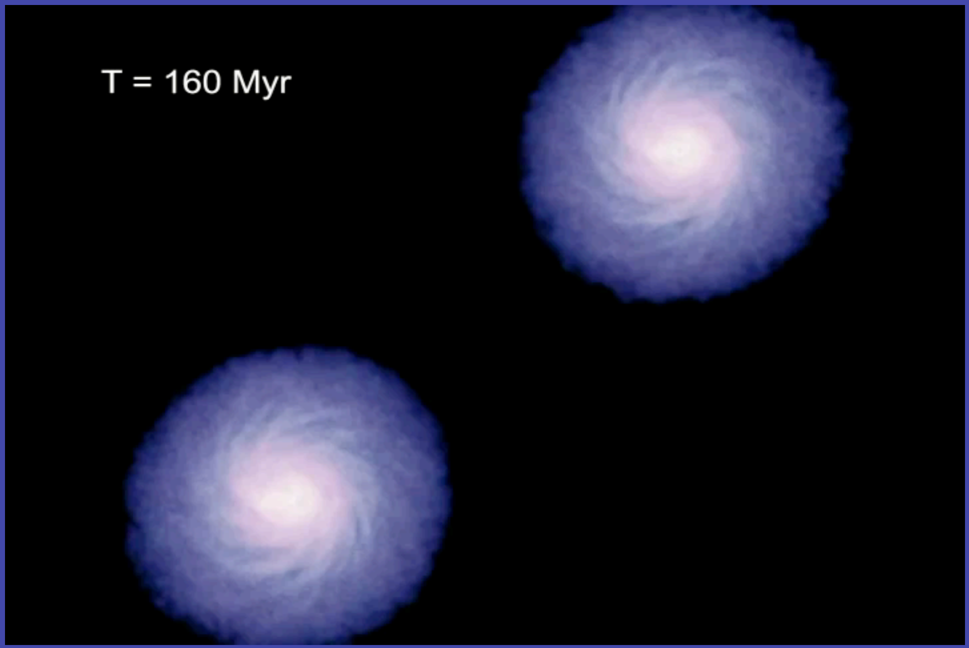
- star formation produces stellar mass black holes which grow by collision/accretion
- explosions may trigger more star formation
- Galaxy mergers: drive gas towards the center of the galaxy, producing star formation and feeding BHs.
- Mergers more common in early Universe?

SMG 123616.1+621513

Chandra "Deep Field" observations shows two sources; followup ground-based submm observations with the JCMT show that the sources are associated with merging/interacting galaxies.



Merger Simulation



brightness=intensity

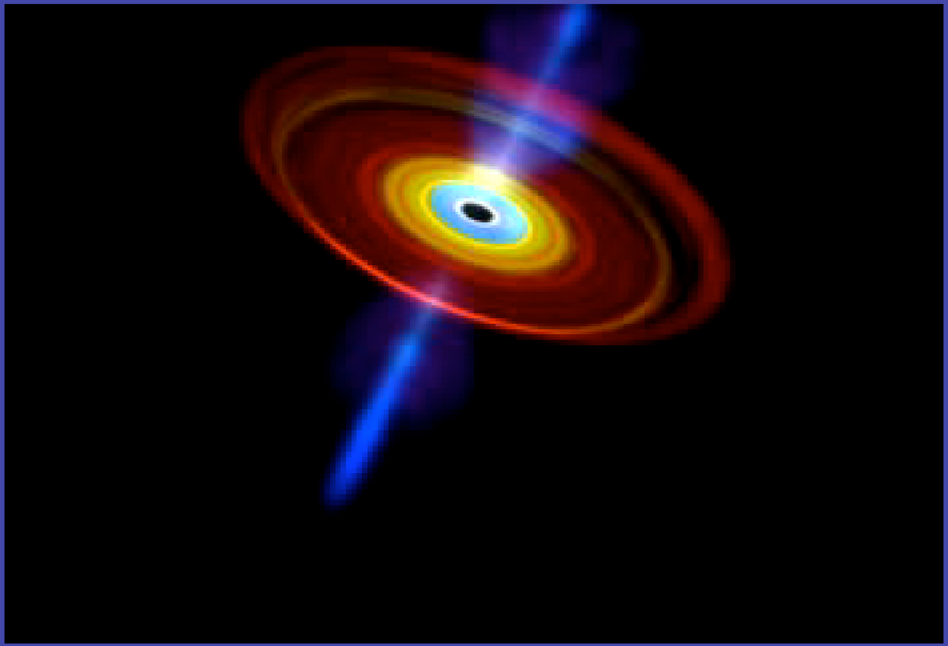
color=temperature

Fe Lines

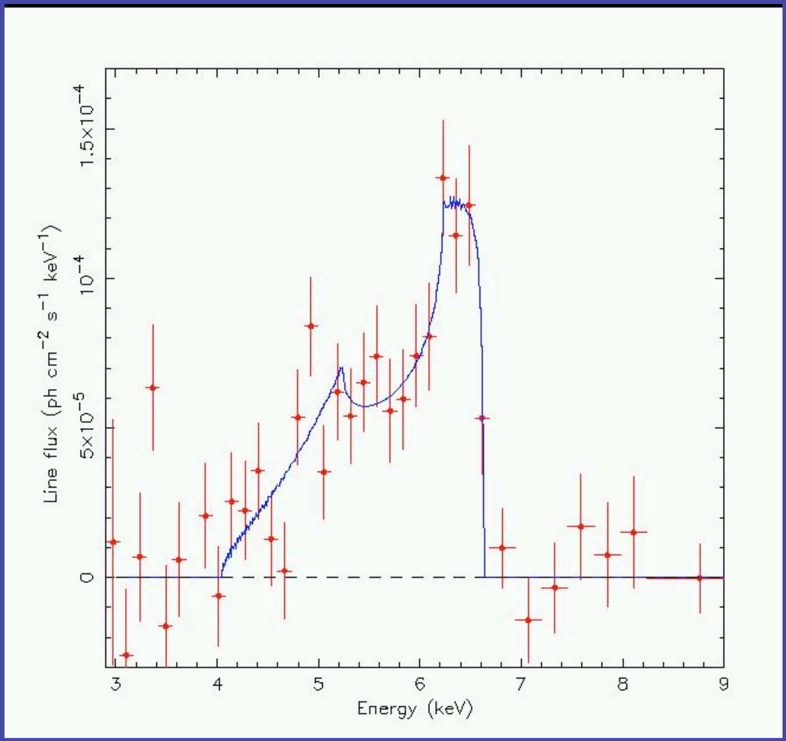
Emission from knots of iron in the accretion disk will give rise to doppler shifted Fe line profiles

Analysis of such line profiles gives:

- distance from the knot to the event horizon
- mass of the black hole



Example: MCG-6-30-15



Tanaka et al., 1995, Nature 375, 659

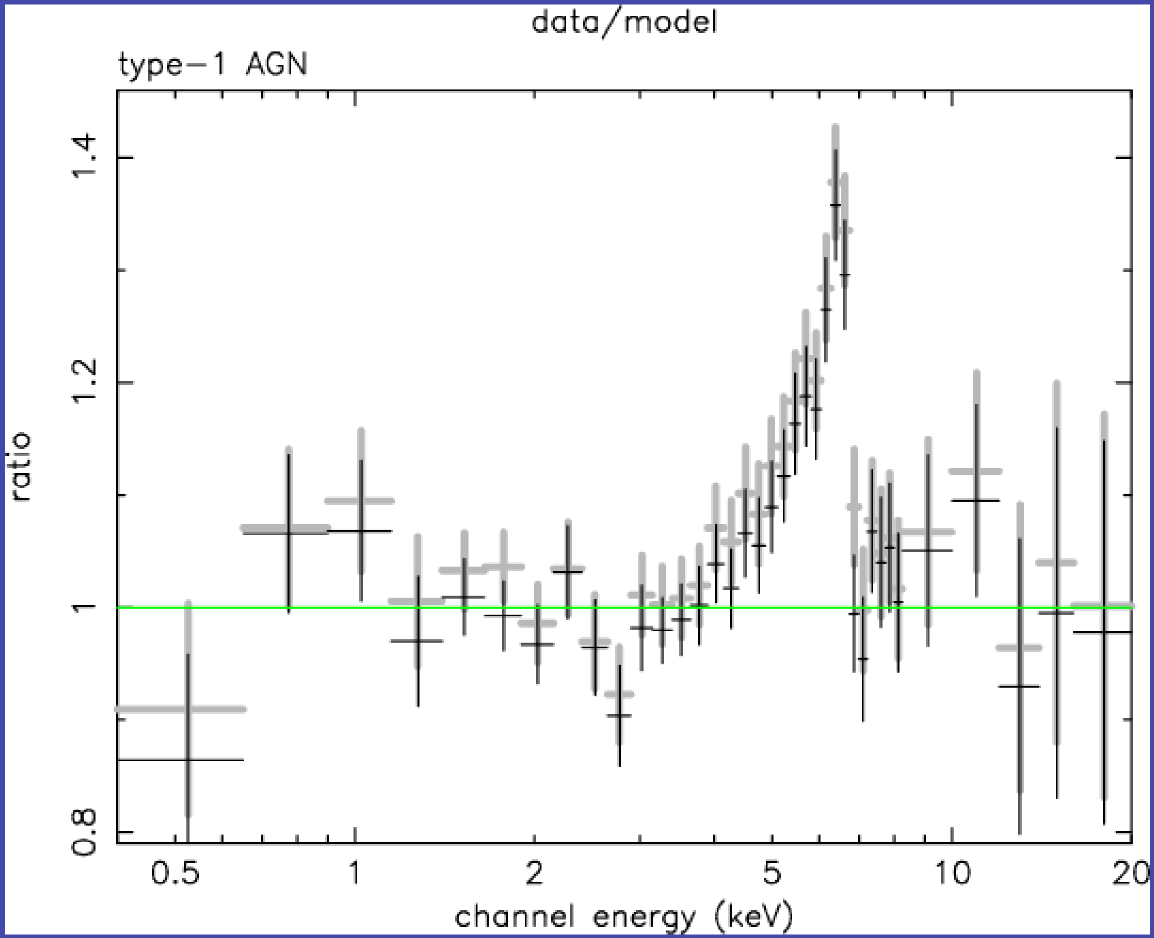
ASCA X-ray spectrometer observations of the Fe line profile in MCG-6-30-15 show very broad, double-peaked profile

indicates distortion by strong gravity near a black hole

speed roughly 0.3c

distance from black hole about 3-10 R_{sch}

XMM Observations of Lockman Hole Galaxies



AGN identified in XMM/EPIC observations of the Lockman Hole field show strong distorted excess above a simple power-law near Fe K line

consistent with emission in the accretion disk

indicates emission inside ISCO for non-rotating black hole: SMBH rotation?

Fe abundance about 3x solar

Streblyanska et al., 2005, A&A, 432, 395

Metallicity

XMM/EPIC spectra of Lockman Hole AGN suggests greater than solar amount of Fe;

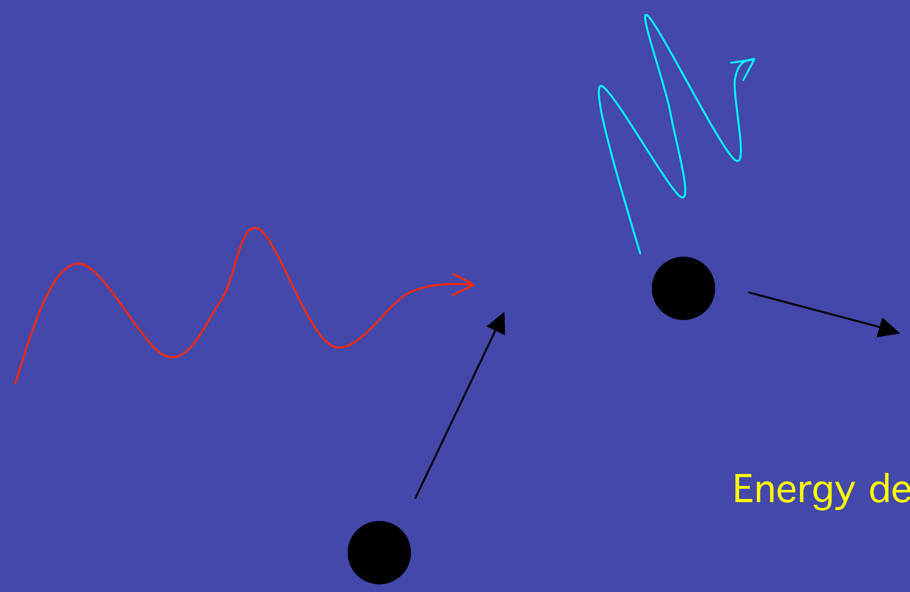
Absorption edge studies of X-ray spectra of a radio quiet AGN (George et al., 1997, ApJ 491, 508) suggests Fe/O 10x solar value.

Suggests high star formation rate in at least some of these galaxies

Acceleration

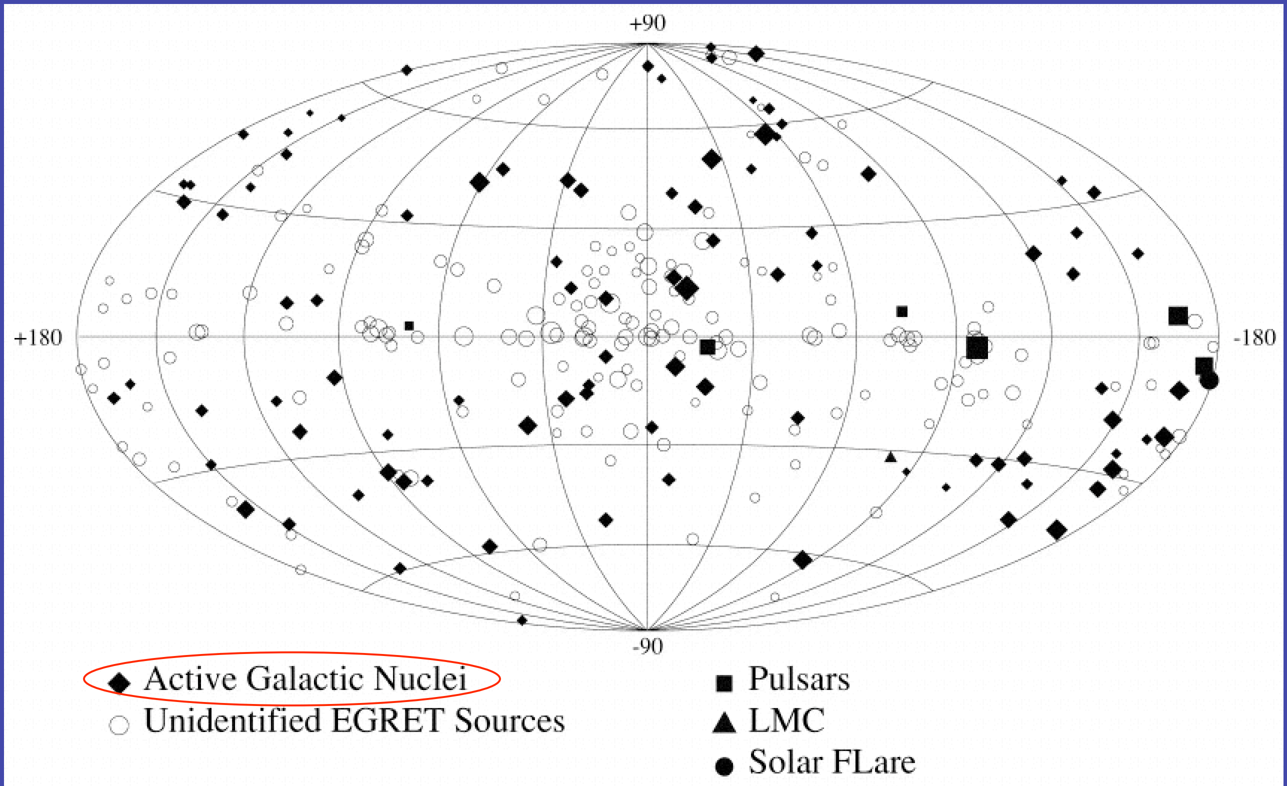
High energy emission (hard X-ray, Gamma-ray) produced by inverse Compton scattering

UV, soft X-ray photons scattered off relativistic electrons



Energy density of photons increases as γ^2

Gamma-Ray Detections



Detections from the 4th CGRO/EGRET catalog.

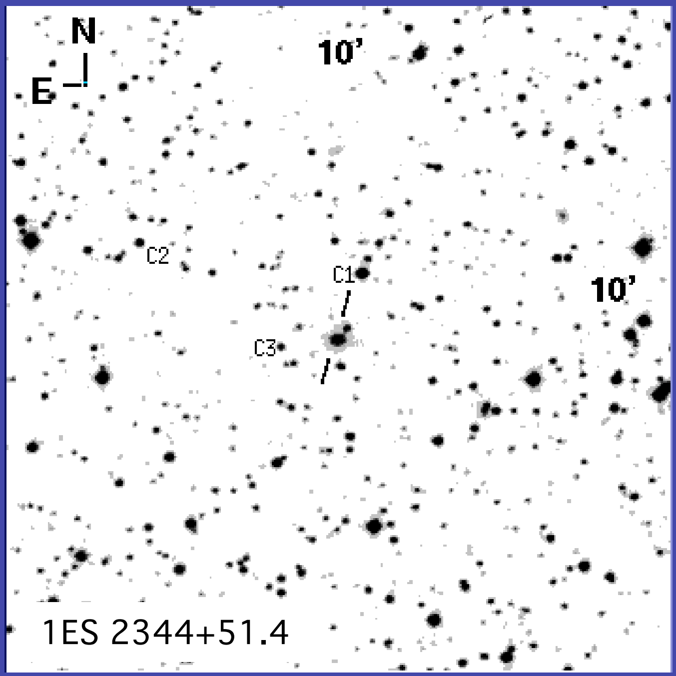
All AGNs detected except 1 are blazars

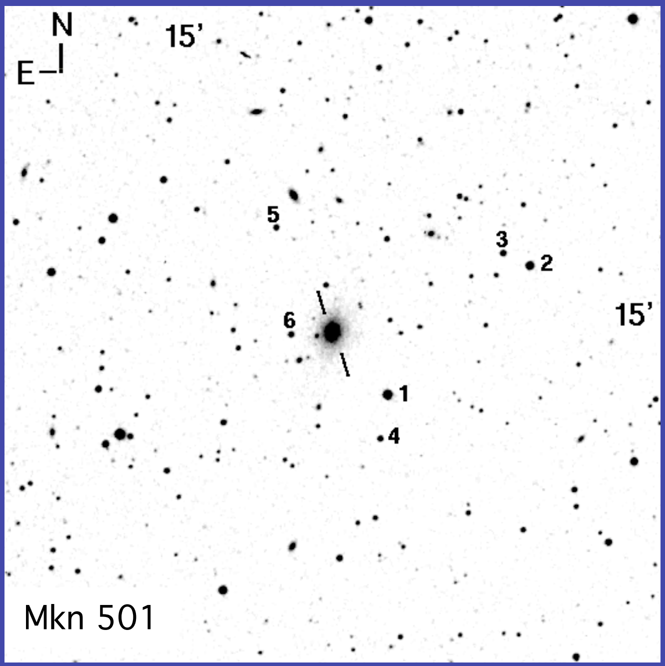
Hartman et al., 1999, ApJ Suppl. Ser., 123, 79

Ultra High Energy Emission

Atmospheric cerenkov detectors searching for ultra-high-energy TeV (10^{12} eV) sources found 3 sources

Optical followup show that all the TeV sources appear to be AGN

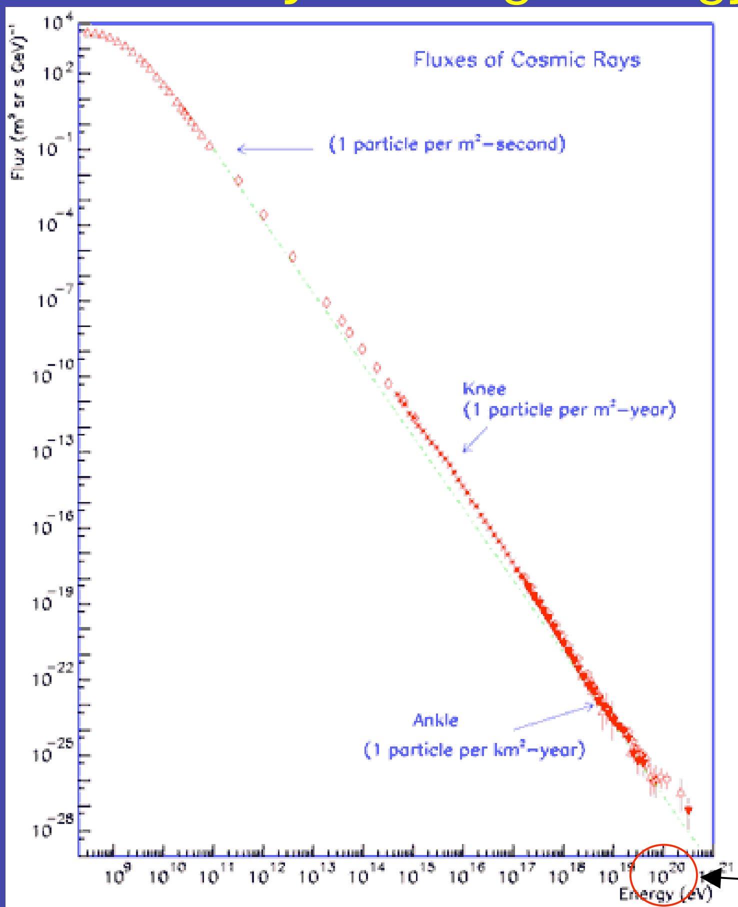




http://www.phys-astro.sonoma.edu/observatory/research/agn/agnp.html

Cosmic Rays

Cosmic Rays are high energy subatomic particles.



Most CRs with $E<10^{15}$ eV produced within the Milky Way

UHECRs: $E>10^{15}$ eV (1000 TeV, 1 PeV)

Not re-directed by magnetic fields

flux: < 1 particle m^{-2} yr^{-1}

Source of UHECRs a mystery

suspicion: AGNs? GRBs?

but CRs lose energy via pion production by interaction with cosmic microwave background ("GKZ cutoff", Greisen, Zatsepin and Kuzmin) which should limit UHECRs to < $1.5x10^8$ ly

tennis ball @ 180 mph

data from J. Swordy;
http://www.scielo.br/scielo.php?pid=S0103-97332001000200015&script=sci_arttext&tlng=en

Diffuse X-ray Background

DXRB: Discovered in 1962 (first cosmic background to be discovered)

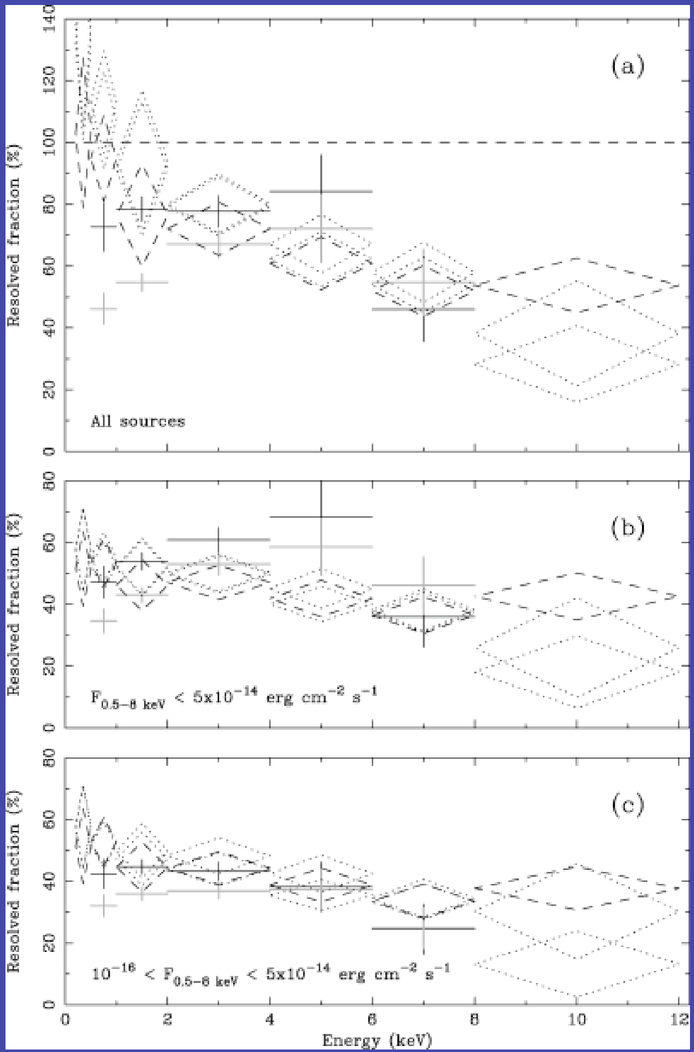
at soft X-ray energies, diffuse million K gas within the Galaxy

at E>1 keV, “diffuse” emission made from unresolved point sources, mainly AGN

70-80% of the 0.5-2 keV background resolvable into point source (Hasinger et al. 1998) based on ROSAT observations

Deep observations at higher energies (5-10 keV) in the Lockman Hole and the Chandra Deep Fields only account for ~60% of the hard X-ray background

Remaining emission has a spectrum consistent with a population of obscured AGN with $0.5<z<1.5$ and column densities (=nD) of $10^{22}<NH<10^{24}$ atoms cm^{-2} (Worsley et al. 2005, MN 357, 1281).



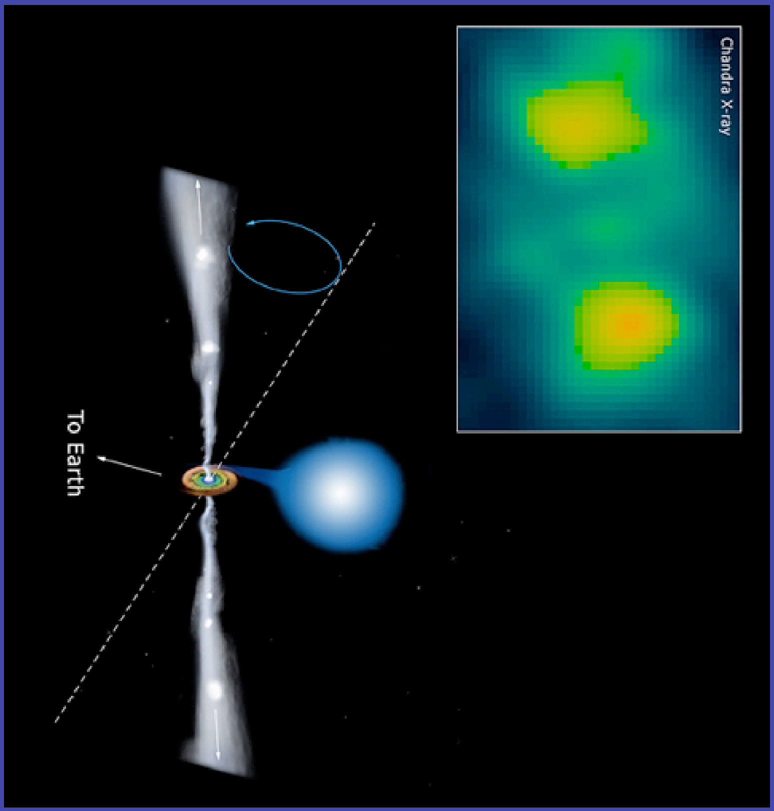
Microquasars

Accreting black hole binaries in the Galaxy show similar phenomena to AGN: high luminosities, rapid variability, jets

Because they're closer the energetics of the system are easier to study

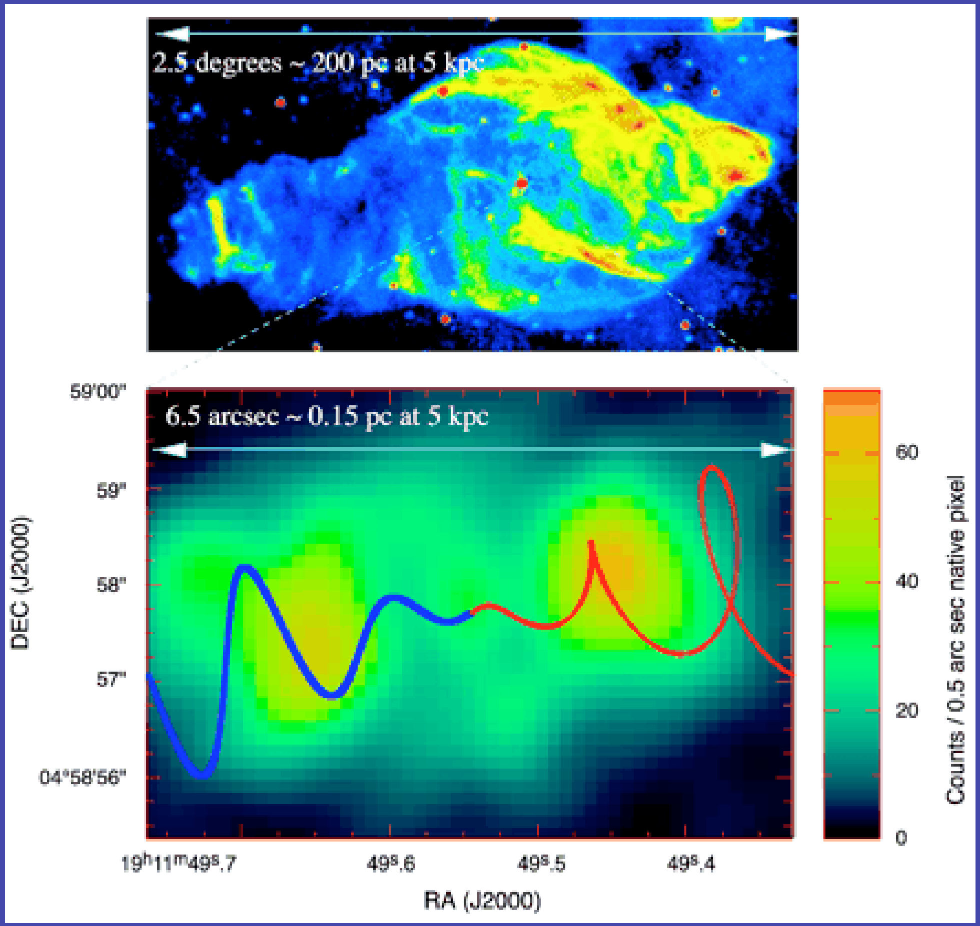
SS433

Detected in an emission line survey. 1st set of spectra in 1978 showed H-lines show large blue and redshifts (v~±40,000 km/s) simultaneously



Emission lines produced in relativistic jets emanating from a black hole surrounded by an accretion disk.

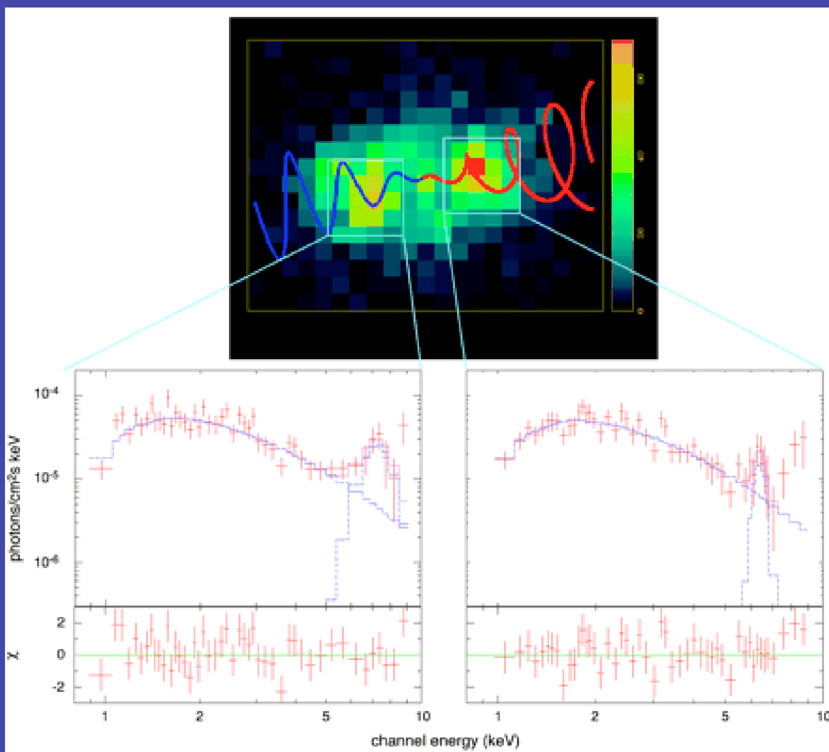
SS433 & W50

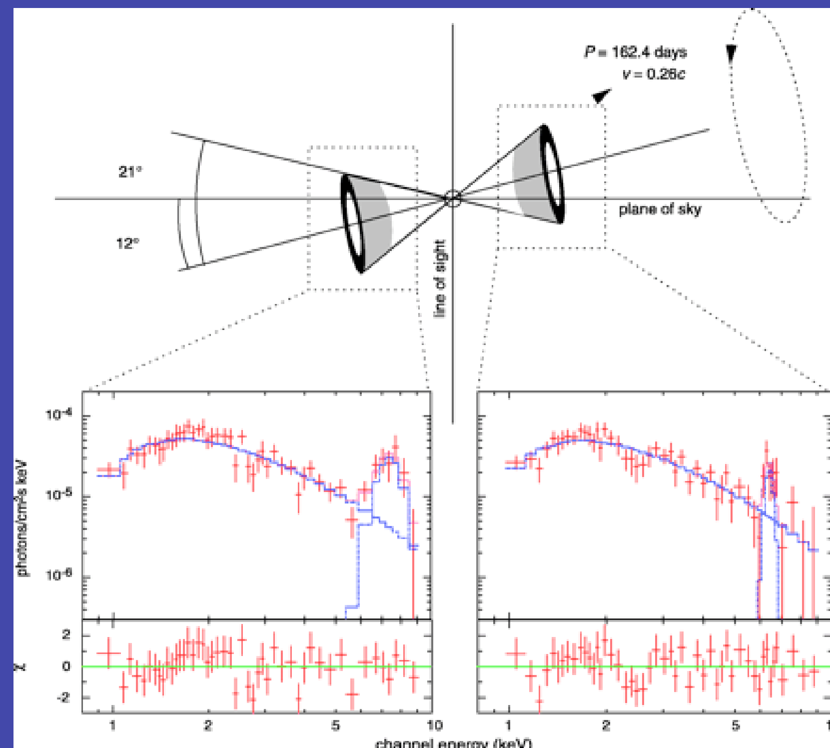


orientation of jet matches orientation of W50, the SNR that surrounds SS433: shows interaction of SNR with jet

blue/red lines show precessional motion of jet (approaching/receding)

SS433: resolving the X-ray Jet





Spatially resolved X-ray spectra show significant differences in the Fe K link profile

Modelling the shape of the Fe line profile variation allows determination of jet geometry

Summary

Active galaxies are useful probes of the Universe out to large distances

Many different type of AGN phenomena can be explained with a single model by only changing the orientation wrt the line of sight

Single model: accretion disk around black hole

Similar to galactic BH sources which can be more easily observed

Fe K lines good probe of the model