Ratio of kinetic-to-bolometric luminosity at the "cold" disk accretion onto black holes

S.V.Bogovalov
National research nuclear university (MEPHI)
Moscow, Russia

High ratio of the kinetic luminosity of jets over the bolometric luminosity of disks:observations

1. M87 L_{bol} ~ 10^{42} erg/s (Biretta et al. 1991); L_{jets} ~ 10^{44} erg/s (Bicknell & Begelman 1996, Reynolds et al. 1996)

2. Fermi LAT data (Ghisselini et al. , Nature, 515, 376, 2014)The hole family of blazars detected by Fermi LAT in gamma-rays demonstrates that the kinetic luminosity of the jets dominates the bolometric luminosity.

3. Our Galaxy (HESS, Nature, 531, 476, 2016) Luminosity of the disk ~ 10^{36} ergs/s. Kinetic luminosity of PeV protons is of the order 10^{38} ergs/s.

4. 3C454.3 The luminosity of the galaxy in bursts of gamma-rays ~ 10^{50} ergs/s. Eddington luminosity < 5 10^{47} ergs/s !!!!If to take into account relativistic busting, the kinetic luminosity exceeds Eddington luminosity (Aharonian, Barkov, Khangulyan, ApJ. 2017)

Two options

1. The main source of the jet is the energy of rotation of the SMBH

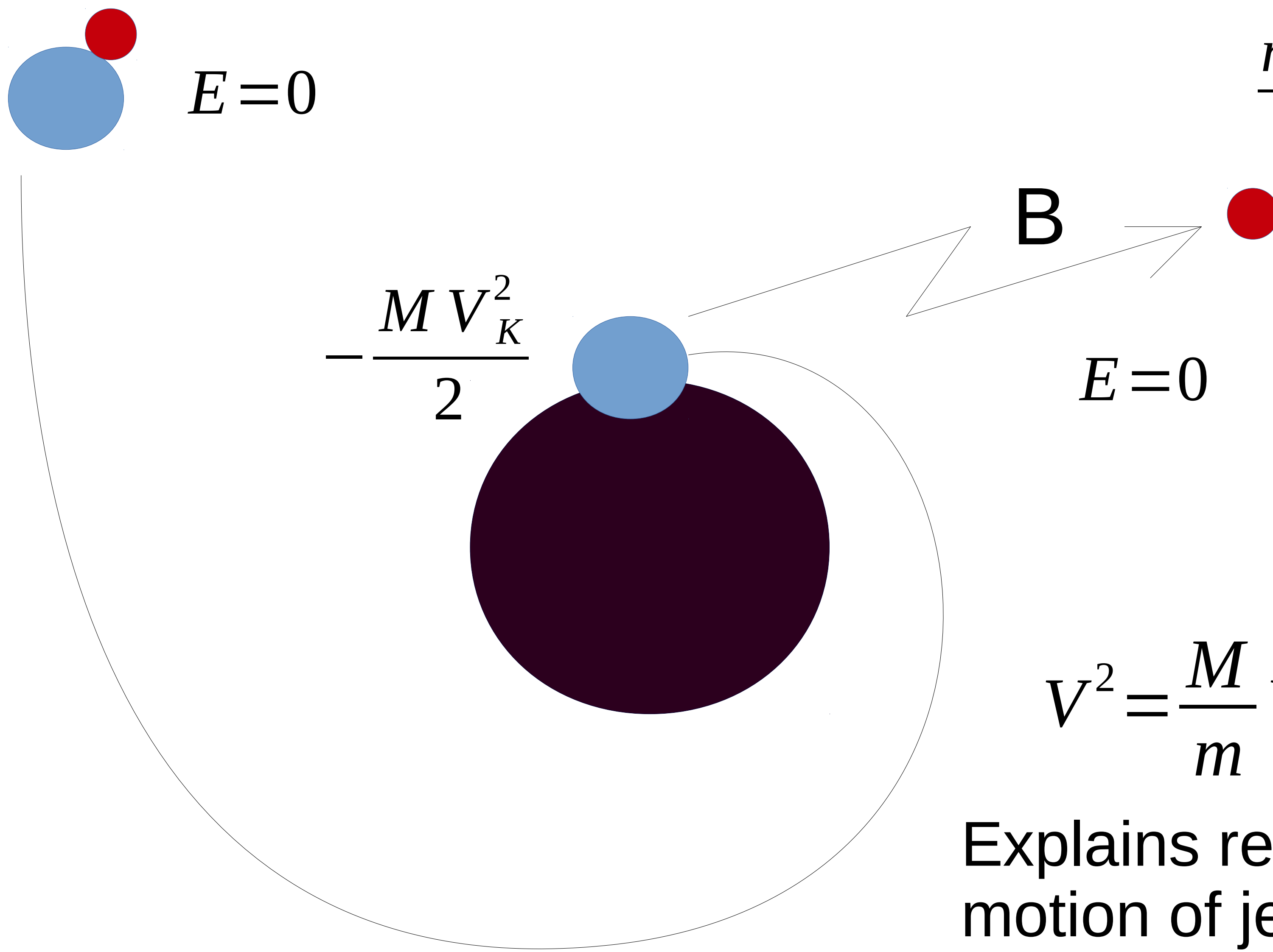
- Blandford - Znajek (1977) effect explains everything
- Indeed at the maximal possible angular momentum the kinetic luminosity of the jet achieves $3Mc^2$ (McKinney, J. C., Tchekhovskoy A., Blandford R.D., 2012).
- Is this sufficient? Apparently Yes. Especially if the accretion is radiationally inefficient.

An alternative model - «cold» disk accretion.

2. The only source of energy is the accretion.

The luminosity of the disk is suppressed because almost all the energy of accretion goes into jets. Almost nothing into radiation.

Energy budget at the «cold» disk accretion



$$E=0$$

$$-\frac{M\,V_K^2}{2}$$

$$\frac{mV^2}{2}=\frac{MV_K^2}{2}$$

$$E=0$$

$$V^2=\frac{M}{m}V_K^2 \gg V_K^2$$

Explains relativistic motion of jets

Magnetic field and rotation of the star

Without magnetic field every proton of the wind carries out only its own angular momentum

$$l = m_p V_k R_0 = m_p \Omega R_0^2$$

In the magnetic field every proton carries out

$$l = m_p \Omega R_A^2 = m_p \Omega R_0^2 \lambda, \quad \lambda = \left(\frac{R_A}{R_0} \right)^2$$

R_A is the Alfvenic radius where the velocity of the plasma equals to the local Alfvenic velocity

$$R_A > R_0$$

Examples

Solar wind : R_A ~ 6 R_0

Pulsars: $R_A=c/\Omega$

Magnetic field provides very efficient mechanism of the loss of angular momentum and rotational energy of stars and pulsars

What about accretion disks?

Two most importants questions

1. Can the outflowing wind to carry out angular momentum and all the released energy (rotational and gravitational)?

2. If yes. What will be the ratio of the kinetic power of the outflow over the bolometric luminosity of the disk?

Equation of the angular momentum balance in the disk

$$\dot{M}\frac{\partial r V_K}{\partial r} = \frac{\partial}{\partial r} 4\pi r^2 \alpha \rho v_s^2 h - r^2 \langle B_\varphi B_z \rangle |_{wind} \,.$$

$$if \quad \alpha \rho v_s^2 h \gg \frac{1}{4\pi} \langle B_\varphi B_z \rangle r$$

Shakura & Sunyaev (1973)
accretion takes place

Condition for the «cold» accretion

$$\frac{4\pi \alpha \rho v_s^2}{\langle B_\varphi B_z \rangle} \left(\frac{h}{r} \right) \ll 1$$

$$4\pi \alpha \rho v_s^2 \approx \langle B_\varphi B_z \rangle \quad inside\ the\ disk$$

Wind — disk connection at the «cold» accretion

$$\frac{\partial \dot{M}}{\partial r} - 4\pi r \rho v_z |_{wind}. = 0.$$

$$\dot{M} \frac{\partial r V_K}{\partial r} + r B_z B_\varphi |_{wind}. = 0$$

$$\frac{1}{2} \frac{\partial \dot{M} V_K^2}{\partial r} + 4\pi r \rho E_{tot} |_{wind}. = 0$$

$$E_{tot} = \frac{V_K^2}{2} - \frac{GM}{r} - r\Omega \frac{B_z B_\varphi}{4\pi\rho v_z}$$

+ full system of equations describing the MHD wind outflow from the disk

Numerical technology

1. Specify the magnetic field distribution at the base of the wind (at the disk surface)

$$B^2|_{wind\,.} = a\,few \times \left(-\dot{M}\,\frac{\partial\, r V_k}{r^2\,\partial r}\right)$$

2. Specify ρv_z, $\dot{M}(r=3r_g)$ and calculate $\dot{M}(r)$.

3. Calculate the wind flow from the disk and B_φ at the base.

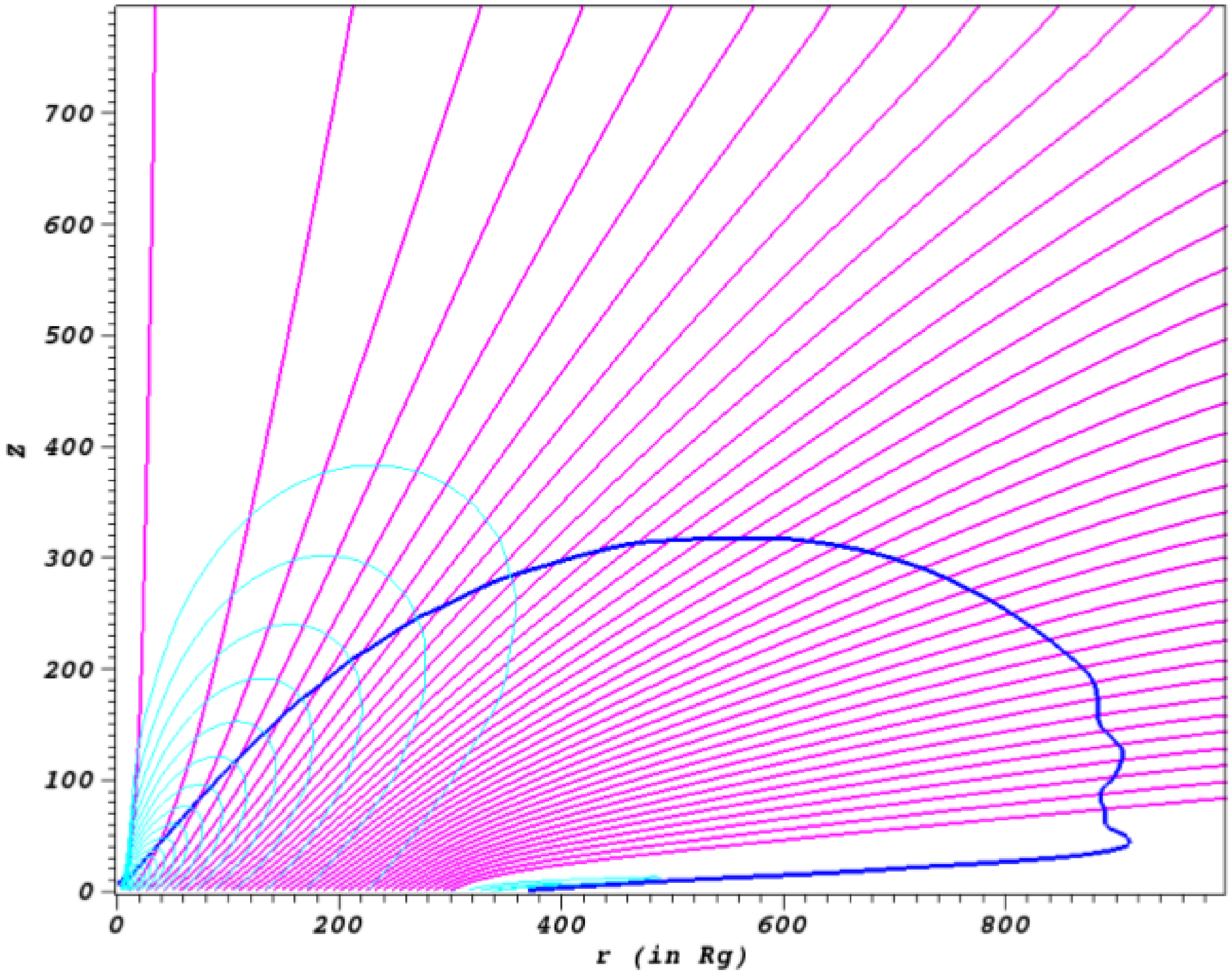
4. Check if the momentum equation satisfied? (If yes, success)!

5. Correction of ρv_z and $\dot{M}(r)$

Answer on the first question is positive.

A selfconsistent analytical solution of the problem in selfsimilar approximation (Bogovalov & Kelner, IJMPD 2010).

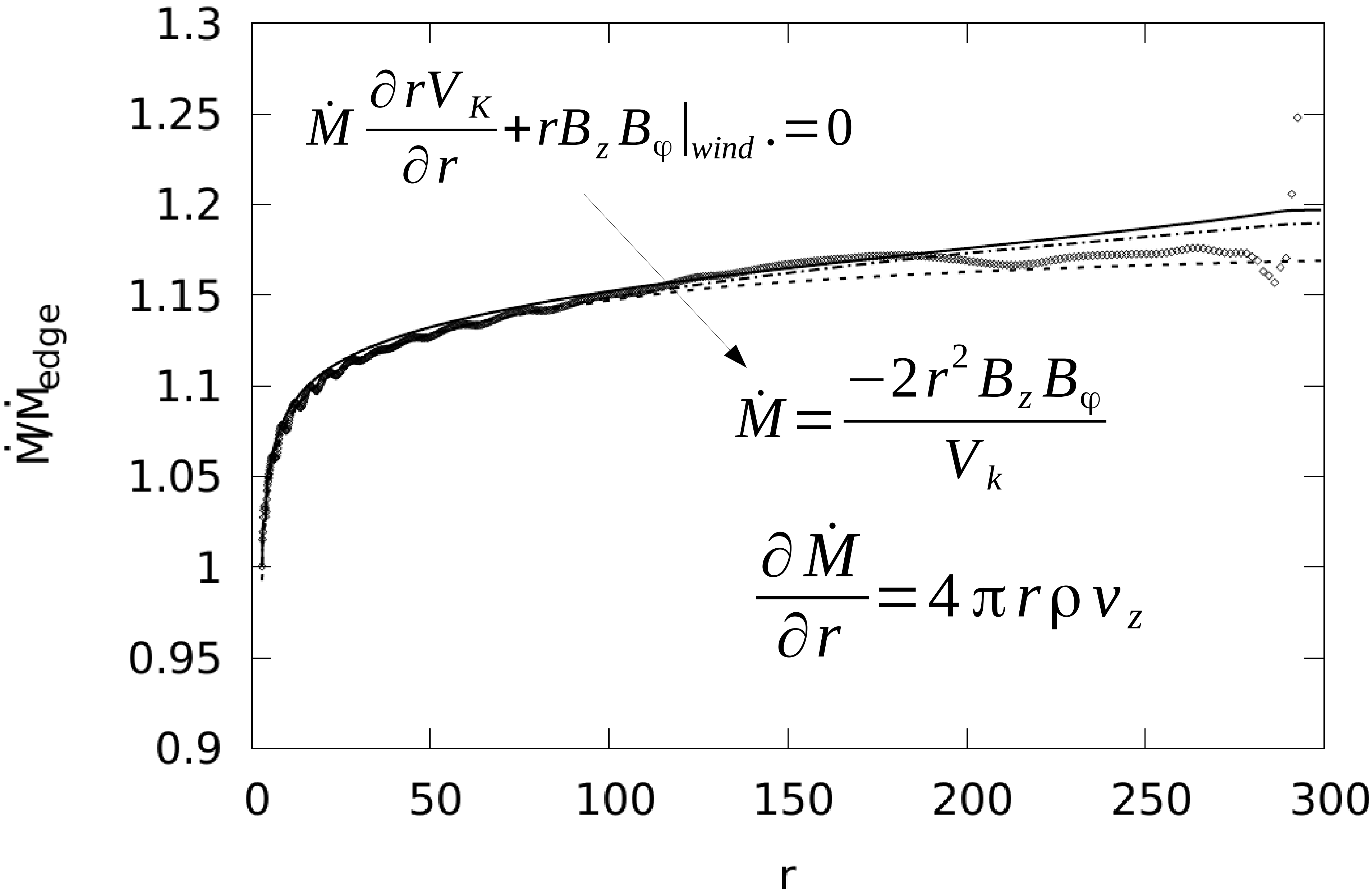
Numerical model of the selconsistent "cold" accretion



Bogovalov & Tronin, Astron. Letters (2017)

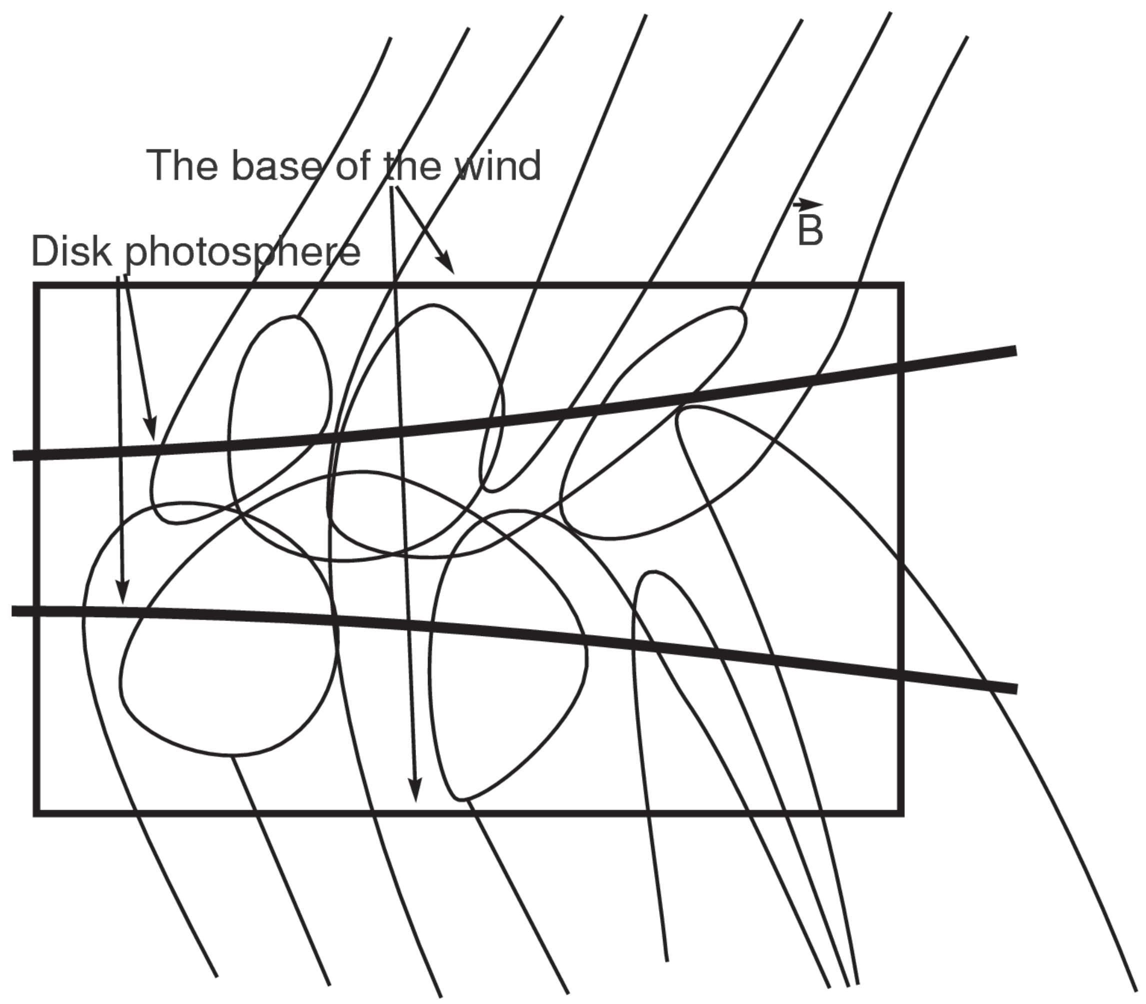
Bogovalov & Tronin, IJMPD (2018)

Selfconsistency of the numerical solution means that the accretion is consistent with the outflow (angular momentum and mass conservation equations are fulfilled)



What is the answer on the second question?

The higly likely structure of the magnetic field in the disk



The chaotic structure of the magnetic field gives the largest luminosity of the disk

Heating of the disk

The minimal possible magnetic field at the base of the wind (much less the magnetic field in the Shakura&Sunayev disk)

$$B^2|_{wind} . \approx \langle B_\varphi B_z \rangle |_{wind} . = -\dot{M} \frac{\partial r V_k}{r^2 \partial r}$$

Connection with the field inside the disk

$$B^2 \approx \langle B_r B_\varphi \rangle = \beta \langle B_\varphi B_z \rangle |_{wind} .$$

The conventional assumption of α-disk model of Shakura&Sunayev(1973)

$$\langle B_r B_\varphi \rangle \approx 2 \pi \alpha \rho v_s^2$$

Condition for the «cold» accretion

$$\frac{2\beta h}{r} \ll 1$$

In classical geometrically thin disks $\frac{h}{r} \ll 1$ (Shakura & Sunyaev,1973)

$\beta > 1$ is allowed

The ratio of the kinetic energy flux over the bolometric luminosity

Surface luminosity $$Q = -\alpha \rho v_s^2 h r \frac{\partial \Omega}{\partial r}$$

Kinetic energy luminosity $$L_{kin} = \dot{M} \frac{V_K^2}{2} = \dot{M} c^2 / 12$$

$$\frac{L_{kin}}{L_{bol}} = 71 (m \alpha)^{1/8} \dot{m}^{-1/4} \beta^{-5/4}$$ For Thomson scattering

$$\frac{L_{kin}}{L_{bol}} = 101 (m \alpha)^{2/17} \dot{m}^{-3/17} \beta^{-20/17}$$ For free-free absorption

$$\dot{m} = \dot{M} / \dot{M}_{Edd} \qquad m = M / M_{\odot}$$

http://arxiv.org/abs/1805.03610

Fundamental plane of black holes

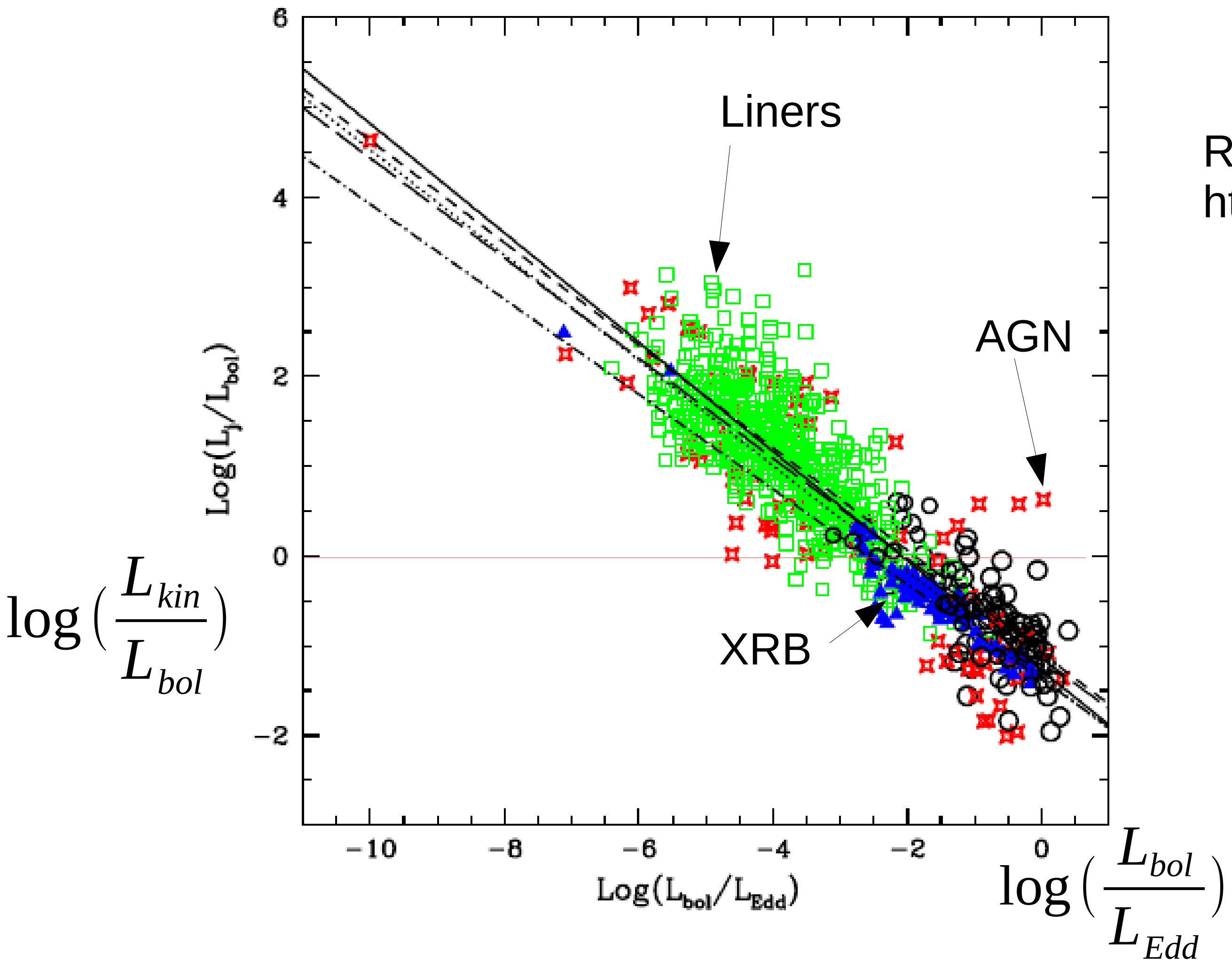


Figure 2. The log of the ratio of beam power to bolometric accretion disk luminosity is shown versus the log of the dimensionless bolometric luminosity for the sources shown in Fig. 1.

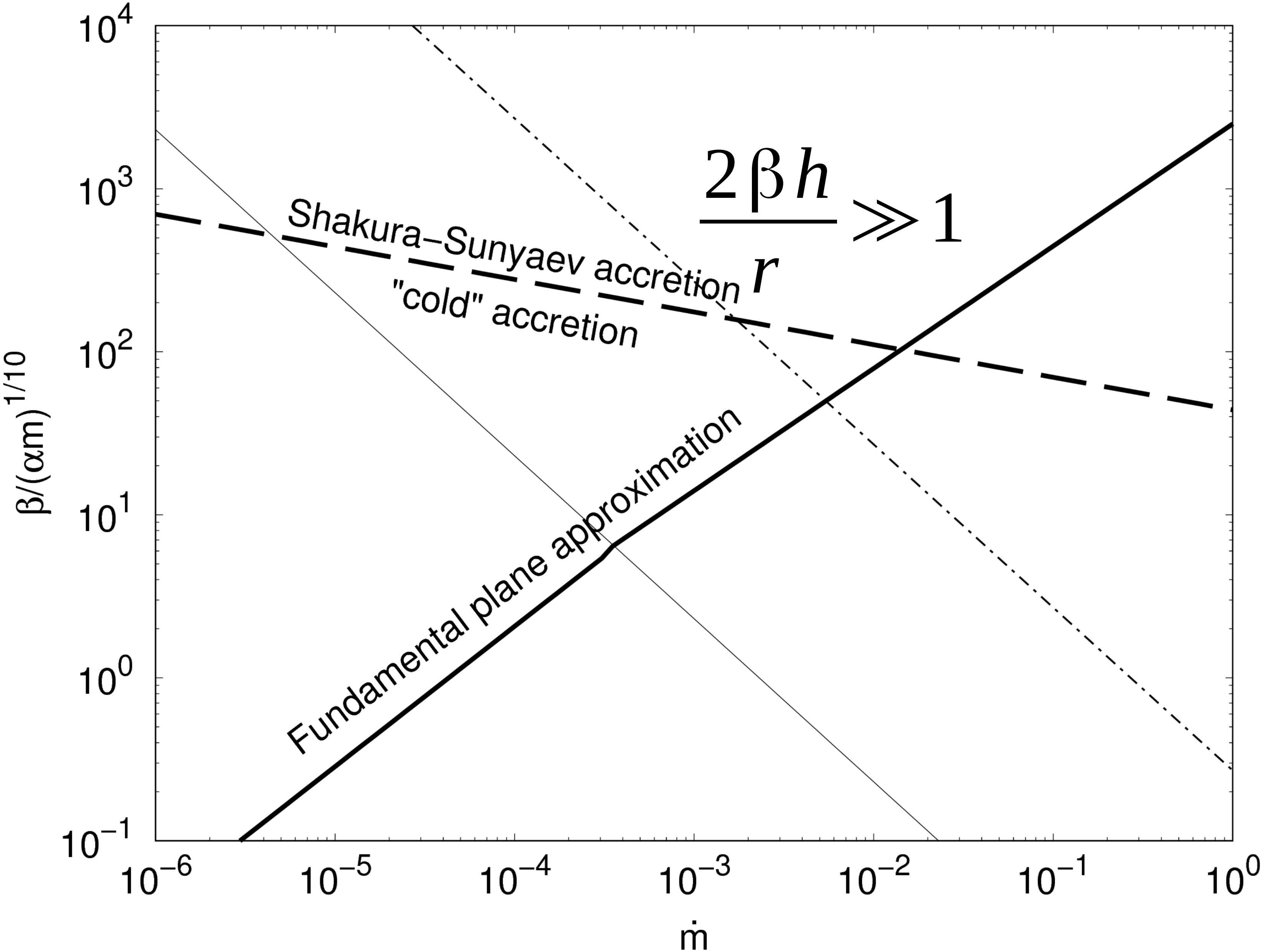
R. A. Daly, et al.
https://arxiv.org/abs/1606.01399

Define β from fundamental plane of BH

$$\beta = 2.5 \cdot 10^3 \dot{m}^{3/4} (\alpha m)^{1/10}$$ For Thomson scattering

$$\beta = 5.7 \cdot 10^3 \dot{m}^{0.86} (\alpha m)^{1/10}$$ For free-free absorption

The regimes of accretion on the plane $\beta - \dot{m}$



Two specific objects

M87

$$L_{kin} = 10^{44} \quad erg/s, \quad m = 3.5 \cdot 10^{9}, \quad \dot{m} = L_{kin}/L_{Edd} = 2 \cdot 10^{-4}$$

$$\beta = 27, \qquad L_{bol} = 10^{42} \quad erg/s$$

Sgr A*

$$L_{bol} = 10^{36} \quad erg/s, \quad m = 4 \cdot 10^{6}$$

$$\beta = 0.9, \quad \dot{m} = 8 \cdot 10^{-6}, \quad L_{kin} = 4.4 \cdot 10^{39} \quad erg/s$$

The model of «cold» disk accretion succesfully passed through 2 tests

1. Numerical modelling confirms that the disk accretion onlly due to the wind outflow is possible. The fully selfconsistent solution is obtained in the numerical experiments.
2. Even in the worse case of fully turbulent magnetic field inside the disk the luminosity of the disk is below the kinetic energy flux of jets provided that

$$\frac{2\beta h}{r} \ll 1$$

The model of “cold” accretion is well healthy child

Thank you!