Magnetic connection model for launching relativistic jets in AGN

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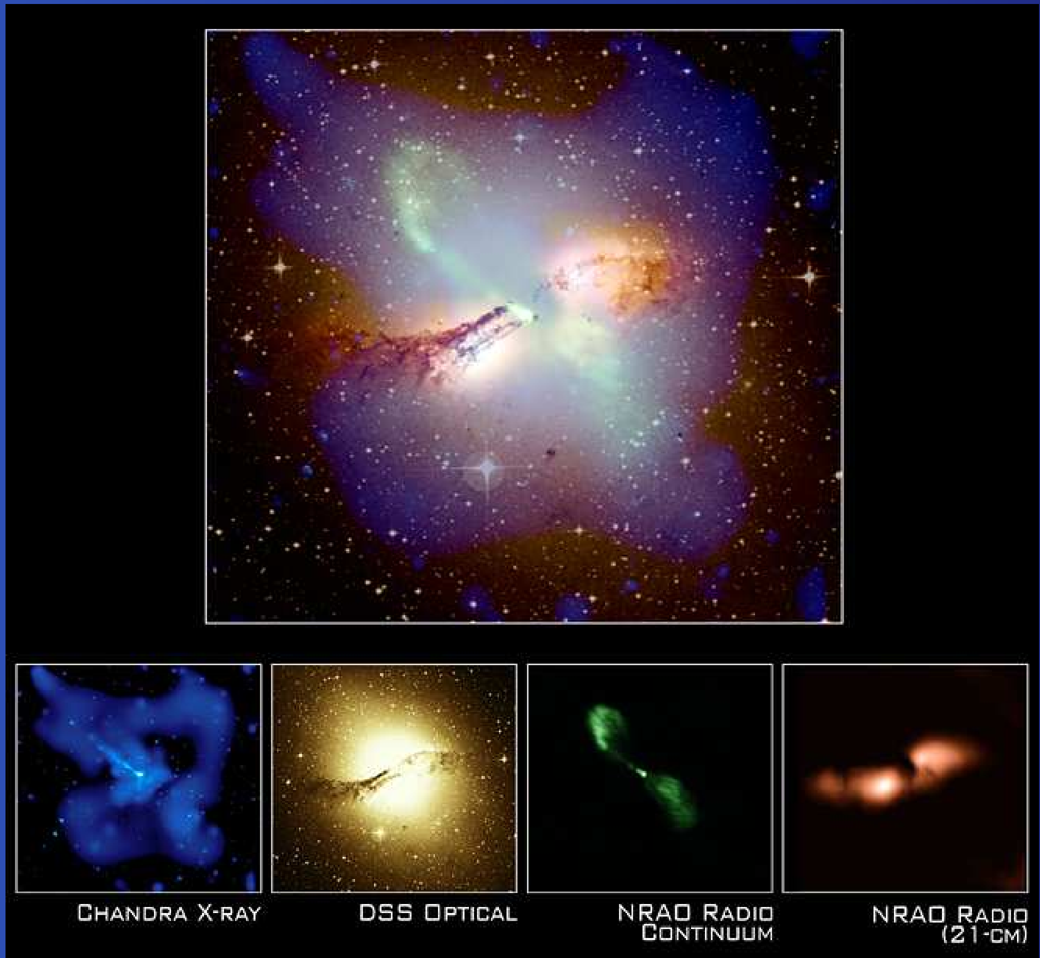
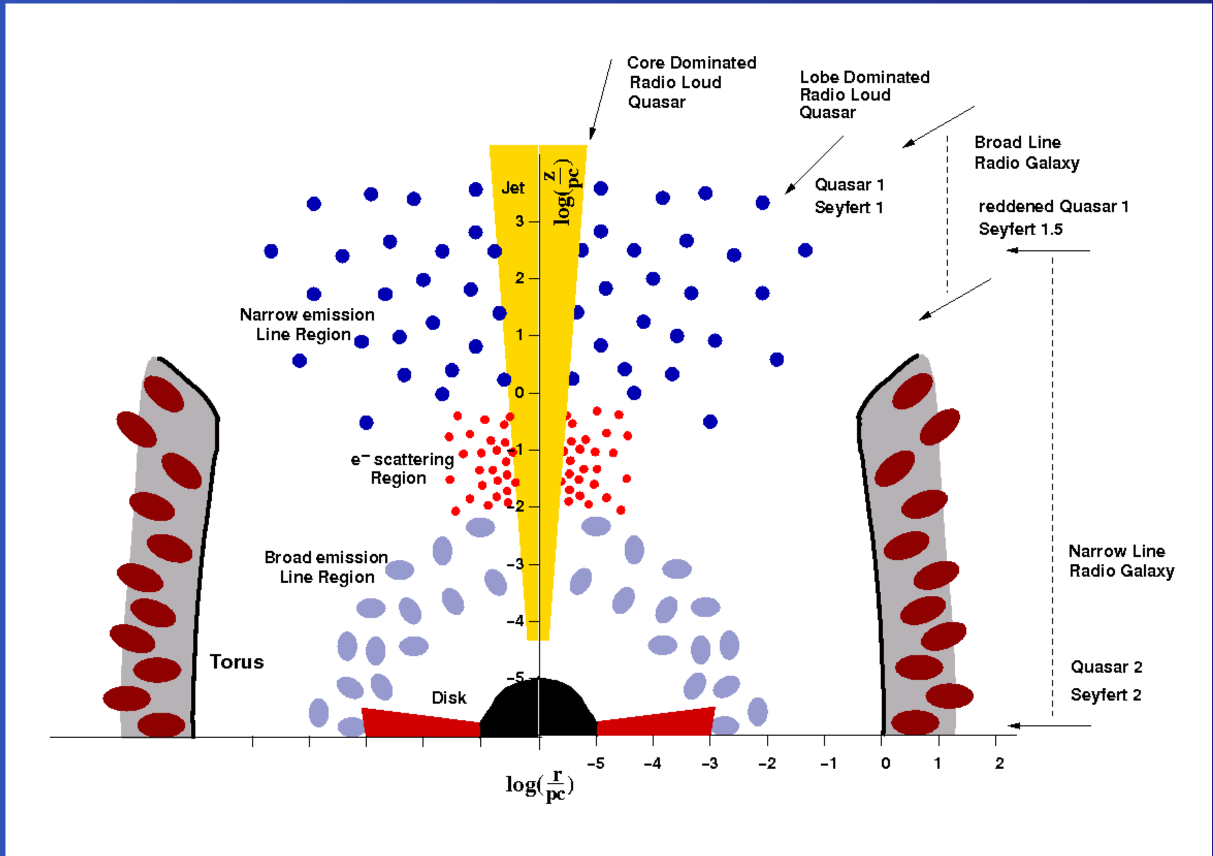
  - Relevance to the observational data
- Conclusions and remarks

Introduction: AGN – Centaurus A



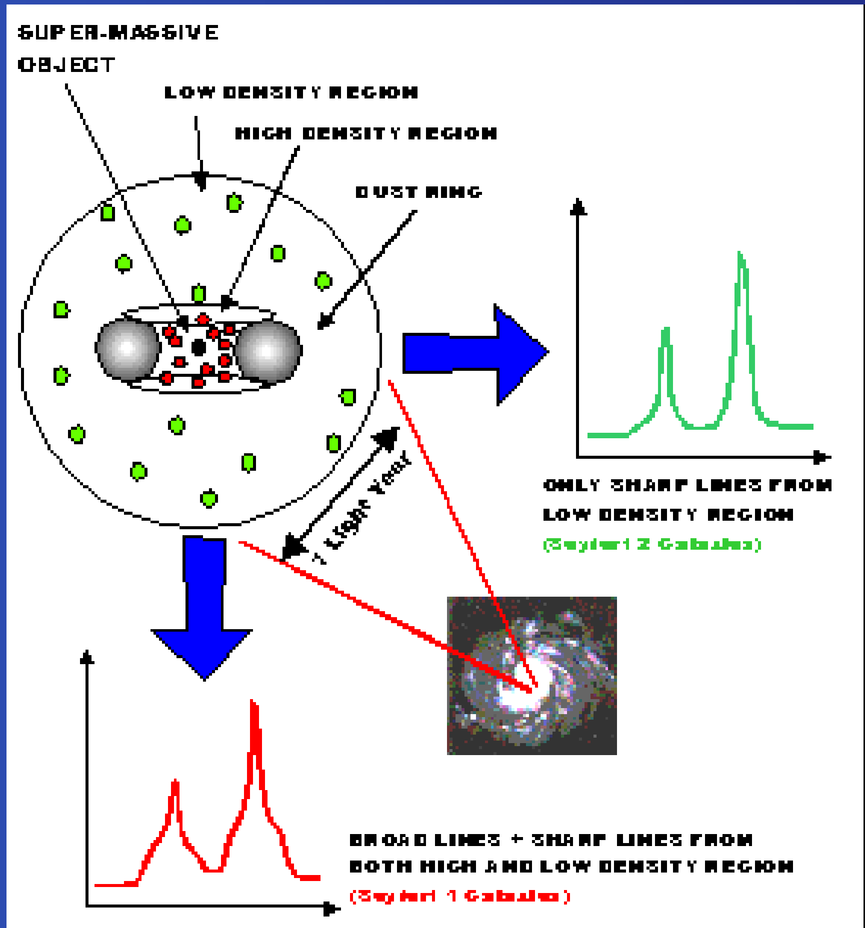
From *http://chandra.harvard.edu*

Introduction: clasification of AGN



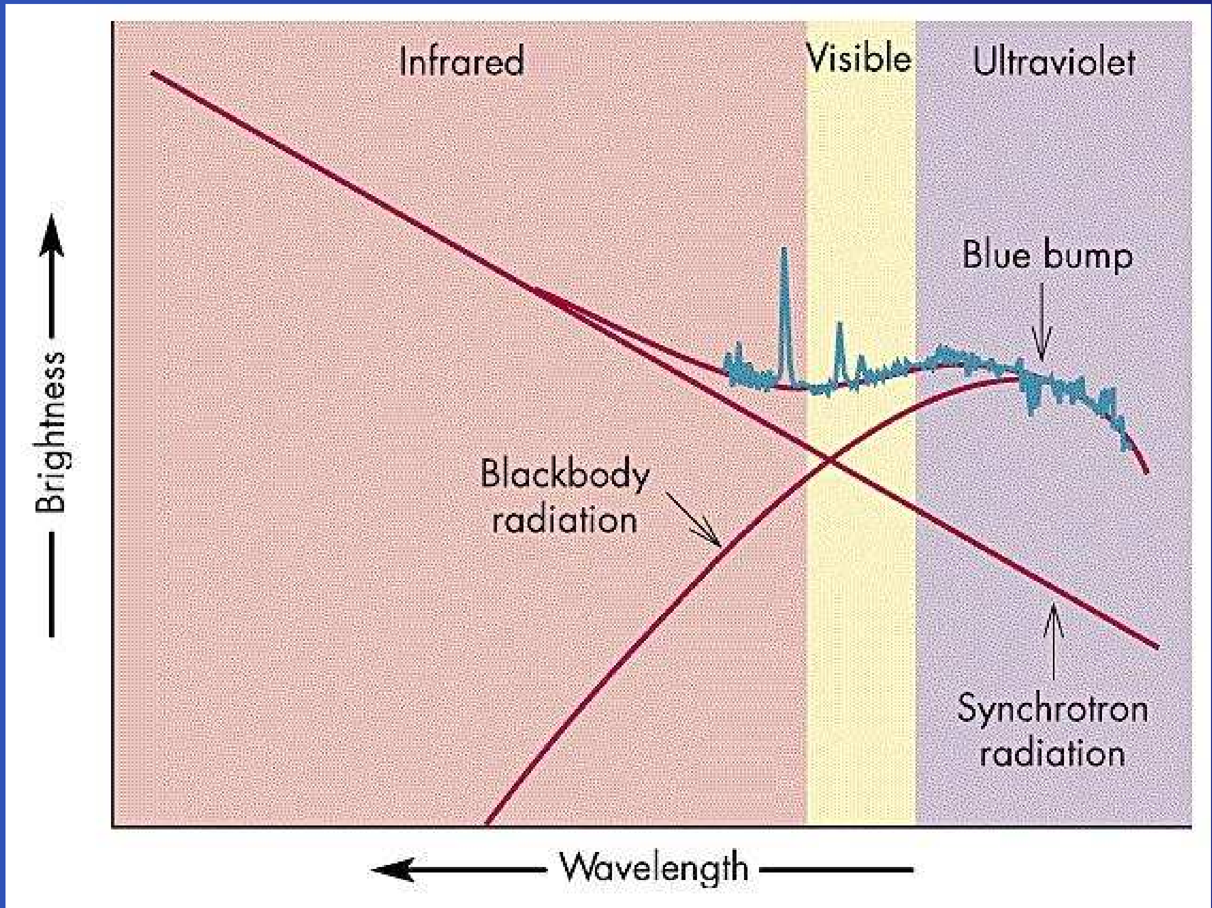
From *Zier, C. – PhD thesis*

Introduction: clasification of AGN



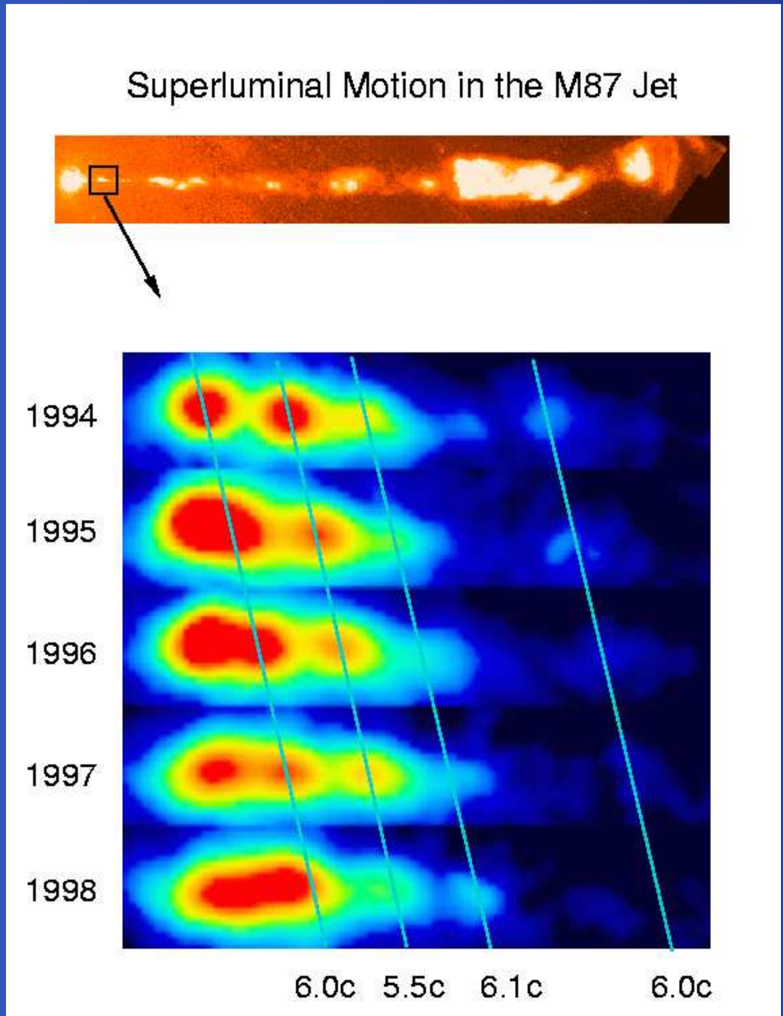
From *www.astrogeo.va.it/astronom/spettri/seyferen.htm*

Introduction: clasification of AGN



From *www.oulu.fi/astronomy/astrophysics/pr/head.html*

Introduction: clasification of AGN



Birreta, J. (1999)

HST images

Introduction

What is the origin of the energy for launching relativistic jets?

- accretion power; disk models: <u>thin</u> (Novikov & Thorne, 1973), <u>ADAF</u> (Narayan & Ly, 1995), etc.
- BH spin power; Blandford-Znajek mechanism (1977)

From *http://chandra.harvard.edu*

Introduction: Kerr metric

- for a BH of mass M and angular momentum J, the metric equations in cylindrical coordinates (t–time, r–radius, ϕ–azimuthal angle, z–hight above equatorial plane):

$$ds^2 = g_{tt}dt^2 + 2g_{t\phi}dtd\phi + g_{\phi\phi}d\phi^2 + g_{rr}dr^2 + g_{zz}dz^2\,,$$

$$ds^2 = -e^{2\nu}dt^2 + e^{2\psi}\left(d\phi - \omega dt\right)^2 + e^{2\mu}dr^2 + dz^2\,,$$

$$e^{2\nu} = \frac{r^2\Delta}{A},\; e^{2\psi} = \frac{A}{r^2},\; e^{2\mu} = \frac{r^2}{\Delta},\; \omega = 2r_{\rm g}aA^{-1}\,,$$

$$\Delta = r^2 - 2r_{\rm g}r + a^2\,,\ \text{and}\ A = r^4 + r^2a^2 + 2r_{\rm g}ra^2\,,$$

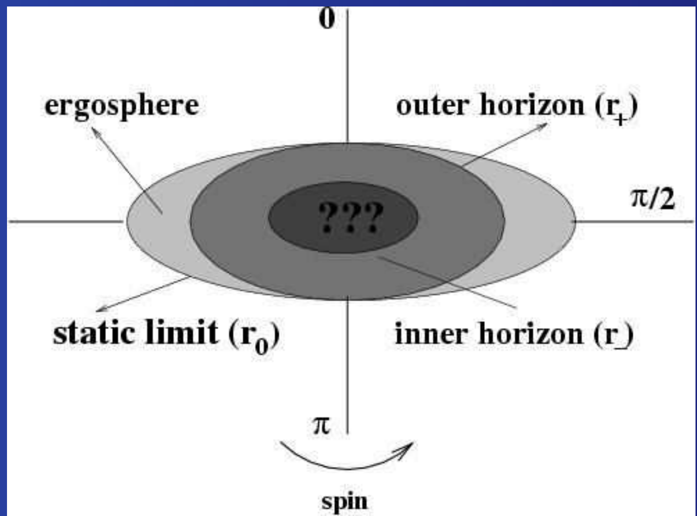
$r_{\rm g} = \frac{GM}{c^2}$ (gravit. radius), $a_* = \frac{a}{r_{\rm g}} = \frac{J/Mc}{r_{\rm g}}$ (BH spin parameter)

Introduction: Kerr metric

- horizon radius:

$$r_{\rm H} = r_{\rm g}[1 + \sqrt{1 - a_*^2}]$$

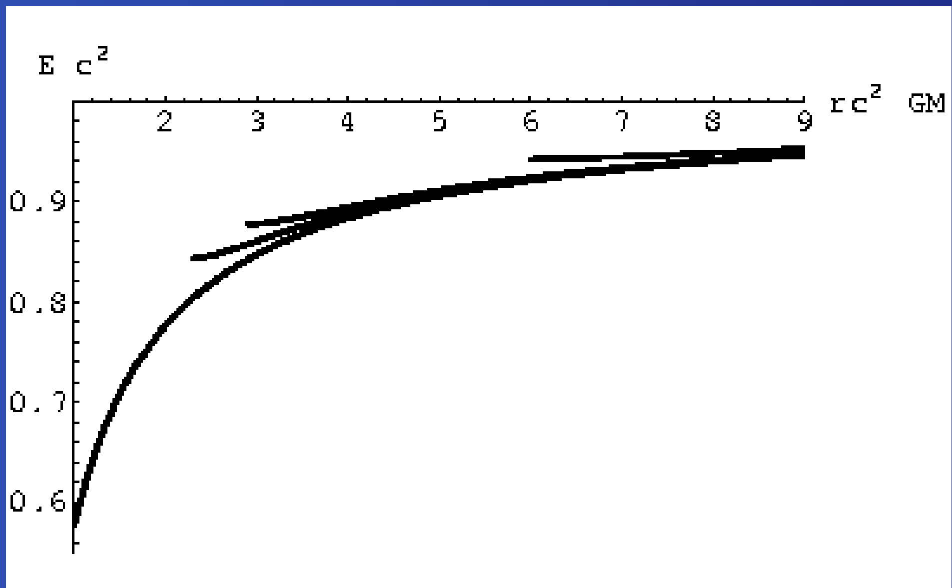
- static limit: $r_{\rm sl} = 2r_{\rm g}$, in the BH equatorial plane
- $\boxed{-1 \leq a_* \leq 1}$



Introduction: grav. potential energy

- particles specific energy orbiting around the BH

$$\boxed{E^{\dagger} = \frac{r_*^{3/2} - 2r_*^{1/2} \pm a_*}{r_*^{3/4}\left(r_*^{3/2} - 3r_*^{1/2} \pm 2a_*\right)^{1/2}}},$$ Bardeen et al. 1973



Introduction

- innermost stable orbit (Bardeen et al. 1973)

$$r_{\rm ms} = r_{\rm g}\left\{3 + z_2 - \left[(3 - z_1)\,(3 + z_1 + 2z_2)\right]^{1/2}\right\} \,,$$

where

$$\begin{aligned} z_1 &= 1 + \left[1 - (a/r_{\rm g})^2\right]^{1/3}\left[(1 + a/r_{\rm g})^{1/3} + (1 - a/r_{\rm g})^{1/3}\right] \\ z_2 &= \left[3\,(a/r_{\rm g})^2 + z_1^2\right]^{1/2} \end{aligned}$$

Introduction: BH rotational energy

- irreducible mass of the BH:

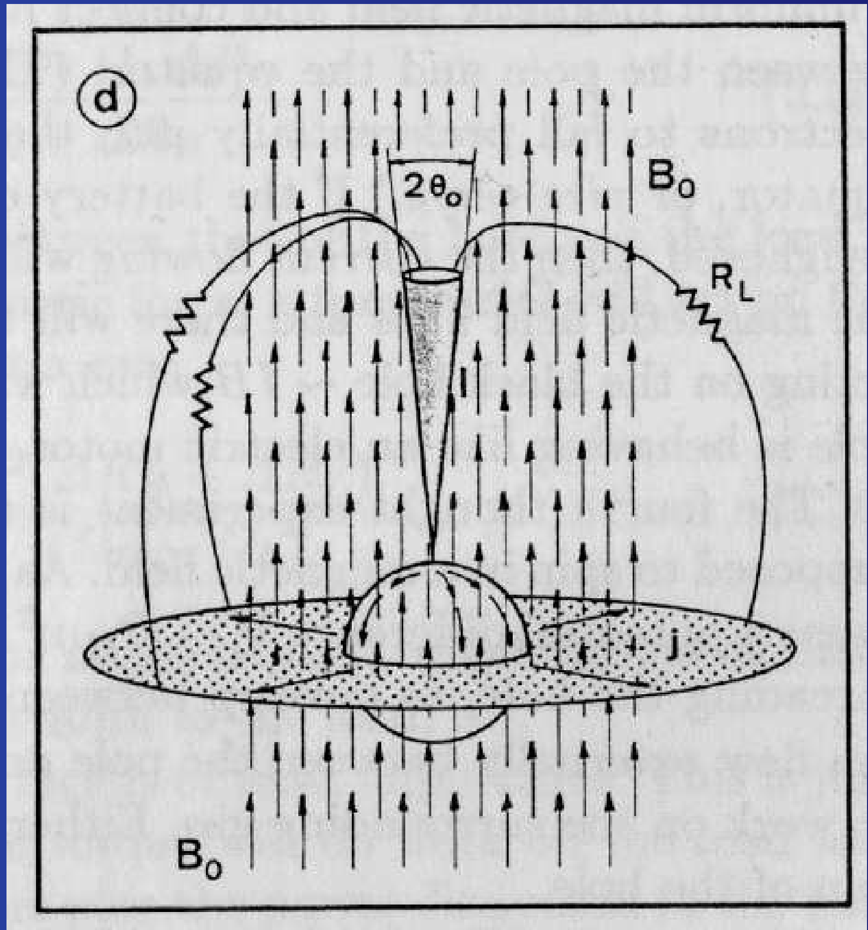
$$M^2 = M_{irr}^2 + \frac{J}{4M_{irr}^2}$$

- Blandford-Znajek process:

$$\boxed{L_{BZ} = \frac{1}{32}\omega^2 B_p^2 r_H^2 c\, a_*^2}$$

$$\omega^2 = \Omega_F(\Omega_H - \Omega_F)/\Omega_H^2$$

for $\Omega_F = 1/2$ –> $L_{BZ} = L_{BZ}^{max}$
(Thorne et al. 1986)



Introduction: magnetic connection mod

- First mentioned by Zeldovich & Schwartzman and quoted in Thorne 1974, may occur and change the energy-angular-momentum balance of the accreted gas in the disk, and then by Blandford (1999)
- Li (1999-2002) – first detailed and quantitative derivation of the energy and angular momentum transferred by magnetic connection from the BH to the accretion disk
- Wang et al. (2006) – toy model for magnetic connection in a black hole accretion disk based on a poloidal magnetic field generated by a single electric current flowing, in the equatorial plane, around a Kerr BH
- Both models provide the energy radiated by the accretion disk – no jets

Jets formation models/simulations

- Jet-disk symbiosis model: radio quasars consist of a maximal jet with a total equipartition (i.e., the magnetic energy flow of the jet is comparable to the kinetic jet power) and the total jet power is a large fraction of the disk power (Falcke & Biermann, 1995)
- GRMHD simulations (Komissarov 2004, Mizuno 2006, Hawley & Krolik 2006)
- GR Particle-in-cell simulations (Watson & Nishikawa 2006)
- Force-free time-steady Poynting dominated jet (McKinney, 2006)
- 2D GRMHD of jet formation driven by a magnetic field produced by a current loop near a rapidly rotating BH; the magnetic flux tubes bridge the region between the BH ergosphere and the corotating accretion disk (Koide, 2006)

Magnetic connetion model for jets

- Basics assumptions of the model
- Results:
  1. Launching power of the jets
  2. Efficiency of launching the jets
  3. Spin evolution of the black hole
- Relevance to the observational data
- Conclusions and remarks

Designed for...

- rapidly spinning black holes
- both Eddington and low accretion rates

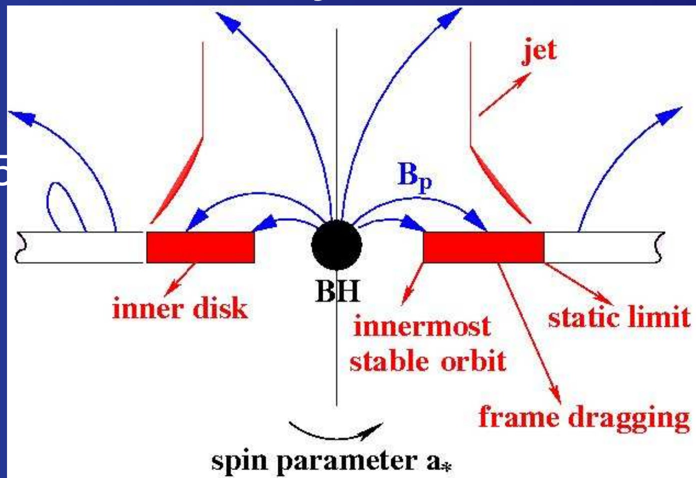
Motivated by...

- high-energy spectra and low luminosity of some AGN – for low accretion rates the BH rotational energy can drive the jets
- our goal – estimation of BH spin parameter by observing their jets

Basis assumptions of the model

- Kerr BH of $M \simeq 10^9 M_\odot +$ thin accretion disk
- inner disk extends from the static limit to the innermost stable orbit
- BH rotational energy is extracted through the closed magnetic field lines that connect the BH to the accretion disk, increasing the energy released by the inner disk
- accretion process in the inner disk occurs mostly due to the BH magnetic torque on the disk
- $q_{jets} = \frac{\dot{M}_{jets}}{\dot{M}_D} \cong 0.05$, Falcke & Biermann ('95

  $\dot{M}_D = \dot{m}\dot{M}_{Edd}, \quad \dot{M}_{Edd} \simeq 10^{27} g/s$



Conservation laws for disk structure

- Angular momentum conservation:

$$\boxed{\frac{d}{dr}\left[\left(1-q_{jets}\right)\dot{M}_D c L^\dagger\right]+4\pi r H=4\pi r J L^\dagger}$$

angular momentum transported by disk accreting mass
+ angular momentum transferred from BH to disk
= angular momentum carried away by the jets

– $L^\dagger =$ specific angular momentum of particles
– $H =$ flux of angular momentum transferred from BH to accretion disk
– $J =$ flux of energy flow into the jets

Conservation laws for disk structure

- Energy conservation:

$$\boxed{\frac{d}{dr}\left[\left(1-q_{jets}\right)\dot{M}_D c^2 E^{\dagger}\right]+4\pi r H \Omega_D = 4\pi r J E^{\dagger}}$$

energy flow in the disk + rate of magnetic torque on the disk = energy flow into the jets

– $E^{\dagger} =$ specific energy of particles
– $\Omega_D =$ Keplerian angular velocity of the disk particles
– magnetic torque on the disk surfaces:

$$T_{HD} = 2\int_{r_1}^{r_2} 2\pi r H dr$$

1. Derivation of jets launching power

- flux of angular momentum transferred from BH $\longrightarrow$ disk

$$H = \frac{1}{8\pi^3 r}\left(\frac{d\Psi_D}{c\,dr}\right)^2 \frac{\Omega_H - \Omega_D}{(-dR_H/dr)}\,,$$ Li 2002

- Defining the launching power of the both jets as

$$P_{jets} = 2\int_{r_{ms}}^{r_{sl}} 2\pi J E^{\dagger} r dr\,,$$

$$\begin{aligned} P_{jets} &= (1-q_{jets})\,\dot{M}_D c^2\left[E^{\dagger}\,(r_{sl}) - E^{\dagger}\,(r_{ms})\right] \\ &+ \frac{1}{2\pi^2}\int_{r_{ms}}^{r_{sl}}\left(\frac{d\Psi_D}{c\,dr}\right)^2 \frac{\Omega_H - \Omega_D}{(-dR_H/dr)}\Omega_D dr \end{aligned}$$

1. Derivation of jets launching power

- surface resistence of the BH (stretched horizon)

$$dR_H = R_H \frac{dl}{2\pi r_H}$$, where $R_H = 4\pi/c = 377$ ohm, Thorne et al. (1986)

- magnetic flux threading the accretion disk surface is

$$d\Psi_D = B_D^p (dS)_{z=0}$$

- area between two equatorial surfaces of a Kerr BH

$$(dS)_{z=0} = \sqrt{\det g_{(r\phi)}}\, dr\, d\phi\,,$$

$$\det g_{(r\phi)} = \begin{vmatrix} g_{rr} & g_{r\phi} \\ g_{\phi r} & g_{\phi\phi} \end{vmatrix} = \begin{vmatrix} e^{2\mu} & 0 \\ 0 & e^{2\Psi} \end{vmatrix} = \frac{A}{\Delta}$$

1. Derivation of jets launching power

How to find the magnetic field threading the disk??

1. Derivation of jets launching power

How to find the magnetic field threading the disk??

$$B_H^p = \zeta B_D^p(r_{ms}) \,, \quad \text{where } \zeta \geq 1$$

$$B_D^p = B_D^p(r_{ms}) \left(\frac{r}{r_{ms}}\right)^{-n} = \frac{B_H^p}{\zeta} \left(\frac{r}{r_{ms}}\right)^{-n}$$

$$\boxed{\left(B_H^p\right)^2 \sim \frac{\dot{M}_{Edd} c}{4\pi a^2} E^\dagger \left(r_{ms}\right)}$$

For a rapidly spinning BH with $a_* \simeq 1$:

$$B_H^p \sim 10^4 \left(\frac{M}{10^9 M_\odot}\right)^{-1/2} \text{ gauss}$$

1. Derivation of jets launching power

- using the continuum of the magnetic field $d\Psi_H = d\Psi_D$

$$B_H^p 2\pi r_H \, dl = -B_D^p \left(\frac{A}{\Delta}\right)^{1/2} 2\pi \, dr$$

then the mapping is

$$(-dR_H/dr) = \frac{2}{c\, r_H^2} \cdot \frac{1}{\zeta} \left(\frac{r}{r_{ms}}\right)^{-n} \left(\frac{A}{\Delta}\right)^{1/2}$$

- using the dimensionless parameters:
  - BH spin parameter $a_* = a/r_g$, where $-1 \leq a_* \leq +1$;
  - dimensionless radius $r_* = r/r_g$;
  - dimensionless angular velocity $\Omega_* = \Omega/(cr_g^{-1})$;
  - accretion rate in terms of the Eddington accretion rate $\dot{m} = \dot{M}_D/\dot{M}_{Edd}$.

1. Derivation of jets launching power

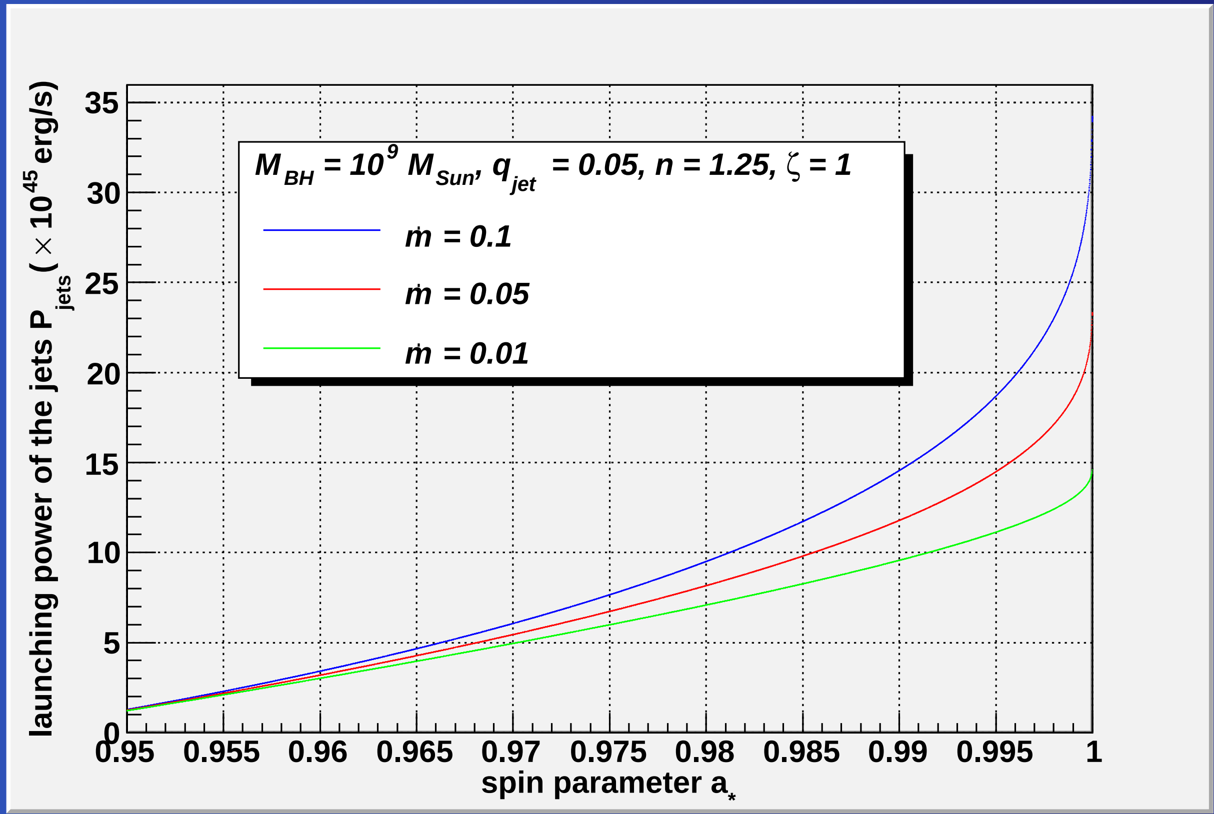
$$
\begin{aligned}
P_{jets} &= \dot{m}\dot{M}_{Edd}c^2(1-q_{jets})\left[E^{\dagger}(r_{sl_*}) - E^{\dagger}(r_{ms_*})\right] \\
&+ \dot{M}_{Edd}c^2 C_* \int_{r_{ms*}}^{r_{sl*}} r_*^{1-n} R_*^{1/2}\left(\Omega_{H_*} - \Omega_{D_*}\right)\Omega_{D_*} dr_*
\end{aligned}
$$

$$
C_* = \frac{r_{H_*}^2 r_{ms_*}^n}{4\pi\zeta a_*^2} E^{\dagger}(r_{ms_*}), \quad R_* = \frac{1 + a_*^2 r_*^{-2} + 2a_*^2 r_*^{-3}}{1 - 2r_*^{-1} + a_*^2 r_*^{-2}} .
$$

$$
\boxed{P_{jets} = P_{jets}^{acc} + P_{jets}^{rot}}
$$

- choosing the parameters:
  - $n = 5/4$, by scaling the Kelperian velocity with the Alfven velocity (Blandford & Payne)
  - $\varsigma = 1$, for maximizing the launching power of the jets

Launching power of the jets vs. spin parameter



2. Efficiency of launching the jets

We define the efficiency of launching the jets

$$\boxed{\eta = \frac{P_{jets}}{\dot{m}\dot{M}_{Edd}c^2 + P_{jets}^{rot}}}$$

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accretion disk BH rotational energy

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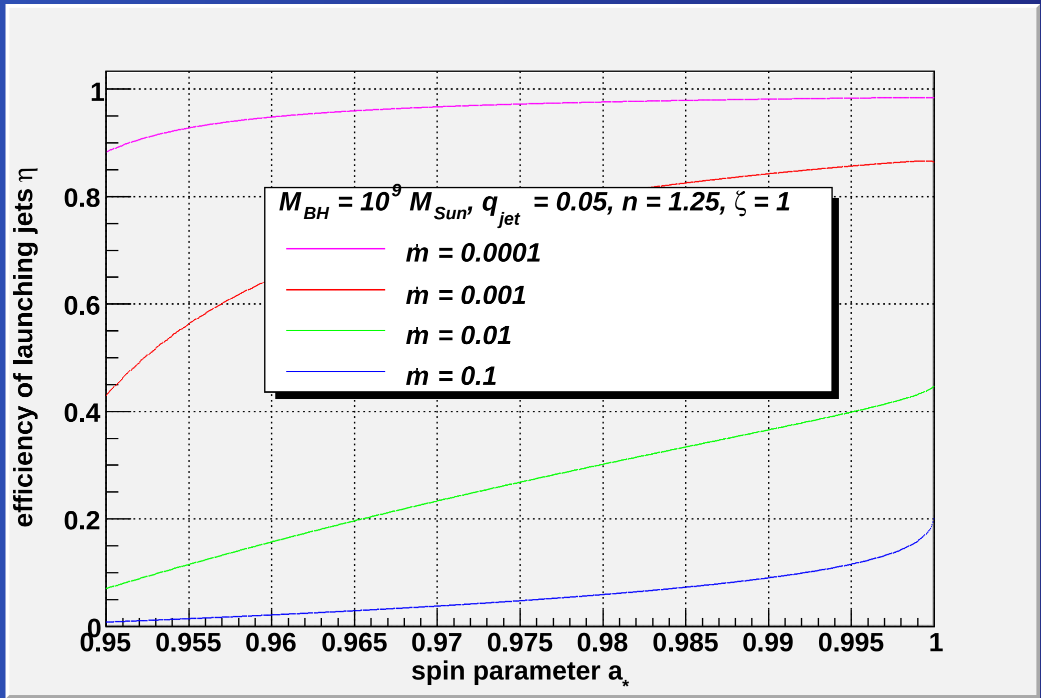


2. Efficiency of launching the jets

$\dot{m}$	$P_{jets}[\times 10^{45} erg/s]$	P_{jets}^{rot}/P_{jets}
1	241.04	0.05
0.1	35.34	0.35
0.01	14.77	0.84
0.001	12.71	0.98
0.0001	12.50	0.99

- for the Eddington accretion rate, only 5% from the jets power comes from the BH rotation, the rest comes from the accreting mass flow
- for low accretion rates, almost 100% of the jets power comes from the BH rotation

For low accretion rates, the jets can be driven due to the extraction of the BH rotational energy!!

3. Spin evolution of the BH

- The angular momentum and energy transferred from the BH to the accretion disk by magnetic torques

$$c^2\left(\frac{dM}{dt}\right)_{HD} = -2P_{HD}\,, \qquad \left(\frac{dJ}{dt}\right)_{HD} = -2T_{HD}$$

where $P_{HD} = \Omega_H T_{HD}$

- The total angular momentum and energy transferred between the BH and the accretion disk

$$c^2\left(\frac{dM}{dt}\right)_{tot} = (1-q_{jets})\,\dot{M}_D c^2 E^{\dagger}_{ms} + c^2\left(\frac{dM}{dt}\right)_{HD}$$

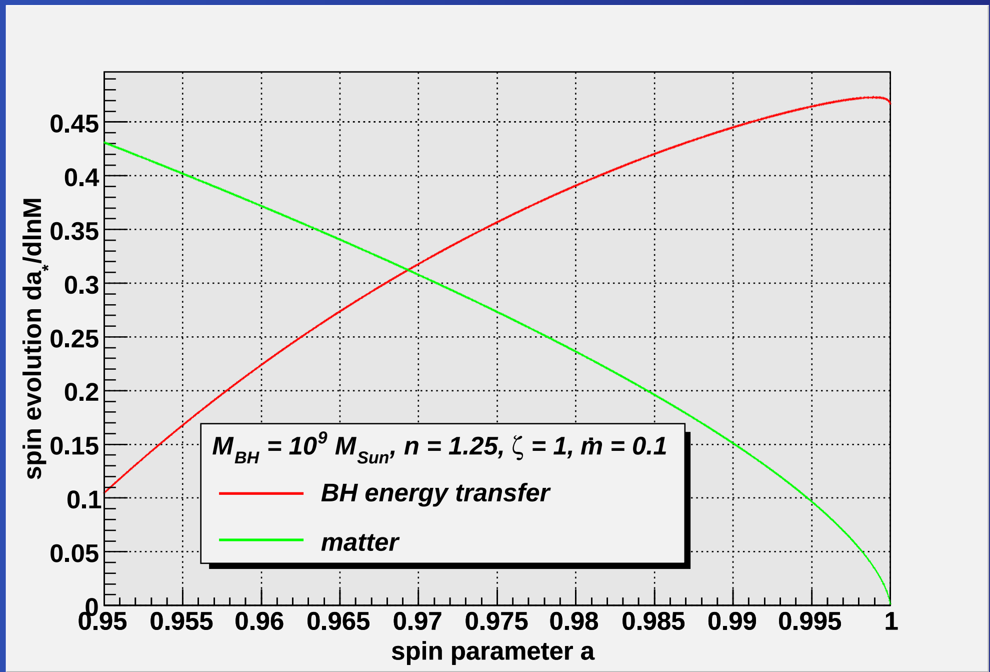
$$\left(\frac{dJ}{dt}\right)_{tot} = (1-q_{jets})\,\dot{M}_D L^{\dagger}_{ms} + \left(\frac{dJ}{dt}\right)_{HD}$$

3. Spin evolution of the BH

$$\boxed{\frac{da_*}{d\,lnM} = \frac{c}{GM}\left(\frac{dJ}{dM}\right) - 2a_*}$$

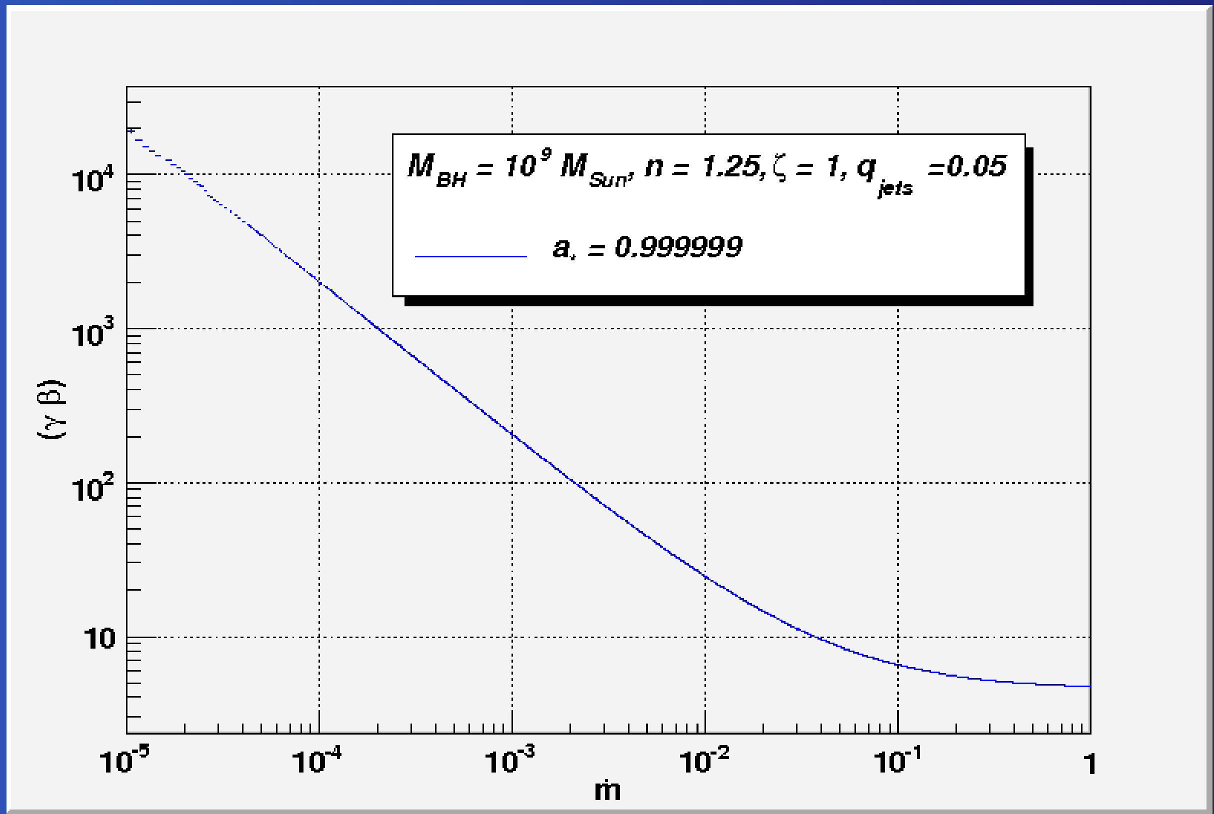
– green line = driving torque by which the matter spin-up the BH

– red line = counteracting torque due to the BH rotational energy transfer to the disk

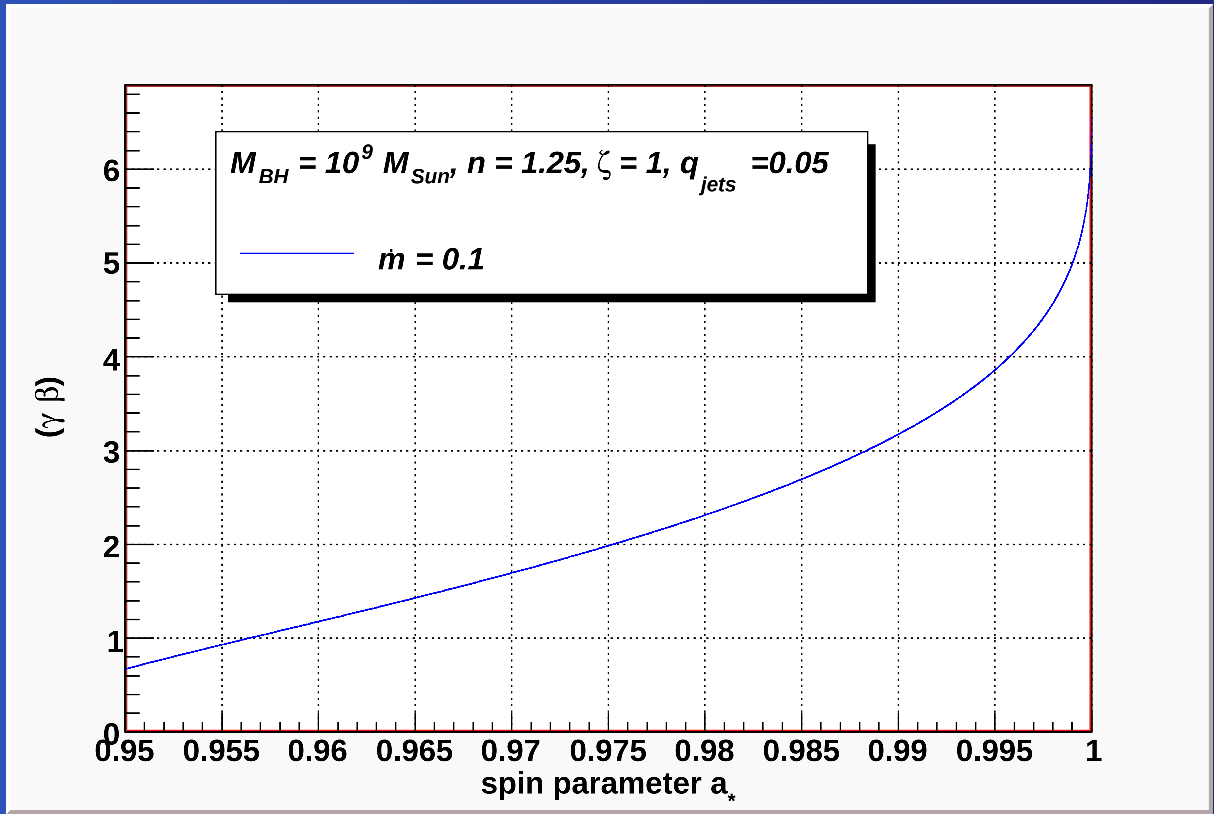


Relevance to the observational data

1. IF almost all the jets power is transferred to the jets particles as kinetic energy

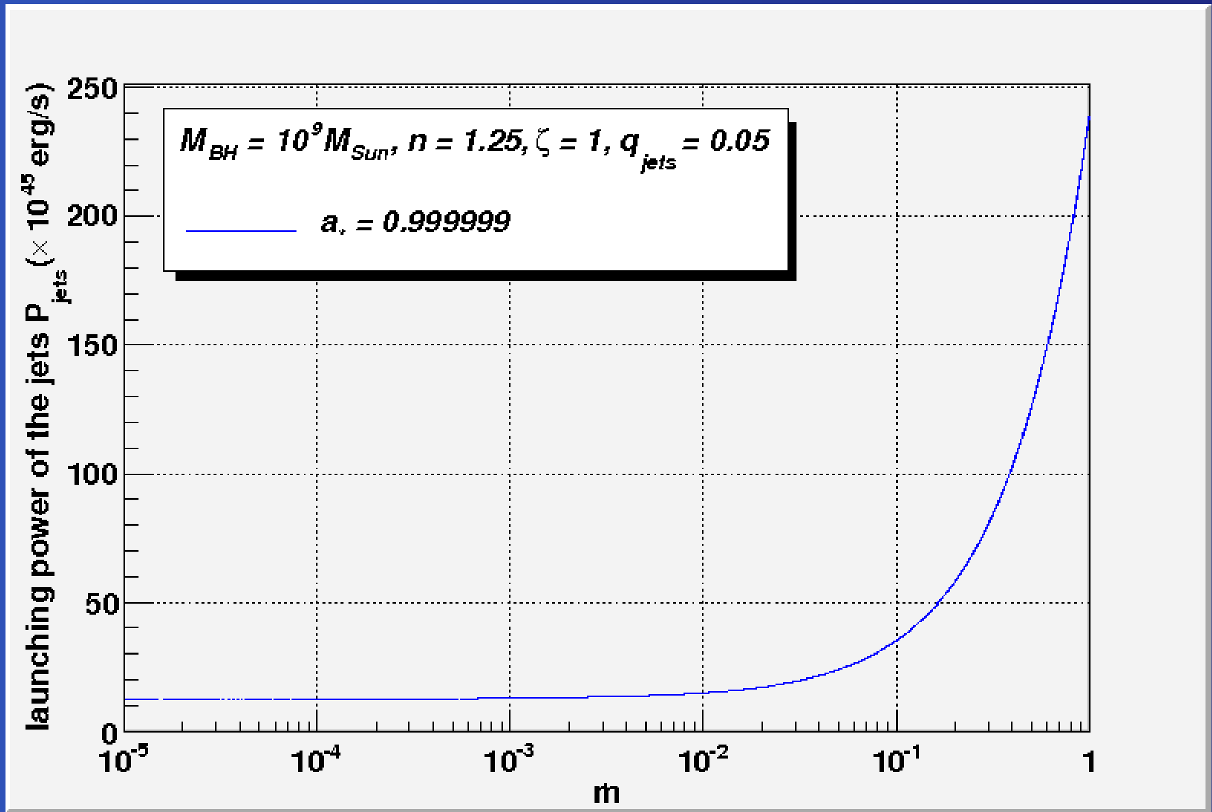


Relevance to the observational data



Relevance to the observational data

2. Testing the launching power of the jets by using the radio emission and BH mass in AGN available from data



Conclusions and remarks

- we calculated the launching power of the jets, the efficiency of launching the jets and the spin evolution of the black hole in the case of Eddington accretion rate and low accretion rates
- for low accretion rates the contribution of the rest mass energy of the accreting mass is low (e.g., 0.16% of the jet power, for $\dot{m} = 0.01$). In this cases, the jets can be powered by the energy extracted from the black hole rotation
- we show possible tests of the model with respect to the observational data

Future work: testing the model with observational data