Launching Relativistic Jets from Spinning Black Holes

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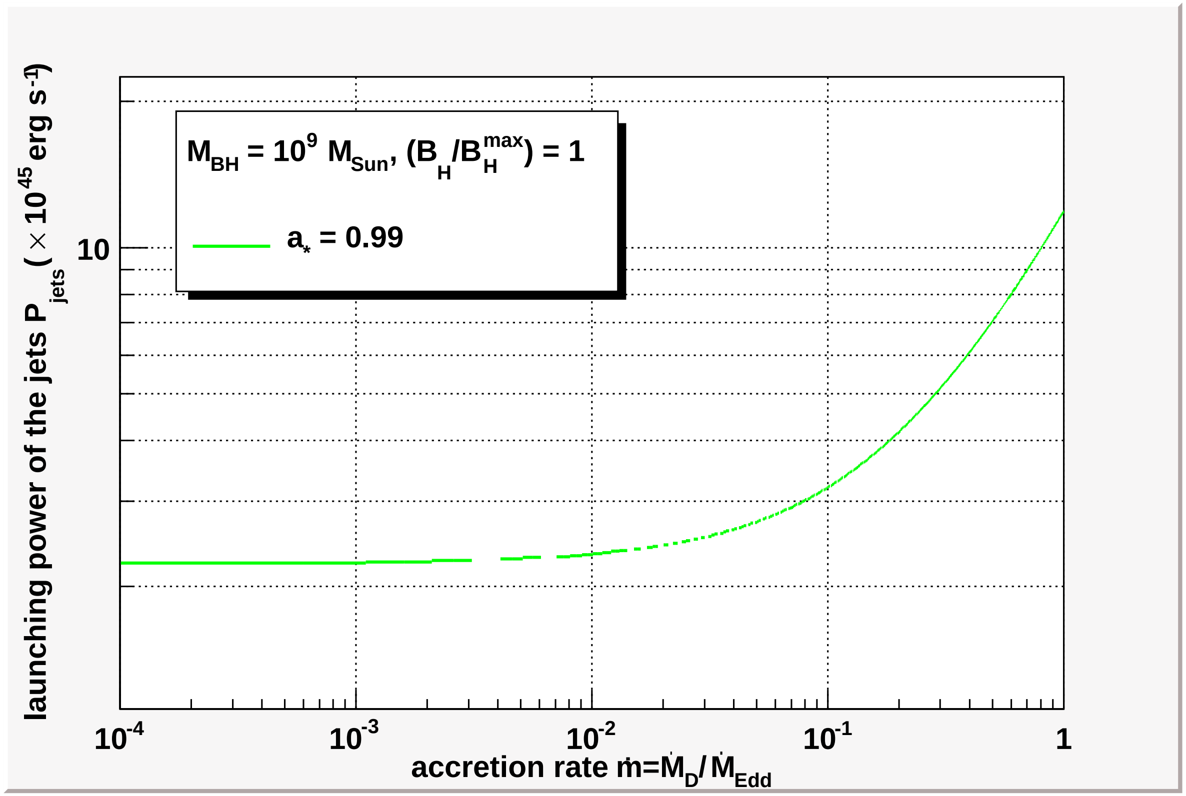
Content

- **Magnetic connection model** for launching relativistic jets in AGN
- UHECR contribution from spin-down power of BH
- GRMHD simulations of jets formation from Kerr BH

Magnetic Connection Model for Launching Relativistic Jets in AGN

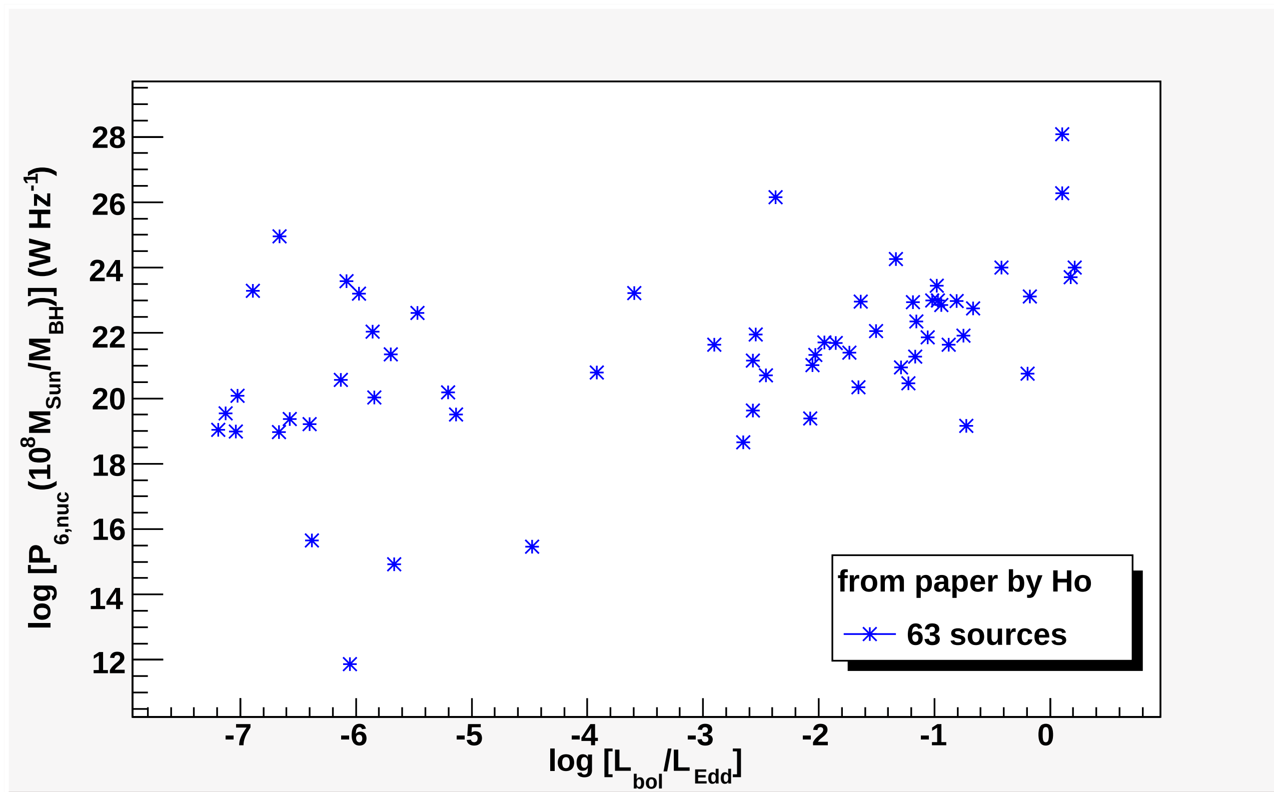
Reasons

- mass flow out from the accretion disk
- link to the observations



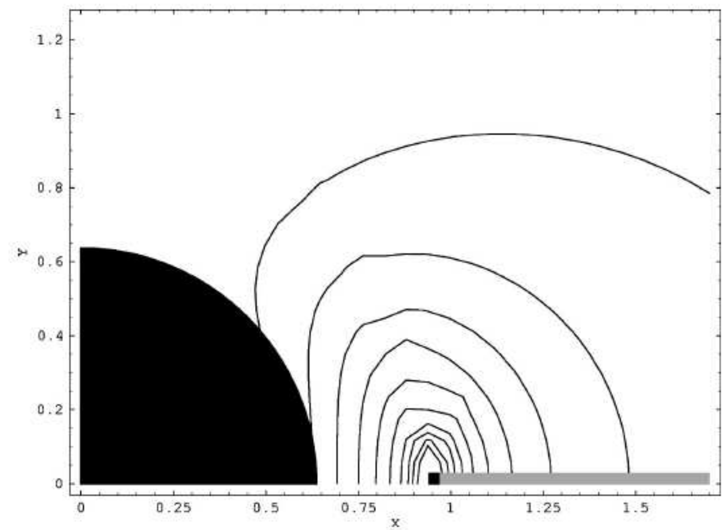
Reasons

Using data from Ho, L. C. 2002, ApJ 564, 120



Magnetic connection

- 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 Thorne et al. (1986), Blandford (1999)



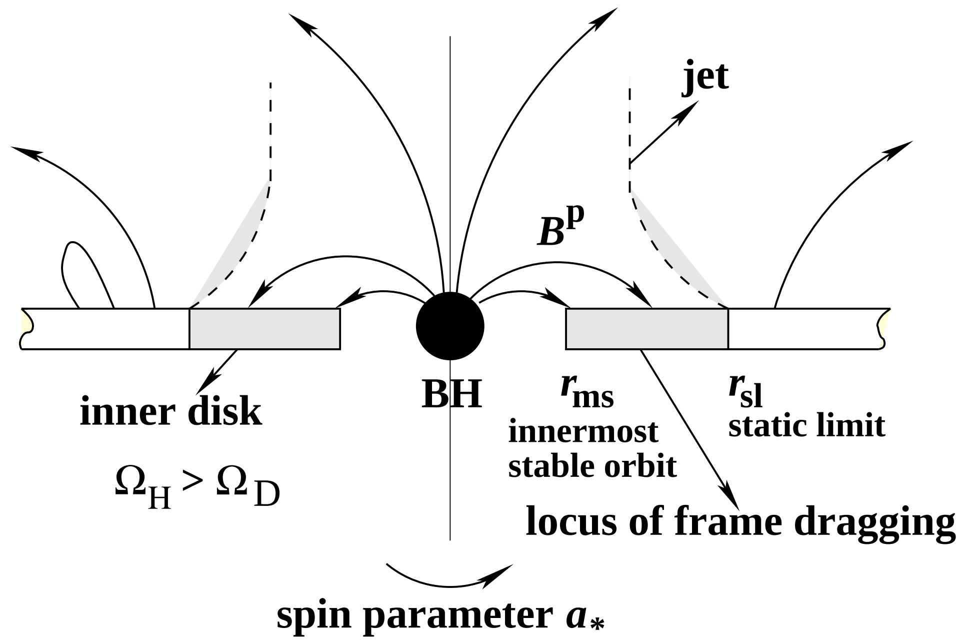
Li 2002 ApJ 567, 476

- Li (1999-2002) – first detailed and quantitative derivation of energy and a.m. transferred by magnetic connection from BH to accretion disk; closed magnetic field generated by a current loop at the edge of the disk

Magnetic connection

- Uzdensky (2004, 2005) – magnetic connection structure by solving Grad-Shafranov equation (Schwarzschild & Kerr BHs)
- Wang et al. (2002, 2007) – 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

Assumptions



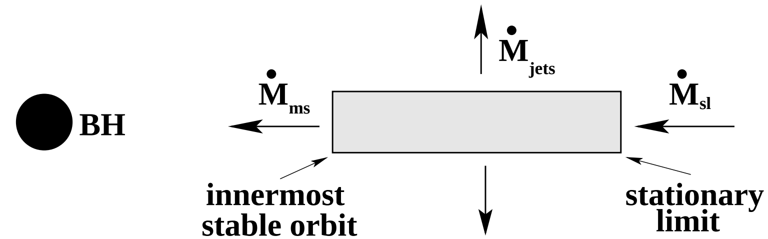
- Kerr BH of $M \simeq 10^9 M_\odot +$ thin accretion disk
- inner disk extends from the static limit to the innermost stable orbit
- BH rotational energy is extracted through the closed magnetic field lines that connect the BH to the accretion disk, increasing the energy released by the inner disk; this energy is used to launch the jets
- accretion process in the inner disk occurs mostly due to the BH magnetic torque on the disk; the removed disk angular momentum is carried away by the jets
- particles from the disk flow along the closed magnetic field lines and eventually cross them

Mass flow rate into the jets

- vertical mass flow

$$\dot{M}_{\rm jets} = \dot{M}(\rm r_{sl}) - \dot{M}(\rm r_{ms})$$

$$\dot{M} = -2\pi\sqrt{-g}\,\Sigma\,\bar{v}^{\hat{r}}\,\mathcal{D}^{1/2}$$



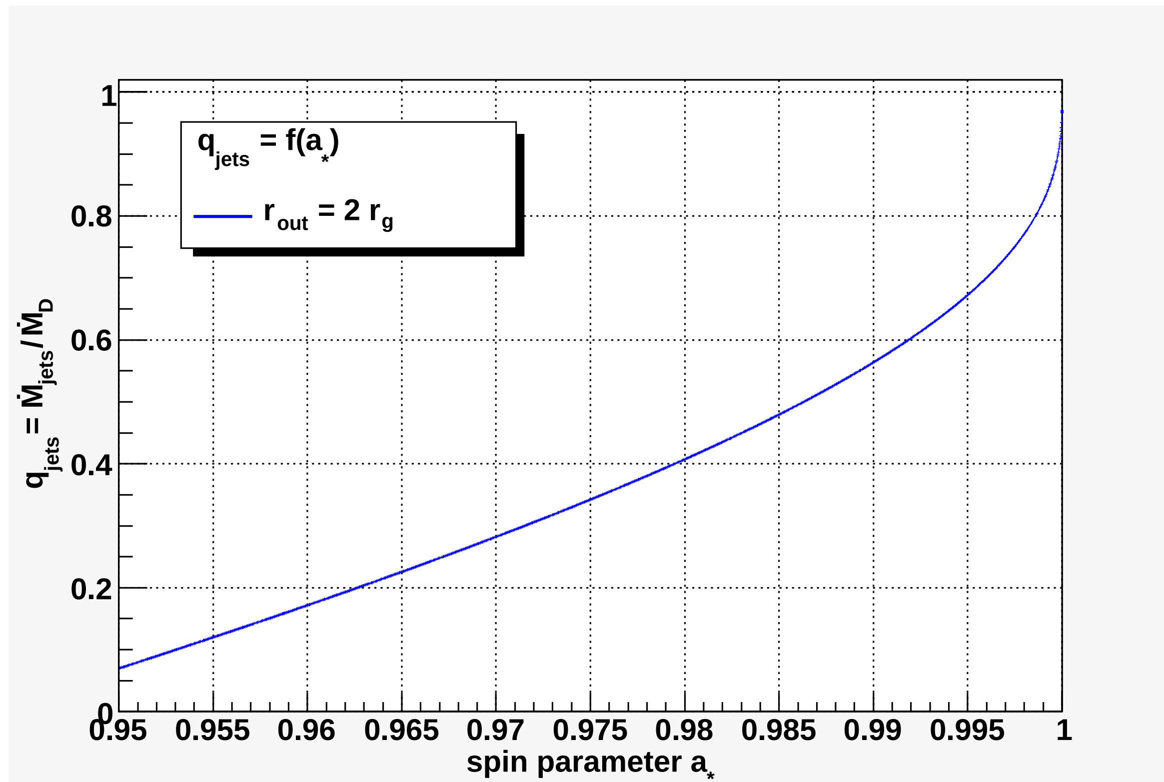
$$\dot{M}_{\rm jets} = q_{\rm jets}\dot{M}_{\rm D} = \dot{m}\dot{M}_{\rm Edd}\left[1 - \frac{\dot{M}(\rm r_{ms})}{\dot{M}(\rm r_{sl})}\right]$$

$$\Sigma\bar{v}^{\hat{r}} \propto r^{p}$$

$$\boxed{\sqrt{-g}\,\mathcal{D}^{1/2}}$$

$$q_{\rm jets}(a_*) = 1 - \frac{r_{\rm ms_*}}{r_{\rm sl_*}}\cdot\left(\frac{1-2/r_{\rm ms_*}+a_*^2/r_{\rm ms_*}^2}{1-2/r_{\rm sl_*}+a_*^2/r_{\rm sl_*}^2}\right)^{1/2}$$

Mass flow rate into the jets



$$a_* = 0.999999 \rightarrow q_{\rm jets} \simeq 0.98$$
$$a_*^{lim} = 0.9982 \rightarrow q_{\rm jets} \simeq 0.78$$
$$a_* = 0.95 \rightarrow q_{\rm jets} \simeq 0.07$$
$$r_{\rm out} > 2r_{\rm g} \rightarrow q_{\rm jets} > 0 \text{ if } a_* > 0.755$$

Conservation laws

Use the conservation laws derived by Page & Thorne (1974) including MC and jet launching:

- angular momentum consevation law

$$0 = \int_{\mathscr{V}} \nabla \cdot \boldsymbol{J} (-g)^{1/2} dt dr dz d\varphi = \int_{\partial \mathscr{V}} \boldsymbol{J} \cdot d^3 \boldsymbol{\Sigma} = \int_{\partial \mathscr{V}} T_\varphi{}^\alpha d^3 \Sigma_\alpha$$

$$= \left\{ \int_{-H}^{+H} \int_t^{t+\Delta t} \int_0^{2\pi} [\rho_0 (1 + \Pi) u_\varphi u^r + t_\varphi{}^r + u_\varphi q^r + q_\varphi u^r] (-g)^{1/2} d\varphi dt dz \right\}_r^{r+\Delta r}$$

$$+ \left\{ \int_r^{r+\Delta r} \int_t^{t+\Delta t} \int_0^{2\pi} [\rho_0 (1 + \Pi) u_\varphi u^z + t_\varphi{}^z + u_\varphi q^z + q_\varphi u^z] (-g)^{1/2} d\varphi dt dr \right\}_{-H}^{+H}$$

$$+ \{\text{total angular momentum in the 3-volume}\}_t^{t+\Delta t} .$$

- MC torque and flux of a.m. transferred from BH to disk (Li 2002)

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

$$H = \frac{1}{8\pi^3 r} \left(\frac{d\Psi_{\rm D}}{c\, dr} \right)^2 \frac{\Omega_{\rm H} - \Omega_{\rm D}}{(-dR_{\rm H}/dr)}$$

Conservation laws

- angular momentum consevation law

$$\frac{d}{dr}\left[\left(1-q_{\rm jets}\right)\dot{M}_{\rm D}cL^{\dagger}\right]+4\pi rH=4\pi rJL^{\dagger}$$

a.m. carried by accreting mass of the inner disk + a.m. transferred from the BH to the inner accretion disk = a.m. carried away by jets

- energy consevation law

$$\frac{d}{dr}\left[\left(1-q_{\rm jets}\right)\dot{M}_{\rm D}c^{2}E^{\dagger}\right]+4\pi rH\Omega_{\rm D}=4\pi rJE^{\dagger}$$

energy transported by accreting mass + energy transferred by MC = energy flow along the jets

- launching power of jets

$$P_{\rm jets}=2\int_{r_{\rm ms}}^{r_{\rm sl}}2\pi JE^{\dagger}rdr$$

Launching power of the jets

$$P_{\rm jets} = (1 - q_{\rm jets})\, \dot{M}_{\rm D} c^2 \left(E^{\dagger}_{\rm sl} - E^{\dagger}_{\rm ms} \right) + 4\pi \int_{r_{\rm ms}}^{r_{\rm sl}} r H \Omega_{\rm D} dr$$

- magnetic flux threading the inner disk surface

$$\Psi_{\rm D} = \int B_{\rm D} (dS)_{z=0}\,, \quad (dS)_{z=0} = \sqrt{\det g_{(r\phi)}}\, dr\, d\phi$$

- poloidal magnetic field threading the inner disk surface

$$B_{\rm D} = B_{\rm D}(r_{\rm ms}) \left(\frac{r}{r_{\rm ms}} \right)^{-n} = \frac{B_{\rm H}}{\zeta} \cdot \left(\frac{r}{r_{\rm ms}} \right)^{-n}$$

- resistance between two magnetic surfaces threading the horizon $dR_{\rm H} = R_{\rm H} \frac{dl}{2\pi r_{\rm H}}$, $R_{\rm H} = 4\pi/c = 377$ohm

Launching power of the jets

- BH generates a potential difference driving electric current around a circuit and the energy to do this comes from the BH rotation (Znajek 1978)
- set the potential drop to the energy of the particles carried into BH, in an early epoch when the BH accretes at the Eddington limit; gives the maximum value of the magnetic field threading the horizon

$$(B_{\rm H}^{\rm max})^2 = \frac{\dot{M}_{\rm Edd}c}{4\pi(a^{\rm lim})^2}E^{\dagger}_{\rm ms}(a^{\rm lim}) = 0.56\times 10^4\left(\frac{M}{10^9 M_\odot}\right)^{-1/2}\ {\rm G}$$

- continuum of the magnetic field (Wang et al. 2006)

$$B_{\rm H}2\pi r_{\rm H}\,dl = -B_{\rm D}\left(\frac{A}{\Delta}\right)^{1/2}2\pi\,dr$$

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

Launching power of the jets

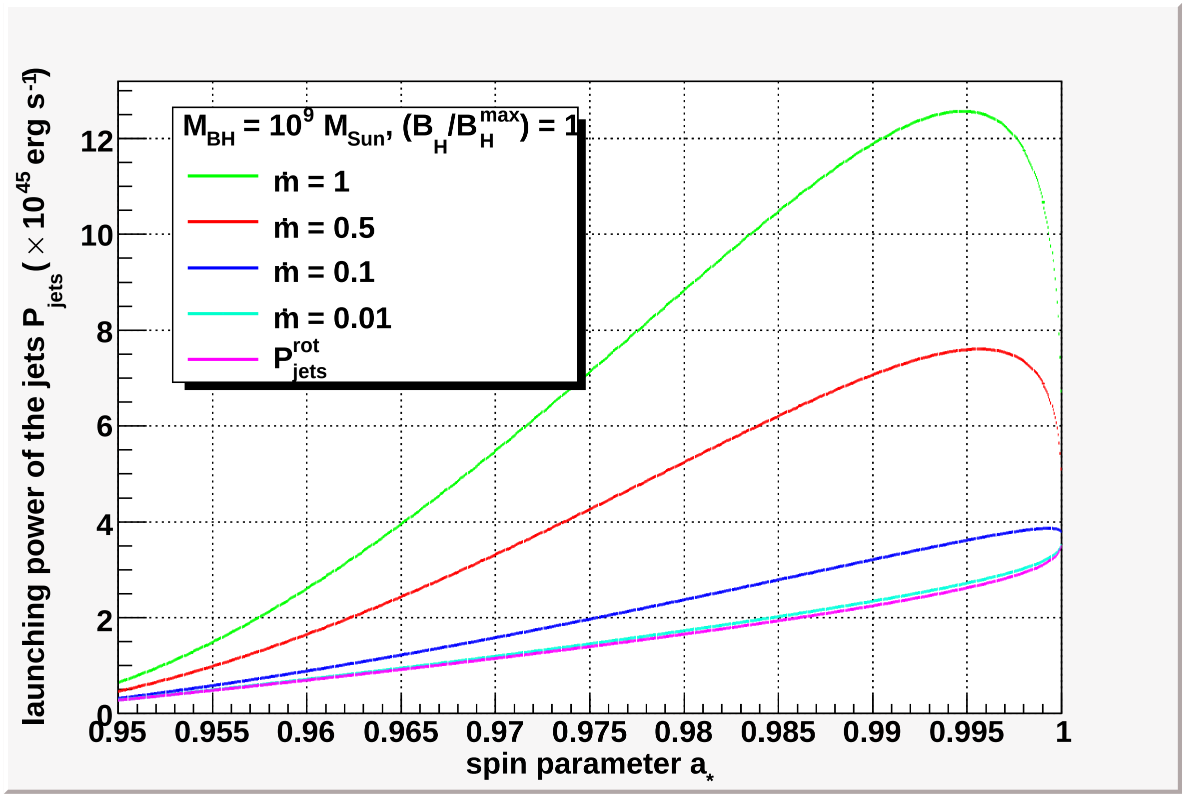
$$
\begin{aligned}
P_{\rm jets} \quad &= \quad \dot{m}\dot{M}^{\dagger}_{\rm Edd}c^2\varepsilon^{-1}(1-q_{\rm jets})\left(E^{\dagger}_{{\rm sl}_*}-E^{\dagger}_{{\rm ms}_*}\right) \\
&+ \quad \dot{M}^{\dagger}_{\rm Edd}c^2C^*\left(\frac{B_{\rm H}}{B^{\rm max}_{\rm H}}\right)^2\int_{r_{{\rm ms}_*}}^{r_{{\rm sl}_*}} r_*^{1-n}{\rm R}_*^{1/2}\left(\Omega_{{\rm H}_*}-\Omega_{{\rm D}_*}\right)\Omega_{{\rm D}_*}dr_*
\end{aligned}
$$

$\zeta = 1$, gives the maximum for $P_{\rm jets}$

$n = 2$, frozen magnetic field

$$P_{\rm jets} = P^{\rm acc}_{\rm jets} + P^{\rm rot}_{\rm jets}$$

Launching power of the jets



Spin evolution of the black hole

Content

- change of mass and a.m. of BH by accretion (Bardeen 1970) $dM = E^{\dagger}_{\rm ms}\, dM_0$ and $dJ = J^{\dagger}_{\rm ms}\, dM_0$

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

- equations for the evolution of the mass and angular momentum of the BH with MC

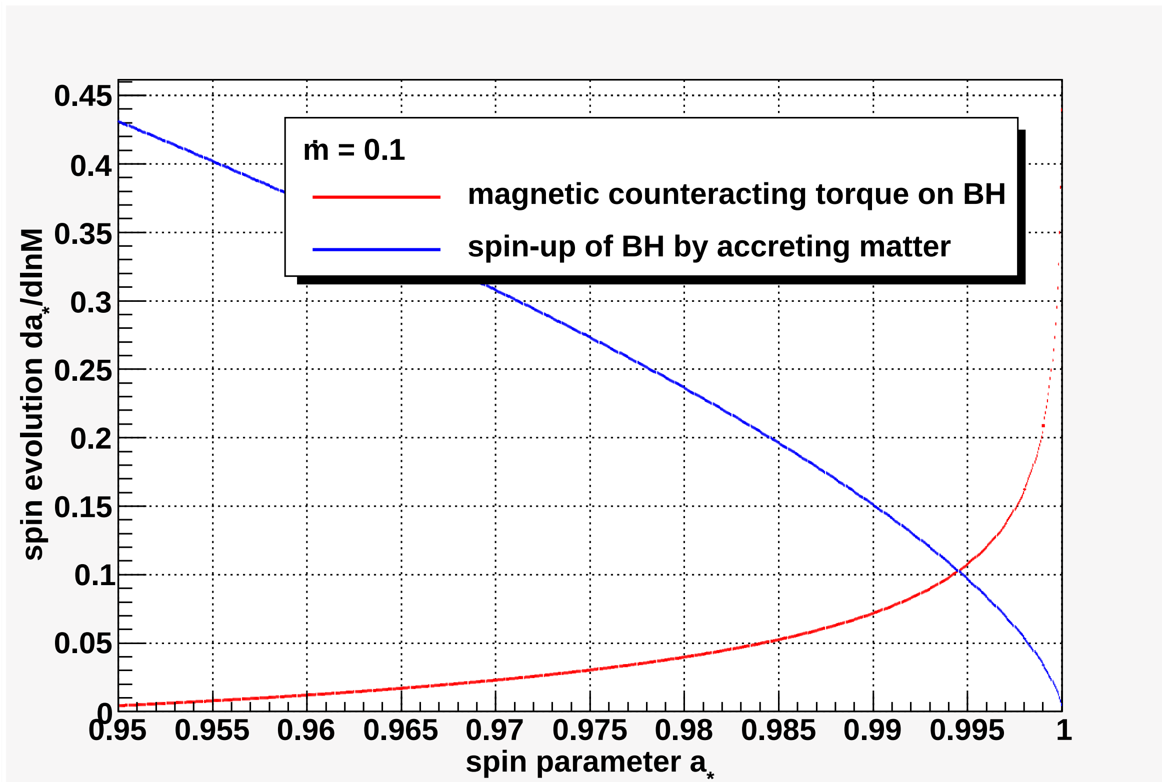
$$c^2\left(\frac{dM}{dt}\right) = (1 - q_{\rm jets})\, \dot{M}_{\rm D} c^2 E^{\dagger}_{\rm ms} + c^2\left(\frac{dM}{dt}\right)_{\rm HD},$$

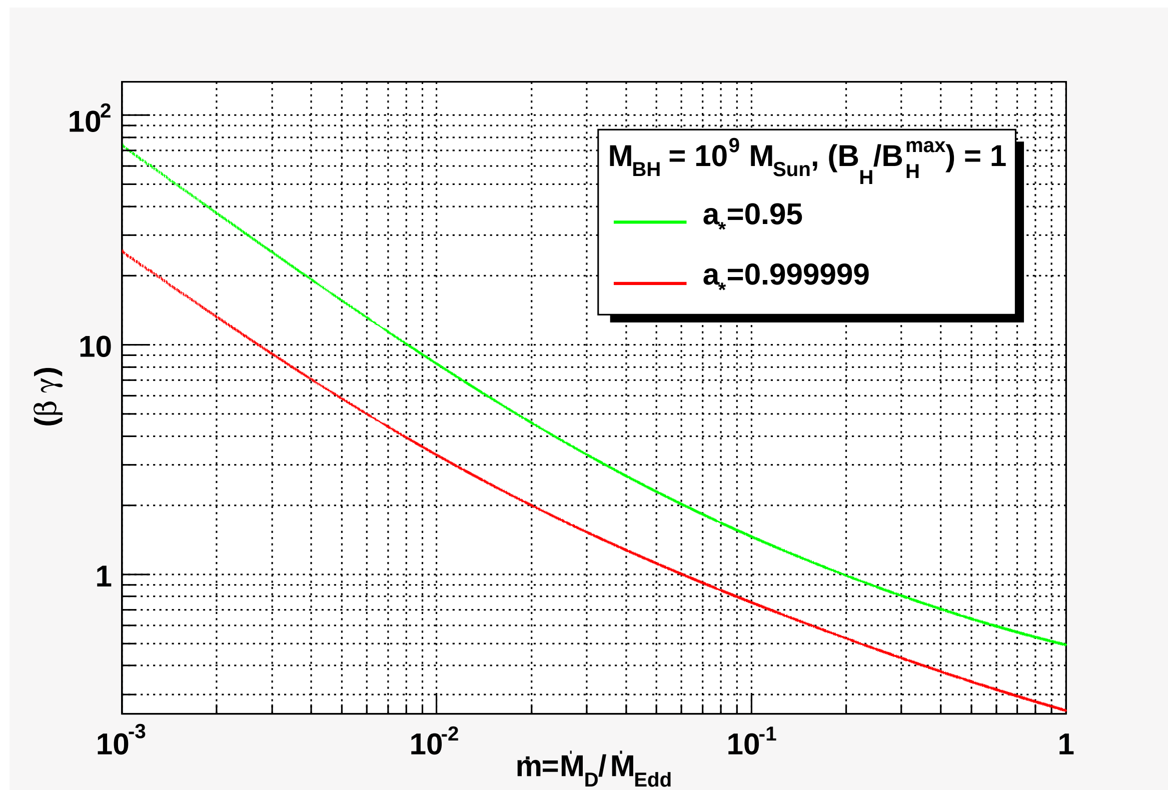
$$\left(\frac{dJ}{dt}\right) = (1 - q_{\rm jets})\, \dot{M}_{\rm D} L^{\dagger}_{\rm ms} + \left(\frac{dJ}{dt}\right)_{\rm HD}.$$

- total spin evolution of BH

$$\left(\frac{da_*}{d\, lnM}\right)_{\rm HD} = \left(\frac{da_*}{d\, lnM}\right)_{\rm total} - \left(\frac{da_*}{d\, lnM}\right)_{\rm matter}$$

Spin evolution of the black hole

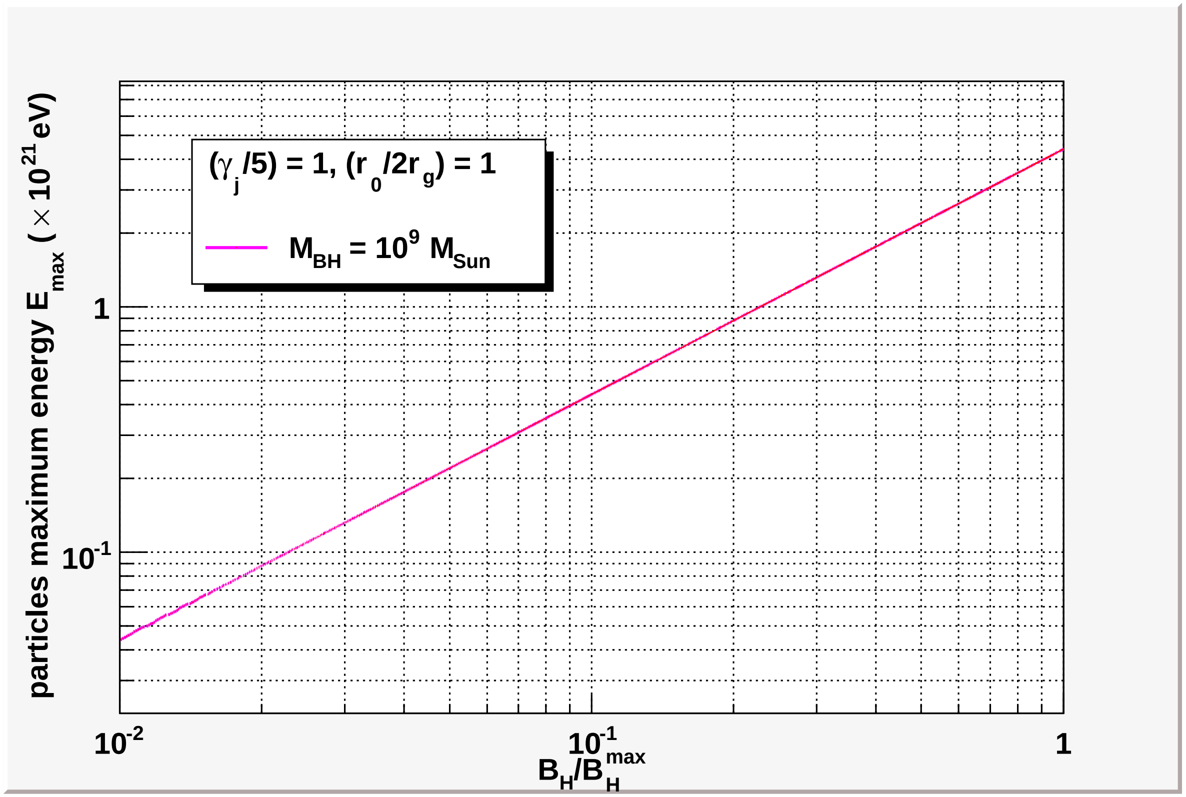




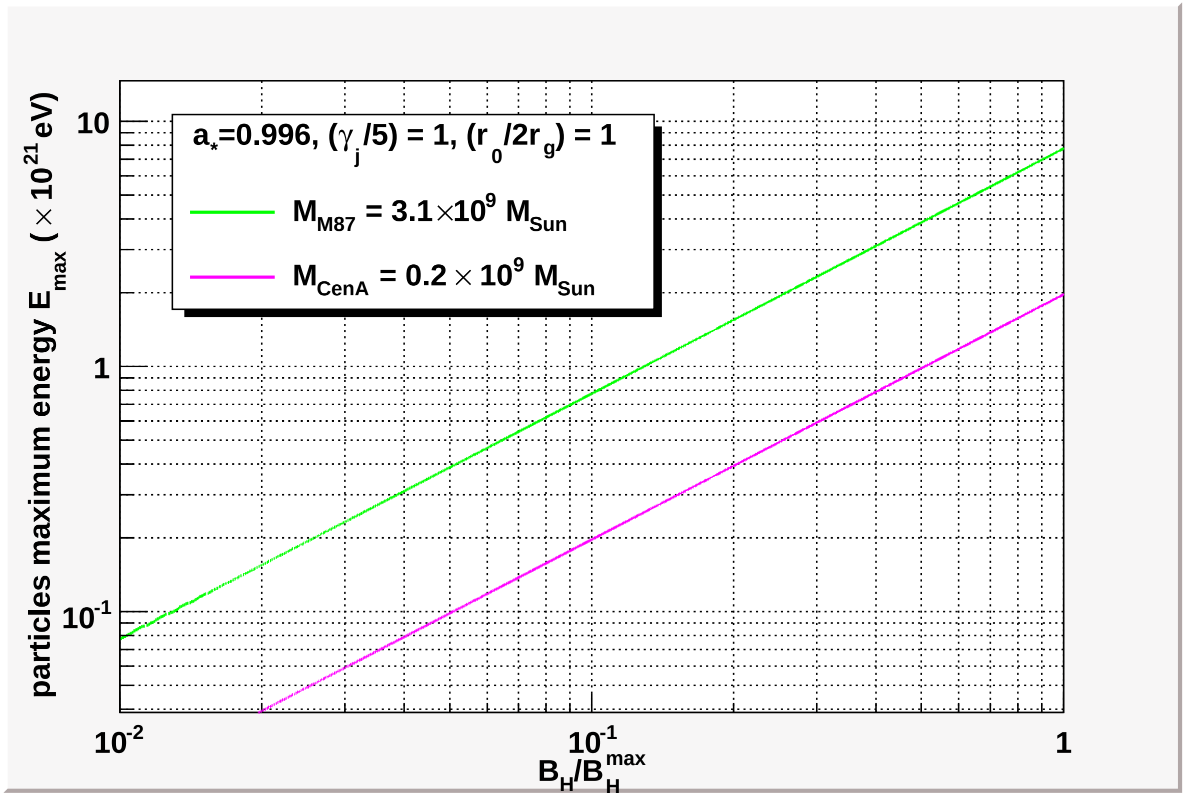
$(\beta\gamma)$ of the jets as function of the accretion rates

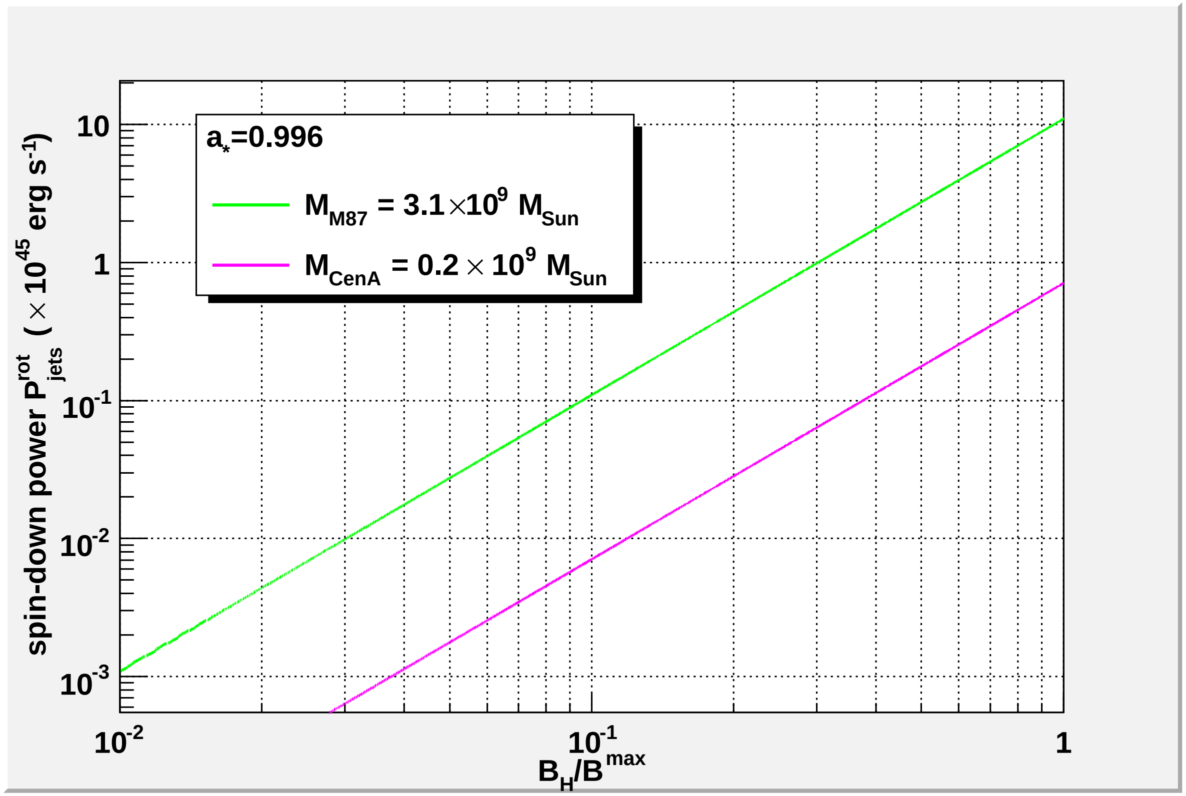
- particles maximum energy: $E_{\rm max} = qBz\theta$

$$E_{\rm max} = 4.4 \times 10^{21} \left(\frac{M}{10^9 M_\odot}\right)^{1/2} \left(\frac{B_{\rm H}}{B_{\rm H}^{\rm max}}\right) \left(\frac{\gamma_{\rm j}}{5}\right) \left(\frac{r_0}{2\, r_{\rm g}}\right) \text{(eV)} .$$



Relevance


a_*=0.996, $(\gamma_j/5)$ = 1, $(r_0/2r_g)$ = 1
M_{M87} = 3.1×10^9 M_{Sun}
M_{CenA} = 0.2 × 10^9 M_{Sun}
particles maximum energy E_{max} (× 10^{21} eV)
10
1
10^{-1}
10^{-2}
10^{-1}
1
B_H/B_H^{max}


a*=0.996
M_M87 = 3.1×10^9 M_Sun
M_CenA = 0.2 × 10^9 M_Sun
spin-down power P^rot_jets (× 10^45 erg s^-1)
B_H/B^max
10
1
10^-1
10^-2
10^-3
10^-2
10^-1
1

Relevance

- The factor between the Poynting flux transported by the jets and the particles maximum energy (Lovelace 1976):

$$P \sim E_{\rm max}^2$$

- to 10^{47} erg/s corresponds 10^{21} eV
- Cen A: 10^{43} erg/s and M87: 10^{42} erg/s – cannot accelerated protons to 10^{21} eV?

Conclusions

- Jets launched in the context of the magnetic connection !?
- Crossing of the magnetic fieled lines...
- Angular momentum transported by the jets?
- Just a toy model...
- Reasonable?

UHECR contribution from spin-down power of BH

Content

GRMHD simulations of jets formation from Kerr BH

GRMHD simulations of jets formation from Kerr BH