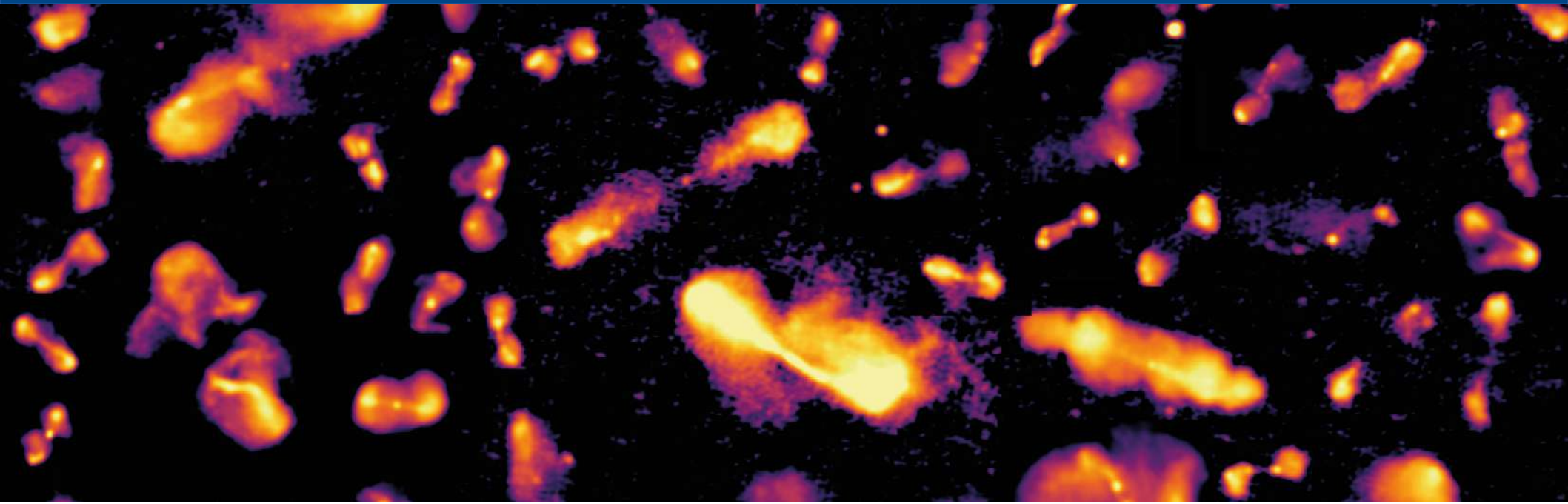
Physics of AGN jets: from launch to radio emission



Martin Hardcastle

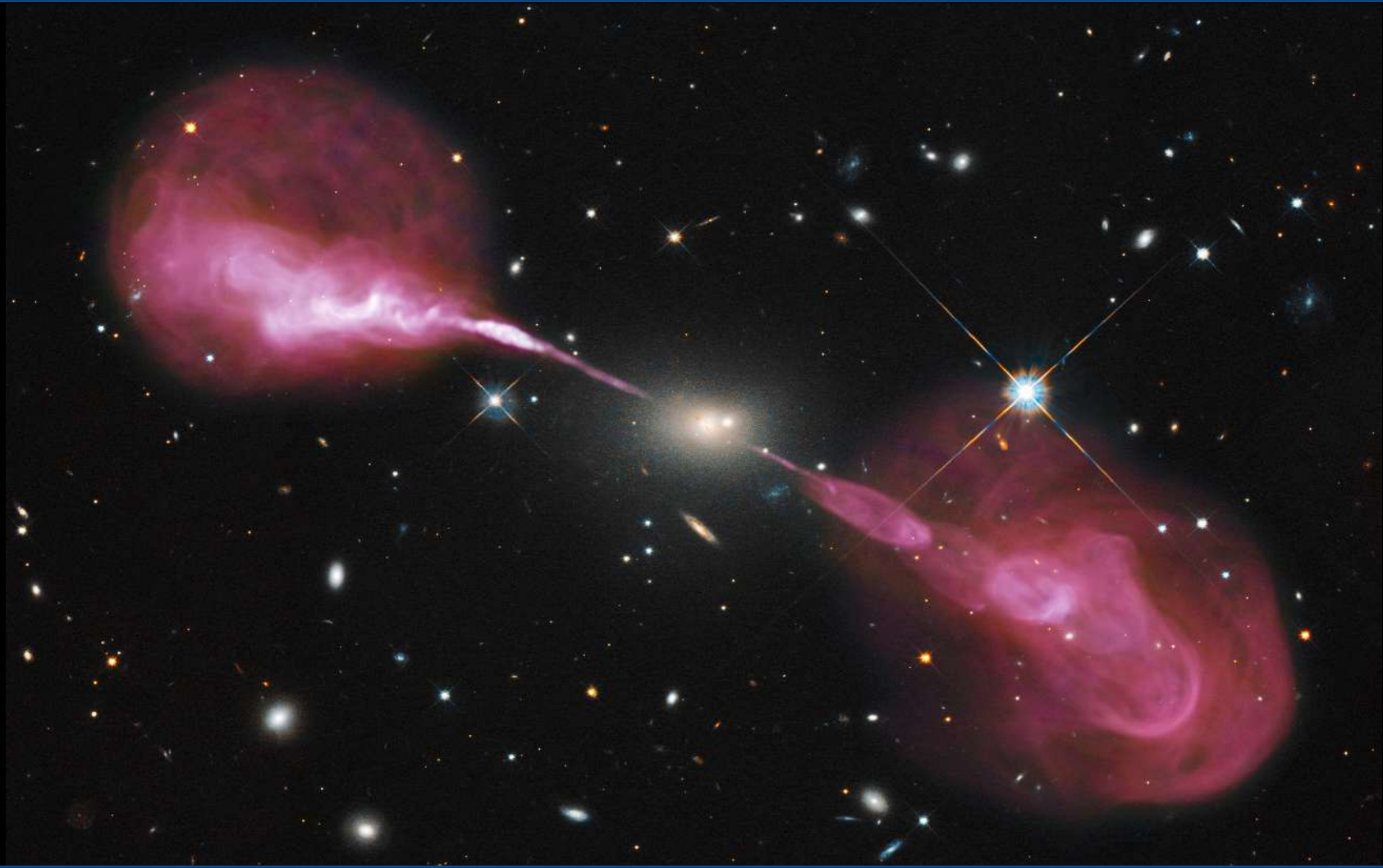
INAF PhD School “Franchesco Lucchin”, Bertinoro, October 2026

University of Hertfordshire UH

Section 1: What is an AGN jet and where does its energy come from?

- Introduction
- The central engine
- The accretion system
- Jet launching mechanisms
- Basic properties of AGN jets
- An overall view of the system

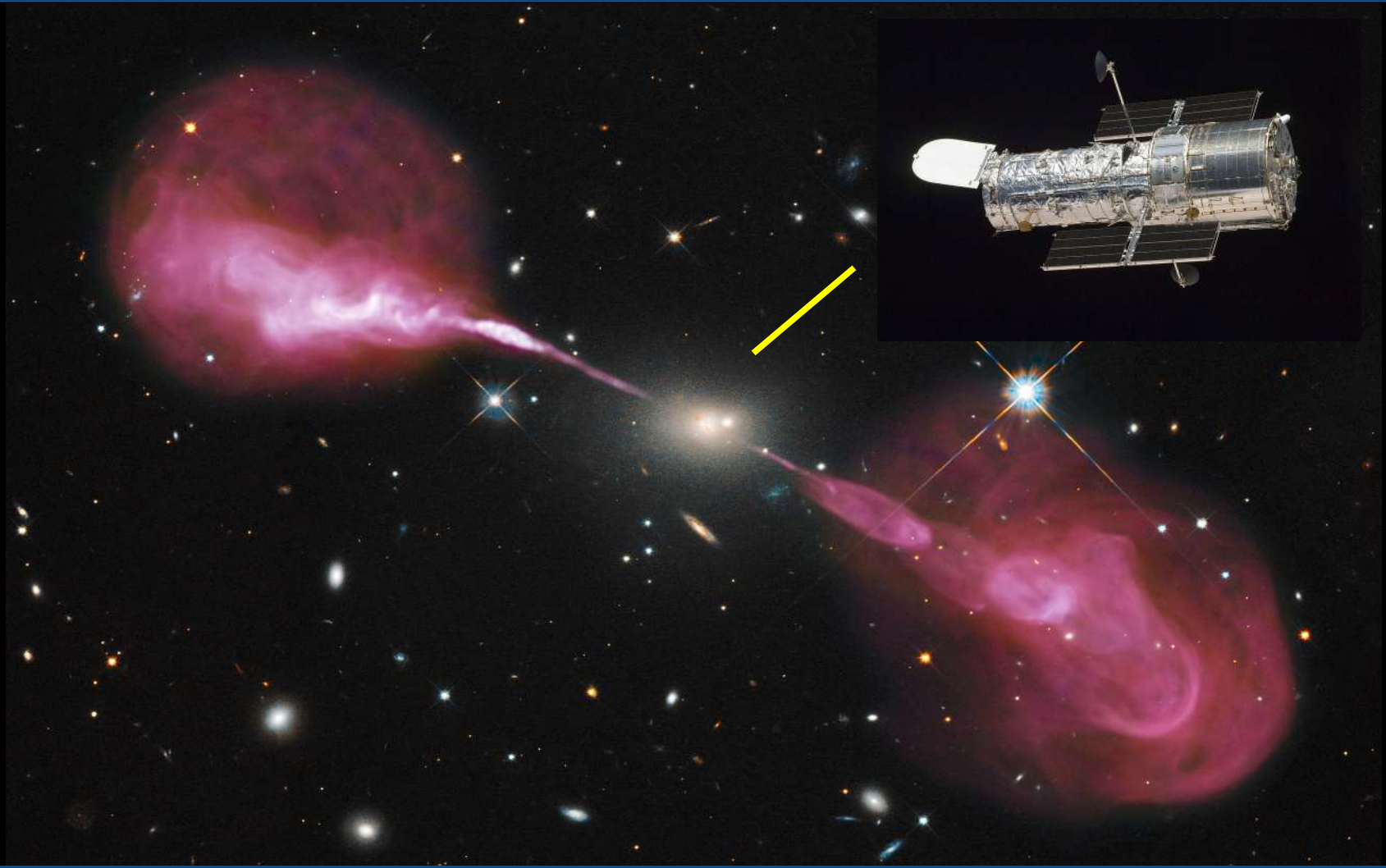
Radio AGN



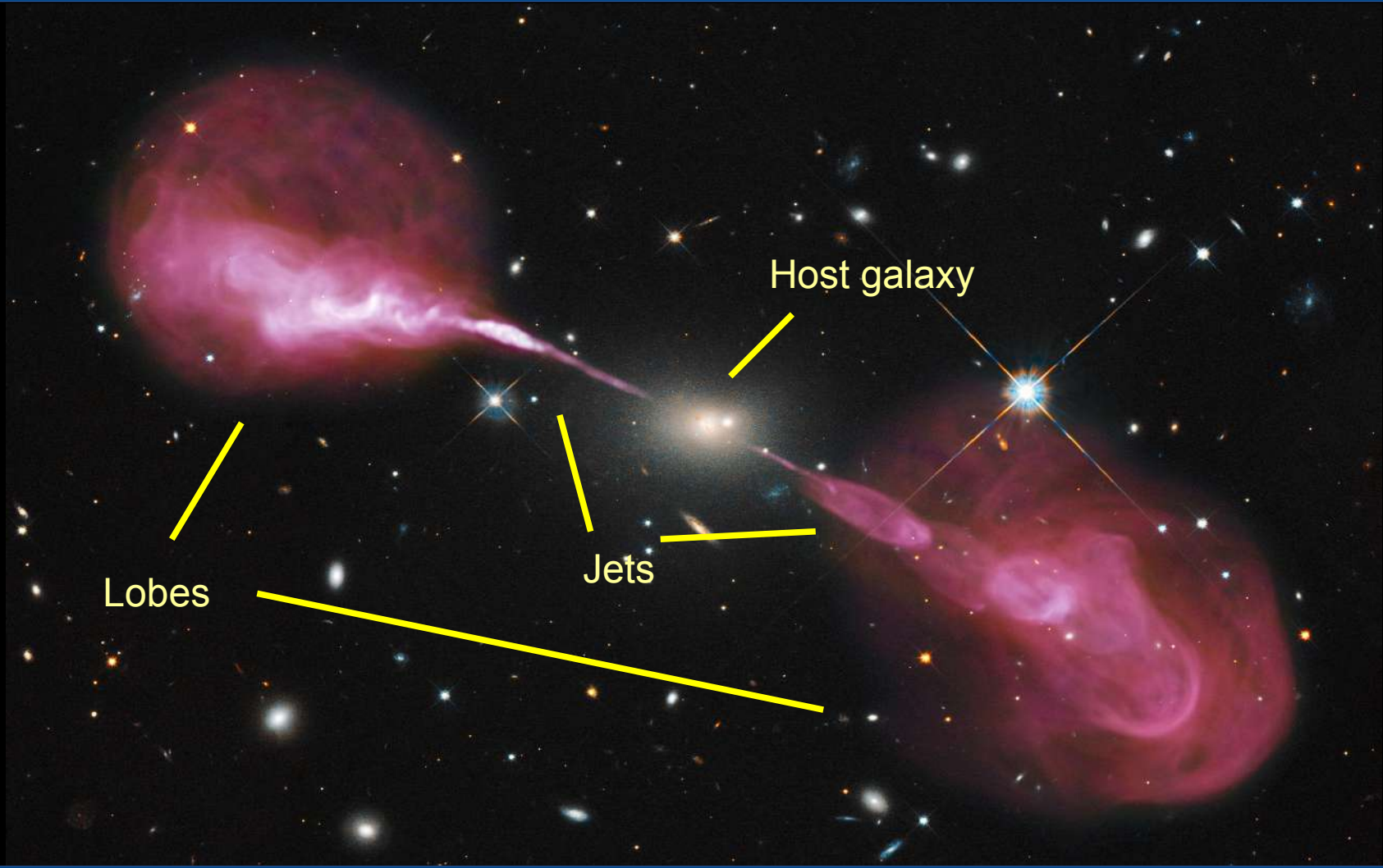
Radio AGN



Radio AGN



Radio AGN



Radio AGN are everywhere



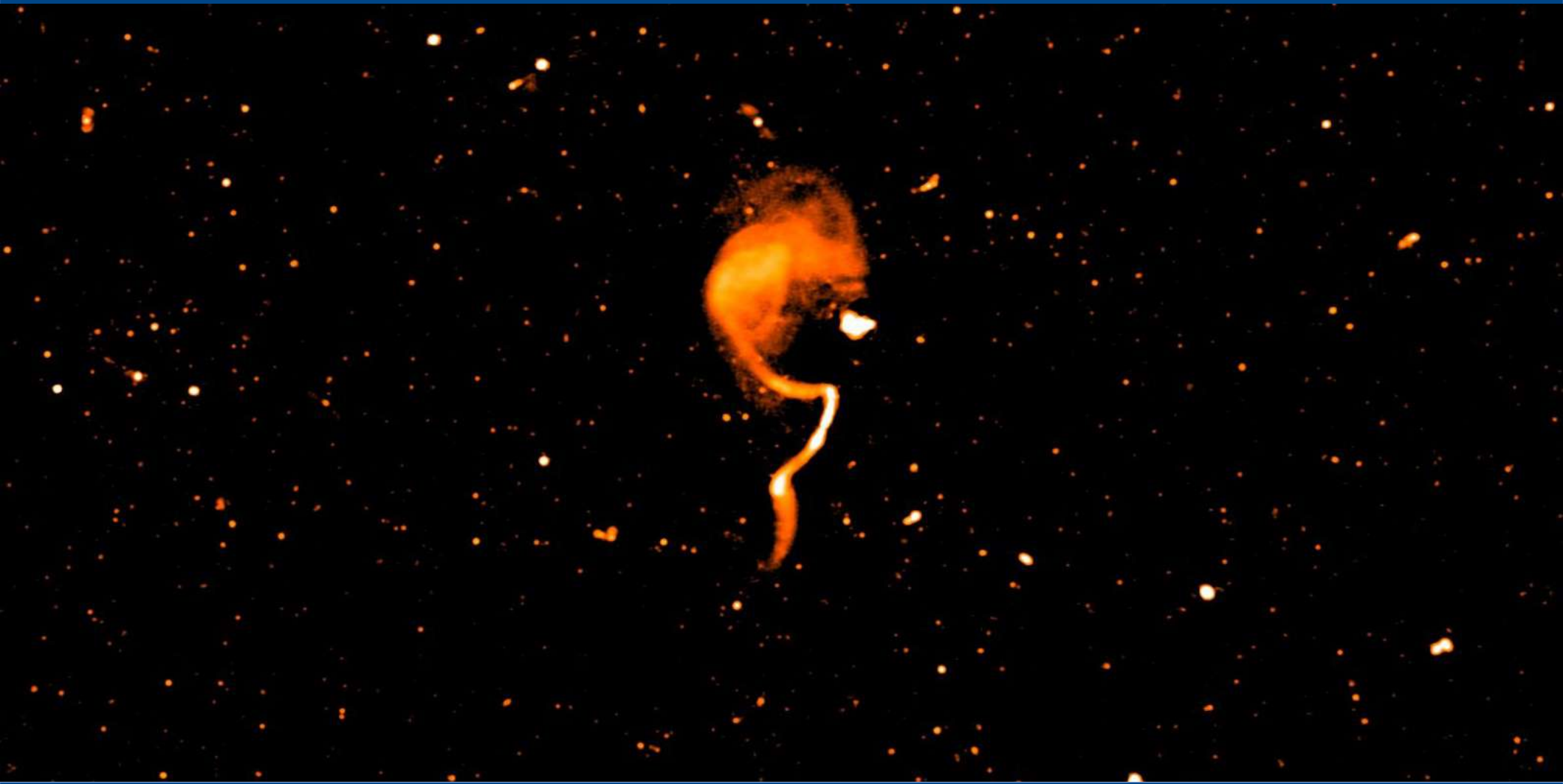


Shimwell+25

5.8°

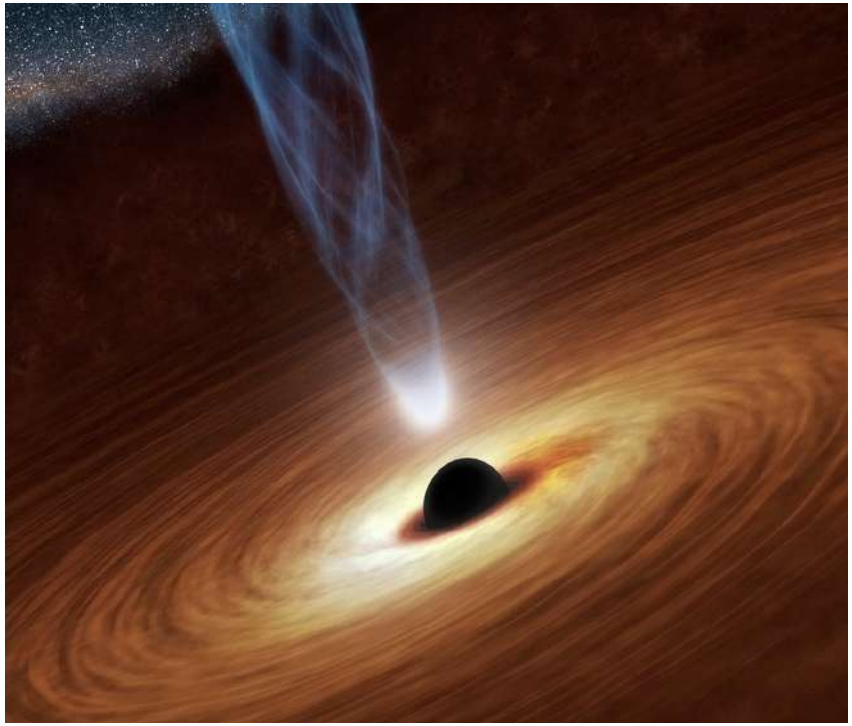


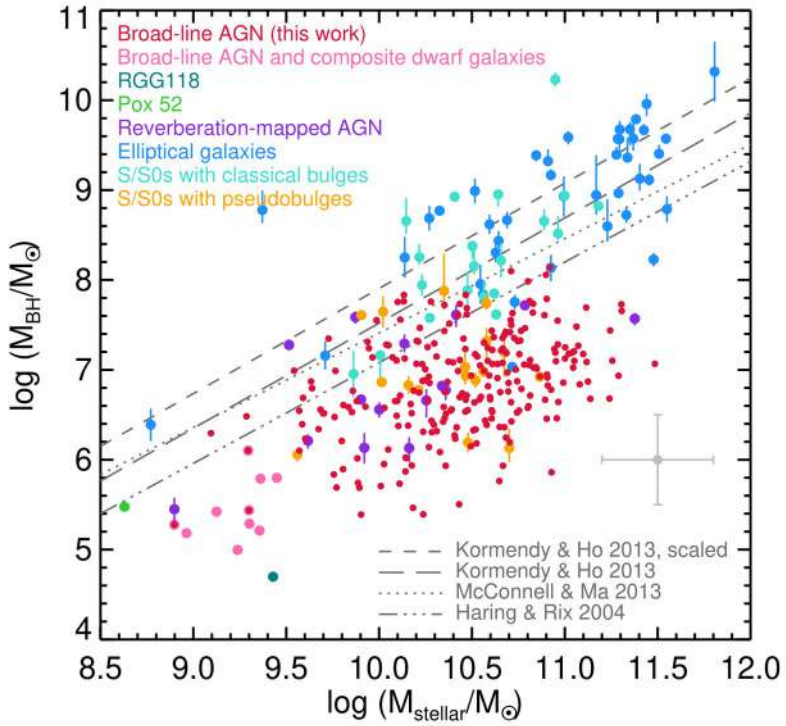
Radio AGN are everywhere



The central engine

- AGN in general are fundamentally driven by accretion onto a central supermassive black hole (SMBH).
- SMBH are ubiquitous in massive galaxies and their mass scales with the galaxy mass





Reines + Volonteri 15

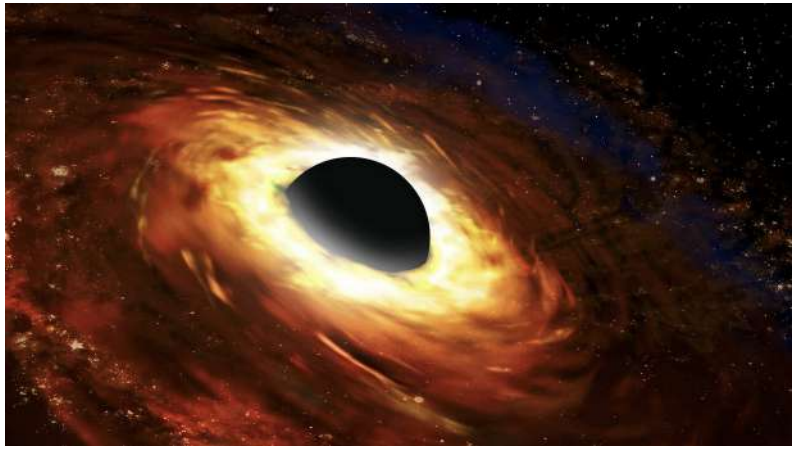
The classical AGN picture

- The best understood AGN (quasars etc) accrete through geometrically thin, optically thick, radiatively efficient accretion disks
- The black hole has a characteristic radius $r_g = \frac{2GM}{c^2}$ for a non-rotating black hole
- Material falls in from large distances at a rate $\dot{M}$ set by processes in the host galaxy
- Gravitational potential energy is efficiently dissipated in the disk
- Material cannot retain a stable orbit within the innermost circular stable orbit (ISCO) which for a non-rotating black hole is at a radius $r_{ISCO} = 3 r_g$
- We expect energy dissipation in the disk to be given by

$$L_{bol} = \xi \dot{M} c^2$$

where ξ is an efficiency factor of order 10% (0.06 for a non-rotating black hole, up to 0.423 for a maximally rotating BH with a co-rotating disk).

- AGN powers can be up to order of 10^{41} W which requires accretion rates of around 200 solar masses per year.



Some complications: (1) Eddington and accretion mode

- The Eddington limit given by

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

  is a maximum luminosity for an accretion disk beyond which the accreting material will be blown away by the radiation it generates.

- From above this corresponds to a mass accretion rate

$$\dot{M} = \frac{4\pi G M m_p}{\xi c \sigma_T} = 2.1 \times 10^{-8} M \ \mathrm{yr}^{-1}$$

  Accretion at close to/higher than this rate cannot form a thin disk because the disk will be inflated by radiation pressure.

- It turns out that accretion at less than **a few per cent of this rate** also cannot form a thin disk because the density is too low for the disk to cool efficiently – in this case we get an advection-dominated accretion flow (ADAF, e.g. Narayan + Yi 95)

- Most accreting SMBH are likely to be ADAFs!

Some complications (2) Viscosity and magnetic fields

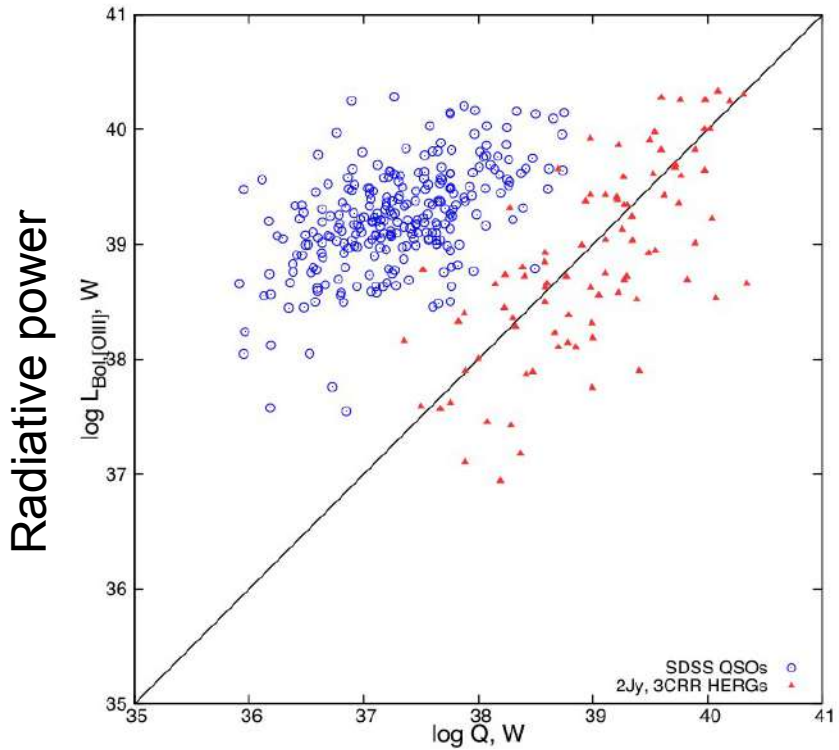
- Dissipation in the disk requires the disk to be viscous
- Originally this viscosity was thought to be turbulent viscosity, but this does not really work
- Need to invoke *magnetic fields in the accretion disk*

It was, of course, recognized early on that magnetic fields could transport angular momentum through Maxwell stresses, $-B_r B_\phi / 4\pi$, but unless the magnetic pressure were near the thermal pressure, it was expected that the effective α would be relatively small. As it turns out, magnetic fields render the disk linearly unstable to the *magneto-rotational instability* (Balbus and Hawley 1991, MRI) even when (and, indeed, *only* when) the magnetic field is weak. The MRI can be visualized intuitively in the form of a spring connecting two orbiting masses (Balbus and Hawley 1998), one in a slightly lower orbit than the other. Because angular velocity decreases with R, $\Omega \propto R^{-3/2}$, the inner mass pulls ahead of the outer mass. This causes the spring to stretch; the tension force pulls back on the inner mass, and pulls forward on the outer. The effect of this is to transfer some angular momentum from the inner to the outer mass, but in doing so the inner mass drops to a lower orbit, increasing its angular velocity, increasing the relative separation of the masses and increasing the spring tension force. The process runs away unless the spring is strong enough to force the masses to remain together, which happens only if the tension exceeds the orbital dynamical force. If we replace the spring with a magnetic field, the spring tension is replaced with the magnetic tension associated with the Maxwell stress. In a magnetized disk the linear stability requirement is no longer the Rayleigh criterion,

Balbus, Fendt, Hardcastle +15

Some complications (3) jets

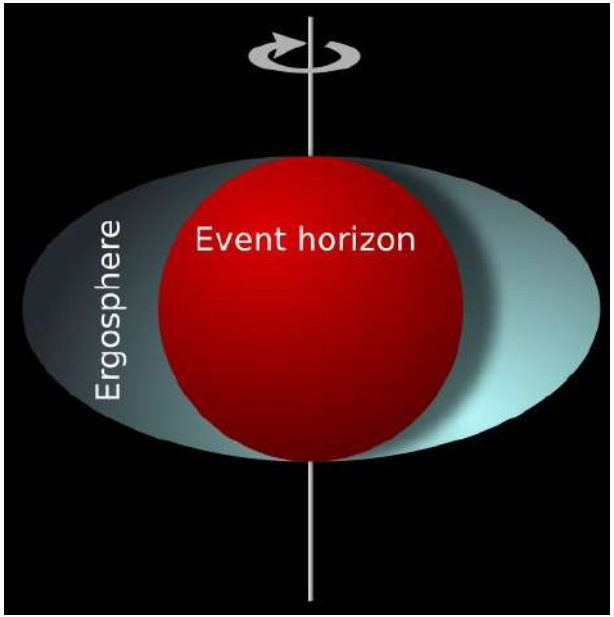
- In addition to the radiative power *L* for a radiative AGN we can also define the jet power *Q*, the power being carried away from the black hole by the jets.
- If accretion power was the only controlling parameter then all SMBH would have jets that would carry the same amount of energy relative to the accretion power – which we can estimate directly for radiatively efficient systems like quasars.
- But subject to caveats about measuring *Q* which we will return to later, this is absolutely not the case. Some quasars have little or no jet-related radio emission.
- Something else must at least partly be responsible for controlling the jet power… we turn to that next!



Right: Mingo+ 14 compare jet powers for radio AGN with quasars

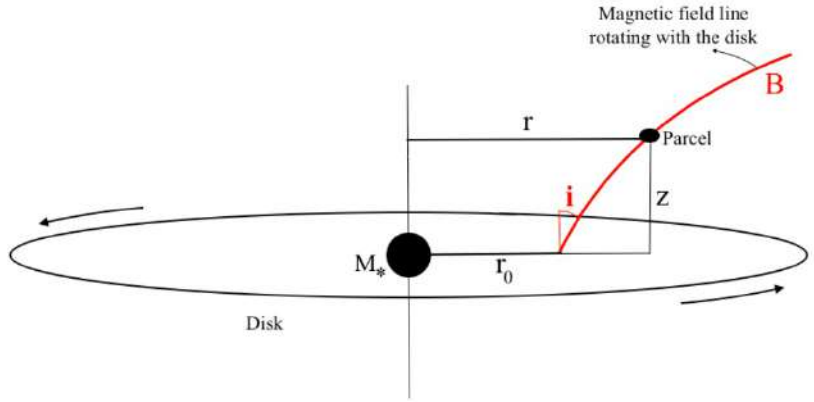
Jet generation mechanisms

- A jet generation mechanism needs to be able to make a jet emerge from close to the central SMBH
- Jets need to achieve high speeds (both observationally and because they need to escape from the SMBH)
- Jet axes must be determined by some long-lived property of the system since jets are clearly capable of being stable on timescales of millions of years
- Models must be capable of generating jets from systems both with and without radiatively efficient accretion disks
- Models must allow the energetic particles in the jet to be generated far from the intense radiation environment of the disk
- Most models involve the *magnetic fields* that are believed to be present in the accretion disk
- A key question is whether the power in the jets comes directly from the accretion disk or whether it is related to properties of the black hole/accretion system.
- Penrose (1969) showed that the *spin* of a rotating black hole can be a source of energy in some circumstances.



Blandford-Payne mechanism (Blandford & Payne 1982)

- Blandford-Payne mechanism: magnetocentrifugal acceleration
- Plasma from the disk can be flung out along open ~ poloidal field lines if they are inclined to the disk
- Would create a ‘wind’ of material originating in the disk
- Not clear if it works in the case of ADAFs

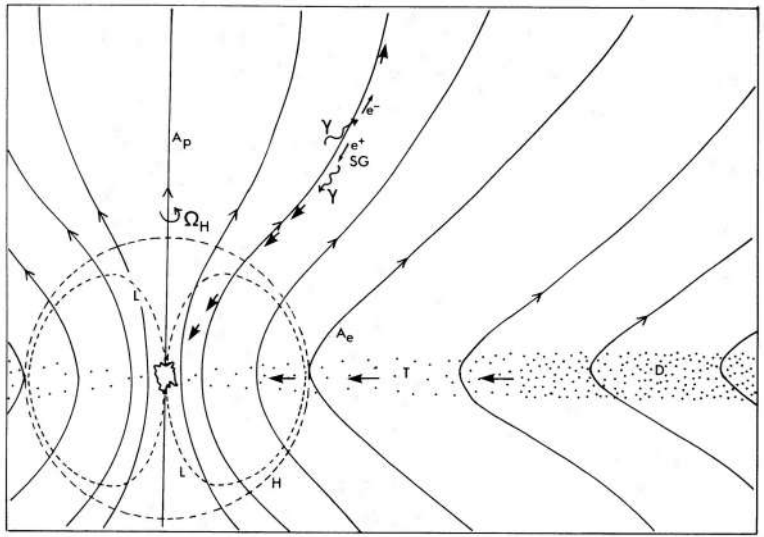


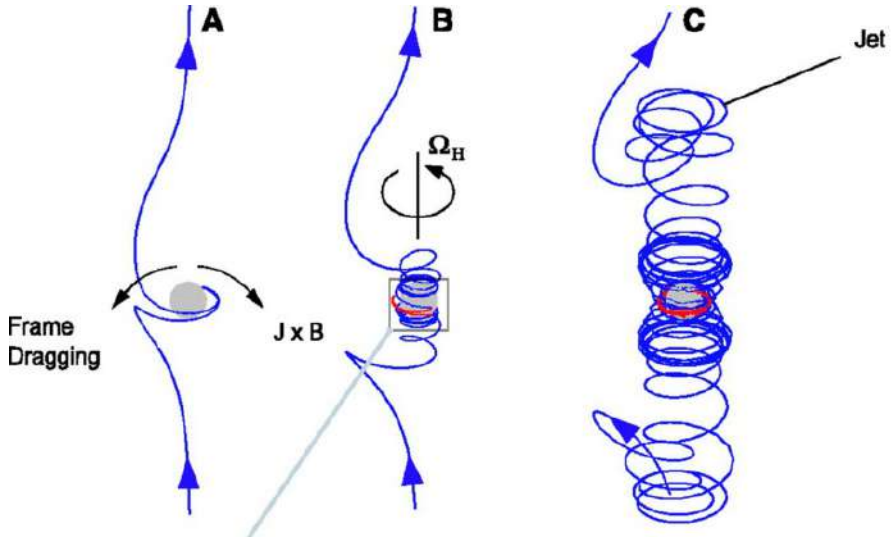
Right: figure from Jafari 19

Figure 2. Magneto-centrifugal mechanism proposed by Blandford & Payne (1982): A parcel of plasma, at radius r and height z above the disk, moving along a magnetic field line whose footpoint on the disk lies at the radius r_0. The field line and the parcel rotate with rotational velocity $\Omega_0 = (GM_*/r_0^3)^{1/2}$ so the parcel's velocity is $v = r\Omega_0$. Matter can move along the magnetic field lines co-rotating with the disk in a similar manner that a bead would move on a string when it experiences a centrifugal force along the string. The effective potential for the parcel is given by eq.(22). This potential is basically the sum of the gravitational potential energy and the "effective kinetic energy" per mass of the parcel, the latter given by $v^2/2 = (r\Omega_0)^2/2 = (GM_*/2r_0)(r/r_0)^2$. The parcel can accelerate along the field lines provided that the field has a large bending angle; $i \geq 30°$.

Blandford-Znajek mechanism (Blandford & Znajek 1977)

- Poloidal magnetic field is carried inwards by the accretion flow
- Close to a rotating black hole the field is pushed into the black hole ergosphere where the forced co-rotation of space-time twists up the field, increasing the energy density
- The energy density above the spin axis of the black hole causes an initially electromagnetic outflow in which pairs can be produced





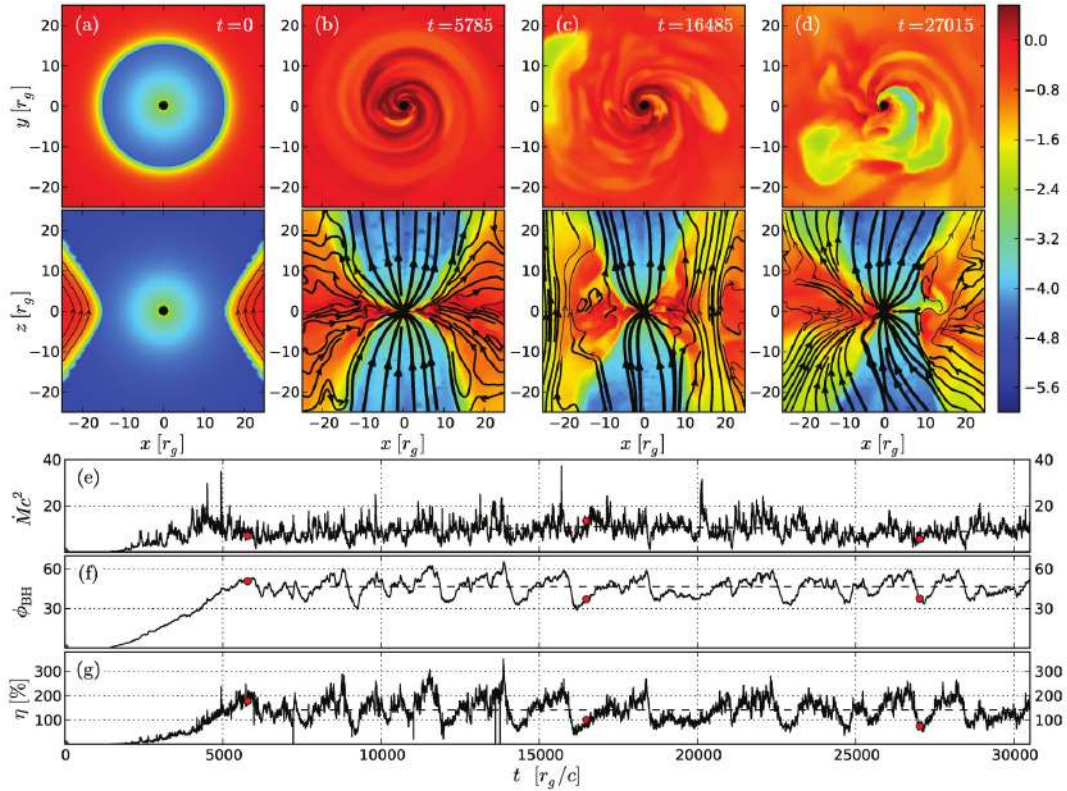
Left: Blandford + Znajek 77

Right: Semanov+ 04

Why the B-Z mechanism is correct

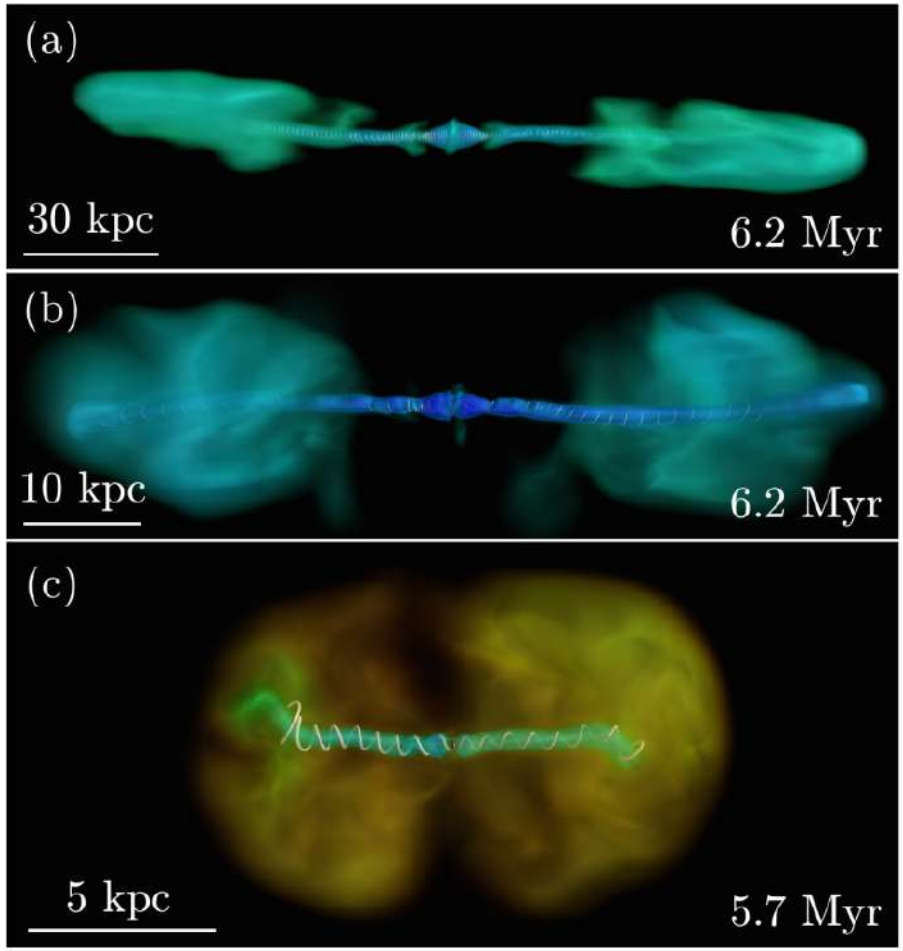
- GRMHD simulations show jets spontaneously emerging from simulations with the correct physics (e.g. Tchekhovskoy+11, right).
- Depends on spin and the integrated magnetic flux accreted onto the black hole, *not directly on mass accretion rate*
- Jet initial direction is aligned with the black hole spin axis
- For strongly magnetized (MAD) disks the efficiency of energy extraction can exceed 100%, i.e. the BH spin energy is being tapped
- Jet power comes from the combination of black hole spin, field strength and black hole mass: roughly (Hardcastle & Croston 20; see also Tchekhovskoy 15)

$$P_{\rm BZ} \propto (BaM_{\rm BH})^2$$



The relativistic flow

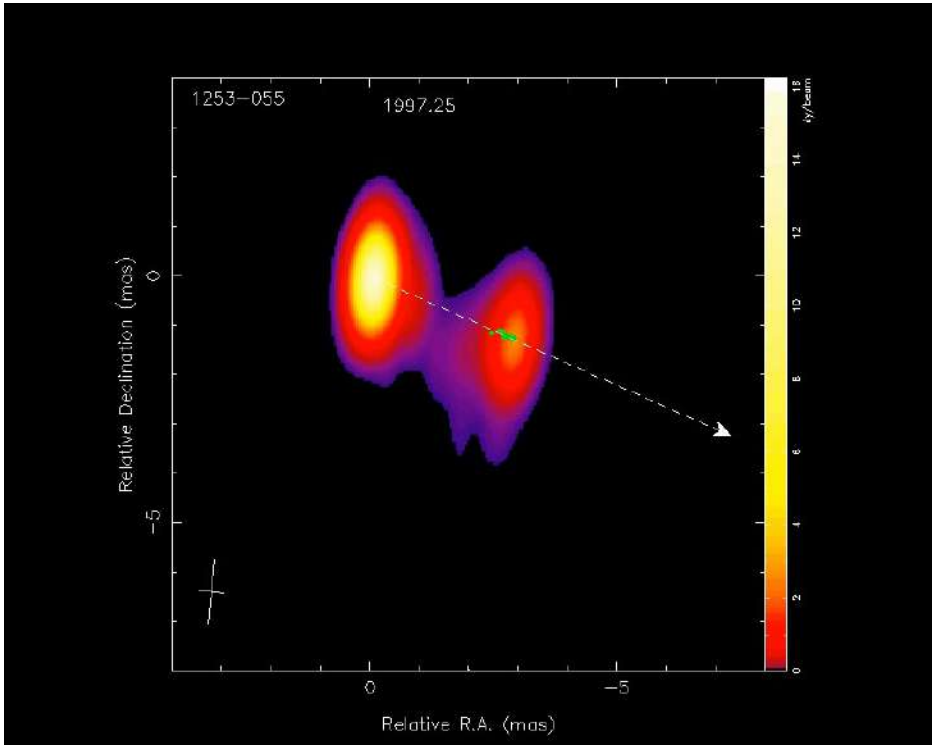
- The picture is then the following:
  - Black hole spin and magnetic fields drive outflows whose power is proportional to spin and black hole mass and whose energy source is a combination of spin and accretion power
  - Energy is transported out as energy in fields (Poynting flux) and later high-energy particles
  - The jets propagate out potentially to large scales forming the radio lobes that we saw earlier (details of radio lobe evolution will be in tomorrow's lecture)



Right: Simulations from Tchekhovskoy + Bromberg 2016

Some questions you should be asking yourself

- Why do we see radio emission from the jets?
  - Radio emission is synchrotron radiation from high-energy particles. We will cover how these particles get to high energies and why they radiate in this way later on.
- What are the jets made of?
  - Initially magnetic fields (Poynting flux) but particles must be involved too. The jet material is thus a *magnetized plasma*. Such a plasma could be made of electrons and positrons only or electrons and protons, or a mixture of the two. Stars will certainly dump some baryons into the jets as we will see shortly, but it is plausible that all jets are initially electron/positron.
- How fast are the jets?
  - They must emerge from the black hole at relativistic speeds. This can give rise to strong special relativistic effects such as Doppler boosting and apparent superluminal motion. Speeds can be measured directly with VLBI monitoring on small scales



VLBA monitoring of 3C279 from MOJAVE (Homan+ 03)

Section 1 summary

- Central engine of all AGN is a supermassive black hole (SMBH) and the energetic output is driven by accretion onto it
- Accretion can be radiatively efficient (quasars etc) or inefficient (e.g. the black hole in our own Galaxy).
- Radio AGN are distinguished by powerful jets that are ejected from close to the SMBH and can propagate out to large scales. These can come from radiatively efficient *or* inefficient systems.
- The best explanation for jet generation is a Blandford-Znajek type mechanism in which magnetic fields interact with the black hole ergosphere. Some of the energy in the jets then comes from spin-down of the black hole.
- Spin, black hole mass and the magnetic flux transported to the event horizon all contribute to the jet power.

Section 2: Dynamics of the jets

- Initial jet dynamics
- Jet collimation scale
- Jet termination and shocks
- Jet instabilities
- Entrainment and deceleration

Jet dynamics

- Assume that the jet is now a magnetized plasma with an internal pressure and density propagating into some environment. The jet is initially supersonic with respect to the external sound speed.
- The jet expands freely while the ram pressure (momentum flux) and internal pressure of the jet are >> the external environmental pressure. Once that's not true the jet must recollimate.
- The jet power, the jet speed and the external density define a characteristic length scale L_1 (Alexander 06)
- Then we can write a condition on the recollimation scale L_{1a} (Krause 12), where we assume external density is constant for the moment
- Beyond this scale the jet is collimated by the external medium (or by a lobe if present). Its opening angle becomes low or zero.

$$L_1 = 2\sqrt{2}\left(\frac{Q_0}{\rho_x v_j^3}\right)^{1/2}$$

$$\frac{L_1}{\mathrm{pc}} = 56\left(\frac{Q_0}{10^{39}\,\mathrm{W}}\right)^{1/2}\left(\frac{\rho_x}{10^{-22}\,\mathrm{kg\,m^{-3}}}\right)^{-1/2}\left(\frac{v_j}{c}\right)^{-3/2}.$$

$$\left(\frac{L_{1a}}{L_1}\right)^2 = \frac{\gamma}{4\Omega} M_x^2 \sin^2\theta, \qquad (3)$$

where γ is the ratio of specific heats in the environment, $\Omega = 2\pi(1-\cos\theta)$ the solid angle of the jet and M_x the Mach number with respect to the ambient sound speed.

Lobes and jet termination

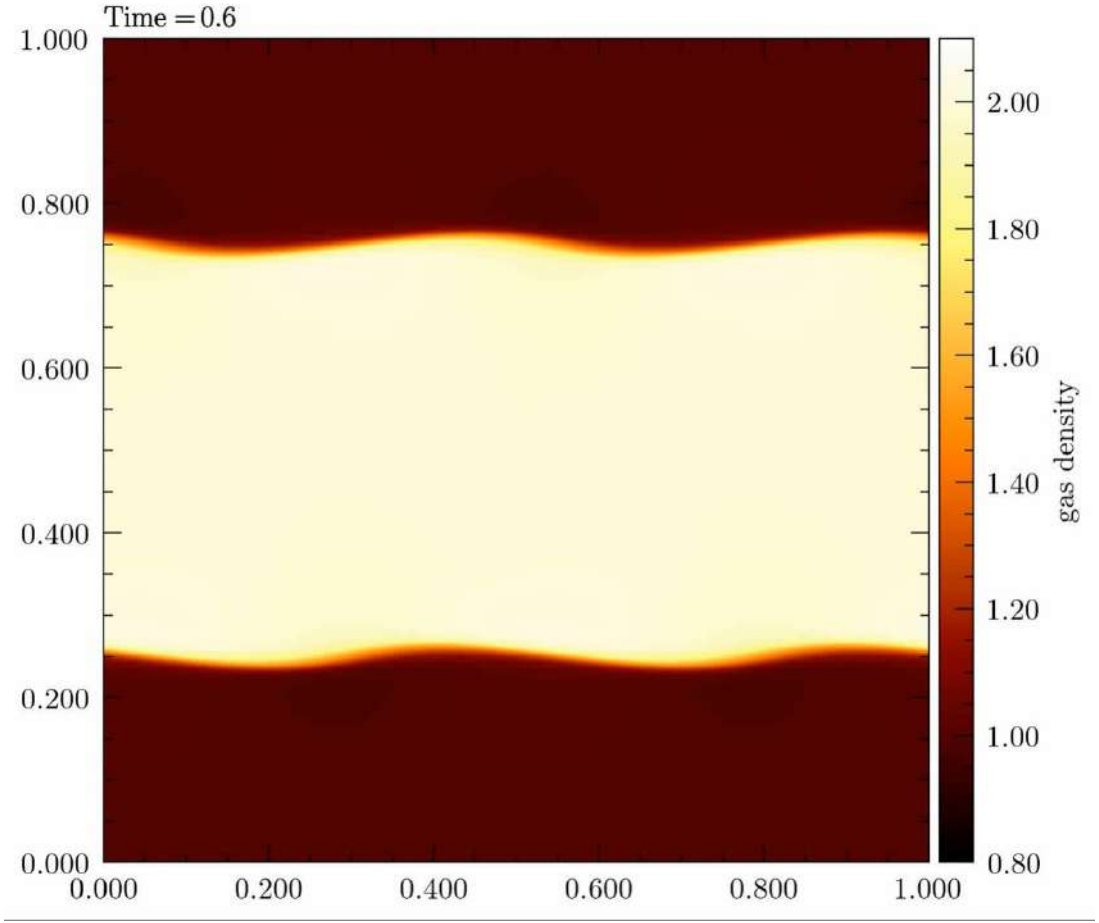
- The jet will start to form a lobe or cocoon if the jet density falls below the external density (meaning that it can inflate a bubble of light material). This happens at L_{1b} in a conical jet.
- If the jet is not recollimated it will reach a scale where the jet ram pressure falls below the external pressure, L_{1c}
- This causes the jet to terminate its forward motion and a shock may form (if the jet is supersonic wrt its own internal sound speed)
- If the jet is recollimated the length scale may be longer and the position of the shock will be wherever the end of the jet is.
- If $L_{1a} > L_{1b}$ a cocoon forms and the jet is collimated by the material in that rather than by the ambient medium.
- If $L_{1c} > L_{1b}$ (as it always is) then a source with lobes will have jets that end in shocks at the end of the cocoon, provided nothing else happens to the jet first!

$$\left(\frac{L_{1b}}{L_1}\right)^2 = \frac{1}{4\Omega}.$$

$$\left(\frac{L_{1c}}{L_1}\right)^2 = \frac{\gamma}{4\Omega} M_x^2.$$

Stability of collimated jets

- In principle collimated jets are Kelvin-Helmholtz unstable (boundary layer of two moving fluids) which would lead to a turbulent mixing layer.
- In practice large-scale K-H structures are not seen – maybe suppressed by magnetic fields or by the fact that the jets are relativistic?
- Dynamically important magnetic fields would give rise to the kink instability (probably also not seen)
- Vast literature on jet stability (e.g. Perucho 12)



Doppler boosting and jet deceleration

- Special relativistic effects modify the appearance of relativistic jets
- The apparent brightness of a box of plasma moving at a speed $\beta = v/c$ towards the observer is changed by a factor

$$D^{2+\alpha}$$

where

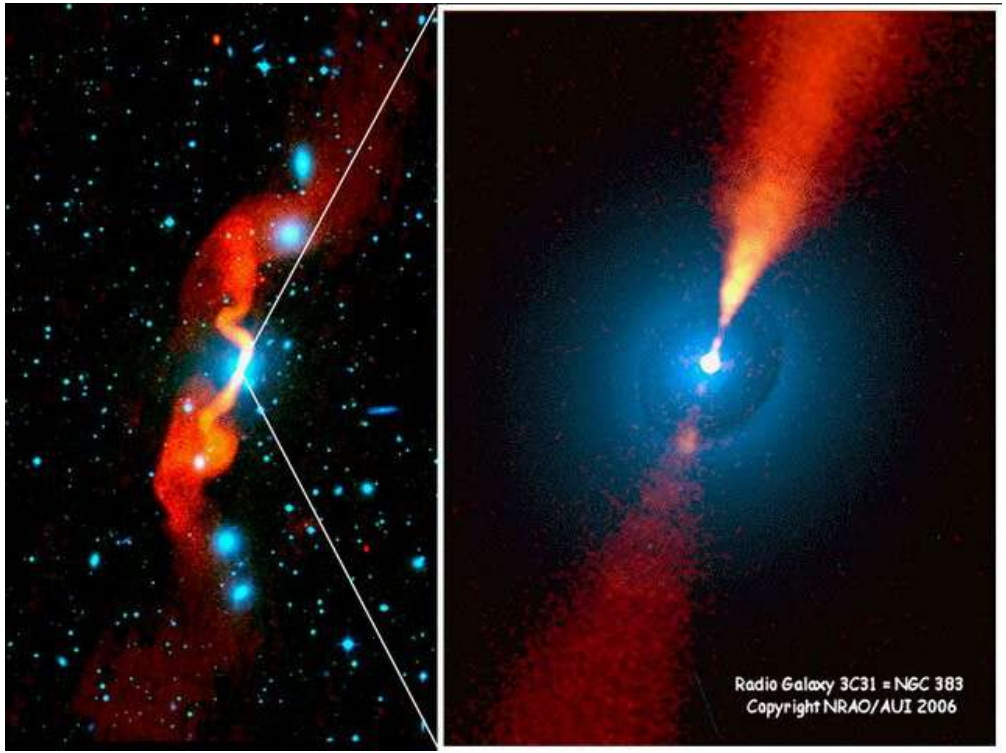
$$D = \frac{1}{\gamma\left(1-\beta\cos\theta\right)}$$

and

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

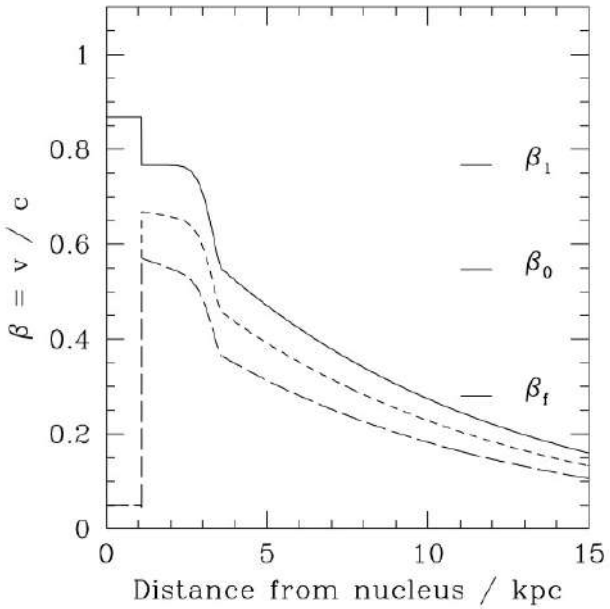
A receding jet has a change of sign

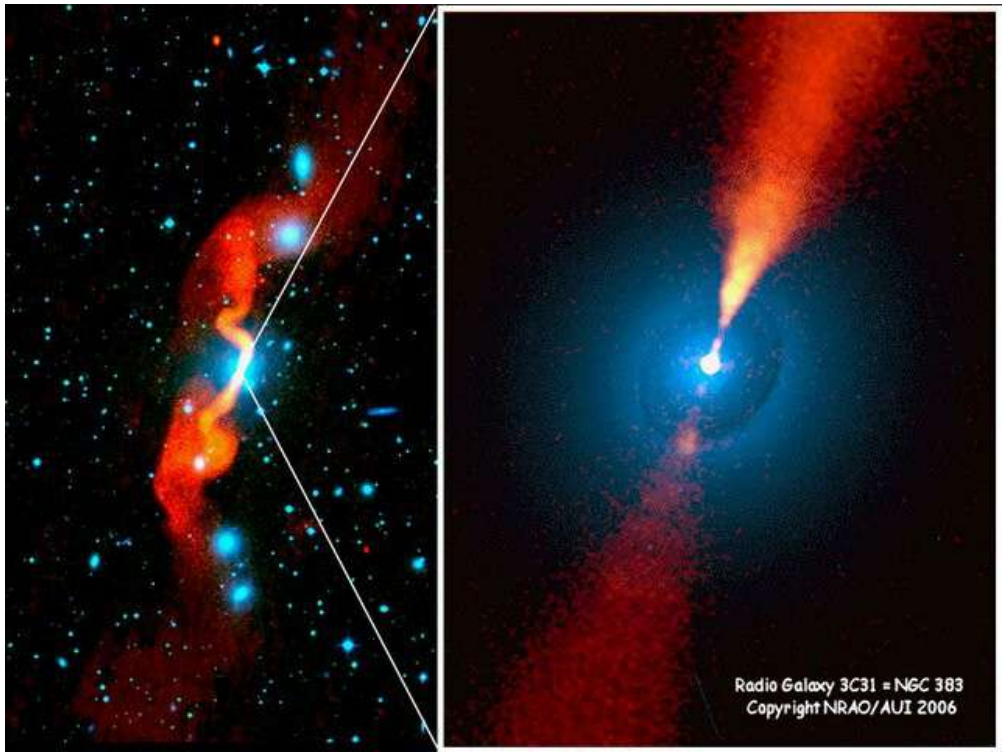
- This means that the receding jet can be much fainter than the approaching one, or even invisible...



Doppler boosting and jet deceleration

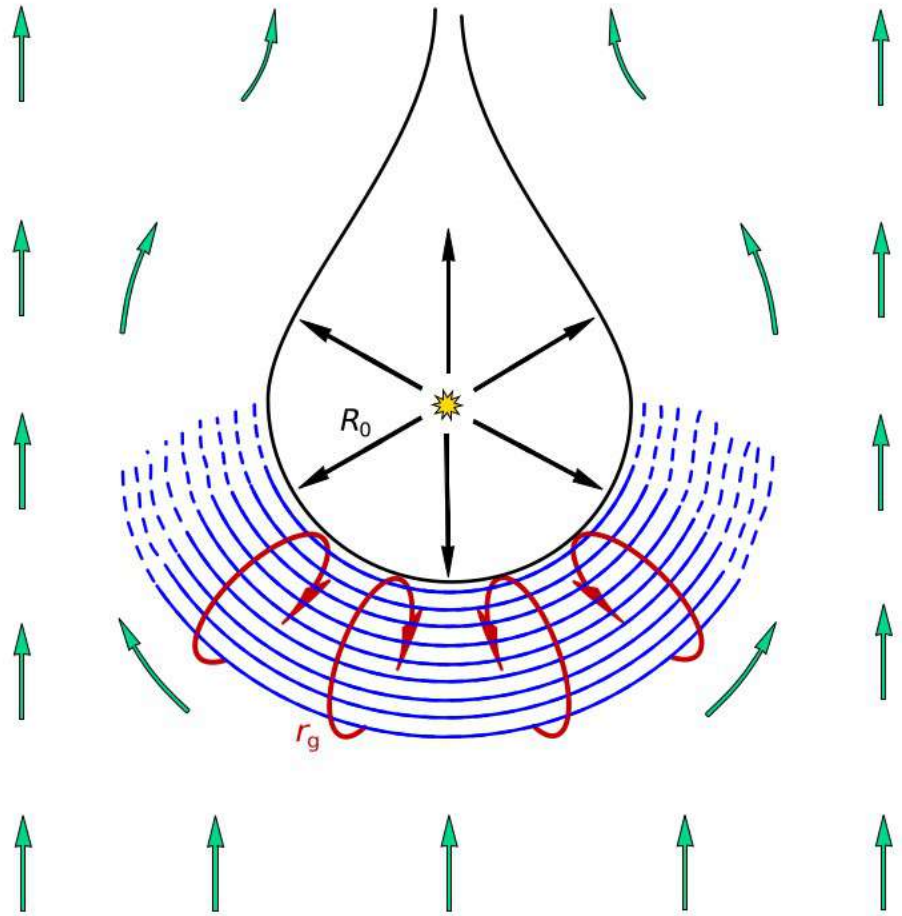
- In the case of some radio galaxies like the one to the left we see that the brightness of the jets is very asymmetrical on small scales and very symmetrical on large scales.
- If this is the result of Doppler boosting then the jet must be decelerating.
- Modelling this together with the relativistic aberration of polarized radio emission gives us a model of the velocity field (e.g. Laing+Bridle 02).





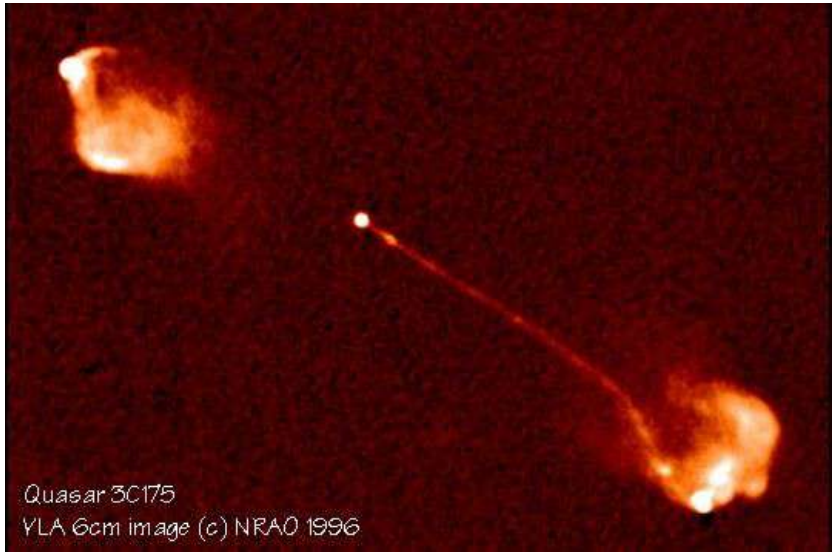
Doppler boosting and jet deceleration

- What could cause jet deceleration?
- Since momentum flux is at least approximately conserved, jets that slow down must get heavier
- Light jets can be decelerated by entrainment of external or internal thermal material, e.g. from the environment through the edges of the jet or from stellar winds (e.g. Bowman+ 96).
- Entrainment from stellar winds is a required process and can account for observed jet deceleration in some cases, but probably not all (e.g. Wykes +15).



Some jets don't decelerate!

- Doppler boosting evidence suggests that other jets don't decelerate significantly on observable scales
- In these cases jet speeds remain relativistic and observed jets are often one-sided
- Jet sidedness and brightness distributions are consistent with speeds $\beta \sim 0.6$
- These jets are moving supersonically with respect to the external sound speed and likely to their internal sound speed as well and there must be an abrupt jump in the speed in the jet material at some point (since the jet does not extend to infinity)
- This means that we need to pause to consider *shocks* driven by supersonic motions.
- These may include at the end of the jet, in jet-star interactions, or outside the expanding lobes...

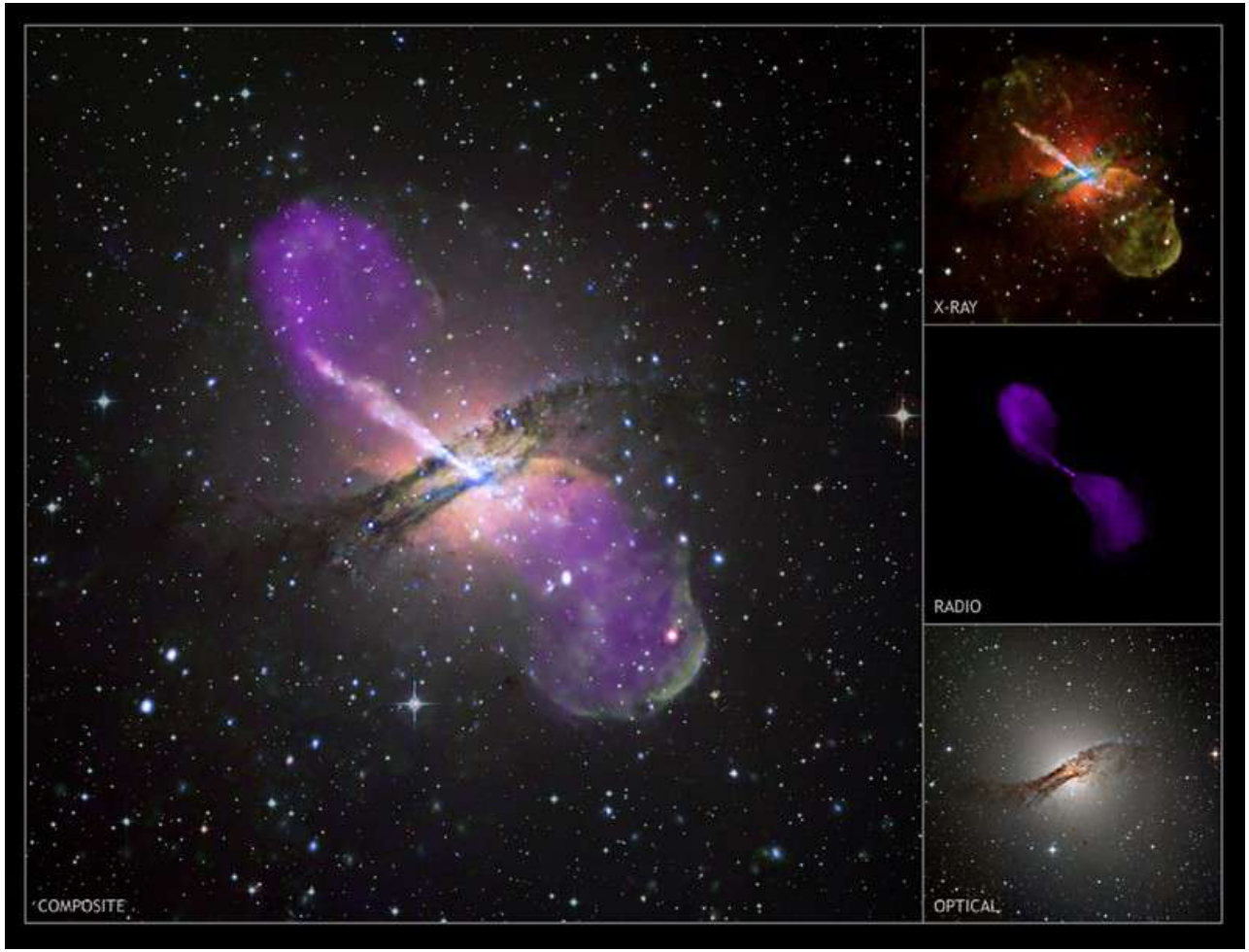


Shocks

Shocks are produced when a disturbance propagates through a fluid at supersonic speeds

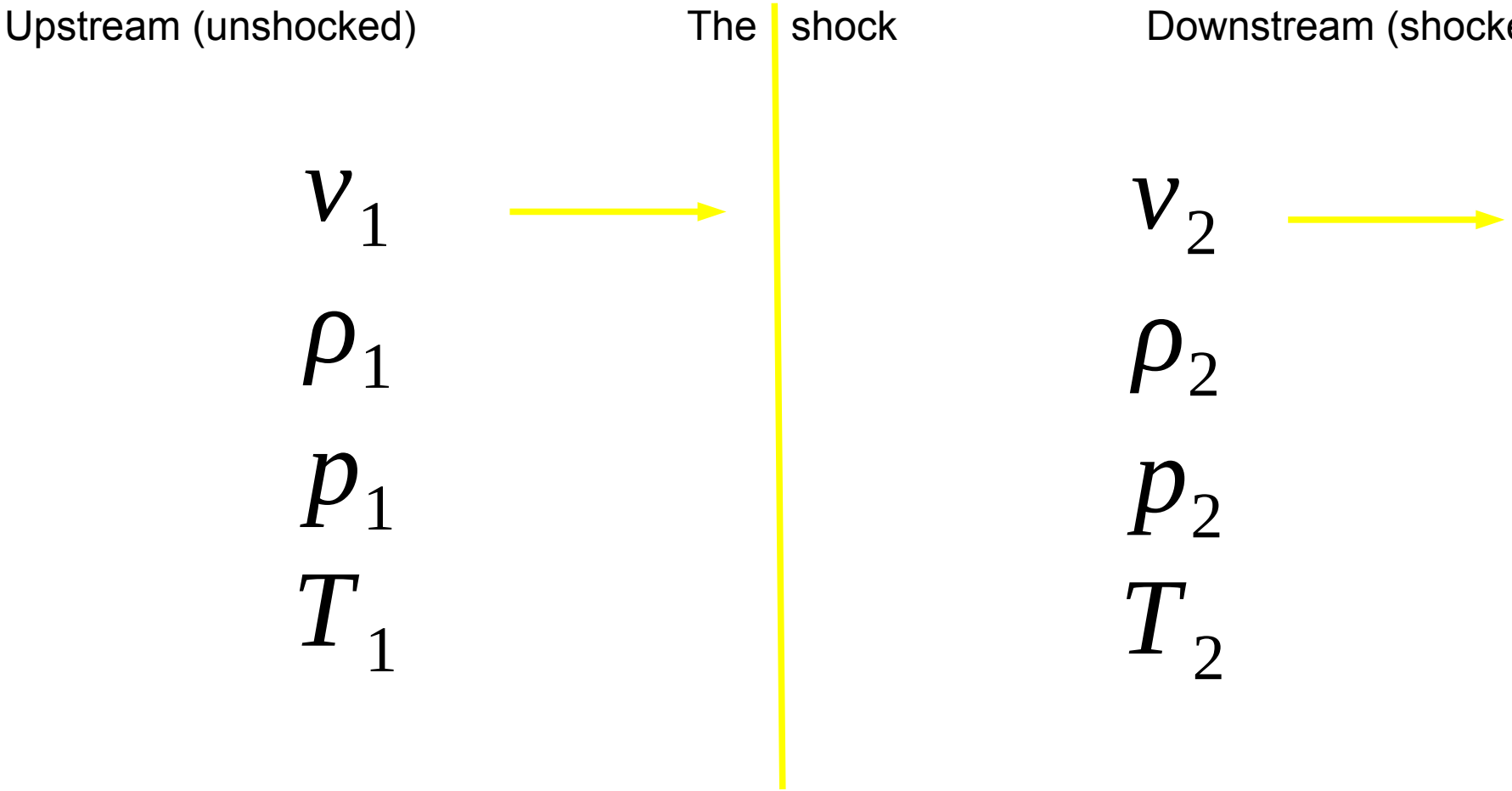


Shocks



Here the radio lobe of Centaurus A (purple) pushes a Mach 8 shock through the external medium (Croston+ 09)

Physical quantities in the frame of a planar shock



The jump conditions and their consequences

$$\rho_1 v_1 = \rho_2 v_2$$

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$

$$\rho_1 v_1 \left(w_1 + \frac{1}{2} v_1^2\right) = \rho_2 v_2 \left(w_2 + \frac{1}{2} v_2^2\right)$$

$$w = \frac{\Gamma p}{(\Gamma - 1)\rho}$$

$$\frac{v_2}{v_1} = \frac{\Gamma - 1 + 2/\mathcal{M}_1^2}{\Gamma + 1}$$

$$\frac{\rho_2}{\rho_1} = \frac{\Gamma + 1}{\Gamma - 1 + 2/\mathcal{M}_1^2}$$

$$\frac{p_2}{p_1} = \frac{2\Gamma\mathcal{M}_1^2 + (1 - \Gamma)}{\Gamma + 1}$$

$$\frac{T_2}{T_1} = \frac{\left[2\Gamma\mathcal{M}_1^2 + (1 - \Gamma)\right]\left[\Gamma - 1 + 2/\mathcal{M}_1^2\right]}{(\Gamma + 1)^2}$$

The jump conditions and their consequences

- The downstream speed becomes subsonic ($M_1 > 1$)
- The density increases across the shock up to a constant value (=4 for a non-relativistic gas with $\Gamma = 5/3$)
- The pressure can be increased to arbitrarily high values...
- ... and so can the temperature since $p = nkT$

$$\frac{v_2}{v_1} = \frac{\Gamma - 1 + 2/\mathcal{M}_1^2}{\Gamma + 1}$$

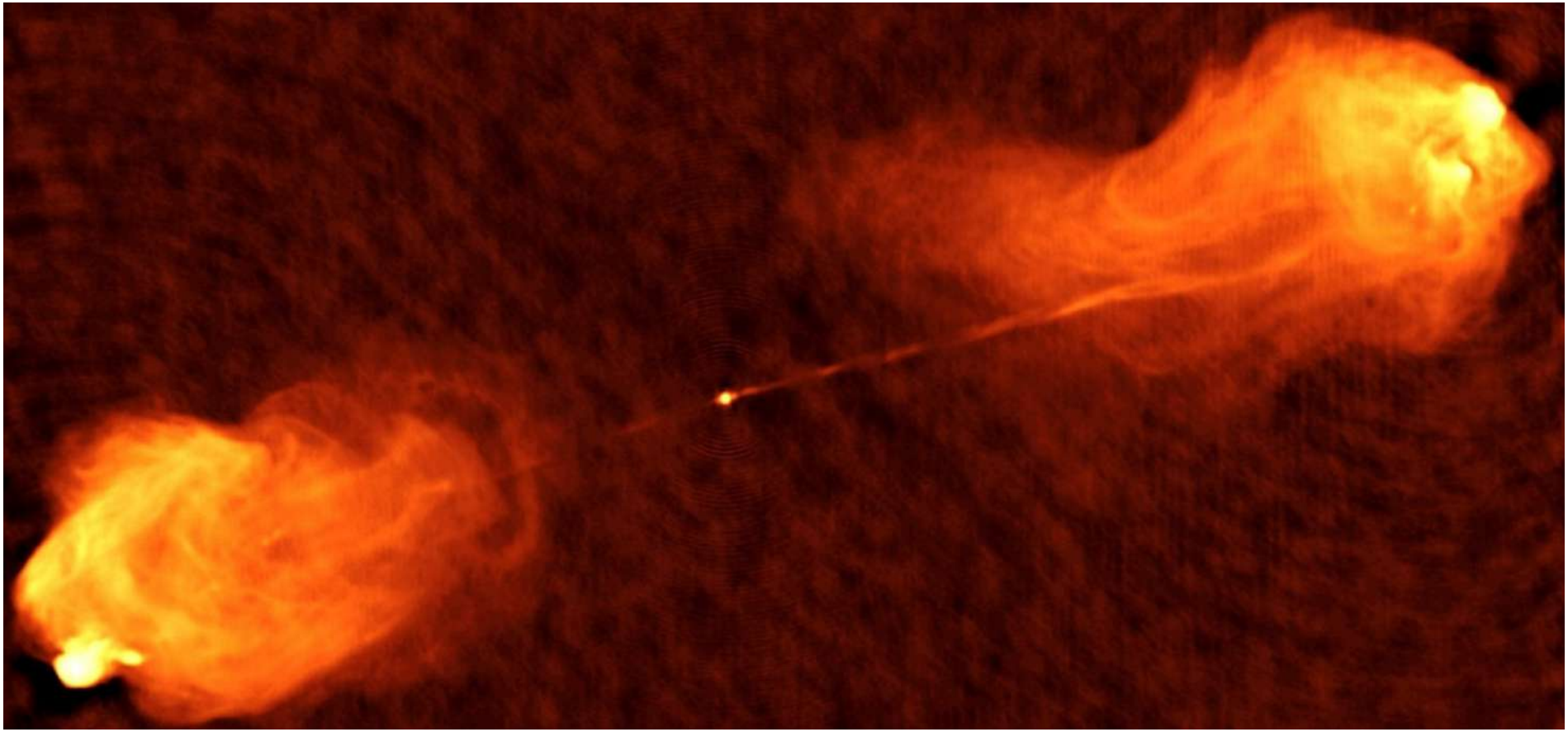
$$\frac{\rho_2}{\rho_1} = \frac{\Gamma + 1}{\Gamma - 1 + 2/\mathcal{M}_1^2}$$

$$\frac{p_2}{p_1} = \frac{2\Gamma\mathcal{M}_1^2 + (1 - \Gamma)}{\Gamma + 1}$$

- Shocks heat and compress a gas or plasma.
- (If magnetized, they also increase the field strength)

$$\frac{T_2}{T_1} = \frac{\left[2\Gamma\mathcal{M}_1^2 + (1 - \Gamma)\right]\left[\Gamma - 1 + 2/\mathcal{M}_1^2\right]}{(\Gamma + 1)^2}$$

Hotspots as jet termination shocks



Hotspots as jet termination shocks

- Hotspots are likely to be (magneto)hydrodynamical shocks as in these simulations by Horton+ 23, together with particle acceleration which we will describe in the next section
- Multiple hotspots may be the result of the jet changing direction (‘precession’)

Coloured surfaces are isobars

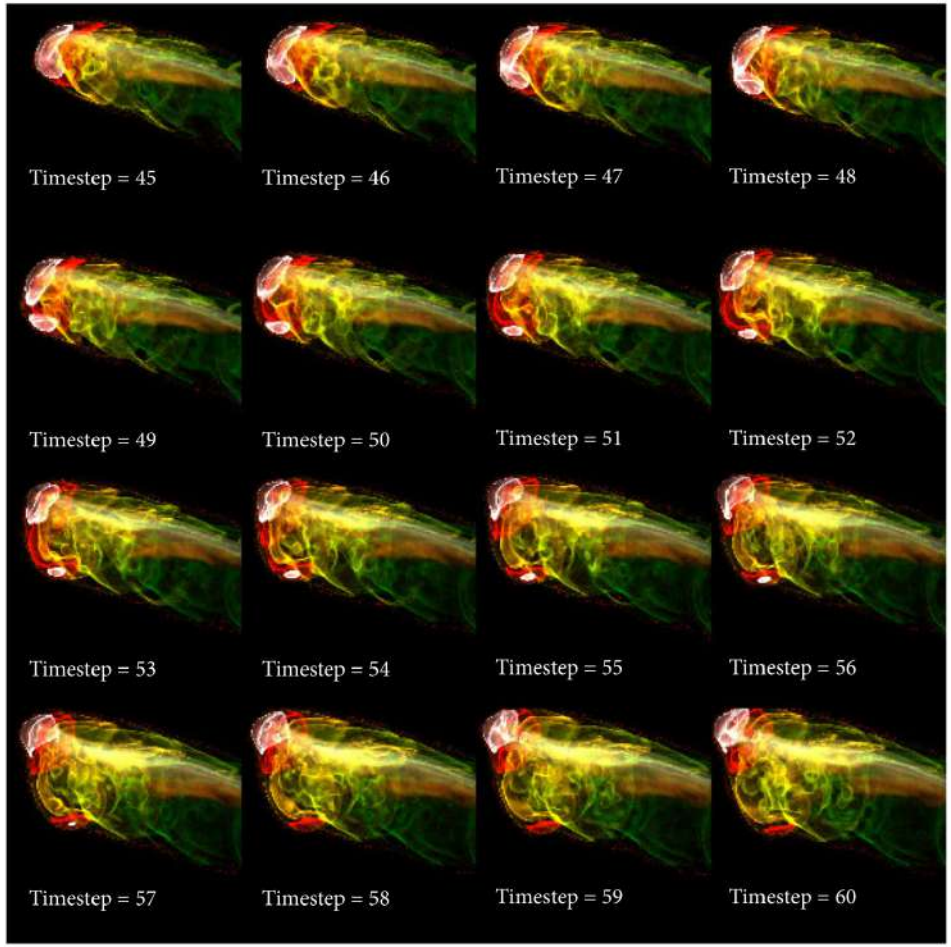
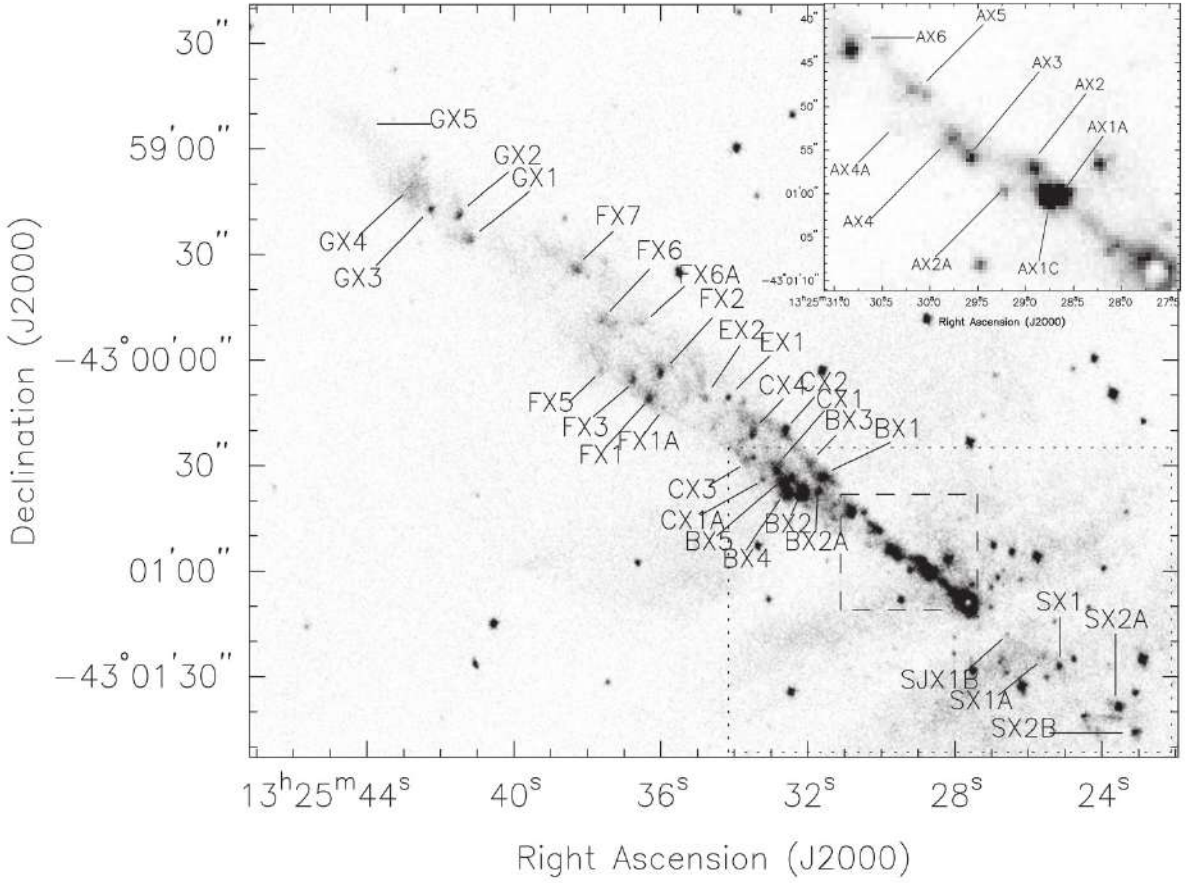


Figure 2. As Fig. 1, showing the evolution of the hotspot splitting event, running from time-steps 45 to 60 representing a duration of 1.8×10^6 yr.

Shocks internal to jets?

- Cen A in the X-ray, Goodger+ 10
- Jet shows relativistic proper motions
- Could some or all of these X-ray knots be jet/stellar wind interactions leading to shocks (Hardcastle+ 03, Wykes +15)
- Some of them are moving and so probably not...





Section 2 summary

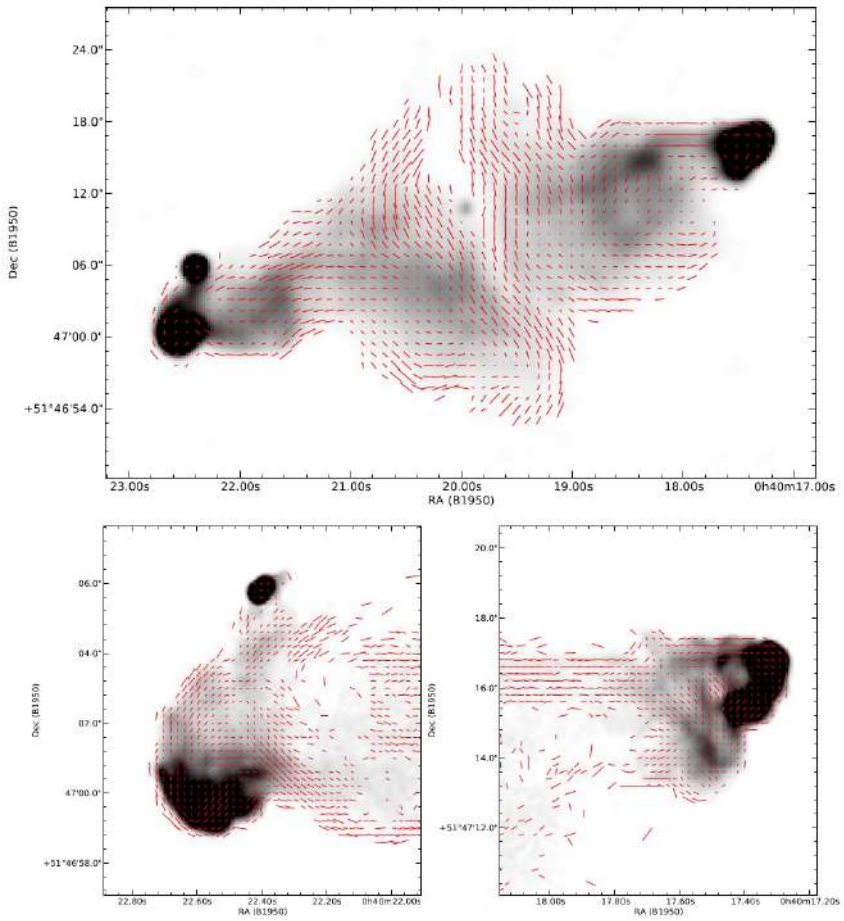
- Initially conical jets necessarily become collimated on small scales as their internal pressure drops.
- Collimated jets can propagate for large distances.
- Light jets will generate lobes (‘cocoons’) which stabilize and collimate the jet further.
- Smooth jet deceleration comes from entrainment of heavier material from the environment or from stellar winds.
- If the jet remains supersonic until the end then shocks at the jet termination give rise to regions of increased pressure (hotspots).
- Internal local interactions may also generate shocks.

Section 3: radiation mechanisms and particle acceleration

- Synchrotron radiation
- Inverse-Compton process
- Particle acceleration at shocks and elsewhere

Synchrotron radiation

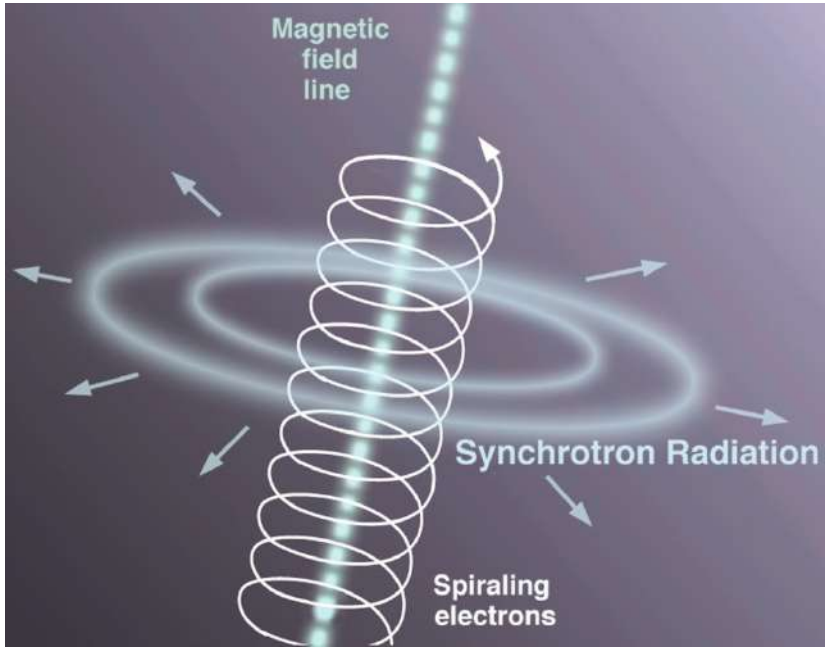
- The radio and in some cases optical and X-ray emission from radio AGN is synchrotron emission (e.g. Shklovskii 55, Baade 56)
- We know this because of its high degree of polarization and very broad-band spectrum.
- Understanding the physics of radio AGN involves understanding synchrotron emission and its sister process inverse-Compton emission, and also understanding why these processes are relevant.



Right: polarized 8-GHz radio emission from a radio galaxy (Hardcastle 15).

Synchrotron radiation

- We already know from discussion of jet generation that the jet starts off as a light, magnetized plasma.
- Charged particles move in helices (spirals) in magnetic fields
- In classical electromagnetism all electromagnetic radiation is the result of acceleration of charges (Larmor's formula)
- Thus a particle moving around a field line acts like a dipole and loses energy to radiation.
- Synchrotron emission emerges when the particle is fully relativistic (that is Lorentz factor >> 1).
- It is naturally polarized because the emission comes out perpendicular to the magnetic field.



Synchrotron radiation

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m\mathbf{v}) = q\mathbf{v}\times\mathbf{B}$$

F=ma with Lorentz force

$$\omega = \frac{qB}{\gamma m}$$

Angular frequency

$$a_\perp = \omega v_\perp = \frac{qBv_\perp}{\gamma m} = \frac{qBv\sin\theta}{\gamma m}$$

Acceleration

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{q^2\gamma^4}{6\pi\varepsilon_0 c^3}\left[\mathbf{a}^2+\gamma^2\left(\frac{\mathbf{v}.\mathbf{a}}{c}\right)\right] = \frac{q^2\gamma^4}{6\pi\varepsilon_0 c^3}\frac{q^2B^2v^2\sin^2\theta}{\gamma^2m^2} = \frac{q^4B^2}{6\pi\varepsilon_0 cm^2}\frac{v^2}{c^2}\gamma^2\sin^2\theta$$

Larmor's formula for energy loss

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -2\left(\frac{q^4}{6\pi\varepsilon_0^2c^4m^2}\right)\beta^2 c\frac{B^2}{2\mu_0}\gamma^2\sin^2\theta$$

Tidy up: for electrons term in brackets is Thomson cross-section

$$\left\langle\frac{\mathrm{d}E}{\mathrm{d}t}\right\rangle = 2\sigma_T\beta^2 c\frac{B^2}{2\mu_0}\gamma^2\int\frac{1}{2}\sin^3\theta\,\mathrm{d}\theta = \frac{4}{3}\sigma_T\beta^2 c\frac{B^2}{2\mu_0}\gamma^2$$

Average over all pitch angles (assumed random)

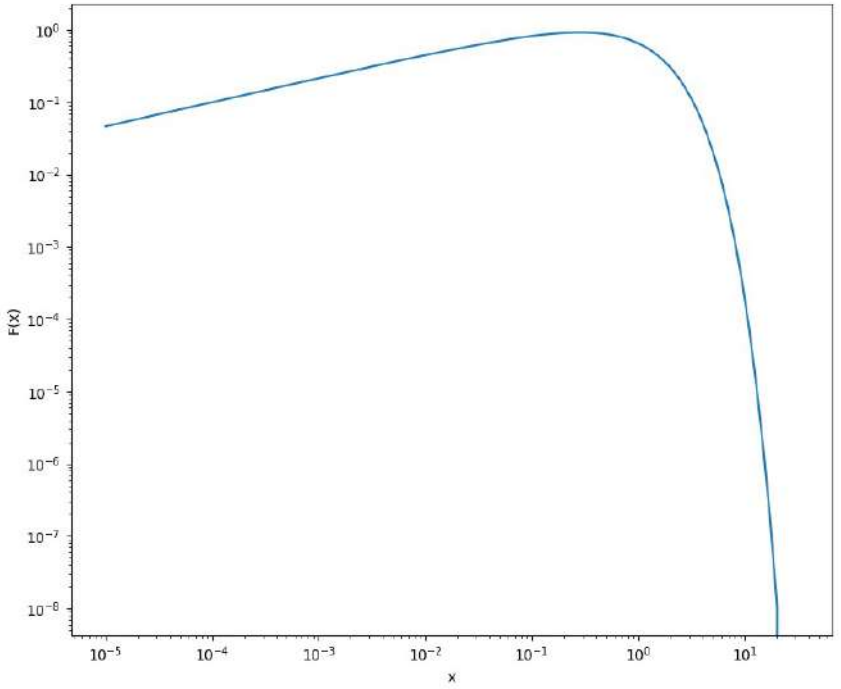
Synchrotron spectrum of one electron (not derived)

- Single-electron spectrum has a peak at a critical frequency and a fast decline above the peak.

$$j(\omega) = \frac{\sqrt{3}Bq^3 \sin\theta}{8\pi^2 \varepsilon_0 cm} F'(x)$$

$$F'(x) = x \int_x^\infty K_{5/3}(z)\mathrm{d}z$$

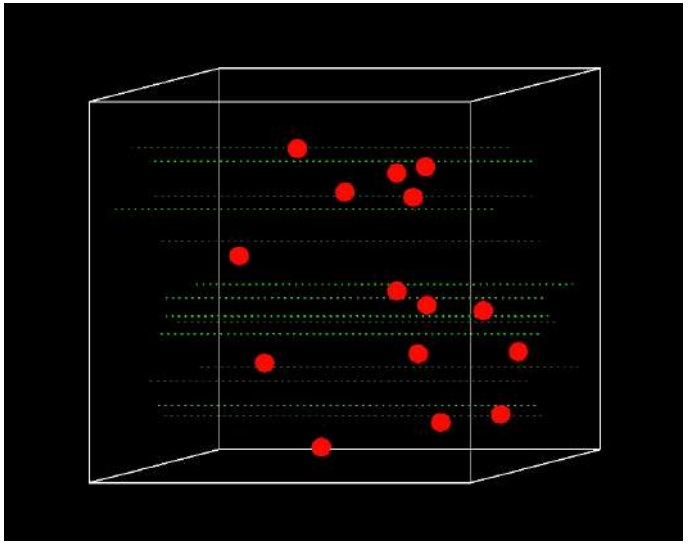
$$x = \omega/\omega_c = \frac{\omega}{\frac{3}{2}\gamma^2 \frac{qB}{m} \sin\theta} = \frac{4\pi m^3 c^4}{3q} \frac{\nu}{E^2 B \sin\theta}$$



Synchrotron spectrum: ensemble of electrons

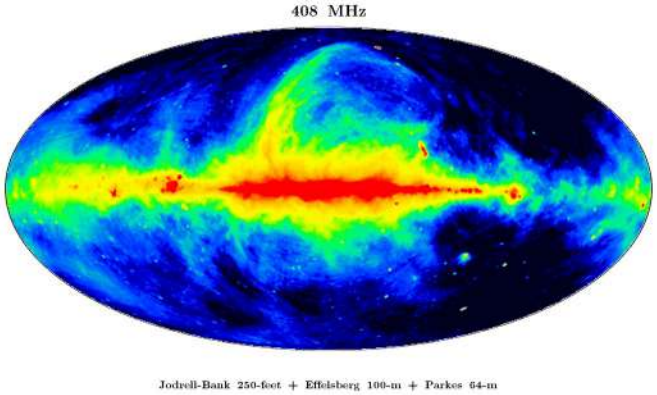
- We get the spectrum of all the electrons by integrating over all electron energies/Lorentz factors

$$J(\nu) = \int_{E_{min}}^{E_{max}} j(\nu) N(E) \mathrm{d}E = \frac{\sqrt{3} B e^3 \sin\theta}{4\pi\varepsilon_0 c m_e} \int_{E_{min}}^{E_{max}} F(x) N(E) \mathrm{d}E$$



- Synchrotron spectra are often power laws extending over large ranges in frequency. Since $F(x)$ is strongly peaked this implies that the electron energy distribution is similarly a power law. Hold that thought…

- Synchrotron emission dominates the low-frequency radio sky.



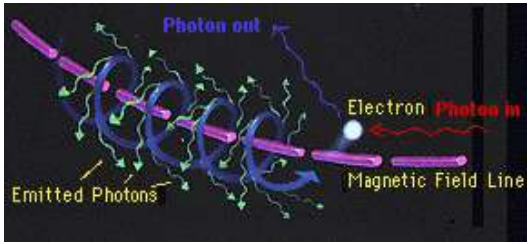
Inverse-Compton scattering

- In the observer's frame, a relativistic electron interacts with a relativistic electron and is scattered to higher energy
- In the rest frame of the electron, this is Thomson scattering – the photon comes in and scatters elastically on the stationary electron – but the energy density is changed in the electron frame as the photons are Doppler shifted
- Possible to show from this that

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) = \left(\frac{\mathrm{d}E'}{\mathrm{d}t'}\right) = \frac{4}{3}\gamma^2\sigma_T c U_{\mathrm{rad}}$$

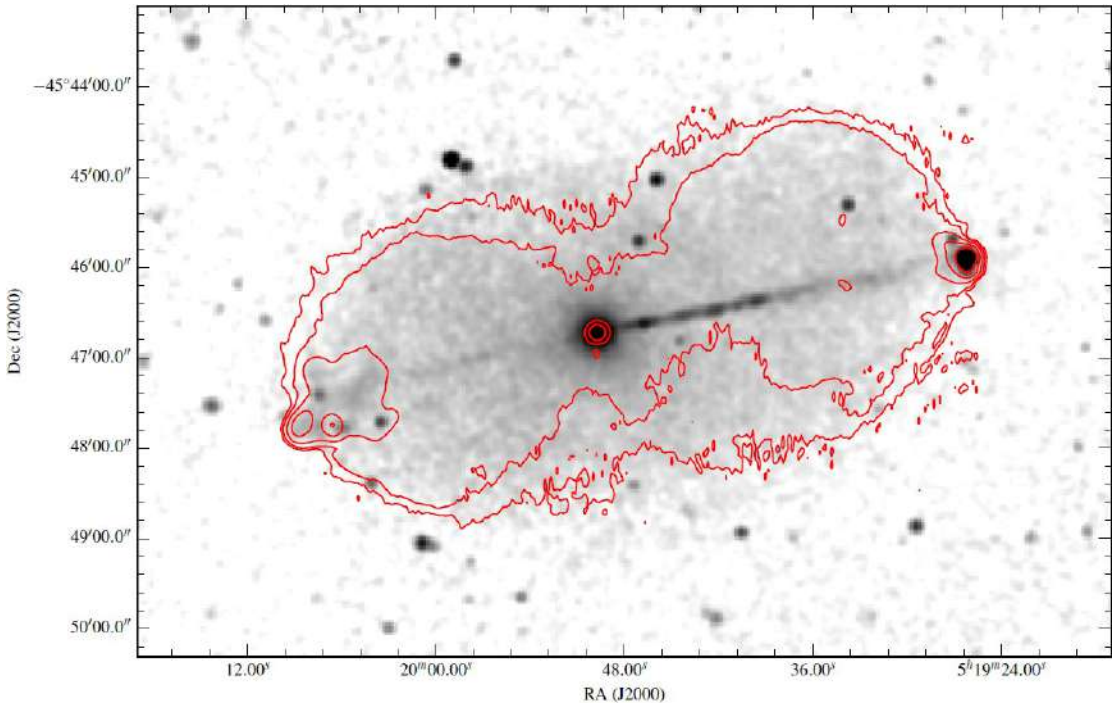
- Notice the similarity to synchrotron radiation! The energy loss rate here depends on the energy density in the photons not the magnetic field but otherwise it is much the same.
- Photons are scattered to higher energy according to

$$\bar{\nu}_1 = \frac{4}{3}\gamma^2\nu$$



Inverse-Compton scattering

- In radio AGN inverse-Compton is mostly seen in the X-ray.
- Typically CMB photons (around 10^{11} Hz) are scattered to X-ray energies (around 10^{17} Hz) which requires electron Lorentz factors around 1000.
- As energy densities in the CMB increase as $(1+z)^4$ this is an important loss process at high redshift.
- For anisotropic photon fields or high-energy effects spectral calculations can be complicated – see e.g. Brunetti 00, Hardcastle & Croston 11.



Right: X-ray greyscale and radio contours for Pictor A, Hardcastle+ 16). Jet and hotspot X-ray emission is thought to be synchrotron not inverse-Compton.

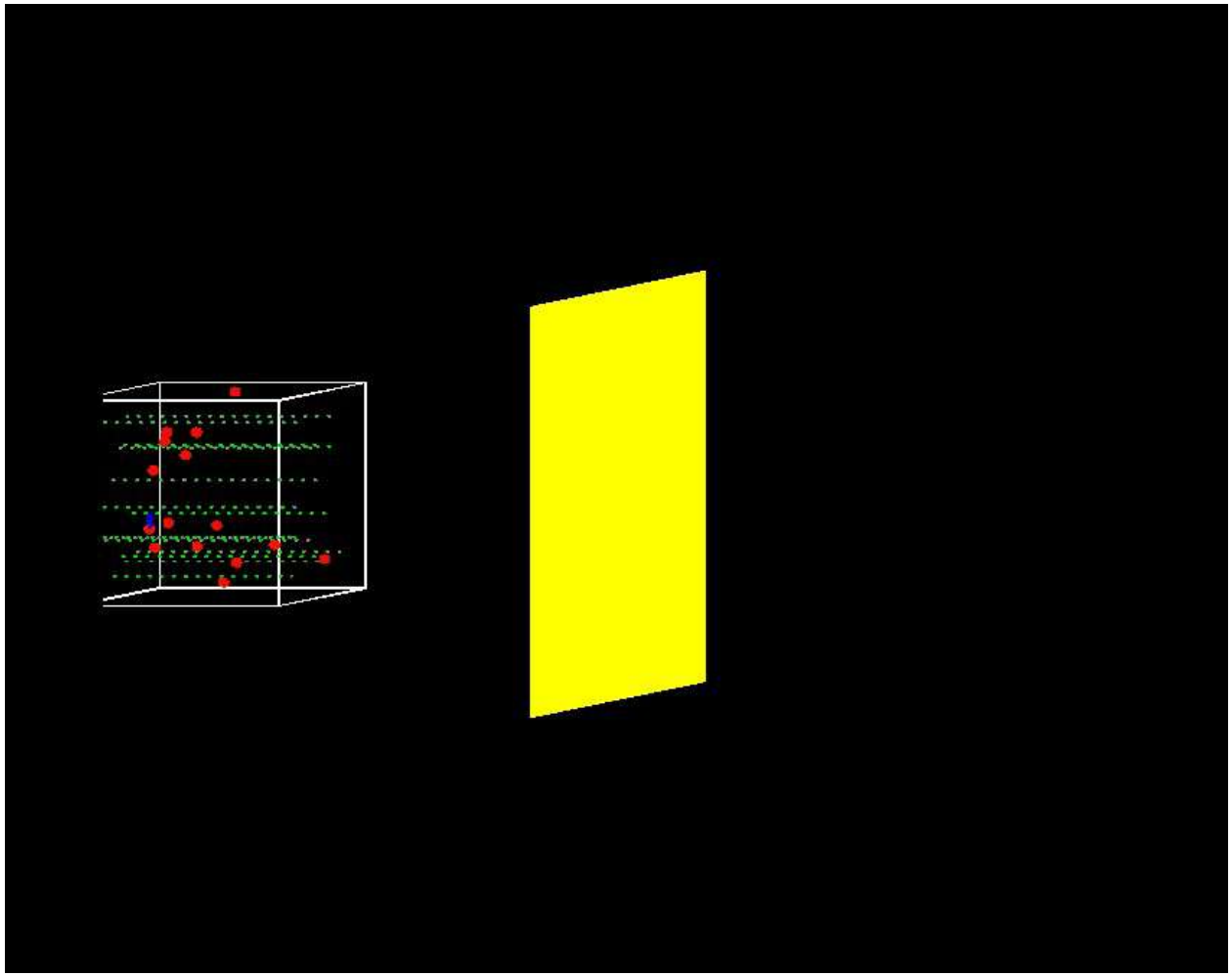
Particle acceleration

- We said earlier that synchrotron spectra are indicative of power-law energy spectra which have to go up to very high (relativistic) energies.
- If particles were in thermal equilibrium we would expect a Maxwell-Boltzmann distribution of energies, which has an exponential cutoff to high energies:

$$p(E) = \frac{2}{\sqrt{\pi}} \frac{1}{(k_B T)^{3/2}} \sqrt{E} \exp(-E/k_B T)$$

- So how do we get to a power-law distribution of energies?
- The processes that can do this are called ‘particle acceleration’ processes.
- Note that here ‘particle acceleration’ means giving a particle more energy – like a particle accelerator. It does not refer to the acceleration of particles around field lines seen in synchrotron radiation. Nor does it mean that the bulk speed of the particles gets higher; it most likely does the opposite...

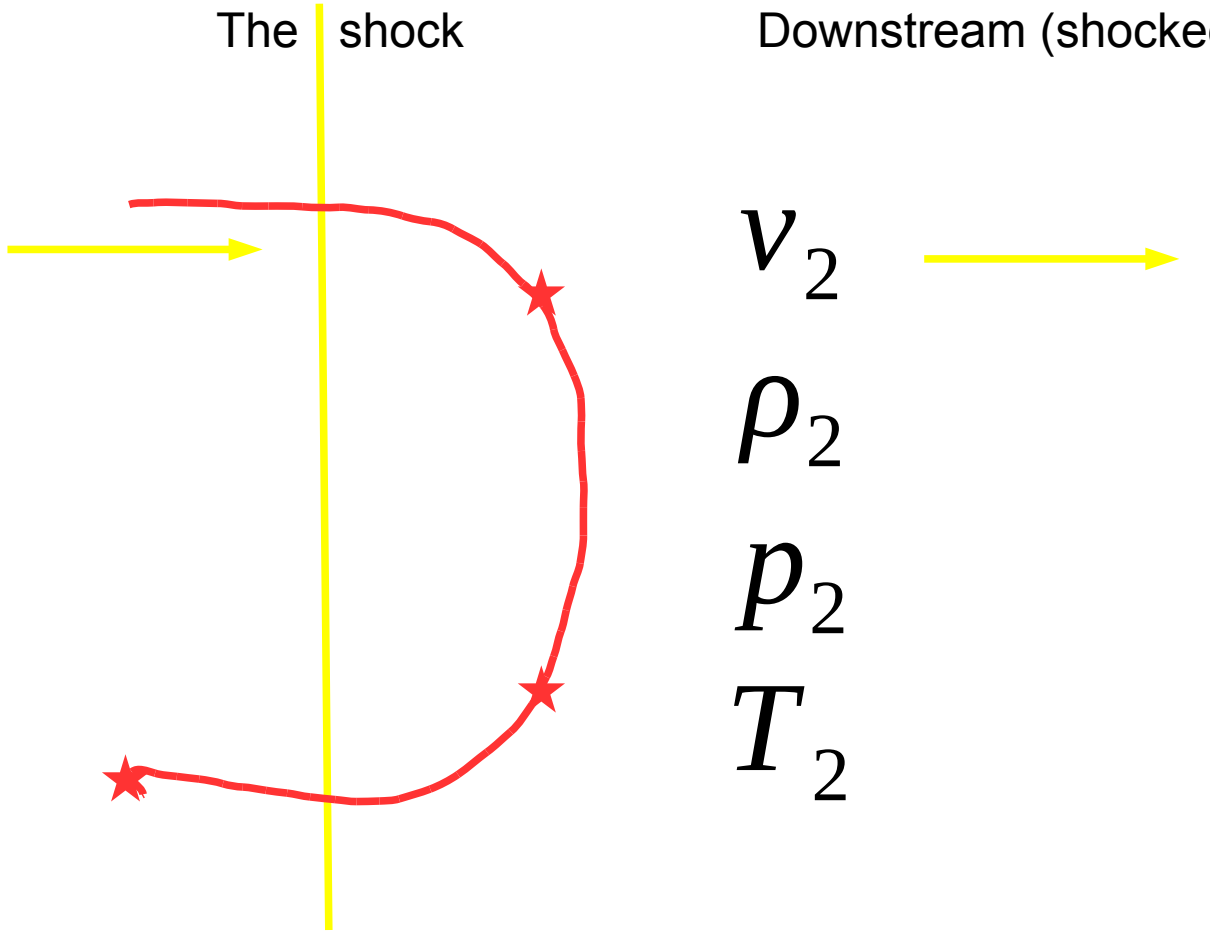
Particle acceleration



Particle acceleration at strong shocks

Upstream (unshocked) | The shock | Downstream (shocked)

v_1 ρ_1 p_1 T_1



v_2 ρ_2 p_2 T_2

Particle acceleration at strong shocks

- The following argument is due to Bell 78
- In a strong shock the velocity jump between the upstream and downstream regions of the shock is $v = 3v_1/4$.
- A particle with initial energy E on one side of the shock crosses the shock, energy in the other side E':
- Shock is non-relativistic:
- Fractional increase in energy on crossing the shock:
- Integrate over all angles:
- Assume that the particle's direction is re-isotropized, so that it can re-cross in the same way:
- This is called first-order Fermi acceleration because it is first-order in v/c.

$$E' = \gamma_v (E + p_x v)$$

$$E' = E\left(1 + \frac{v}{c}\cos\theta\right)$$

$$\frac{\Delta E}{E} = \frac{v}{c}\cos\theta$$

$$\left\langle \frac{\Delta E}{E} \right\rangle = 2\frac{v}{c}\int_0^{\frac{\pi}{2}} \cos^2\theta \sin\theta \mathrm{d}\theta = \frac{2v}{3c}$$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4v}{3c}$$

Particle acceleration at strong shocks

- Also known as diffusive shock acceleration
- Note the key requirement that velocities re-isotropize – otherwise the particle can't recross the shock
- Now thought that the particles themselves can generate electromagnetic turbulence which helps to scatter them (e.g. Sironi +15)
- Also requires a tail of energetic particles to start with otherwise they won't cross the shock efficiently – suprathermal particles?
- Bell goes on to show that with a finite probability of leaving the shock regions this produces a power-law distribution of energies:

$$N(E) = N_0 E^{-p}$$

- For a strong pure hydrodynamical shock $p = 2$.
- For weaker shocks $p > 2$
- For relativistic shocks $p = 1.7 – 2.2$ (Peacock 81, Heavens & Drury 88).

Particle acceleration in turbulence

- In turbulence there are many scatterers but they are moving in random directions with respect to each other
- This gives rise to *second-order Fermi acceleration* (Fermi 49, Blandford & Eichler 87) or *stochastic acceleration* where

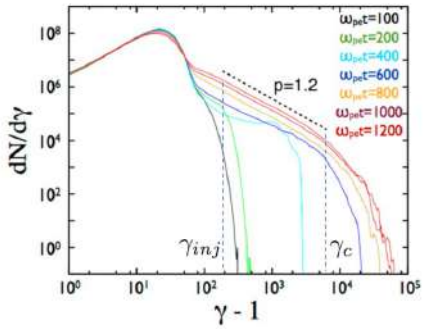
$$\frac{\Delta E}{E} \propto \left(\frac{v}{c}\right)^2$$

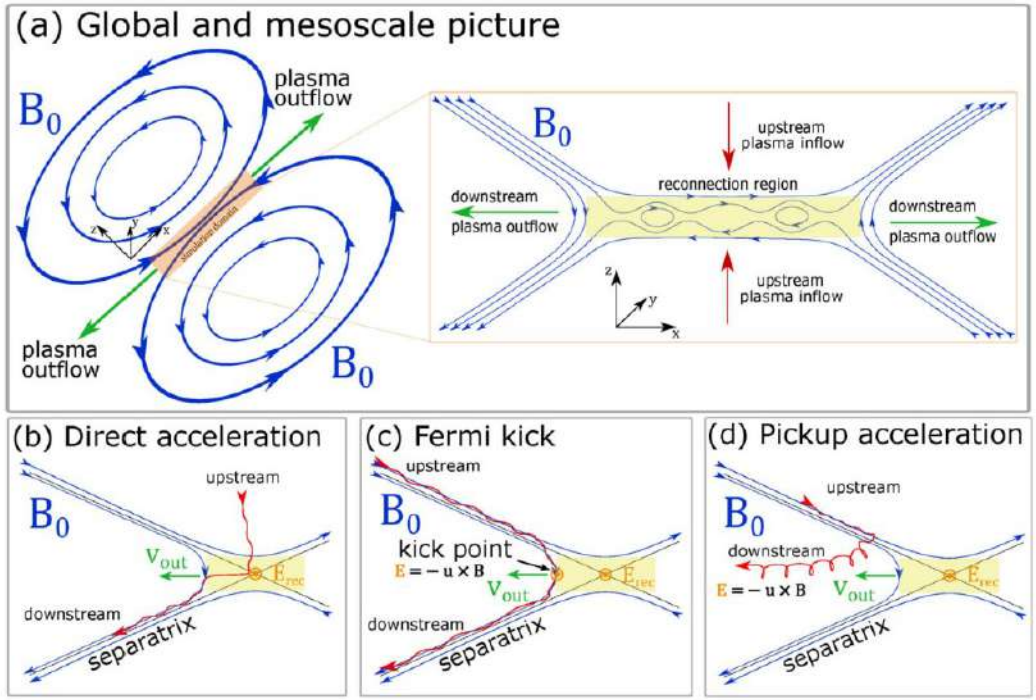
- For typical speeds of bulk motion in the external medium $v << c$ and so this is much less efficient at accelerating particles.
- However if there is bulk relativistic turbulence this process can be efficient at accelerating particles to very high energies over time. This could be relevant to the lobes of radio galaxies (e.g. Stawarz+Petrosian 08, Hardcastle +09).
- The values of the power-law index p in this model are model-dependent.

Particle acceleration in magnetic reconnection

- In highly magnetized relativistic plasmas (magnetic energy density >> plasma rest mass energy density)
- Direct conversion of magnetic field energy density into particle energy density
- Thought to be relevant to the early phases of jet evolution when the jet is magnetically dominated: could also be relevant elsewhere (e.g. in large-scale jets, Hardcastle +16)
- Topological changes in the field, releasing rapid bursts of energy
- Acceleration by reconnection electric field (b), Fermi acceleration by ejected plasma (c) or being swept up in the ejecta (d)
- Simulations show a power-law spectrum which can be very flat ($p \sim 1$).

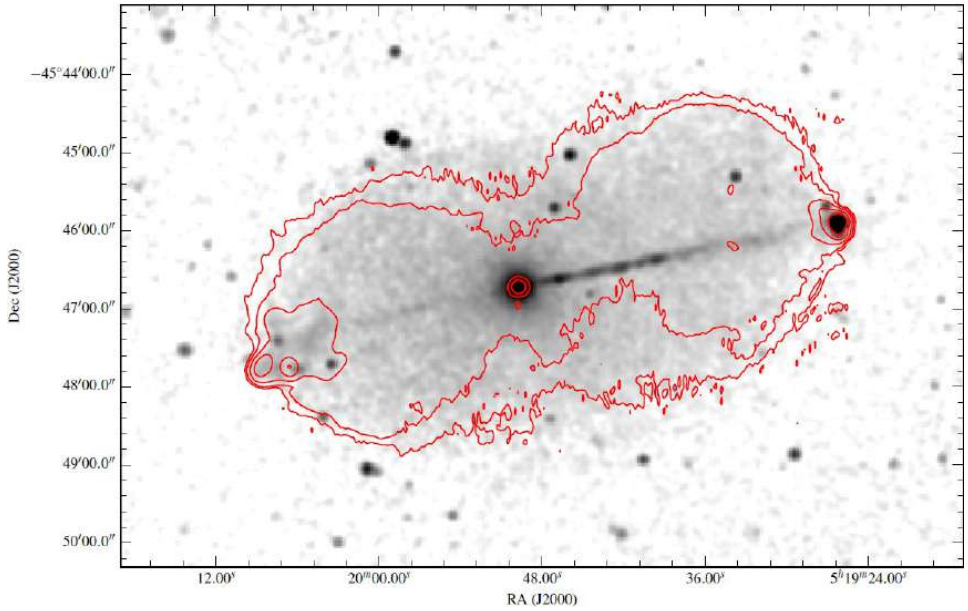
See Guo+24 review
Figures from
Guo+20 (left) &
French+23 (right)

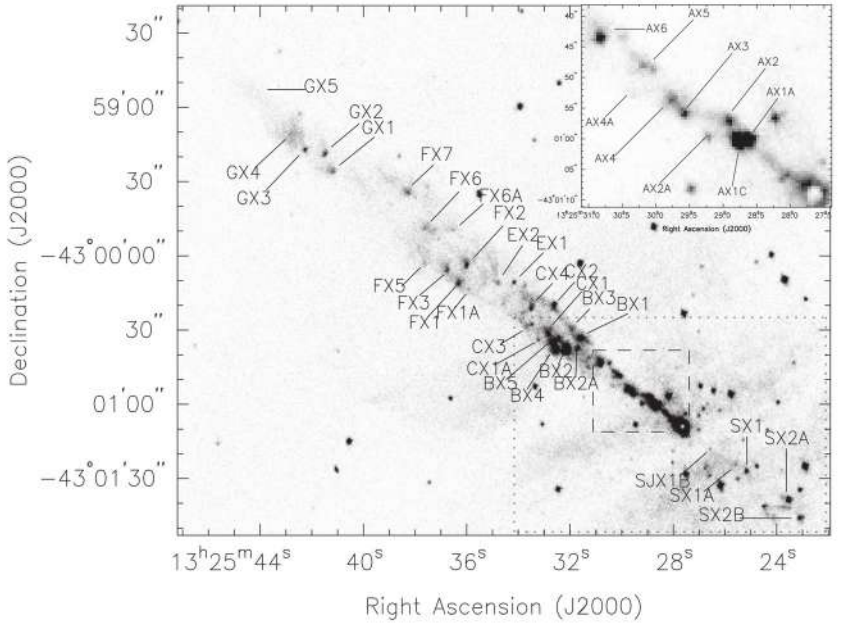




Locating particle acceleration

- Regions of high-energy particle acceleration will have flat radio spectrum because a flat power law of electrons is injected
- They are also the regions where synchrotron emission in X-ray or optical is likely to be visible as synchrotron emission at these frequencies has a very short loss timescale.
- X-ray synchrotron comes from in and near jets and hotspots – the latter are likely to be shocks, the acceleration mechanism in other regions is not so clear...





Section 3 summary

- The radio emission (and sometimes optical and X-ray emission) from radio AGN is due to the synchrotron process from relativistic electrons (and positrons if present).
- Inverse-Compton emission is a sister process in which the same electrons scatter ambient photons to high energies – the CMB always operates as a photon field for this process
- Loss rates for both processes have the same energy dependence
- Electron energy spectra appear to be power laws
- Power-law energy spectra can be produced by:
  - Diffusive shock acceleration (at strong shocks)
  - Stochastic/turbulent acceleration (in hot plasmas/relativistic turbulence)
  - Magnetic field reconnection (in highly magnetized plasmas)
- Particle acceleration in radio AGN seems to be located in jets and hotspots.

Section 4: Plasma diagnostics and physical conditions

- Energy density in the jets and lobes from equipartition / minimum energy
- Magnetic field strengths in the lobes from inverse-Compton emission
- Particle content
- Jet bulk speeds
- Magnetic field configurations from polarization observations
- Spectral ageing and its pitfalls

Equipartition and minimum energy

- We saw previously that

$$J(\nu) = \frac{\sqrt{3}Be^3 \sin\theta}{4\pi\epsilon_0 c m_e} \int_{E_{min}}^{E_{max}} F(x)N(E)\mathrm{d}E$$

- For simplicity consider a power-law electron distribution $N(E) = N_0 E^{-p}$
- Then we find

$$J(\nu) = CN_0\nu^{-\frac{(p-1)}{2}} B^{\frac{(p+1)}{2}}$$

$$C = c(p)\frac{e^3}{\epsilon_0 c m_e}\left(\frac{m_e^3 c^4}{e}\right)^{-(p-1)/2}$$

- Now consider the case where the field is in equipartition with the particles, which we can write

$$\frac{B^2}{2\mu_0} = (1+\kappa)\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} EN(E)\mathrm{d}E$$

Equipartition and minimum energy

- With our power-law assumption we can integrate to get

$$\frac{B^2}{2\mu_0} = (1+\kappa)N_0 I$$

$$I = \begin{cases} \ln(E_{\max}/E_{\min}) & p = 2 \\ \frac{1}{2-p}\left[E_{\max}^{(2-p)} - E_{\min}^{(2-p)}\right] & p \neq 2 \end{cases}$$

- But now we can eliminate N_0 from the above and solve for B:

$$B = \left[2\mu_0(1+\kappa)\frac{J(\nu)}{C}\nu^{\frac{(p-1)}{2}} I\right]^{\frac{2}{p+5}}$$

- If you can measure the emissivity at a single frequency, you can estimate the equipartition B (making some assumption for the non-radiating particle energy density factor κ).

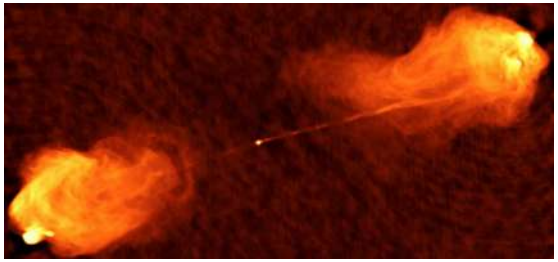
Equipartition and minimum energy

- Why is the equipartition field strength important?
  - It is a quite natural expectation for a magnetized plasma since reconnection will reduce the field for $B >> B_{eq}$ and instabilities will increase it for $B << B_{eq}$

$$B = \left[2\mu_0 (1+\kappa) \frac{J(\nu)}{C} \nu^{\frac{(p-1)}{2}} I \right]^{\frac{2}{p+5}}$$

  - It is close to the minimum-energy field which we could calculate in a similar way by differentiating the total energy wrt *B* (Burbidge 1956).
- Hence equipartition magnetic field strengths ought to provide a reasonable estimate of the field strengths in real radio sources
- From the equipartition field strength we can trivially calculate the energy density

$$U = U_e + U_B = 2U_B = \frac{B^2}{\mu_0}$$



- This allows for calculations of lobe energetics
  - Field strengths ~ 1 nT
  - Energy densities a few x 10^{-13} J m^{-3} – Total energies ~ 10^{53} J

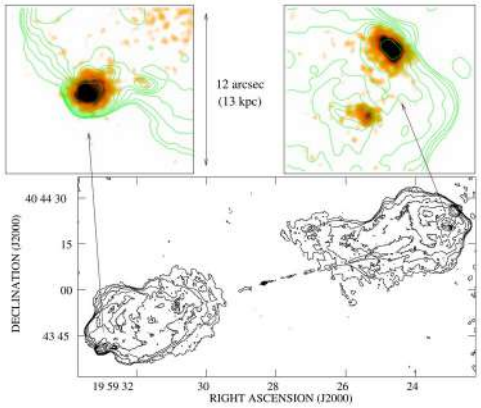
Inverse-Compton measurements of the magnetic field

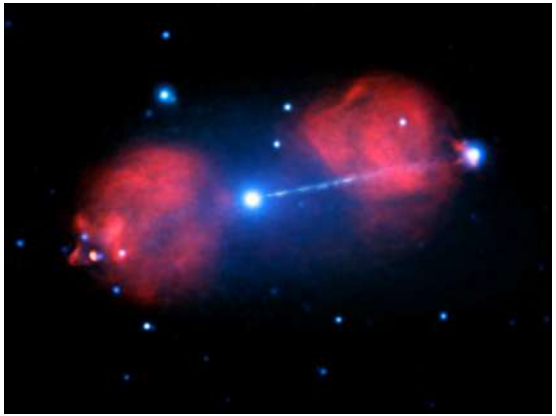
- Inverse-Compton emissivity also depends on electron spectrum. In a simple case (Hardcastle +98)

$$J_{\rm ic}(\nu_1) = m_e^2 c^4 \nu_1 \sigma_T \int_{E_{\rm min}}^{E_{\rm max}} \frac{N(E)}{E^2} \int_{\nu_{\rm min}}^{\nu_{\rm max}} \frac{3c}{4\nu_0^2} U_{\nu_0} f(x) {\rm d}\nu_0 {\rm d}E$$

$$x = \frac{\nu_1}{4\gamma^2 \nu_0} \qquad f(x) = 2x \ln x + x + 1 - 2x^2$$

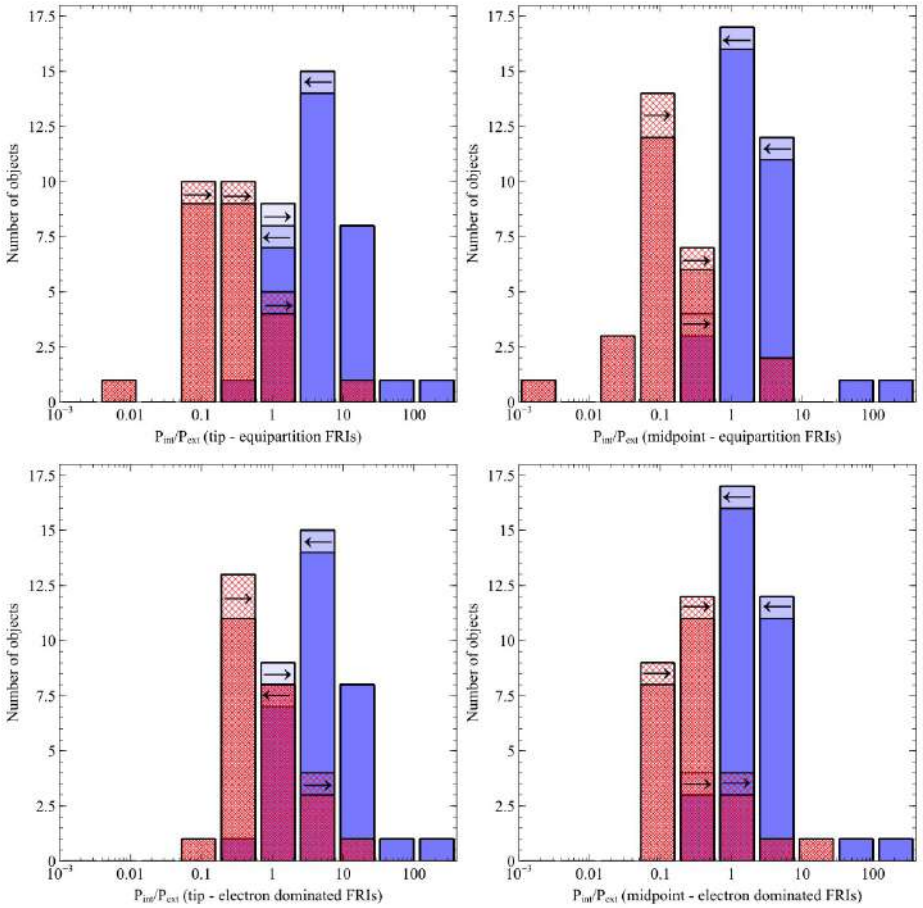
- Key point is that we get another linear dependence on N_0 $\quad J_{ic}(\nu_1) \propto N_0 \nu^{-(p-1)/2}$
- That means that we have two constraints for two unknowns (N_0 and B) and can find both!
- Applied to radio galaxy lobes, jets and hotspots and typically finds field strengths a factor of a few below equipartition values (Hardcastle +04, Croston +05, Ineson +17).





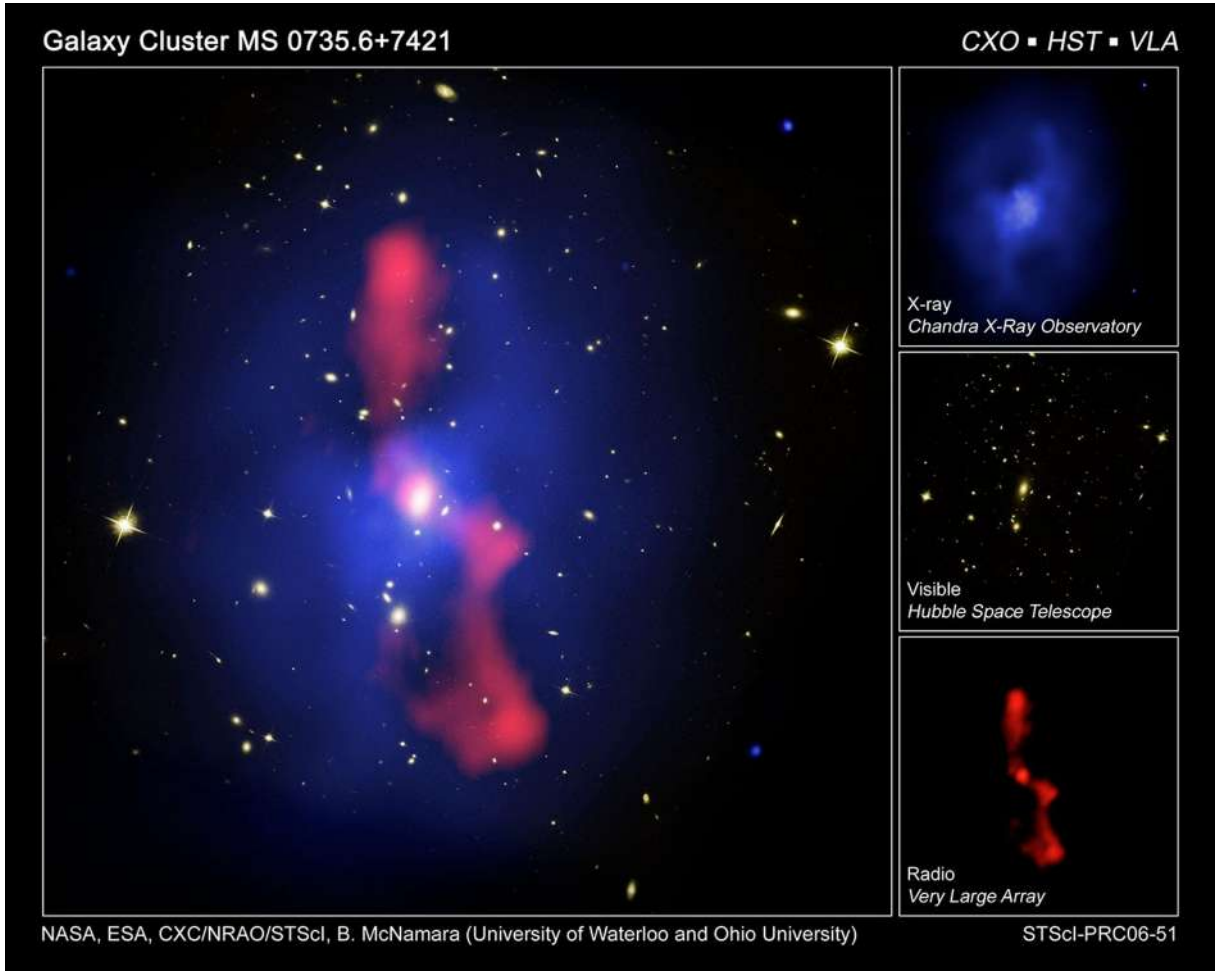
Particle content

- Very plausible that jets as initially injected by Blandford-Znajek are electron-positron.
- On the largest scales for the most powerful sources inverse-Compton measurements give lobe pressures very comparable to the pressures in the external environment on the assumption of pure electron-positron. So it's possible to believe that these lobes really are dominated by pairs.
- On the other hand low-power radio galaxies do nc appear to have enough pressure in their lobes without another population of non-radiating particles
- We know that these objects are the ones whose jets entrain matter and decelerate – can the entrained matter make the difference?
- See Croston+18 for the latest on this...



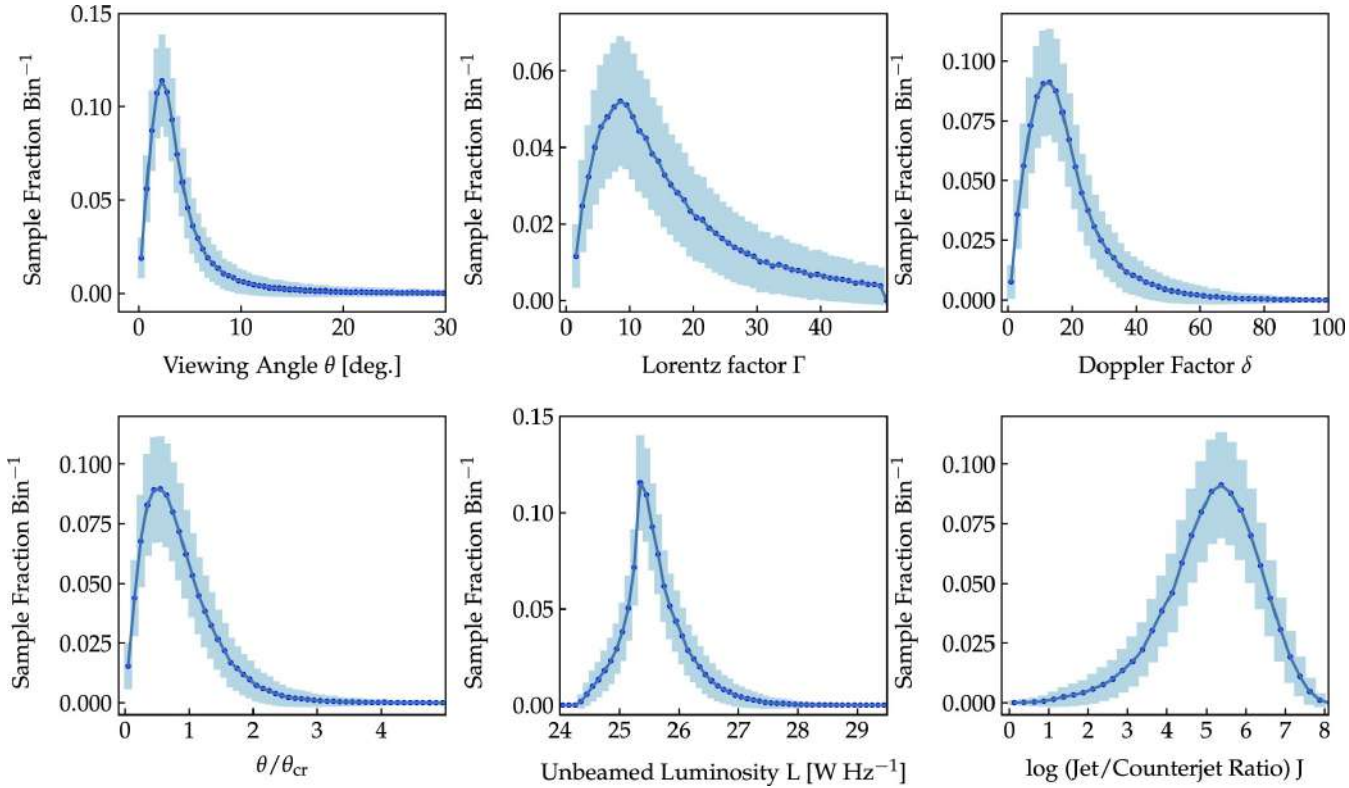
Particle content

- Observations of X-ray ‘cavities’ and low-frequency polarization prove that even in these sources lobes are not filled with thermal material at the same density as the external environment. It must be much lower in density and hotter.



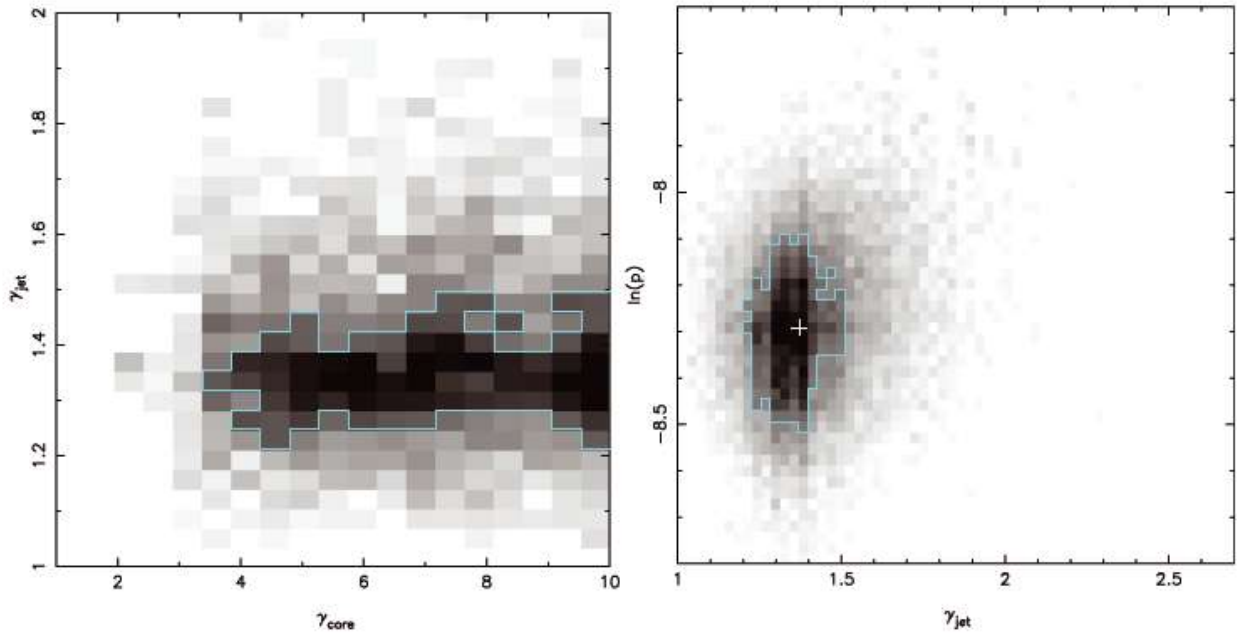
Jet bulk speeds

- Constraints very different on pc and kpc scales
- On pc scales direct bulk motion can be seen in highly beamed objects and this constrains the Lorentz factor distribution (e.g. Lister +19)



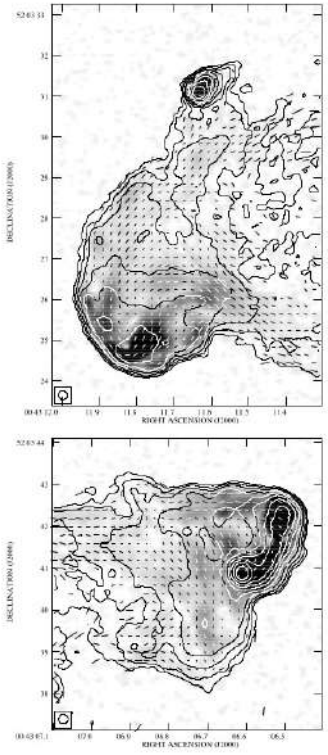
Jet bulk speeds

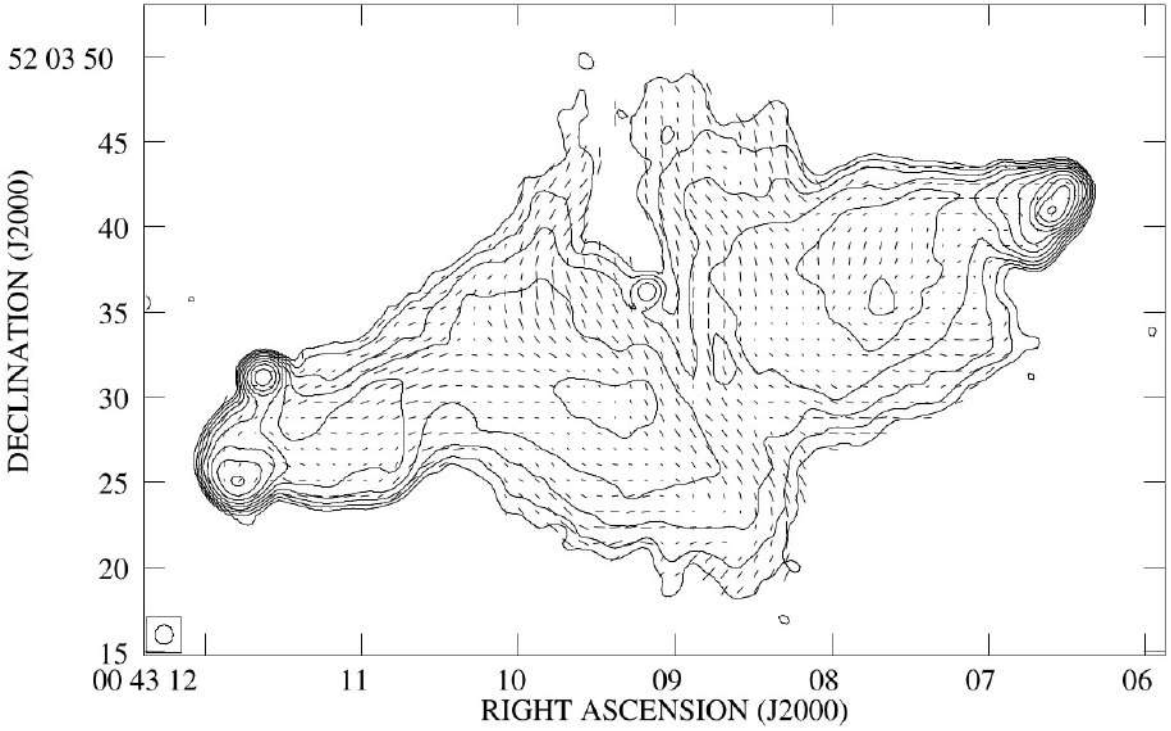
- On kpc scales we know some jets decelerate from relativistic to sub-relativistic speeds.
- For the powerful objects where the jets don't decelerate we can use Doppler boosting to estimate a characteristic speed – on large scales $v \sim 0.6c$ (Mullin & Hardcastle 09)
- These very different speeds imply either strong deceleration on small scales or (more likely) highly structured jets, perhaps with much higher speeds persisting to large scales in a Doppler-suppressed core.



Polarization and magnetic fields

- Polarization observations tell us the *direction* of ordered magnetic fields (remember synchrotron is polarized perp. to the B-field). Normal to plot ‘B-vectors’
- High fractional polarization shows that there is large-scale order – if field was tangled on small scales it would cancel out





- Faraday rotation and depolarization effects from the external medium complicate the picture at low frequencies (see Annalisa’s talk later in the week)

Hardcastle+97, image from Pudritz+12

Spectral ageing

- Recall that we said for synchrotron emission

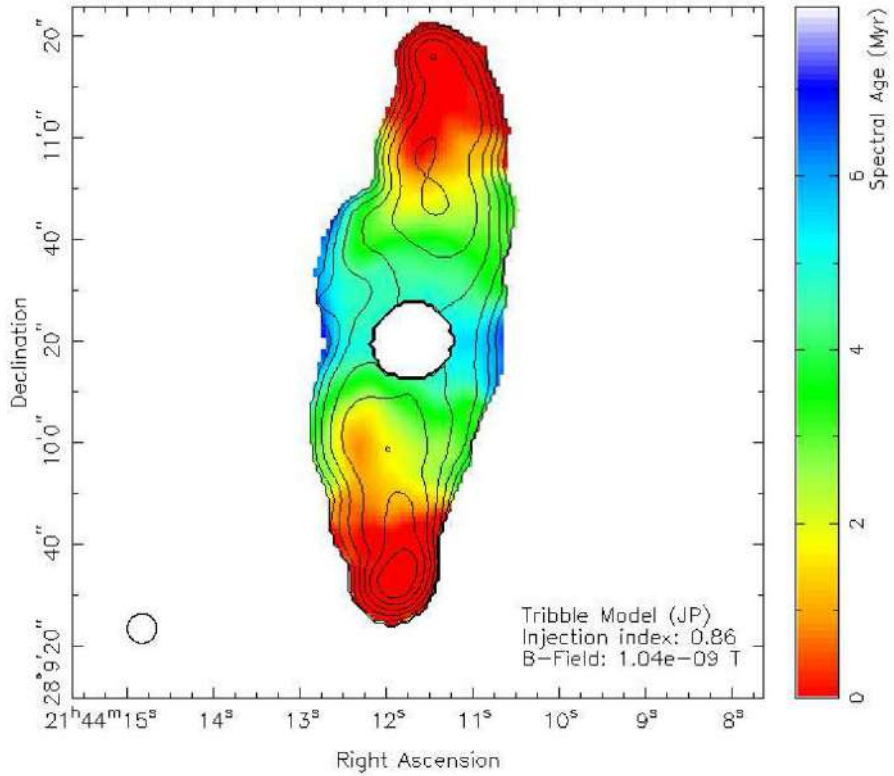
$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}t} \right\rangle = 2\sigma_T \beta^2 c \frac{B^2}{2\mu_0} \gamma^2 \int \frac{1}{2} \sin^3\theta \, \mathrm{d}\theta = \frac{4}{3} \sigma_T \beta^2 c \frac{B^2}{2\mu_0} \gamma^2$$

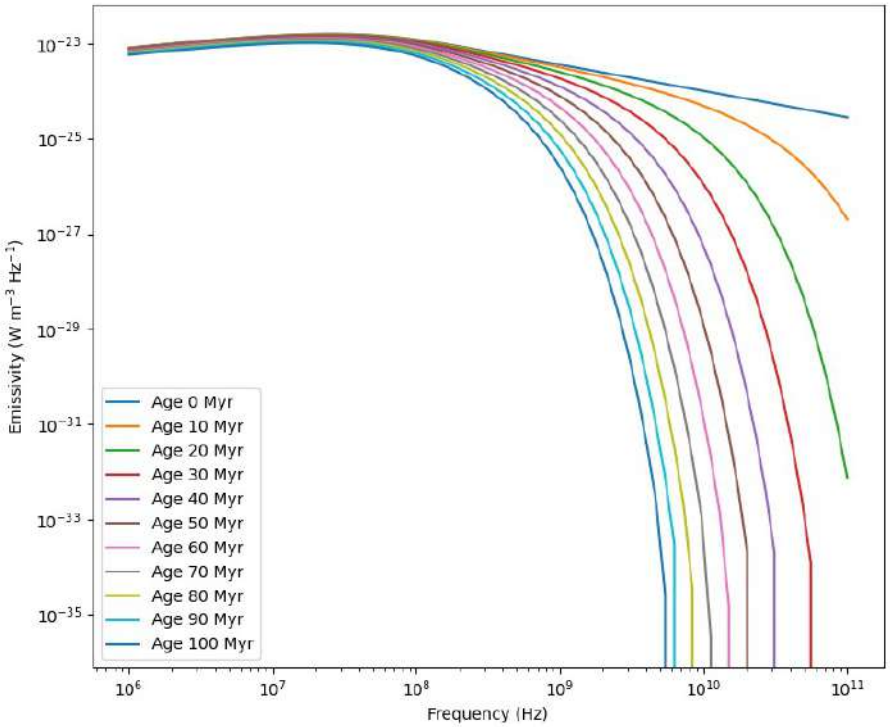
- This means that

$$\frac{\mathrm{d}E}{\mathrm{d}t} \propto B^2 E^2 \rightarrow \tau = \frac{E}{\mathrm{d}E/\mathrm{d}t} \propto \frac{1}{B^2 E}$$

- The loss timescale for high-energy electrons is higher than for low-energy electrons.
- Loss rate is proportional to magnetic field energy density (and IC photons)
- We expect an evolution of the electron spectrum from an initial power-law form
- This can be solved analytically (e.g. Rybicki & Lightman)
- Fitting these spectra to regions in radio galaxies allows us to make a map of ‘spectral age’ or ‘radiative age’.
- We will return to these ages tomorrow...

Spectral ageing





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Typical physical conditions for a powerful radio lobe

Property	Typical value	From
Magnetic field strength	1 nT	Inverse-Compton + synchrotron / equipartition
Pressure	5×10^{-13} Pa	Energy density/3
Effective density	10^{-29} kg m^{-3}	Energy density/c^2
Bulk speed in jet	0.5 c	Doppler boosting
Volume	10^{65} m^3	Measurement from radio observation
Energy stored	10^{53} J	From above
Spectral age	50 Myr	Ageing fits

Section 4 summary

- We have seen how measurements of physical conditions in radio galaxies can be made
- Constraining conditions like magnetic field strength and pressure in the lobes often needs multi-frequency observations
- Radio-emitting regions are low-density but high-pressure
- Bulk speeds can be highly relativistic
- Radiative loss timescales can be tens to hundreds of Myr

Synthesis (take-home messages)

- Jets are generated close to the SMBH, probably by a Blandford-Znajek type process where the spin energy of the BH can be tapped
- Initially overpressured and relativistic light jets collimate and propagate into the host galaxy
- Jets inflate lobes (cocoons, bubbles) and can propagate within them
- Jet deceleration dissipates energy: shocks can lead to particle acceleration
- Physical conditions in the large-scale structures can be assessed in a variety of ways, but confirm that low densities, high pressures, significant ordered magnetic field and high bulk speeds are present even on scales of hundreds of kpc.

Further reading

- Most of the basic physics here is well covered by Longair, *High Energy Astrophysics* which I follow in notation throughout
- For more detail on radiation processes see Rybicki & Lightman, *Radiative Processes in Astrophysics*
- For a relatively recent book on jet physics see Contopoulos, Gabuza & Kylafis (eds), *The Formation and Disruption of Black Hole Jets*
- For an overall review of radio-loud AGN physics, observations and connection to feedback see Hardcastle & Croston 20