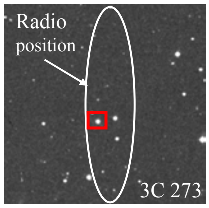
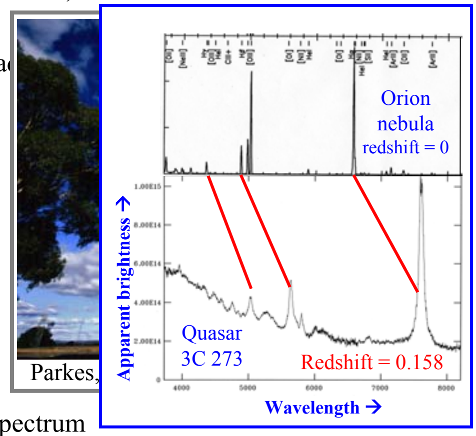
How do we know??

- **Luminosity** = (apparent brightness) x distance^2
- **Apparent brightness:**
  - Discovered quasars from their ra





  - But… *which object???*

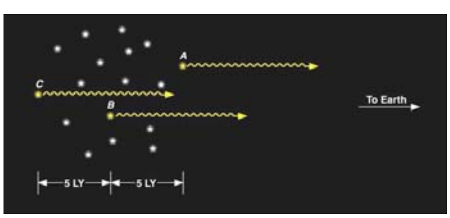
- **Distance:** Now measure optical spectrum
  - *Doppler shift* of wavelength of light

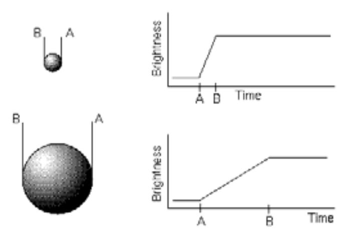
    ➔ velocity of recession (redshift) due to expansion of Universe.

    ➔ huge distance ➔ **huge luminosity!**

How do we know??

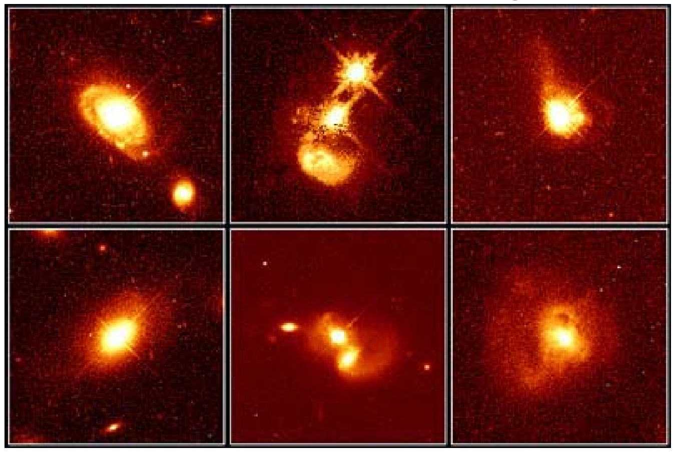
- **Size of quasars:**
  - They change brightness in short time (weeks, days. hours).





➔ **Size = light-weeks, light-days, light-hours.**

Quasars: events in centers of galaxies

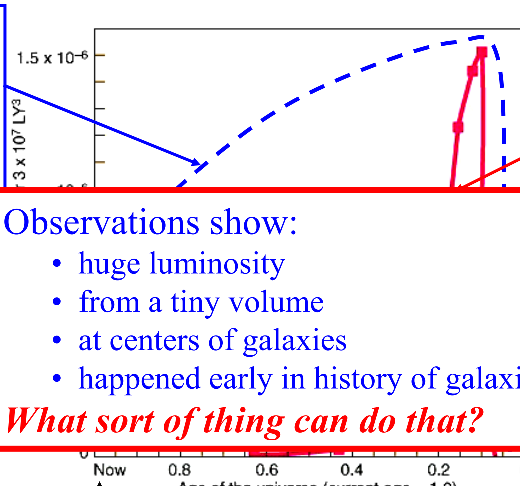


- Hubble Space Telescope images.
  - Quasars are bright star-like objects at centers of faint galaxies.

Most Quasars Lived and Died Long Ago

Rate at which stars are formed in galaxies.

Number of Quasars per unit volume



Observations show:

- huge luminosity
- from a tiny volume
- at centers of galaxies
- happened early in history of galaxies

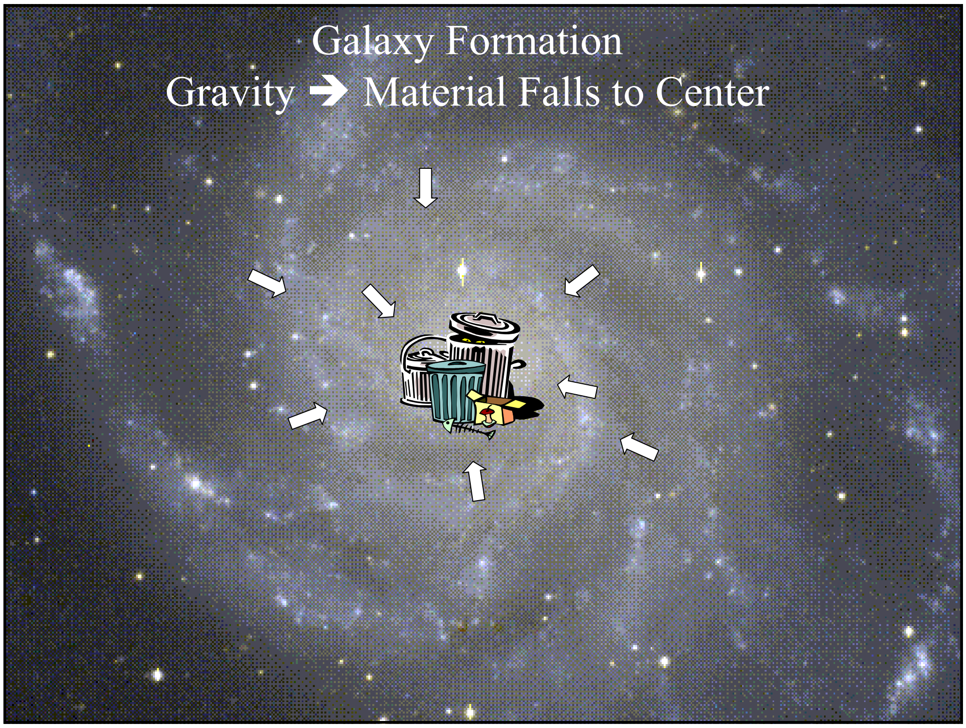
What sort of thing can do that?

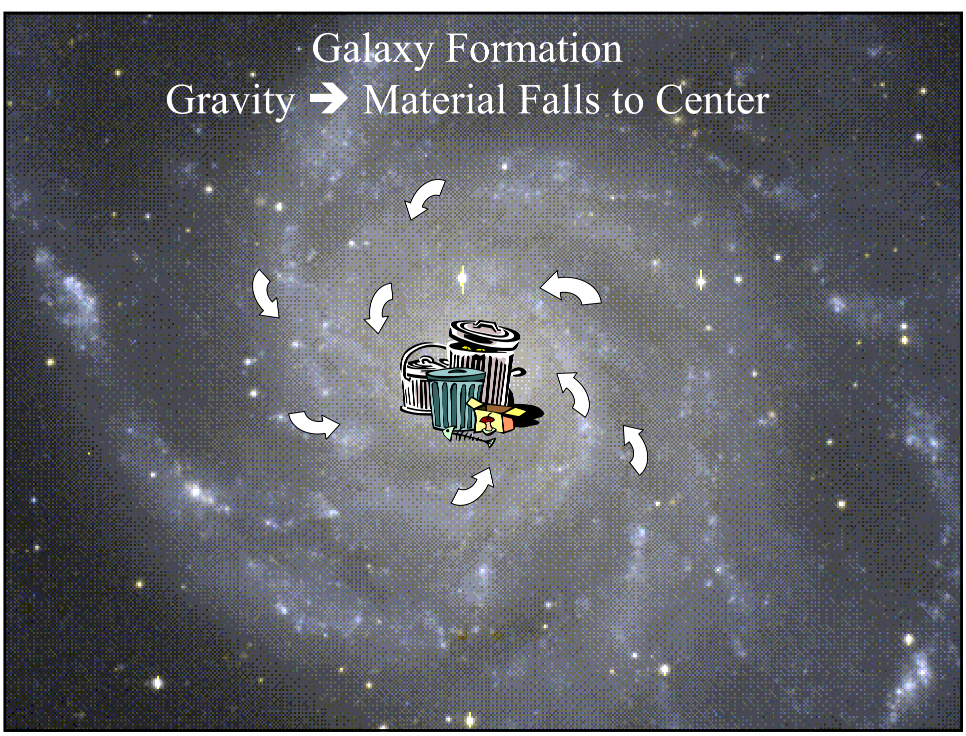
Conclusion:
Quasars are events in young galaxies.

Now
= 14 billion yrs

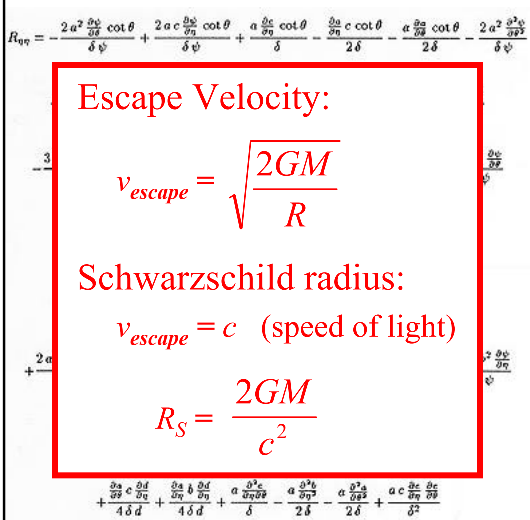
← time

Formation of universe


Galaxy Formation
Gravity ➔ Material Falls to Center


Galaxy Formation
Gravity ➔ Material Falls to Center

High density ➔ Strong Gravitational Field ➔ Black Hole



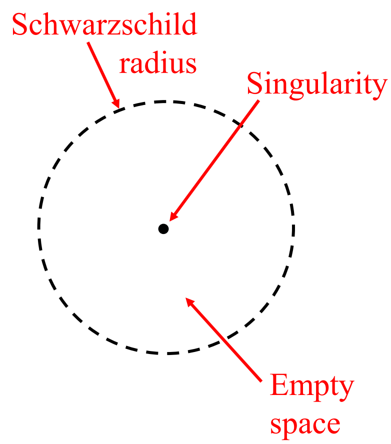
Escape Velocity:

$$v_{escape} = \sqrt{\frac{2GM}{R}}$$

Schwarzschild radius:

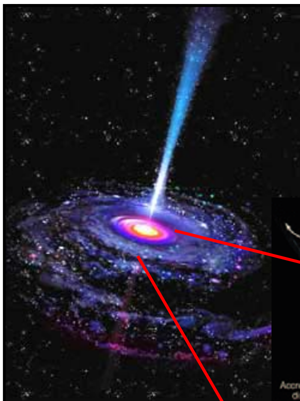
$$v_{escape} = c \quad \text{(speed of light)}$$

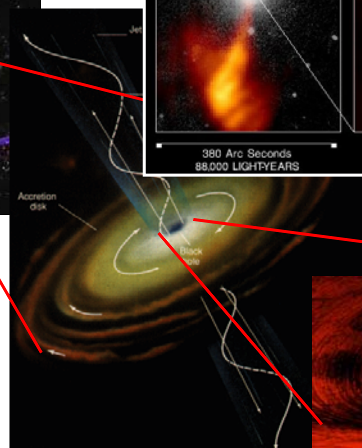
$$R_S = \frac{2GM}{c^2}$$

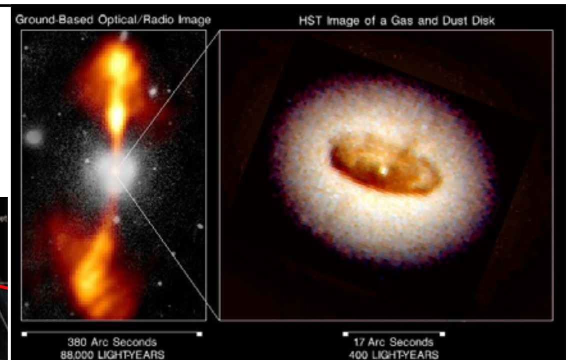


Accretion Disks

- Well-studied phenomena in local binary star systems
  - "cataclysmic variables"
- Angular momentum ➔ material cannot fall directly onto central mass.
- Binary stars ➔ "thin" accretion disks
  - Material works its way in toward center due to viscosity.







The Source of the Luminosity:

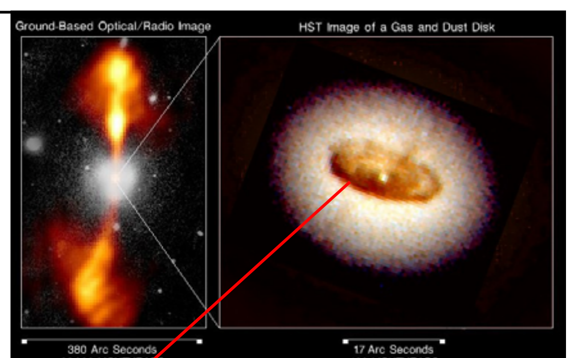
- Matter falls onto accretion disk.
- Disk heats up & glows.

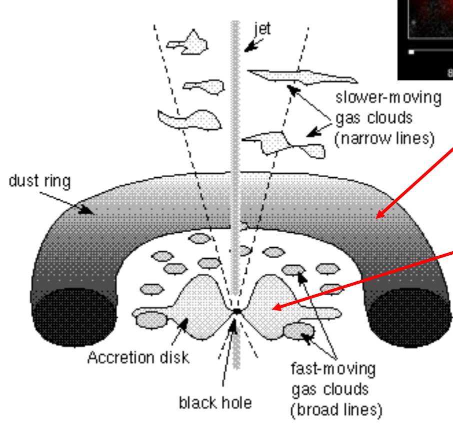
- Also, Blandford-Znajek mechanism.
  - extract BH rotational energy

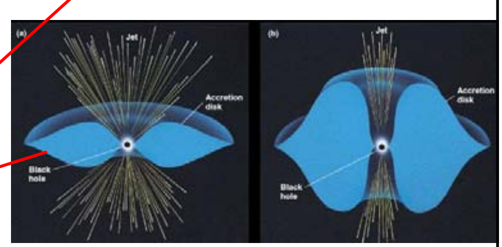
Black Hole

Energy Source:

- Gas, stars fall into $10^8 M_\odot$ black hole.
- Gravitational potential energy ➔ thermal energy ➔ light







Accretion disk + Black Hole + Jets