

NUMERICAL MODELING OF THE WINDS FROM RELATIVISTIC OBJECTS

S. Bogovalov¹, F. Aharonian^{1,4}, I. Tronin¹, S.
Romanikhin¹, G. Ustyugova¹, A. Koldoba²,
D. Khangulyan³

1- National research nuclear university, MEPhI,
Moscow, Russia

2-Moscow institute of physics and technology,
Moscow, Russia

3-Institute of Space and Astronautical Science/JAXA,
Japan

4-Dublin Institute for Advanced Studies, Ireland

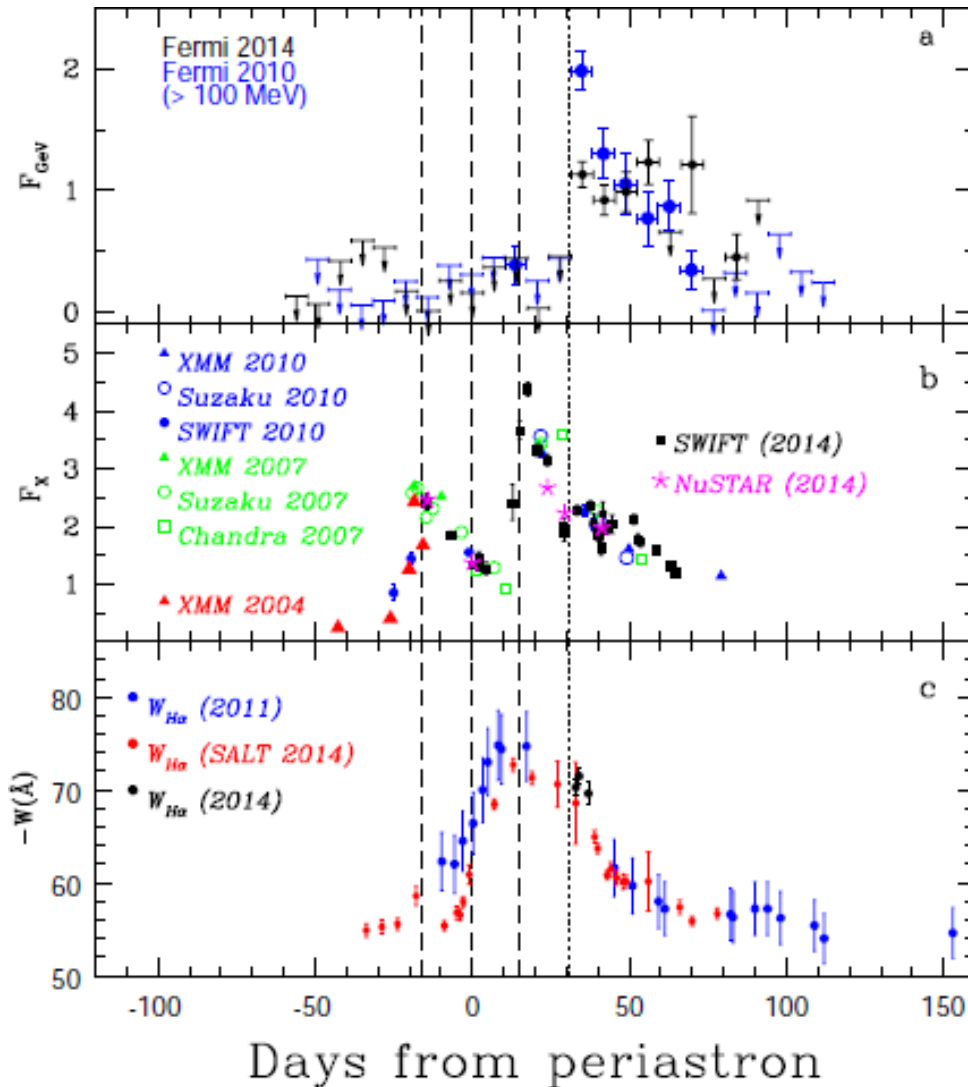
Basic milestones

1. Interaction of the winds in the binary system
PSR1259-63/SS2883
2. Formation of disk-like outflows from Be stars.
3. Cold disk accretion in AGNs.

Interaction of the winds in the binary system

PSR1259-63/SS2883:

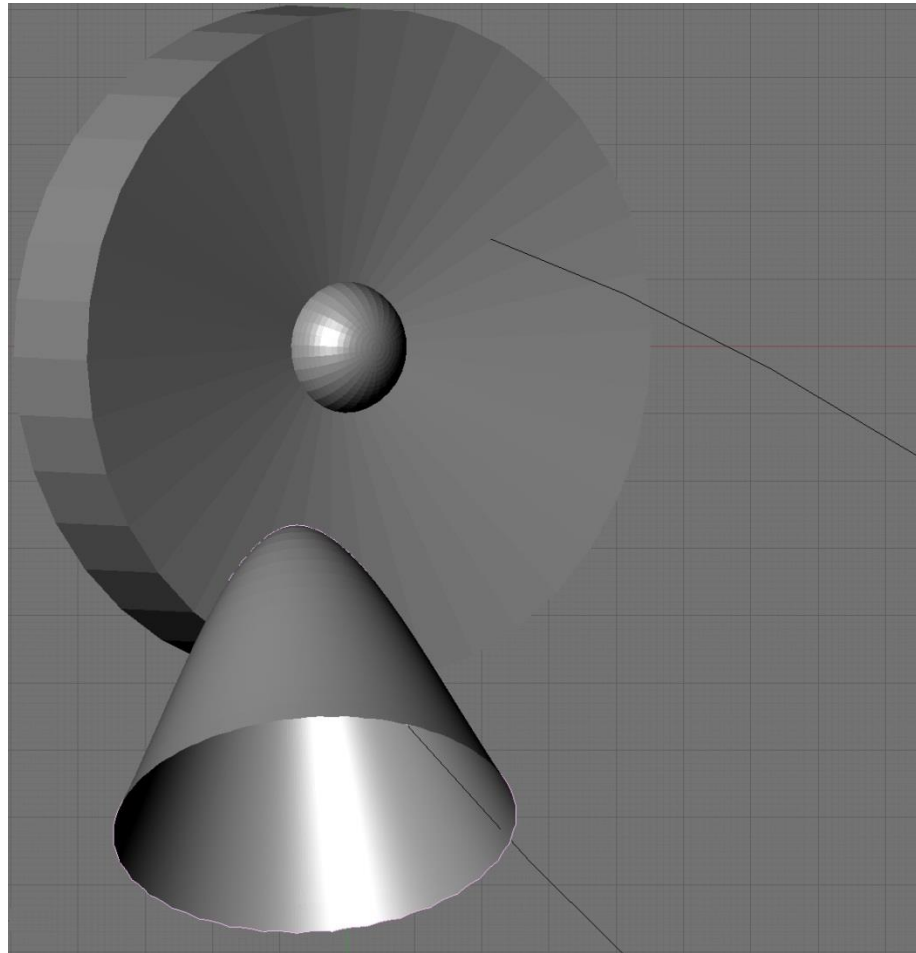
Motivation



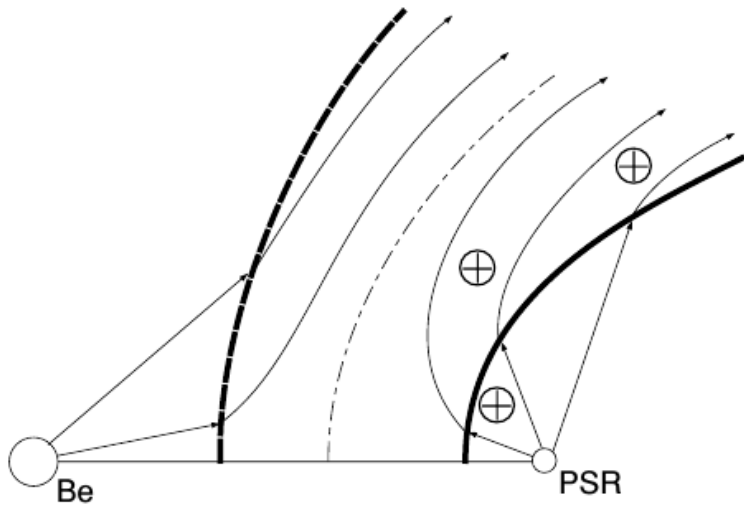
The gamma-rays luminosity equals to the rotational losses of the pulsar.

50-70 % of the rotational energy is radiated in gamma-rays (Cernyakova et al. 2014)

Binary system



Interaction of the winds



Bogovalov et al., 2008

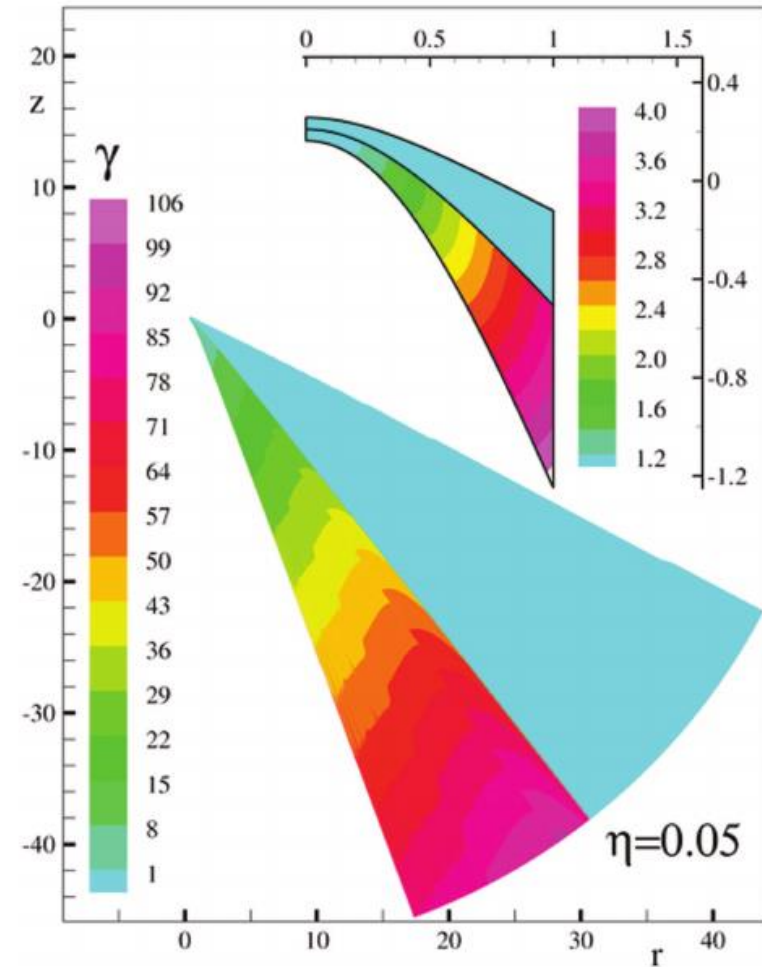
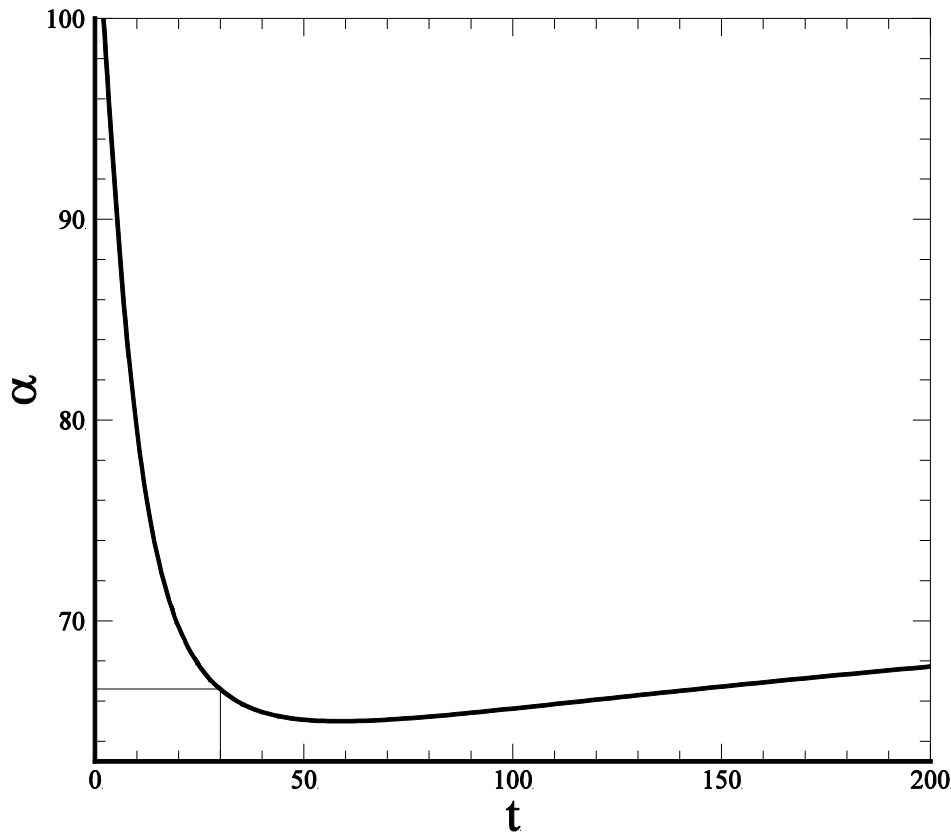


Figure 9. The post-shock flow for $\eta = 0.05$. The color represents the bulk Lorentz factor.

Dependence of the angle between the line connecting stars and direction to observer



The flare occurs when the tail of the relativistic plasma flow is directed to us.

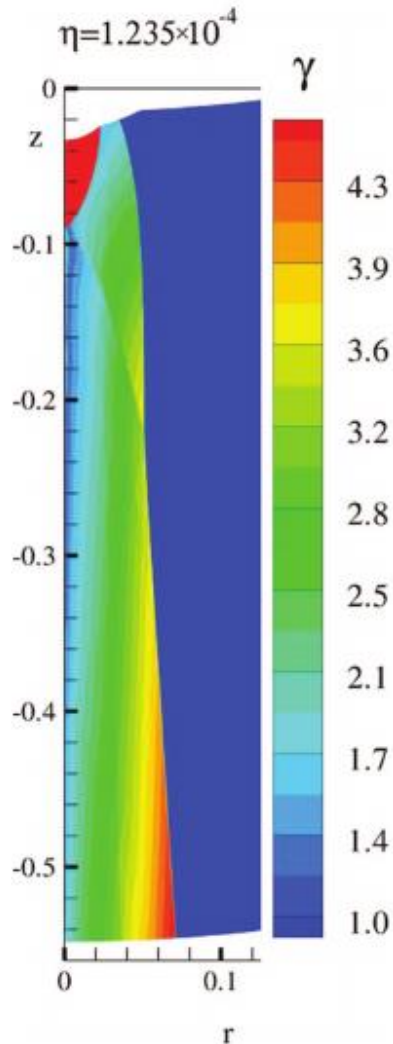
It is attractive to explain the flare as the appearance of Earth in the cone of the relativistic flow of the post shocked plasma.

However, the flux of energy appears 10 times below of the observed. (Khangulyan et.al.,2014)

Is it possible to obtain flux of gamma rays exceeding the rotational losses of the pulsar?

- In principle yes if the opening cone of the relativistic post shocked flow is small enough to provide relativistic boosting.
- We can provide the relativistic boosting by strong dominance of the wind from Be star or by magnetization of the wind.

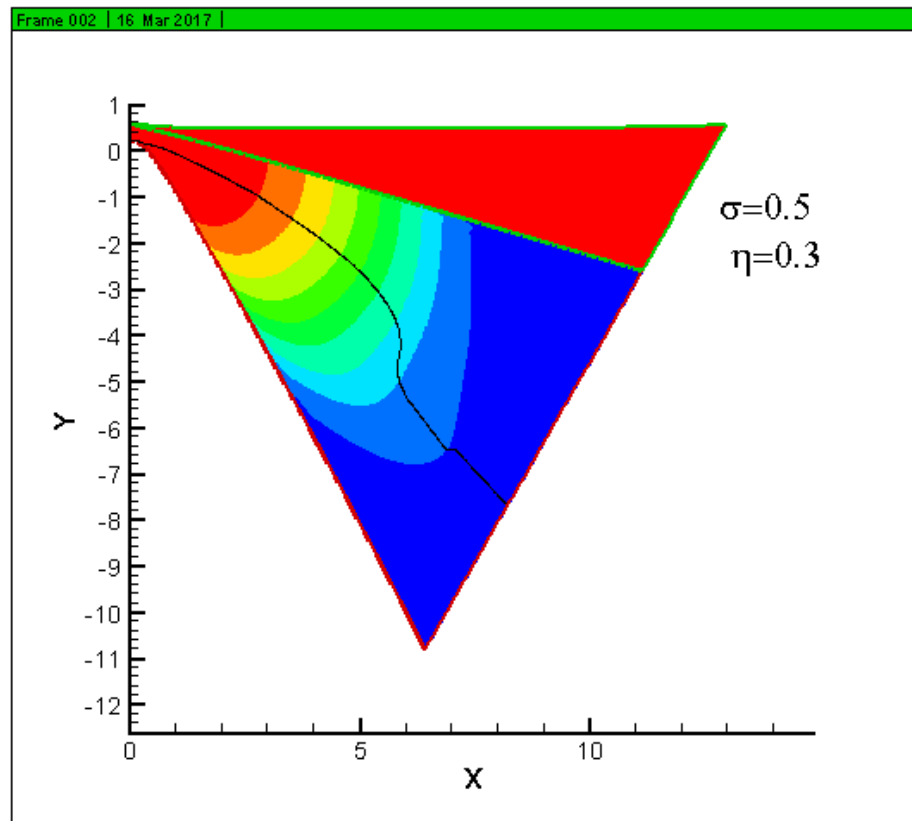
Our objective is to investigate case of moderate magnetization ~ 1



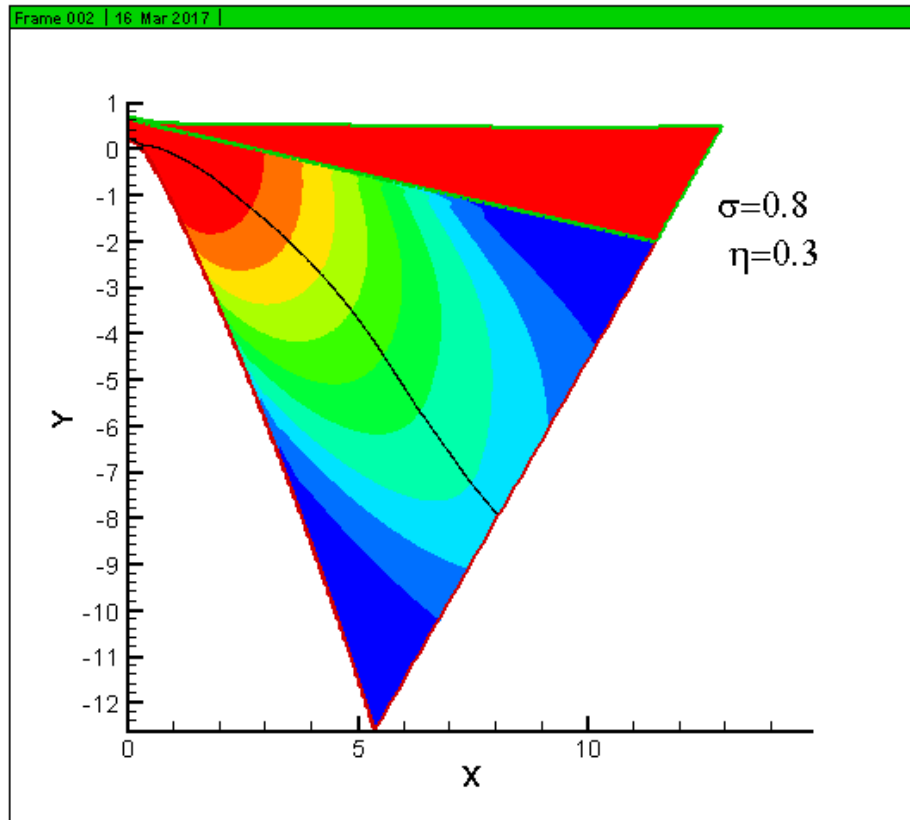
Low magnetization $\bar{\sigma} < 0.1$ have been considered earlier (Bogovalov et.al. MNRAS, 2012). No impact on the flow.

Now we consider the case when $\bar{\sigma} \sim 1$

Increase the magnetic field.



Increase the field once more



Basic conclusion

- Magnetic field does not reduce the opening angle of the post shocked relativistic flow.
- This angle increases with magnetization.
- Amplification of the gamma-rays due to the relativistic boosting is possible only at strong dominance (low η) of the momentum flux in the nonrelativistic wind from the companion star over the momentum flux of the pulsar wind.

Formation of disk-like outflows from Be stars

The velocity of rotation ~ 0.8 critical velocity.

Two models

1. The wind compressed disk
2. Decretion disks

No satisfactory direct numerical simulation of the process of formation of the disks.

Motivation

In any case we deal with outflow (wind) from the fast rotating star. Only in the first case the viscosity is neglected while in the second case the turbulent viscosity is important.

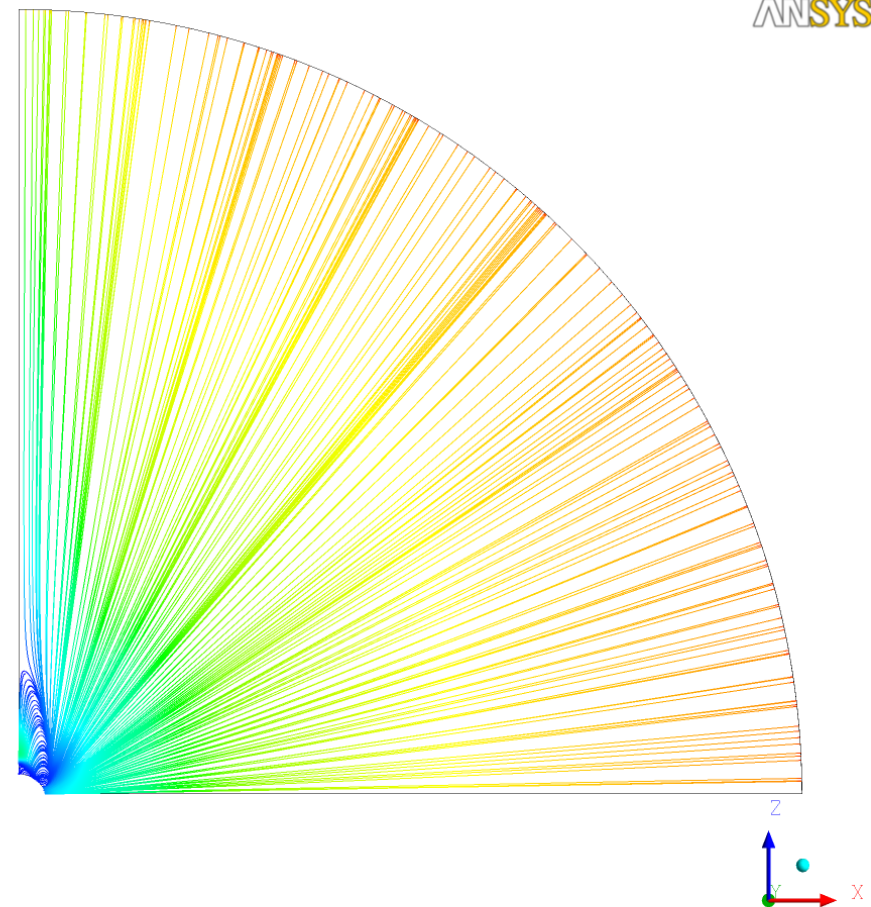
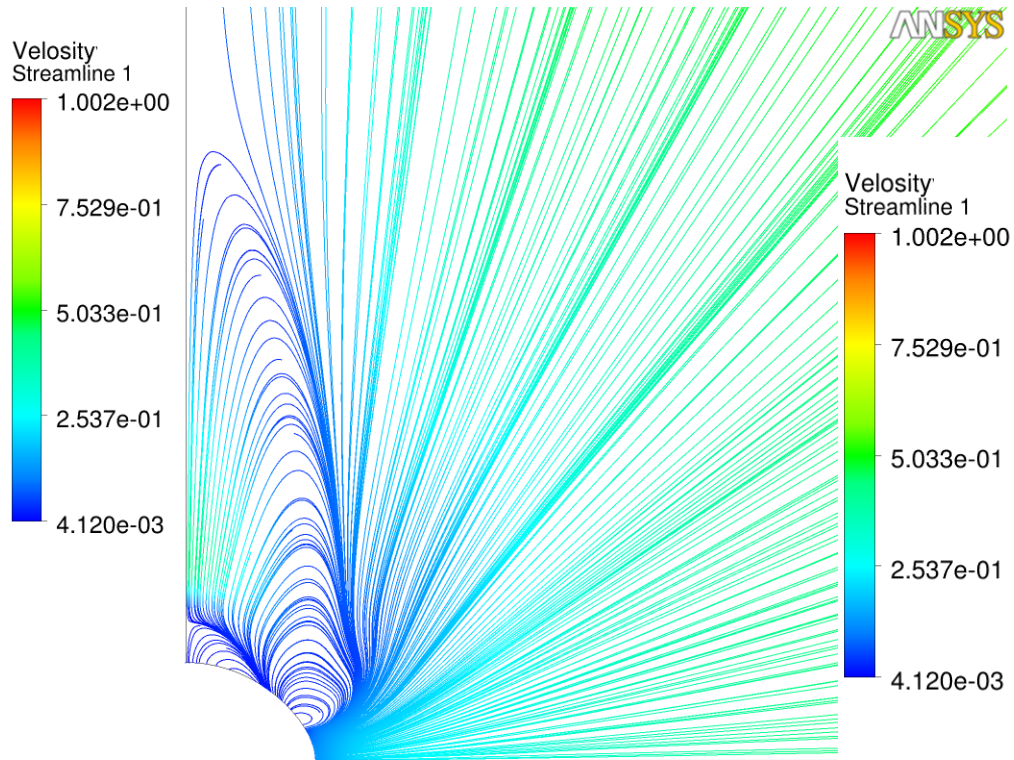
Let us consider the simplest case of the Parker wind from fast rotating star.

Why the disk like outflow is not formed in this case?

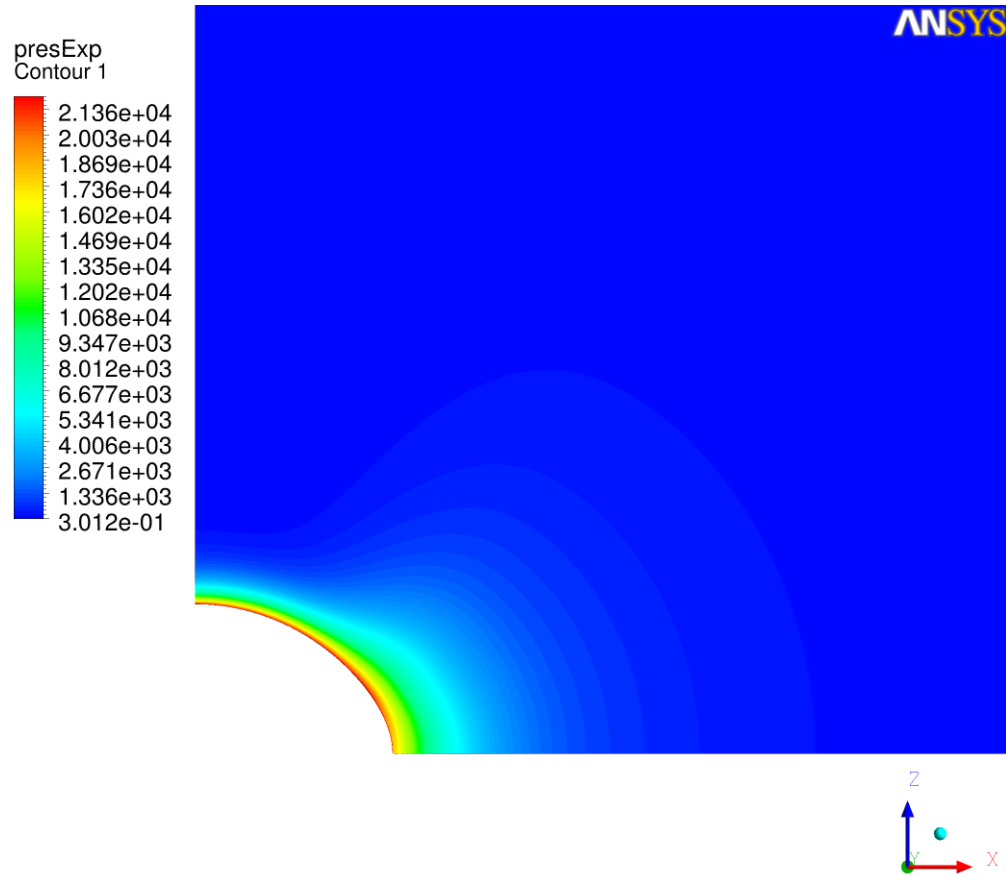
New elements in the model

1. Nonspherical surface of the star.
(In the model with the spherical surface nonphysical flow along the star surface to the equator appears (wind compressed model).
2. The code has been modified to incorporate strong gradients of pressure (unphysical mass fluxes)
3. Different models of turbulence have been used (Very high Reynolds numbers).

Results (velocity 0.8 critical)



Pressure distribution



Conclusions

1. In the model of the Parker wind the disk is not formed.
2. The initial disk like outflows expands quickly filling all the space. The outflow from the polar region is suppressed.
3. The level of turbulence generated in the conventional models is not sufficient to provide formation decretion disk. Additional mechanism of turbulence generation (MRI) is necessary.

“Cold” disk accretion in AGNs

The work is motivated by the increasing flow of the observational data demonstrating that the kinetic flux in jets from AGNs exceeds the bolometric luminosity.

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

M87

Kinetic luminosity of jets $\sim 10^{44}$ erg/s
(Bicknell & Begelman, 1996, Reynolds et al. 1996)

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

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

- The whole 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 $\sim 10^{37}$ 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 $\sim 10^{50}$ ergs/s
- Eddington luminosity $< 5 \cdot 10^{47}$ 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

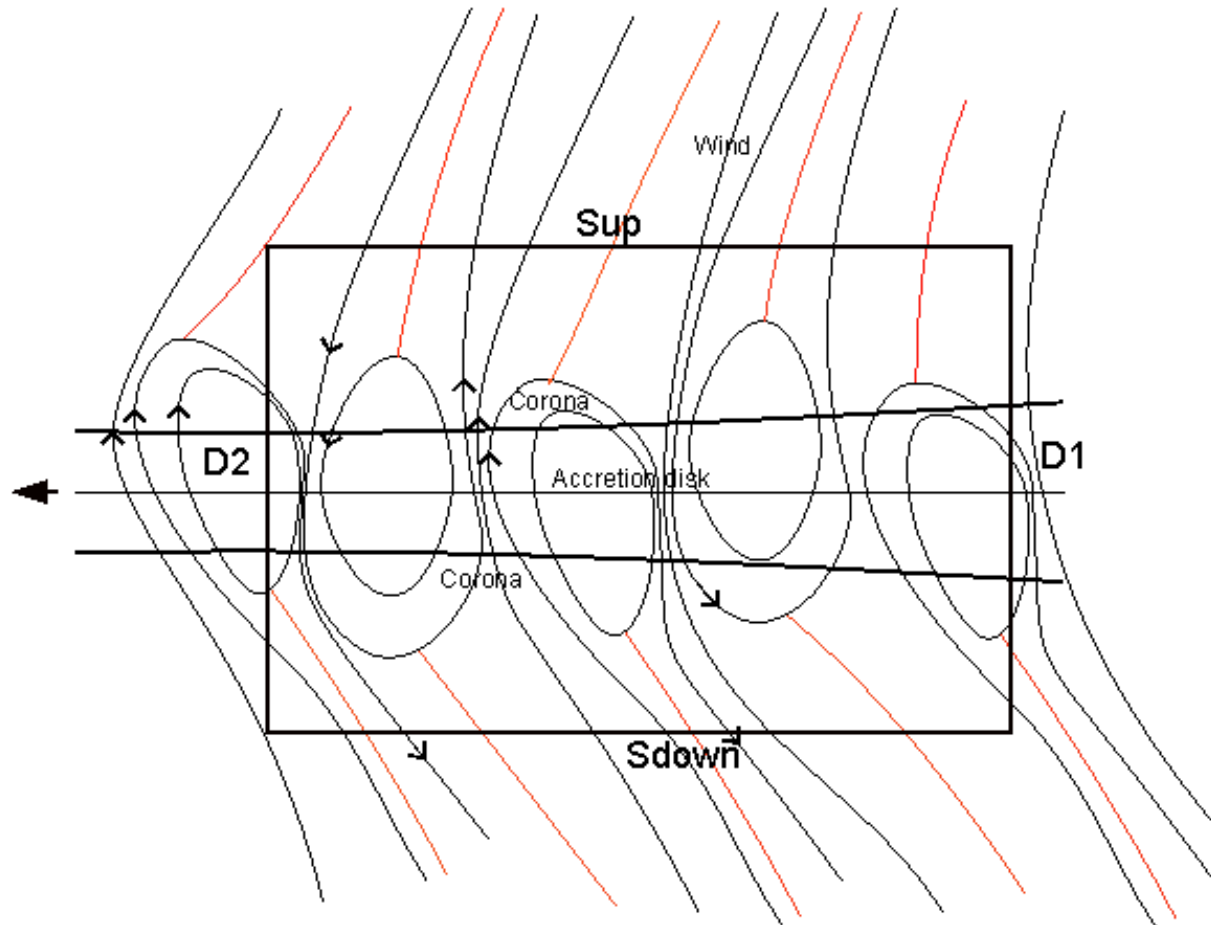
1. The source of energy is not the accretion
2. The luminosity of the disk is suppressed. All the accreted energy goes into jets.

Conventional approach

- Blandford - Znajek (1977) effect + advection dominated disks 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

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

Averaging gives $\langle \frac{\partial \rho v_i}{\partial t} \rangle = 0;$

Integration over the selected volume gives

$$\begin{aligned}
& \int_{D2} \left(\rho v_r v_\varphi + \tau_{\varphi r} - \left\langle \frac{1}{4\pi} (B_r B_\varphi) \right\rangle \right) dS \\
& - \int_{D1} \left(\rho v_r v_\varphi + \tau_{\varphi r} - \left\langle \frac{1}{4\pi} (B_r B_\varphi) \right\rangle \right) dS + \\
& \quad \left\{ \alpha \rho C^2 \right\} \\
& + 2 \int_S \left(\rho v_z v_\varphi + \tau_{\varphi z} - \left\langle \frac{1}{4\pi} (B_z B_\varphi) \right\rangle \right) dS = 0
\end{aligned}$$

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

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

$$\alpha \rho C^2 \approx \frac{1}{4\pi} B^2 \text{ and } h \ll r.$$

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

$$\frac{\partial \dot{M}}{\partial r} - 4\pi r \rho v_z|_{wind} = 0;$$
$$\dot{M} \frac{\partial r V}{r \partial r} + r B_z B_\phi|_{wind} = 0;$$

V – Keplerian velocity

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

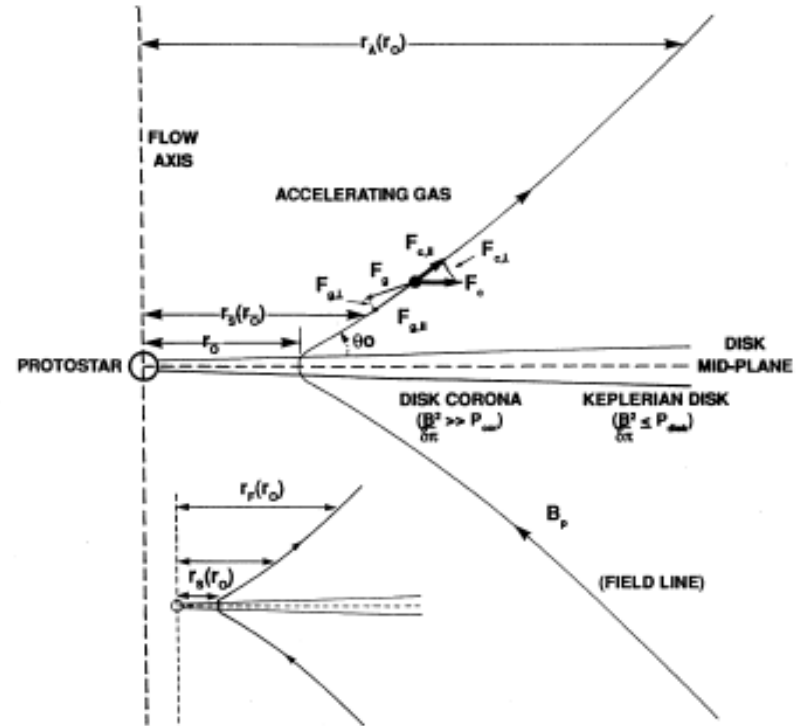
E – total energy per particle +
Ideal MHD equations for wind.

The wind cools the disk

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

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

Pay attention that the Energy can greatly exceed Keplerian energy



If $\lambda > 3/2$, 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

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

Shakura & Sunyaev

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

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

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.

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.

Verification

Integrals along field lines

1. Angular velocity $\Omega = (v_\varphi - \frac{B_\varphi v_p}{B_p})/r$

2. Ratio $F = B_p/4\pi\rho v_p$

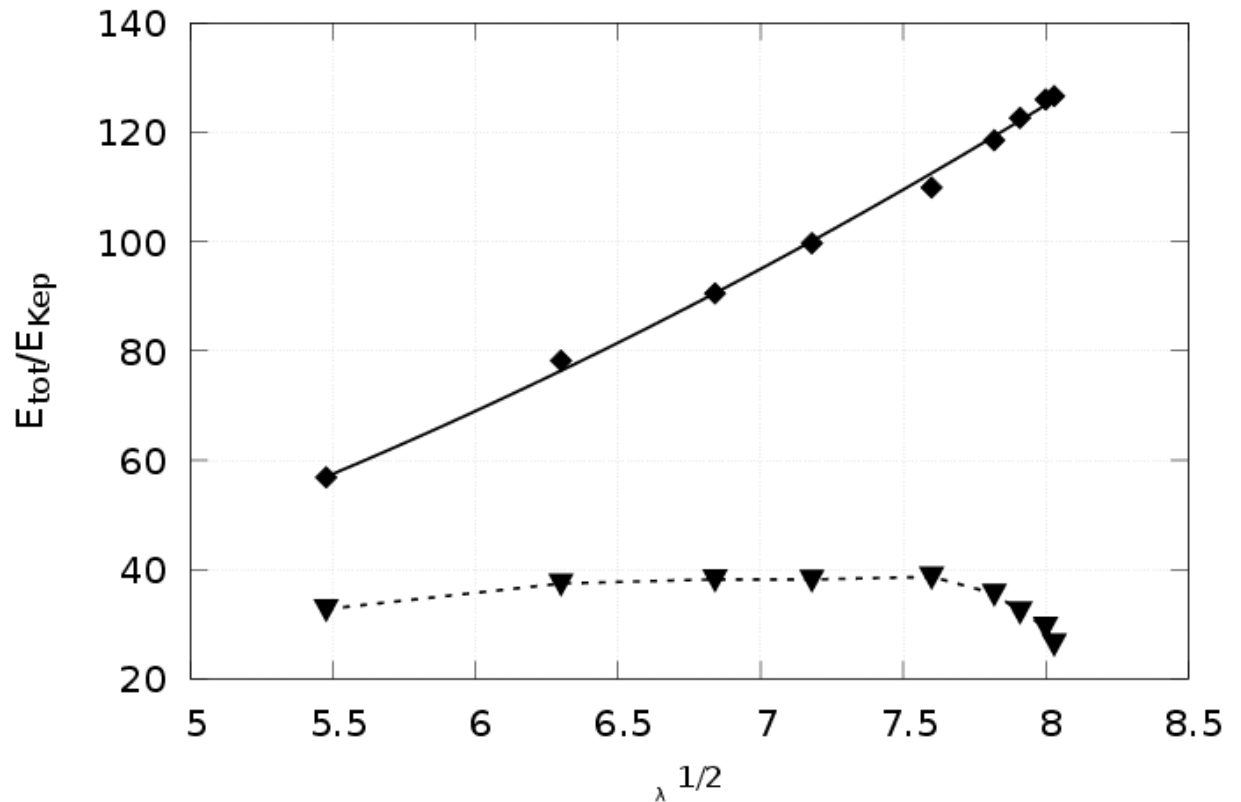
3. $r v_\varphi - r F B_\varphi = L$

4. $\frac{v^2}{2} - \frac{GM}{r} - \Omega r F B_\varphi = E$

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

Acceleration of the plasma

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



Basic properties of the cold disk accretion

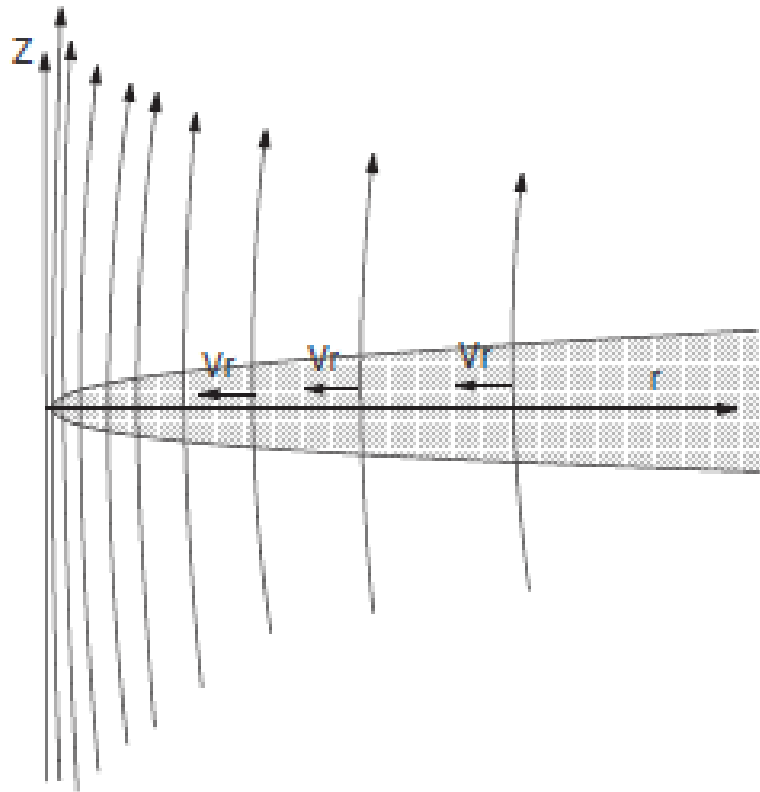
- The accretion due to the wind outflow should be rather common phenomena (no exotics physics is necessary)
- The wind can efficiently cool the disk. The disk remains cold and therefore the kinetic luminosity of the outflow can essentially exceed the bolometric one.
- The magnetic field of the disk is smaller or similar to the magnetic field in the Shakura & Sunyaev model.
- The selfsimilar and selfconsistent 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.

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.**

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

Bisnovatyi-Kogan &
Ruzmaikin, 1974, 1976

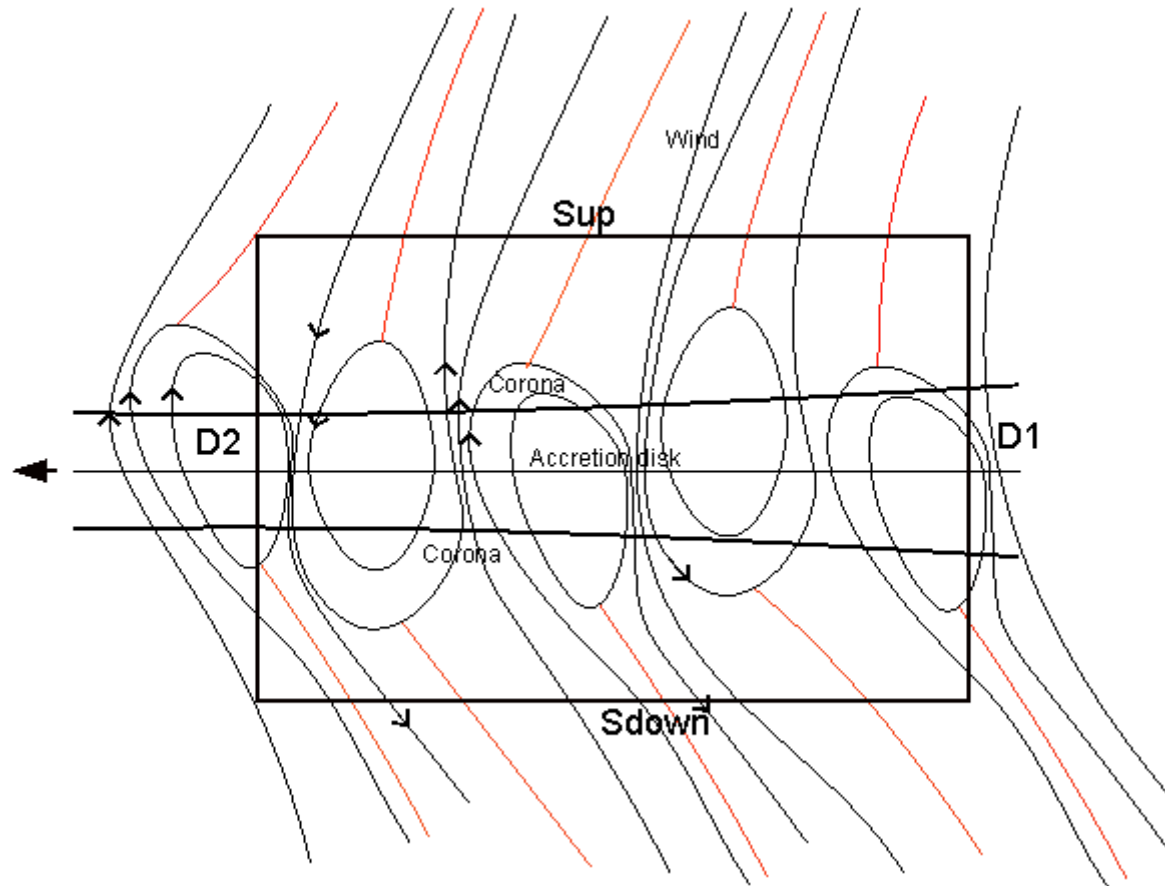


Velocity of diffusion

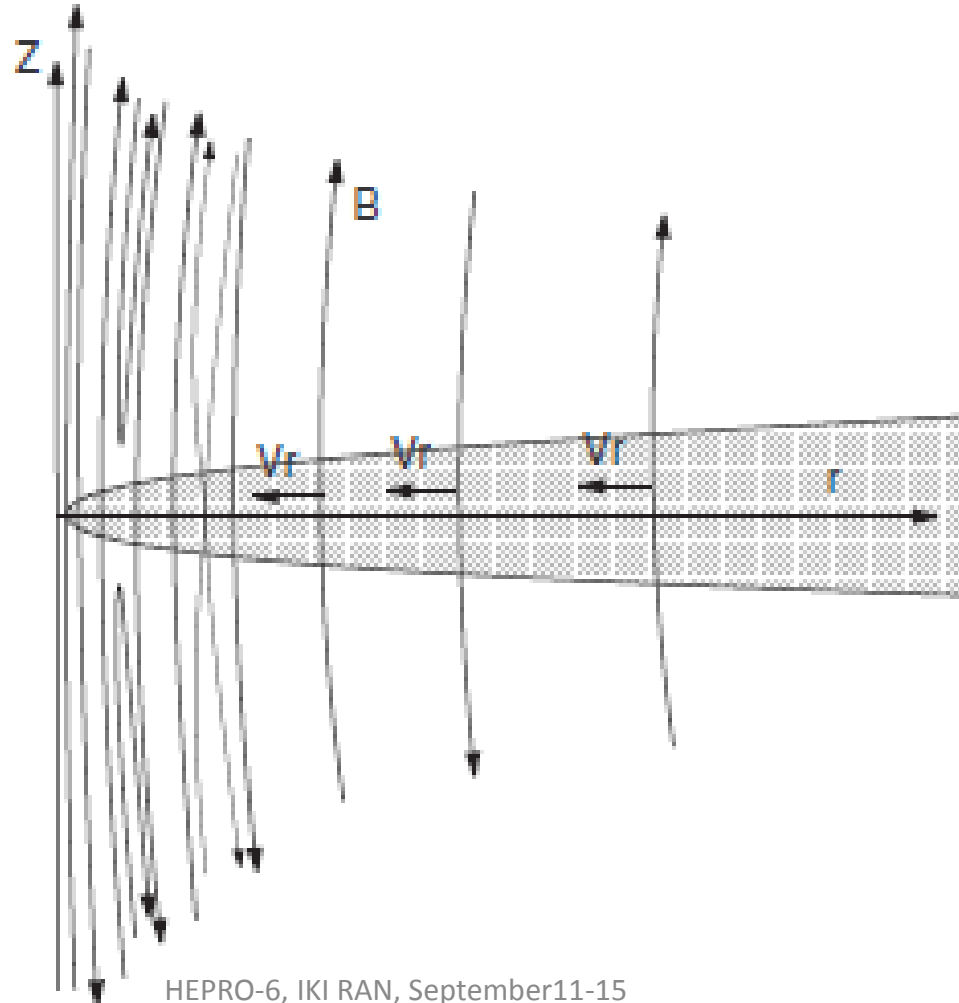
$$v_r \approx \frac{c^2}{4\pi\sigma r}$$

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)

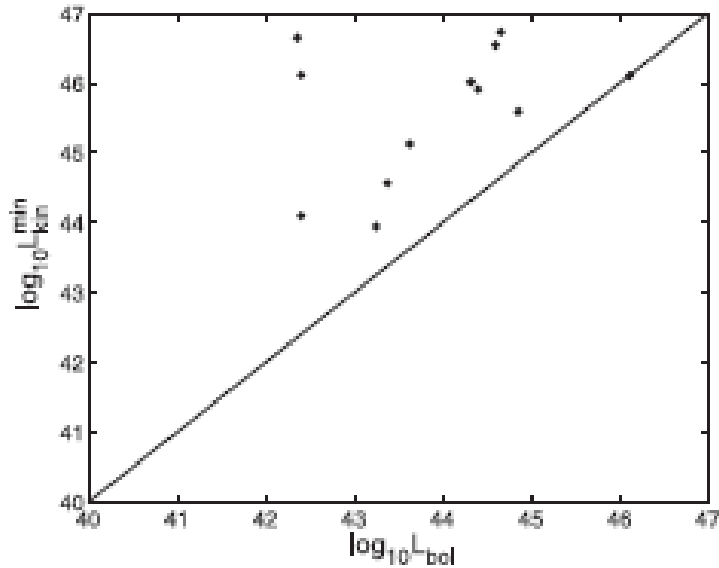


Fig. 4 Relation between $L_{\text{kin}}^{\text{min}}$ and L_{bol} . The line represents $L_{\text{kin}}^{\text{min}} = L_{\text{bol}}$.

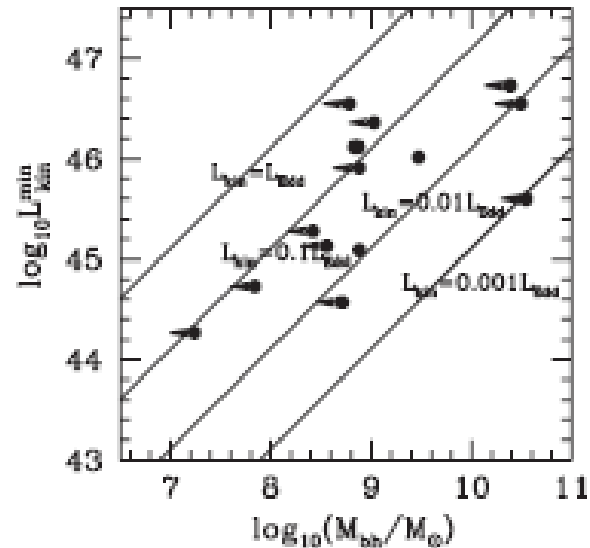


Fig. 5 Relation between $L_{\text{kin}}^{\text{min}}$ and M_{bh} .