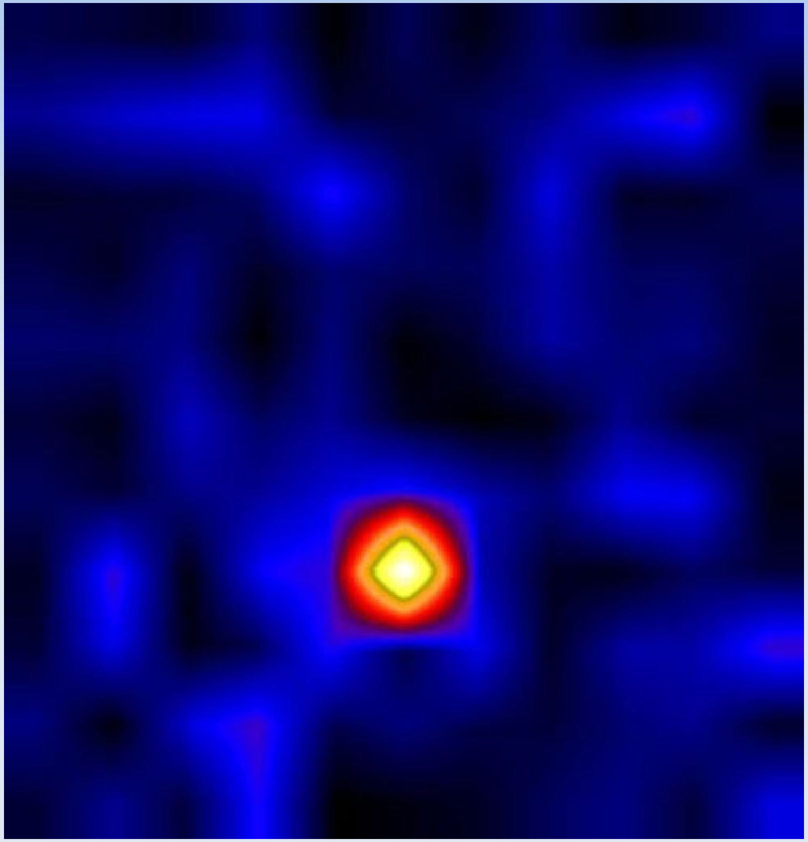
Compact Stars



Lecture 7

Summary of the previous lecture

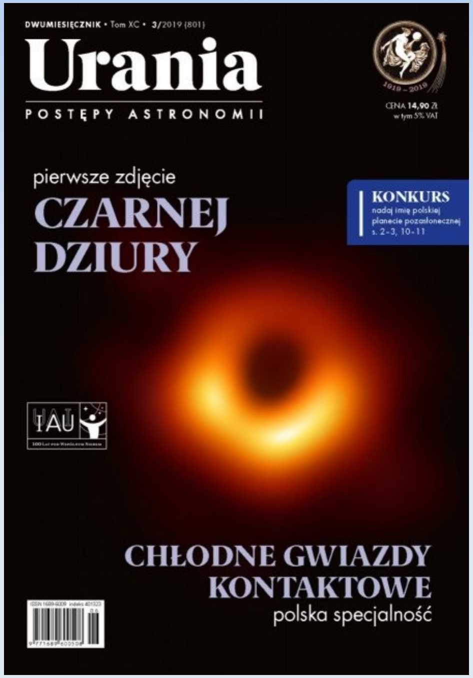
- I talked about microquasars, accreting compact stars in X-ray binaries, which produce jets.
- An example source, GRS 1915+105 is accreting stellar mass black hole. It exhibits apparently superluminal motions of radio blobs ejected from its core.
- Similar motions were observed in radio quasars – cores of distant galaxies. Microquasars are scaled-down quasars.
- This projection effect, and Doppler boosting of intensity, are related with relativistic speeds of jet blobs. Their emission is due to the synchrotron process.
- Jets are common an the Universe and appear in many types of sources, not only (micro) quasars.

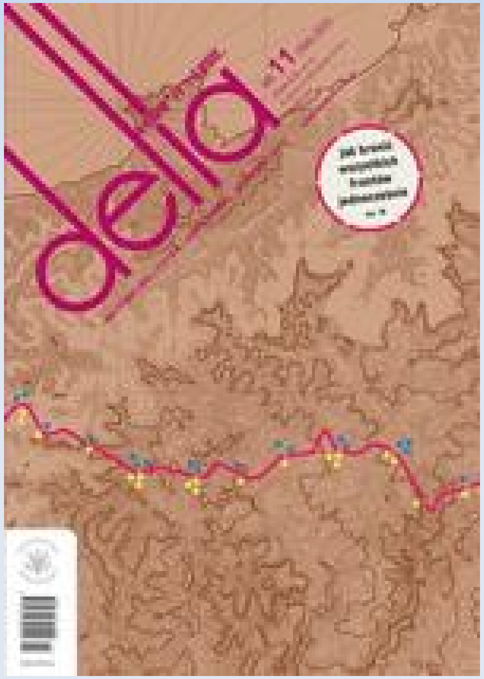
Reminder: quasars

- Quasars are seen on radio maps
- They may emit blobs – isolated patches of high intensity of synchrotron radiation
- Radio lobes are extended structures, powered by the large scale jet
- The morphology of a radio quasar is core-dominated or jet-dominated
- Some suspected to have intermittent activity, or be re-activated

Polish astronomical terminology

- Popular science magazines: ”Delta”, ”Urania”
- TV series ”Astronarium”
- Internet portals, e.g. astronet.pl
- Wikipedia





Quasars, AGN and supermassive black holes

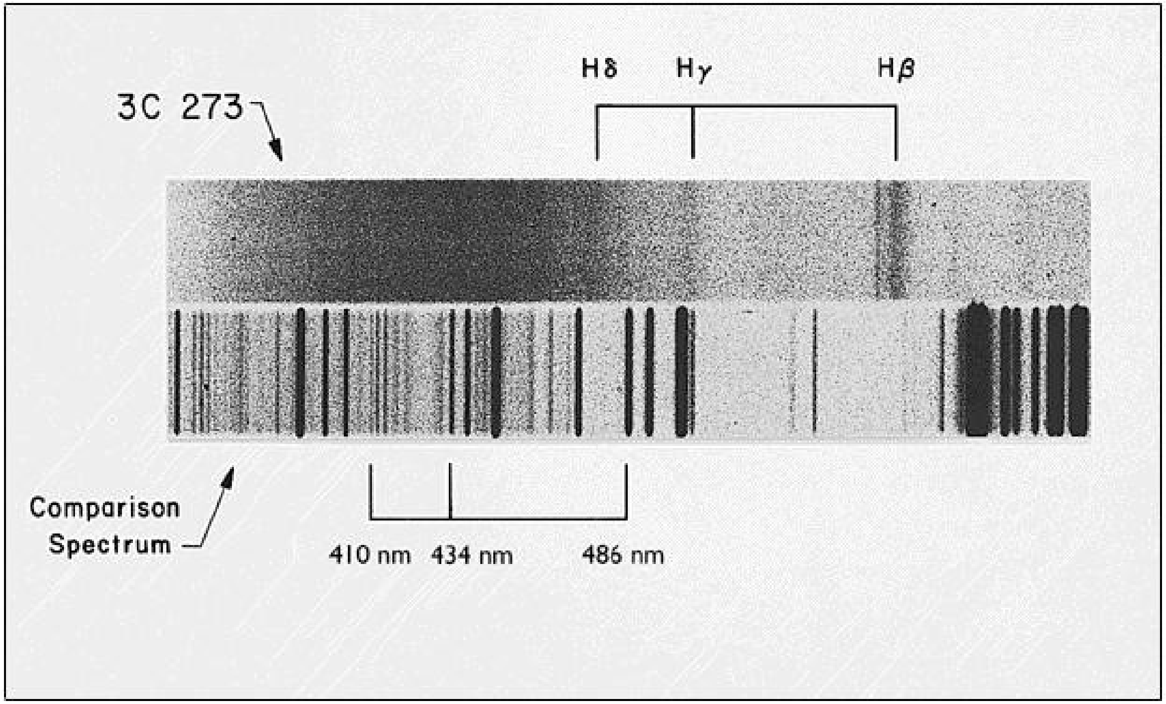
- Today we will start from active galaxies
- Some of them exhibit jets, seen in Optical light like in M87
- I will discuss properties of these large (kpc-)scale jets, and the primary feature of AGN: the emission lines, narrow and broad
- I will present solutions of Kerr black holes and discuss possible mechanism of jet power extraction from a rotating black hole

Active galaxies

- They are related to quasars, are distant galaxy centers and contain supermassive black holes
- First object BL LAC (supposed to be a variable star) observed in 1929
- 1943: Carl Seyfert, classfied some spiral nebulae by their strong emission lines and bright nuclei
- 1963: Maarten Schmidt, observed quasar 3C 273 (star like object with a large redhift)
- 1980's: common name 'active galaxies' was used for quasars and Seyfert galaxies

Active galaxies

- Emission lines of Hydrogen come in spectral series, with wavelengths given by the Rydberg formula. For other elements: perturbation analysis.
- Hydrogen Lyman series correspond to the transitions of electron to the energy level n=1. Balmenr series: n=2. Paschen series n=3.



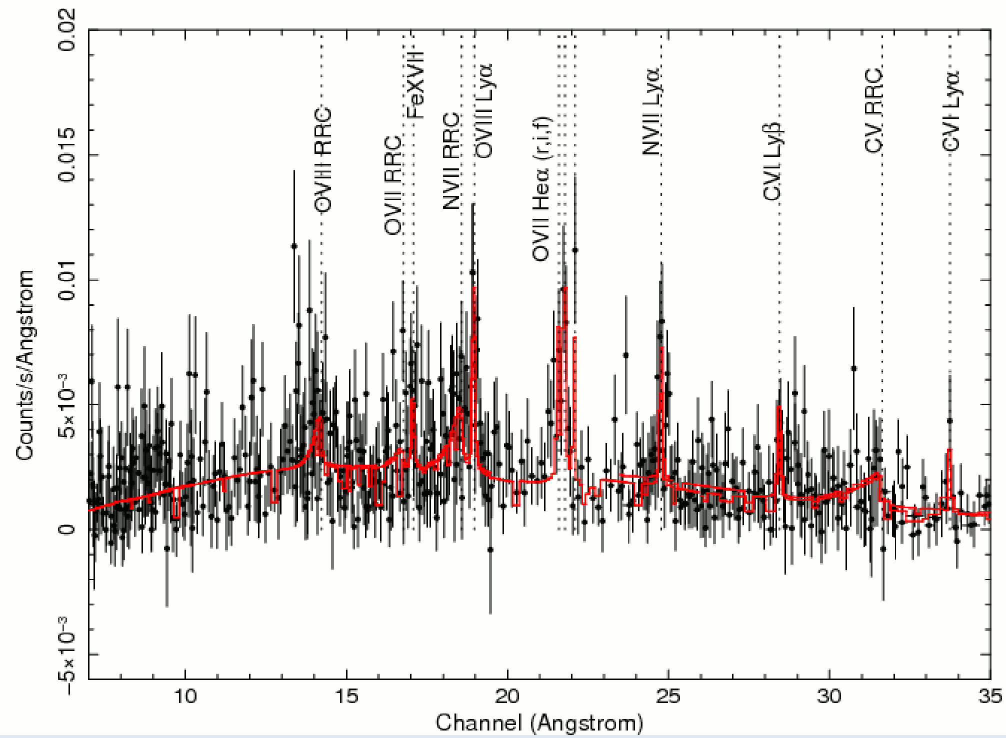
Schmidt M. (1963), Nature

Determined z=0.158 for this radio-loud QSO

Active galaxies

- Strong emission lines are formed in the gas irradiated by X-ray photons due to fluorescence
- Lines are naturally broad due to quantum effects. Additionally, collisions and turbulences lead to broadening

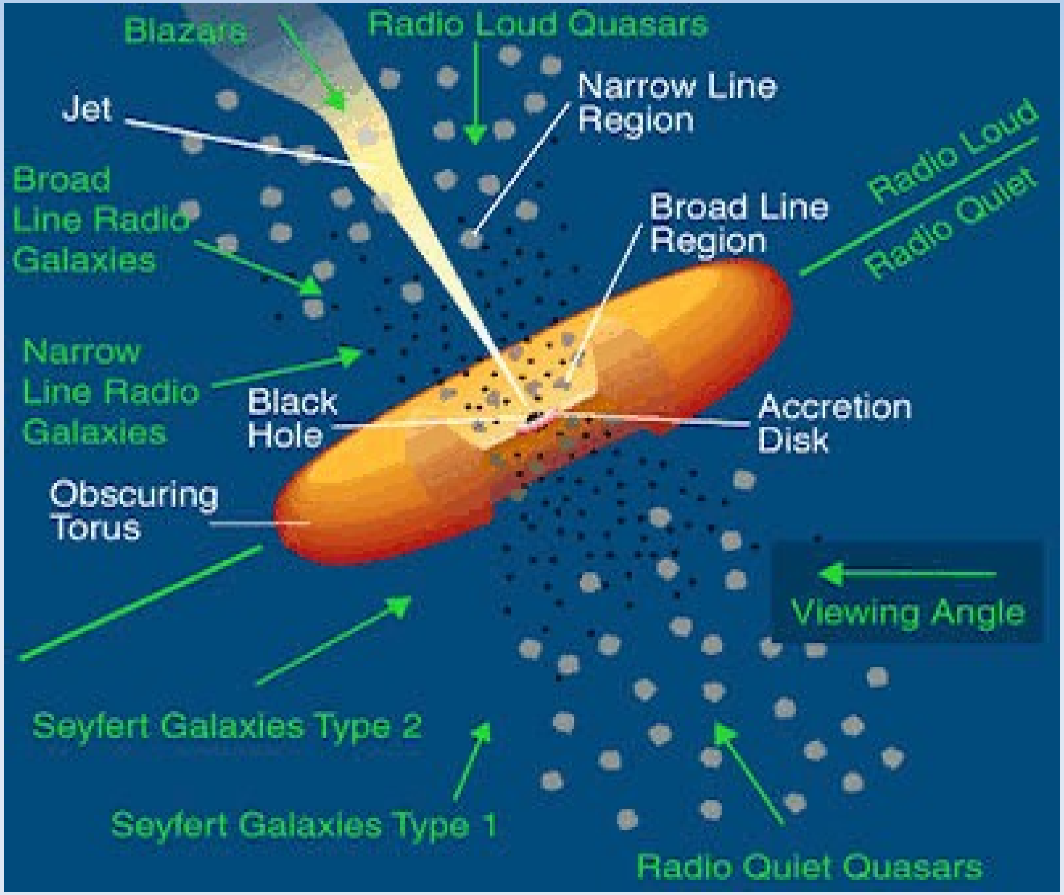
Longinotti et al. (2008), spectrum of Mrk 335



- Seyfert 1 galaxies: broad (~10,000 km/s) and narrow (~1,000 km/s) emission lines
- Seyfert 2 galaxies: only narrow lines

Active galaxies

- Unification scheme: in Seyfert 2 galaxies the region of broad emission lines is schielded from the observer by a dusty torus
- The distinction between Sy1 and Sy2 is based on orientation
- Intermediate types of objects (Sy 1.2, Sy 1.5, …) are classified.



- Radio loud objects have

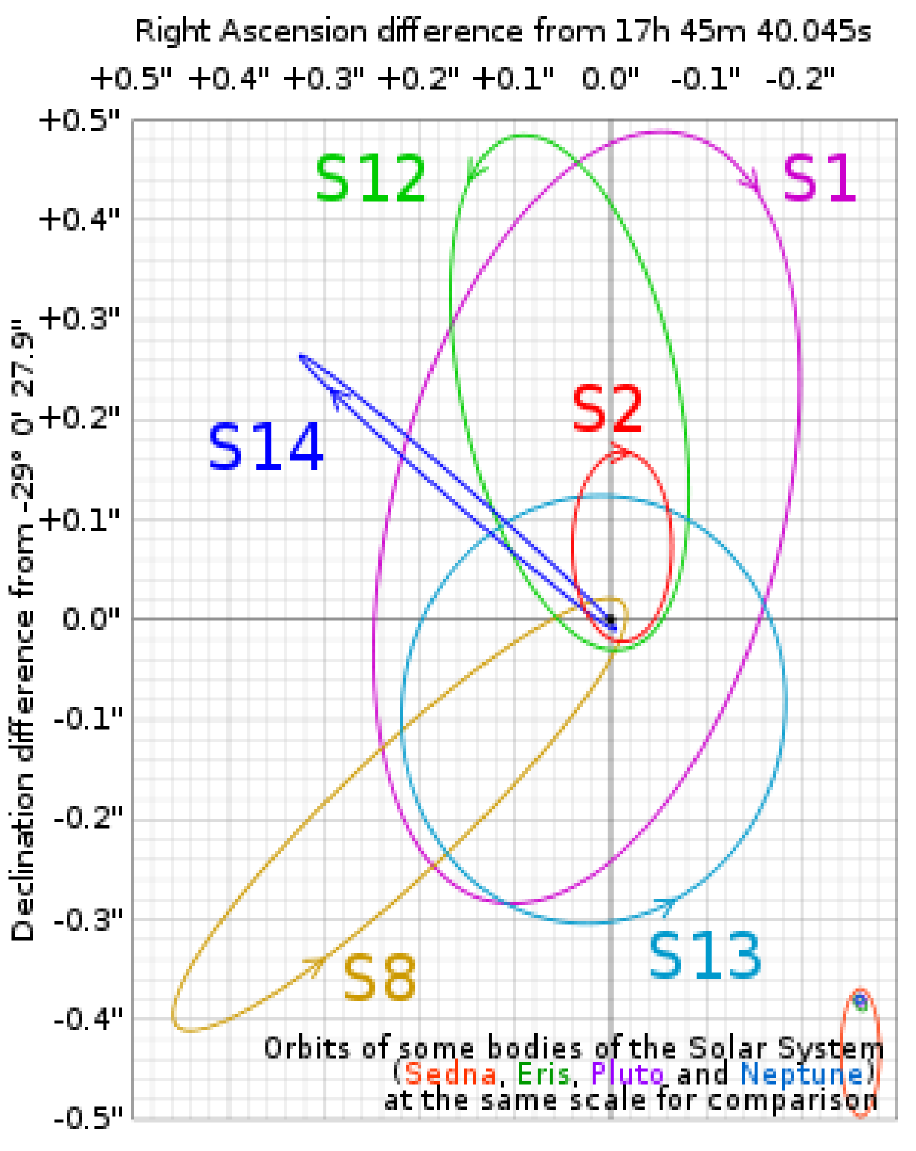
log (F(5 Ghz)/F(B)) > 1.

BH mass estimations in AGN

- Supermassive black holes may be 'weighted' by several methods:
  - Dynamics of single stars close to the nucleus (center of our Galaxy)
  - Velocity dispersion of stars close to the nucleus (nearby weakly active galaxies)
  - Surface brightness correlation with mass
  - Reverberation mapping: measuring of Hβ line width and estimation of broad line region size
  - Doppler shift of H_20 maser line at 22 Ghz
  - Broad band energy spectrum (model dependent)
  - Power Density Spectrum (compared with Cyg X-1)

Our Galaxy Center

- Orbits of stars close to Sgr A* helped to determine the mass of central object to 4.1×10^6 Solar masses (Ghez et al. 2008)
- This mass must be contained within the region of the size of Uranus orbit
- Accretion rate very low, disk presence is doubtful
- Some suggestions for jet ejection (e.g. Li et al. 2013)

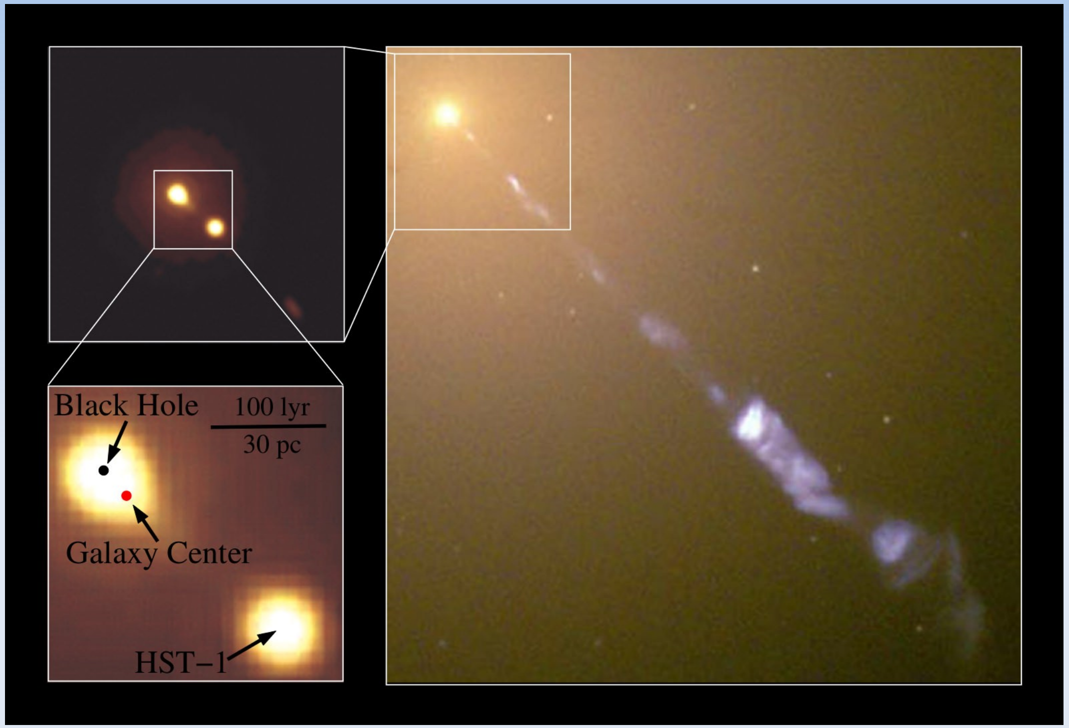


AGN Luminosity states

	Very Bright	QSO	Sy1	Faint
L/L_{Edd}	1	0.3	0.03	1.e-6
M_{BH}	1.e10	1.e9	1.e6-1.e8	>1.e6
Disk presence	yes	yes	yes	no?
R_{in} [R_{Schw}]	3	3	10-20	
T_{in} [keV]	0.004	0.004	0.004	
PL/Disk flux	0.02	0.1	0.4	
f_0 [Hz]	?	?	1.e6-1.e8	

Extragalactic jets

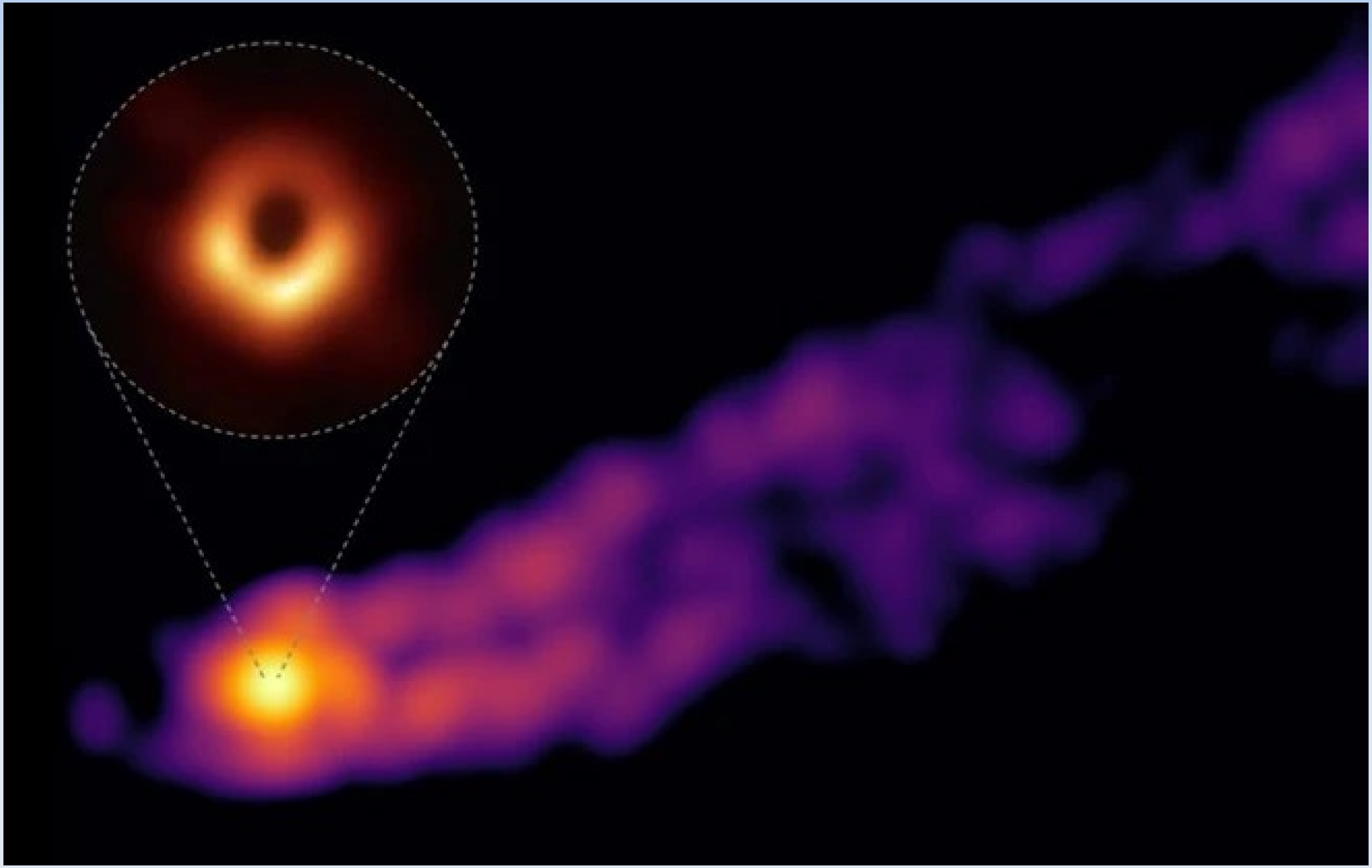
- Giant, collimated plasma outflows associated with some AGN.
- First detected in M87 (Curtis 1918)
- Originate in the vicinity of a supermassive black hole (Salpeter 1964)



HST-1 is a knot in the jet from the SMBH

Large scale: from BH radius: $r=10^{-4}\ M_{BH}/10^{9}\ M_{Sun}$ [pc] to the Mpc distance of hot spots

M87: black hole produces jet



Large scale radio jet and black hole shadow imaged by the Event Horizon Telescope

Content of the jets

- Giant stream of flow, containing relativistically moving particles and magnetic fields, and/or Poynting flux, either of which could dominate the local energy density
- The 'medium' responsible for delivering the power generated in the nucleus of the galaxy may (but does not have to) be the same as the nonthermal plasma responsible for emission

Composition of the jets

- Continuum jet emission (radio, optical, X-rays) originates as synchrotron emission from relativistic electrons, gyrating in a magnetic field.
- Jet content must include not only electrons. The Inverse Compton losses off the cosmic microwave background photons would prevent the survival of electrons with Lorentz factors > 1000 for the time required to travel all the way to the end of some jets (Harris & Krawczynski 2006).
- Jets must also contain protons, electrons with gamma< 1000 and possibly neutrons.
- Some models postulate transformation of initially electromagnetically dominated jet to a particle-dominated jet further downstream

Inverse Compton radiation

- Rate of loss of energy of the electron ($m_e c^2 >> \gamma h \nu_0$) in an isotropic radiation field is

$$-dE/dt = (4/3)\ \sigma_T\ c\ \gamma^2\ \beta^2\ u_{rad}$$

where u_{rad} is the total energy density.

- If electrons lose energy by both Syn and IC, the ratio of total luminosities is $L_{IC}/L_{Syn} = u_{rad}/u_B$
- Spectral energy distribution for a monoenergetic electron:

$$F(\nu, \nu_0, \gamma) = X(1 + X - 2X^2 + 2X \ln X)$$

with $X = \nu/(4\ \gamma^2\ \nu_0)$ for photons scattered from frequency ν_0 up to ν.

Inverse Compton radiation

- The luminosity for a number spectrum of electrons $N(\gamma)d\gamma$ and photon number oper unit volume $n(\nu_0)d\nu_0$ is

$$L_\nu = 3hc\sigma_T \int\int n(\nu_0) N(\gamma) F(\nu, \nu_0, \gamma) d\nu_0 d_\gamma$$

and is power-law with the same spectral indices relation as for Synchrotron.

- The mean frequency of upscattered photons

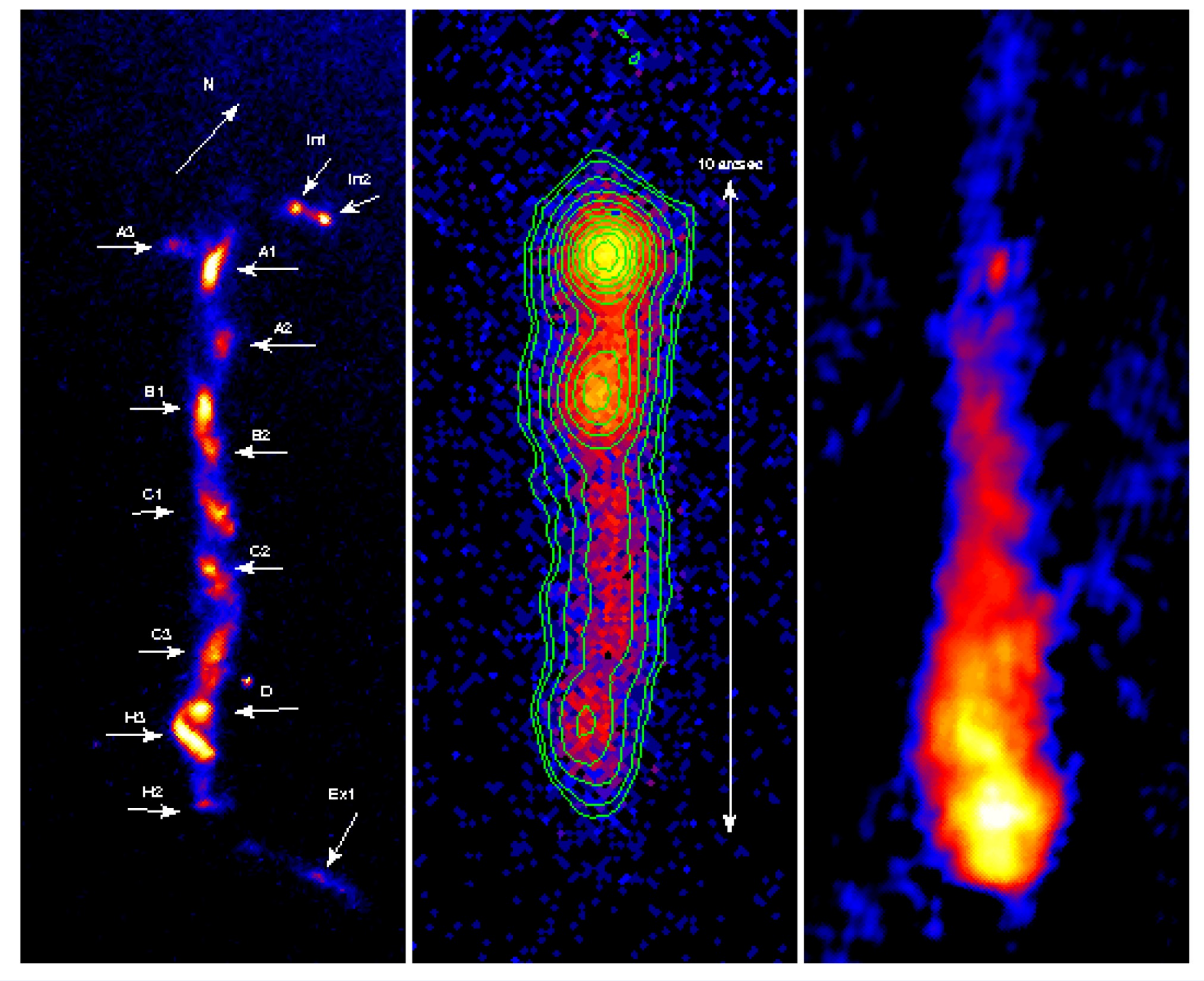
is $\nu = 4/3\ \gamma^2\ \nu_0$

- For photons of energies comparable to electrons, the Thomson cross-section must be replaced by Klein-Nishina. The electrons will loose a significant fraction of their energy in a single scattering.

Structure of the jets

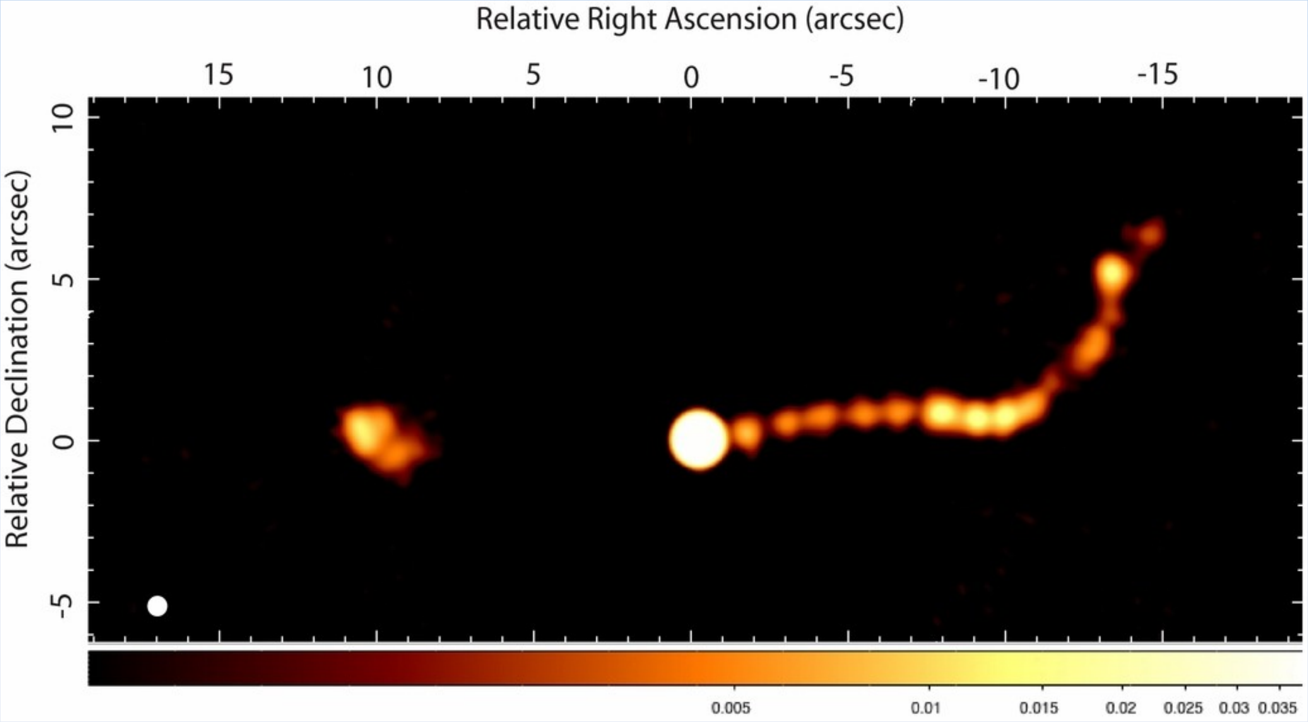
- Knots are localized brightness enhancements
- Explained by the particle acceleration in shocks (standing waves, Kelvin-Helmholtz instabilities)
- Alternatively. They may be due to the changing beaming factor:

$\delta^{-1} = \Gamma\ (1-\beta \cos \theta)$



Images of the jet in 3C 273 (HST, Chandra and Merlin)

PKS 0637

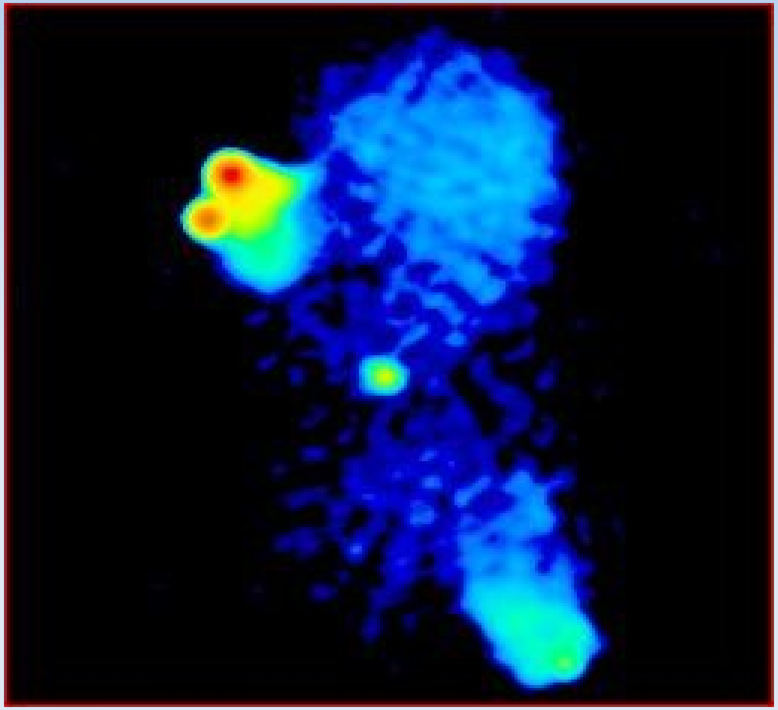


ATCA image of PKS 0637−752 at 17.7 GHz. The color scale is logarithmic between a minimum and maximum surface brightness of 0.5 and 38 mJy beam−1, respectively.

(Godfrey et al., 2012, ApJ, 758, L27)

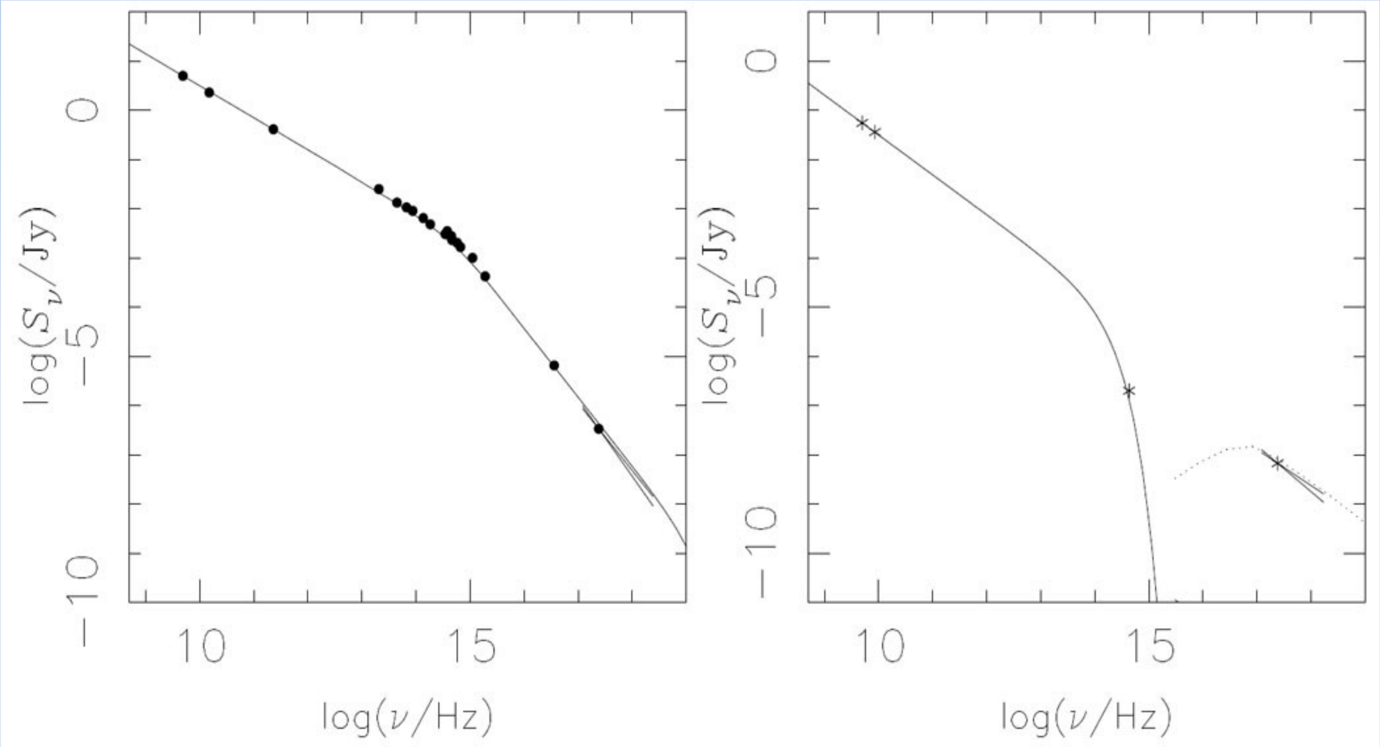
Hot spots

- Terminate hot spots arise due to emission from decelerated jet
- X-ray emission is explained with the SSC (Synchrotron Self-Compton) models
- Average magnetic field strength may be close to the equipartition value with the particle energy density
- Larger X-ray intensity in some cases may indicate the B field strengths below equipartition or extra components (synchrotron, Inverse Compton)



VLA image of the jet in 3C 351 at 1417 MHz

Spectral energy distribution



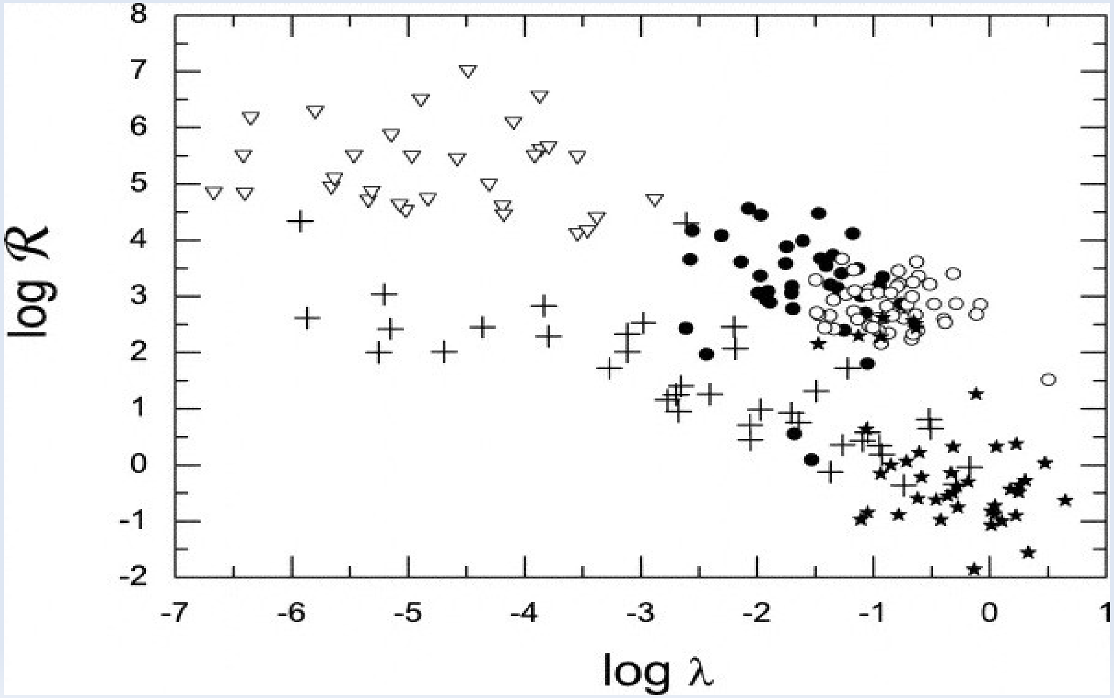
Spectra of the M 87 and PKS 0637 jets (integrated emission from knots A, B and C), data from Boehringer et al. (1993), fitted by D. Worrall with broken power-law synchrotron model

Dychotomy of AGN

- Jets are found in radio-loud AGN and not in radio-quiet
- External circumstances only cannot be responsible for that (i.e. morphological types of galaxies)

Anticorrelation of radio loudness with Eddington ratio.

Sikora, Stawarz & Lasota (2007)



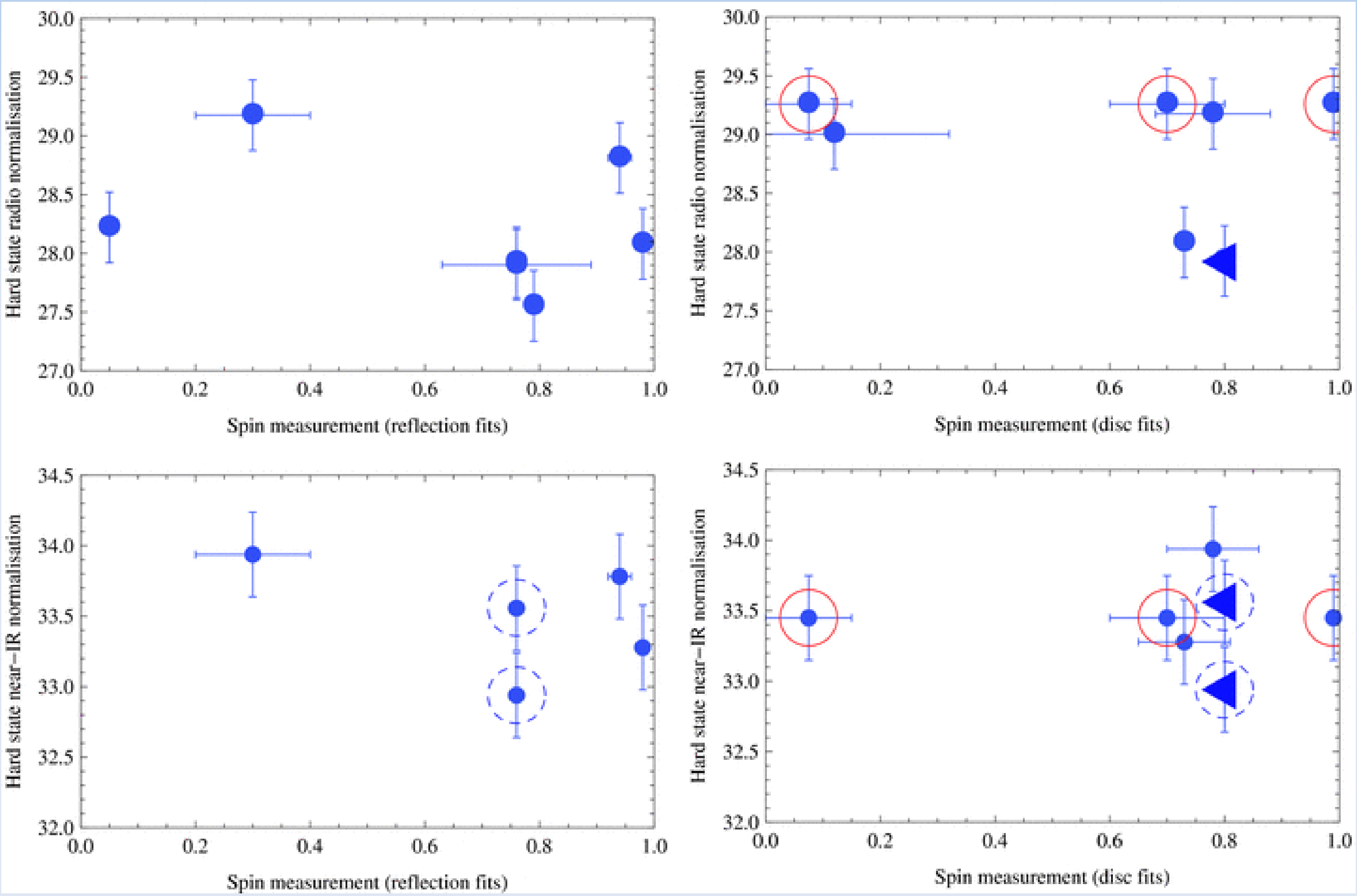
BLRGs are marked by filled circles, radio loud quasars by open circles, Seyfert galaxies and LINERs by crosses, FR I radio galaxies by open triangles, and PG quasars by filled stars.

Accretion mode or BH spin?

- SSL07 suggested that the normalization of the Raddio Loudness – Eddington Ratio dependence is determined by the black hole spin.
- This implies that central black holes in giant elliptical galaxies have (on average) much larger spins than black holes in spiral/disk galaxies.
- For BHXBs, the spin paradigm is invoked e.g. by McClintock & Narayan (2012)

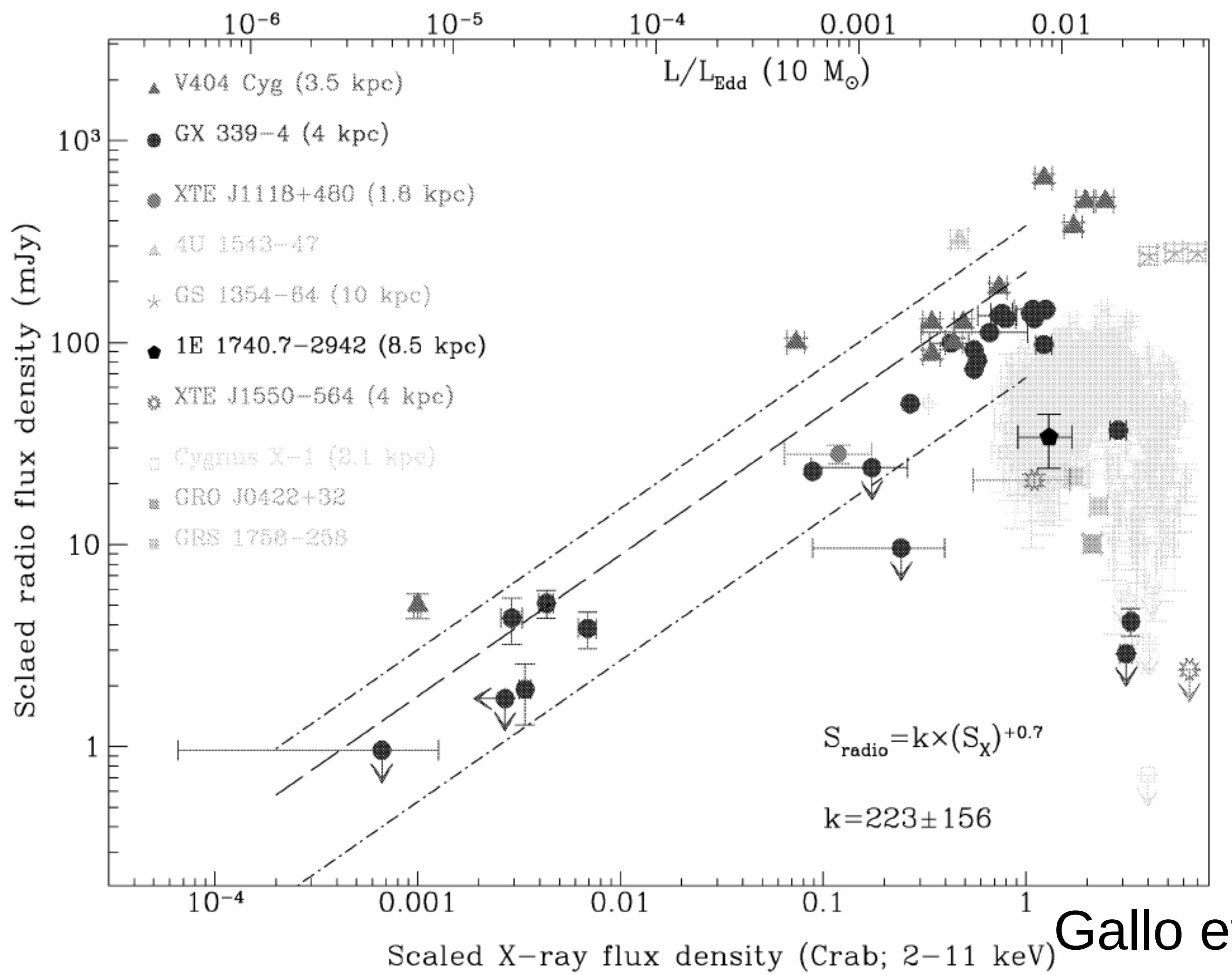
Jet power in BHXBs

Fender, Gallo & Russell, 2010



BH X-ray binaries: no evidence for spin dependence of jet power

Correlation between X-ray and Radio luminosities



Gallo et al. (2003)

Figure 2. The radio flux density (mJy) is plotted against the X-ray flux density (Crab) for a sample of 10 hard state BHs (see Table 1), scaled to a distance of 1 kpc and absorption corrected (this means that the axes are proportional to luminosities). On the top horizontal axis we indicate luminosity, in Eddington units for a 10-$M_\odot$ BH, corresponding to the underlying X-ray flux density. An evident correlation between these two bands appears and holds over more than three orders of magnitude in luminosity. The dashed line indicates the best fit to the correlation, that is $S_{radio} = k(S_X)^{+0.7}$, with $k = 223 \pm 156$ (obtained by fixing the slope at +0.7, as found individually for both GX 339−4 and V404 Cygni; see Section 4.1). Errors are given at the 3σ confidence level and arrows also represent 3σ upper limits.

Break

Origin of jets

- The estimated jet velocity is of order of escape velocity from the central object
- The jet must be produced in the vicinity of the central object, at inner regions of an accretion disk

What may help driving the jet

- Central object fast rotation (near break up)
- Compactness of the star: detemines the escape velocity and so the jet speed
- High luminosity: radiation pressure driven winds (Proga & Drew 1997)
- Funnel (ADAF flow in AGNs or slow winds in Planetary Nebulae) may provide a collimation
- Boundary layer between accretion disk and star

Potential energy sources

- Potential energy sources connected with central objects:
  - magnetosphere/disk interface, or stellar surface (YSOs)
  - Supercritical accretion rate (SS 433)
  - Hot central star (nuclear burning): Pne, SSS
  - Rotation of central star

In the remaining part of this lecture, we will consider mainly spin paradigm

Rotating and non rotating black holes

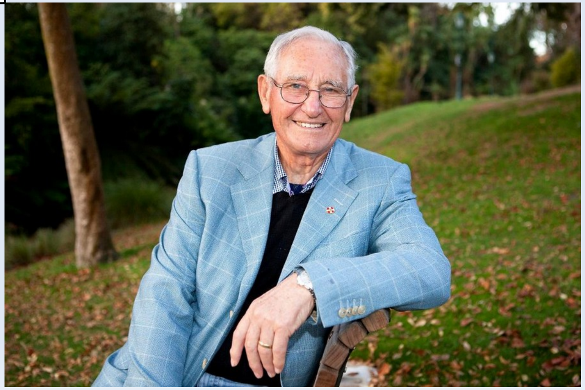
- Schwarzschild metric (units c=G=1)

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

- Kerr metric

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \\ + \left(r^2 + a^2 + \frac{2Mra^2}{\Sigma} \sin^2\theta\right) \sin^2\theta d\phi^2 - \frac{4Mra\sin^2\theta}{\Sigma} dt\, d\phi$$

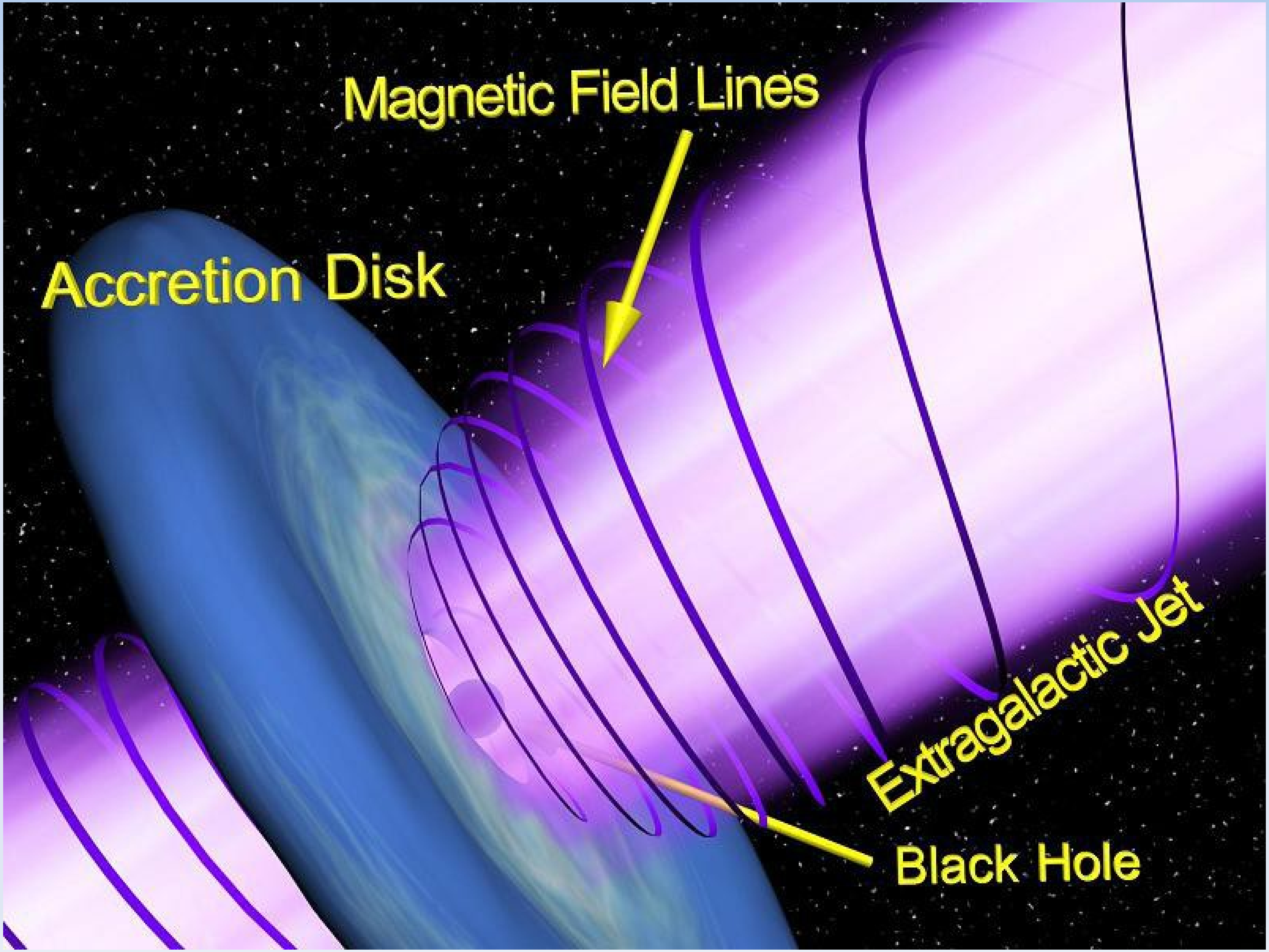
where a=J/M is angular momentum



$$\Sigma = r^2 + a^2 \cos^2\theta$$

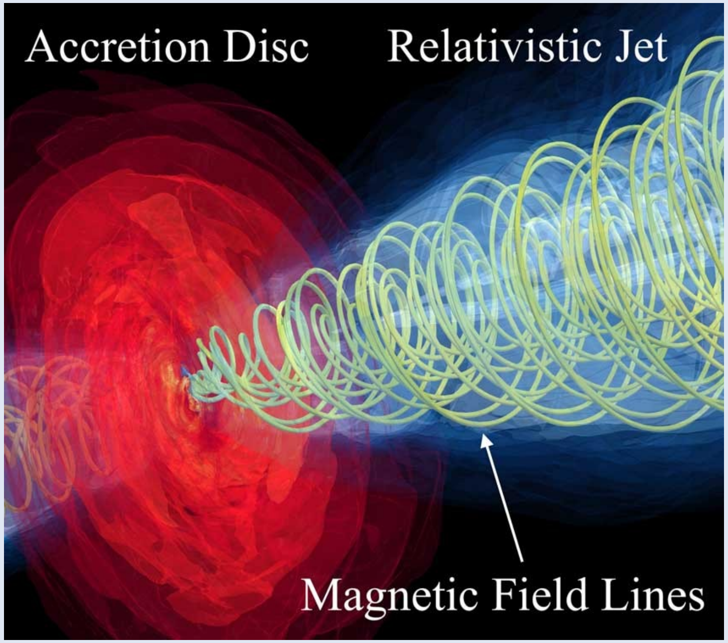
$$\Delta = r^2 - Mr + a^2$$

How BH jets are formed: artistic vision



MHD simulation

The black hole (M87*) shoots a jet of plasma at near the speed of light, a so-called relativistic jet, on a scale of 6,000 light years. The tremendous energy needed to power this jet probably originates from the gravitational pull of the black hole, but how a jet like this comes about and what keeps it stable across the enormous distance is not yet fully understood.



3D model from publication by Alejandro Cruz-Osorio et al., 2021, Nature Astronomy

Magnetic field

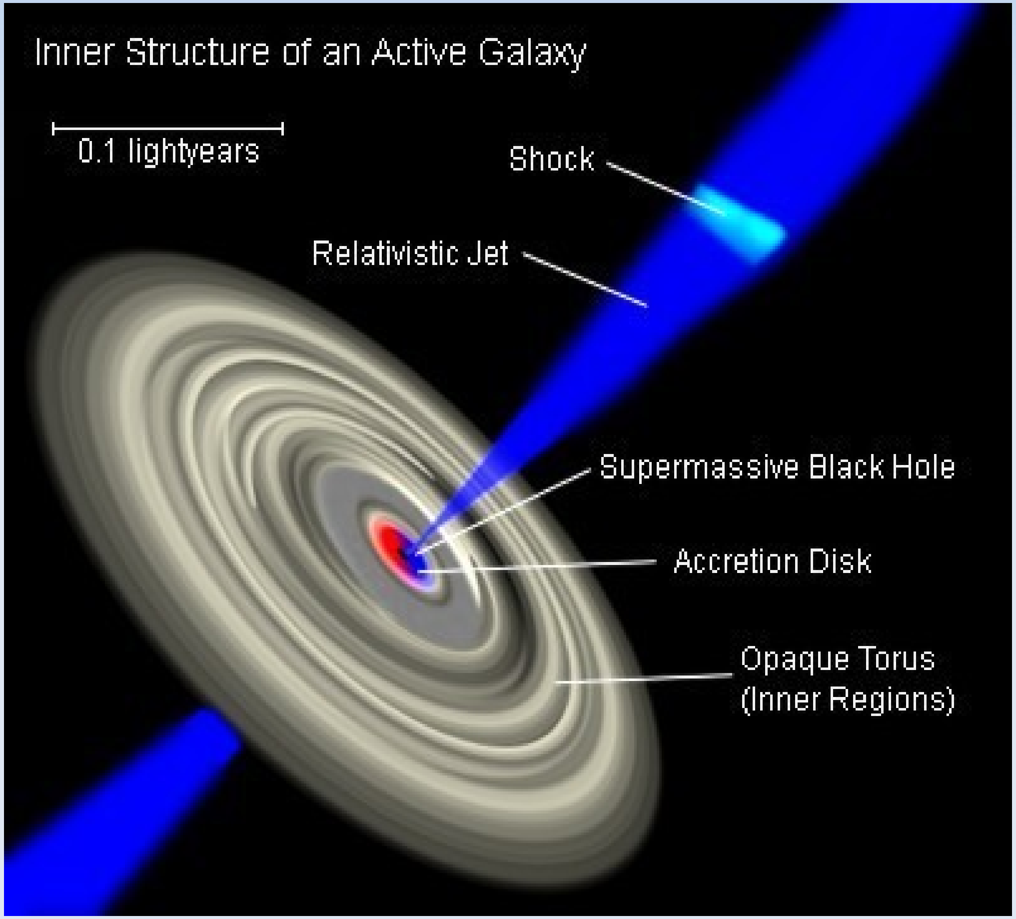
- Magnetically driven jets were studied by (Blandford 1976, Blandford & Payne 1982; Spruit 1996). Some fraction of magnetic flux is in open field lines; ionized material is forced to follow the lines. Lines are corotating with the disk at their foot, so centrifugal force accelerates the outflow.
- The acceleration stops at Alvfen surface, where the kinetic energy density is comparable to magnetic energy density.
- Collimation occurs outside this surface.

Origin of large scale B field around black hole

- Magnetic field may be advected with accreting matter in the disk (length scale of order of R)
- Field is generated locally (length scale of order of H) by the disk dynamo (Tout and Pringle 1996) and is responsible for the disk viscosity (Balbus and Hawley 1991).

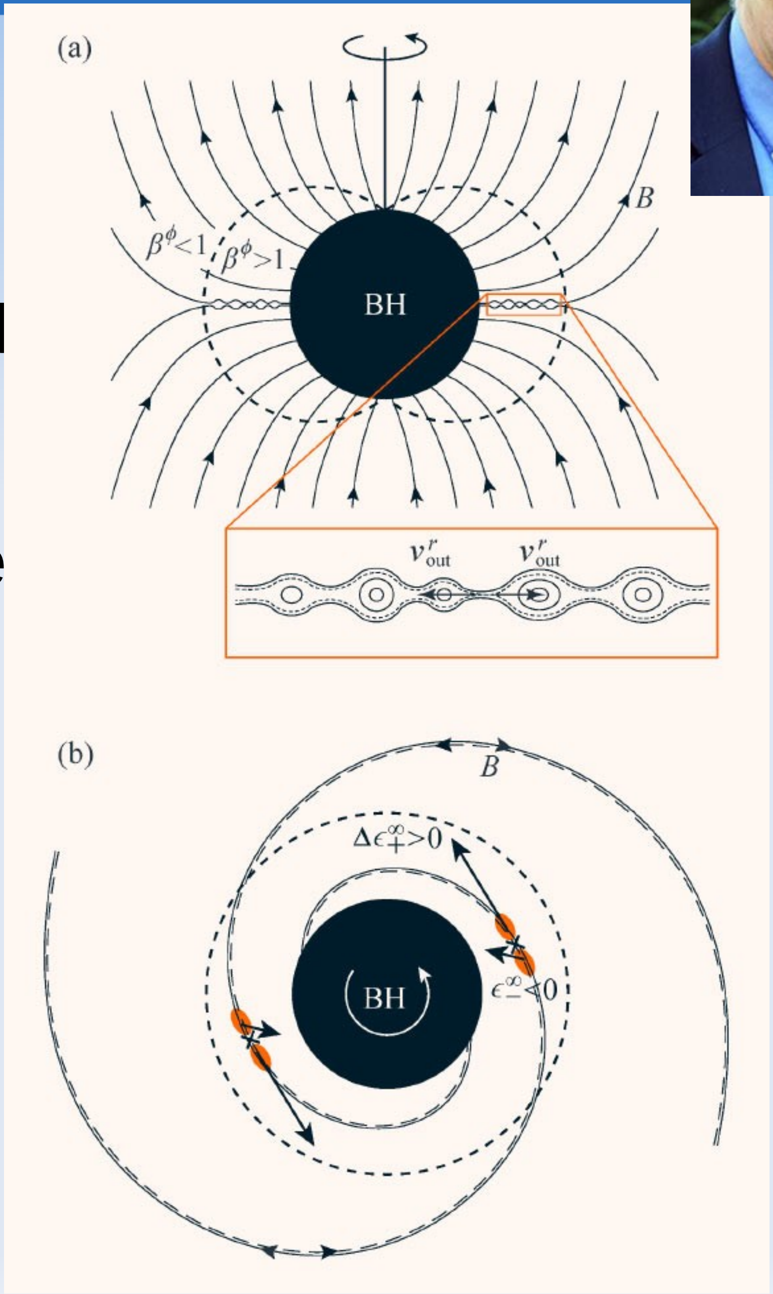
Jet puzzle

Powerful jets are produced by systems in which on top of accretion disk, threaded by a vertical field, there is an additional source of energy, possibly connected with the central object



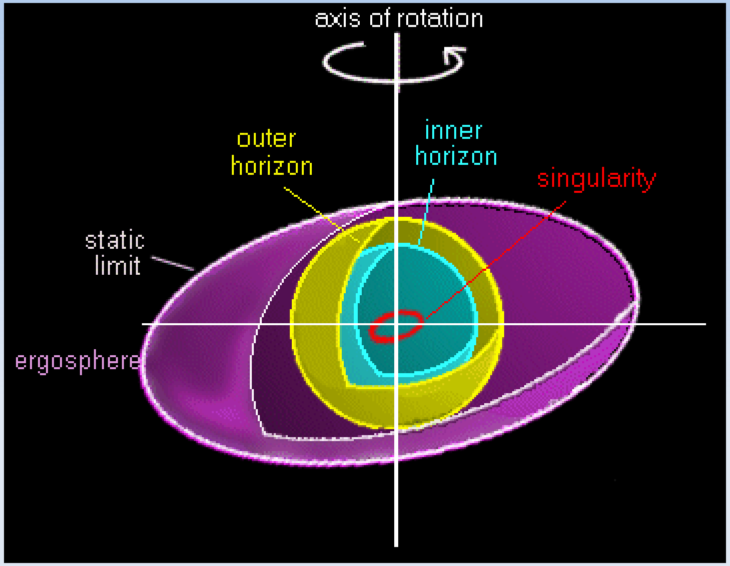
Blandford-Znajek process

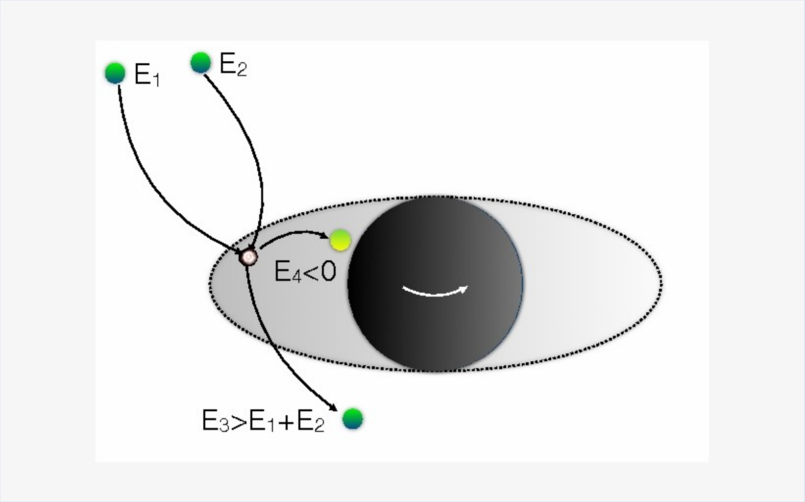
- Blandford & Znajek (1977) proposed that if the disk contains ordered magnetic field with large perpendicular component then both energy and angular momentum can be transported away via magnetized relativistic wind.
- The 'pulse-like' electrodynamical model can give rise to pair of jets, moving perpendicular to the disk



Penrose process

- The Penrose process is acting in the black hole ergosphere
- The infalling particles are split into two parts. One of them with negative energy (from the point of view of distant observer) falls into black hole.
- The other particle goes back out to infinity and extracts energy, on the cost of BH rotational energy

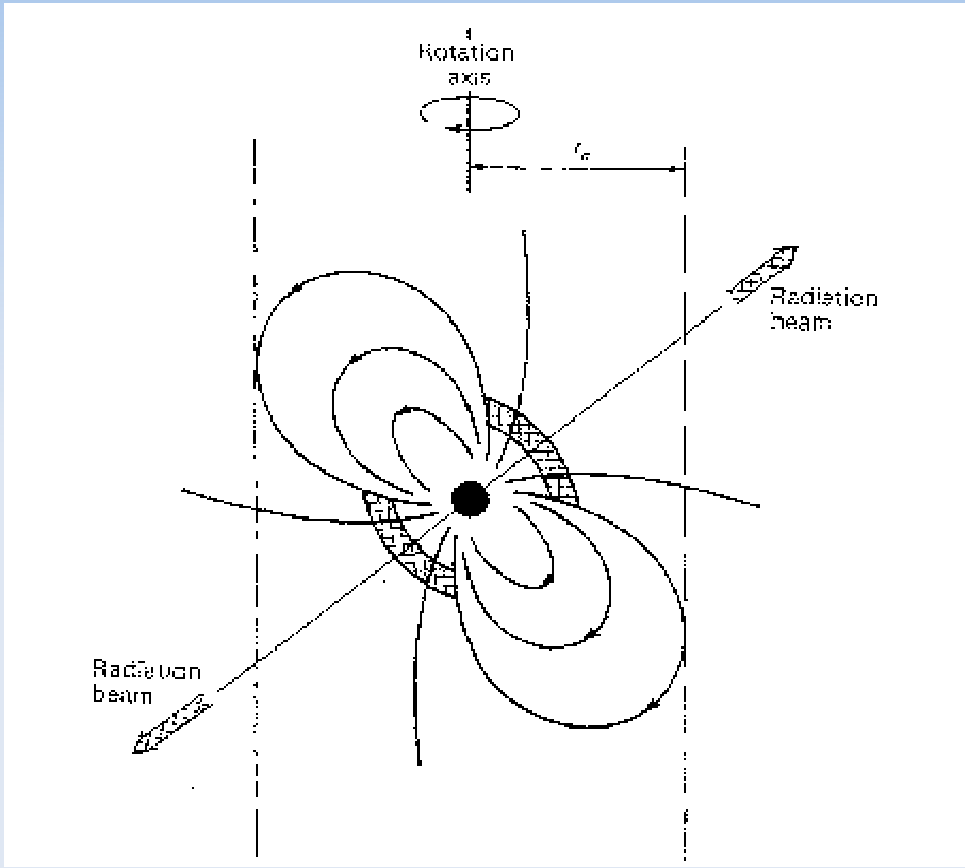




Analogy to pulsar magnetosphere

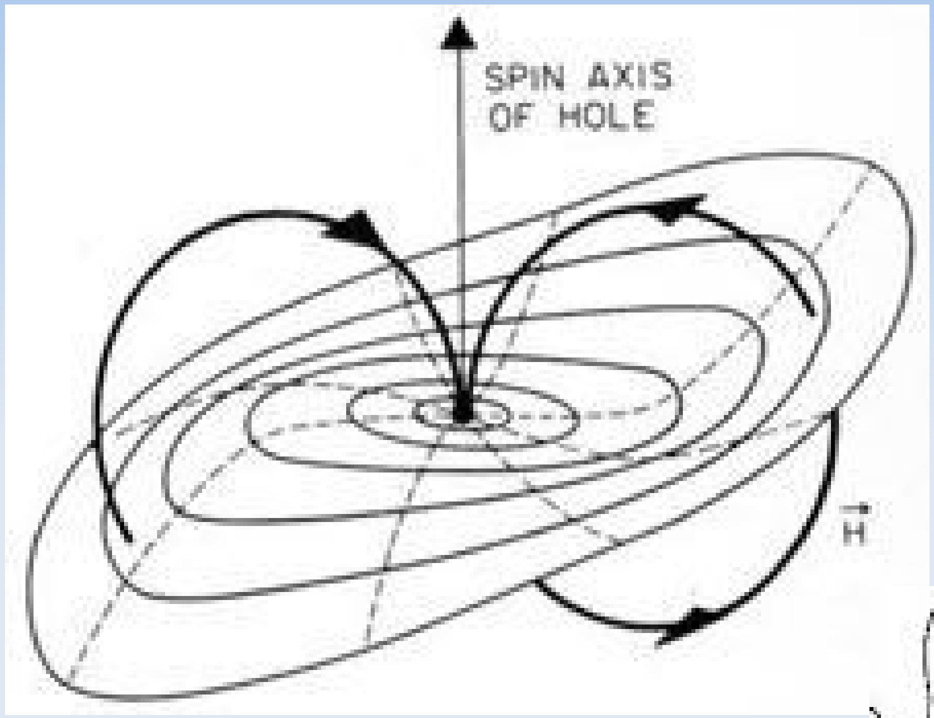
Magnetic field lines act as electric wires : charged particles move along the lines towards weaker B field and back.

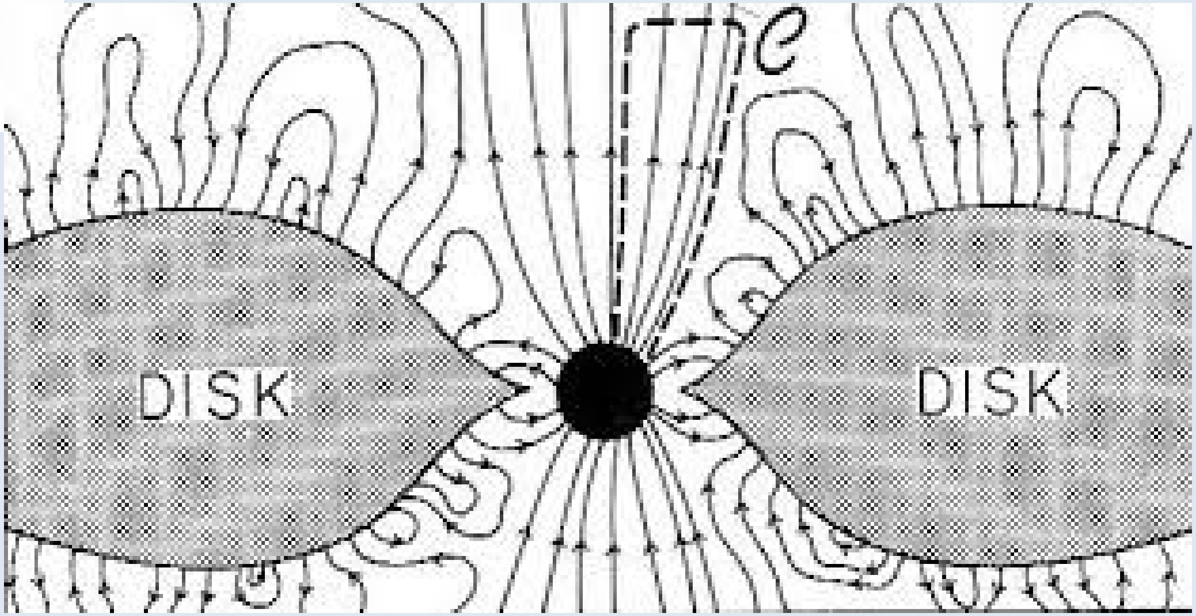
In this electric loop, the Poynting flux is driving the star's rotational energy towards weak B field.



Process proposed by Goldreich & Julian (1969) for rotating neutron stars → pulsars

Black hole magnetosphere





Thorne, Price, McDonald (1986)

BH spin measurements: continuum fitting

Table 1. Spin Results to Date for Eight Black Holes[a]

	Source	Spin a_*	Reference
1	GRS 1915+105	> 0.98	McClintock et al. 2006
2	LMC X–1	$0.92^{+0.05}_{-0.07}$	Gou et al. 2009
4	M33 X–7	0.84 ± 0.05	Liu et al. 2008, 2010
3	4U 1543–47	0.80 ± 0.05	Shafee et al. 2006
5	GRO J1655–40	0.70 ± 0.05	Shafee et al. 2006
6	XTE J1550–564	$0.34^{+0.20}_{-0.28}$	Steiner et al. 2010b
7	LMC X–3	< 0.3[b]	Davis et al. 2006
8	A0620–00	0.12 ± 0.18	Gou et al. 2010

[a]Errors are quoted at the 68% level of confidence.

[b]Provisional result pending improved measurements of M and i.

McClintock et al. 2011

BH spin: Iron line profile

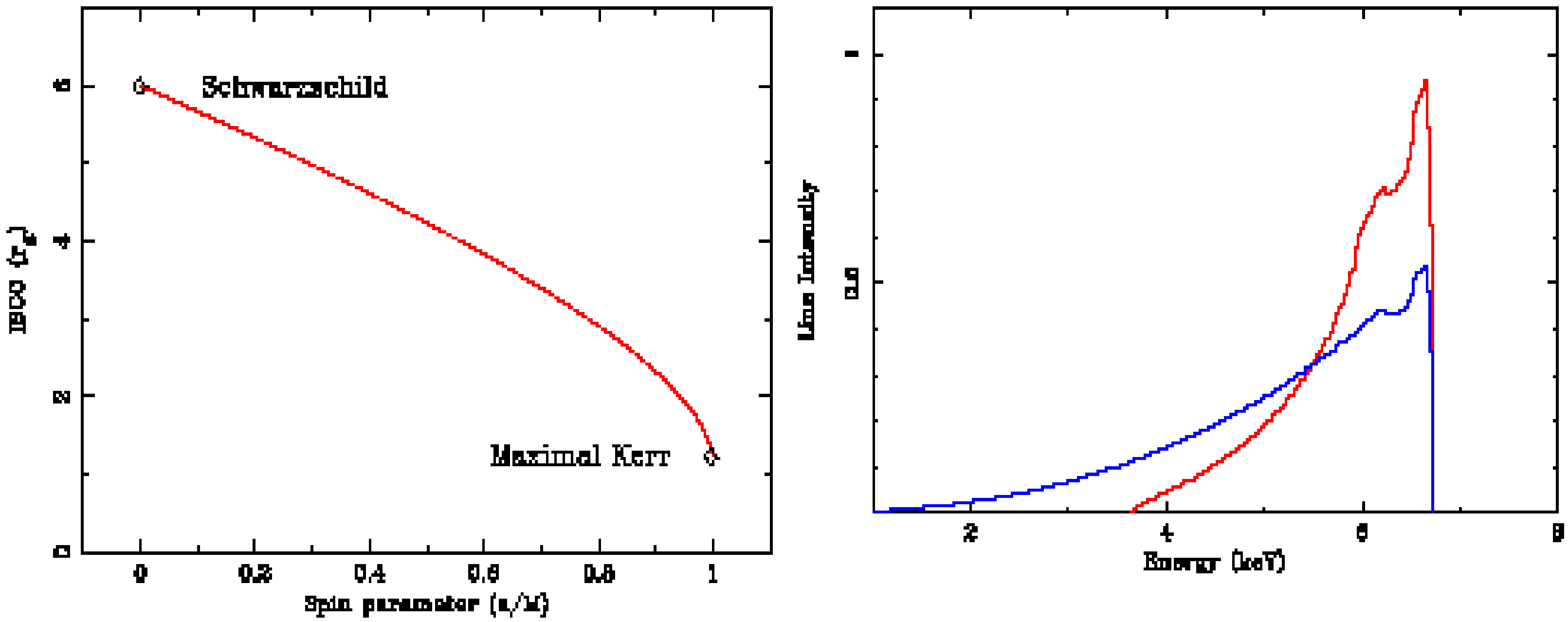
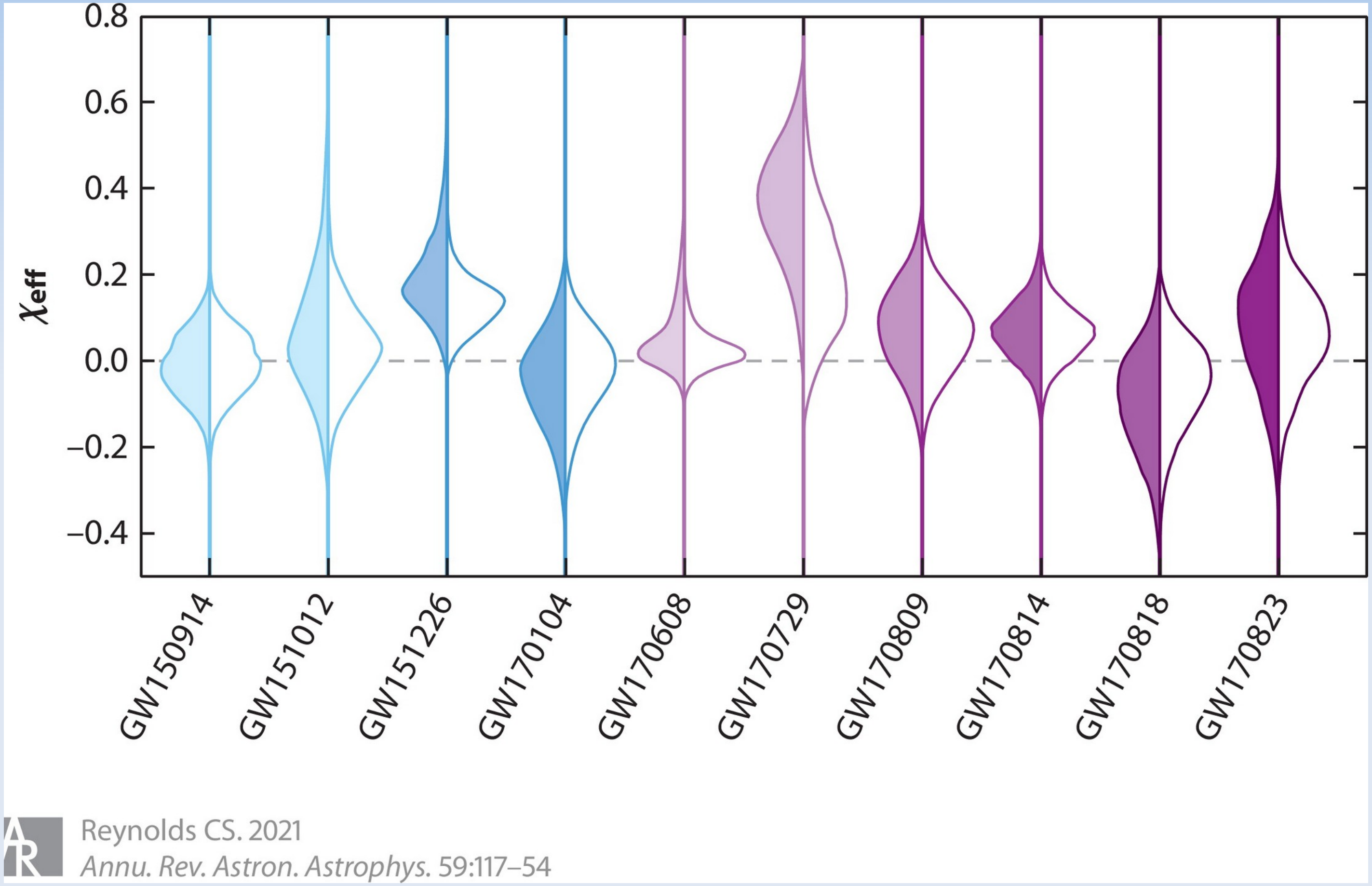


Figure 1: *Left*: The dependence of the innermost stable circular orbit (ISCO) on the black hole spin parameter is shown here, from Schwarzschild ($a = 0$) to maximal Kerr ($a = 0.998$) solutions. *Right*: The line profiles predicted in the case of Schwarzschild (red) and maximal Kerr (blue) black holes are shown here. It is the extent of the red wing and its importance relative to the blue wing that allow black hole spin to be determined with disk lines. (Adapted from Fabian & Miniutti 2006).

BH spins: constraints from GW



Probablility distributions of effective spins for LIGO-detected black holes. Left shades: standard priors (component masses, spin values and orientations). Right shades: Population-informed priors.

Next week

- Gamma ray bursts
- Jet collimation and acceleration
- Jet profiles, and variability
- Central engines properties - hyperaccretion

Further reading suggested:

- C. Reynolds; ”Observational constraints for black hole spins” Annual Review of A&A(2021)
- S. Komissarov; ”On the nature of the Blandford-Znajek mechanism”. arXiv:astro-ph/0211141 (2002)