Gamma-ray bursts, jet formation and unsolved problems

1. Short introduction to gamma-ray bursts

Gamma-ray bursts were detected as a part of military USA mission. Vela satellites sentitive to gamma-rays were put into orbit to test whether Soviet Union follows the treaty signed in 1963 and do not perform nuclear tests. On July 2, **1967**, at 14:19 UTC, the Vela 4 and Vela 3 satellites detected a flash of gamma radiation unlike any known nuclear weapons signature. More bursts were detected, scientists started to work on it and concluded that the bursts were of extra-terrestial origin. The discovery was declassified and published in **1967** by the team (Klebesadel et al.).

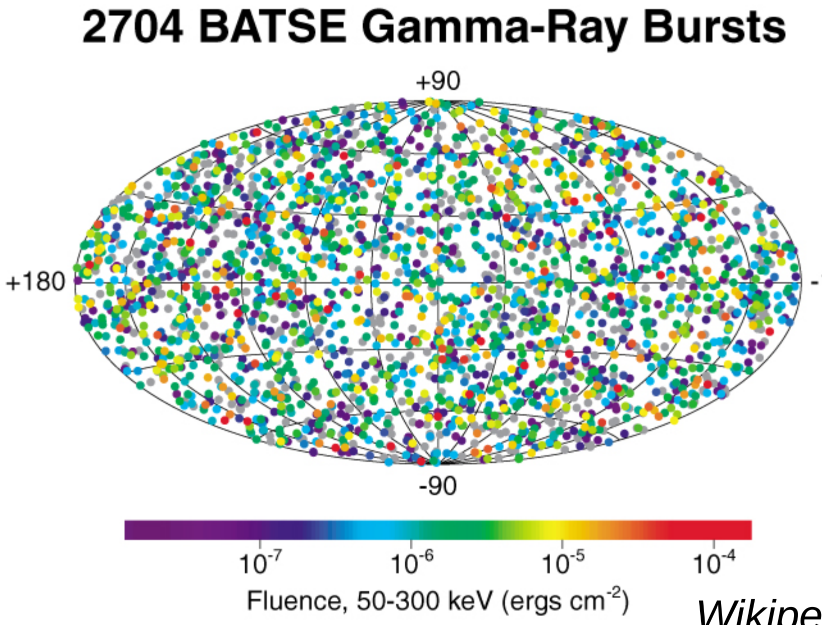
Artistic image of a gamma-ray burst; Credit: NASA, ESA and M. Kornmesser

That opened a long-standing discussion of the distance and origin of the bursts, and models suggested all the range of possibilities – from the Solar System origin (colliding comets in Oort cloud) to cosmological distances (hypernovae). Paczyński argued for cosmological distances in a famous Paczyński-Lamb debate in 1995.

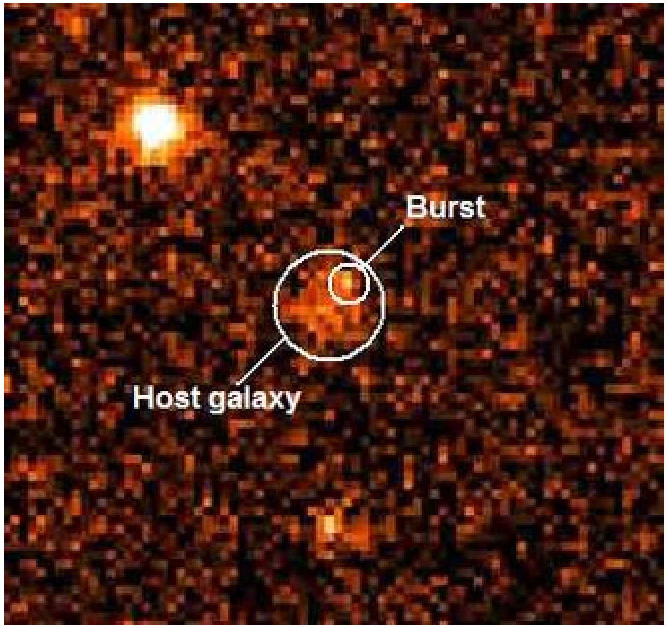
1. Short introduction to gamma-ray bursts

Thousands of gamma-ray bursts were detected by BATSE instrument on board of Compton Gamma Ray Observatory satellite (1991-2000).

But the issue of the distance was settled by the detection of the gamma-ray (GRB 970228) by the **Beppo-Sax satellite** (much smaller than BATSE !) and subsequent detection of the corresponding fading emission in X-rays by the same satellite.

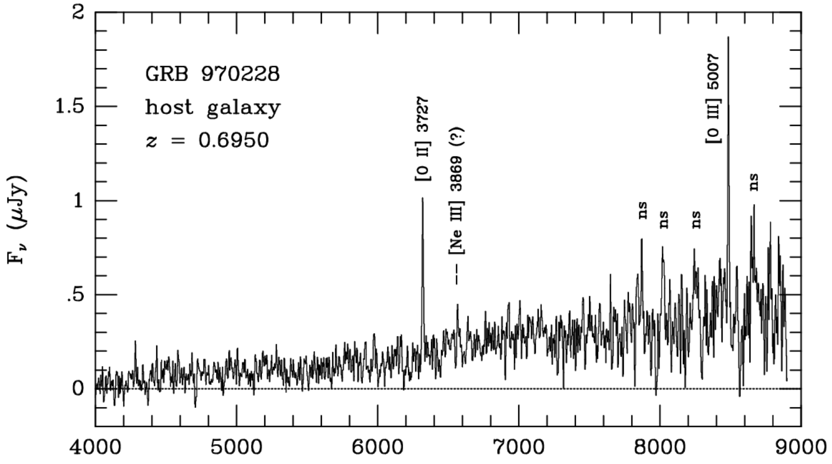


Wikipedia



Wikipedia

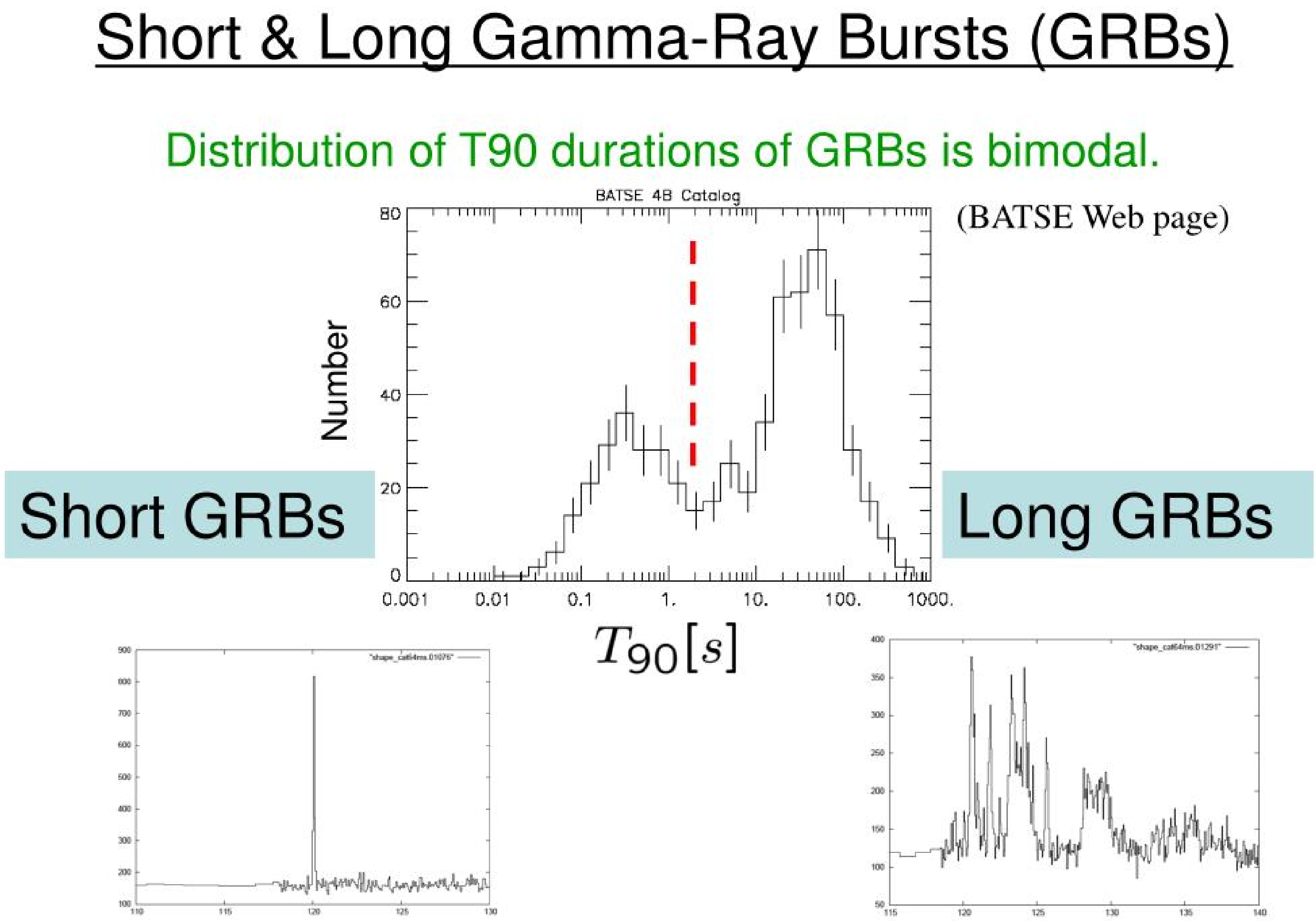
The break-through was due to much better spatial resolution of X-rays. The X-ray detection immediately pointed towards the host galaxy, and the optical observations revealed the exact redshift of the burst host galaxy (z = 0.695).



From a review of Bloom et al. (2001)

1. Short introduction to gamma-ray bursts

Currently we know that gamma-ray bursts are of two types, and come from two different phenomena, both happening at cosmological distances.



Short & Long Gamma-Ray Bursts (GRBs)

Distribution of T90 durations of GRBs is bimodal.

(BATSE Web page)

Short GRBs

Long GRBs

- **Short gamma-ray bursts**

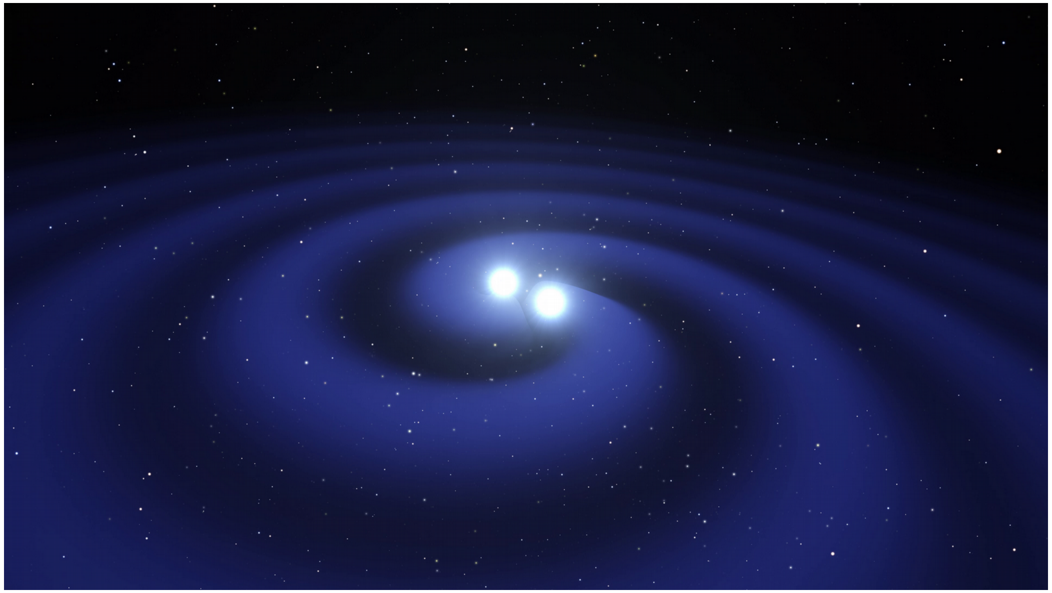
  - last generally less than 2 seconds
  - appear in all types of hosts
  - observed as **kilonova** event (much lower total energy)
  - physically are caused by coalescence of two neutron stars or a a neutron star and a stellar mass black hole
  - detected also in gravitational waves (GW170817)

- **Long gamma-ray bursts**

  - last generally more than 2 seconds
  - appear in late type hosts
  - observed as hypernova event (much higher total energy)
  - physically are caused by the collaps of a massive star finishing its nuclear fuel

1. Short introduction to gamma-ray bursts

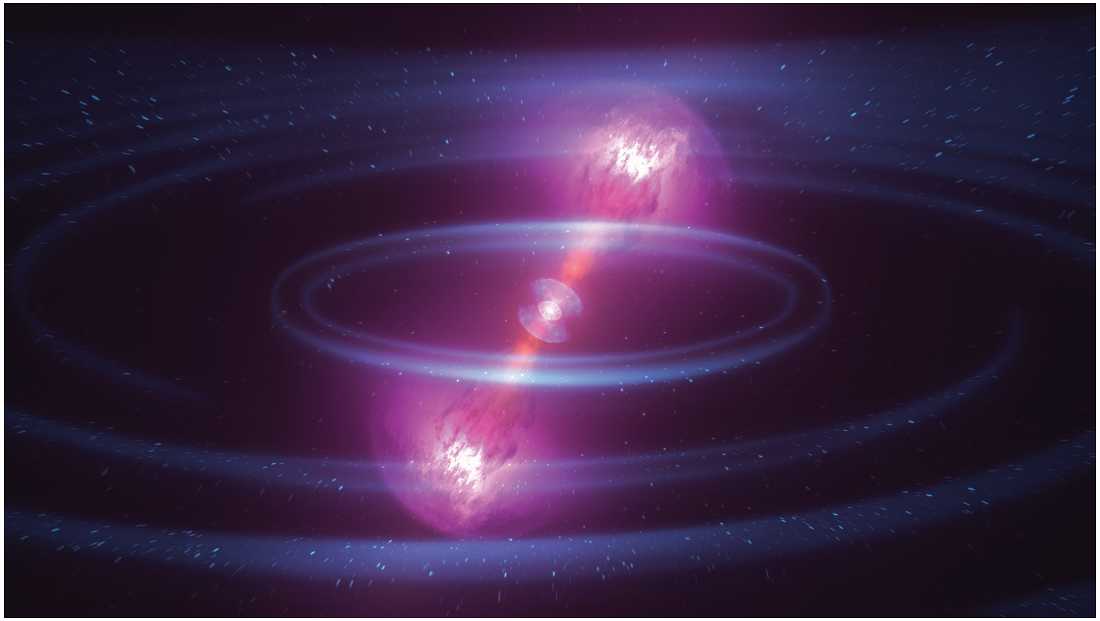
The stages: (i) inspiralling, with emission of gravitational waves
(ii) coalescence, jet apperance, formation of a black hole



ESA

Images are just illustration, numerical GR allows to perform computations of the process, observations done in GW and electromagnetic signal.

- **Short gamma-ray bursts**



https://www.simonsfoundation.org/report2017/stories/center-for-computational-astrophysics-neutron-star-mergers/

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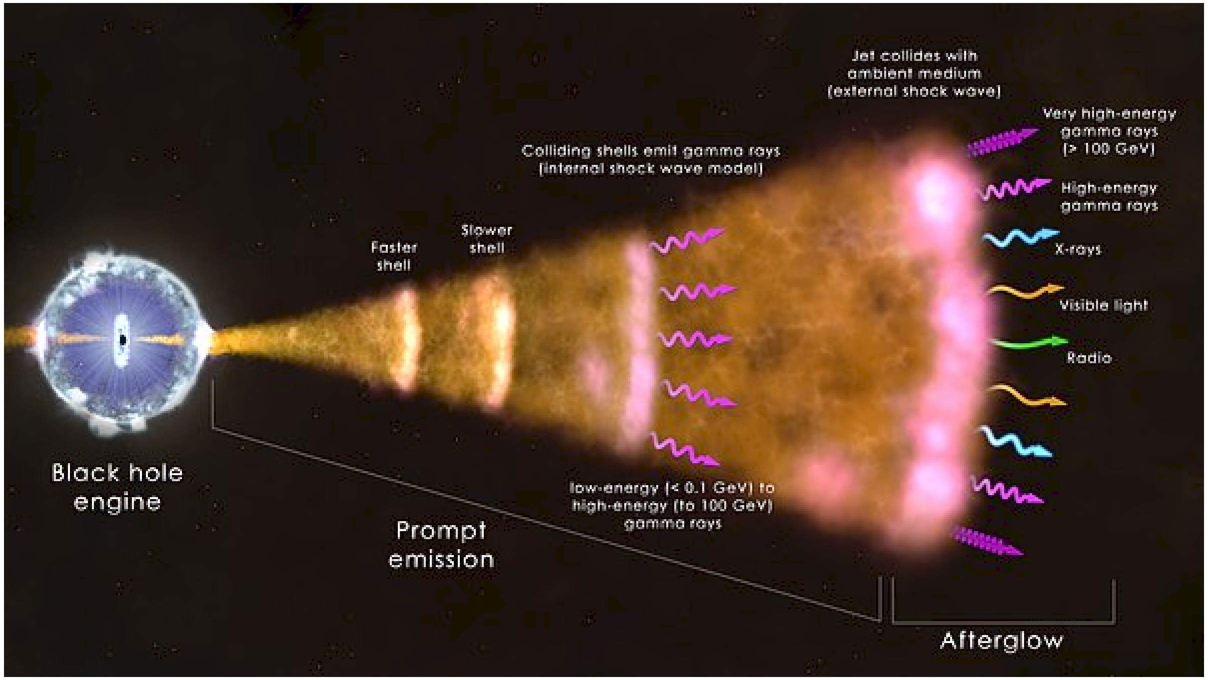
1. Short introduction to gamma-ray bursts

Long gamma-ray bursts are the most luminous single sources of energy in the Universe: accretion onto a newly formed low mass black hole is about 0.1 Ms/s, Eddington ratios 10^{13}, isotropic luminosity 10^{52} erg/s.

Stages: (i) colapse of the stellar core due to the loss of nuclear power
(ii) formation of a central black hole and surrounding accretion disks
(iii) ejection of the envelope



wikipedia

- **Long gamma-ray bursts**

- last generally more than 2 seconds
- appear in late type hosts
- observed as hypernova event (much higher total energy)
- physically are caused by the collaps of a massive star finishing its nuclear fuel

Jet has to drill a hole through the stellar material

Accretion disks cool through neutrino emission.

Not all supernovae lead to gamma-ray bursts. Lower metallicity required? No jet? Wrong jet orientation?

2. Jets in nature: how we identify the presence of the jet?

Jets are the most spectacular phenomena related to accretion and they frequently determine the object appearance. They can be ultra-relativistic (gamma-ray bursts), and they extend at distances orders of magnitude larger than the size of the central black hole. Jets in some AGN are well resolved since they can form structures much larger than the host galaxy. Nevertheless, the exact mechanism leading to jet formation and the jet content are still under discussion. In this lecture we will concentrate mostly on relativistic jets.

Artistic image of a gamma-ray burst; Credit: NASA, ESA and M. Kornmesser

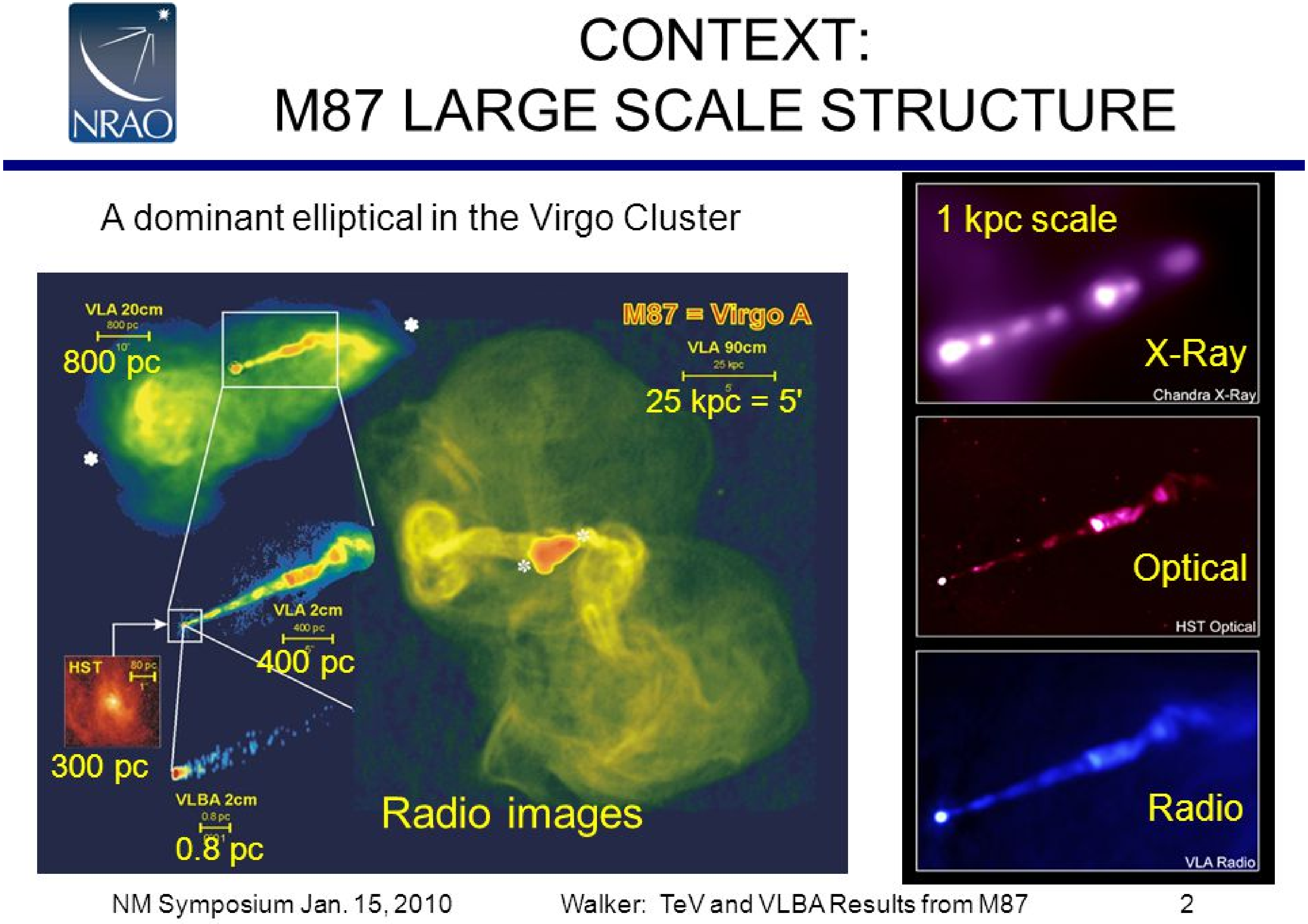
How we identify the presence of the jet?

- Directly from the map
- Indirectly from the map (motion of ejected blobs)
- Variability timescales, spectral time evolution, estimates of the Doppler boosting

1. How we identify the presence of the jet?

- Directly from the map

Black holes in active galactic nuclei are the largest ones from the point of view of the angular resolution (vide M87 seen with EHT). Thus jets are well resolved in the case of many AGN.



CONTEXT:
M87 LARGE SCALE STRUCTURE

A dominant elliptical in the Virgo Cluster

NM Symposium Jan. 15, 2010 Walker: TeV and VLBA Results from M87 2

M87 is actually a very nice example of the large scale radio emission as well as collimated jet emission in radio, optical and X-ray band. (synchrotron !).

Extended lobes are powered by the jet carrying the energy from the direct vicinity of a black hole.

2. How we identify the presence of the jet?

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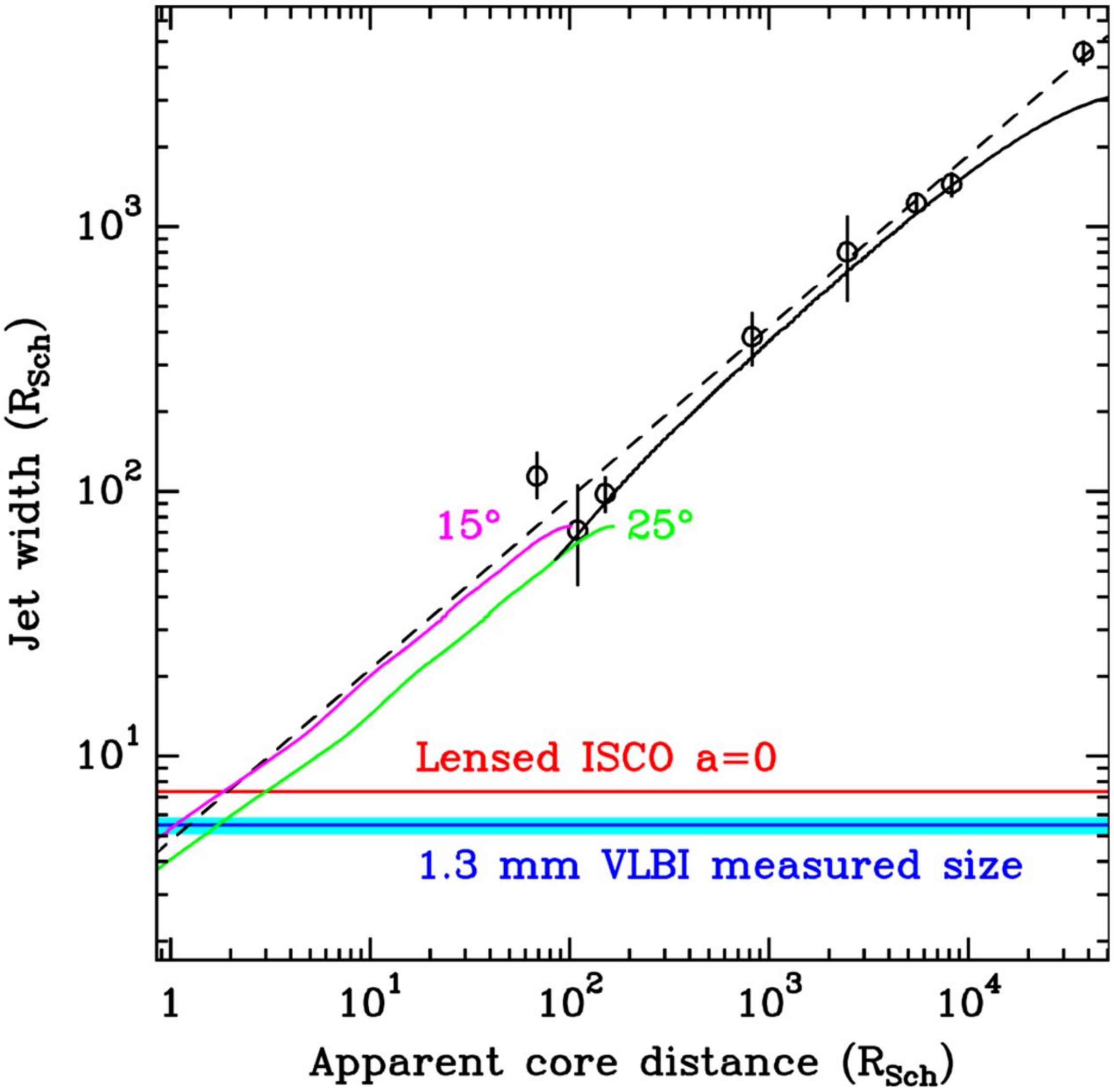


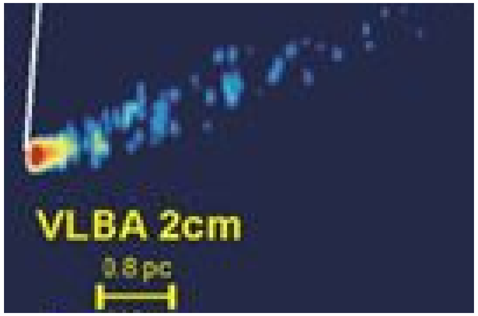
Jet size in M87 from Doeleman et al. (2012)

Jet collimation is slow, partially because it is measured in projection, but also it physically progresses slowly:

Here

width ~ $(\text{distance})^{0.69}$

So the jet width becomes relatively narrower with the distance. It is well collimated at a distance of 10 000 R_{Schw} from the central black hole (i.e. at 1 pc).



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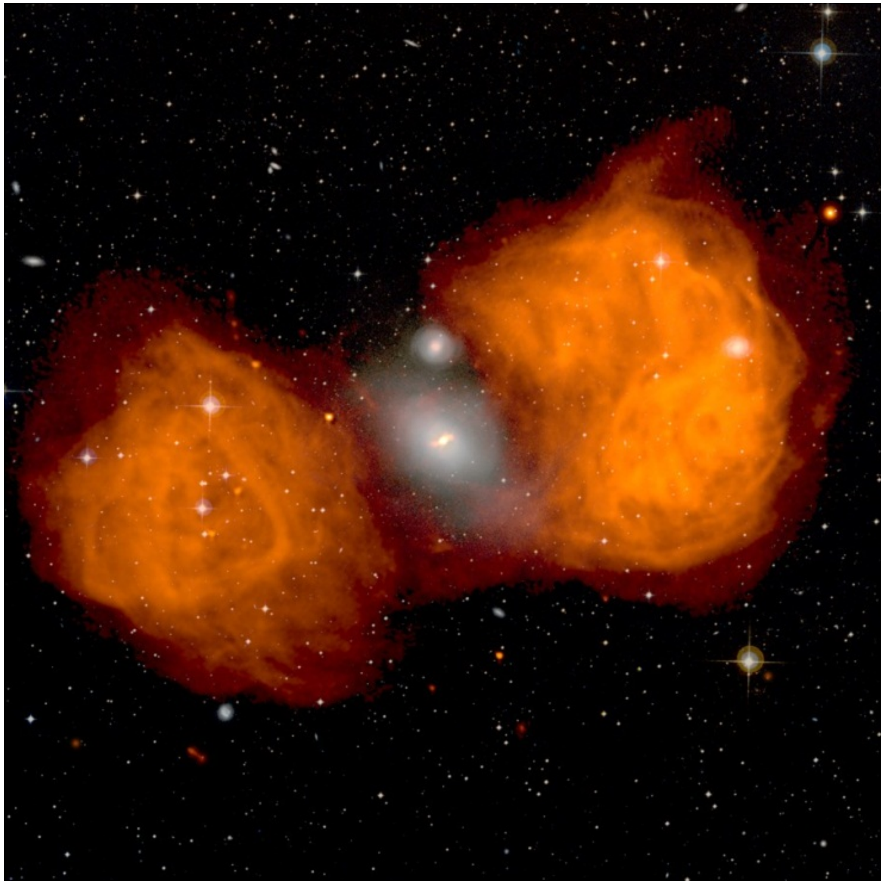
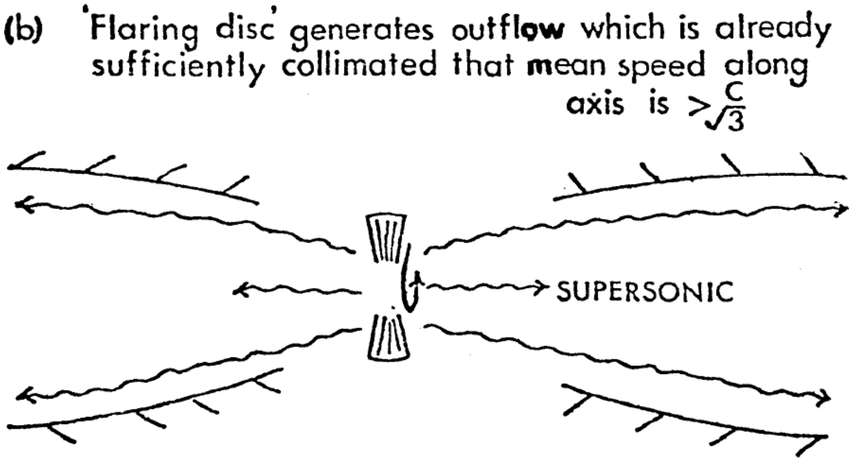


The Giant Radio Lobes of Fornax A. The orange lobes are clouds of gas which give off radio emission. Credit: Ed Fomalont (NRAO) et al., VLA, NRAO, AUI, NSF.

When first radio-galaxies were discovered after the II World War, the resolution of the maps was low, and we could see only extended blobs, occasionally much larger than the galaxy. The energy contect and synchrotron cooling rate required continuous supply of power, and jets were proposed.



Plot from Rees (1976).

The issue was cleared at the end of 70' when extended, well collimated radio jets started to be discovered.

2. How we identify the presence of the jet?

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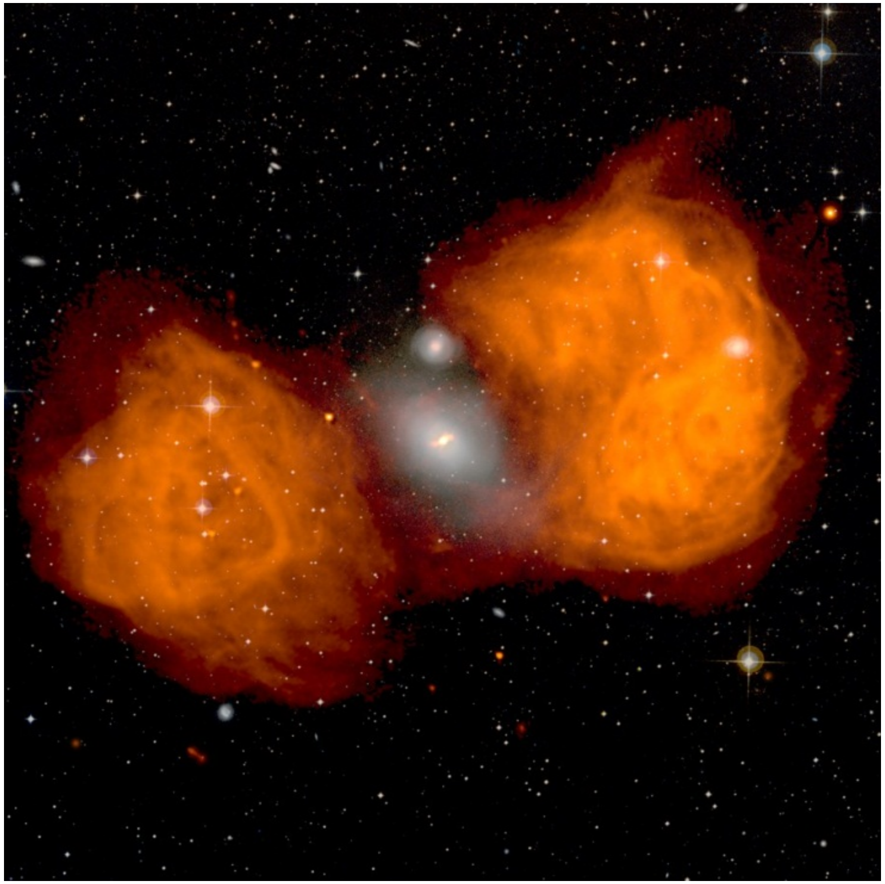

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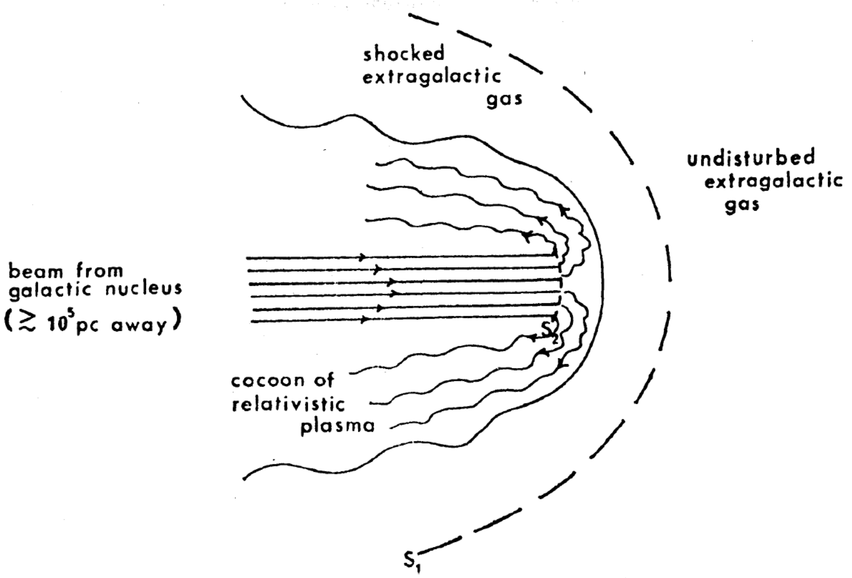


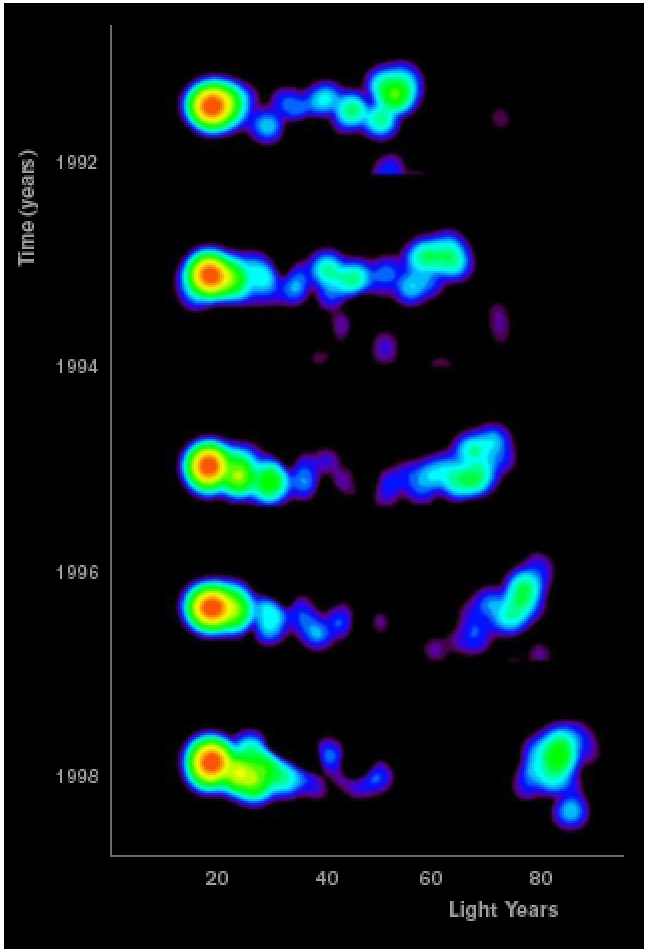
Plot from Rees (1976) – formation of the jet head.

The issue was cleared at the end of 70' when extended, well collimated radio jets started to be discovered.

2. How we identify the presence of the jet?

- Indirectly from the map (motion of ejected blobs)

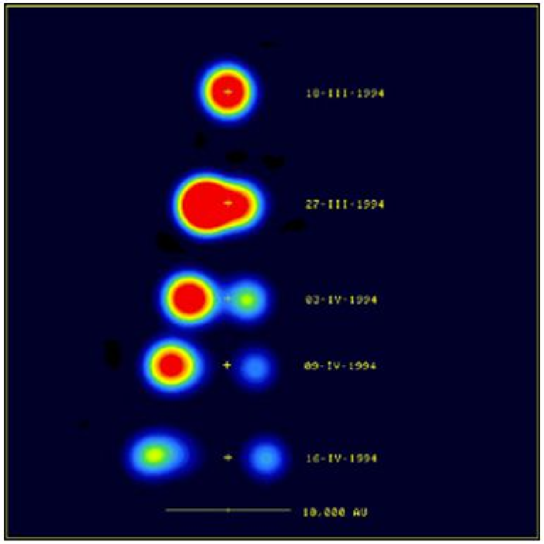
Jets do not always look stationary, at some objects (higher Eddington ratio) they look more like subjequent blob ejections in the same direction.



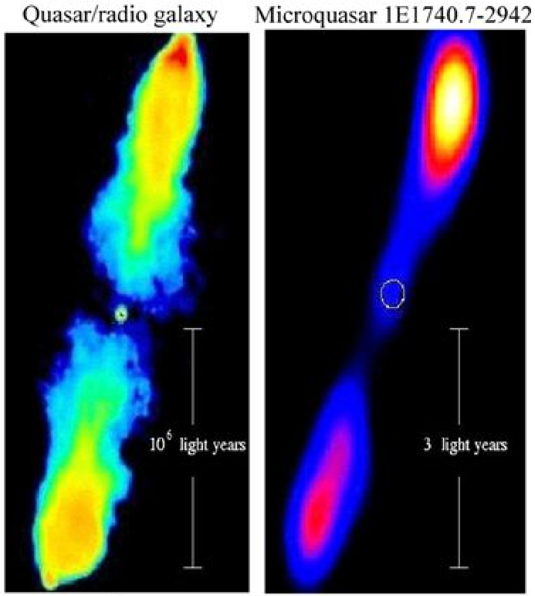
Super-luminal motion of the blobs in the jet of the blazar 3C 279 (http://discordancy.report/3c-279-and-3c-273/)

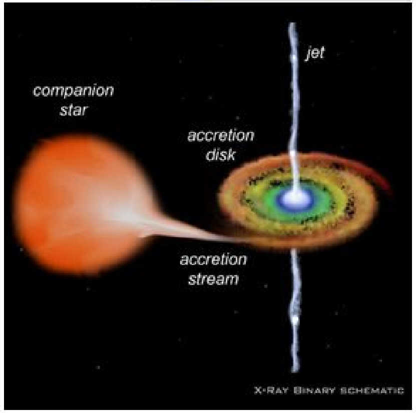
Relativistic Jets in Microquasars

Observed in radio



Superluminal motion in microquasar GRS 1915+105; V_{app} =1.5c



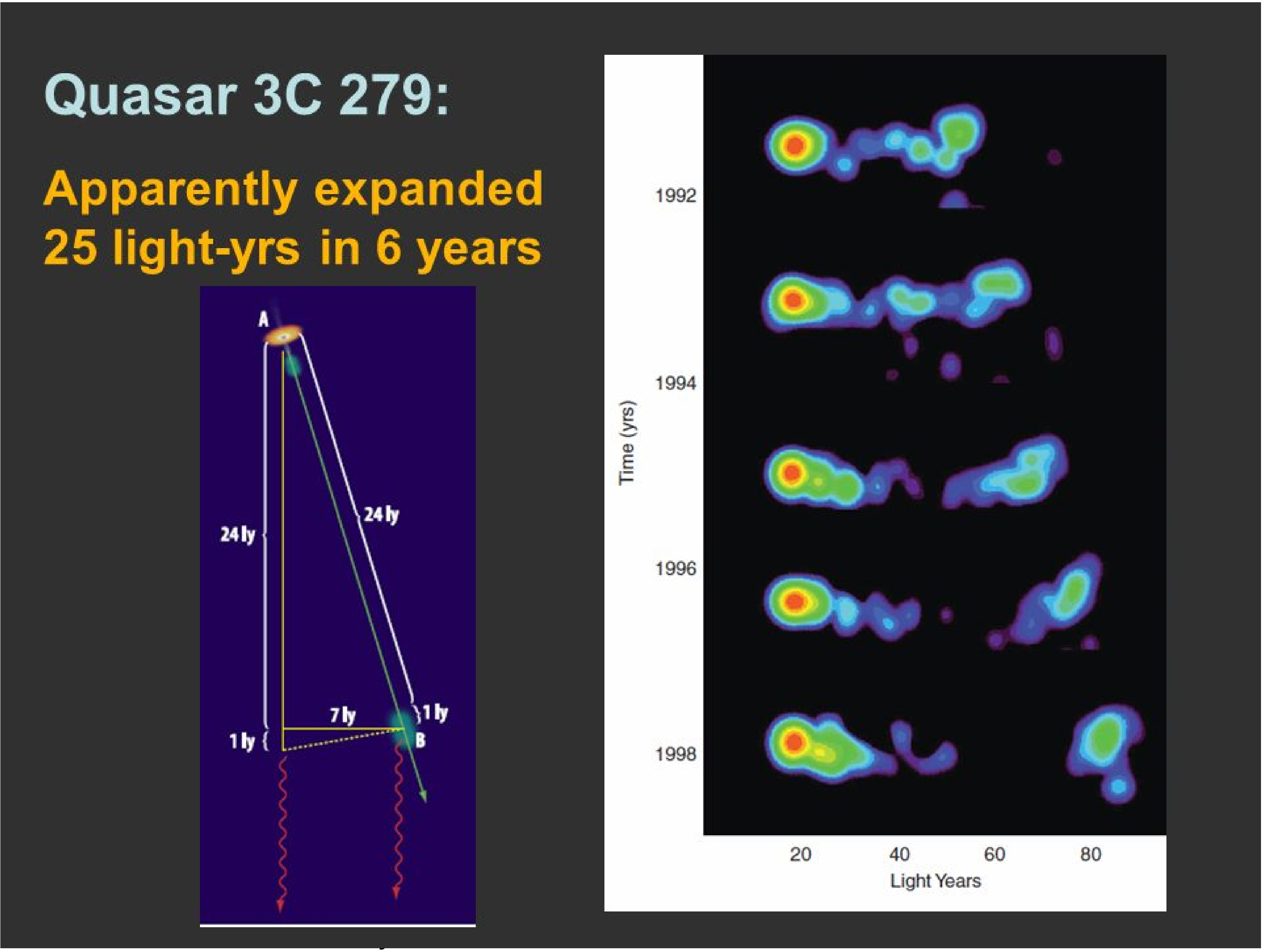


Microquasar is a scaled down (by a factor of 10^6) version of active galactic nuclei

From presentation of Yosuke Mizuno

2. How we identify the presence of the jet?

- Indirectly from the map (motion of ejected blobs)



Quasar 3C 279:

Apparently expanded 25 light-yrs in 6 years

Super-lumina
3C 279 and its explanation from Mitch Begelman's course.

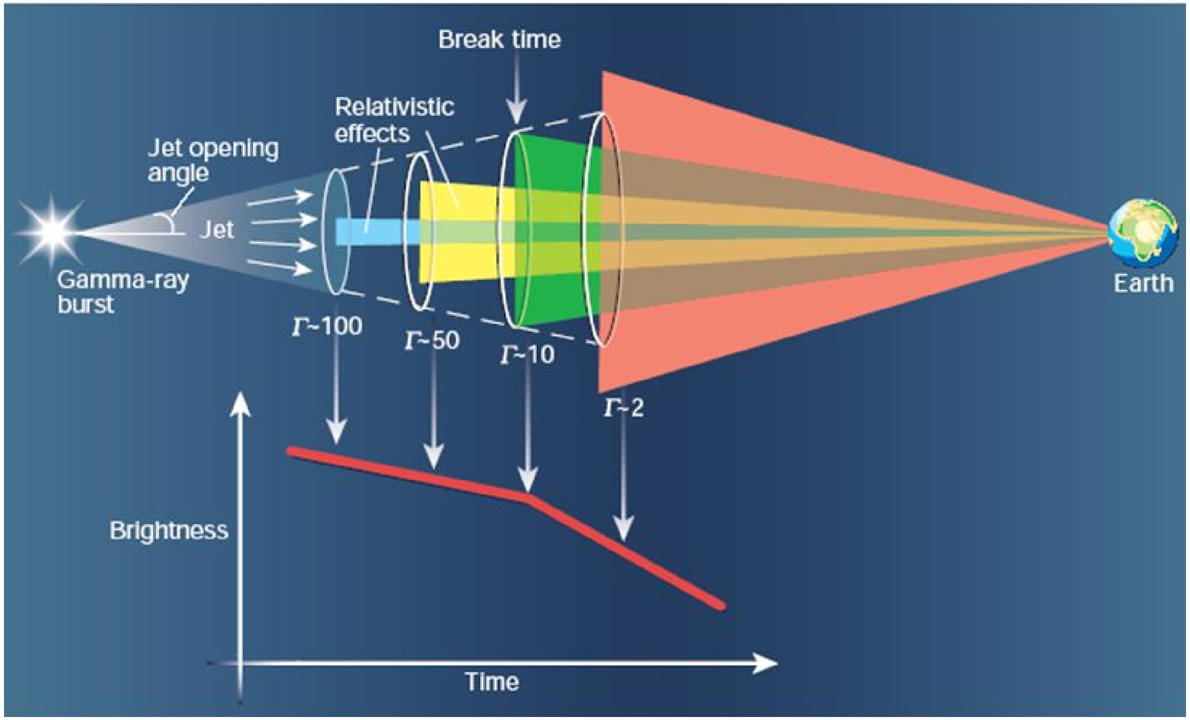
2. How we identify the presence of the jet?

- Indirectly from variability, spectra ….

In the case of gamma-ray bursts the prompt emission is spatially unresolved. The approximate angular width of the jet (that is, the degree of spread of the beam) can be estimated directly by observing the achromatic "jet breaks" in afterglow light curves: a time after which the slowly decaying afterglow begins to fade rapidly as the jet slows and can no longer beam its radiation as effectively.

Observations suggest significant variation in the jet angle from between 2 and 20 degrees (wiki).

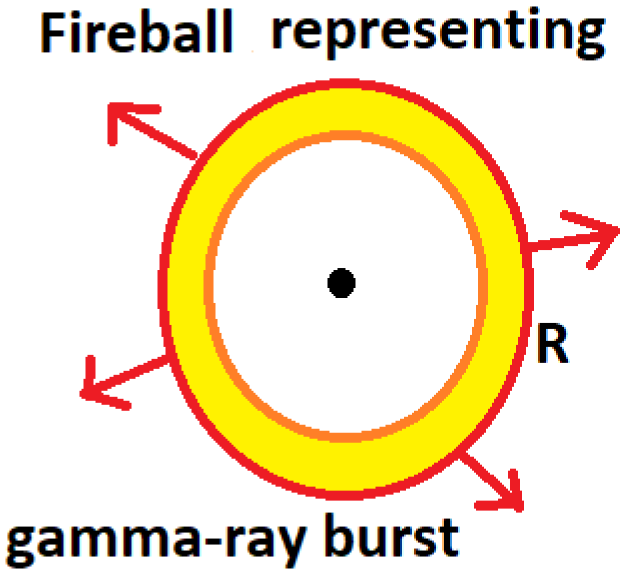
Opening angle and light curve break



From presentation of Shuang-Nan Zhang (2008)

3. Measurement of the Doppler factor of the jet

In the case of gamma-ray bursts, we do not see the jet, but rough estimates of the Doppler factor of the fireball explosion were immediately done at the basis of their energetics (e.g. Piran 1999).



Since the luminosity is enormous, and emission seen in hard gamma-rays the immediate danger to the engine is rapid electron-positron pair creation.
The optical depth for the photon collision in a shell is

$$\tau_{\gamma\gamma} = \frac{\sigma_T N}{4\pi R^2}$$

Here N is the total number of photons, R is the radius. The radius can be estimated from the minimum variability timescale of τ of 10 ms ($R < \tau c = 3000$ km), the number of photons from the total energy E divided by $m_e c^2$, and the total energy E from the observed energy and the known distance.

If we compute $\tau_{\gamma\gamma}$ this way we will get the value which is orders of magnitude larger than 1. On the other hand, spectra of gamma-ray bursts have power law shape implying optically thin emission, i.e. $\tau_{\gamma\gamma} << 1$.

Thus the procedure has to be modified. If we instead postulate that the fireball expands with relativistic speed we have an additional factor there (see Piran 1999)

$$\tau_{\gamma\gamma} \approx \frac{10^{13}}{\gamma^{(4+2\alpha)}} f_p \left(\frac{F}{10^{-7}\mathrm{ergs/cm^2}}\right) \left(\frac{D}{3000\ \mathrm{Mpc}}\right)^2 \left(\frac{\delta T}{10\ \mathrm{msec}}\right)^{-2} \quad (10)$$

which includes the Doppler boosting and the spectral slope. In order to get $\tau_{\gamma\gamma} << 1$ **we need γ about 100 – 1000.**

3. Measurement of the Doppler factor of the jet

In blazars, if we have radio maps of moving blobs, it is possible to estimate the viewing angle and the jet speed, although these quantities are coupled. But we have a lightcurve, it is possible to use the variability timescale for that purpose.

For example, Hovatta et al. (2009) calculated the Lorents factor in several blazars using the timescales of the flares to calculate the **brightness temperature**

$$T_{\mathrm{b,var}} = 1.548 \times 10^{-32} \frac{\Delta S_{\max} d_{\mathrm{L}}^2}{\nu^2 \tau^2 (1+z)},$$

And by comparing it to expected universal brightness temperature of 10^{11} K they got the observed Doppler factor

$$D_{\mathrm{var}} = \left[\frac{T_{\mathrm{b,var}}}{T_{\mathrm{b,int}}}\right]^{1/3}.$$

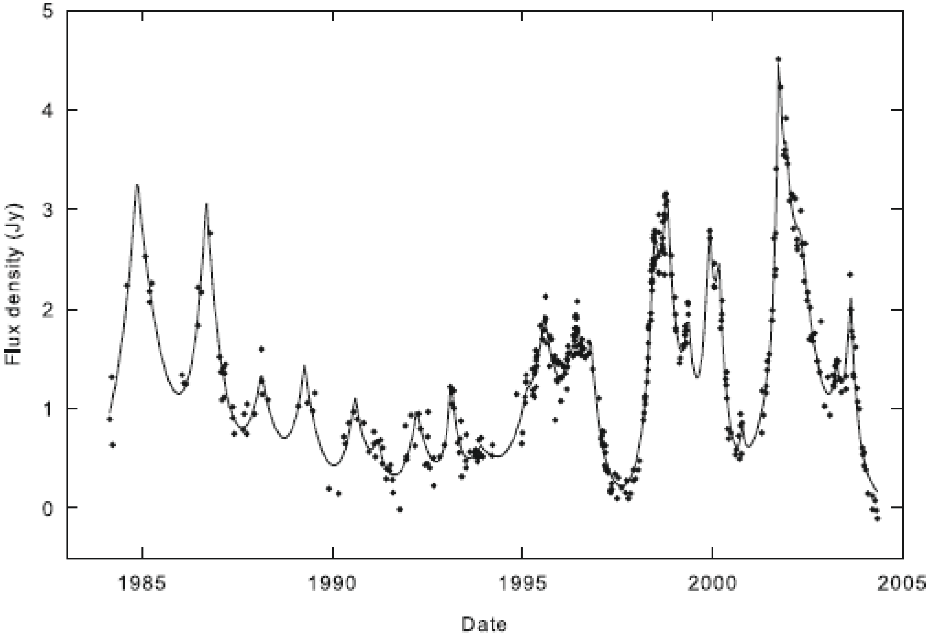


Fig. 1. Flux curve of the HPQ source 1156+295 (points) decomposed into exponential flares (solid line) at 22 GHz.

And combining it with the apparent blob velocity they obtain the intrinsic Lorents factor of the jet and the viewing angle independently:

$$\Gamma_{\mathrm{var}} = \frac{\beta_{\mathrm{app}}^2 + D_{\mathrm{var}}^2 + 1}{2D_{\mathrm{var}}}$$

$$\theta_{\mathrm{var}} = \arctan \frac{2\beta_{\mathrm{app}}}{\beta_{\mathrm{app}}^2 + D_{\mathrm{var}}^2 - 1}.$$

Such determinations are not very simple but seem to give reasonably accurate values (factor 2 ?).

4. Doppler factor of the jet in various systems - summary

Gamma-ray bursts	100	
Blazars	20	
Seyfert galaxies	1	no evidence of relativistic boosting (e.g. Lal, Shastri & Gabuzda 2011, presence of a kpc radio structure)
Microquasars	1 – 5	(Liodakis et al. 2017)
Cataclysmic variables	1	tentative marginal detection of radio from one source (Körding et al. 2011)
Tidal Disruption Events	2	(first detection: Swift J164449.3+573451, Zauderer et al. 2011)
Young Stellar Objects	1	(typically 100 to 1000 km/s, Anglada et al. 2018)
Ultraluminous X-ray sources (ULX)	1	(v = 0.2c in Holmberg II X-1, Cseh et al. 2014)

Doppler factor Γ = 2 corresponds to the velocity of about 0.9 c.

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

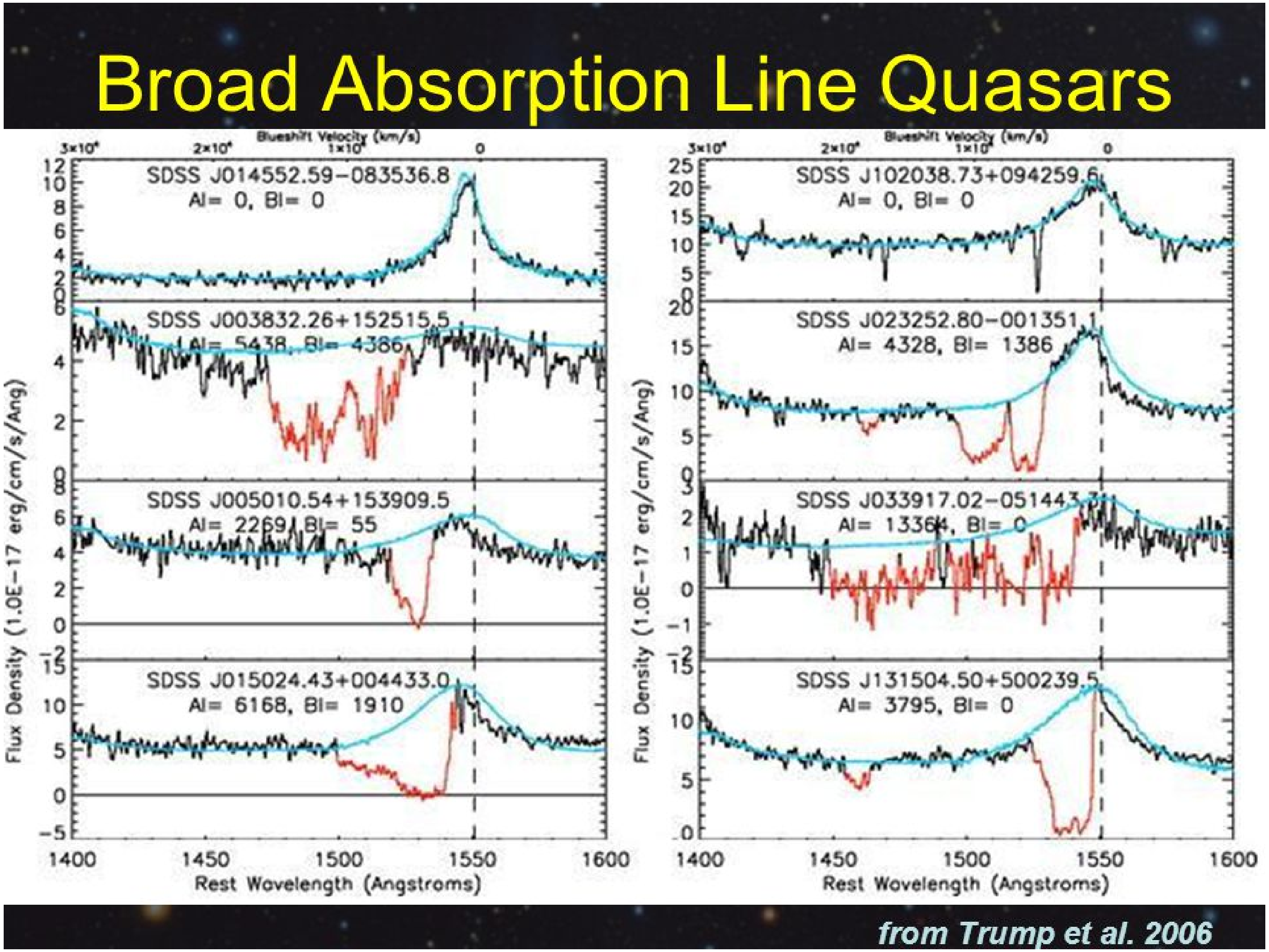
Sources which do not contain black holes do not produce relativistic jets.

Sources containing black holes may (or may not) produce relativistic jets.

5. Jet acceleration – what cannot work

It is not simple to give the eact mechanism but it is clear that relativistic jets cannot be accelerated by radiation.

Winds in AGN can be accelerated by radiation – Broad Absorption Line (**BAL**) features indicate that the wind is accelerated by radiation pressure through line absorption. The maximum velocities are up to several times 10^4 km/s.

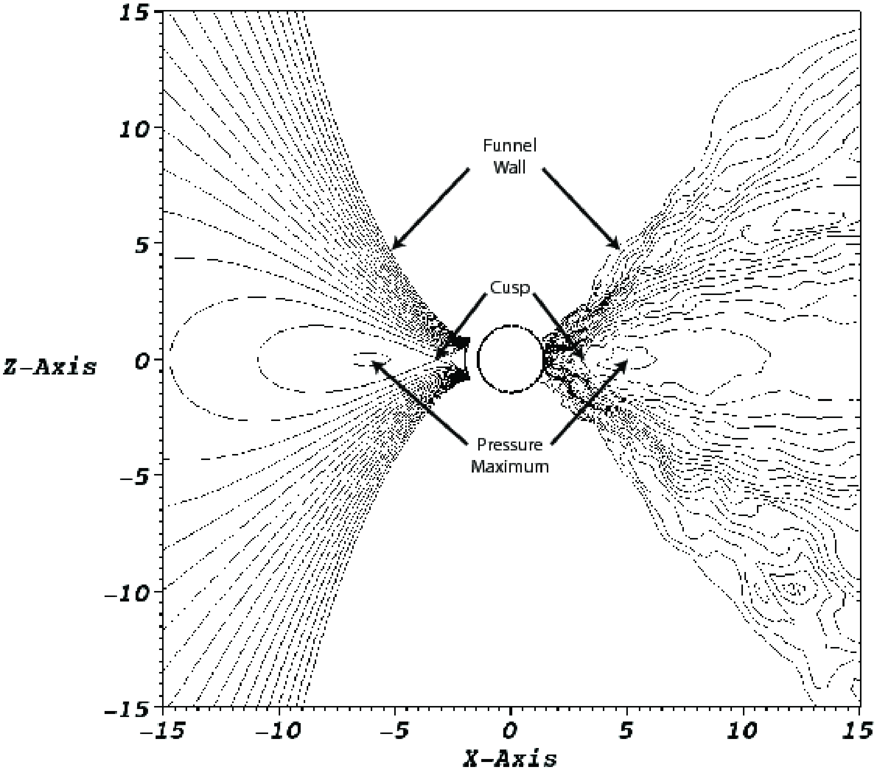

Broad Absorption Line Quasars

from Trump et al. 2006

This is still a small fraction of the light speed (0.1 c), so this is not a relativistic outflow.

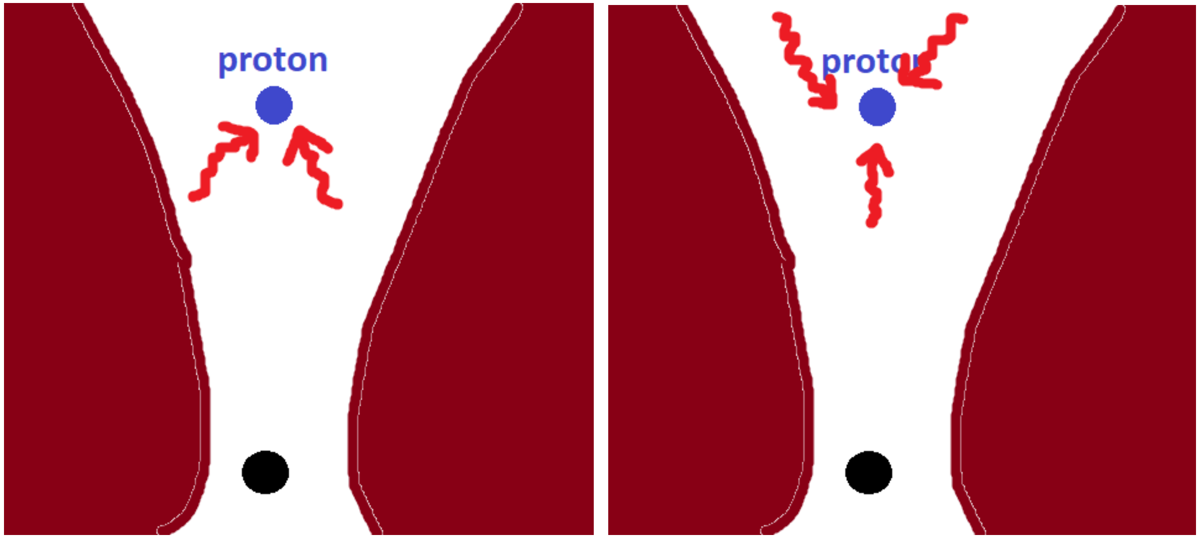
5. Jet acceleration – what cannot work

It is not simple to give the eact mechanism but it is clear that relativistic jets cannot be accelerated by radiation. In the late 70ties, in Warsaw Paczyński & co. Developed a theory of thick disks – Polish donuts.



From Lei, Abramowicz et al. (2008)

Sikora & Wilson (1981) considered a photon and particle acceleration in the radiation field of a Polish Donut. The conclusion was that the maximum speed for a proton is 0.4 c only, and for pure pair plasma higher, corresponding to Γ = 3. Not more. The explanation:



Observer sees the photons as arriving from the bottom but if the proton moves relativistically, due to the ligh aberration it sees photon as comming from the top thus decelerating it instead of accelerating.

So radiative acceleration mechanism of relativistic jet is ruled out.

6. Jet acceleration – what can work

Two main ideas remain. Both require the presence of the accretion flow and large scale magnetic field. But they work differently.

Blandford – Payne (1982)

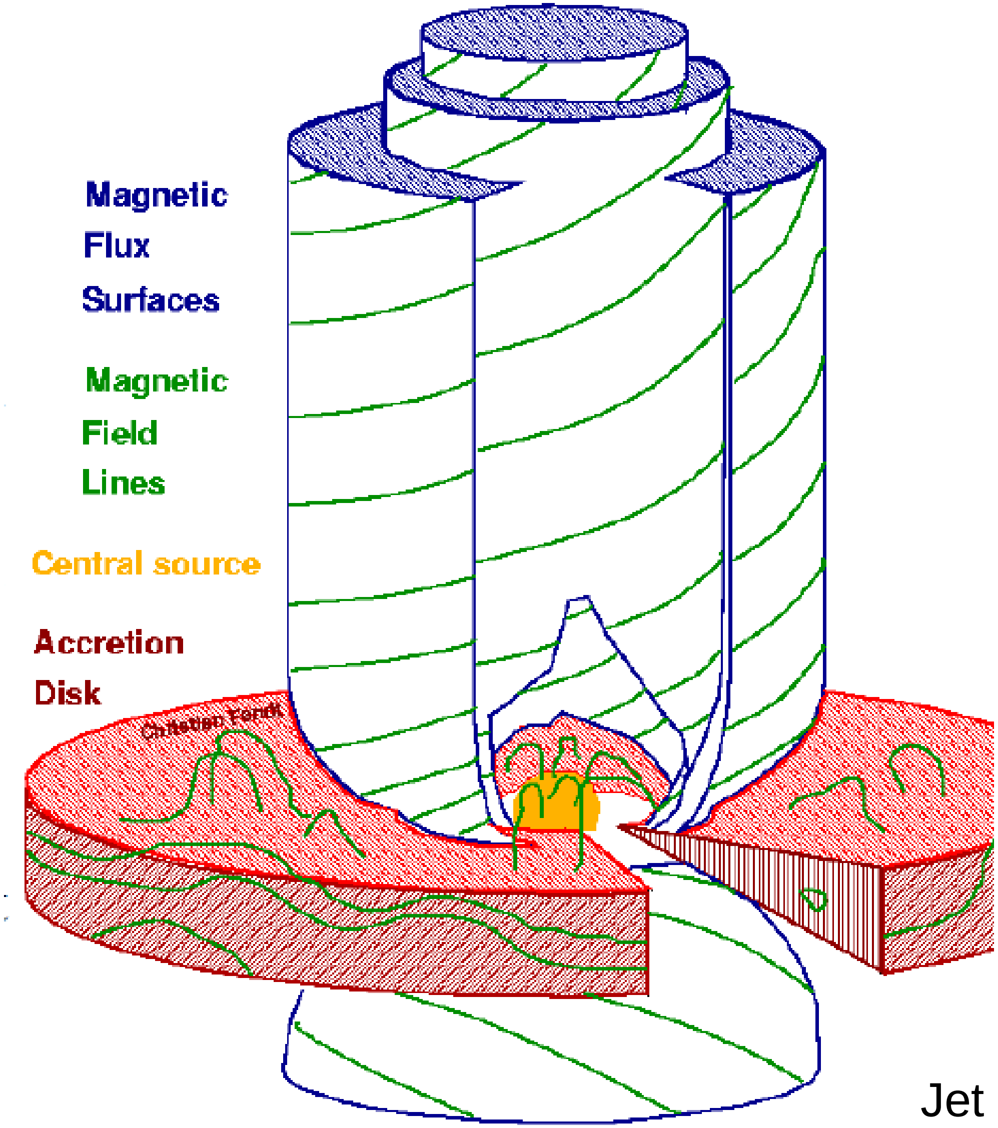
cited: 2782

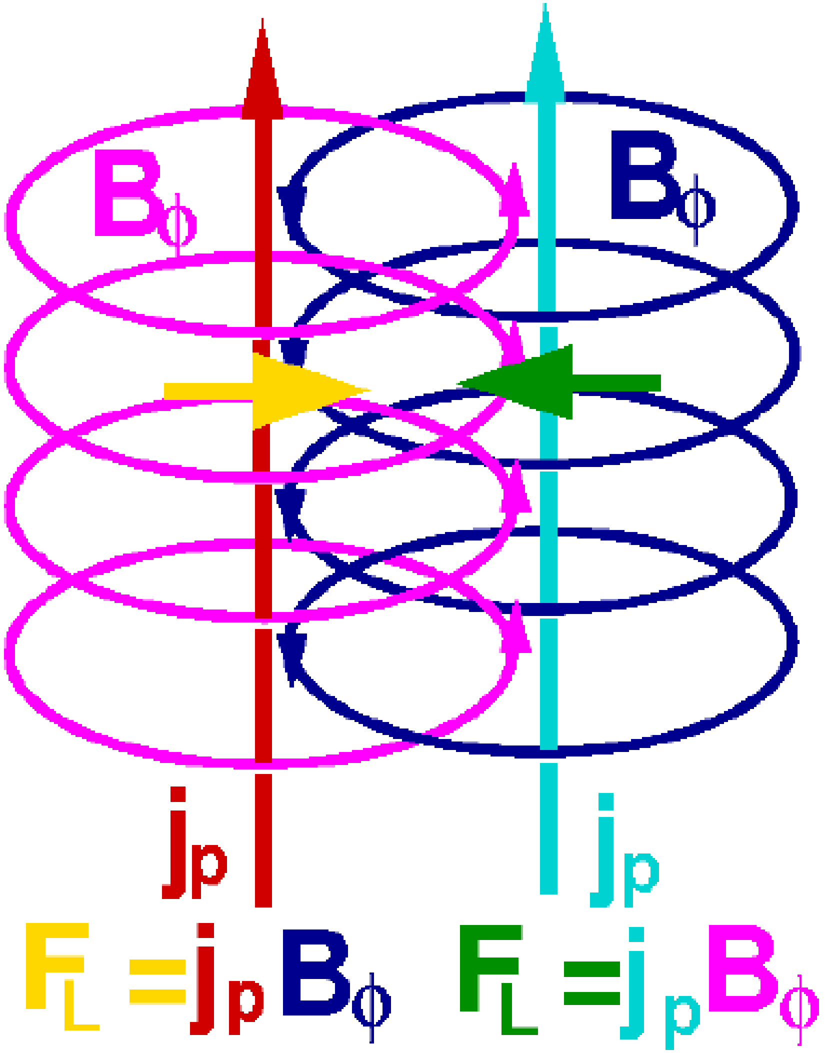
Blandford – Znajek (1977)

cited: 2951

6. Jet acceleration: Blanford & Payne 1982

The mechanism of Blanford & Payne (1982) requires the presence of the large scale magnetic field component.





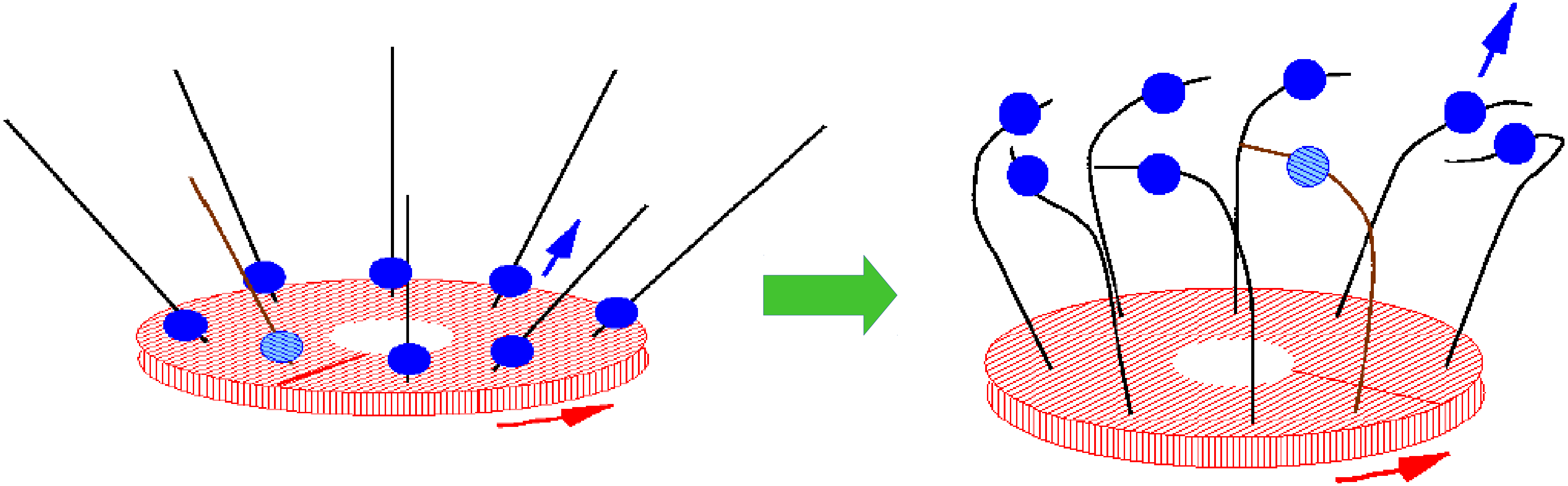
From Christian Fendt's lecture

Jet is like a bundle of wires, carrying electric current, they attract each other which provides a collimation mechanism.

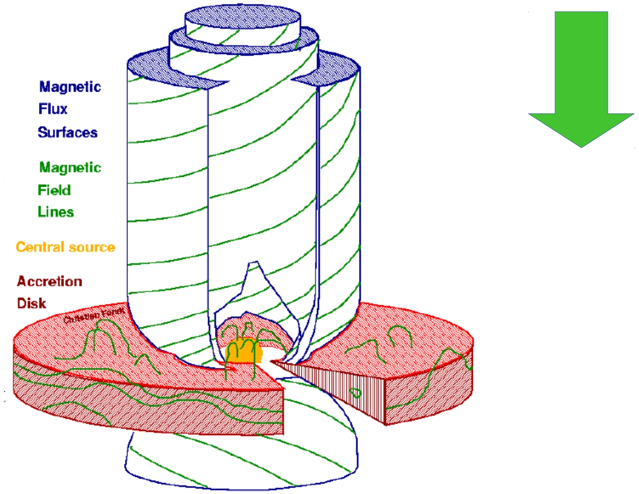
6. Jet acceleration: Blanford & Payne 1982

Jet formation proceeds in the following way:

- Magnetic field lines are frozen into the accretion disk and corotate with it
- If they are initially highly inclined they lead to formation of centrifugally diven wind
- If they are less inclined, then the field lines lead to acceleration of material and ejection
- Poloidal field leads to formation of the toroidal field
- Toroidal filed provides the jet confinement; requires net electric current

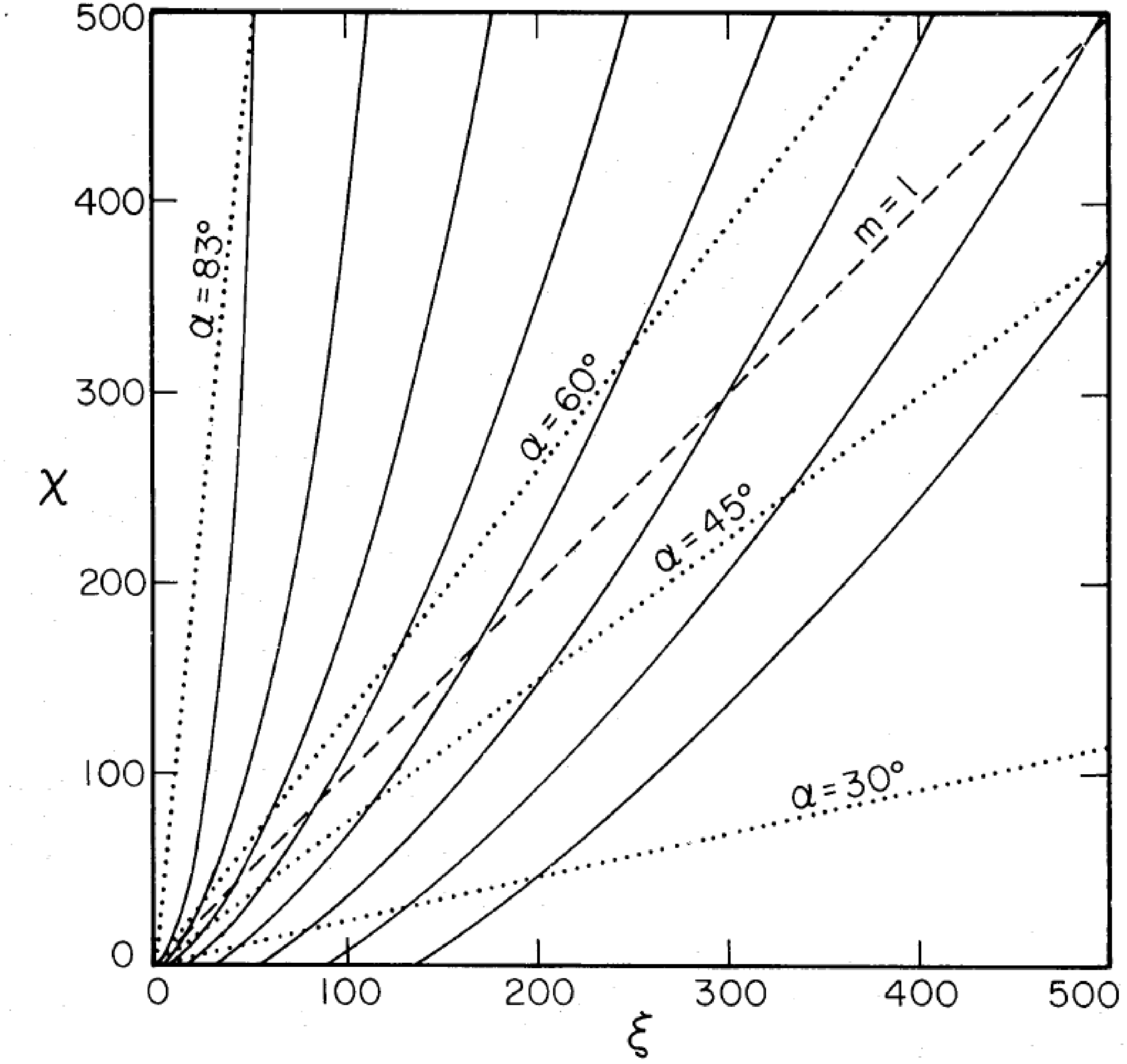


Blanford & Payne (1982) derived self-similar solution for the final setup which describes both the wind and the jet part.



6. Jet acceleration: Blanford & Payne 1982

The characteristic property of the flow is that the lines curve up, unlike in radiatively accelerated disk winds.



‘standard’ solution $\kappa = 0.03$, $\lambda = 30$.

$$\lambda \equiv \frac{l}{(GMr_0)^{1/2}}$$

$$\kappa \equiv k\,(1 + \xi_0'^2)^{1/2}\,\frac{(GM/r_0)^{1/2}}{B_0},$$

Here l is the specific angular momentum, and κ measures the magnetic field strength.

The underlying assumptions: self-similar behaviour, and

$$B(r, \phi, 0) \propto r^{-5/4}$$

6. Jet acceleration: Blanford & Znajek 1977

This mechanism is based on etirely different concept.

Non-rotating black hole cannot decrease its mass, according to GR. Hawking radiation is possible, and a black hole evaporation but (i) it is certainly negligible for massive black holes (works for black holes smaller than 10^{14} g) (ii) it is not clear whether it works at all.

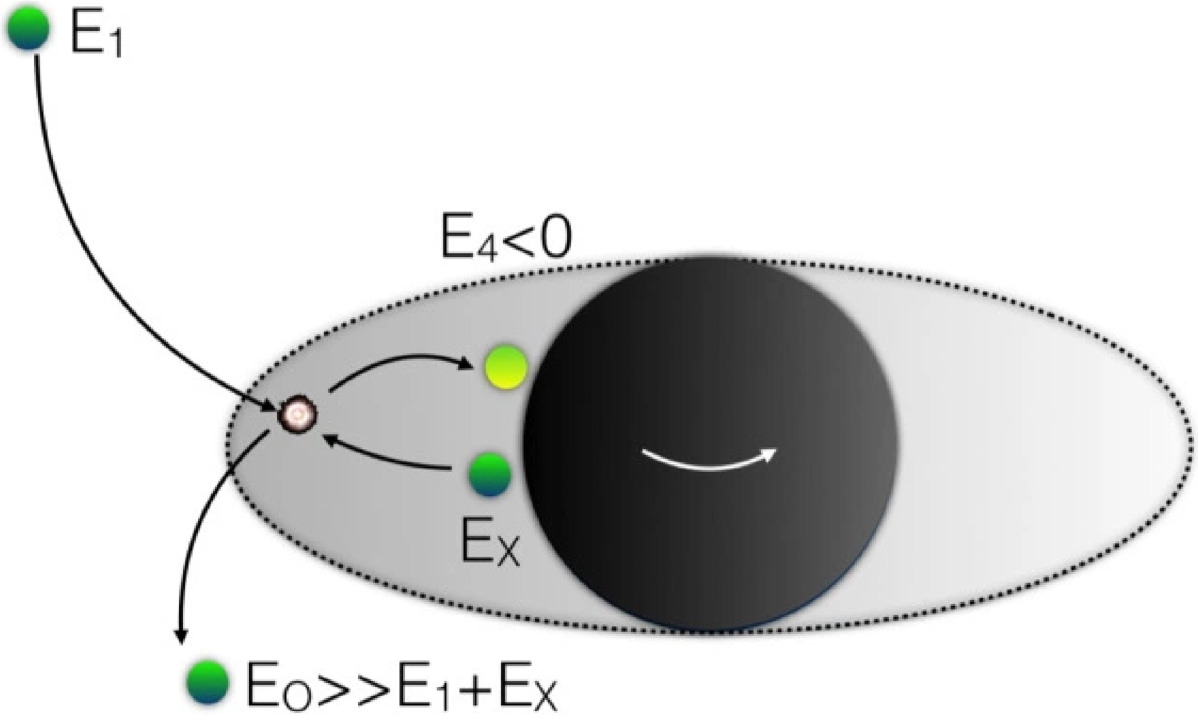
Rotating black hole has some part of energy in the form of rotation; this rotational energy can be extracted.

Rotational energy:	0	$a = 0$ (non-rotating black hole)
	$0.29Mc^2$	$a = 1$ (maximally rotating black hole)

Exemplary process of energy extraction: Penrose processes

- decay of a particle in the ergosphere
- collision of particles in the ergoshere

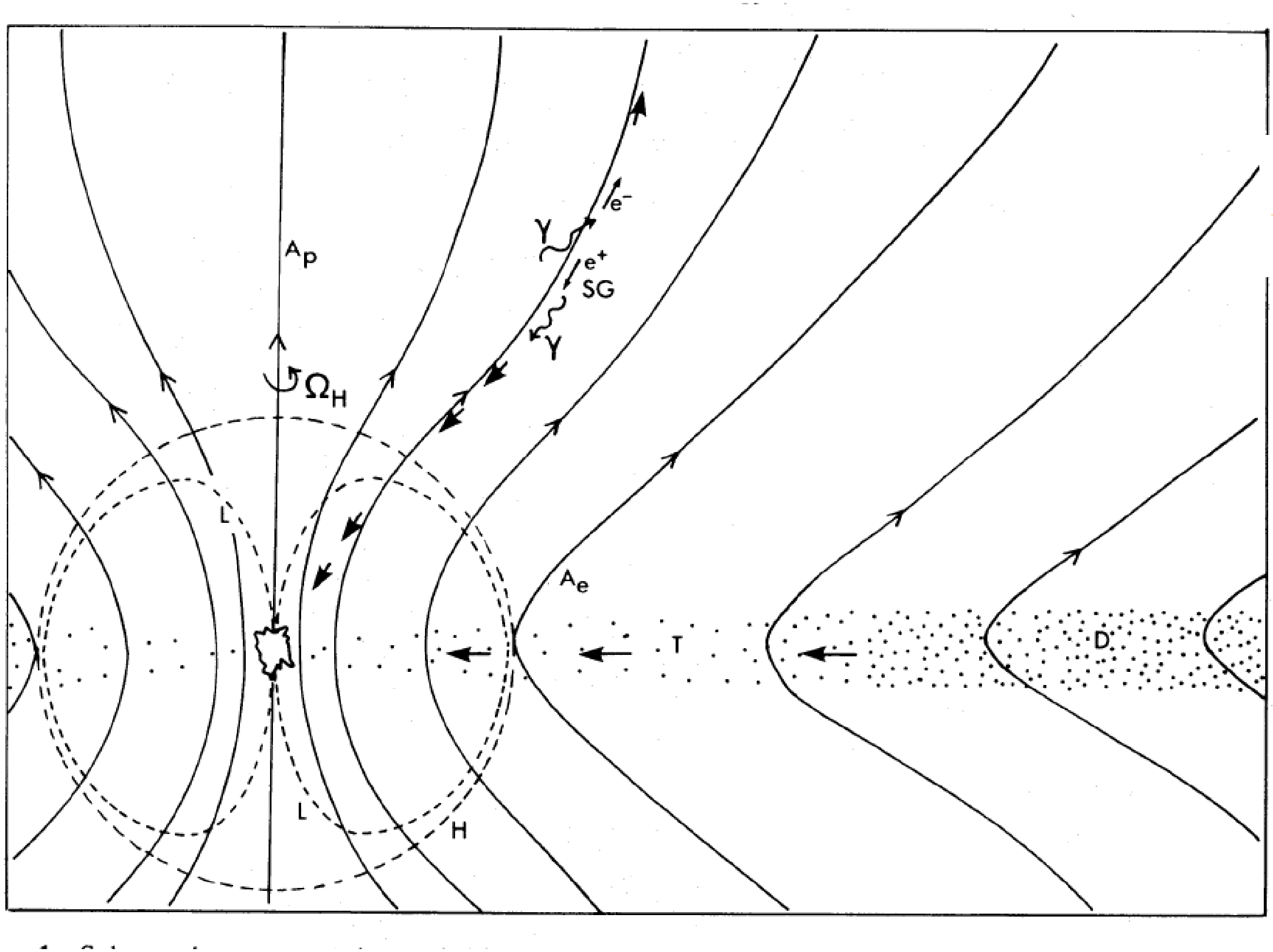
The final infalling particle can have very large negative energy, and the outgoing one carries away excess energy. This slows down the black hole.



Example from https://arxiv.org/abs/1510.06764

6. Jet acceleration: Blanford & Znajek 1977

In Blanford & Znajek (1977) instead of a Penrose process the external magnetic field from the accretion disk is used, and this extrenal magnetic field present in the black hole ergoshere extracts the angular momentum and the rotational energy from the black hole.



Here the magnetic field lines are passing through the horizon. On the next plot the geometry is modified, but the mechanism still works.

The possible gain in the luminosity is

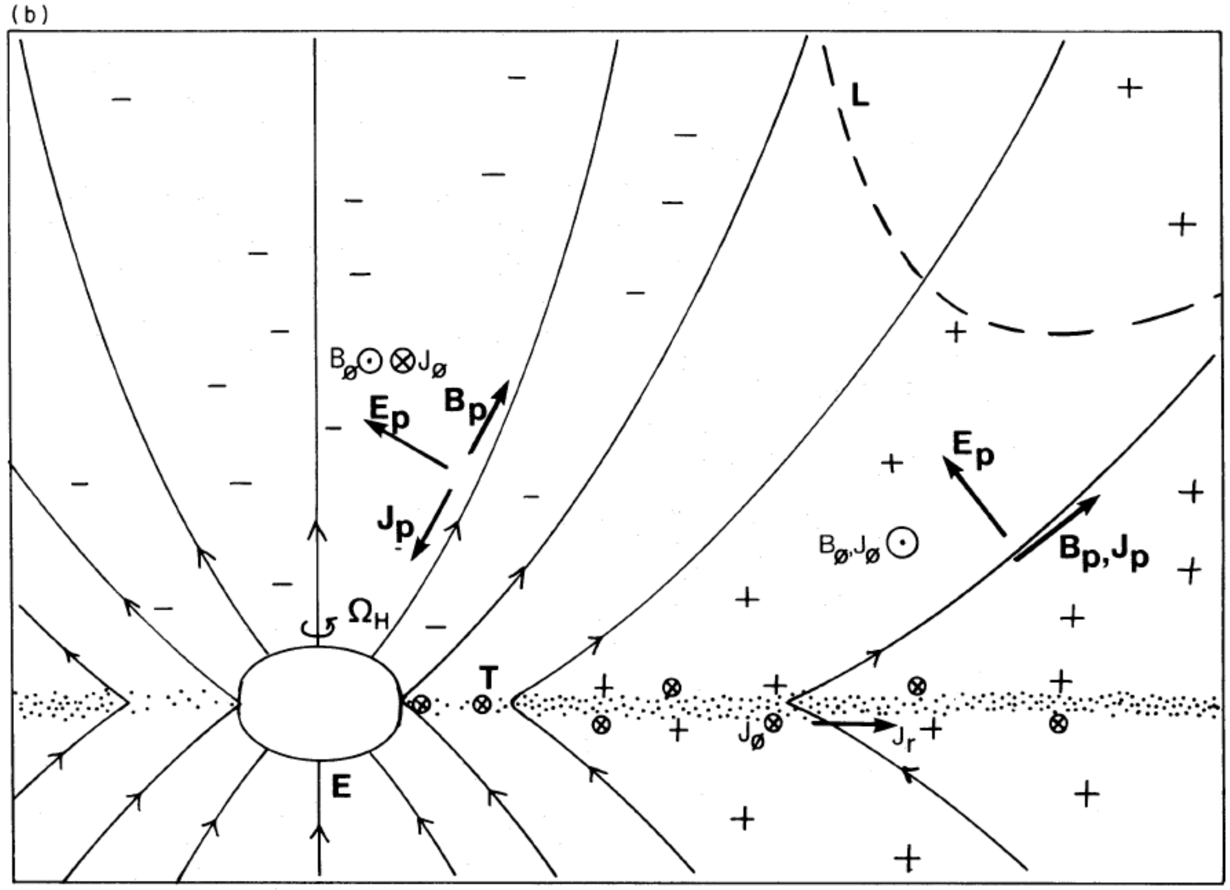
$$L_{BZ} = \frac{1}{32}\frac{\Omega_F(\Omega_H - \Omega_F)}{\Omega_H^2} B_H^2 r_H^2 a^2 c,$$

Here r_H is the black hole horizon radius, Ω_F and Ω_H the angular velocities, and B_H is the magnetic field at the horizon (see e.g. Das & Czerny 2011).

Important property of the mechanism is the strong dependence on the black hole spin, a.

6. Jet acceleration: Blanford & Znajek 1977

In Blanford & Znajek (1977) instead of a Penrose process the external magnetic field from the accretion disk is used, and this extrenal magnetic field present in the black hole ergoshere extracts the angular momentum and the rotational energy from the black hole.



The possible gain in the luminosity is

$$L_{BZ} = \frac{1}{32}\frac{\Omega_F(\Omega_H - \Omega_F)}{\Omega_H^2} B_H^2 r_H^2 a^2 c,$$

Here r_H is the black hole horizon radius, Ω_F and Ω_H the angular velocities, and B_H is the magnetic field at the horizon (see e.g. Das & Czerny 2011).

Here the magnetic field lines are not passing through the horizon but they are discontinuus. In ideal MHD, with no matter, this is still uncorrect as far as I understand it.

Important property of the mechanism is the strong dependence on the black hole spin, a.

6. Jet acceleration: Blanford & Znajek 1977

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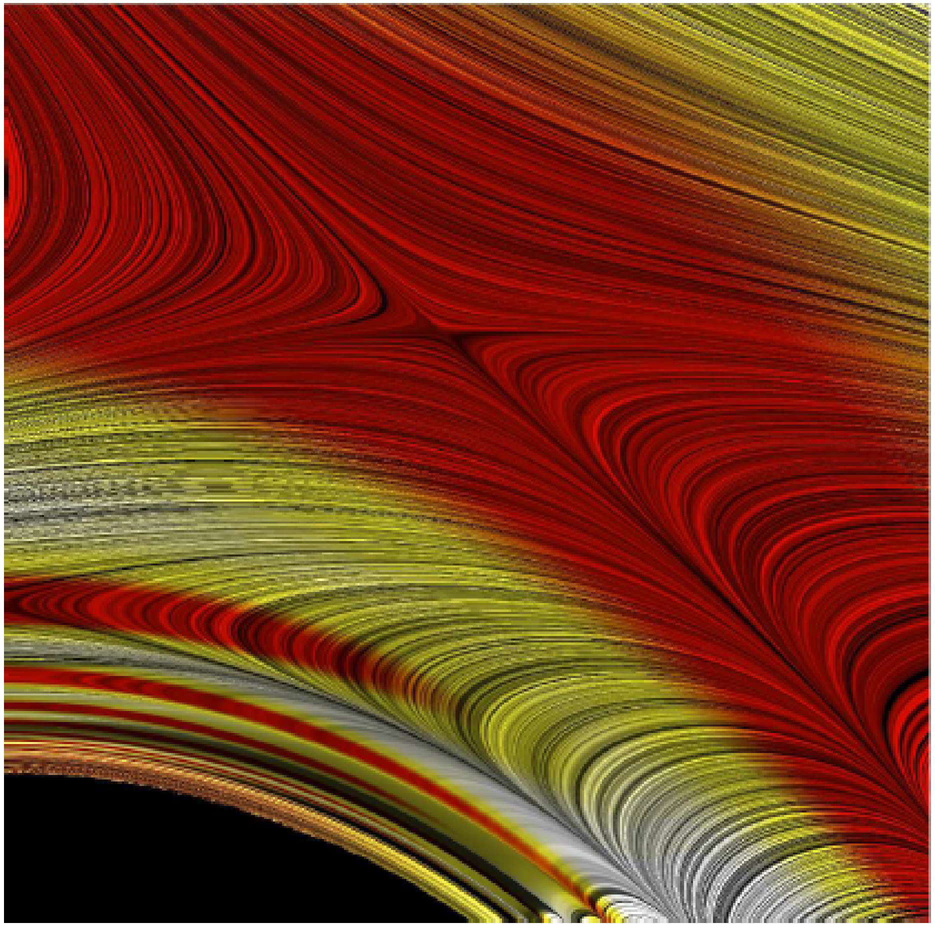


At least for the maximally rotating black hole, the magnetic field is expelled due to the analog of the Meissner effect. Here cross-section of the solution in the equatorial plane for a = 1 (Karas et al. 2011).

The possible gain in the luminosity is

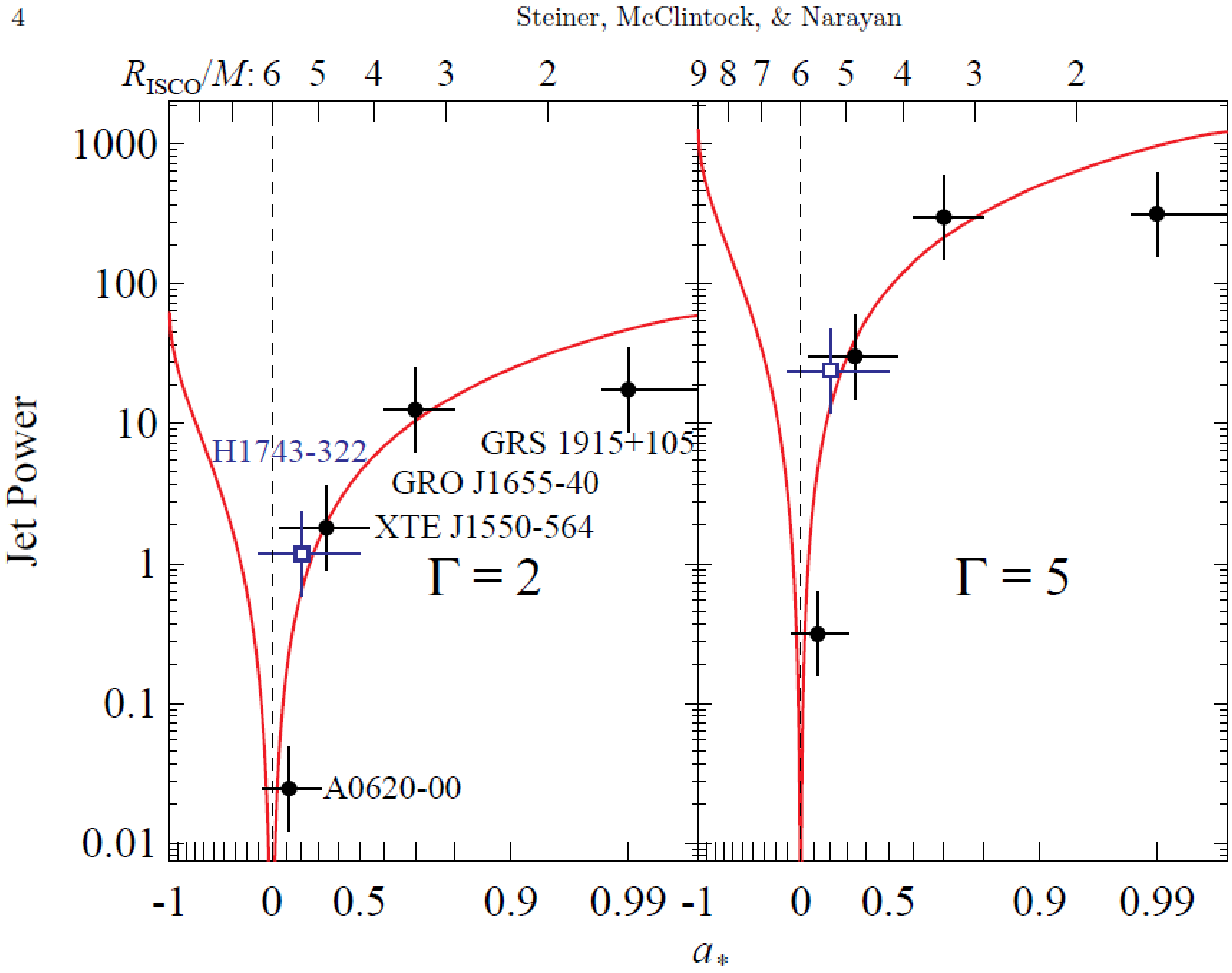
$$L_{BZ} = \frac{1}{32}\frac{\Omega_F(\Omega_H - \Omega_F)}{\Omega_H^2} B_H^2 r_H^2 a^2 c,$$

Here r_H is the black hole horizon radius, Ω_F and Ω_H the angular velocities, and B_H is the magnetic field at the horizon (see e.g. Das & Czerny 2011).

Important property of the mechanism is the strong dependence on the black hole spin, a.

7. Jet-spin observational relation

The easiest way to distinguish between BZ and BP should be through the black hole spin determination. BZ should be very inefficient for a < 0.3 (dependence as a^2). For a few galactic sources with a measured black hole spin the jet power seems to match BZ mechanism but we actually need measurements for many blazars to supplement the conclusion since blazar jets are much more relativistic.

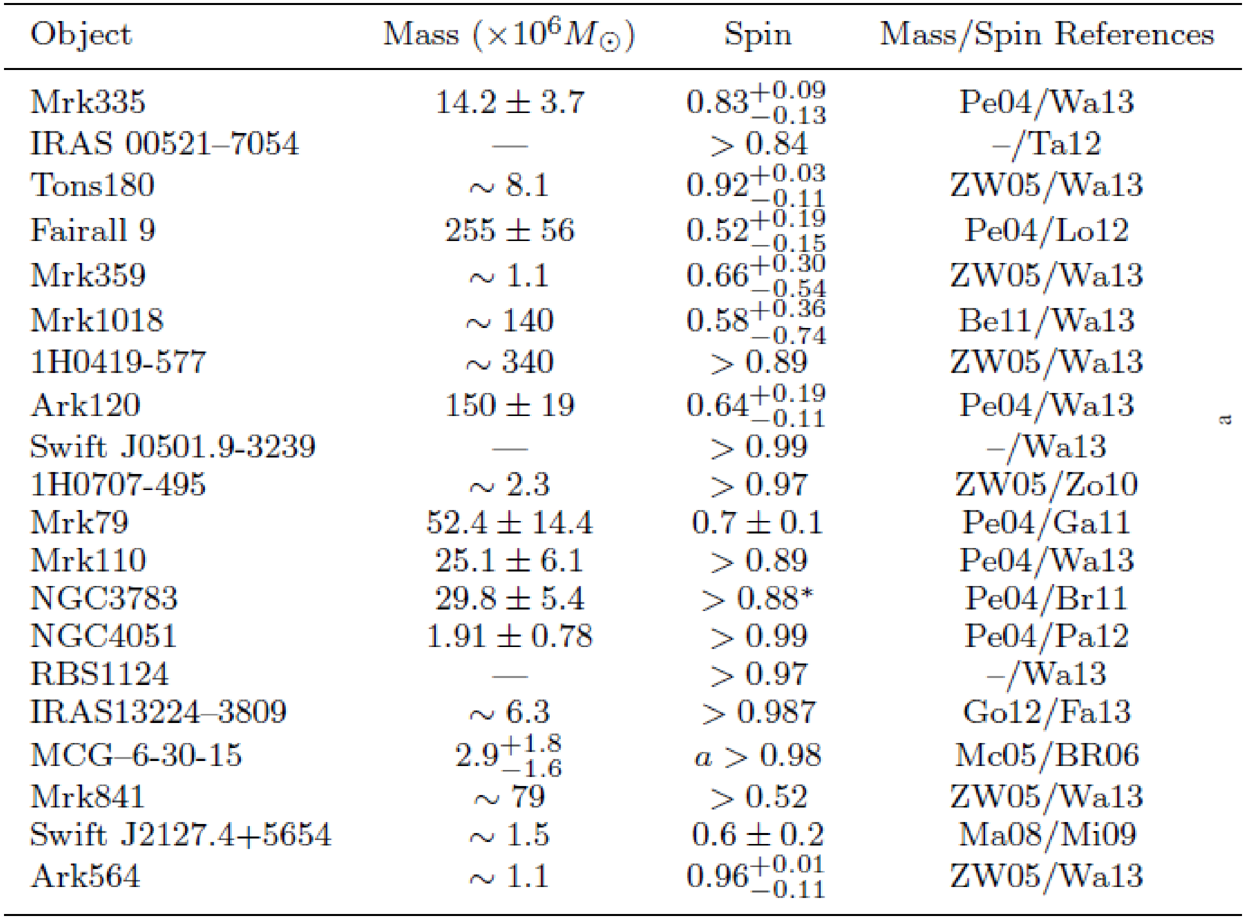


Steiner et al. (2012).

7. Jet-spin observational relation and RQ – RL dichotomy for AGN

About 10 % of AGN are classified as radio-loud and has strong jets, the remaining are radio-quiet. It is tempting to associate that with high spin-low spin division. On the other hand, the presence or absence of the jet is likely related to the large scale magnetic field dragged efficiently (or not) from the interstellar space to the nucleus (e.g. Sikora et al. 2013).

Spin measurements are done only for **radio quiet AGN**, from the shape of Kalpha iron line in X-rays. Spins are large but this is (most likely) observational bias – broader lines in brigher sources (higher efficiency of accretion) are more easy to measure.



Object	Mass ($\times 10^6 M_\odot$)	Spin	Mass/Spin References
Mrk335	14.2 ± 3.7	$0.83^{+0.09}_{-0.13}$	Pe04/Wa13
IRAS 00521–7054	—	> 0.84	–/Ta12
Tons180	~ 8.1	$0.92^{+0.03}_{-0.11}$	ZW05/Wa13
Fairall 9	255 ± 56	$0.52^{+0.19}_{-0.15}$	Pe04/Lo12
Mrk359	~ 1.1	$0.66^{+0.30}_{-0.54}$	ZW05/Wa13
Mrk1018	~ 140	$0.58^{+0.36}_{-0.74}$	Be11/Wa13
1H0419-577	~ 340	> 0.89	ZW05/Wa13
Ark120	150 ± 19	$0.64^{+0.19}_{-0.11}$	Pe04/Wa13
Swift J0501.9-3239	—	> 0.99	–/Wa13
1H0707-495	~ 2.3	> 0.97	ZW05/Zo10
Mrk79	52.4 ± 14.4	0.7 ± 0.1	Pe04/Ga11
Mrk110	25.1 ± 6.1	> 0.89	Pe04/Wa13
NGC3783	29.8 ± 5.4	$> 0.88^*$	Pe04/Br11
NGC4051	1.91 ± 0.78	> 0.99	Pe04/Pa12
RBS1124	—	> 0.97	–/Wa13
IRAS13224–3809	~ 6.3	> 0.987	Go12/Fa13
MCG–6-30-15	$2.9^{+1.8}_{-1.6}$	$a > 0.98$	Mc05/BR06
Mrk841	~ 79	> 0.52	ZW05/Wa13
Swift J2127.4+5654	~ 1.5	0.6 ± 0.2	Ma08/Mi09
Ark564	~ 1.1	$0.96^{+0.01}_{-0.11}$	ZW05/Wa13

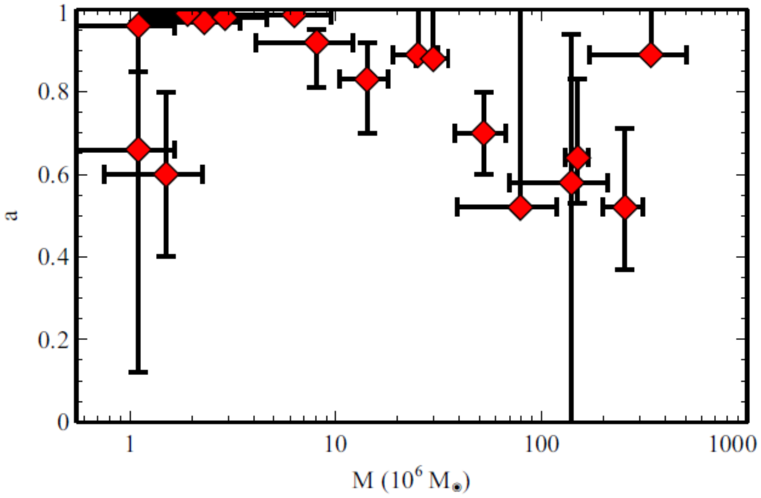


Table and plot from Reynolds (2013)

8. Jet presence - absence in X-ray novae

As we talked in lecture 9, X-ray novae go through an evolutionary cycle as a result of the ionization instability in the outer part of the disk.

The system shows the presence of the jet (either steady jet, or blobby ejections) in some of the states.

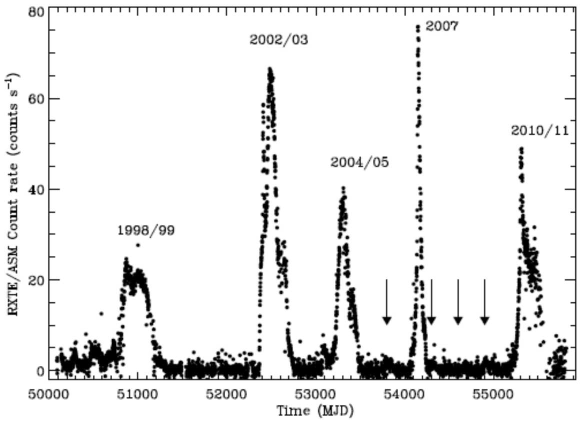
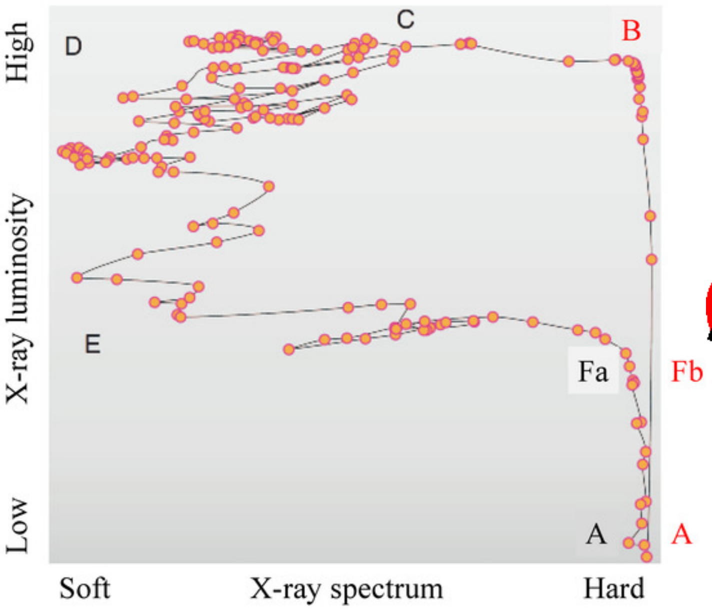
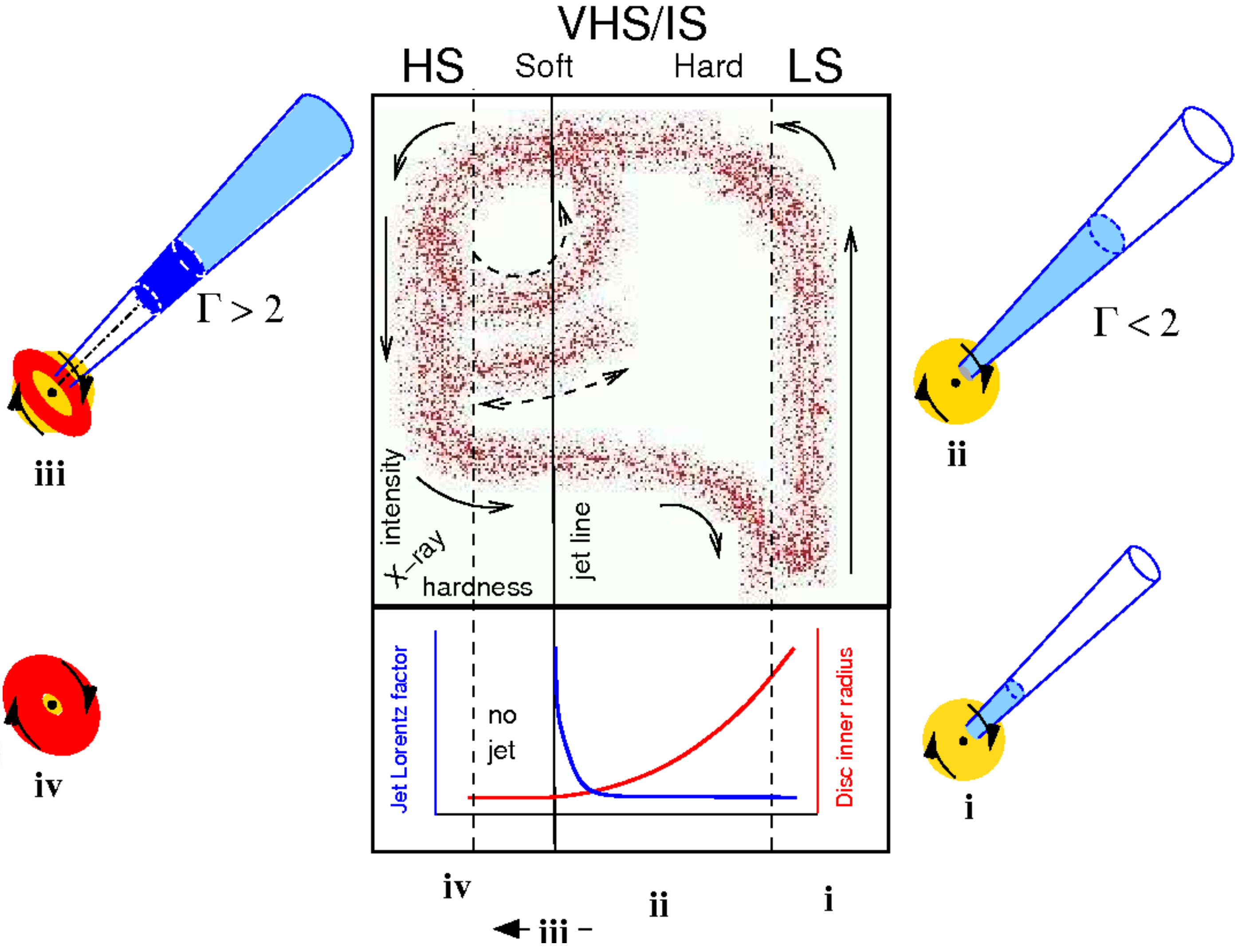


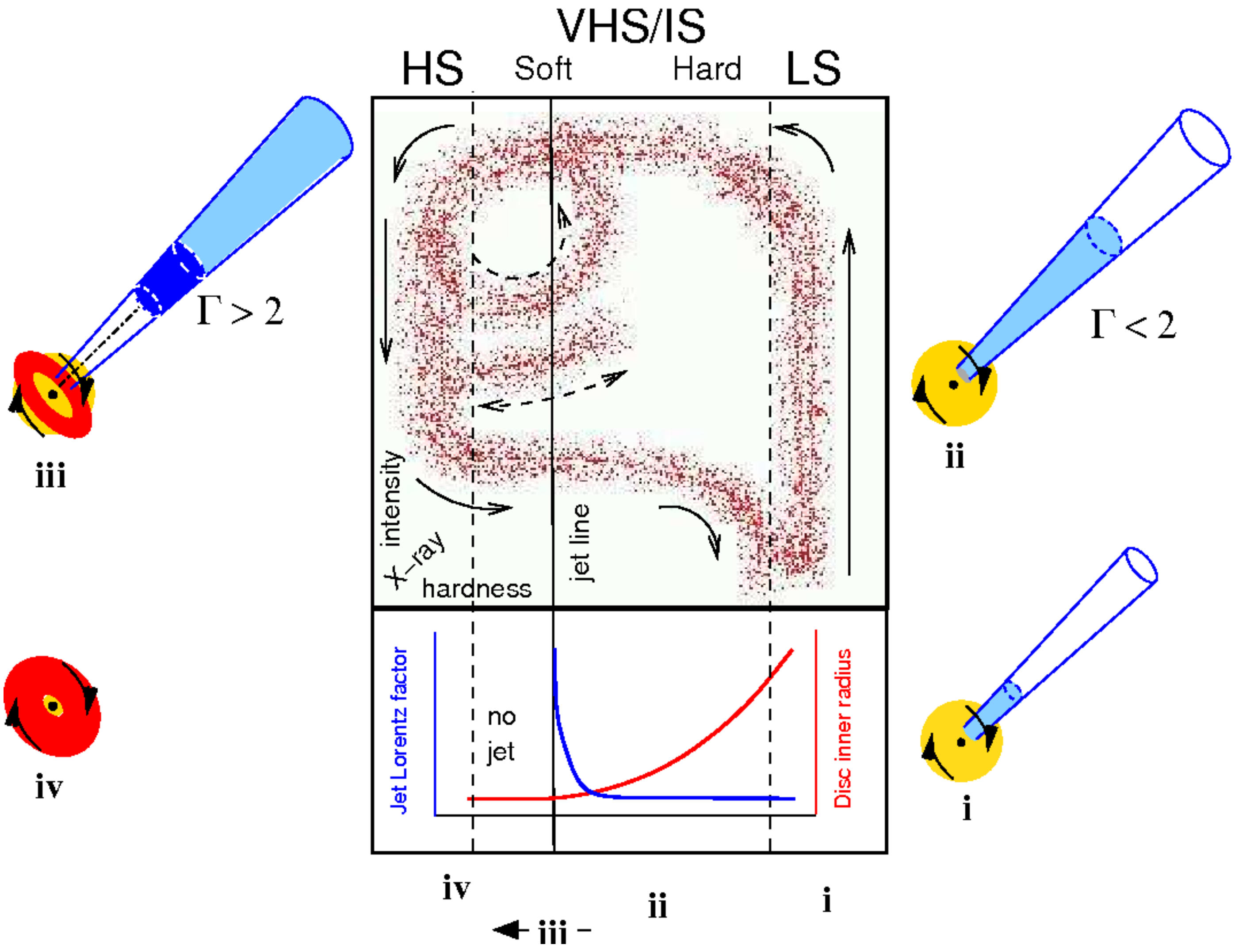
Figure 2. *RXTE*/ASM soft X-ray (1.5-12 keV) light-curve of GX 339−4 for all RXTE lifetime (January 1996 to December





8. Jet presence - absence in X-ray novae

The system shows the presence of the jet (either steady jet, or blobby ejections) in some of the states. The jet (formation ? collimation ?) requires the presence of the large scale magnetic field, and this in turn requires geometrically thick accretion flow.



Such a geometrically thick flow is in a natural way present in the gamma-ray bursts, but also in X-ray binaries when the inner flow is either hot (inner ADAF), or there is a strong coronal flow on the top of the cold disk.

If only standard Keplerian disk (geometrically thin, optically thick) is present, the jet dies.

Schematic plot from Fender et al. (2004).

9. Summary

- Jets form due to the presence of magnetic field
- Jets require geometrically thick accretion flow
- Highly relativistic jets seem to form only in systems with black holes
- We still do not know what is the basic mechanism (BZ, BP)

No homework