Magnetically driven wind from black hole accretion disk in AGNs

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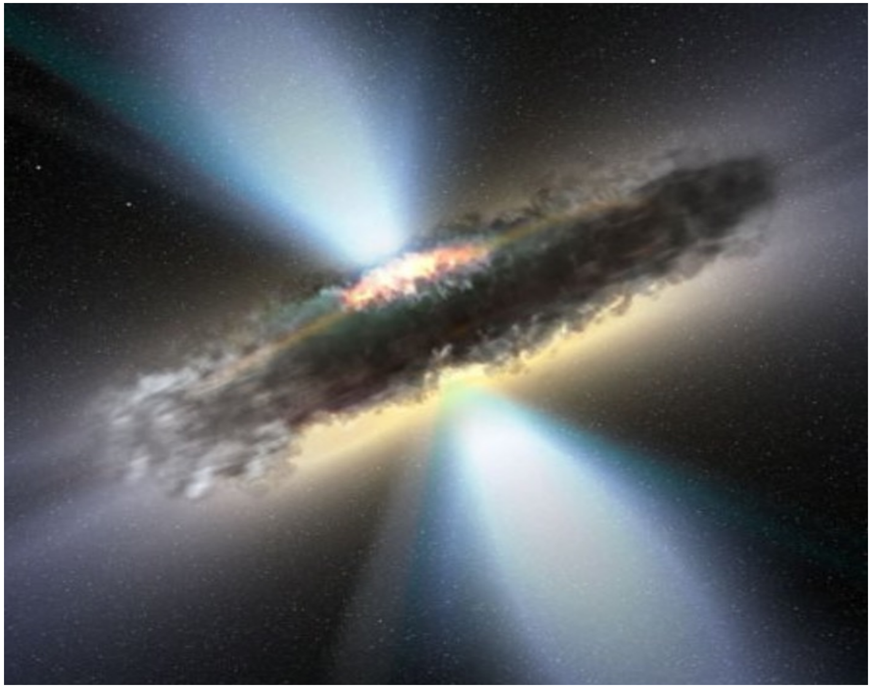
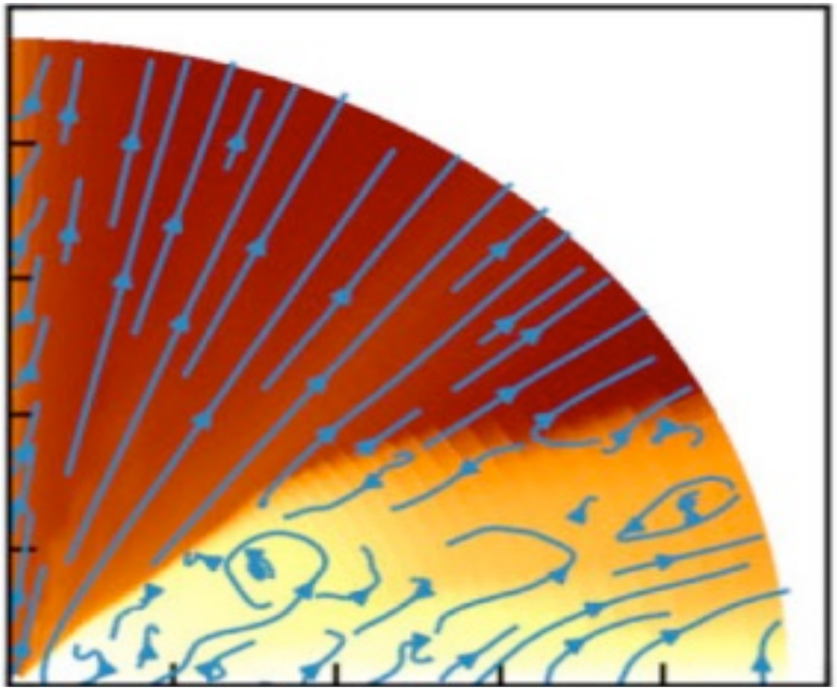




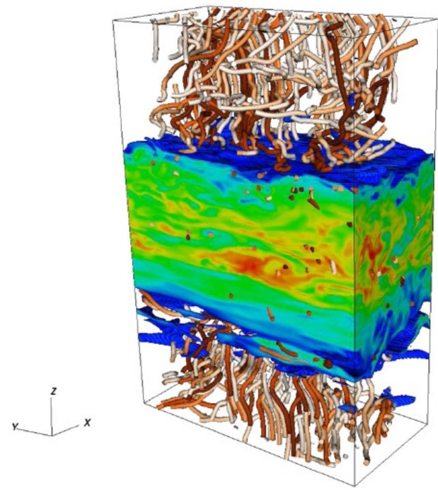
Previous works on magnetically driven wind

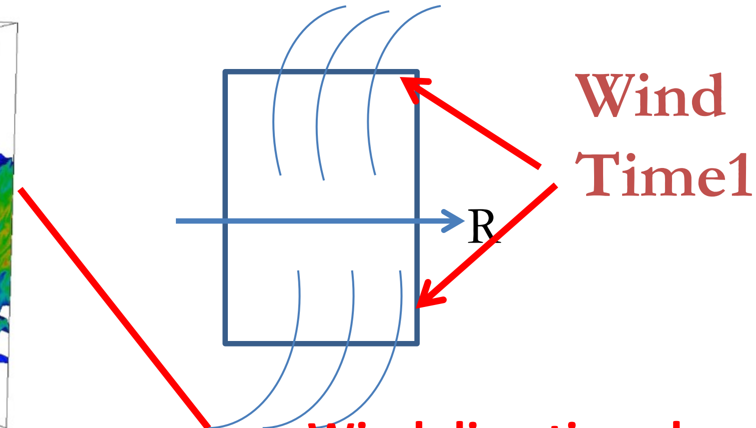
- **Analytical works:**
  - Many assumptions (e.g., not resolving disk; magnetic configuration; strength)
- **MHD global simulations :**
  - Proga (2003): not resolving disks; artificial cooling
  - Zhu & Stone (2018): relatively thick disk (artificial cooling)
- **MHD shearing box simulations:**
  - Well resolving disk;
  - Can not obtain true properties of wind (e.g., wind direction, mass flux…)

Existing Magnetic driven wind work: Shearing box simulations

Bai & Stone 2013

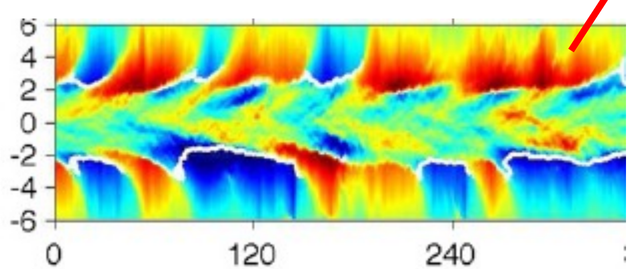
Due to symmetry of gravity to the box center, black hole can be in either radial direction

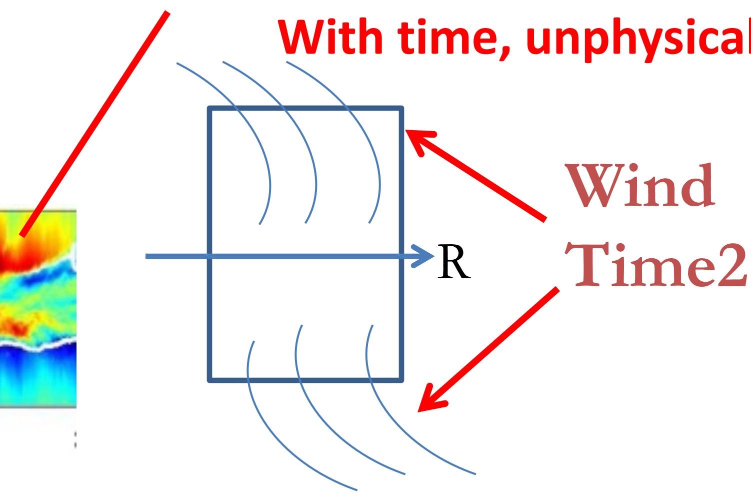




Wind direction changes With time, unphysical !

Dynamo makes the radial field changing direction





Global simulations are needed!

Magnetically driven AGN accretion disk wind

- Previous analytical works usually assume isothermal or adiabatic gas evolution.
  - How accurate are these assumptions?
- By using the exact cooling function to re-study B field driven wind model.
- Whether is the ultra-fast wind magnetically driven?

Basic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\rho \frac{\partial v_r}{\partial t} + \rho(\mathbf{v} \cdot \nabla) v_r = -\frac{\partial P}{\partial r} + \rho g_r + f_{\mathrm{B},r} + \rho \left(\frac{v_\theta^2}{r} + \frac{v_\phi^2}{r} \right)$$

$$\rho \frac{\partial v_\theta}{\partial t} + \rho(\mathbf{v} \cdot \nabla) v_\theta = -\frac{\partial P}{\partial \theta} + \rho g_\theta + f_{\mathrm{B},\theta} - \rho \left(\frac{v_\theta v_r}{r} - \frac{v_\phi^2}{r \tan\theta} \right),$$

$$\rho \frac{\partial v_\phi}{\partial t} + \rho(\mathbf{v} \cdot \nabla) v_\phi = f_{\mathrm{B},\phi} - \rho \left(\frac{v_\phi v_r}{r} - \frac{v_\phi v_\theta}{r \tan\theta} \right),$$

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho e \mathbf{v}) = -P \nabla \cdot \mathbf{v} + \rho \mathbf{L},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

$$\rho L = n^2 (\Gamma_{\mathrm{Compton}} + \Gamma_{\mathrm{X}} - \Lambda)$$

$$\Gamma_{\mathrm{Compton}} = 8.9 \times 10^{-36} \xi (T_{\mathrm{X}} - 4T)$$

$$\Gamma_{\mathrm{X}} = 1.5 \times 10^{-21} \xi^{1/4} T^{-1/2} (1 - T/T_{\mathrm{X}}),$$

$$\Lambda = 3.3 \times 10^{-27} T^{1/2} + \left[1.7 \times 10^{-18} \exp(-1.3 \times 10^5 / T) \times \xi^{-1} T^{-1/2} + 10^{-24} \right] \delta.$$

Exact cooling functions are employed!

initial conditions

- A Keplerian disk at the midplane.

$$\rho_{\theta=\pi/2}(r) = \begin{cases} 5.24 * 10^{-4}(M_{\mathrm{BH}}/\mathrm{M}_\odot)^{-1}(\varepsilon/\eta)^{-2}(r/r_{\mathrm{s}})^{3/2} & r \le r_{\mathrm{crit}}, \\ 4.66(M_{\mathrm{BH}}/\mathrm{M}_\odot)^{-7/10}(\varepsilon/\eta)^{2/5}(r/r_{\mathrm{s}})^{-33/20} & r > r_{\mathrm{crit}}. \end{cases}$$

- An hydrostatic atmosphere above the midplane

$$\rho_0(r,\theta) = \rho_{\theta=\pi/2}(r)\exp\left(-\frac{GM_{\mathrm{BH}}}{2c_{\mathrm{s}}^2 r\tan^2\theta}\right)$$

- The temperature

$$T_{\theta=\pi/2}(r) = T_{\mathrm{in}}\left(\frac{r}{r_{\mathrm{in}}}\right)^{-3/4},$$

- B field

$$A_\phi(r,\theta) = B_0(r\sin\theta)^{3/4}\frac{m^{5/4}}{(m^2+\tan^{-2}\theta)^{5/8}}$$

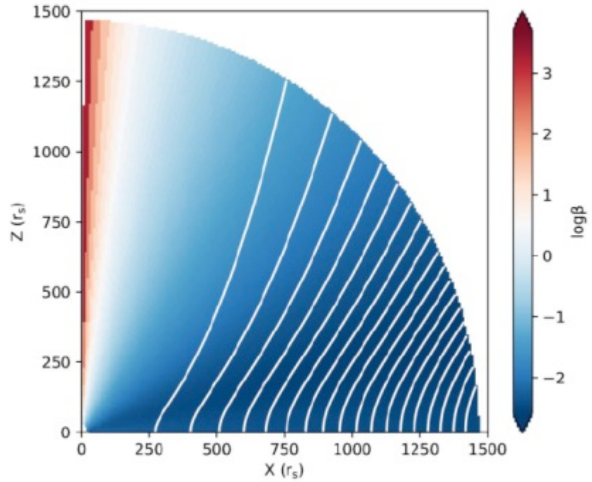
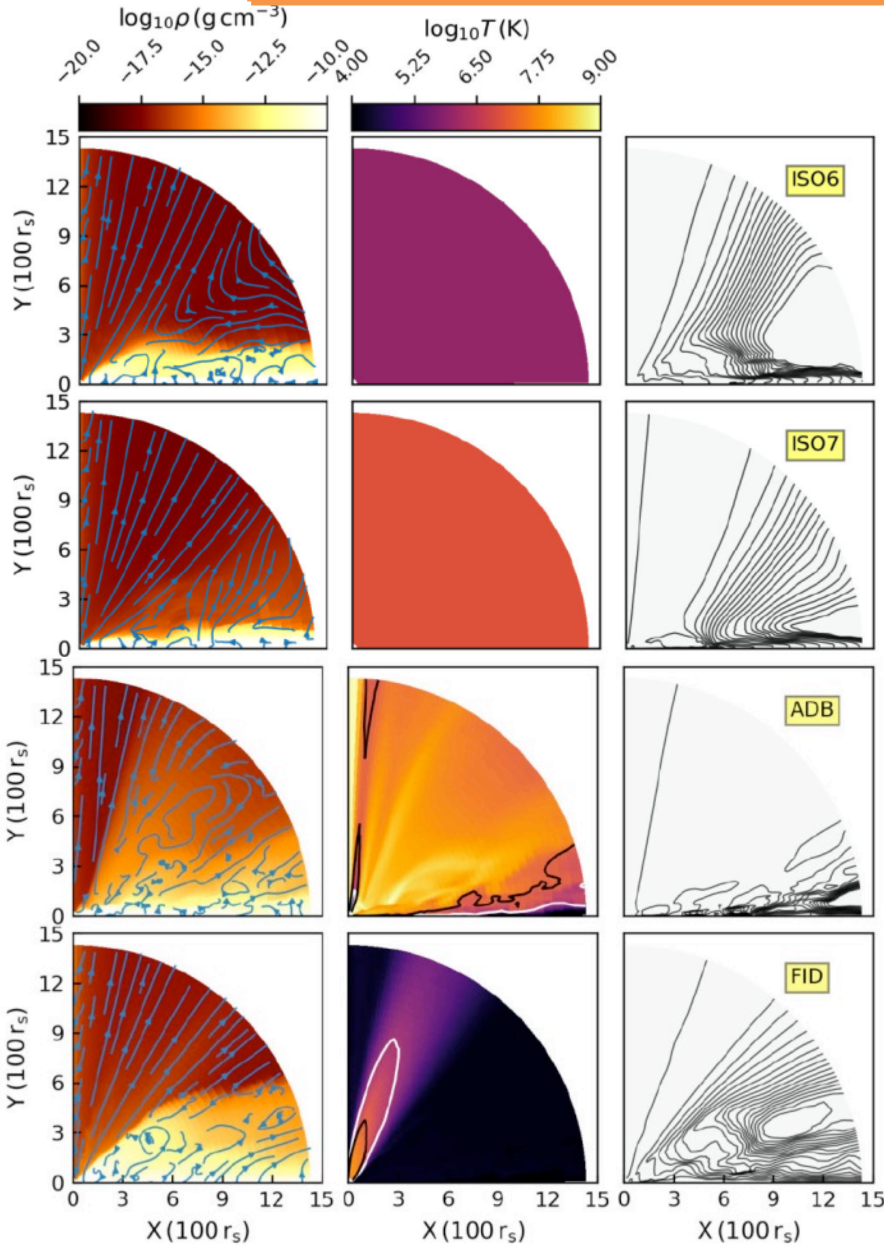


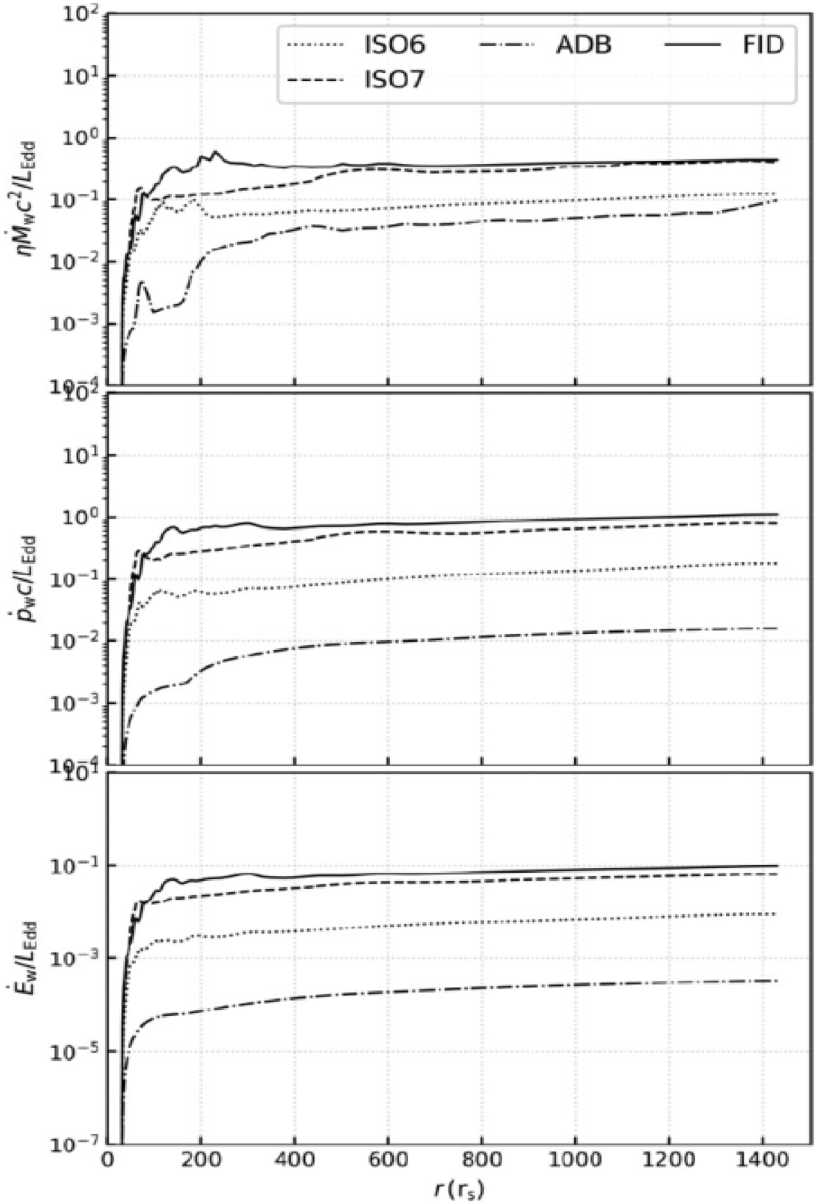
Figure 1. Colour map shows the logarithmic plasma beta and white curves represent the magnetic field lines. The initial β is about 10^8 on the disc surface, i.e. the first layer of grid above the equator.

Results: general structure



- The opening angle of wind differs significantly, which will result in different feedback efficiencies.
- The temperature of wind differs significantly, which affects the identification (in X-ray or UV) of winds.
- The configuration of B field differs much.

Results: fluxes



- The mass flux, momentum flux and kinetic power in the fiducial model is highest.
- Most of the wind is from the region 100-200 Rs.
- Outside 200Rs, the fluxes are almost constant of radius.
- The kinetic power of wind in the fiducial model can be as high as the AGN luminosity of 0.1 L_Edd.

Results: angular distribution

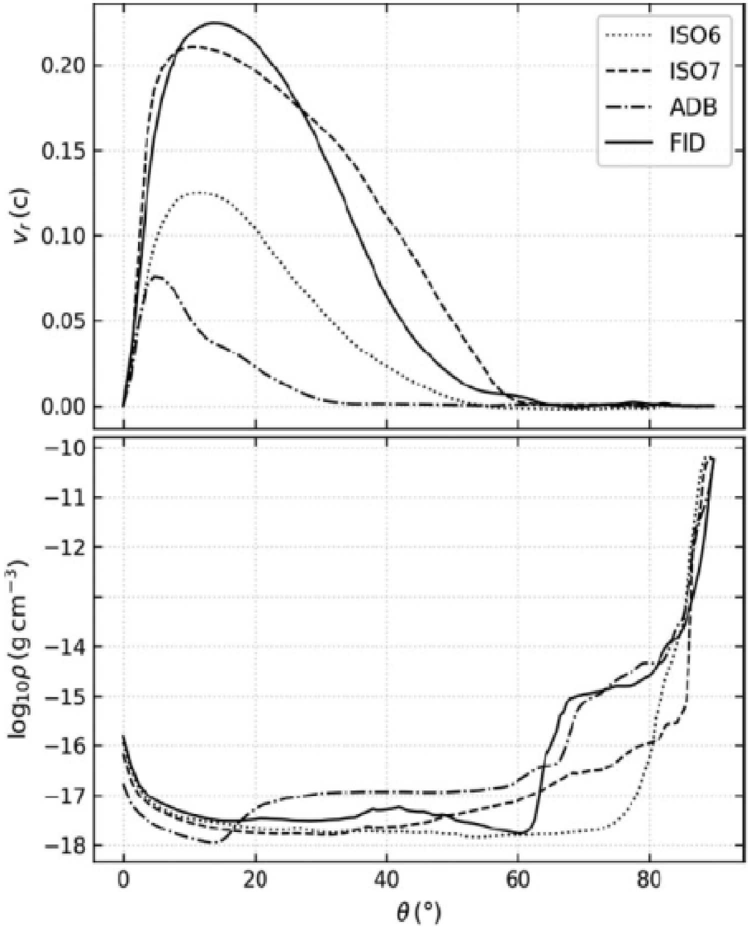
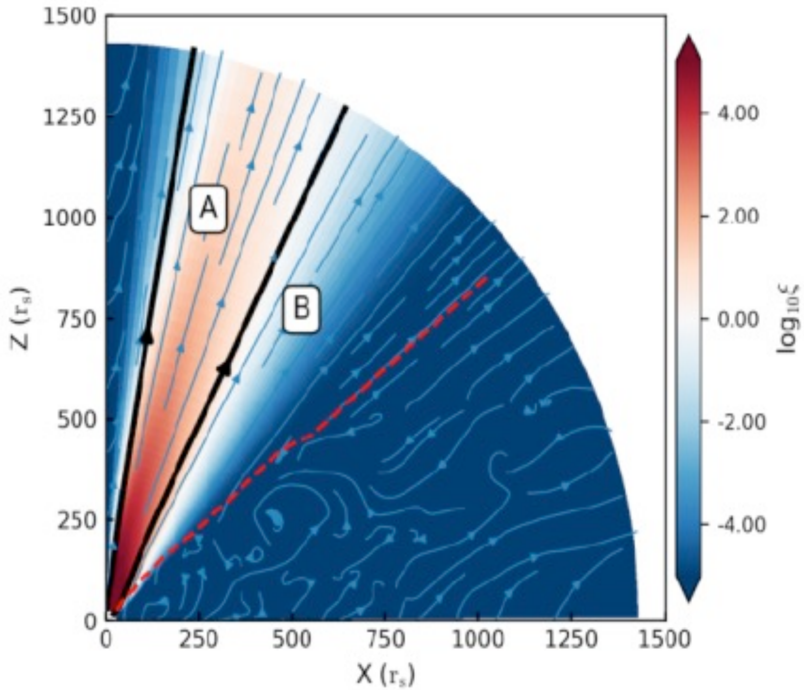


Figure 8. Angular profile of time-averaged radial velocity (upper panel) and logarithmic density (lower panel) at the outer radial boundary.

- The winds most occupy the region of theta < 60 degree.
- The highest velocity is in the region 0 < theta < 20 degree.
- The highest velocity in the fiducial model can be 0.23c.
- In the adiabatic or isothermal model, the velocity of wind can be highly underestimated.

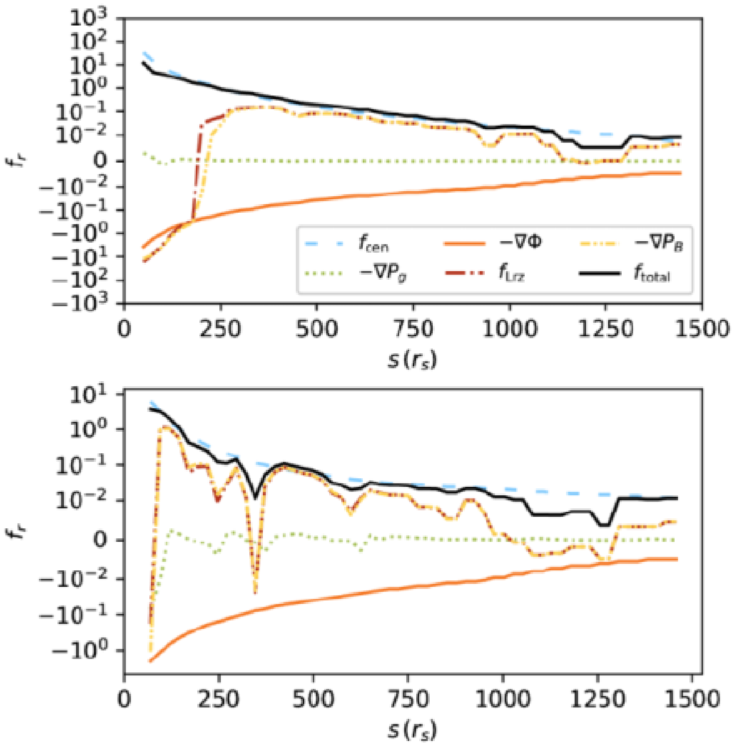
Results: ionization



(a) Time-averaged logarithmic ionization parameter ξ (colormap) overlaid by selected streamlines (black curves) labelled as A and B (thick black curves) for model FID.

- The ionization parameter varies significantly with viewing angles
- The region theta < 10 degree and theta > 30 degree corresponds to UV absorbers
- The region 10 < theta < 30 roughly corresponds to X-ray absorbers

Results: acceleration



(b) The radial time-averaged acceleration along streamline A (top panel) and B (bottom panel) for model FID. The radial accelerations are centrifugal force (blue dashed line), gas pressure gradient force (green dotted line), gravity (orange solid line), magnetic pressure gradient force (yellow dash-dotted line), Lorentz force (red dash-dotted line) and total force (black solid line), respectively. All the forces are in code unit.

- The gas pressure gradient force is negligible
- The wind is mainly **accelerated by the combination of centrifugal and magnetic pressure gradient forces** (with centrifugal forces slightly larger)
- The wind in the high inclination angle satisfy ***the BP driven*** model

Results: comparison to UFOs

- Ultra-fast outflows (UFOs) are commonly observed in AGNs.
  - On accretion disk scale.
  - Velocity: greater than 10000km/s
  - Ionization parameter $10^{2.5}$-$10^{5.5}$
  - Column density 10^{22}-10^{24}

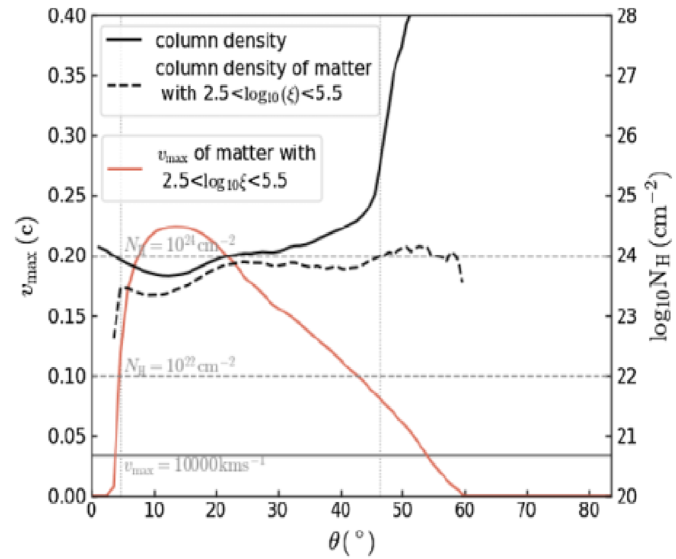
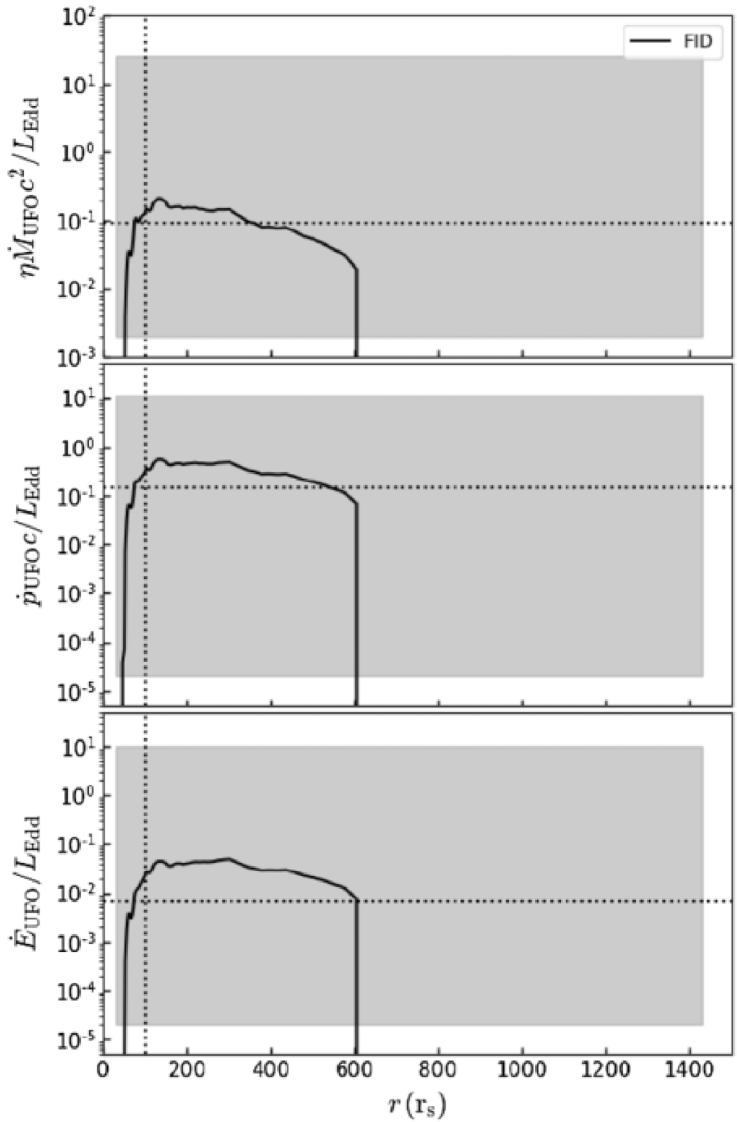


Figure 11. Column density (black solid line), column density of gas with 2.5 < logξ < 5.5 (black dashed line), and maximum velocity of the gas with 2.5 < logξ < 5.5 (red line). The horizontal axis is viewing angle (or θ angle). The vertical axis on the left-hand side shows the value of velocity (red line). The vertical axis on the right-hand side shows the value of column density (black solid and black dashed lines). The horizontal solid line marks the velocity of 10 000 km s^{-1}. The horizontal dashed lines mark column density of 10^{22} and 10^{24} cm^{-2}. The vertical dotted lines mark $\theta = 4.7$ and 45.6° where the disc winds satisfy the UFO conditions in between.

- The UFOs is distributed in the region of 5 < theta < 45 degree.
- The covering factor is 30.6%, which is close to the lower limit of the fraction of UFOs in AGNs.

Results: comparison to UFOs



- Inside 600Rs, the mass flux, momentum flux and kinetic power of UFOs are well consistent of observations.

- However, outside 600Rs, there is no wind satisfying the conditions of UFOs. The observed UFOs need also other driven mechanism.

Summary

- Both the isothermal and adiabatic assumptions can not be applied to study magnetically driven wind.

- The UFOs can also not be driven by only MHD process.

Thank you！