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GALAXY FORMATION AND EVOLUTION

PAP 318, 5 op, autumn 2022
B119, Exactum

Lecture 13: Formation of active galaxies

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TODAY WE WILL COVER

1. The population of AGNs and their classification.
2. Physics of the AGNs: The central engine.
3. Continuum and line emission from AGNs.
4. The various components of the standard AGN model.
5. The formation and growth of AGN at high and low redshifts.
6. Feedback and the impact of AGNs on the evolution of galaxies.

The lecture notes correspond to:

- MBW: pages 618-651 (§14.1-14.4)

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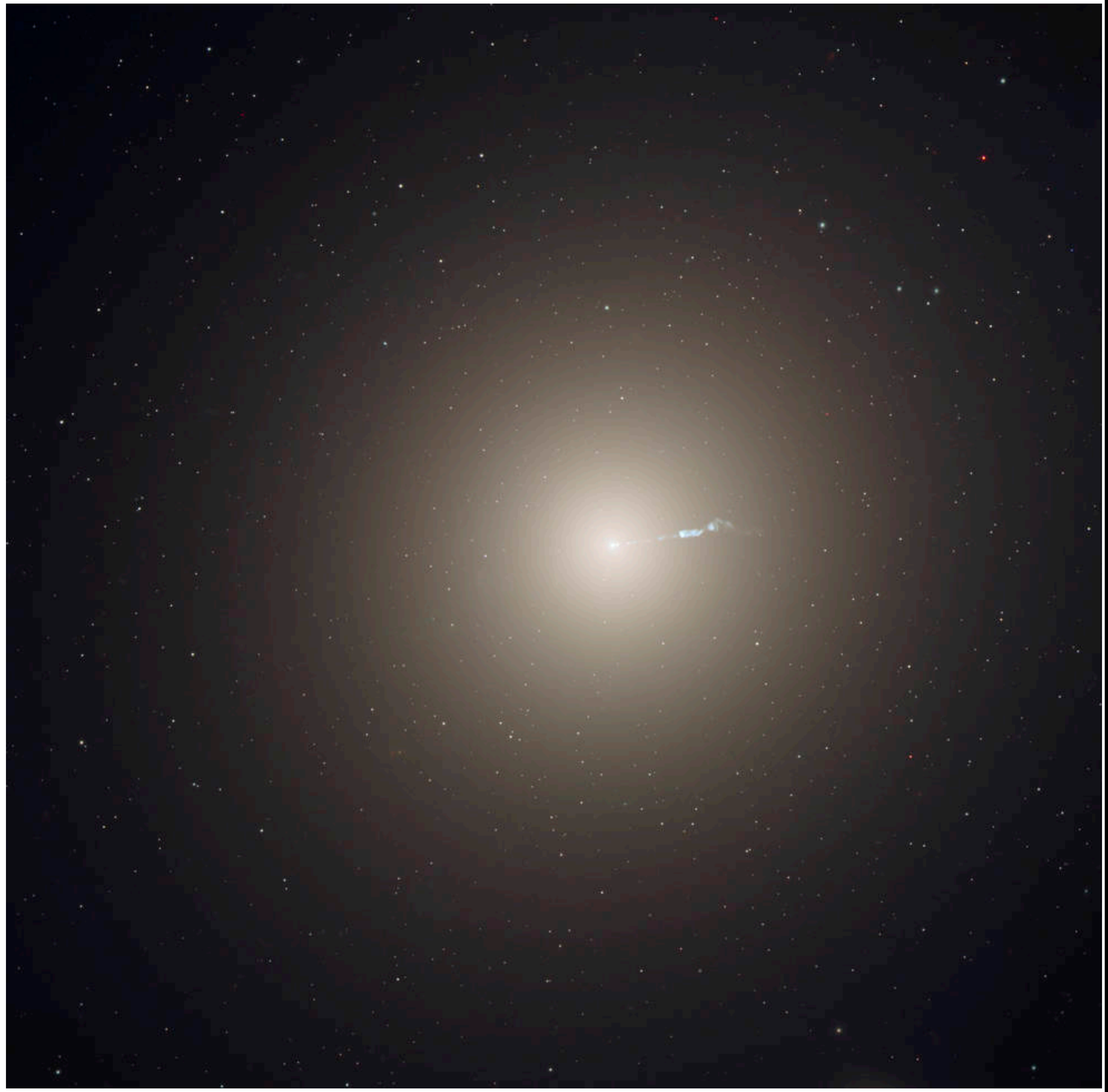
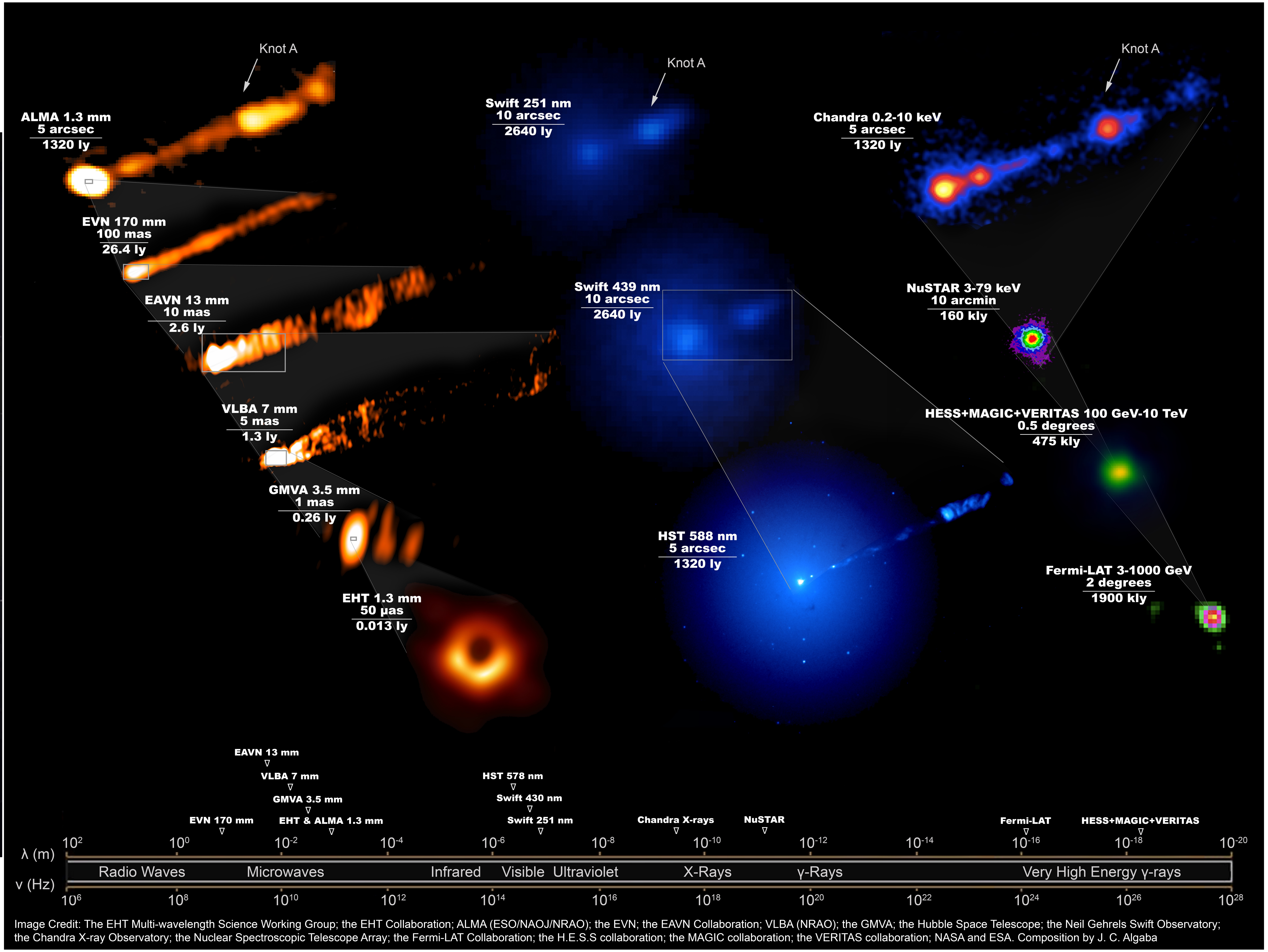
13.1 ACTIVE GALAXIES



Credits: NASA, ESA, HST



13.1.1 ACTIVE GALACTIC NUCLEUS

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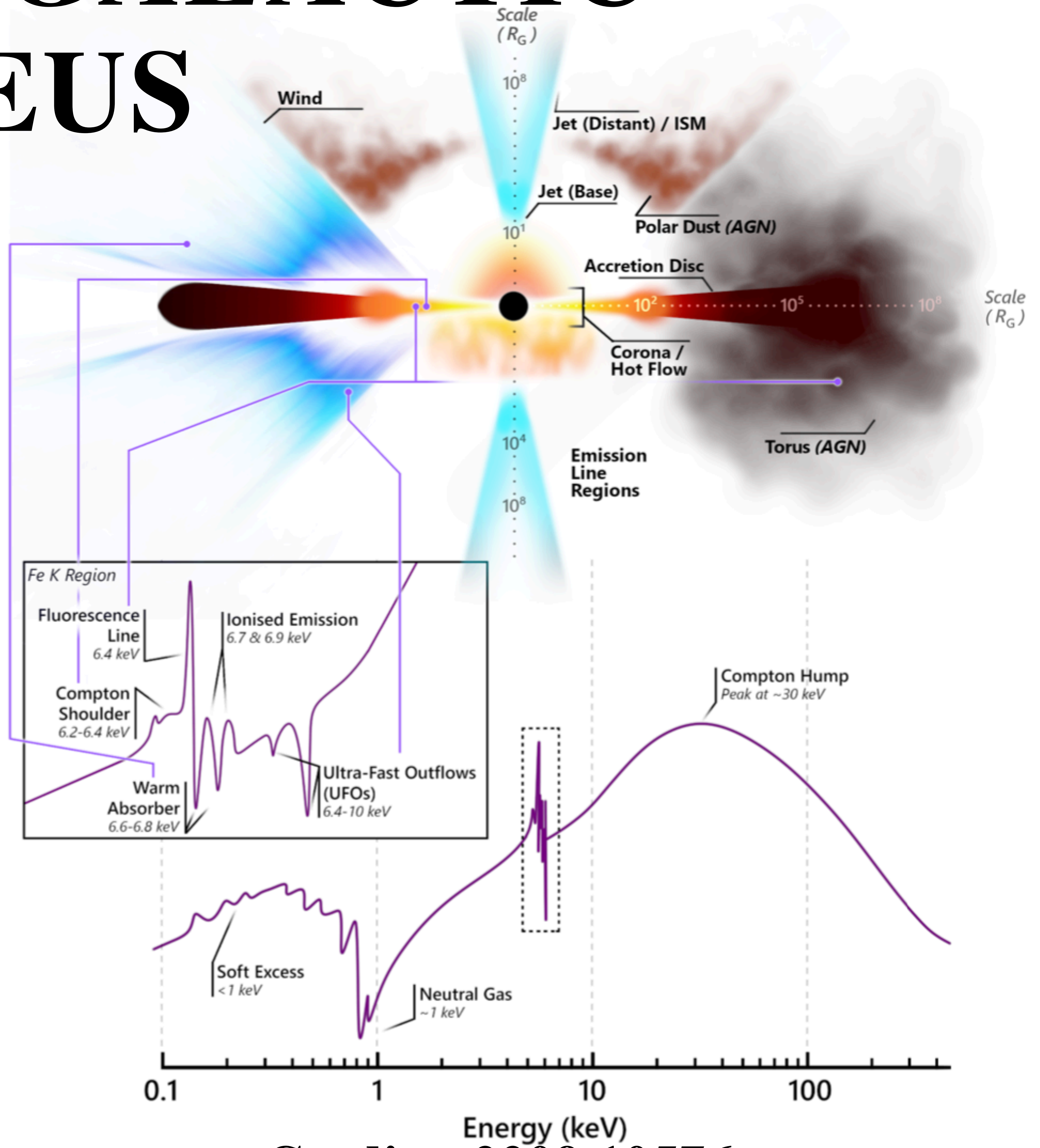
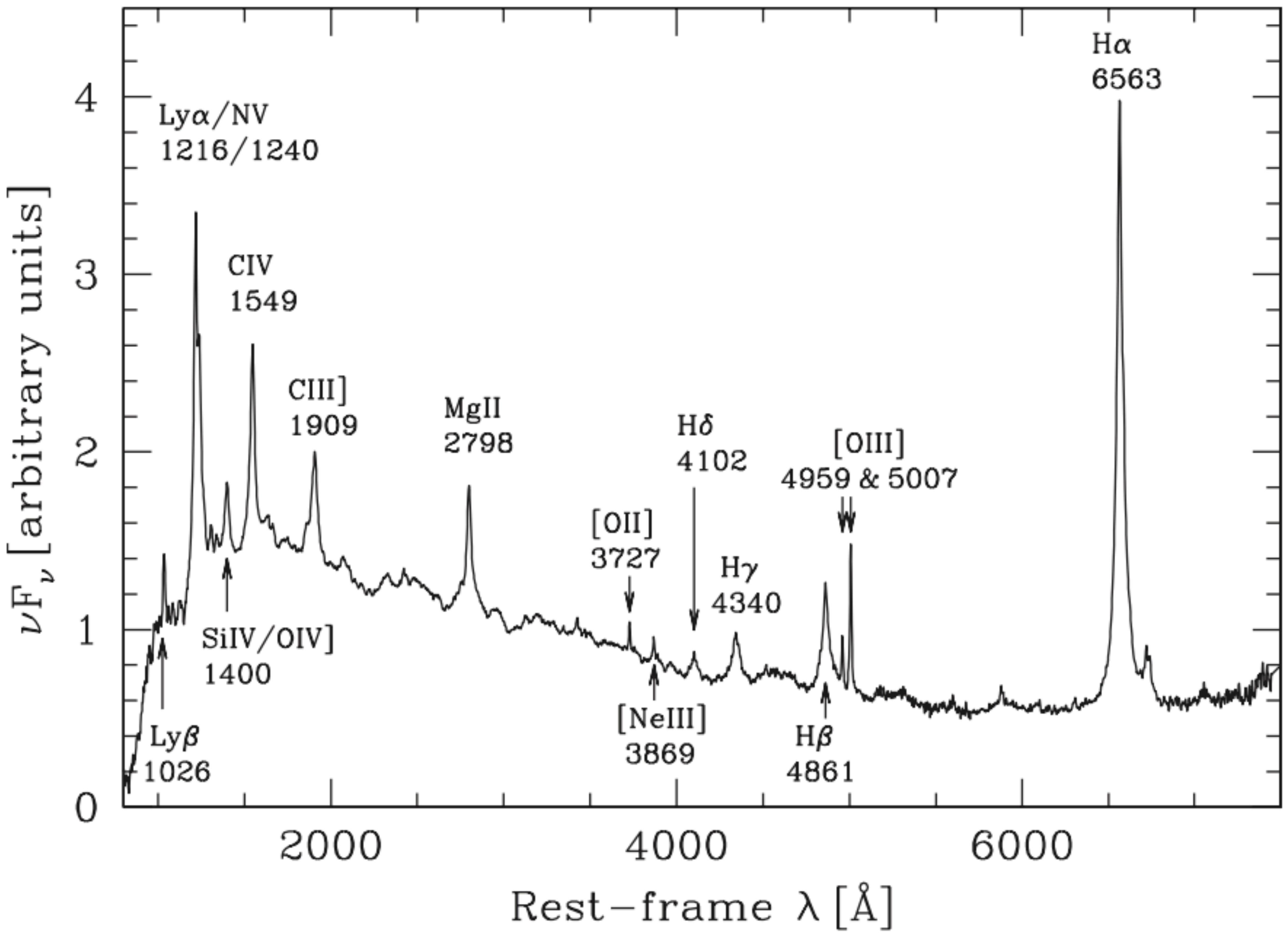
- The spectra of normal galaxies is roughly the sum of the Planck spectra corresponding to the temperatures of their stars
- However, some galaxies have a spectral energy distribution that is much broader than expected from a collection of stars, gas and dust. These galaxies typically emit non-thermal radiation over the full wavelength regime from radio to X-rays.
- The non-thermal emission emanates from a very small central region, often less than a few parsecs across, which is called the AGN.



Credits: 2209.10576

13.1.2 AGN CLASSIFICATION

- **An object is classified as AGN if one or more of the following properties are observed:**
  - **A compact nuclear region much brighter than a region of the same size in a normal galaxy.**
  - **Non-stellar, i.e. non-thermal continuum emission.**
  - **Strong emission lines.**
  - **Variability in the continuum emission and/or in emission lines on relatively short time-scales (days/weeks).**



Credits: Fig. 14.1, MBW

13.1.3 AGN CLASSIFICATION

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- **Seyfert galaxies: characterised by a spiral-like morphology with bright star-like nuclei. Seyfert galaxies are subdivided into Seyfert I (broad permitted and narrow forbidden lines) and Seyfert II (permitted and forbidden lines are narrow) galaxies. LINERs (low-ionisation nuclear emission line regions) are probably a lower luminosity extension of Seyferts, although nuclear stellar clusters may also give rise to LINER-like activity.**

- **Radio galaxies: have strong radio emission ($P_{1.4GHz} \geq 2 \times 10^{23}$ W Hz^{-1}). Similarly to Seyferts can be divided into broad-line radio galaxies and narrow-line radio galaxies. Often jet-like structures that extend into lobes from the compact central object. A further division can be made into Fanaroff & Riley classes I and II based on their radio morphology.**

13.1.4 AGN CLASSIFICATION

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- **Quasars (quasi-stellar radio source): have properties similar to radio galaxies but unusually blue optical images (emission from the hot accretion disk) and optical surveys revealed that the radio-quiet quasars outnumber the radio-loud quasars by a factor of ~10-100.**
- **BL Lacs: These objects together with the Optically Violently Variable (OVVs) have very strong and rapid optical variability. OVVs show some emission lines, but BL Lacs show no emission lines. Both have relatively strong polarisation on a few % level and radio emission. Most probably we are observing these objects close to the direction of the jet.**

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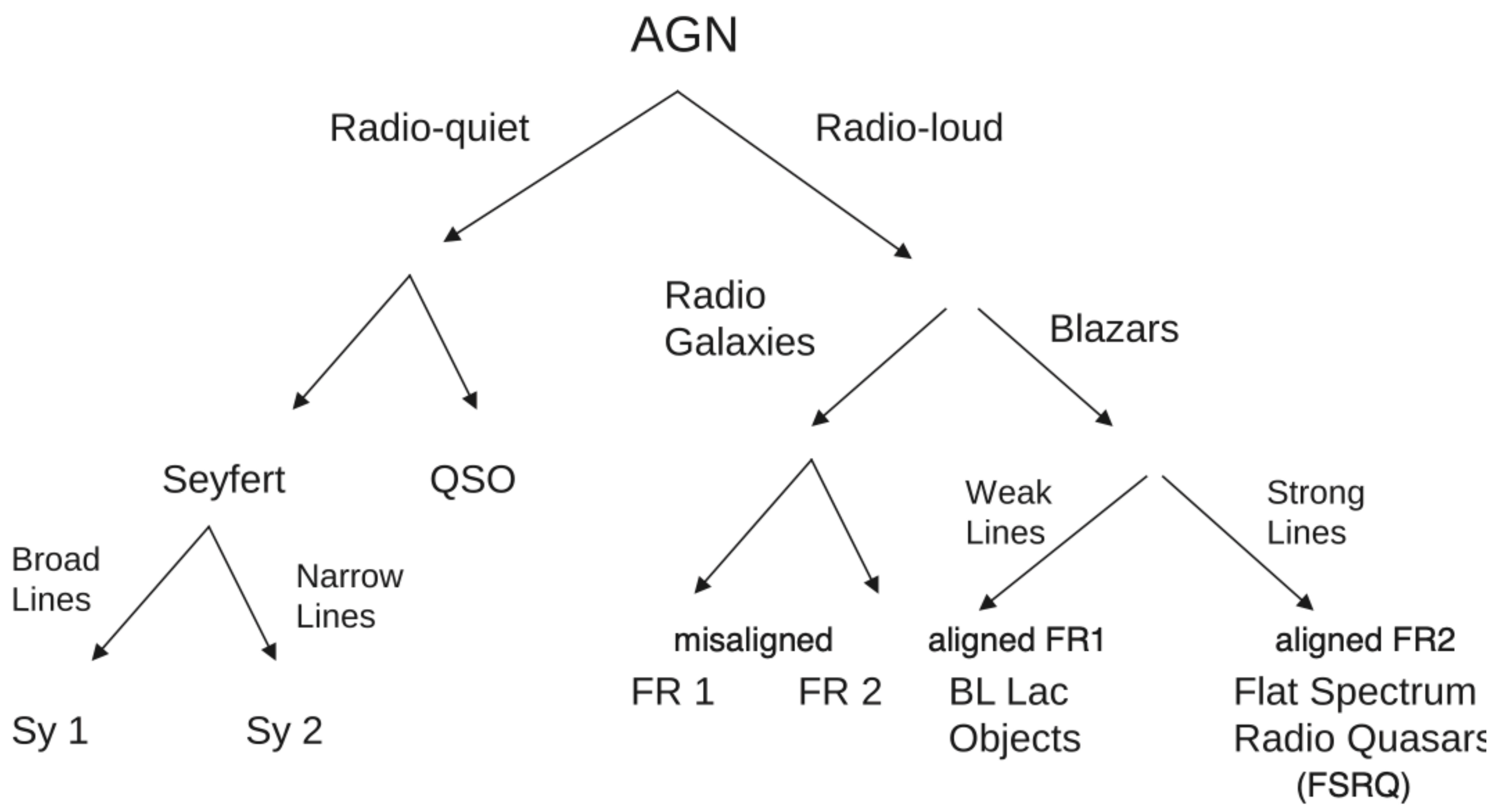
13.1.5 AGN UNIFICATION



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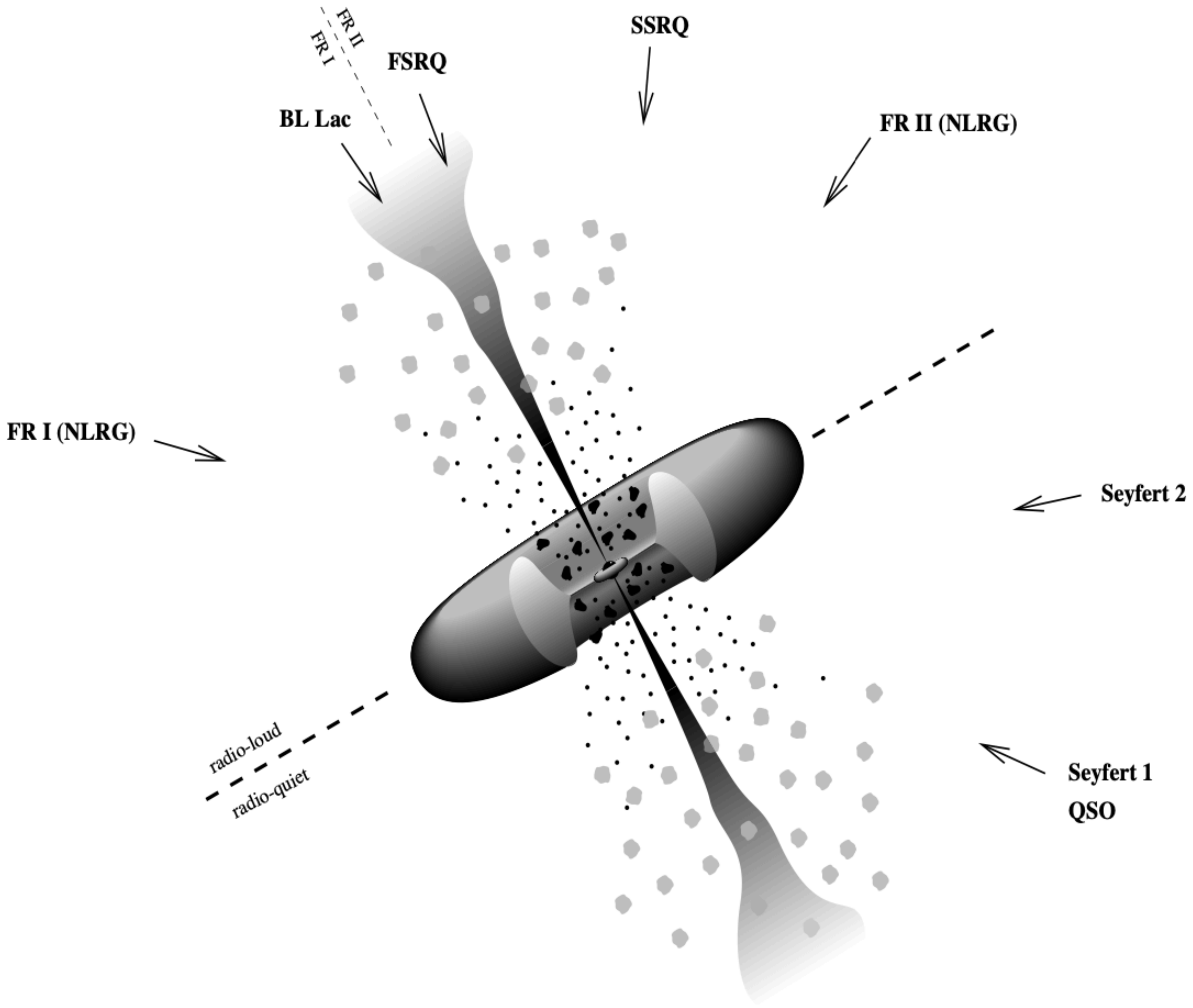
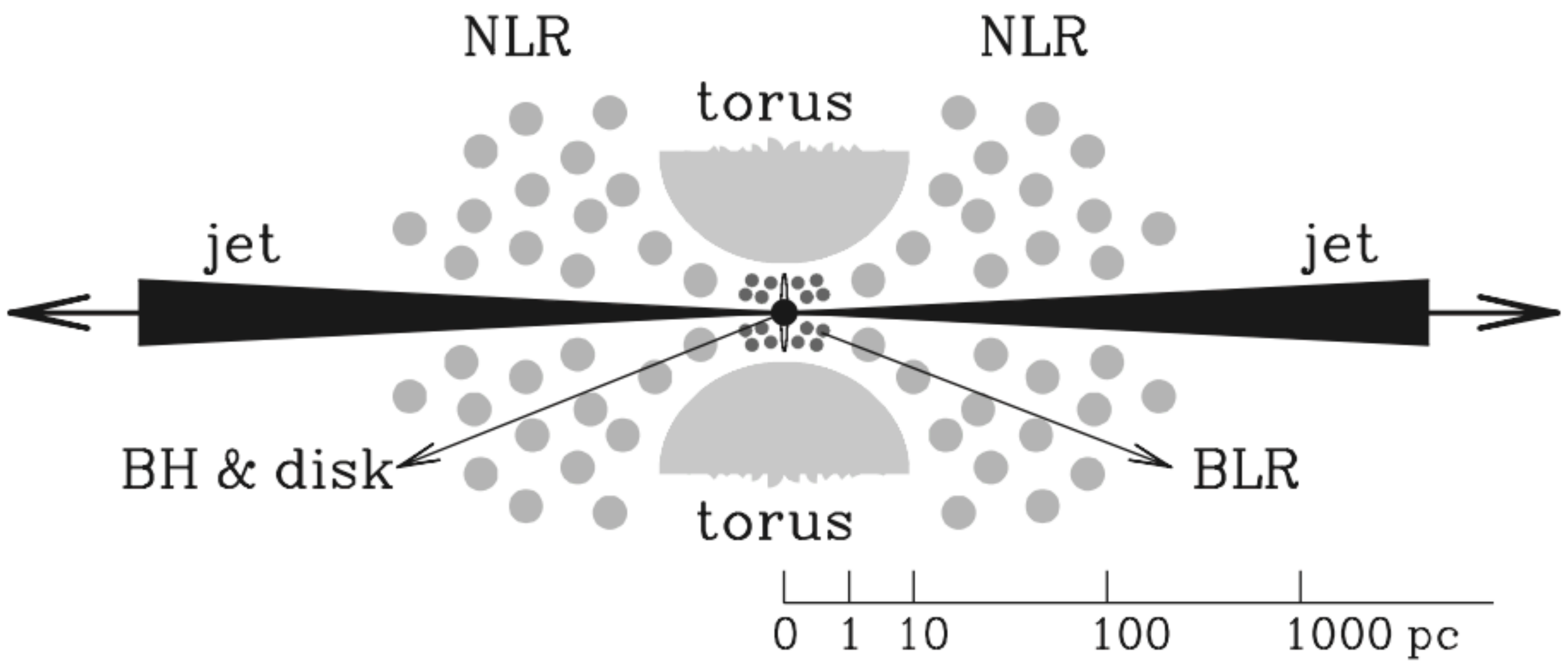


Credits: 0402371

13.2 AGN COMPONENTS

- The small size of the emission region and the large amount of energy output suggest that the central engine is a supermassive black hole (SMBH).
- In addition to the SMBH, the standard model also assumes the existence of a broad-line region (BLR), a narrow-line region (NLR), an accretion disk, a torus and jets.



Credits: Fig. 14.3, MBW

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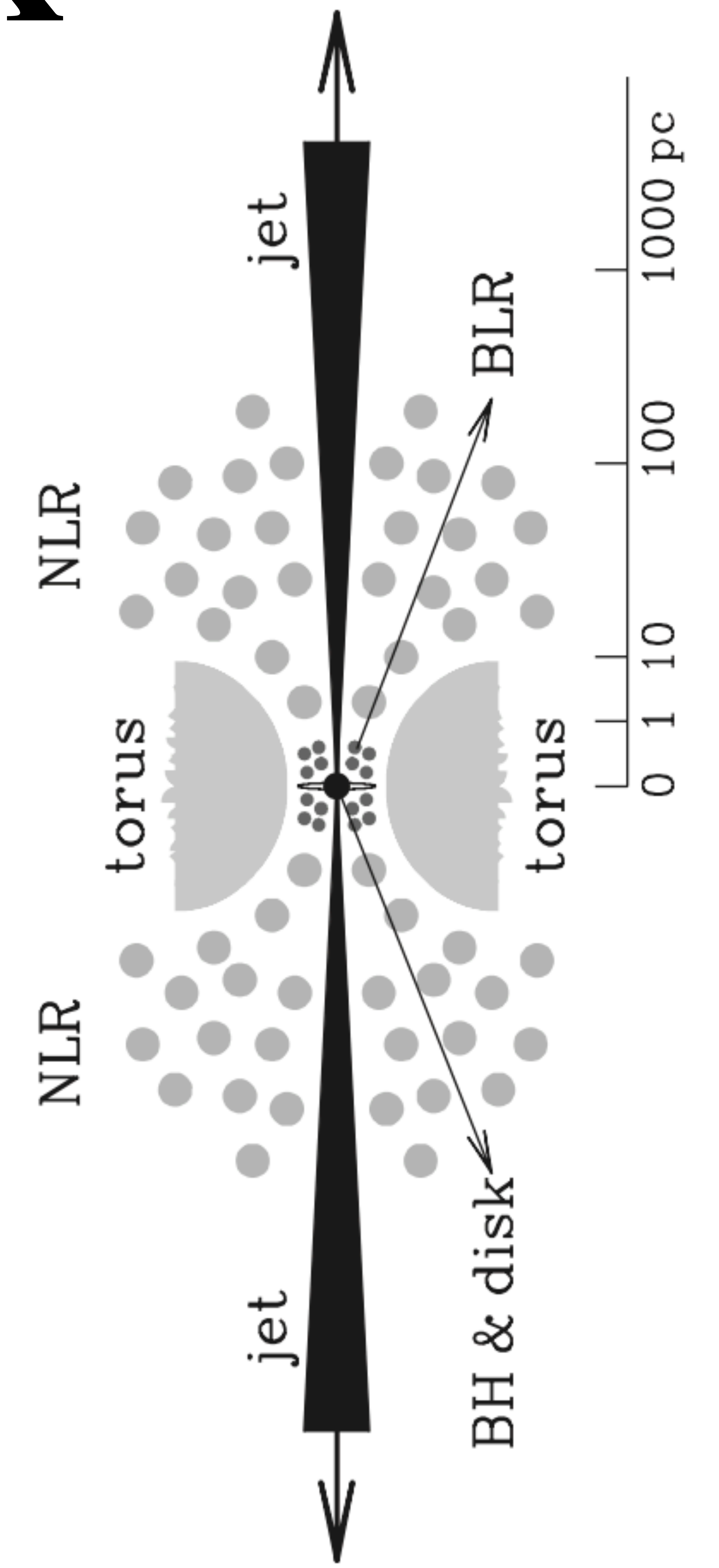
13.2.1 AGN FEEDBACK



Credits: Fig. 14.3, MBW

- **The energy can be estimated by equating the radiation pressure with the gravity on the gas**
- **The pressure at radius *r* is**

$$P_{\rm rad} = \frac{L}{4\pi r^2 c}$$

- **which results in a pressure force**

$$\mathbf{F} = \sigma_T P_{\rm rad}(r) n_e(r)\hat{\mathbf{r}}$$

- **The pressure force should be less than or equal to the gravitational force, in order to stop gas from dispersing.**

$$|\mathbf{F}_{\rm rad}| \leq F_{\rm grav} = \frac{G M_{\rm BH}\rho(r)}{r^2}$$

- **Hence,**
- **This sets an upper limit to the luminosity for a given black hole mass**

$$L_{\rm edd} = \frac{4\pi G c m_p}{\sigma_T} M_{\rm BH} \approx 1.28 \times 10^{46} \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right) \,{\rm ergs^{-1}}$$

13.2.2 AGN FEEDBACK

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- Assuming that the luminosity is powered by the gravitational potential of the BH, in-falling material will release radiation/energy at a rate

$$L = \frac{GM_{\rm BH}}{r}\dot{M}_{\rm BH}$$

- That allows us to define the efficiency at which the rest mass of accreted material is converted into radiation is

$$\epsilon_r = \frac{L}{\dot{M}_{\rm BH}c^2} = \frac{1}{2}\frac{r_S}{r}, \qquad r_s = \frac{2GM_{\rm BH}}{c^2}$$

- Since the bulk of the continuum radiation originates from $r \sim 5r_S$, $\varepsilon_r \sim 0.1$ (whereas for hydrogen fusion $\varepsilon \sim 0.007$). To power an $L \sim 10^{46}$ $ergs^{-1}$ quasar requires an accretion rate of 2 solar masses per year.

13.2.3 ACCRETION DISCS

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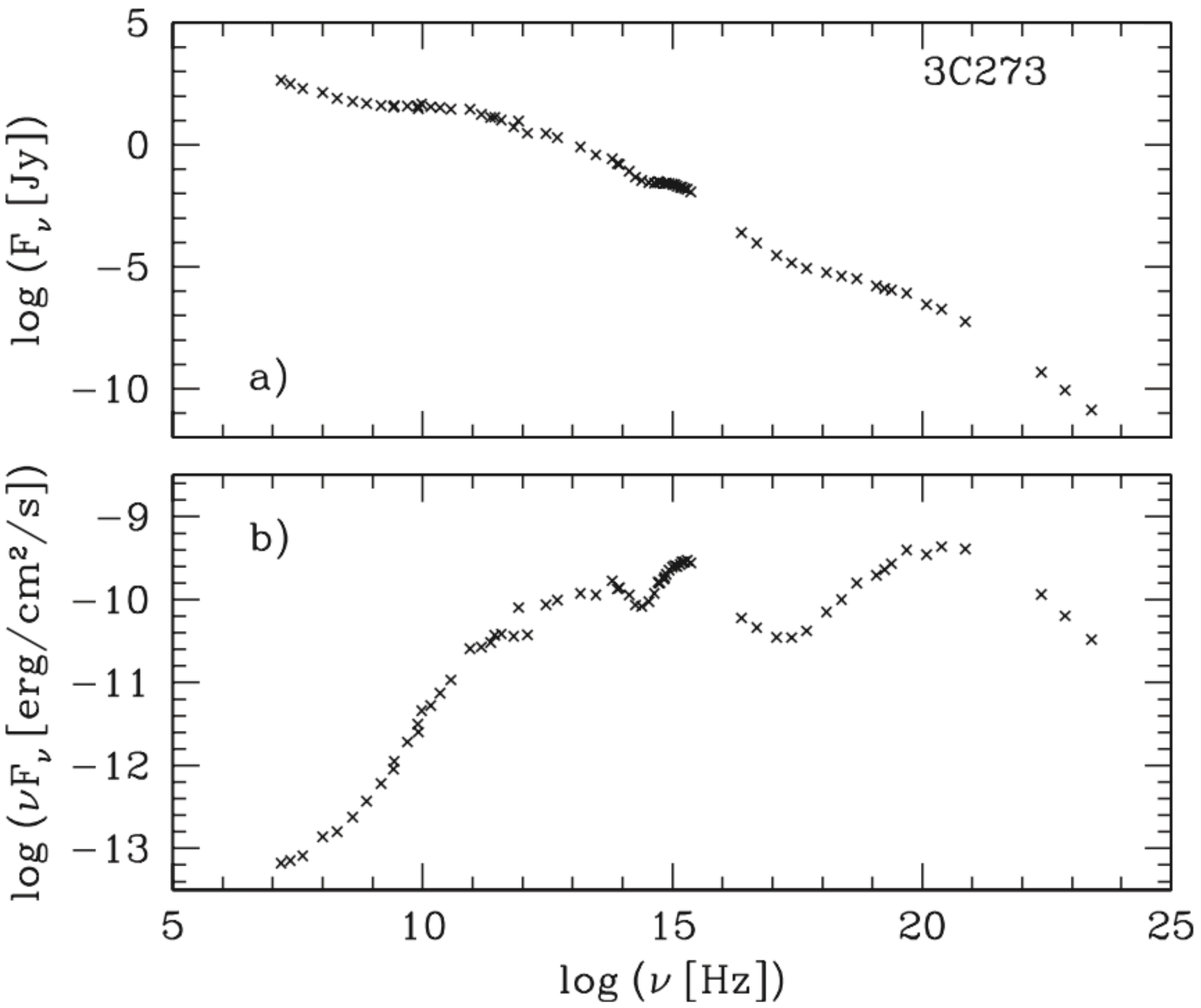
- Since the gas to be accreted by a supermassive BH in general has angular momentum, the accretion will most likely take place through a Keplerian accretion disc.
- Mass is assumed to be moving inwards as a result of angular momentum losses (due to e.g. turbulence and magnetic fields) which emerge from the "friction" between adjacent layers
- The emission of an accretion disk is connected to its temperature structure which can be written as

$$T(R) \sim 6.3 \times 10^5 \left(\frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm edd}}\right)^{1/4} \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{-1/4} \left(\frac{R}{r_S}\right)^{-3/4} \ {\rm K}$$

- and implies that most emission comes from the inner disk, where T is the highest.

13.3 EMISSION

- **AGNs have typically a very broad spectrum, which can roughly be described by a power law**
- **The SED contains the blue bump around 10^{15}-10^{16} Hz and a broad bump around 10^{20}-10^{21} Hz.**
- **A variety of emission mechanisms is involved, with relativistic electrons playing a crucial role.**



Credits: Fig. 14.4, MBW

13.3.1 SYNCHROTRON EMISSION

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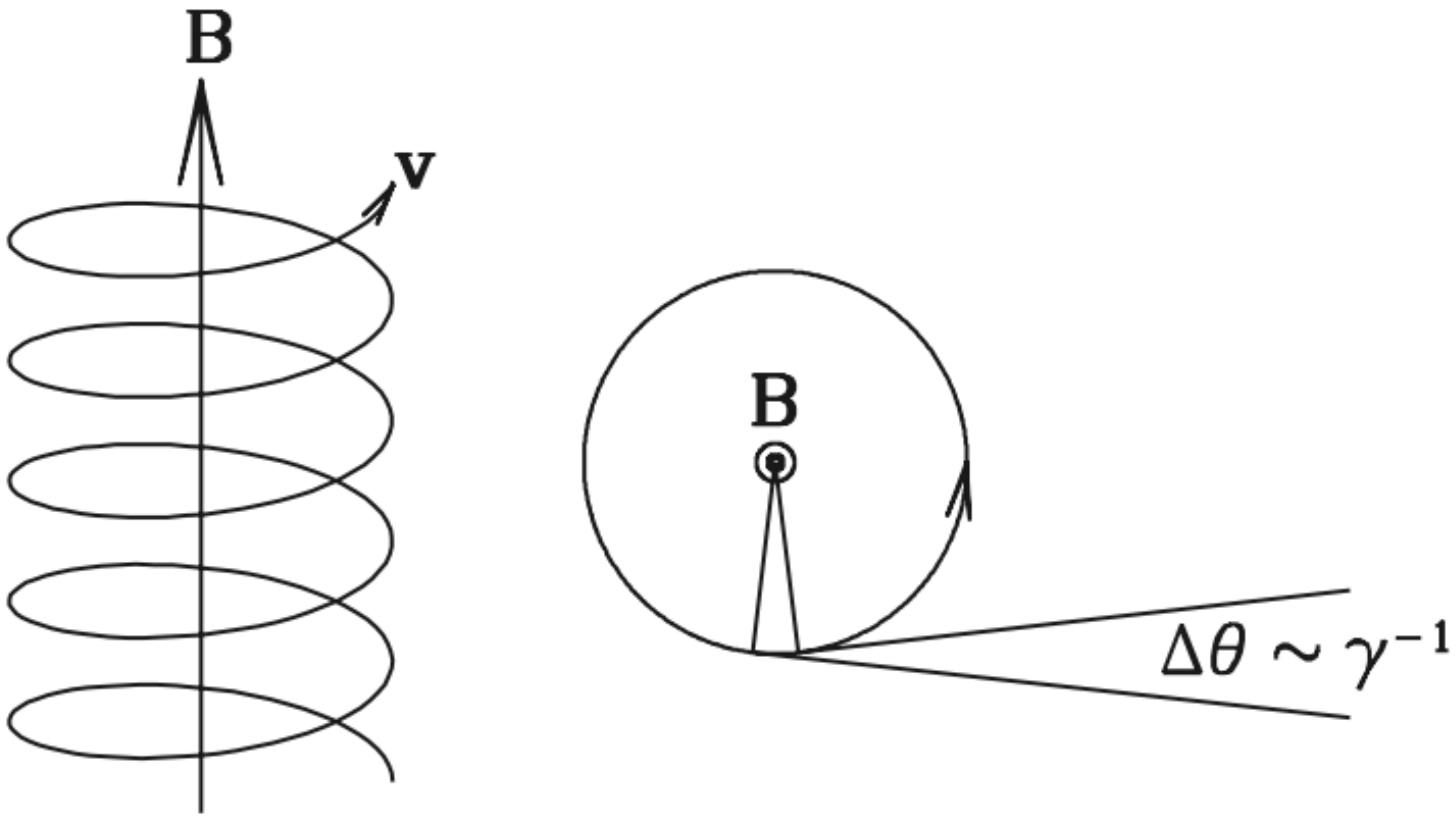
- Accelerated charged particles radiate photons
- Synchrotron emission is generated by relativistic electrons spiralling in a magnetic field. The radiation is beamed into a forward cone with opening angle $\Delta\theta \sim \gamma^{-1}$, where $\gamma=[1-(v/c)^2]^{-1/2}$ is the Lorentz factor.
- Synchrotron radiation is received by an observer as short pulses, whose width and interval contain useful information about the source.



Credits: Fig. 14.5, MBW

13.3.2 INVERSE COMPTON SCATTERING

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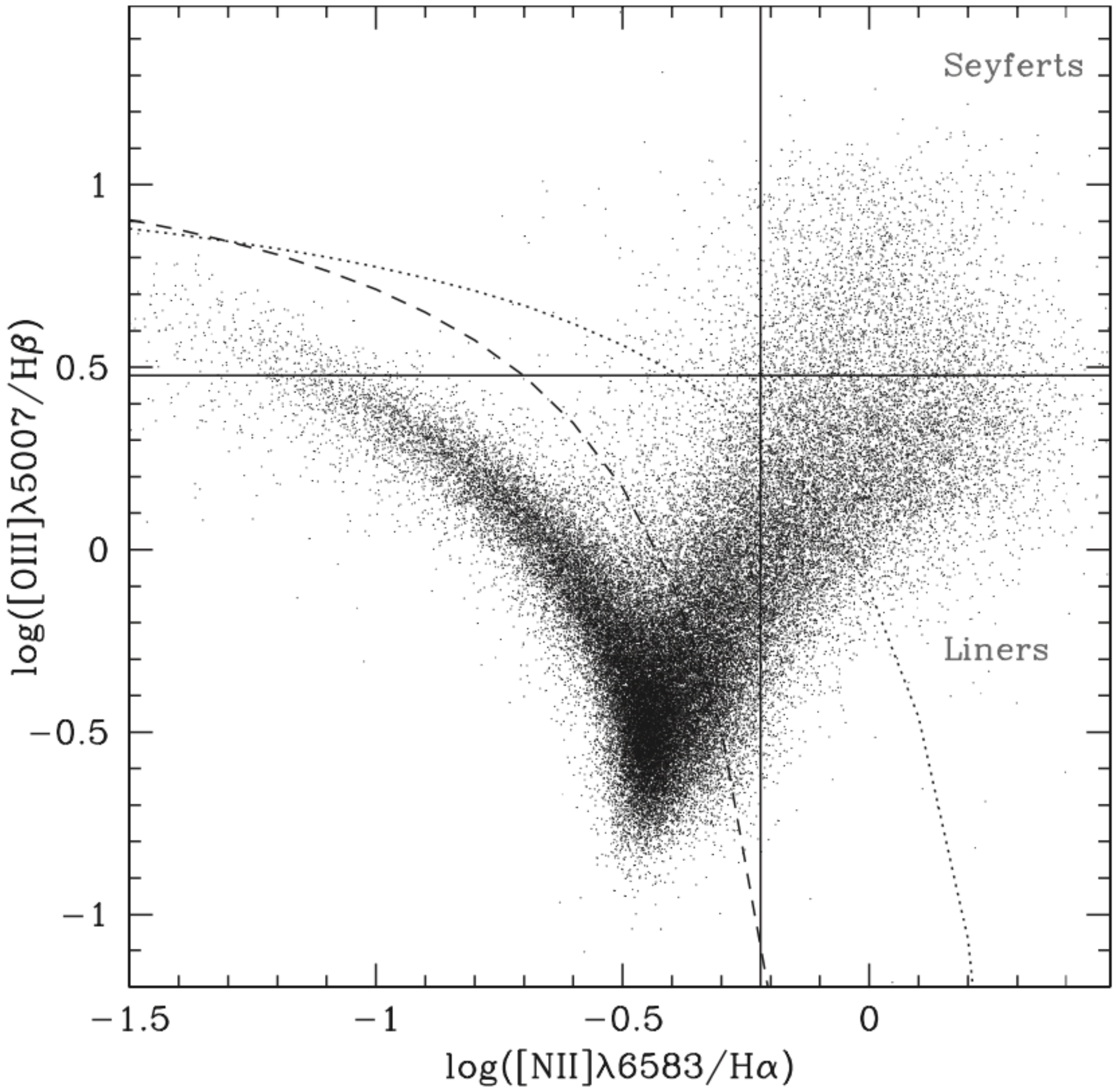
- In this mechanism high-energy electrons scatter inelastically with lower energy photons increasing substantially their energies. The net effect is emission of radiative energy from the electrons typically at X-ray and gamma-ray energies.
- The relative importance between the Compton and synchrotron cooling can be estimated by

$$\frac{\langle P_{IC} \rangle}{\langle P_S \rangle} \sim \left(\frac{T_b}{10^{12}\ \mathrm{K}} \right)^5 \left(\frac{\nu_e}{1\ \mathrm{GHz}} \right)$$

- Above $T_B \sim 10^{12}$ K inverse Compton cooling dominates. This implies that the brightness temperature of the synchrotron emission must in general be below 10^{12} K in order for the electrons to remain relativistic.

13.3.3 EMISSION LINES

- **Emission line ratios can be used to separate active from star-forming galaxies (aka BPT diagram).**
- **The strong UV flux of AGN galaxies results in higher temperature and level of ionisation. On the other hand, star-forming galaxies' spectra contain emissions from the HII regions generated by young massive stars.**



Credits: Fig. 14.6, MBW

13.3.4 EMISSION LINES REGIONS AND TORUS

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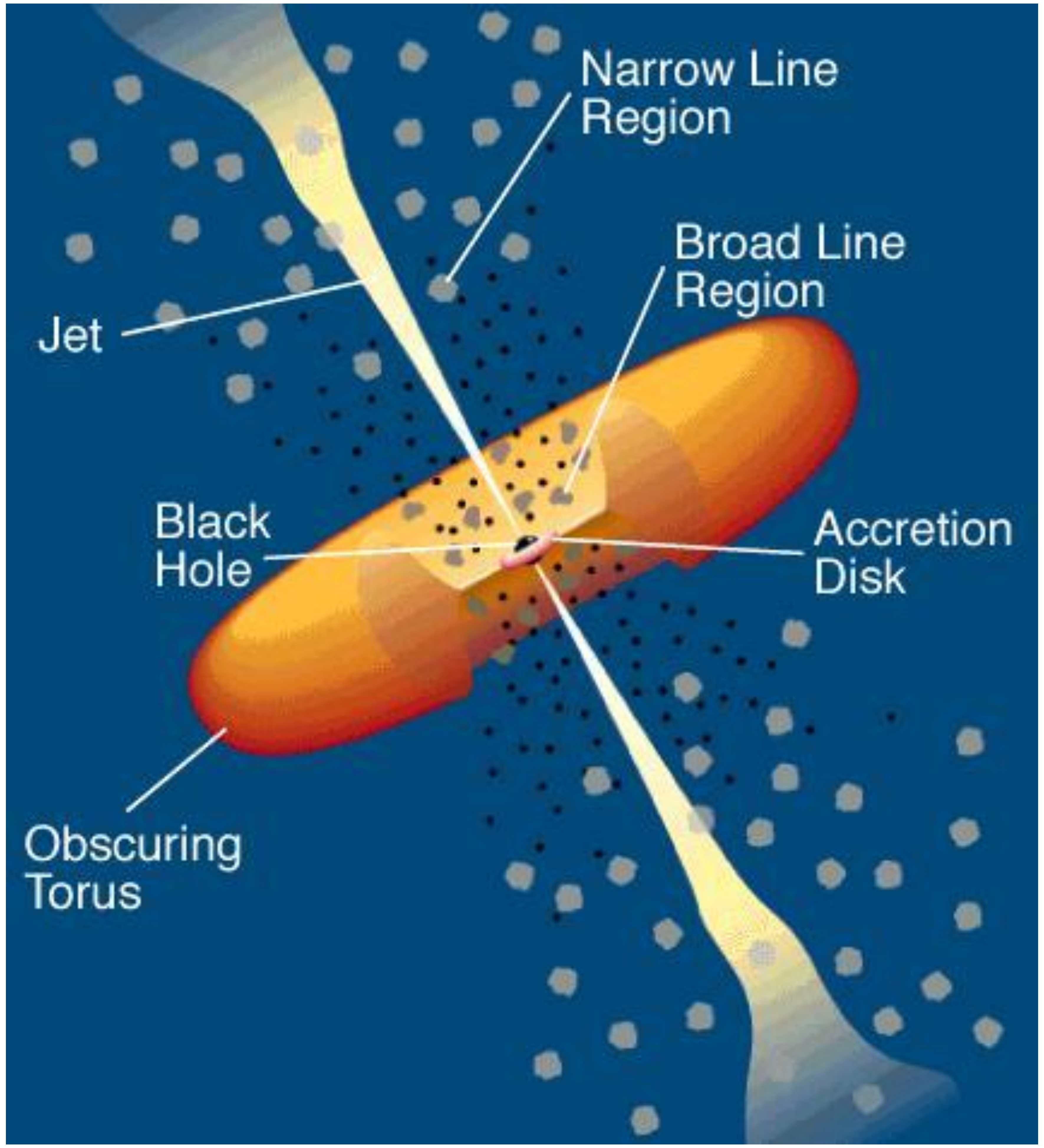
- **Broad-line region: The broad lines with velocity widths of the order of ~1000 km/s suggests that these lines are produced in a small inner region (≲0.5 pc) surrounding the accretion disk.**
- **Narrow-line region: Many AGNs reveal strong narrow lines with velocity widths of ~100 km/s. These lines are produced in a region of size ~50 pc around the central engine.**
- **Obscuring Torus: The innermost region is covered in an obscuring torus, which blocks our line-of-sight in type II AGNs. The torus must have a large column density of gas in order to block the BLR and strong X-ray and UV radiation. The torus is most probably clumpy.**



Credits: Urry & Padovani, 1995

13.4 JETS

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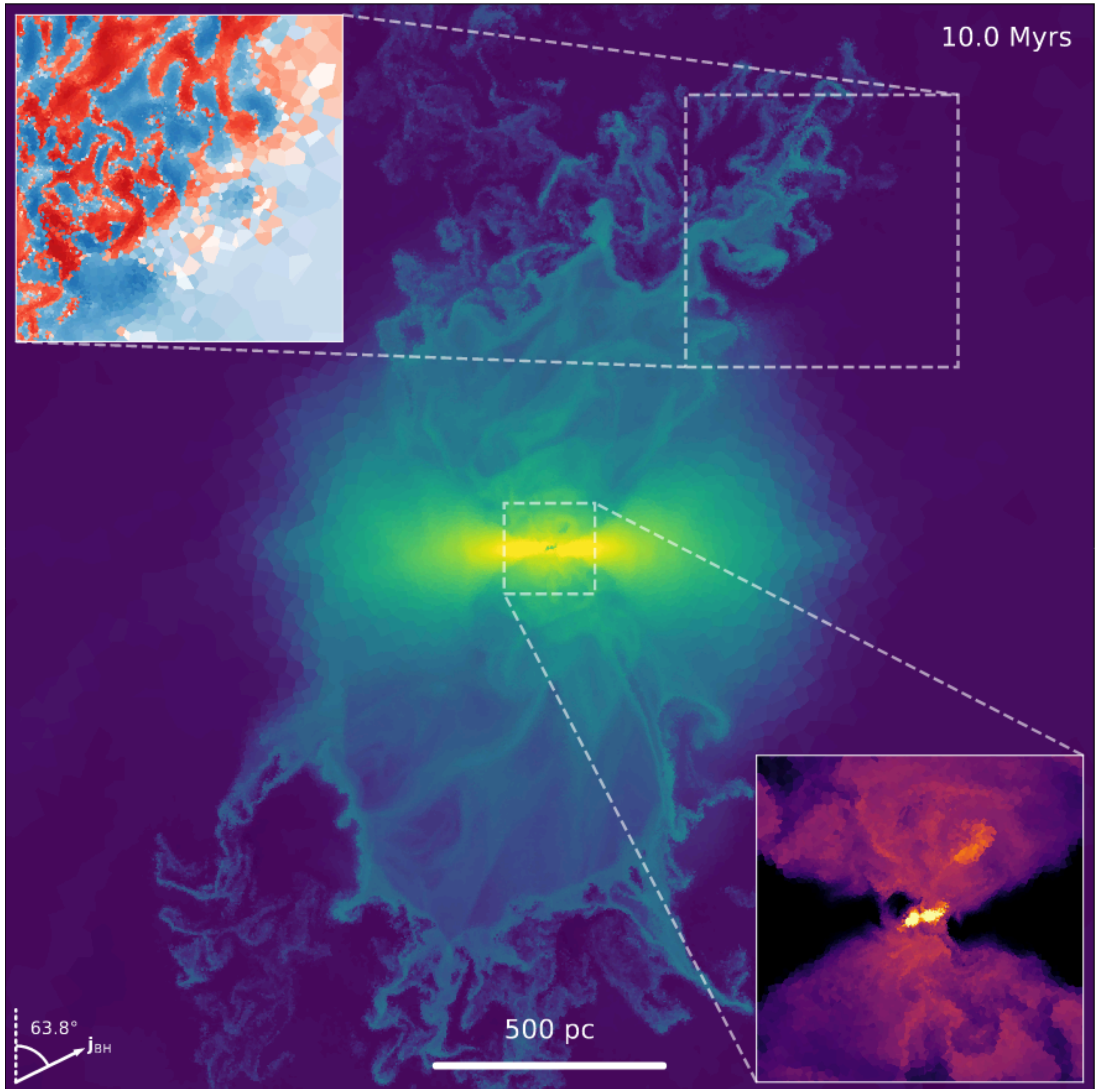
- Jets are collimated outflows of material and are observed in many radio galaxies. In some cases a thin jet with width of ~1 pc is observed to extend continuously from the innermost parsec-scale region of a galaxy to a distance up to several hundreds of kiloparsecs.
- The physics of jets is not fully understood. In the standard model by Blandford&Rees74 what is needed is an internally relativistic fluid and a relatively small pressure gradient in the medium that confines the jet and the initial flow in some direction.
- Superluminal motions: When matter is moving close to the line-of-sight at relativistic velocities apparent superluminal motions can be detected. Another relativistic effect is relativistic beaming, which brightens the approaching jet and dims the receding jet causing apparent one-sided jets.



Credits: Talbot+21, 2011.10580

13.5 FORMATION AND GROWTH OF BLACK HOLES

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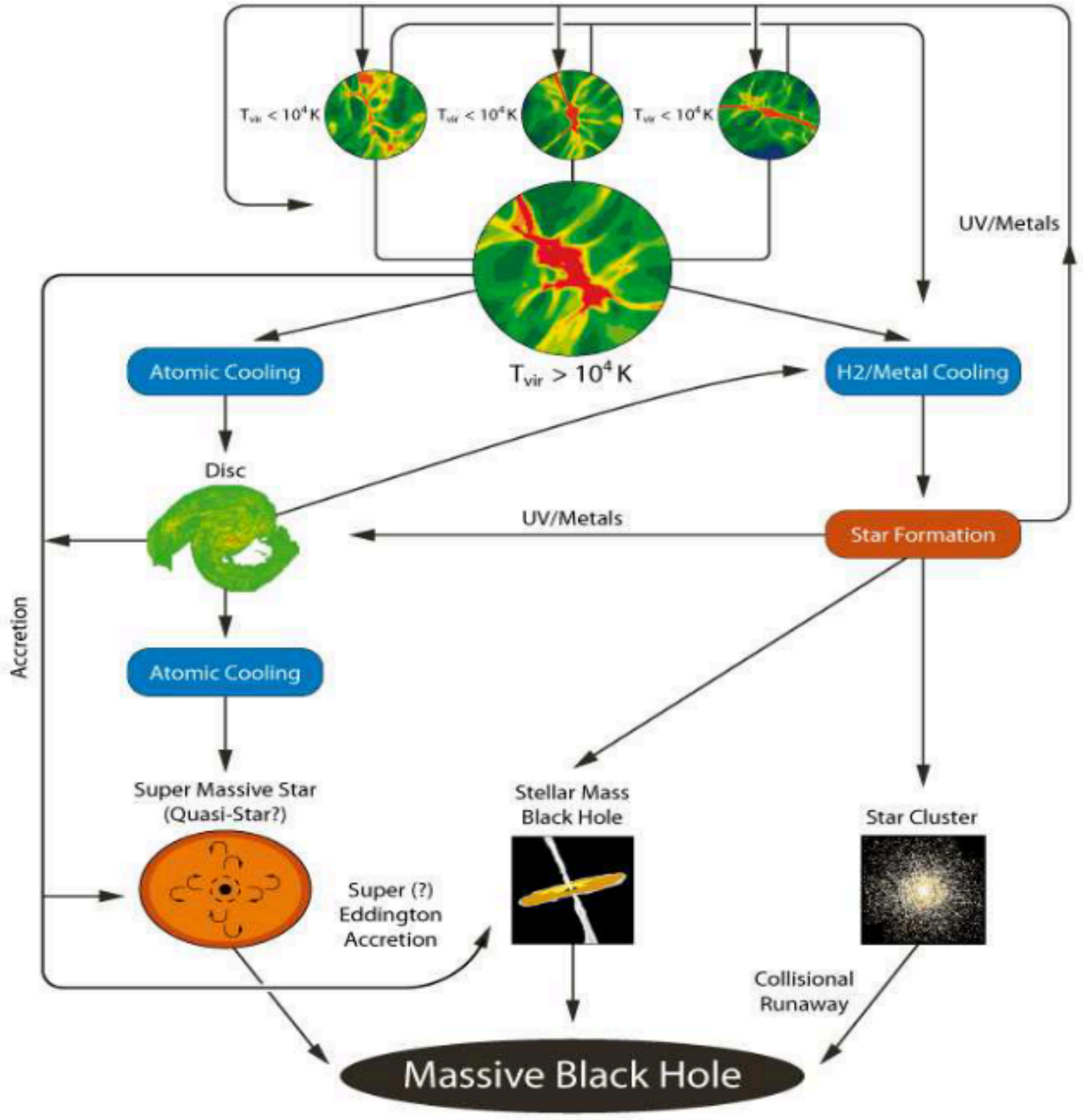
- The formation mechanism of SMBHs at high redshift is uncertain. There are two leading models
  - PopIII remnants: The first stars in the Universe were presumably very massive (>50 $M_\odot$). Black holes formed from the death of these stars should have masses of the order ~10 $M_\odot$.
  - Direct collapse: There were no metals in the early Universe and it is possible that the inefficient cooling resulted in near isothermal collapse of 10^4-10^5 $M_\odot$ gas clouds resulting in more massive SMBHs.



Credits: Regan, 0810.2802

13.5.1 FORMATION AND GROWTH OF BLACK HOLES

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- **One important fact that any theory of AGN formation must take into account is the observation that quasars with MBH~10^9 M$\odot$ exist at z~7 (t~0.7 Gyr).**

- **Since black holes form in collapsed objects, the free-fall time scale of a virialized halo t_{ff}~r_{vir}/V_C~1/[10H(z)] must also be considered. At z~7 t_{ff} is about 50 million years.**

- **If the growth of the SMBH is through radiative accretion the mass accretion can be written as:**

$$\dot{M}_{\rm BH} = \frac{L}{\epsilon_r c^2} = \left(\frac{L}{L_{\rm edd}}\right)\frac{M_{\rm BH}}{\epsilon_r t_{\rm edd}} \quad t_{\rm Edd} = \frac{\sigma_T c}{4\pi G m_p} \approx 4.4\times 10^8 \text{ yr}$$

- **If L/Ledd and ε_r are independent of time:**

$$M_{\rm BH}(t) = M_{\rm BH,0}\, e^{t/t_{\rm BH}}$$

$$t_{\rm BH} = (L/L_{\rm edd})^{-1}\epsilon_r t_{\rm edd} \approx 4.4\times 10^7 (\epsilon_r/0.1)(L/L_{\rm edd})^{-1} \text{ yr}$$

13.5.2 FORMATION AND GROWTH OF BLACK HOLES

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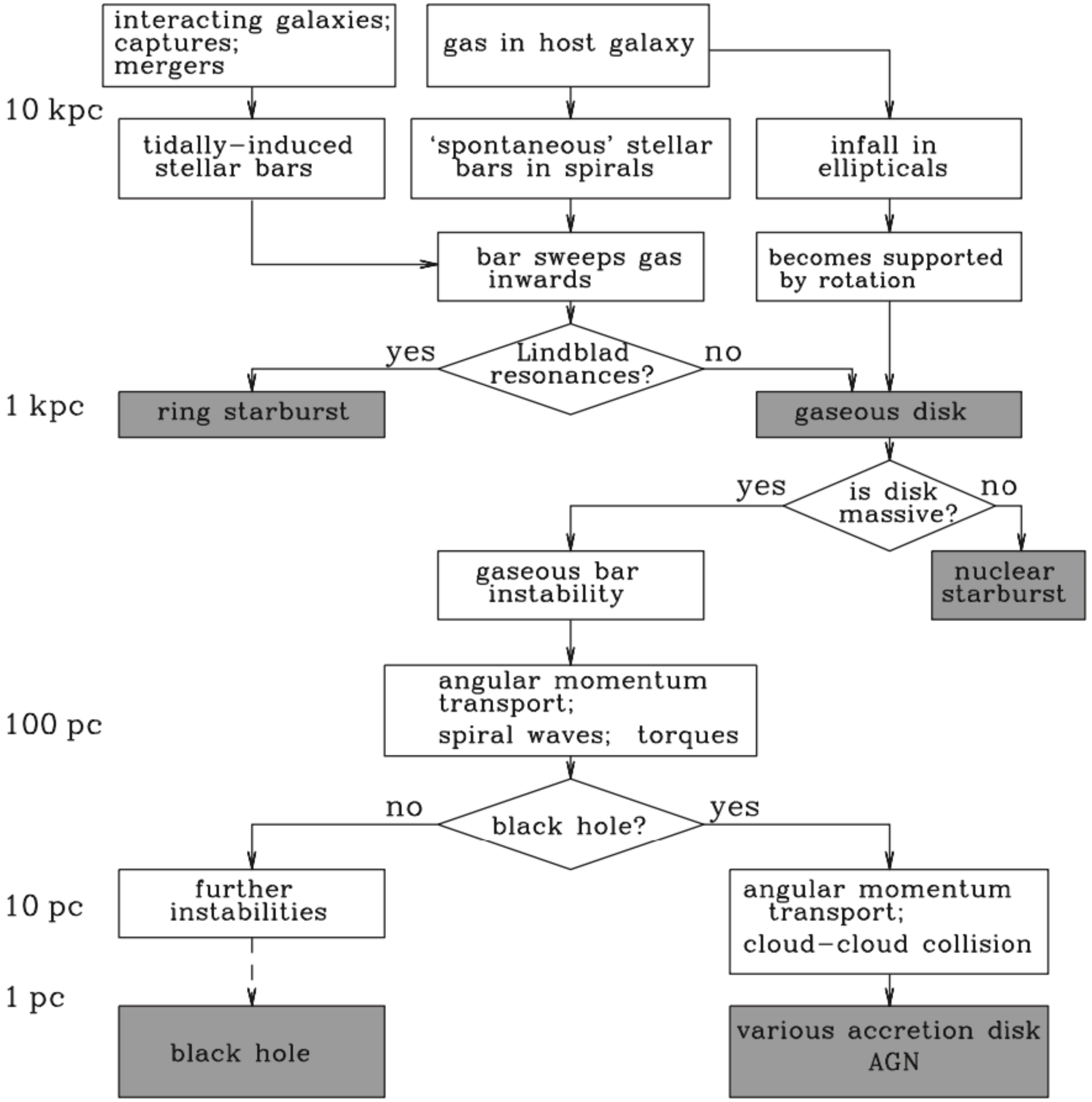
- **The time required for a black hole to reach M_{BH}~10^8 $M_\odot$ depends on the seed mass. If the seed mass $M_{BH,0}$=100 $M_\odot$ we require 14 e-foldings to grow to 10^8 $M_\odot$**

$$t \approx 14 t_{\rm BH} \approx 6 \times 10^8 \left(\frac{\epsilon_r}{0.1}\right)\left(\frac{L}{L_{\rm edd}}\right)^{-1} \ \mathrm{yr}$$

- **In order to achieve a sufficiently high growth rate, either the gas accretion should be at a super-Eddington rate or the radiative efficiency should be very low.**



Credits: Fig. 14.7, MBW

13.5.3 FORMATION AND GROWTH OF BLACK HOLES

- A key step towards understanding the formation of AGN is to identify the mechanisms that can effectively bring gas to the centre of the host galaxy and feed the SMBH.
- The amount of gas involved in SMBH formation is only a small fraction of the total mass of the host galaxy. The problem is that the available gas in the galaxy needs to lose its angular momentum. The specific angular momentum is $j \sim (GMR)^{1/2}$. A parcel of gas with $M \sim 10^{11}\ M_\odot$ and at $R \sim 10$ kpc needs to reduce its angular momentum by a factor of 10^4 to move to ~0.1 pc away from a $10^8\ M_\odot$ BH.
- The prime mechanisms for achieving this is mergers between galaxies, which generate strong tidal torques. Another possible mechanism is internal secular processes in massive disks that cause bar instabilities and radial gas inflows.

13.5.4 FORMATION AND GROWTH OF BLACK HOLES

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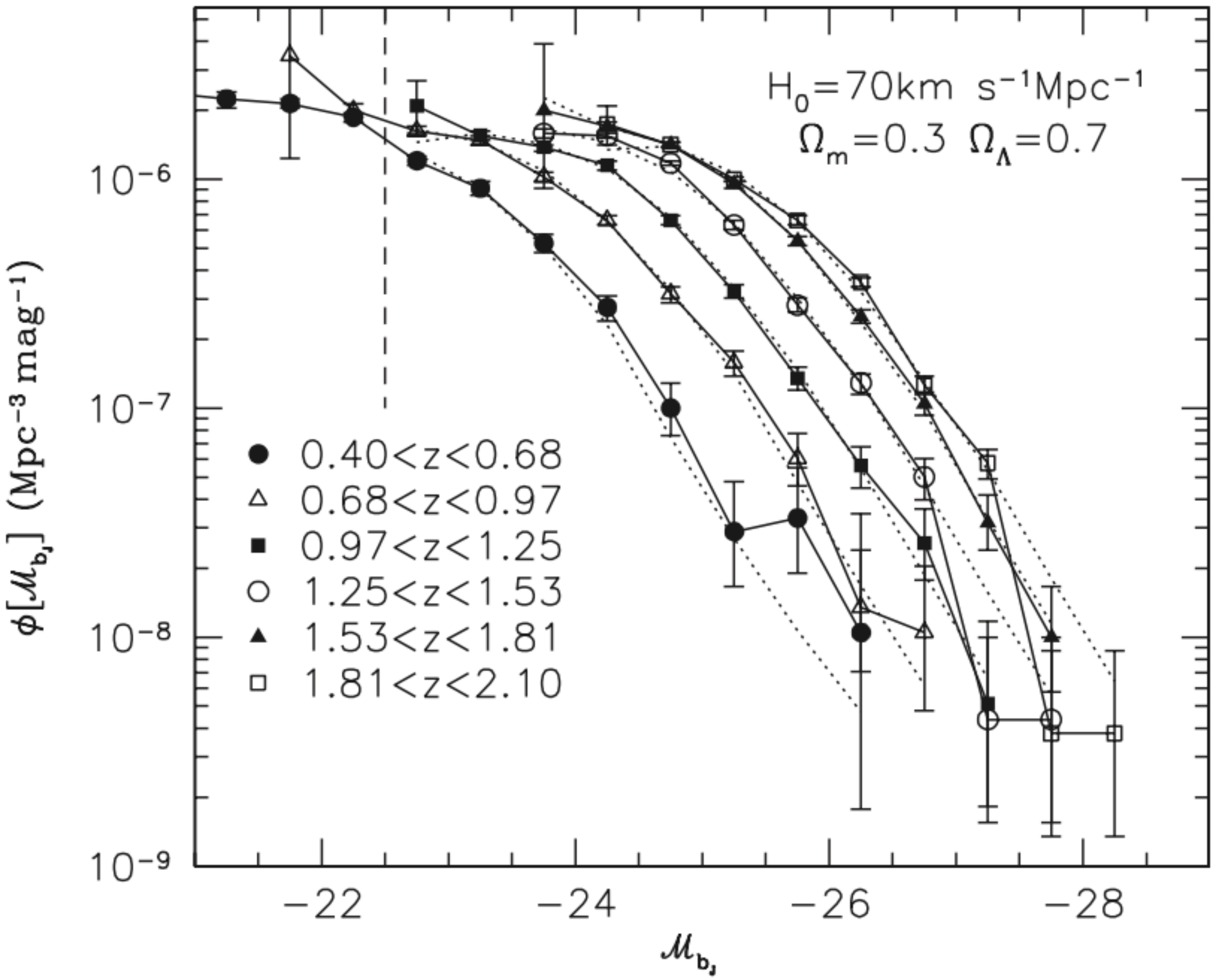
- The formation scenario discussed above implies strong evolution in the AGN population.
- The observed luminosity function of quasars can be fitted by the luminosity function with β_1=3.9 and β_2=1.5

$$\phi(L,z)dL = \phi^*(z)\left\{\left[\frac{L}{L^*(z)}\right]^{\beta_1} + \left[\frac{L}{L^*(z)}\right]^{\beta_2}\right\}^{-1}\frac{dL}{L^*(z)}$$

- The data shows that the number density is independent of redshift.



Credits: Fig. 14.8, MBW

13.5.5 AGN FEEDBACK

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- AGNs can release a huge amount of energy during their lifetimes, $$\frac{dE}{dt} = \epsilon \dot{M}_{\rm BH} c^2$$
- where $\varepsilon=\varepsilon_r+\varepsilon_m$ is an efficiency factor the combines the radiative and mechanical feedback efficiencies.
- We can compare this energy output to the binding energy of the galaxy, which according to the virial theorem is $W \sim -M_{gal}\sigma^2$:

$$\frac{E}{|W|} \sim \frac{\bar{\epsilon} M_{\rm BH}}{M_{\rm gal}} \left(\frac{c}{\sigma}\right)^2$$

- $M_{BH}/M_{gal} \sim 10^{-3}$ and for $\sigma \sim 300$ kms^{-1}, the ratio is $E/|W|=10^3\varepsilon$ indicating that the AGN energy can easily surpass the total binding energy of the galaxy.
- There are two outstanding questions: 1) What is the value of the feedback efficiency ε and 2) how effective is the coupling of the feedback energy to the surrounding gas.

13.5.5 AGN FEEDBACK: THERMAL

- **In radiative feedback models the radiative efficiency is about $\varepsilon_r \sim 0.1$ in bright AGNs. This energy can in principle feed back into the environment through both radiation pressure and radiative heating.**
- **UV photons from the AGN can ionise the surrounding medium in galaxies and in the intergalactic medium. This heating can significantly suppress gas cooling and star formation.**
- **If the host galaxy of an AGN contains a significant amount of dust the radiation from the central AGN can be effectively channelled into the surrounding gas by dust absorption.**
- **Radiation pressure can accelerate small amounts of matter to the very high observed velocities ($v \sim 0.2c$).**
- **The feedback efficiencies are highly uncertain, but the common assumption is that about ~5% of the total radiative energy is coupled to the gas, resulting in an overall efficiency of ~0.5%**

13.5.6 AGN FEEDBACK: MECHANICAL

- **During the low-accretion mode of an AGN, when the accretion rate of the SMBH is much lower than the Eddington rate, AGN feedback is believed to proceed mainly through radiatively inefficient, mechanical forms, such as radio jets and lobes.**
- **Evidence for such energy feedback can be seen in a number of elliptical galaxies at the centres of galaxy clusters, which contain X-ray cavities filled with relativistic gas.**
- **During the expansion of jet-powered bubbles we can assume that there is no radiative cooling in the bubbles, because the gas density is low and the temperature is high. The expansion of the bubble will slow down as material is swept up, but during the supersonic phase energy will be deposited in the medium through shocks. AGN feedback has been important in all massive galaxies as they contain relic SMBHs.**

WHAT HAVE WE LEARNT?

- **AGNs are characterised by broad spectral energy distributions consistent with the fact that the radiation is of a non-thermal origin, such as synchrotron and inverse Compton radiation.**
- **The AGN population can be explained by the unification model in which the differences between different AGN populations is mainly related to our observed line-of-sight. In type I AGNs we have a more direct view and observe the broad-line regions, whereas in type II AGNs the torus obscures the radiation and we can only see the narrow-line regions.**
- **SMBHs can form either from Pop III remnants (~10-100 $M_\odot$) or by direct collapse of gas clouds (~10^4-10^5 $M_\odot$). The growth of the SMBHs is limited by the Eddington limit and growing to the observed masses of SMBHs by z~7 is difficult.**
- **AGNs affect the growth of massive galaxies through radiative and mechanical feedback and the SMBHs presumably co-evolve with their host galaxies as manifested in the M_{BH}-s relation.**