

# Active Galaxies

The formation and evolution of AGN  
AGN and galaxy formation

November 12, 2024

University of Rochester

## Origins of the central SMBH

Clearly, the SMBH must be quite different in origin from the stellar-mass black holes produced at the end of the lifetimes of massive stars. Since stars do not form larger than about  $100M_{\odot}$ , SMBHs could not have arisen via a stellar collapse.

In fact, the origin of supermassive black holes is not well understood.

- ▶ Leading models include primordial black holes, or black holes formed from ultra-dense dark matter cores in proto-galaxy nuclei.

A black hole's mass grows at a rate

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

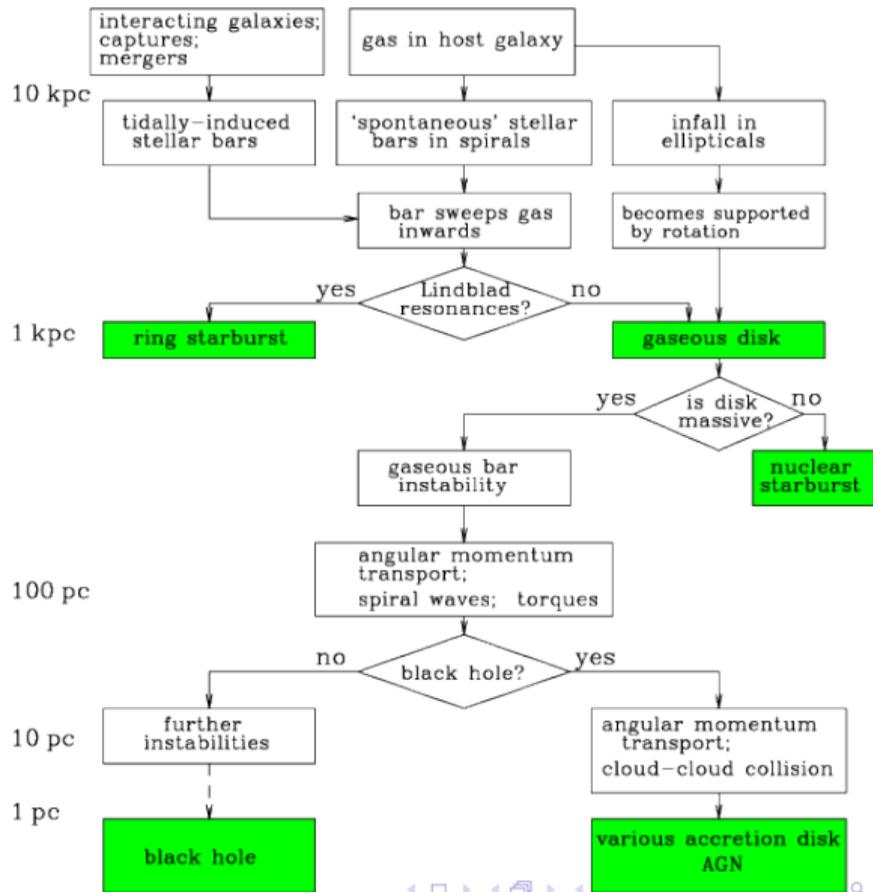
where

$$t_{\text{BH}} = \left(\frac{L}{L_E}\right)^{-1} \epsilon t_E \approx 4.4 \times 10^7 \text{ yr} \left(\frac{\epsilon}{0.1}\right) \left(\frac{L}{L_E}\right)^{-1}$$

# Fueling the central SMBH

In order for the central SMBH to be an AGN, it must be actively accreting material.

Therefore, no matter the formation scenario for the SMBH, a process must exist to funnel gas to the galactic center in order to fuel the SMBH.



## Observational signatures of merger source

If galaxy mergers are the source of AGN, then we should observe a surplus of mergers with AGN signatures relative to the number of non-merging galaxies containing AGN.

The hierarchical formation scenerio predicts a higher rate of merging galaxies at high redshifts. In addition, these galaxies would be more gas-rich.

We should then expect to observe the number density of AGN increase with time, peak, and then fall back off. And, we would expect today's early-type galaxies to host more AGN than late-type galaxies.

## Bondi accretion

The gas within today's early-type galaxies is too hot to condense onto the central region.

When the gravitational force overcomes the specific thermal energy of the gas around the central SMBH, though, Bondi accretion will occur within a radius

$$r_A \sim \frac{GM}{c_s^2}$$

For a black hole with mass of  $10^9 M_\odot$ , the Bondi accretion rate is only  $\sim 0.04 M_\odot/\text{yr}$ . While this is 500 times less than the corresponding Eddington rate, it is enough to sustain the jets.

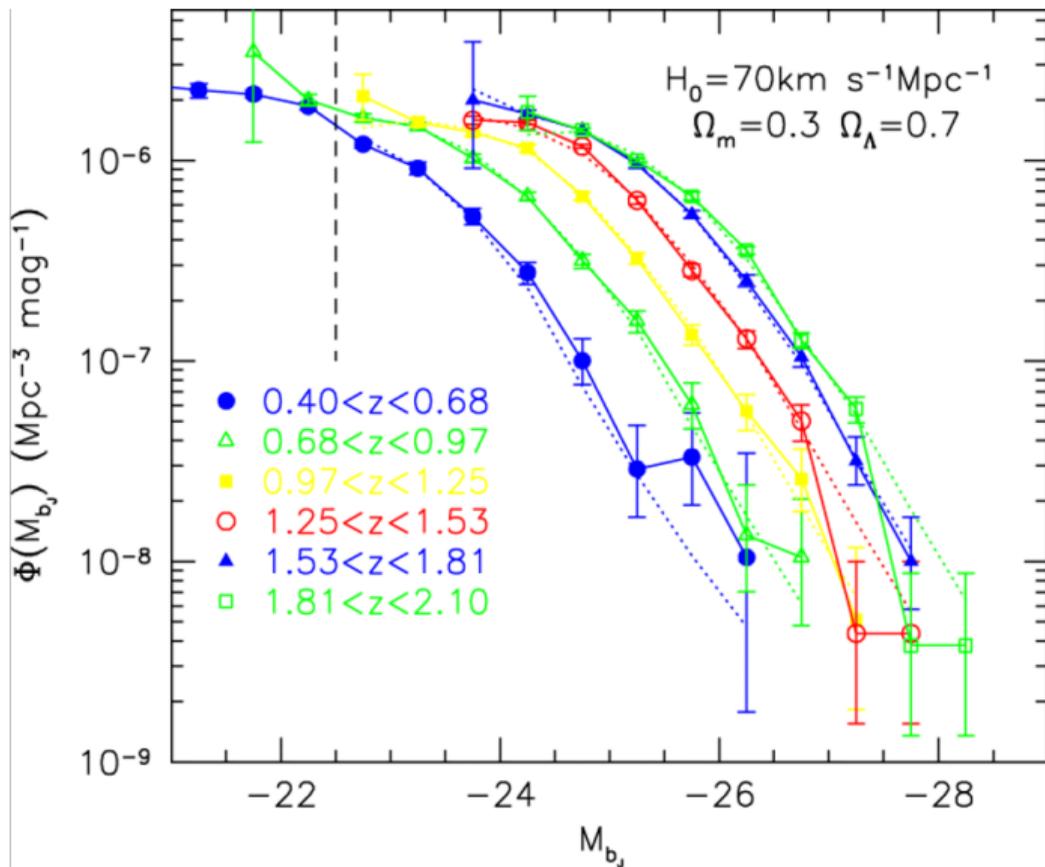
# Luminosity function of QSOs

The luminosity function of QSOs is well-described by

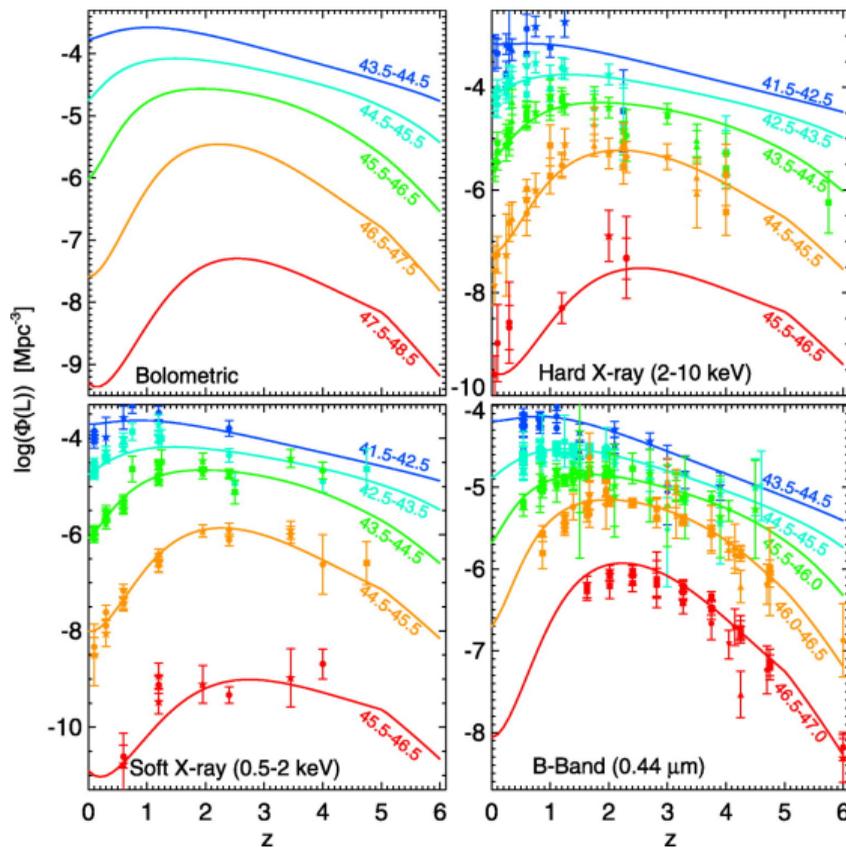
$$\phi(L, z) dL = \phi^*(z) \left[ \left( \frac{L}{L^*(z)} \right)^{\beta_1} + \left( \frac{L}{L^*(z)} \right)^{\beta_2} \right]^{-1} \frac{dL}{L^*(z)}$$

where

$\phi^*$  is independent of  $z$   
 $L^*(z) \propto L^*(0)(1+z)^k$  with  $k \sim 3.45$



# Number density evolution of QSOs



# Implications for AGN formation

If AGN are hosted by massive dark matter halos, then we would expect to see a steady increase in the number of halos hosting AGN with decreasing redshift.

If AGN activity is triggered by mergers, then we would expect a decrease in AGN activity below  $z \lesssim 3$ , since

- ▶ There are fewer galaxies to merge.
- ▶ Galaxies are less gas-rich.
- ▶ AGN feedback is more effective.
- ▶ The galaxies capable of hosting AGN are in environments which are too hot.

## AGN v. galaxy

How does the energy output of an AGN compare to the binding energy of a galaxy?

The total power output of the AGN is

$$\frac{dE}{dt} = \epsilon \frac{dm}{dt} c^2$$

By integrating, we find that the total energy produced by the AGN over its lifetime is

$$E = \bar{\epsilon} M_{\text{BH}} c^2$$

Assuming that the galaxy is in virial equilibrium, its gravitational binding energy is

$$U \sim -M_{\text{gal}} \sigma^2$$

# AGN v. galaxy

The ratio of these energies is then

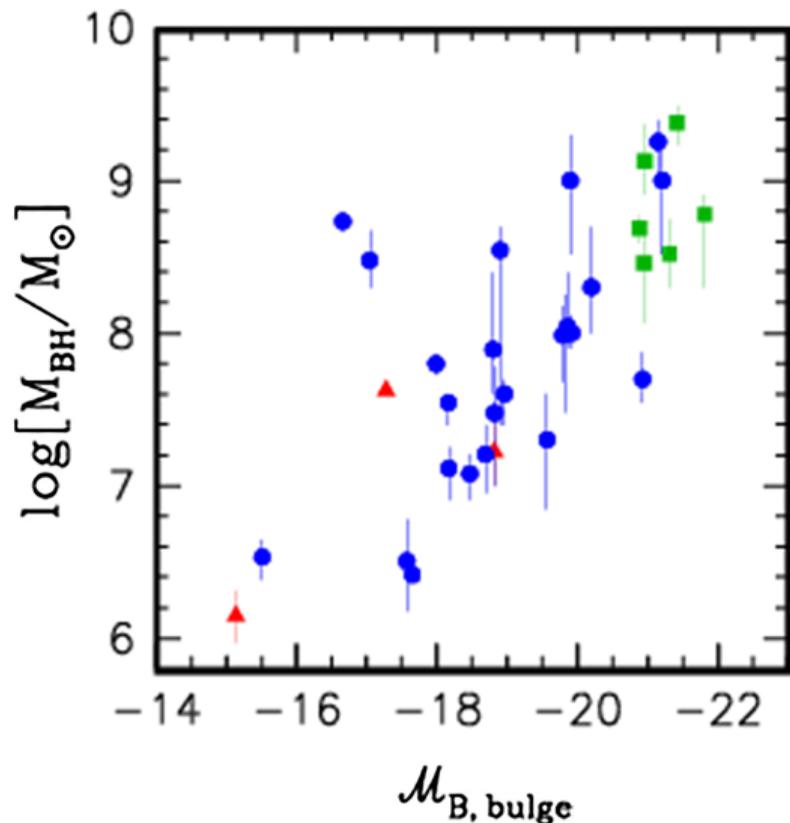
$$\frac{E}{|U|} \sim \frac{\bar{\epsilon} c^2 M_{\text{BH}}}{\sigma^2 M_{\text{gal}}}$$

Observations show us that

$$M_{\text{BH}}/M_{\text{gal}} \sim 10^{-3}.$$

For a massive galaxy ( $\sigma \sim 300$  km/s),

$$E/|U| \sim 10^3 \bar{\epsilon}.$$



## Radiative feedback

UV and X-ray photons produced by the AGN can photoionize the surrounding atoms and heat the gas through photoionization.

- ▶ The resulting heat can suppress gas cooling, and therefore star formation, especially in low-mass halos.

If there is a significant amount of dust present, the radiation output will be absorbed by the dust grains.

- ▶ If the resulting pressure is strong enough, the gas and dust will be expelled from the center of the galaxy in a momentum-driven wind.

Compton heating can transfer energy from the photons to low-energy electrons in an ionized gas.

# Mechanical feedback

When a SMBH is accreting well below the Eddington accretion rate, the feedback is dominated by radiatively inefficient mechanical forms: radio jets and lobes.

This feedback will typically form large cavities ( $\sim 50$  kpc in radius) in the X-ray luminous gas within a cluster; these “bubbles” are filled with relativistic gas.

The typical kinetic power associated with this feedback from the central cluster galaxy is  $\sim 45$  erg/s, more than enough to halt the radiative cooling of the intracluster gas.