Oxford Physics: Part C Major Option Astrophysics

High-Energy Astrophysics

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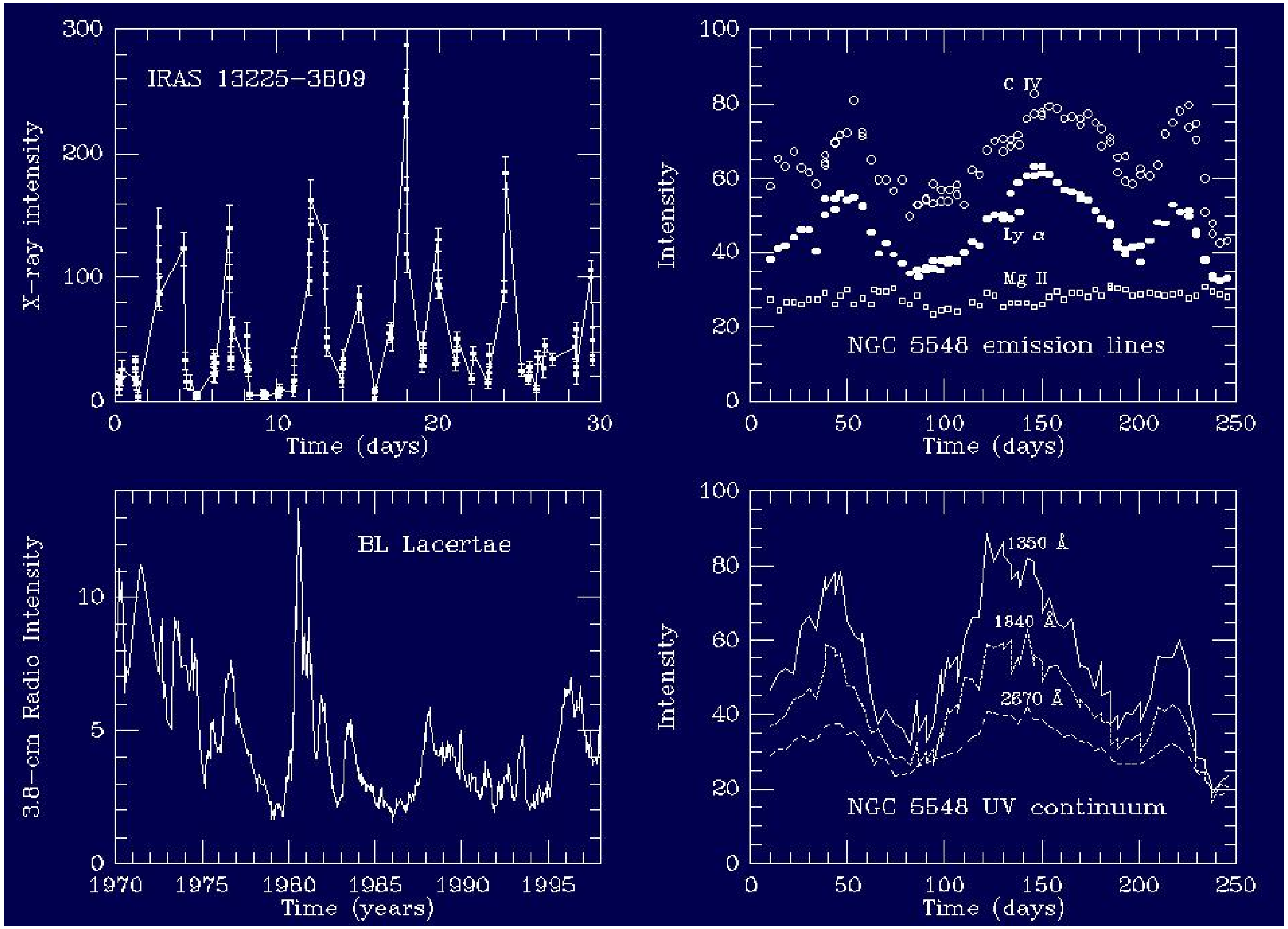
Today's lecture: Black Holes and jets Part I

- Evidence for Black Holes in AGN
- Ideas about jet production
- Superluminal motion *and doppler beaming*
- *Orientation models*

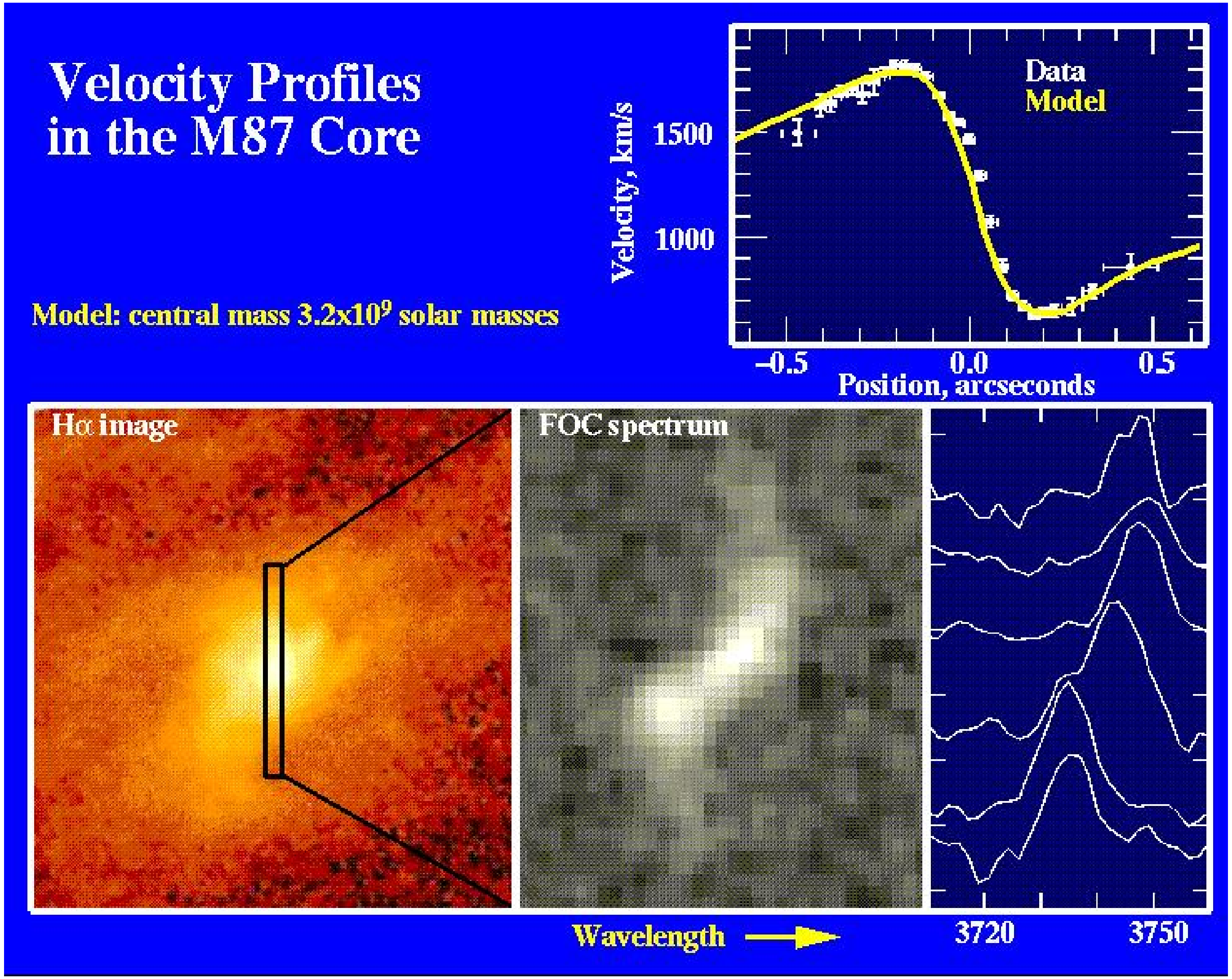
Evidence for black holes in AGN

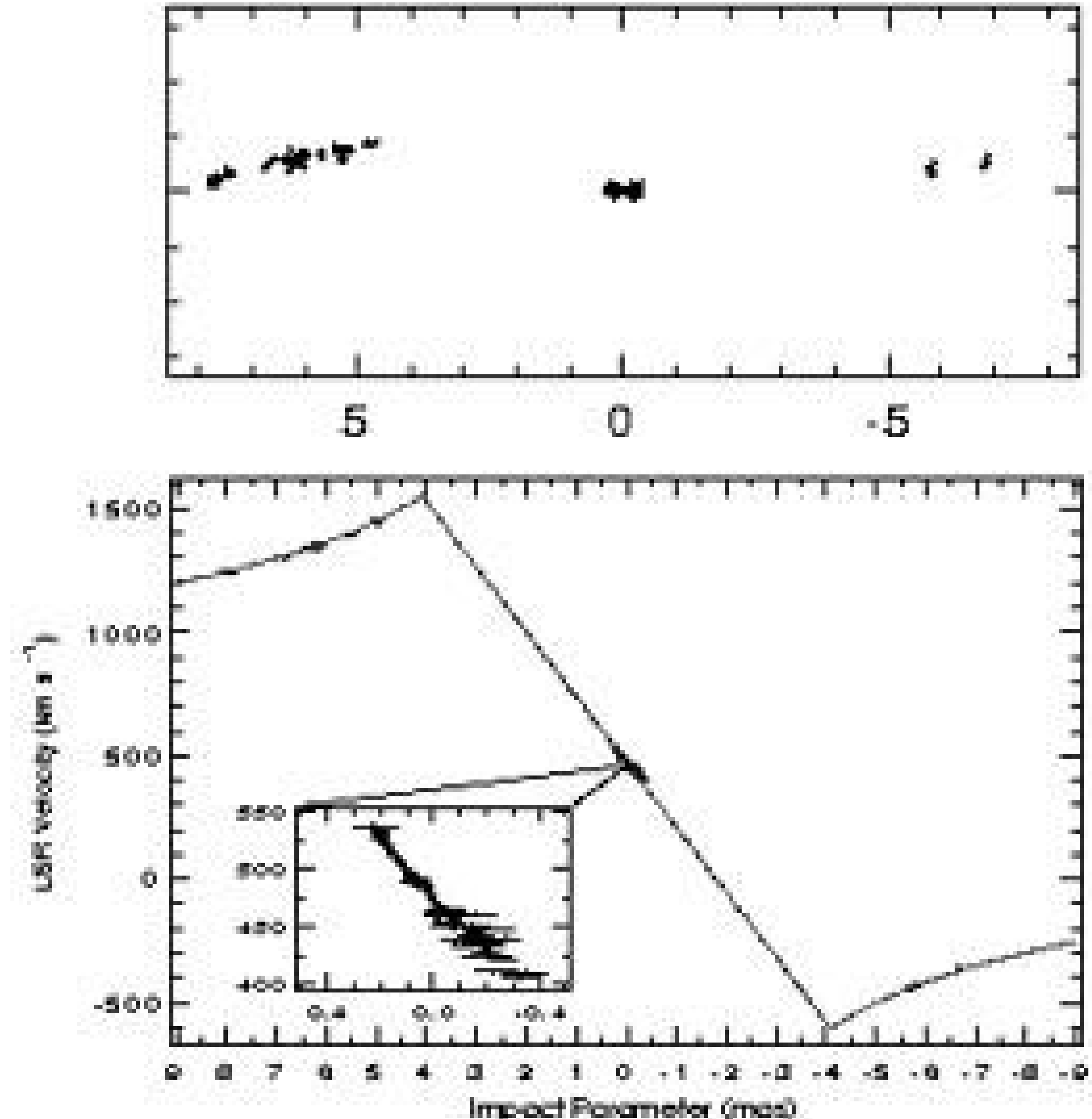
There are several canonical pieces of evidence that supermassive black holes really are there at the heart of AGN. Among these are:

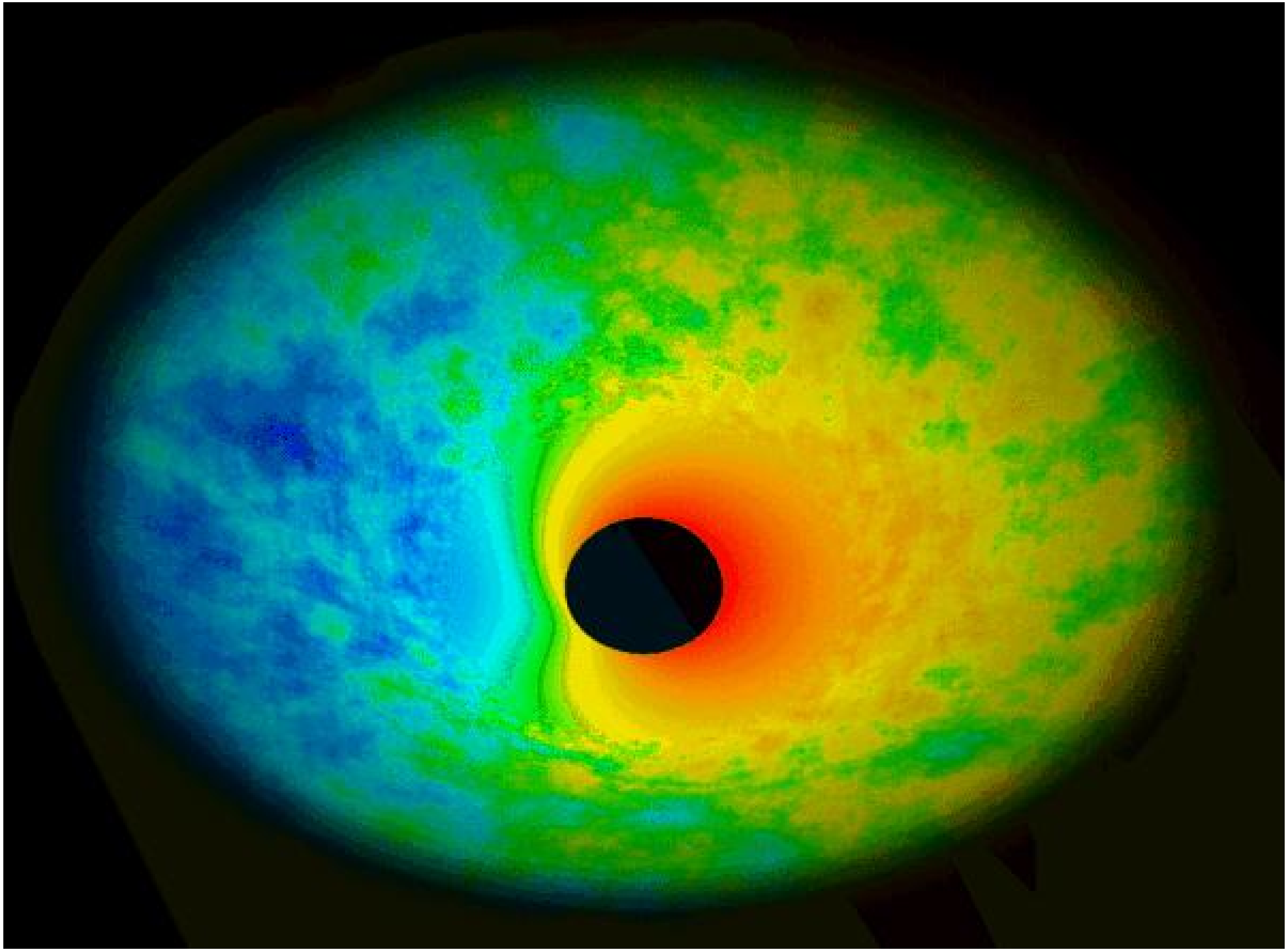
- Variability (in combination with Eddington luminosity).
- Stellar velocity dispersions.
- Rotation speeds inferred from emission lines.

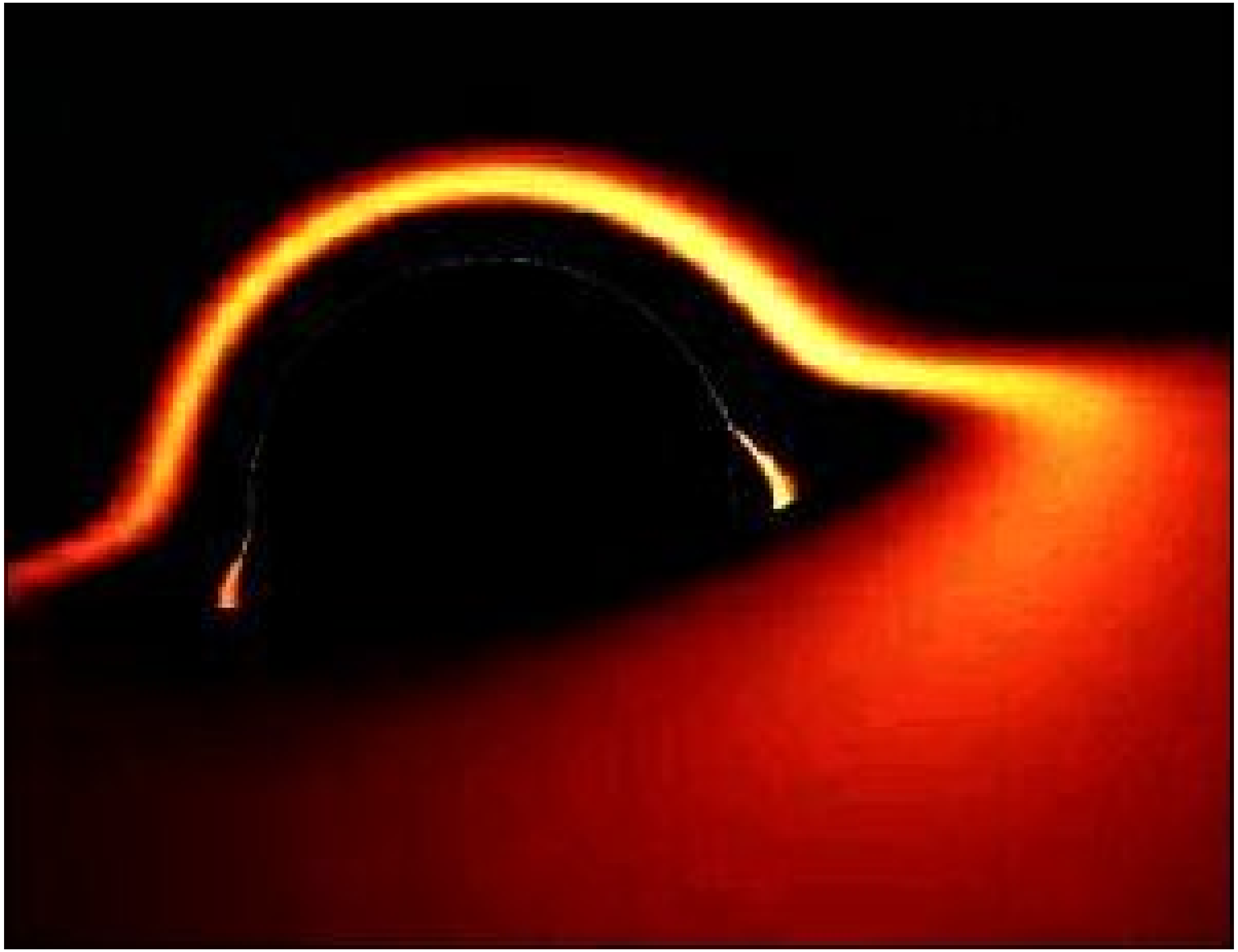


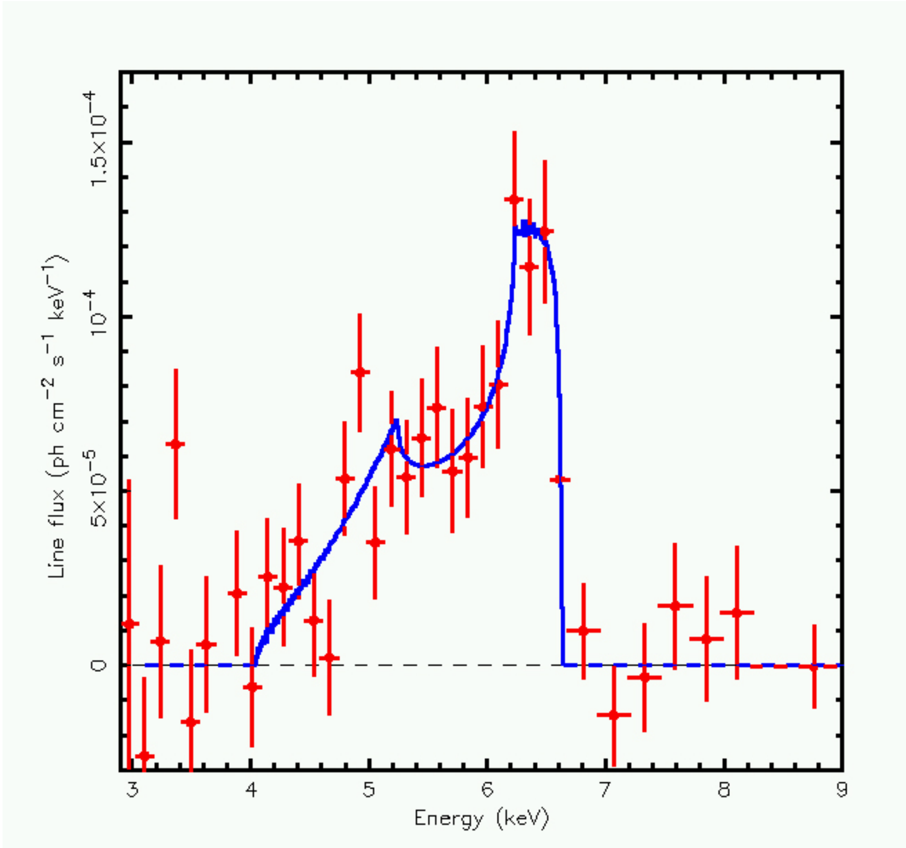
IRAS 13225-3809
X-ray intensity
Time (days)
C IV
Ly α
Mg II
NGC 5548 emission lines
Intensity
Time (days)
BL Lacertae
3.8-cm Radio Intensity
Time (years)
1350 Å
1840 Å
2670 Å
NGC 5548 UV continuum
Intensity
Time (days)

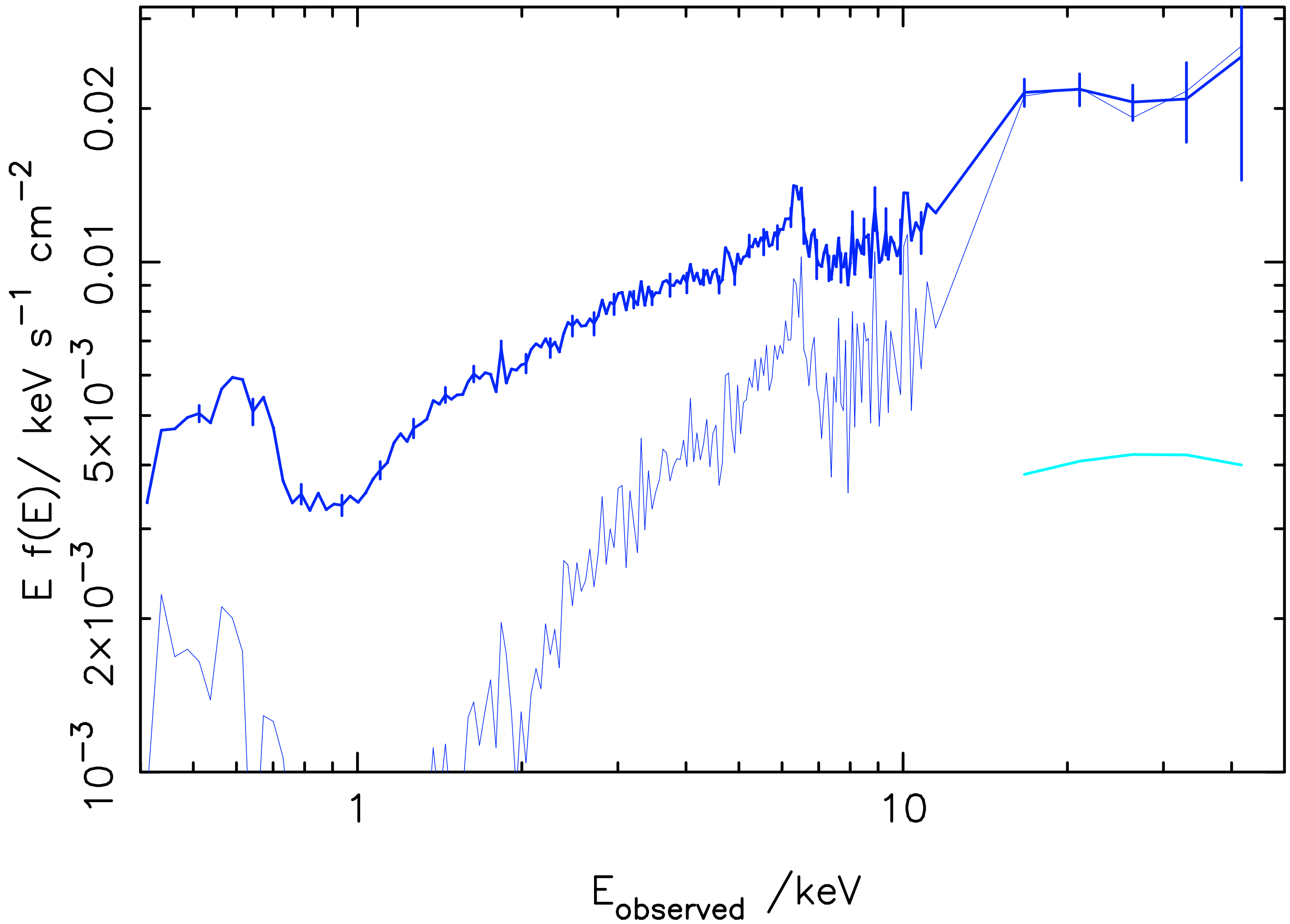

Velocity Profiles
in the M87 Core
Model: central mass 3.2x10^9 solar masses
Data
Model
Velocity, km/s
1500
1000
–0.5
0.0
0.5
Position, arcseconds
Hα image
FOC spectrum
Wavelength
3720
3750


5
0
-5
1500
1000
500
0
-500
LSR Velocity (km s⁻¹)
9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9
Impact Parameter (mas)
0.4
0.0
-0.4

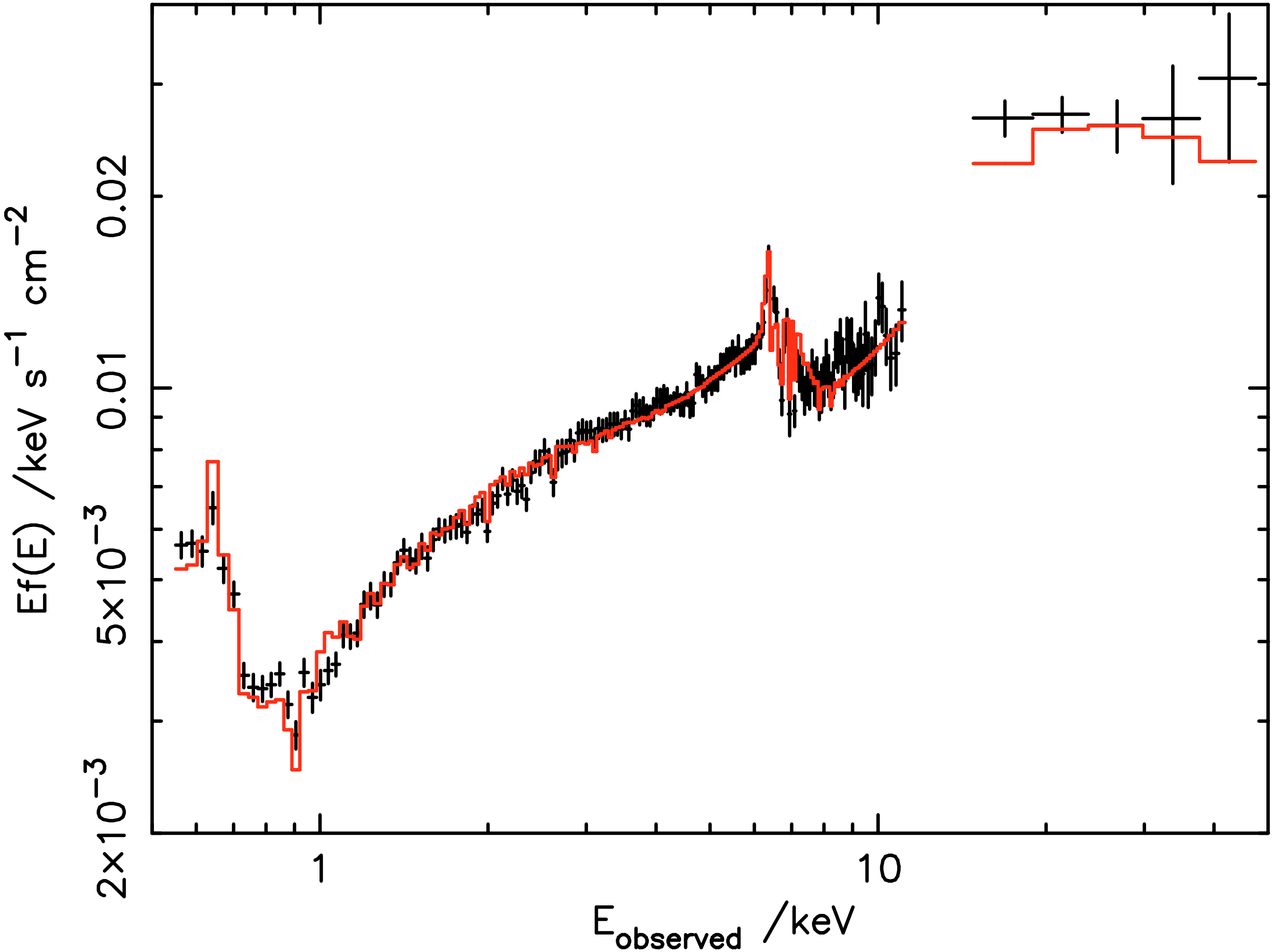





Line flux (ph cm^{-2} s^{-1} keV^{-1})
1.5×10^{-4}
10^{-4}
5×10^{-5}
0
3
4
5
6
7
8
9
Energy (keV)



E f(E)/ keV s^{-1} cm^{-2}
10^{-3}
2×10^{-3}
5×10^{-3}
0.01
0.02
1
10
$E_{observed}$ /keV



Ef(E) /keV s^{-1} cm^{-2}
0.02
0.01
5×10^{-3}
2×10^{-3}
1
10
E$_{observed}$ /keV

Models for jet production

We are now near the boundaries of our understanding of AGN and stellar-mass jet-producing engines. The very central question still remains unanswered: just how is the jet created in the first place?

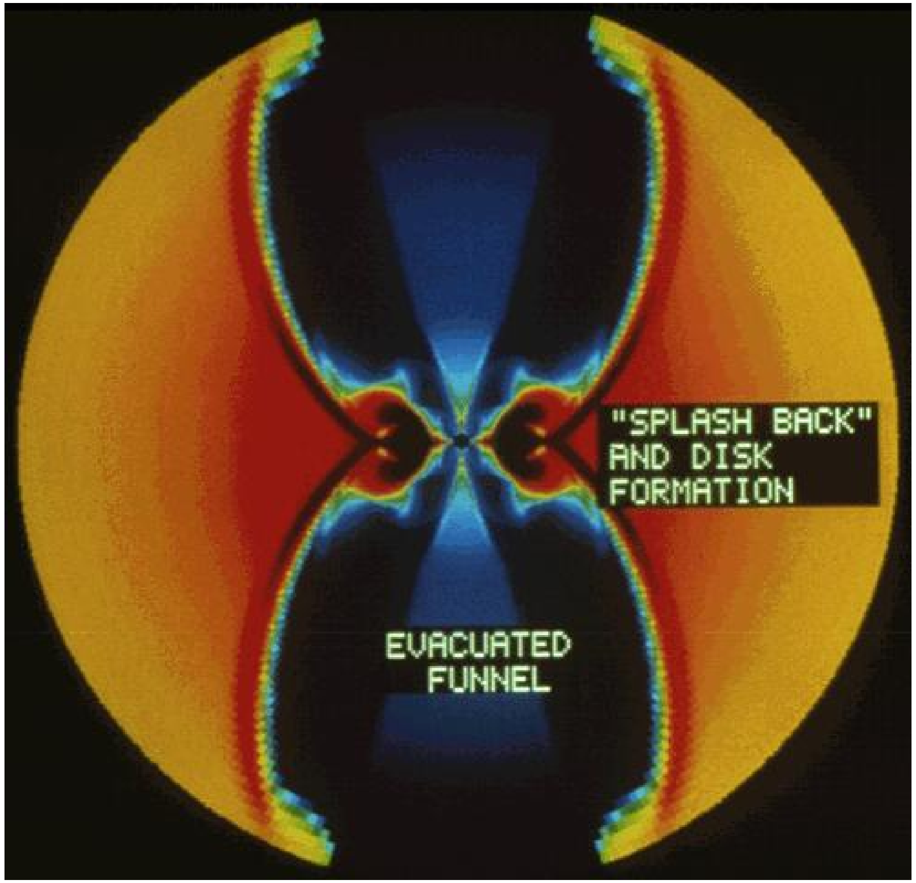
Jet production I: pure radiation pressure

- Geometrically thick accretion disc disc as "funnel".

- A bloated inner accretion disc would have extremely high radiation density at its centre. This would provide a poorly collimated but powerful outflow. Then *reconfinement shock* creates collimated jet.

- Detailed shape of nozzle requires full GR calculation; questions about stability, efficiency. How sure are we of bloated disc?

- Creating the jet as a positron/electron plasma by pair production has problems: Compton drag would quench a powerful jet.



Numerical simulation of jet-producing “funnel” at the centre of a thick accretion disc.

Jet production II: Magnetic Fields

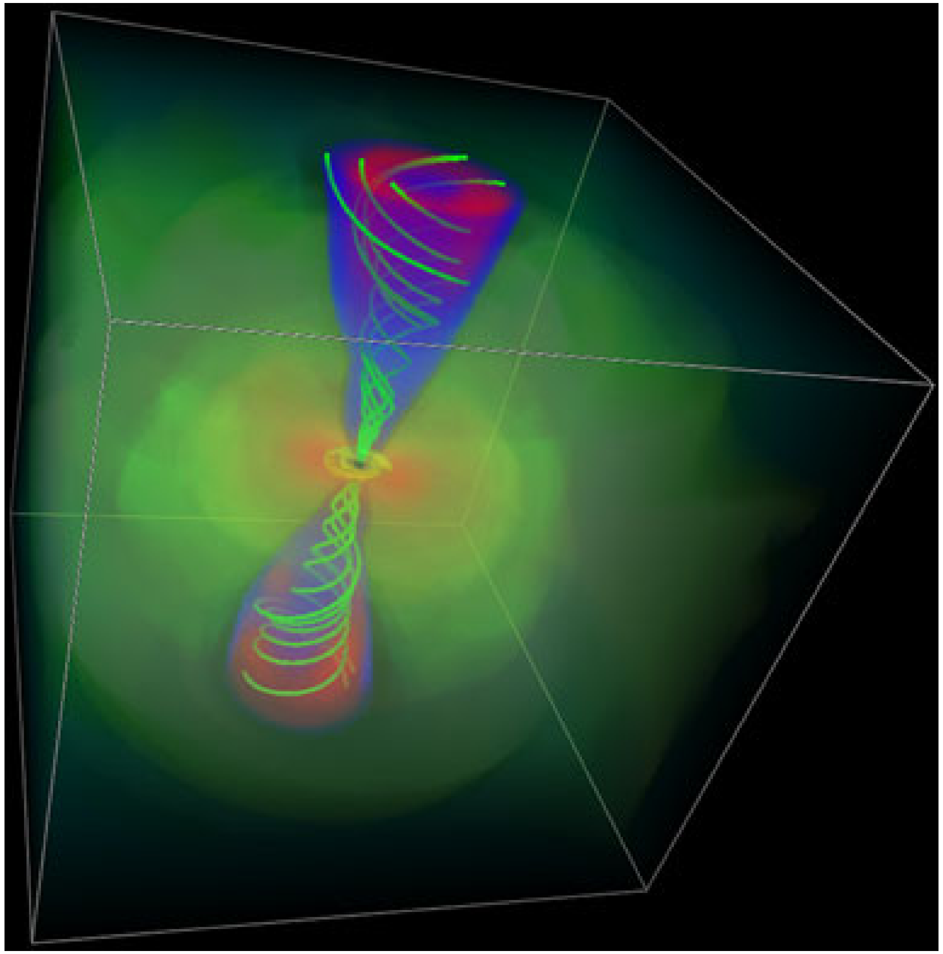
- A toroidal **B** is a natural mechanism to collimate the jet.

- It is possible to extract energy from the black hole: it can *conduct* and so can produce a dynamo effect.

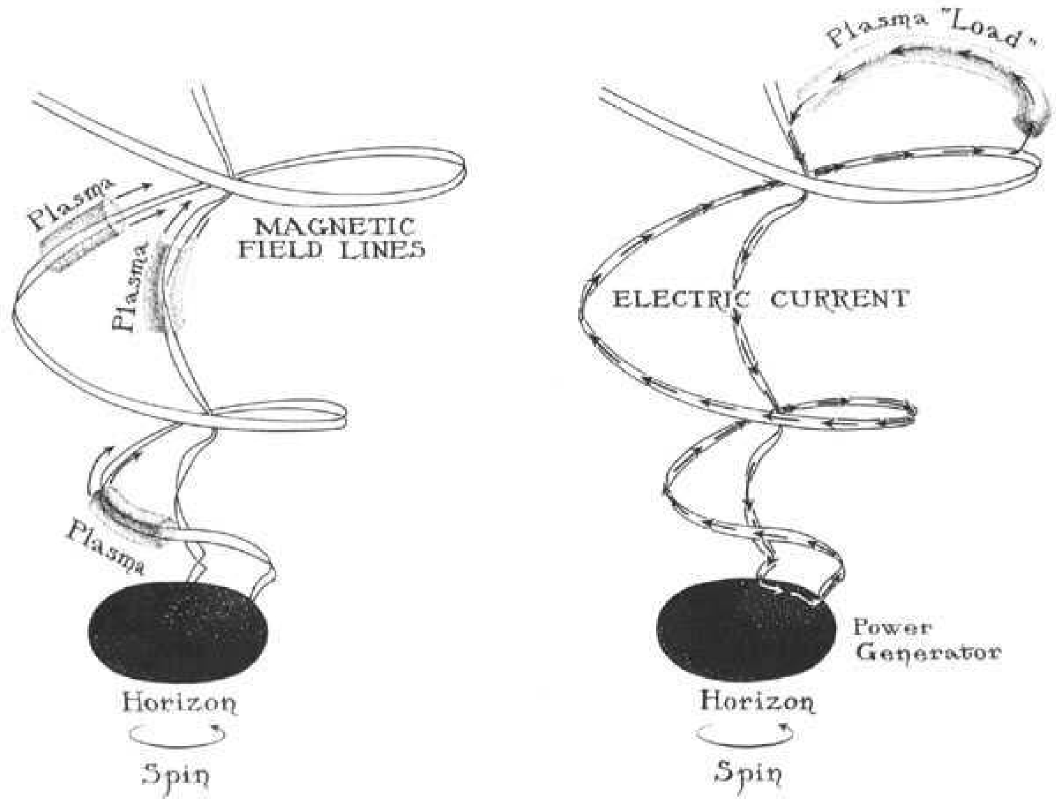
- Whatever the exact manifestation we know that **B** fields must likely be strong near to SMBH because infalling material has carried and compressed **B** from the ISM of the host galaxy.

- Mechanism needs a thin disc. How certain?

McKinney & Blandford GRMHD simulation



Magnetic fields: The Blandford-Znajek mechanism



Black hole horizon has resistance of empty space (377 Ω)!

Current passing through circuit is

$$I = \frac{\int \mathbf{v} \times \mathbf{B} \cdot \mathrm{d}\mathrm{l}}{R_H + R_L}$$

Order of magnitude: maximally rotating Kerr hole, set $R_H \sim R_L$, set B energy density near hole similar to gas pressure near hole. Power $I^2 R$ works out to be:

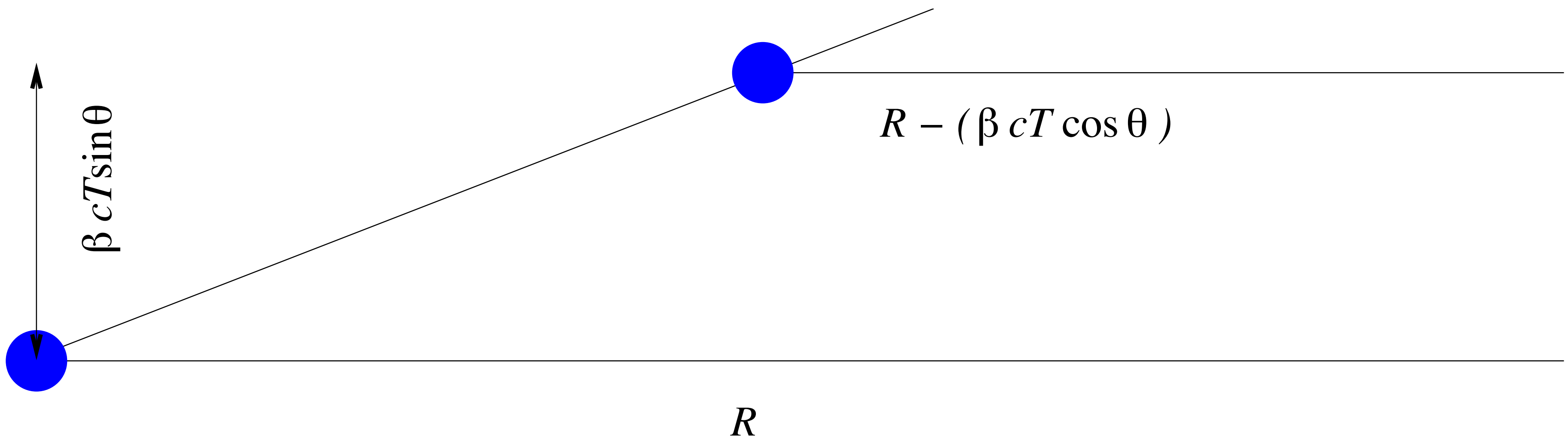
$$P \sim 10^{38} \frac{M_{\mathrm{BH}}}{10^9 M_\odot} \mathrm{W}$$

Which is available to accelerate particles away from the black hole.

Superluminal motion

The existence of jets in AGN means that spherical symmetry is broken. But we cannot take an individual active galaxy and rotate it to see what it looks like from a different angle. Hence a large amount of effort has been devoted to making statistical inferences about different types of AGN, and detailed observations of observational effects which should be orientation dependent. The underlying motive is, of course, to make as simple a model as possible, in which many of the observationally diverse types of AGN are the same type of beast, just viewed from a different position.

The most spectacular of these was proposed theoretically in the early days of AGN studies by Martin Rees, and with modern techniques it can be readily observed in many quasars with bright jets: *superluminal motion*.


β cTsinθ
R − (β cT cos θ)
R

Superluminal motion: calculation

In this calculation we will assume that the quasar and observer are at rest w.r.t. each other in flat spacetime. A full calculation including cosmological terms masks the intrinsic physics here (and, indeed, we now know of superluminal microquasars within the Galaxy, for which this treatment is exact).

Let us assume that a quasar lies at a large distance R from the observer, and its jet is inclined to the line-of-sight at an angle θ. Suppose a "blob" of bright emission in the jet—say a shock travelling up the jet— leaves the nucleus and and travels up the jet at speed βc.

The observer sees the blob leave the nucleus at time

$$t_1 = \frac{R}{c}$$

Now let the blob propagate up the jet for some time T in the frame of the nucleus. After this time, the blob has a *transverse* separation

$$\Delta X = \beta c T \sin\theta$$

Remember the observer can only measure the component of separation in the plane of the sky.

Superluminal motion: calculation contd.

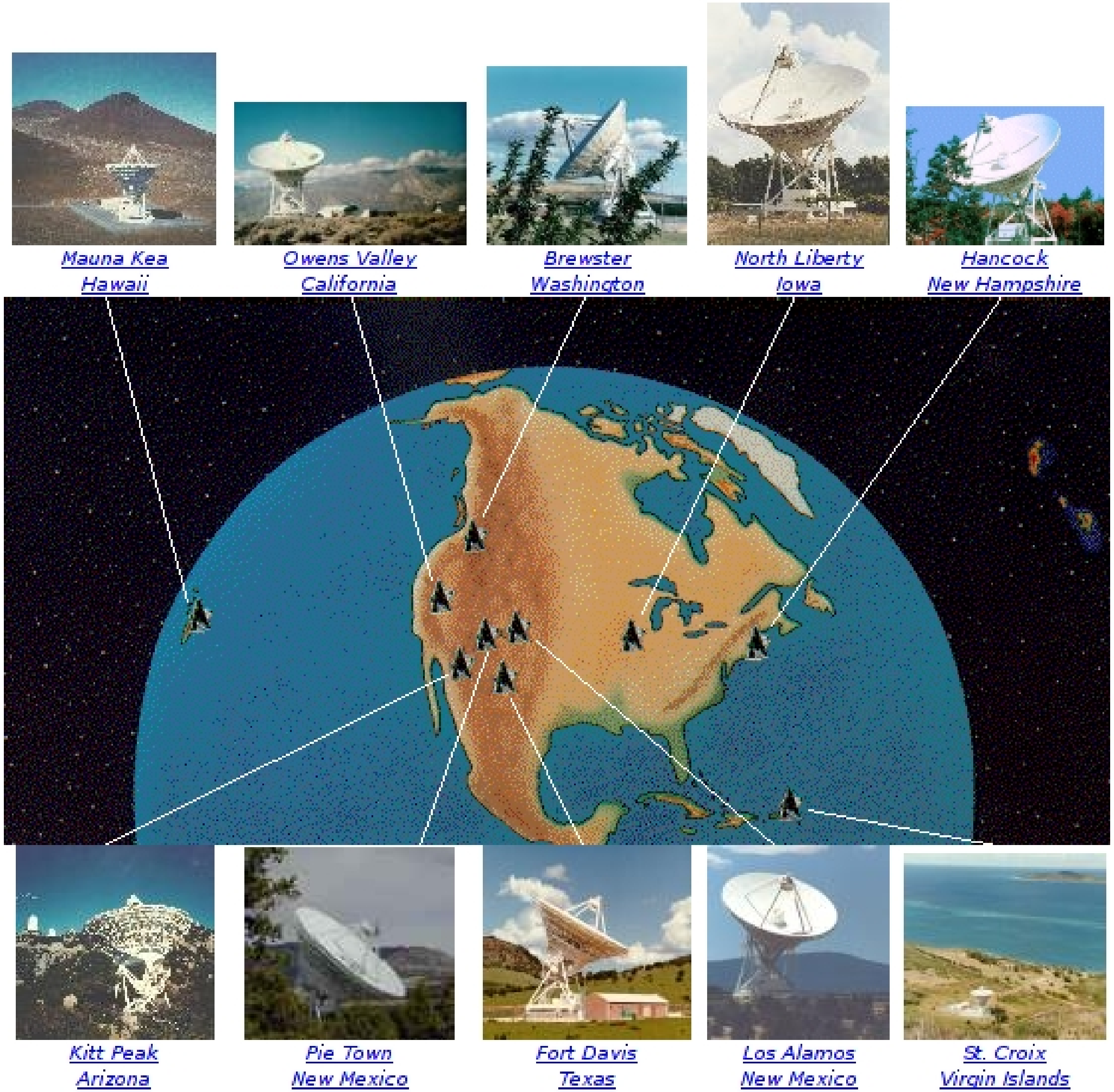
Now consider the time at which the observer *sees* the blob reaching this distance from the nucleus. The light is emitted at time T but only has to travel a distance $R - \beta c T \cos\theta$. So the observer sees the blob reach position ΔX at time

$$t_2 = \frac{R}{c} + T(1 - \beta \cos\theta)$$

Hence the apparent transverse velocity is

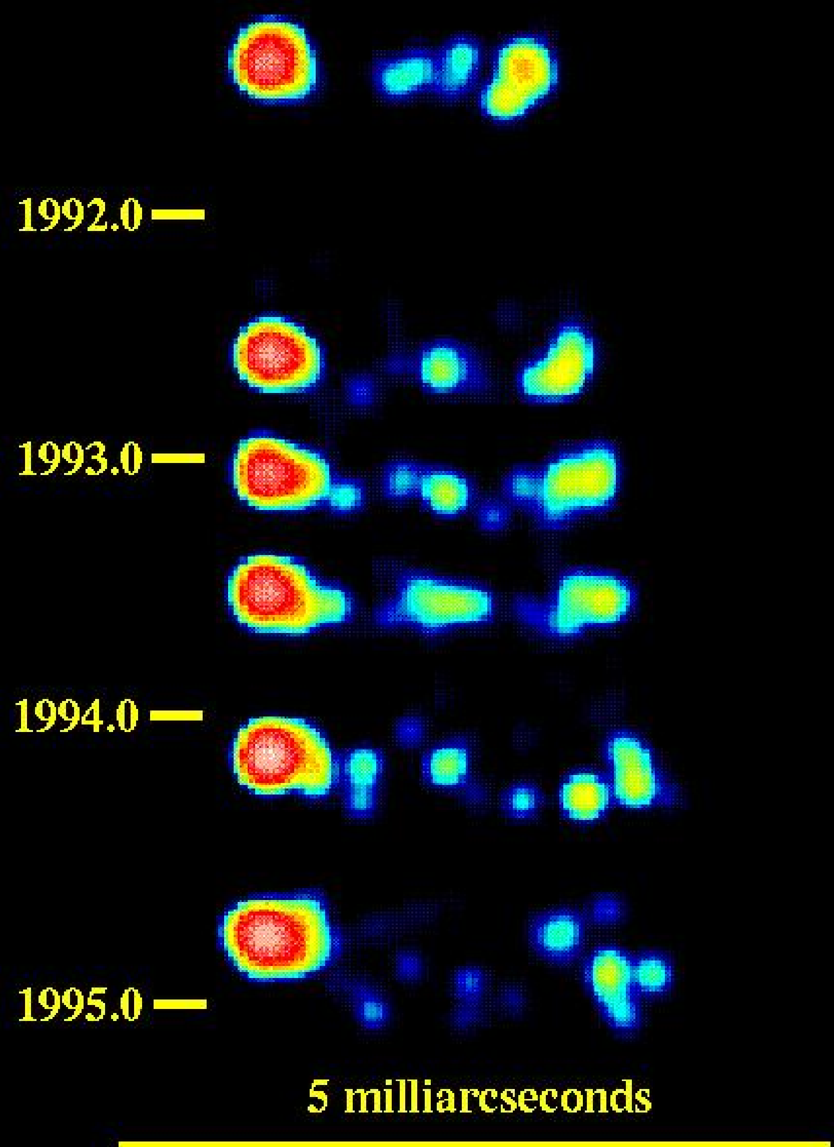
$$\begin{aligned}\beta_{\mathrm{app}} c &= \frac{\Delta X}{t_2 - t_1} \\ &= \frac{\beta c \sin\theta}{1 - \beta \cos\theta}\end{aligned}$$

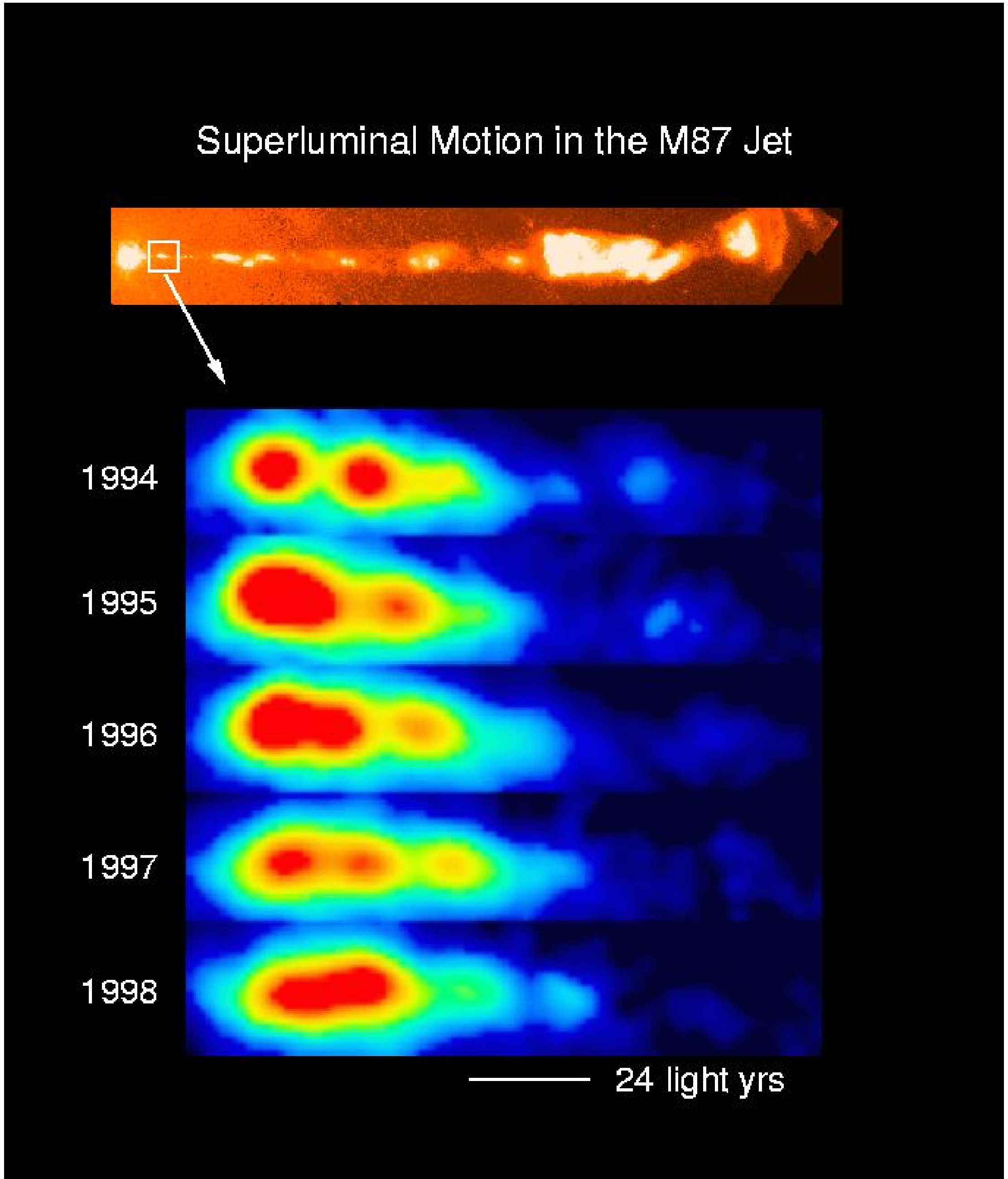
So for β close to 1 and small θ, we can easily observe $\beta_{\mathrm{app}} > 1$. Values of β_{app} up to $\sim$ 5—10 are measured.


Mauna Kea
Hawaii
Owens Valley
California
Brewster
Washington
North Liberty
Iowa
Hancock
New Hampshire
Kitt Peak
Arizona
Pie Town
New Mexico
Fort Davis
Texas
Los Alamos
New Mexico
St. Croix
Virgin Islands

3C 279

Superluminal Motion





Superluminal Motion in the M87 Jet
1994
1995
1996
1997
1998
24 light yrs

Superluminal motion: population statistics.

The *maximum* value of $\beta_{\rm app}$ which can be produced by a jet arises when $\beta = \cos\theta$, for which...

$$\beta_{\rm app} = \gamma\beta$$

...the proof of which is on the next question sheet.

By taking the upper limit of $\beta_{\rm app}$ in large samples of quasars, we infer that the bulk motion in the jets typically has $\gamma \sim 5$ to 10.

The *distribution* of $\beta_{\rm app}$ in the quasar population can then be used to infer their distribution in line-of-sight angle. We find that quasar jets are not isotropically distributed in angle: they preferentially point towards us. More on this shortly.

Caveats for superluminal motion measurements. . .

- How certain are we that one component is being followed?

- Is the “core” really the core—self absorption varies with observing frequency and the measured “central” component not necessarily be the very centre of the core.

- How to deal with accelerating/decelerating blobs?

Doppler boosting of relativistic jets

The radiation emitted by a blob of jet material will be relativistically Doppler boosted towards (or away from) the observer. Here we shall calculate how the effects the observed *brightness* of the jet.

First we recall the Doppler Factor for radiation emitted by a source moving at an angle θ to the line of sight:

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

where γ is the usual Lorentz factor and $\beta = v/c$. Photons are received in the observed frame at a rate D times the rate they are emitted. To calculate the brightness in the observed frame, we must consider two other factors.

Doppler boosting of relativistic jets contd.

First, the solid angle subtended in the observed and emitted frames is different; the emitted radiation is preferentially beamed towards the direction of motion. Angle transforms as

$$\mathrm{sin}\theta' = D\mathrm{sin}\theta$$

and so solid angle transforms as

$$\mathrm{d}\Omega' = D^2\mathrm{d}\Omega$$

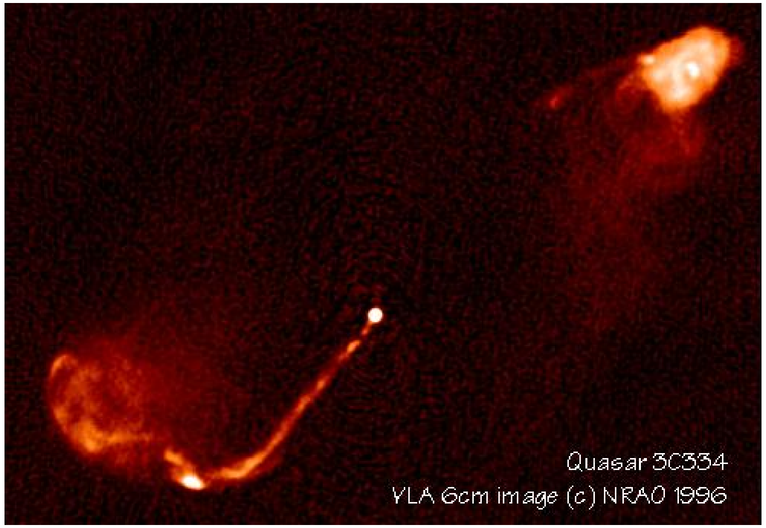
Second, photons received at some particular energy in the observed frame will have been emitted at a different energy. Using our parametrisation of the spectrum $S_\nu \propto \nu^{-\alpha}$, we find that the total observed brightness for a source varies as

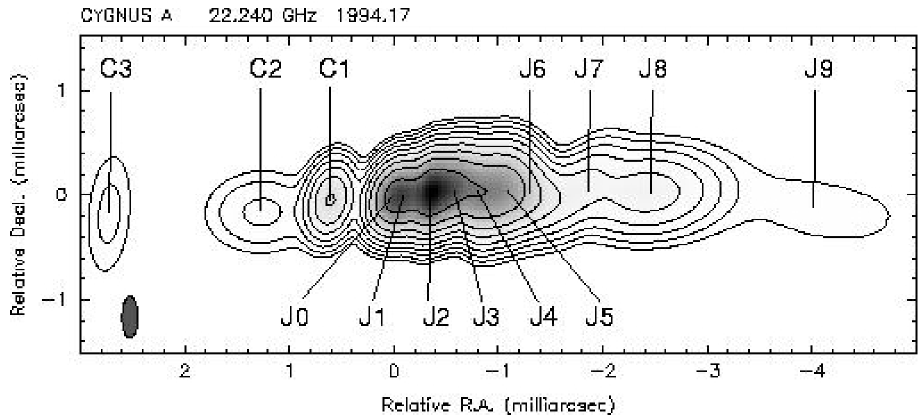
$$B_{\mathrm{obs}} = B_{\mathrm{em}} D^{3+\alpha}$$

N.B. the emission from a blob approaching us is Doppler boosted and the brightness is *increased*; a receding blob has its emission Doppler boosted away from us and its brightness is *decreased* by this factor.

Doppler boosting and jet "sidedness"

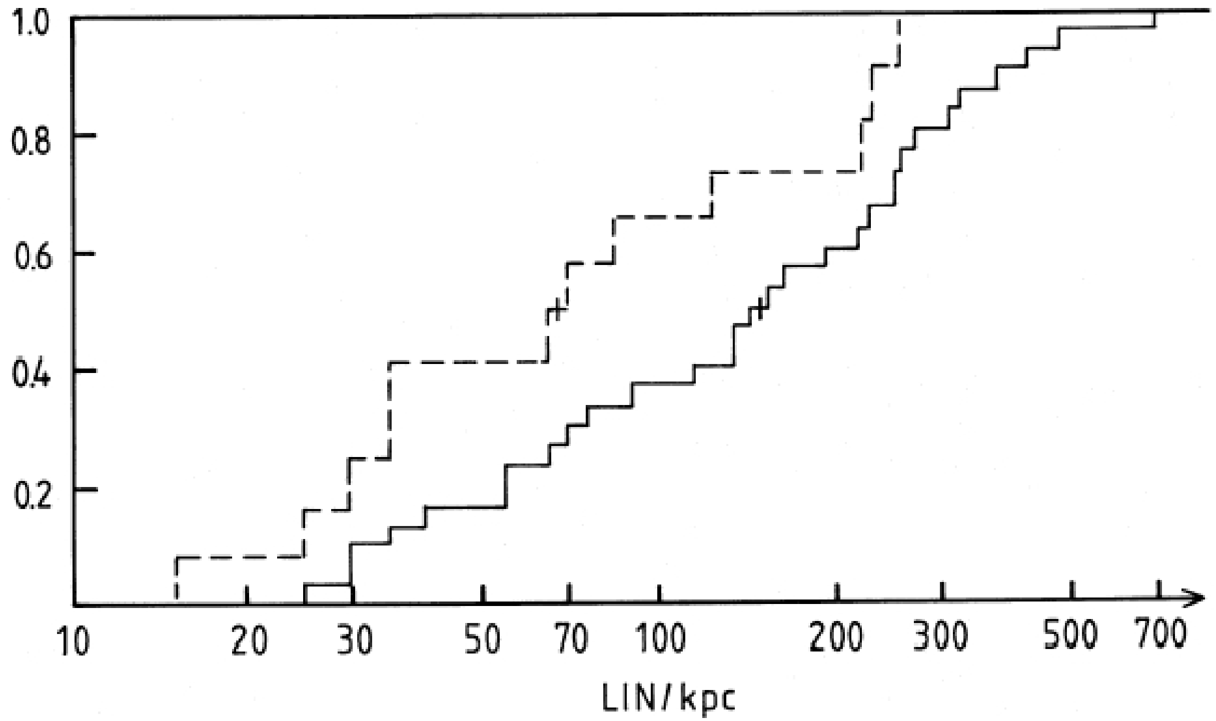
This Doppler boosting gives us one of the main clues that quasars and radiogalaxies are the same type of object, but viewed from different orientations. Looking at large samples of objects we find that the quasars tend to have one very bright jet and often no sign of a counterjet; radiogalaxies on the other hand often exhibit a jet and a counterjet.





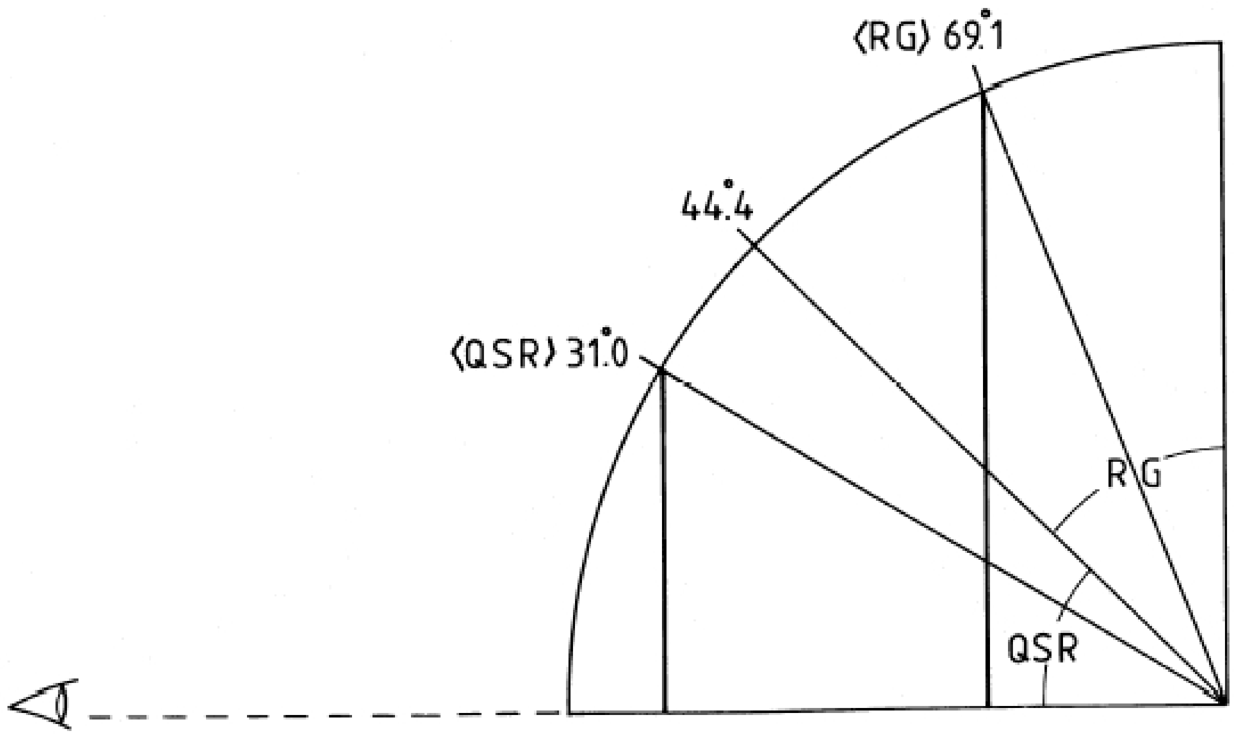
Quasar/radiogalaxy unification

This picture of the quasars “pointing towards us” is neatly supported by the fact that their average projected size is smaller than that of the radiogalaxies:



Cumulative histogram of quasar and radiogalaxy projected sizes.

Quasar/radiogalaxy unification



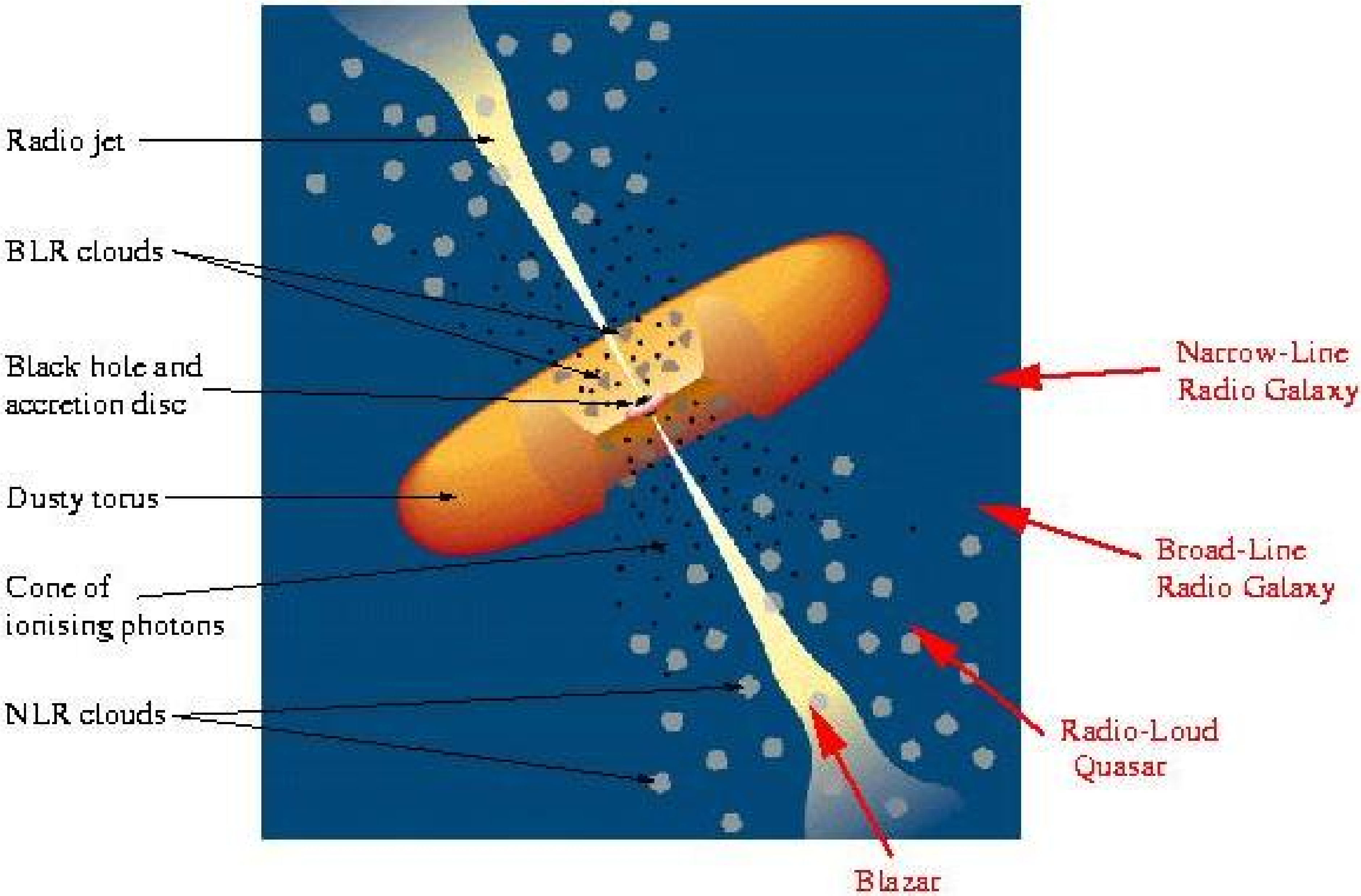
The ratio of quasar to radiogalaxy mean sizes implies that quasars are seen at an angle of less than $\approx 45^\circ$ to the line of sight.

Quasar/radiogalaxy unification

A large body of evidence now exists to support models of orientation-based unification of different classes of AGN. To first order, we can split AGN at any given luminosity into two classes.

- In Type I AGN, we can see the nuclear region directly. The jet axis points towards us and we observe strong Doppler boosting of the jets. Usually the optical/UV continuum emission from the accretion disc, broad emission lines from high-velocity clouds near the nucleus, are visible.

- In Type II AGN, our point of view is more “sideways on”. Our view of the nucleus is obscured by a dusty torus of material beyond the accretion disc. In objects with powerful jets, these tend to be nearly symmetric. Optical emission lines are narrow, originating the in the interstellar medium well away from the nucleus.


Radio jet
BLR clouds
Black hole and accretion disc
Dusty torus
Cone of ionising photons
NLR clouds
Narrow-Line Radio Galaxy
Broad-Line Radio Galaxy
Radio-Loud Quasar
Blazar