Plasma outflow from dissipationless accretion disks

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The key problems at the accretion

- Mechanism of the angular momentum loss
- Mechanism of the gravitational energy loss

Conventional (Shakura&Sunyaev) model

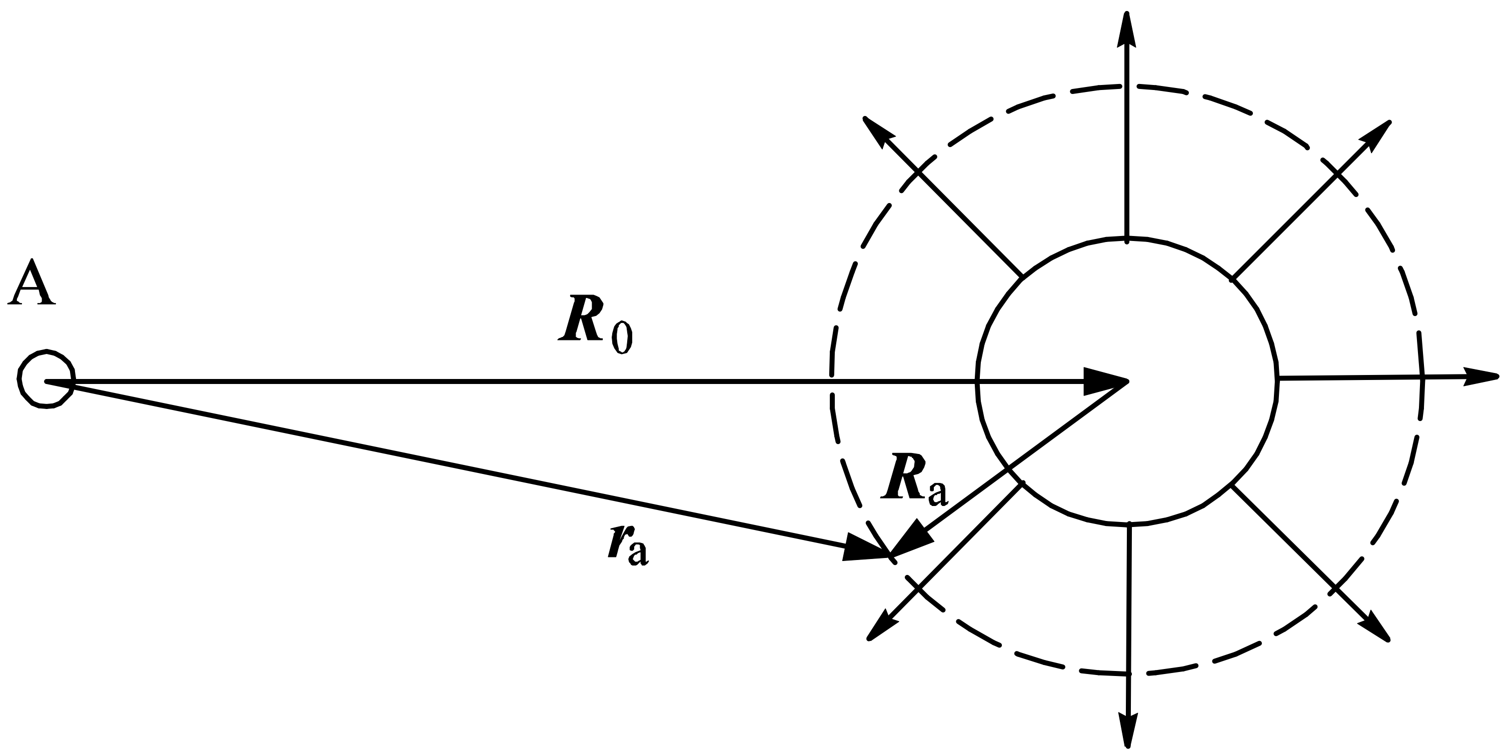
- Angular momentum is transported outward from the center due to viscous stresses

- Viscosity is provided predominantly by the turbulence and the magnetic field.

Alternative general mechanism of the angular momentum loss

- Angular momentum loss due to magnetized wind.

Sun is the nearest astrophysical object which loss angular momentum by the solar wind.


A
$\boldsymbol{R}_0$
$\boldsymbol{R}_a$
$\boldsymbol{r}_a$

The mechanism of the angular momentum loss by the wind.

- Initially a particle have angular momentum

$$\Omega R^2$$

- The particle carries out the angular momentum

$$\Omega R_A^2$$

- The difference $\Omega(R_A^2 - R^2)$ is carried out from the rotating object.

- The angular momentum losses of the rotating object is defined

$$\dot{L} = \dot{m}\Omega(R_A^2 - R^2)$$

The accretion disks eject winds

- Observations of jets from AGN’s, YSO and microquasars. Independence of the nature of the central object.
- Theory. Blandford & Payne(1982) have demonstrated that the plasma is unstable on the surface of the disk provided that the magnetic field lines leave the disk under the angle less than 60 degrees.

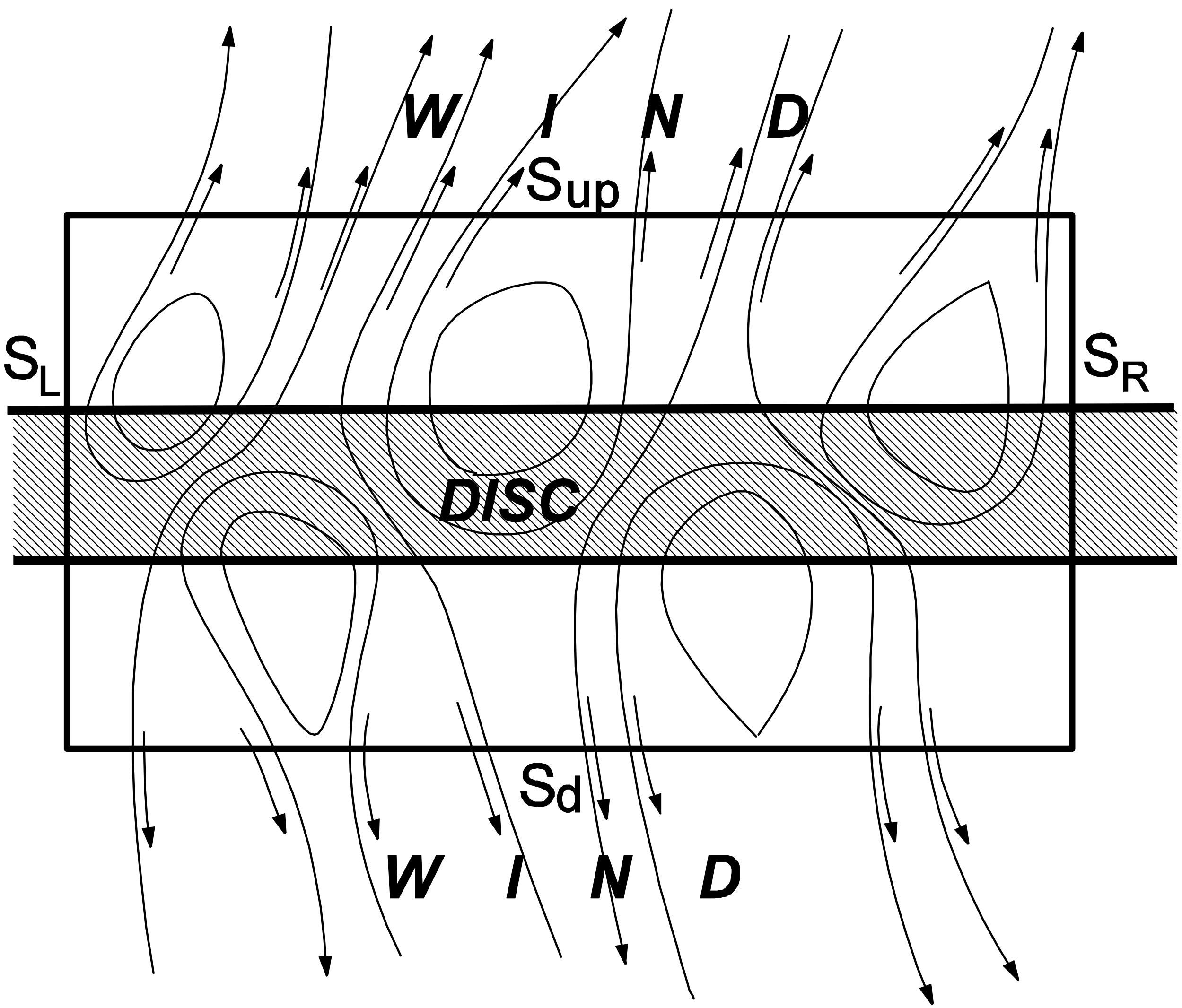
Therefore the disks must loss the angular momentum due the matter outflow.

- The question is:

How efficient are the angular momentum losses of the disks compared with the momentum losses due to the viscous stresses?

- Pelletier & Pudritz (1992) pointed out that the wind could provide more efficient angular momentum losses compared with the viscous stresses.
- They discussed that it is possible to neglect totally the viscosity in the accretion disks.
- Why they did not refused from dissipative processes totally?

A fragment of the disk



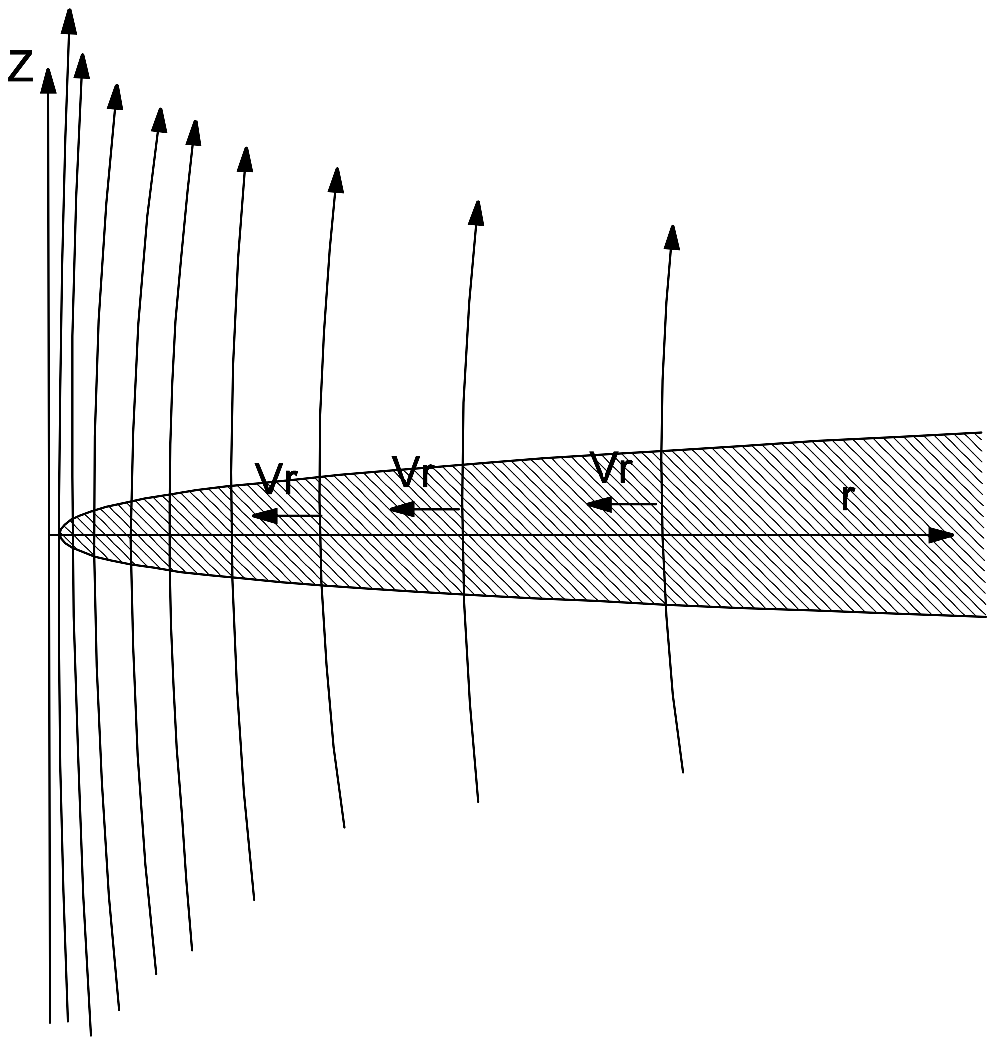
Equation of the angular momentum conservation.

$$\Delta(r^2 \rho v_r v_\varphi h) - \Delta(\frac{1}{4\pi} r^2 B_r B_\varphi h) + 2(r\rho v_\varphi v_z - \frac{1}{4\pi} r B_\varphi B_z) r\Delta r = 0.$$

$$\Delta \dot{M} r v_\varphi - \Delta 2\pi r^2 \frac{B_r B_\varphi}{4\pi} h + 2\rho v_z S_{up} (r v_\varphi - \frac{rB\varphi}{4\pi} \frac{B_z}{\rho v_z}) = 0.$$

$$\frac{B_r B_\varphi}{4\pi} = \alpha \rho_D V_s^2$$

Advection of the magnetic field of one polarity



Equations for advection of one polarity magnetic field

$$\frac{\partial B}{\partial t} = rotE$$

$$\frac{\partial \Phi}{\partial t} = 2\pi r E_\varphi \quad \Rightarrow \quad E_\varphi = 0.$$

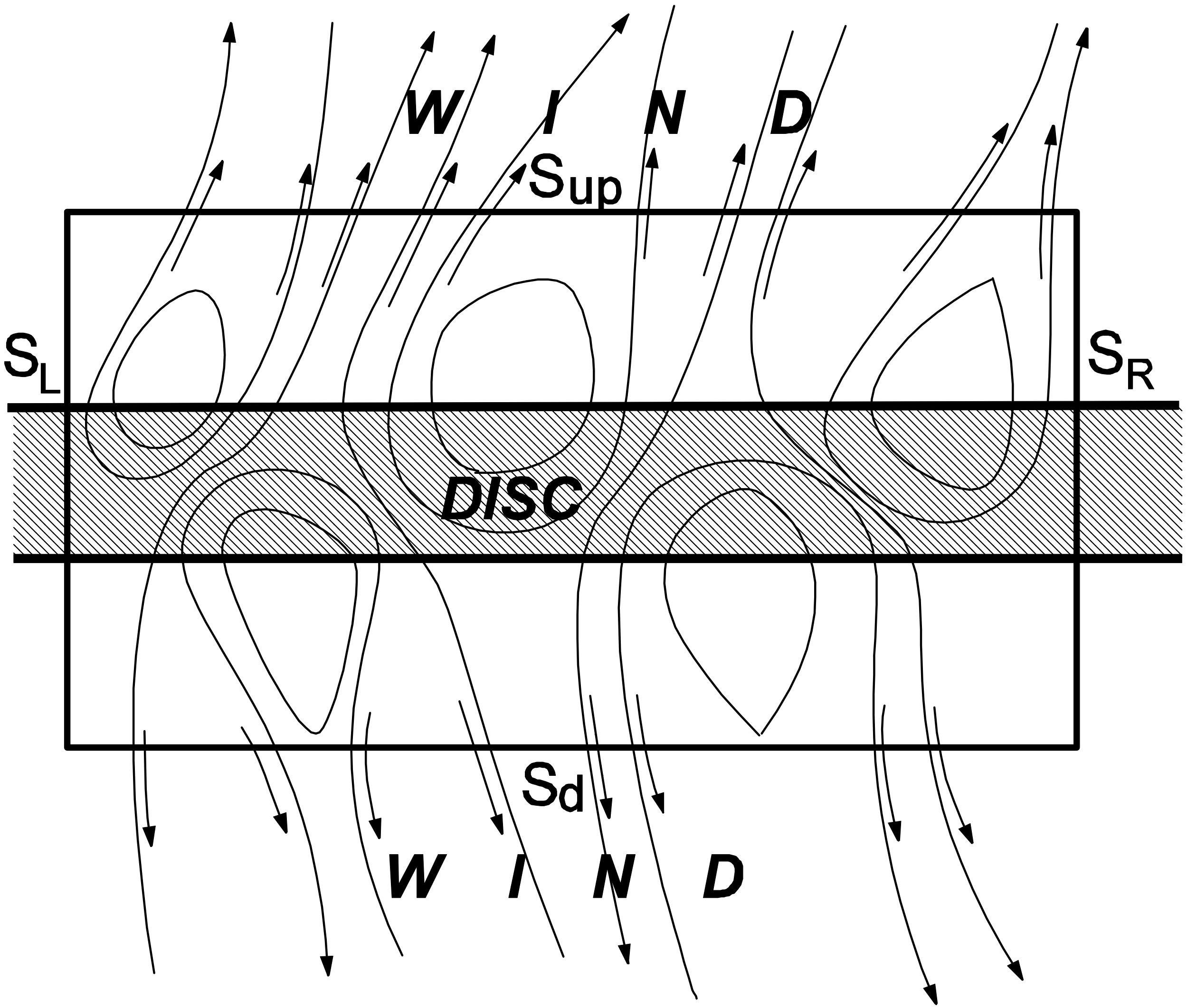
$$j = \sigma(E + [vB]).$$

$$(rotB)_\varphi = \sigma(E_\varphi + [v_z B_r - v_r B_z]), \quad v_z B_r = 0.$$

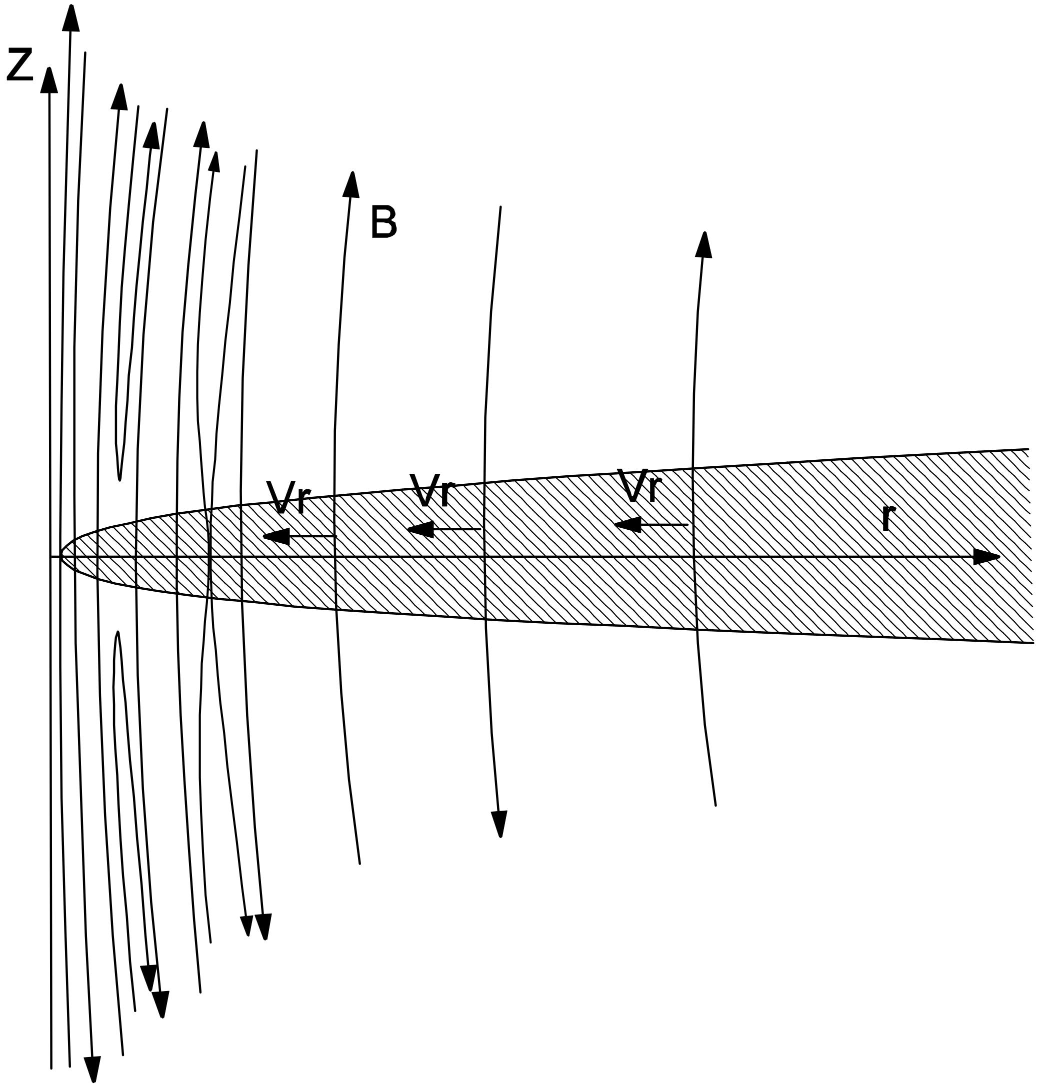
$$(rotB)_\varphi = -\sigma v_r B_z.$$

Advection of one polarity magnetic field demands low resistivity of the plasma

Realistic magnetic field in the disk



Simplified structure of the magnetic field in the disk.



Advection of variable polarity magnetic field

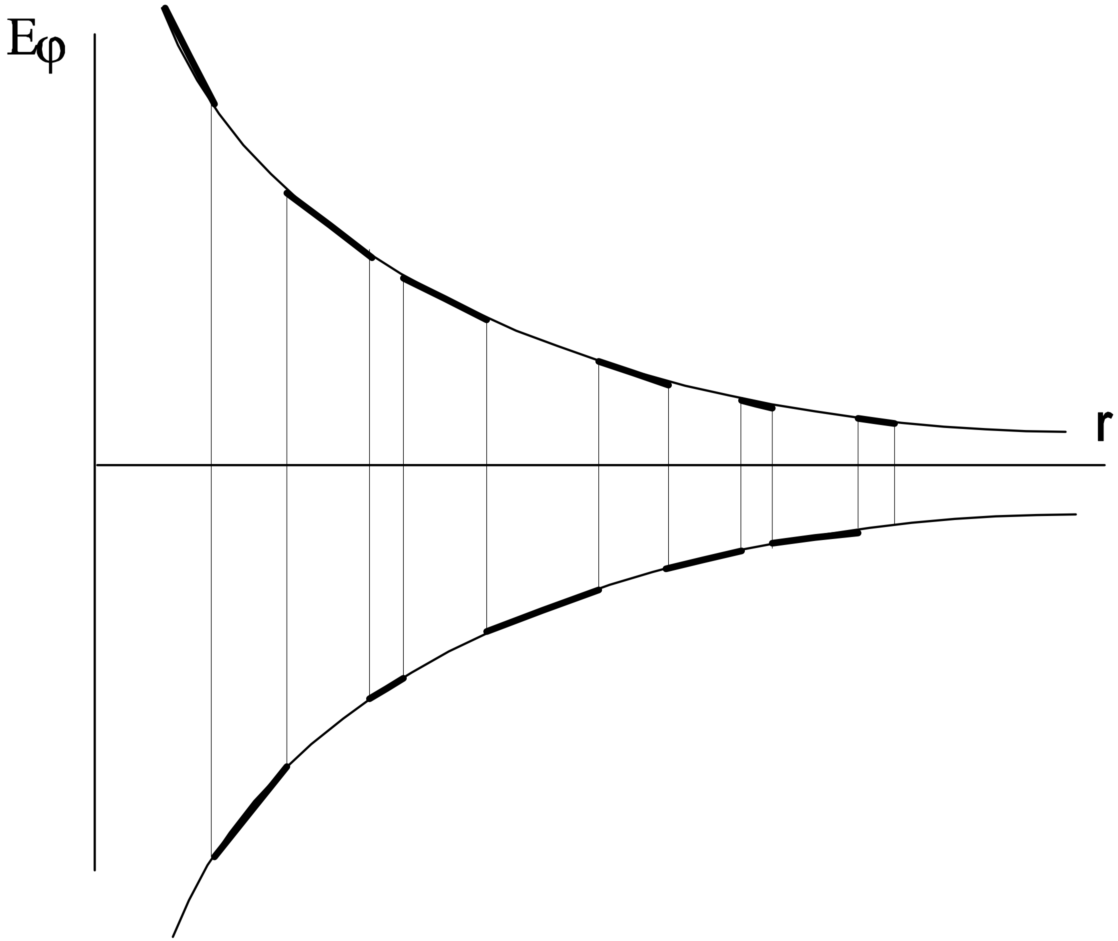
$$< \frac{\partial \Phi}{\partial t} >= 0. \quad \text{Total magnetic flux.}$$

$$\text{Steady state flow} \quad \Rightarrow \frac{\partial |B|}{\partial t} = 0.$$

$$\frac{\partial \Delta \Phi}{\partial t} = r_2 E_{\varphi 2} - r_1 E_{\varphi 1} \quad \Rightarrow \quad |E_\varphi| = \frac{A}{r}$$

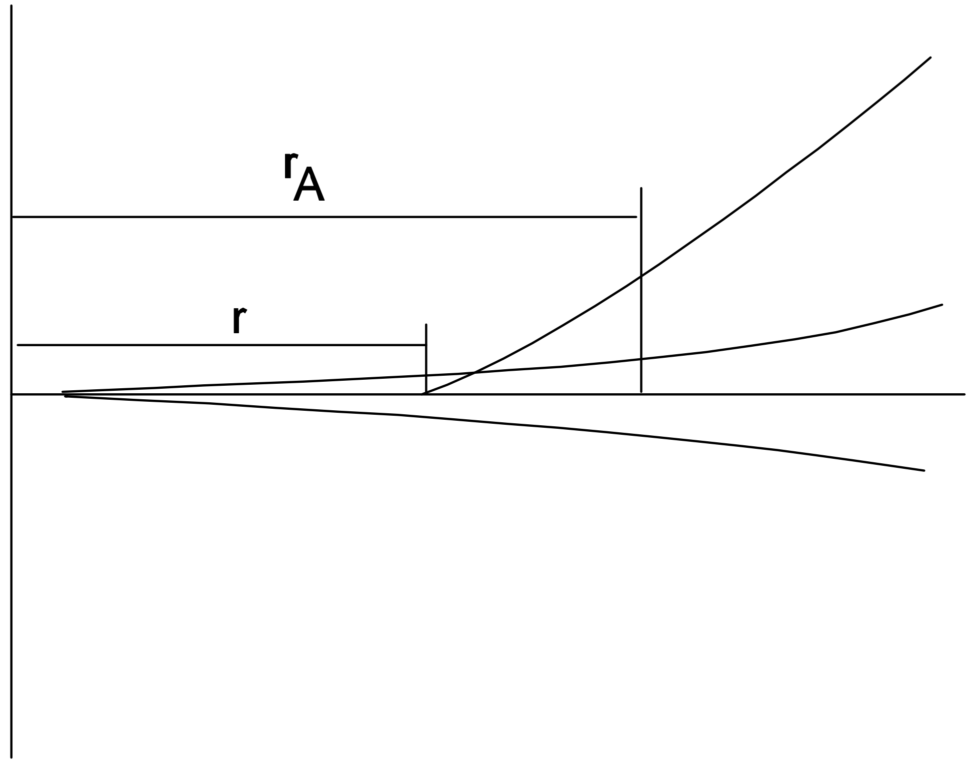
Our basic statement: Magnetic field is advected to the center, toroidal magnetic field is not equal to zero.

Snapshot of the toroidal electric field.



Disk-wind connection

- Disk and wind are connected by the conservation laws.



Mass conservation law

$$\frac{\partial}{r\partial r}\left(r\int_{-h/2}^{h/2}\rho v_r\,dz\right)_{disc}+\left(2\rho v_z\right)_{wind}=0.$$

$$\dot{M}=-2\pi r\int_{-h/2}^{h/2}\rho v_r\,dz.$$

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

- Angular momentum conservation law

$$
-\int_{-h/2}^{h/2} r^2 \rho v_\varphi v_r \, dz \bigg|_{r1} + \int_{-h/2}^{h/2} r^2 \rho v_\varphi v_r \, dz \bigg|_{r2} +
$$

$$
+ \frac{1}{4\pi} \int_{-h/2}^{h/2} r^2 B_r B_\varphi \, dz \bigg|_{r1} - \frac{1}{4\pi} \int r^2 B_r B_\varphi \, dz \bigg|_{r2} +
$$

$$
+2 \left(r \rho v_\varphi v_z - \frac{1}{4\pi} r B_\varphi B_z \right)_{S_{up}} r \, dr = 0.
$$

$$\frac{\partial}{r\partial r}\left(r^2 v_\varphi \int_{-h/2}^{h/2} \rho v_r \, dz\right)_{disc}$$

$$+2\left(r\rho v_\varphi v_z - \frac{1}{4\pi} r B_\varphi B_z\right)_{wind} = 0.$$

$$\frac{\partial}{\partial r}\left(r V_k \dot{M}\right)\bigg|_{disc} - \frac{\partial \dot{M}}{\partial r}\left(r V_k - \frac{r B_\varphi}{f}\right)\bigg|_{wind} = 0.$$

$\left(r V_k - \frac{r B_\varphi}{f}\right)_{wind}$ equals to $L = r_A^2 \Omega_k$

$$\frac{\partial}{\partial r}(r V_k \dot{M}) - \frac{\partial \dot{M}}{\partial r} r_A(r)^2 \Omega_k(r) = 0, \quad \Omega_k(r) = \sqrt{\frac{GM}{r^3}}$$

Interesting dependence of the accretion mass rate on the radius

$$\ln\left(\frac{\dot{M}}{\dot{M}_{\max}}\right) = -\int_r^{r_{\max}} \frac{dr^2}{4(r_A^2(r) - r^2)},$$

$r_A = \lambda r$ then

$$\dot{M} = \dot{M}_{\max} \exp\left(-\frac{1}{4}\int_r^{r_{\max}} \frac{dr^2}{r^2(\lambda^2 - 1)}\right)$$

Assume λ - constant

$$\dot{M} = \dot{M}_{\max} \left(\frac{r}{r_{\max}}\right)^{\frac{1}{2(\lambda^2-1)}}$$ (Ferreira & Pelletier 1993).

Energy conservation

$$\frac{1}{r}\frac{\partial}{\partial r}\int_{-h/2}^{h/2} r\rho v_r\, dz \left(\frac{V_k^2}{2} - \frac{GM}{r}\right)_{disc}$$

$$+2\left(\rho v_z\left(\frac{v^2}{2} - \frac{GM}{R}\right) + \frac{1}{4\pi}[E\times B]_z\right)_{wind} = 0.$$

$$\frac{\partial}{\partial r}\left.\frac{\dot{M}V_k^2}{2}\right|_{disc} + \frac{\partial \dot{M}}{\partial r}\left(\frac{v^2}{2} - \frac{GM}{r} - \frac{V_k B_\varphi}{f}\right)_{wind} = 0.$$

We use notations that $\frac{1}{4\pi}\frac{[E\times B]_z}{\rho v_z} = \frac{\Omega_k r B_\varphi}{f}$

Necessary condition to go to infinity is $\frac{v^2}{2} - \frac{GM}{r} - \frac{\Omega_k r B_\varphi}{f} > 0.$

$$\left(\frac{v^2}{2} - \frac{GM}{r} - \frac{\Omega_k r B_\varphi}{f}\right)_{wind} = E \qquad E = (2\lambda^2 - 3)\frac{GM}{2r}.$$

Ferreira & Pelletier, 1993

Outflow is possible only at $\lambda > \sqrt{3/2}$

- Outflow from the disk occurs with initial zero poloidal velocity and Kepler toroidal velocity.

Self-similarity assumption

$$\mathbf{v}(r,z,\phi) = r^{-\delta_v}\,\tilde{\mathbf{v}}(z/r,\phi)\,,$$

$$\rho(r,z) = r^{-\delta_\rho}\,\tilde{\rho}(z/r)\,,$$

$$\mathbf{B}(r,z,\phi) = r^{-\delta_B}\,\tilde{\mathbf{B}}(z/r,\phi)\,.$$

$$\mathbf{v}(r,z,\phi) = r^{-1/2}\,\tilde{\mathbf{v}}(z/r,\phi)\,,$$

$$\rho(r,z) = r^{-\delta}\,\tilde{\rho}(z/r)\,,$$

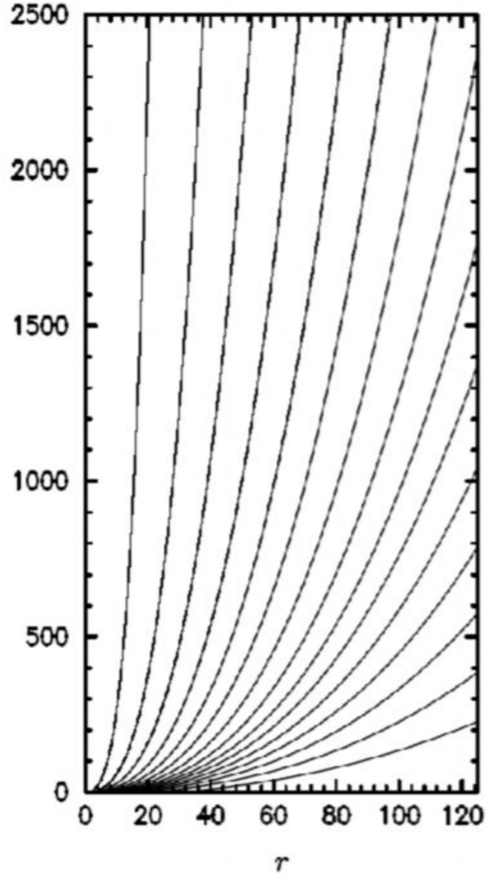
$$\mathbf{B}(r,z,\phi) = r^{-\frac{(1+\delta)}{2}}\,\tilde{\mathbf{B}}(z/r,\phi)\,.$$

$$| E_\varphi | = \frac{A}{r} = v_r B_z$$

Does not impose any restrictions on δ because we do not assume that v_r follows to the selfsimilarity prescriptions.

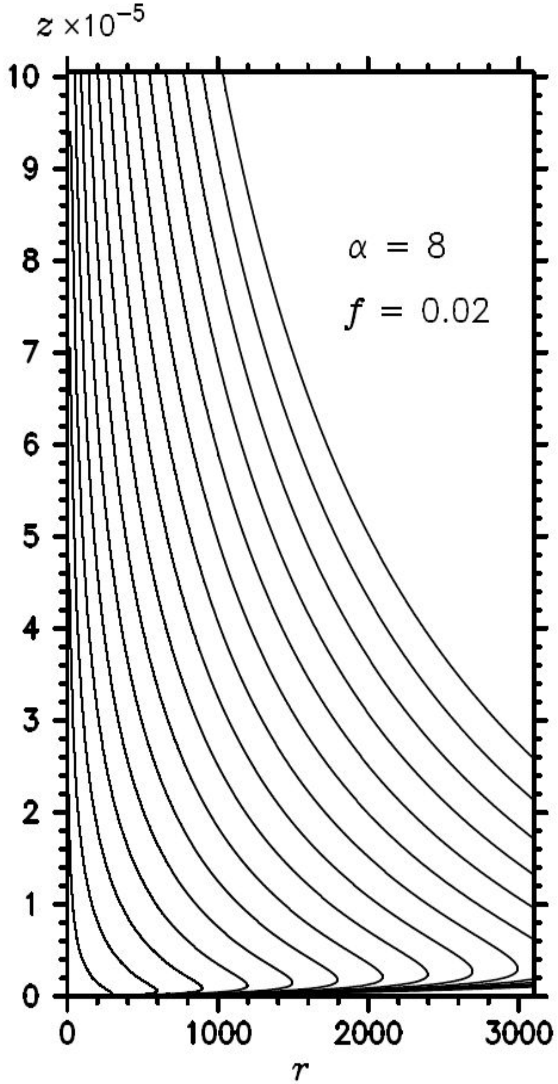
$$\delta = \frac{3\lambda^2 - 4}{2(\lambda^2 - 1)}$$

Basic properties of the outflow



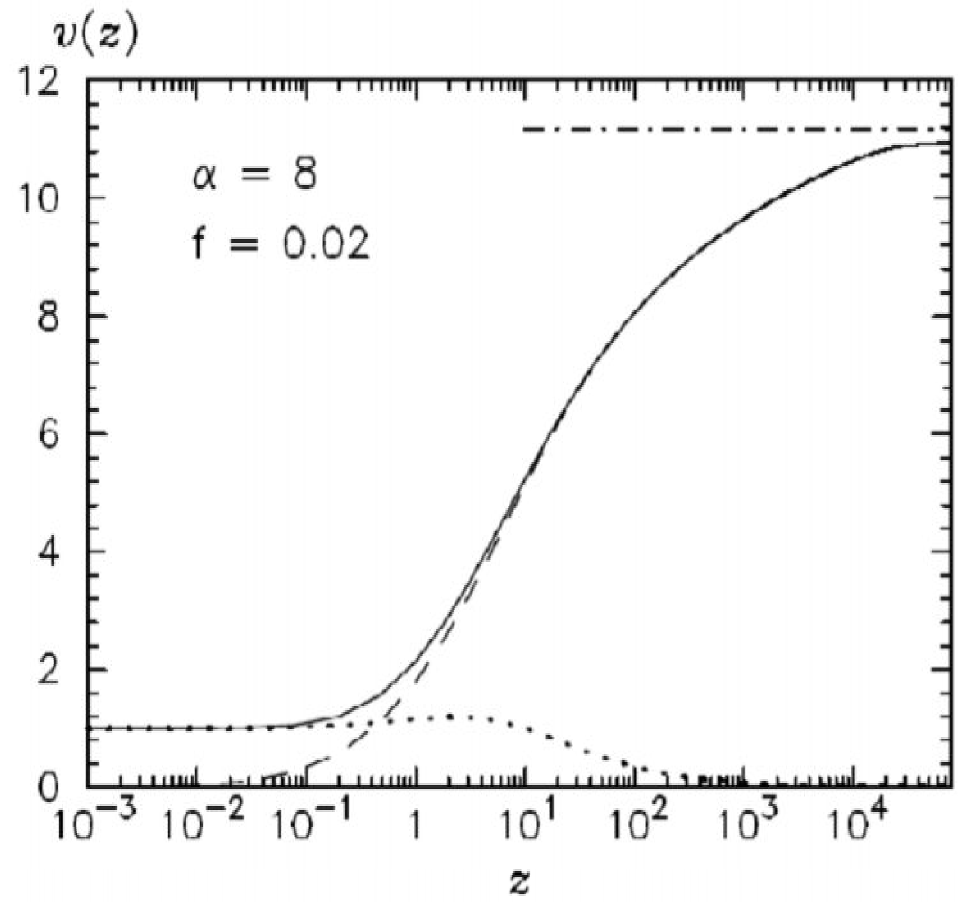
The filed lines for the solution corresponding to $\alpha = 5$, $f = 0.1$.

λ

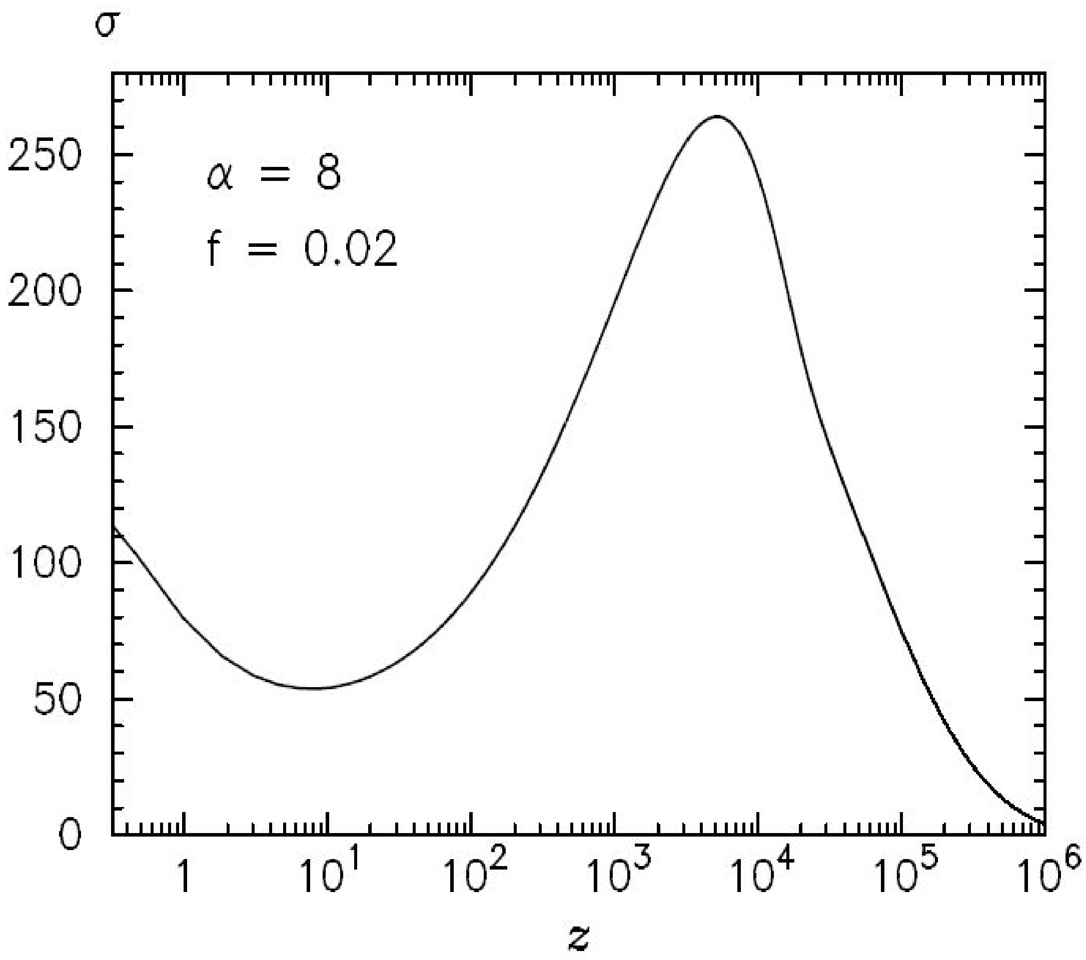


The filed lines for the solution corresponding to $\alpha = 8$, $f = 0.02$.

Variation of the velocity along a field line



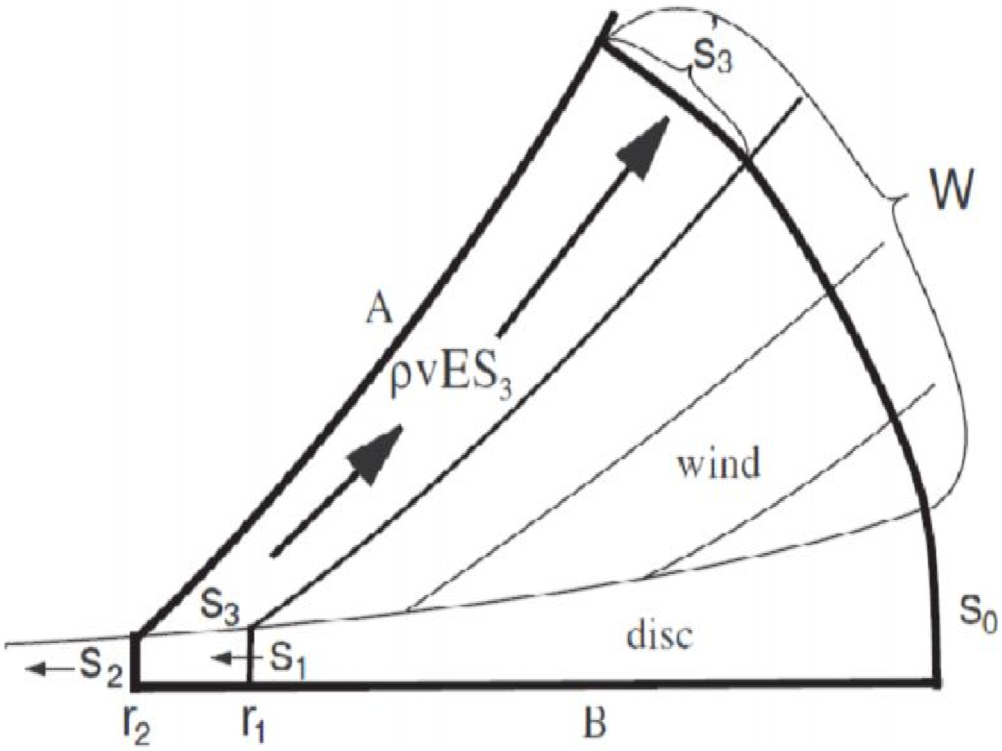
Magnetization of the plasma



Some interesting properties of the accretion

1. Energetic paradox.

$$\dot{M}(r_1)\,\frac{GM}{2r_1} - \dot{M}(r_2)\,\frac{GM}{2r_2} + (E\rho v_z S_3)_{wind} = 0.$$



$$-\dot{M}(r_2)\,\frac{GM}{2r_2} + \int_W E\rho v_p\, dS = 0.$$

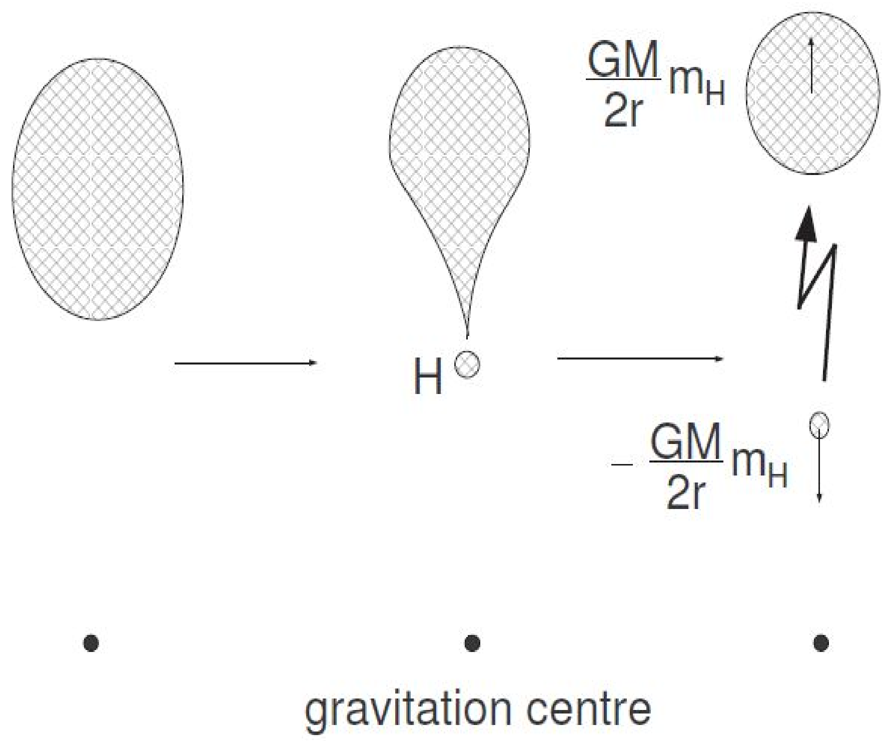
Kinetic luminocity of the wind

$$L_W = \dot{M}\frac{GM}{2r_{in}} = \dot{M}\frac{V_K^2}{4}.$$

Maximal energy of particles in the wind has energy

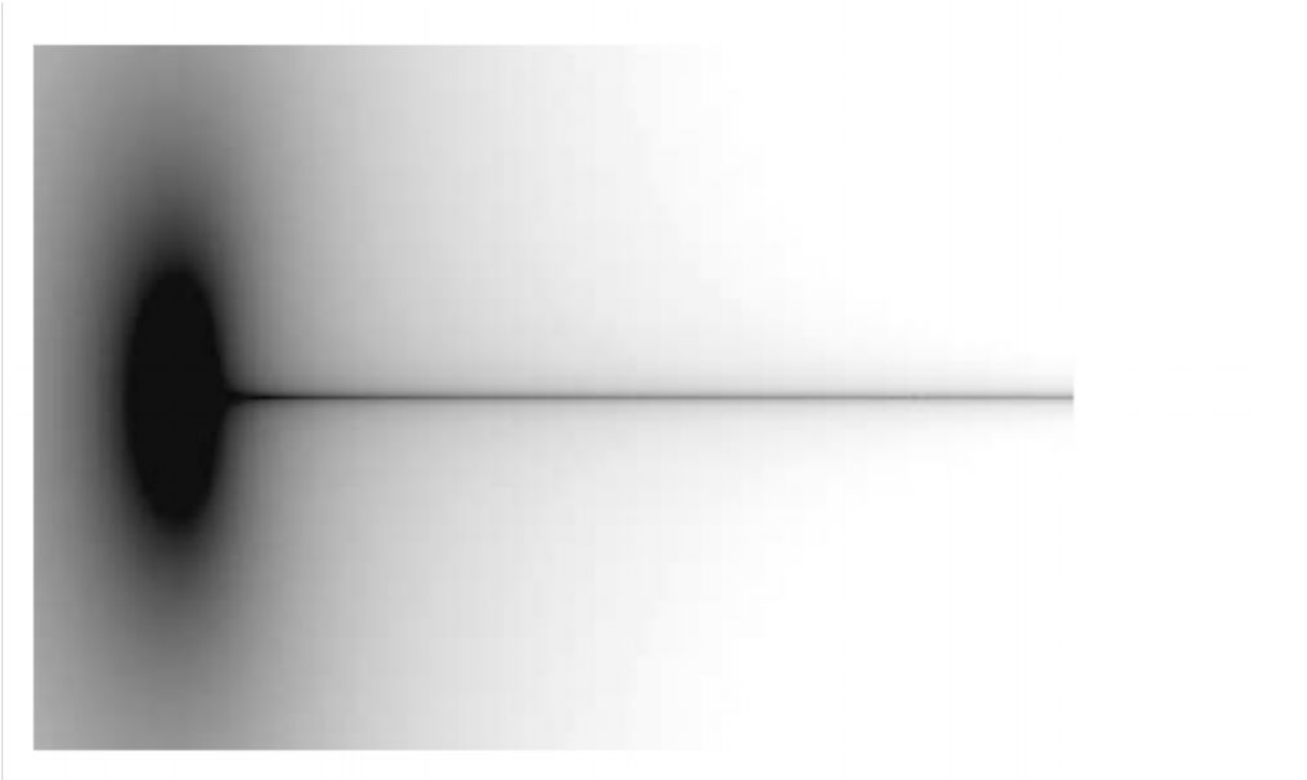
$$\mathrm{E} = (2\lambda^2 - 3)\frac{mV_K^2}{4}$$

MHD analog of the Penrouse process



Ejection of the plasma from the center of the disk

$$\rho v = \frac{\dot{M}_{\max}}{2\left(\alpha^2 - 1\right) r^2} \left(\frac{r}{r_{\max}}\right)^{\frac{1}{2(\alpha^2-1)}} .$$



Astrophysical implications

1. Low luminosity accretion disks

2. Very efficient ejection with the ratio $\frac{L_{bol}}{L_W} << 1$

3. Plasma ejection from the very center of the accretion disk.