Active galactic nuclei (AGN)

Relativistic Astrophysics and Cosmology: Lecture 10

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Pre-lecture question:

How do you weigh a black hole?

Last time

- Accretion disks, accretion luminosity & radiative efficiency
- Black hole accretion dynamics

This lecture

- Active galactic nuclei & quasars
- Saggitarius A*
- AGN feedback

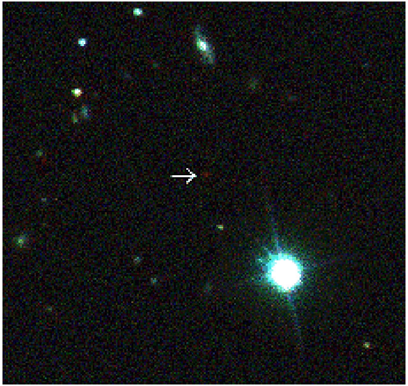
Next lecture

- Jets

Basic Observations

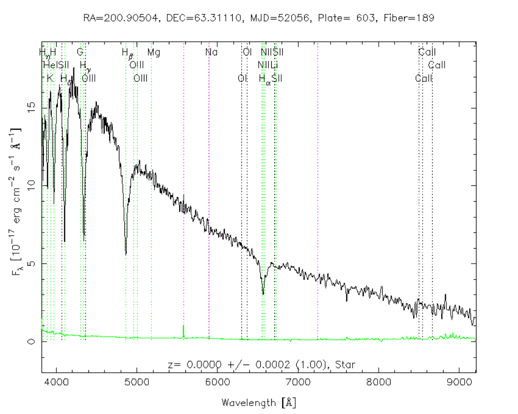
- In some galaxies we observe a compact central region of much higher than normal luminosity $10^{36} - 10^{40}$W.
- Sometimes varies on timescales shorter than a day (upper limit to the size of the 'central engine').
- The radiation spans many different wavebands; in the optical and infrared bands it does not come directly from the 'central engine' (can be absorbed and re-emitted by clouds of gas or dust).
- Classification:

  low luminosity Seyfert galaxies.
  high-luminosity Quasars (quasi-stellar radio source).
- Their evolution as a function of cosmic time/distance puts constraints on models of the cosmos.



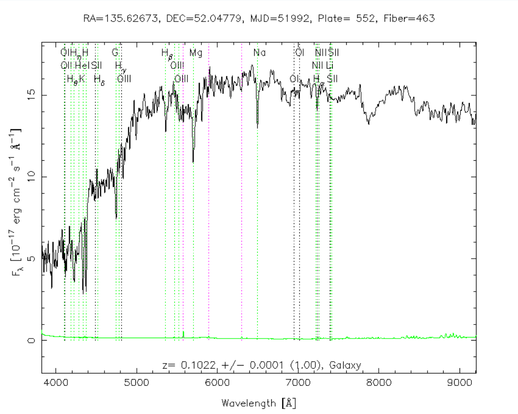
- Arrow points at a quasar at redshift $z = 6.2$ from SDSS.
- To a human eye, indistinguishable from a star.

Stellar spectrum



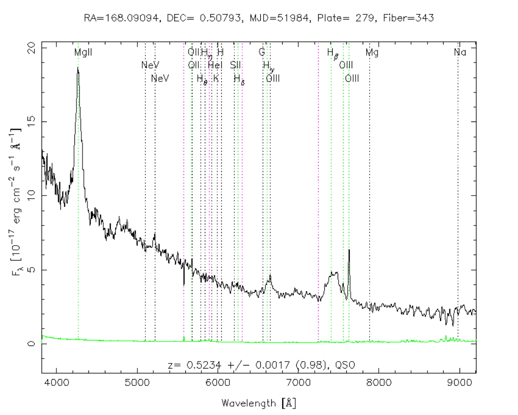
- Red thermal (blackbody) spectrum
- Note absorption lines (thermally broadened)

Galactic spectrum

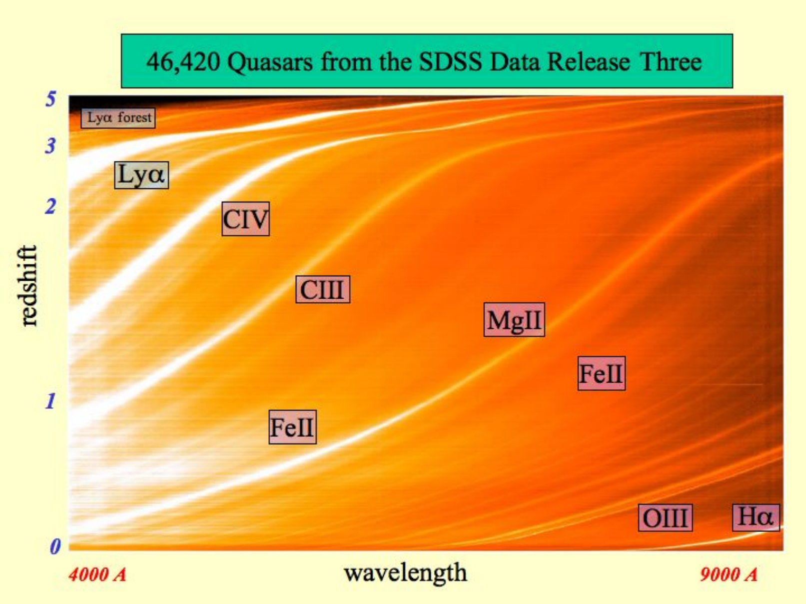


- Much bluer spectrum (star forming)
- Intergalactic medium absorption lines sharper

Quasar spectrum



- Strong broadened emission lines (permitted) come from close to AGN at high velocity.
- Fewer absorption lines.
- Narrow lines are from gas clouds further out fluorescing from UV light further from central region.



- Image composed of 46,420 quasar spectra, observed all over the universe, stacked by redshift.
- Each horizontal line of pixels in the image is one of the previous spectra, colour coded by height.
- Striking similarity between quasar spectra.
- Steady redward shift, which we can use to constrain cosmological theories.

Interpretation of AGN

- The power output for AGN is due to accretion onto a BH of $\sim 10^{6-9} M_\odot$.
- Recall from last lecture accretion luminosity $\boxed{L \sim \frac{GM\dot{M}}{R}}$ and efficiency $\boxed{\epsilon = \frac{L}{\dot{M}c^2}}$.
- For a BH $\epsilon \sim 0.1$ – much of the kinetic energy and some of the radiation emitted by infalling gas is swallowed by the BH.
- Can derive some simple scaling laws:
- Turn the Eddington limit around to derive a lower bound for the mass of the system given the observed luminosity $\boxed{M > \frac{L\sigma_T}{4\pi G m_p c}}$ $\Rightarrow$ BH in most luminous quasars $> 10^9 M_\odot$.
- The orbital timescale for material in the innermost stable orbit around a BH is about $10^{-4}(\frac{M}{M_\odot})$sec $\Rightarrow$ characteristic timescale for the variability of radiation emitted near BH.

Emission frequency of AGN

- Suppose there were an accretion disc around the hole:
  - the surface area of the disc $\sim M^2$,
  - the emission per unit area $\frac{\dot{M}}{M^2} \sim M^{-1}$,
  - blackbody spectra means the power radiated per unit area $\sim T^4$,
  - so the characteristic black-body temperature $\sim M^{-\frac{1}{4}}$.
- For supermassive holes, $\sim 10^9 M_\odot$, the primary thermal output would therefore be in the UV, rather than X-rays for solar mass black holes $\sim 10 M_\odot$ (though there is generally also strong X-ray emission from hotter optically thin gas, probably in a 'corona' above the disc).
- Some of the UV is absorbed by clouds of gas further away from the hole (at typical distances $\approx 10^4 r_s$), and reprocessed into emission lines, as in a gaseous nebula.

Emission profile of AGN

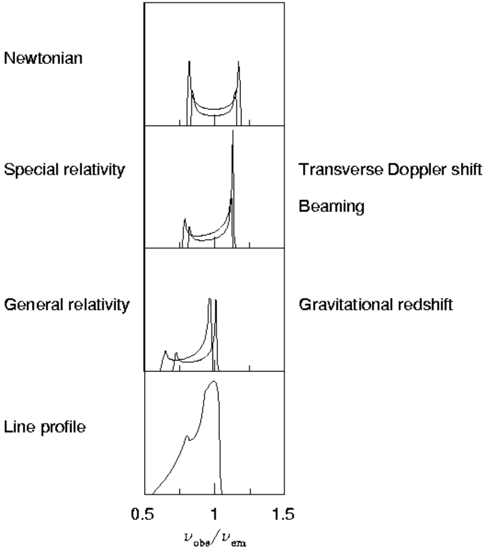
- High luminosity AGN in which the AGN outshines the host galaxy are known as quasars. They require a power production mechanism with high efficiency.
- If spectral lines are emitted from the surface of a disc, we would expect a characteristic two-peaked profile. This is now detected for X-ray emission lines and shows the expected gravitational redshift as well as Doppler shifts. The redward extent of the line may be used to determine the spin of the black hole.

$$(1+z)_{\mathrm{orb}} = \gamma\left(1+\frac{v}{c}\sin i\right), \qquad (1+z)_{\mathrm{grav}} = \left(1-\frac{2GM}{rc^2}\right)^{-1/2},$$

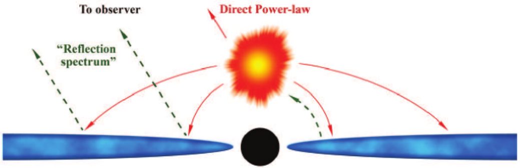
  so total redshift is

$$(1+z) = \left(1-\frac{2GM}{rc^2}\right)^{-1/2}\left(1-\frac{v^2}{c^2}\right)^{-1/2}\left(1+\frac{v}{c}\sin i\right).$$

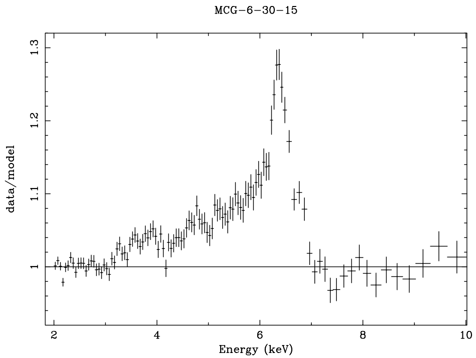
- For a non-spinning Schwarzschild black hole we obtain $(1+z)_{\mathrm{max}} = 3/\sqrt{2}$.



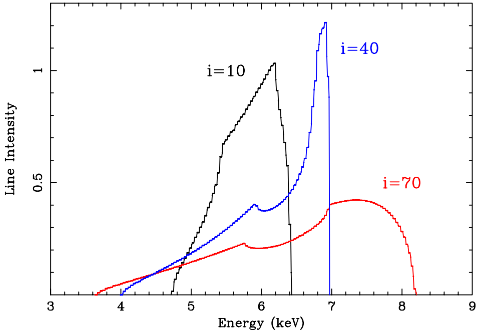
- Hard X-ray continuum, produced by Comptonization above the accretion disc, irradiates the disc $\Rightarrow$ relativistically-broadened iron emission lines in the spectrum of nearby active galaxies.
- The resultant backscattered emission spectrum $\equiv$ reflection spectrum.
- The reflection spectrum can appear strong due to light bending effects close to the black hole (i.e. at radii of a few r_g).
- Even more complicated for a Kerr BH!



Reflection spectra provide a way to measure the spin of the black hole if a broad iron line is detected. The shape of the blue (high energy) wing of the line is mostly determined by Doppler shifts and is thus most sensitive to disc inclination. The extent of the red (low energy) wing of the line depends most on the gravitational redshift of the innermost disk region. Model fitting of the whole shape gives both spin and inclination.



- Broad iron line seen in AGN X-ray spectrum.



- Response of iron line to disc inclination.

Formation of black holes

- Lay conception might be that a galaxy's supermassive black hole (SMBH) is a "binding agent" (you should be able to argue quantitatively that this can't be the case).
- SMBHs instead form in a "bottom up" approach
- Gas would naturally tend to accumulate in the centre of any galaxy (the bottom of potential well). A supermassive star may form, but this is unstable and quickly collapses to black hole.
- A massive star might alternatively build up by collisions and coalescence of stars in a dense central cluster.
- Any black hole that formed would subsequently grow by accretion of gas, or even of entire stars.
- Initially it was thought that AGN's were therefore "decorative" constructs in galaxies, but as we shall show, accretion luminosity acts as a "central engine" to galactic processes.

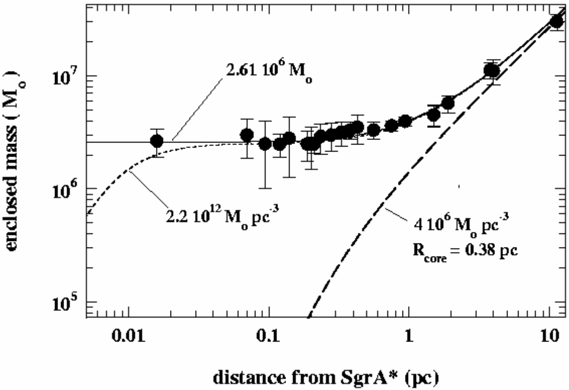
Quasar lifetimes and demography

- The e-folding timescale for the mass of an object radiating at the Eddington luminosity $L_{\rm Edd} = \frac{4\pi G M_{\rm bh} m_p c}{\sigma_T}$ with efficiency $L = \epsilon \dot{M} c^2$, accreting at rate $\dot{M}_{\rm bh} = (1-\epsilon)\dot{M}$.

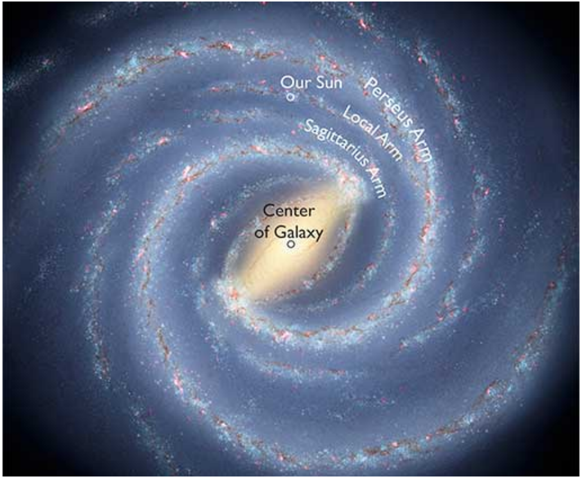
$$\tau_{\rm qso} \sim \frac{M_{\rm bh}}{\dot{M}_{\rm bh}} = \frac{M_{\rm bh}}{(L_{\rm Edd}(1-\epsilon)/\epsilon c^2)} = \frac{c\sigma_T \epsilon}{4\pi G m_p (1-\epsilon)} = 4\times 10^8 \frac{\epsilon}{1-\epsilon} \ \ \mathrm{yr}$$

- The characteristic lifetime for powerful AGN is $\sim 1\%\ t_{\rm Hubble} \Rightarrow 100$ e-folds of quasars.
- The number of quasars observed is $\sim 1\%$ of number of galaxies. It therefore has long been suspected that every galaxy goes through a 'quasar phase' after it forms.
- Dead quasars would be massive black holes lurking in the centres of galaxies, quiescent because they are not being fuelled by accretion — these are indeed now seen in most galaxies.

- The orbital speed of a star at distance $r(\gg r_s)$ from a black hole is $v_{orb} \simeq c\sqrt{\frac{r_s}{r}}$.
- The characteristic speeds of stars (called dispersion) in the central bulge of a galaxy are 100–300 km/sec (i.e. $3 \times 10^{-4}c - 10^{-3}c$).
- Therefore a central black hole would substantially modify the motions of any stars within $10^6 - 10^7 r_s$ of the hole.
- Analogous to an accretion radius.
- Can use this to determine the mass of the central black hole in our galaxy.

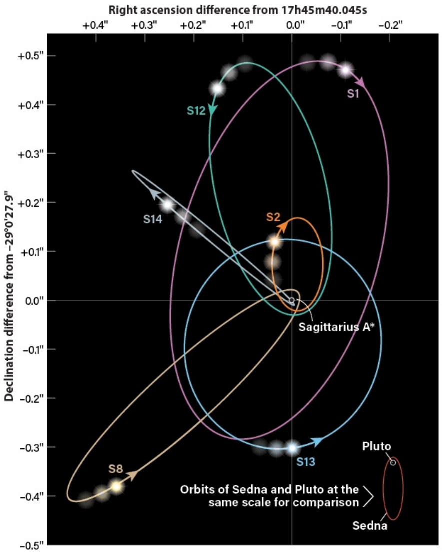


Our Milky way galaxy & its black hole



- The galactic bulge is visible in the night sky.
- Galactic centre has a supermassive BH.
- This is termed "Saggitarius A*".

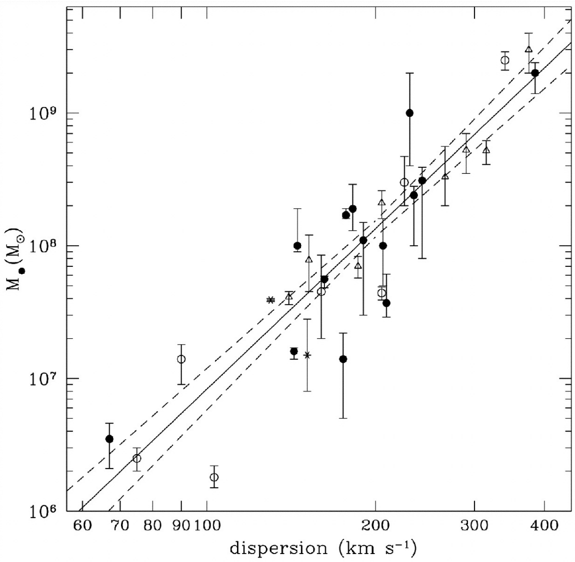
Orbits around Saggitarius A*



- Time-lapse image over 20 years shows complete orbits of some stars, some moving at over 1000 km/s.
- Can use this data to fit to measure the mass of the "missing" black hole mass of $4.3 \times 10^6 M_\odot$.
- The emission due to accretion onto the black hole is very low, which is surprising since the region is gas rich.
- Genzel & Ghez awarded the Nobel Prize in physics 2020.
- High-precision measurements of these provide confirmation of General relativity against modified theories of gravity [arxiv:2108.06286].

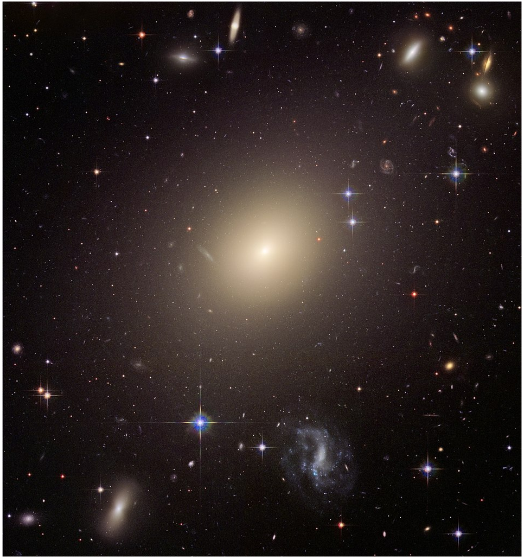
Black-hole galaxy mass correlation

- The masses of black holes in many other nearby galaxies have been determined by spectroscopic means, measuring the Doppler shifts induced due to the motion of stars or gas clouds. This has lead to the discovery of a correlation between the mass of the central black hole and the mass of the spheroidal part of the host galaxy (i.e. the non-disc part), with $M_{BH} \approx 10^{-3} M_{\text{spheroid}}$.
- The existence of such a correlation indicates some coupling between a central black hole in a galaxy and its mass.
- This may have arisen due to feedback between the energy produced by the black hole when growing and the gas in its host.



AGN radiative feedback

- Is there enough energy for AGN radiation to feedback and affect host structure?
- We'll consider elliptical galaxies since feedback better understood there.
- The binding energy of a galaxy is of order $M_{\rm gal}\sigma^2$.
- The energy released by accretion from a central black hole is $0.1 M_{\rm BH} c^2 \approx 10^{-4} M_{\rm gal} c^2$ $\Rightarrow$ the ratio of the energy from the black hole to the binding energy of the galaxy is $\sim 10^{-4} c^2/\sigma^2$.
- σ is typically $< 300\,{\rm km/s} \Rightarrow$ ratio is at least 100 $\Rightarrow$ only 1 per cent of the energy from accretion deposited into the galaxy is needed to unbind it.



How does the interaction take place?

- It may result from radiation pressure acting on dusty gas clouds before they form stars.
- Dust is common in galaxies, making up about one percent of the interstellar medium.
- Small dust particles absorb and scatter UV radiation very strongly, such that the effective interaction cross-section of interstellar dust and gas is about 500 times greater than the Thomson cross section.
- This makes the effective Eddington limit for such gas about 500 times less than for ionized dust-free gas: $L_{\mathrm{Eff}} = \dfrac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{Eff}}}$.
- An accreting black hole can therefore be sub-Eddington for the ionized gas which it accretes, yet super-Eddington for the interstellar medium of its host galaxy.
- $\Rightarrow$ drive gas out of the host galaxy, thereby stemming its own fuel as well as gas for further star formation, until $M_{\mathrm{BH}} \sim 0.02 M_{\mathrm{gal}}$.

- The radiation from accreting black holes leads to an energy density in space of $\mathcal{E}_{\rm acc}$, and a growth in the mean density of black holes of $\frac{\epsilon}{(1-\epsilon)}\rho_{\rm BH}c^2$, where ϵ is the radiative efficiency of the accretion flow.
- With time the Universe expands leading to the same relative drop in density of both factors. However the radiation suffers a loss due to redshift, leading at the present time to

$$\mathcal{E}_{\rm acc}(1+z) = \frac{\epsilon}{(1-\epsilon)}\rho_{\rm BH}c^2,$$

  where z is the mean redshift at which the accretion occurs.
- $\mathcal{E}_{\rm acc}$ can be measured from the summed spectra of AGN and $\rho_{\rm BH}$ can be estimated from the mass function of galaxies together with the $M_{\rm BH} - M_{\rm gal}$ relation.
- Results show agreement if $\epsilon \sim 0.1$, indicating that most black holes have a spin of $a \sim 0.5$ and that massive black holes have grown by accretion.

Summary

- Active galactic nuclei (AGN) are supermassive black holes at the centre of galaxies.
- These have a distinct observational signature as objects called Quasars.
- Observed via their accretion disks, the properties of which allow us to determine the mass.
- AGN act as the central engine in galaxies, forming in a bottom-up approach with important feedback effects on their host galaxy.

Next time

Jets