We apply the closed-box model:

$$M_s(\geq u) = (1-u)M \Rightarrow \frac{M_s(\geq u)}{M_{s,0}} = \frac{1-u}{1-u_0} \tag{254}$$

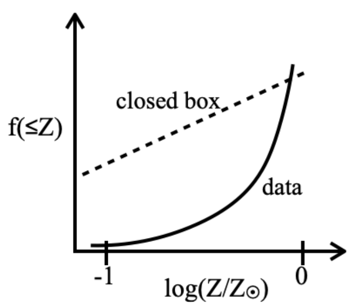
where $M_s(\geq u)$ is the mass of stars formed while the gas fraction was $\geq u$ and $..._0$ refer to present-day values.

Then the stellar mass fraction $M_s(\geq u)/M$ was made from gas with $Z \leq y\ln(1/u)$ and we can rewrite the stellar mass fraction using $u = e^{-Z/y}$ and $u_0 = e^{-Z_0/y}$:

$$\frac{M_s(\leq Z)}{M_{s,0}} = \frac{1-e^{-Z/y}}{1-u_0} = \frac{1-u_0^{Z/Z_0}}{1-u_0}\ . \tag{255}$$

Then we can get the fraction of stellar mass with metallicity $\leq Z$:

$$f(\leq Z) = \frac{M_s(\leq Z)}{M_{s,0}} = \frac{1-u_0^{Z/Z_0}}{1-u_0}\ . \tag{256}$$



However, the model does not agree well with the data because the model is incomplete (infalls, variations in the IMF, etc.).

3.G Active galaxies (AGN)

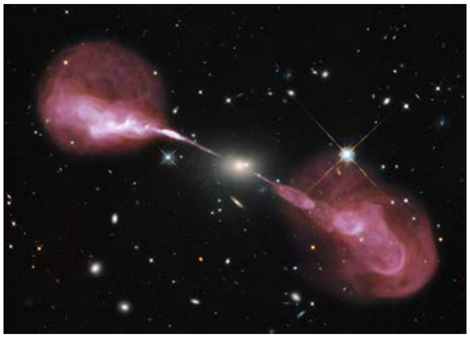
AGN is Active Galactic Nucleus.
Definition:

- Galaxies whose total luminosity is dominated by radiation not produced in stars. Stars produce near-UV, optical, and near-IR light in blackbodies. Other sources may emit radio or X-ray light.
- The energy generation is associated with a point-like source at the nucleus of the galaxy ($\sim$ black hole with mass $10^6 - 10^9 M_\odot$).

AGN types:

- Radio galaxies:

- high radio luminosity $L_{\text{radio}} \geq 10^{18} L_{\odot}$
- radio emission from two external regions (radio lobes)
- energized by jets (particle acceleration $E_e \sim 10^{12}$ eV
- $\sim 50\%$ E0/S0 galaxies, $\sim 50\%$ quasars
- synchrotron emission of electrons



Hercules A galaxy

NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

- Quasars/QSO:
  - Quasar (quasi-stellar radio source): optical point source with radio jet
  - QSO (quasi-stellar object): like a quasar but no radio emission
  - Quasars and QSO's are similar phenomena, 90% of optically found QSO's are radio quiet, $\sim 10\%$ are radio loud
  - mostly found in elliptical galaxies
  - $L_{\text{quasar}} \sim 10^{45-48}$ erg/s
  - synchrotron jets between 0.1 pc-1 Mpc
  - maximum space density $\sim z = 2 - 3$

Einstein Cross gravitational lens

J.Rhoads, S.Malhotra, I.Dell'Antonio (NOAO)/WIYN/NOIRLab/NSF.

- BL Lac objects:
  - quasar with enhanced continuum emission
  - highly variable
  - extremely luminous
  - highly polarized
  - jet pointing towards observer

Markarian 501 galaxy

Sloan Digital Sky Survey on Wikimedia Commons.

- Seyfert galaxies:

- spiral galaxies
- bright unresolved nuclei (less luminous than quasars)
- $L \approx 10^{42} - 10^{45}$ erg/s


Spanish Dancer galaxy

Structure of AGN physics:
Sizes: changes of state of the emission region propagate at maximum speed c. Variability means state change:

$$\Delta t_{\text{variable}} c \sim r_{\text{emission}} \tag{257}$$

In the radio/optical band:

$$\Delta t_{\text{variable}} \sim 1 - 10 \text{ days}$$
$$r_{\text{emission}} \sim 10^{-3} - 10^{-2} \text{ pc}$$

At TeV energies:

$$\Delta t_{\text{variable}} \sim 1 \text{ day}$$
$$r_{\text{emission}} \sim 10^{-3} \text{ pc}$$

We can compare this to the Schwarzschild radius for a black hole with mass $M_\bullet$:

$$R_s = \frac{2GM_\bullet}{c^2} \tag{258}$$

which gives a size for various masses:

$$\begin{aligned} M_\bullet &= 10^6 M_\odot \to R_s = 10^{-7} \text{ pc} \\ M_\bullet &= 10^7 M_\odot \to R_s = 10^{-6} \text{ pc} \\ M_\bullet &= 10^9 M_\odot \to R_s = 10^{-4} \text{ pc} \end{aligned} \tag{259}$$

which gives the variability in the vicinity of a supermassive black hole.

We can consider various possible energy sources for the observed variability:

- Stars: $N_* = 3 \times 10^8$ O-type stars in the central region to get the necessary luminosity (O stars have luminosity of $\sim 10^{5.5} L_\odot$), but this leads to a stellar density that is too high and would be unstable.
- Supernovae: the energy of a supernova is $E_{\text{SN}} \sim 10^{52}$ erg, so we would need 10^{10} supernovae within 10^{-3} pc in 10^7 years. This would require producing 10^{10} stars continually, which has the same problem as the source being stars (too dense and unstable).
- We need accretion onto a supermassive black hole to create the luminosity.

Accretion onto supermassive black holes (SMBH):
Idea: a supermassive black hole ($M_\bullet \sim 10^6 - 10^{9.5}\mathrm{M}_\odot$) accretes $10^{-4} - 10\ \mathrm{M}_\odot/$ yr. Jets and nonthermal radiation are created by the accretion disk (gravitational energy is converted to thermal energy and radiation).

The radiative efficiency of this process is $\frac{1}{16}$, so the luminosity of the accretion disk is approximately given by:

$$L_{\mathrm{acc}} \approx \frac{1}{16}\dot{m}c^2 \tag{260}$$

which means that 1 g of material produces approximately 10^6 kwh. We can compare the efficiency of an accretion disk ($\frac{1}{16}$) to the efficiency of hydrogen burning, which is 0.007 (so $L_{\mathrm{H-burning}} \approx 0.007\dot{m}c^2$).

The *Eddington luminosity* is the maximum possible AGN luminosity, which is reached when the radiation pressure exceeds the gravitational acceleration per area. This comes from processes like Thomson scattering. The radiation pressure is given by

$$P_\gamma = \frac{E}{c} = \frac{h\nu}{c}\ . \tag{261}$$

We can write the momentum per time (equivalent to force) as L/c, so the pressure is force per area

$$P_{\mathrm{total}} = \frac{L}{4\pi r^2 c}\ . \tag{262}$$

We find where the radiative force on a fully ionized plasma (i.e. the force on an e^-) exceeds the gravitational force on a proton for a black hole of mass $M_\bullet$:

$$\begin{aligned} F_{\mathrm{rad}} &> F_{\mathrm{grav}} \\ \frac{L}{4\pi r^2 c}\sigma_T &> \frac{GM_\bullet m_p}{r^2} \end{aligned} \tag{263}$$

where σ_T is the Thomson cross section, so the radiative force on an electron is $F_{\mathrm{rad}} = \sigma_T P_{\mathrm{total}}$. This gives the Eddington luminosity

$$\boxed{L_{\mathrm{edd}} = \frac{4\pi c G M_\bullet m_p}{\sigma_T} = 1.3\times 10^{38}\frac{M_\bullet}{M_\odot}\mathrm{erg/s}}\ . \tag{264}$$

To achieve AGN luminosities, the SMBH must be massive enough to to be blown apart.

This leads to the *Eddington accretion rate*, which is the maximal possible accretion rate possible for an accretion disk. This is reached for when L_{acc} exceeds L_{edd}:

$$\begin{aligned} L_{\mathrm{acc}} &> L_{\mathrm{edd}} \\ \frac{1}{16}\dot{m}c^2 &> 1.3\times 10^{38}\frac{M_\bullet}{M_\odot}\mathrm{erg/s} \end{aligned} \tag{265}$$

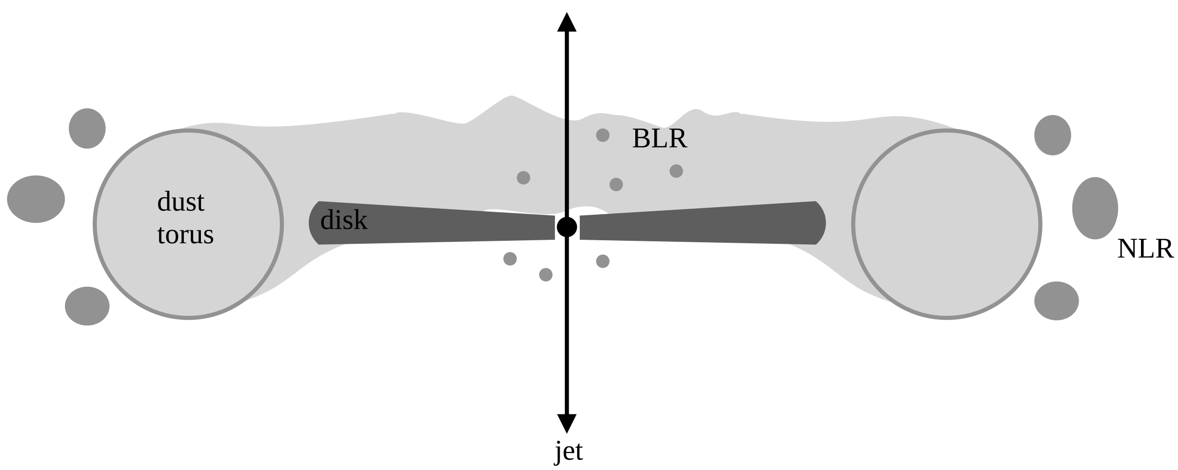
so $\dot{m}_{\mathrm{edd}}$ occurs when the two are equal:

$$\dot{m}_{\mathrm{edd}} = 5\times 10^{-10}\frac{M_\bullet}{M_\odot}\frac{M_\odot}{\mathrm{yrs}}\ . \tag{266}$$

An accretion disk is formed when gas spirals in from large distances until the innermost stable orbit (ISCO). Viscous processes in the disk lead to heating to temperatures $T \sim 10^8\,\mathrm{K}$. This is highly efficient in releasing energy.

Unified model of AGN:
Different AGN types are manifestations of the same phenomenon:

- SMBH at the center with $M_\bullet \sim 10^6 - 10^{10} \mathrm{M}_\odot$
- An accretion disk extending to $\sim 100 - 1000 r_s$ emits the X-ray, UV, optical, and TeV radiation
- Jets are made of radio synchrotron radiation from strong magnetic fields
- A dust torus from $\sim 1\,\mathrm{pc}$ to $\sim 50 - 100\,\mathrm{pc}$ produces IR emission
- Broad line region (BLR) formed from clouds of thick gas within $\sim 0.1 - 1\,\mathrm{pc}$ (velocities are faster near the black hole, $v \sim 10^4\,\mathrm{km/s}$
- Narrow line region (NLR) formed from clouds of thin gas within $\sim$few pc (farther away from the black hole, $v \sim 100 - 1000\,\mathrm{km/s}$. Slower velocities leads to less broadening of lines scattered in the clouds, hence narrow line region).



The observed manifestation depends on the viewing angle and the accretion rate. For example, BL Lac objects have a line of sight directly down the jet and a high accretion rate.