14.16.1

$\Rightarrow t_{cool} \simeq 5\times10^{17}\,s = 1.5\times10^{10}\,yrs$ = Hubble time!

So gas cools very slowly, all Es should have hot gas, explains why they not forming stars.

---

5. Active galaxies / galactic nuclei

→ Seyfert, 1943, discovered that 1% of nearby Ss have a bright point source at the centre

→ Seyfert galaxies.

→ Optical spectra show intense broad emission lines

⇒ high velocity ionised gas.

→ Two distinct types

Type I – v. broad lines ($1000_s\ km\,s^{-1}$)

Type II – relatively narrow lines ($100_s\ km\,s^{-1}$)

→ Also found to be X-ray sources

Type I – unabsorbed X-ray spectra

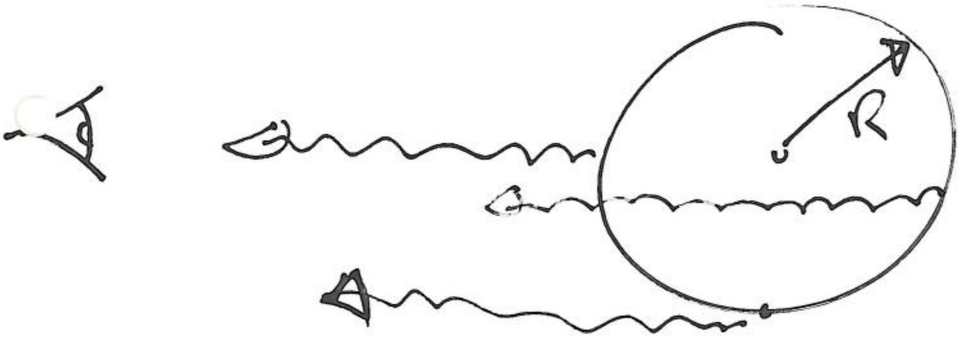
Type II – strongly absorbed X-ray spectra.

14.16.2

The nature of active galactic nuclei (AGN).

AGN are observed to vary rapidly, on time scales as short as 1 hour.

Variability to constrain the size of the object.



observe a range of time delays due to light travel time across the object

$$\Delta t \sim \frac{R}{c}$$

So if an object varies on $\Delta t \sim 1$ hour

$$\Rightarrow \underline{\underline{R \lesssim 10^{12} m = 7AU}}$$

So AGN emission must arise from a region $\simeq$ Solar system, <u>much</u> smaller than galactic scales (e.g. nearest stars, ~ 1pc, ~ 10^5AU).

2nd constraint, luminosity places a limit on the mass of an object, limited by the Eddington limit, L_{Edd}, luminosity at which an object is disrupted by its own radiation pressure.

Radiation pressure from photon momentum:

$$p = \frac{E}{c} \quad \text{— energy of photon}$$

Energy flux from an object

$$f = \frac{L}{4\pi r^2} \quad \begin{matrix} L \text{ — luminosity} \\ 4\pi r^2 \text{ — area of shell} \end{matrix}$$

$$\text{momentum flux} = \frac{f}{c} = \frac{L}{4\pi r^2 c}$$

The fraction of this flux transferred to material depends on its opacity.

Assume opacity is dominated by e^- scattering, which is the lowest plausible opacity, and wavelength independent.

Consider average force on each e^-

$$F_{e^-} = \frac{\sigma_T L}{4\pi r^2 c}$$

Thomson cross-section for e^- scattering $= 6.65\times10^{-29}\,\mathrm{m}^2$

For Eddington limit, equate the radiation force with gravity

$$\frac{\sigma_T L_{Edd}}{4\pi \cancel{r^2} c} = \frac{G M m_p}{\cancel{r^2}}$$

mass of central object

mass of a proton.

(note e^- & p^+ held together by the electric force).

$$\Rightarrow L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

$$= 1.5\times10^{31}\frac{M}{M_\odot} \quad (W)$$

A powerful AGN can have $L \sim 5\times10^{39}$ W.

$$\Rightarrow M > 3.3\times10^{8} M_\odot \quad !$$

So must fit $\sim 10^8 M_\odot$ into a region the size of our Solar system.

$\Rightarrow$ supermassive black hole.

Only plausible source of energy is accretion

– the release of grav. potential energy from a falling object.

$$E_{acc} = \frac{GMm}{R_{min}} - \cancel{\frac{GMm}{R_{max}}}$$

– max energy release from a compact object (maximising $\frac{M}{R}$).

Radius of a B.H. (event horizon) can be estimated by equating escape velocity to c.

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

Schwarzschild radius.

for $M \sim 10^8 M_\odot \Rightarrow R \sim 8$ AU.

subst $\frac{M}{R}$ for a B.H.

$$\Rightarrow E_{acc} = \frac{\cancel{G}\overset{m}{\cancel{M}}c^2}{2\cancel{G}} = \frac{1}{2}mc^2$$

mass of infalling material.

so half the rest mass energy of infalling material is potentially liberated.

c.f. with ~1% of rest mass liberated by nuclear fusion.

Can we grow these B.Hs. by accretion?

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

← accretion rate.

luminosity.

radiative efficiency factor (some energy can be advected into the B.H.).

To explain luminosities of A.G.N., need $\frac{dm}{dt} \sim 1 M_\odot/y$ ($\sim 10^{39}$ W).

Equate L with L_{Edd} & rearrange.

$$\frac{dM}{dt} = M \frac{4\pi G m_p}{\epsilon c \sigma_T}$$

Solve by integrating.

$$\int_{M_0}^{M} \frac{1}{M} \cdot dM = \frac{4\pi G m_p}{\epsilon c \sigma_T} \int_0^t dt$$

initial mass →

$$\underline{M = M_0 e^{t/\tau}} \qquad \tau = \frac{\epsilon c \sigma_T}{4\pi G m_p}$$

Assume $M_0 \simeq 10 M_\odot$, which is available from a single supernova, want $M \sim 10^9 M_\odot$ (maximum seen in AGN)

$$\Rightarrow \frac{M}{M_0} = 10^8 = e^{t/\tau} \quad \Rightarrow t = 8\times10^8 \,\mathrm{yr}$$

$\lesssim$ Hubble time (10^{10} yr).

Two other types of A.G.N discovered.

① Radio galaxies

- brightest radio sources in the sky,
- dual-lobed emission, fed by jets of material from a galactic nucleus.

e.g. Cygnus A, $d = 100\,\mathrm{Mpc}$, $L_{radio} \simeq 10 L_{m.w.}$

- optical spectra of central objects show strong broad emission lines,
- Type I & II objects seen.
- most radio galaxies are E_s, thought that recent mergers has stirred up the gas and increased accretion rate onto B.H.

② Quasars (quasi-stellar radio source).

- Bright point sources, associated with strong radio emission.
- strong broad emission lines.

  e.g. 3C48 $z = 0.37$

  $\Rightarrow d \sim 1500$ Mpc

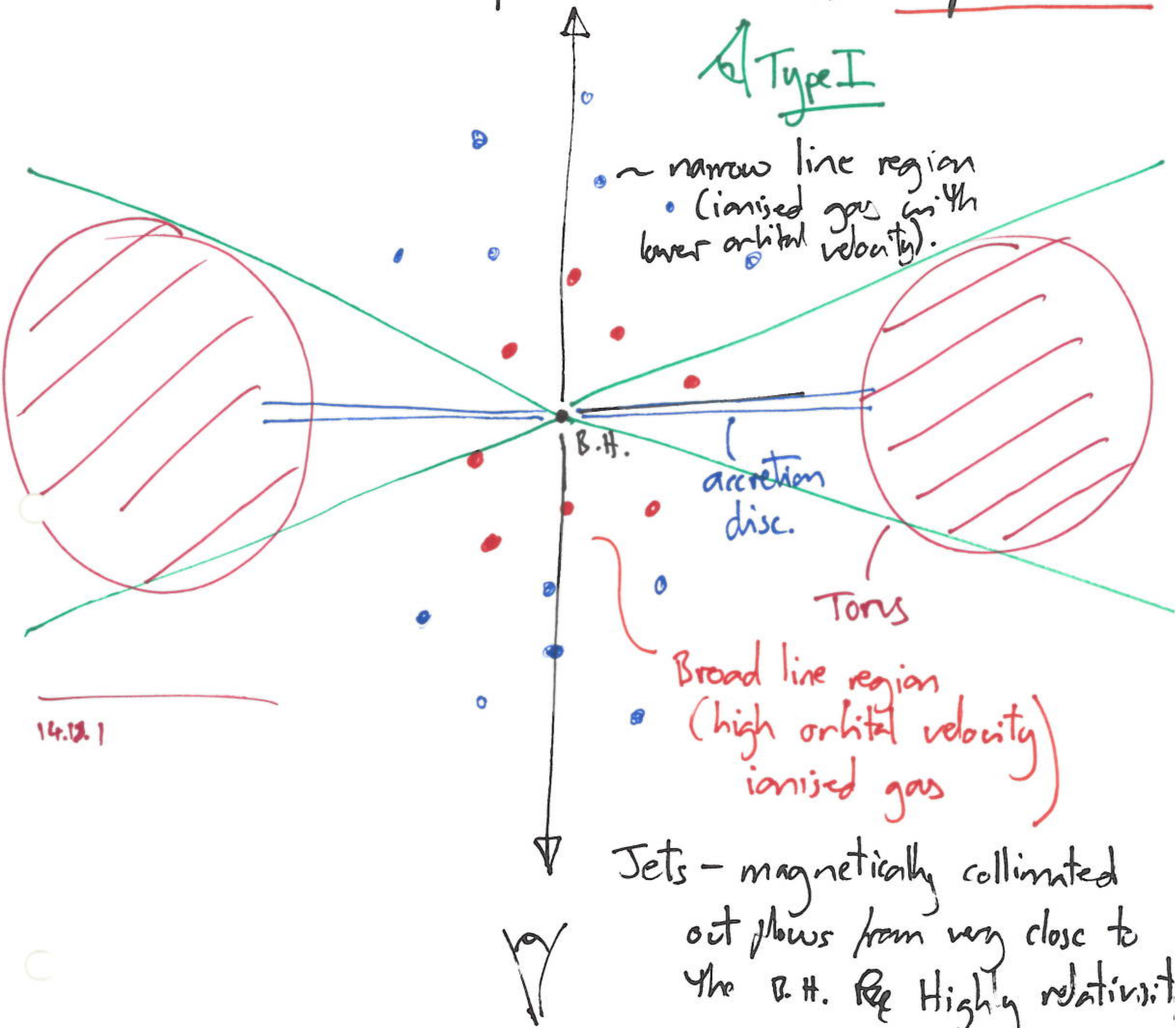
  $\Rightarrow L \sim 10^2 - 10^5 L_{m.w.}$

  so look like point sources because the AGN is much more luminous than the galaxy.
- type I & II objects seen + jets
- non-radio emitting versions "radio quiet"

  $\Rightarrow$ QSO (quasi-stellar objects).

14.17.5
+14.18.1

All AGN now explained within the Unified model



14.18.1

Jets – magnetically collimated outflows from very close to the B.H. Ree Highly relativist

Blazars, intense highly variable emission beamed by jet.

Type I – can see the broad line region, and the X-ray emission from inner accretion disc.

Type II – can only see the narrow line region, and X-rays absorbed by the torus.

14.18.2

Type II

14.18.3

We see radio loud / quiet versions of type I & II AGN, associated with presence / absence of jet, may be related to Lacc. accretion rate.

Crucial supporting evidence:

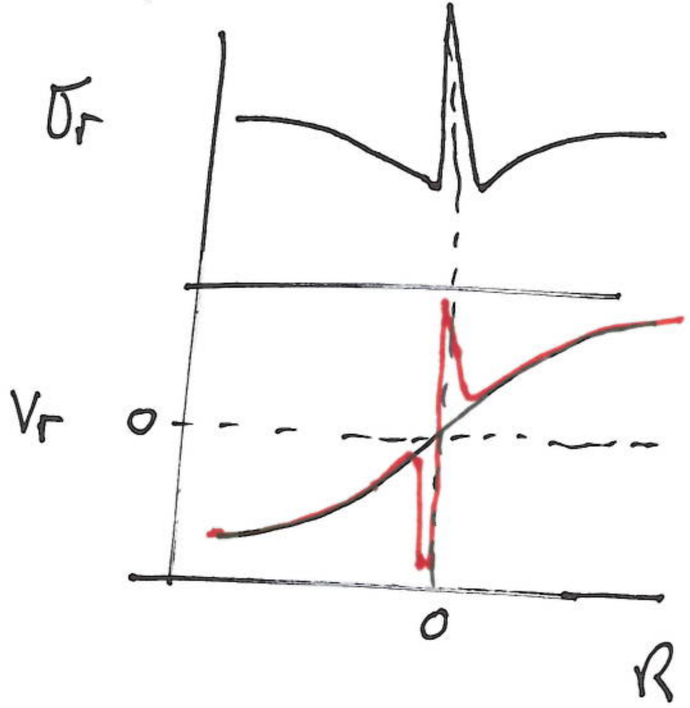
- → Type I spectra hidden in the polarised (scattered) light of Type II objects.
- → NGC 4151 transitioned from Type I to Type II.

14.18.4

Supermassive BHs in normal galaxies.

→ SMBHs were thought to be rare, until the discovery of many in normal galaxies.

→ e.g. M31



Recall,

$$M(<R) = \frac{5\sigma_r^2 R}{G}$$

$$M(<R) = \frac{V^2 R}{G}$$

⇒ compact mass at the centre of M31

$$M = 3\times10^7 M_\odot$$

and $\frac{M}{L} \geqslant 300$.

→ many more examples discovered with HST

→ implies all giant galaxies were once active galaxies.

Also, in M.W.?!

- → observations in the infra-red (to avoid dust extinction) with adaptive optics (to reach high spatial resolution), have ~~were~~ revealed high velocity stars, very close to Galactic centre.

- → orbit of each star constrains enclosed mass

- → Best example, S2

$P_{orb} = 15.2$ yrs $\quad a = 0.119''$ (semi-major axis)

use Kepler's 3rd law, $\quad R_{\odot} = 8$ kpc

$$P^2 = \frac{4\pi^2}{GM} a^3$$

$$\Rightarrow M(<R) = 3.74 \times 10^6 M_{\odot}$$

~~Per~~ Closet separation $= 0.0155''$

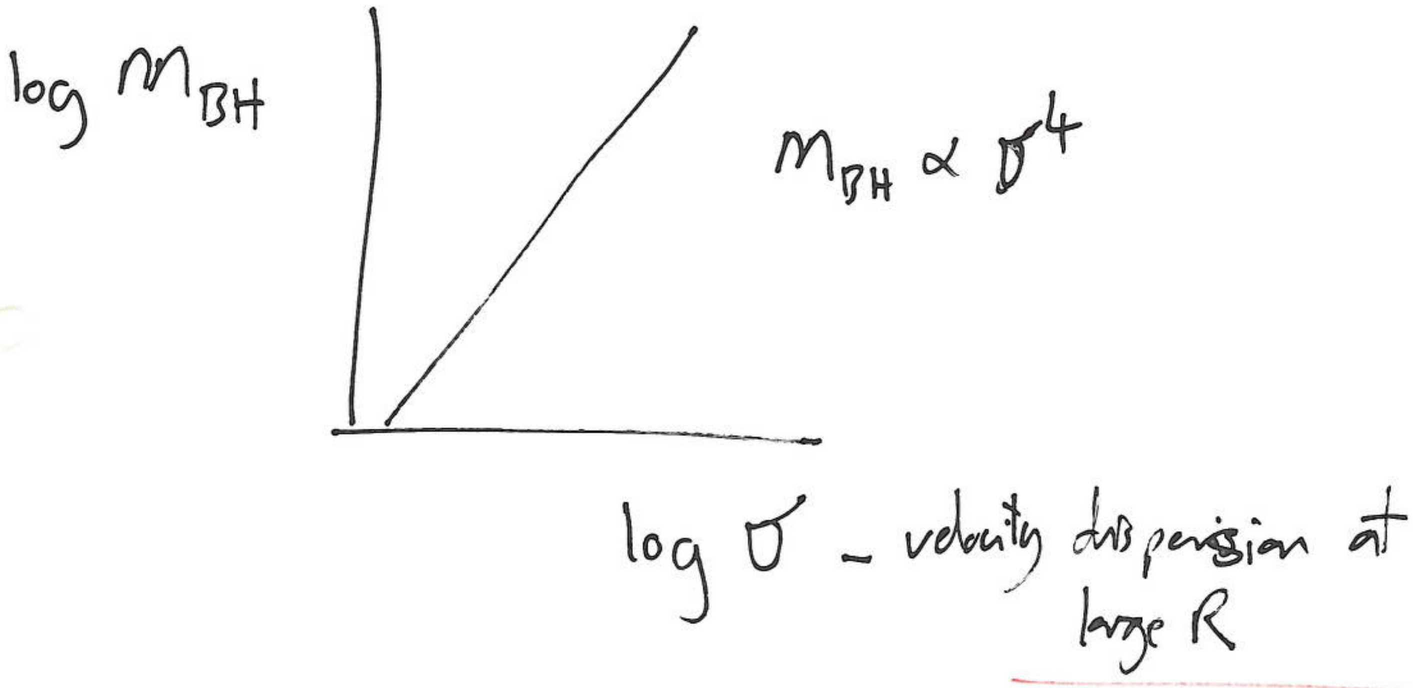
$$\Rightarrow R_{B.H.} \lesssim 124 \text{AU}$$

$$\Rightarrow \rho_{B.H.} \gtrsim 4.1 \times 10^{15} M_{\odot} \text{pc}^{-3}$$

⇒ must be a B.H.!

14.18.6
+
14.19.1

→ The mass of BHs has be found to correlate with properties of the galaxy, tightest correlation is the M-σ relation,



14.19.1

How can these properties know about each other? (the M_{BH} is negligible on the scale of the galaxy).

Most interpretations based AGN feedback.

Recall, $L_{acc} \leq L_{Edd} \propto M_{BH}$

at Eddington limited accretion rates we expect much of L_{acc} in K.E. of outflowing winds (driven by radiation pressure).

Eventually K.E. of wind can overcome grav. binding energy of gas in the galaxy ⇒ clear gas from galaxy ⇒ stop star formation ⇒ stop B.H. growth.

Recall, $U = -\frac{3}{5}\frac{GM_{gal}^2}{R}$ and $\sigma^2 = \frac{3}{5}\frac{GM_{gal}}{R}$

↑ binding energy of uniform sphere

$\Rightarrow U \propto \sigma^4$

Balancing U & K.E. of outflow

$\Rightarrow M_{BH} \propto \sigma^4.$