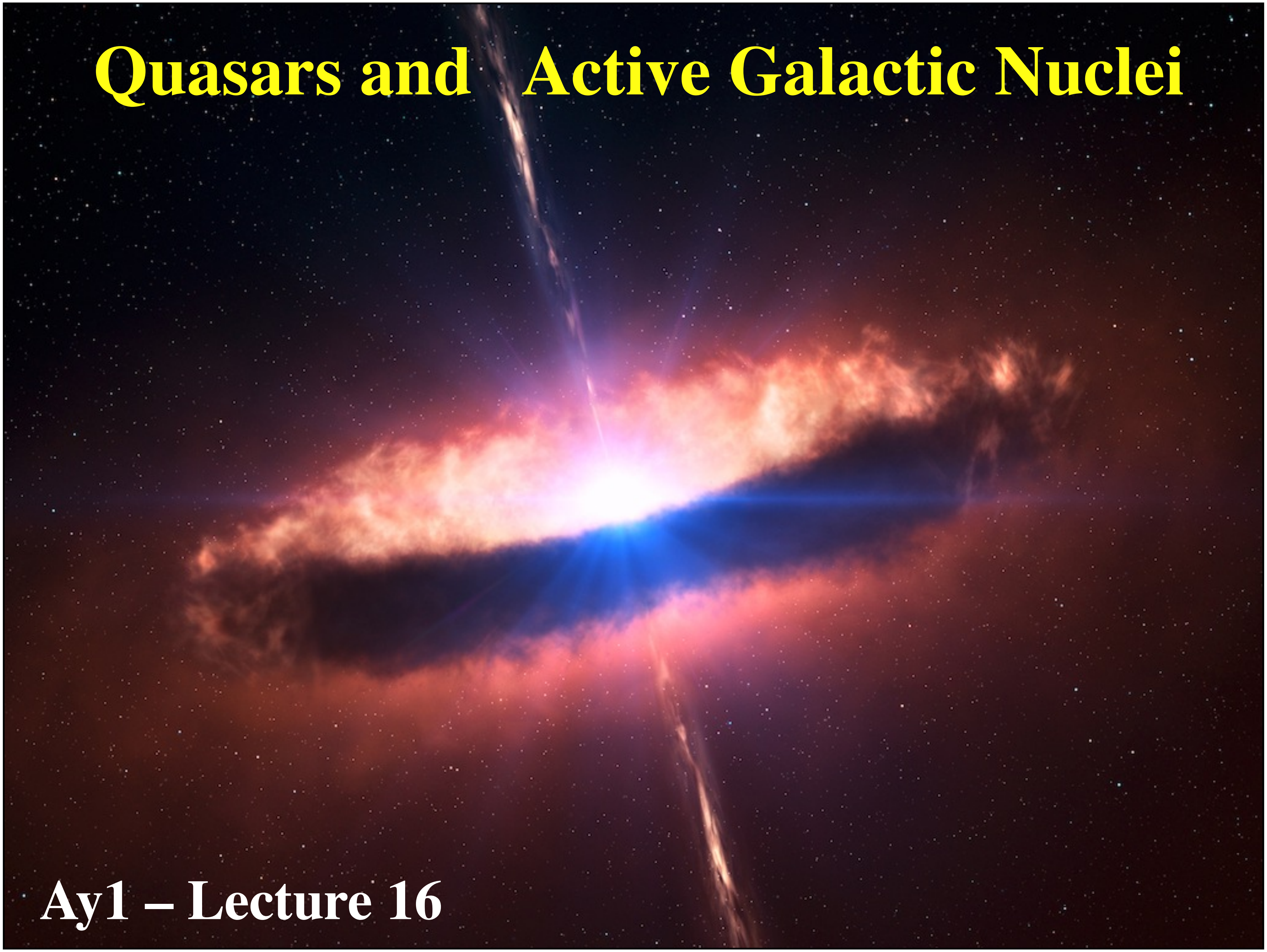
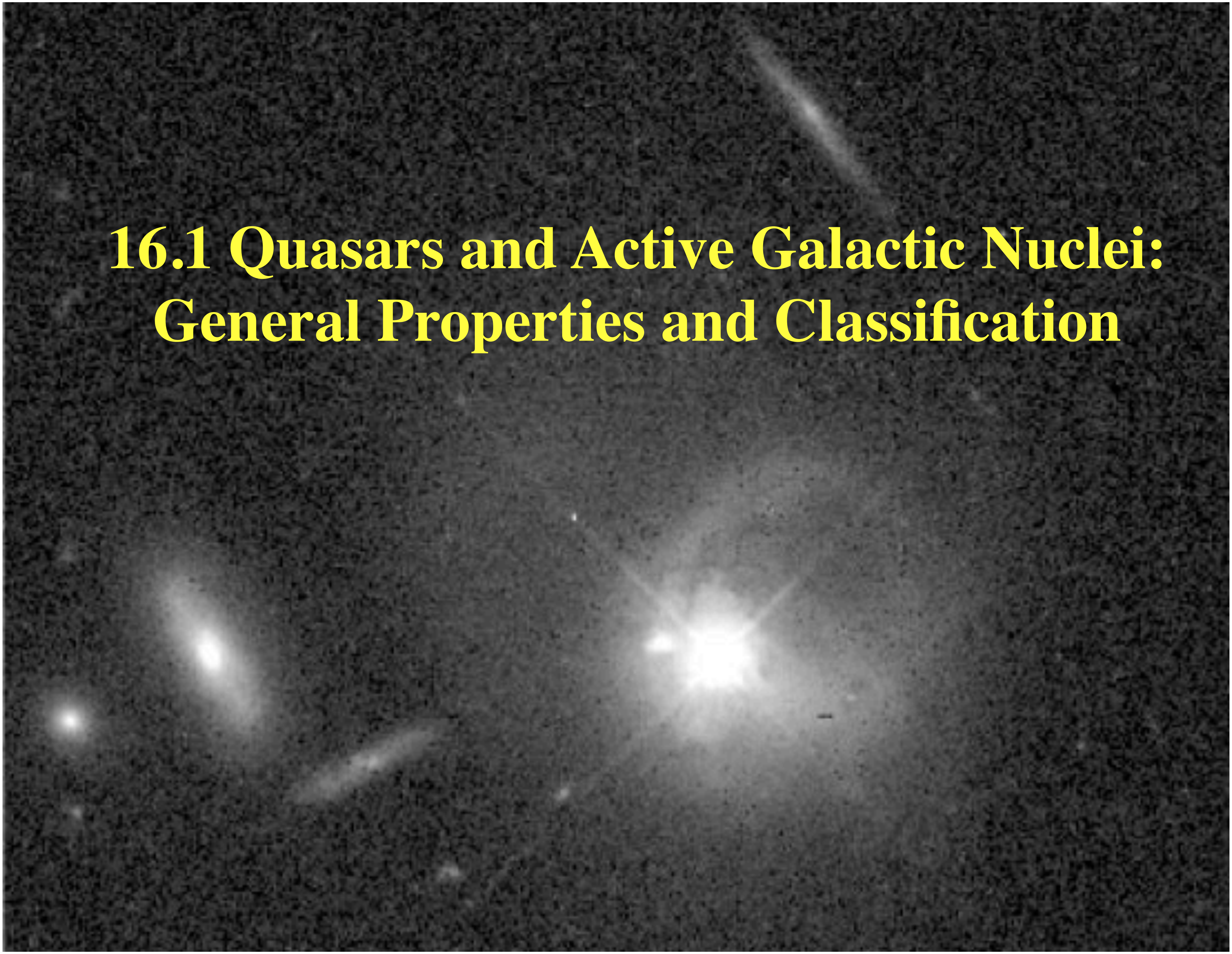
Quasars and Active Galactic Nuclei



Ay1 – Lecture 16

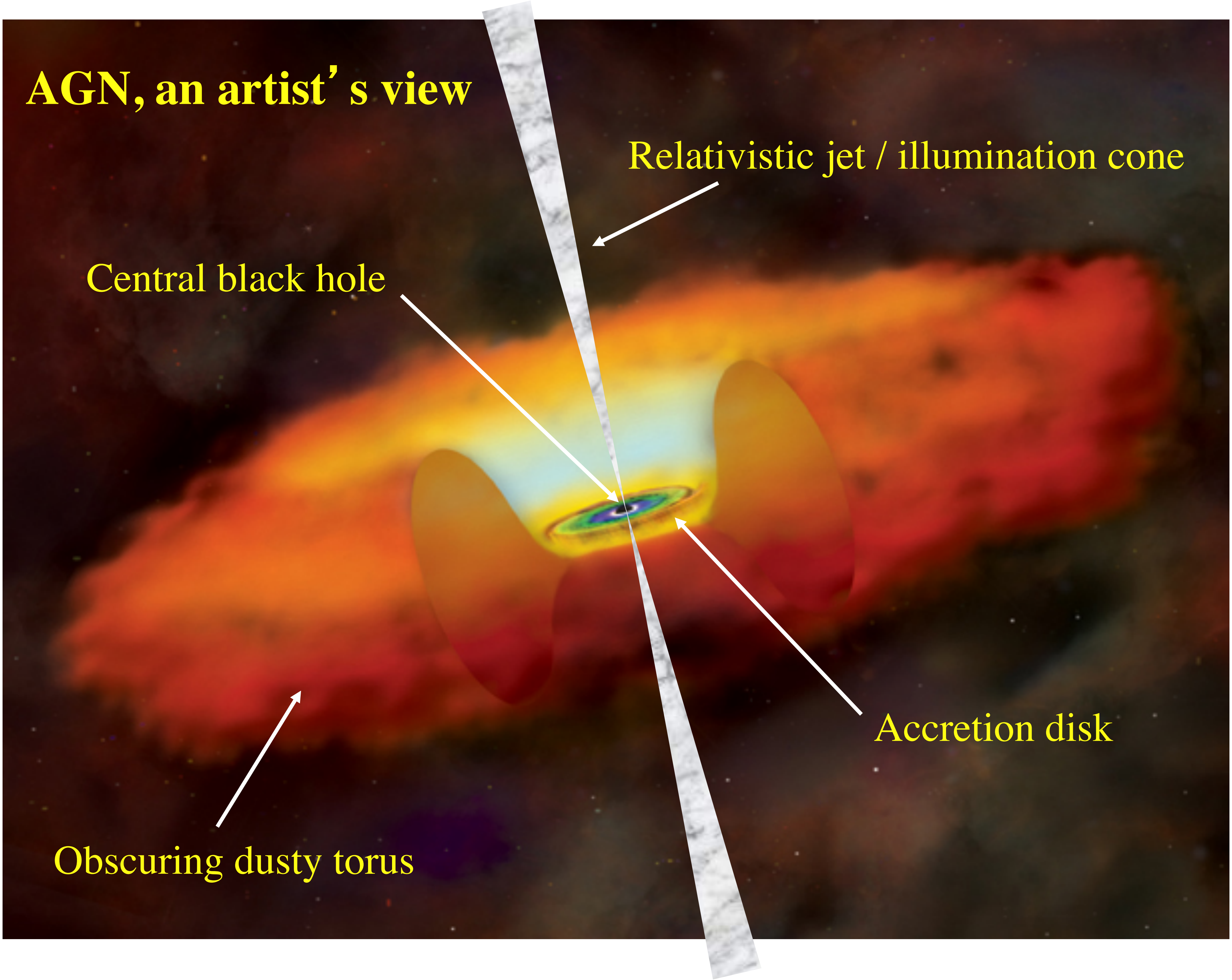


16.1 Quasars and Active Galactic Nuclei: General Properties and Classification

Quasars and Active Galactic Nuclei

- Highly energetic manifestations in the nuclei of galaxies, powered by accretion onto supermassive massive black holes
- Empirical classification schemes have been developed, on the basis of the spectra; but recently, various unification schemes have been developed (~ the same underlying phenomenon)
- Evolve strongly in time, with the comoving densities of luminous ones increasing by ~ 10^3 from $z \sim 0$ to $z \sim 2$
- At z ~ 0, at least 30% of all galaxies show some sign of a nuclear activity; ~ 1% can be classified as Seyferts, and ~ 10^{-6} contain luminous quasars
- We think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase

AGN, an artist's view

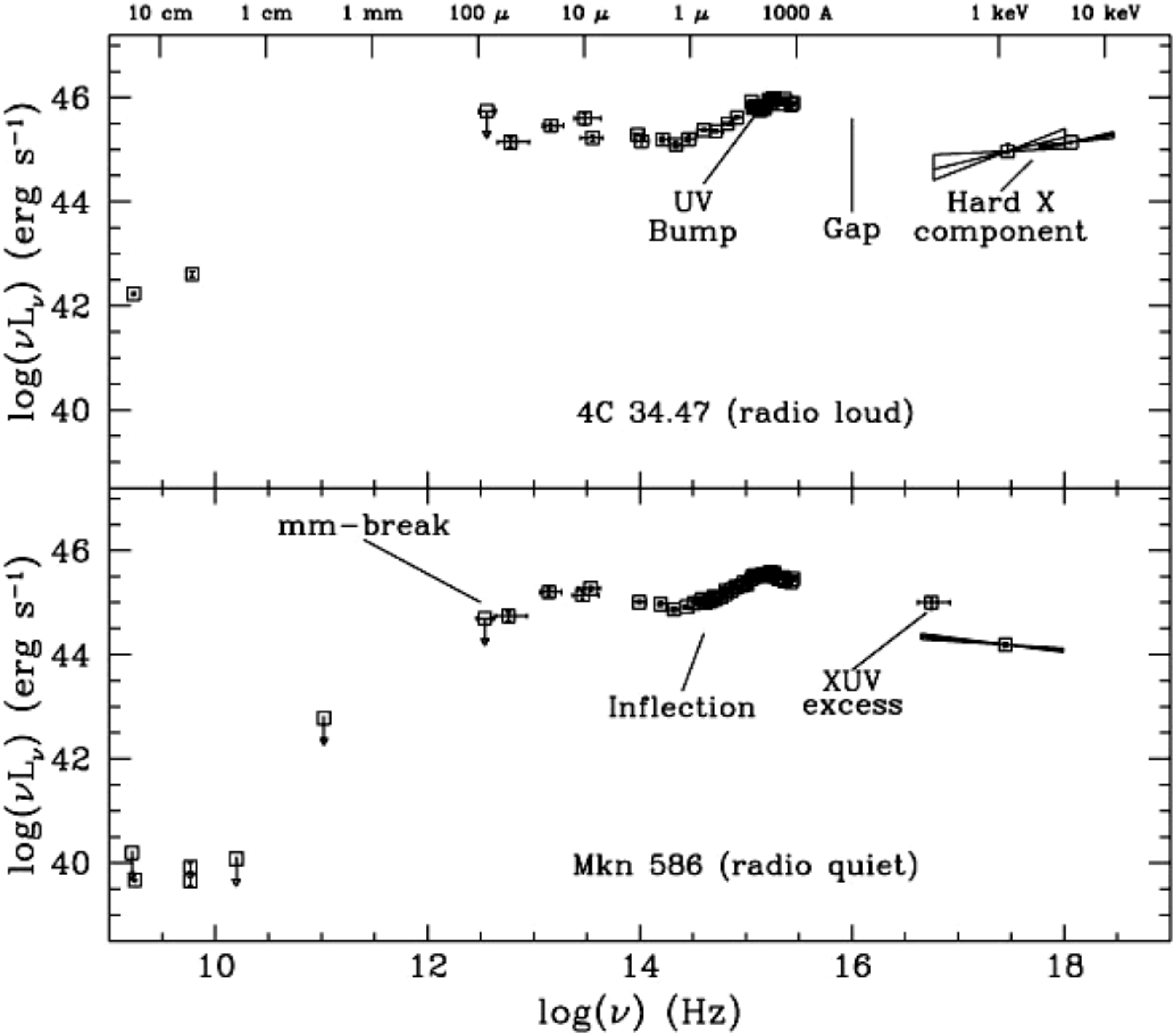


Observable Properties of AGN

- Emission over a broad range of frequencies, radio to γ-rays
  - Nonthermal radio or X-ray emission is a good way to find AGN
  - Generally bluer spectra than stars: "UV excess"
  - Colors unlike those of stars, especially when modified by the intergalactic absorption
- Presence of strong, broad emission lines in their spectra
- Can reach large luminosities, up to $\sim 10^{15}\ L_\odot$
- Strong variability at all time scales
  - Implies small physical size of the emission region
- Central engines unresolved
- Undetectable proper motions due to a large distances

All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects

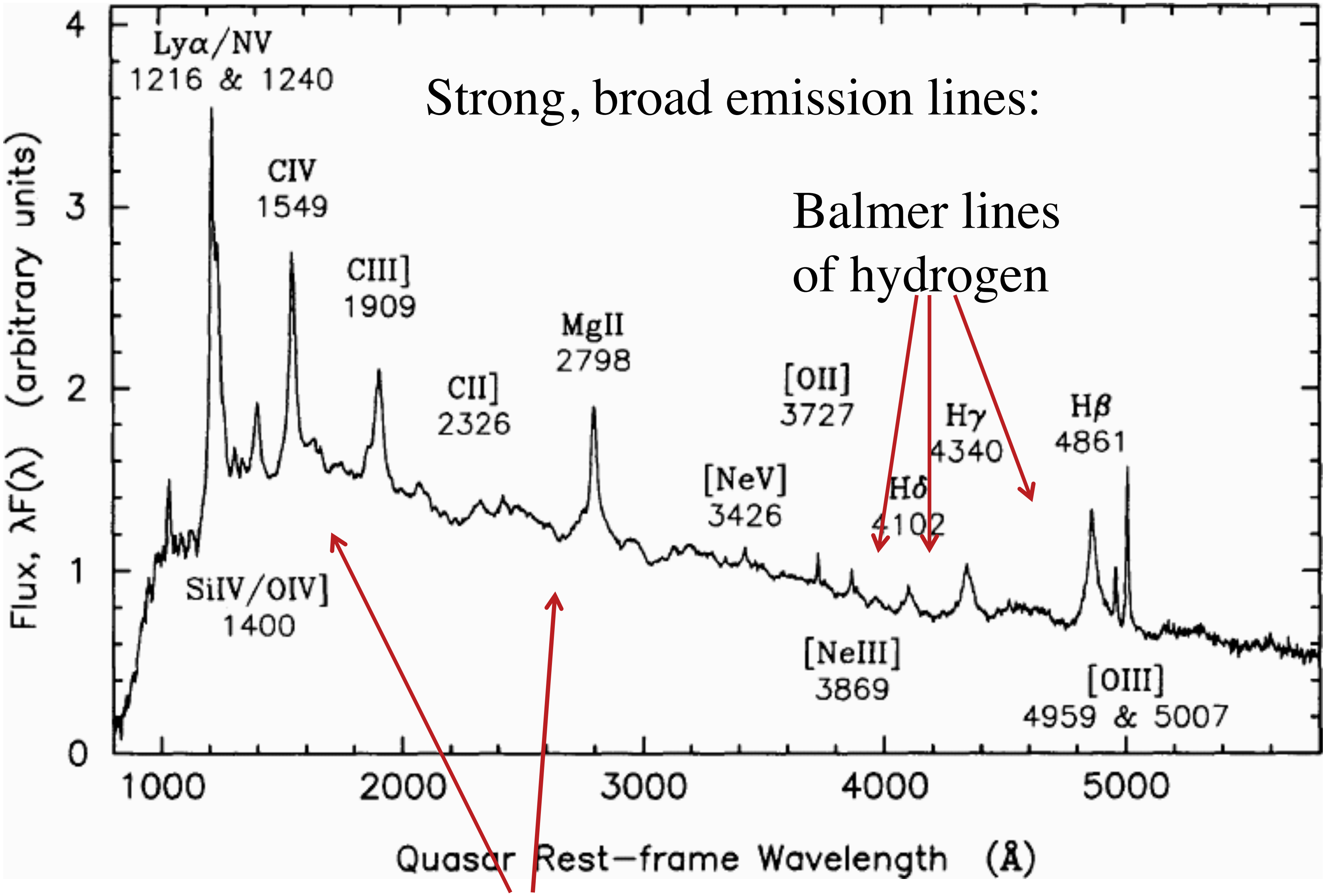
Broad-Band Spectra of Quasars



Radio
Loud

Radio
Quiet

UV-Optical Spectra of Quasars



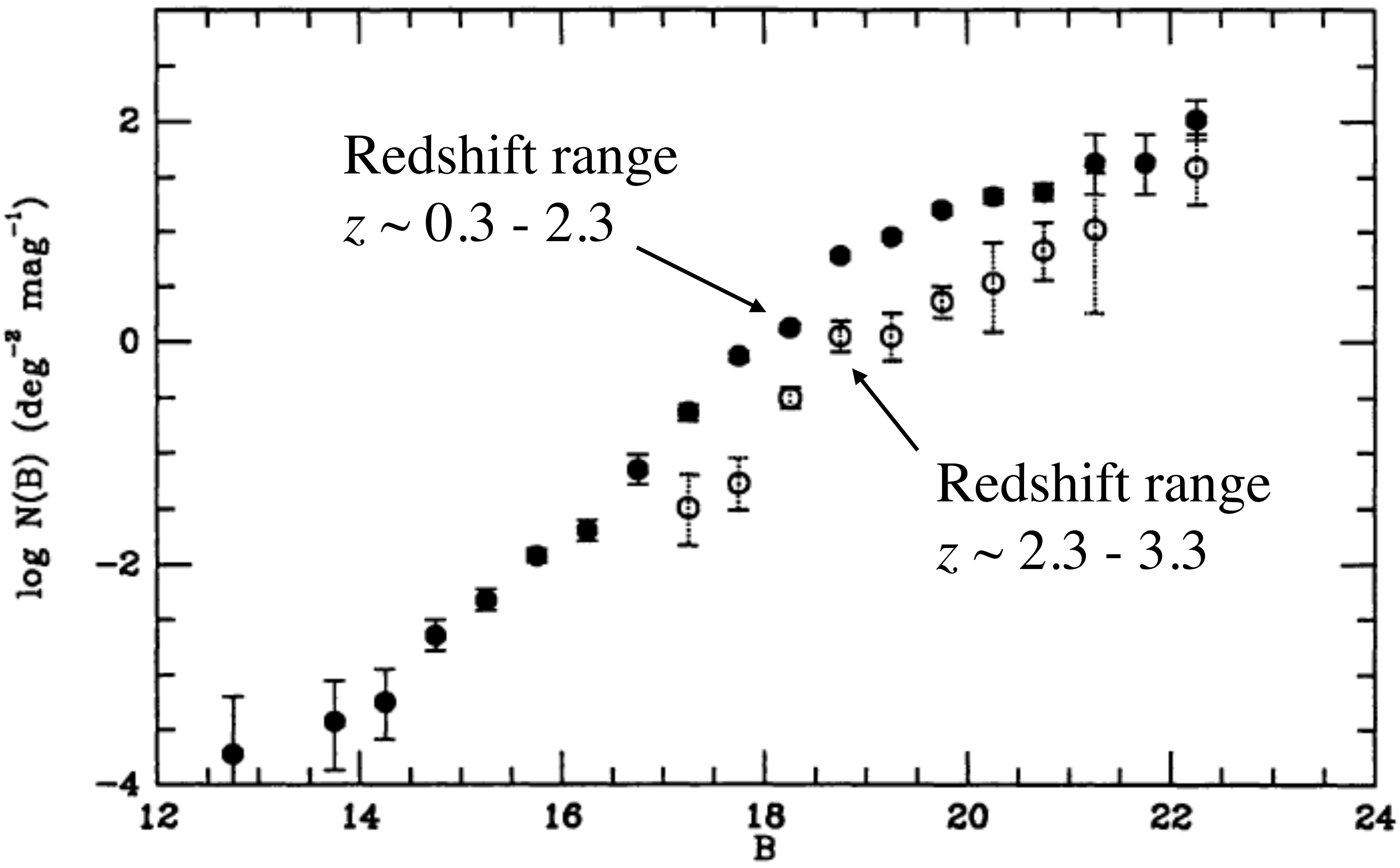
Strong, broad emission lines:

Balmer lines
of hydrogen

Prominent lines of abundant ions

Quasar Counts

For the unobscured, Type 1 QSOs; they may be outnumbered by the obscured ones. Down to ~ 22th mag, there are ~ 100 deg^{-2}; down to ~ 29th mag, probably a few hundred more ➞ a total of a few × 10^7 over the entire sky, or ~ 1 per 1000 faint galaxies



Redshift range
z ~ 0.3 - 2.3

Redshift range
z ~ 2.3 - 3.3

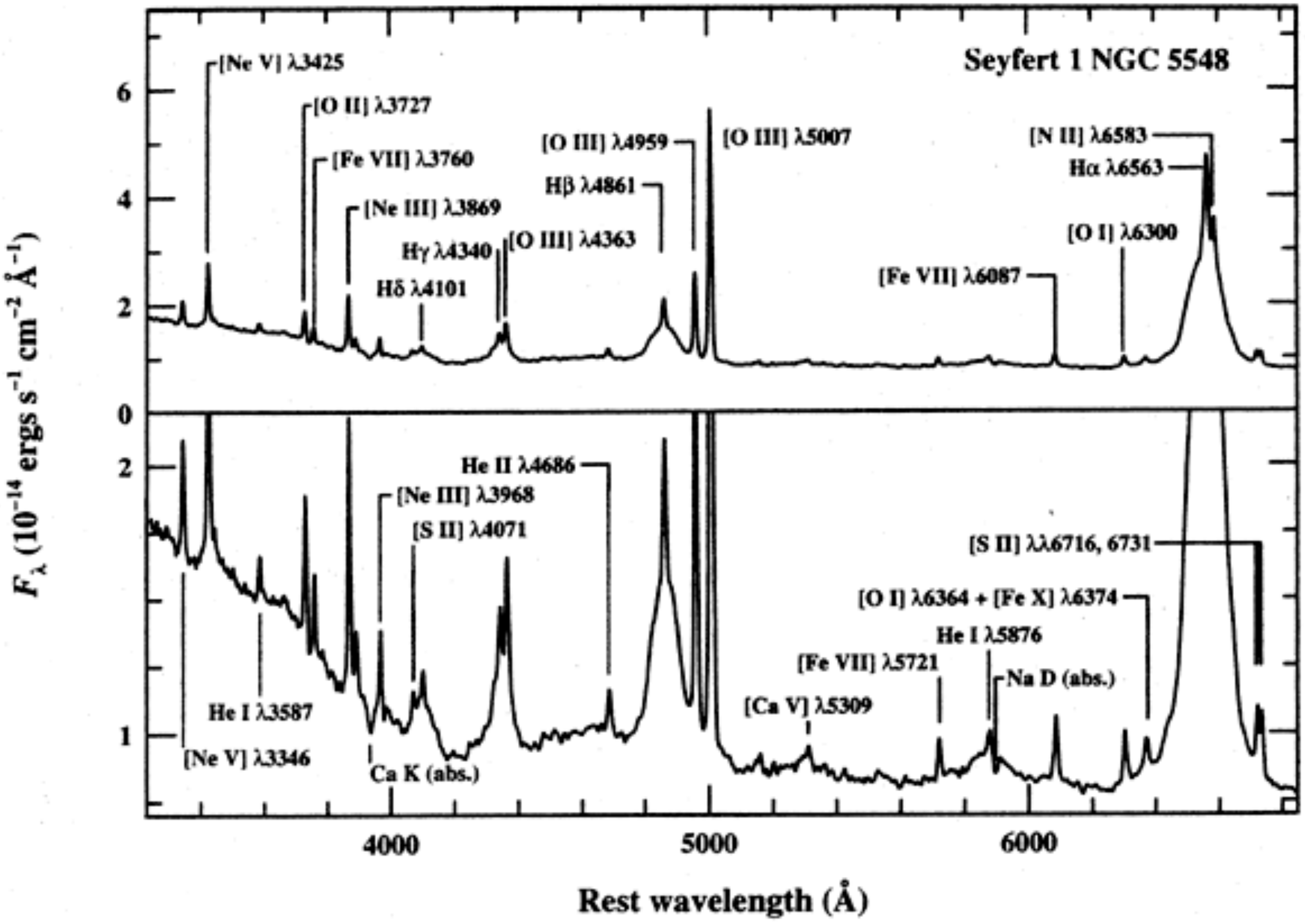
AGN Classification

- According to radio emission:
  - Radio loud: radio galaxies (RGs) and quasars; F-R types I and II
  - Radio quiet (but perhaps not entirely radio silent)
- According to optical spectrum:
  - Narrow-line RGs, Seyfert 2’s; Liners
  - Broad line RGs, Seyfert 1’s, quasars
- According to optical luminosity:
  - Seyfert to quasar sequence, range of radio powers, etc.
- Special types:
  - Blazars (aka BL Lac’s) and optically violently variable (OVV) objects
- These classifications are largely parallel
- Some distinction may reflect real, internal physical differences, and some may be simply orientation effects
  - This is the central thesis of the AGN unification models

Types of Seyfert Galaxies

Type 1 Seyfert galaxies have in their spectra:

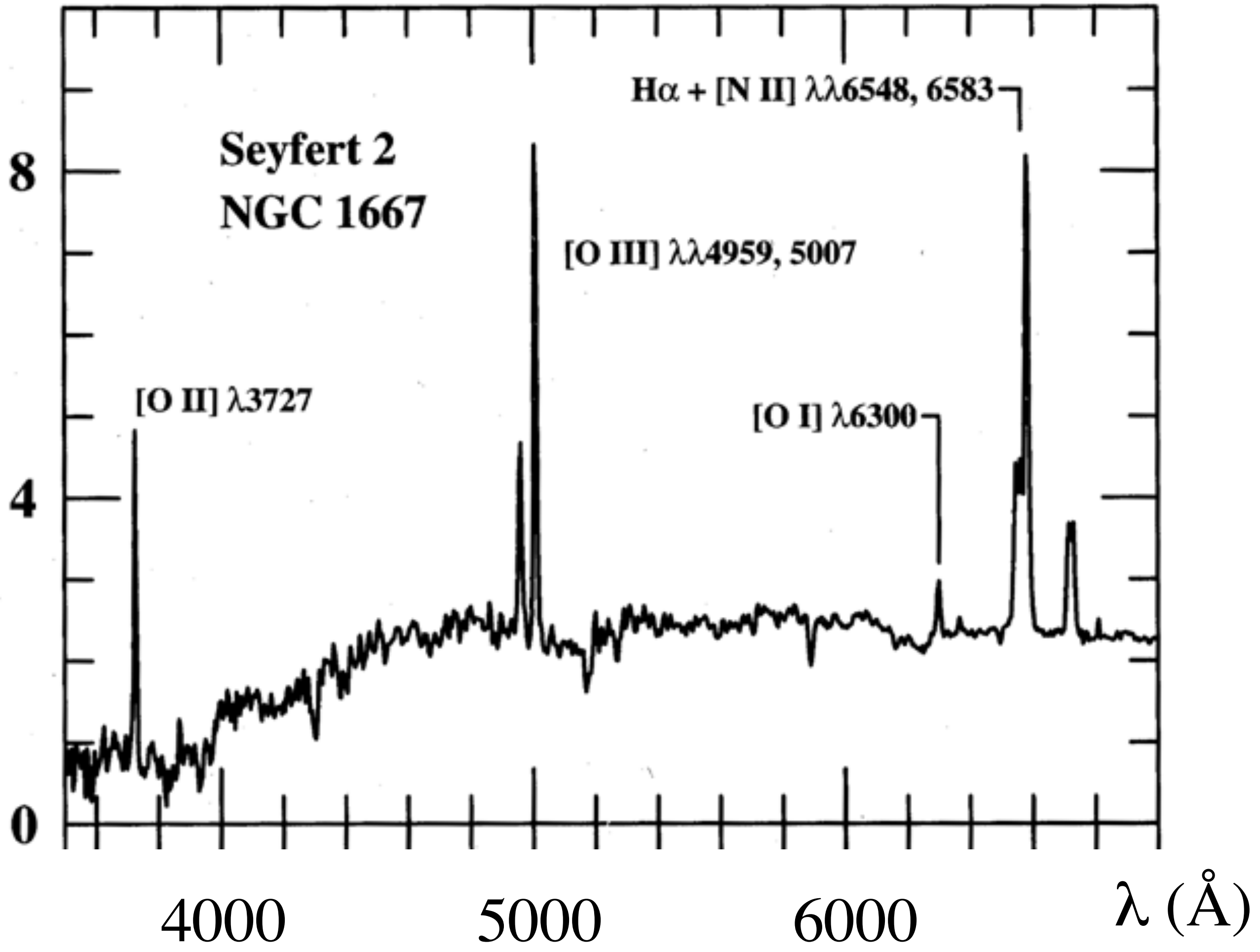
- **Narrow emission lines**, with a width of several hundred km/s
- **Broad emission lines**, with widths up to 10^4 km/s



They also have brighter and bluer nuclei

Types of Seyfert Galaxies

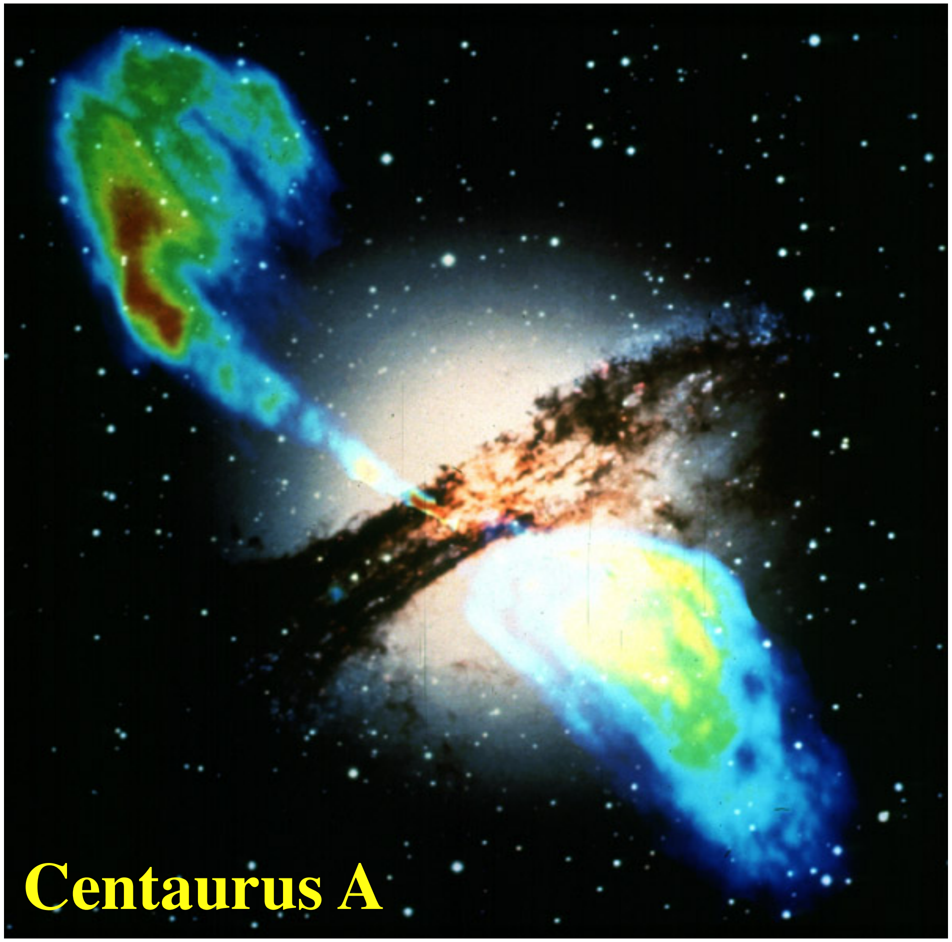
Type 2 Seyfert galaxies have only the narrow line component:

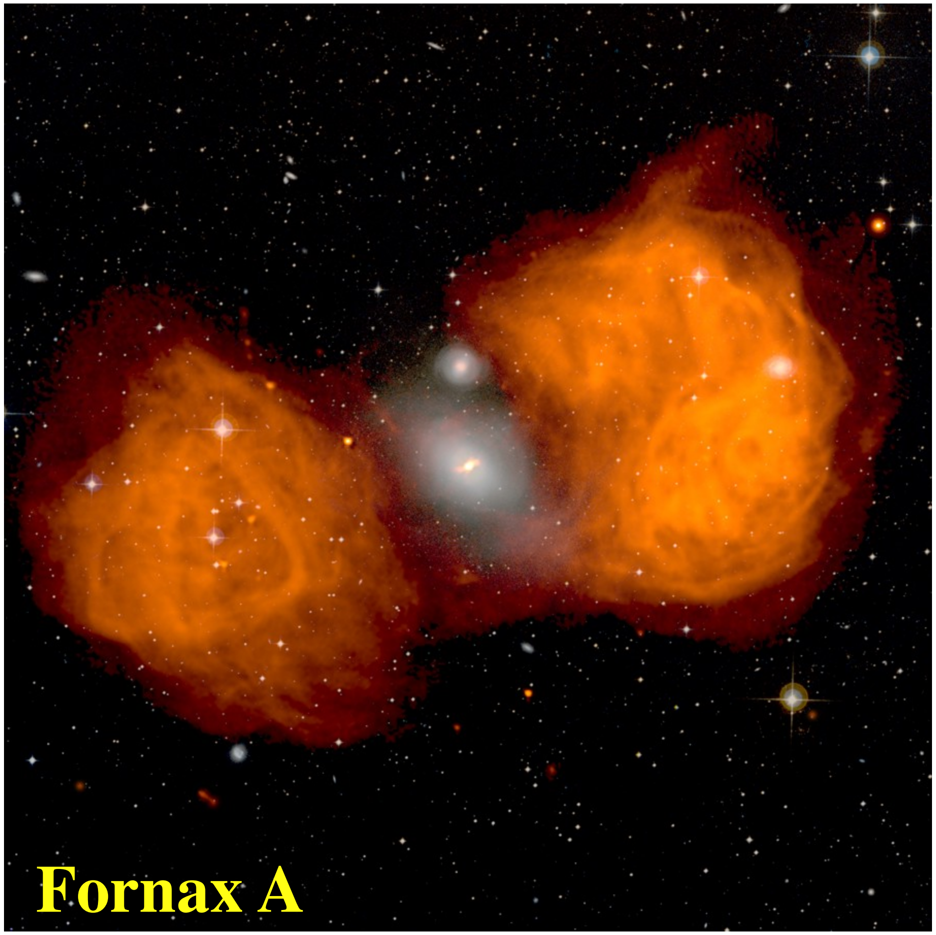


Both types have high ionization, forbidden lines
(= transitions not easily observed in the lab)

Radio Galaxies: Typical Examples

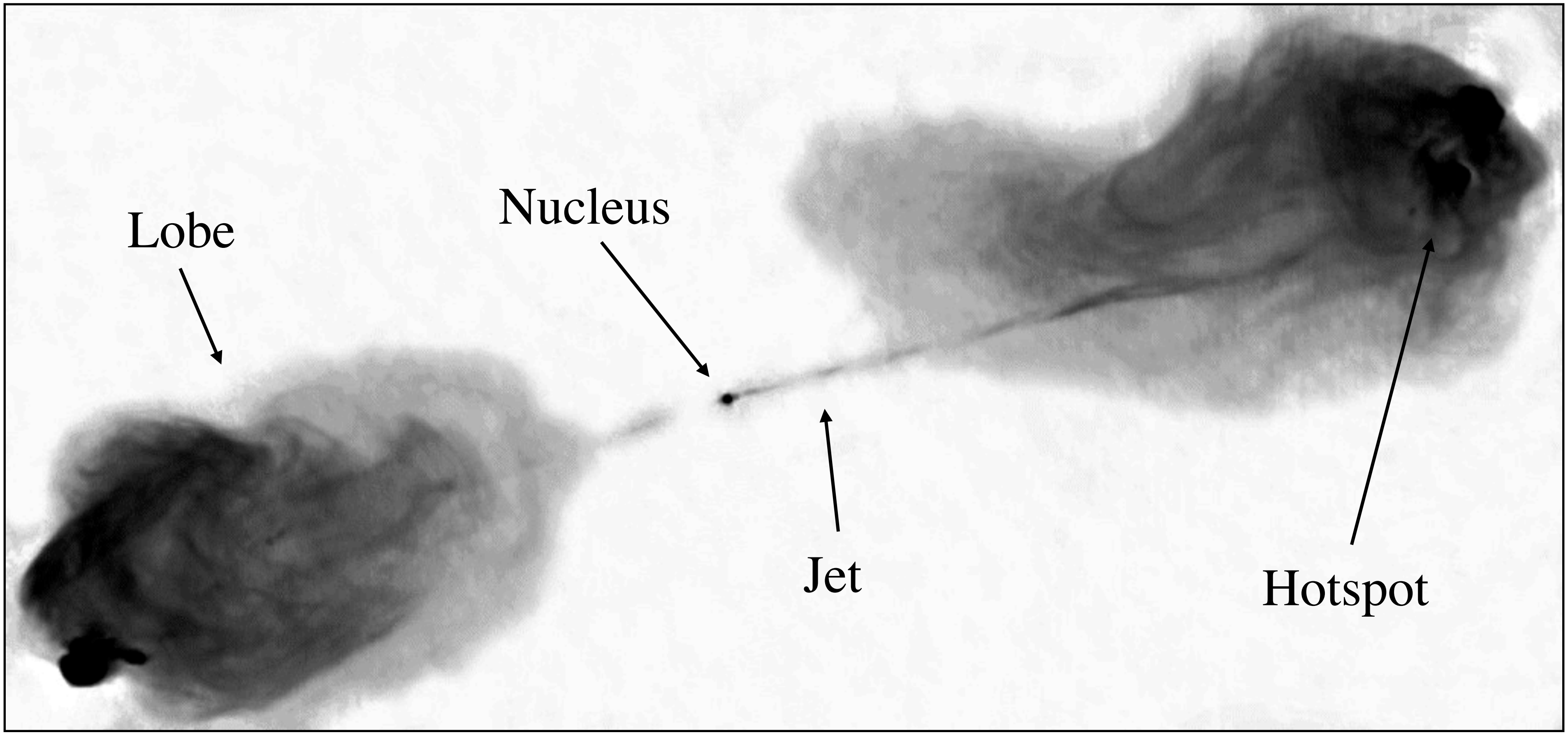
Radio overlayed on optical images





Energy stored in radio lobes can reach ~ 10^{60} - 10^{61} erg. If jet lifetime is ~ 10^{8} yrs, the implied mechanical luminosities are ~ 10^{12} - 10^{13} $L_{\odot}$

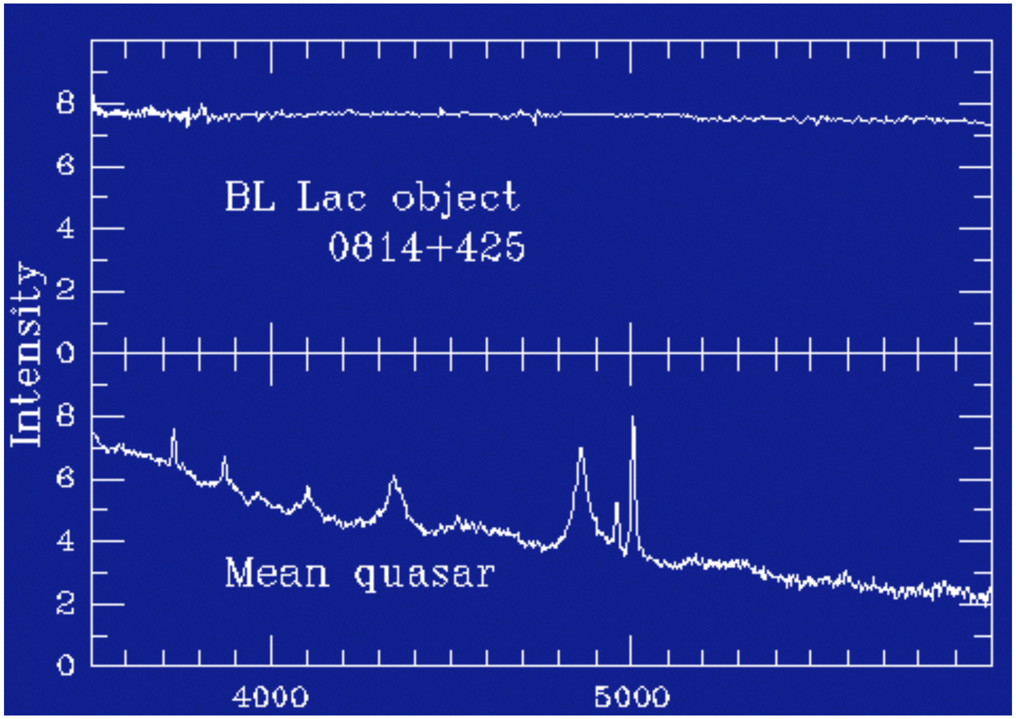
Cygnus A: A Modern VLA Radio Map

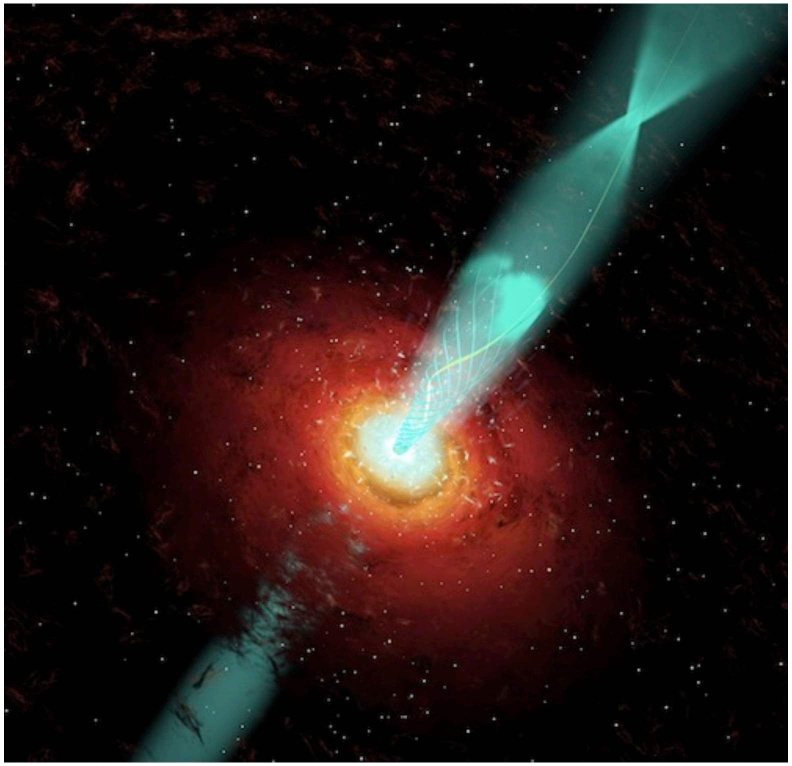


For more good radio images, see the VLA image gallery at
http://www.nrao.edu/imagegallery/php/level1.php

BL Lacs (Blazars)

Named after the prototype BL Lacertae. They have strong, blue, variable continua, and lack strong emission *or* absorption lines in their spectra:

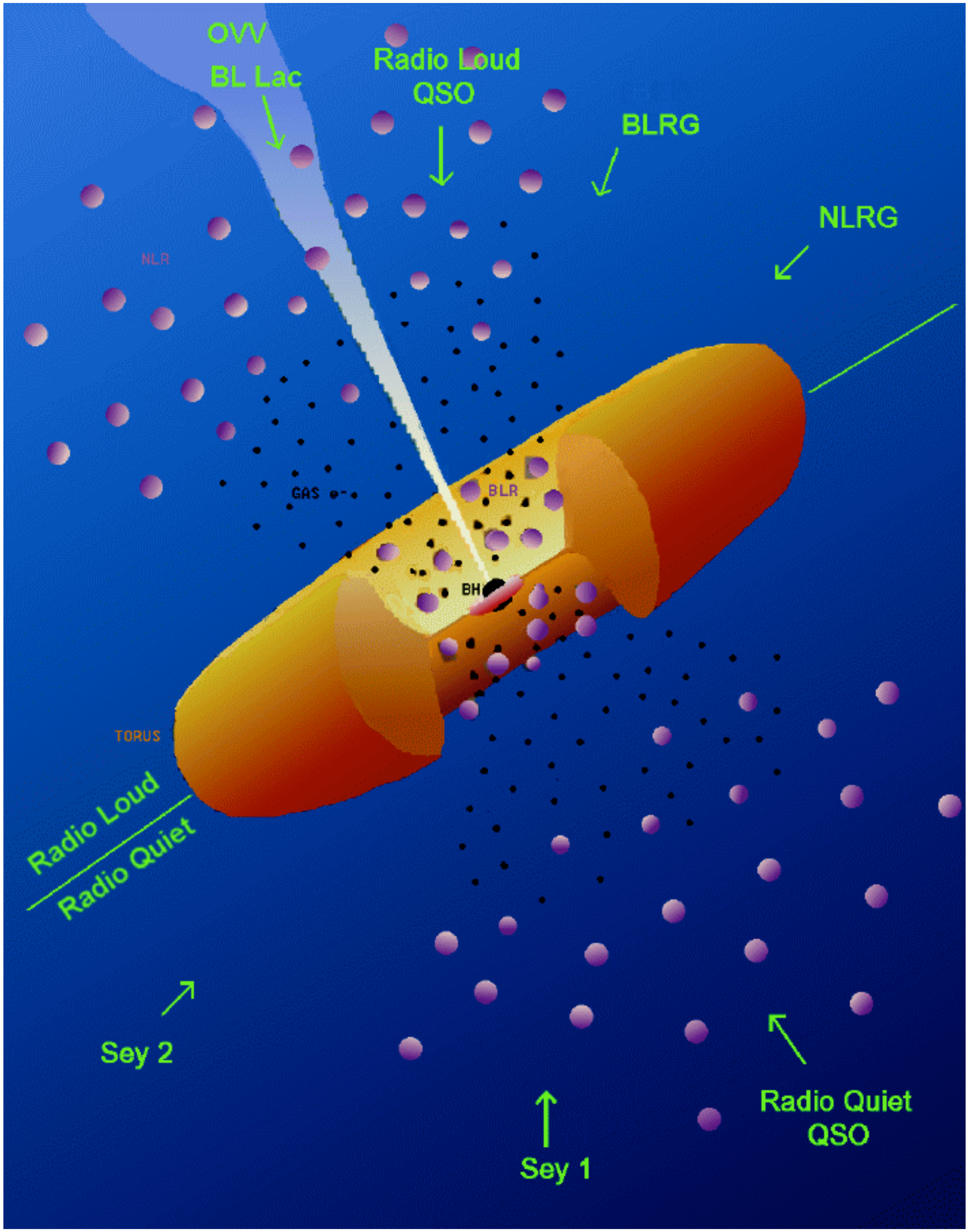




They are radio-loud quasars, viewed along the relativistic jet

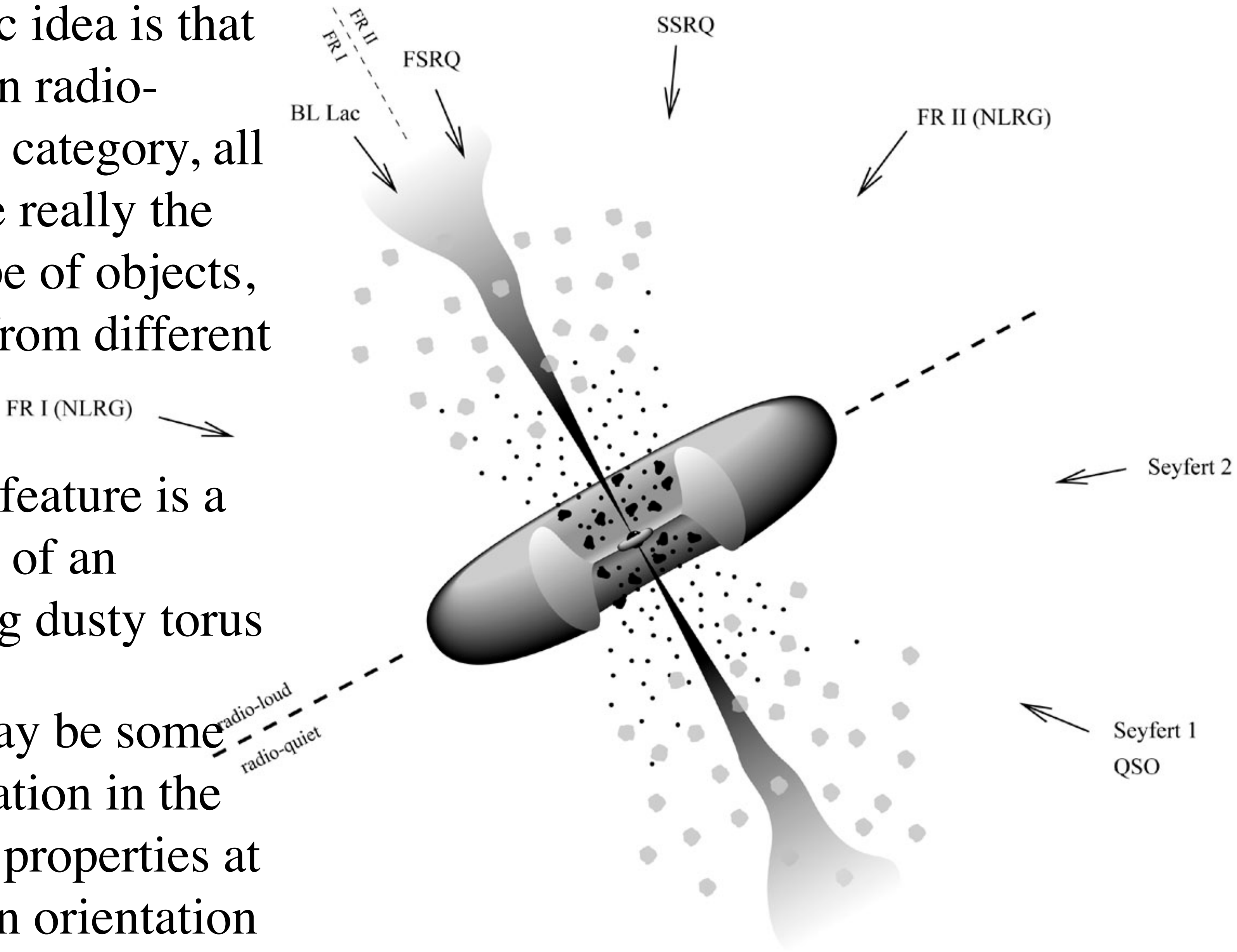
Relativistic beaming amplifies any variations in intensity

16.2 AGN Unification Models



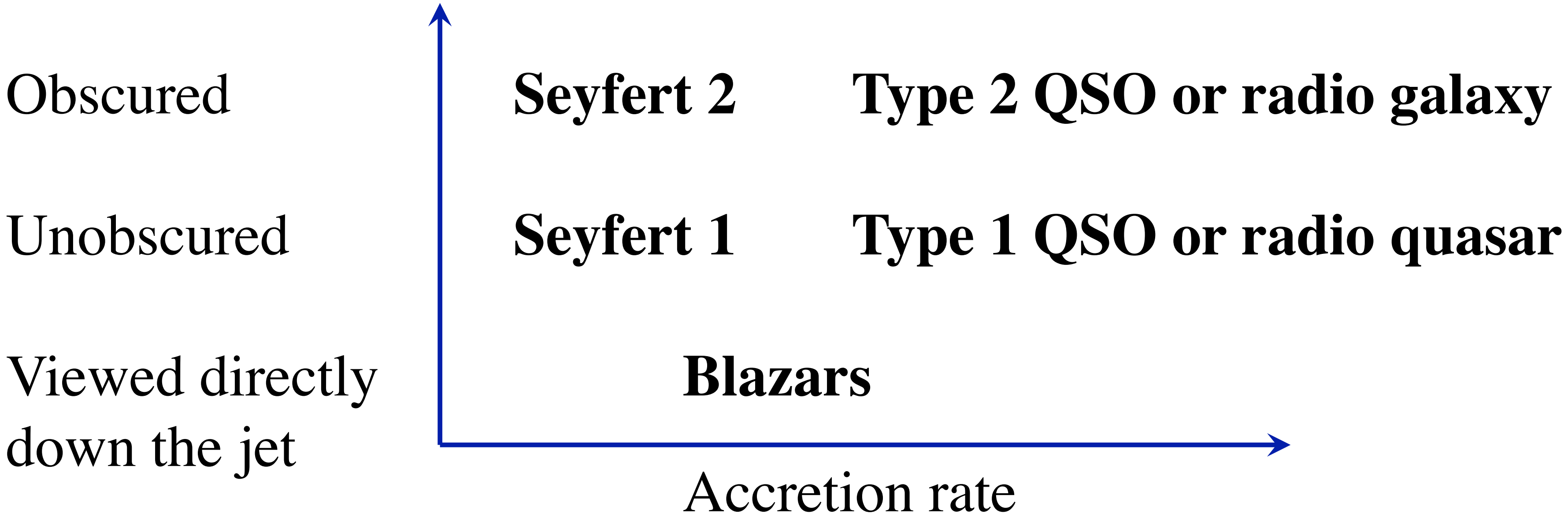
Unification Models for AGN

- The basic idea is that in a given radio-loudness category, all AGN are really the same type of objects, viewed from different angles
- The key feature is a presence of an obscuring dusty torus
- There may be some real variation in the physical properties at any given orientation



AGN Unification

It is now reasonably secure to also fit quasars and blazars, and the radio loud equivalents, into this unified scheme:



Obscured

Seyfert 2

Type 2 QSO or radio galaxy

Unobscured

Seyfert 1

Type 1 QSO or radio quasar

Viewed directly down the jet

Blazars

Accretion rate

Type 2 or highly obscured luminous AGN are also needed to make up the hard X-ray background. Populations of such objects have been found recently both in the optical and X-ray surveys

Radio Loud vs. Radio Quiet

Possible physical reason why some AGN are radio loud, and others are radio quiet is the ***spin*** of the SMBH:

Radio loud	**Radio quiet**
High spin black holes	Low spin black holes
Produce jets, which are the origin of radio emission (note: blazars are radio loud)	No jets
Jets powered by spin energy extracted from black hole	Spectrum produced by the accretion disk (blackbody + nonthermal emission)
Also have accretion disks	

Radio Loud vs. Radio Quiet

Where do the SMBHs get their angular momentum? It is very hard to do via accretion, since the infalling material must come in on nearly radial orbits in order to hit the small target BH

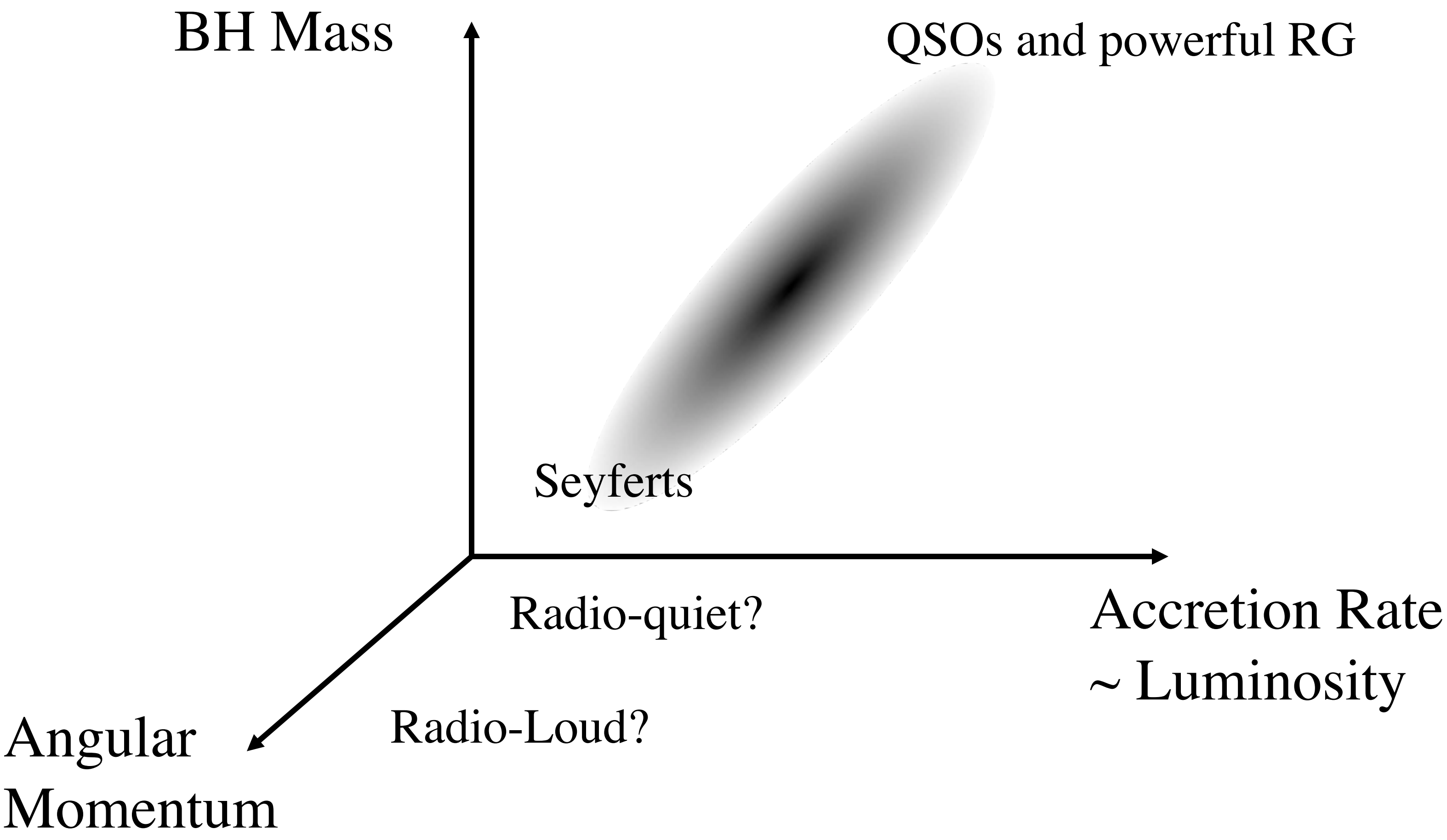
A plausible source is ***mergers***, where the orbital angular momentum of two merging BHs is converted to an internal angular momentum of the product

> Black hole mergers may produce gravitational wave signals, detectable by LISA (if not LIGO)

This scenario would also help explain why powerful radio sources seem to favor giant ellipticals as hosts, and cluster environments (that's where most large E's are) - and ellipticals are more likely to be products of large mergers

It all must depend on the details of the growth processes of SMBHs in the early universe, and that is still not well understood

AGN: A Physical Classification



BH Mass

QSOs and powerful RG

Seyferts

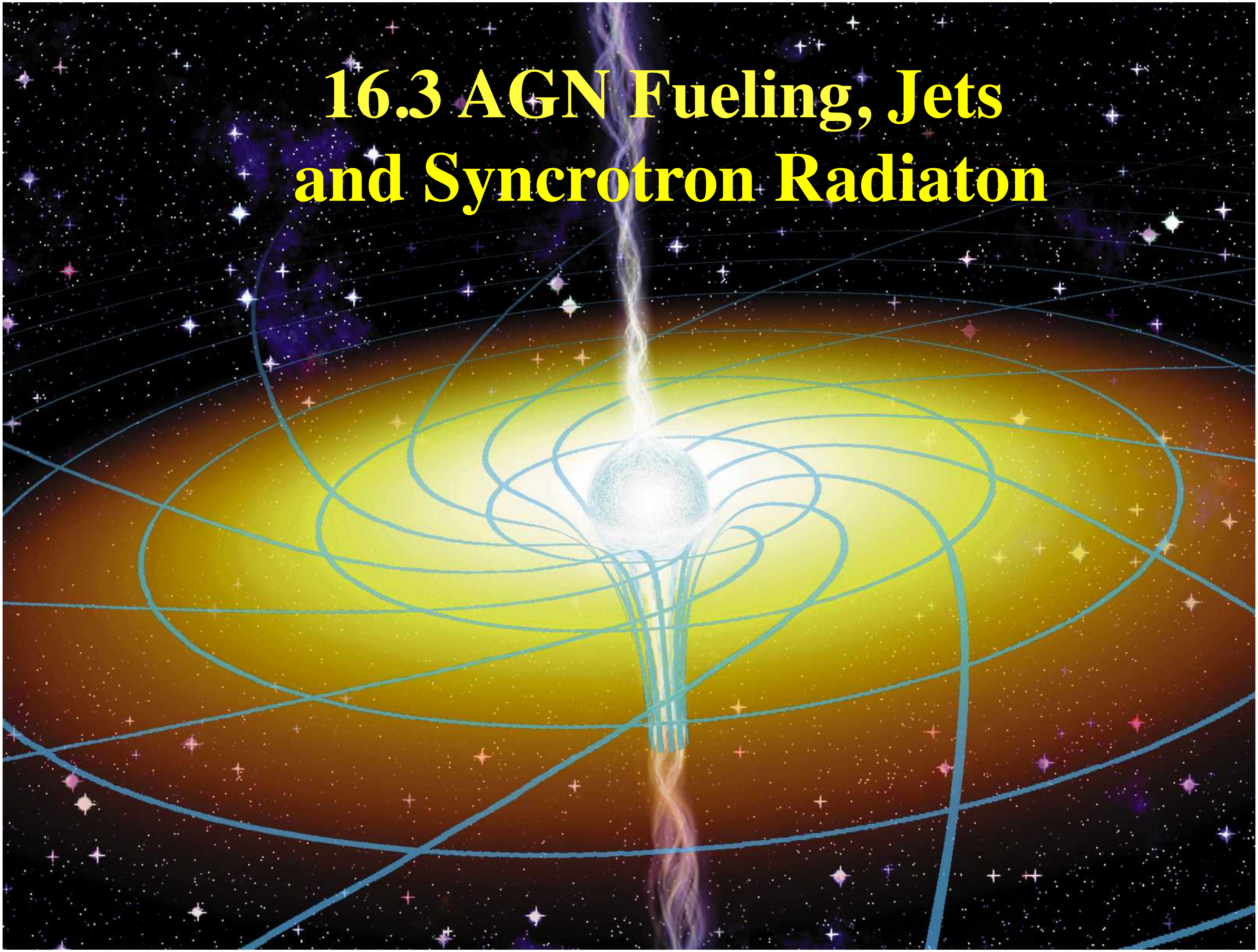
Radio-quiet?

Radio-Loud?

Accretion Rate
~ Luminosity

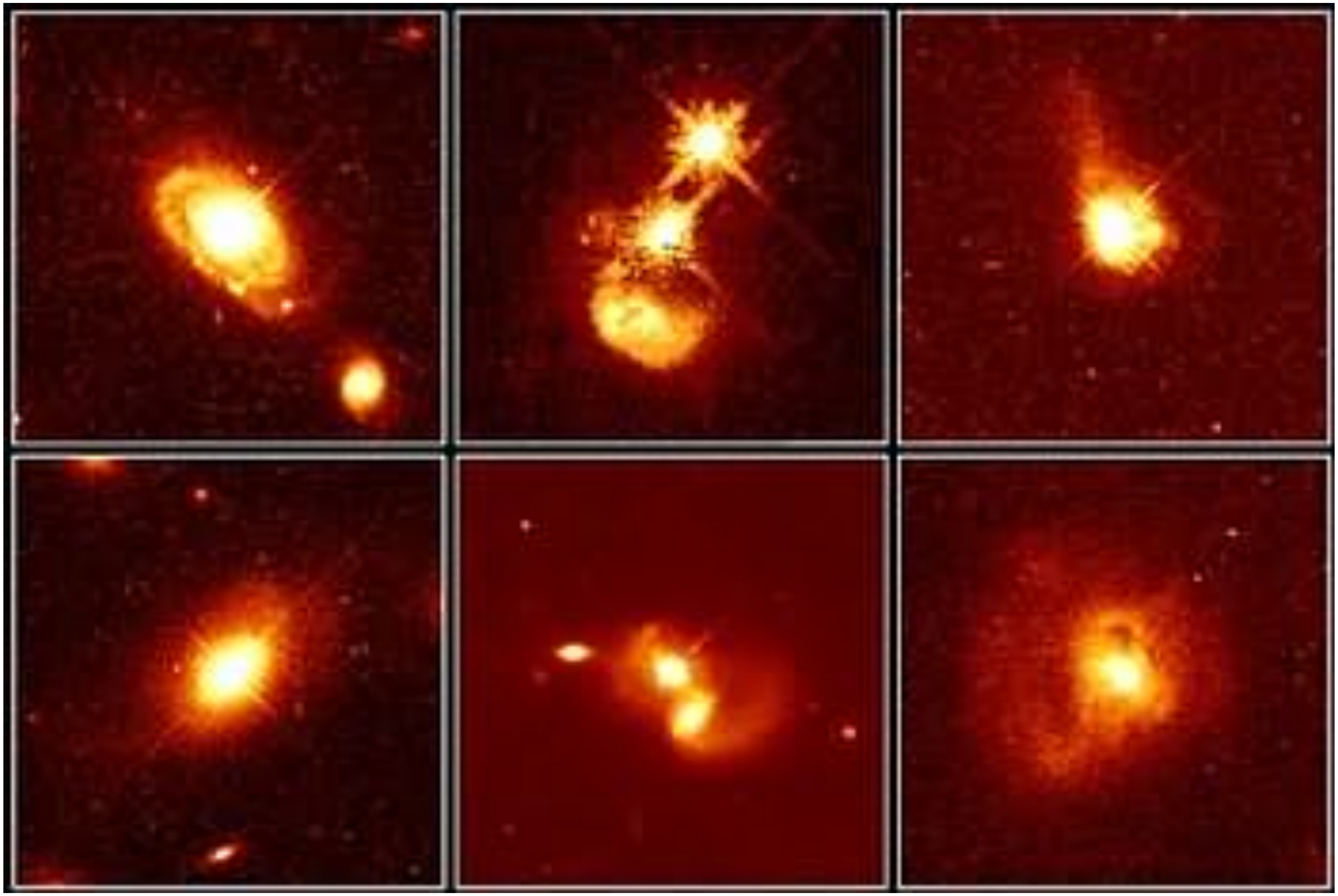
Angular
Momentum

… but in addition, there will be some dependence on the viewing orientation



16.3 AGN Fueling, Jets and Syncrotron Radiaton

What Makes Quasars “Quase” ?



HST Images of QSO hosts, indicative of interacting systems

Where Does the Energy Come From?

- Accretion onto the central supermassive black holes provides the only known viable answer
- The fuel comes from ~ kpc scales (or larger) and ends near the ***Schwarzschild radius***,

  $$R_s = \frac{2GM}{c^2}$$

  (actually, the relevant radius is the smallest stable orbit, at a few R_s). For a $M_\bullet \sim 10^8\, M_\odot$, $R_s \sim 3 \times 10^8$ km ~ 10^{-5} pc
- The binding energy for a mass element m is: $E_b(R) = G\, m\, M_\bullet / R$
- In order for it to be accreted over many orders of magnitude in radius, it has to release the amount of energy comparable to E_b namely $G\, m\, M_\bullet / R_{min} = m\, c^2 / 2$, where $R_{min} \sim$ a few R_s

➡ ***Accretion to black holes can result in the energy release comparable to the rest mass energy!*** Usually a ~ 10% net efficiency is assumed, still much larger than the 0.1% energy conversion efficiency of thermonuclear reactions.

Fuelling Active Galactic Nuclei

Recall the **Eddington Luminosity**

$$L = \frac{4\pi G c m_p}{\sigma_e} M = 1.26 \times 10^{38} \left(\frac{M}{M_{sun}} \right) \text{erg s}^{-1}$$

In order to produce the luminosities of $L_{AGN} \sim 10^{44} - 10^{46}$ erg s^{-1}, we need BHs with masses of *at least* $M_{\bullet} \sim 10^6 - 10^8 M_{\odot}$

A mass δm at $r = \infty$ has $E_{pot} = 0$. As it falls to radius r:

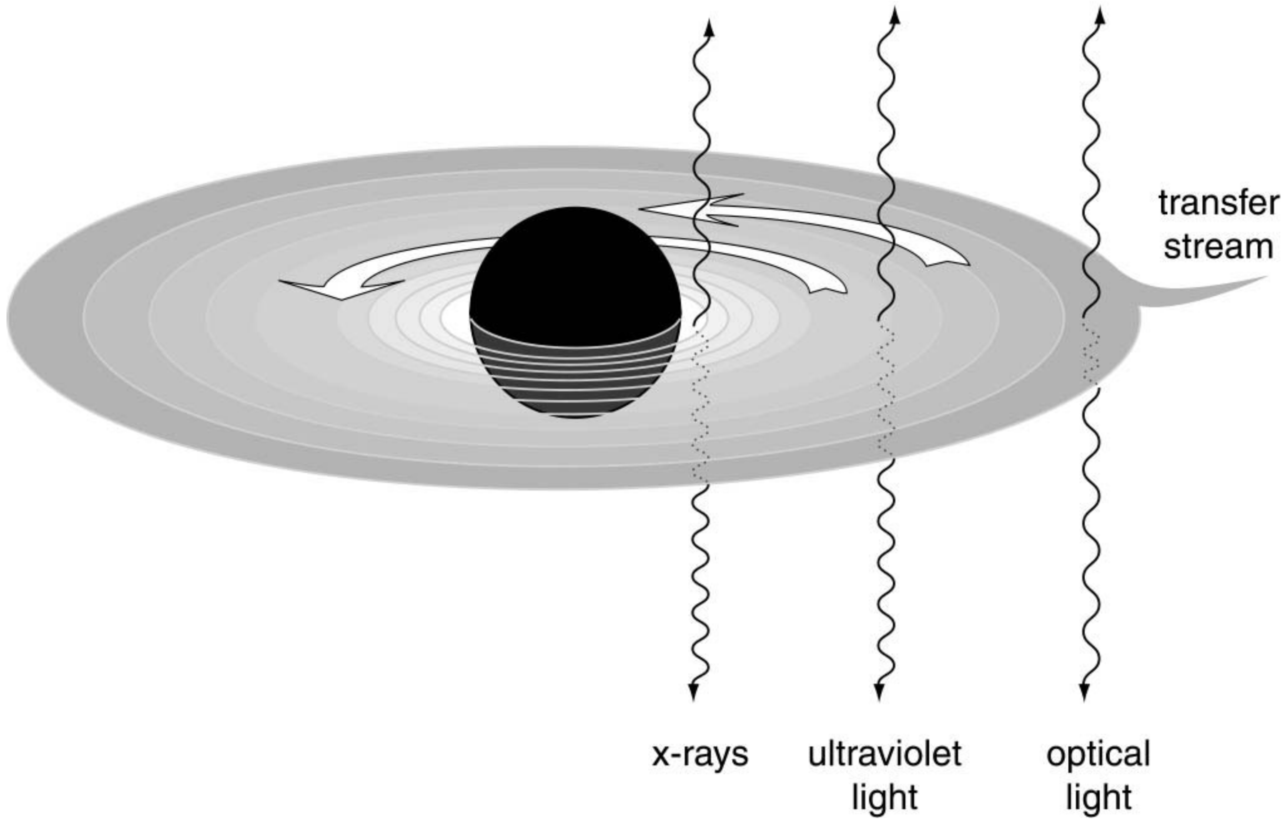
$$\delta E = \frac{G M_{BH} \delta m}{r} \longrightarrow L \approx \frac{G M_{BH} \dot{M}}{r}$$

This is really an upper limit - not all the potential energy will be radiated as the gas falls in…

Note that since $L \sim M$ (Eddington) and also $L \sim dM/dt$, the accretion process and the BH growth is *exponential*

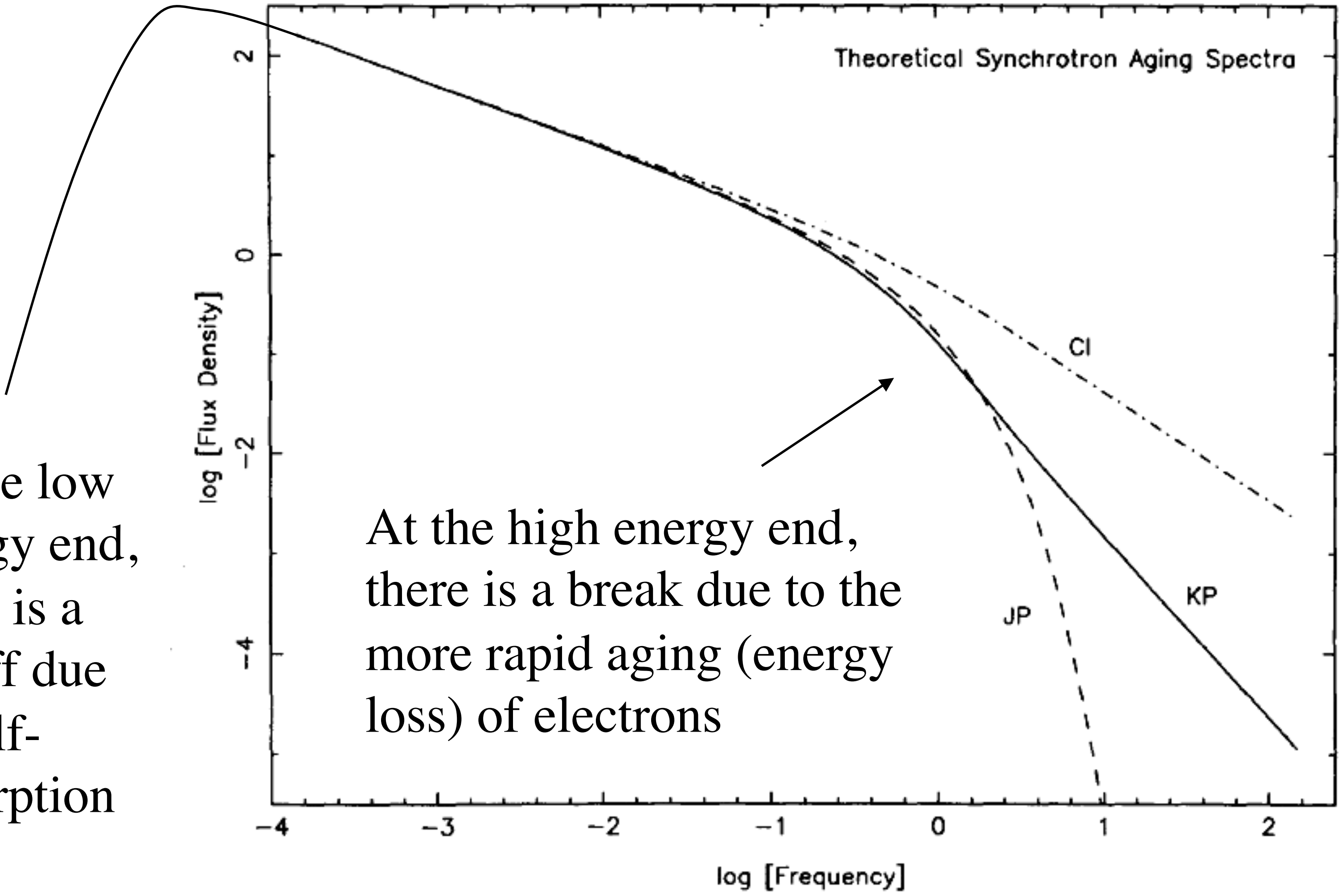
Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself



Synchrotron Radiation

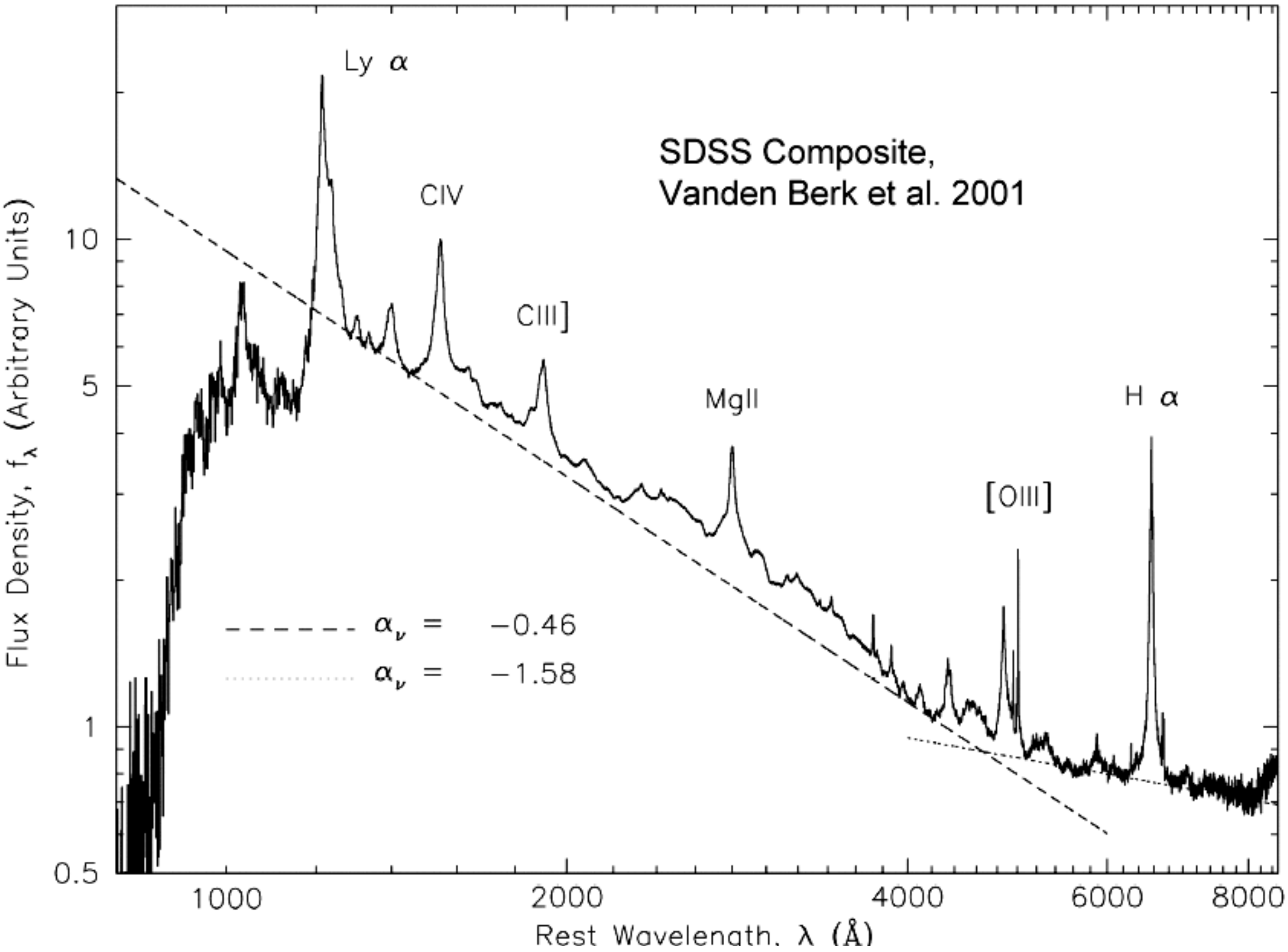
If the distribution of electron energies is a power-law (a common case), so will be the emergent spectrum, $P(\nu) \sim \nu^{\alpha}$, but with cutoffs



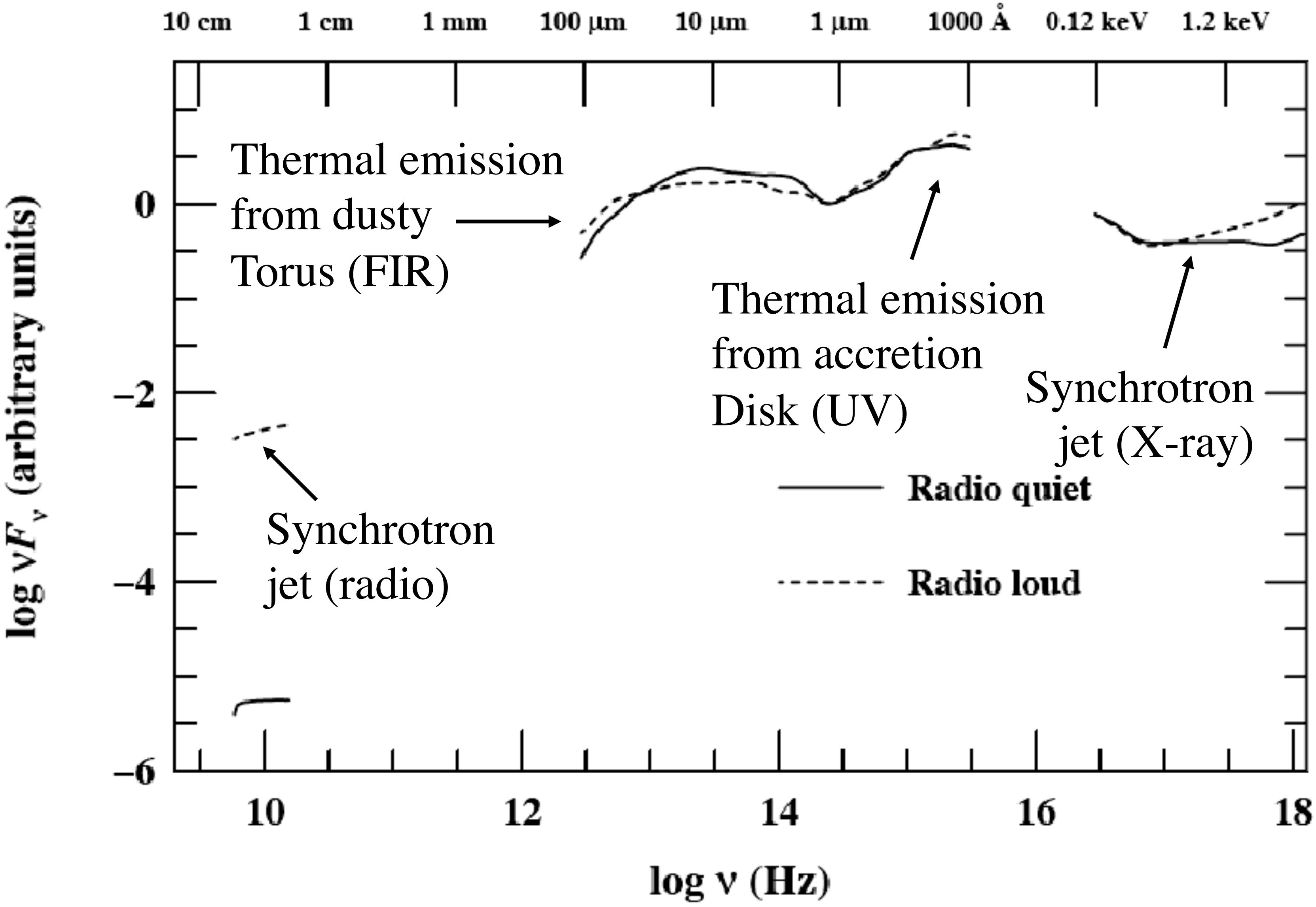
At the low energy end, there is a cutoff due to self-absorption

At the high energy end, there is a break due to the more rapid aging (energy loss) of electrons

Power-Law Continua in QSO Spectra



Explaining the Broad-Band Spectral Energy Distribution in AGN



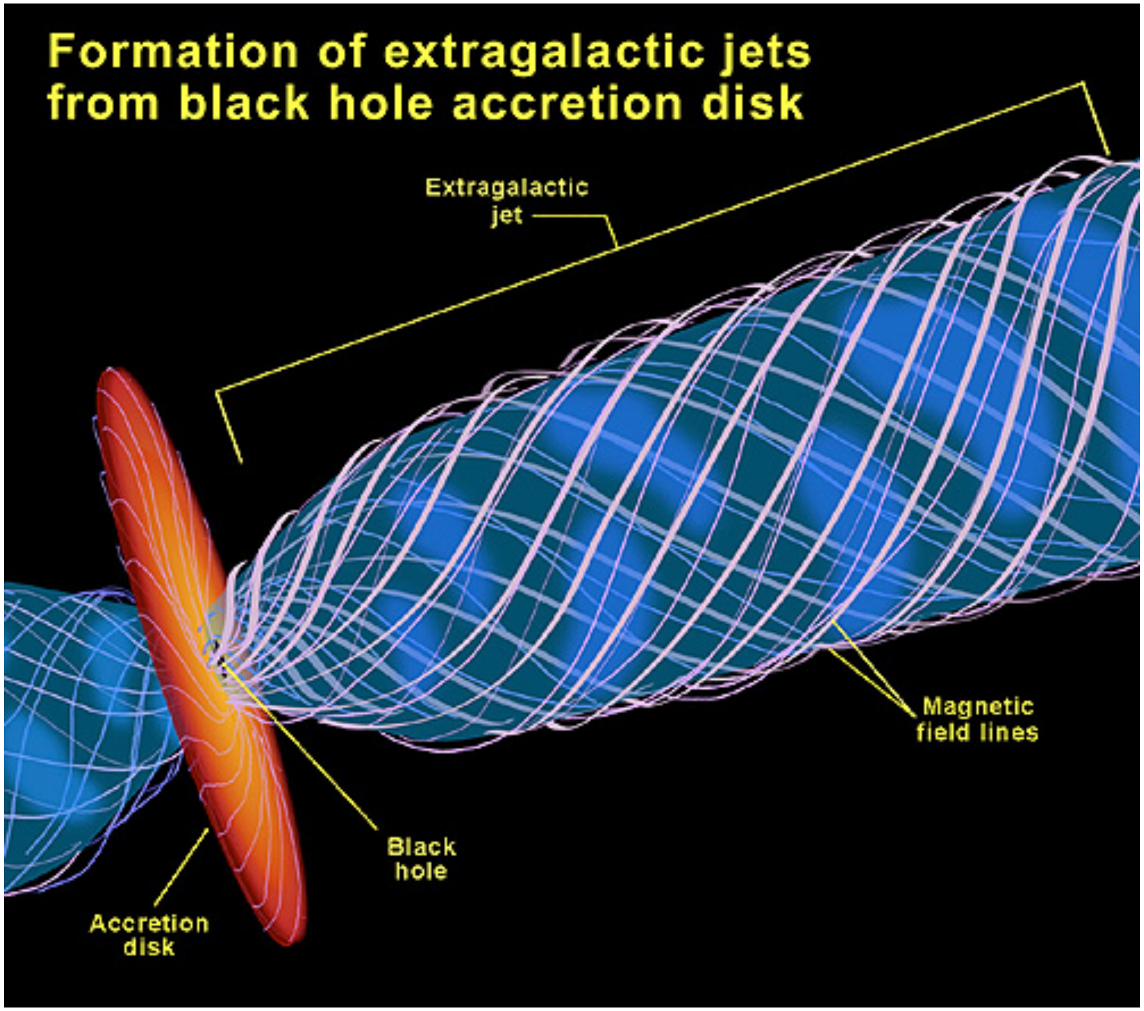
Thermal emission from dusty Torus (FIR)

Thermal emission from accretion Disk (UV)

Synchrotron jet (X-ray)

Synchrotron jet (radio)

The Origin of AGN Jets



Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

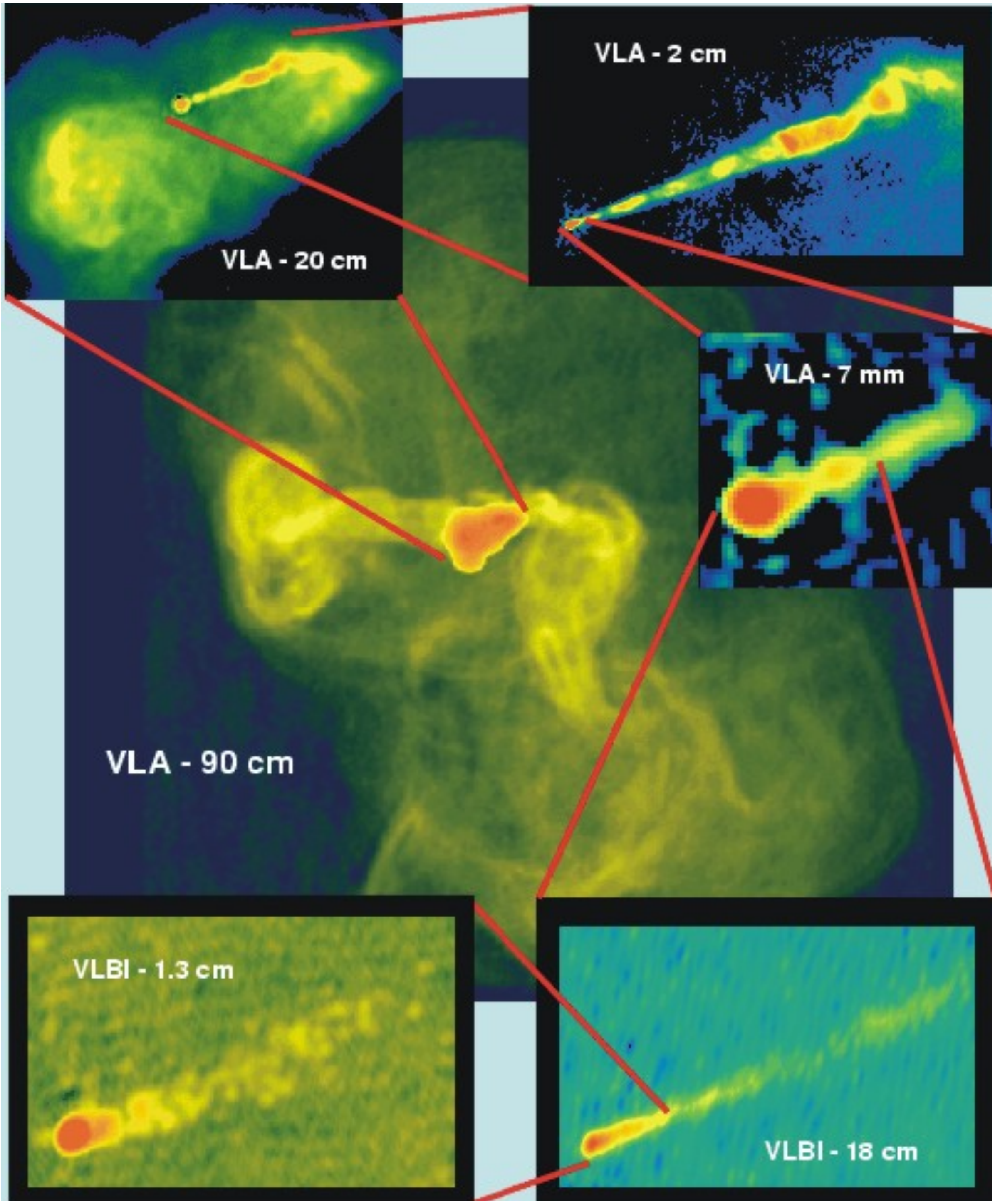
This saps the rotational energy of the disk and/or the BH itself; aside from radiation, mechanical energy is carried by the jets to lobes

Collimated Radio Emission (Jets)

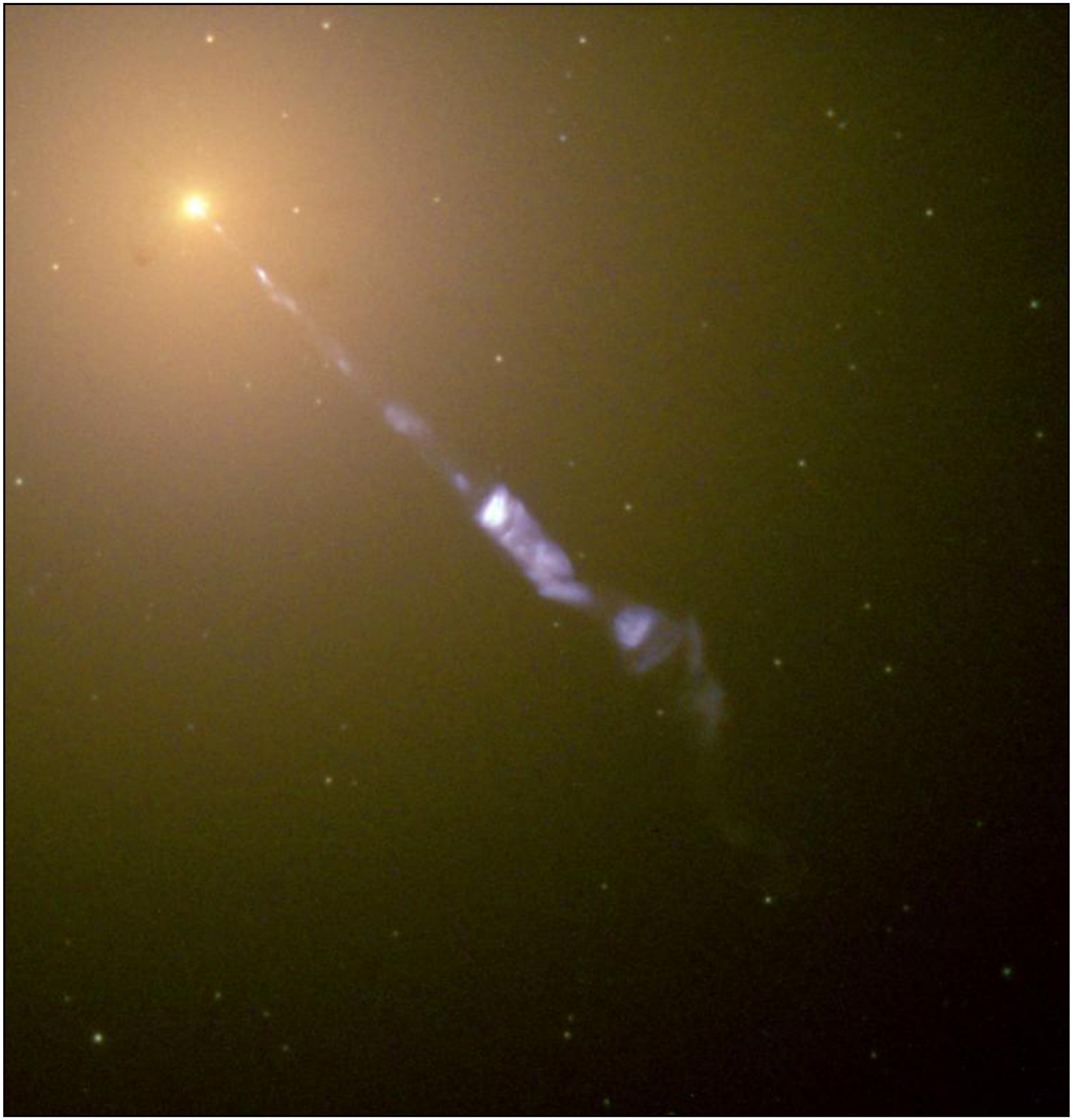
An example of M87 = Virgo A

Generally present in most non-thermal radio sources

Persists over many orders of magnitude in linear scale



… and in some cases in the visible light as well (M87 here)

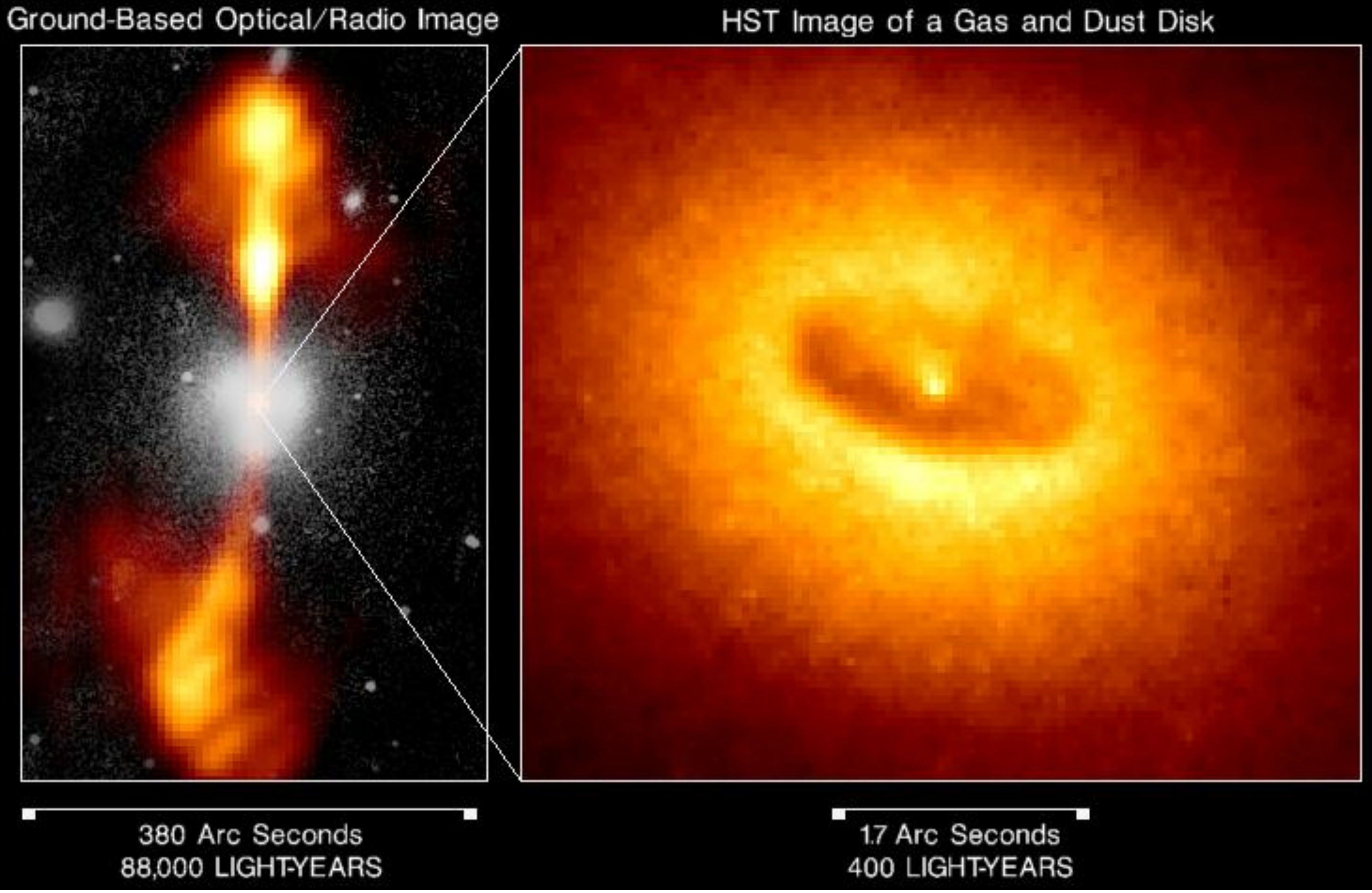


The origin of the emission is the synchotron mechanism: accelerated particles moving in a magnetic field

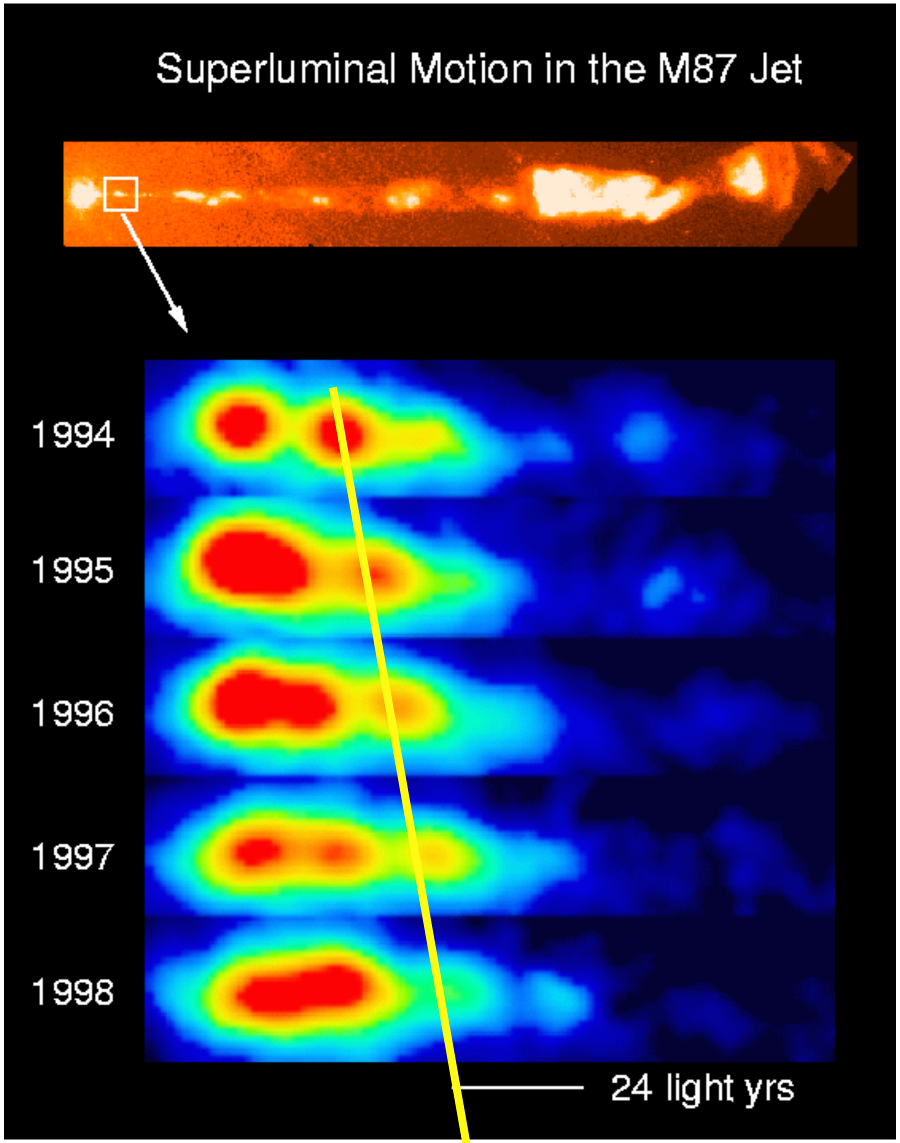
Core of Galaxy NGC 4261

Radio jets orthogonal to the nuclear disk

The nuclear disk: accretion disk, and/or obscuring torus?



Apparent Superluminal Motions

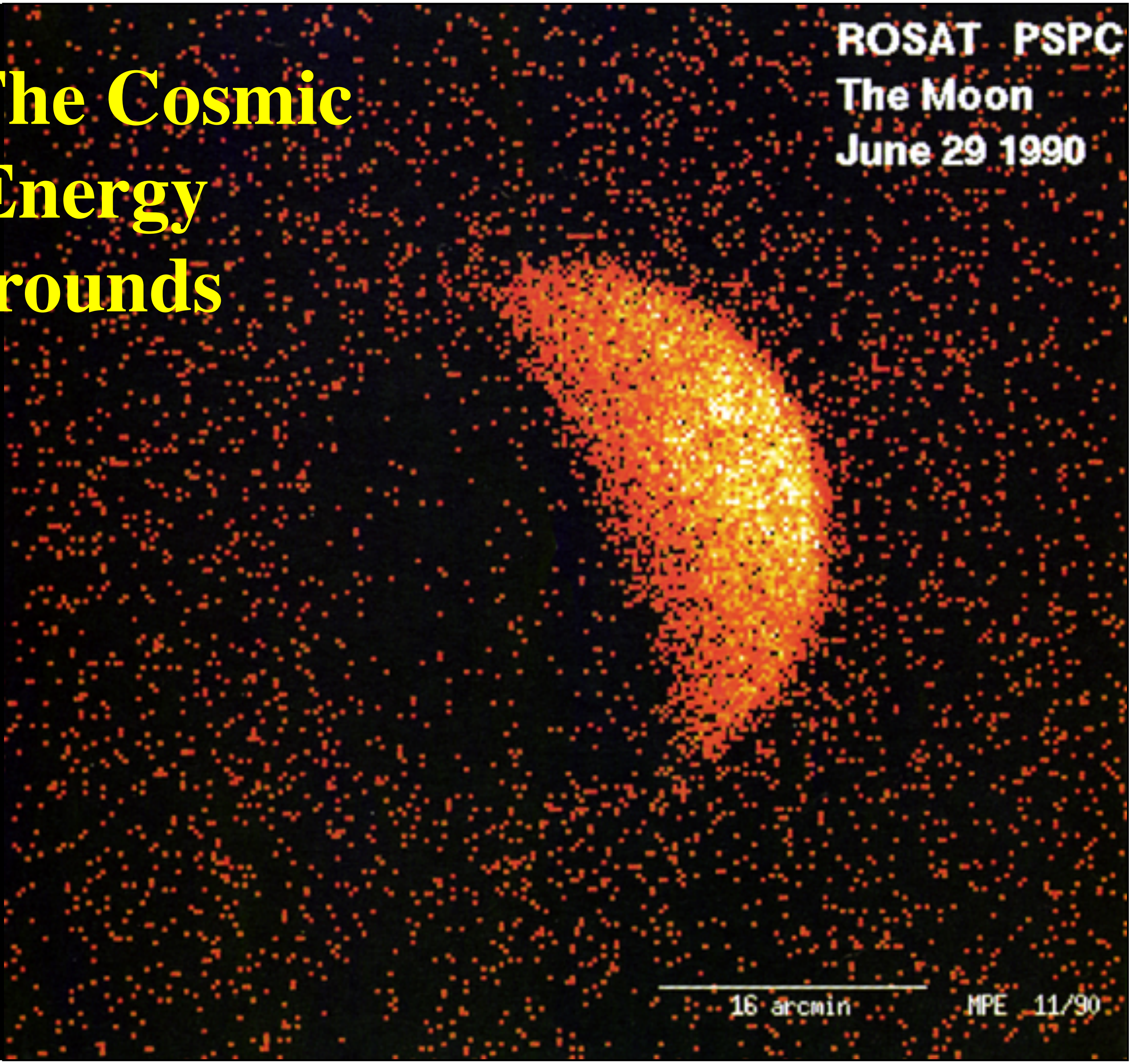


On small scales, jets near the nucleus often show hotspots or knots which can be seen to move with time, e.g., in M87, with apparent speeds exceeding the speed of light!

It is *an optical illusion caused by the relativistic time dilation*

Apparent transverse speed ~ 6 *c*!

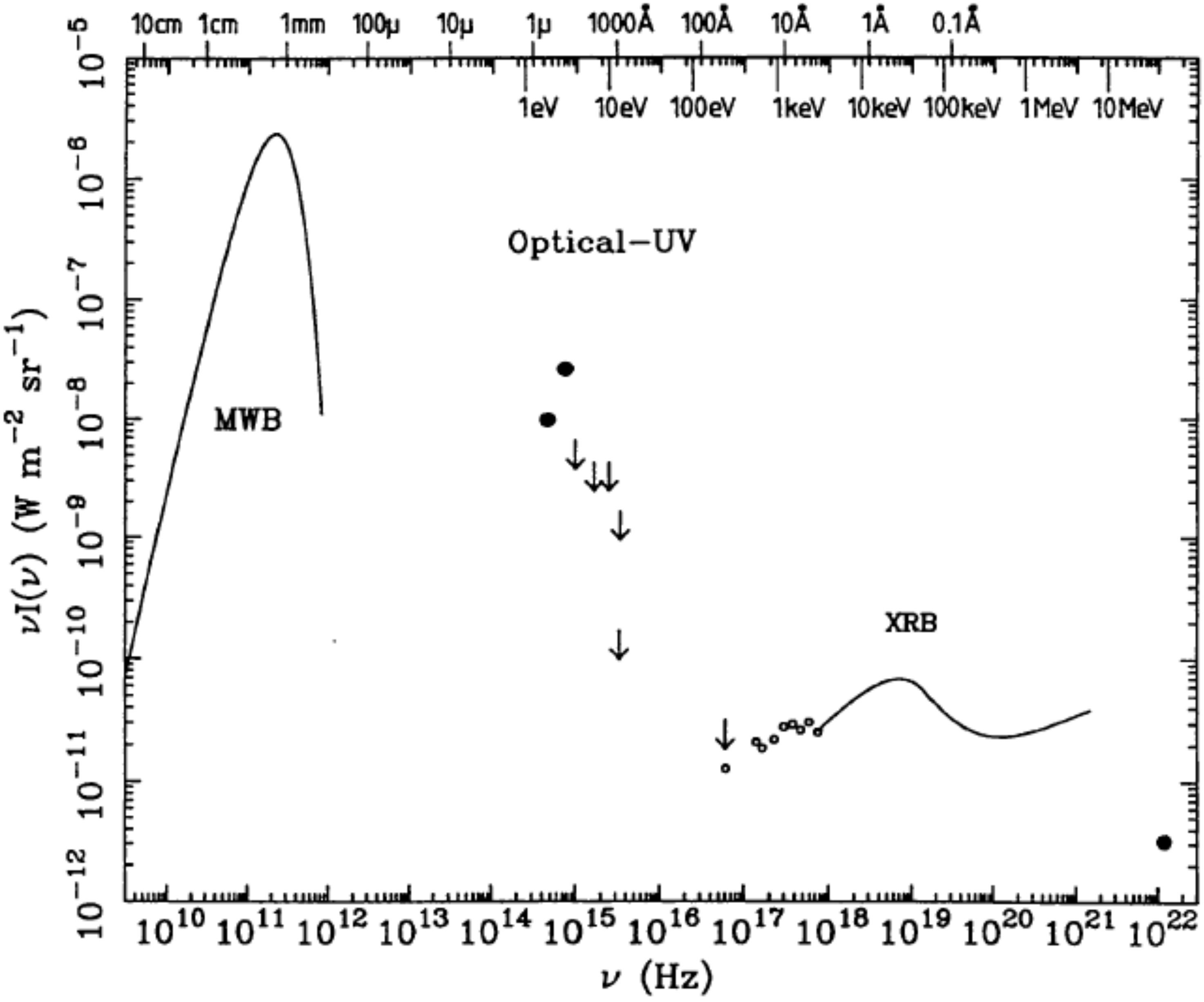
16.4 The Cosmic High Energy Backgrounds



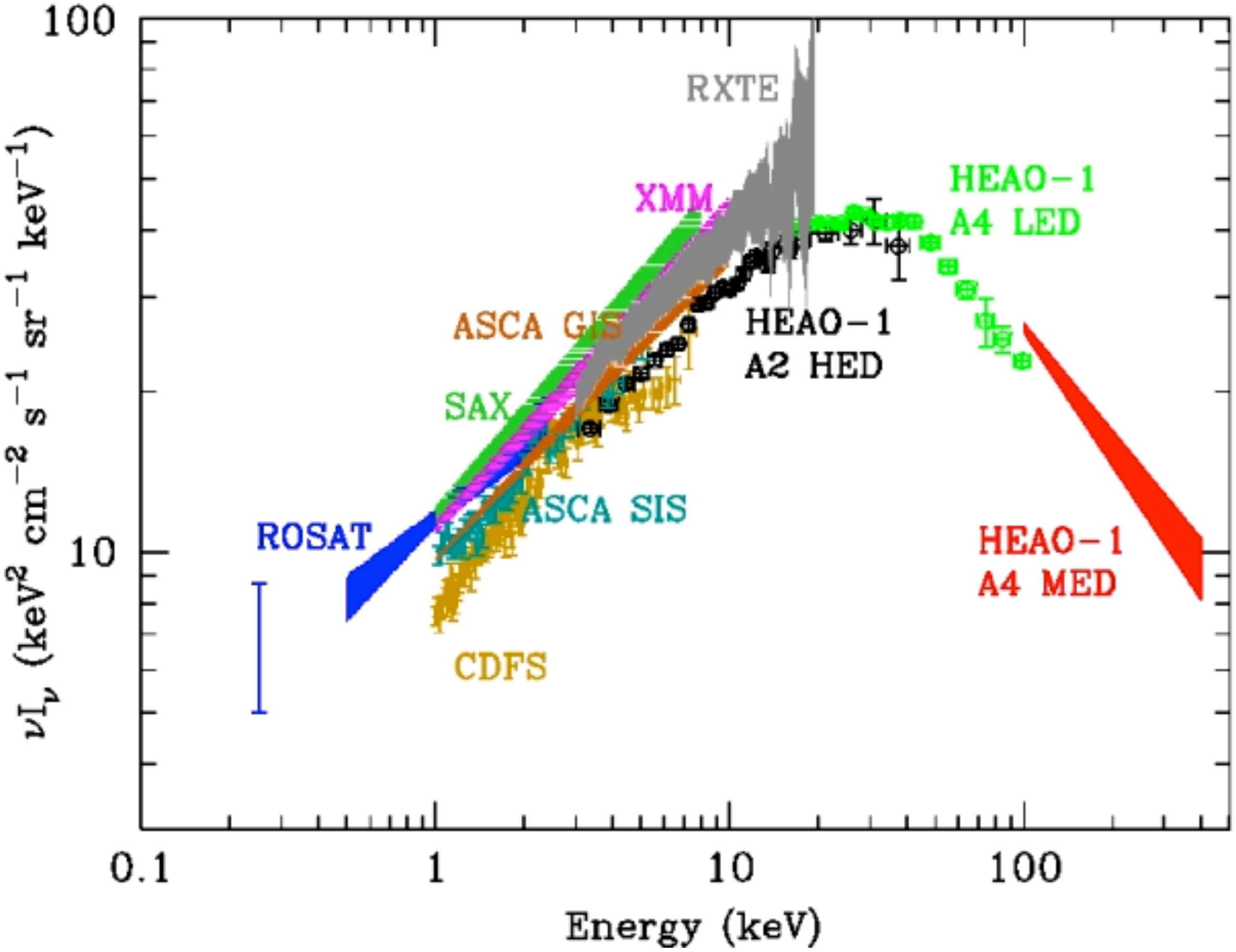
The Cosmic X-Ray Background

- Discovered in 1962 (nearly at the same time as CMBR, in the first X-ray astronomy rocket flight, by R. Giacconi et al. (Nobel Prize in 2002)
- A few percent of the energy density of the diffuse optical/IR backgrounds: $u_{\mathrm{XRB}} \sim 10^{-17}$ erg/cm^3, $u_{\mathrm{Opt/FIR}} \sim$ a few × 10^{-15} erg/cm^3, $u_{\mathrm{CMB}} \sim$ a few × 10^{-13} erg/cm^3
- Now believed to be generated almost entirely by AGN, many of them obscured by dust (hard X-rays go through): the bulk of it is resolved by deep X-ray observations
- The puzzle was to explain the energetics and the spectrum shape at the same time; this required the existence of a substantial obscured (Type 2) AGN population, which has now been found
- The cosmic γ-ray background is mainly due to beamed AGN, but some more exotic components are still possible

The Cosmic X-Ray Background (CXRB)



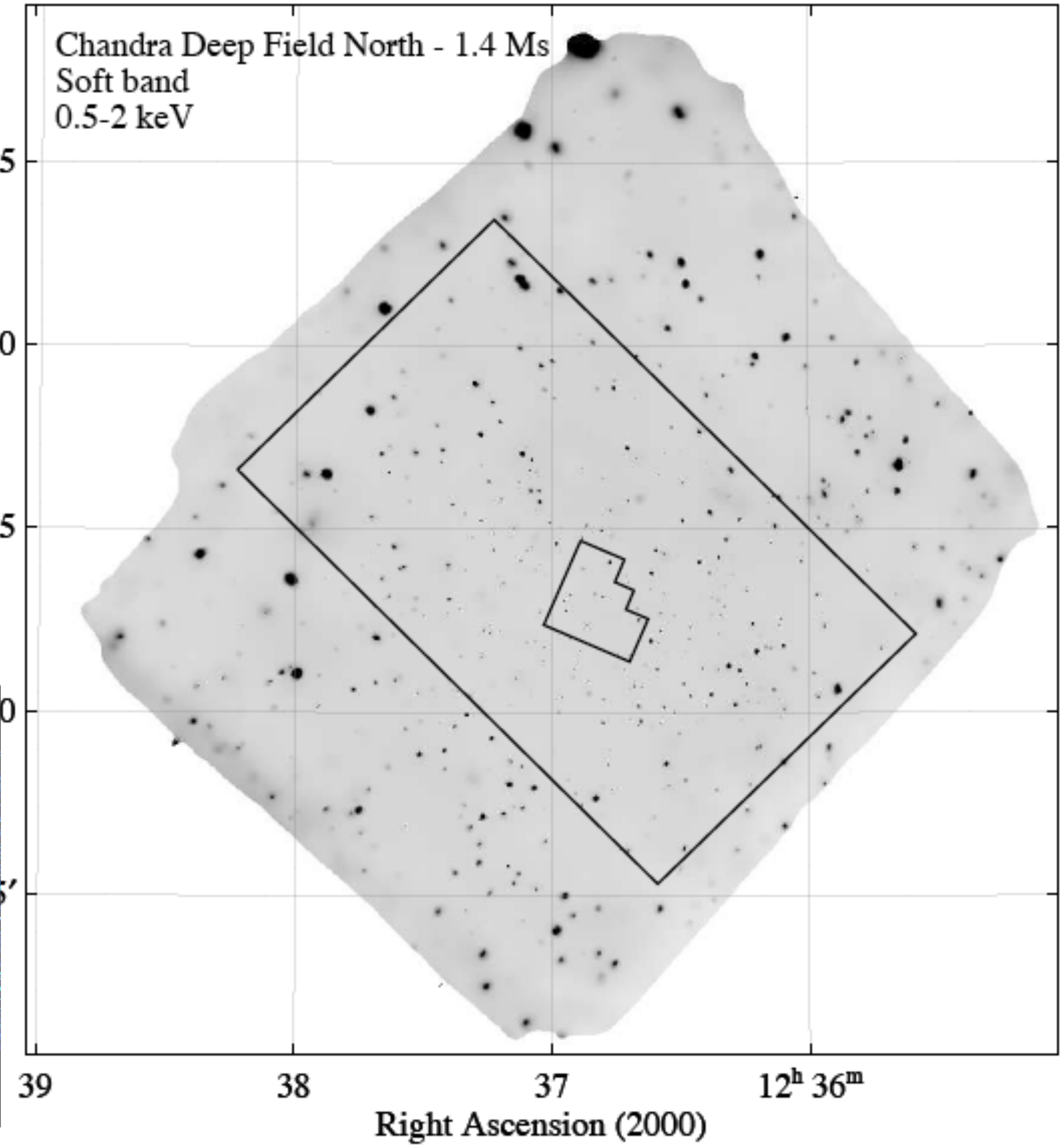
The Spectrum of the CXRB



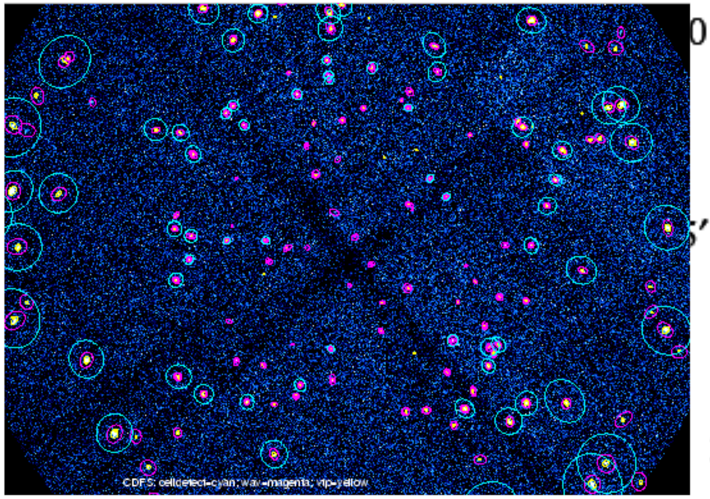
It does not look like an AGN spectrum, but it looks just like the thermal bremsstrahlung of hot plasma (like in a cluster). We now know that is just a coincidence: it is really a sum of the redshiftted AGN spectra, some of which are reflected from the thick dust

Resolving the CXRB

Deep X-ray imaging of fields where there is already deep HST imaging and ground based spectroscopy, also followed in radio, IR, etc.

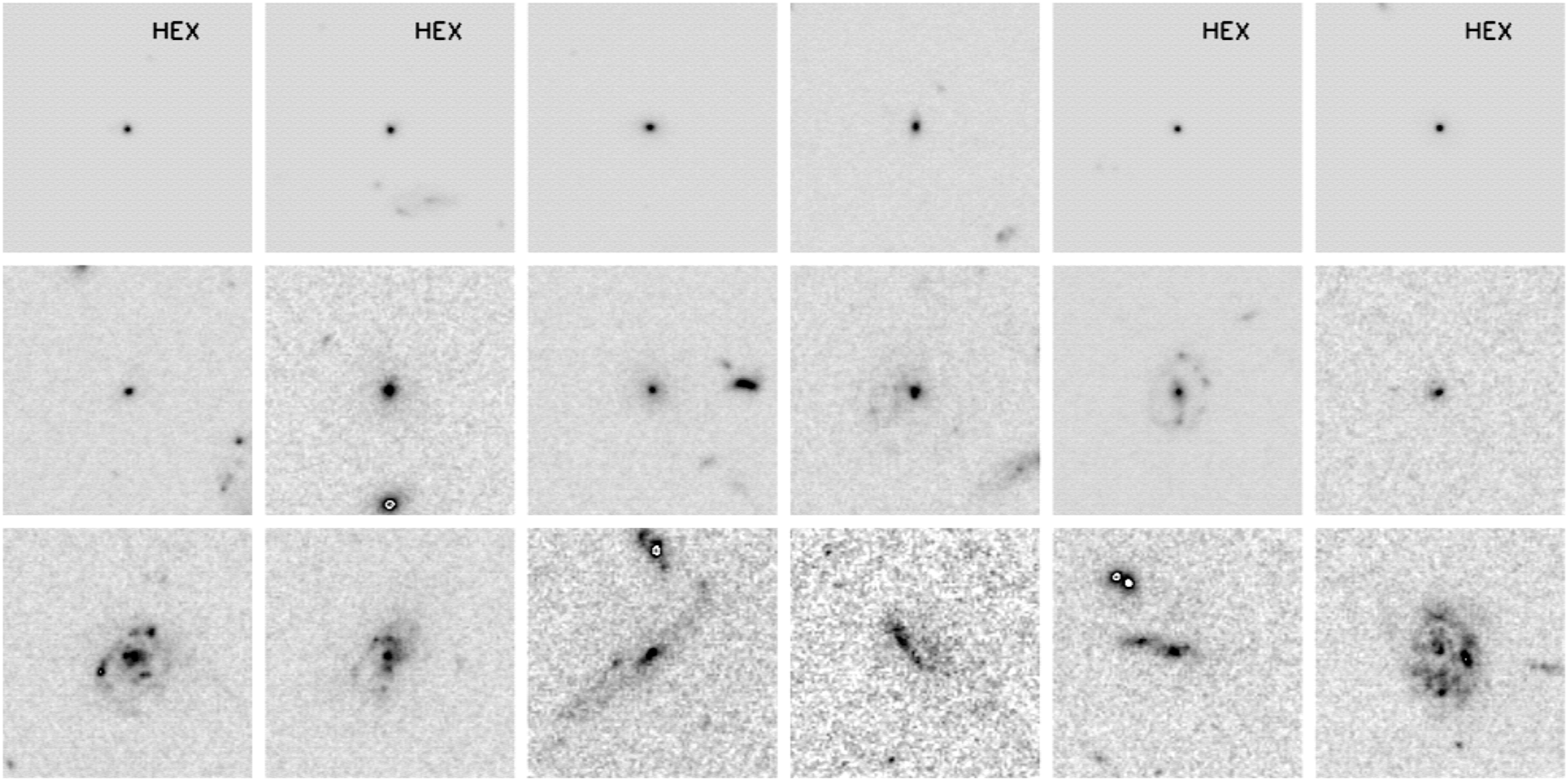


Chandra deep field



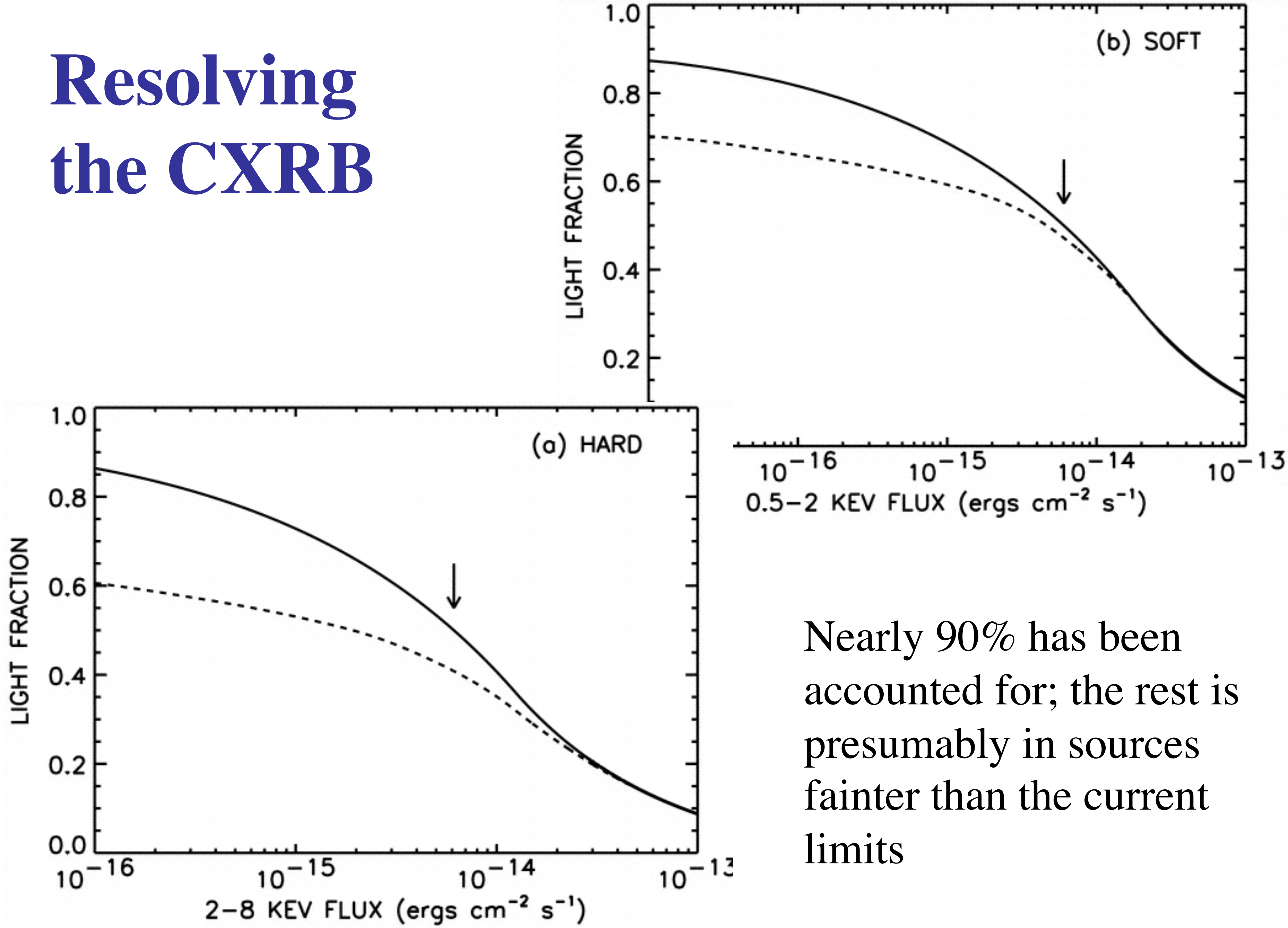
Identifying the Faint X-Ray Sources

Samples of sources:



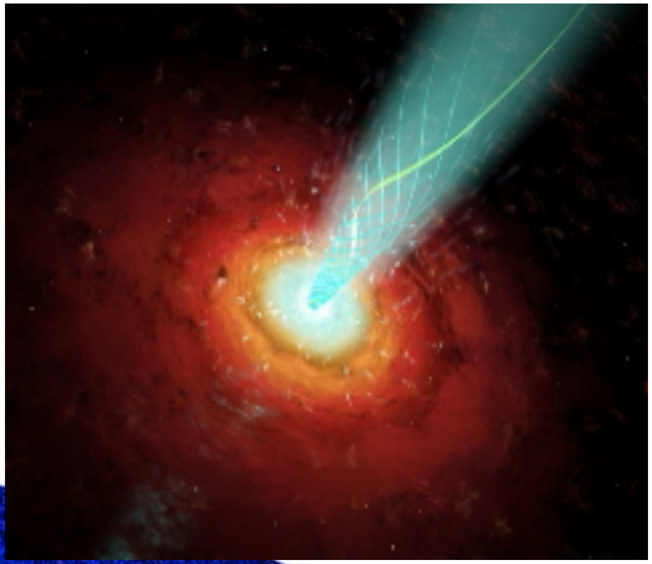
A mixed bag: some QSOs, some galaxies … possibly with hidden AGN

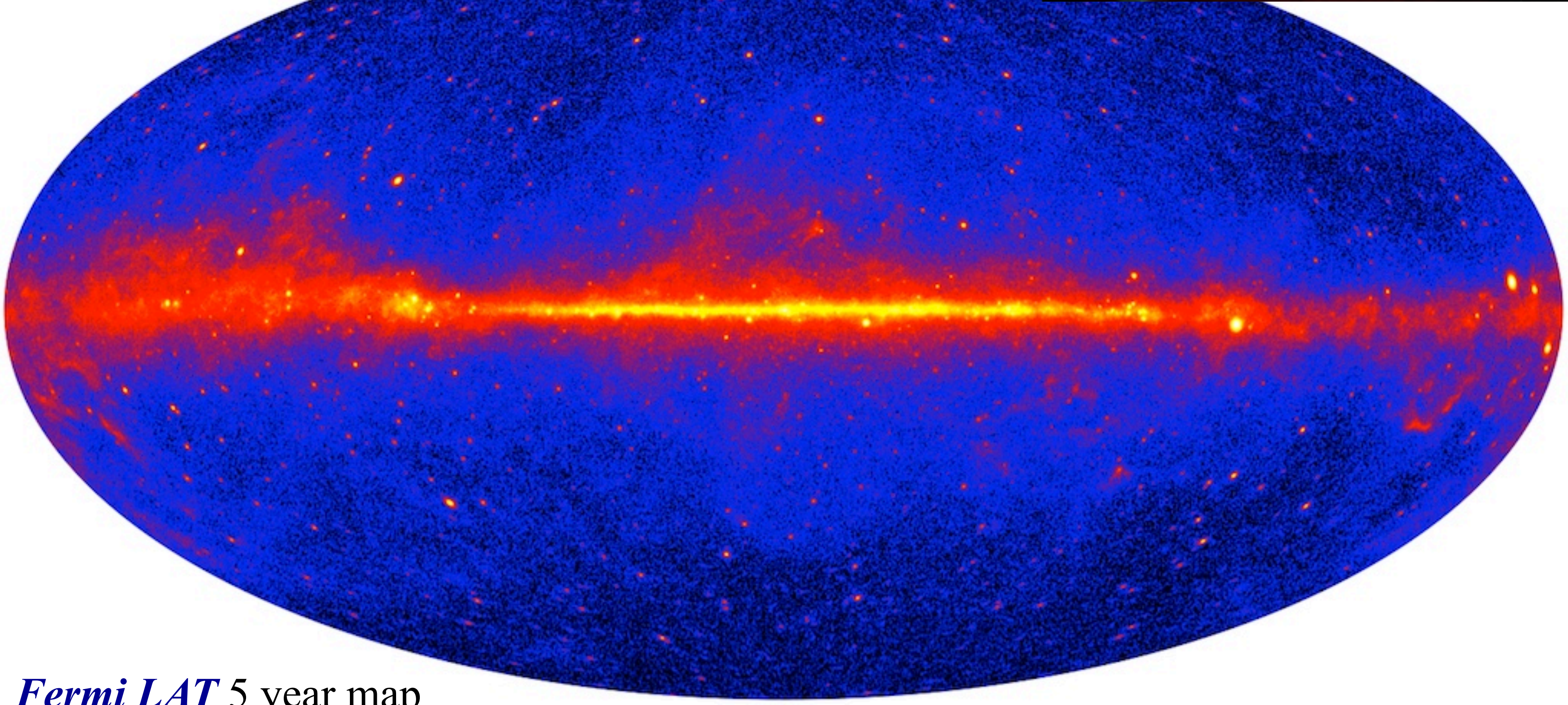
Resolving the CXRB



Nearly 90% has been accounted for; the rest is presumably in sources fainter than the current limits

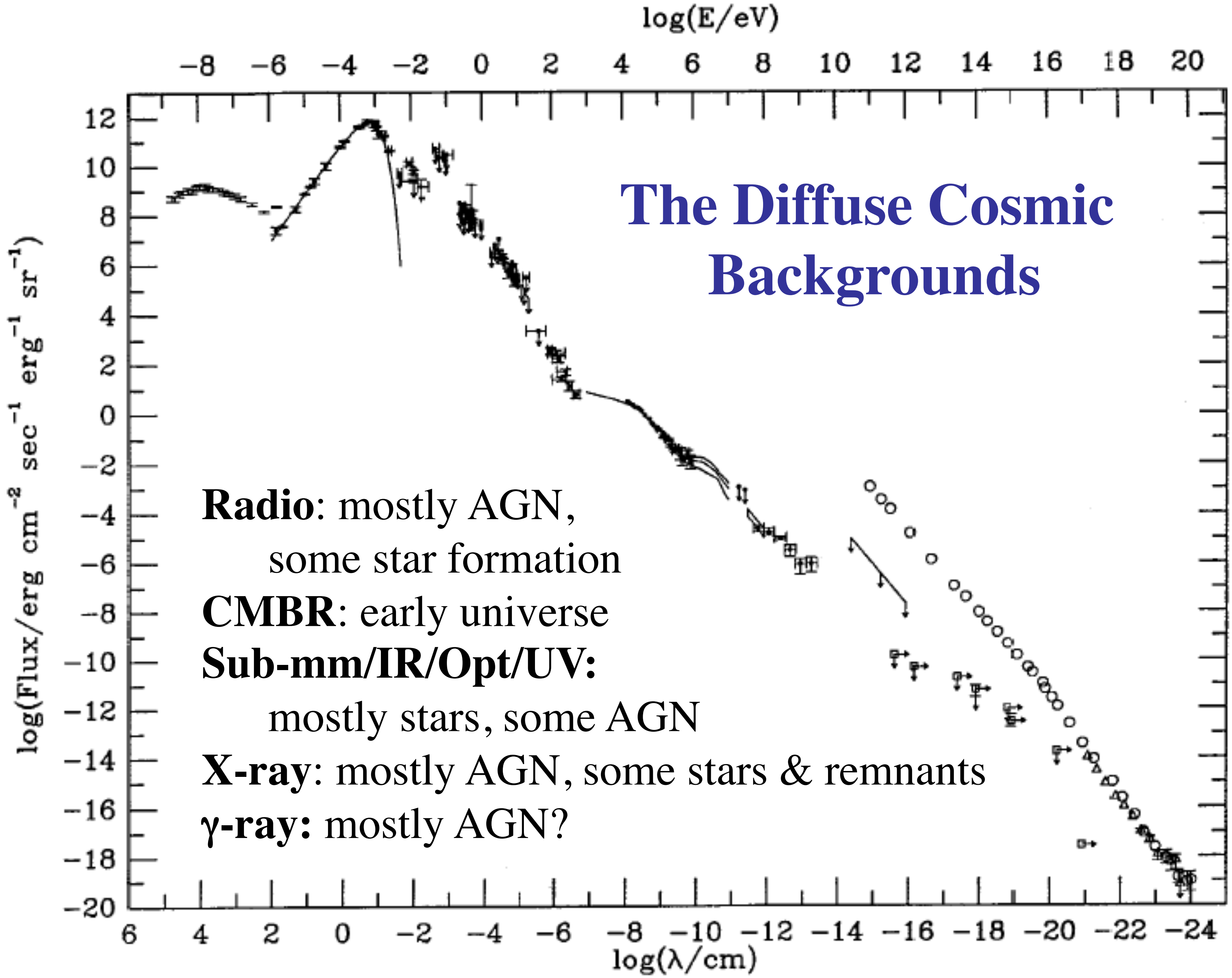
Beamed AGN (Blazars) are (probably) the Principal Extragalactic γ-Ray Sources





Fermi LAT 5 year map

The Diffuse Cosmic Backgrounds



Radio: mostly AGN,
some star formation

CMBR: early universe

Sub-mm/IR/Opt/UV:
mostly stars, some AGN

X-ray: mostly AGN, some stars & remnants

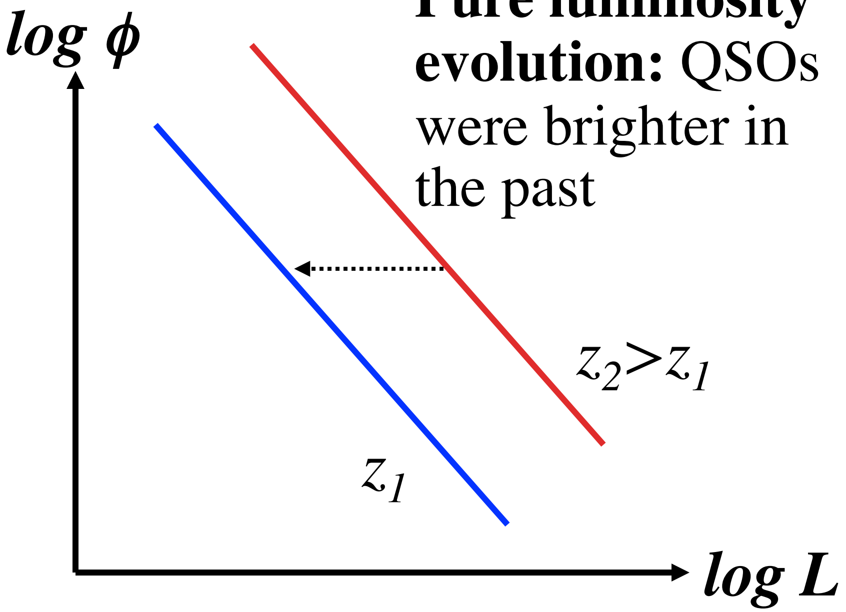
γ-ray: mostly AGN?

16.5 AGN Formation and Evolution

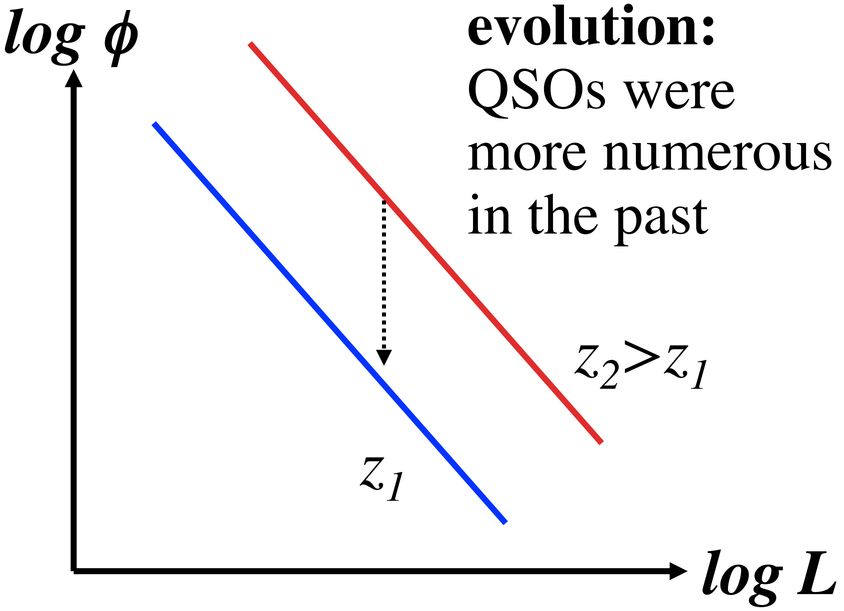
Quasar Evolution

- How is the luminosity function of QSOs, and their total comoving density changing in redshift?
- This may help us understand better the origins of the AGN activity and their relation to galaxy evolution
- QSO numbers increase rapidly with redshift, but are luminosities or densities changing? For a pure power-law luminosity function, the answer is ambiguous:

Pure luminosity evolution: QSOs were brighter in the past



Pure density evolution: QSOs were more numerous in the past

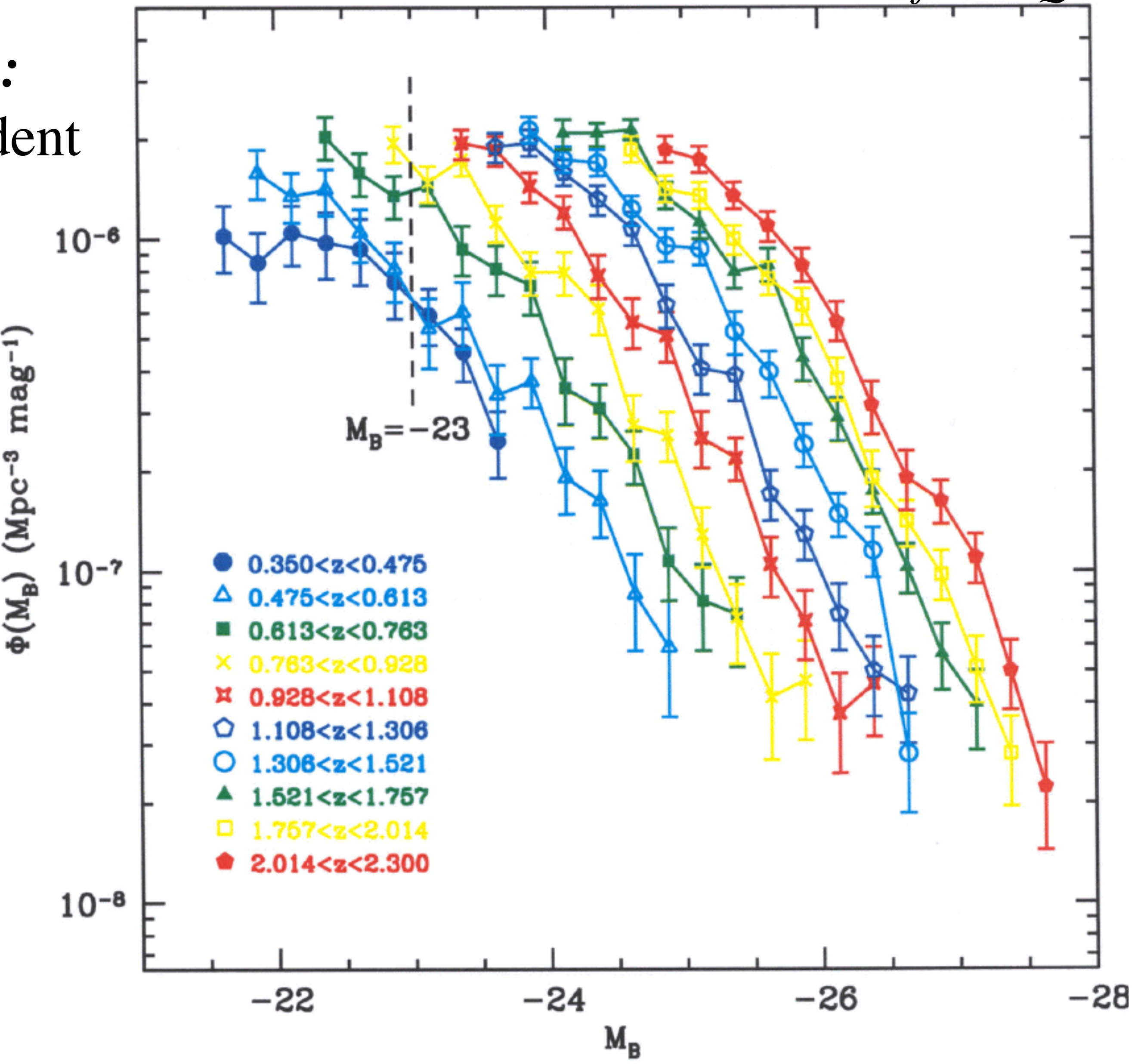


Quasar Evolution

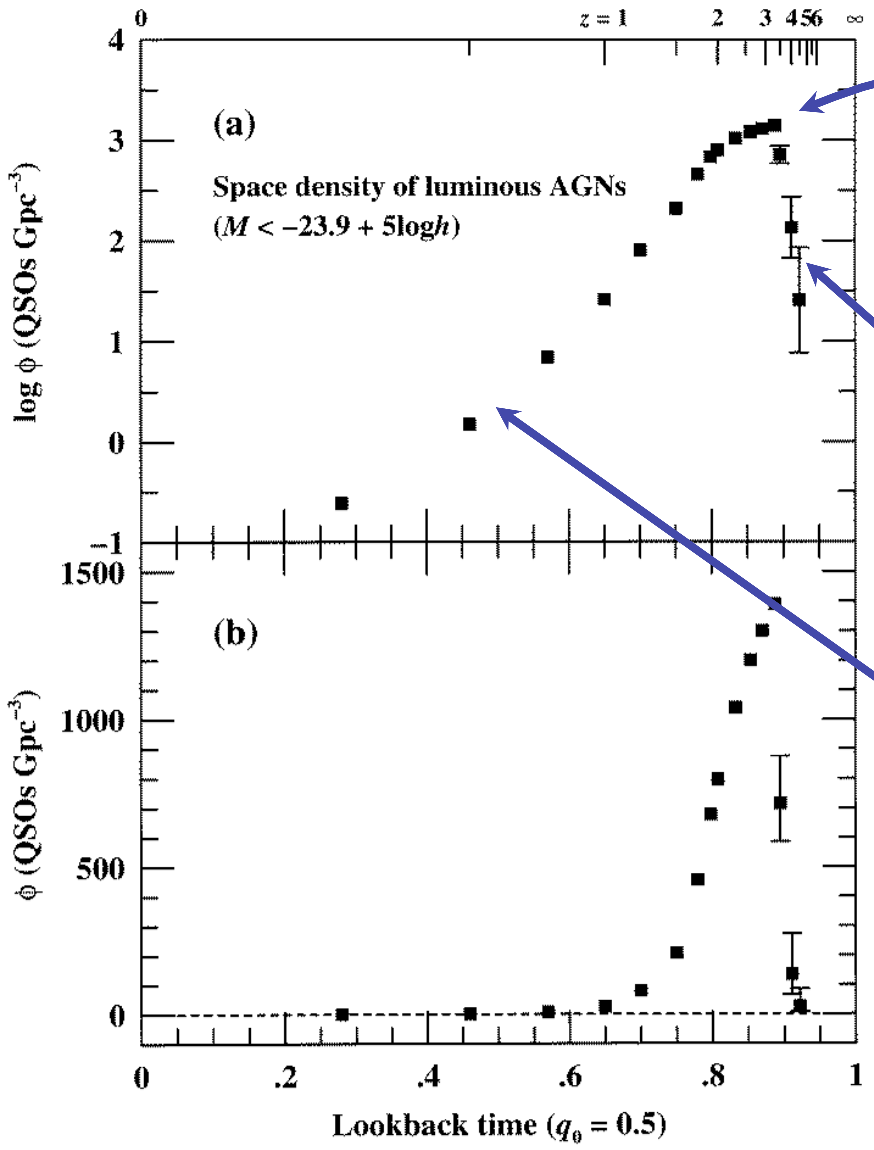
Results from 2QZ

The answer is ***both:*** Luminosity-dependent density evolution

Luminous QSOs evolve faster at higher redshifts, and the shape of the QSO LF changes: there is a break, with a flatter slope at lower luminosities



The History of the Comoving Number Density of Quasars



The Peak of the Quasar Era at z ~ 2 - 3: The Maximum Merging Epoch?

The Rise of Quasars: Initial Assembly of the Host Galaxies, Growth of the SMBHs

The Decline at Low *z*' s: Diminishing Fueling Events

Newly (re)ignited AGN can then regulate the growth and star formation in their hosts, through radiative and mechanical energy input feedback, and determine some of the fundamental properties of the host galaxies (and drive the observed correlations)

(Di Mateo, Springel, Hopkins, et al., and many others…)

AGN Feedback

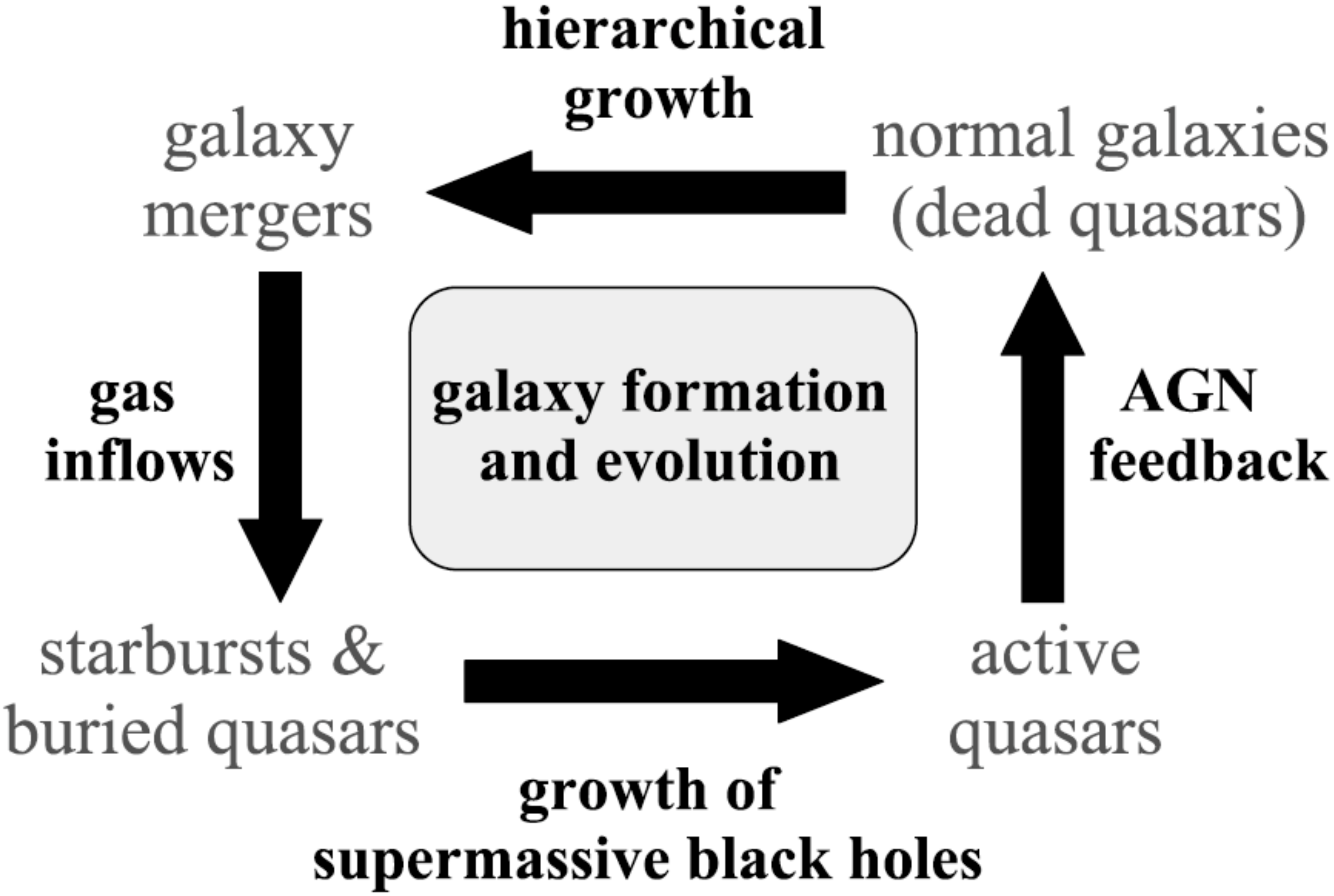
Radiative energy input:

- Ionizes the host ISM and cluster IGM, curtailing star formation
- Drives a galactic wind due to coupling with the gas, expels the chemically processed material into the IGM
- Comparable mechanical energy input from the jets (mainly important in clusters?)
- Note:

$$E_{AGN} \sim L_{AGN}\, t_{AGN} \sim 10^{12}\, L_{\odot}\ 10^{7}\ \text{yr} \sim 10^{60}\ \text{erg}$$

$$E_{bind.gal.} \sim M_{gal}\, V_{gal}^{2} \sim 10^{12}\, M_{\odot}\ (200\ \text{km/s})^{2} \sim 10^{60}\ \text{erg}$$

The Synergy of Galaxies and SMBHs



hierarchical growth

galaxy mergers

normal galaxies (dead quasars)

gas inflows

galaxy formation and evolution

AGN feedback

starbursts & buried quasars

active quasars

growth of supermassive black holes

(from P. Hopkins)

The Nature of the BH "Seeds"

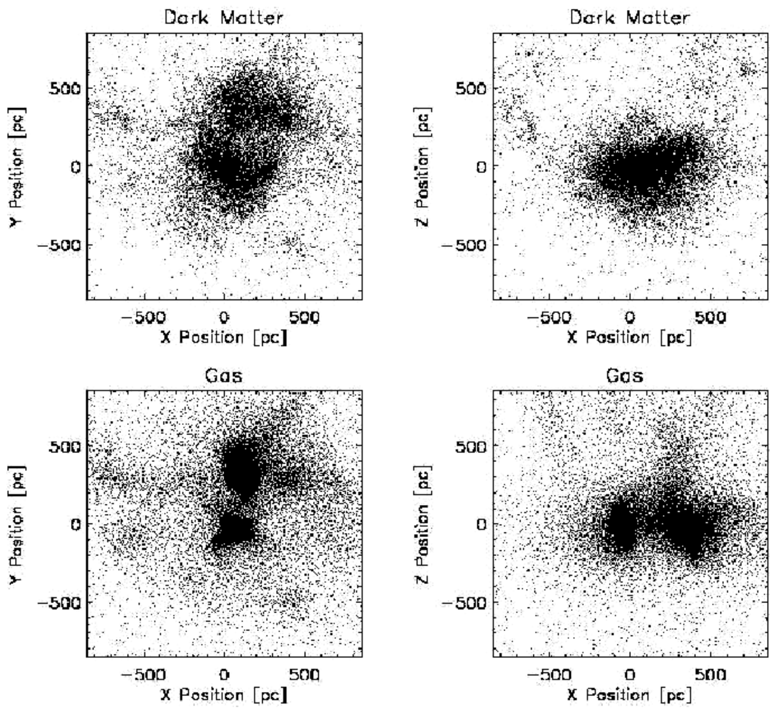
Some plausible choices include:

- Primordial, i.e., created by localized gravitational collapses in the early universe, e.g., during phase transitions
  - No evidence and no compelling reasons for them, but would be very interesting if they did exist; could have "any" mass…
- Remnants of Pop. III massive stars: $M_{seed} \sim 10 - 100\ M_\odot$
  - Could be detectable as high-*z* GRBs
- Gravitational collapse of dense star clusters, or runaway mergers of stars: $M_{seed} \sim 10^2 - 10^4\ M_\odot$
- Direct gravitational collapse of dense protogalactic cores

More than one of these processes may be operating …

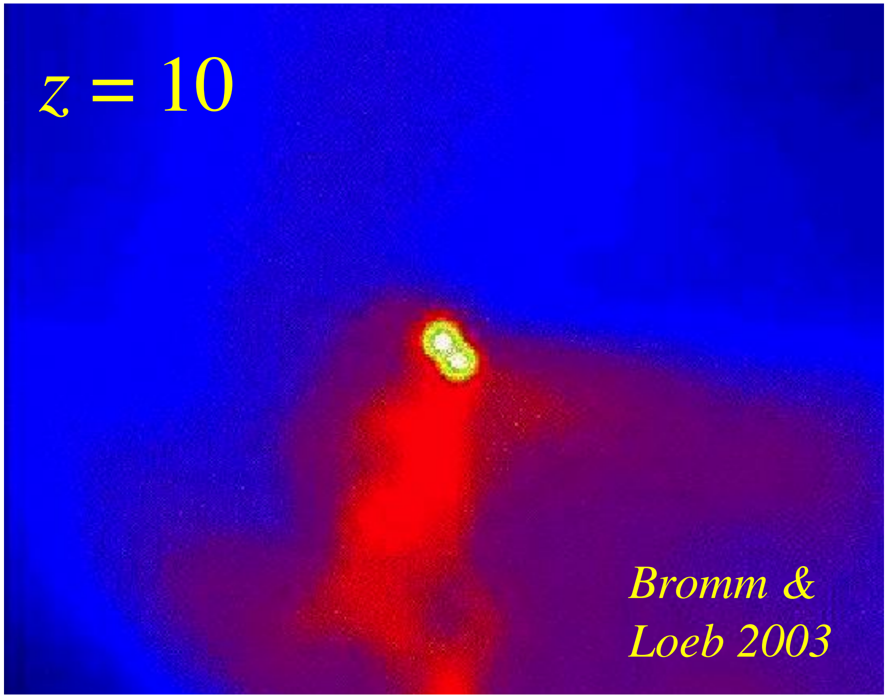
The process must be very rapid in order to produce observed luminous quasars at high redshifts, with $M_{bh} \sim 10^9\ M_\odot$

Pop III Black Holes and the Origin of AGN



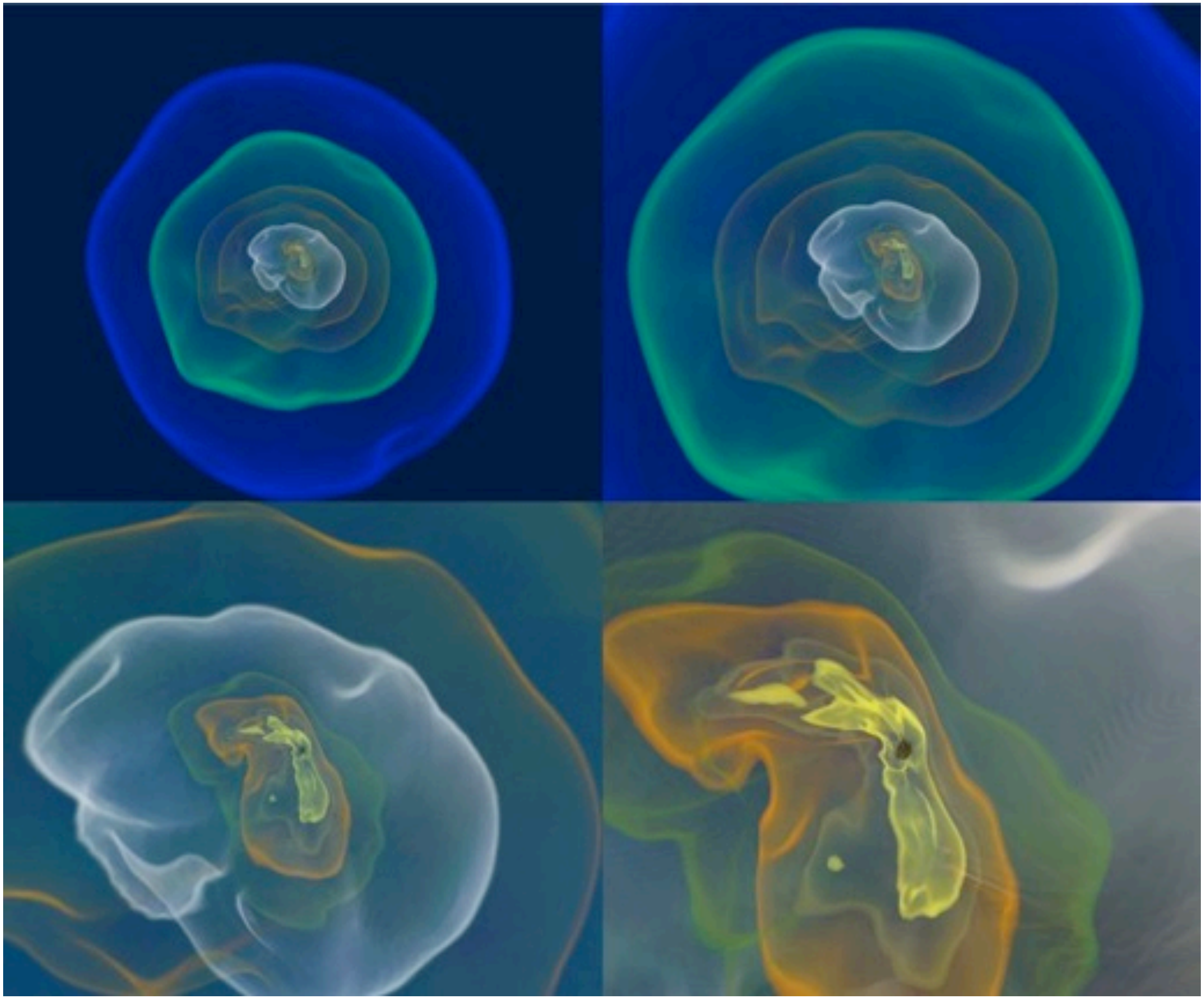
- Explosions of massive Pop III stars can produce relict BHs with $M_\bullet \sim$ few - $10^2\ M_\odot$
- Direct collapse of zero-spin mini-halos may lead to BHs with $M_\bullet \sim 10^4$ - $10^6\ M_\odot$

- They can grow through rapid accretion and merging to become central engines of AGN (SMBH)
- Mergers of these early BHs may generate gravitational waves detectable by LISA



Bromm & Loeb 2003

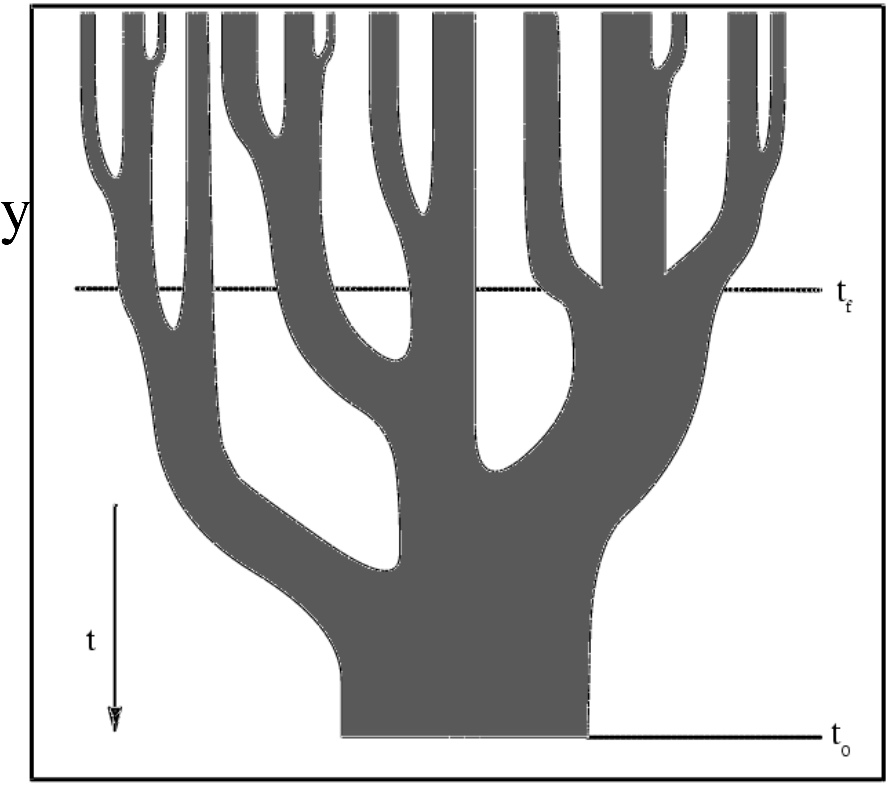
Formation of a SMBH by Direct Collapse



Numerical simulation by Wise, Turk, Abel (KIPAC)

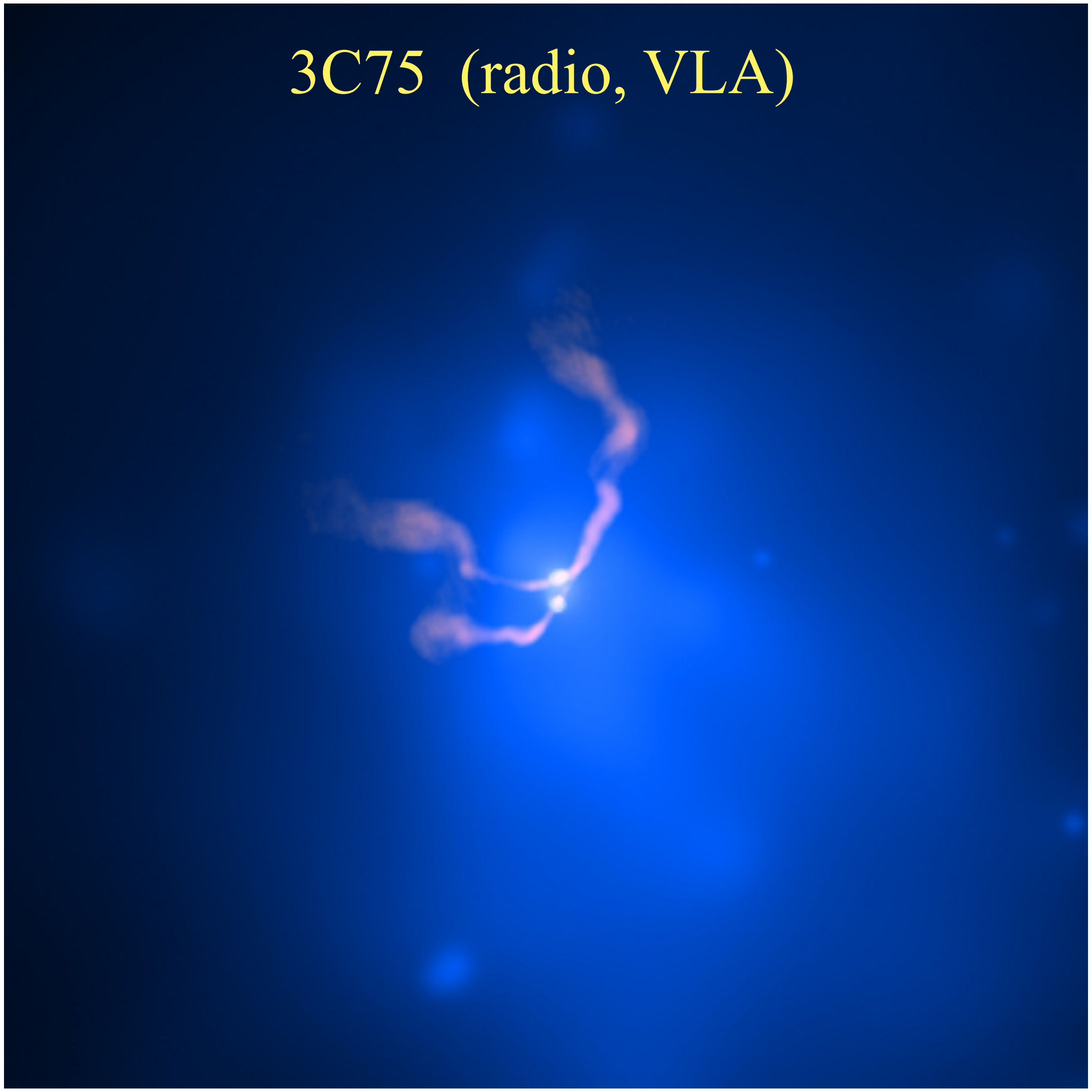
SMBH Growth Mechanisms

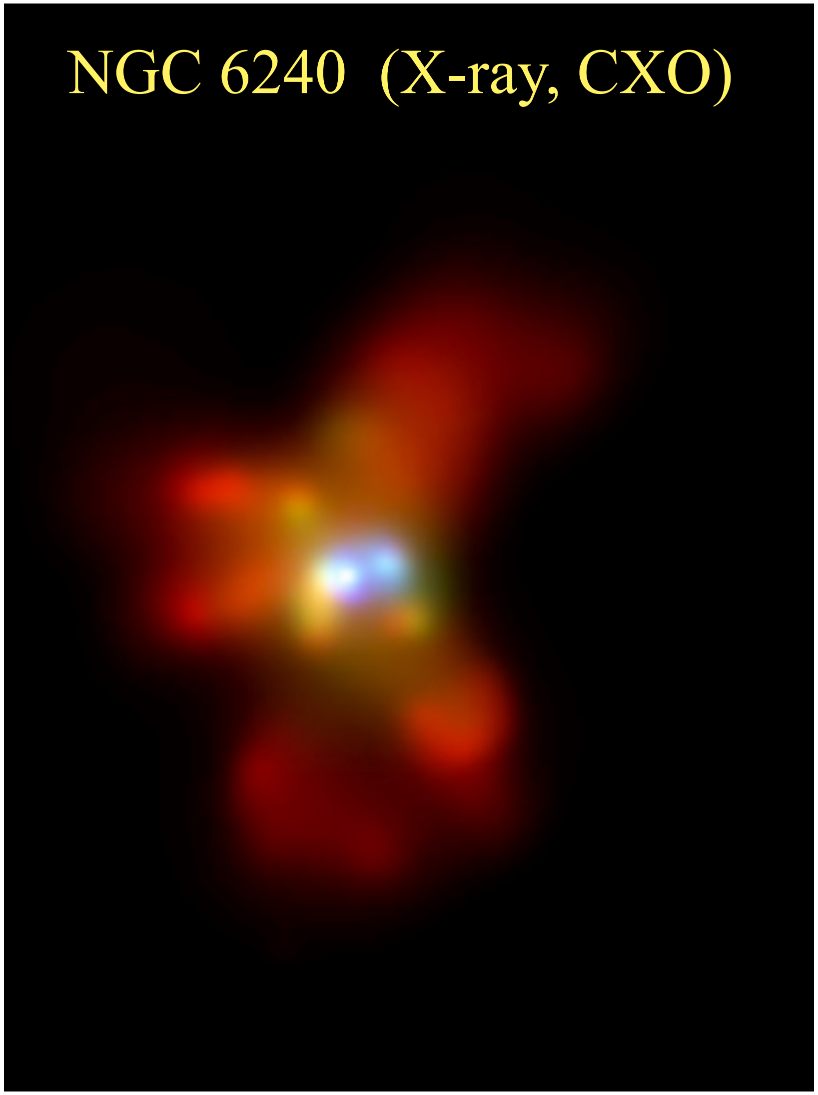
- In a hierarchical picture, as galaxies merge so will their BH’s
  - Some may get ejected in 3-body interactions; their subsequent fate may be interesting
- This can naturally lead to the establishment of the SMBH - host galaxy correlations, which may be also sharpened by the AGN feedback



- Note that BH merging simply *re-arranges* the distribution of the collapsed mass; *collapsed mass grows by accretion*, following the BH seed collapse
- This fueling/build-up may be especially effective in mergers

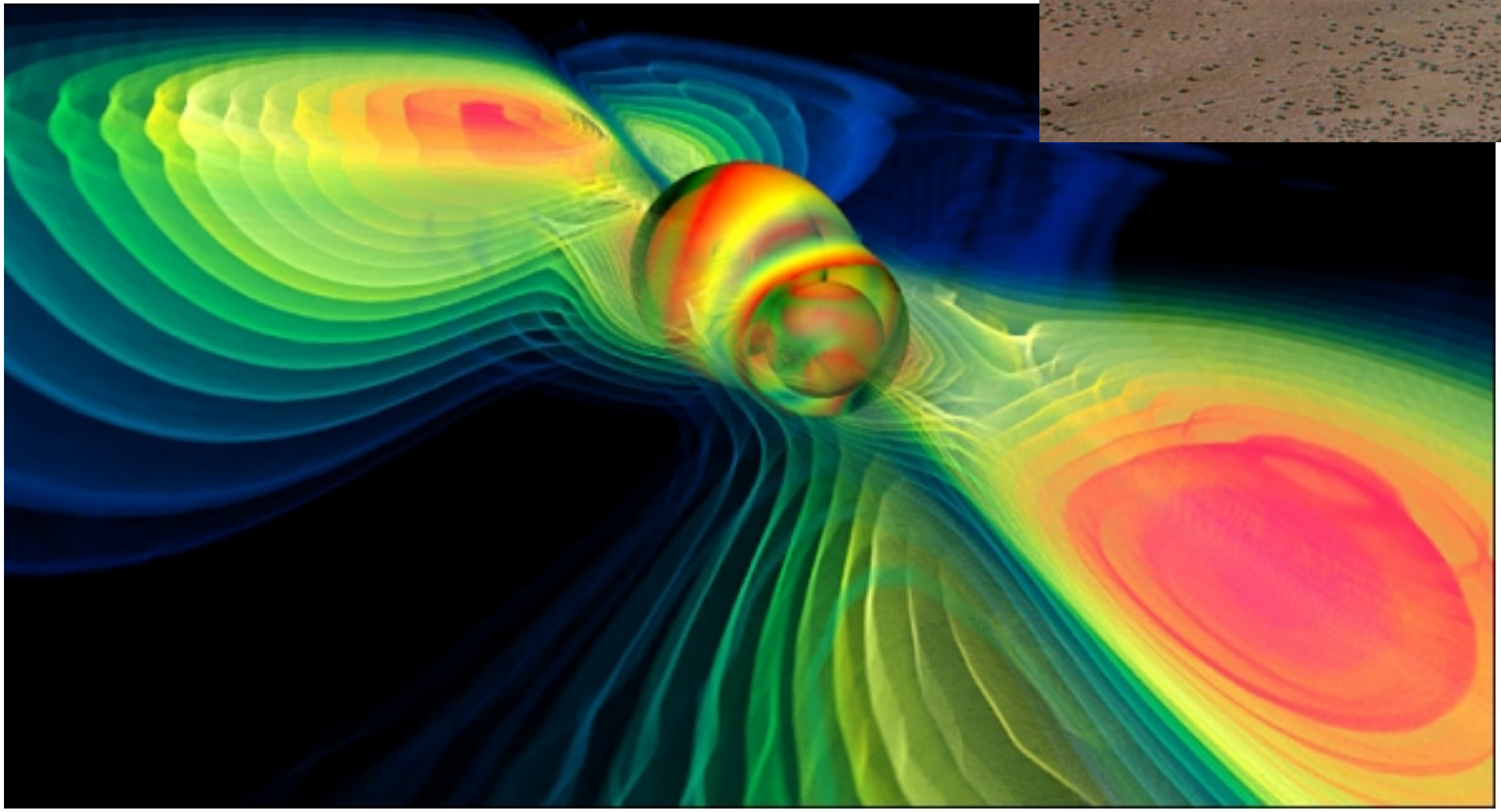
Pre-Merger SMBH Binaries Are Observed at Low Redshifts


3C75 (radio, VLA)


NGC 6240 (X-ray, CXO)

Observable Signatures of BH Mergers

Merging BHs are expected to be gravitational wave sources, but there could also be some observable electromagnetic signatures



LIGO