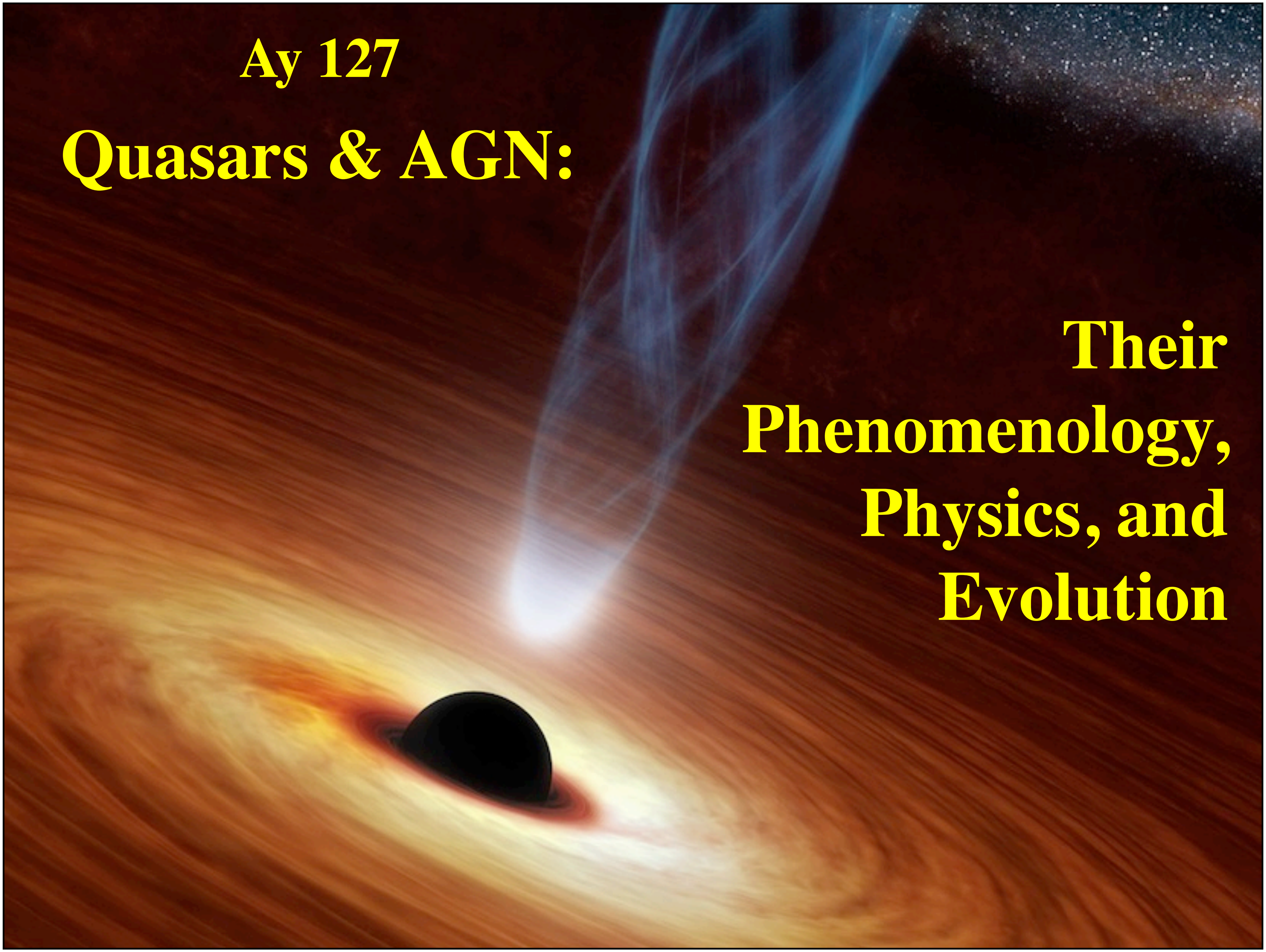
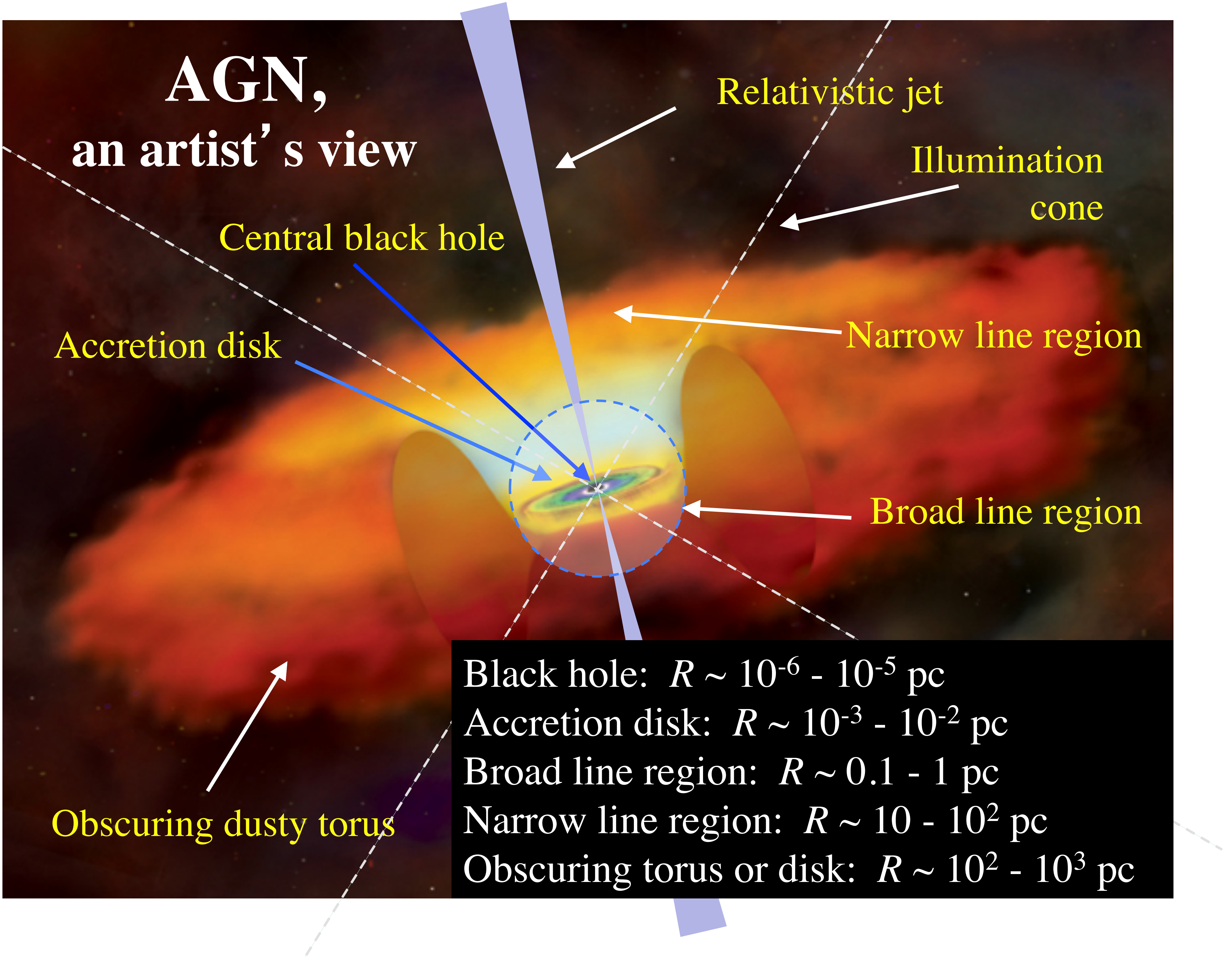

Ay 127
Quasars & AGN:
Their
Phenomenology,
Physics, and
Evolution

Quasars and AGN

- They are highly energetic manifestations in the nuclei of galaxies, believed to be powered by accretion onto massive black holes
- Empirical classification schemes and various types have been developed, on the basis of the spectra; but recently, various unification schemes have been developed to explain AGN as different appearances of the same underlying phenomenon
- Quasars/AGN are observed to evolve strongly in time, with the comoving densities of luminous ones increasing by $\sim 10^3$ from $z \sim 0$ to $z \sim 2$
- At $z \sim 0$, at least 30% of all galaxies show some sign of a nuclear activity (mostly low level); $\sim 1\%$ can be classified as Seyferts (moderately luminous), and $\sim 10^{-6}$ contain luminous quasars
- However, we think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase



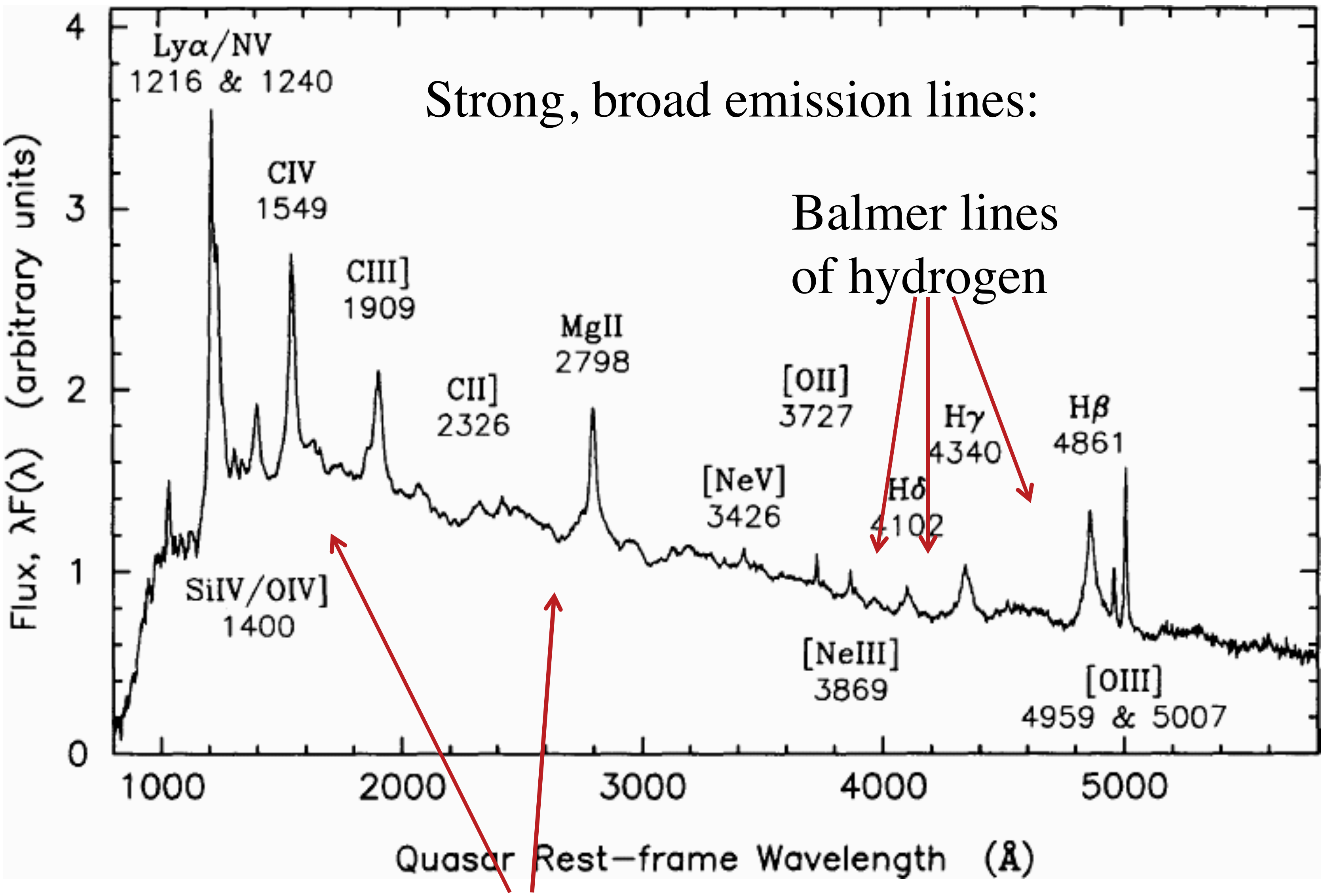
AGN,
an artist's view
Relativistic jet
Illumination cone
Central black hole
Accretion disk
Narrow line region
Broad line region
Obscuring dusty torus
Black hole: $R \sim 10^{-6}$ - 10^{-5} pc
Accretion disk: $R \sim 10^{-3}$ - 10^{-2} pc
Broad line region: $R \sim 0.1$ - 1 pc
Narrow line region: $R \sim 10$ - 10^{2} pc
Obscuring torus or disk: $R \sim 10^{2}$ - 10^{3} pc

Observable Properties of AGN

- Energy emission over a broad range of frequencies, from radio to gamma 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, usually 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
- Zero proper motions due to a large distances

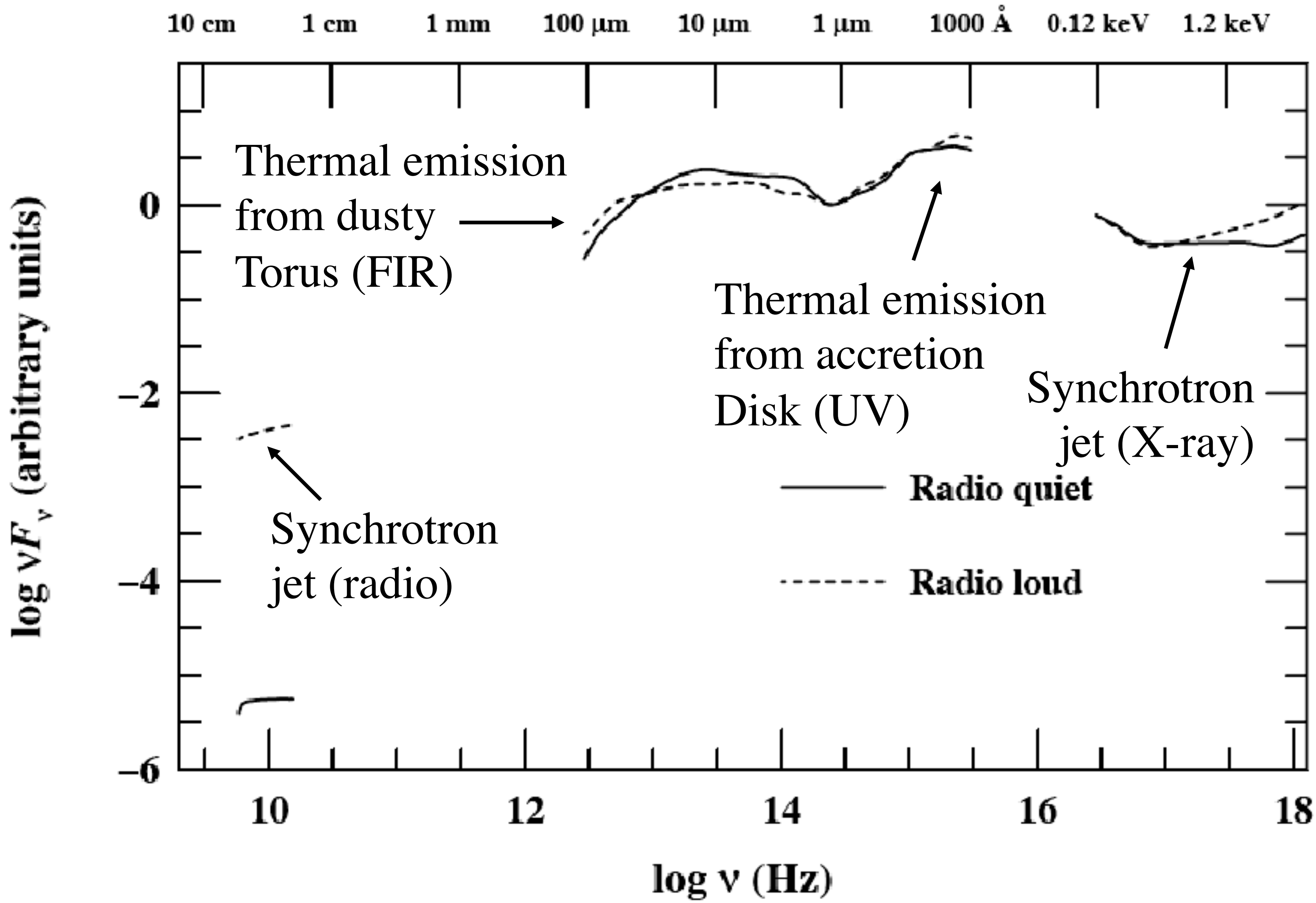
All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects

UV-Optical Spectra of Quasars



Prominent lines of abundant ions

Explaining the Broad-Band Spectral Energy Distribution in AGN



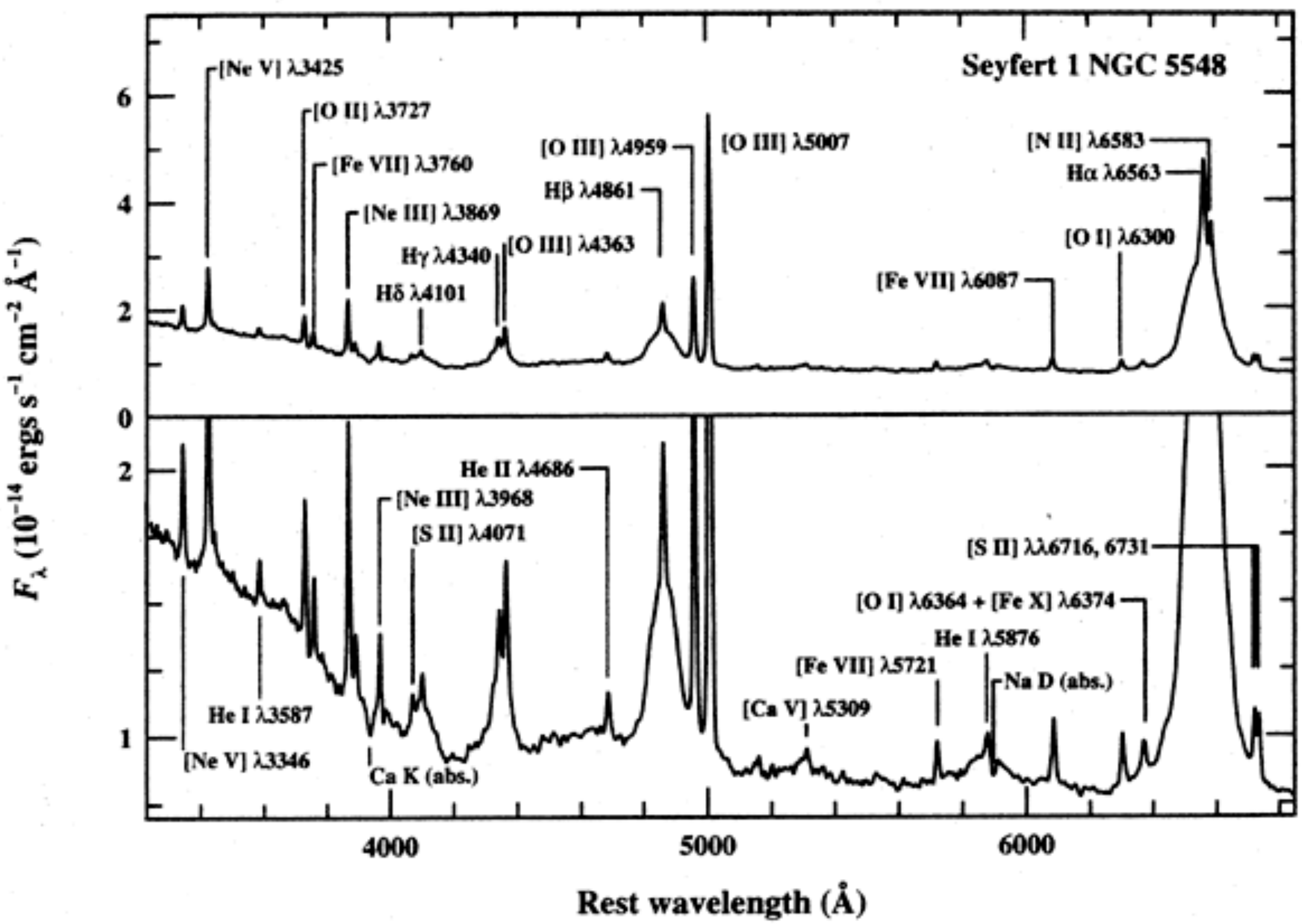
AGN Classification

- 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:

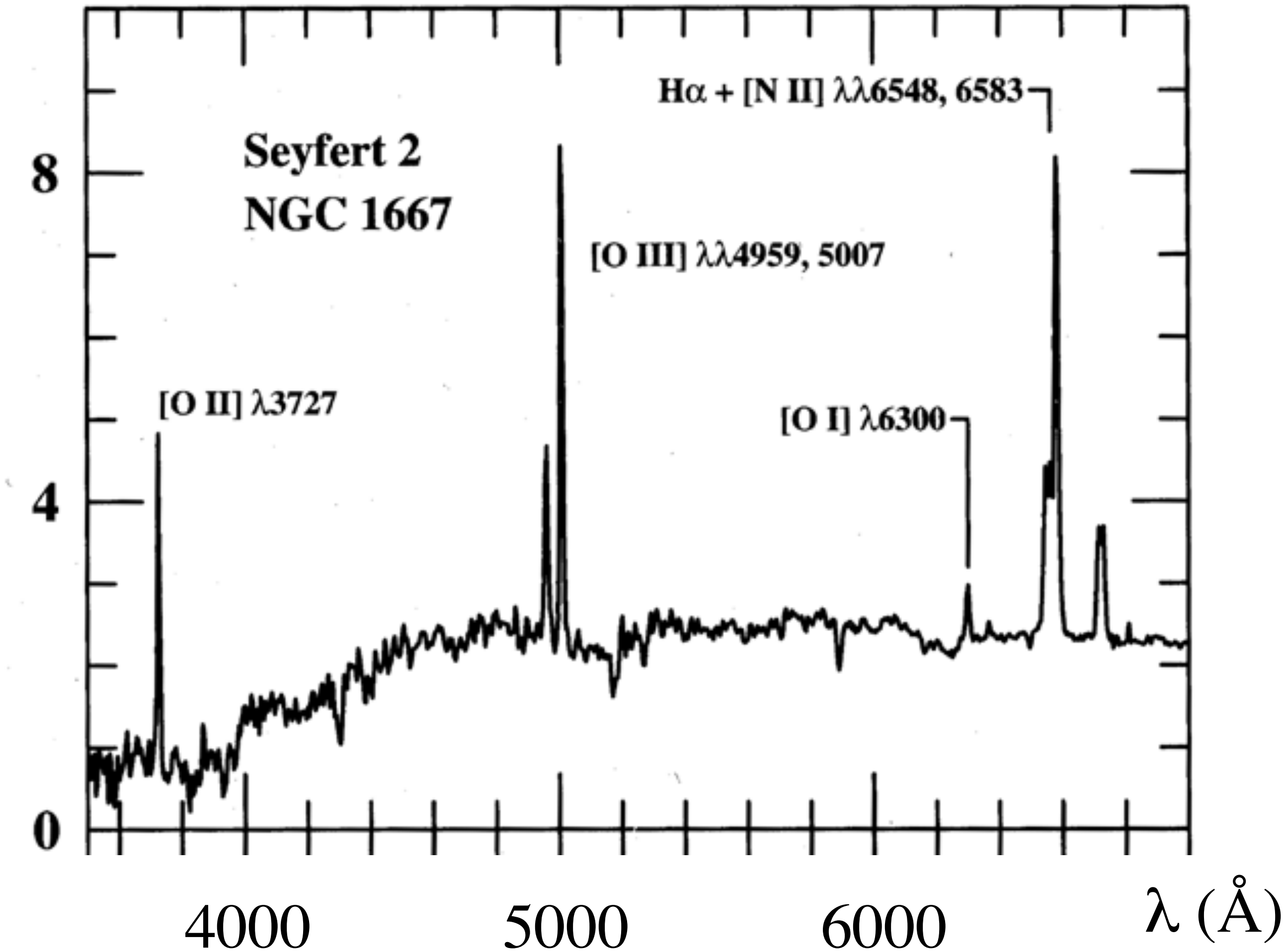
- **Narrow emission lines**, with a width of several hundred km/s
- **Broad emission lines**, with widths up to 10^4 km/s



They also have brighter and bluer nuclei

Types of Seyfert Galaxies

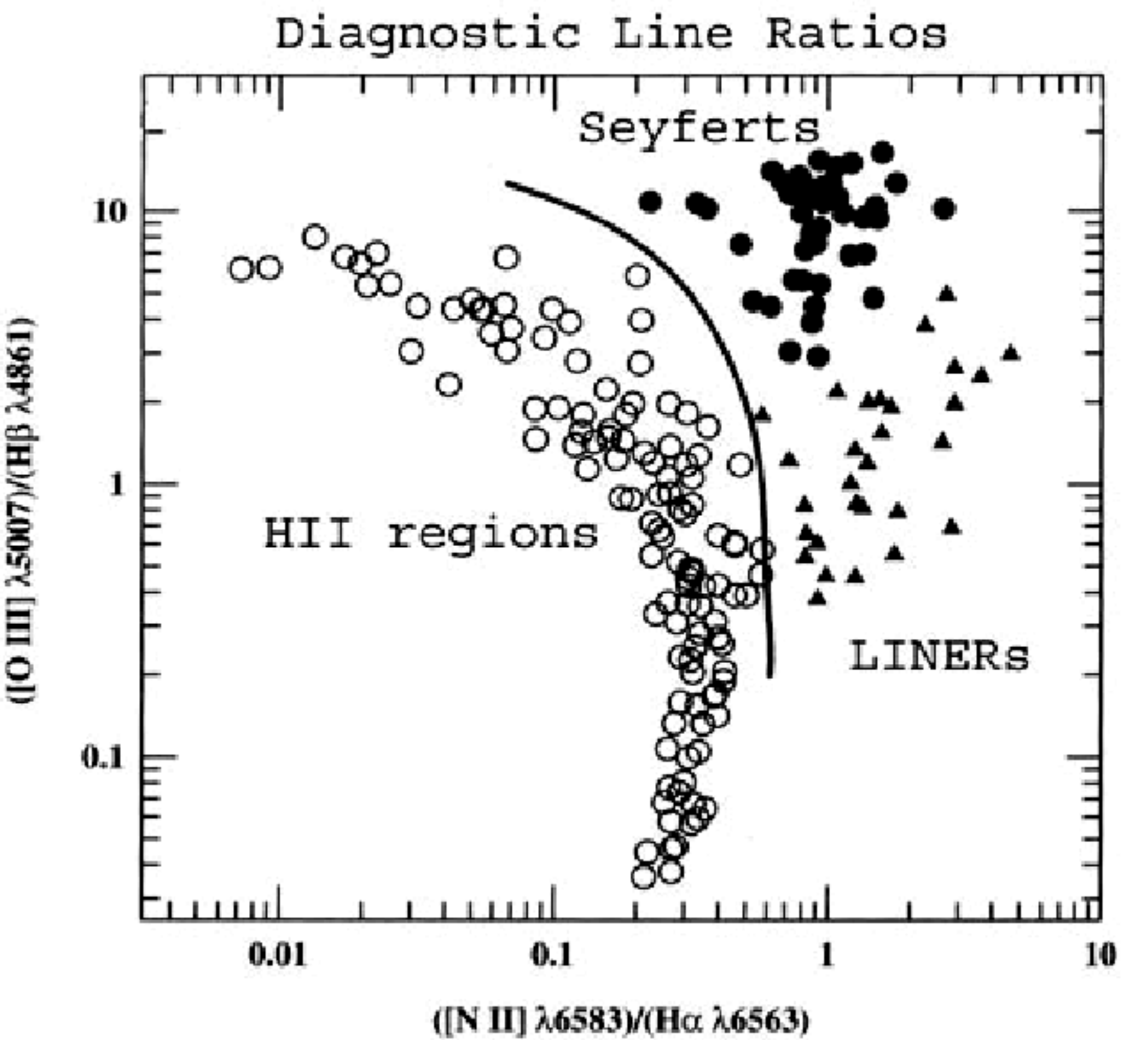
Type 2 Seyfert galaxies have only the narrow line component:



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

Spectroscopic Diagnostics

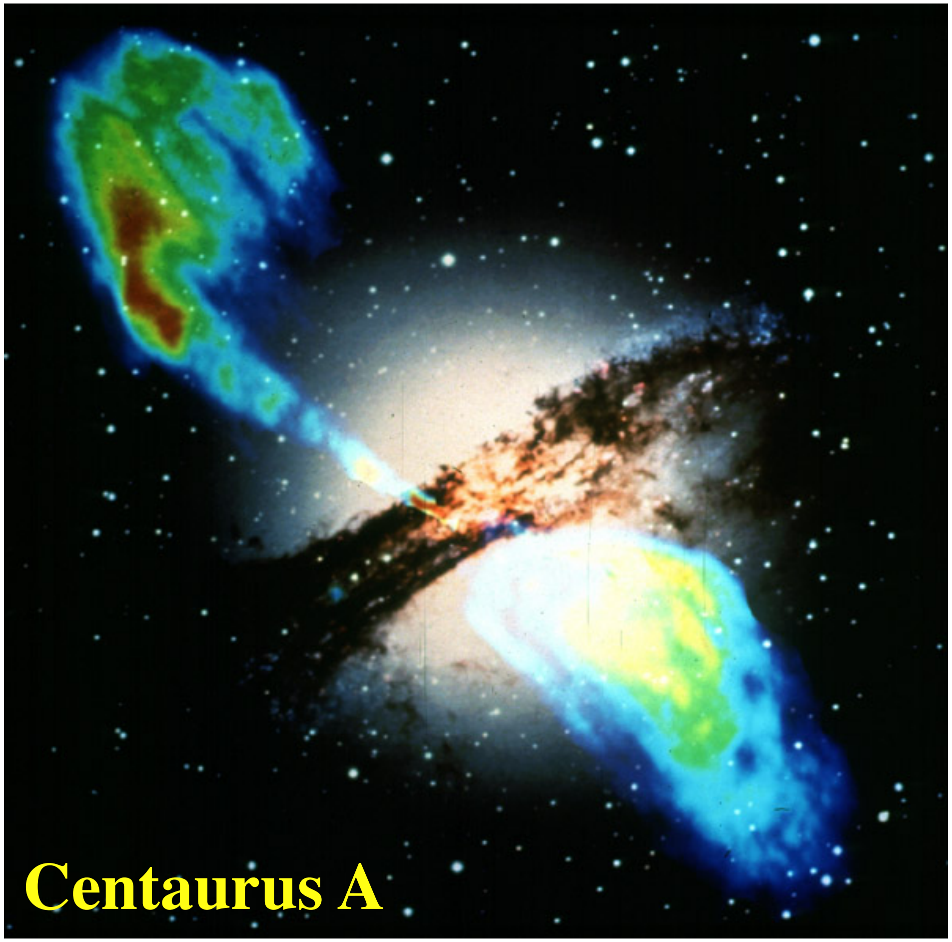
Intensity ratios of various emission lines depend on the spectrum of the ionizing continuum radiation: to get lines from high energy levels (e.g., ionizing potentials of tens of eV), one needs "hard" spectra with lots of high energy (UV / soft X-ray) photons.

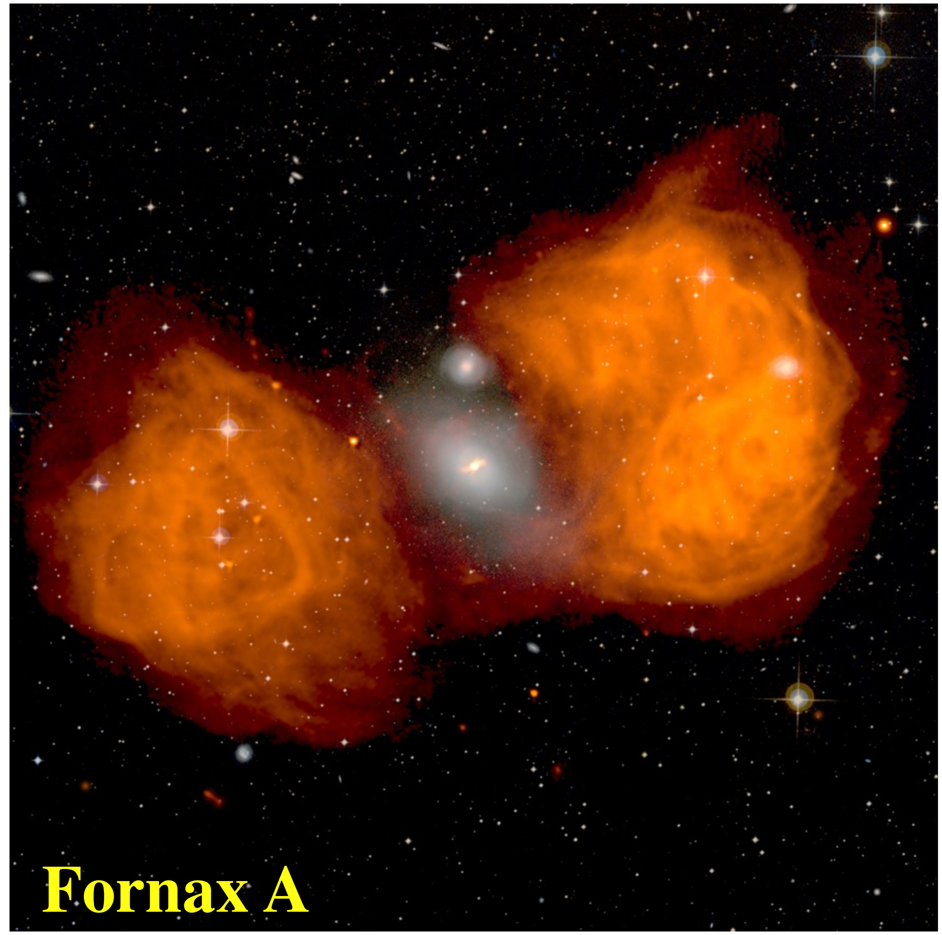


Accretion disks can provide those in AGN, while objects powered by star formation have much "softer" spectra

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} $L_{\odot}$

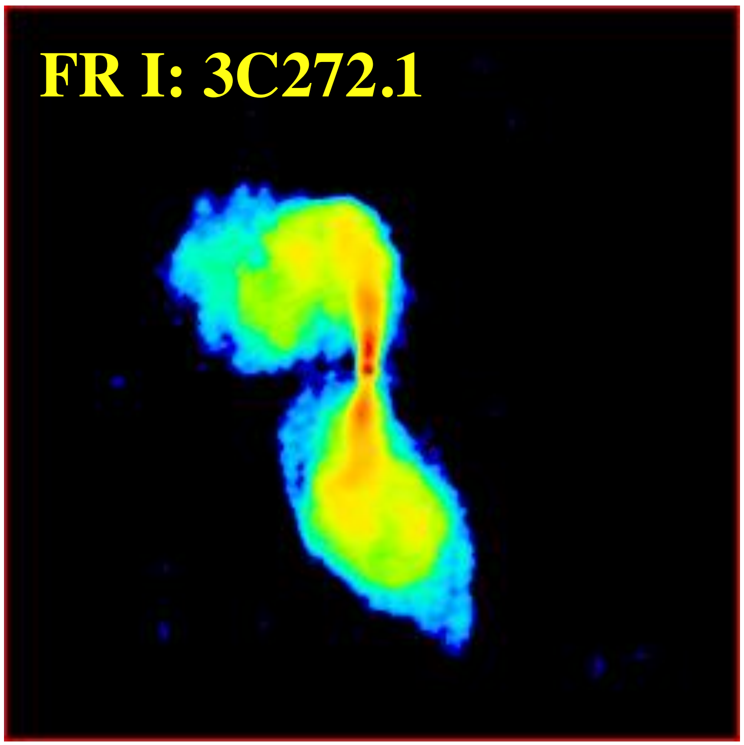
Radio Source Classification

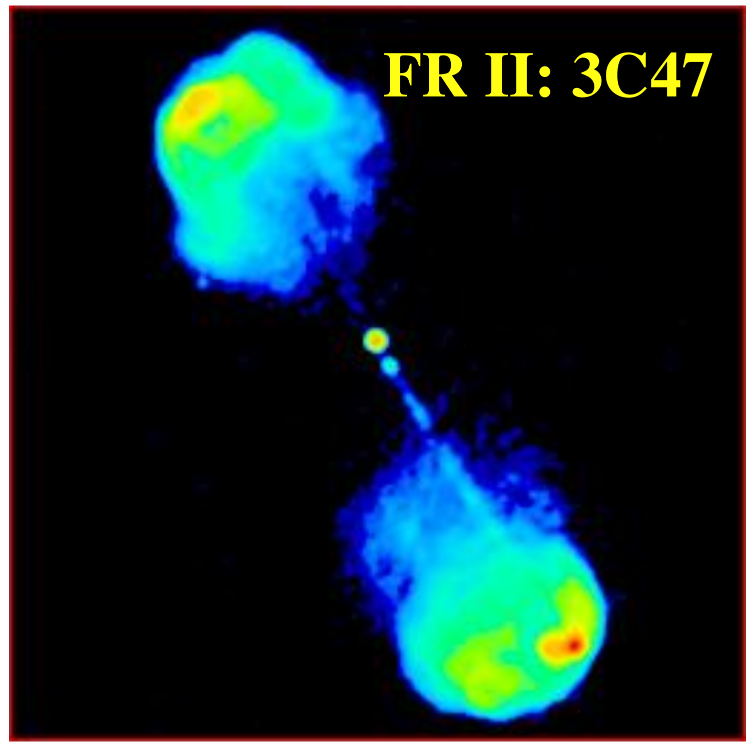
Fanaroff-Riley Type I (FR I): Separation between the points of peak intensity in the lobes < 1/2 the largest size of the source

Edge darkened radio jets, slower jet speeds, lower radio power

Fanaroff-Riley Type II (FR II): Separation between the points of peak intensity in the lobes > 1/2 the largest size of the source

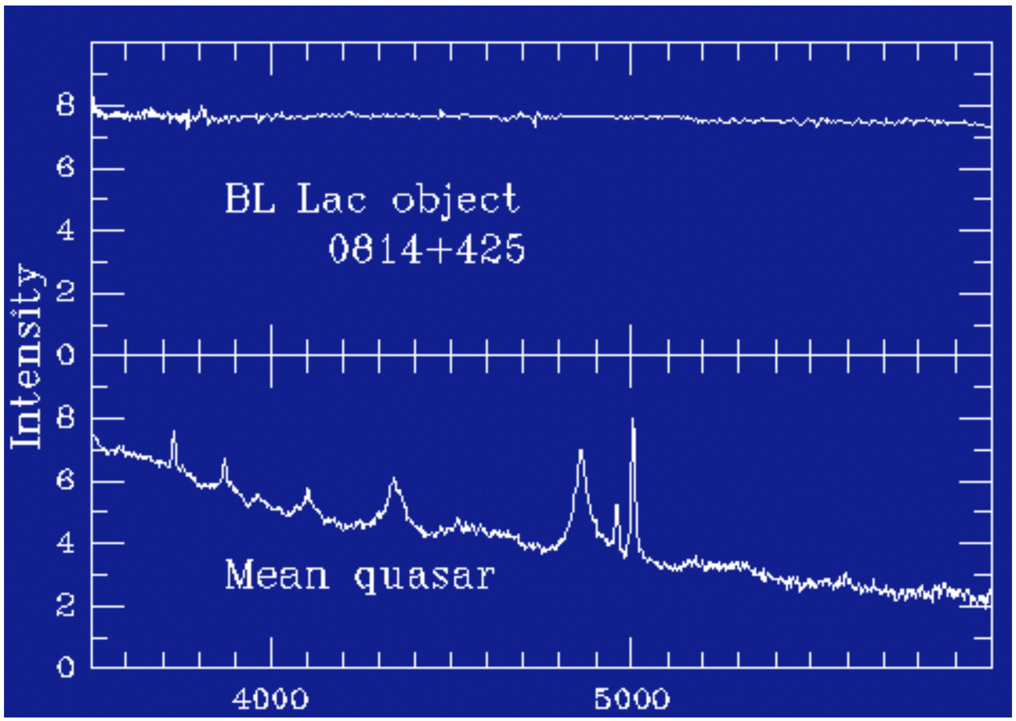
Edge brightened radio jets, speeds $\sim 0.1c$, higher radio power

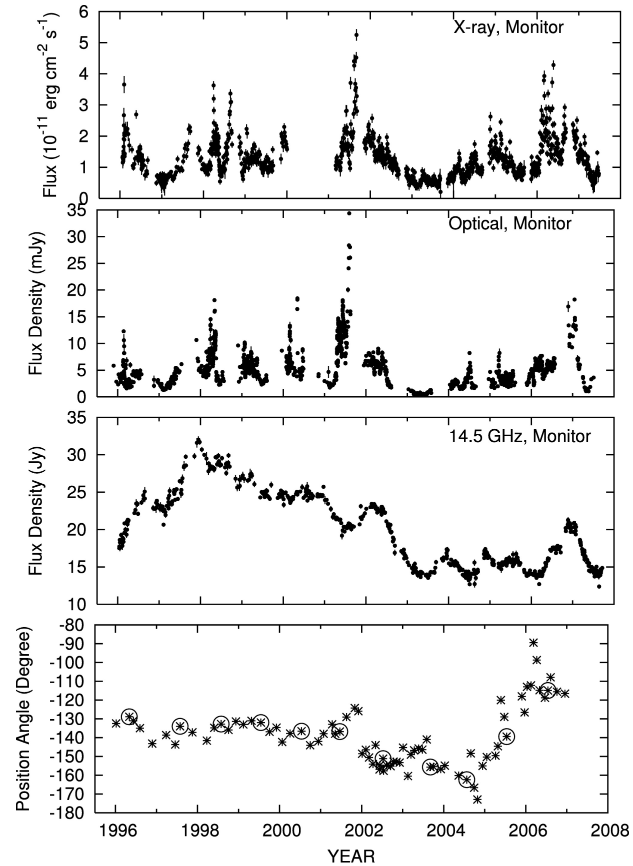




BL Lacs (Blazars) and OVVs

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





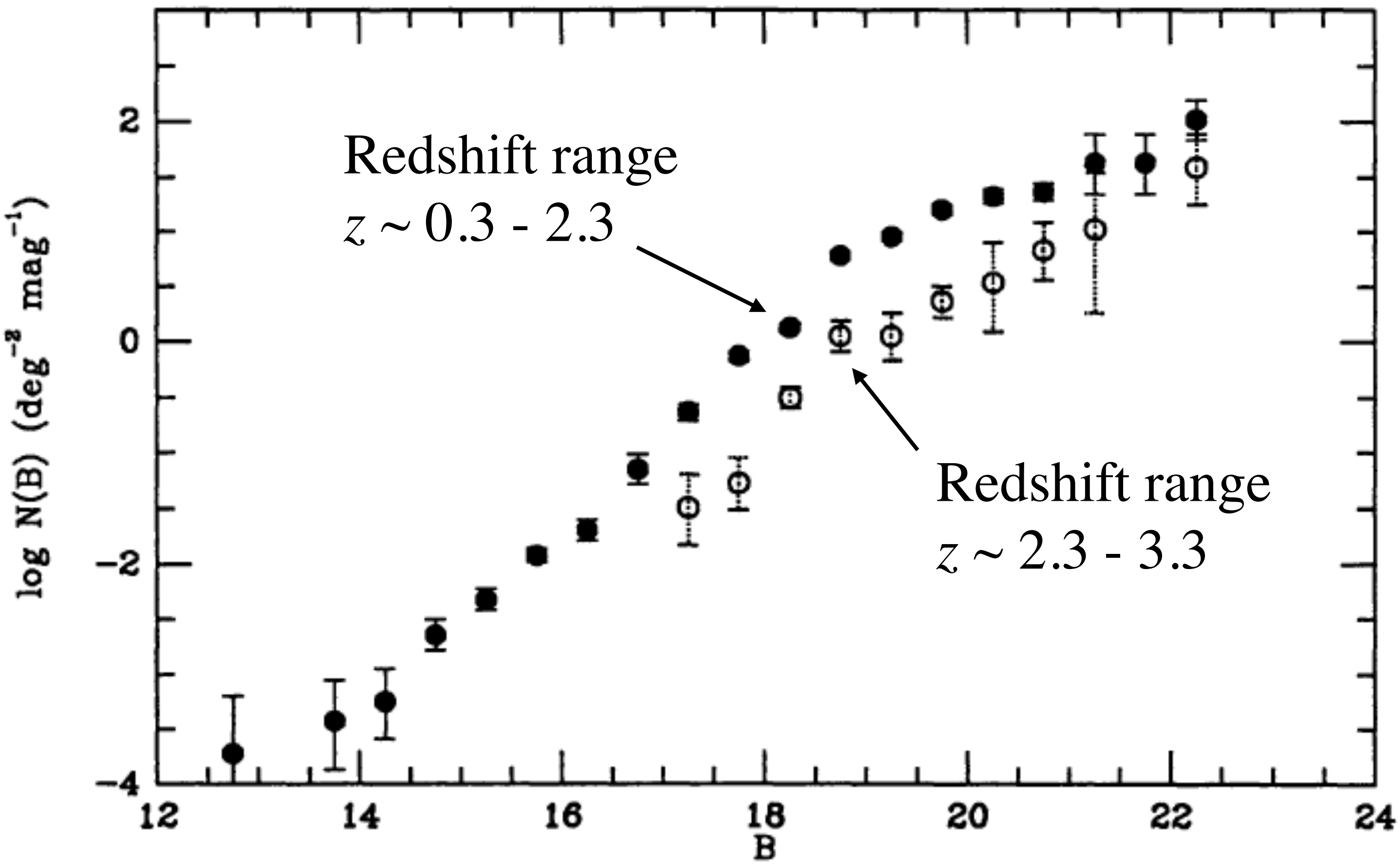
Related class are **optically violent variables**. All AGN are variable, but OVVs show large variations (> 0.1 mag) in optical flux on short timescales (< day), and much stronger at longer time scales

Quasar Surveys

- In order to study QSOs (and other AGN), we first have to find them, in large numbers, and hopefully in a systematic fashion
  - This is especially important for studies of their evolution
- Recall that ***each discovery method has its own biases***
- Nowadays the most popular technique is to use colors to separate QSOs from normal stars
  - In optical, one can also use slitless spectroscopy, variability, and zero proper motions
- Soft X-ray (up to a few keV) and optical selection find the same types of relatively unobscured objects; hard X-ray selection and FIR/sub-mm detect more obscured populations; radio finds both
- Next: multi-wavelength, survey cross-matching in the Virtual Observatory framework - will help with the selection effects

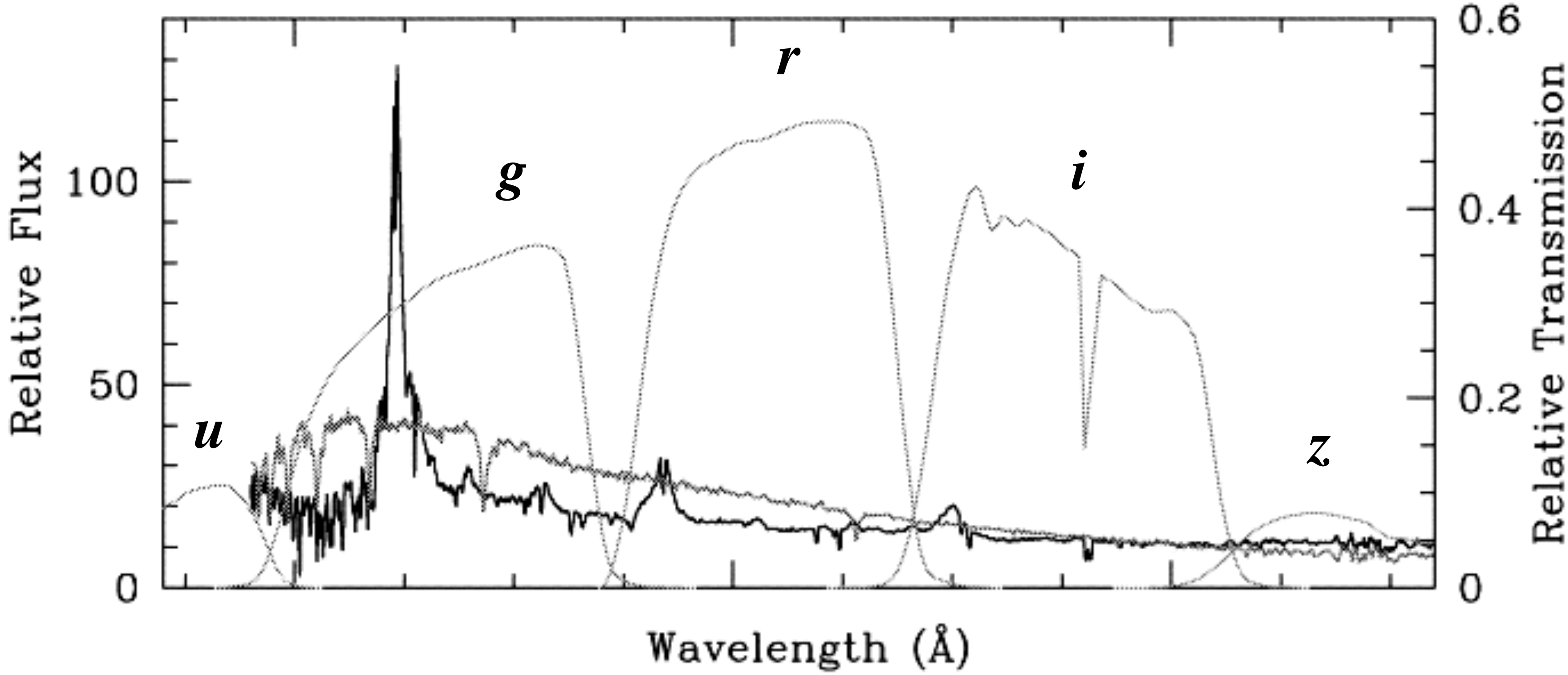
Quasar Counts

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



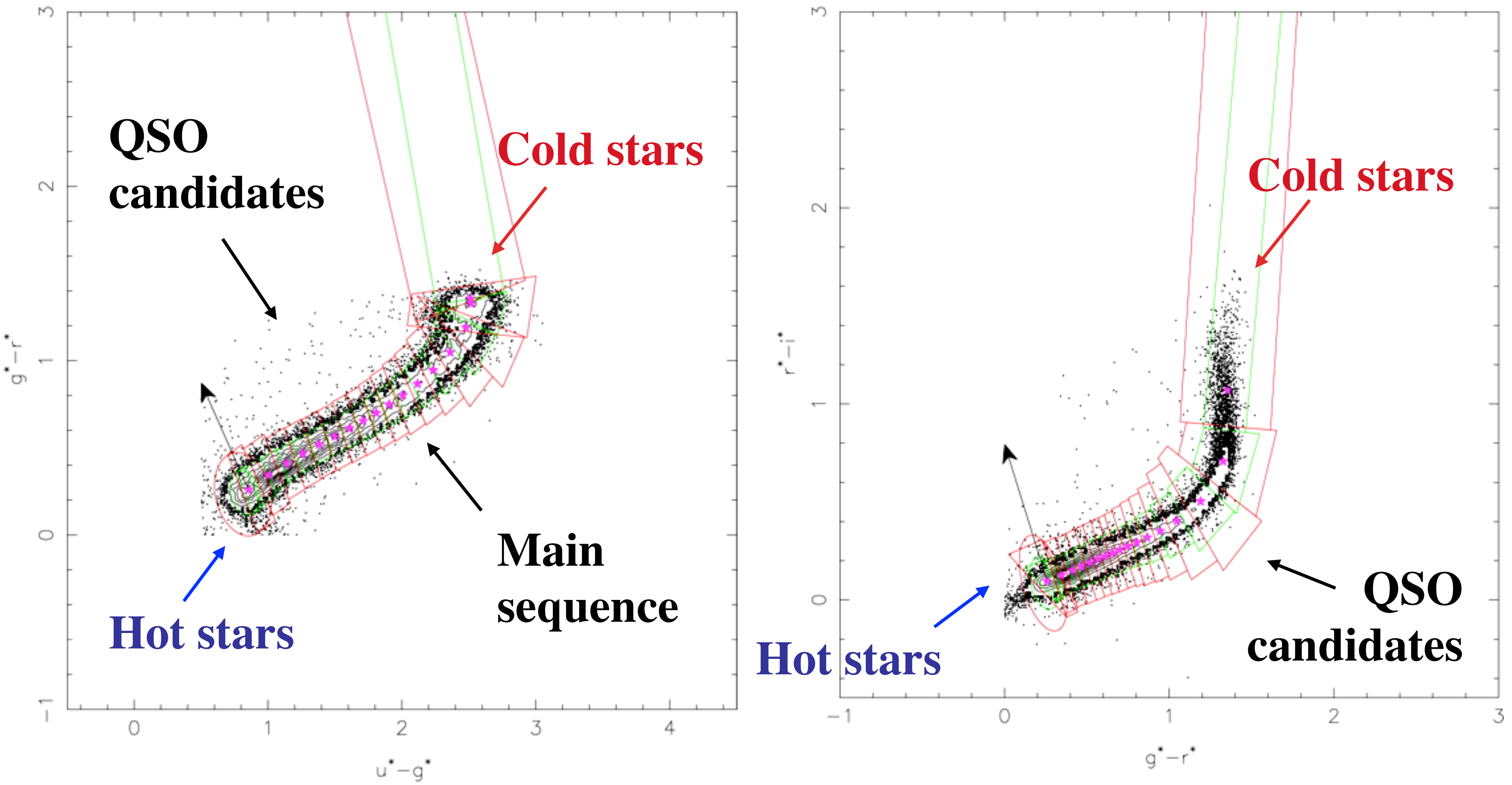
SDSS Quasar Survey

Ratios of fluxes in different survey filters (=colors) are in general different for QSOs and for stars - even though both look “stellar” on the images. The colors will change with redshift as different features (emission lines, continuum breaks) shift from one filter to another. For each redshift range, a different filter combination would be the optimal one for QSO selection

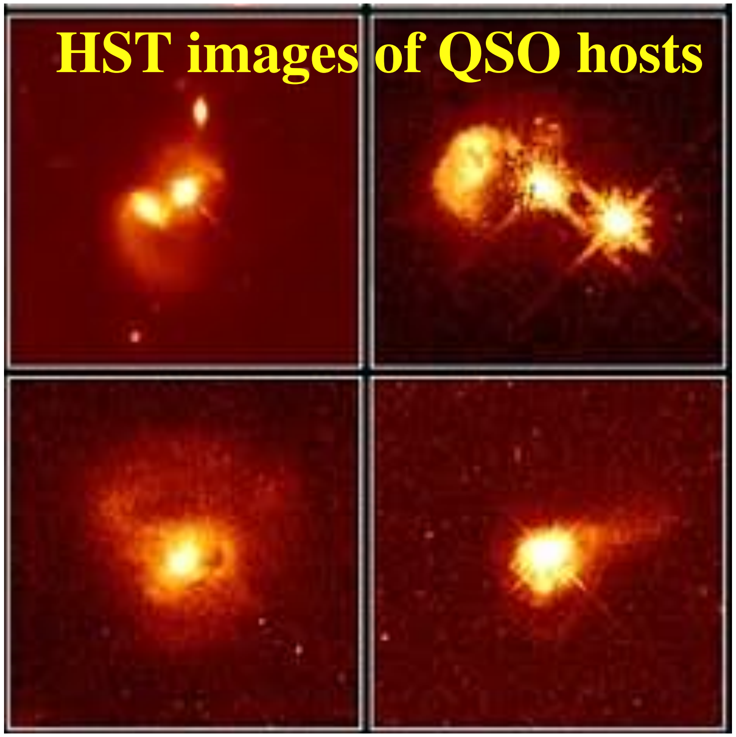


SDSS Quasar Survey

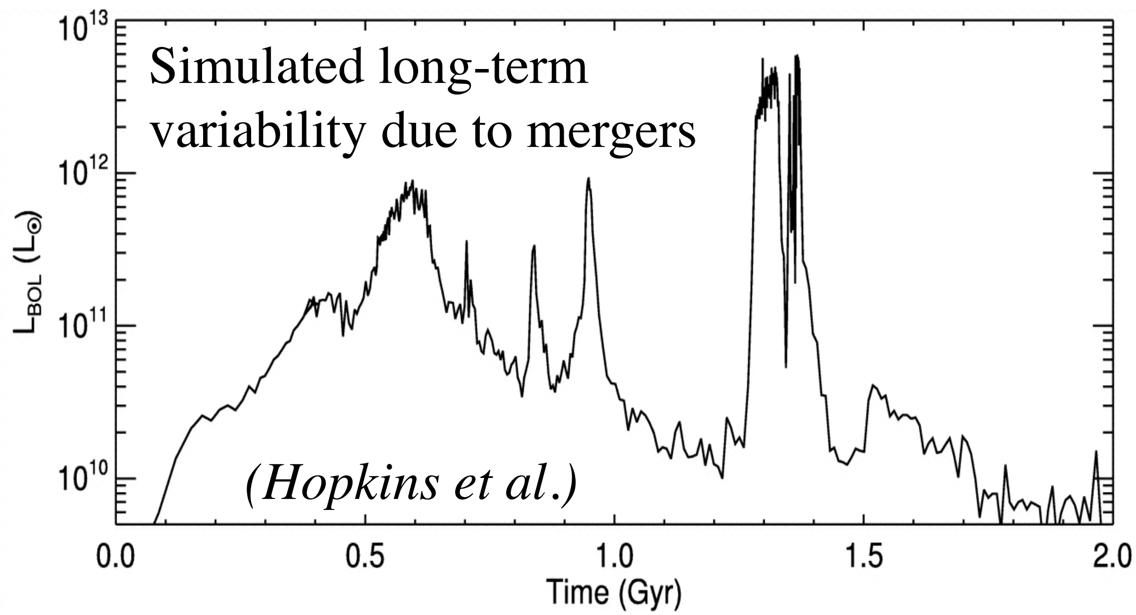
Examples of color selection of QSOs, as outliers away from the stellar locus



Quasar Fueling and Variability



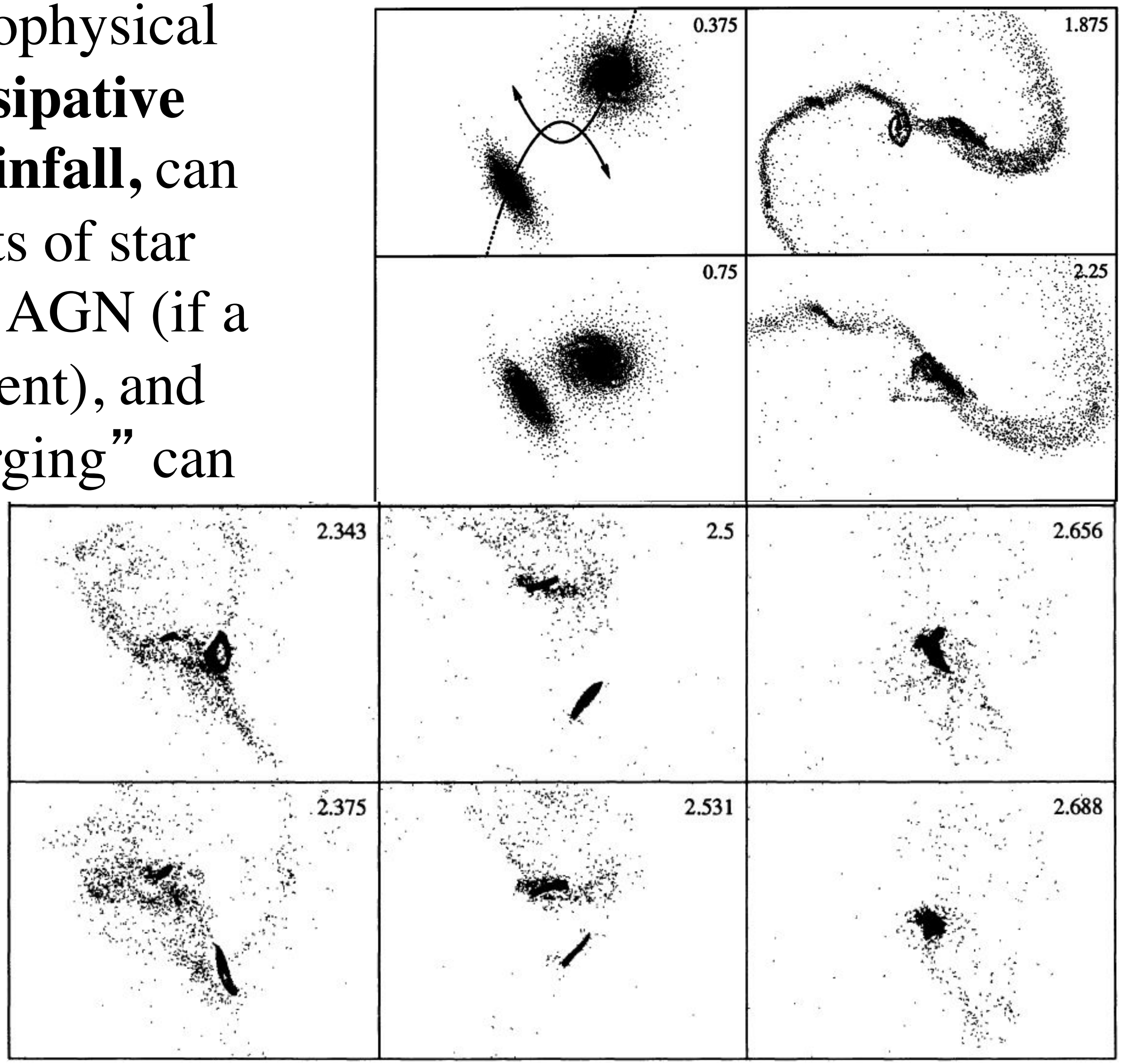
Fuel supply fluc's -> Luminosity var's



For **AGN in general**, at (observable) short scales, variability probes the instabilities in the accretion disks, and minor fueling events

It can be used to constrain the physics of accretion, and the duration of QSO lifetimes (or minor episodes)

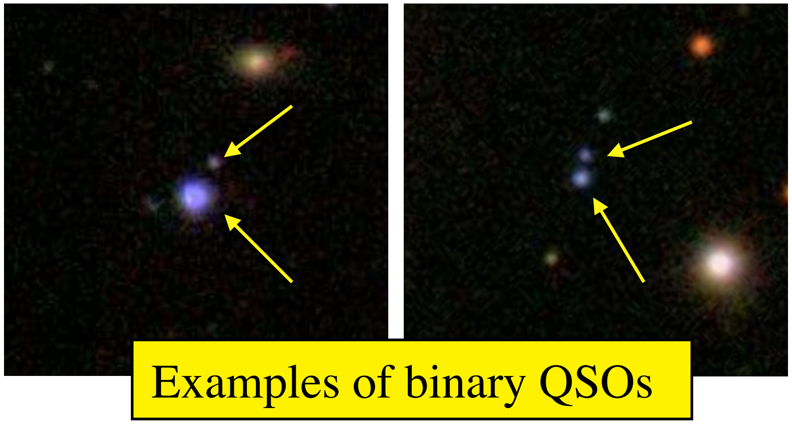
The same astrophysical processes, **dissipative mergers and infall,** can fuel both bursts of star formation and AGN (if a SMBH is present), and even "dry merging" can add to the growth of both in a hierarchical picture

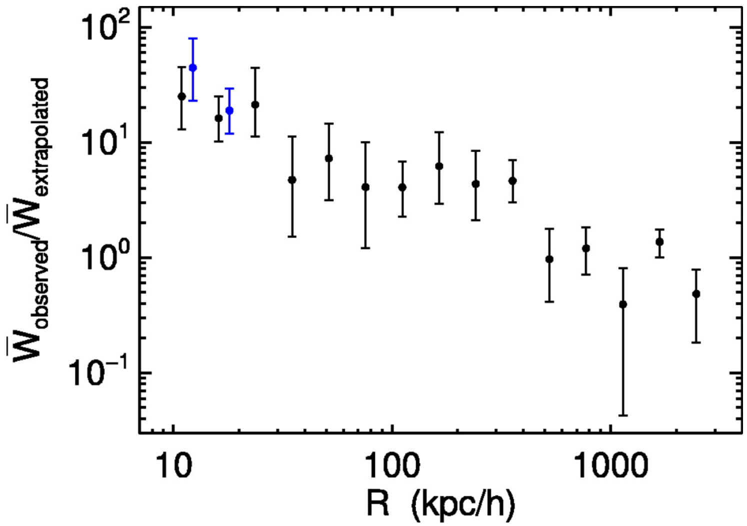


Barnes & Hernquist 1996

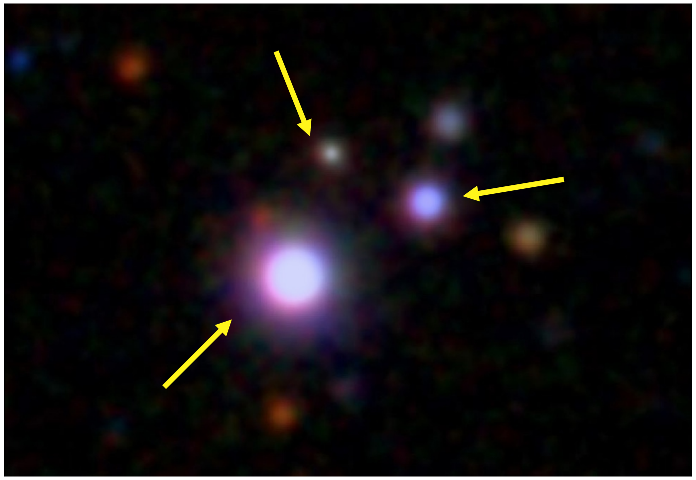
Small-Scale Clustering of Quasars

Much stronger than expected, implying that interactions are responsible for the origins of QSO activity





← Ratio of the observed clustering amplitude of $z > 2$ QSOs to that of the galaxy halos, from CDM simulations. But at lower z's, there is no excess! A change in the QSO triggering mechanism?



← The first physical triple QSO known, QQQ 1432–0106 at $z = 2.076$. Extremely unlikely, unless interactions are involved. How many more are there?

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.

The Black Hole Paradigm for AGN

Black holes are completely specified by their mass M, angular momentum J, and charge Q (likely ~0): the *no-hair theorem*

Schwarzschild black hole: $Q = 0, J = 0$

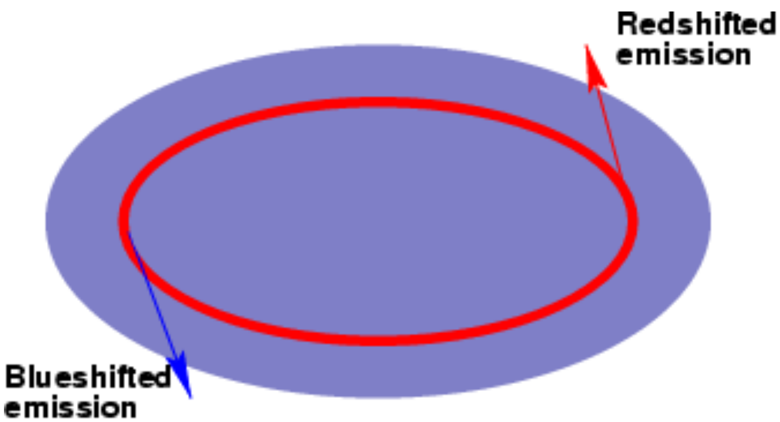
Spherically symmetric. Solution has two important radii:

- An **event horizon** at Schwarzschild radius: $$R_s = \frac{2GM}{c^2}$$
- The last stable circular orbit radius: $$R_{ms} = \frac{6GM}{c^2}$$
  Outside R_{ms} test particles can orbit indefinitely in stable circular orbits, inside R_{ms} they spiral rapidly past the event horizon into the BH. This defines the inner edge of the gas disk in AGN and sets a minimum orbital period, ~ hours for the $M_\bullet \sim 10^7$ - $10^8\ M_\odot$

Evidence for SMBHs From X-Ray Spectroscopy

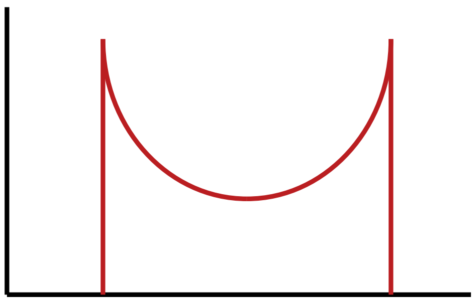
Measuring of the spectral line profiles in the inner parts of the accretion disk, close to the SMBH, offers another test for the presence of SMBHs in AGN

Fe lines in the X-rays come from the innermost parts of the disk, and are used for this test



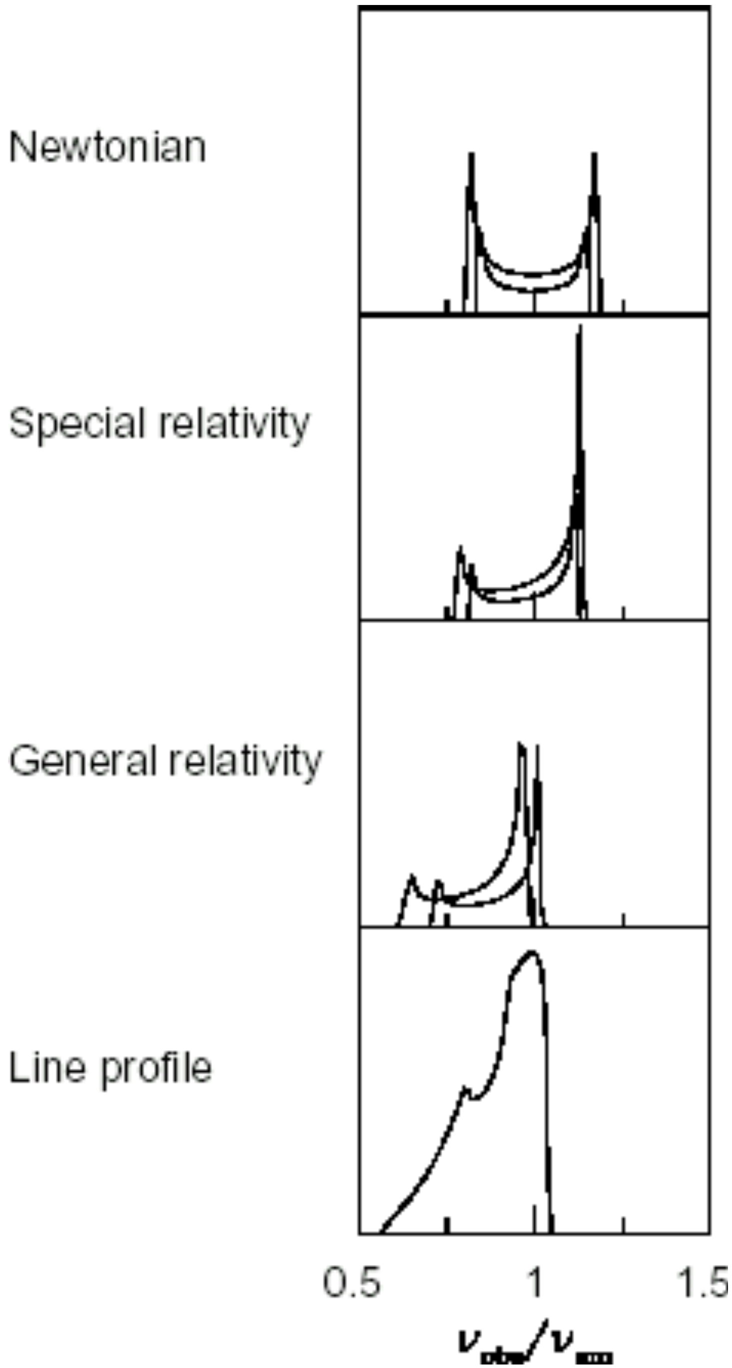
Newtonian case:

$$\frac{\Delta \nu}{\nu} = \frac{v_{obs}}{c}$$



Characteristic "double-horned" profile from a Doppler shift will only work for a Newtonian disk

But in a relativistic case, several new effects appear …



Relativistic disk: several new effects

Newtonian profile from single annulus

Transverse doppler effect: "moving clocks appear to run slow". Observed frequency is reduced compared to rest frame value by factor $(1 - v^2 / c^2)^{-1/2}$

Beaming: Boosts blue wing of the line, attenuates red wing

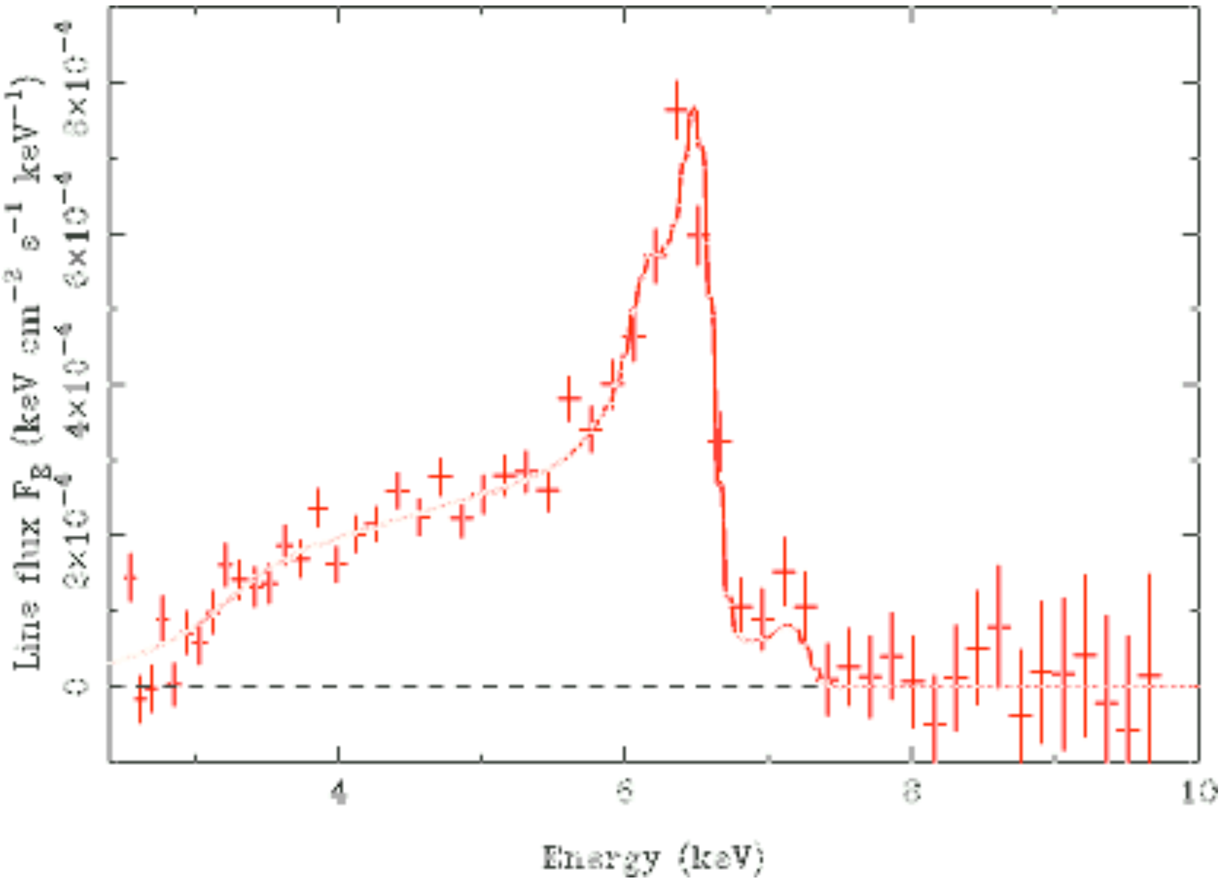
Gravitational redshift

Further shifts profile to lower energies

Integrate over all disk radii and predict:

Broad, asymmetric line profile with a sharp cutoff at high E

… And the Observations Show:



Fe line profile for the Seyfert galaxy MCG-6-30-15

(Observation with XMM-Newton)

Fe line profile is found to be often extremely broad, and the detailed modeling of the line shape favors a rapidly spinning BH

Possibly the best proof to date of presence of BHs in AGN

Eddington Limit

For an AGN with an observed bolometric luminosity L, we can estimate the *minimum* mass of the black hole involved:

Suppose the gas around the BH is spherically symmetric, and fully ionized hydrogen.

At distance r, energy flux is: $$F = \frac{L}{4\pi r^2}$$

The corresponding momentum flux, which would produce the radiation pressure, is: $$P_{rad} = \frac{L}{4\pi r^2 c}$$

Force exerted on the gas depends upon the opacity, but the *minimum* force is due to the absorption by free electrons, given by the Thomson cross-section:

$$\sigma_e = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65 \times 10^{-25}\ \text{cm}^2$$

The resulting *outward* radiation pressure force on a single electron is: $$F_{rad} = \frac{L\sigma_e}{4\pi r^2 c}$$

Eddington Limit, cont.

This has to be balanced by the inward force due to gravity of a central point mass *M*:

$$F_{grav} = \frac{GM(m_p + m_e)}{r^2} \approx \frac{GMm_p}{r^2}$$

We include the proton mass since electrons and protons are coupled electrostatically

Setting $F_{rad} = F_{grav}$, and solving for *L*:

$$L = \frac{4\pi Gcm_p}{\sigma_e} M$$

The Eddington Luminosity

This is the *maximum luminosity* which an isotropically emitting source with a mass *M* could have

$$= 1.26 \times 10^{38} \left(\frac{M}{M_{sun}}\right) \text{ erg s}^{-1}$$

Invert the formula:

$$M_E = 8 \times 10^5 \left(\frac{L}{10^{44} \text{ erg s}^{-1}}\right) M_{sun}$$

Fuelling Active Galactic Nuclei

So, in order to produce the observed AGN luminosities of $L \sim 10^{44}$ - 10^{46} erg s^{-1}, we need BHs with masses of *at least* $M_\bullet \sim 10^6$ - 10^8 $M_\odot$. But how fast must gas be accreted?

Define the efficiency of the accretion process $\boldsymbol{\eta}$: $$L = \eta \dot{M} c^2$$

A mass δm of gas at $r = \infty$ has $E_{pot} = 0$. Energy available if the gas spirals in to radius r is:

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

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*

Fuelling Active Galactic Nuclei

Assume that the gas falls in to the last stable orbit at 6 GM / c^2 before being swallowed by the BH.

Estimate of the efficiency is:

$$\eta = \frac{GM_{BH}\dot{M}}{6GM_{BH}/c^2} \times \frac{1}{\dot{M}c^2} \approx 0.17$$

A Newtonian calculation, but gives right order of magnitude ..

Actual efficiency of disk accretion onto a BH is estimated to be:

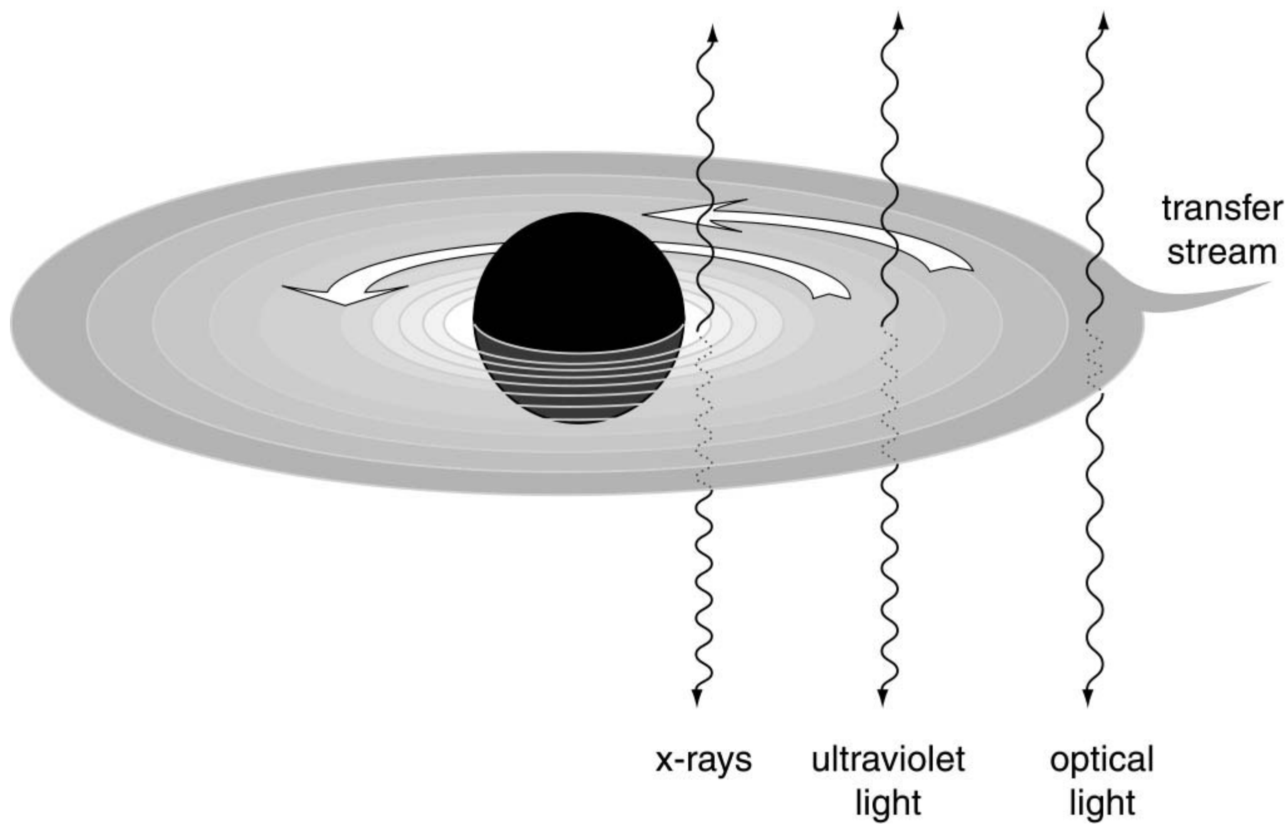
- Schwarzschild BH: $\boldsymbol{\eta} = 0.06$
- Kerr BH (corotating disk): $\boldsymbol{\eta} = 0.42$

Standard estimate is $\boldsymbol{\eta} \sim 0.1$. Using this, mass flow needed to sustain a quasar is:

$$\dot{M} \approx \frac{10^{46}\ \mathrm{erg\ s^{-1}}}{0.1 \times c^2} \approx 10^{26}\ \mathrm{g\ s^{-1}} \approx 2\ \mathrm{Solar\ masses\ yr^{-1}}$$

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



Thermal Emission From Accretion Disks

For a SMBH, the effective disk temperature as a function of radius is:

$$T(R) \approx 6.3 \times 10^5 \left(\frac{\dot{M}}{\dot{M}_E} \right)^{1/4} \left(\frac{M}{10^8 M_{sun}} \right)^{-1/4} \left(\frac{R}{R_s} \right)^{-3/4} \text{ K}$$

Accretion rate at the Eddington luminosity for $\eta = 0.1$

A thermal spectrum at temperature T peaks at $h\nu_{\max} \approx 2.8kT$

An inner disk temperature of ~10^5 K corresponds to peak emission at ~50 nm. Thus, we expect the disk emission in AGN accreting at close to the Eddington limit to be strong in the UV; this is the origin of the broad UV peak in quasar SEDs

Since the emission comes from a range of radii / temperatures, the emergent spectrum is broader than the simple blackbody

Spinning Black Holes

Kerr black hole: $Q = 0$, J and M arbitrary

Axisymmetric solution - hole has a preferred rotation axis.
Define the amount of angular momentum via a dimensionless **spin parameter**:

$$a = \frac{cJ}{GM^2}$$

Maximum angular momentum of a Kerr BH corresponds $\boldsymbol{a} = 1$
Gas can spiral deeper into the potential well before reaching R_{ms} around a Kerr black hole: **more energy can be extracted**

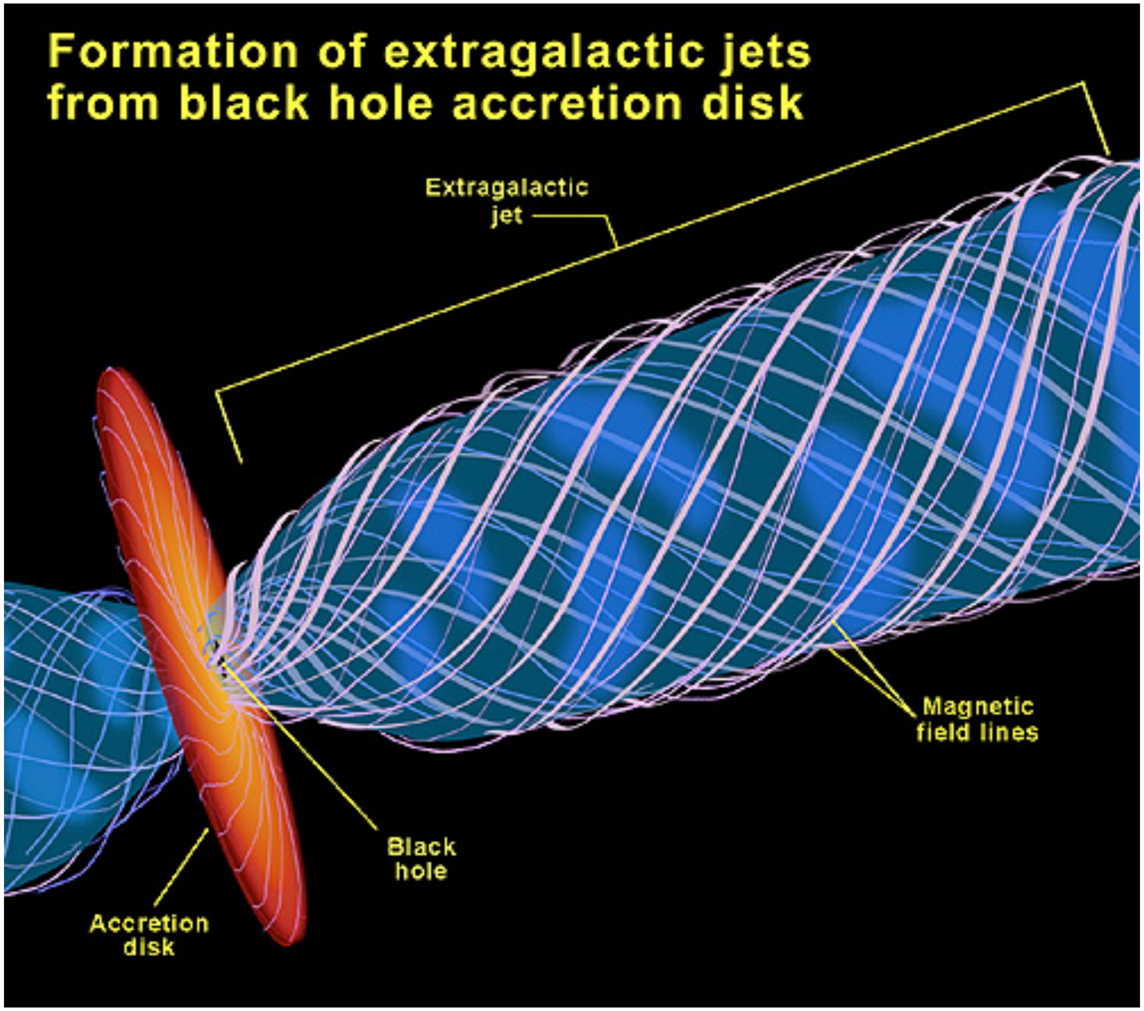
A Kerr black hole has an **irreducible mass**, given by:

$$M_{ir} = \frac{M}{2}\left[\left(1 + \sqrt{1 - a^2}\right)^2 + a^2\right]^{1/2}$$

For $a = 1$, $M_{ir} = 0.707\ M$

($M-M_{ir}$) represents *rotational energy of the BH* which can in principle be extracted, possibly by threading the hole with a large scale magnetic field (the Blandford-Znajek process)

The Origin of AGN Jets

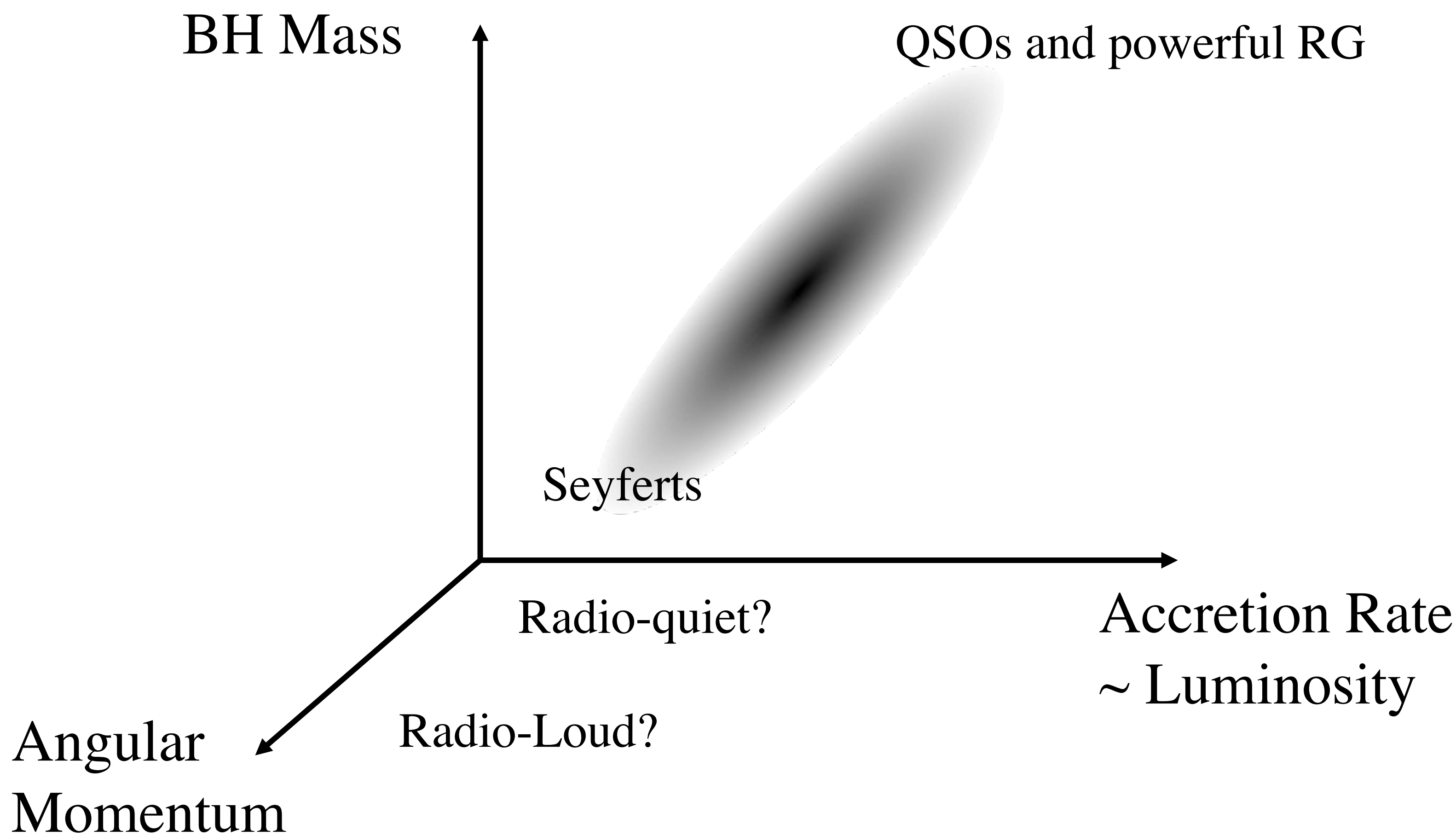


Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

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

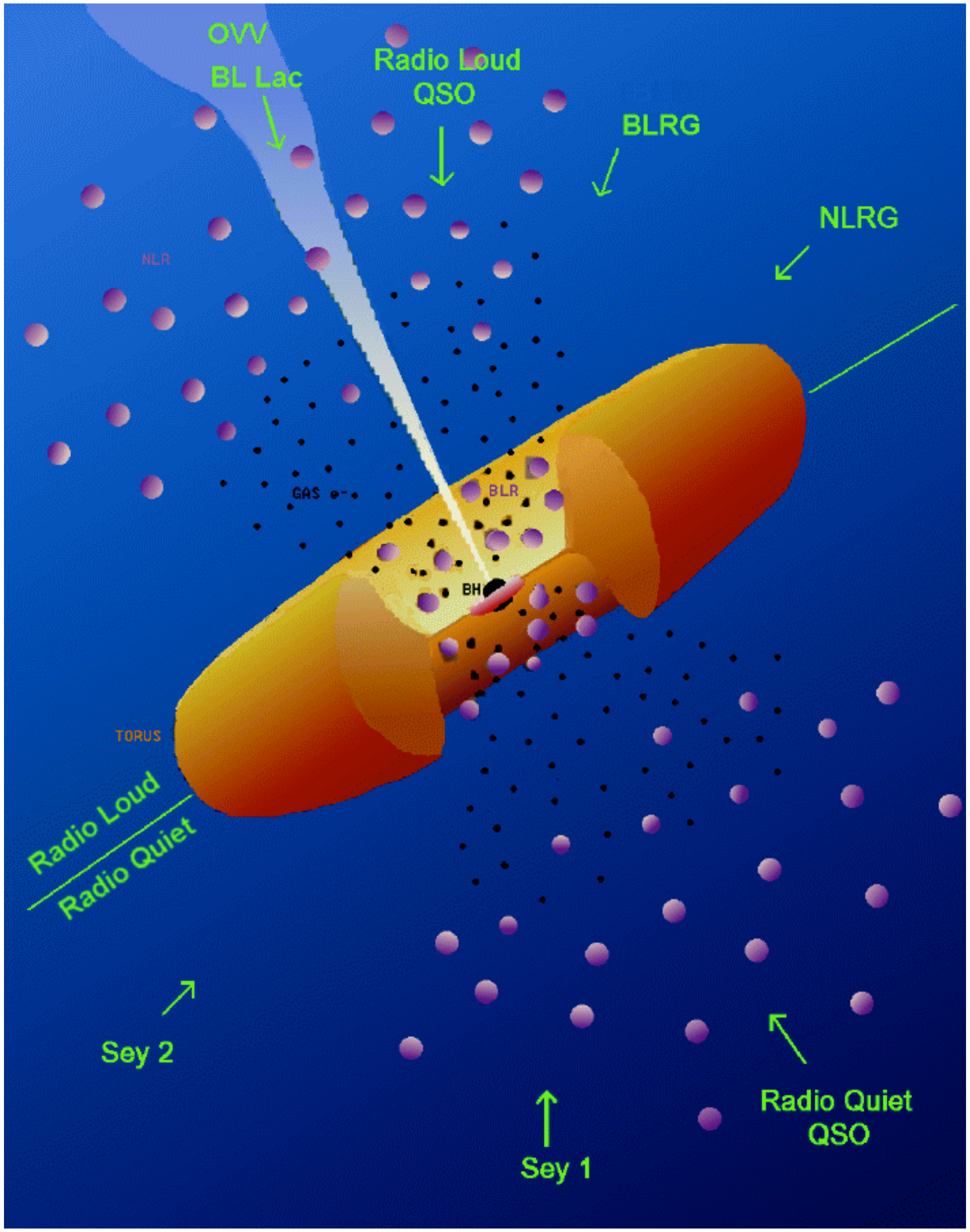
AGN: A Physical Classification



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

Unification Models for AGN

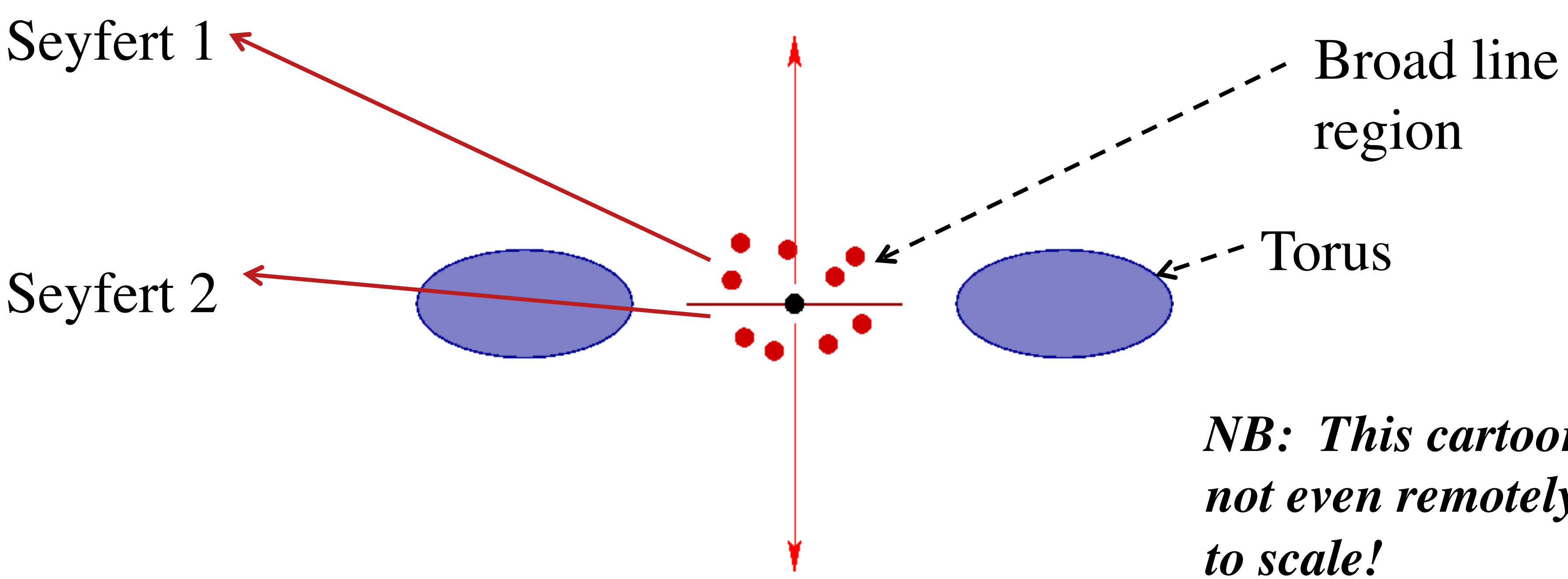
- The basic idea is that in a given radio-loudness category, all AGN are really the same type of objects, but viewed from different angles
- This is almost certainly true, by and large - but there is probably some real variation in the physical properties (other than luminosity) at any given orientation
- There is probably also a variation in the geometries and intrinsic structures



AGN Unification Models

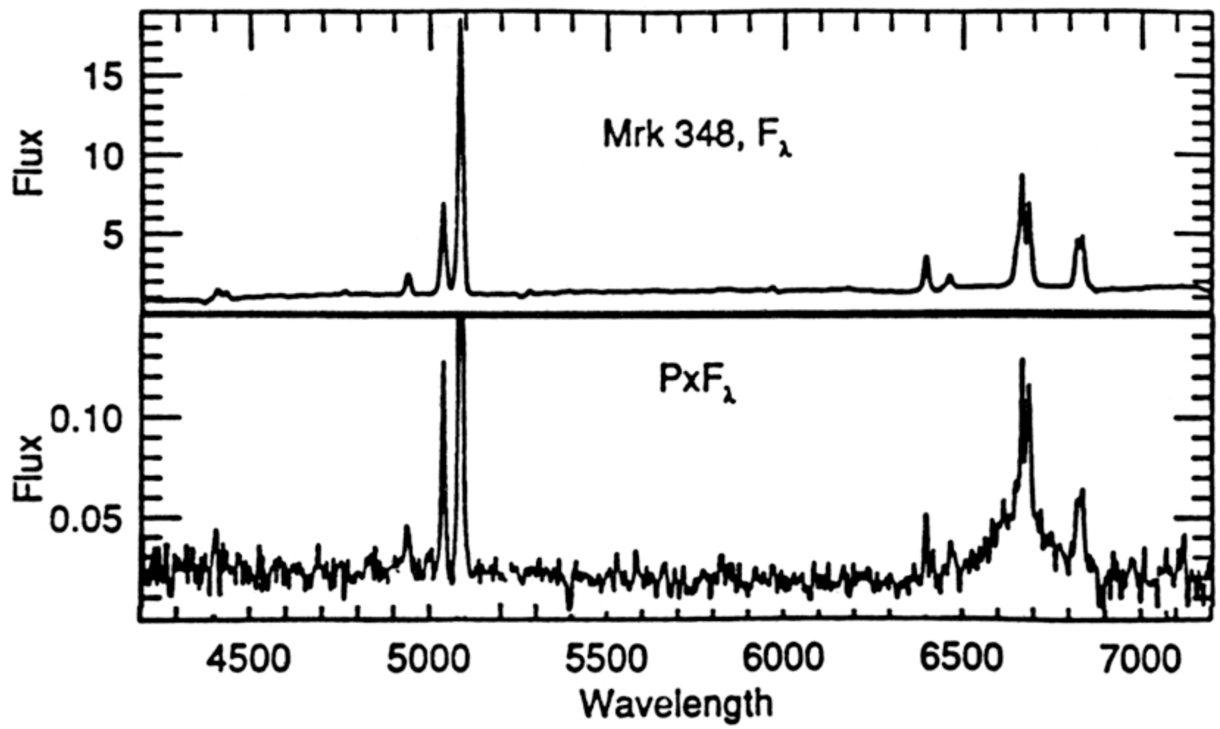
They seek to explain different classes of AGN as being due to different orientations of intrinsically similar systems to the observer's line of sight

Seyfert 1 and Seyfert 2 galaxies: Probably the most secure unification. Basic idea: an obscuring **torus** prevents us seeing the broad line region in Seyfert 2's:



NB: This cartoon not even remotely to scale!

Support for this picture: in some Seyfert 2 galaxies the ***polarized emission*** (e.g., reflected from dust grains) shows broad lines:



This is consistent with the unification, since scattering produces polarization. Conclude:

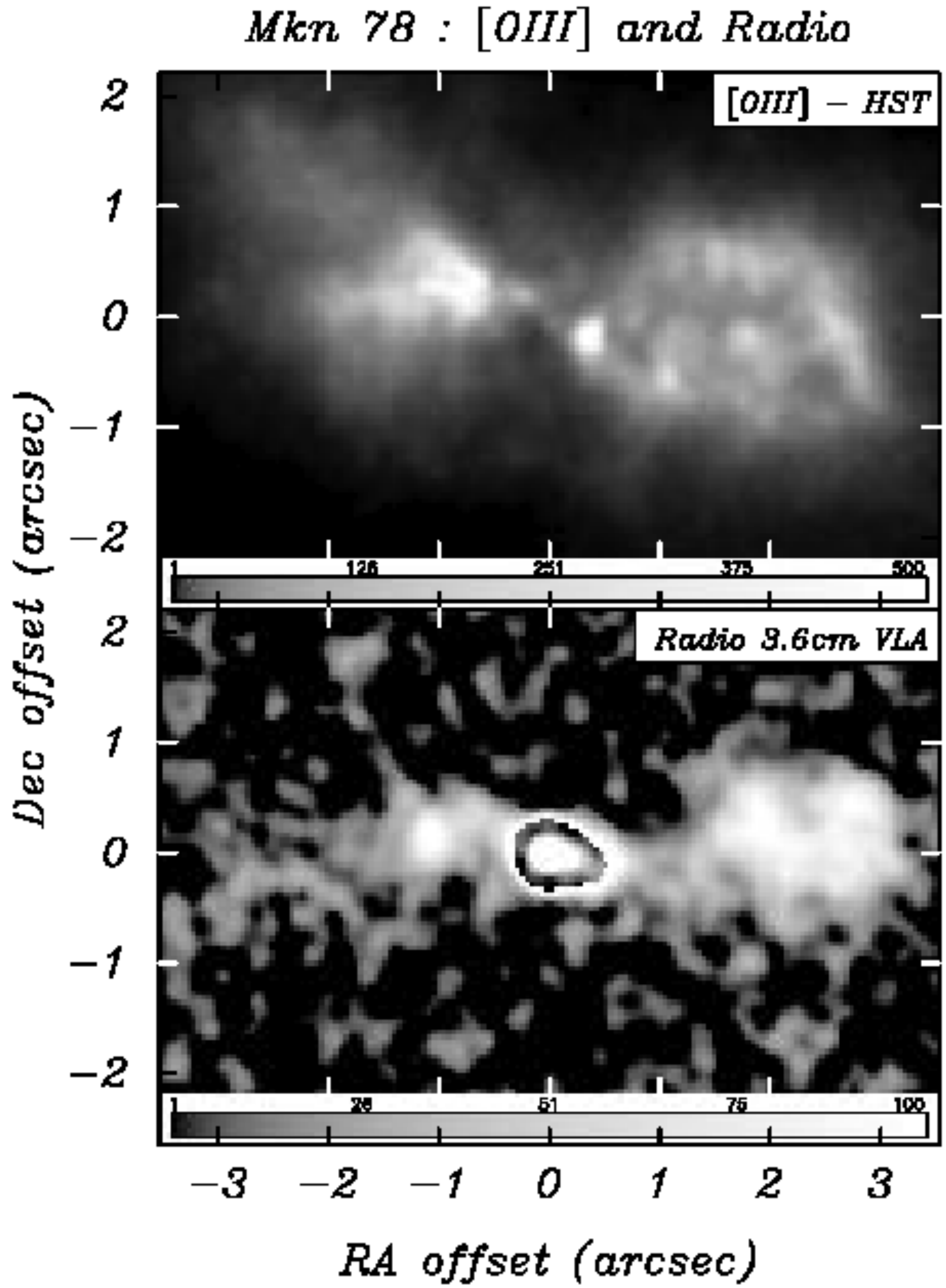
- At least some Seyfer 2's are intrinsically similar to Seyfert 1's
- If this applies to all Seyferts, statistics mean that the torus must block about 3/4 of the sky as seen from the nucleus

Ionization Cones

In addition to the spectro-polarimetry, evidence for anisotropy in AGN comes from images of resolved narrow-line emission region:

The gas seems ionized in cones bracketing the nucleus, which are also aligned with the radio jets (if present)

This is as expected if the rest of the gas does not see the nucleus, due to a toroidal obscuration



AGN Unification

It is now easonably 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

But there are some low-*L*, unobscured AGN, with no broad lines…

Radio Loud vs. Radio Quiet

More ambitious unification schemes aim to explain why some AGN are radio loud, others radio quiet. *Possible* physical difference is the spin of the SMBH:

Radio loud

High spin holes with $\boldsymbol{a} \sim 1$

Produce jets, which are the origin of radio emission (note: blazars are radio loud)

Jets powered by spin energy extracted from black hole

Also have accretion disks

Radio quiet

Low spin holes, $\boldsymbol{a} \ll 1$

No jets

Spectrum produced by the accretion disk (blackbody + nonthermal em.)

Recall: $a = \dfrac{cJ}{GM^2}$

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

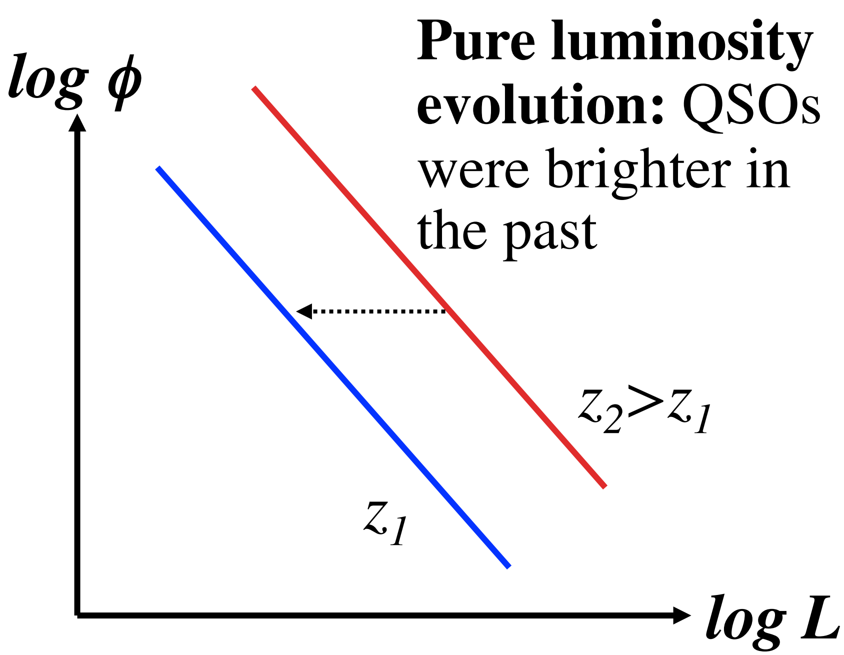
> Black hole mergers may produce gravitational wave signals, detectable by LISA (if not LIGO)

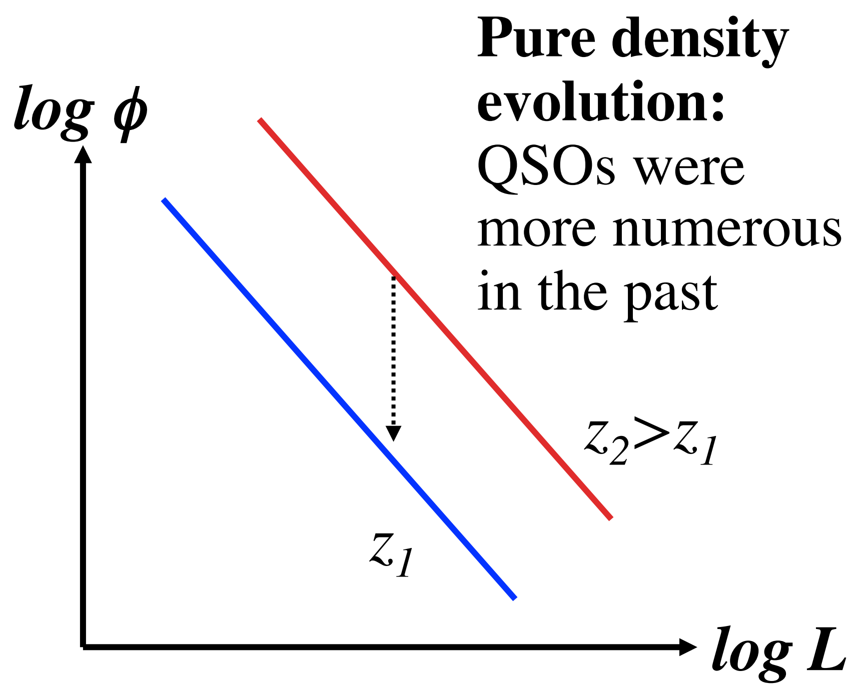
This scenario would also help explain why powerful radio sources seem to favor giant ellipticals as hosts, and cluster environments (that's where most large E's are) - and ellipticals are more likely to be products of large mergers

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

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:



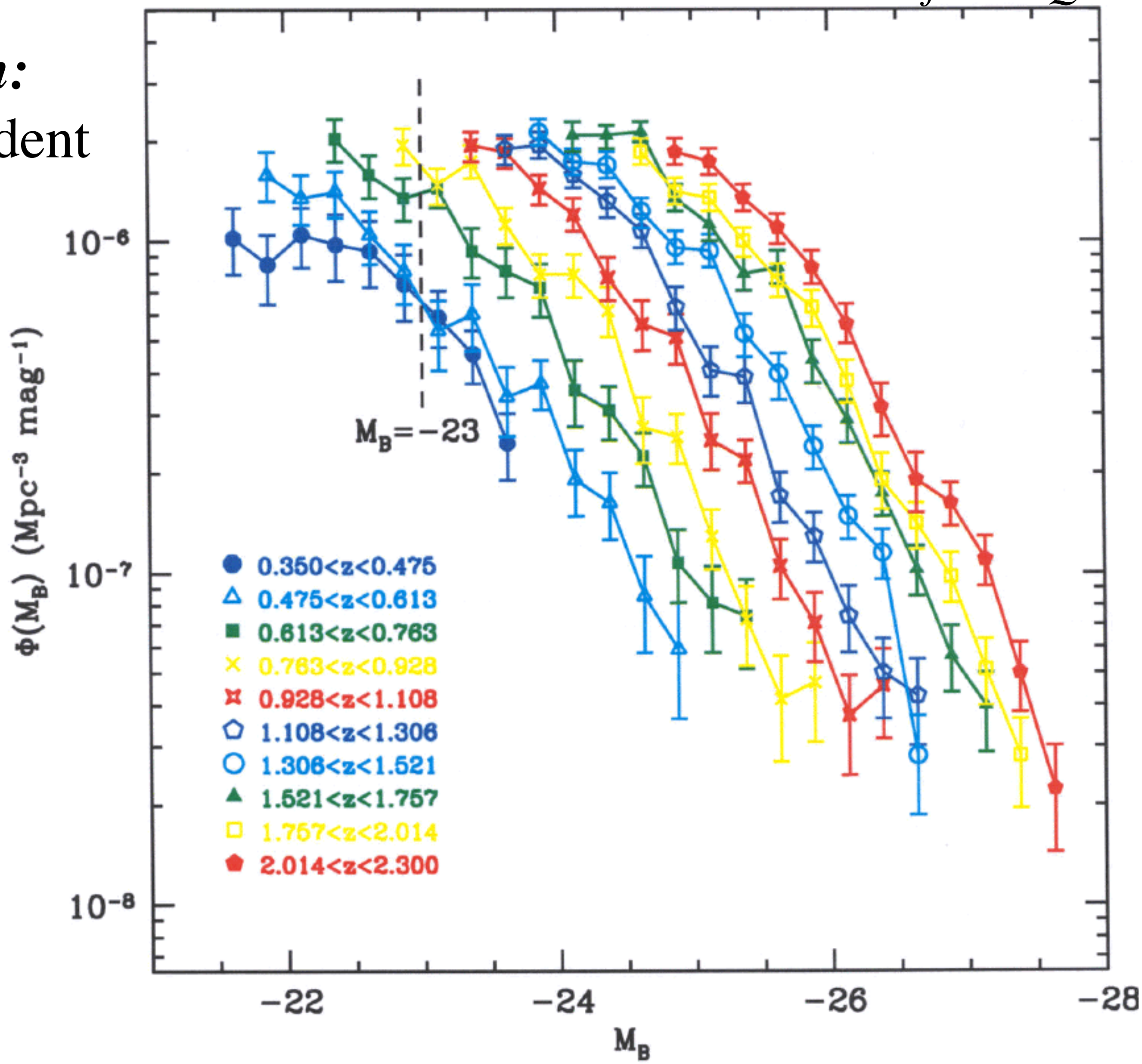


Quasar Evolution

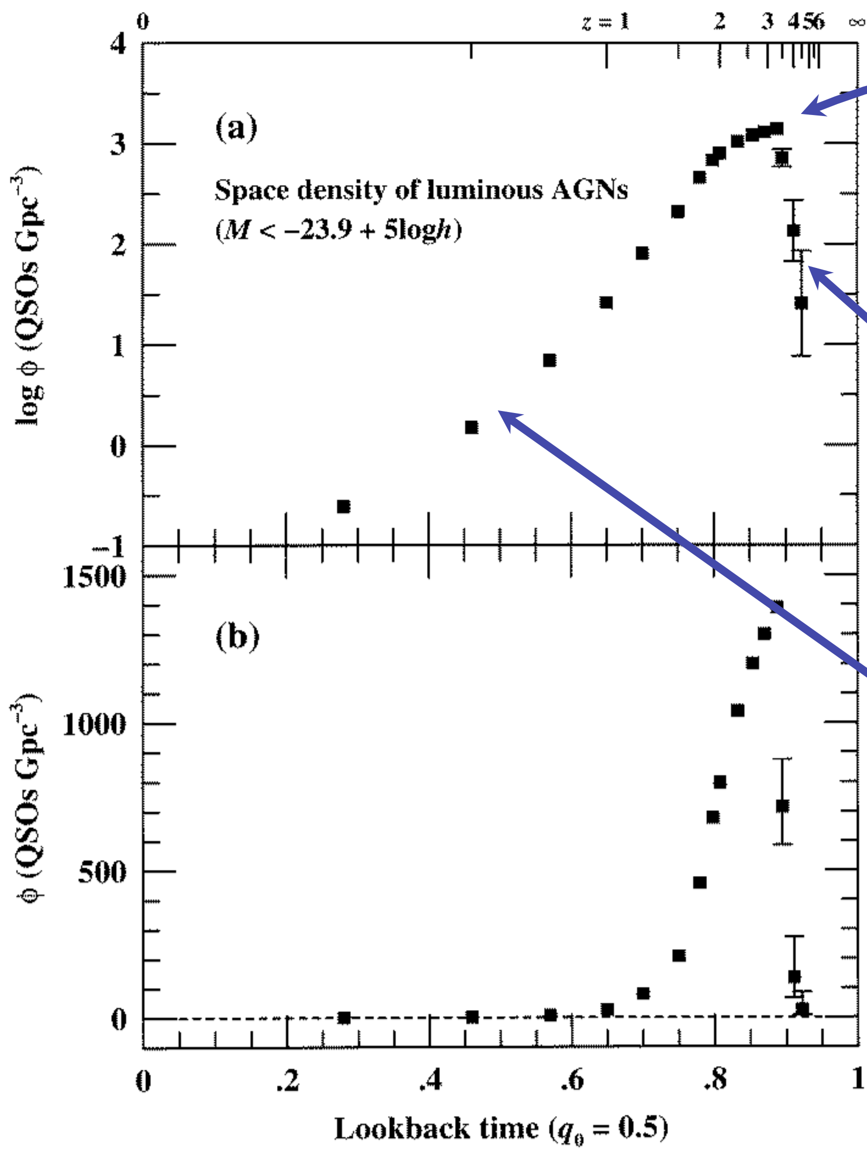
The answer is ***both:***
Luminosity-dependent density evolution

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

Results from 2QZ



The History of the Comoving Number Density of Quasars

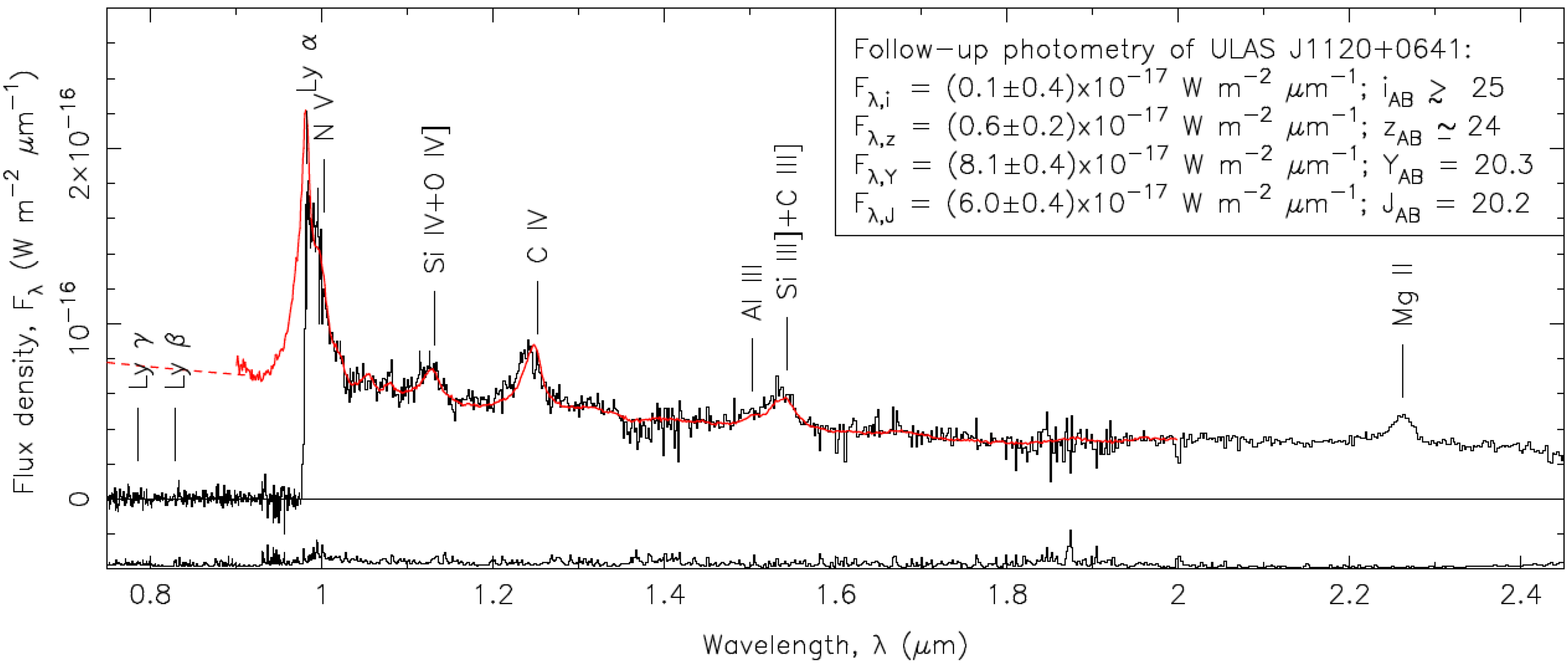


The Peak of the Quasar Era at z ~ 2 - 3: The Maximum Merging Epoch?

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

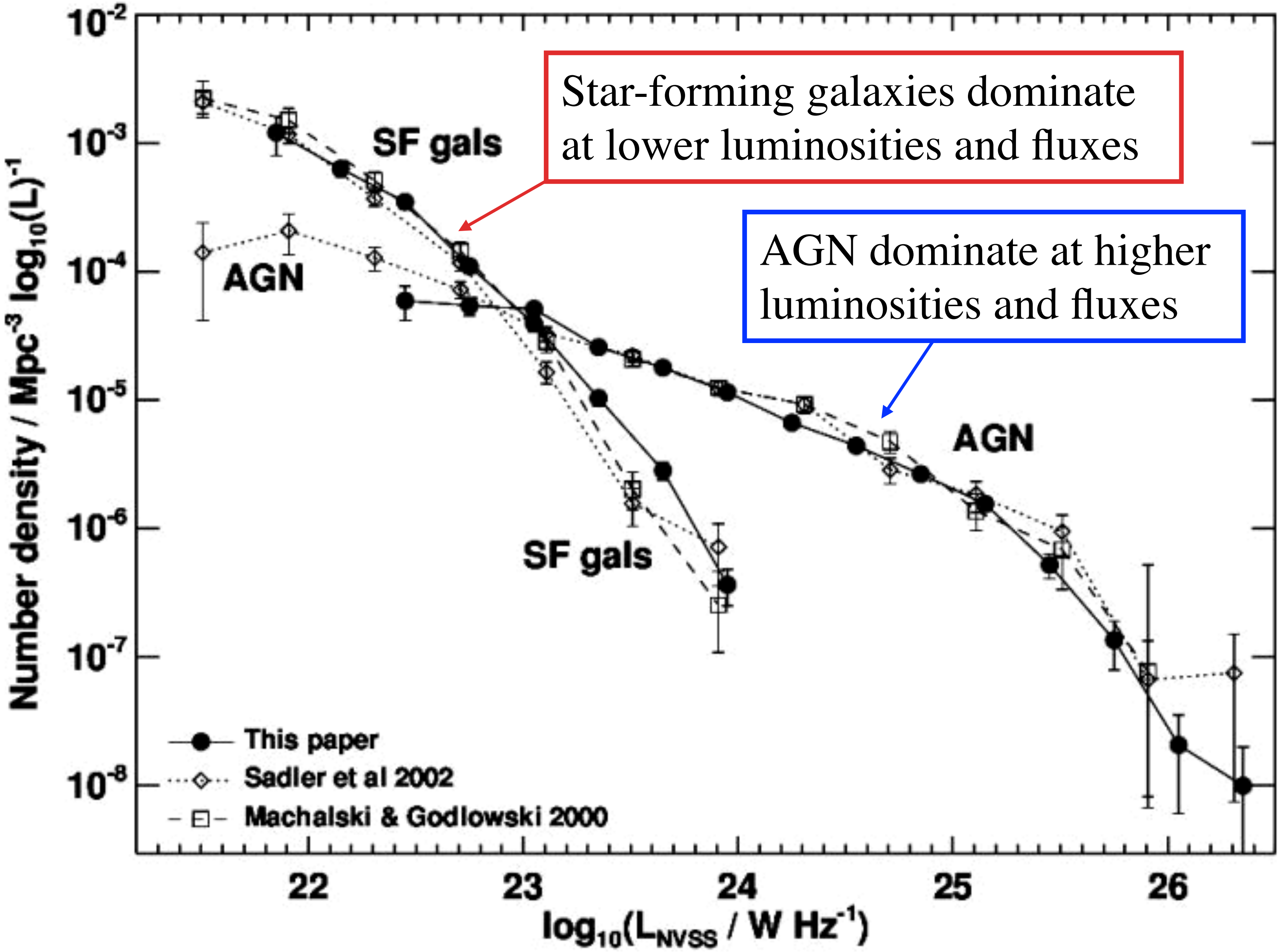
The Decline at Low *z*' s: Diminishing Fueling Events

The Most Distant Quasar Currently Known: ULAS J112001.48+064124.3 at z = 7.085



Found by the UKIDSS survey, using the color break technique (Mortlock et al., the UKIDSS team, 2011, Nature, 474, 616)

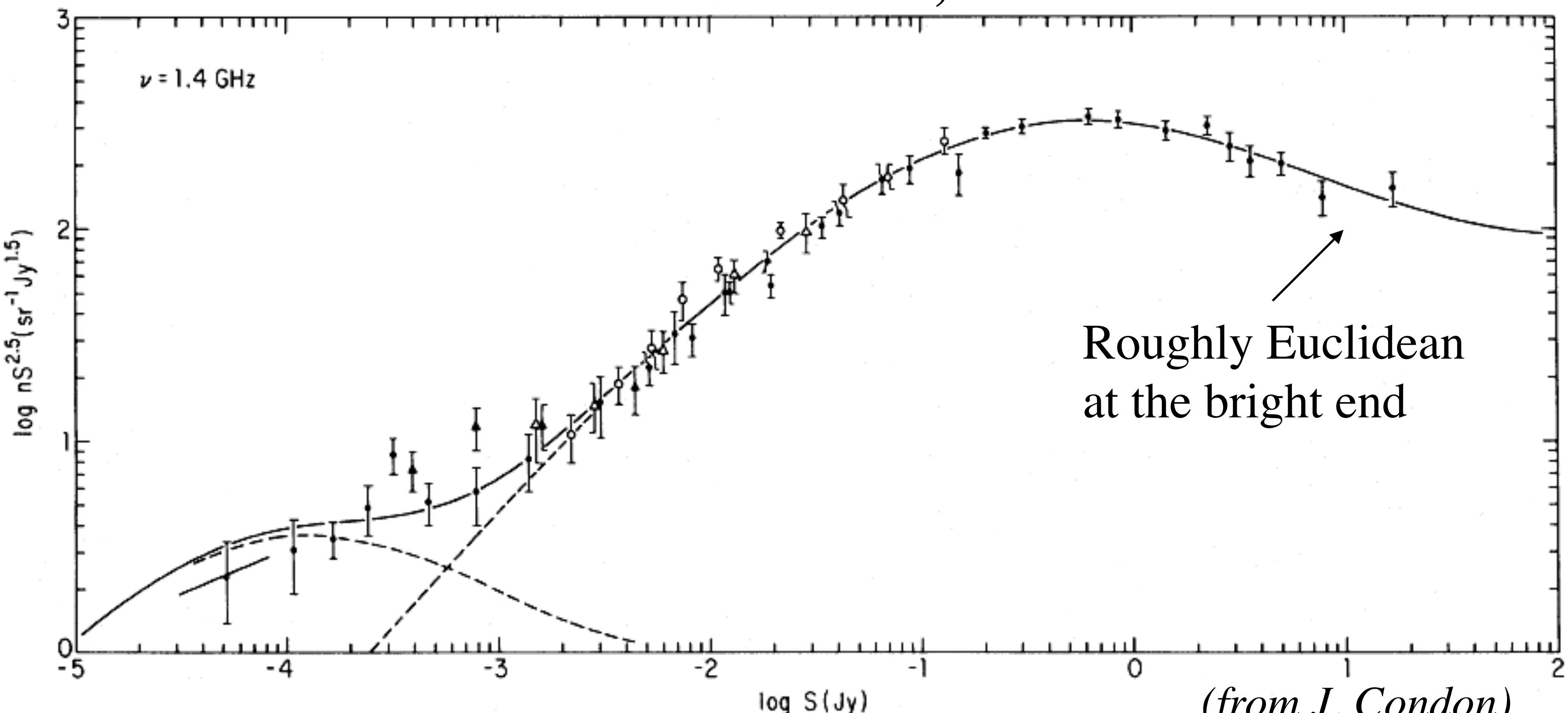
Local Radio Luminosity Function



Evolution of Radio Source Populations

- As far as we can tell, AGN-powered radio sources evolve in the same way as the optically selected quasars, and star formation powered ones in the same way as the star-forming galaxies

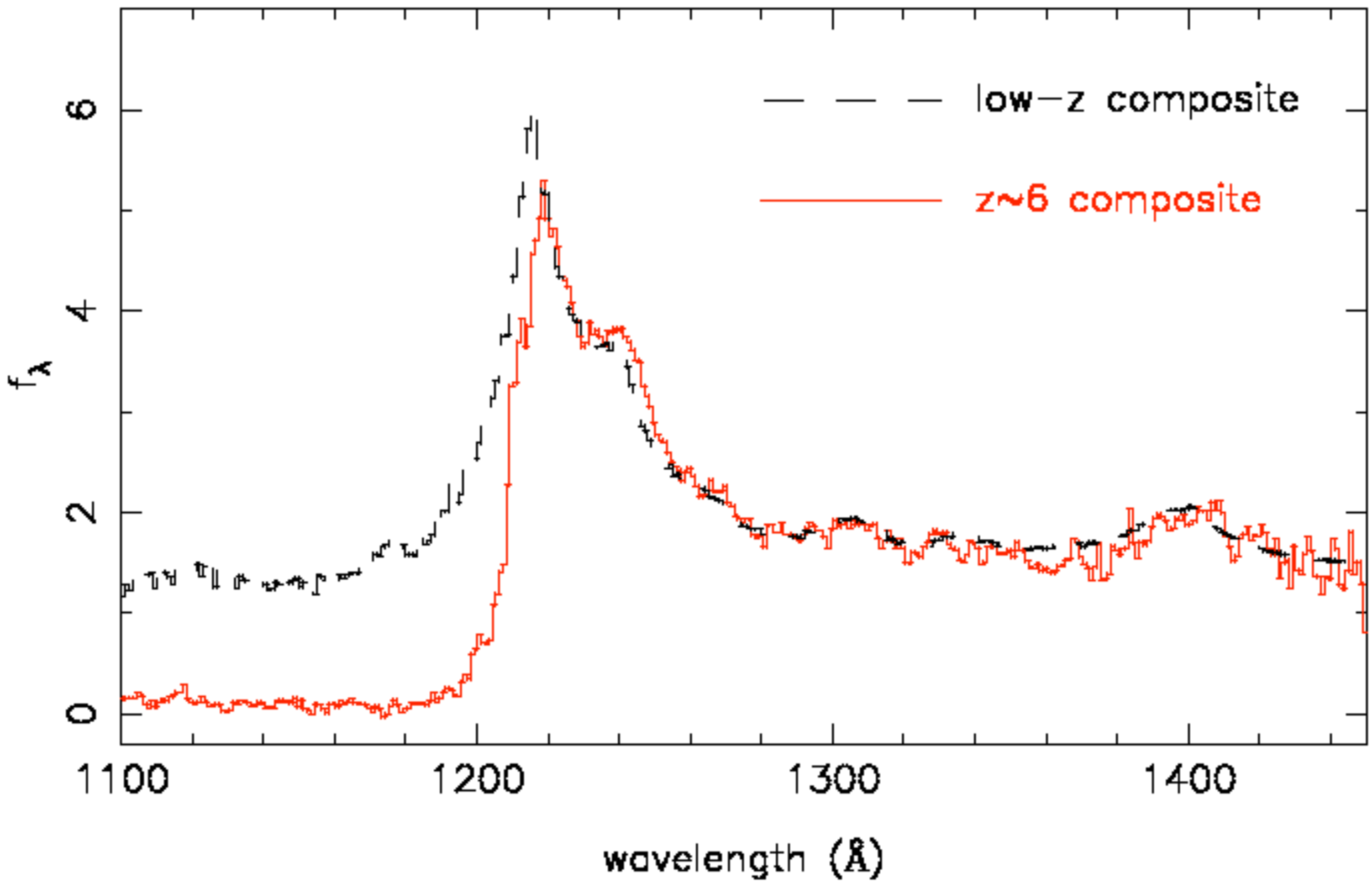
Observed differential source counts; note the normalization



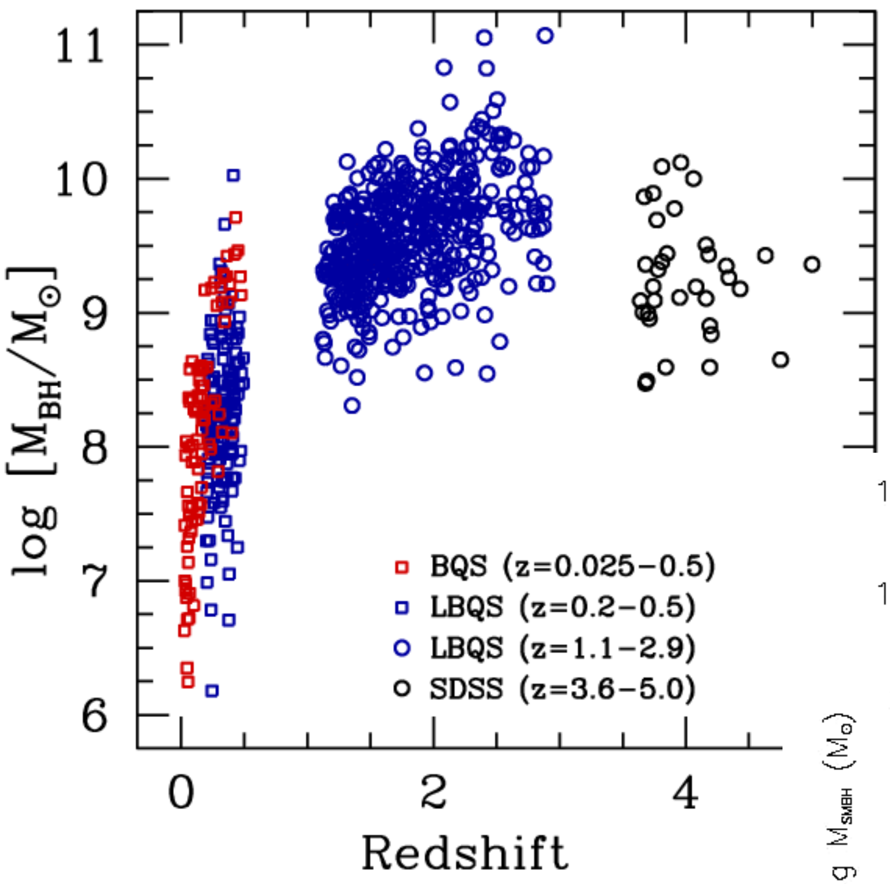
(from J. Condon)

Evolution of Quasar Properties

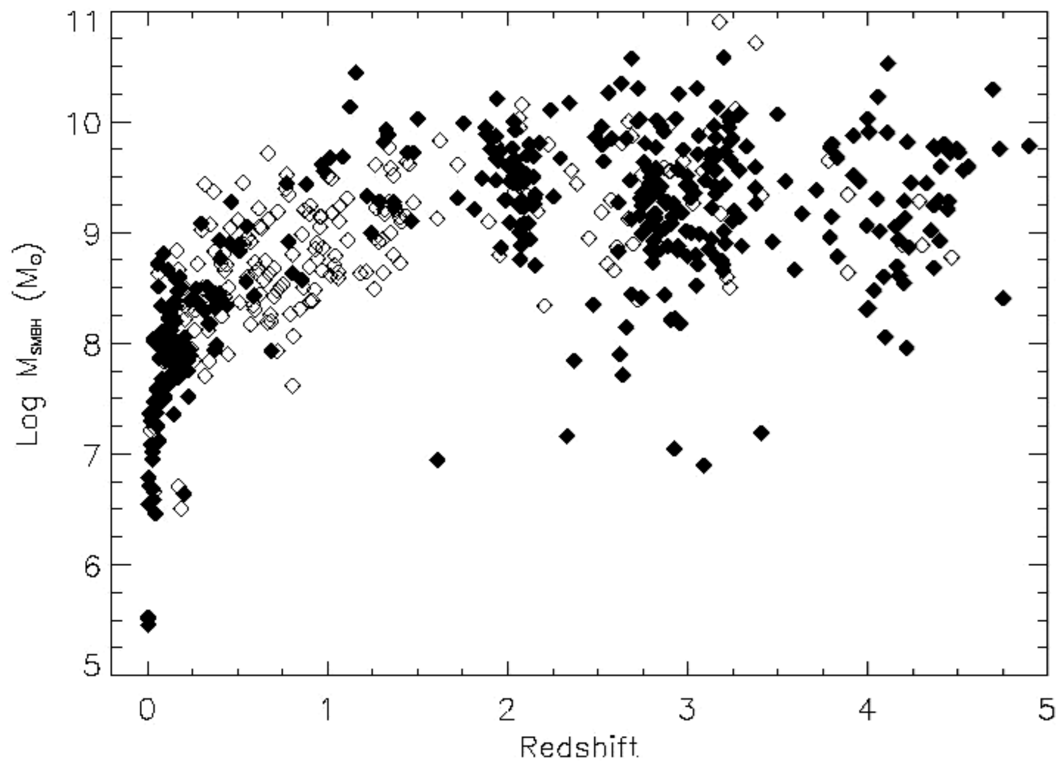
None that we could see, aside from the QLF evolution itself: rapid formation and chemical enrichment of the hosts



Masses of SMBHs in Distant Quasars



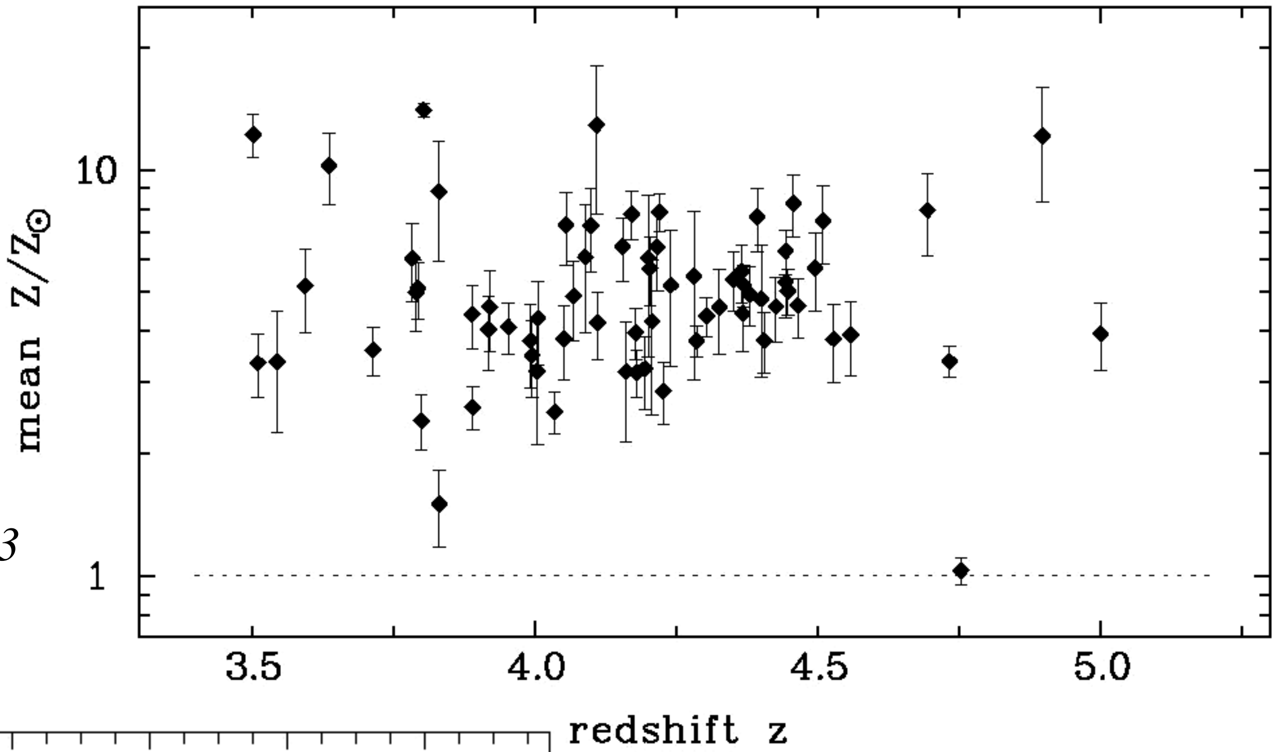
SMBHs with masses of up to ~ 10^{10} $M_\odot$ seem to have been built quickly, already by z ~ 5 - 6

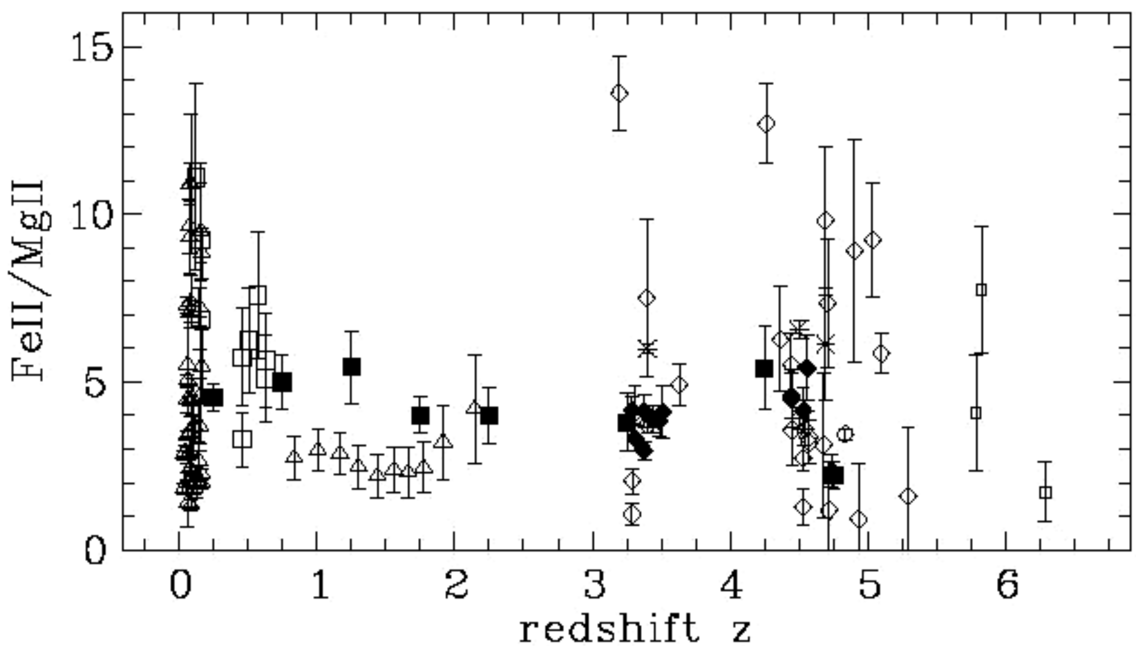


Warner et al. 2003, Vestergaard 2005, etc.

High-z QSOs Are Very Metal Rich!

Hamman, Dietrich, et al. 2003



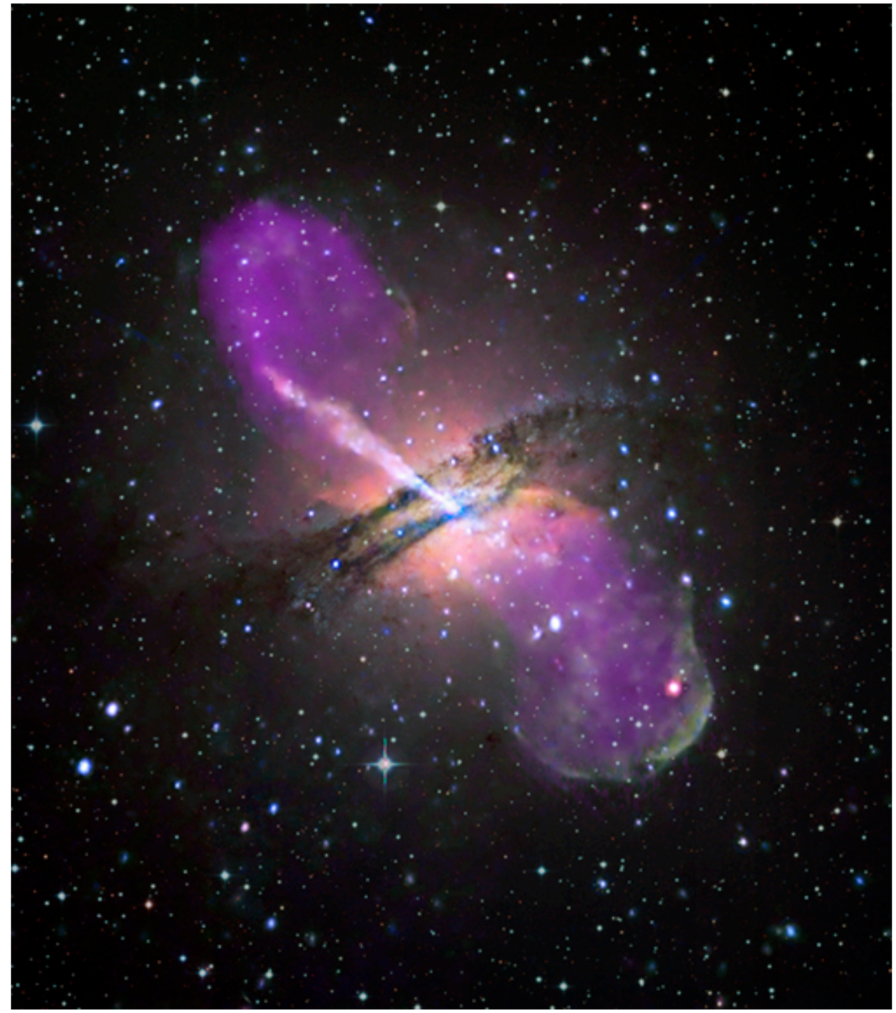


… and their abundance patterns (enhanced Fe/α) are similar to those of ellipticals, suggesting enrichment by type I SNe, with an onset of star formation at $z > 10$

AGN Feedback

Radiative energy input:

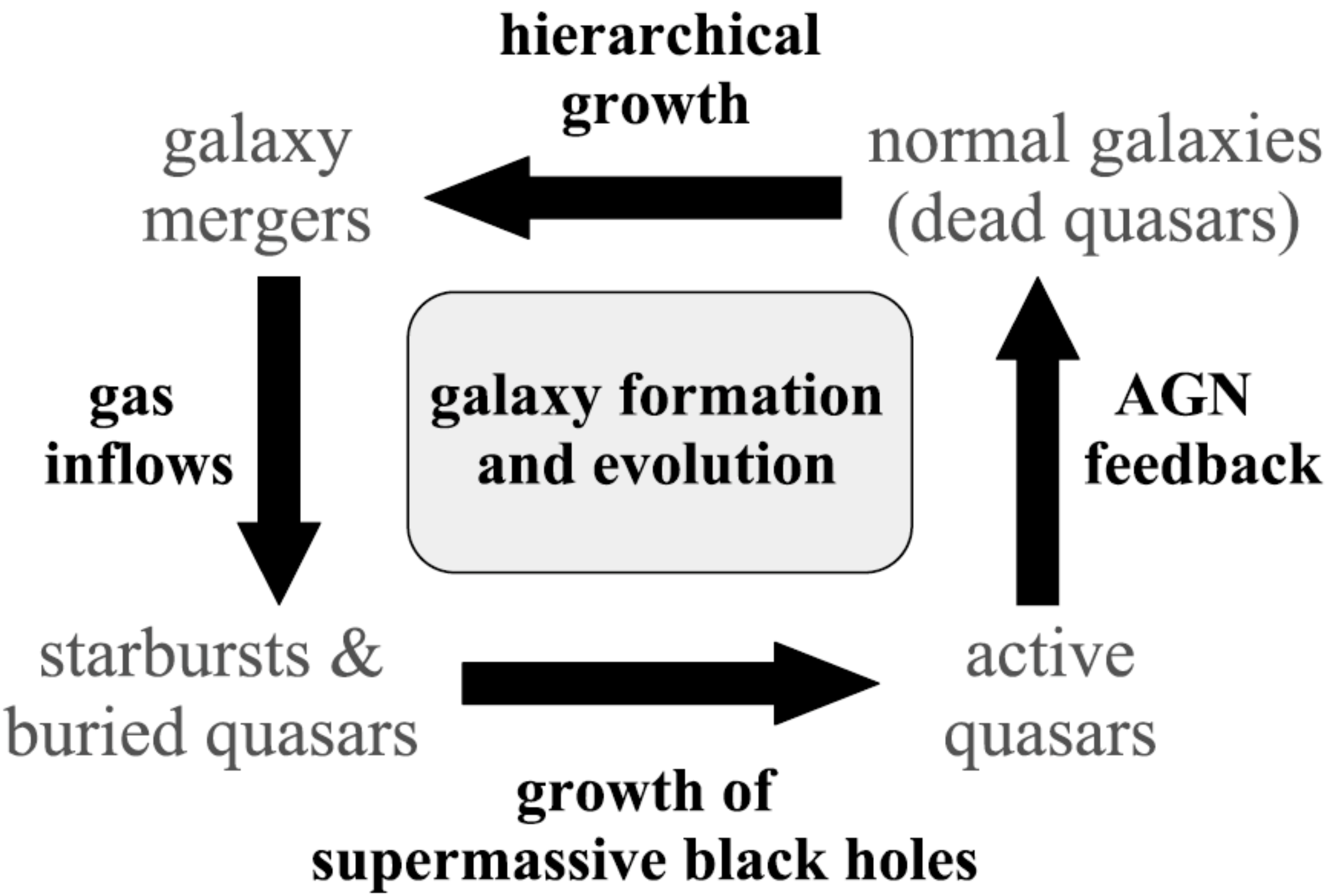
- Ionizes the host ISM and cluster IGM, curtailing star formation
- Negative feedback -> LF cutoff?
- Drives a galactic wind due to coupling with the gas, expels the chemically processed material into the IGM
- Comparable mechanical energy input from the jets (mainly important in clusters?)
- Note:



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

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

The Synergy of Galaxies and SMBHs

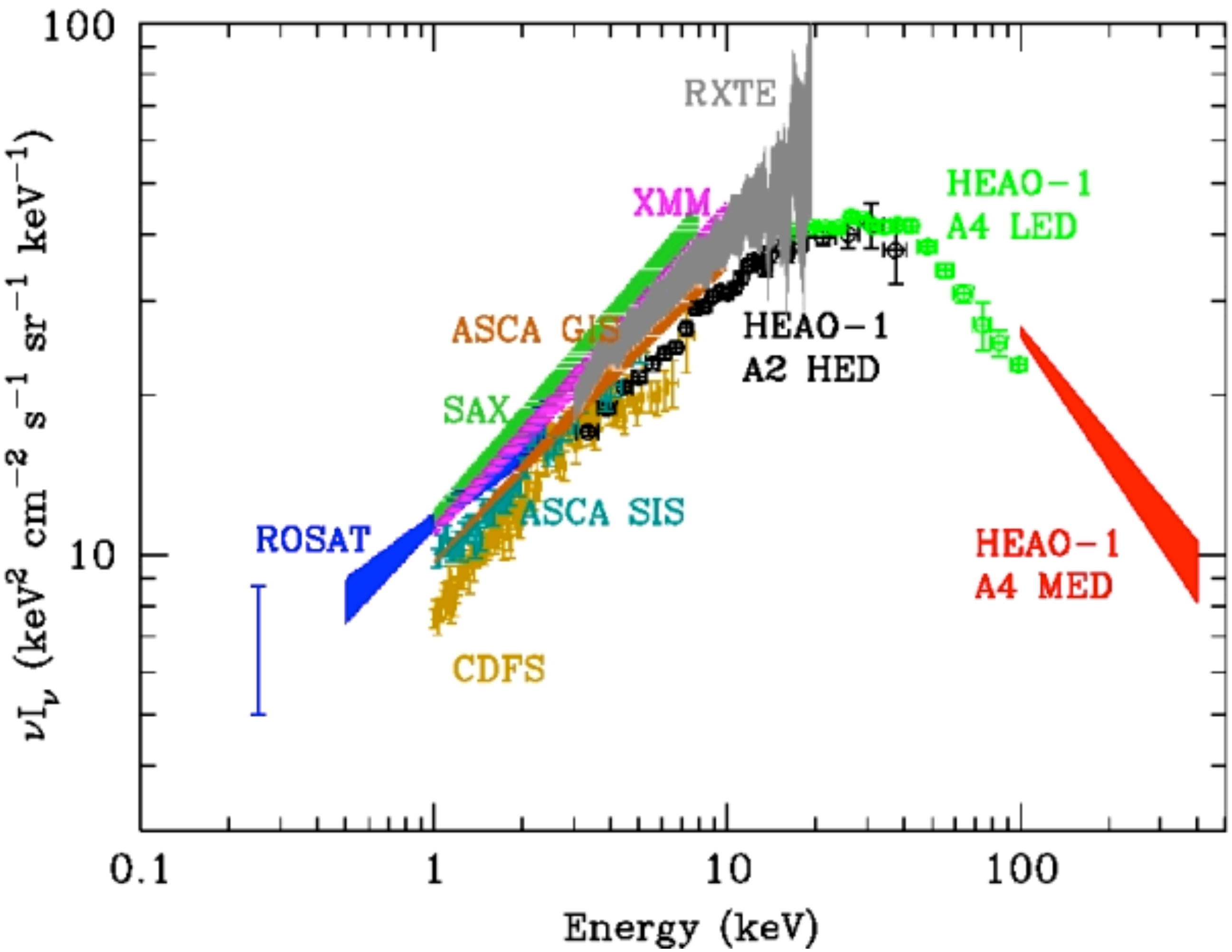


(from P. Hopkins)

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: $u_{XRB} \sim 10^{-17}$ erg/cm^3, $u_{Opt/FIR} \sim$ a few $\times$ 10^{-15} erg/cm^3, $u_{CMB} \sim$ a few $\times$ 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 Spectrum of the CXRB

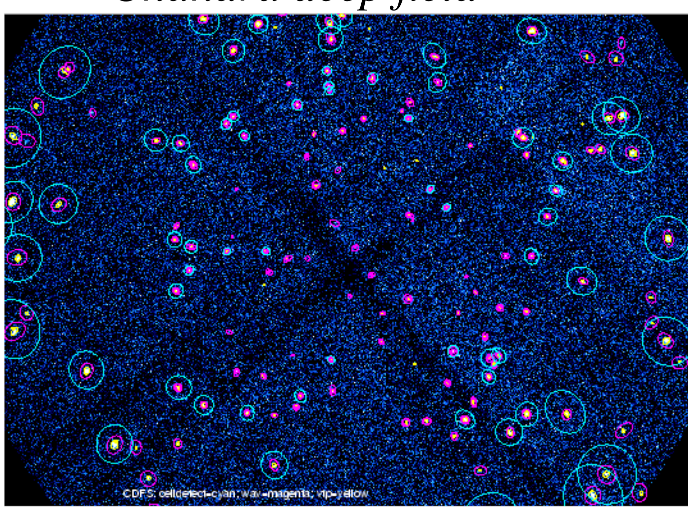


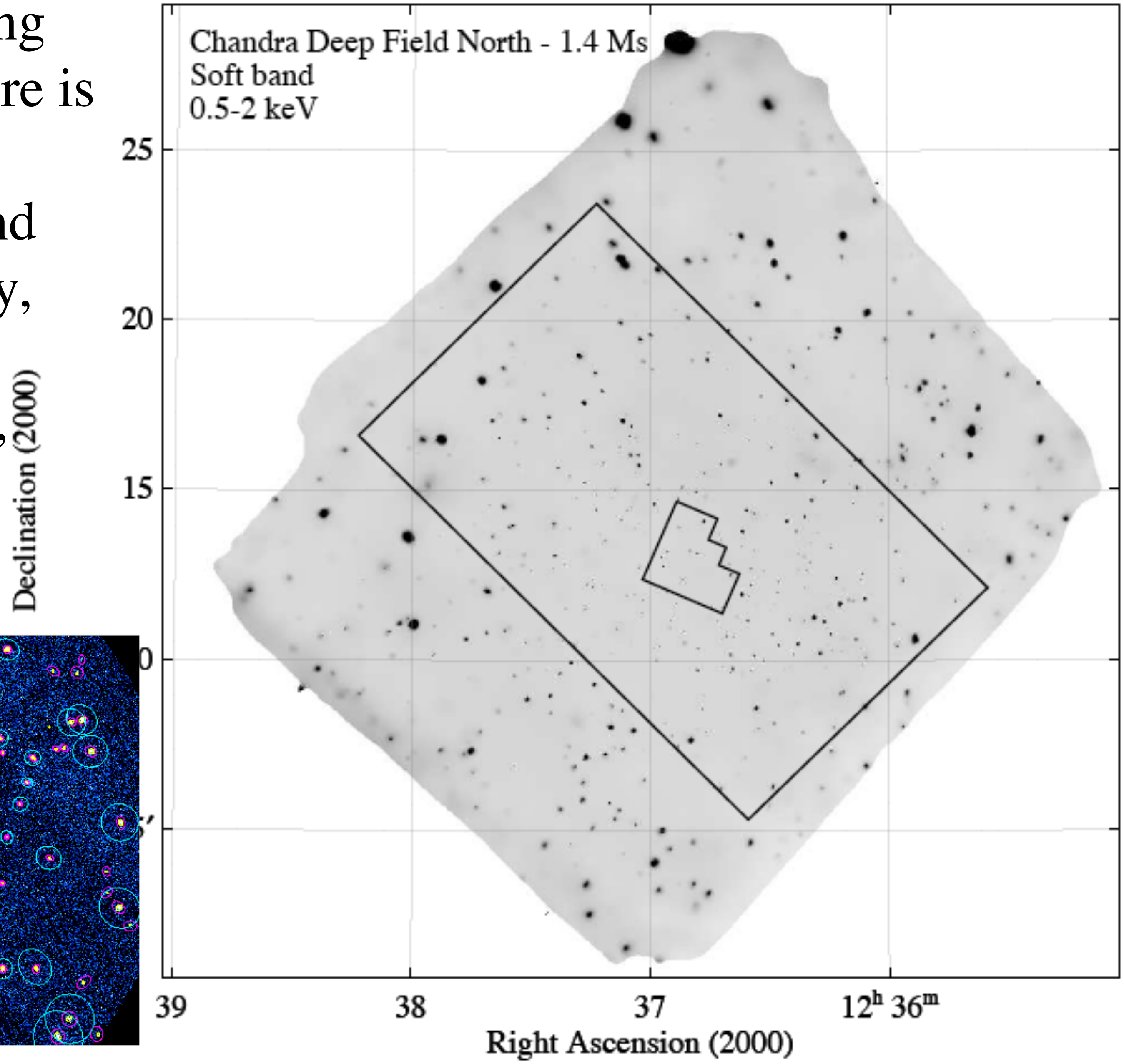
It does not look like an AGN spectrum, but it looks just like the thermal bremsstrahlung of hot plasma (like in a cluster). We now know that is just a coincidence: it is really a sum of the redshiftted AGN spectra, some of which are reflected from the thick dust

Resolving the CXRB

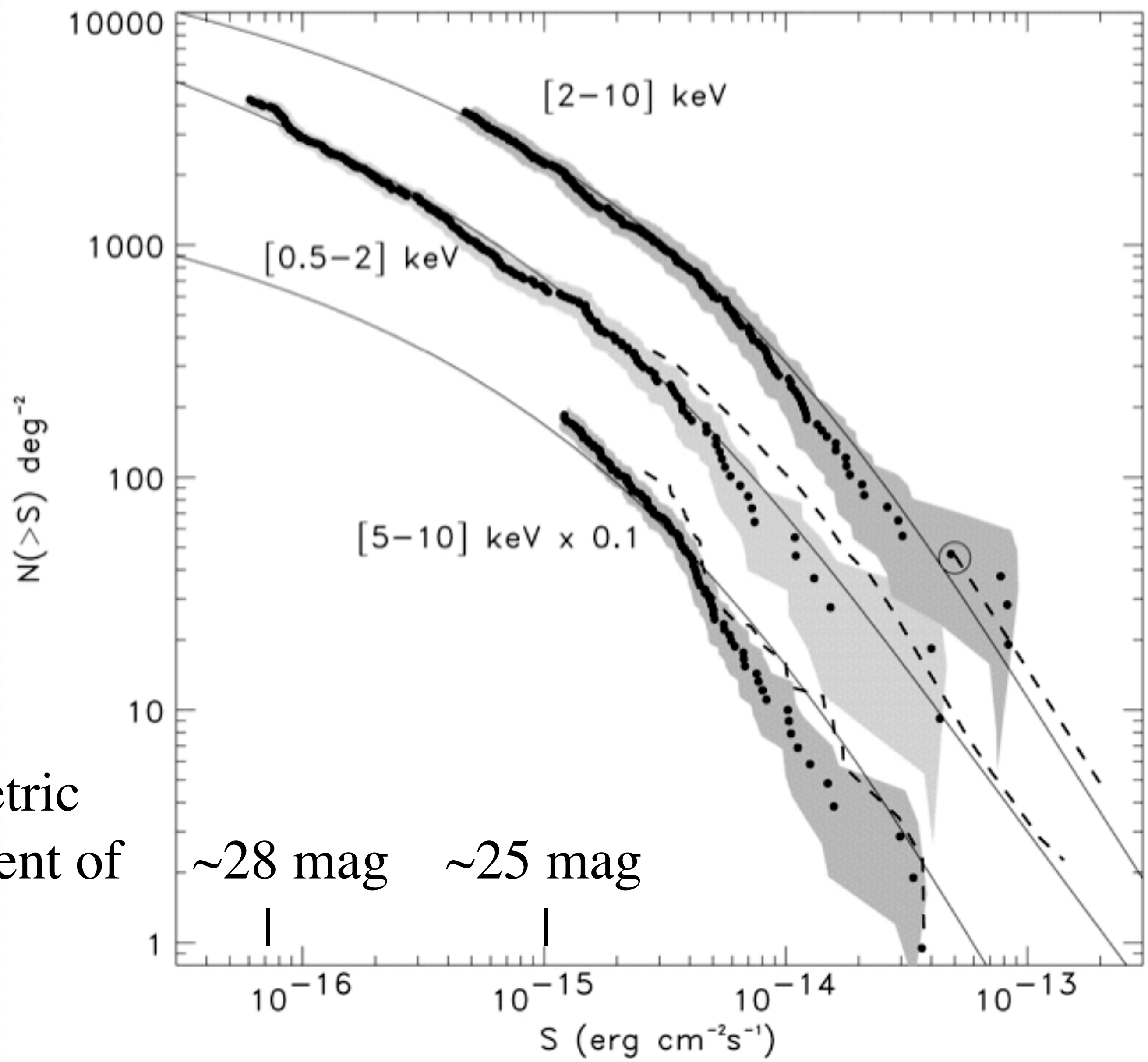
Deep X-ray imaging of fields where there is already deep HST imaging and ground based spectroscopy, also followed in radio, IR (*Spitzer*), etc.

Chandra deep field





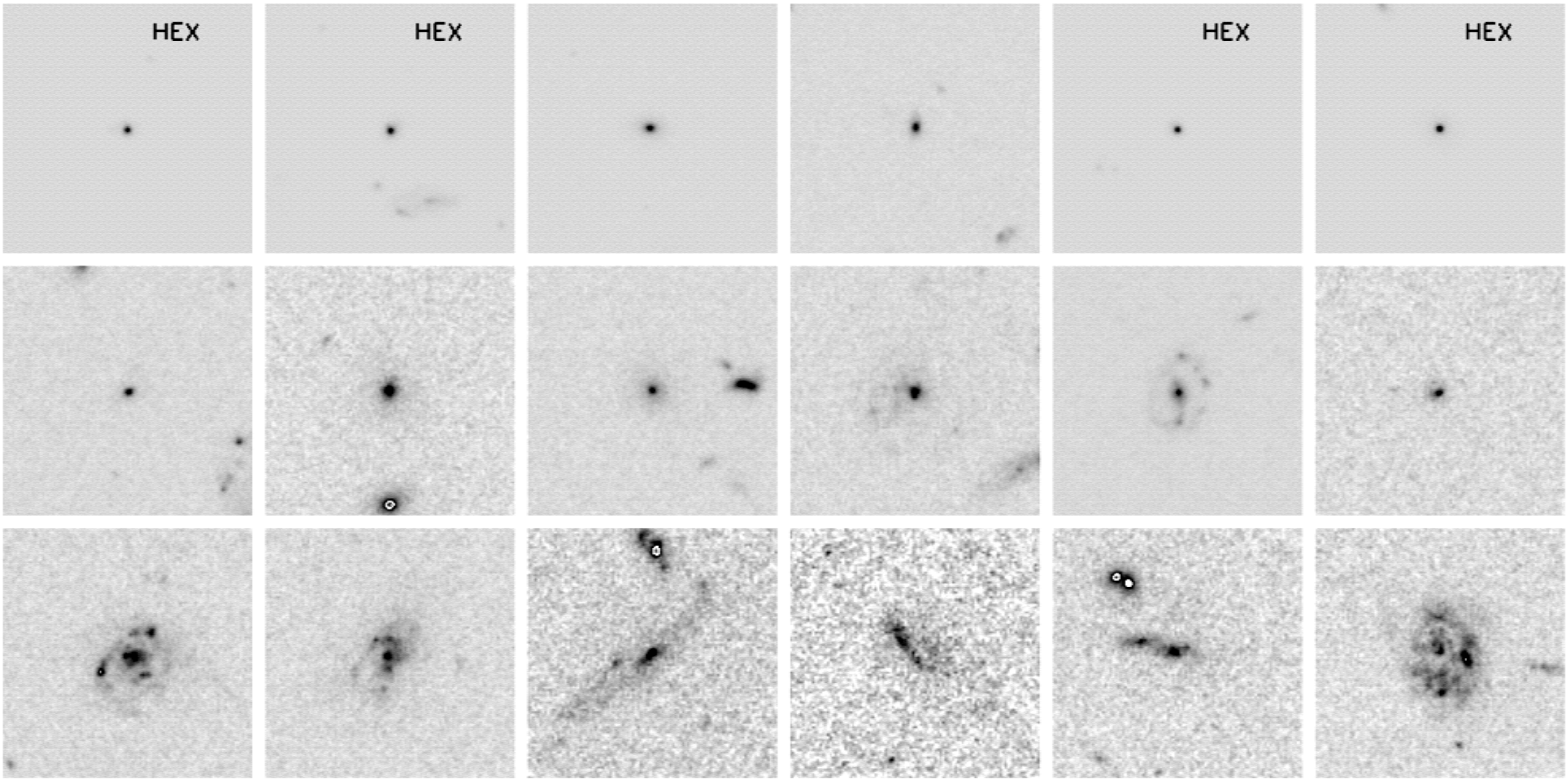
The Deep X-Ray Source Counts



Bolometric equivalent of ~28 mag ~25 mag

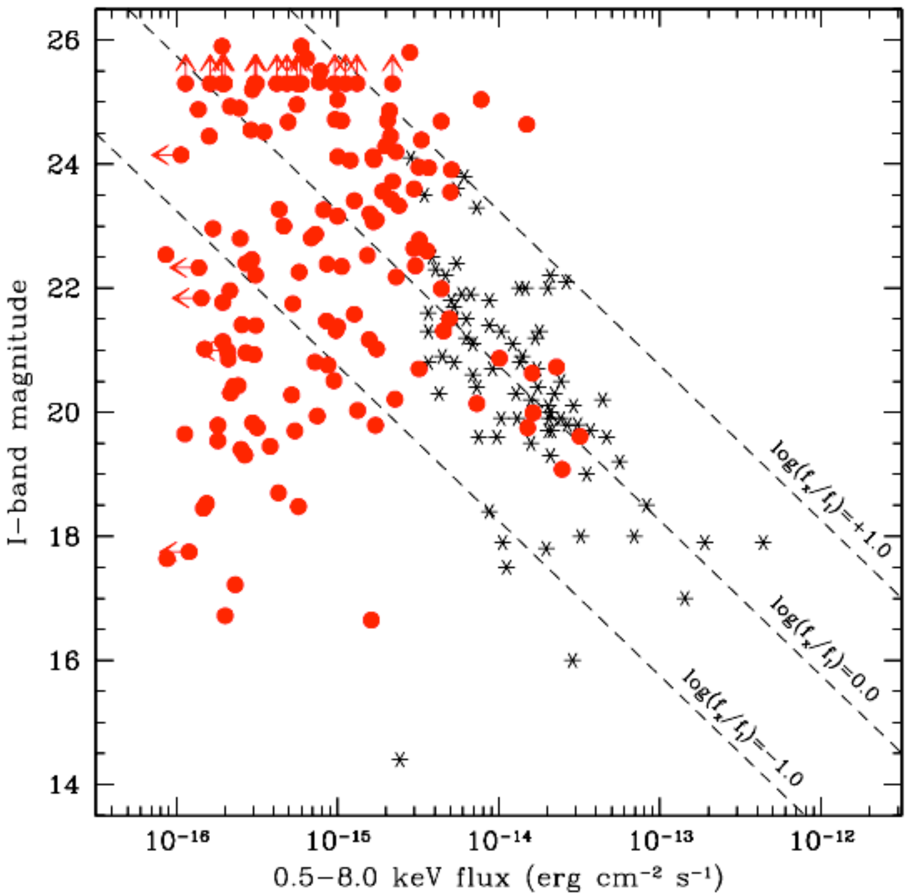
Identifying the Faint X-Ray Sources

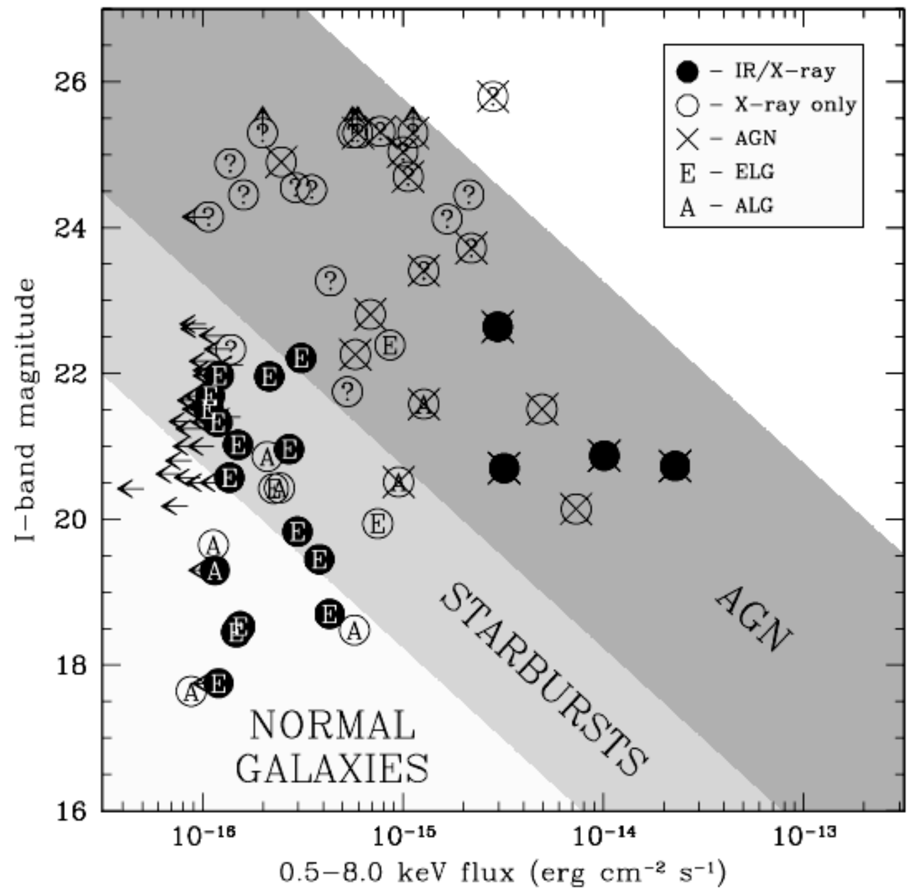
Samples of sources:



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

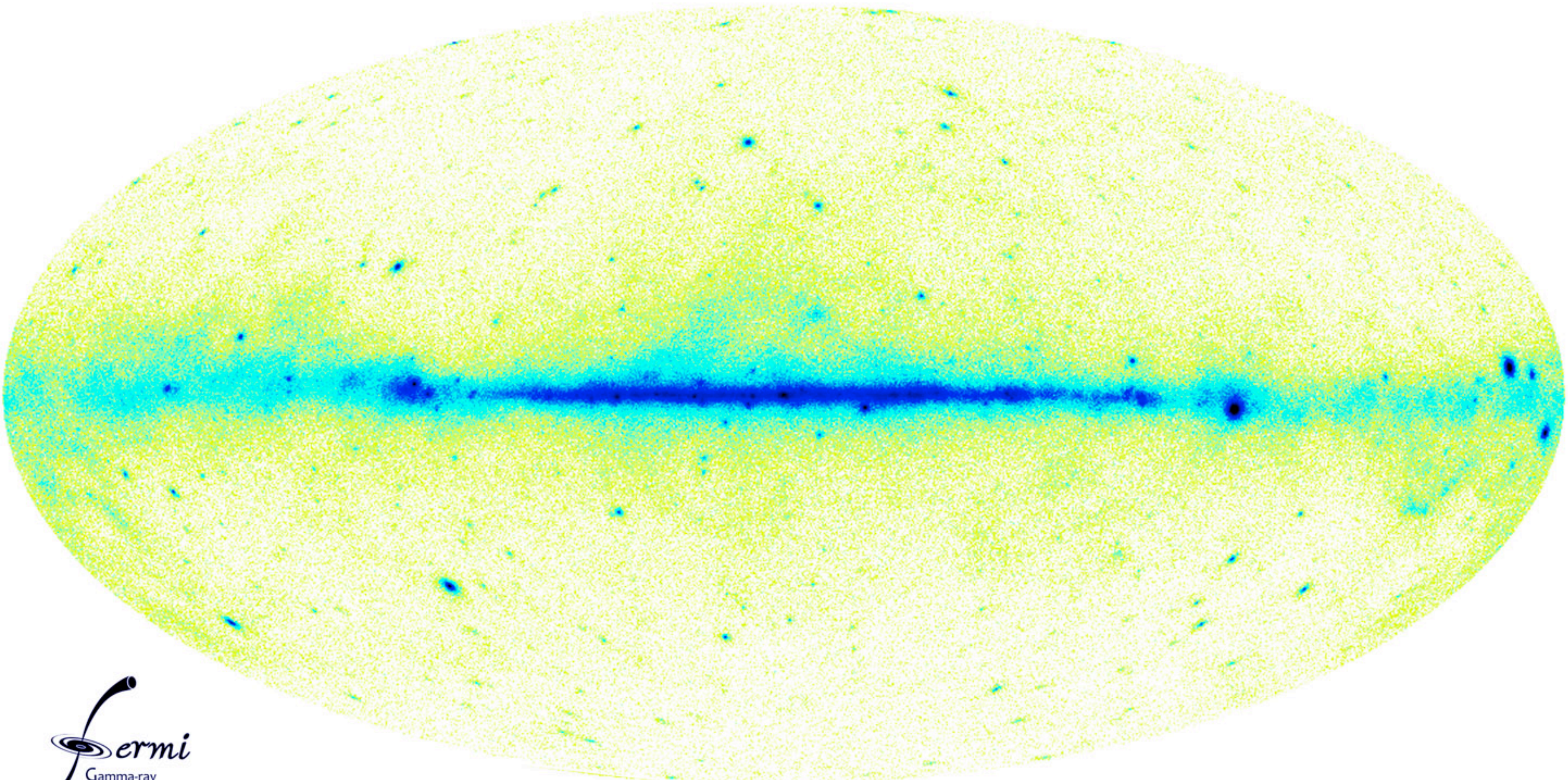
The Nature of X-Ray Sources





A poor correlation between optical/IR and X-ray fluxes
AGN dominate the high-luminosity end, star formers the low end

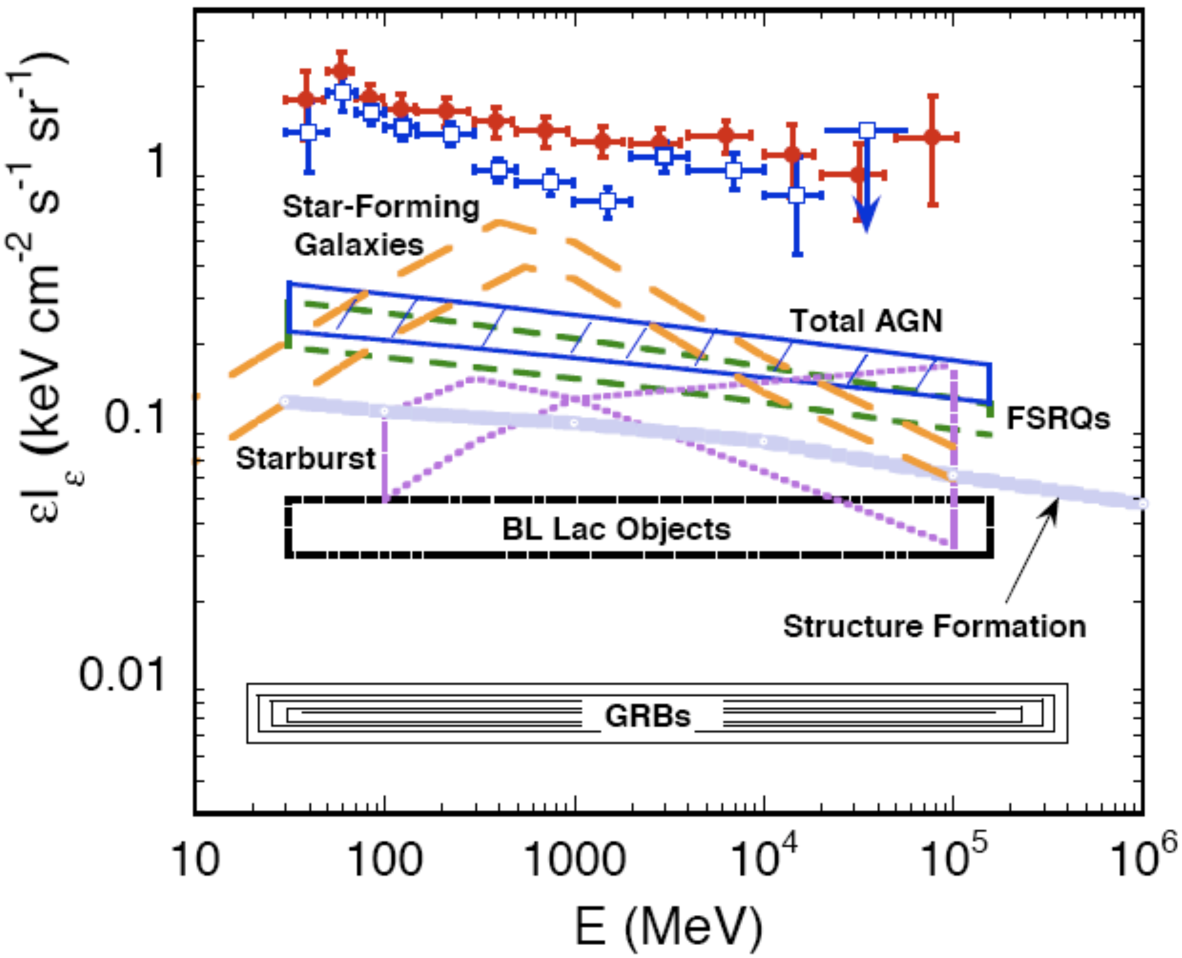
Beamed AGN are the Principal Extragalactic γ-Ray Sources



Fermi LAT first year map

The Origins of the CGRB

Blazars and FSRQ (beamed AGN) dominate the extragalactic γ-ray sky



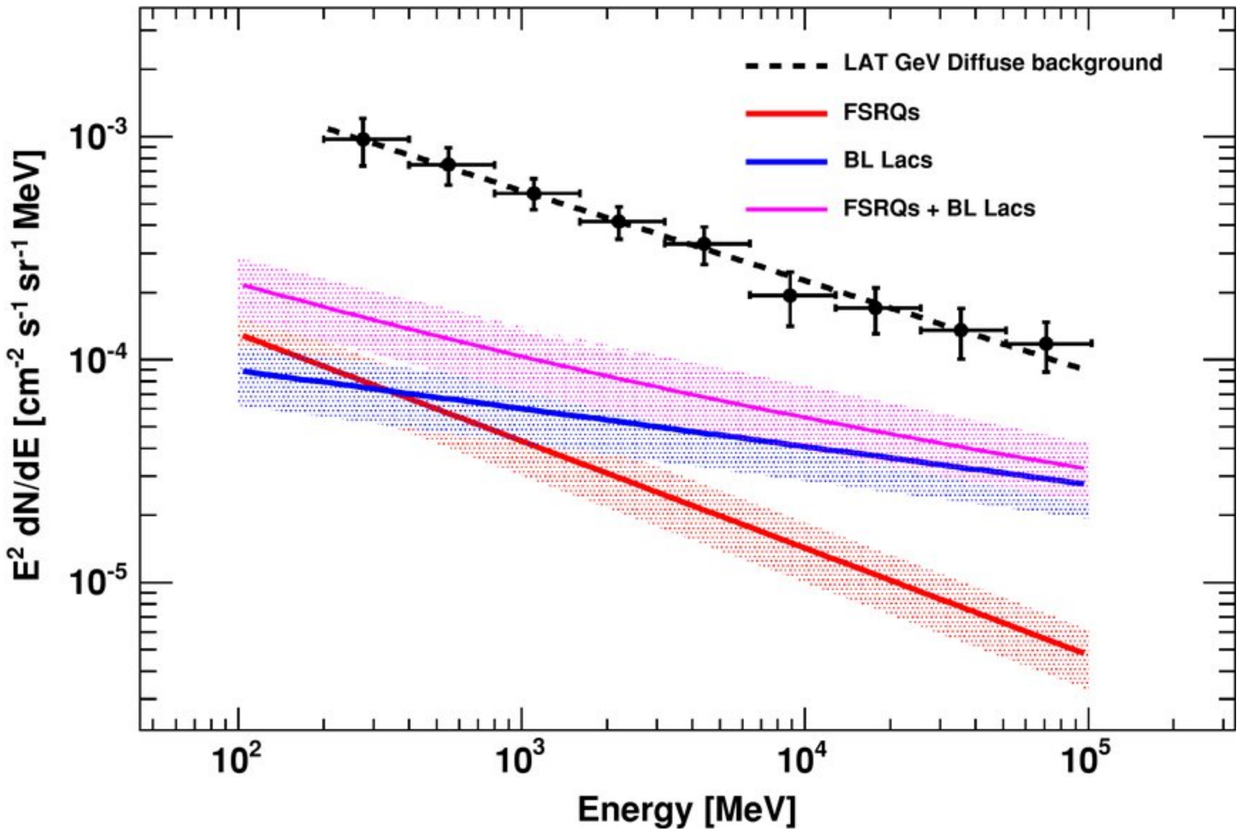
However, there seems to be a significant deficit of sources needed to explain the CGRB, especially at high energies *(Dermer 2006)*

A better understanding of the demographics of beamed AGN is needed

New populations of γ-ray luminous, faint AGN may exist, and may be detectable as variable counterparts of faint γ-ray sources

The Origins of the CGRB

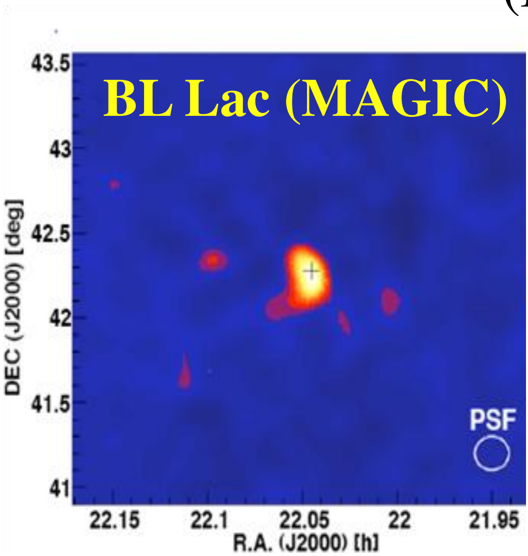
New *Fermi* measurements fail to account for the observed CGRB by integrating the extrapolated source counts *(Abdo et al., 2010, ApJ, 720, 435)*

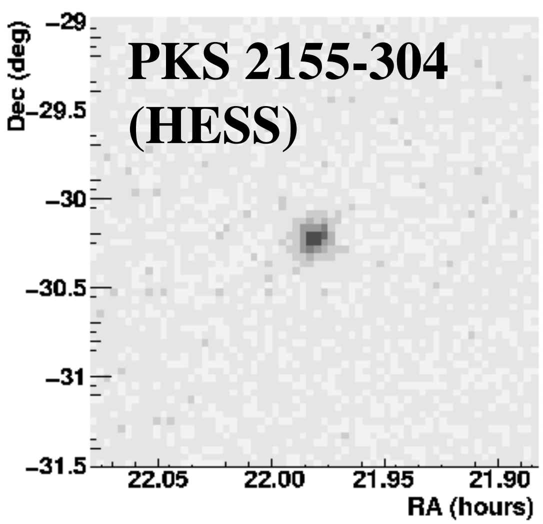


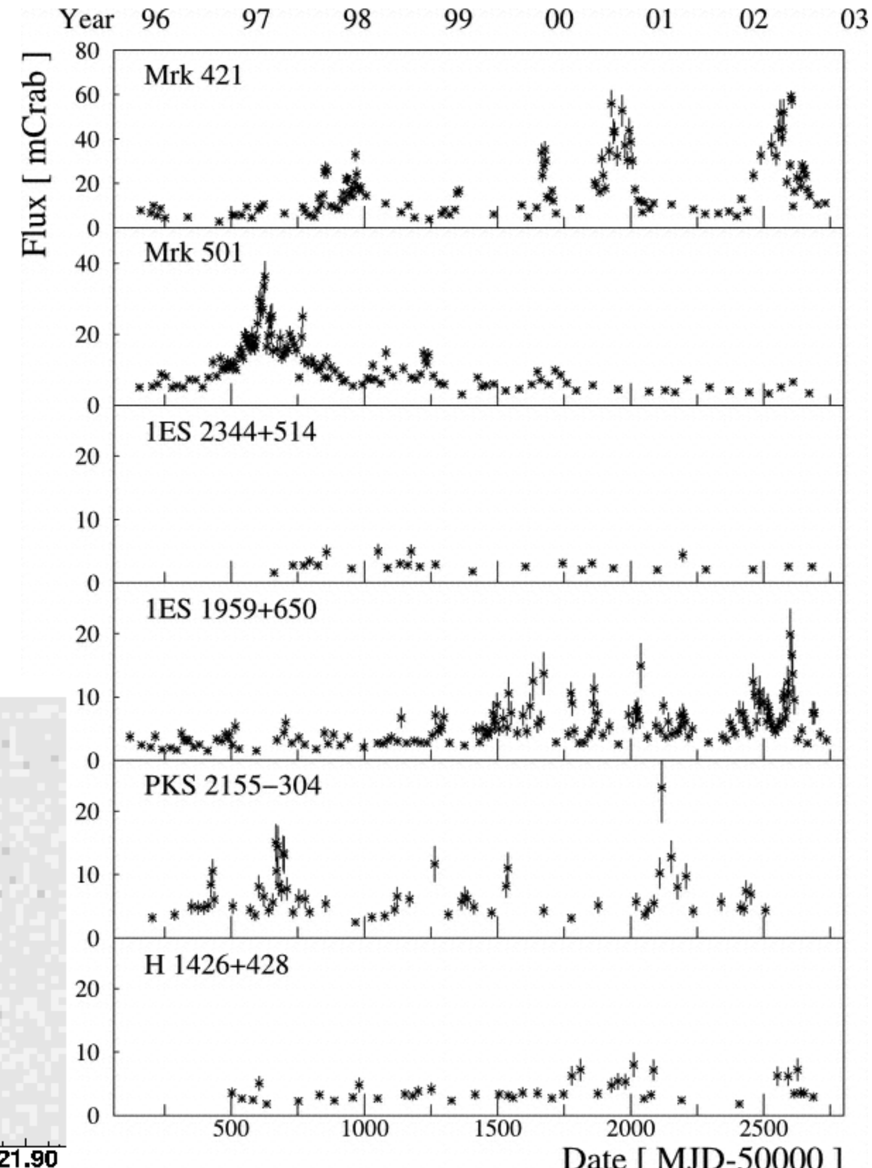
The origin of the “excess” is as yet unknown; it can be some combination of beamed AGN, star-forming galaxies, shocks in clusters, DM annihilation/decay, etc.

The Cosmic Accelerators: TeV γ-ray Detections of Blazars

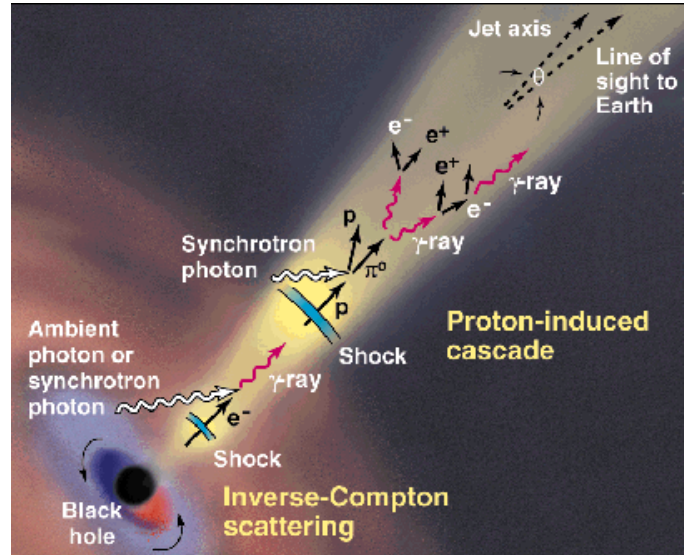
Variability on time scales of minutes implies origin from very compact regions - possibly internal shocks, and bulk Lorentz $\Gamma > 50$ (Begelman et al. 2007)



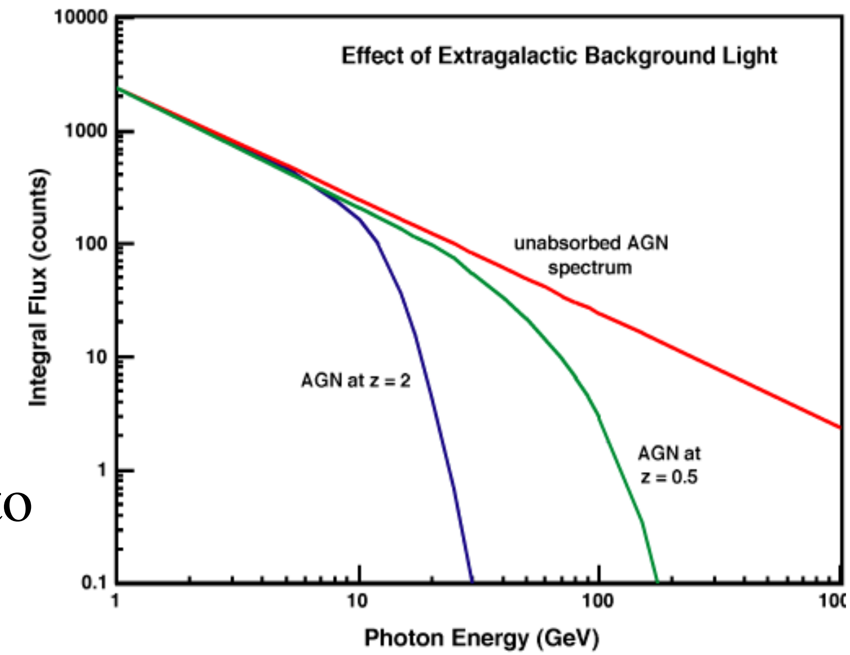


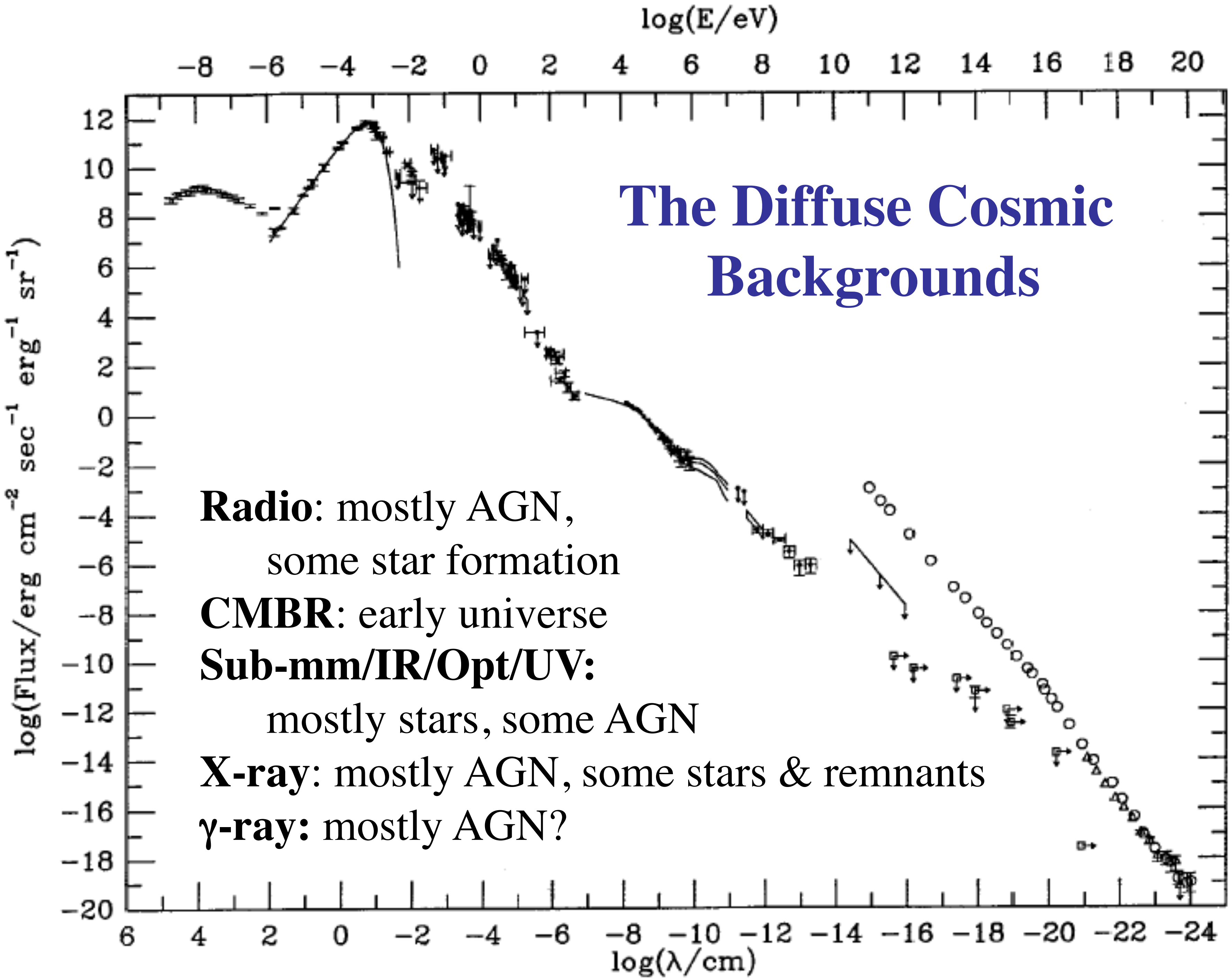


The Many Uses of Blazars



- AGN demographics and evolution
  - Constraints for AGN unification models
  - Origins of the Cosmic γ-Ray Bgd.
  - Possible new AGN sub-populations?
- Understanding the cosmic accelerators
  - AGN jet origins and their physics
  - The UHECR connection? ***Long-term future of particle physics?***
- Astrophysical foregrounds to CMBR fluctuations at high ℓ
- A new probe of the cosmic star formation history, through extragalactic bgd. light as a *f(z)*
  - EBL photon gas is optically thick to high-energy photons




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?
log(E/eV)
log(λ/cm)
log(Flux/erg cm^-2 sec^-1 erg^-1 sr^-1)

Supplementary Slides

Active Galactic Nuclei: Seyferts

- First noted by Fath at Lick Observatory in 1908 (!), who was taking spectra of the nuclei of "spiral nebulae" and noted that NGC 1068 had strong emission lines
- Slipher obtained a higher quality spectrum at Lowell in 1917, noted the lines were similar to planetary nebulae
- In 1926, Hubble noted 3 galaxies with strong emission lines: NGC 1068, NGC 4051, NGC 4151
- In 1943 (~30 years later!), Carl Seyfert recognized that there was a class of galaxies (now known as Seyfert galaxies), with strong, broad high-ionization emission lines and bright nuclei
  - Why this was not remembered when the first spectra of quasars were taken, is a mystery …
- Seyfert nuclei are found in spiral galaxies; up to ~10% of Sa and Sb's are Seyferts; but at a lower level of activity, there are more
- Seyferts have only moderate radio emission (~10^{40} erg/s) but strong x-ray emission (> 10^{42} erg/s)

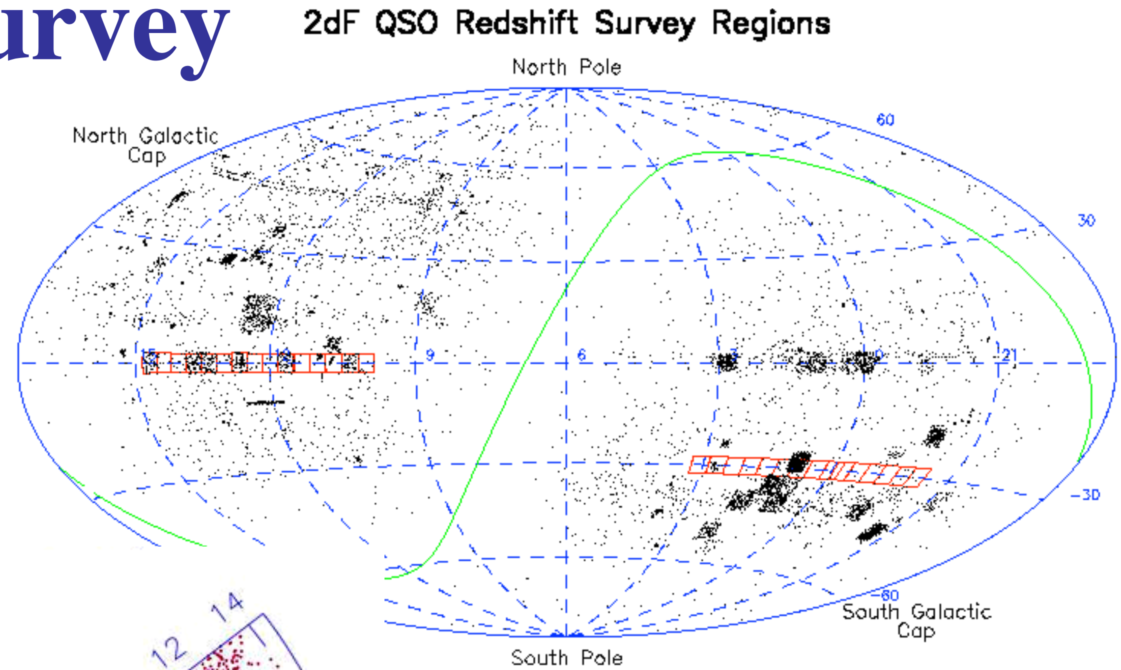
Quasar Surveys and Catalogs

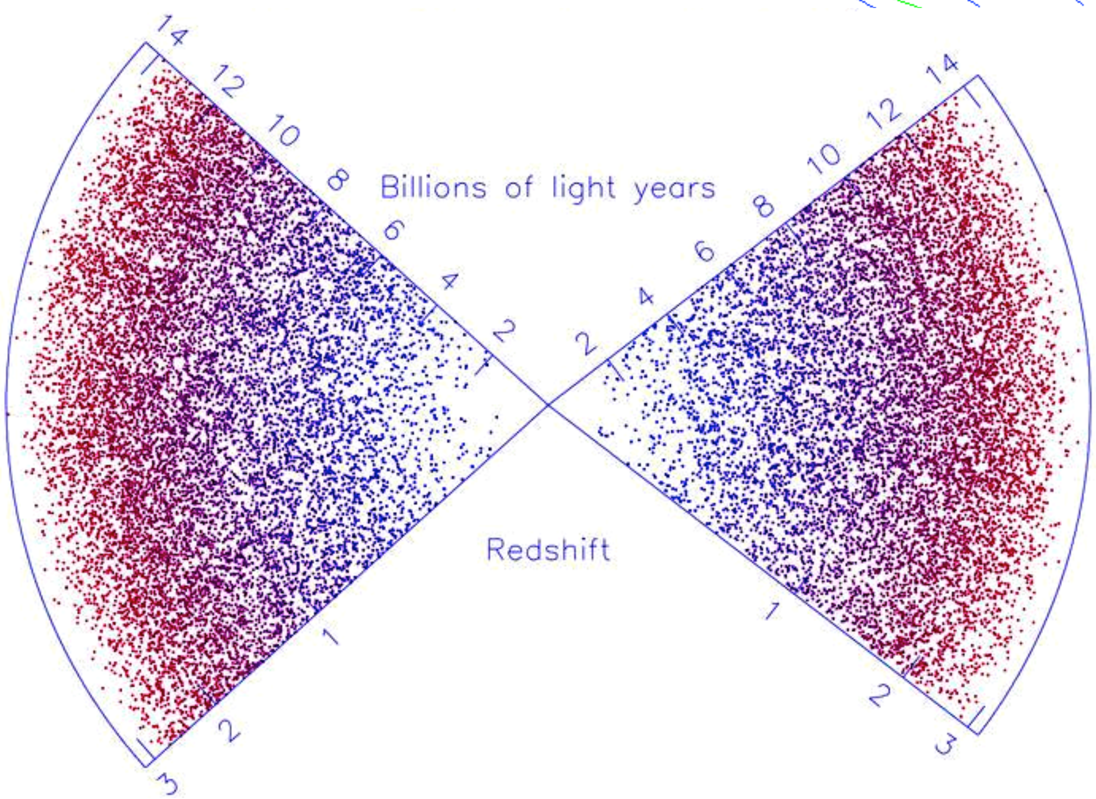
- To date, there are > 200,000 spectroscopically confirmed QSOs
  - And > 1,000,000 additional QSO candidates selected from colors, still awaiting spectroscopy
  - Most come from large systematic surveys, e.g., SDSS and 2QZ
  - Many smaller surveys in the past were done at Palomar, e.g., Palomar Green (PG), Palomar CCD (PC), Palomar Sky Survey (PSS), etc.
  - There were also many searches for emission line objects (some are AGN, some starformers), e.g., Mrk, UM, CSO, KISS, etc.
  - Older heterogeneous catalogs include Hewitt & Burbidge, and Veron & Veron-Cetty compilations
- There are now also > 10^5 X-ray sources catalogued (most are probably powered by AGN)
- There is also probably close to ~ 10^6 radio sources in various catalogs, and many of them are powered by AGN
  - Major radio surveys include: Parkes (PKS), Green Bank (GB), NRAO VLA Sky Survey (NVSS), Faint Images of Radio Sky at Twenty cm (FIRST), etc. etc.

2QZ Quasar Survey

Uses 2dF spectrograph
at the AAT

UV color selection
(limits redshifts to $z < 2.3$)



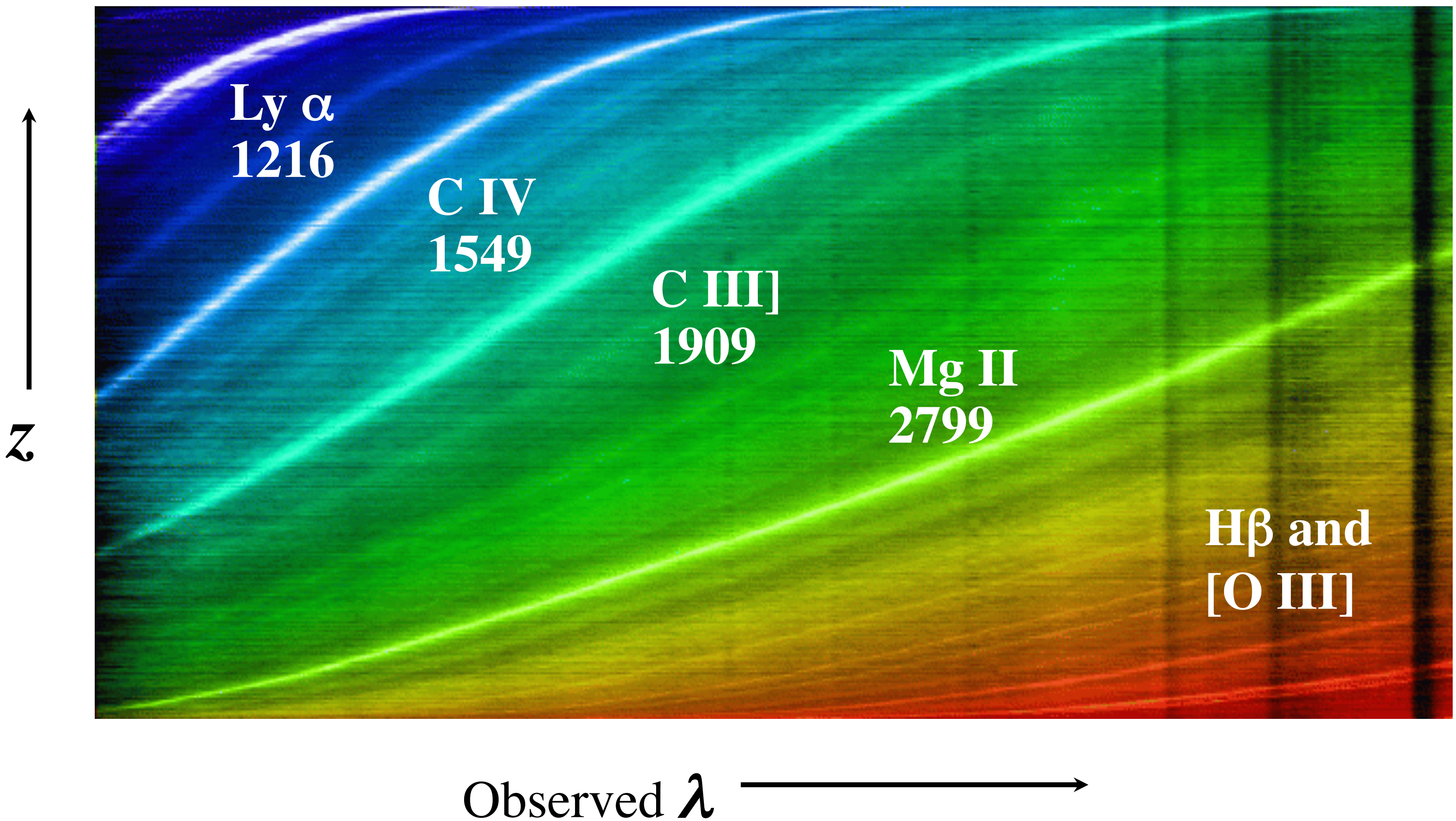


23,424 QSOs

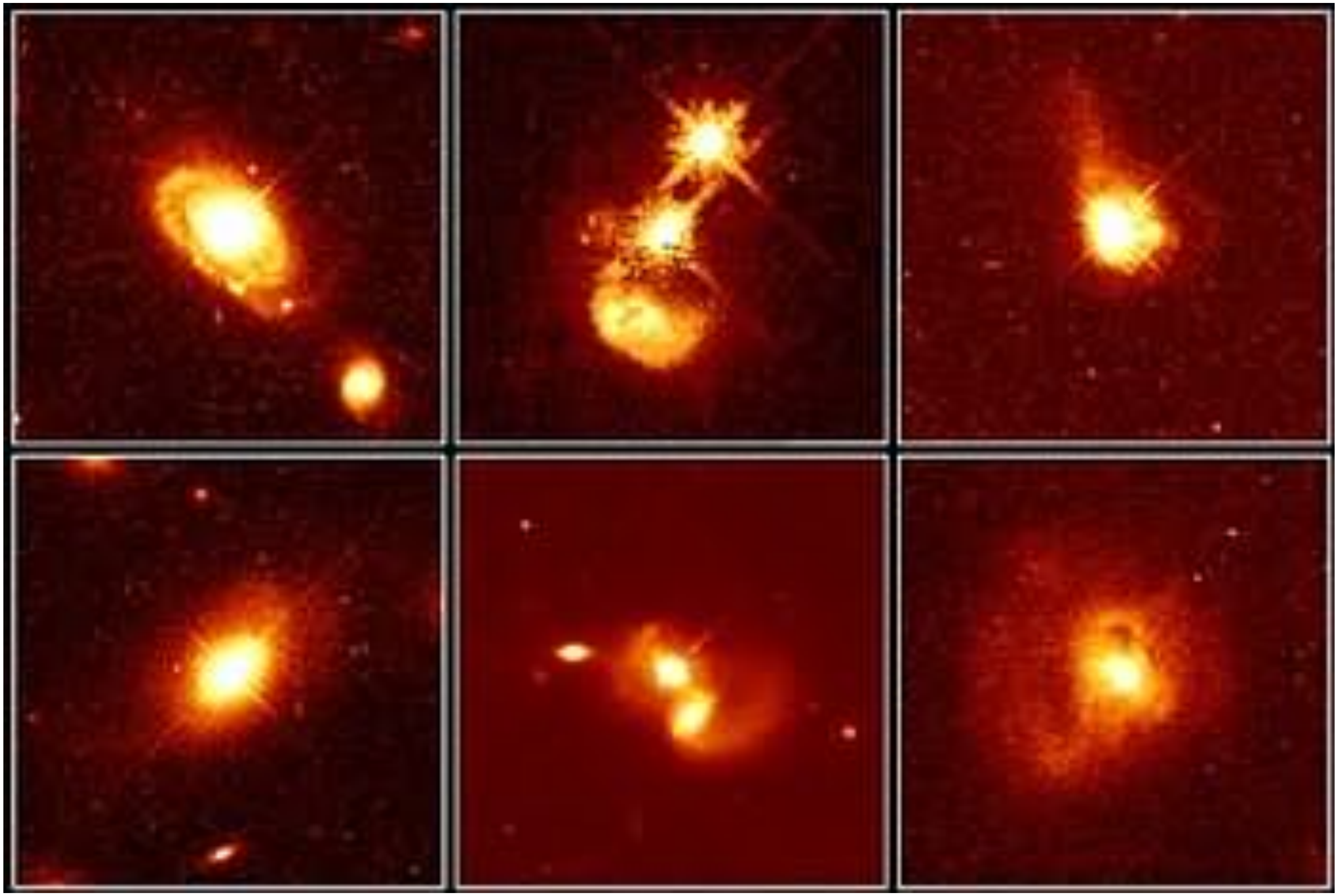
http://www.2dfquasar.org/

2QZ Quasar Survey

Redshift-sorted spectra. Strong emission lines (bright ridges) shift to the red as the redshift increases



What Makes Quasars "Quase" ?



HST Images of QSO hosts, indicative of interacting systems

Synchrotron Emission

Electron moving perpendicular to a magnetic field feels a Lorentz force.

Acceleration of the electron ➡ Radiation (Larmor's formula)

Define the Lorentz factor: $$\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}}$$

For non-relativistic electrons: $\gamma \sim 1$ ➞ **cyclotron radiation**

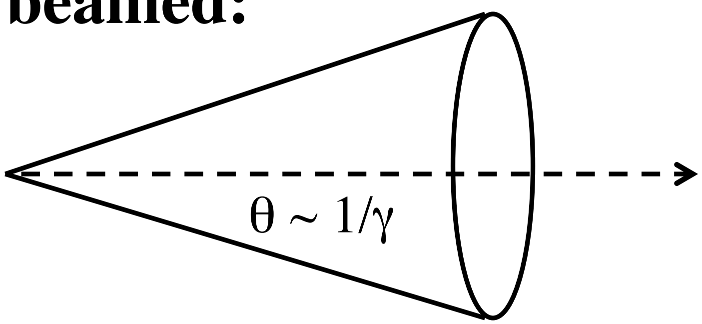
For relativistic electrons: $\gamma >> 1$ ➞ **synchrotron radiation**

Same physical origin but very different spectra …

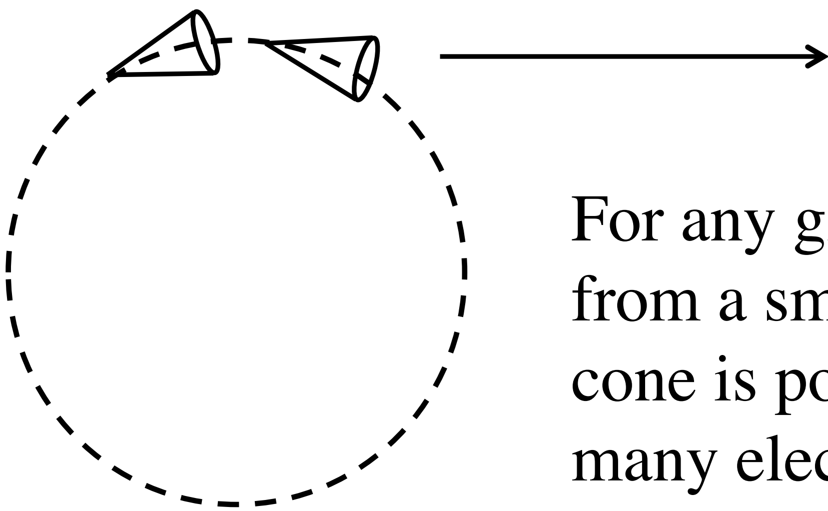
Syncrotron radiation is responsible for all of the observed radio and high energy emission from AGN (and GRBs)

Synchrotron Radiation

If the electrons are moving at close to the speed of light, radiation is **beamed:**



Particle moving with Lorentz factor γ toward observer emits radiation into cone of opening angle $\theta \approx \gamma^{-1}$



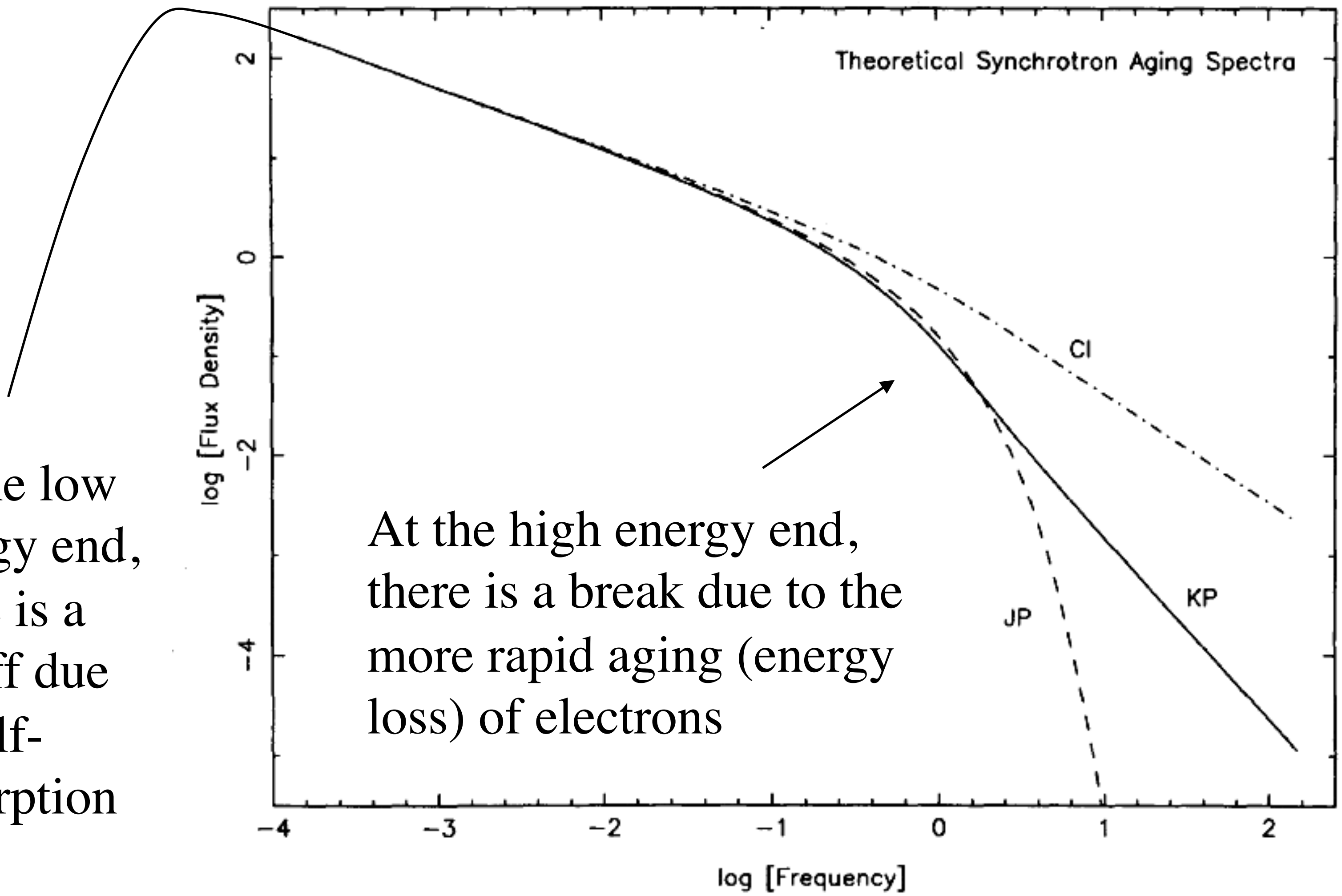
To observer

For any given electron, we only see radiation from a small portion of the orbit when the cone is pointed toward us - but there are many electrons…

The net emergent spectrum depends on the distribution of energies

Synchrotron Radiation

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



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

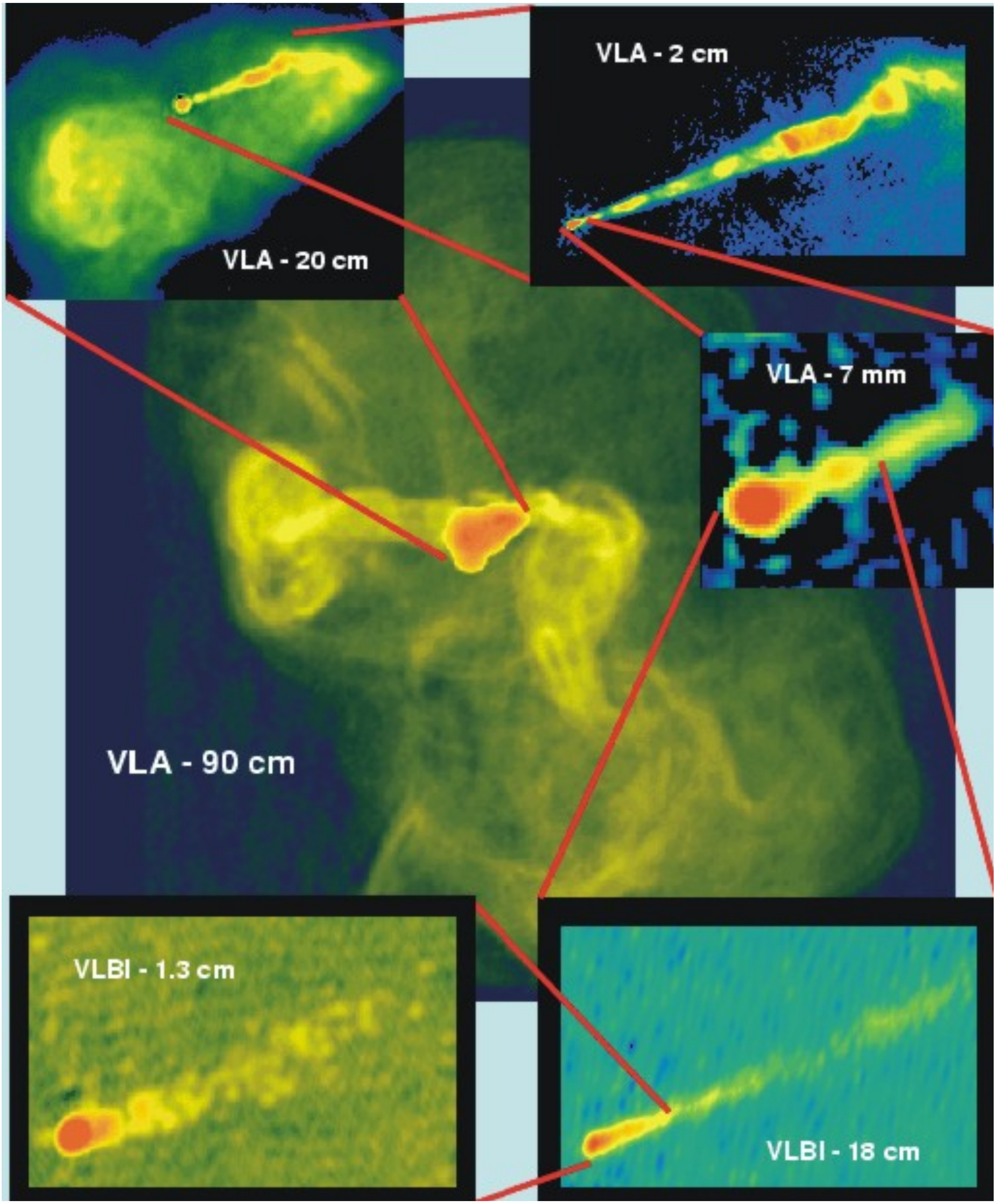
At the high energy end, there is a break due to the more rapid aging (energy loss) of electrons

Collimated Radio Emission (Jets)

An example of M87 = Virgo A

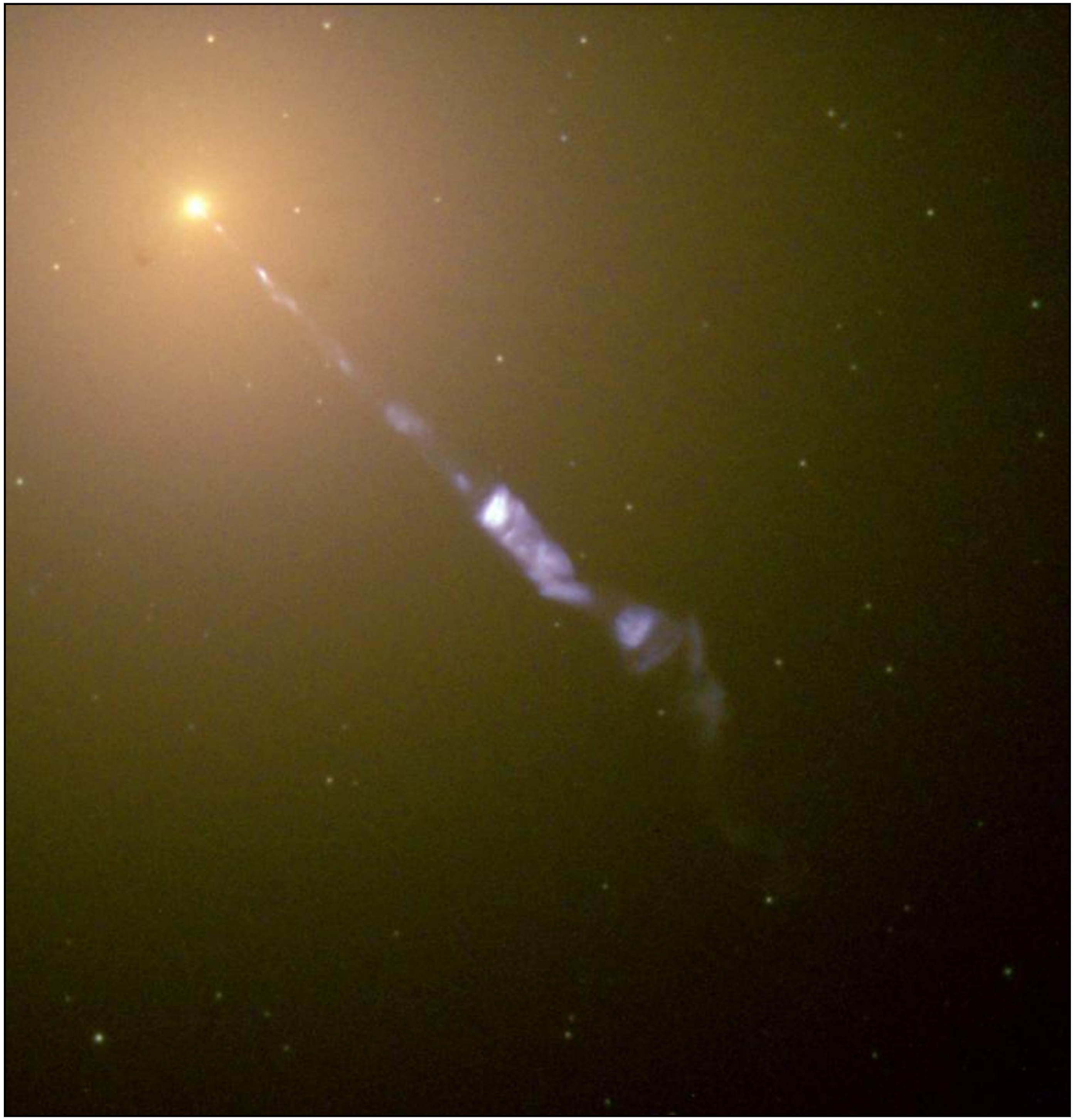
Generally present in most non-thermal radio sources

Persists over many orders of magnitude in linear scale



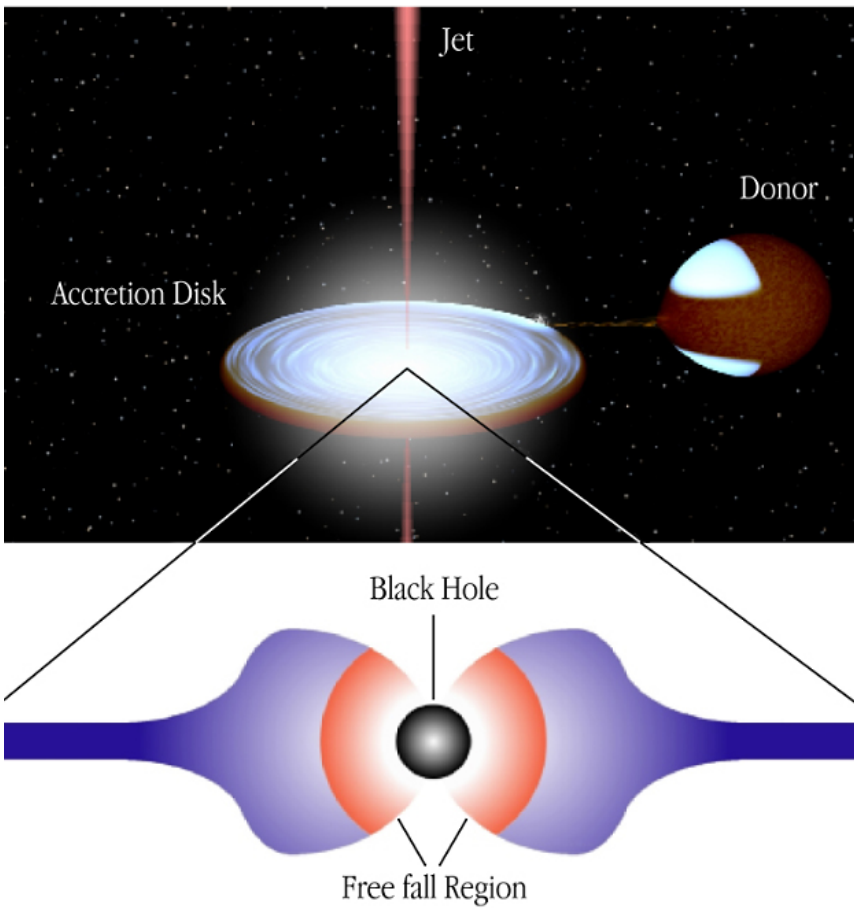
… and in some cases in the visible light as well (M87 here)

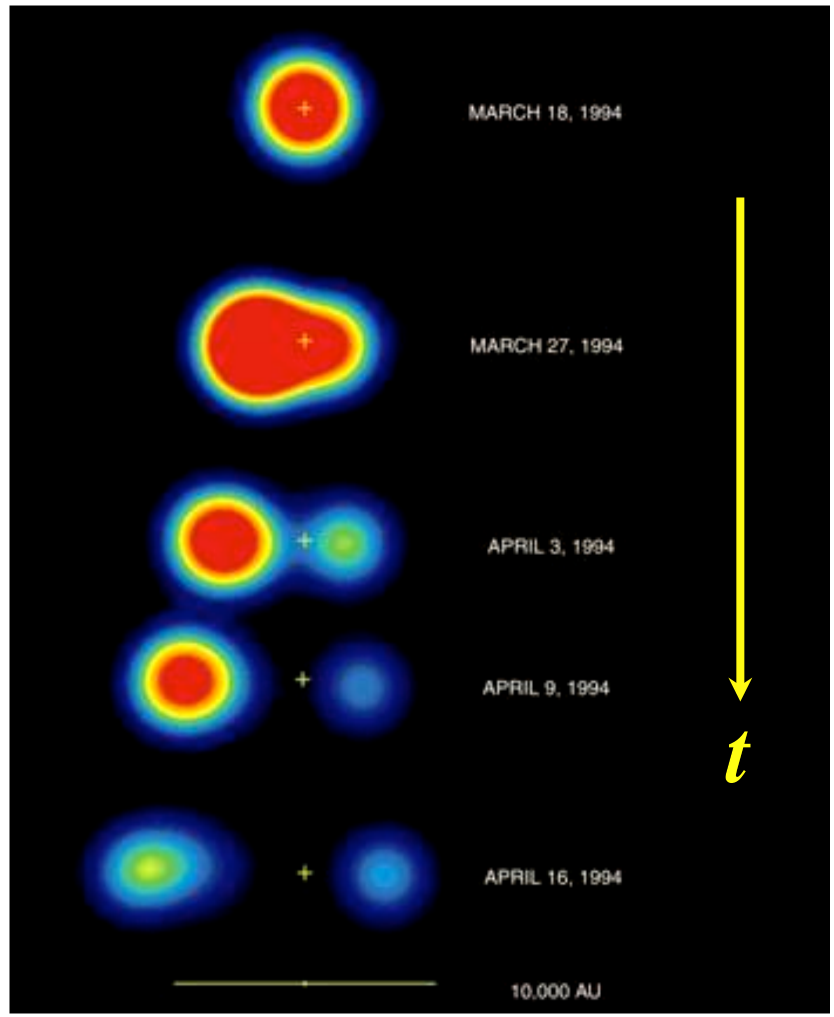
The origin of the emission is the synchrotron mechanism: accelerated particles moving in a magnetic field



Apparent Superluminal Motions

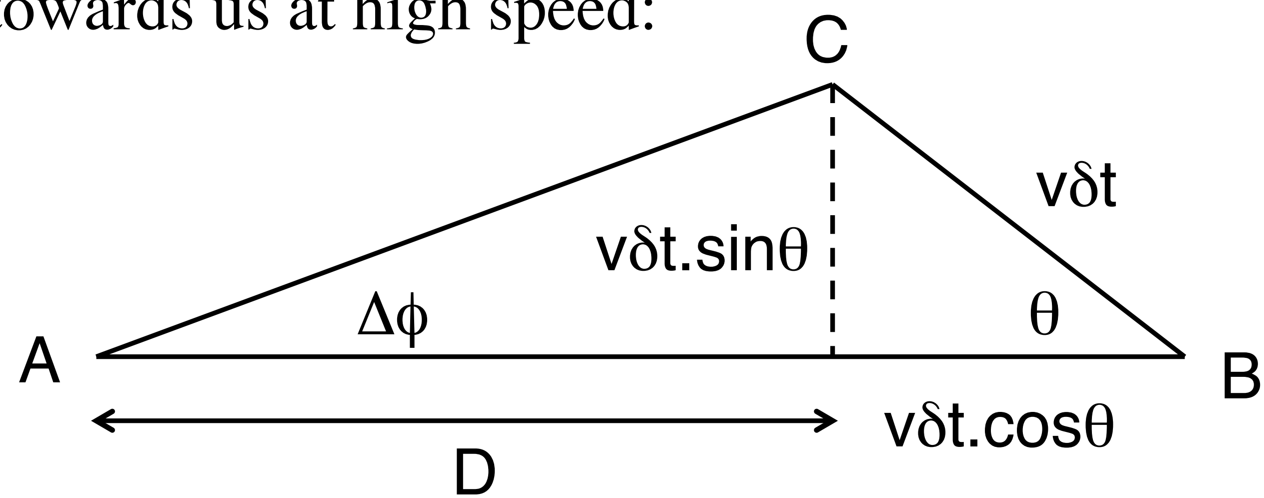
Same phenomenon can also be observed in jets from some Galactic black hole X-ray binaries (e.g. the "microquasars"), e.g., GRS 1915+105:





Explanation of Superluminal Motions

Apparent superluminal motion is *an optical illusion caused by the finite speed of light*. Consider a knot in the jet moving almost directly towards us at high speed:



Source at position B emits a blob of gas with velocity v, at an angle θ to the line of sight to an observer at position A. Some δt later, the blob has moved to position C.

Observer does not know v or θ, but measures δt and angular separation between B and C

Explanation of Superluminal Motions

If the distance D to the source is known, this gives the projected angular separation:

$$\Delta\phi = \frac{v\delta t \sin\theta}{D}$$

Let blob be emitted at time $t = 0$. Observer sees blob being emitted at time t_1:

$$t_1 = \frac{D + v\delta t\cos\theta}{c}$$

… and sees blob reach position C at time t_2:

$$t_2 = \delta t + \frac{D}{c}$$

Time difference is:

$$\Delta t = t_2 - t_1 = \delta t + \frac{D}{c} - \frac{D + v\delta t\cos\theta}{c}$$

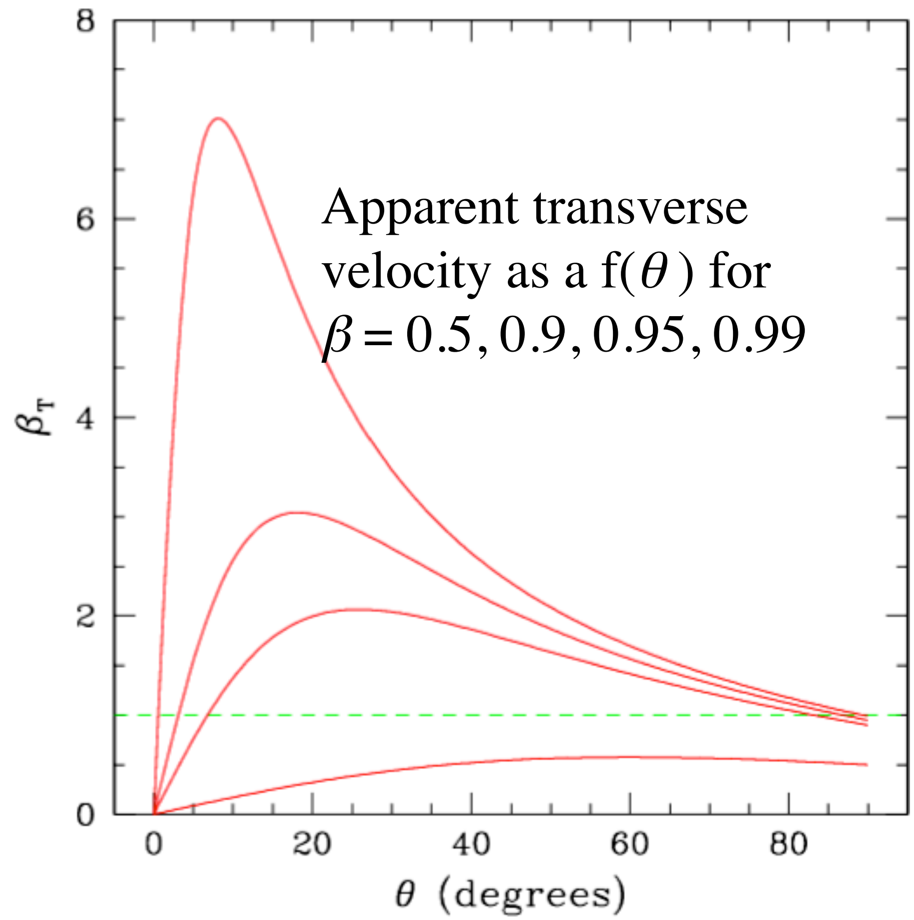
$$= \delta t(1 - \beta\cos\theta)$$

…where $\beta = v / c$

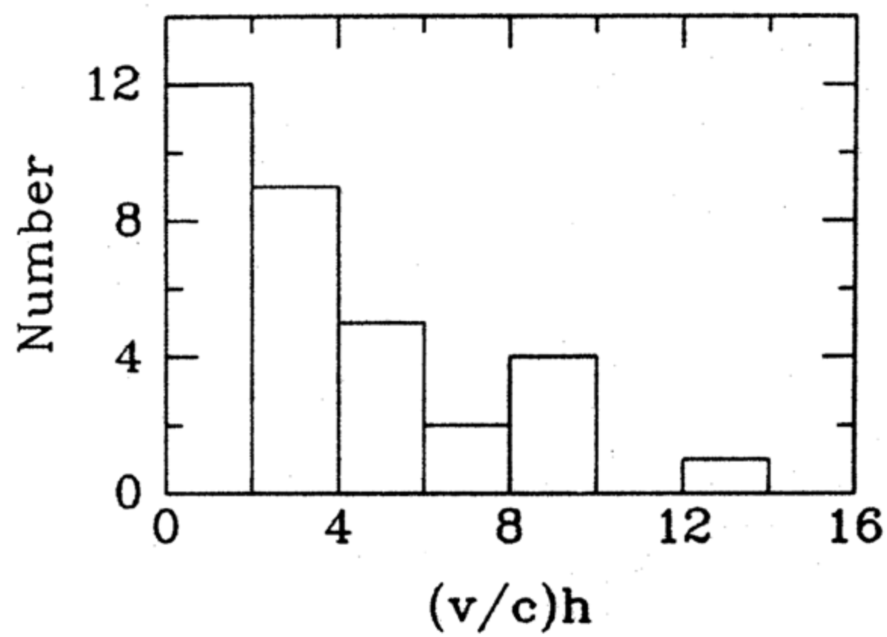
Observer infers a transverse velocity:

$$\beta_T \equiv \frac{v_T}{c} = \frac{1}{c} \times \frac{D\Delta\phi}{\Delta t} = \frac{v\sin\theta}{c(1-\beta\cos\theta)} = \frac{\beta\sin\theta}{1-\beta\cos\theta}$$

For $\beta \sim 1$, and θ small, one can clearly get an apparent transverse velocity $v_T > c$, i.e., $\beta_{\mathrm{T}} > 1$. For $\beta = 0.99$, $\theta = 10°$ gives $\beta_{\mathrm{T}} = 6.9$

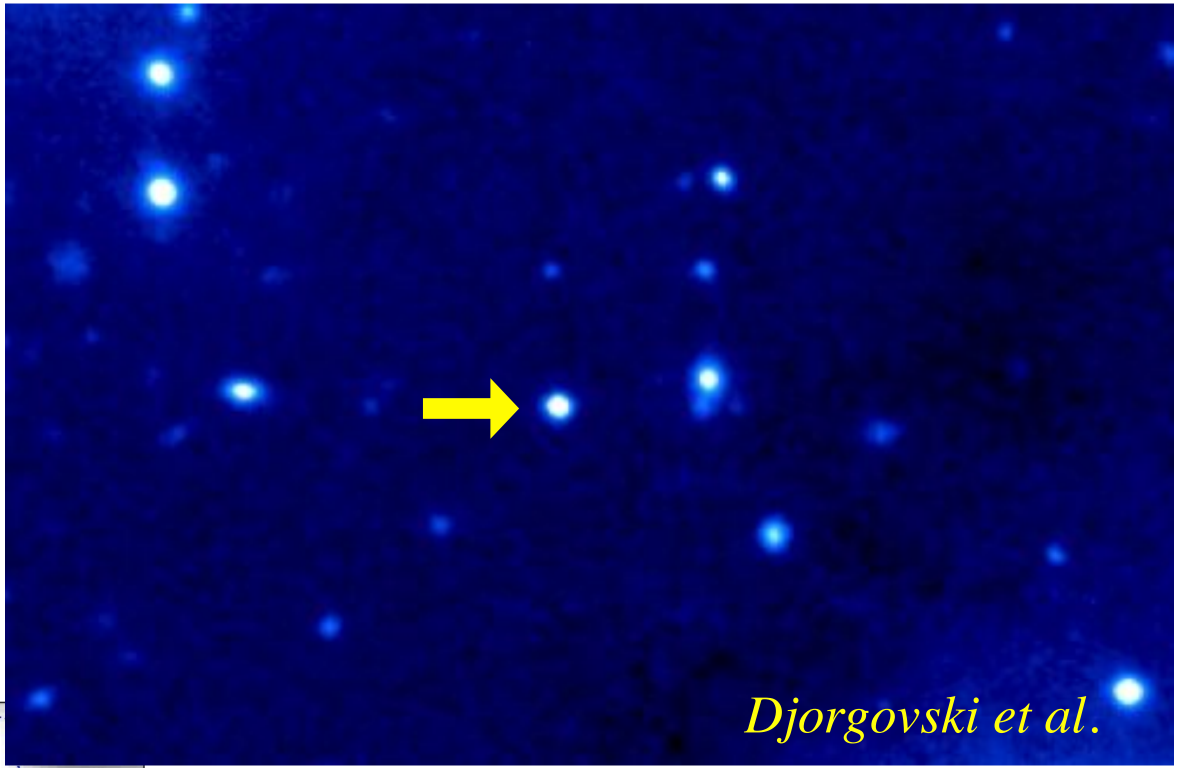


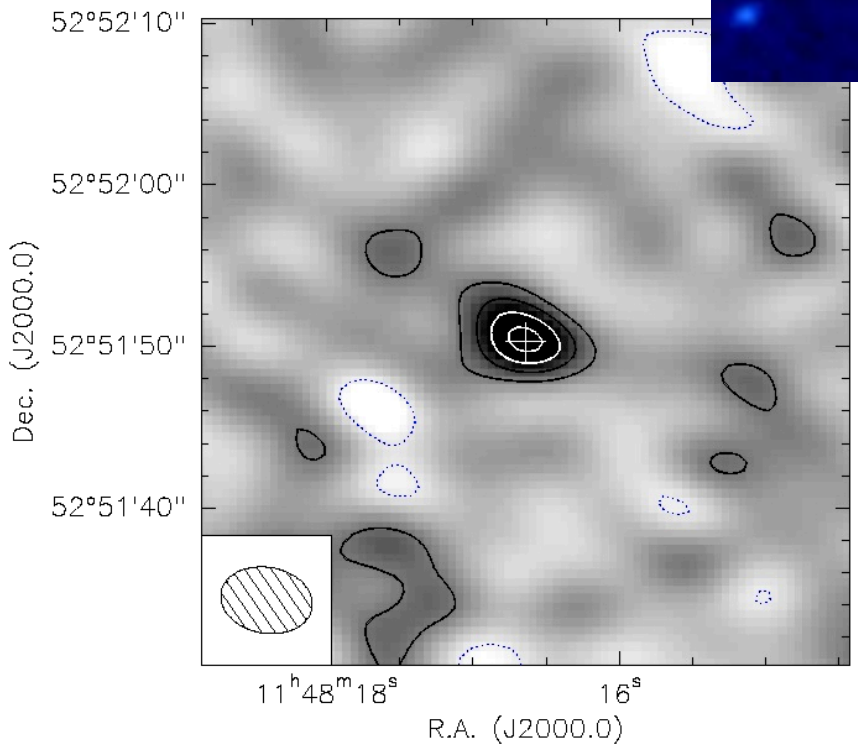
Historgram of observed *v*/*c* in 33 jets:



If real $v > 0.9\,c$, apparent superluminal motion will be seen in majority of sources (assuming random orientations) second

The most distant quasar currently known:
SDSS 1148+5251
$z = 6.41$
(Fan et al. 2003)





⬅ CO Detection! *(Bertoldi et al. 2003)*

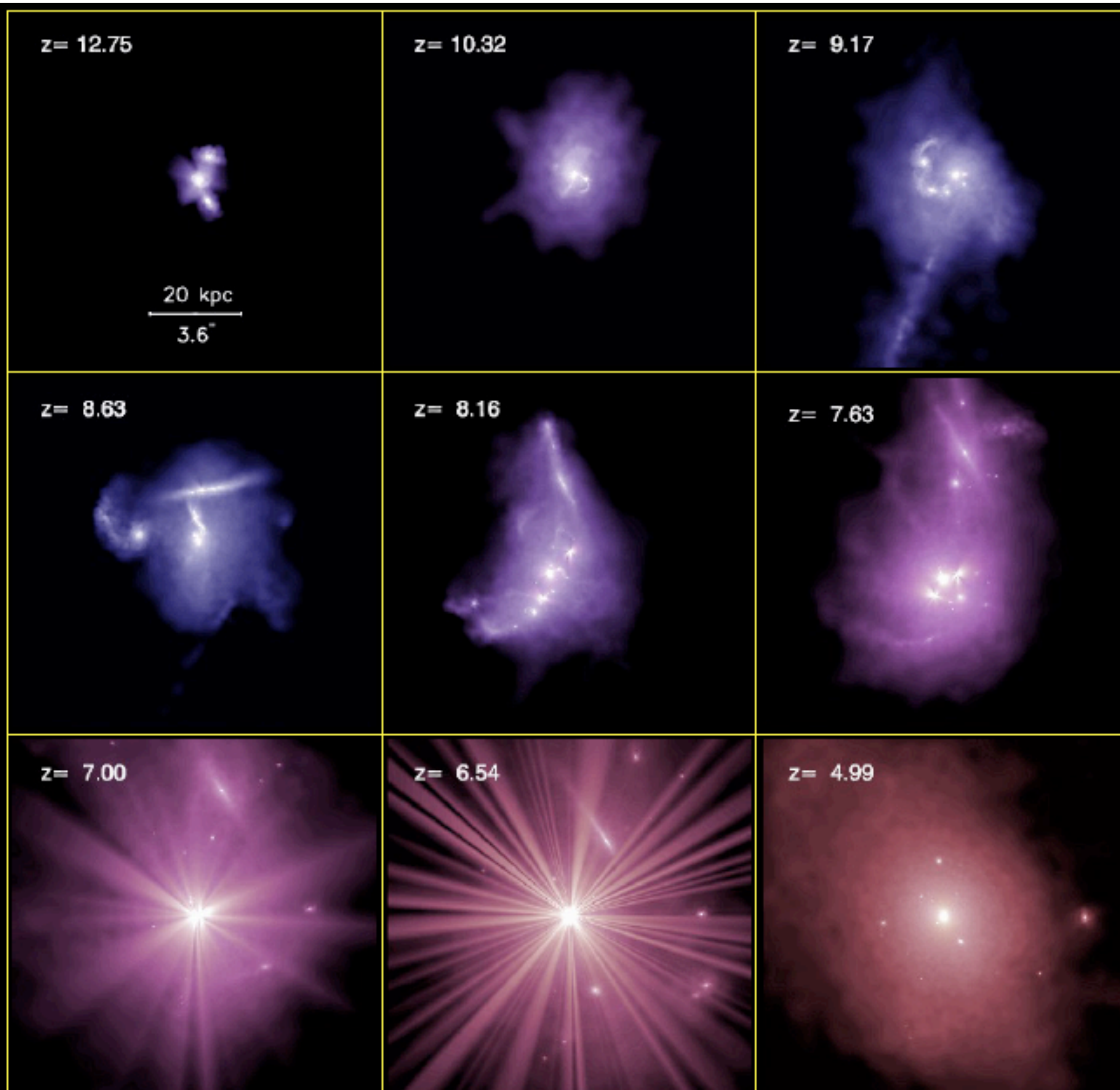
➡ Substantial chemical evolution already at this epoch

Also: $M_{BH} \sim 3 \times 10^9\ M_\odot$!
(Willott et al. 2003)

Hydro-simulation of the hierarchical build-up of an early Sloan quasar

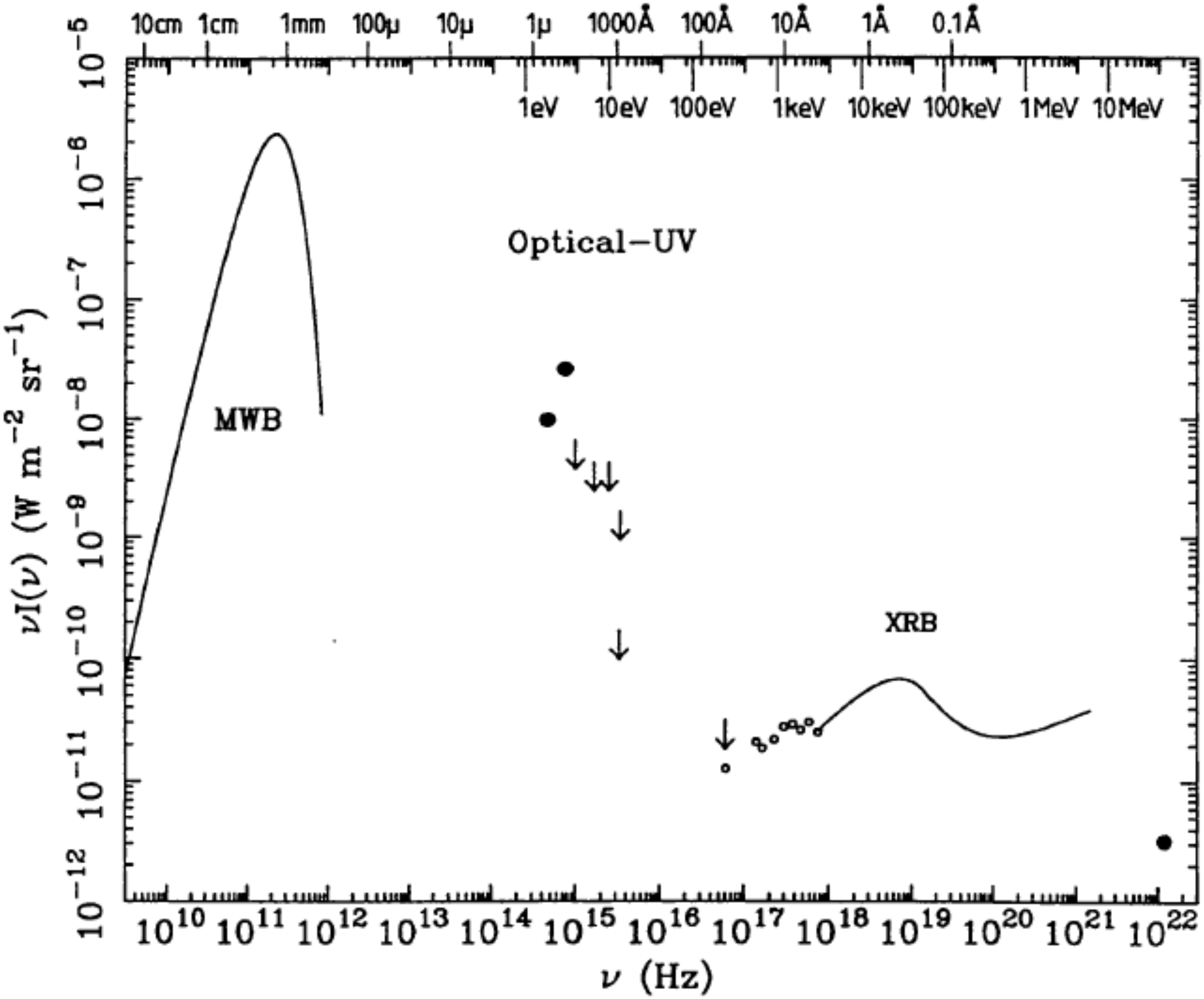
TIME EVOLUTION OF THE PROJECTED STELLAR MASS

(slide from V. Springel)

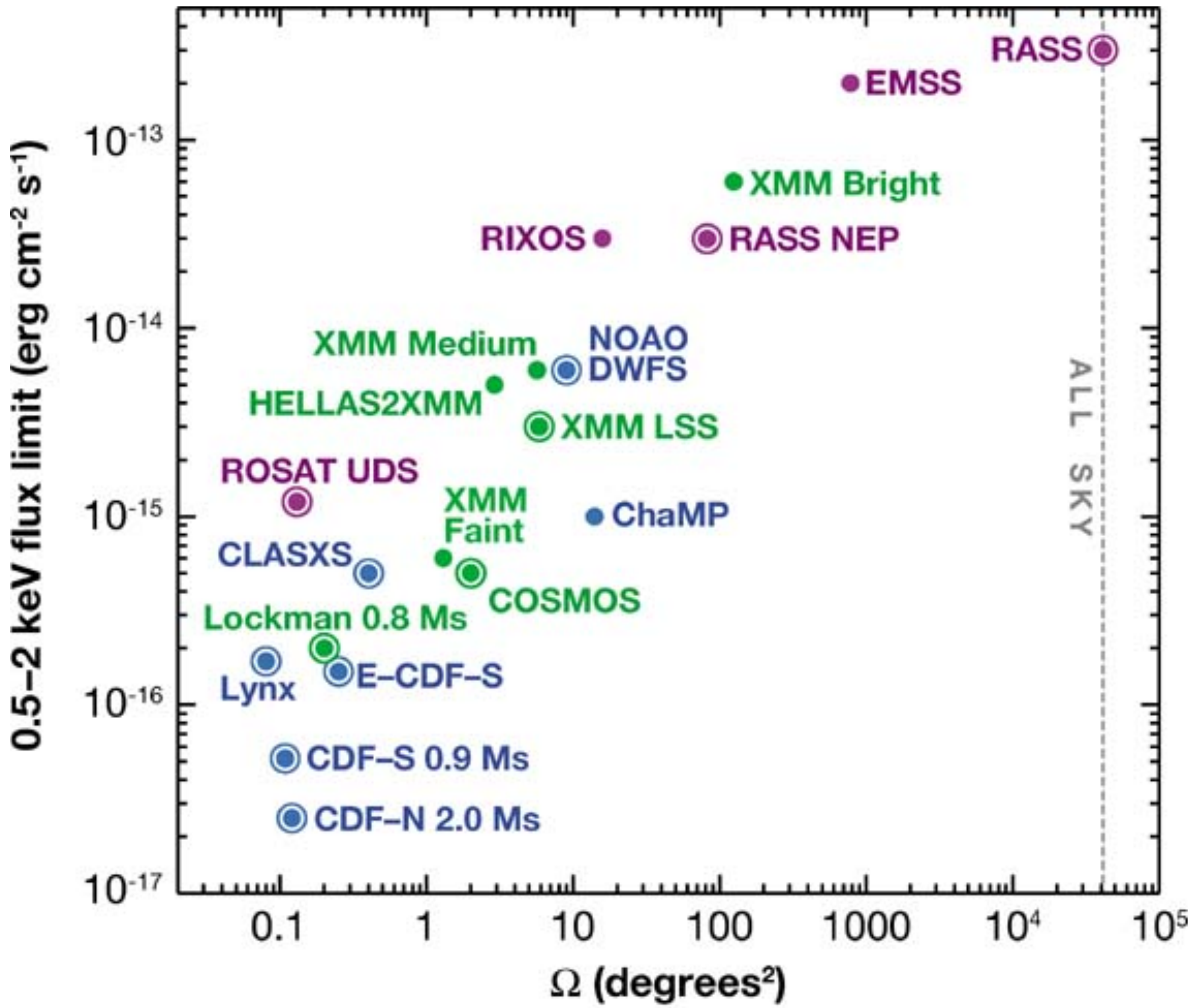


Li et al. (2006)

The Cosmic X-Ray Background (CXRB)

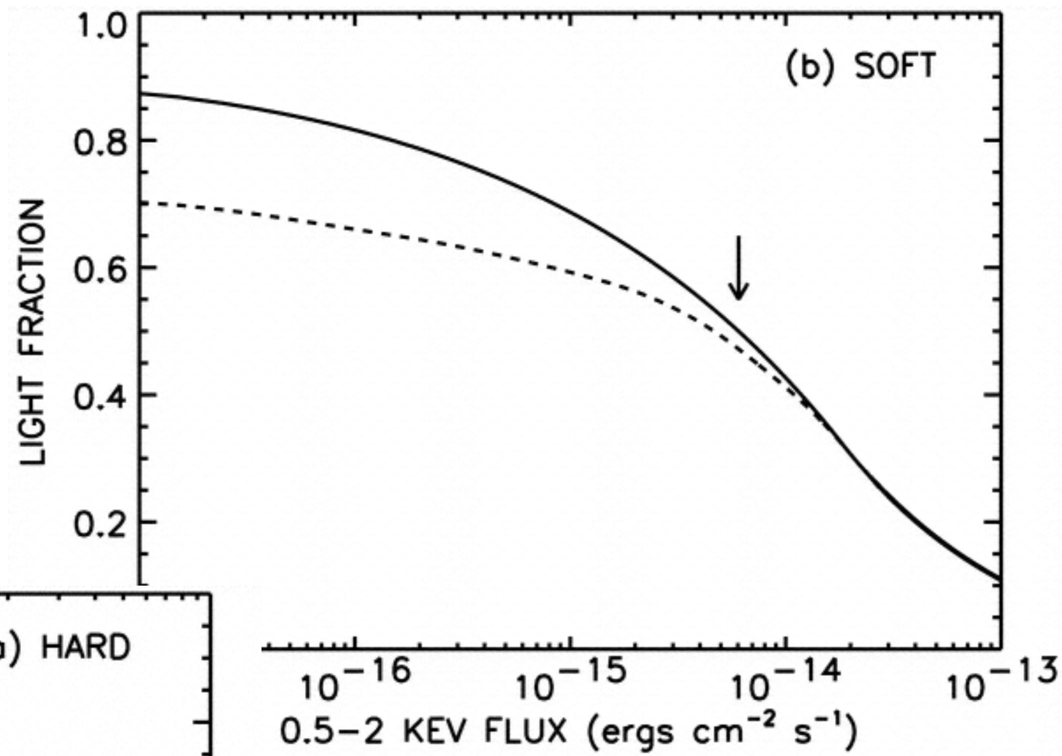


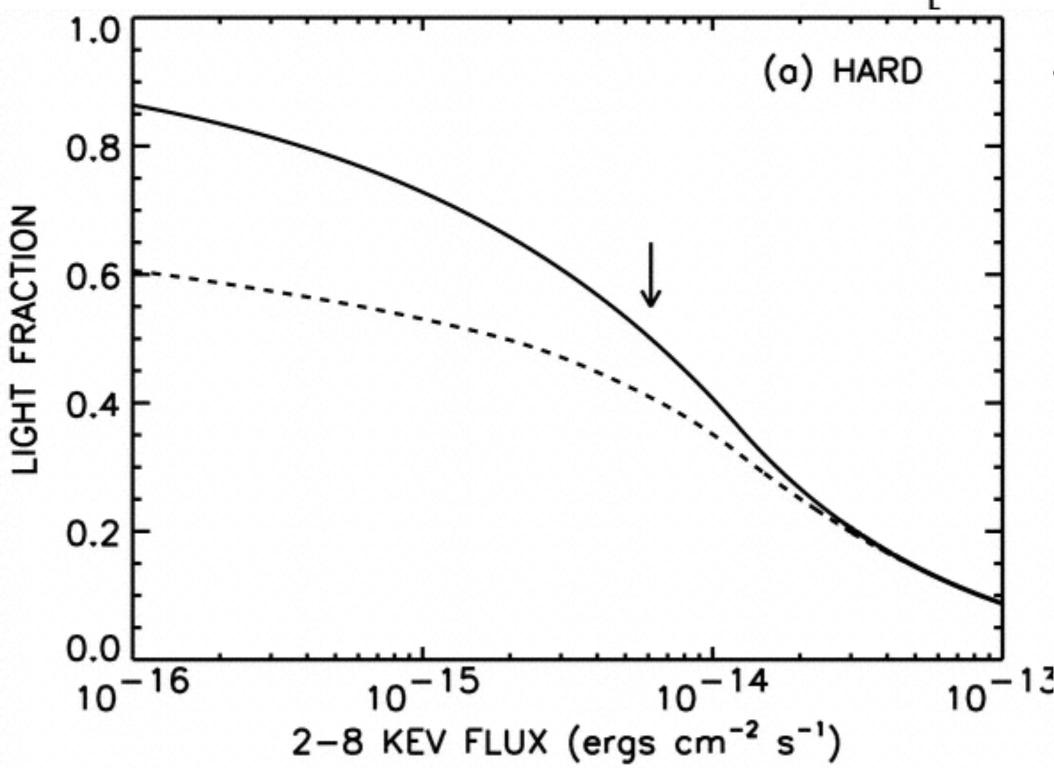
Deep X-Ray Surveys



Brandt, WN and Hasinger, G. 2005
Annu. Rev. Astron. Astrophys. 43: 827–59

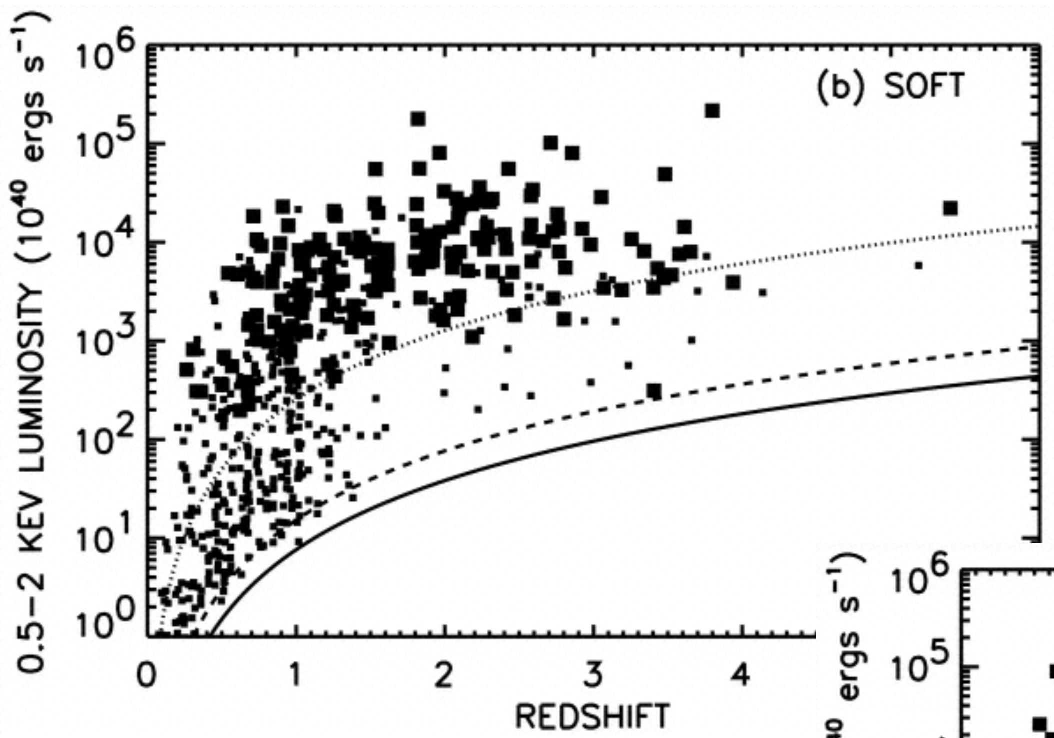
Resolving the CXRB





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

Redshift Distributions of X-Ray Sources



Lines indicate the survey flux limits

Luminosities reach
$L_X \sim 10^{45}$ erg/s
$\sim 10^{12}\ L_\odot$