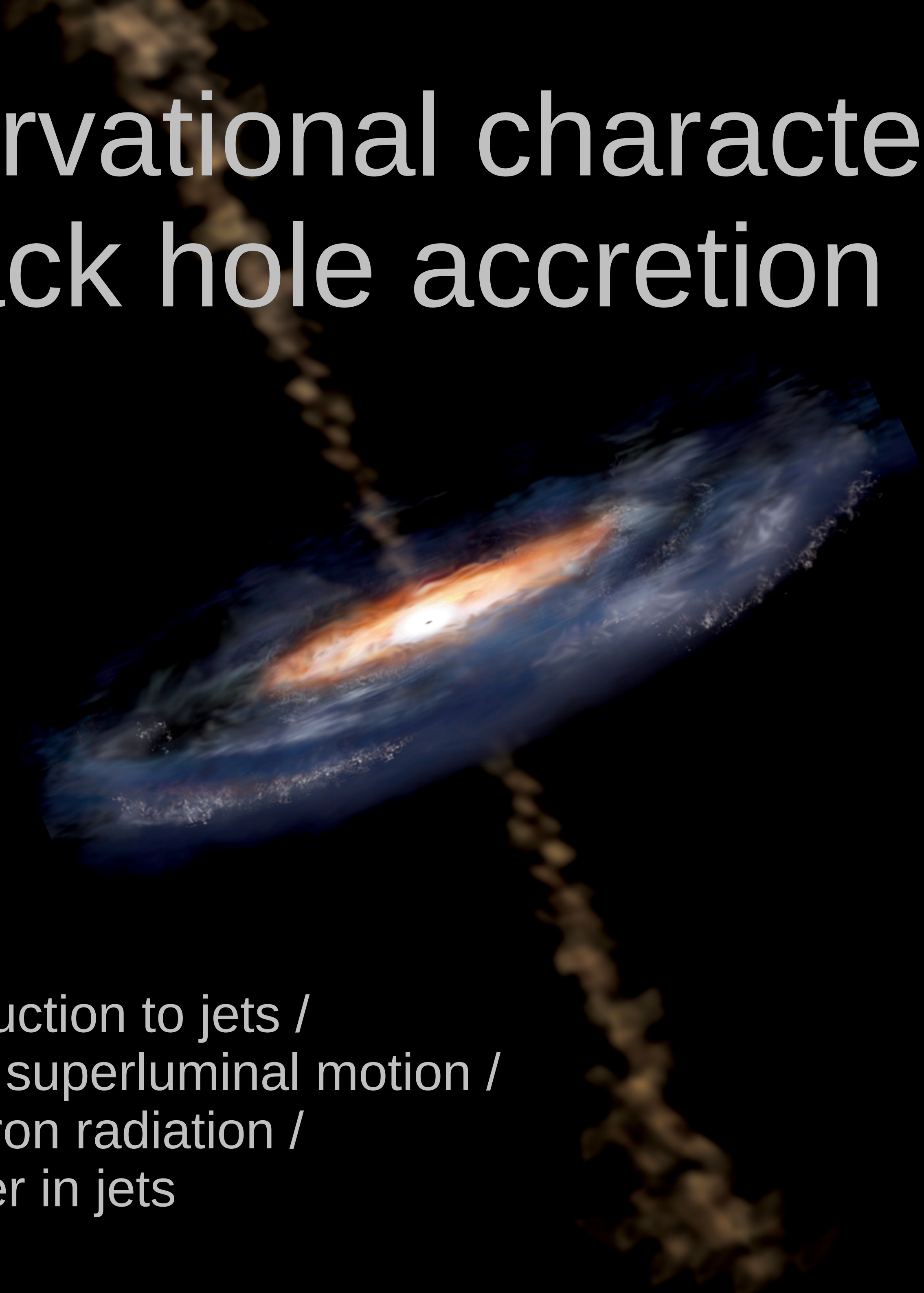
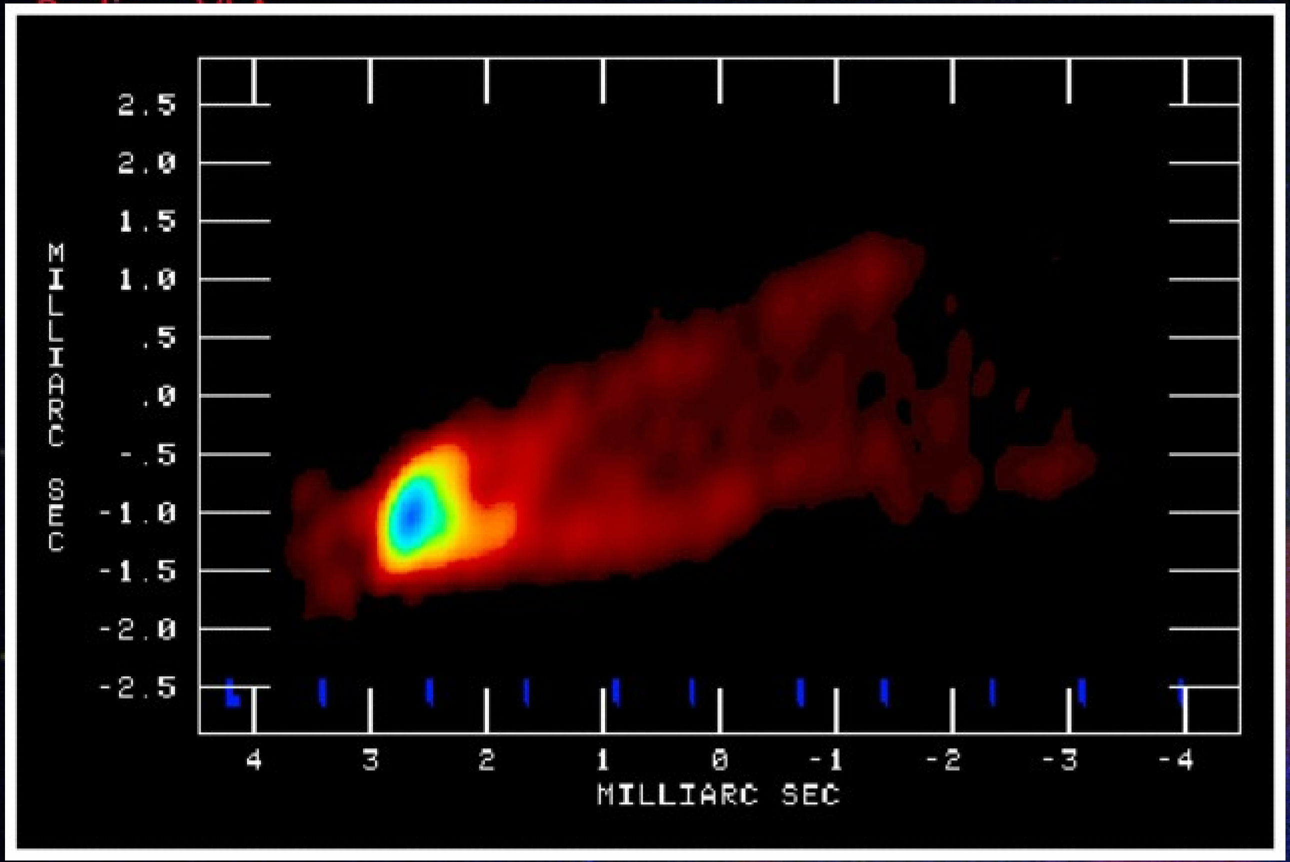
Observational characteristics of black hole accretion



An introduction to jets /
Apparent superluminal motion /
Synchrotron radiation /
The power in jets

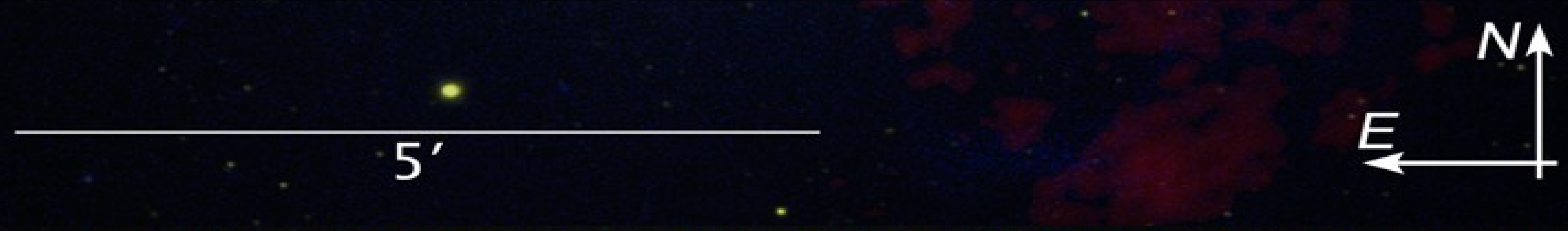
VLBA observations can now probe to ~100 R_G



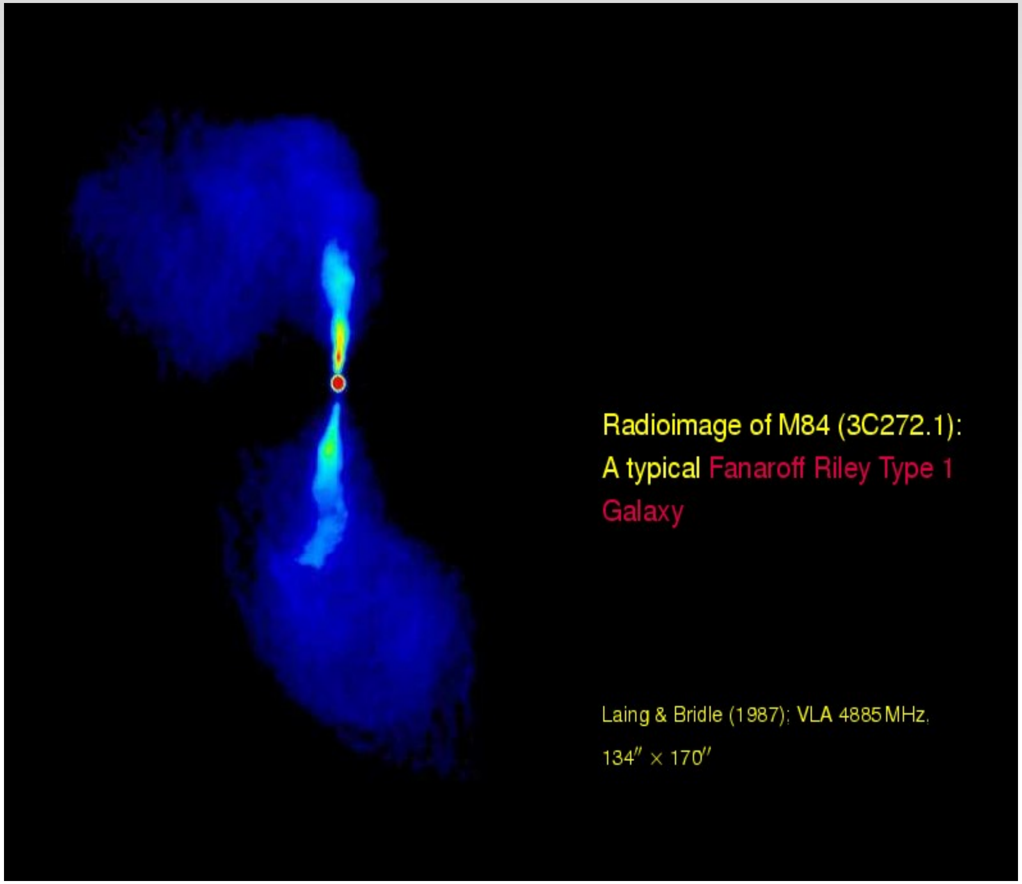
In 1918 Curtis wrote of an image of the nebula M87, describing a '*curious straight ray... connected with the nucleus*'

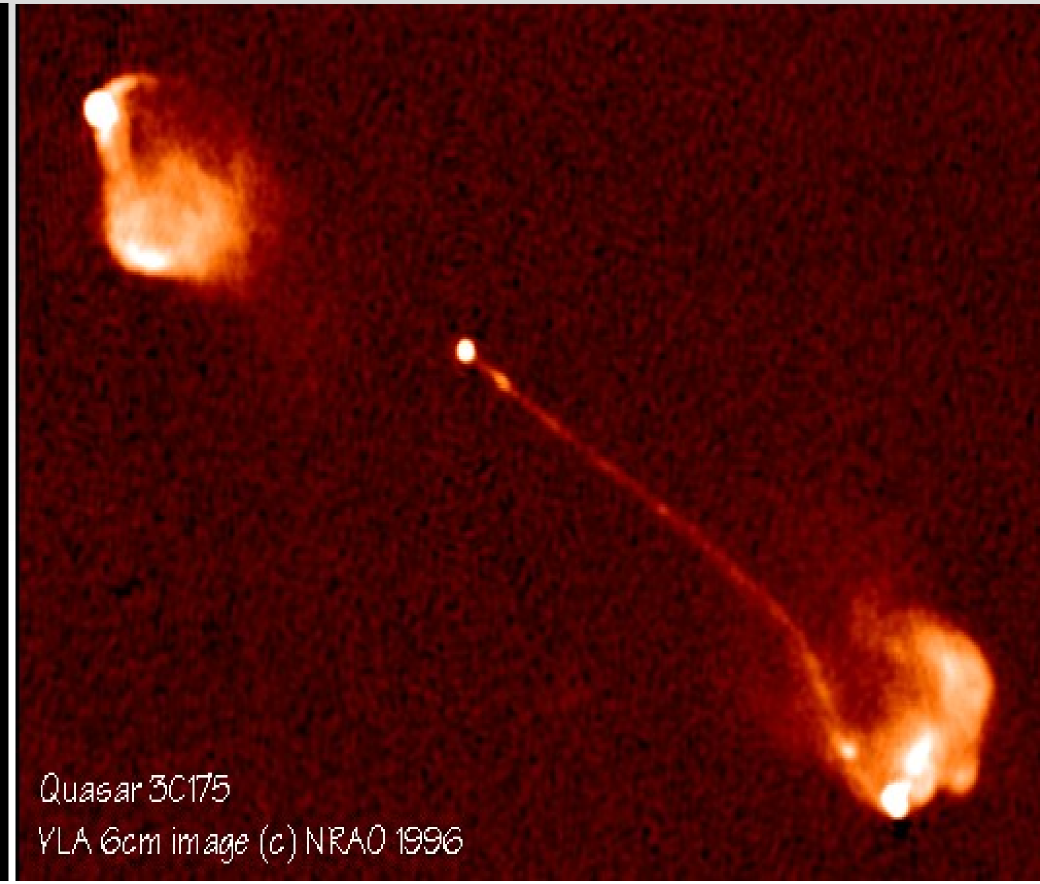
We now know this is the nearest example of a powerful jet from a supermassive black hole. The jet has been resolved to be ~self-similar over a scale range of more than 10^6.

Note that – with Sgr A* – this is the largest angular size of a black hole on the sky



More than 10^7 AGN-jet systems are known





FRI radio galaxies: fairly diffuse jet – lobe structues

FRII radio galaxies: narrow powerful jets, bright hotspots. More powerful?

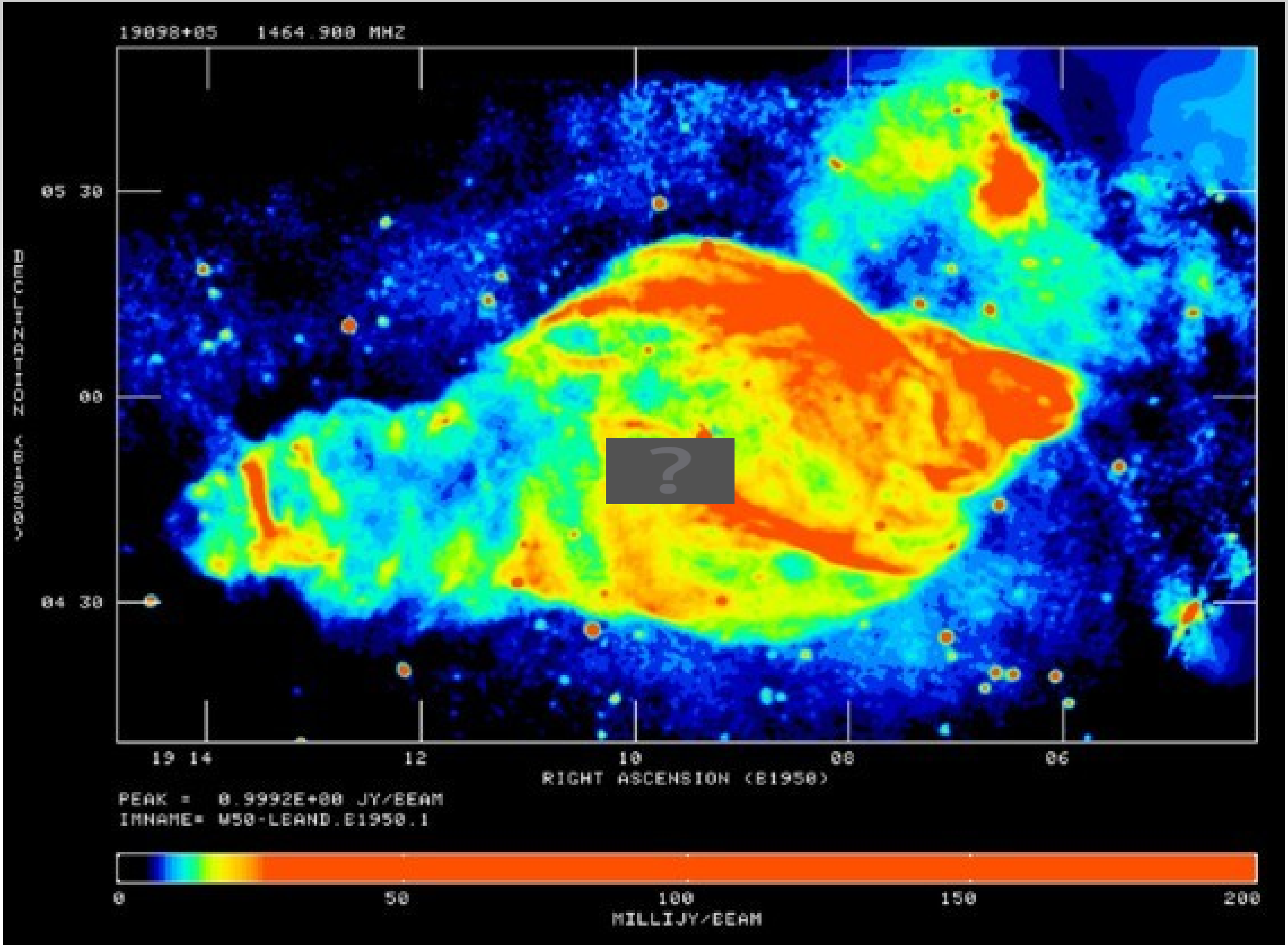
Note that in all radio surveys of the sky radio counts above ~mJy are completely dominated by AGN – the cosmic radio background of accretion (c.f. CXB). Below ~mJy radio emission from starbursts becomes increasingly important.

X-ray binaries do it too: SS 433 (daily VLBA images)

Massive binary with orbital period 13 days and jet precession period 162.5 days (clearly seen in the movie). Not especially X-ray luminous but very powerful jets.

SS 433 (daily VLBA images)

Note the <u>symmetrical</u> ejection of blobs / plasmons.
Hypercritical, obscured accretion. Relevant for AGN growth ? ULX ?



On very large scales the jets from SS 433 are powering / distorting the W50 nebula (inner jet scaled up by a factor ~ x 1000). Average jet power must be > 10^{38} erg/sec

XTE J1550-564: X-rays from the jet

The black hole transient XTE J1550-564 went into outburst in 1998.

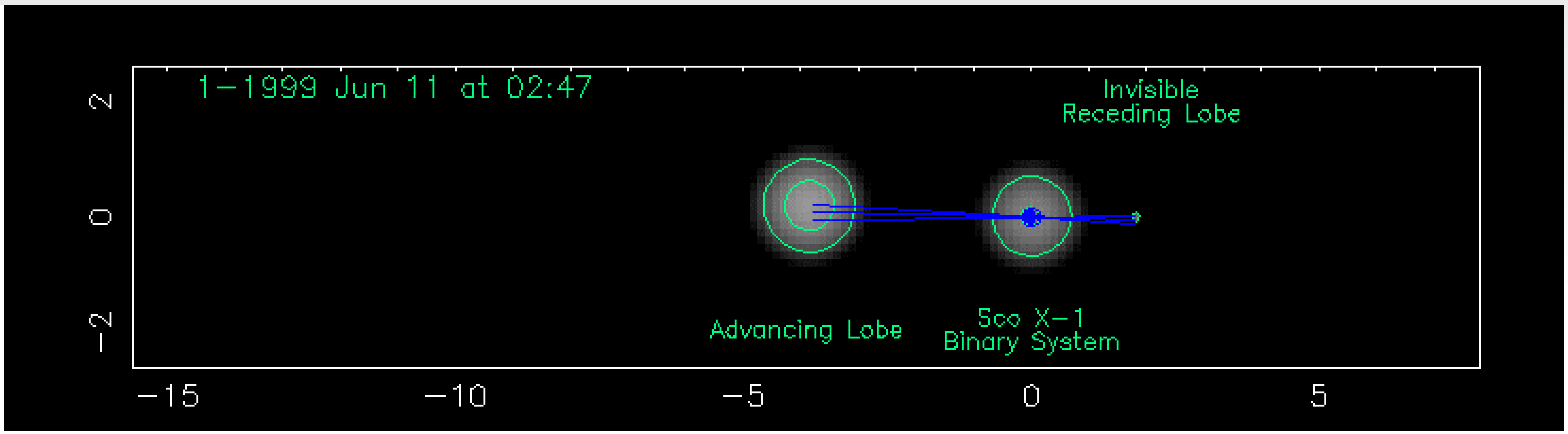
At the time there was a large radio flare which VLBI resolved into a relativistic jet.

Over the next 4 years we found that this jet was decelerating as it pushed on the ISM, resulting in *in situ* acceleration of electrons to TeV energies.

Neutron star X-ray binaries produce jets too

→ you don't need to be a black hole to produce a relativistic jet

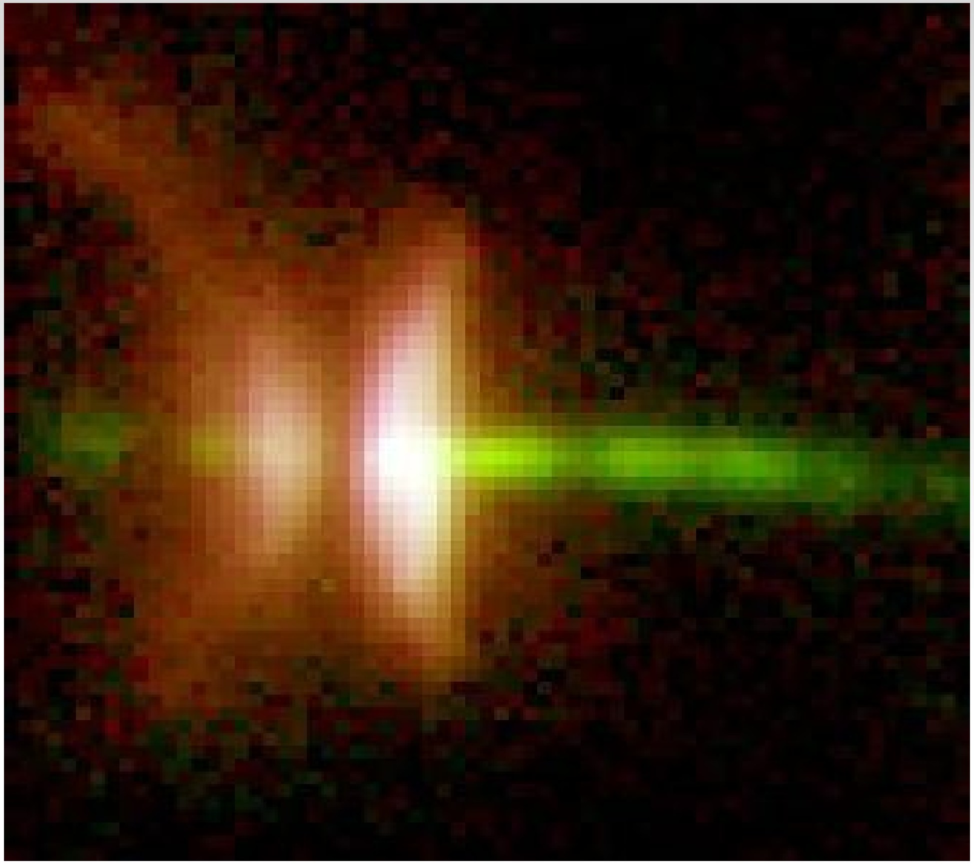
Sco X-1 with VLBA

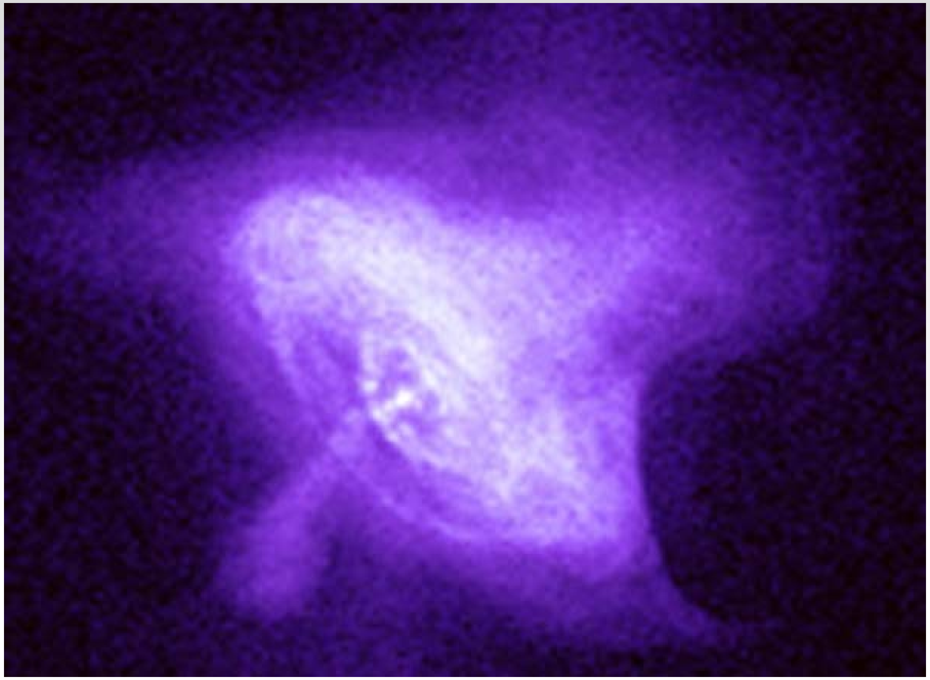


Note apparent brightening of previously ejected blobs by faster moving – but invisible – flow. This is also observed in the neutron star X-ray binary **Cir X-1** where the inferred Lorentz factor of the invisible flow is Γ > 10 !

Is this a neutron star only phenomena ? Some hints of it also in SS 433 X-ray jet (compact object not identified in SS 433)

Jets are produced by other types of systems





The Crab pulsar

Young Stellar Objects

Also, supersoft X-ray sources, gamma-ray bursts, individual massive stars...

Synchroton radiation

The main emission mechanism we see from jets from black holes is **synchrotron emission** (what else ?). In a nutshell this is characterised by

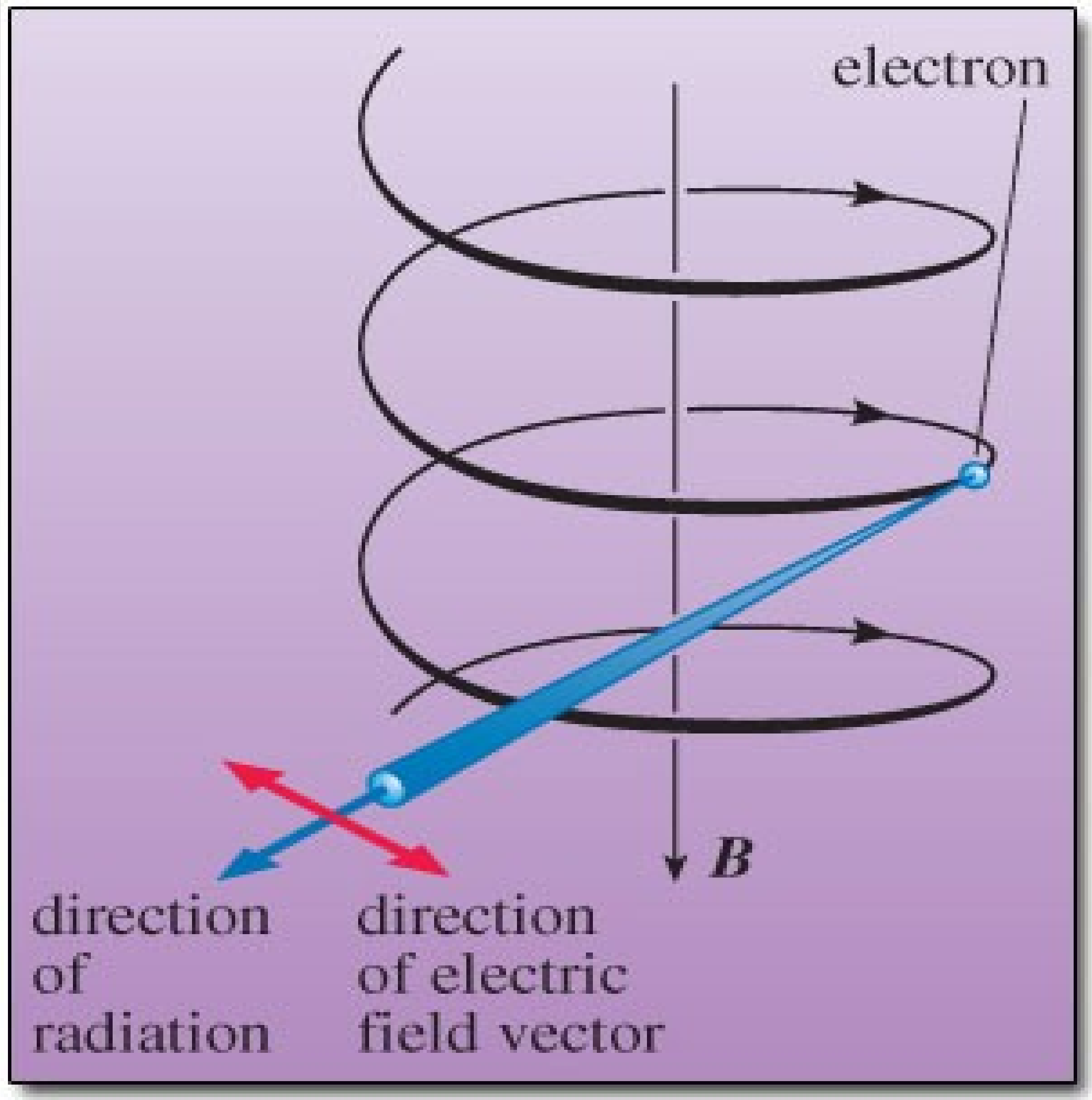
- **'nonthermal'** spectra
- (sometimes) high **brightness temperatures**
- (sometimes) high degrees of **linear polarisation**

'Nonthermal' emission: sometimes used to mean 'spectrum described by a power-law', but this is not very satisfactory (the Rayleigh-Jeans tail of a black body spectrum is a power law, as are most parts of a thermal bremsstrahlung spectrum). I prefer 'arises from a non-thermal distribution of electrons' (i.e. cannot be described by one temperature). In fact you can have both thermal and nonthermal synchrotron emission.

Brightness temperature: the temperature of the black body required to produce the same luminosity for a given source size as observed. 'Typical' thermal processes may reach temperatures of 10^9 K, synchrotron emission has a 'limit' of $T_B \sim 10^{12}$ K. Assuming this limit in turn allows you to calculate the minimum size of synchroton emitting region.

Linear polarisation: Synchrotron emission can produce linear polarisation up to ~70%. The observed range is large: from undetectable to ~50% in some large-scale jets.

Synchroton radiation

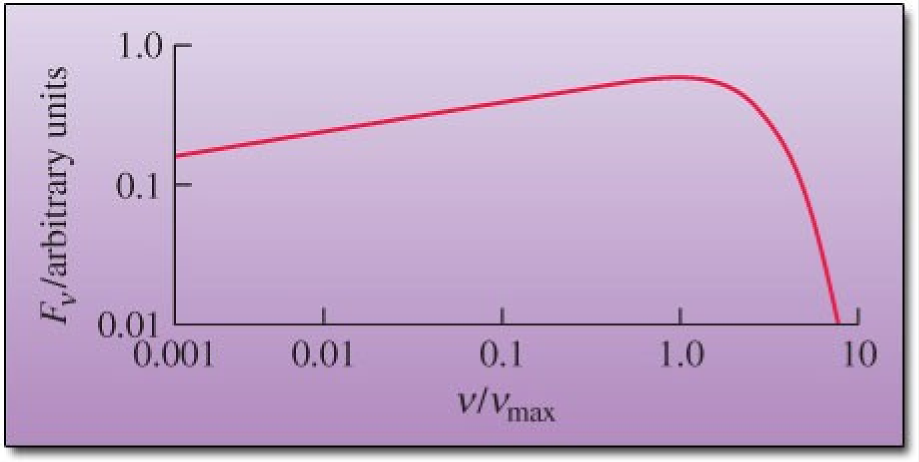


Synchroton emission arises from the spiralling of charged particles in a magnetic field.

It is the relativistic version of cyclotron emission

In cyclotron emission the radiation pattern from the electron is a sinusoid → the observed emission is the Fourier transform of this → single frequency

As the electron becomes more relativistic, its emission is beamed in the forward direction, and the radiation pattern is no longer a sinusoid → Fourier transform produces a broad spectrum of frequencies



The synchrotron emission from a single electron (or positron) covers a range of frequencies.

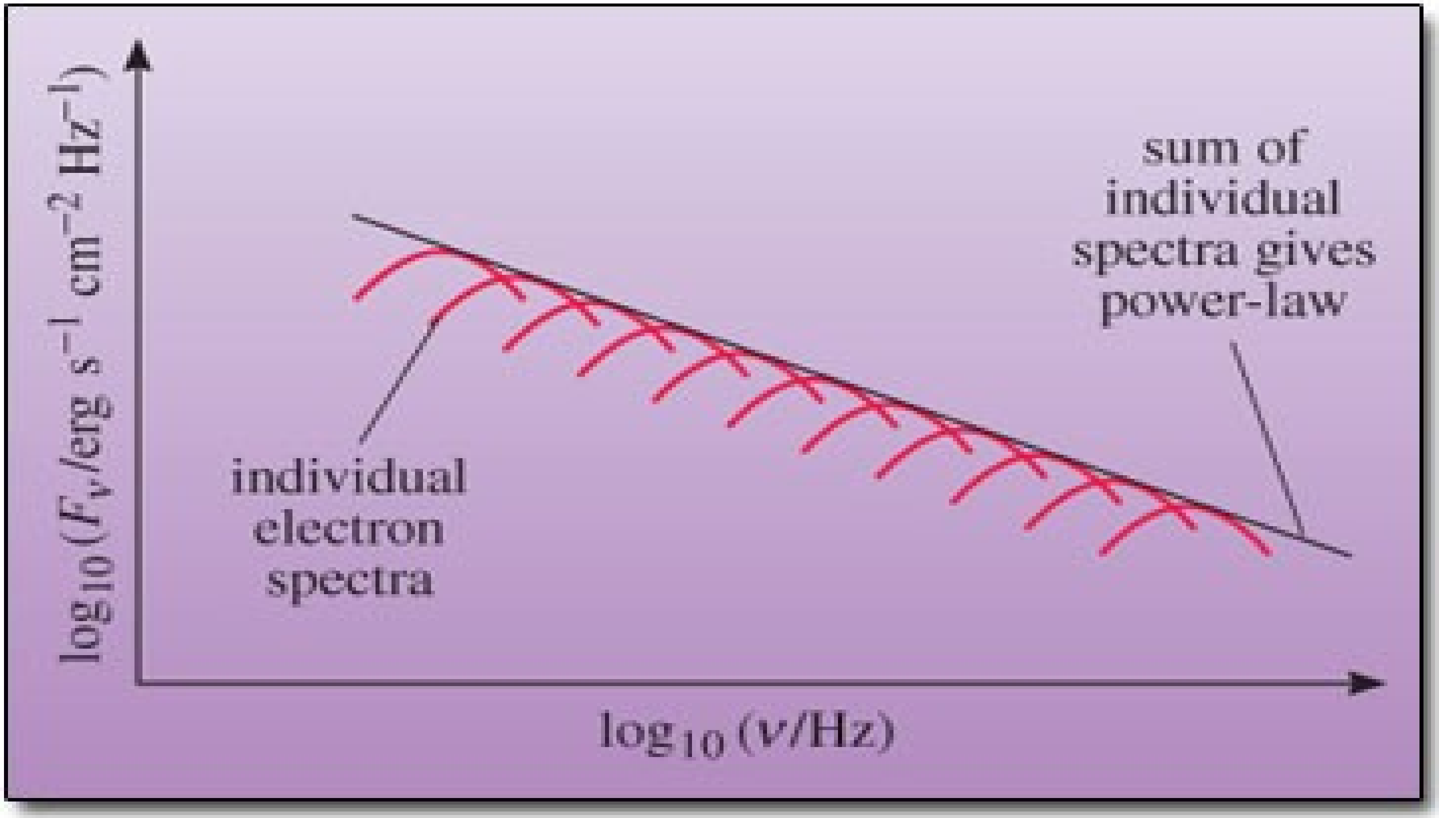
The peak frequency $\nu_{max} \propto E^2$

Where E is the particle energy

A power-law distribution of particle energies over a large range will produce a superposition of individual electron spectra and produce a power-law in emission.

Q: Does the shape of the individual emission spectrum affect the overall spectrum ?

A: not really (only at low energies in GRBs)

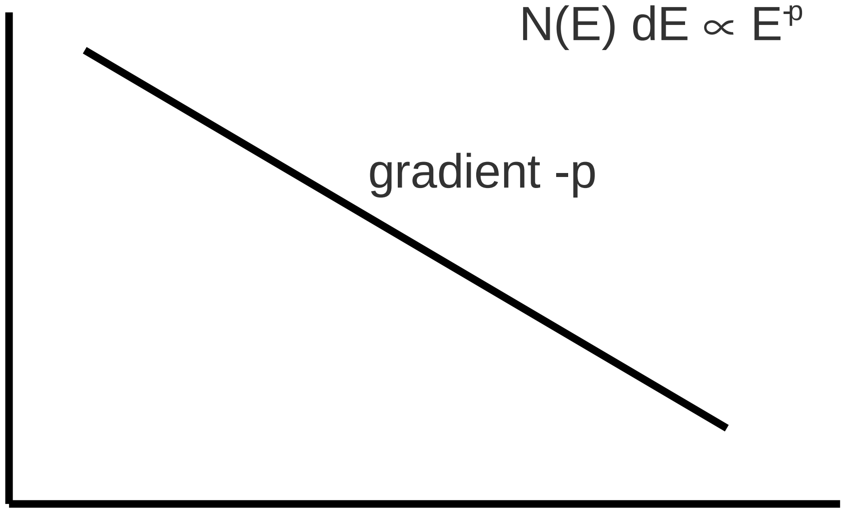


So why would there be a power-law distribution of particles ?

Shock acceleration: anything moving at faster than the local sound speed will cause a shock. In astrophysics this occurs in many scenarios, including essentially <u>all situations in which mass is rapidly ejected into space</u> e.g.

– relativistic jets
– gamma-ray burst afterglows
– supernova explosions

In all of these cases you tend to get shock-accelerated electrons and amplified/compressed magnetic field
→ synchrotron emission



$N(E)\,dE \propto E^{-p}$

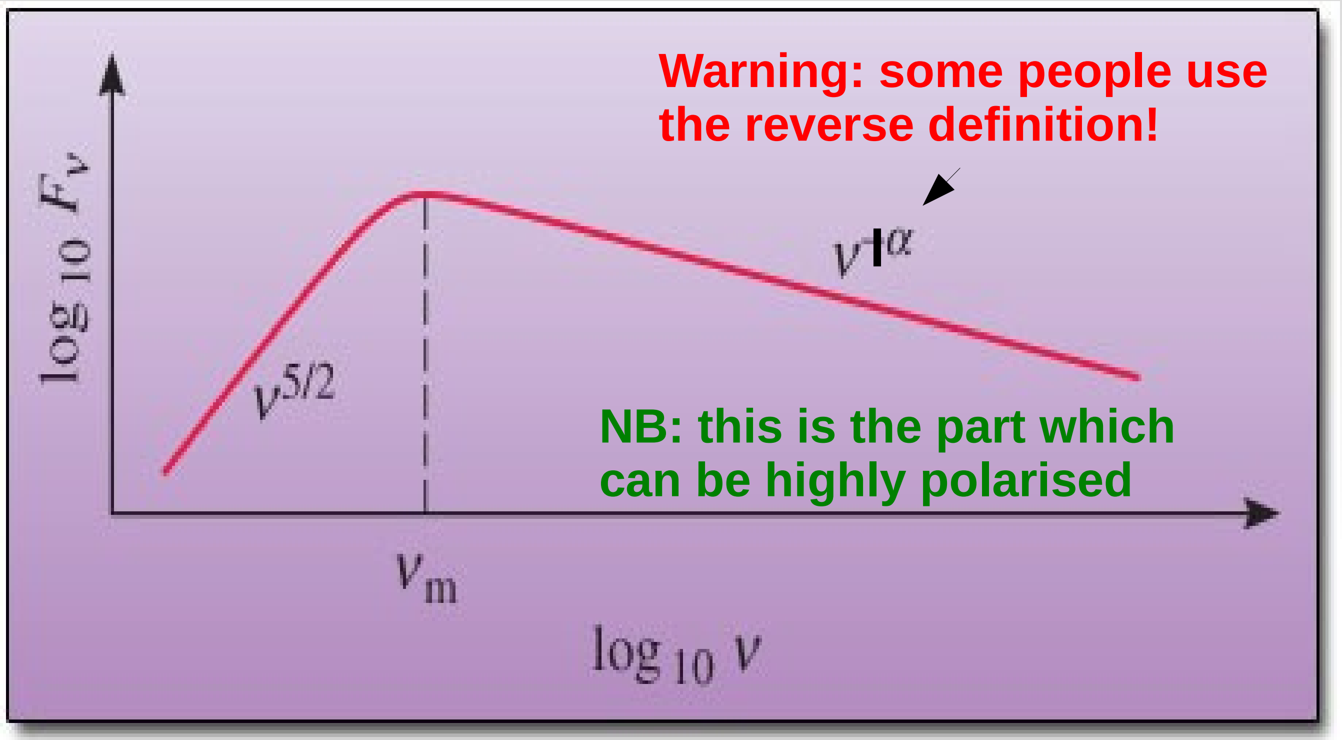
Most shock modelling predicts p ~ 2.1

The overall spectrum of synchrotron emission

This is a typical synchrotron spectrum for a cloud of relativistic electrons + B field.

At low frequencies the synchrotron emission is self-absorbed and has a **spectral index +2.5**

(this is different to the self-absorbed part of a thermal spectrum [a.k.a. Rayleigh-Jeans tail])



At higher frequencies the emission is optically thin. A power-law distribution of electrons $N(E)\,dE \propto E^{-p}$ will produce a power-law spectrum $F_\nu \propto \nu^{\alpha}$ where the relation is

$$\mathbf{p = 1 - 2\alpha}$$

Spectral index is typically observed to be $-1 < \alpha < -0.5$
This corresponds to $2 < p < 3$ – consistent with modelling (or the other way round...)

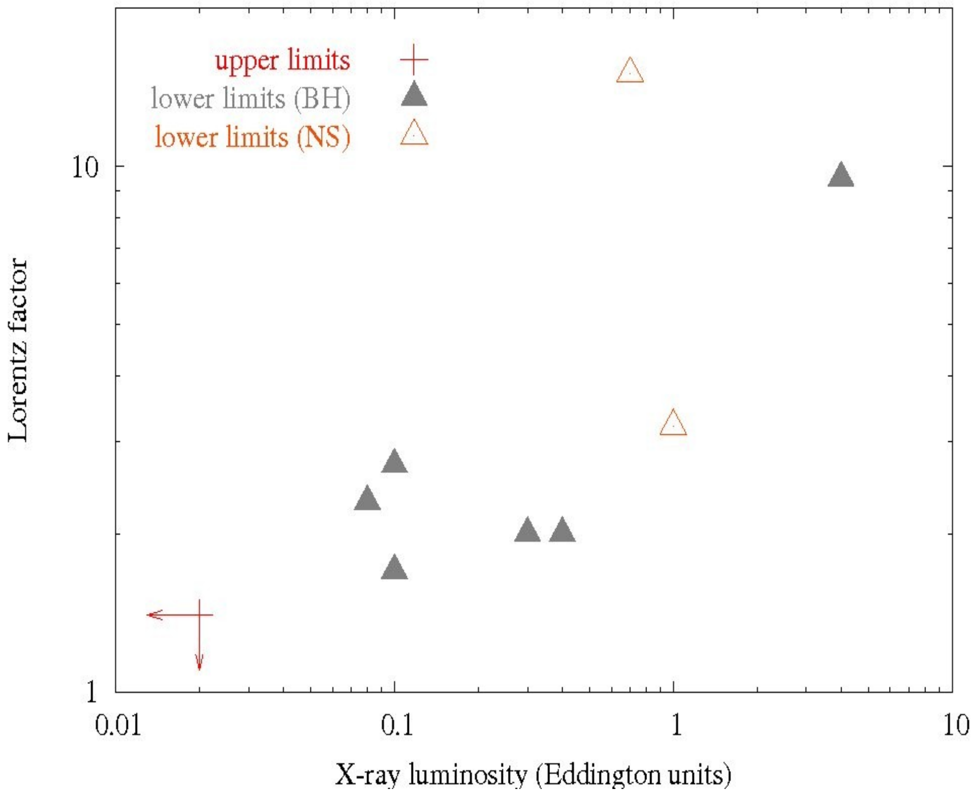
The speed of jets

Jets from AGN and X-ray binaries have been observed to travel at speeds > 0.999 c

… so fast, that its better to measure this in terms of the Lorentz factor

$$\Gamma = (1 - \beta^2)^{-1/2}$$

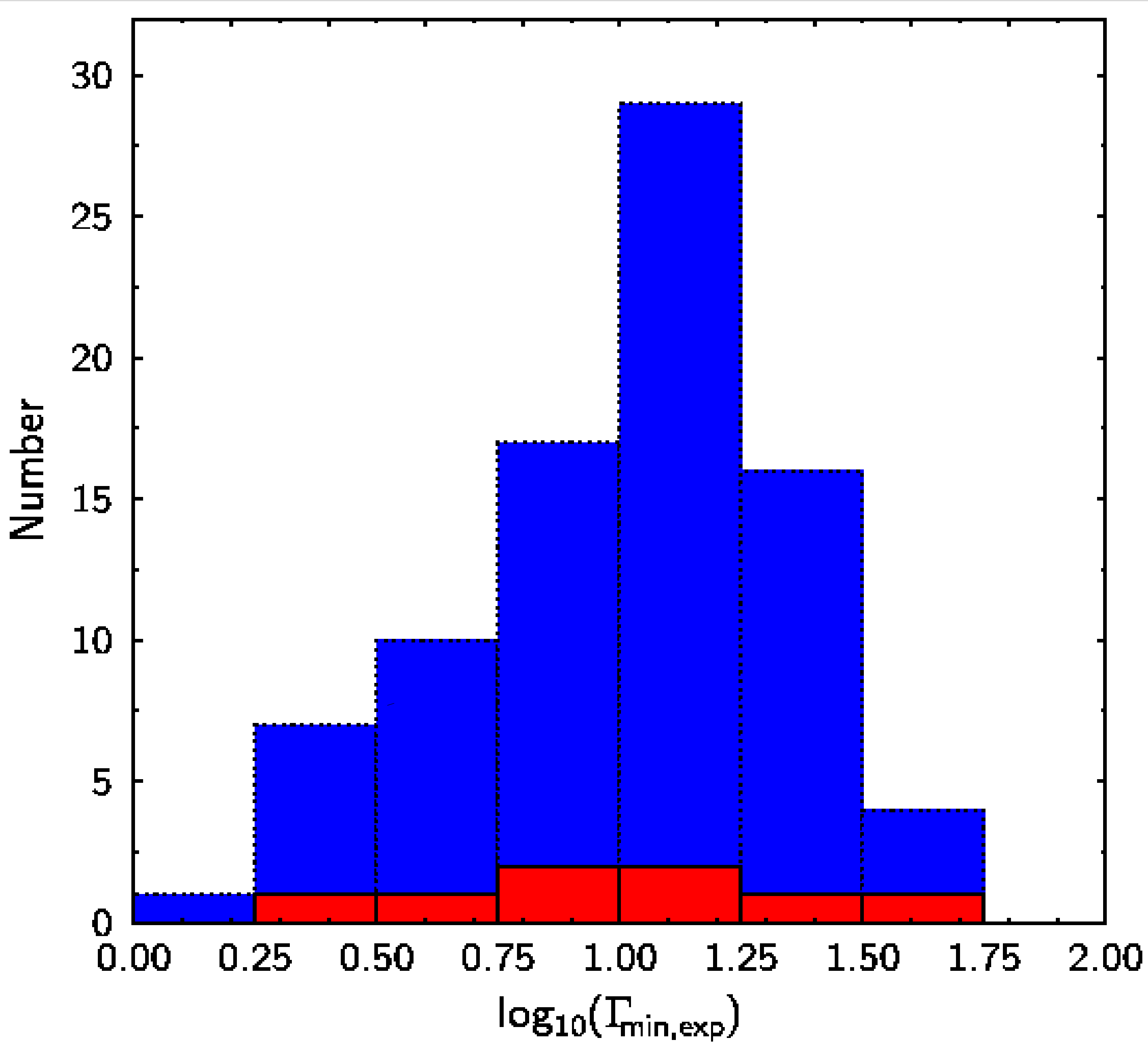
For several X-ray transients we can make direct measurements of jet proper motions. However, these <u>only provide lower limits on the Lorentz factor of the jet.</u>



NB1: because of the relatively narrow distribution, we believe that jets in the low/hard state are not highly relativistic

NB2: Neutron stars can make highly relativistic jets !

AGN BH X-ray binaries



Like FRIIs, X-ray binary jets are **very highly collimated** (< few degrees)

We may use this as a means of calculating the Lorentz factor assuming that this apparent lack of lateral expansion is caused by time dilation (caveat, caveat, caveat).

Alternative explanations for the collimation require confinement of the jet by the ISM or by a magnetic field

Daily images of the black hole X-ray binary GRS 1915+105 taken with MERLIN in 1997

The source is at an estimated distance of 11 kpc

The proper motions observed for the approaching component corresponded to ~25 mas / day

What is the derived velocity for the jets ?

Tip:

1 as @ 1 pc = 1 A.U.

1 A.U. = 1.5 x 10^{13} cm

1 as @ 1 pc = 1 A.U.

→ 1 mas @ 1 kpc = 1 A.U.

→ 25 mas @ 11 kpc = 25 x 11 = 275 A.U.

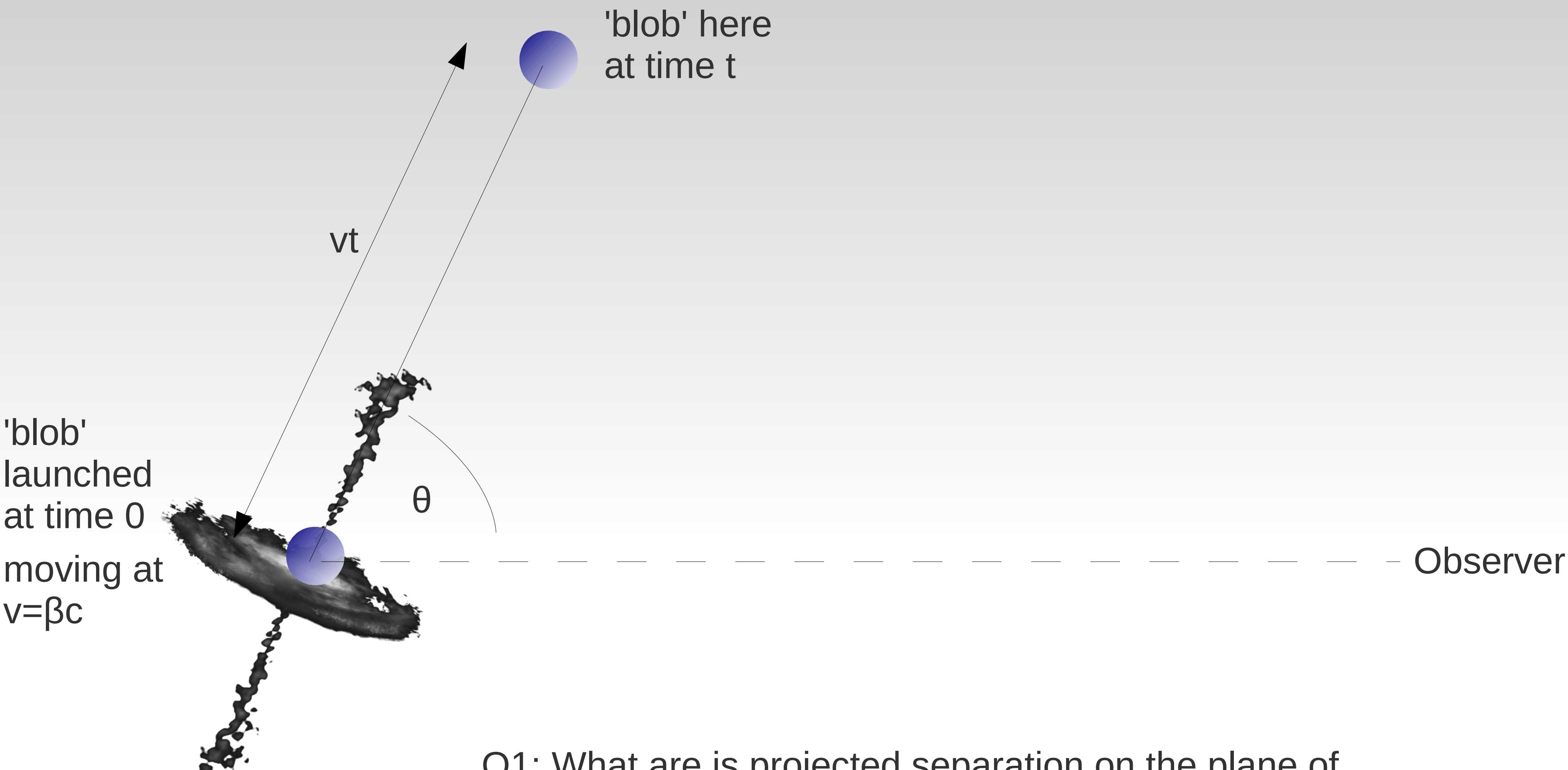
275 A.U. = 4 x 10^{15} cm

This was covered in one day → v = (4 x 10^{15} cm) / (86400.0) = 4.6 x 10^{10} cm / sec

= 1.5 c

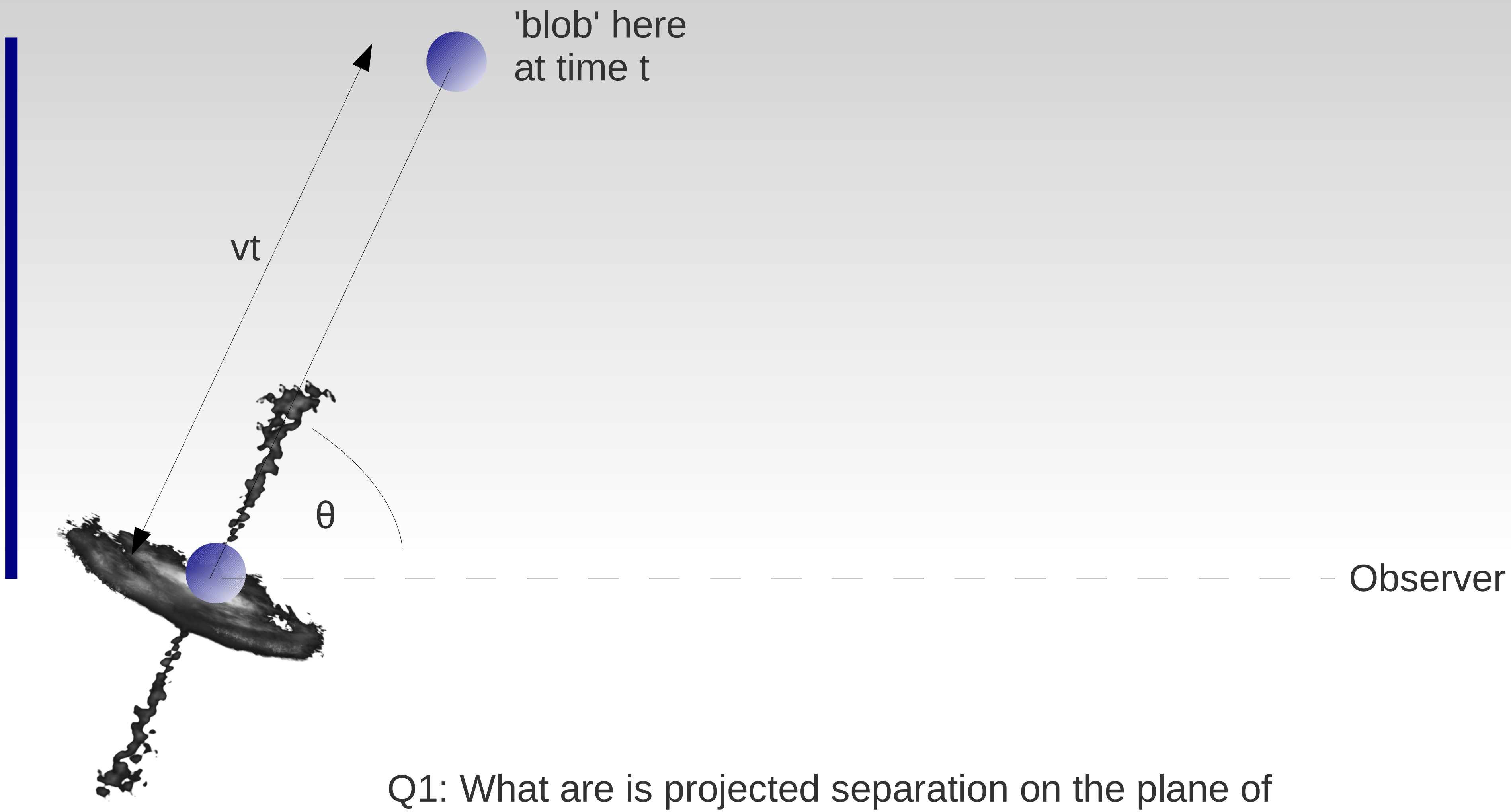
(alternatively you may note that 1 A.U. Is 8 1/3 light minutes, and 8 1/3 x 275 = 2290. One day is 1440 min so the source travelled 2290 light minutes in 1440 real minutes → speed of ~1.5 c)

How is this possible ?



Q1: What are is projected separation on the plane of the sky ?

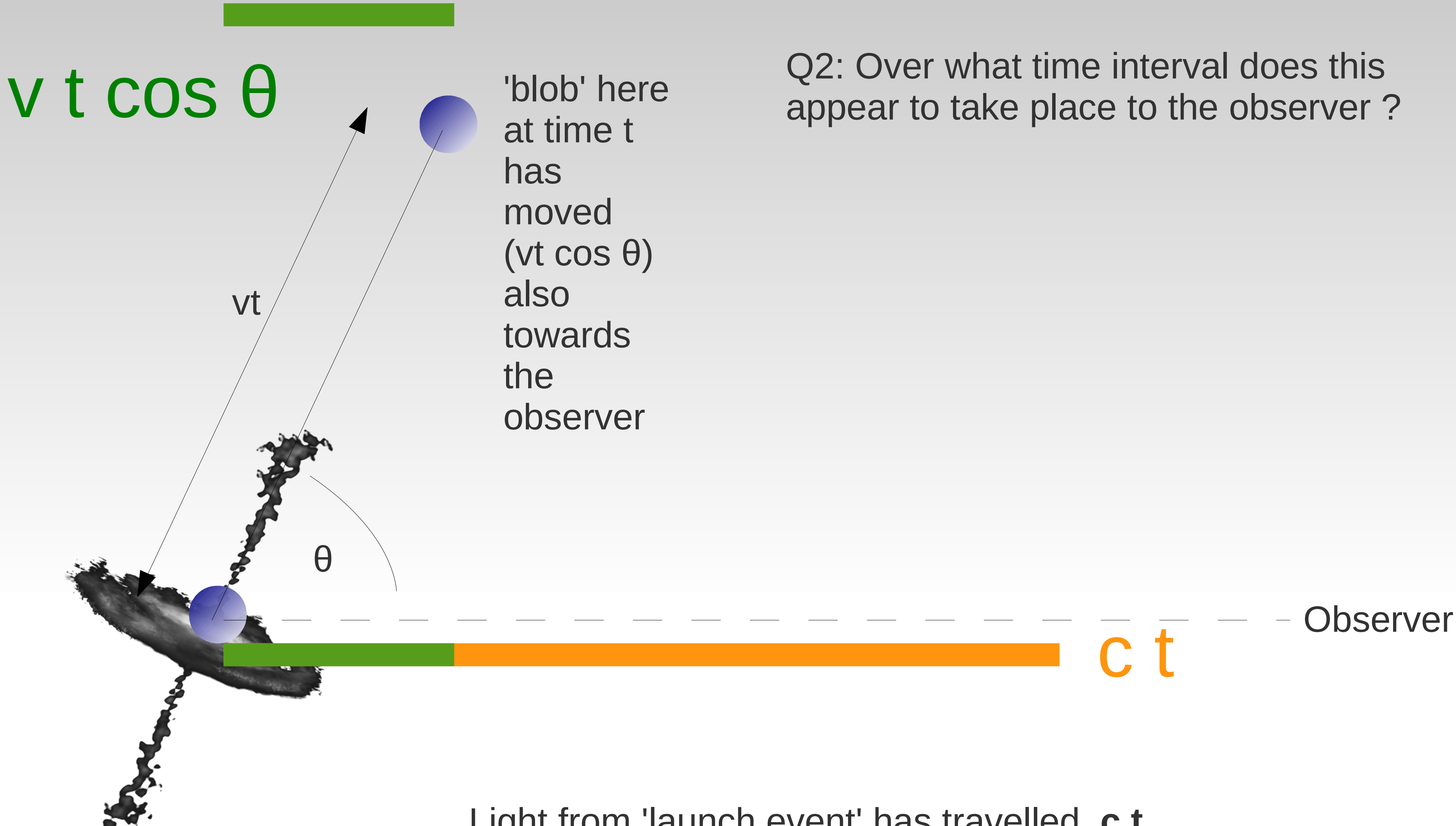
Q2: Over what time interval does this appear to take place to the observer ?



Q1: What are is projected separation on the plane of the sky ?

$$v\,t\,\sin\theta$$

Q2: Over what time interval does this appear to take place to the observer ?

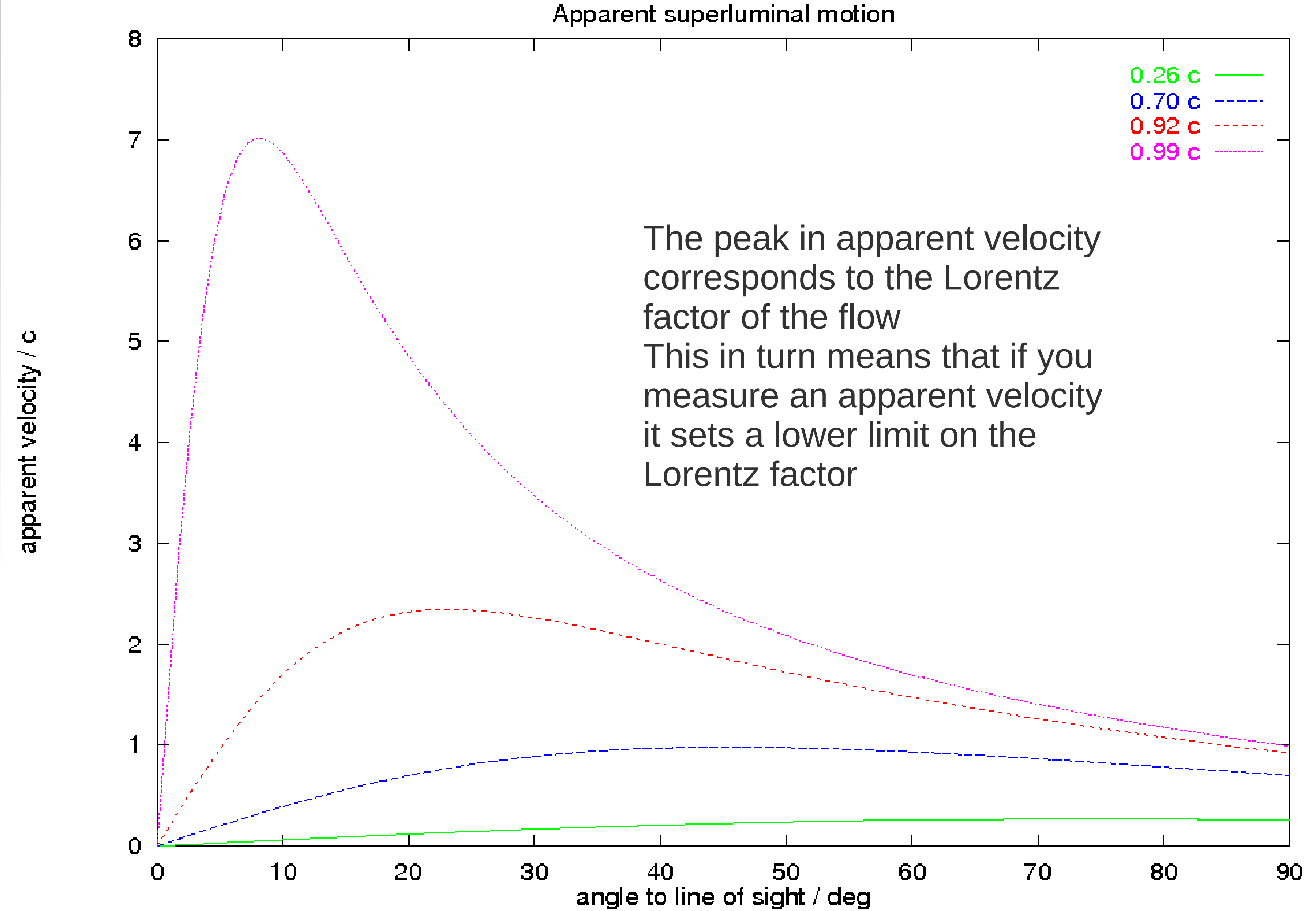


Light from 'launch event' has travelled **c t**

Light from blob at time t is **(c t – v t cos θ)** behind light from launch
Divide by **c** to get the difference in arrival times: **(t – β t cos θ)**

Apparent velocity v_{app} = (v t sin θ) / (t – β t cos θ)

Cancel t, divide by c β_{app} **= (β sin θ) / (1 – β cos θ)**



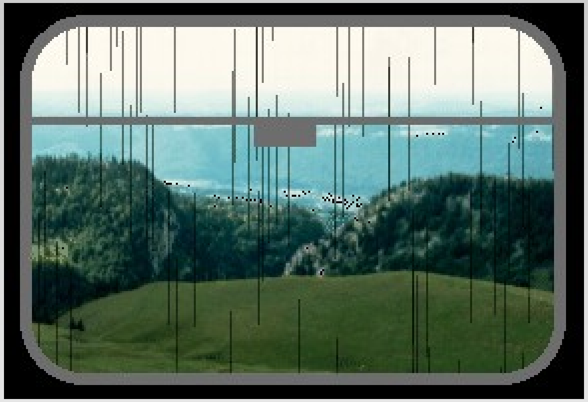
The peak in apparent velocity corresponds to the Lorentz factor of the flow

This in turn means that if you measure an apparent velocity it sets a lower limit on the Lorentz factor

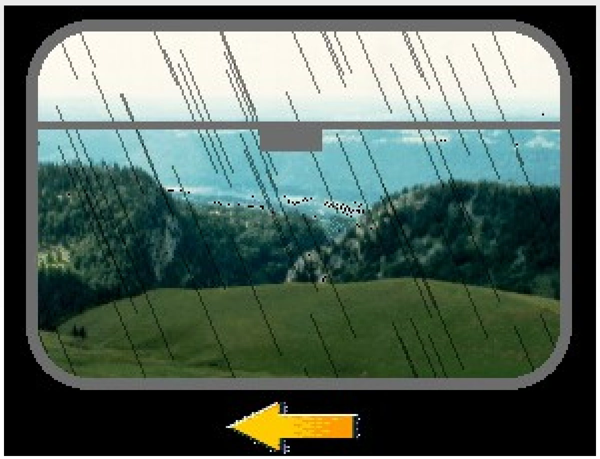
Q: Is this apparent superluminal motion a **relativistic** effect ?

A: Yes and **no.** There are no Γs. But it does rely on the speed of light being non-additive (however you can still get the same effect with additive speed of light.)

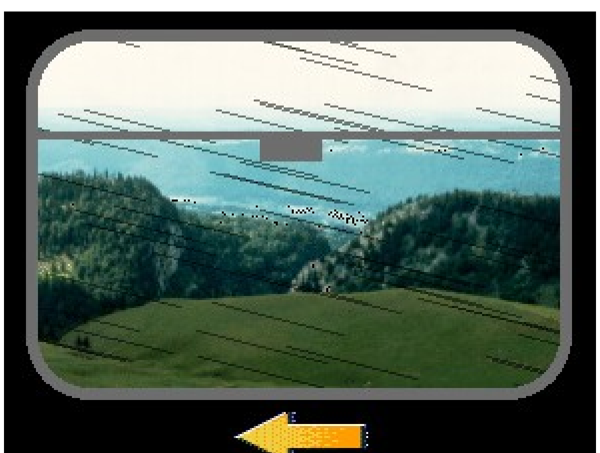
Aberration of light



at rest



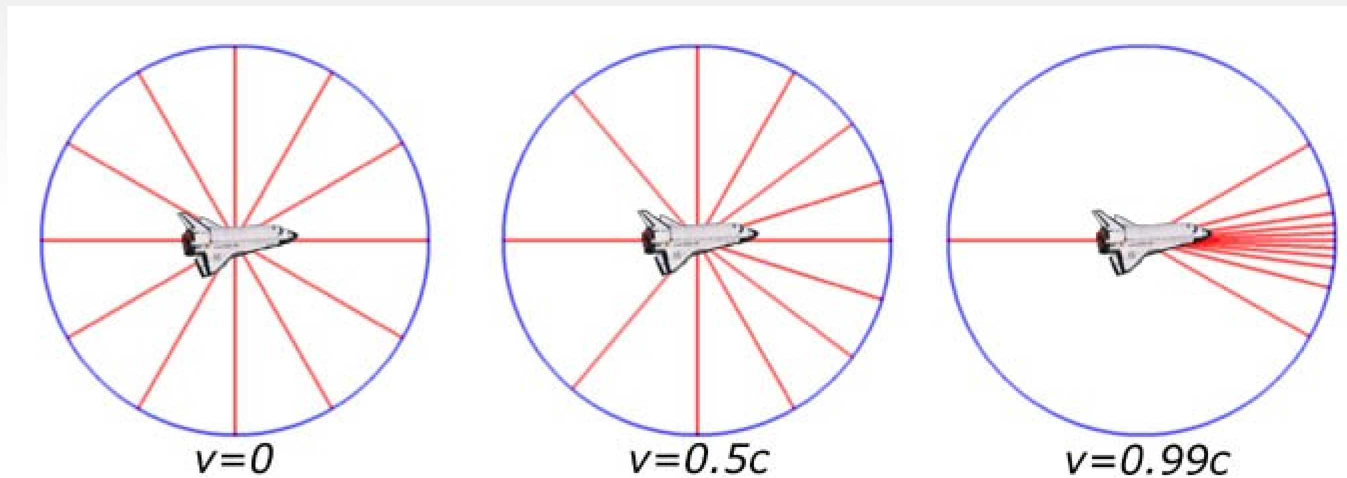
60 km/s



250 km/s

Classical aberration can be well observed in falling rain

Driving / cycling fast results in more rain appearing to come 'head on'



Relativistic aberration takes place in jets which are (often) moving at >0.9c

The radiation from these jets is strongly beamed in the forward direction (as well as Doppler shifted)

The 'beaming' angle is ~ 1 / Γ (radians)

This is why FR II radio jets are often observed to be one-sided