Magnetic field topology in galactic winds

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Contents

• Introduction

Magnetic field topology

given by magnetic field line configuration:

$$\frac{d\mathbf{r}}{dl} = \frac{\mathbf{B}[\mathbf{r}(l)]}{|\mathbf{B}[\mathbf{r}(l)]|} \qquad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

Galactic winds

MS 1512-cB58

GALACTIC WINDS

- complex phenomenon in close and distant galaxies
- Lynds & Sandage(1963)
- Burbidge & Rubin(1964)
- Burke(1968)
- Johnson & Axford; Mathews & Baker (1971)

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GALAC

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- Burke(1968)
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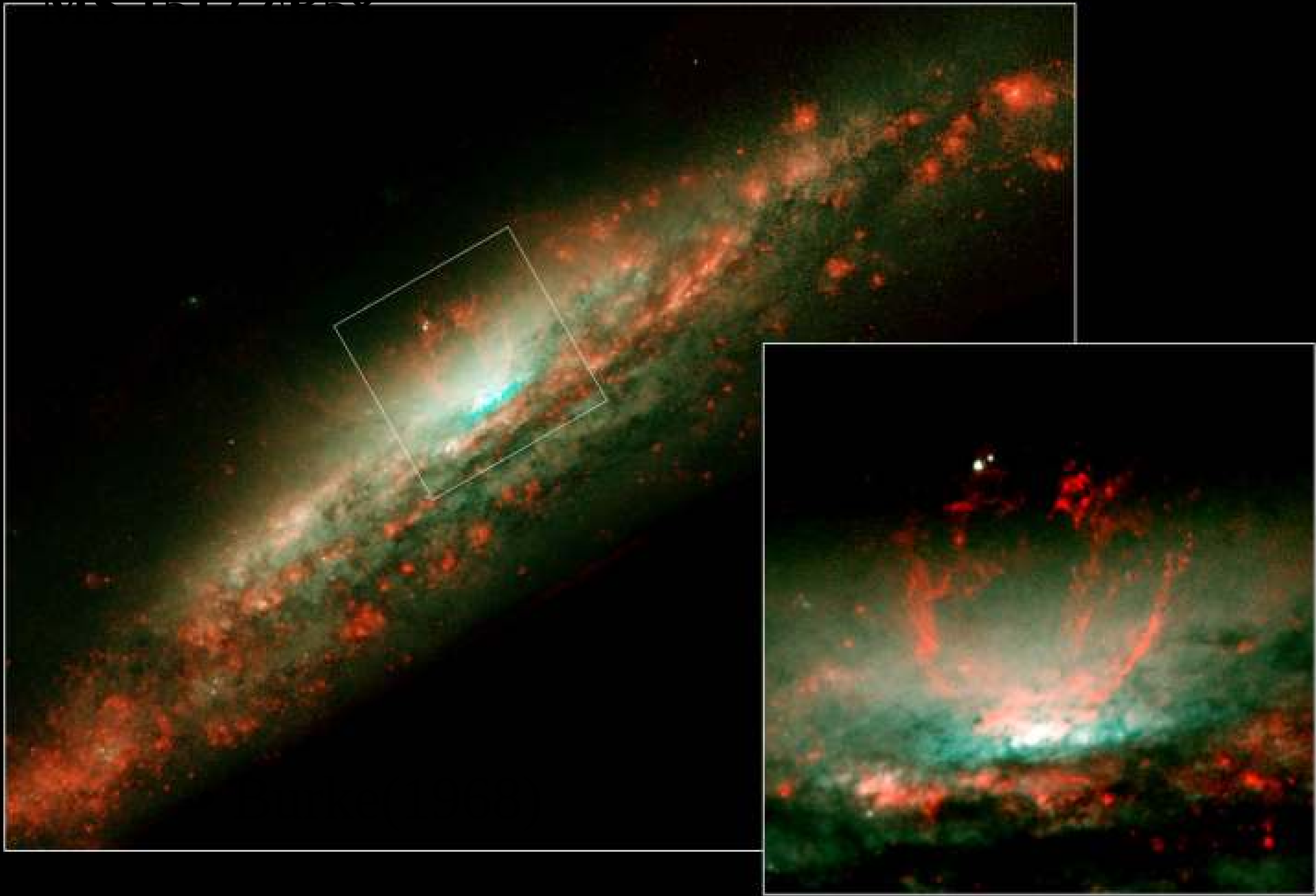
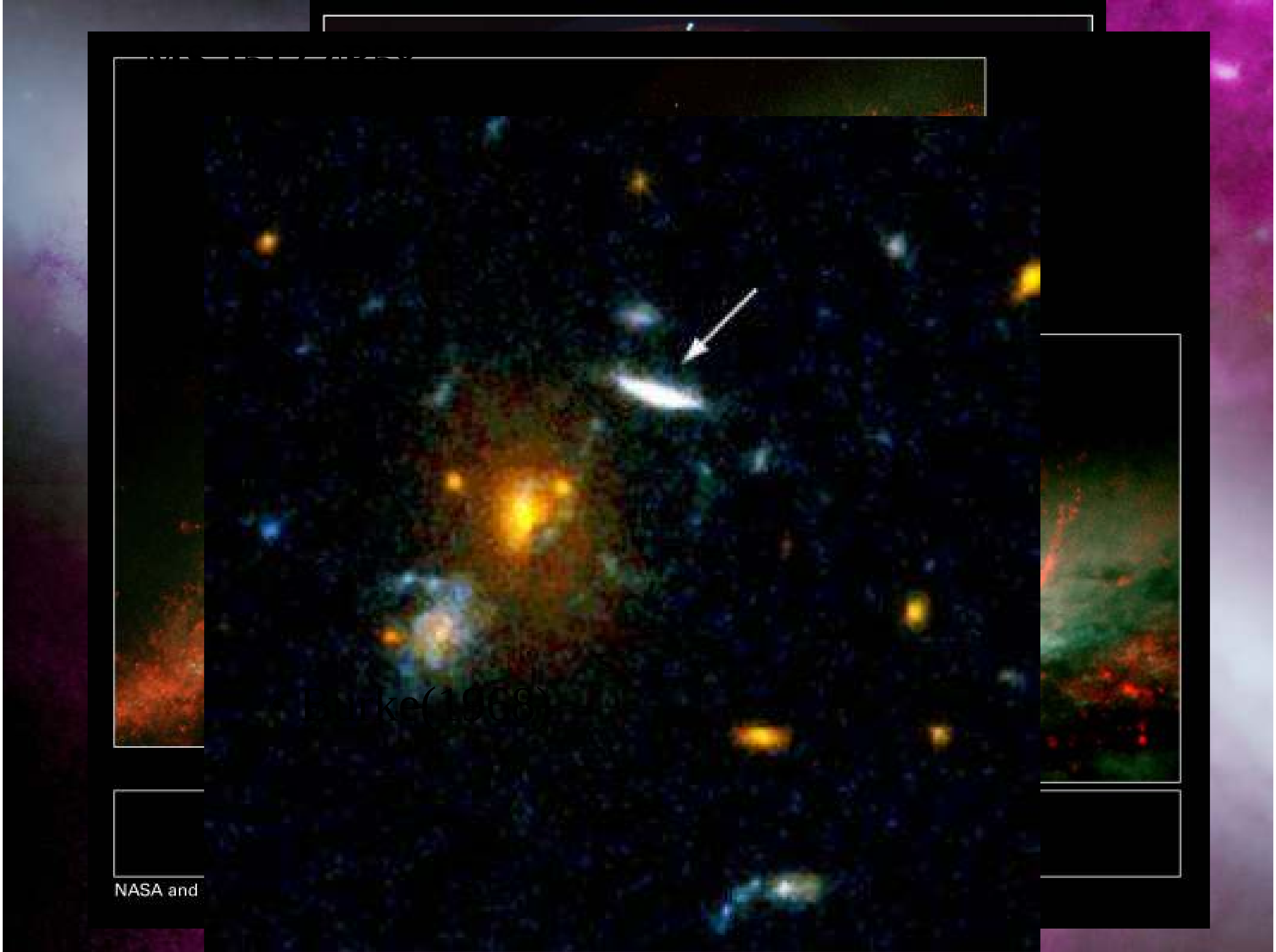


Galaxy NGC 3079
Hubble Space Telescope • WFPC2

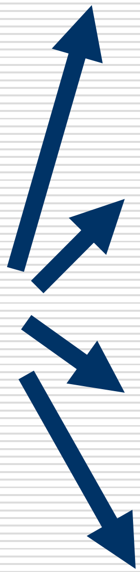
NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28


NASA and

• Basic concepts & Assumptions

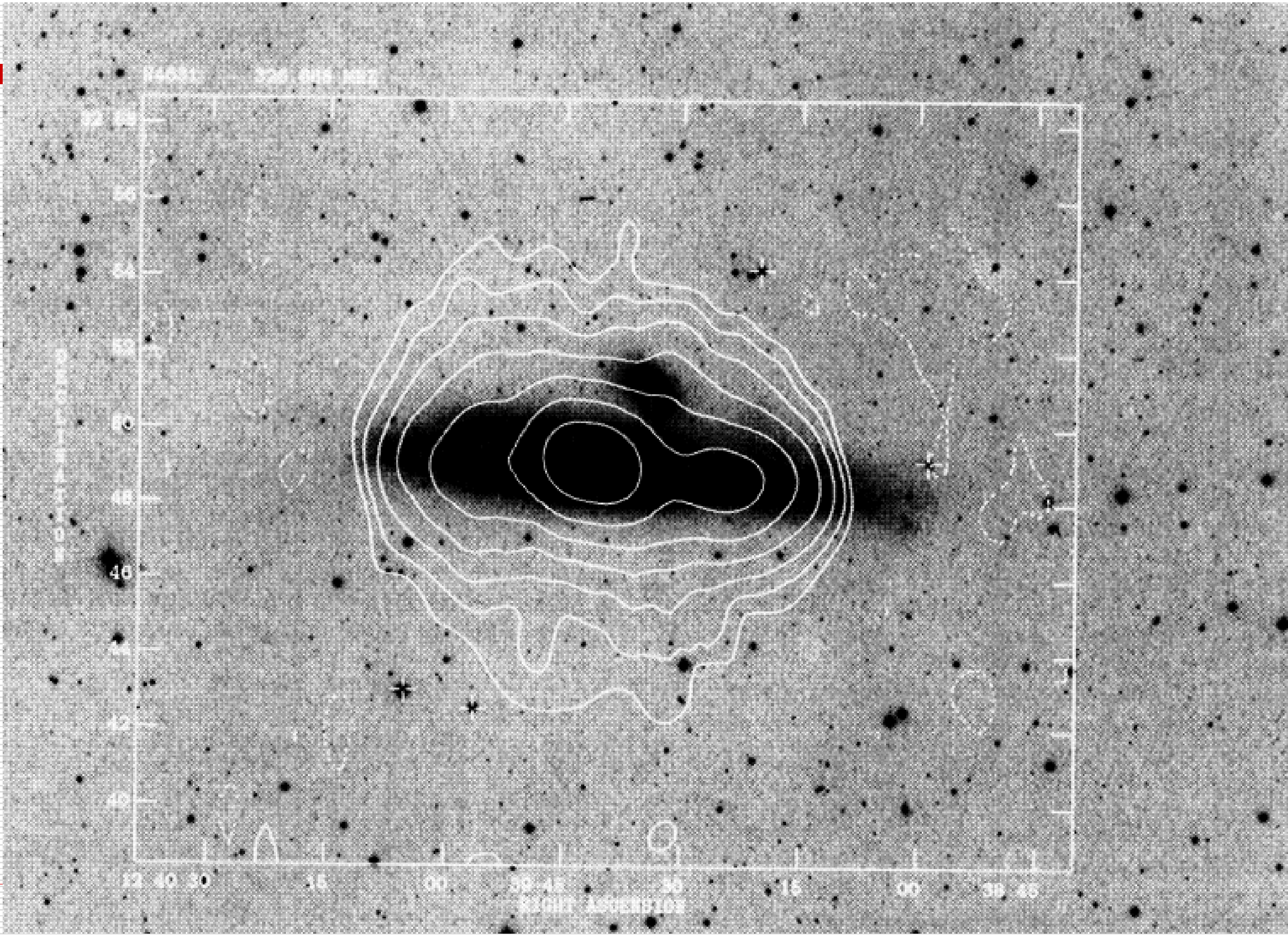
- **Galaxy as a complex system**
- **The outflow known as Galactic Wind**

• The components of the system



- **background plasma**
- **magnetic field**
- **Alfvén wave field**
- **cosmic rays**

- **Basic concepts & Assumptions**
  - **NGC 4631**



• Basic concepts & Assumptions

- Sources and sinks of mass and momentum are disregarded

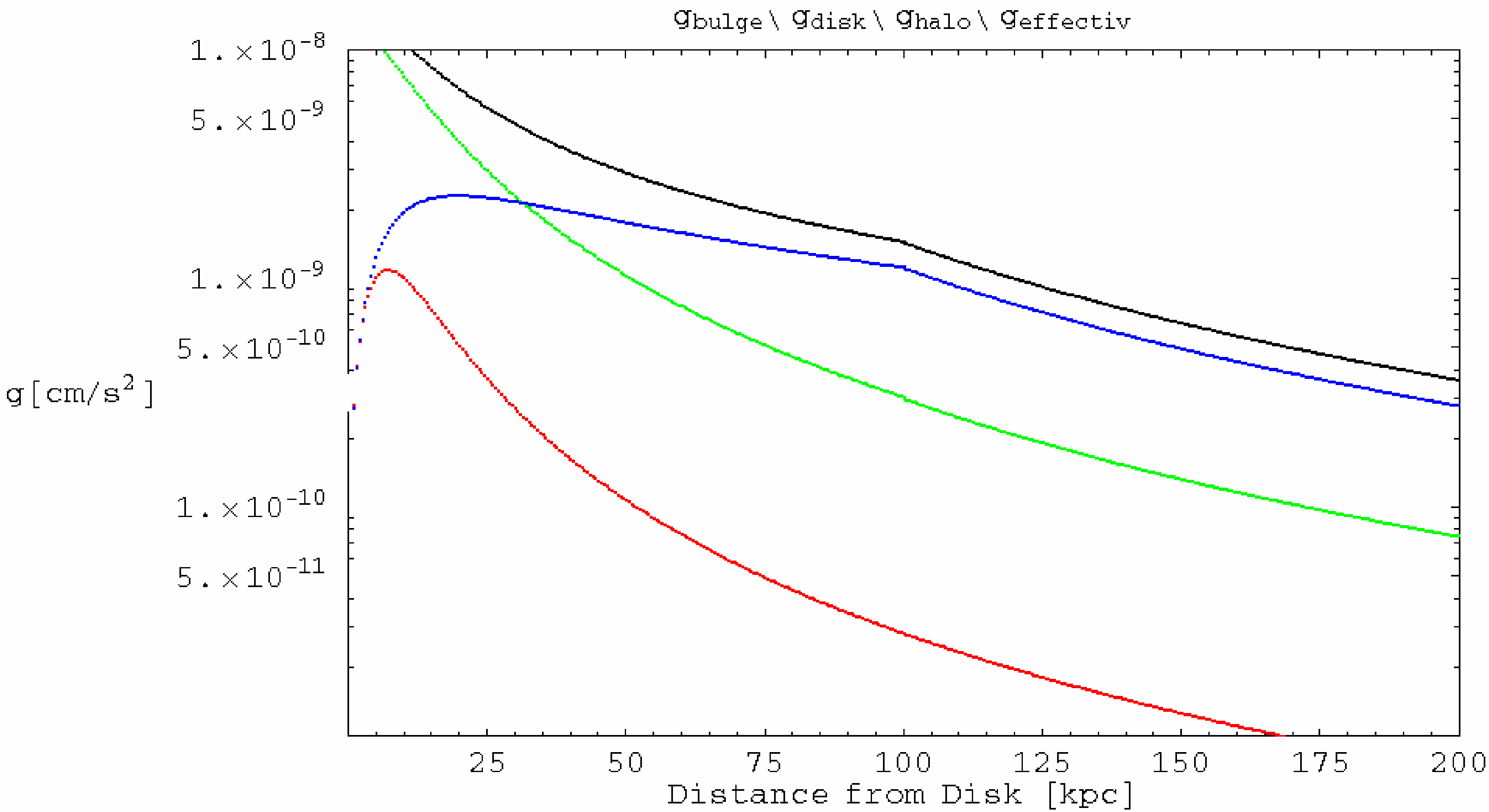
- The magnetic field is anchored in the galactic plane
- The flow is considered over a time scale of at least A Galactic rotation time

- External heating and radiative cooling of the thermal gas is ignored and the gas is assumed adiabatic

- No external wave sources or damping effects, the waves are generated by resonant interaction with CR

- Steady-state and frozen-in formalism assumed

• Simple galactic wind model without rotation



• Simple galactic wind model without rotation

• **Mass model by Habe and Ikeuchi with a bulge-disk component as proposed by Miyamoto and Nagai**

$$\Phi_{B,D} = \frac{G * M_1}{\sqrt{r^2 + \left(a_1 + \sqrt{z^2 + b_1^2}\right)^2}} + \frac{G * M_2}{\sqrt{r^2 + \left(a_2 + \sqrt{z^2 + b_2^2}\right)^2}}$$

• **and a dark matter halo, distributed spherically symmetrically around the disk, like the one discussed by Innanen**

$$\Phi_H = \Phi o - \frac{G * M_{Ho}}{Rb} \left(Log[1 + x] + 1/(1 + x)\right)$$

• **Outward magnetic flux tube with the cross section:**

$$A(z) = A_0\left[1 + \left(\frac{z}{Zo}\right)^2\right]$$

• The relevant equations describing interaction between the four components are represented by:

• **conservation laws**

$$\mathrm{div}\,\{\rho u\} = 0,$$

$$\mathrm{div}\left\{\rho u : u + \left(Pg + Pc + \frac{\langle(\delta B)^2\rangle}{8\pi}\right)\cdot I\right\} = -\rho\,\nabla\Phi,$$

$$\mathrm{div}\left\{\rho u\left(\frac{1}{2}u^2 + \frac{\gamma g}{\gamma g - 1}\frac{Pg}{\rho} + \Phi\right) + \frac{1}{\gamma c - 1}\left(\gamma c Pc\,(u + va) - \bar{k}\,\nabla\right) \frac{\langle(\delta B)^2\rangle}{\pi}\left(\frac{3}{2}u + va\right)\right\} = \Gamma - \Lambda$$

$$\mathrm{div} B = 0$$

• The relevant equations describing interaction between the four components are represented by:

• **cosmic ray transport equation and wave energy exchange equation**

$$\mathrm{div}\left\{\frac{\gamma c}{\gamma c - 1}\,(u - v_a)\,P_c - \frac{\bar{k}}{\gamma c - 1}\,\nabla P_c\right\} = (u + v_a)\,\nabla P_c + Q$$

$$\mathrm{div}\left\{\frac{\langle(\delta B)^2\rangle}{4\pi}\left(\frac{3}{2}\,u + v_a\right)\right\} = u\,\nabla\left(\frac{\langle(\delta B)^2\rangle}{8\pi}\right) - v_a\,\nabla P_c - L$$

$$\gamma g - 1 \quad \rho$$

$$\frac{1}{\gamma c - 1}\,(\gamma c P_c\,(u + v_a) - \bar{k}\,\nabla \qquad \mathrm{div}B = 0 \qquad \frac{\langle(\delta B)^2\rangle}{\pi}\left(\frac{3}{2}\,u + v_a\right)\Big\} =$$

$$\Gamma - \Lambda$$

• The simplified equations

$$\rho u A = \mathrm{const}$$

$$\frac{dp_g}{dz} = \gamma_g \frac{p_g}{\rho} \frac{d\rho}{dz}$$

$$\frac{dp_c}{dz} = \gamma_c \frac{p_c}{\rho} \left(\frac{M_A + \frac{1}{2}}{M_A + 1} \right) \frac{d\rho}{dz}$$

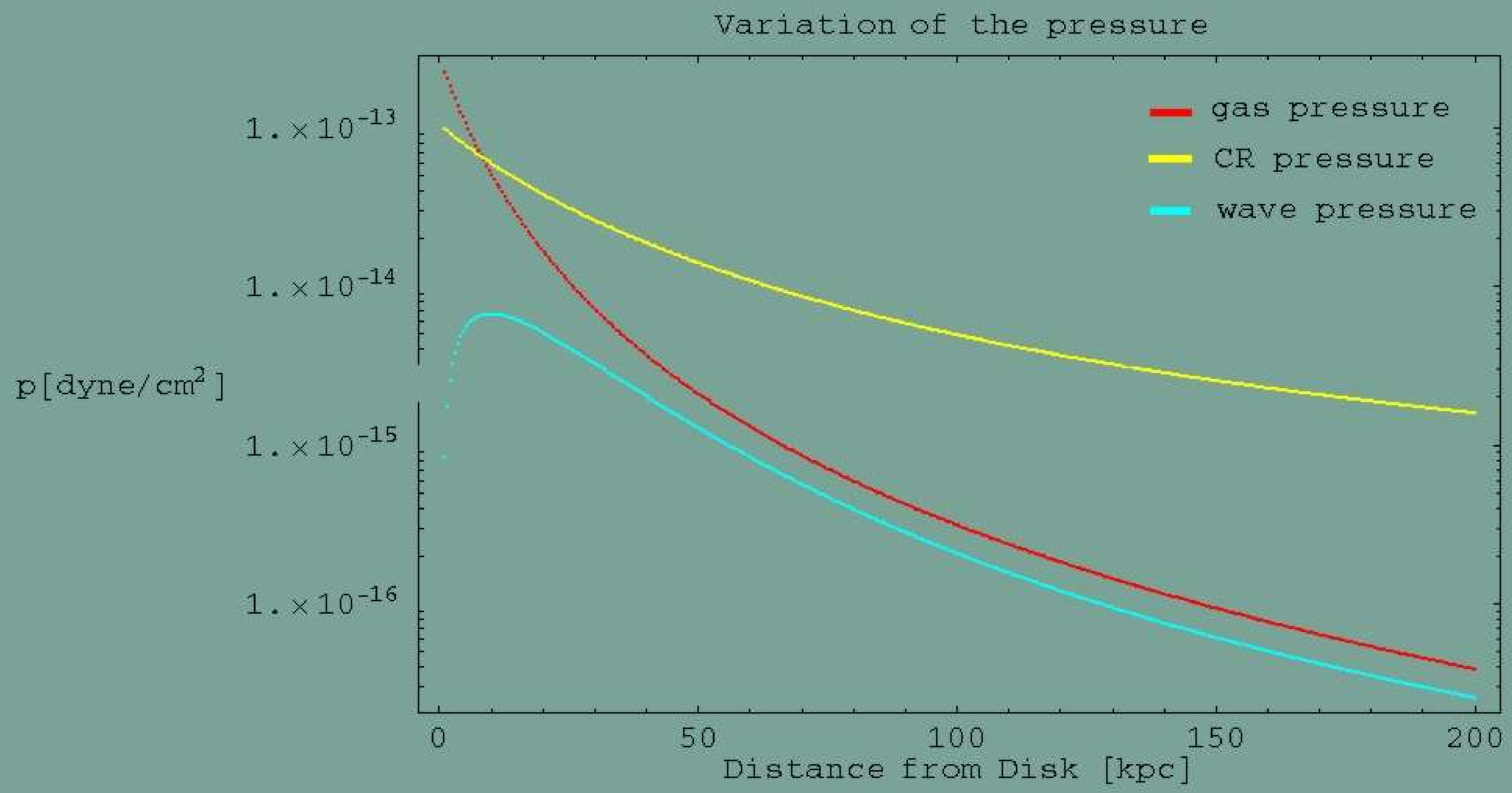
$$\frac{dp_w}{dz} = \frac{1}{2\,(M_A + 1)} \left(3\,(M_A + 1) \frac{p_w}{\rho} \frac{d\rho}{dz} - \frac{dp_c}{dz} \right)$$

$$\frac{1}{u} \left(u^2 - c_*^2\right) \frac{du}{dz} = c_*^2 \frac{1}{A} \frac{dA}{dz} + g_{eff}(z)$$

- **Method of solution is to integrate from reference level to infinity and finding the critical point by iteration**

- **Results**
  - **Variation of the pressure**
  - **Variation of velocities**
  - **Variation of density**
  - **Outflow velocity to large distances**
  - **Magnetic field component**

• **Method of solution is to integrate from reference level to infinity and finding the critical point by iteration**



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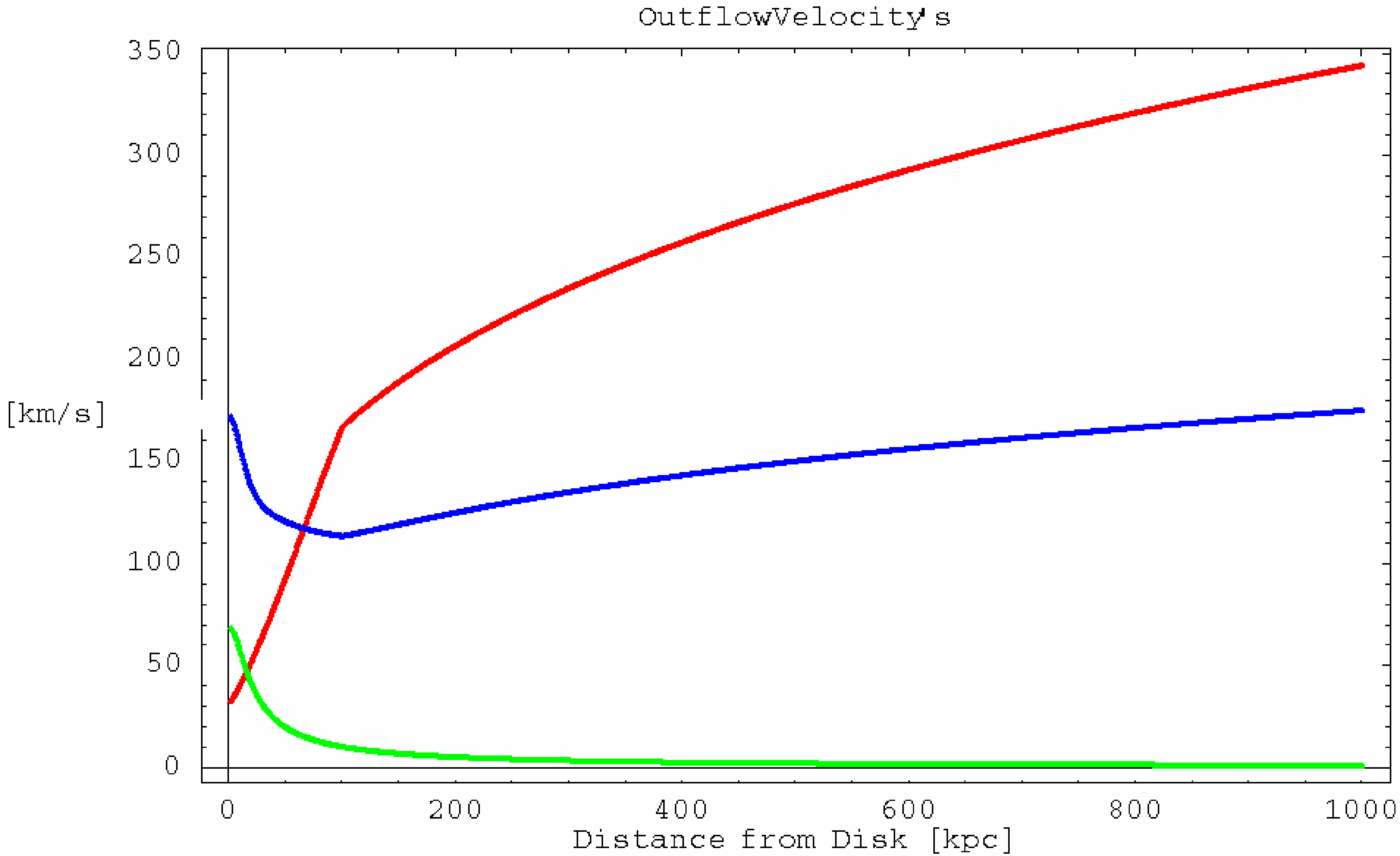

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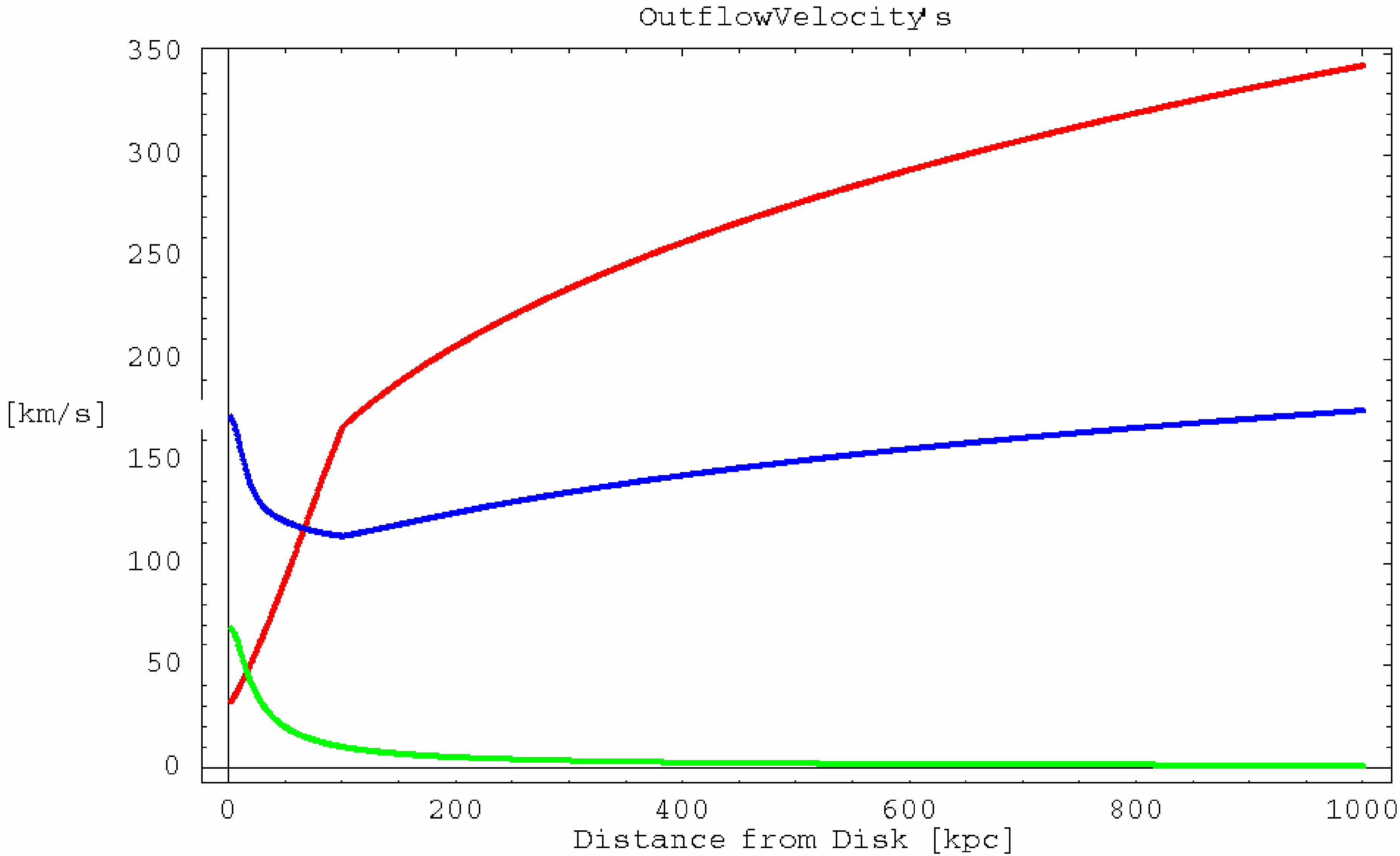

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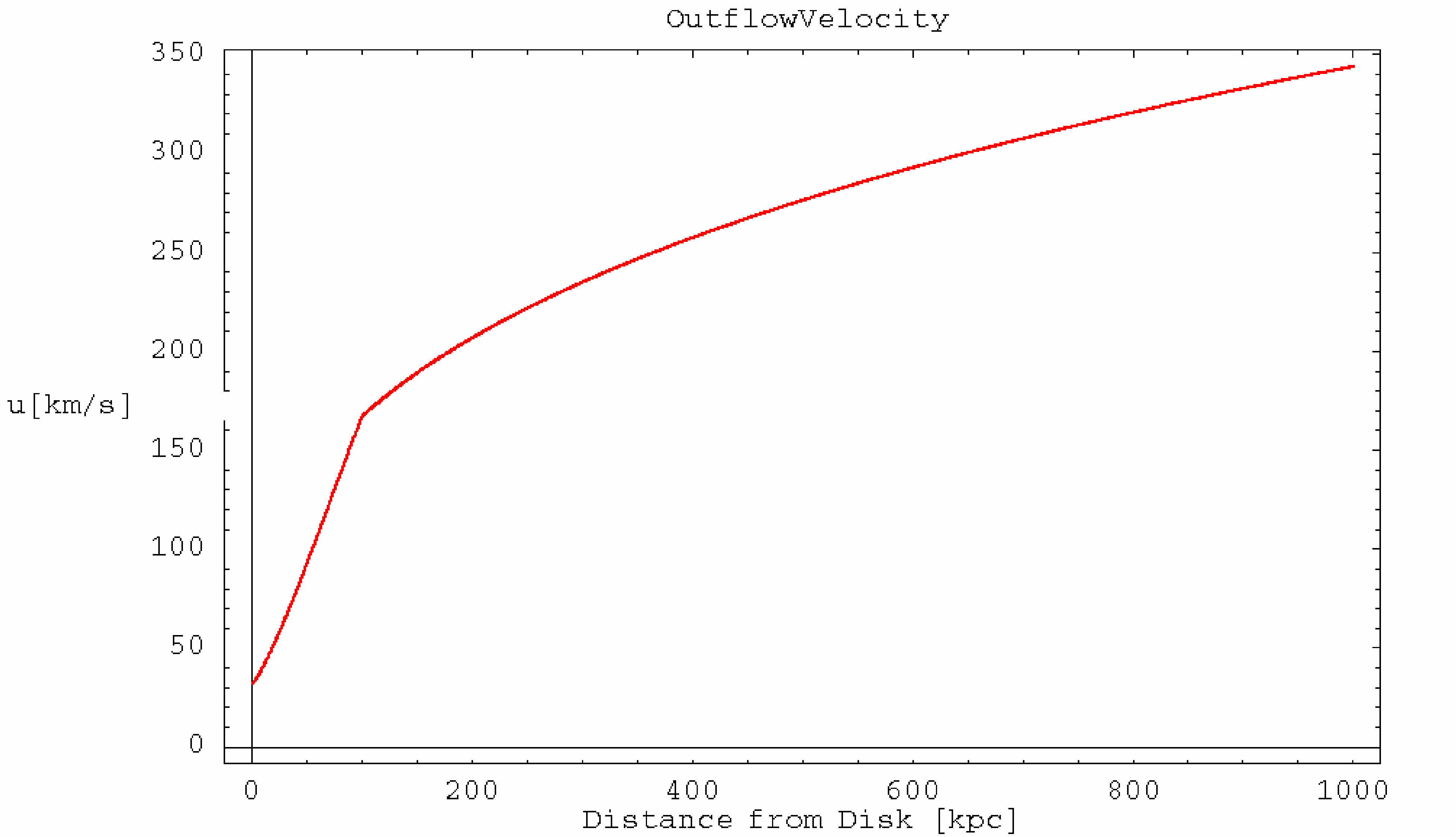

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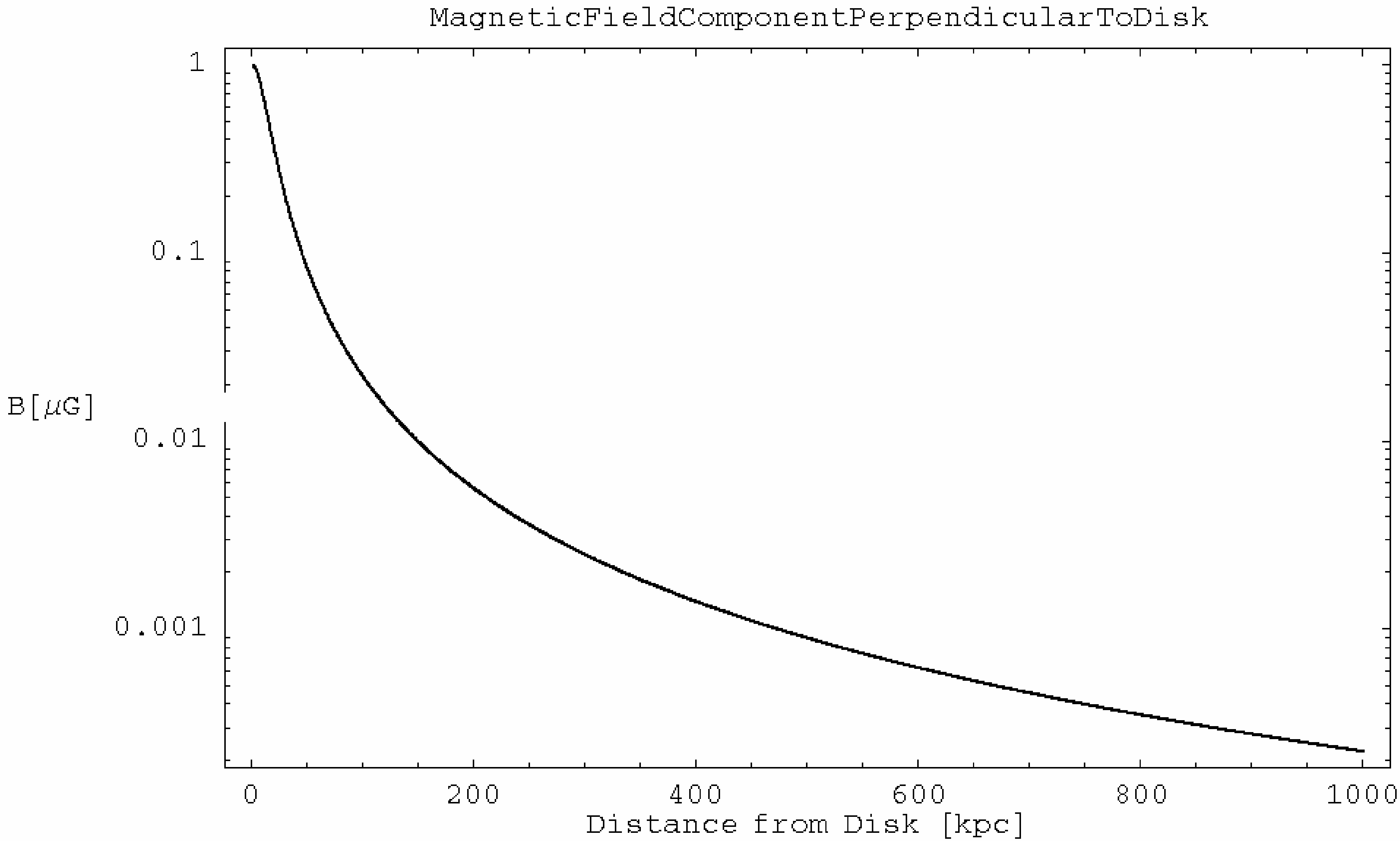
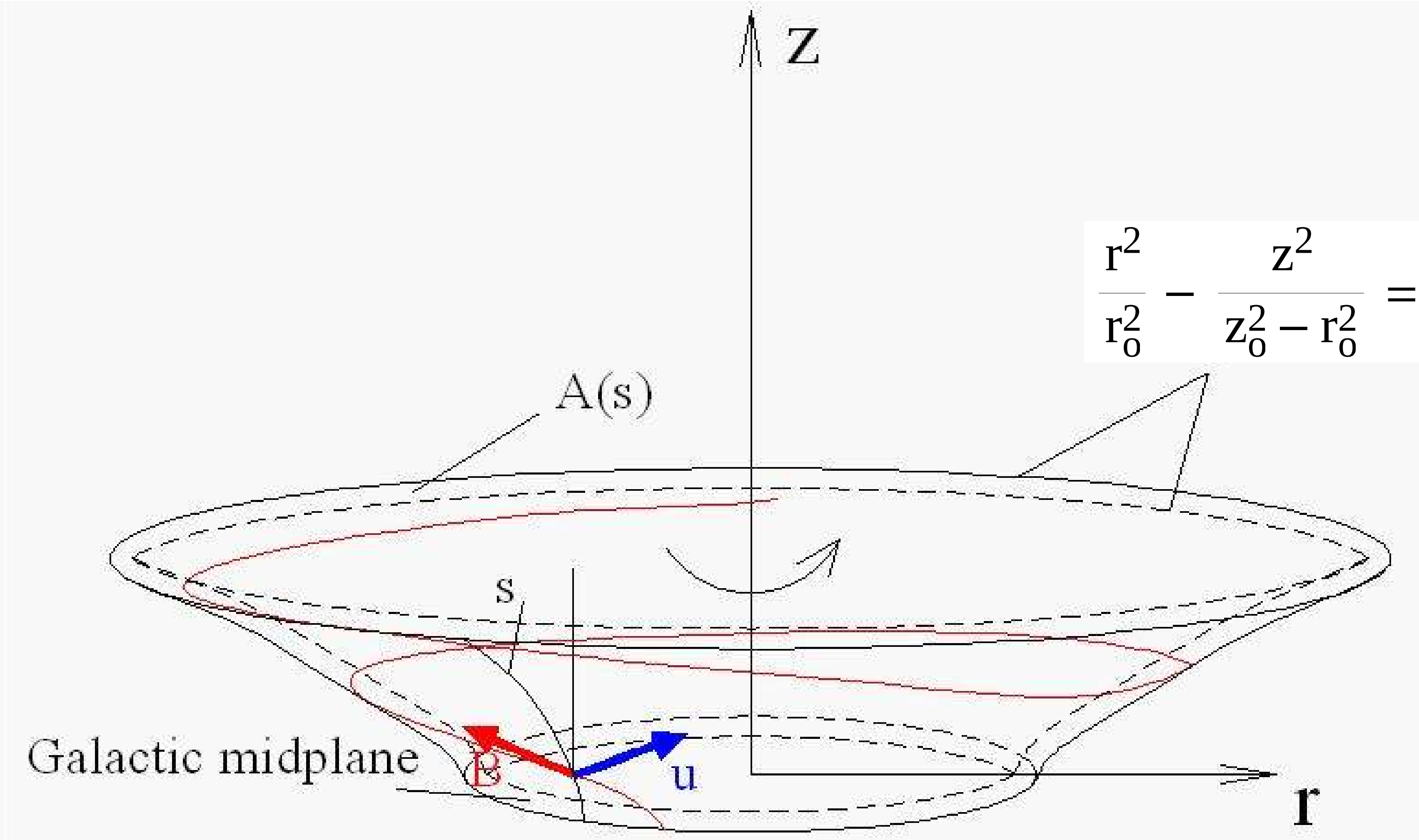
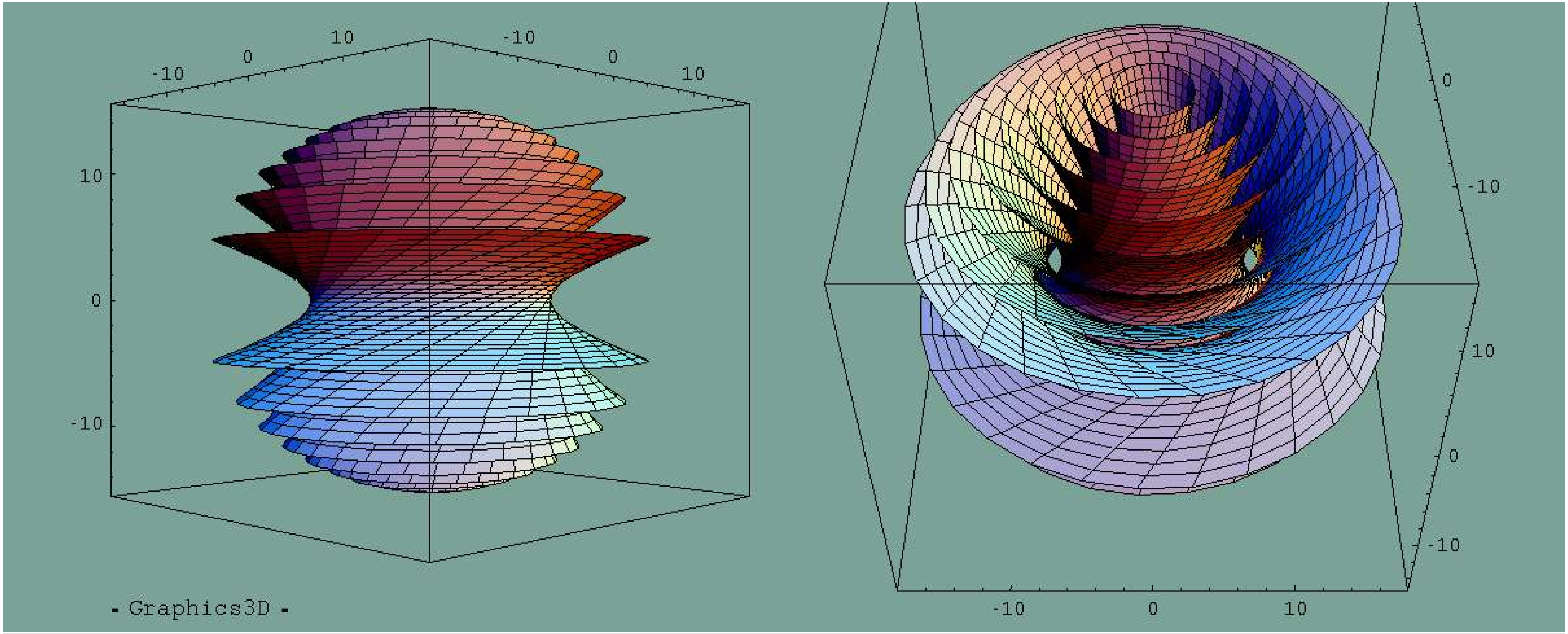


• Galactic wind model with rotation and complex flux tube geometry



$$\frac{r^2}{r_o^2} - \frac{z^2}{z_o^2 - r_o^2} = 1$$

• Galactic wind model with rotation and complex flux tube geometry



- **The simplified equations**

$$A(s)\,\rho u = \text{const}$$

$$\rho\left(u\frac{\partial u}{\partial s} - \frac{u_r}{u}\frac{u_\varphi}{r}\right) = -\frac{\partial}{\partial s}(P_g + P_c) - \frac{1}{8\pi r^2}\frac{\partial}{\partial s}\left(r^2 B_\varphi{}^2\right) + \rho\frac{\partial \Phi}{\partial s}$$

$$\frac{1}{A}\frac{\partial}{\partial s}A\left[\rho u\left(\frac{u^2}{2} + \frac{u_\varphi}{2} + \frac{\gamma_g}{\gamma_g - 1}\frac{P_g}{\rho} - \Phi\right) - \frac{rBB_\varphi}{4\pi}\Omega r + \left(\frac{\gamma_c}{\gamma_c - 1}(u + v_a)P_c - \frac{D}{\gamma_c - 1}\frac{\partial P_c}{\partial s}\right)\right] = -\Lambda$$

$$A \cdot B = \text{const.}$$

$$\frac{1}{A}\frac{\partial}{\partial s}A\left(\frac{\gamma_c}{\gamma_c - 1}(u + v_a)P_c - \frac{D}{\gamma_c - 1}\frac{\partial P_c}{\partial s}\right) = (u + v_a)\frac{\partial P_c}{\partial s}$$

• **Method of solution is to determine the gas and the CR pressure in terms of the gas density**

$$P_c = P_{co} * \left(\frac{uo + v_{ao}}{uo * \frac{\rho}{\rho o} + v_{ao} \left(\frac{\rho}{\rho o} \right)^{1/2}} \right)^{\gamma c}$$

$$P_g =$$

$$P_{go} \left(\frac{\rho}{\rho o} \right)^{1+\gamma c/2} + \frac{\gamma_c{}^2 * P_{co}}{\gamma_c - 1} \frac{v_{ao}}{uo} \left(\frac{\rho}{\rho o} \right)^{1+\gamma c/2}$$

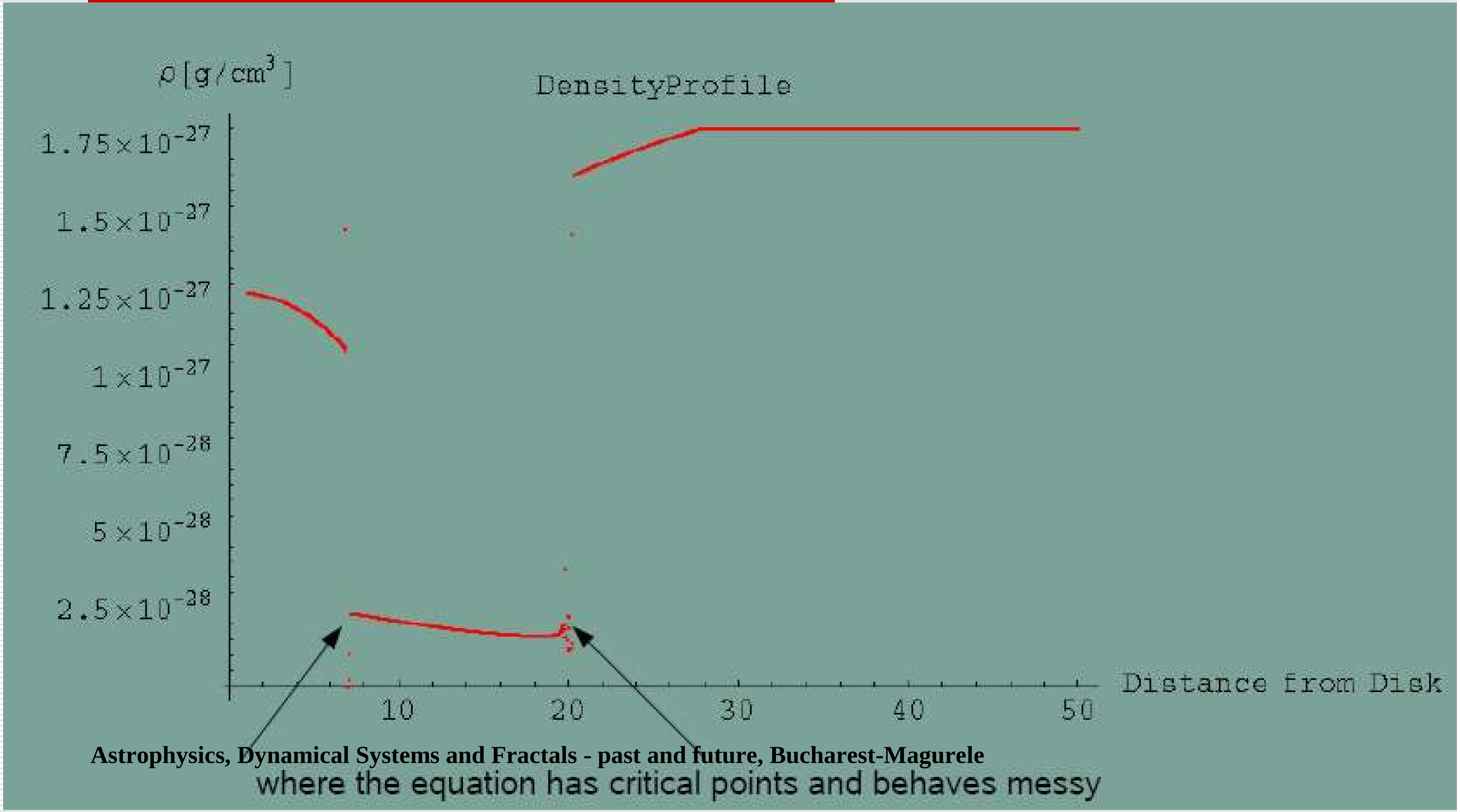
$$\left(1 + \frac{\gamma_c + 1}{2 * \gamma_c} \frac{v_{ao}}{uo} - \left(\frac{uo + v_{ao}}{uo * \left(\frac{\rho o}{\rho} \right)^{1/2} + v_{ao}} \right)^{\gamma c} \left(\left(\left(\frac{\rho}{\rho o} \right)^{-1/2} + \frac{\gamma_c + 1}{2 * \gamma_c} \frac{v_{ao}}{uo} \right) \right) \right)$$

• **and then to resolve the transcendental equation for the gas density with a set of boundary conditions**

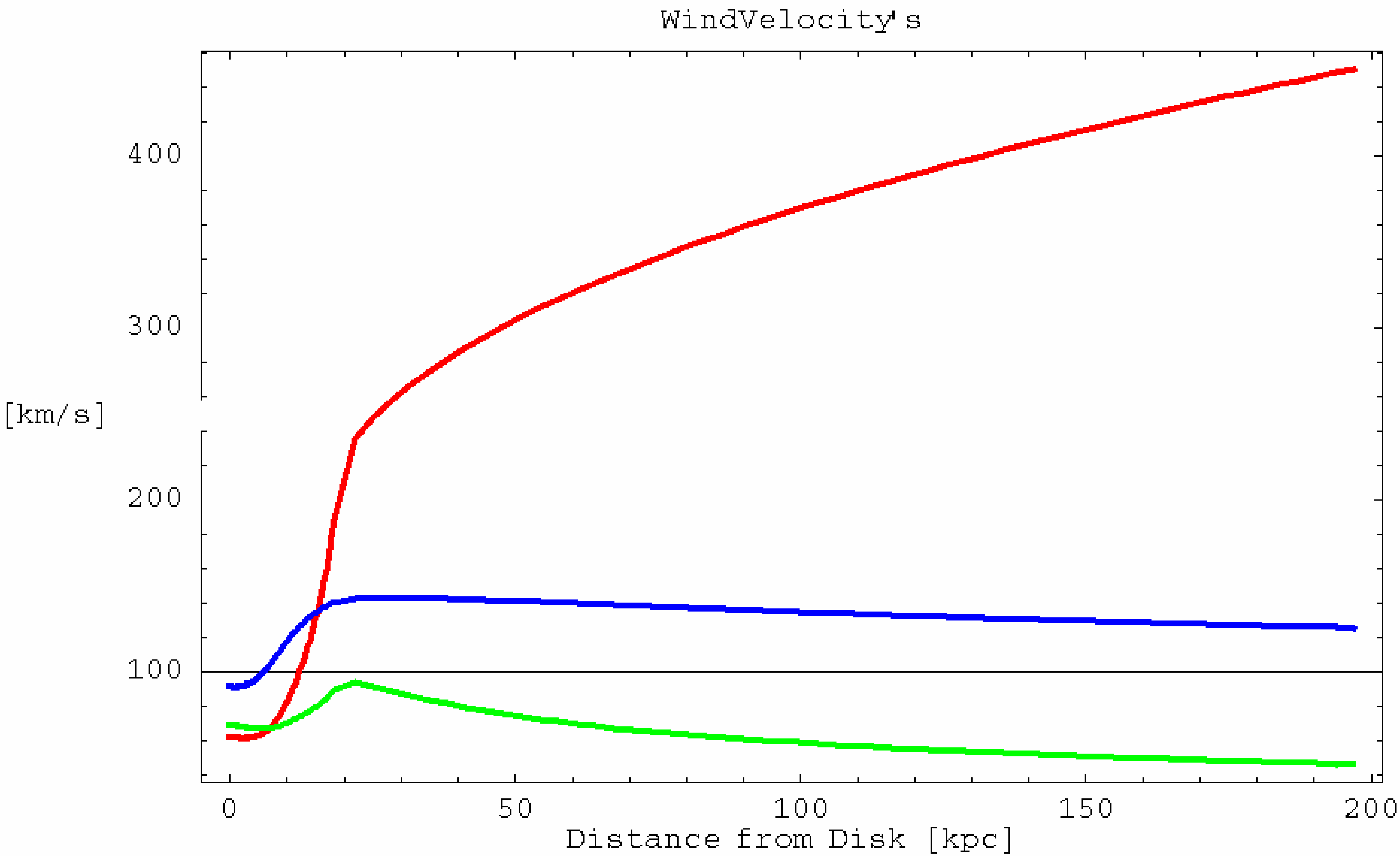
$$\frac{u^2}{2} + \frac{u_\varphi{}^2}{2} - \Omega * r * u_\varphi + \frac{\gamma_g}{\gamma_g - 1}\frac{P_g}{\rho} - \Phi + \frac{\gamma_c}{\gamma_c - 1}\left(\frac{u + v_a}{u}\right)\frac{P_c}{\rho} = \text{const.}$$

• **ensuring the smooth passage of the solution through all critical points**

• **and then to resolve the transcendental equation for the gas density with a set of boundary conditions**



• **Results for density profiles and velocities**



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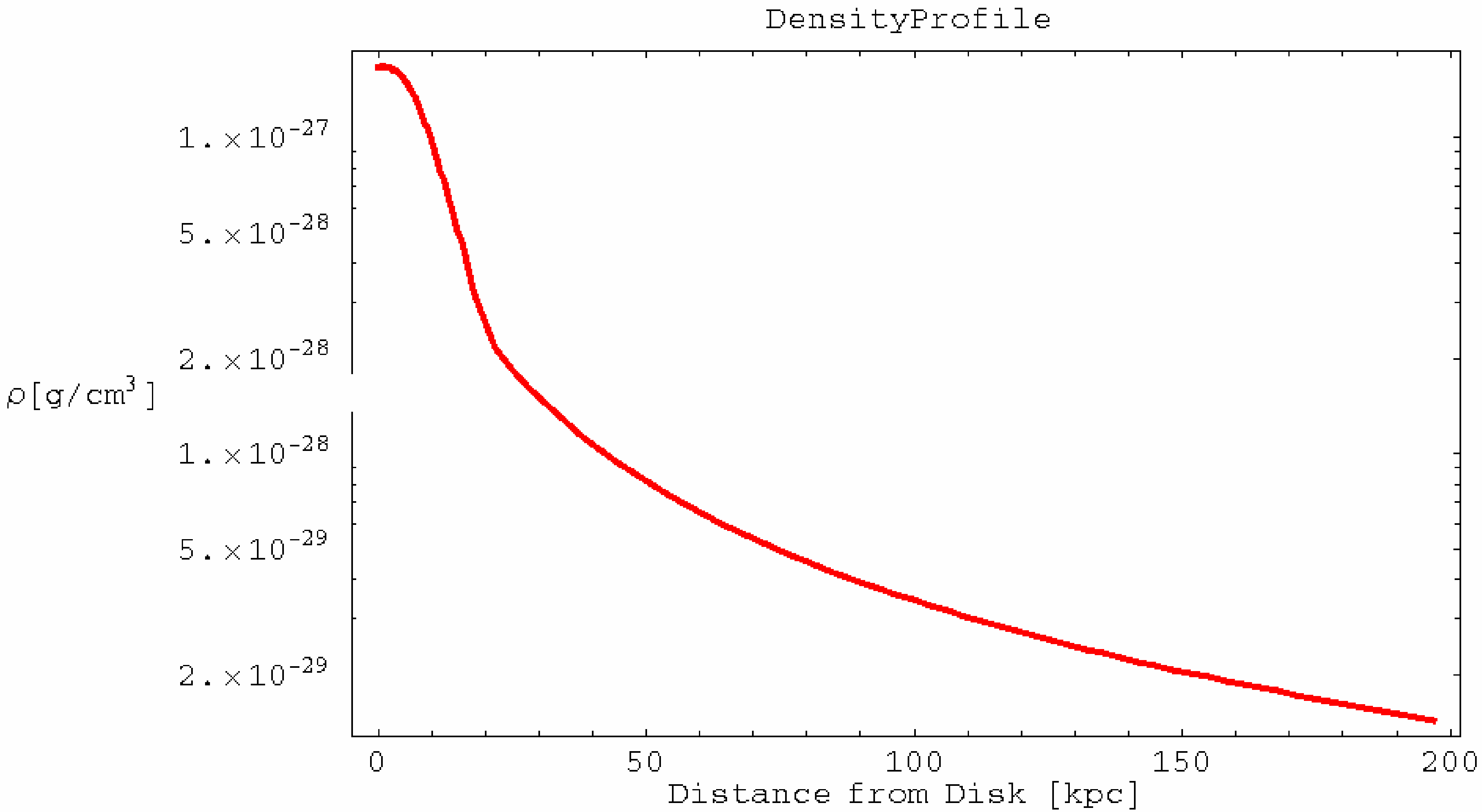

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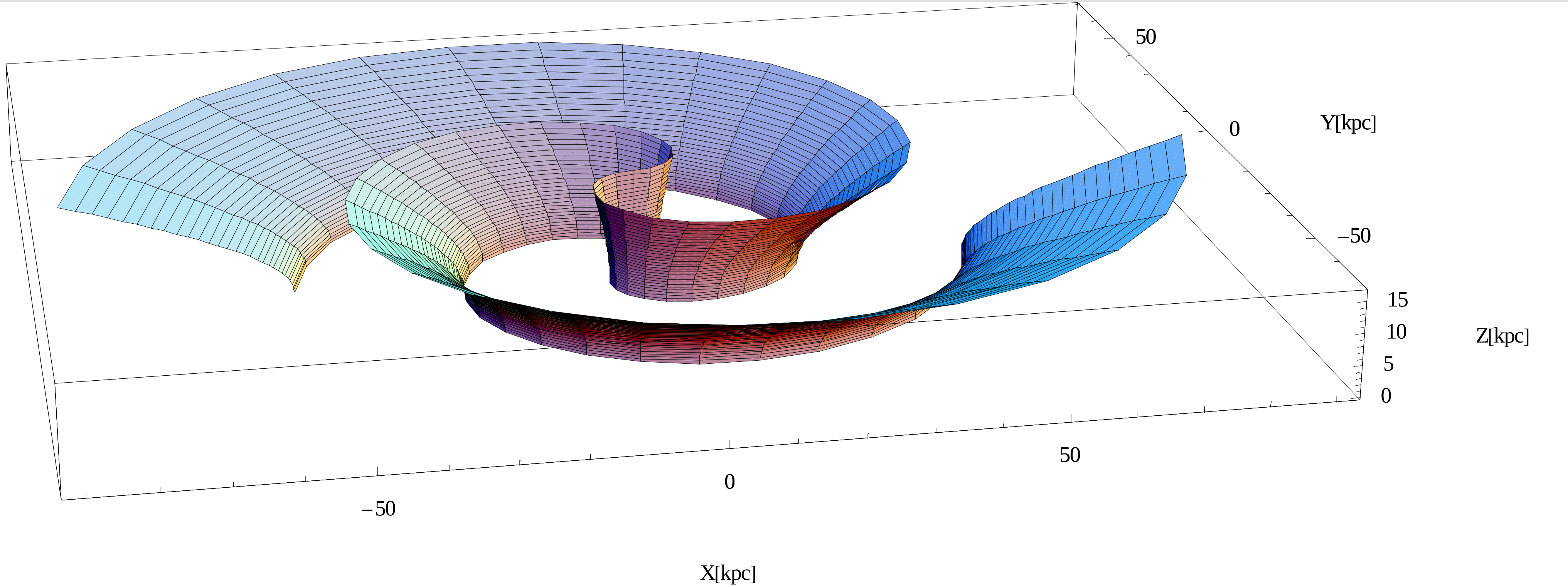

• Conclusions

• develop an semi-analytical galactic wind in a rotating galaxy as a working tool

• magnetic field configuration for propagation of energetic particle into the halo and disk

• determining the mass loss rate and angular momentum loss

• matching the boundary conditions with accurate observations

• the characteristics of outflows in early universe

• Parker $\alpha\omega$-dynamo


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