Physics of “cold” disk accretion due to the wind from the disk.

S.V.Bogovalov

National research nuclear university (MEPHI)

MOTIVATION
Some of AGN's produce jets with kinetic luminosity exceeding the bolometric luminosity of the AGN

The amount of the objects with such properties increases.

Observational data (kinetic luminosity of jets vs bolometric luminosity of disks)

M87

Kinetic luminosity of jets ~ 10^{44} erg/s (Bicknel&Begelman, 1996, Reinolds et al. 1996)

Bolometric luminosity M87 10^{42} erg/s (Biretta et al. , 1991)

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.

Our Galaxy (HESS, Nature, 531, 476, 2016)

- Luminosity of the disk ~ 10^{37} ergs/s

- Luminosity in gamma-rays ~ 1 TeV is of the order 10^{39} ergs/s.

- Kinetic luminosity in protons 100 times exceeds bolometric luminosity of the disk?

3C454.3

- The luminosity of the galaxy in bursts of gamma-rays ~ 10^{50} ergs/s

- Eddington luminosity < 5 10^{47} ergs/s !!!!

- The source of the energy is not the accretion ?
- Or the machine producing the jets is so efficient that all the gravitational energy goes into jets and nothing into radiation?

Two options

1. The source of energy is not the accretion

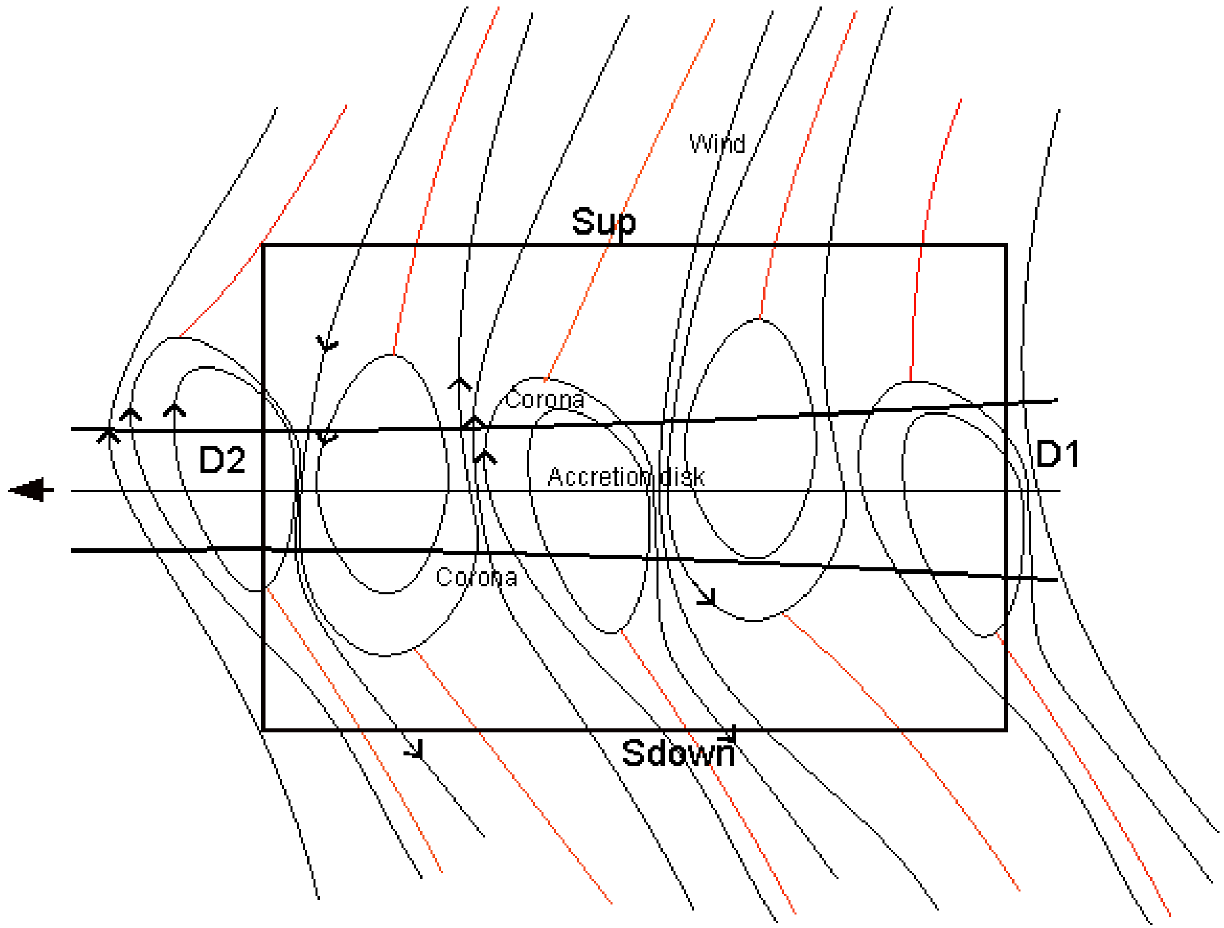
2. The luminosity of the disk is suppressed. All the accreted energy goes into jets.

Conventional approach

- 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.

But alternative mechanism also exists!

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 $< \frac{\partial \rho v_i}{\partial t} >= 0$;

Integration over the selected volume gives

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

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

$$\{ \qquad \alpha\rho C^2 \qquad \}$$

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

$$\Delta\left(\int(\rho v_r v_\varphi + \alpha\rho C^2)2\pi r dz\right) - 2\left(\rho v_z v_\varphi - \frac{1}{4\pi}B_z B_\varphi\right)2\pi r\Delta r = 0$$

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

If $\alpha\rho C^2 h \ll \frac{1}{4\pi}B_z B_\varphi r$, the wind carries out all the angular momentum

A simple estimates

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

It is difficult to avoid a conclusion that in some regimes of accretion matter losses the angular momentum due to the wind rather than due to viscous stresses (Pelletier G. & Pudritz R.E. 1992).

Therefore it is interesting to consider another limiting case when all the angular momentum is carried out by the wind

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 – total energy per particle +

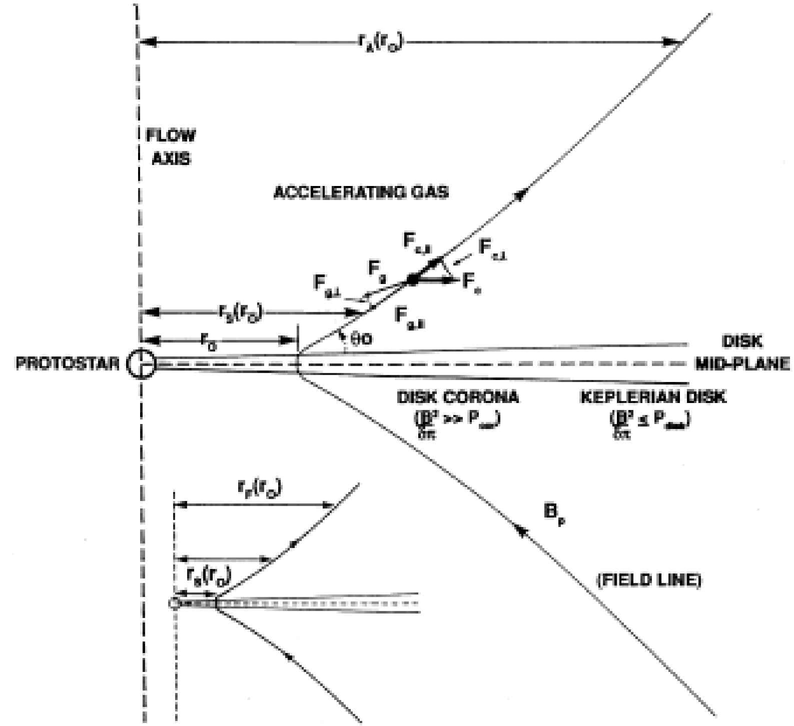
Ideal MHD equations for wind.

The wind cools the disk

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

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

Pay attention that the Energy can greatly exceed Keplerian energy



If λ > 3/2, the wind carries out all the excess of energy. Disk is not heated!

Estimates of the magnetic field at the inner edge of the disk

$$B_{wind} \geq 1.2\ 10^8\ \dot{m}^{1/2} m^{-1/2}$$

Shakura & Sunyaev

$$B \leq 10^8 m^{-\frac{1}{2}} \qquad \left(\dot{m} > \frac{1}{170}(\alpha m)^{-\frac{1}{8}}\right)$$

$$B \leq 1.5\ 10^9\ \alpha^{1/20} \dot{m}^{2/5} m^{-9/20}$$

The magnetic field in the wind model is less or close to the magnetic field in the Shakura & Sunyaev models.

Alternative approach

- The angular momentum and energy is carried out by the wind. Viscosity does not play any role.
- Disk remains cold. The ratio of the kinetic luminosity over the bolometric luminosity can be arbitrary high.

Grenoble version of the model

This approach has been explored by J. Ferreira et al . 1997-2014 (Grenoble University) with an assumption that the matter diffuses across the magnetic field lines. Low level of electrical conductivity is necessary to provide diffusion of the matter across the field lines. Again strong turbulence is necessary.

The matter can fall down onto the center together with the magnetic field

- No needs in any dissipation!

Selfsimilar and selfconsistent solution of the dissipationless accretion (J.Ferreira, 1997; Bogovalov & Kelner , 2010)

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

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

very close to Blandford & Payne (1982) solution.

Numerical modeling

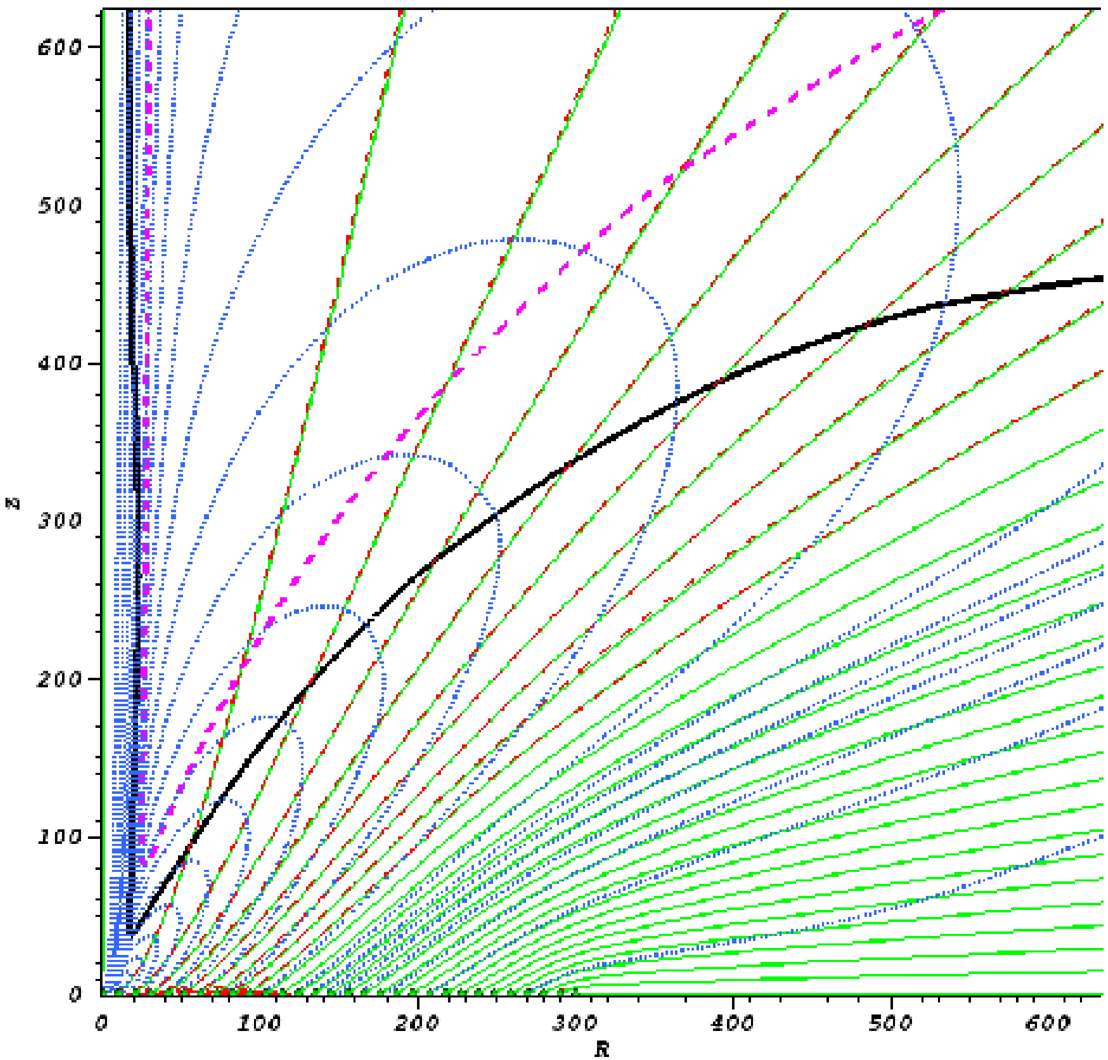
The main objective

Development of model with dissipationless outflow for relativistic case

We start with nonrelativistic case

1. To develop method
2. Verify in comparison with analytical results.
3. To check conditions of outflow at the violation of the selfsimilarity
4. To make sure that the centrifugal force is able to accelerate plasma to the energy many time exceeding Keplerian energy.

Solution



Verification

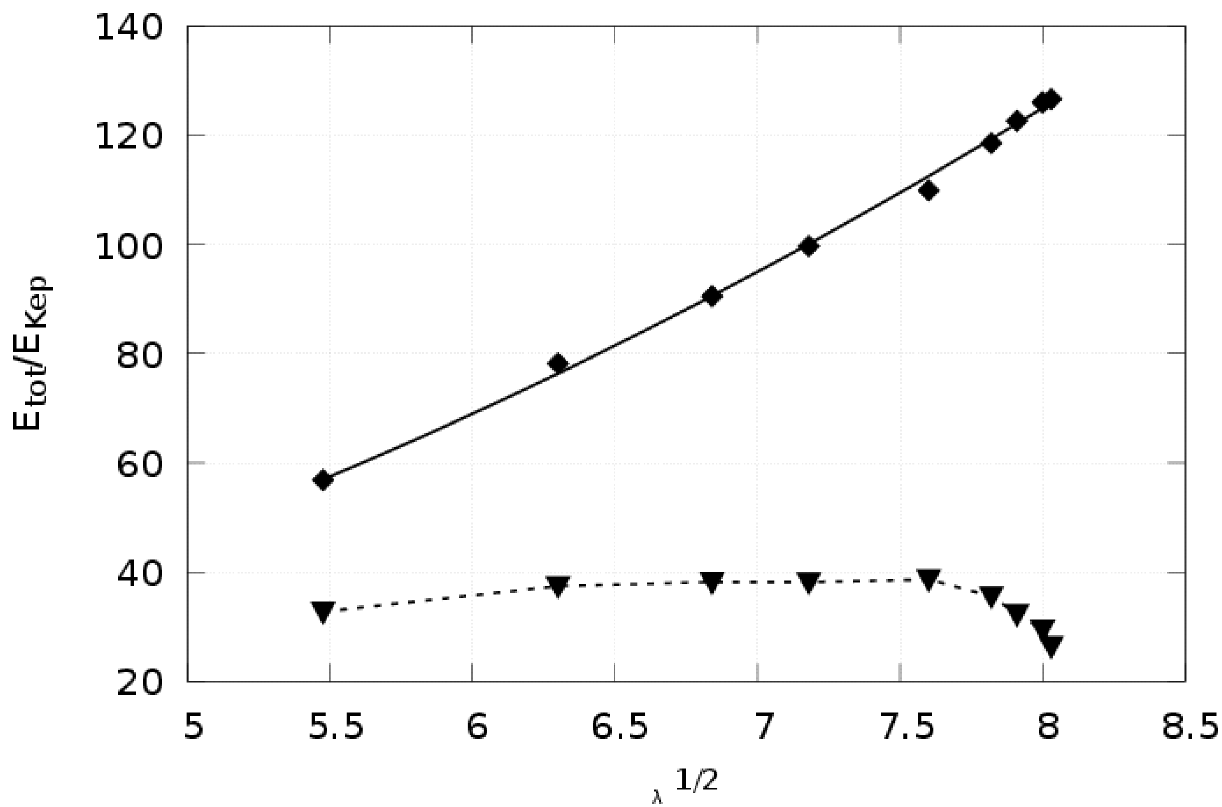
Integrals along field lines

1. Angular velocity $\Omega = (v_\varphi - \frac{B_\varphi v_p}{B_p})/r$
2. Ratio $\mathrm{F} = B_{\ p}/4\pi\rho v_p$
3. $rv_\varphi - \mathrm{rF}B_\varphi = \mathrm{L}$
4. $\frac{v^2}{2} - \frac{GM}{r} - \Omega rFB_\varphi$=E

All integrals along the field lines are constant in the limits of fraction of percent.

Acceleration of the plasma

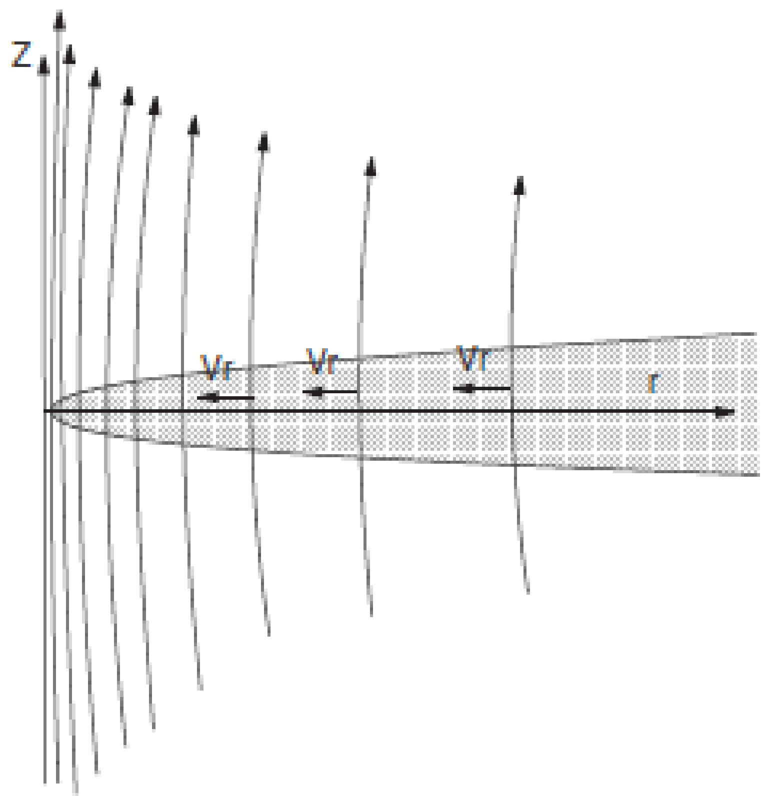
- $E = \frac{(2\lambda - 3)\mathrm{GM}}{2\mathrm{r}}, \quad \lambda = (\frac{r_A}{\mathrm{r}})^2$



Conclusion

- The accretion due to the wind outflow can be rather common phenomena
- The wind can efficiently cool the disk. The disk remains cold and therefore the kinetic luminosity of the outflow can essentially exceed the bolometric one.
- The magnetic field of the disk is smaller or similar to the magnetic field in the Shakura & Sunyaev model.
- The selfsimilar and numerical solutions confirm existence of such a regime of accretion.
- The energy of the particles in the wind can essentially exceed the keplerian energy at the orbit. Potentially can explain high Lorentz factors in the jets.

Accumulation of the magnetic field. No way for its annihilation inside 3 r_g



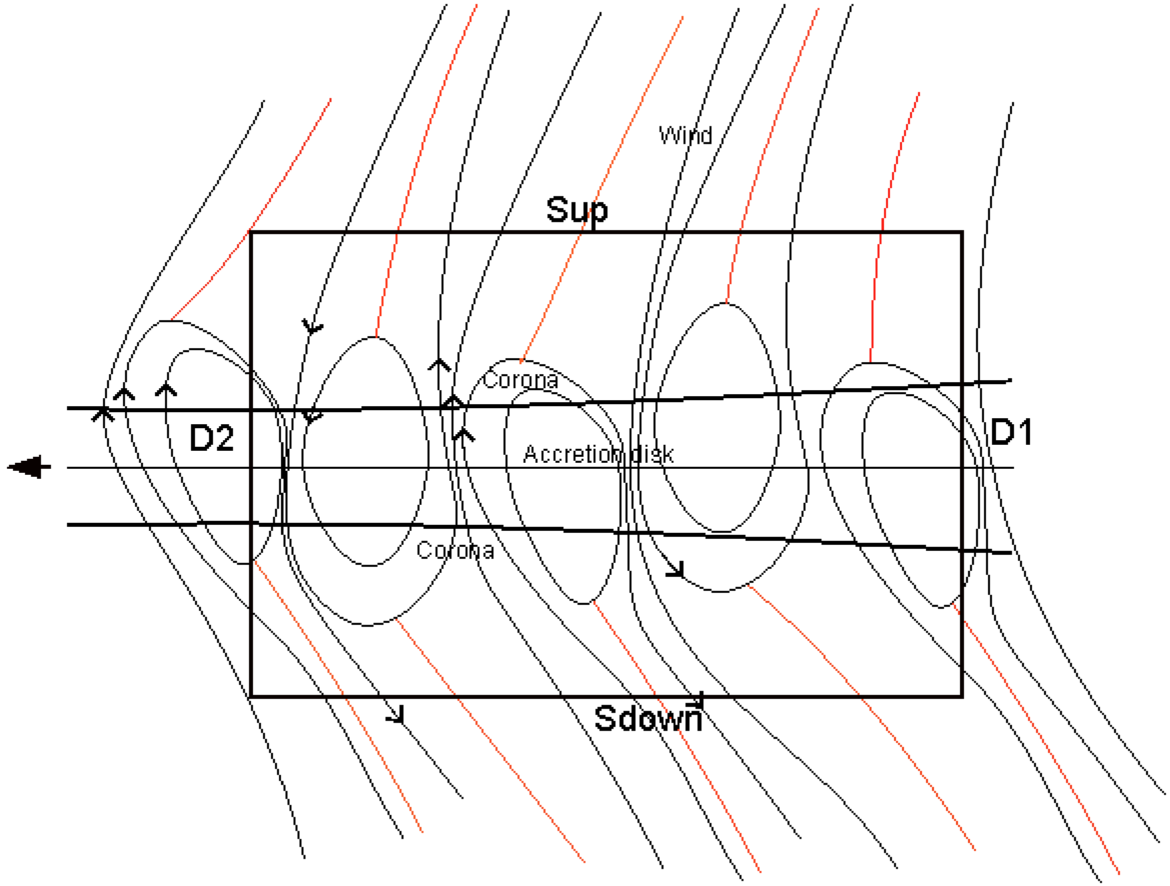
Bisnovatyi-Kogan & Ruzmaikin, 1974,1976

Velocity of diffusion

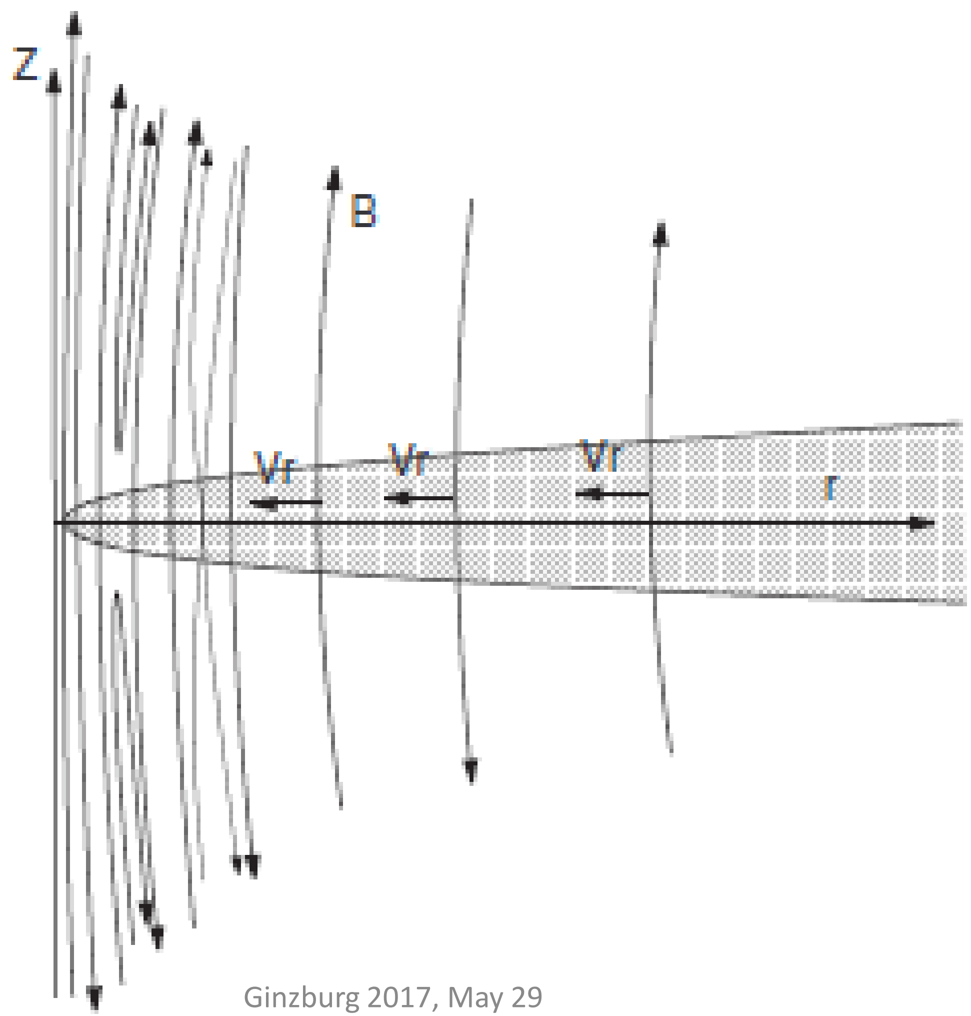
$$v_r \approx \frac{c^2}{4\pi\sigma r}$$

Gives $v \approx 10^{-10}\frac{cm}{s}$ for our Galaxy at the inner edge of the disk. Strong turbulence is necessary to reduce electrical conductivity of the plasma

Real magnetic field



Full magnetic flux falling onto the center equals to zero.



VLBI data (M.Li. Ma et al, 2008)

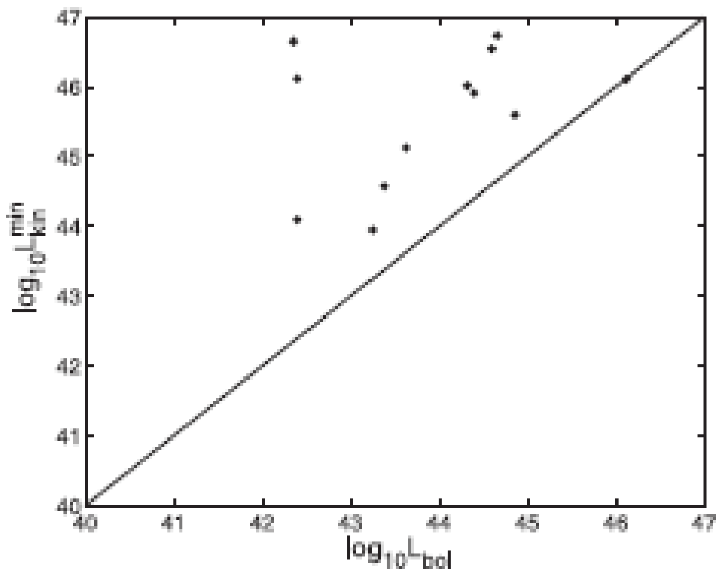


Fig. 4 Relation between $L_{\rm kin}^{\rm min}$ and $L_{\rm bol}$. The line represents $L_{\rm kin}^{\rm min} = L_{\rm bol}$.

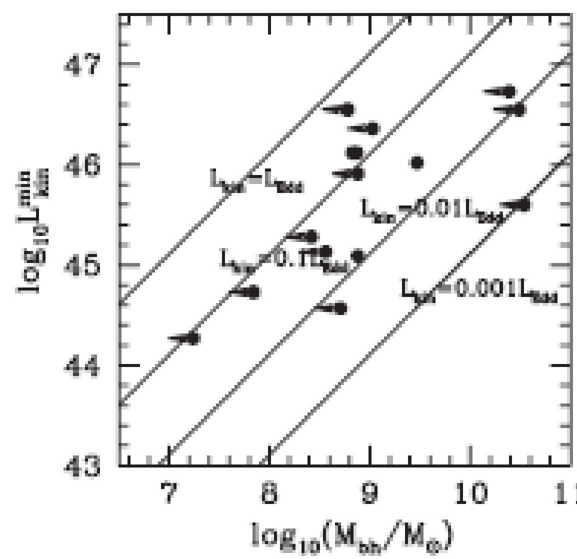


Fig. 5 Relation between $L_{\rm kin}^{\rm min}$ and $M_{\rm bh}$.