Galaxies, Cosmology and Dark Matter

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Chapter 9

Active Galactic Nuclei

Typical signs of nuclear activity are:

- compact, very bright centers, $R_{nucl} \simeq 3pc$
- spectra with strong emission lines
- ultraviolet-excess
- jets and double radio sources with $R_{jet} \sim kpc - Mpc$
- variability over the whole spectrum on short timescales: $t_{var} \sim minutes \ldots days$
- AGN luminosities:

$$L_{nuc} = 10^{45} - 10^{48} \frac{erg}{s} \simeq 10^{12} - 10^{15} L_{\odot}$$

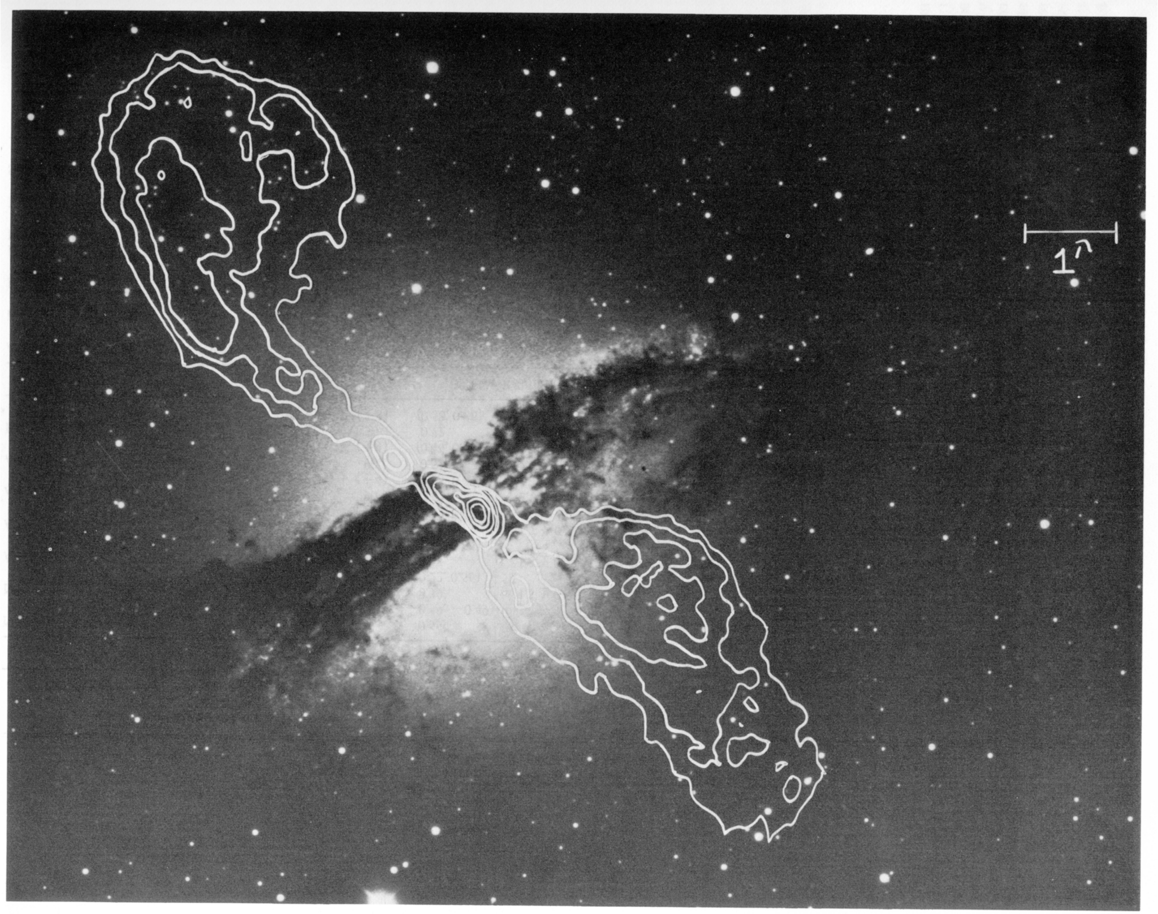
9.1 AGN Types

9.1.1 Radio Galaxies

Radio galaxies emit extremely high radio luminosities: $L_{\text{radio}} \geq 10^8 L_\odot$
E.g., Cygnus A is the second brightest radio source on the northern sky, with a luminosity $L_{\text{radio}} \sim 10^{11} L_\odot$ Cygnus A is a typical radio galaxy and was discovered in 1946 by Hey. 1954 Baade and Minkowsky identified it optically with a giant elliptical galaxy, showing dark dust lanes and a central emission of H_α lines. The radio emission comes from two extended emission regions (radio lobes) outside of the galaxy. The radio lobes receive their energy from jets which originate in the nucleus and extend $0.2Mpc$. The radio radiation is produced by synchrotron emission of relativistic electrons. $\Rightarrow$ **Radio galaxies are giant particle accelerators with $E_e \simeq 10^{12}$ eV**

Radio surveys found radio ‘galaxies’ up to redshifts of $z = 4 - 5$. About 50% of these are (relatively nearby) E0/S0 galaxies, and 50% are quasars. The jets typically extend between 0.1 and 0.5 Mpc. Jets may appear one-sided because of ‘Doppler-boosting’.

The Radio Galaxy Centaurus A:



see: (1983) *ApJ*, **273**, 128

9.1.2 Quasars

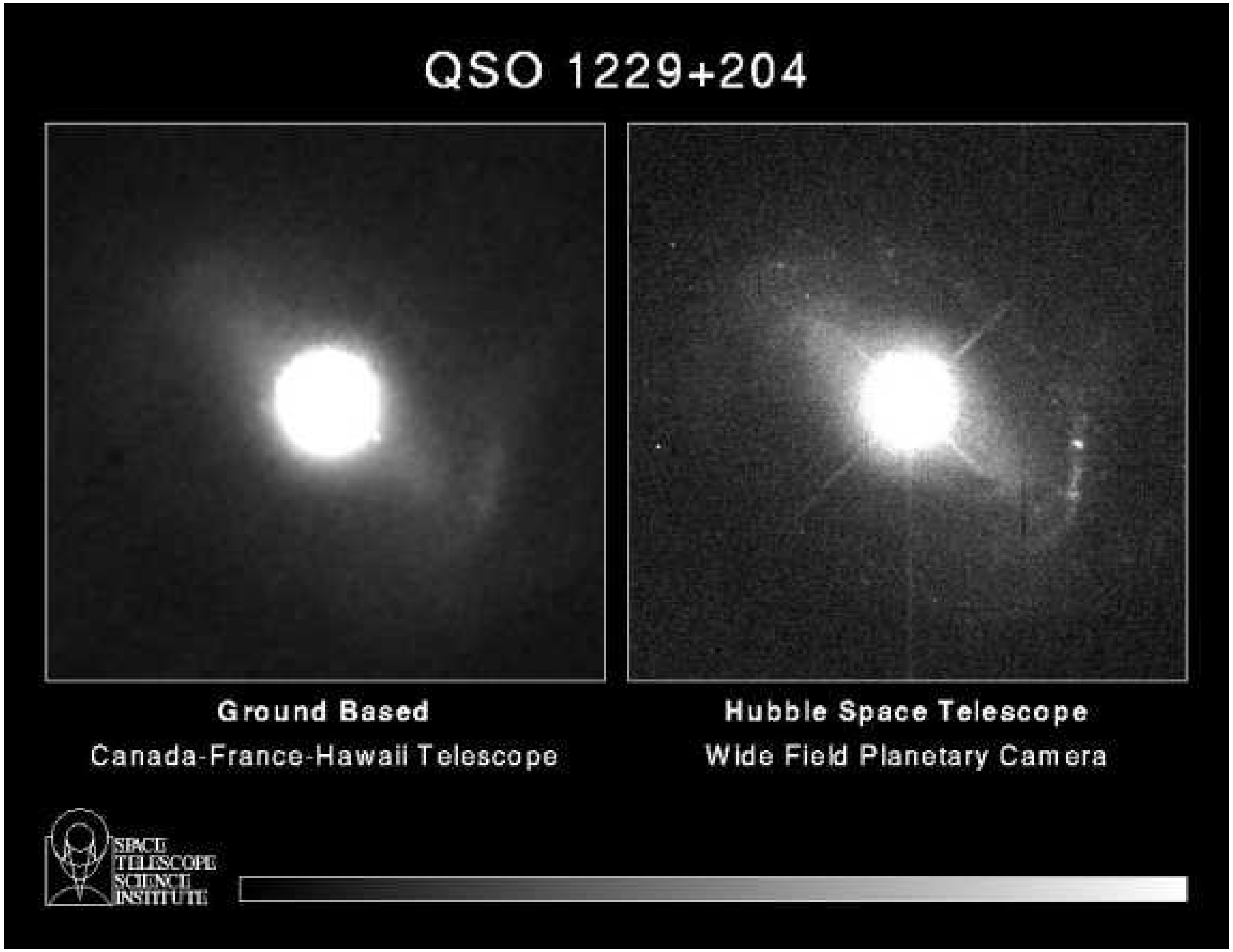
1963 M. Schmidt discovered that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta\ldots}$, MgII, OIII …which are redshifted by $z = 0.158 \Rightarrow v_{rad} = 47400\frac{km}{s}$. So, the object was called a **QUAsi StellAr Radio source** → QUASAR.

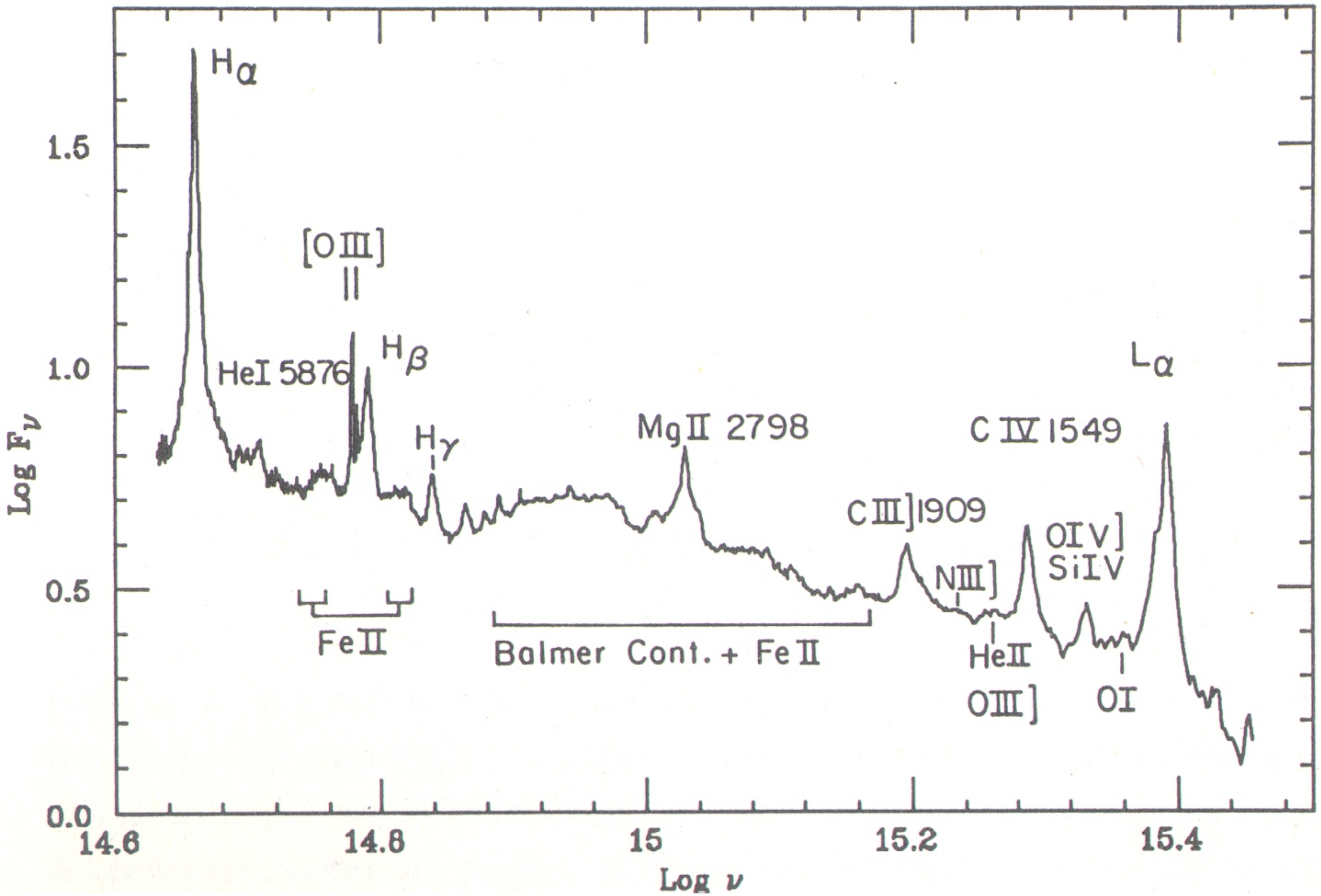
In 1965 A. Sandage discovered many more objects which show the typical qualities (colours, spectra, redshift, luminosity) of 3C273 but are missing the radio emissions, these are called ⇒ **Quasi Stellar Objects** → QSO.

Today it is established that Quasars and QSO’s are similar phenomena, but 90% of the optically found QSOs are **radio quiet** and 10% are **radio loud**.

Quasars are particularly bright and compact centers of galaxies which outshine the rest of the galaxy. Quasars are mostly found in elliptical galaxies.

The Quasar QSO 1229+204:




Hα
[OIII]
HeI 5876
Hβ
Hγ
MgII 2798
CIV 1549
Lα
CIII]1909
OIV]
SiIV
NIII]
HeII
OIII]
OI
FeII
Balmer Cont. + FeII
1.5
1.0
0.5
0.0
Log F_ν
14.6
14.8
15
15.2
15.4
Log ν

Quasar Statistics:

- luminosities: $L_{\text{quasar}} \simeq 10^{45-48} \frac{erg}{s}$
- variability in the complete electromagnetic spectrum
- synchrotron jets extending between 0.1pc and 1Mpc.
- about 10^4 quasars are known, of these 10% are radio loud but many surveys continue to discover quasars (e.g. SLOAN Digital Sky Survey)
- redshifts: $z = 0.1...5.8$, maximum space density around $z = 2...3$ (today we have roughly: 10^{-5} Quasars/galaxy, and at $z = 2$: 10^{-2} Quasars/galaxy). If quasars live long, then only one out of 100 galaxies forms a quasar (⇒ 1% of all galaxies contains a black hole). If quasars are short-lived: $\Delta t_{QSO} \simeq 10^7 yrs$, then all luminous galaxies were once active and all contain a black hole.

9.1.3 BL Lac Objects

BL Lac Objects are quasars with enhanced continuum emission and (almost) no emission lines. They are:

- highly variable
- extremely luminous
- highly polarized

⇒ Presumably the jet is pointing to us and we directly look into the central machine.

9.1.4 Seyfert Galaxies

First discovered in 1943 by Seyfert and Slipher, these are **spiral galaxies** showing:

- very bright unresolved nuclei, with luminosities $L \simeq 10^{42-45} \frac{erg}{s}$ (less luminous than Quasars)
- line emission of highly ionized atoms which **cannot** be produced by stars
- sometimes very broad lines of the permitted hydrogen lines (Seyfert 1, otherwise Seyfert 2).
- a wide range of variability in the broad lines and the continuum (even including their disappearance) in a time range from hours to days. This implies that the **Broad-Line-Region** (BLR) has a size of $\frac{1}{100}pc \leq R_{\text{BLR}} \leq 1pc$

9.2 Structure of the Active Galactic Nuclei

9.2.1 Sizes

The variability of AGN can be used to gather information about the size of the emission region. Assuming, that the state of the emission region is changed by a physical process, two timescales are important:

$\tau_{process}$: time scales for synchrotron radiation, heating, cooling, acceleration ...

Δt: crossing time needed to cross the emission region

$$\boxed{\Delta t \gg \tau_{process}}$$

If a state change spreads with c, then the size of the emission region will be:

$$l_{emis} = c \cdot \Delta t$$

For the observed timescale of the variability Δt_{obs} applies:

$$\Delta t_{obs} = \tau_{process} + \Delta t$$

In any case applies:

$$\boxed{c \cdot \Delta t_{obs} \propto l_{emis}}$$

Characteristic time and length scales

radio/optical	$\Delta t_{obs} \simeq 10d$	$\Rightarrow$	$l_{emis} \simeq 0.01pc$
radio/optical	$\Delta t_{obs} \simeq 1d$	$\Rightarrow$	$l_{emis} \simeq 10^{-3}pc$
TeV	$\Delta t_{obs} \simeq 1h$	$\Rightarrow$	$l_{emis} \simeq 10^{-5}pc$

In comparison: Schwarzschild radius $R_S = \frac{2GM_{BH}}{c^2}$

$\frac{M}{M_\odot}$	R_S
10^6	$10^{-7}pc$
10^8	$10^{-5}pc$
10^9	$30^{-4}pc$

$\Rightarrow$ variability in the vicinity of super massive black holes?

9.2.2 Luminosity source

Stars

Assuming O stars with a luminosity $L_\star \simeq 10^{5.5} L_\odot$ and a typical mass $M_\star \simeq 50 M_\odot$, then to reproduce the luminosity of the AGN $L_{total}^{AGN} = N_\star \cdot L_\star$ a total number of $N_\star = 3 \cdot 10^8$ O stars (with a mass $M = N_\star \cdot M_\star = 10^{10} M_\odot$) would be needed.
This would result in a stellar density

$$n_\star = \frac{N_\star}{\frac{4\pi}{3}\left[\frac{l}{2}\right]^3} \geq 2 \cdot 10^{14} pc^{-3}$$

and a mean distance

$$l_\star = \left[\frac{1}{n_\star}\right]^{1/3} \leq 750 R_\odot \simeq 25 \cdot (2R_\star)$$

- Such a high stellar density would lead to dynamical instabilities.
- Observations of AGNs do not show stellar spectra.

$\Rightarrow$ This scenario is impossible. (It even gets worse with smaller stars)

Supernovae

The brightest supernovae reach in the maximum $10^{10}L_\odot$. So 10^4 supernovae in the maximum would be permanently needed, or, because of $E_{SN} \simeq 10^{52}erg$ up to 10^{10} supernovae within $l \leq 10^{-3}pc$ in 10^7 years.

- This would need the formation of 10^{10} stars that are permanently producing supernovae, resulting in the same problems as the last scenario
- A successive formation of stars while the supernovae explode is impossible
- No supernova spectra were observed

The standard model of AGNs: Accretion onto massive black holes

The AGN contains a **black hole** with a mass $M \simeq 10^6 \ldots 10^{9.5} M_\odot$ that accretes $10^{-4} \ldots 10 \frac{M_\odot}{yr}$ gas from surrounding disk. The **jets** and the **nonthermal radiation** are created by the rotating magnetosphere of the **accretion disk**. (Transformation of gravitational energy into thermal energy and radiation)

For bringing an object of mass m from $R = \infty$ onto a circular orbit around compact object of the mass M_{BH} applies:

$$\frac{mv^2}{R} = \frac{GM_{BH}m}{R^2}$$

The energy is released by friction in the accretion disk:

$$\begin{aligned} E_{Acc} &= E_\infty - E_R \\ &= 0 - \left[\frac{1}{2}mv^2 - \frac{GM_{BH}m}{R}\right] \\ &= \frac{1}{2}\frac{GM_{BH}m}{R} = \frac{1}{2}|E_{pot}| \end{aligned}$$

Using the Schwarzschild radius $R_S = \frac{2GM_{BH}}{c^2}$:

$$\boxed{L_{Acc} = \frac{dE_{Acc}}{dt} = \alpha \frac{R}{R_S} \frac{dm}{dt} c^2; \quad \alpha \lesssim \frac{1}{4}}$$

An exact calculation (relativistic approach, matter disappears in the black hole) yields:

$$\boxed{L_{Acc} \simeq \frac{1}{16} \dot{m} c^2} \quad 1g \rightarrow 10^6 \; kWh$$

For comparison, the efficiency of hydrogen burning is:

$$\boxed{L_{H-burn} \simeq 0.007 \dot{m} c^2}$$

Accretion is an effective way to transform mass into energy!

$$L_{Acc} \simeq 4 \cdot 10^{45} \frac{erg}{s} \left[\frac{\dot{m}}{M_\odot / yr} \right]$$

The maximum possible energy emission, the **Eddington Luminosity** L_{max} is reached, when the radiation pressure generated by the accretion is higher than the gravitational acceleration per area.

Energy flux through a surface with Radius R is:

$$\frac{L}{4\pi R^2}$$

resulting in the radiation pressure:

$$\frac{L}{4\pi R^2 c}$$

With the Thomson cross-section of e^- and p:

$$\begin{aligned}\sigma_{Te^-} &= \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65 \cdot 10^{-25} cm^2 \\ \sigma_{Tp} &= \left(\frac{m_e}{m_p}\right)^2 \cdot \sigma_{Te^-}\end{aligned}$$

it follows that the radiation pressure works only on the e^- (but the protons get also accelerated because of electromagnetic coupling). Accretion stops, when:

$$\frac{L}{4\pi R^2 c}\sigma_{Te^-} \geq \frac{GM_{BH}}{R^2}(m_p + m_{e^-})$$

i.e., at the **Eddington Luminosity**:

$$L_{Edd} = \frac{4\pi c G M_{BH} m_p}{\sigma_{Te^-}} \quad \text{independent of R!}$$

or:

$$\boxed{L_{Edd} = 1.3 \cdot 10^{38} \frac{M_{BH}}{M_\odot} \left[\frac{erg}{s}\right]}$$

This implies

$$M_{BH} \geq 10^7 M_\odot$$

for Seyfert galaxies, and

$$M_{BH} \simeq 10^9 M_\odot$$

for quasars. Using

$$L_{Acc} \simeq \frac{1}{16}\dot{m}c^2 = L_{Edd}$$

yields the maximum accretion rate:

$$\dot{m}_{Edd} \simeq 5 \cdot 10^{-10} \frac{M_{BH}}{M_\odot} \left[\frac{M_\odot}{yrs}\right]$$

Typical temperatures of accretion disks

can be derived by assuming that the energy $L_{Edd}/2$ is released through thermal emission between R_S and $2R_S$

$$\frac{L_{Edd}}{2} = \sigma_B T^4 \left(4\pi R_S^2 - \pi R_S^2\right) \simeq \sigma_B T^4 3\pi R_S^2$$

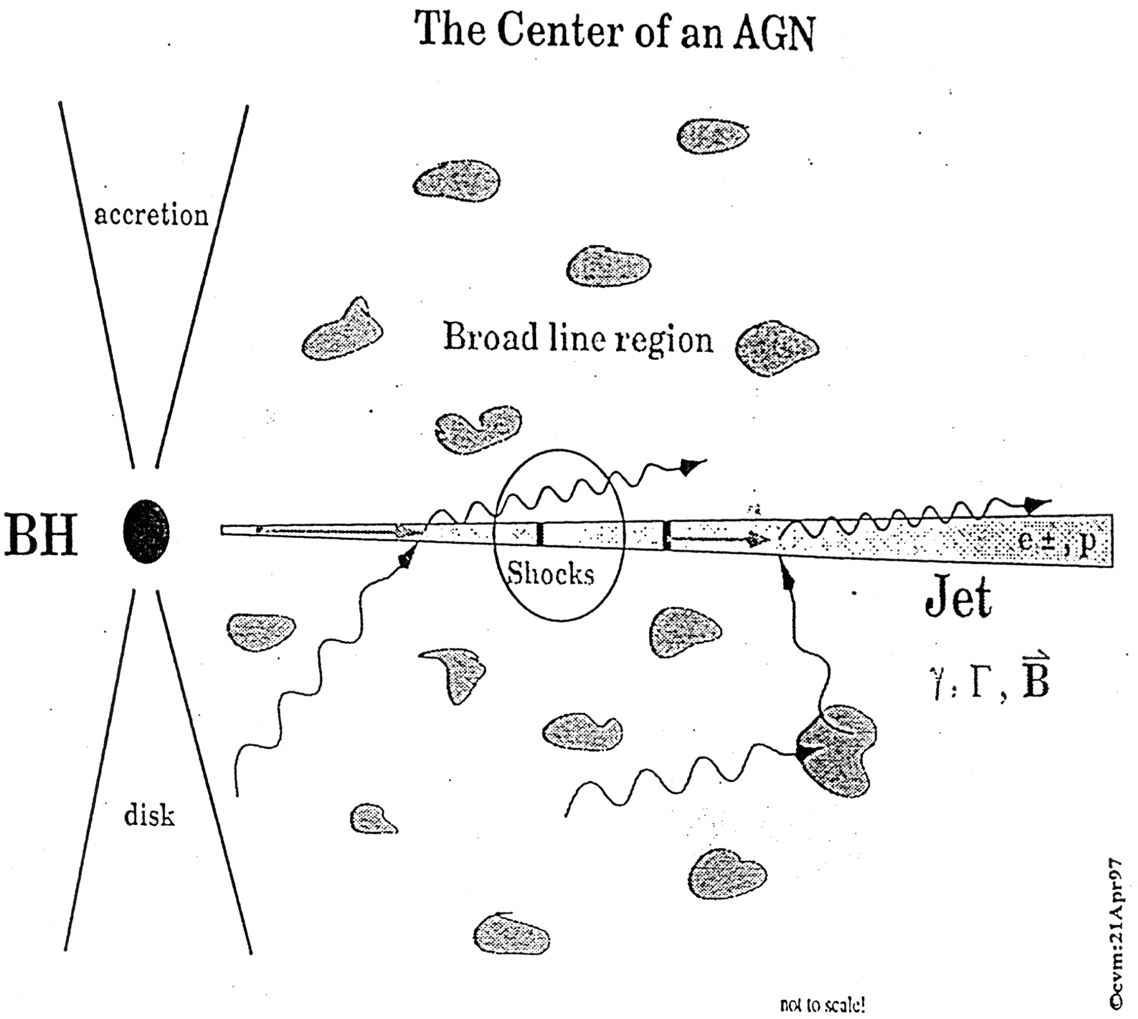
then one obtains for the temperature:

$$\Rightarrow T \simeq 3 \cdot 10^7 K \left[\frac{M_{BH}}{M_\odot}\right]^{-1/4}$$

i.e. for a typical quasar:

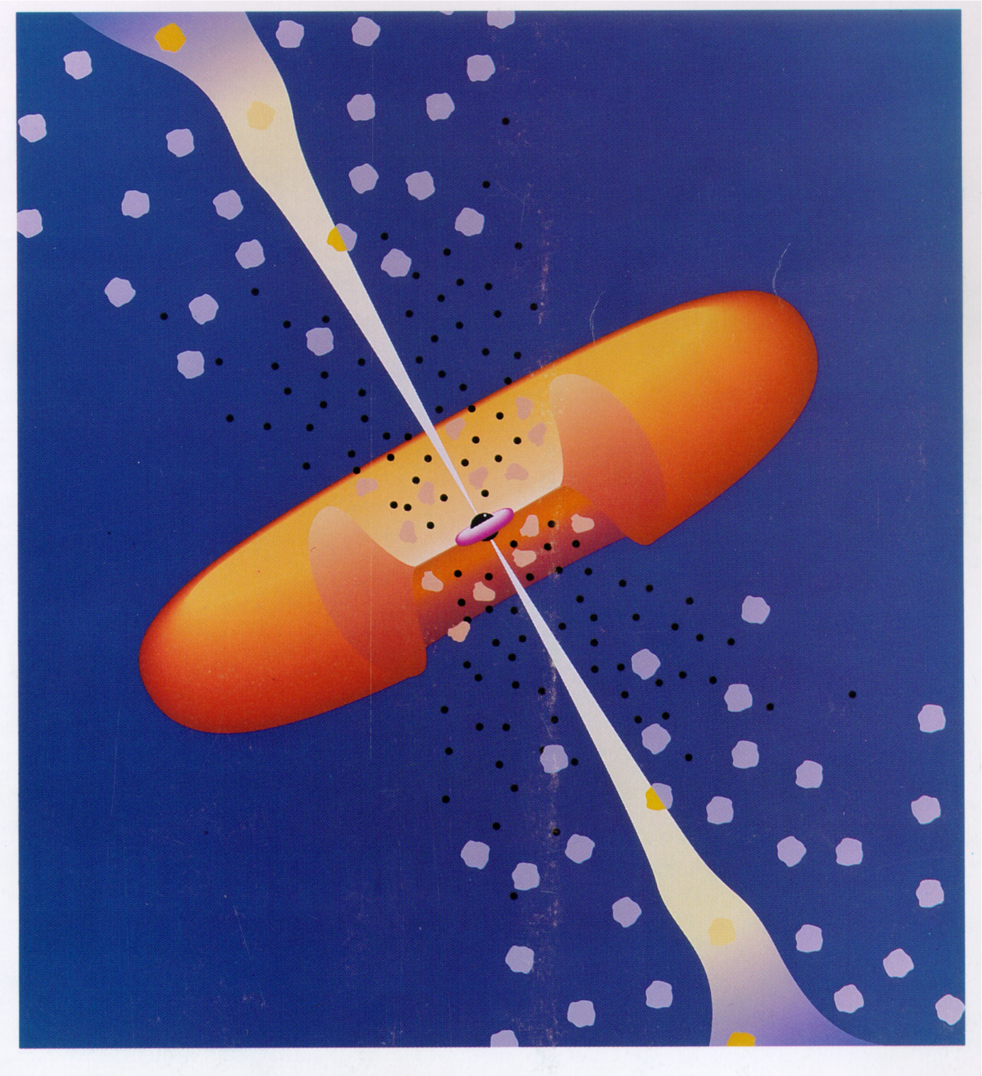
$$\Rightarrow T_{Acc}^{quasar} \simeq 10^5 K \Rightarrow \text{ Radiation in the UV}$$

$\Rightarrow$ The accretion disks of smaller black holes are hotter


The Center of an AGN
accretion
Broad line region
BH
Shocks
e±, p
Jet
γ: Γ, $\vec{B}$
disk
not to scale!
©cvm:21Apr97

9.3 The Unified Model of the Active Galactic Nuclei

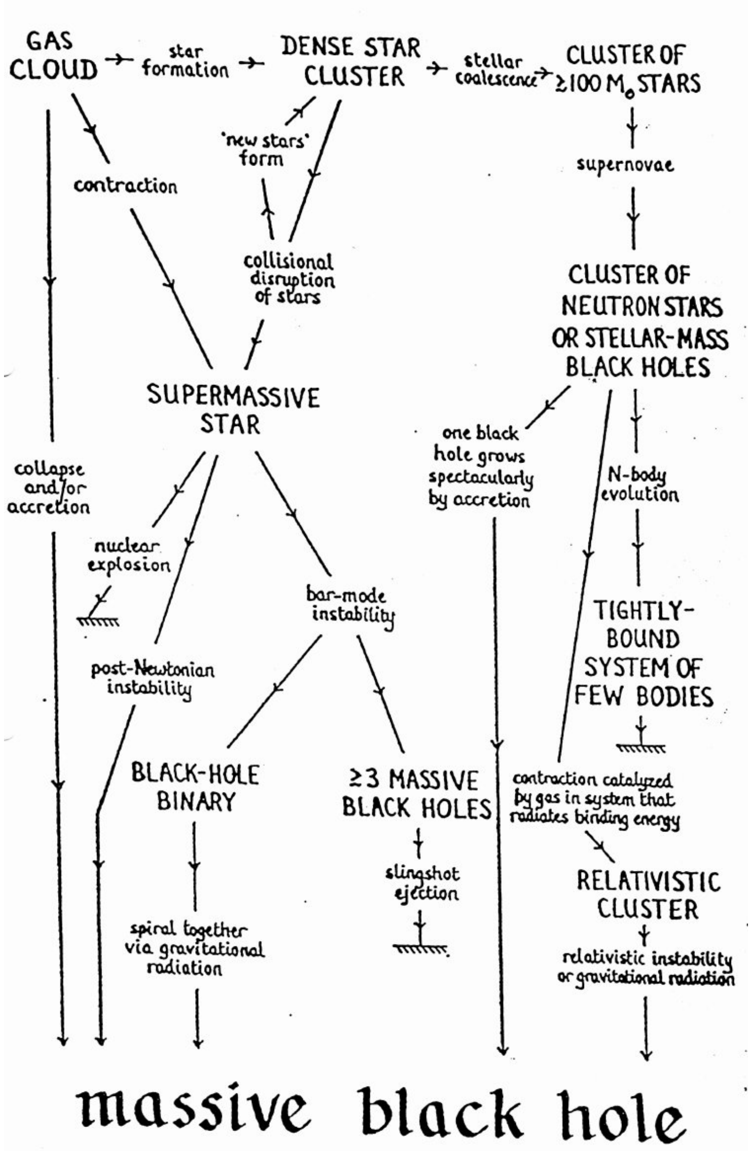
- Black Hole in the center: $M_{BH} \sim 10^6 \dots 10^{10} M_\odot$.
- Accretion disk extending to $\sim 100 - 1000 R_S$, that is emitting radiation in the X-ray, EUV, UV, . . . optical and TeV.
- Broad line region: Clouds of thick gas ($n_e \simeq 10^9 - 10^{10} cm^{-3}$) that are moving with $v_{BLR} \lesssim 10^4 \frac{km}{s}$ around the black hole and extend to $\sim 0.1 \dots 1pc$. Emission of broad allowed lines.
- Narrow line region: Clouds of thin gas ($n_e \lesssim 10^5 cm^{-3}$) that are moving with $v_{NLR} \simeq 10^2 - 10^3 \frac{km}{s}$ around the black hole and extend to some pc. Emission of narrow allowed and forbidden lines.
- Dust/molecular torus with inner radius: $\sim 1pc$ and outer radius: $\sim 50 - 100pc$ produces IR - mm emission.
- Jets: Synchrotron radiation over the whole spectrum on scales from $0.1 - 10^6 pc$.



The diversity of AGN types can be explained by the aspect angle under which we observe the AGN and the evolution AGNs.

AGN type	line of sight	evolution
BL Lac	directly into the jet	$\dot{M}$ strong, jet
radio loud quasar	$\theta \simeq 20^\circ - 70^\circ$	$\dot{M}$ maximum, jet with $v_{jet} \sim c$
radio galaxy	$\theta \simeq 20^\circ - 90^\circ$	$\dot{M}$ mean, jet with $v_{jet} < c$
radio quiet quasar	$\theta \simeq 20^\circ - 70^\circ$	$\dot{M}$ maximum, no jet
Seyfert	$\theta \simeq 20^\circ - 70^\circ$	$\dot{M}$ weaker, no jet

AGN type	emission lines		host galaxies	
	broad	narrow	type	luminosity
strong radio galaxy	strong/weak	strong/weak	E	high
weak radio galaxy	weak	weak	E	high
BL Lac	none	none/weak	E	high
radio quiet quasar	strong	strong/weak		high
Seyfert	none, strong/weak	strong/weak	Sa- Sbc	



Formation paths for supermassive black holes.