«Cold» disk accretion onto black holes

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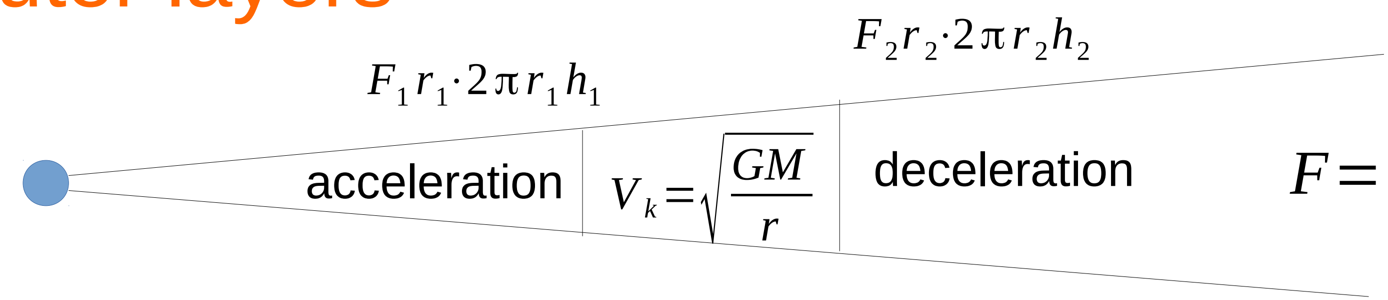
Physics of α-disks

The accretion occurs due to the angular momentum transfer from inner layers to the outer layers



$$F = \mu r \frac{d\Omega}{dr}$$

$$\frac{d \Delta m r V_k}{dt} = F_2 r_2 \cdot 2\pi r_2 h_2 - F_1 r_1 \cdot 2\pi r_1 h_1$$

The only important assumption about viscosity

$$\mu = \rho * v_t * l \qquad v_t = \alpha * v_s$$

Luminosity and spectra do not depend on α - parameter

The only source of energy is the gravitational energy of the accreted matter

Energy released at the transition of the matter from orbit with radius r1 to radius r2 is

$$dL=\dot{M}\,\Delta\left(\frac{V_k^2}{2}-\frac{GM}{r}\right)=-\dot{M}\,\Delta\left(\frac{V_k^2}{2}\right)=4\pi\, r dr\,\sigma\, T^4$$

Bolometric luminosity at accretion onto a black hole is

$$L_{bol}=\dot{M}\,\frac{V_k^2}{2}\approx 0.1\,\dot{M}\,c^2$$

Spectra of black body radiation

$$I_\nu = \frac{16\pi^2 R_0^2 h}{c^2}\left(\frac{kT_0}{h}\right)^{8/3} \nu^{1/3}$$

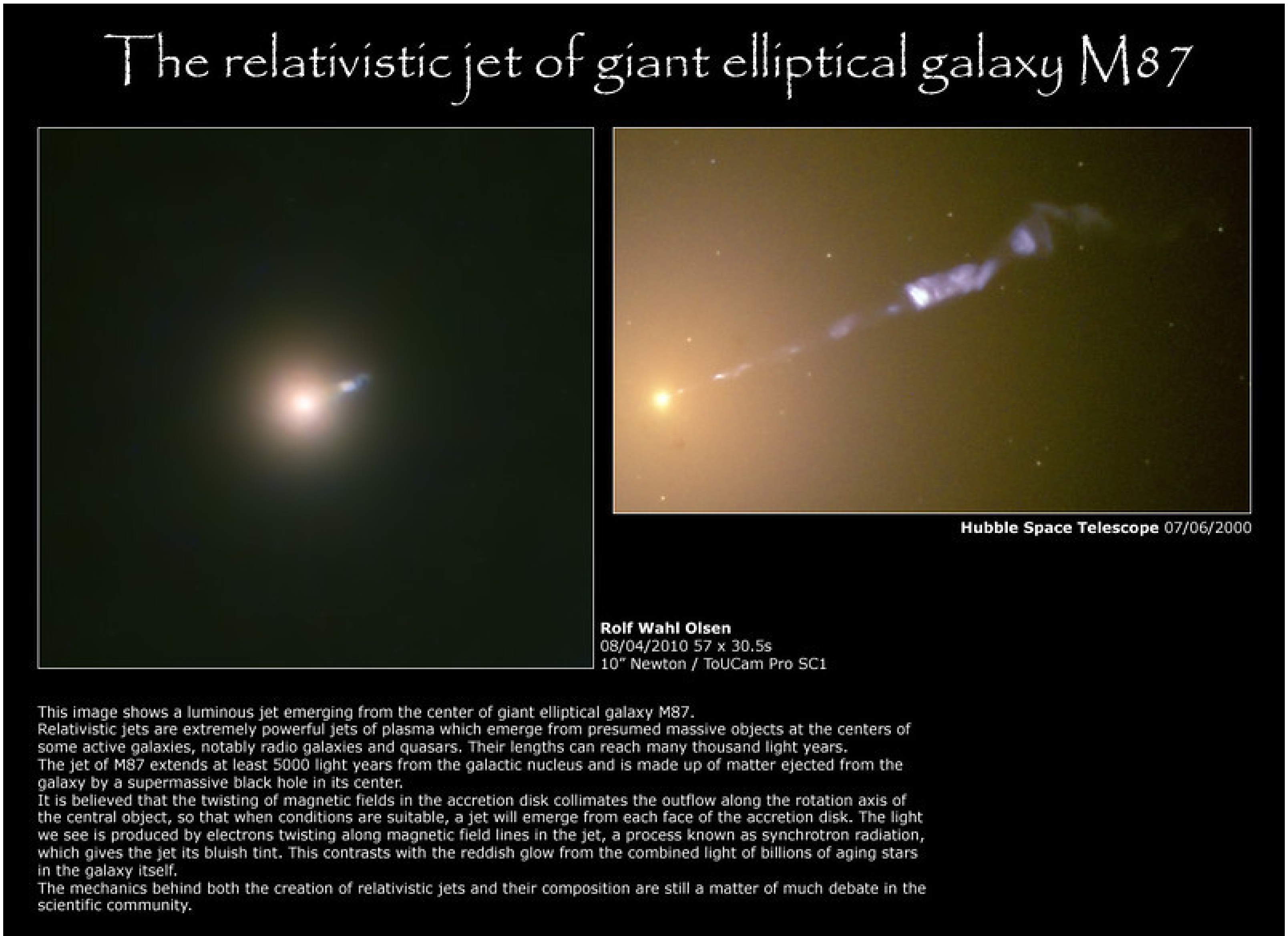
What observations show?

1. At low accretion rates ($< 10^{-2}$, Churazov et al, MNRAS, 2005) the disks are radiatively inefficient

2. Kinetic power of jets greatly exceeds the bolometric luminosity of the disks itself.

Examples below.

«JETS» and luminosity of M87.



Miracle object M87

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

According to Chandra (Di Matteo et al, ApJ, 2003)

$$\dot{M}_{Bondi} \approx 0.1\, \dot{M}_{Sun} / year$$

Or

$$L_{Bondi} \approx 5 \times 10^{44} \quad ergs\, s^{-1}$$

- RIAF disk and L_{jets} ~ $10^{2} L_{bol}$

Galactic Center Sgr A*

$$L_{bol} = 10^{36}\, ers\, s^{-1}$$

$$\dot{M}_{Bondi} \approx 10^{-6} M_{Sun}/year \Rightarrow L_{Bondi} = 6 \times 10^{39}\, ergs\, s^{-1}$$

$$L_{jet} - unknown \quad but$$

HESS (Nature, 531, 476, 2016) have regeistered TeV gamma-radiation of hadronic origin 10 ps around SGR A*. Proton kinetic power should be above 10^{38} ergs s^{-1}

Fermi data

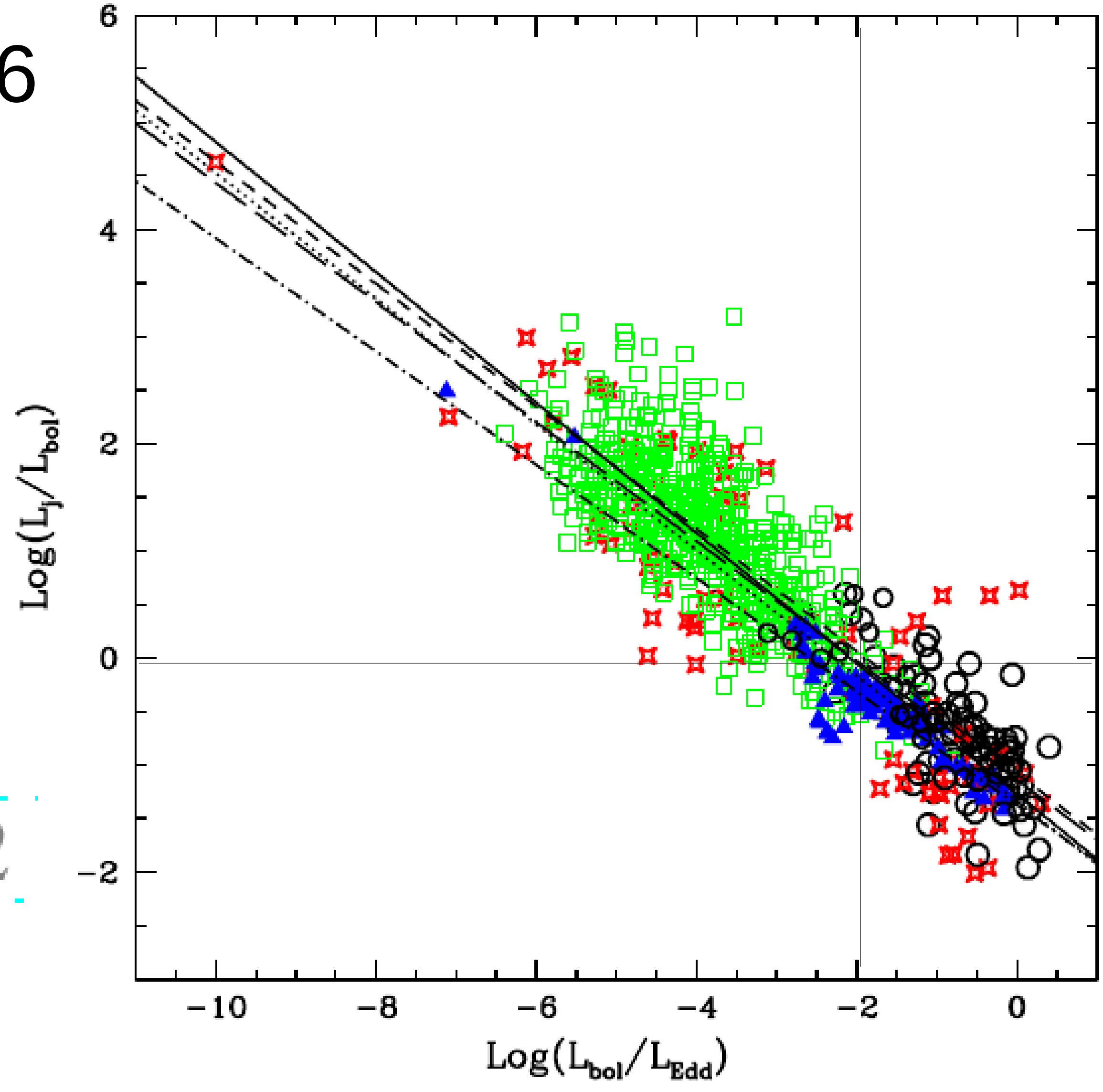
Fermi LAT data (Ghisselini et al. , Nature, 515, 376, 2014)

The hole family of blazars detected by Fermi LAT in gamma-rays demonstrates that the kinetic luminosity of the jets dominates the bolometric luminosity.

Fundamental plane of black holes

- R. A. Daly et al. 2016

arXiv:1606.01399v2



Mon. Not. R. Astron. Soc. **363,** L91–L95 (2005) doi:10.1111/j.1745-3933.2005.00093.x

Supermassive black holes in elliptical galaxies: switching from very bright to very dim

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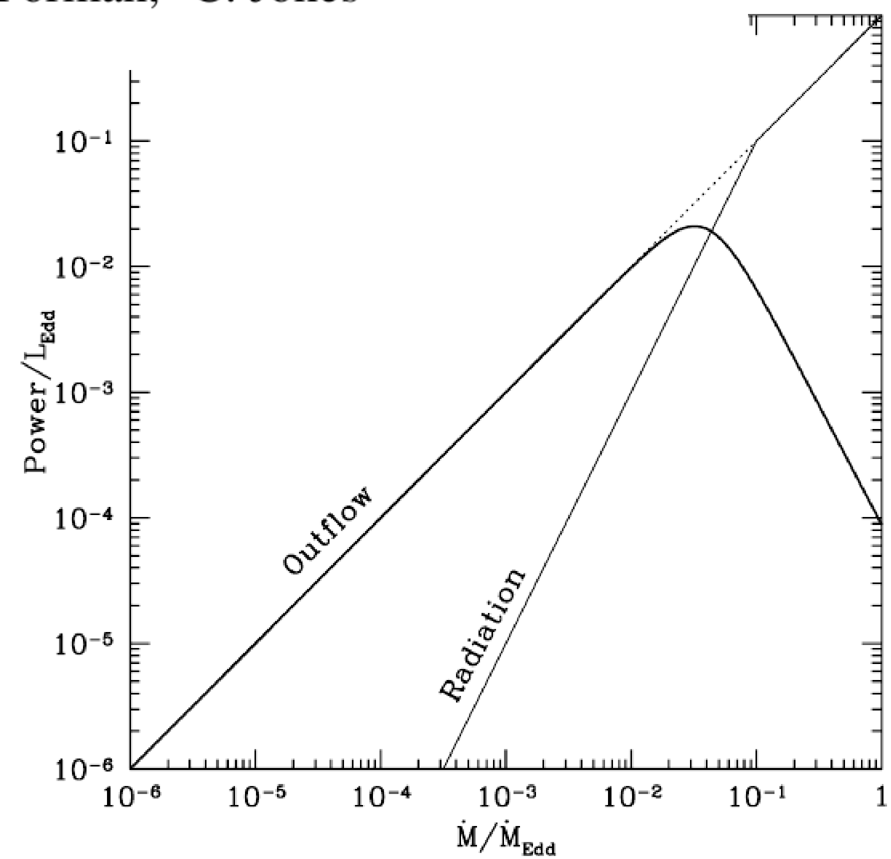


Figure 1. Sketch of black hole energy release as a function of mass accretion rate. At low accretion rates a significant fraction of accretion power goes into an outflow (thick solid line). Above a certain accretion rate, corresponding to the transition to the standard accretion disc mode, the outflow power decreases. The radiative power (thin solid line) is instead very low at low accretion rates and reaches a fixed fraction (~10 per cent) of $\dot{M}c^2$ at accretion rates above 0.01–0.1 of Eddington.

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)

How to explain the reality?

1. RIAF – ADAF, CDAF, ADIOS

The source of energy of jets is not the accretion

Blandford - Znajek (1977) effect explains everything
Indeed at the maximal possible angular momentum
Kinetic luminosity of the jet achieves $3\dot{M}c^2$
(McKinney, J. C., Tchekhovskoy A., Blandford R.D., 2012).
Is this sufficient? Apparently Yes. Especially if ADAF takes place.

Disadvantage - model is very complicated!

More reliable alternative is “cold”accretion.

«cold» disk accretion

The magnetized wind from the disk carries out the majority of the angular momentum. The viscosity is not important. The matter in the disk loss the angular momentum and energy like the Sun, stars, pulsars due to wind rather than due to viscous stresses .

(Blandord & Pyne, MNRAS, 1982).

Magnetic field and rotation of the star

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

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

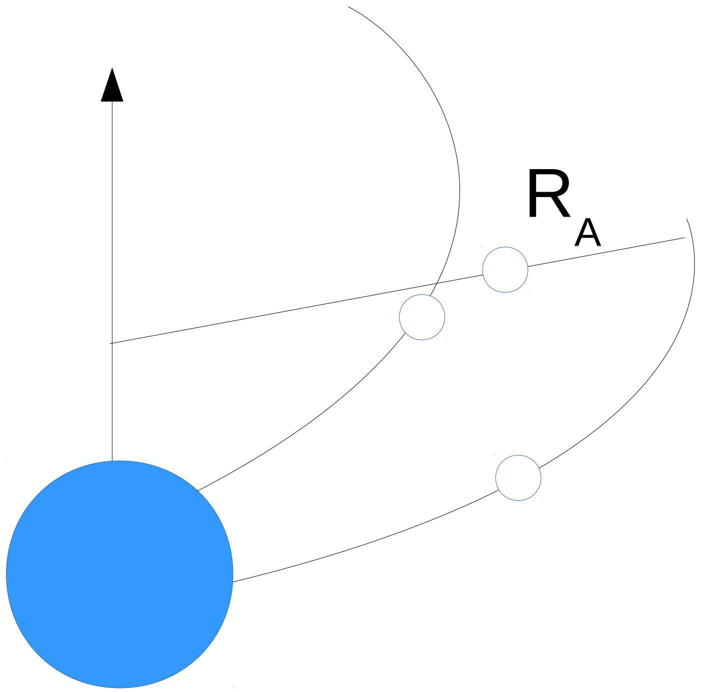
In the magnetic field every proton carries out

$$l = m_p \Omega R_A^2 = m_p \Omega R_0^2 \lambda$$

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

$$R_A > R_0$$

Mechanical analogy of the Alfvenic radius



Examples

Solar wind : $R_A \sim 12\ R_0$

Pulsars: $R_A = c/\Omega$

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

The same must take place in the accretion disks?

The role of the magnetic field in the launch of the winds from disks

Distribution of density across the disk

$$\rho = \rho_0 \exp\left(-\left(\frac{z}{h}\right)^2\right), \qquad h = r\,\frac{C}{V_k}$$

No conditions for the wind formation.

Magnetic field provides mechanism for ejection of plasma from the disk (Blandford & Payn, 1982).

Blandford & Payn mechanism of the plasma outflow from the disk

Blandford & Payne (1982)

Program of research

1. Do solutions describing the “cold’ disk accretion exist? +

2. Do the “cold” accretion provides observed relationship

between kinetic power and bolometric luminosity? +

3. Do “cold” accretion can provide relativistic motion in the jets

With Lorentz factor ~ 10? +-

4. What fraction of the gravitational energy goes into the jet? -

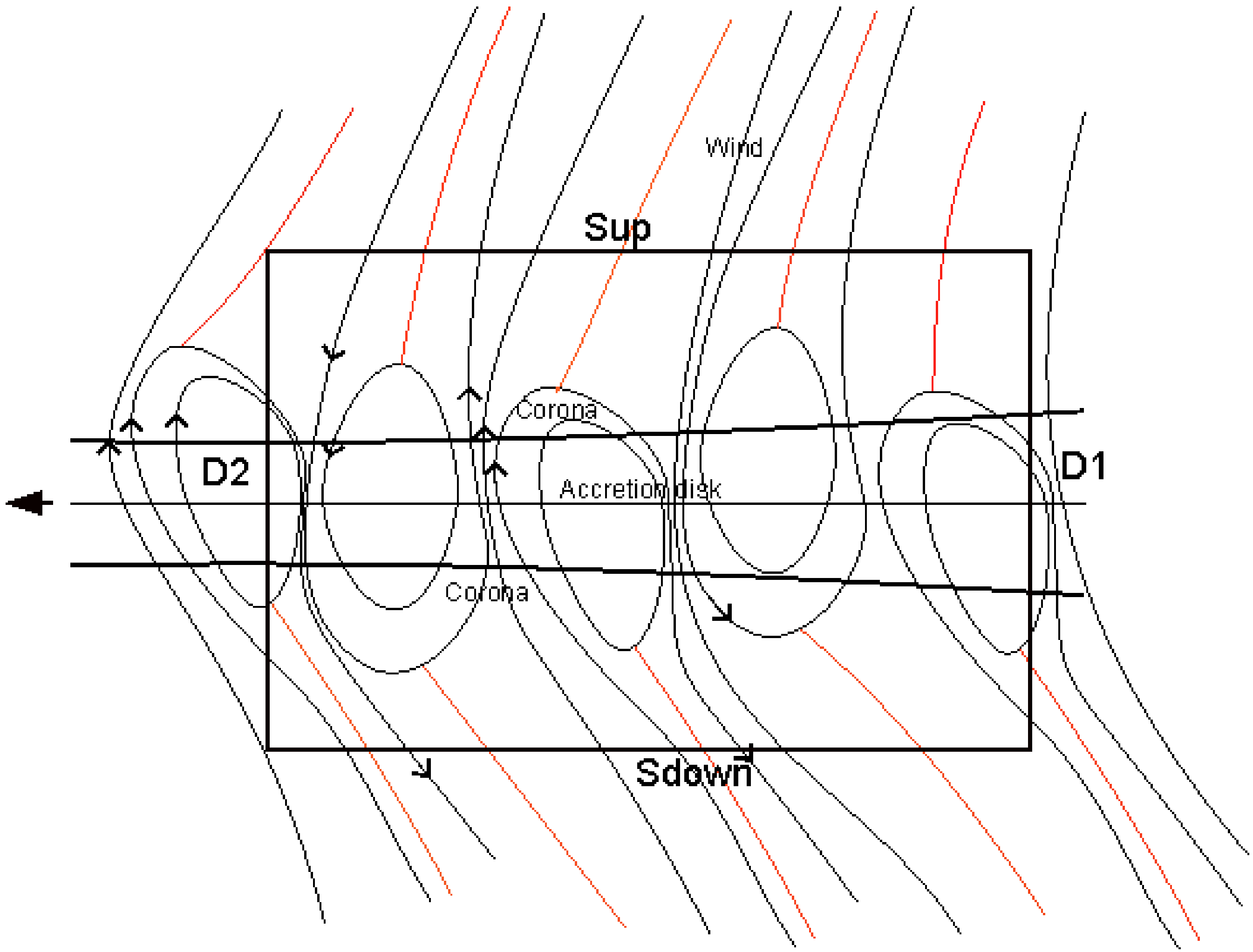
5. The role of “cold” accretion in the spercritical accretion? -

Извлекаем уроки

1. Магнитное поле обеспечивает истечение плазмы с диска.
2. Магнитное поле обеспечивает эффективное торможение плазмы в диске.
Каждый протон уносит не только свой момент импульса, но и момент импульса протонов, оставшихся в диске.

Equations of the disk accretion with the outflow.

Disk structure



Elementary equations

- $\frac{\partial \rho v_i}{\partial t}$=-$\frac{\partial}{\partial x_k}(\rho v_i\, v_k + \tau_{ik} + \mathrm{p}\delta_{ik} - \frac{1}{4\pi}(B_i B_k - \frac{1}{2} B\delta_{ik}))$;

Averaging gives $< \frac{\partial \rho v_i}{\partial t} >= 0$; Pressure is neglected

Integration over the selected volume gives

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k} \rho v_k = 0$$

Integral law of conservation of the angular momentum

$$\int_{D2}\left(\rho v_r v_\varphi + (\tau_{\varphi r} + < \frac{1}{4\pi}\left(B_r B_\varphi\right) >)\right) rdS$$

$$- \int_{D1}\left(\rho v_r v_\varphi + \left(\tau_{\varphi r} + < \frac{1}{4\pi} B_r B_\varphi >\right)\right) rdS +$$

$$+2\int_S \left(\rho v_z v_\varphi + \tau_{\varphi z} - < \tfrac{1}{4\pi}\left(B_z B_\varphi\right) >\right) rdS = 0$$

Viscosity in α -disks

- $$\int_{D2}\left(\rho v_r v_\varphi + (\tau_{\varphi r} + < \frac{1}{4\pi}(B_r B_\varphi) >)\right) rdS$$

$$- \int_{D1}(\rho v_r v_\varphi + (\qquad - \alpha\rho C^2 \qquad) \quad) rdS +$$

$$+2\int_S \left(\rho v_z v_\varphi + \tau_{\varphi z} - < \frac{1}{4\pi}(B_z B_\varphi) >\right) rdS = 0$$

Final equation of the angular momentum balance

- $$\dot{M}\frac{\partial r\dot{V_k}}{\partial r} = \frac{\partial}{\partial r}4\pi r^2\alpha\rho C^2 h - r^2 < B_\varphi B_z > |_{surface}$$

If $\alpha\rho C^2 h \gg \frac{1}{4\pi}B_z B_\varphi r$, the viscous stresses dominate (Shakura & Sunayev, 1973)

- In the Shakura & Sunyaev (1973) model $\alpha\rho C^2 \approx \frac{1}{4\pi}B^2|_{inside}$ and h << r.

If $\alpha\rho C^2 h \ll \frac{1}{4\pi}B_z B_\varphi r$, the wind carries out almost all the angular momentum (Pelletier G. & Pudritz R.E. 1992).

Observations make us to consider the second limiting case.

The system of basic equations

- $$\frac{\partial \dot{M}}{\partial r} - 4\pi r \rho v_z|_{wind} = 0;$$
$$\dot{M}\frac{\partial rV}{r\partial r} + rB_z B_\varphi|_{wind} = 0;$$

V – Keplerian velocity

$$\frac{1}{2}\frac{\partial V^2 \dot{M}}{\partial r} + 4\pi r \rho v_z E|_{wind} = 0;$$

$E = \frac{V^2}{2} - \frac{GM}{r} - r\omega \frac{B_z}{4\pi\rho v_z} B_\varphi$ – total energy per particle +

Ideal MHD equations for wind.

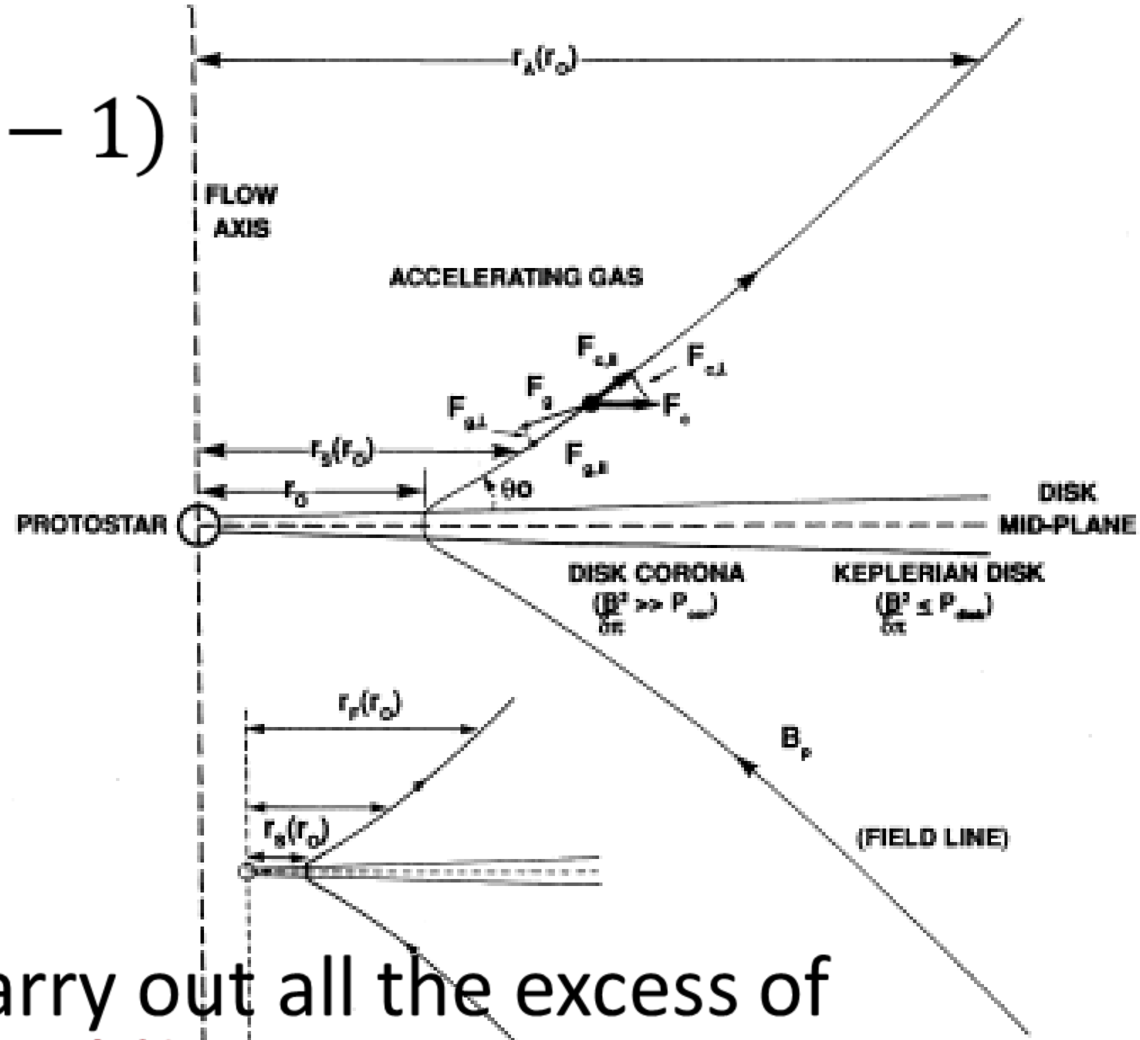
The wind from the disk

- $-rB_z B_\varphi = 4\pi\rho v_z \omega r^2(\lambda - 1)$

Where $\lambda = \left(\frac{r_A}{r_0}\right)^2$.

Pay attention that the Energy can greatly exceed Keplerian energy

$$E = (2\lambda - 3)\frac{V^2}{2},$$



If λ > 3/2, the wind can carry out all the excess of energy. Disk can remain cold!

Solutions

1. Do the solutions of the system of equations

Exist?

Yes. We have selfsimilar fully selfconsistent analytical solutions of the problem (Bogovalov, Kelner 2010, IJMPD)

$$\dot{M} = \dot{M}_0 \left(\frac{r}{3r_g}\right)^{\frac{1}{2(\lambda-1)}}$$

$$B_z \sim r^{-\left(\frac{5}{4}-\frac{1}{4(\lambda-1)}\right)}$$

very close to Blandford & Payne (1982) solution.

and numerical selfconsistent solutions ~~(in press).~~

Published in Astron. Letters.2017.

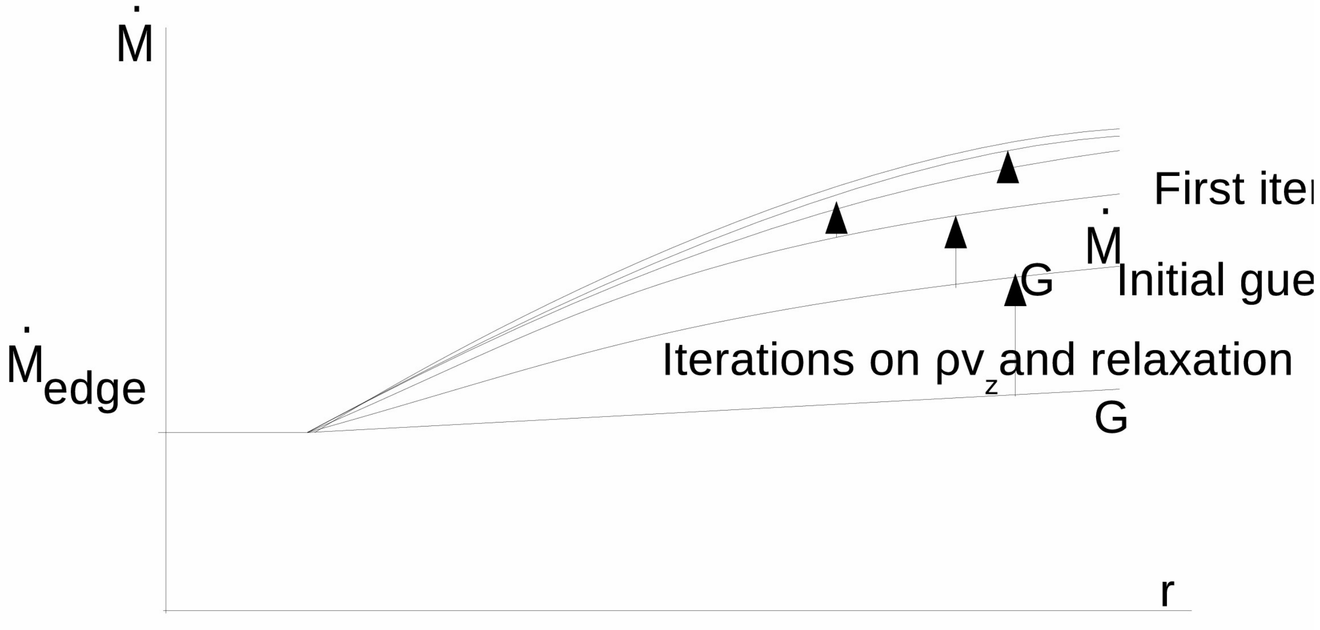
Do solutions exist when the distribution of the magnetic field over the disk is not a simple power law?

To answer this question we need a numerical solution of the **self consistent problem**.

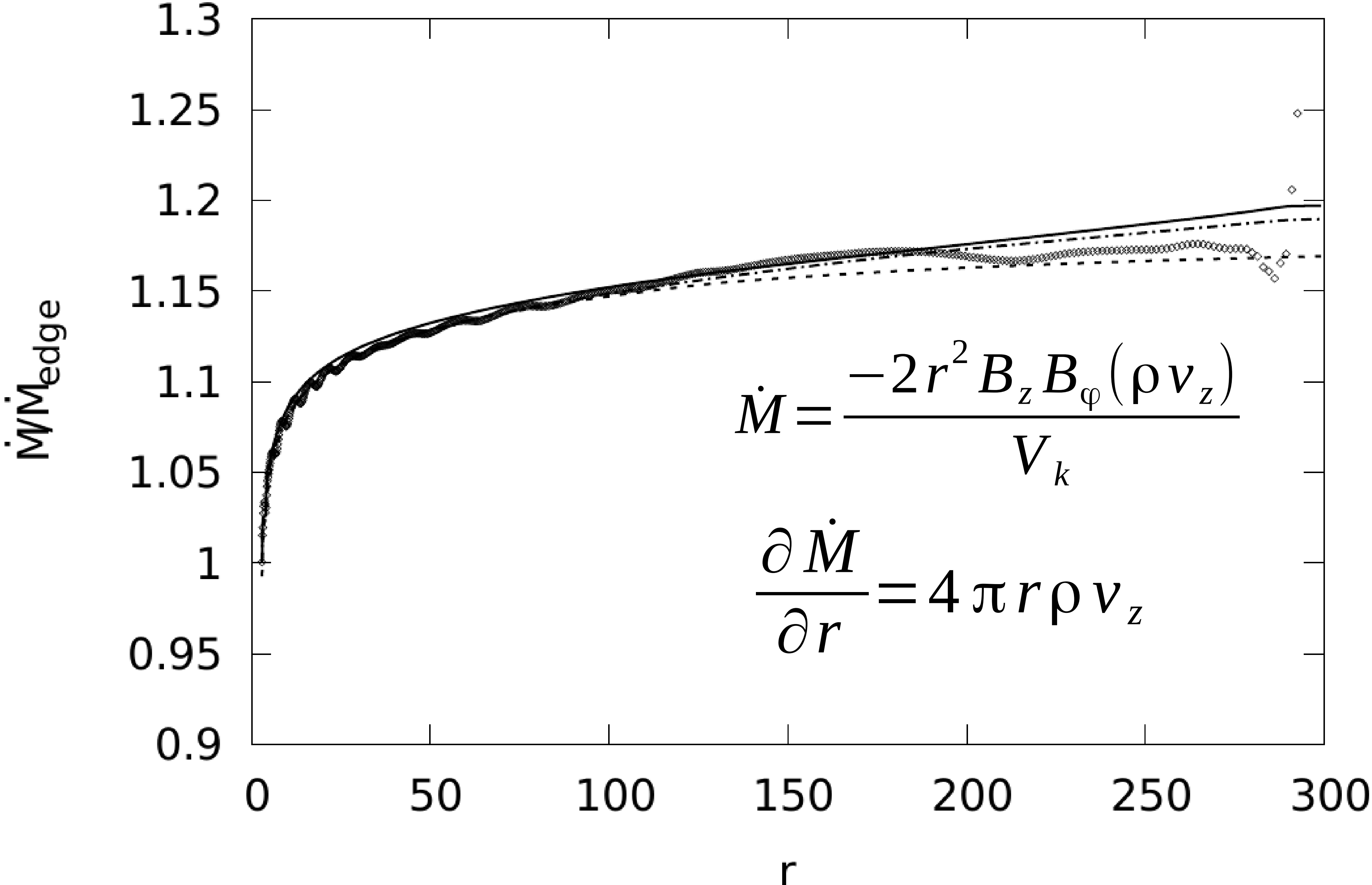
We have developed a numerical technology of solution of this problem with code PLUTO.

The milestones of the technology

1. Specify some distribution of the magnetic flux over disk and accretion rate at the inner edge of the disk M_{edge}.
2. Assume some distribution of the matter flux from the disk ρv_z
3. Solve the problem of the wind outflow from the disk. Then by according to special iterative procedure change ρv_z until the angular momentum Equation will note be satisfied.
4. Solve the mass conservation equation with the determined ρv_z. But the But the angular momentum equation becomes violated. Go to the point N 3.

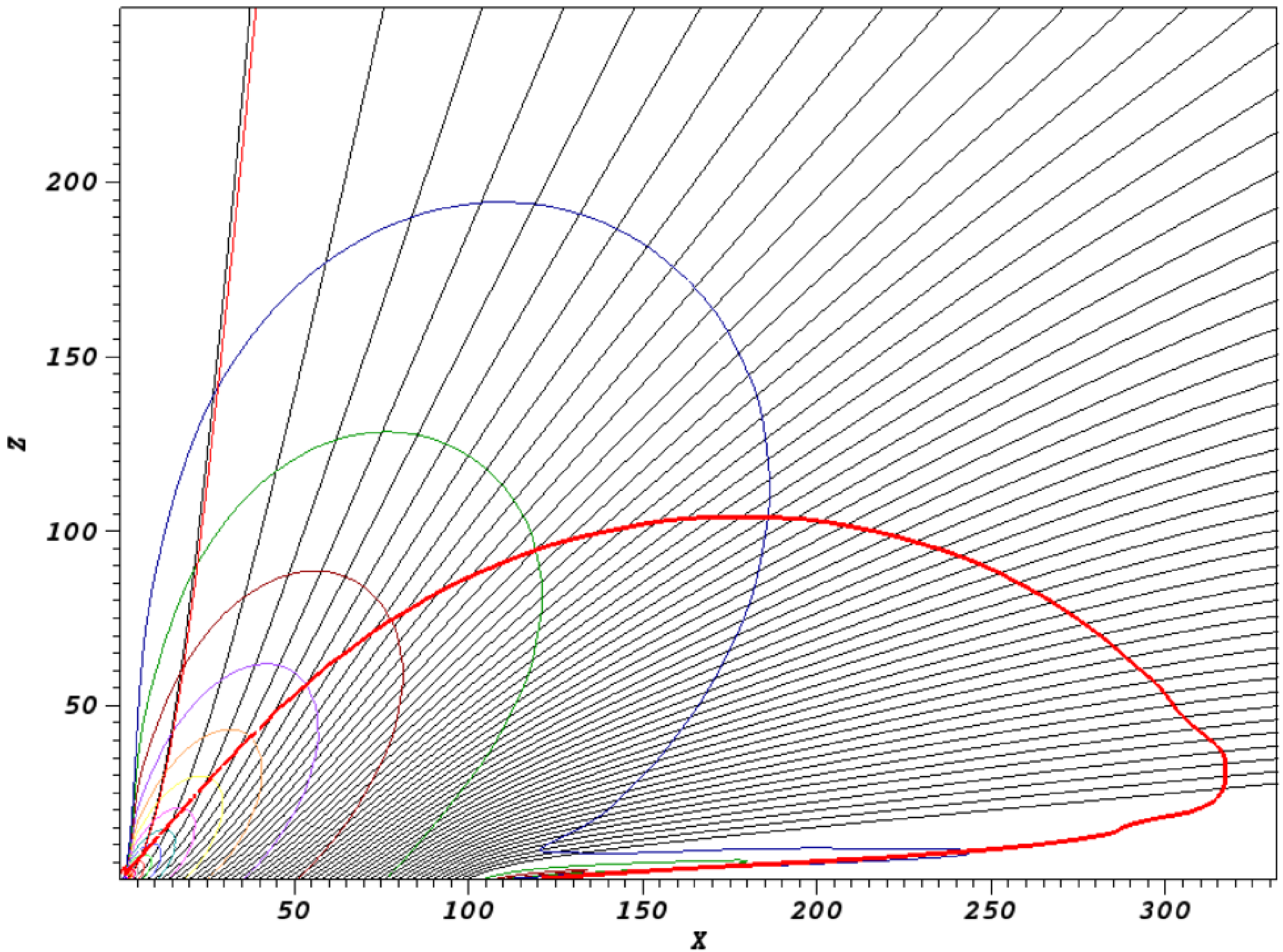


Selfconsistency of the numerical solution means that the accretion is consistent with the outflow (angular momentum and mass conservation equations are fulfilled)



$$\dot{M} = \frac{-2 r^2 B_z B_\varphi (\rho v_z)}{V_k}$$

$$\frac{\partial \dot{M}}{\partial r} = 4 \pi r \rho v_z$$



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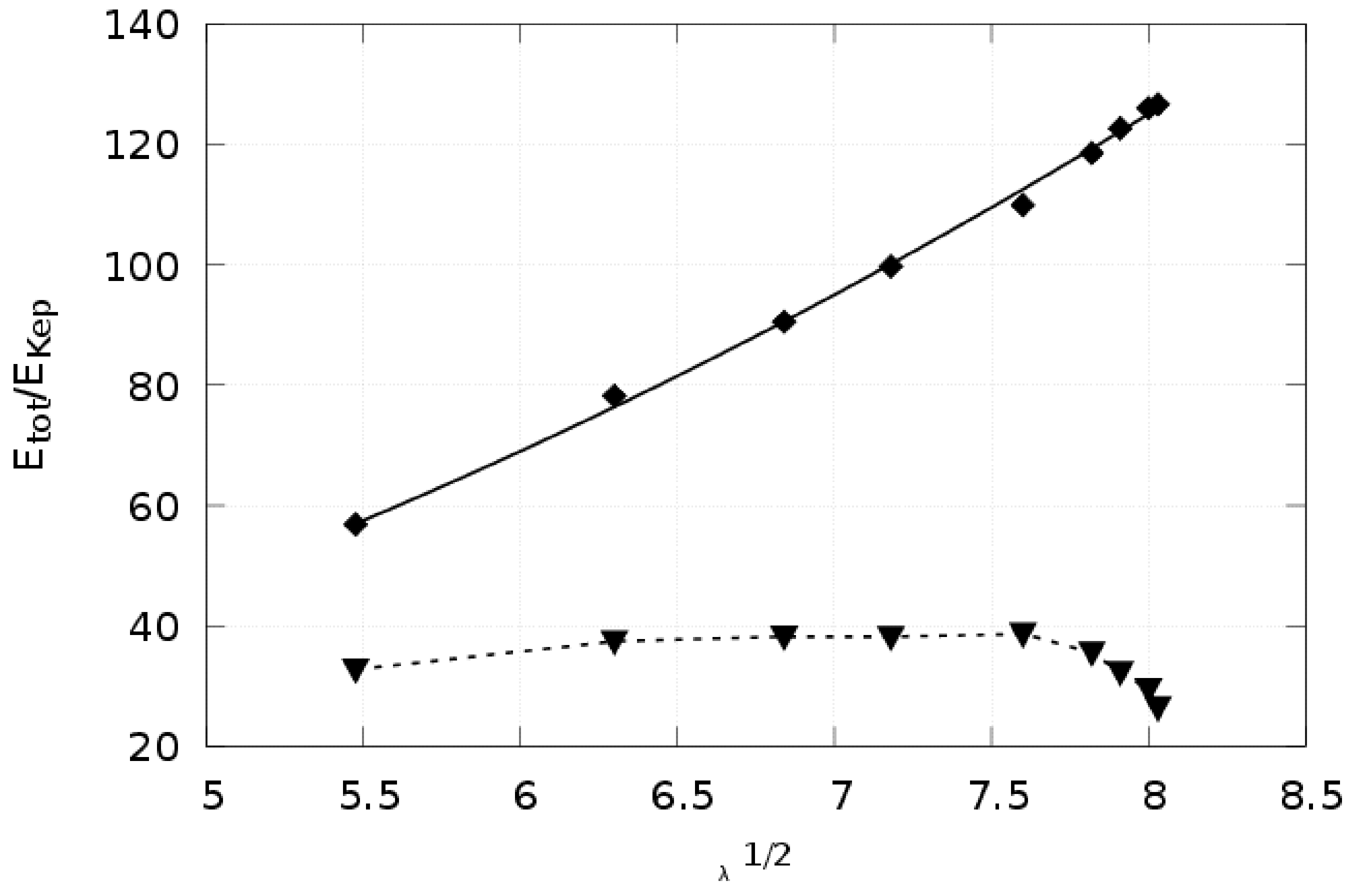
Answer on the 3-th question. Acceleration of the plasma

$$E_{tot} = (2\lambda - 3)\frac{GM}{2r}$$



Answer on the 2-nd question.
What is the ratio of the bolometric to the kinetic luminosity?

Disk can not remain cold.
The presence of the magnetic field on the surface of the disk

$$B_Z B_\varphi \approx B^2_{surfcae} = \frac{\dot{M} V_k}{2 r^2}$$

means that the chaotic magnetic field is present inside the disk.

Assuming that $\theta = \frac{B^2_{disk}}{B^2_{surface}}$ we can estimate the

bolometric luminosity of the disk in the regime of the cold accretion

Heating of the disk

$$Q = t_{r\varphi} rh \frac{\partial \Omega}{\partial r}$$

$$-t_{r\varphi} \approx \frac{B_{disk}^2}{4\pi} \approx \alpha \rho v_s^2$$

After that everything is like in Shakura-Sunyaev paper

Kinetic power of jets

$$L_{jet} = \eta \dot{M} c^2$$

The ratio of the kinetic to bolometric luminosities

$$\frac{L_{bol}}{L_{kin}} = \frac{8}{5}\frac{\theta h}{r}$$

$$\theta = \frac{B_{disk}^2}{B_{surface}^2} \qquad \dot{m} = \dot{M}/\dot{M}_{Edd} \qquad m = M/M_{sun}$$

$$\frac{L_{kin}}{L_{bol}} = 170\,\frac{m^{1/8}\,\alpha^{1/8}}{\dot{m}^{1/4}\,\theta^{5/4}} \qquad \frac{L_{kin}}{L_{bol}} = 228\,\frac{(m\alpha)^{2/17}}{\dot{m}^{3/17}\,\theta^{20/17}}$$

Comparison with fundamental plane of black holes

$$\log \frac{L_{kin}}{L_{bol}} = (A-1)\log(\frac{L_{bol}}{L_{Edd}}) + B$$

$$L_{kin}/L_{Edd} = \dot{m}$$

$$L_{bol} = 3.6 \times 10^{40} m\dot{m}^{2.19} \text{ erg/s}$$

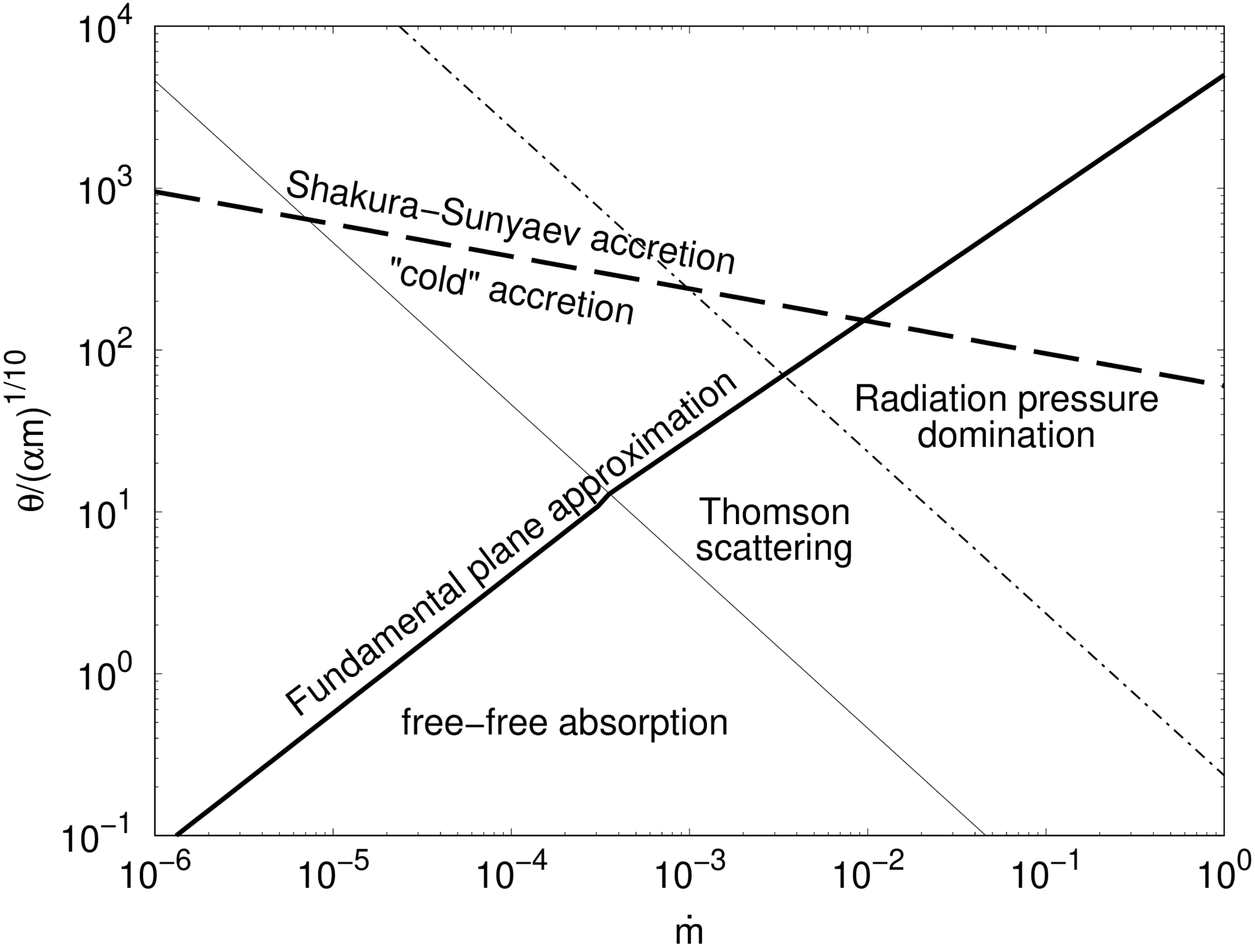
$$\frac{L_{kin}}{L_{bol}} = 3.9 \times 10^{-3}\dot{m}^{-1.19}.$$

$$\theta = 5 \times 10^3 \dot{m}^{3/4}(\alpha m)^{1/10}.$$

$$\theta = 11.2 \times 10^3 \dot{m}^{0.86}(\alpha m)^{1/10}$$

$$\theta = D\dot{m}^{\gamma}$$

Regimes of accretion



Kinetic-to-bolometric luminosity for M87

$$m = 3.5 \cdot 10^{9} \qquad \dot{m} = \frac{L_{kin}}{L_{Edd}} = 2 \cdot 10^{-4};$$

$$\frac{L_{kin}}{L_{bol}} = 95 \qquad L_{bol} = 10^{42} \quad ergs\, s^{-1}$$

Consistent with observation at θ ~ 54
Disk is optically thick

Kinetic-to-bolometric luminosity for Galactic Center

$$m = 4 \cdot 10^{6}; \qquad L_{bol} = 10^{36}\, ergs\, s^{-1};$$

$$L_{kin} = 4.4 \cdot 10^{39} \quad ergs\, s^{-1}$$

$$\theta = 1.7$$

Conclusion

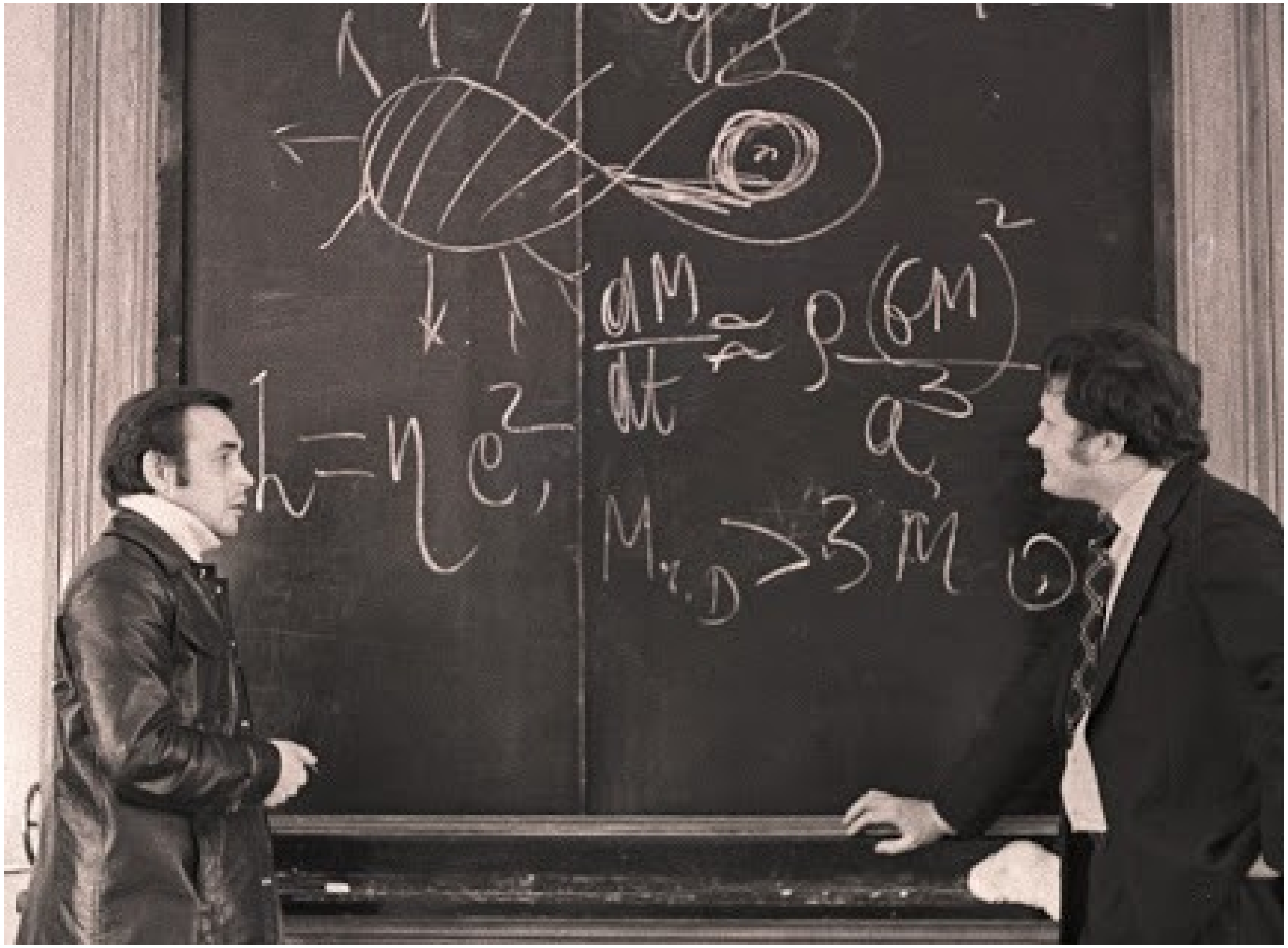
1. The selfconsisten solutions for cold accretion exist (selfsimilar and numerical)

2. The ratio of the kinetic-to-bolometric luminosity is well consistent with obesrvations at the comfortable values of .

3. Plasma can be accelerated by the magnetic field to the values well exceeding the Keplerian energy at the inner edge of the accertion disk. But an additional work is necessary for the final answer.

Classical disk accretion

(theory of α disks, N.I.Shakura, R.A.Sunyaev, 1973)



State prize (2017)