I*M*P*R*S on ASTROPHYSICS at LMU Munich

Astrophysics Introductory Course

Lecture given by:

Ralf Bender and Roberto Saglia

in collaboration with:

**Chris Botzler, Andre Crusius-Wätzel,
Niv Drory, Georg Feulner, Armin Gabasch,
Ulrich Hopp, Claudia Maraston,
Michael Matthias, Jan Snigula, Daniel Thomas**

Powerpoint version with the help of Hanna Kotarba

Fall 2007

Chapter 12

Active Galactic Nuclei (AGN) and Supermassive Black Holes

Typical signs of nuclear activity are (not all present always):

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

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

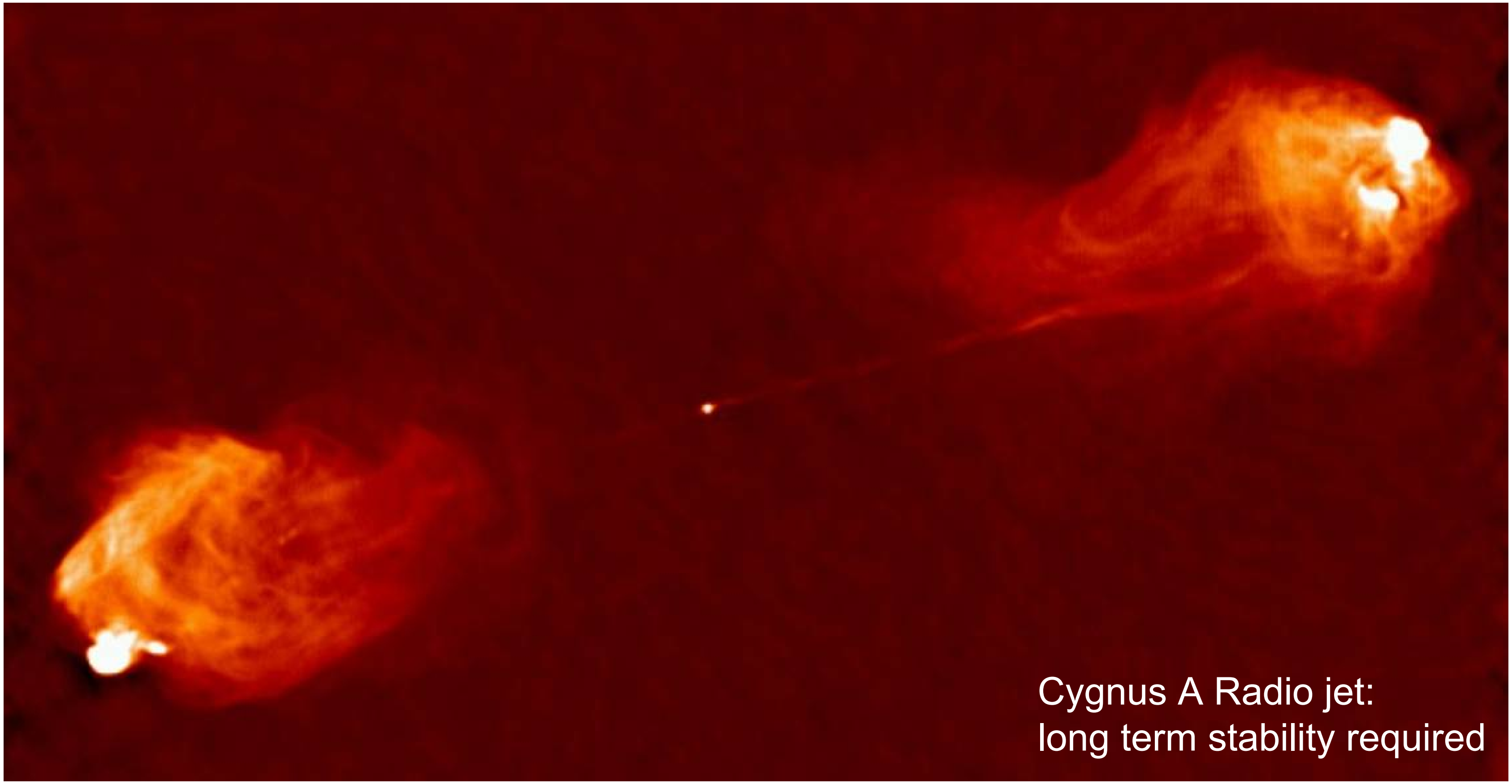
12.1 AGN types

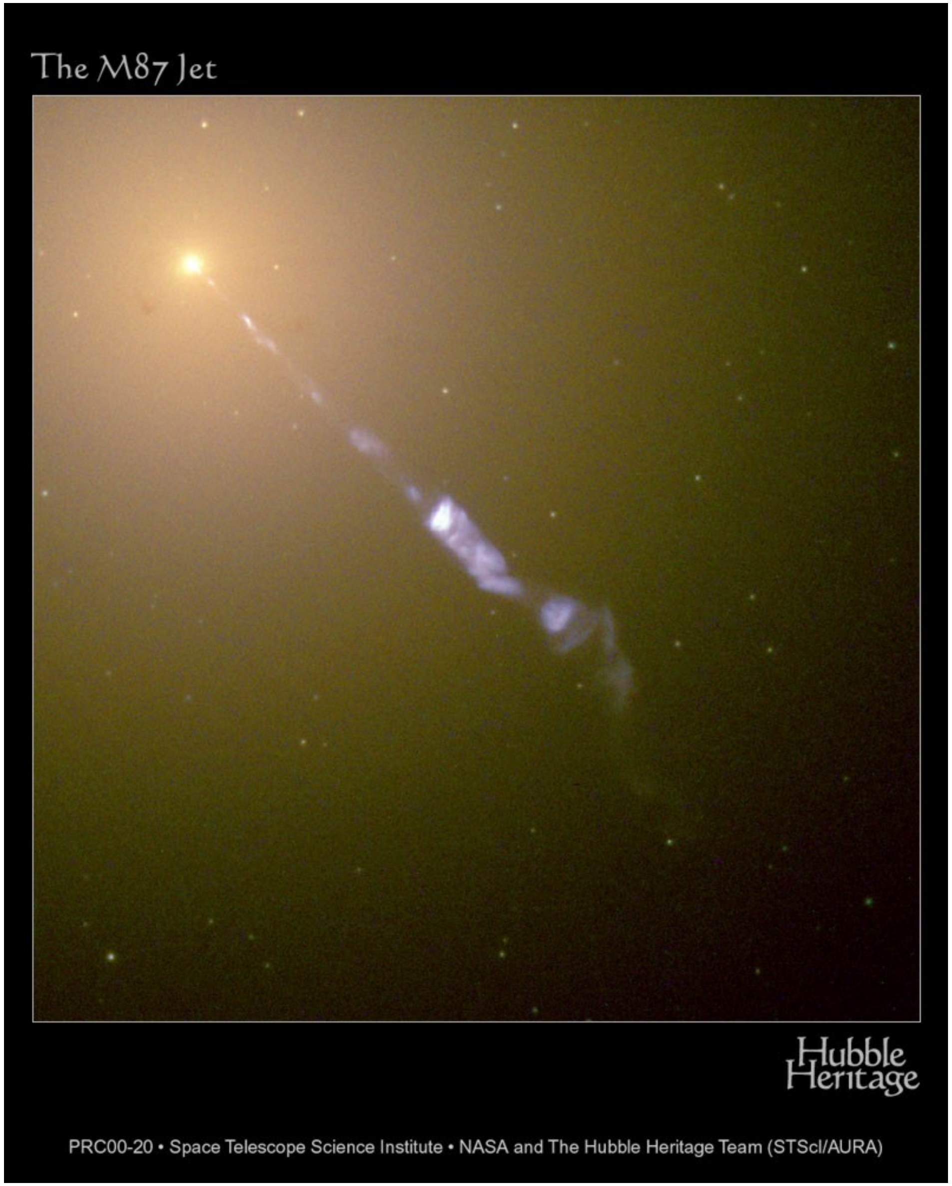
12.1.1 Radio galaxies

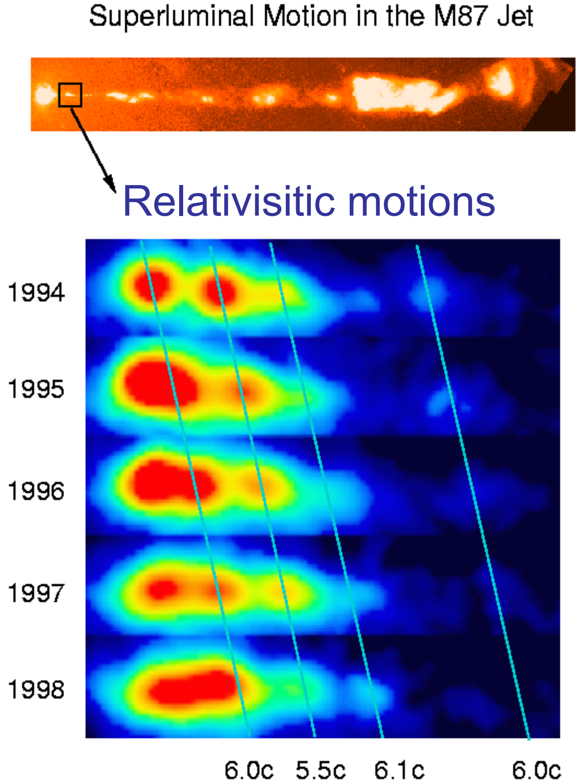
Radio galaxies emit extremely high radio luminosities: $L_{radio} \geq 10^8 L_\odot$
E.g., Cygnus A is the second brightest radio source on the northern sky, with a luminosity $L_{radio} \sim 10^{11} L_\odot$. Cygnus A is a typical radio galaxy and was discovered in 1946 by Hey. 1954 Baade and Minkowsky 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 0.2 Mpc. The radio radiation is produced by synchrotron emission of relativistic electrons. → **Radio galaxies are giant particle accelerators with** $E_e \approx 10^{12}$ **eV**

Radio surveys found radio 'galaxies' up to redshifts of $z = 4 - 5$. Of these about 50% 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'.

Examples of Radio Galaxies





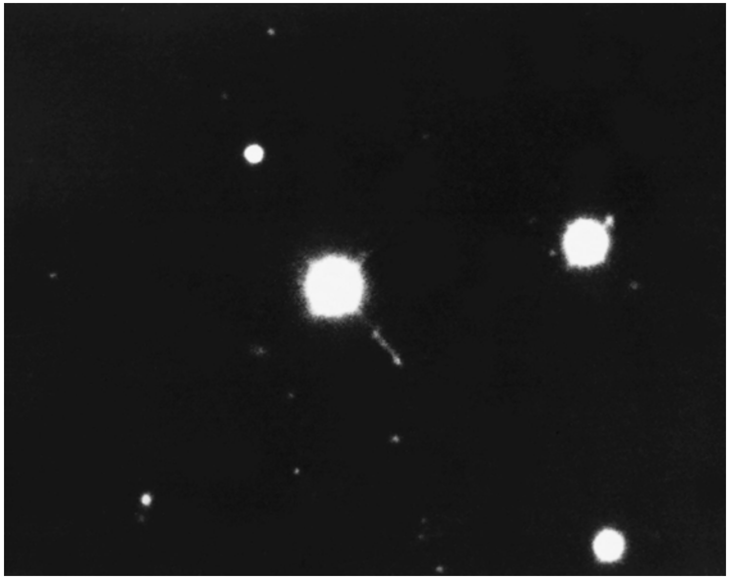


The optical jet of the nearby radio galaxy M 87 (the central galaxy of the Virgo cluster in a distance of about 17Mpc). The jet is highly collimated and shocks are visible within the jet. The emission is synchrotron radiation from relativistic electrons.

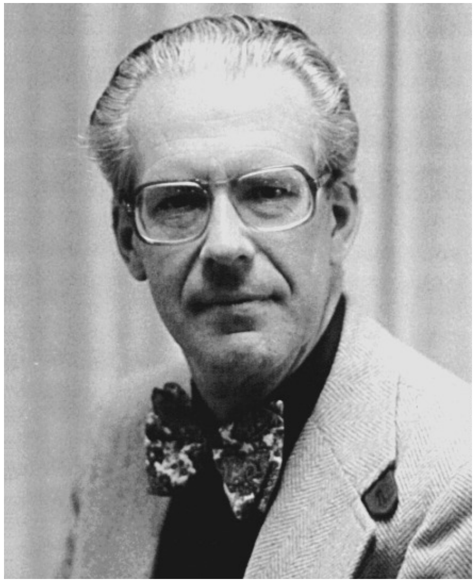
1963

Maarten Schmidt: 3C273, a star-like object with large redshift, Nature (1963):

The stellar object is the nuclear region of a galaxy with a cosmological redshift of 0.158, corresponding to an apparent velocity of 47,400 km/s. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparcsec. This nuclear region would be about 100 times brighter than the luminous galaxies which have been identified with radio sources so far...



3C 273



12.1.2 Quasars

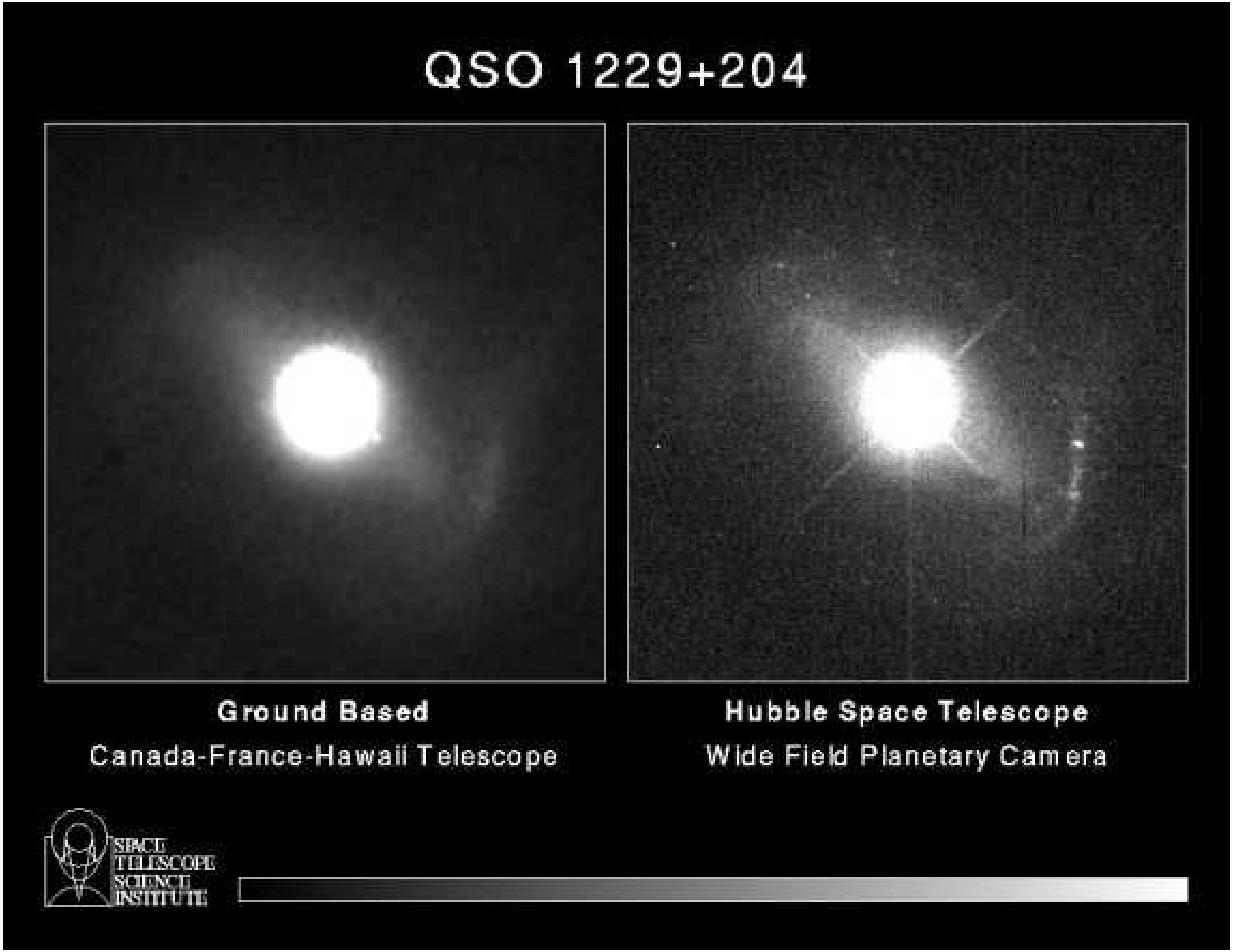
1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta...}$, MgII, OIII . . . which are redshifted by $z = 0.158 \rightarrow v_{rad} = 47400$km/s . So, the object was called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

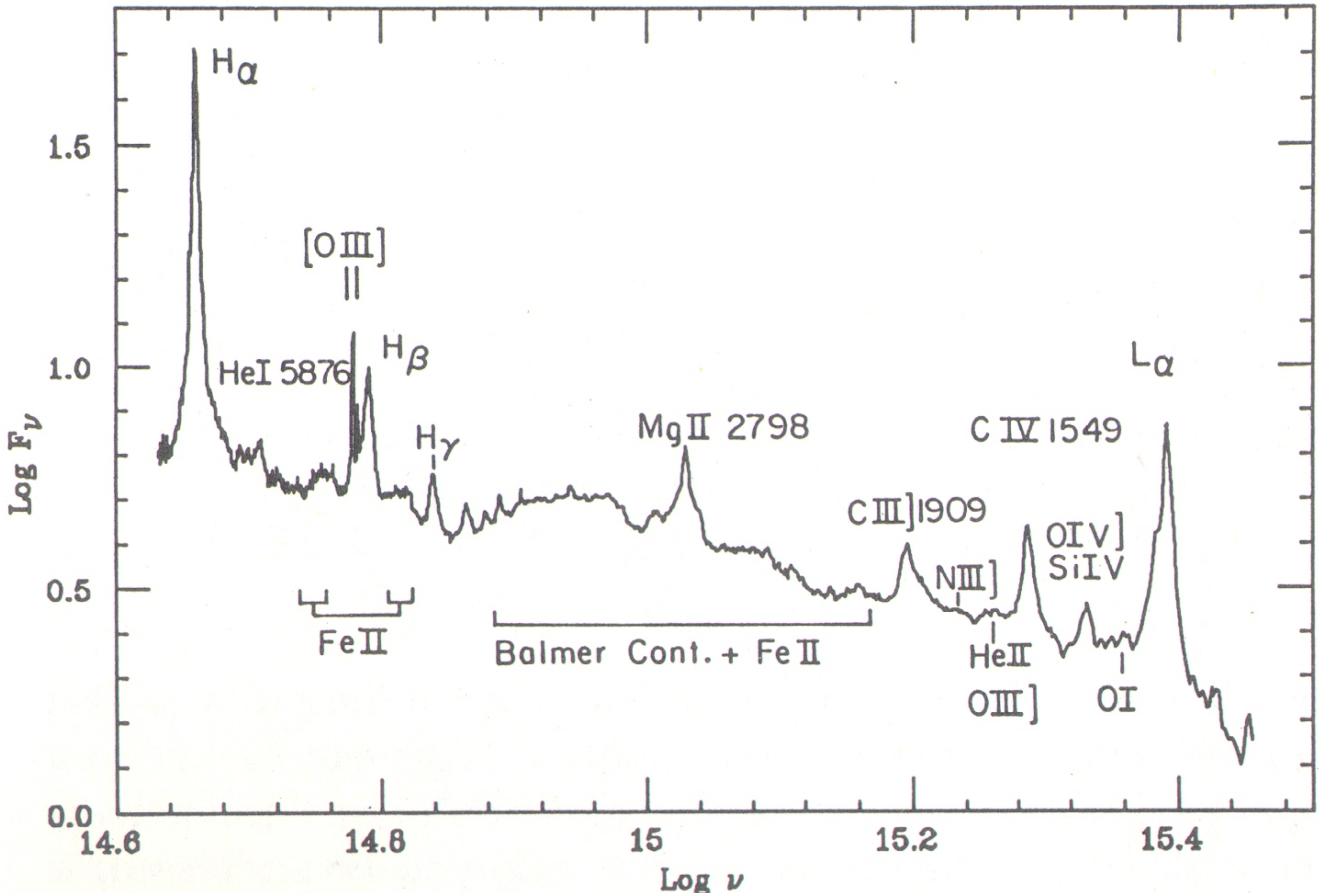
In 1965 A. Sandage discovers many more objects which show the typical qualities (colours, spectra, redshift, luminosity) of 3C273 but are missing the radio emissions, these are called → **Quasi Stellar Objects** → QSO.

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:



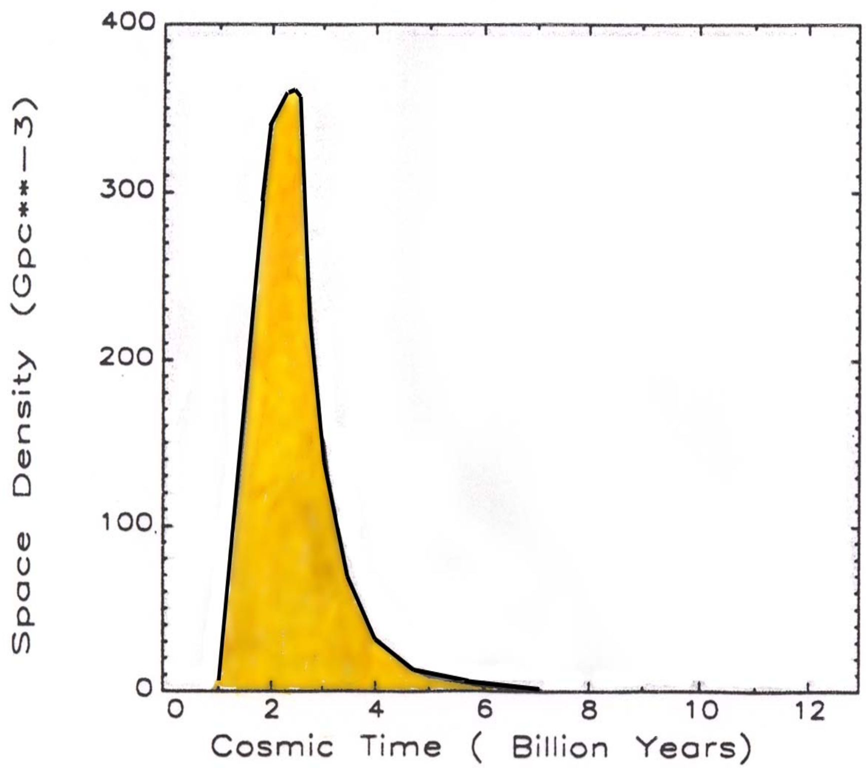


A typical quasar spectrum in the optical and UV range.
(see also diagnostic plots in the ISM Chapter)

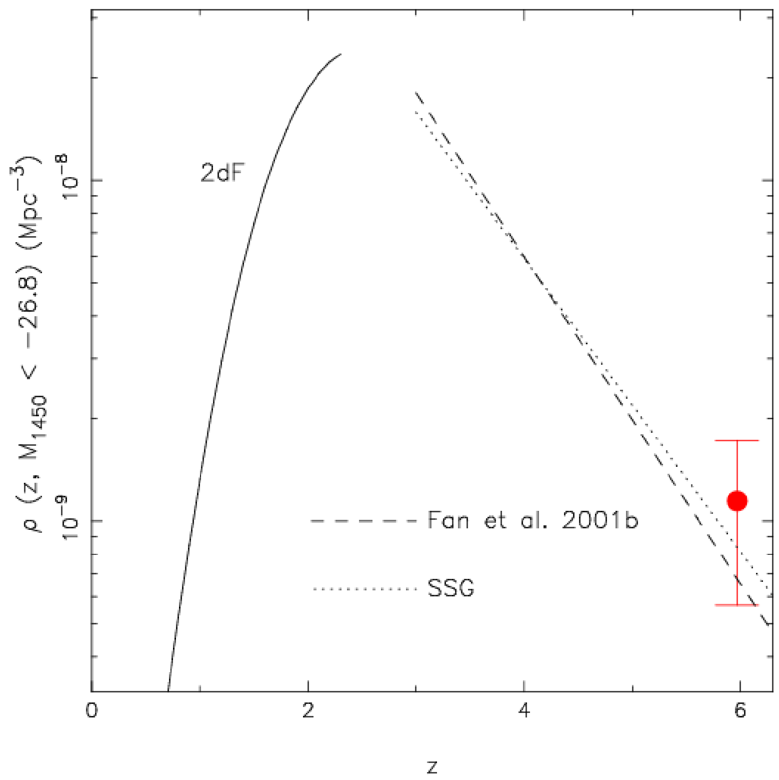
Quasar Statistics:

- luminosities: $L_{quasar} \approx 10^{45-48}$ 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 (roughly we have today: 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: $\Delta t_{QSO} \approx 10^7$yrs, then all luminous galaxies were once active and all contain a black hole.

When Active Galactic Nuclei were most active…



Schmidt, Schneider & Gunn 1991, in *The Space Distribution of Quasars* (ASP),109



Quasars were ~1000 times more numerous per comoving volume at redshifts of 2…3 than today. Where are the local quasar remnants?

12.1.3 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.

12.1.4 Seyfert Galaxies

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

- very bright unresolved nuclei, with luminosities $L \approx 10^{42-45}$ 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 $1/100 \text{ pc} \leq R_{BLR} \leq 1 \text{pc}$

12.2 Structure and physics of AGNs

12.2.1 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 the 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

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

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

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

→ variability in the vicinity of super massive black holes?

12.2.2 Luminosity source

Stars

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

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

and a mean distance

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

- Such a high stellar density would lead to collisions, dynamical instabilities and presumably to a partial collapse of the system.
- Observations of AGNs do not show stellar spectra.

→ 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 $E_{SN} \approx 10^{52}$ 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 luminosity of active nuclei is due to accretion onto black holes. (Zel'dovich 1963)

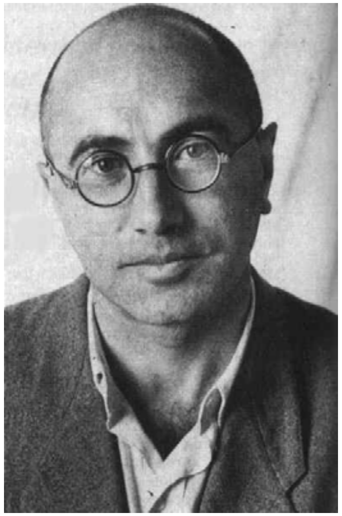
❖ The total energy output from a quasar is at least the energy stored in its radio halo ≈ 10^{54} J, via $E = mc^2$, this corresponds to $10^7\ M_{sun}$.

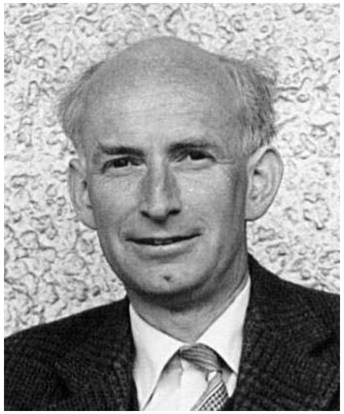
❖ Nuclear reactions have at best an efficiency of 0.6 % (H burning).

❖ So the waste mass left behind in powering a quasar is ≈ $10^9\ M_{sun}$

❖ Rapid brightness variations show that a typical quasar is no bigger than our Solar System.

❖ But the gravitational energy of $10^9\ M_{sun}$ compressed inside the Solar System ≈ 10^{55} J, i.e. 10 times larger than the fusion energy.





"Evidently, although our aim was to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction. The nuclear fuel has ended as an irrelevance." Donald Lynden-Bell (1969)

This argument convinced many people that quasar engines are supermassive black holes that swallow surrounding gas and stars.

The standard model of AGNs: Accretion onto massive black holes

The AGN contains a **black hole** with a mass $M \approx 10^6 \ldots 10^{9.5} M_\odot$ that accretes $10^{-4} \ldots 10$ $M_\odot$/yr gas from a 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).

We have discussed the basics physics of accretion disks in the chapter above and in the Stellar physics chapter. There we showed that accretion onto a black hole can provide the following luminosity:

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

Again, for comparison, the efficiency of hydrogen burning is:

$$\boxed{L_{H-burn} \simeq 0.007mc^2}$$

An estimate of the maximal possible luminosity of an AGN is given by the **Eddington-Luminosity** L_{Edd} (see Chapter 4). It is reached, when the radiation pressure is higher than the gravitational acceleration per area.

$$L_{Edd} = \frac{4\pi G M_{BH} m_p}{\sigma_{Te^-}}$$

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 corresponding maximum accretion rate:

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

The **typical temperatures of accretion disks** have also been derived in chapter 4 where we obtained:

$$T = 1.3 \cdot 10^{7} K \left(\frac{M_{BH}}{M_{\odot}} \right)^{-1/2} \left(\frac{(dm/dt)}{10^{-10} M_{\odot} / yr} \right)^{1/4} \left(\frac{R}{3kmM_{BH} / M_{\odot}} \right)^{-3/4}$$

If we assume R ≈ R_S, then the last bracket is ≈ 1; inserting the Eddington accretion rate, we then get:

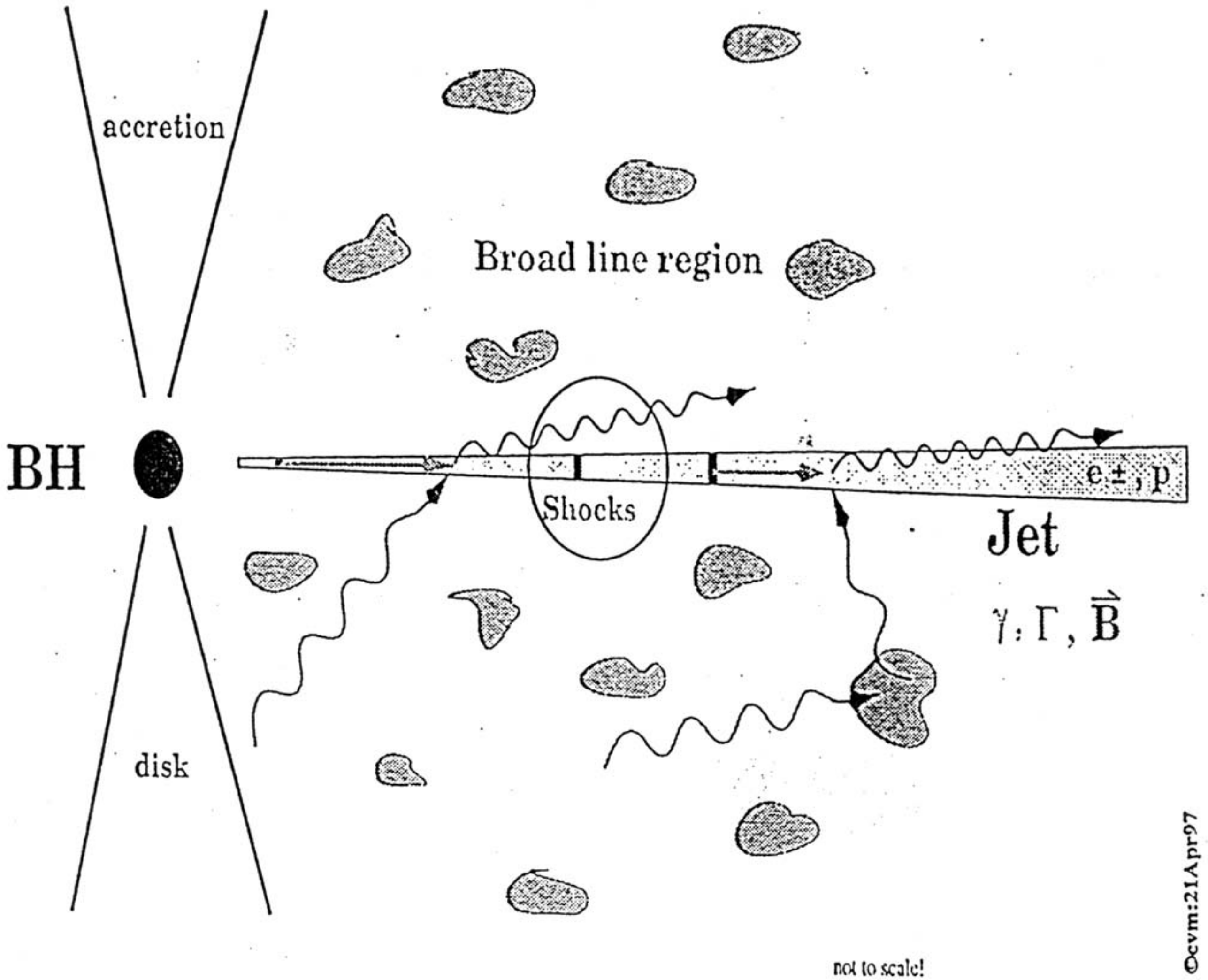
$$\Rightarrow T \simeq 2 \cdot 10^7 K \left[\frac{M_{BH}}{M_\odot} \right]^{-1/4}$$

i.e. for a typical quasar:

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

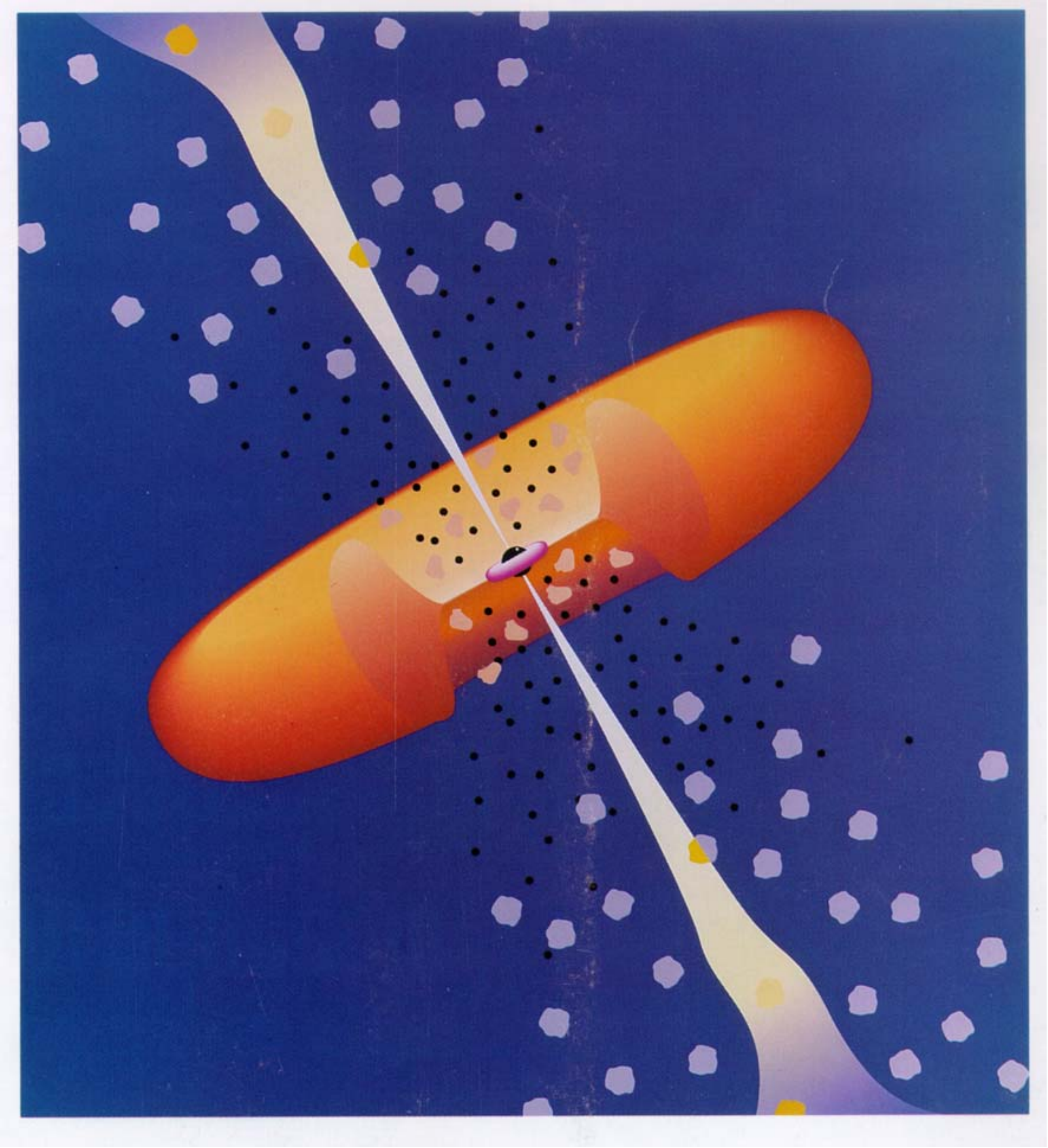
and the accretion disks of smaller black holes are hotter

The Center of an AGN



12.3 The Unified Model of the Active Galactic Nuclei

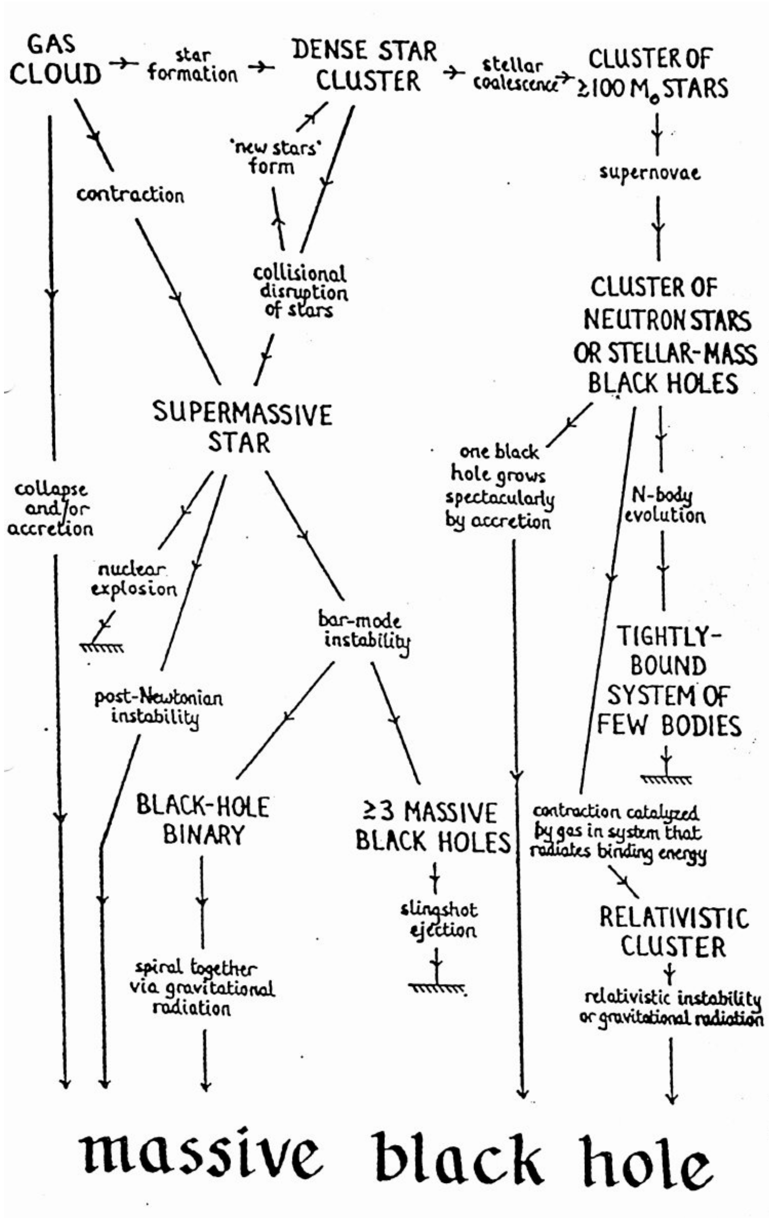
- Black Hole in the center: $M_{BH} \sim 10^6 \ldots 10^{10} M_\odot$.
- Accretion disk extending to ~ 100 − 1000R_S, that is emitting radiation in the X-ray, EUV, UV, . . . optical and TeV.
- Broad line region: Clouds of thick gas ($n_e \approx 10^9 - 10^{10} cm^{-3}$) that are moving with $v_{BLR}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



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

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



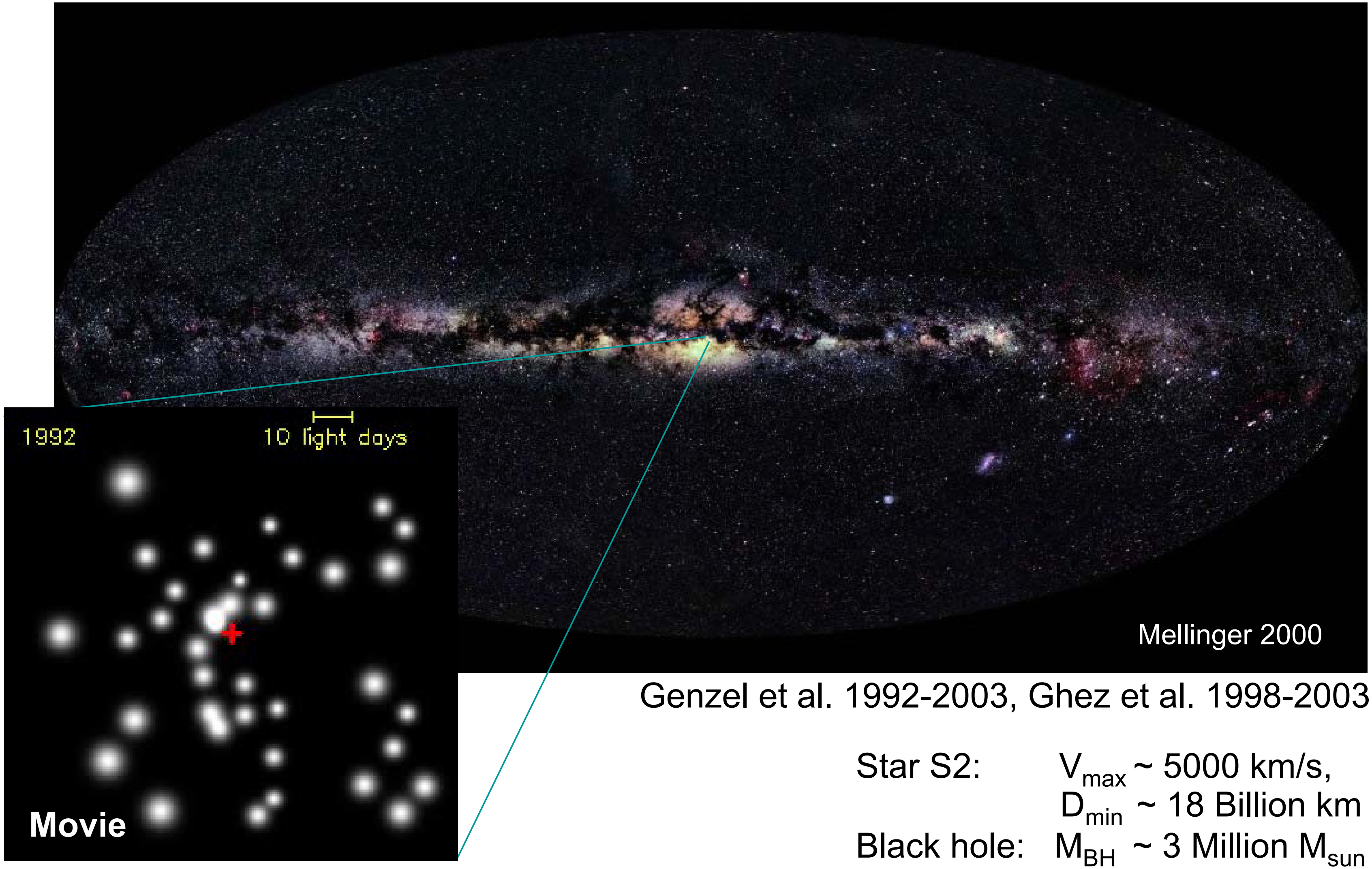
Formation paths for supermassive black holes (by M. Rees).

12.4 Supermassive black holes in nearby galaxies

Some key questions:

- Where are the dead quasars in the local universe? (in all galaxies, in some only?)
- How are black hole masses related to galaxy properties?
- Do all galaxy centers contain massive black holes? Do all massive black holes live in galaxy centers?
- Have we really discovered black holes? (or only clusters of compact objects?)
- What spin do black holes have and what is happening in the immediate vicinity of black holes?
- Can we find binary black holes? Are black holes sources of gravitational radiation?
- When and how are the first massive black holes formed? How do they grow? Did seed black holes of 10^{5-6} M_{sun} exist?
- How do black holes influence the early formation (and evolution) of galaxies (and vice versa)?

The closest confirmed supermassive black hole…
…is found in the Galactic center

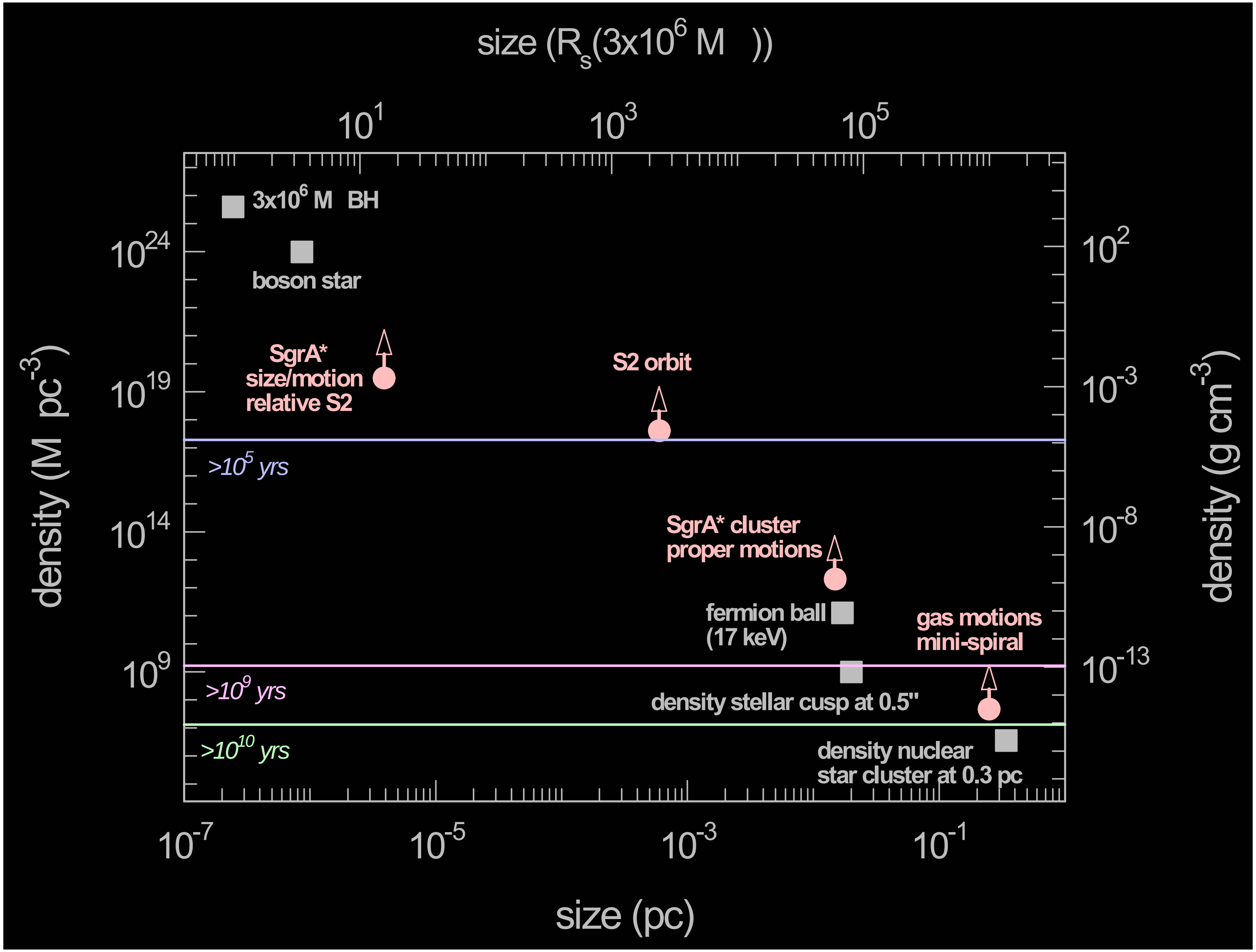


Genzel et al. 1992-2003, Ghez et al. 1998-2003

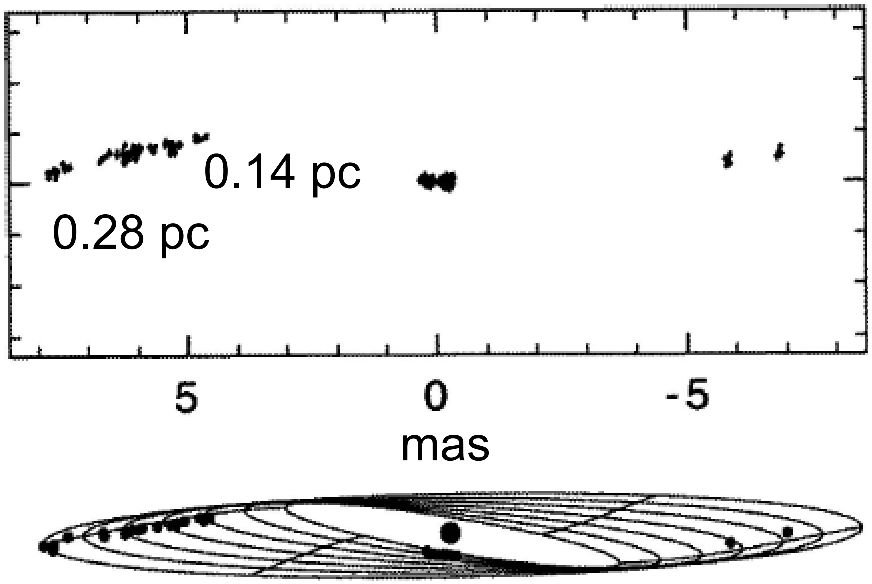
Star S2: V_{max} ~ 5000 km/s,
D_{min} ~ 18 Billion km

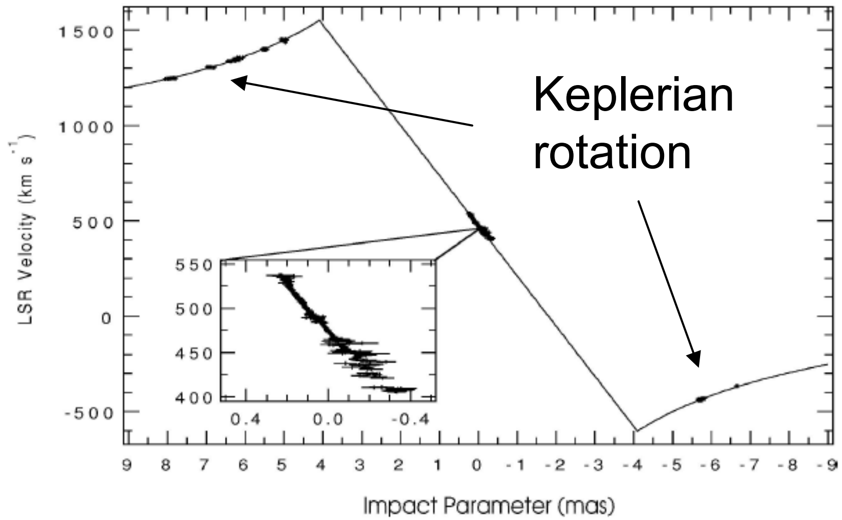
Black hole: M_{BH} ~ 3 Million M_{sun}
R_S ~ 9 Million km

➔ no viable alternatives to a black hole in the Galactic center



Water Masers disks: NGC 4258





Warped disk of gas. Water maser emitting at 2 GHz observable with VLBI reaching 0.5 mas precision.

Inner orbits just 40000 Schwarzschild radii.

$$M_{BH} = 3.9 \times 10^{7} M_{\odot} \qquad \rho > 4 \times 10^{9} M_{\odot} pc^{-3}$$

The Mass of the M 31 black hole

- (3-7)$\times 10^7$ $M_\odot$ (Dressler & Richstone 1988),
- (0.05-1)$\times 10^8$ $M_\odot$ (Kormendy 1988),
- (4-5)$\times 10^7$ $M_\odot$ (Richstone et al. 1990),
- ~7$\times 10^7$ $M_\odot$ (Bacon et al. 1994),
- (0.7-1)$\times 10^8$ $M_\odot$ (Emsellem & Combes 1997)
- (1.5-4.5)$\times 10^7$ $M_\odot$ black hole location (Kormendy & Bender 1999)
- ~1$\times 10^8$ $M_\odot$, eccentric disk model (Peireis and Tremaine 2003)
- ~1.2$\times 10^8$ $M_\odot$, blue cluster dynamics (Bender et al. 2005)

Finding black holes in galaxy centers …

Passive black holes can only be detected if they noticeably influence the motion of stars and gas at radii which we can resolve observationally:

The **radius of influence** R_i for a black hole of mass M_{BH} in a galaxy of a stellar velocity dispersion σ_G is generally very small:

$$R_i \simeq \frac{GM_{BH}}{\sigma_G^2}, \quad \text{or}: \quad \alpha_i \simeq 1'' \left(\frac{M_{BH}}{2\cdot 10^8 M_\odot}\right) \left(\frac{\sigma_G}{200\text{km/s}}\right)^{-2} \left(\frac{D}{5\text{Mpc}}\right)^{-1}$$

(the Schwarzschild radius for these values would correspond to $\sim 10^{-6}$arcsec).

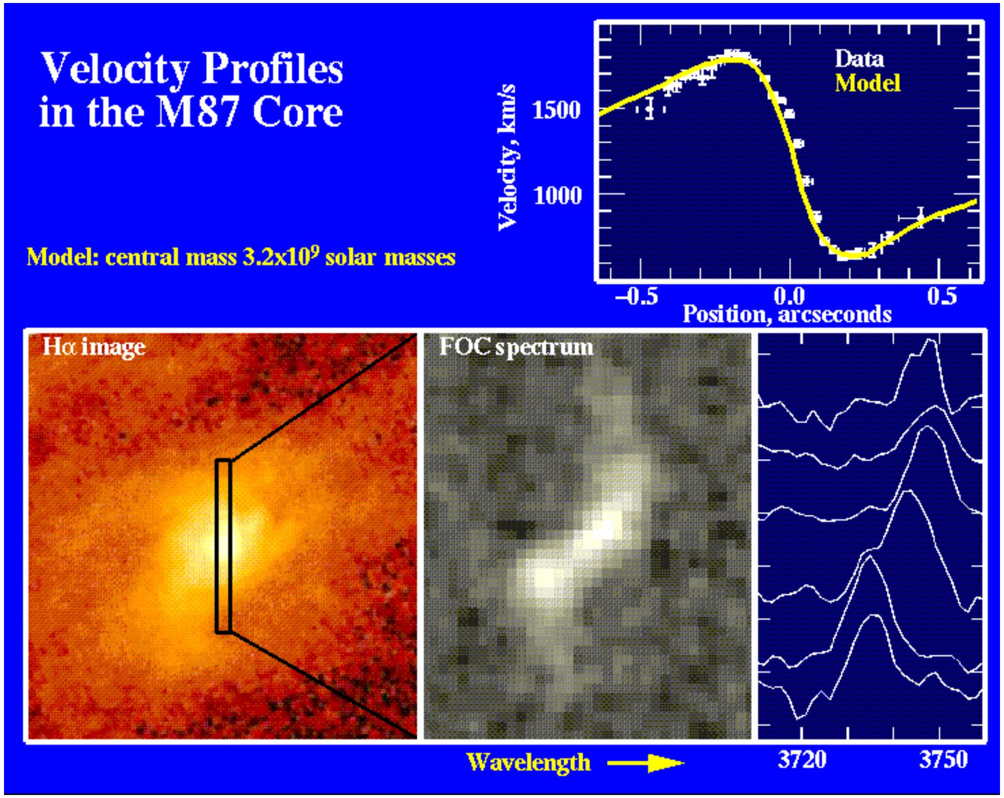
Object	D/Mpc	$M_{BH}/M_\odot$	σ_G/km/s	α_i/"
Galaxy	0.008	$3\cdot 10^6$	100	40
M 31	0.77	$3\cdot 10^7$	160	1.5
Galaxy in Virgo	17	$3\cdot 10^6$	100	0.02
M 31 in Virgo	17	$3\cdot 10^7$	160	0.07
Giant Virgo elliptical	17	$1\cdot 10^9$	300	0.6

→ we need very good spatial resolution → HST or adaptive optics required.

Hubble Space Telescope

Beyond the Galaxy and M31 …

- Rotating gas disks provide a comparatively easy way to find black holes:
  - Gas is collisional and dissipative and prefers circular orbits.
  - Keplerian velocity profiles are good indicators for a central point mass.
  - Caveat: strong non-circular motions can be present if the potential is non-axisymmetric or if non-gravitational forces (radiation) are important.



Harms, Ford et al., HST

❖ Stellar motions are more complicated to model but provide more reliable black hole masses:
- stars move collisionless.
- stellar motion is only affected by gravity.
- however: anisotropy needs to be measured.

Stars in galaxies move **collisionless**, their velocity distribution can be **anisotropic**. For a spherical galaxy, the mass within a radius r is given by (1st moment of collisionless Boltzmann equation):

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left(-\frac{d\ln n}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - (1 - \frac{\sigma_\theta^2}{\sigma_r^2}) - (1 - \frac{\sigma_\phi^2}{\sigma_r^2})\right)$$

where n is the stellar density, V is the rotation velocity and σ_θ^2, σ_ϕ^2, and σ_r^2 are the velocity dispersions in tangential and radial directions. In the case of spherical symmetry $V = 0$ and $\sigma_\theta^2 = \sigma_\phi^2$ – but we can have $\sigma_r^2 \neq \sigma_\phi^2$! This allows to trade mass for anisotropy and vice versa (for a collisional system the last two terms would be zero).

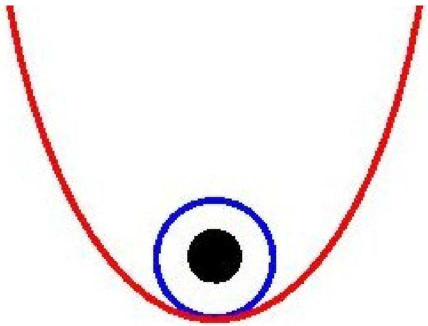
For a collisional ideal gas (similar to the earth atmosphere) we would instead have:

$$\frac{dp}{dr} = -\frac{GM(<r)}{r^2}\rho \qquad \text{and} \qquad p = \frac{\rho}{\mu}k_B T$$

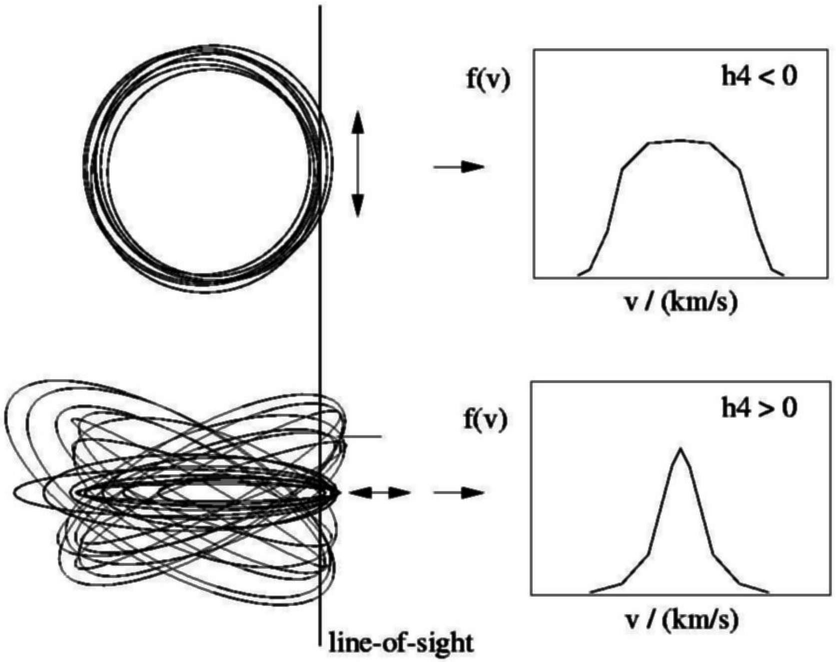
resulting in:

$$M(<r) = r\,\frac{k_B T}{G\mu}\left(-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right)$$

$\Rightarrow$ Higher moments of the velocity distributions have to be measured to constrain the anistropy. This is only possible since a few years.



A simple example of how an unknown orbital structure prevents an accurate mass determination: if only the velocity at the pericenter is known the mass is uncertain by at least a factor 2.



Tangential and radial orbits correspond to different shapes of the line-of-sight velocity distributions.

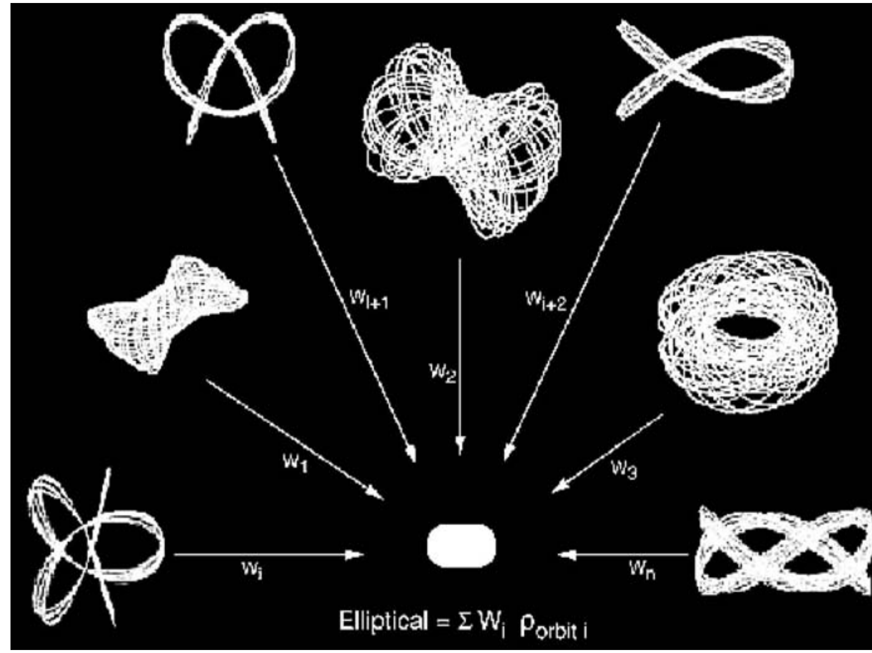
The different shapes can be measured and described by Gauss-Hermite functions (h3 = asymmetric component, h4 = symmetric component).

Modeling of stellar systems using Schwarzschild's method (1979): (Richstone&Tremaine 1988, van der Marel et al. 1998, Gebhardt et al. 2000):

- deproject observed surface brightness profile to derive 3D axisymmetric density distribution of stars (needs inclination)

- choose a mass-to-light ratio for the stars and derive the potential from Poisson's equation; add the potential of the BH

- calculate several thousand orbits with different energies, angular momenta and drop points and derive their time-averaged density distribution

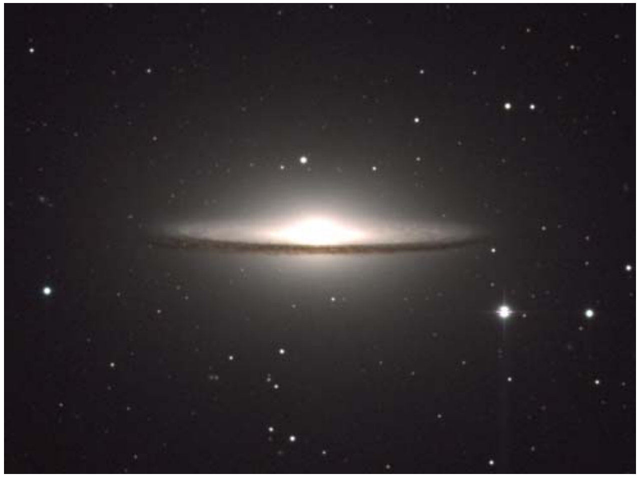


- superimpose the orbits such that:
  (1) the surface brightness distribution is matched,
  (2) the velocity distribution (rotation, dispersion, higher moments) is matched
  (3) the phase space distribution is smooth (e.g. by maximizing the entropy)

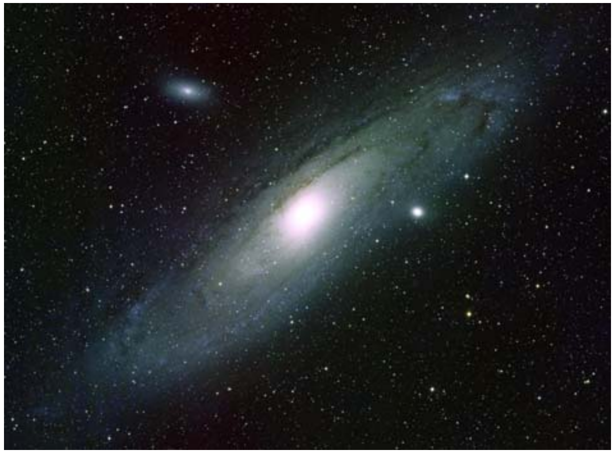
- repeat this procedure for a range of inclinations, stellar mass-to-light ratios and black hole masses.

Demographics of black holes in nearby galaxies

M 87: $M_{BH} \sim 2\ 10^9\ M_{sun}$



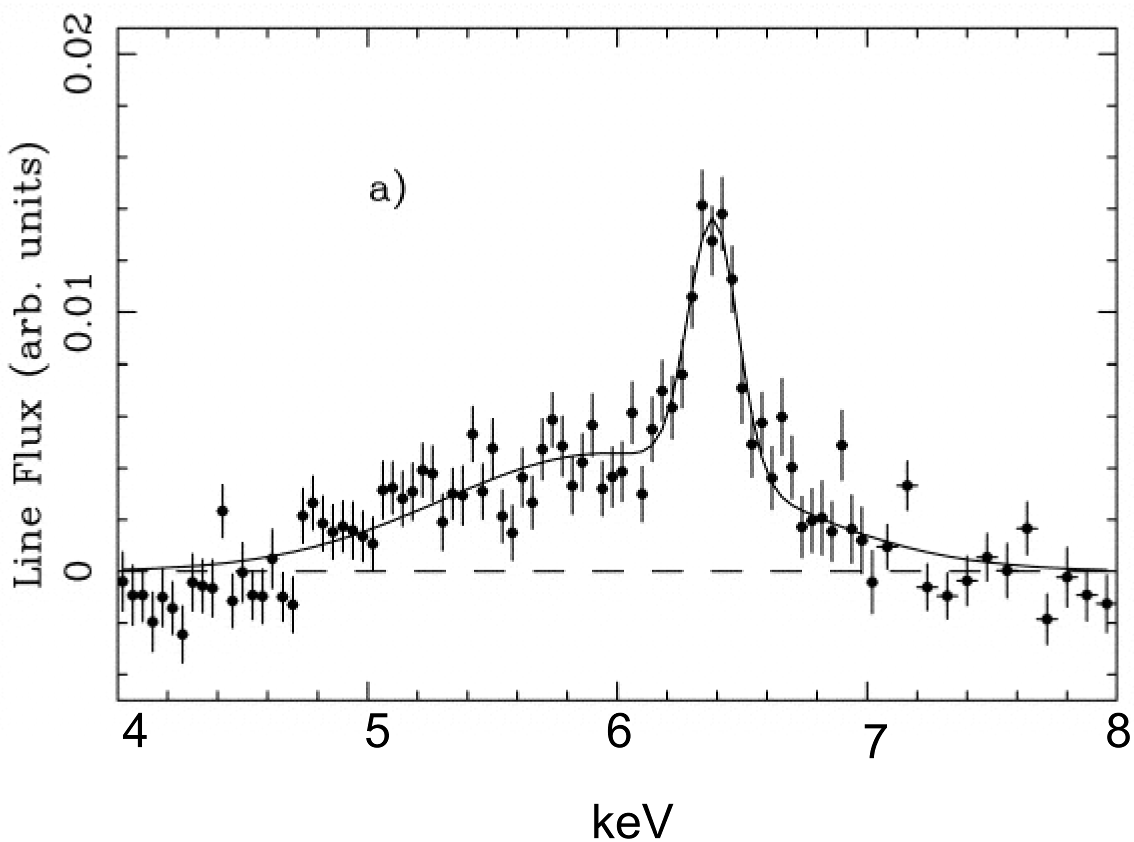
M 104: $M_{BH} \sim 5\ 10^8\ M_{sun}$



M 31: $M_{BH} \sim 1\ 10^8\ M_{sun}$
M 32: $M_{BH} \sim 3\ 10^6\ M_{sun}$

M 33: $M_{BH} < 1500\ M_{sun}$

Kα line emission in X-ray



Nandra et al. 1997, ApJ, 477, 602

Fluorescence Fe emission at 6.4 keV observed in 80% of Seyfert I galaxies thanks to spectroscopic Xray Telescopes (ASCA and XMM).

The line is intrinsically narrow, but seen extremely broadened (2 keV ~ 0.3 c) and skewed.

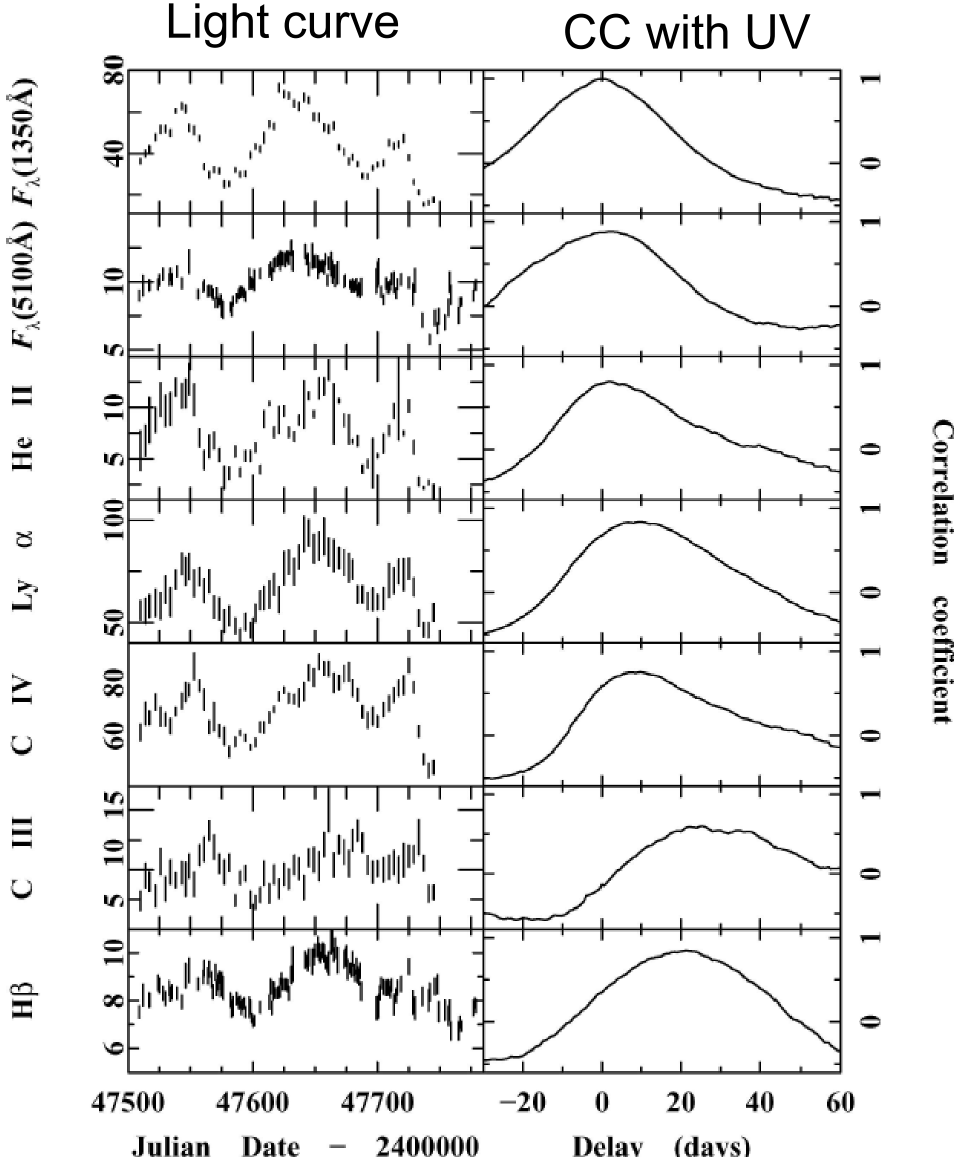
Rapidly rotating disk near SMBH: double horn signature like HI profile of spiral galaxies.

Blue peak: relativistic beaming

Red “peak”: smeared due to Gravitational redshift

Reverberation mapping

NGC 5548



Peterson, 2002

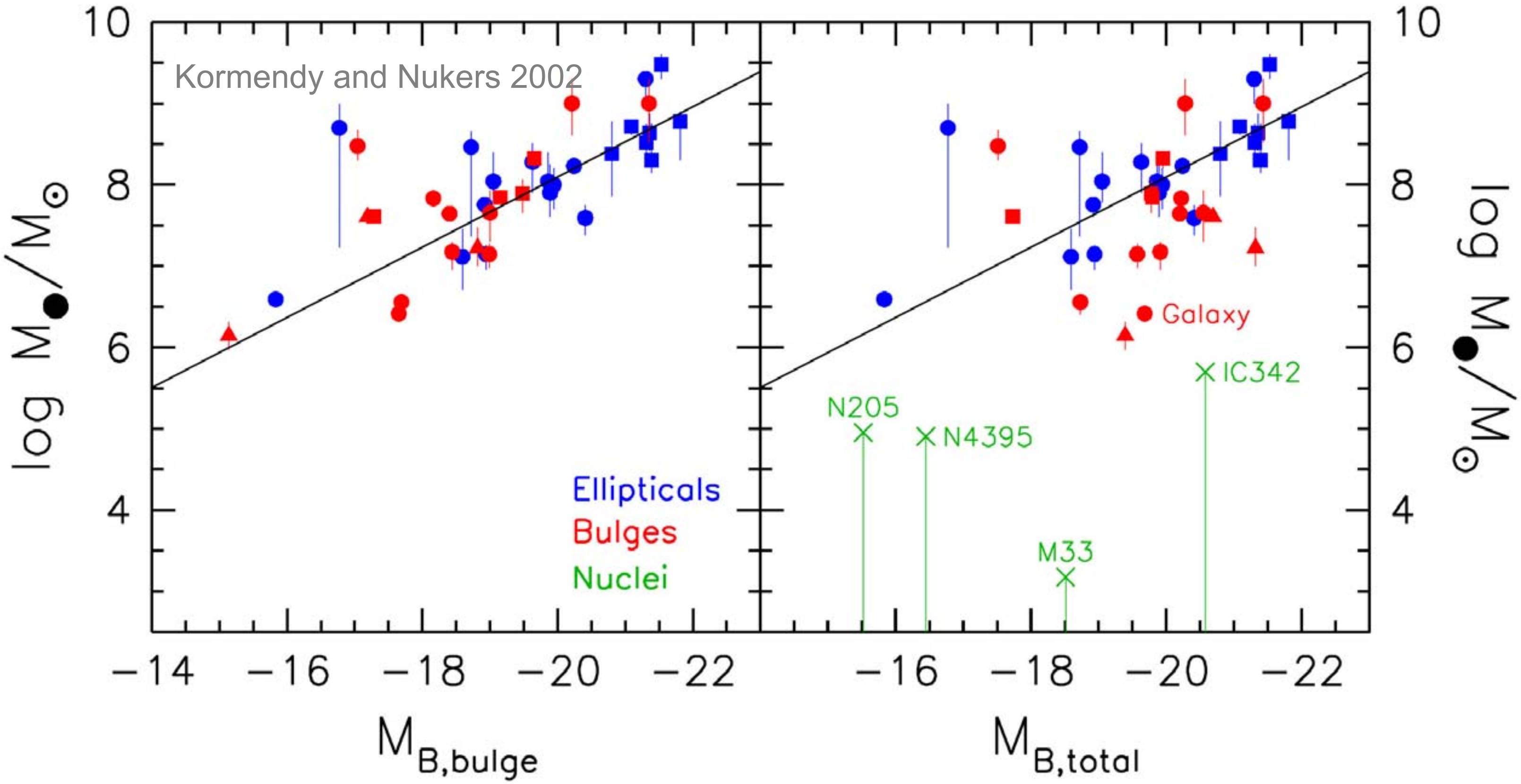
In Seyfert 1 the broad absorption region is visible. Any variation in the ionizing flux continuum will cause a flux variation of the emission lines. The time delay between the variations is proportional to the size r of the region. $r \approx c\Delta t$

Moreover, the width of the lines gives the velocity dispersion σ of the clouds. The virial theorem gives:

$$M_{BH} = fr\sigma^2 / G$$

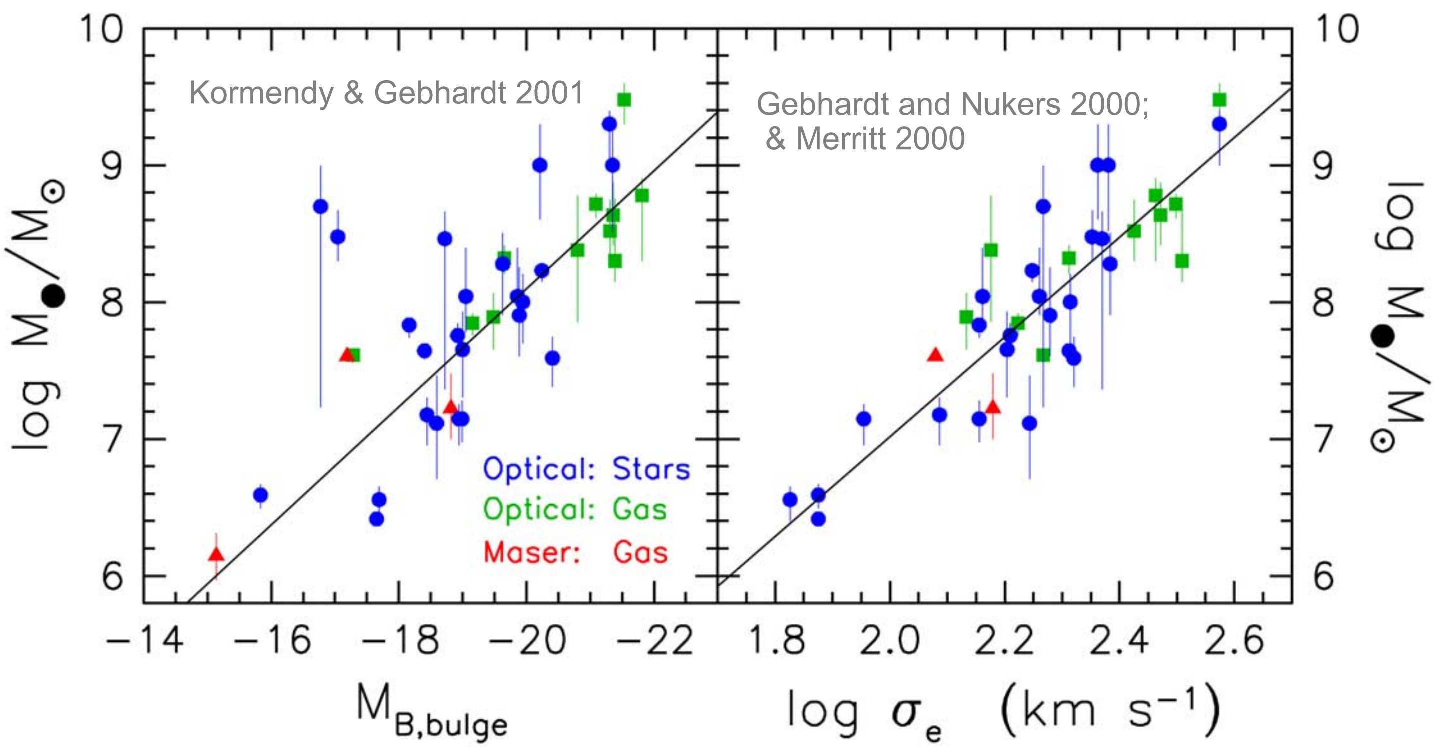
The factor f factories the uncertainties due to geometry. Note that the method does not depend on distance and r can probe regions as small as 1000 Schwarzschild radii.

Demographics of black holes in nearby galaxies



- ❖ All spheroids contain supermassive black holes with: $M_{BH} \sim 0.002\ M_{spheroid}$
- ❖ Pure disk galaxies do not seem to contain black holes.

Demographics of black holes in nearby galaxies



- We see a very tight correlation between BH mass and spheroid velocity dispersion:
  $M_{BH} \sim 0.1\ \sigma^4$ (units: solar masses, km/s)
- At a given mass, more compact bulges contain more massive black holes, i.e., if baryons collapsed and dissipated more than on average, then the BH is bigger.
- Black hole growth and spheroid formation & evolution proceeded in lockstep.