Magnetised Accretion Disks

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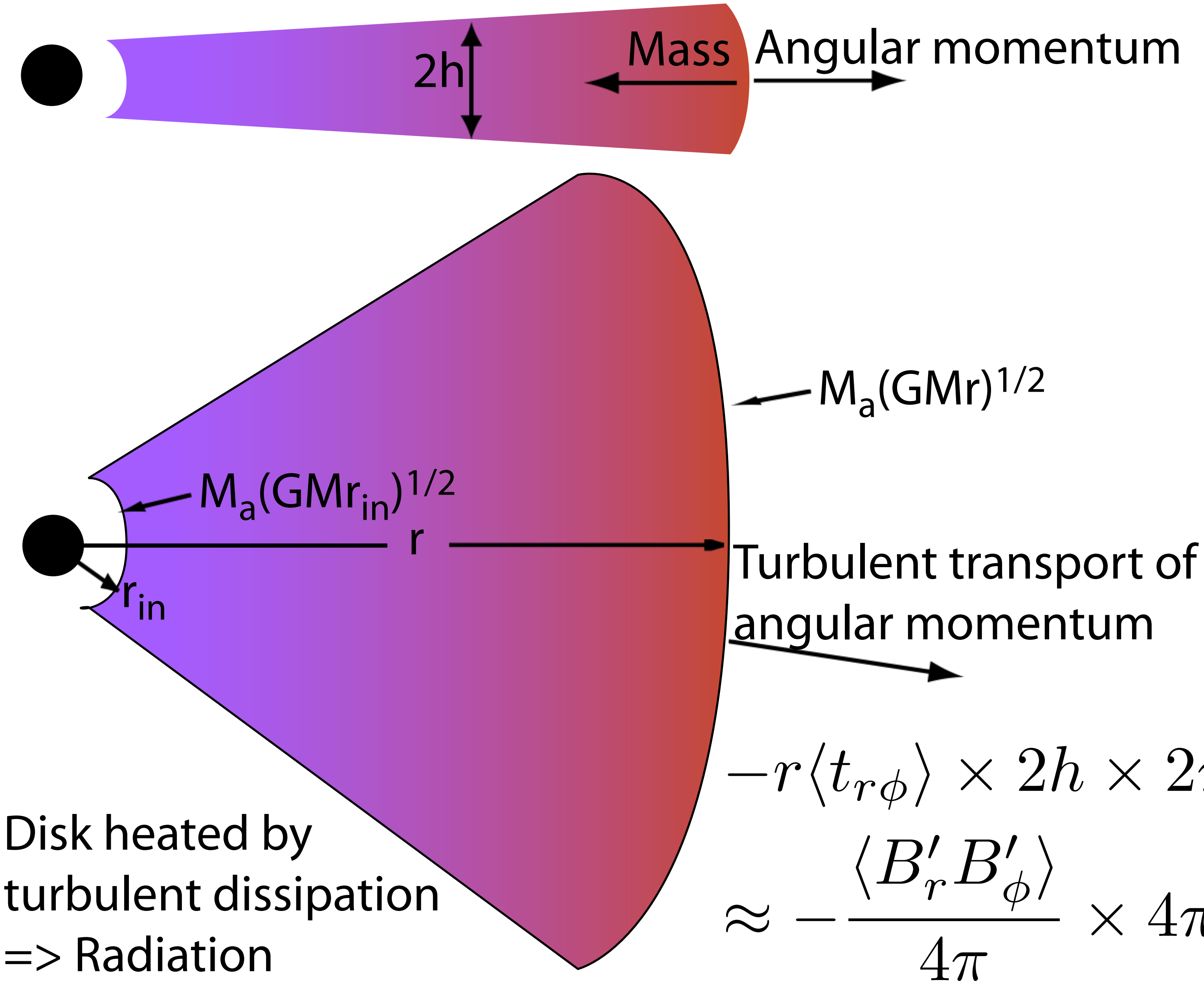
(See Kuncic & Bicknell, Dec 16 ApJ)

The standard model (Shakura & Sunyaev 1973)



Turbulent transport of angular momentum

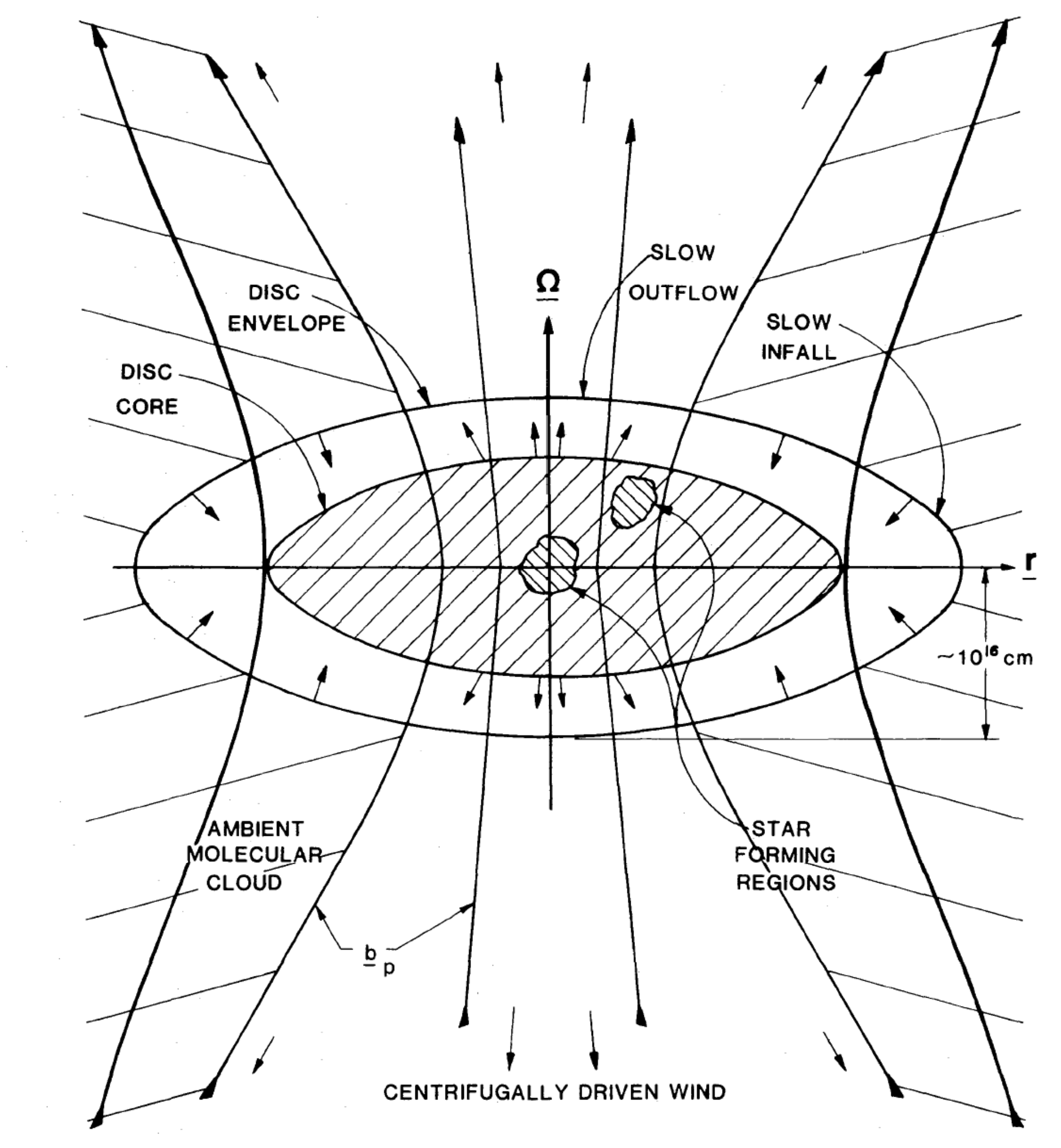
$$-r\langle t_{r\phi}\rangle \times 2h \times 2\pi r$$
$$\approx -\frac{\langle B'_r B'_\phi\rangle}{4\pi} \times 4\pi r^2 h$$

Disk heated by
turbulent dissipation
=> Radiation

Radical departures from the standard model

Blandford & Payne (1982) – Centrifugally driven flows from accretion disks

Pudritz & Norman (1983) – Centrifugally driven flows drive accretion onto protostars



Revision of the standard model incorporating both disk dissipation and magnetically driven flow

- Turbulent stresses due to magnetic fields (Shakura–Sunyaev; Balbus–Hawley)

- In the standard model magnetic fields not incorporated *ab initio*

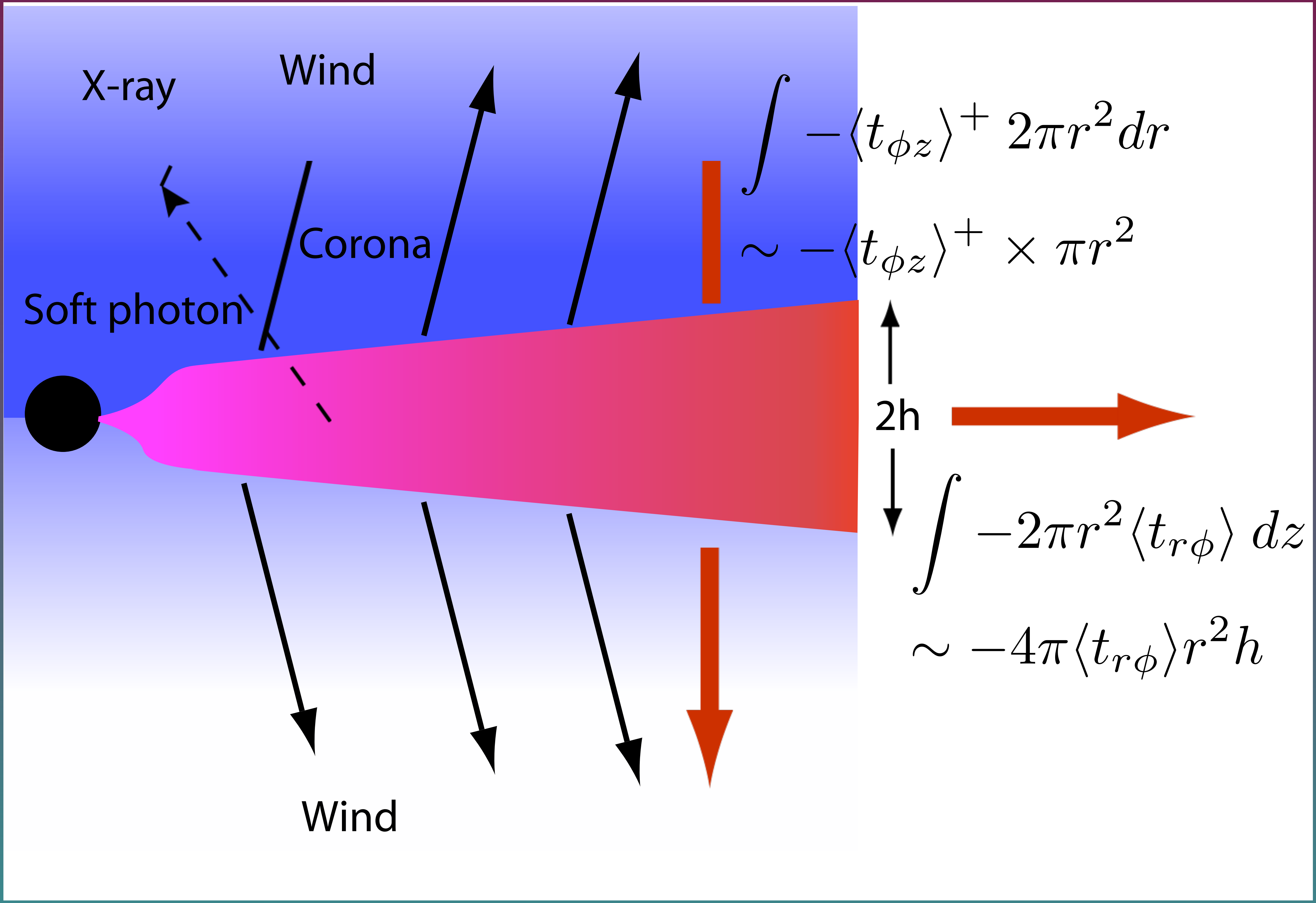
- AGN X-ray emission: Dissipation of gravitational power in corona (Haadt & Maraschi) - how does this happen?

- Winds and jets from accretion discs - relationship to the energy budget

- Radio-loud / radio quiet: Distribution of radio power

- Why do we see powerful radio sources in star-forming environments?

Vertical-azimuthal stress and wind



$$\int -\langle t_{\phi z}\rangle^{+}\, 2\pi r^{2} dr$$

$$\sim -\langle t_{\phi z}\rangle^{+} \times \pi r^{2}$$

$$\int -2\pi r^{2} \langle t_{r\phi}\rangle\, dz$$

$$\sim -4\pi \langle t_{r\phi}\rangle r^{2} h$$

Additional stress important when: $\langle t_{\phi z}\rangle^{+} \sim \frac{h}{r}\langle t_{r\phi}\rangle \sim 10^{-2}\langle t_{r\phi}\rangle$

What are the stresses?

Statistically averaged dynamical quantities

$$\rho = \bar{\rho} + \rho' \qquad \langle \rho' \rangle = 0$$

$$v_i = \tilde{v}_i + v'_i \qquad \langle \rho v'_i \rangle = 0$$

Momentum equations

$$\frac{\partial(\bar{\rho}\tilde{v}_i)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{v}_i\tilde{v}_j)}{\partial x_j} = -\bar{\rho}\frac{\partial \phi_G}{\partial x_i} - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\overset{\langle t_{ij} \rangle}{\left[t^R_{ij} + \langle t^B_{ij} \rangle\right]}$$

$$t^R_{ij} = -\langle \rho v'_i v'_j \rangle \qquad \langle t^B_{ij} \rangle = \frac{\langle B' B'_j \rangle}{4\pi} - \frac{\langle B'^2 \rangle}{8\pi}\delta_{ij}$$

Most significant terms

Standard accretion disk

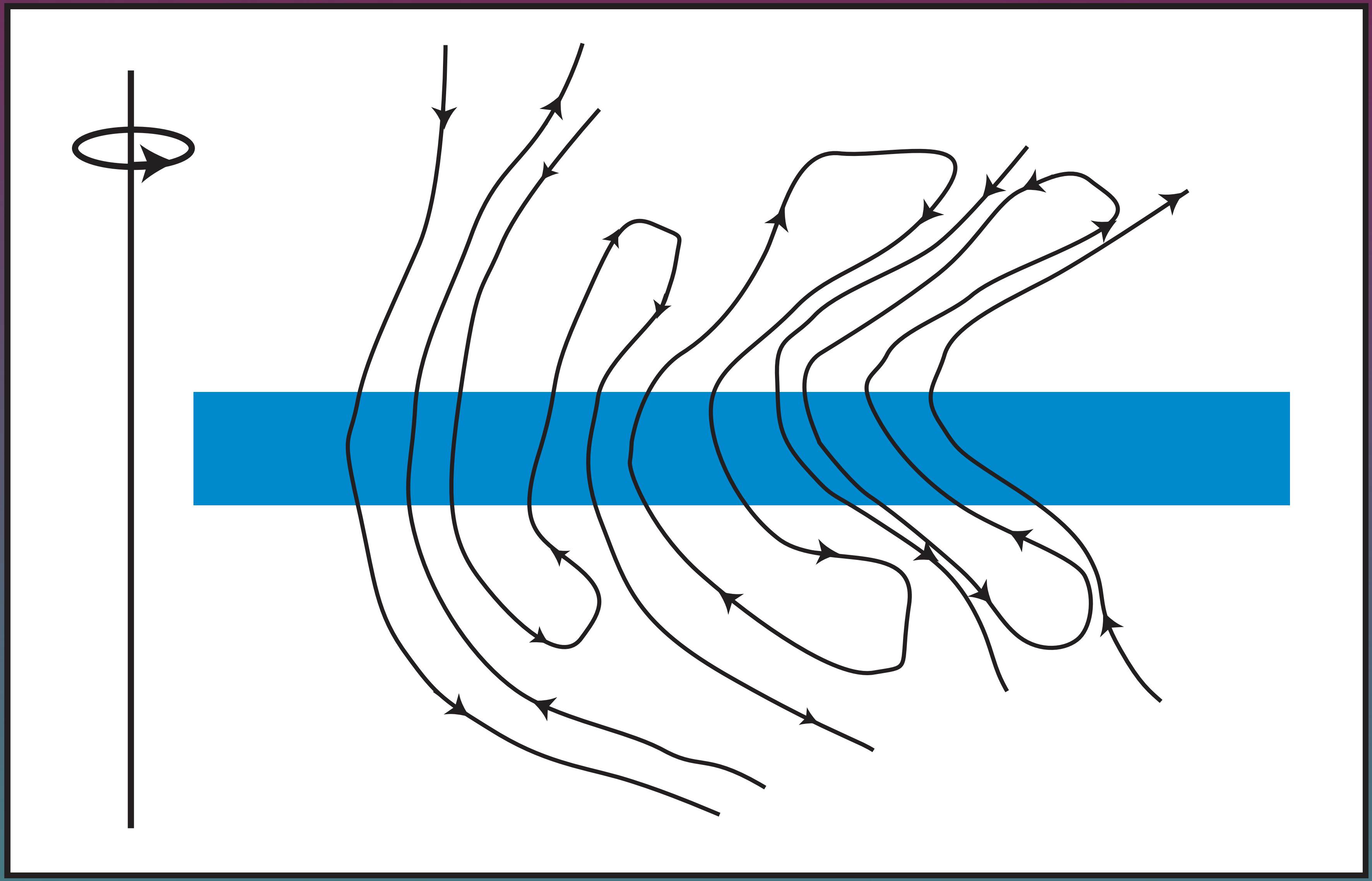
$$\begin{aligned} -\langle t_{r\phi}\rangle &= \text{Radial flux of } \phi \text{ momentum} \\ -\langle t_{\phi z}\rangle &= \text{Vertical flux of } \phi \text{ momentum} \end{aligned}$$

BP, PN, New model

Simulations (Balbus, Hawley, Stone et al.) show that all stresses dominated by magnetic fields

$$\langle t_{r\phi}\rangle \approx \frac{\langle B'_r B'_\phi\rangle}{4\pi} \qquad \langle t_{\phi z}\rangle \approx \frac{\langle B'_\phi B'_z\rangle}{4\pi}$$

Magnetic field configuration



Mean magnetic flux = 0 (non-zero mean to be incorporated later)

Similar to realistic magnetic field configuration proposed in Blandford & Payne

Features of the new model

- Both modes of angular momentum transport self-consistently treated

- Vertical transport requires the existence of a wind to remove the angular momentum transported out of the disk

- A disk wind means that that the accretion rate is no longer constant

- Accompanying the vertical flux of angular momentum, there is also a vertical flux of energy

- Some of this energy will end up in the wind

- Some of the energy could be dissipated in the corona

Angular momentum conservation

$$\frac{d}{dr}\left[\dot{M}_a v_K r + 2\pi r^2 \int_{-h}^{+h} \langle t_{r\phi}\rangle \, dz\right] = r v_K \frac{d\dot{M}_a}{dr} - 4\pi r^2 \langle t_{\phi z}\rangle^+$$

Keplerian velocity

Vertical transport important when $\langle t_{\phi z}\rangle^+ \sim \left(\frac{h_{\rm av}}{r}\right)\langle t_{r\phi}\rangle$

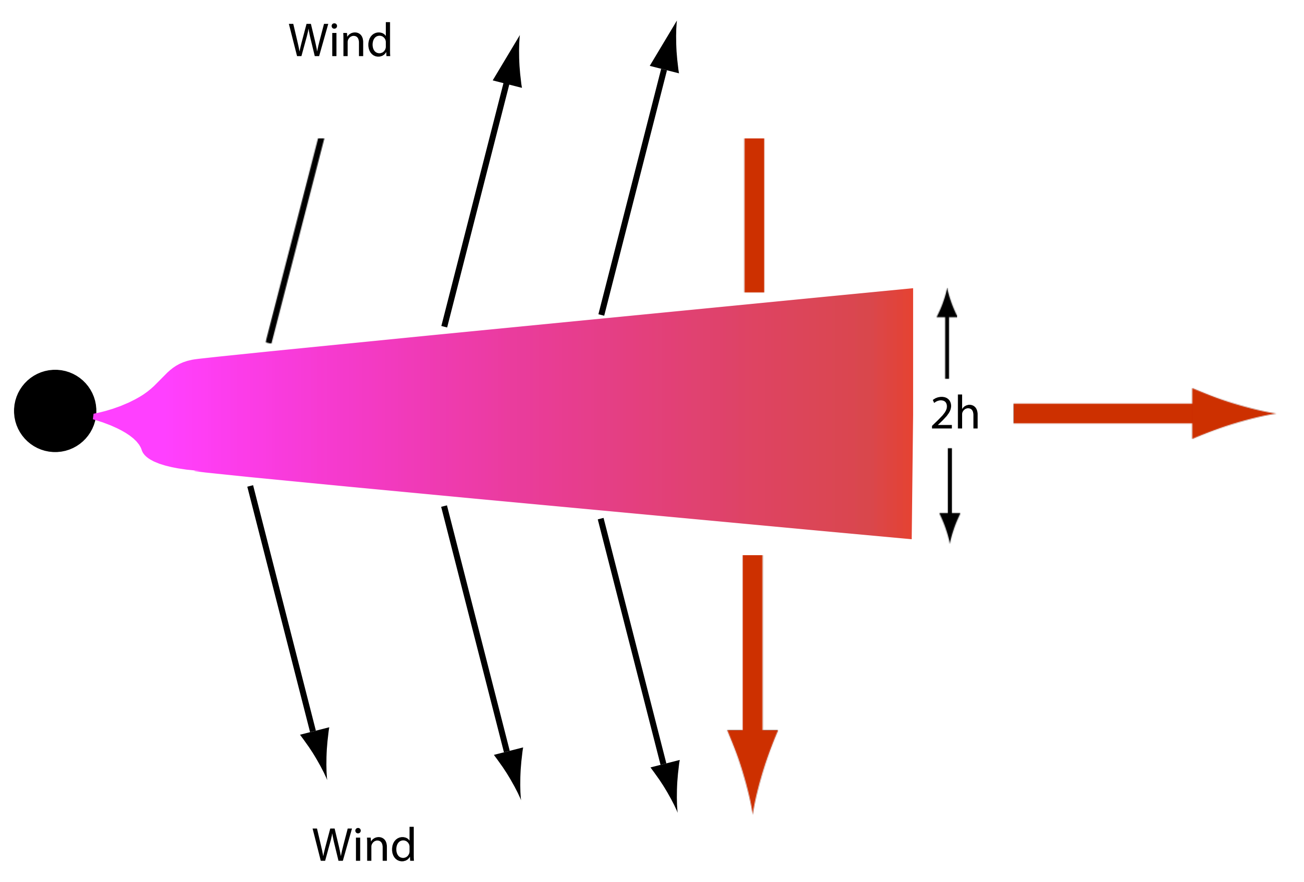
Critical magnetic flux density:

$$\frac{\dot{M}_a}{M_{\rm Edd}}$$

$$B_{\rm crit}^{\rm AM} = \langle B'_\phi B'_z\rangle^{1/2} = \left[\frac{\dot{M}_a V_K}{2r^2}\right]^{1/2}$$

$$\approx 3\times 10^4 \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{-1/2} \dot{m}^{1/2} \left(\frac{r}{r_g}\right)^{-5/4} \text{Gauss}$$

Winds and the Magnetic Switch



Energy flux per unit area of wind ~ (KE+PE) flux + Poynting Flux

Energy flux needs to be +ve for a wind to exist

$$\langle F_z^E \rangle \approx \left(-\frac{1}{2} v_K^2 + v_A^{+2} \right) \frac{1}{4\pi r} \frac{d\dot{M}_a}{dr} - \frac{\langle B'_\phi B'_z \rangle}{4\pi} v_K$$

$$\langle F_z^E \rangle \approx \left(-\frac{1}{2} v_K^2 + {v_A^+}^2 \right) \frac{1}{4\pi r} \frac{d\dot{M}_a}{dr} - \frac{\langle B'_\phi B'_z \rangle}{4\pi} v_K$$

Magnetic switch (Meier et al., 97,99) – transition from loosely collimated wind to jet when coronal Alfven speed ~ Keplerian speed

First part of energy flux +ve when: $v_A^+ > \frac{1}{2} v_K$

However, a wind is possible when:

$$\langle B'_\phi B'_z \rangle > {B_{\rm crit}^{\rm wind}}^2 = \frac{v_K}{2r} \frac{d\dot{M}_a}{dr}$$

cf $${B_{\rm crit}^{\rm AM}}^2 = \frac{v_K}{2r} \frac{\dot{M}_a}{r}$$

So far:

- Existence of a wind and transport of angular momentum perpendicular to the disk are inextricably linked

- The same critical value of the magnetic field is involved in both phenomena

- The critical magnetic field is related to the dimensionless accretion rate:

$$B_{\rm crit}^{\rm AM} \approx 3 \times 10^4 \left(\frac{M_{\rm BH}}{10^8 M_\odot} \right)^{-1/2} \dot{m}^{1/2} \left(\frac{r}{r_g} \right)^{-5/4} \text{Gauss}$$

Energy

$$\begin{aligned}\text{Gravitational Power} &= \frac{1}{2}\frac{GM\dot{M}_a(r_{\rm in})}{2r_{\rm in}} \\ &= \text{Rate of binding energy transport} \\ &\quad\ \text{across inner boundary}\end{aligned}$$

- In the standard model, all of this energy is converted into radiation

- Magnetic field + vertical transport => energy transported perpendicular to the disk by Poynting flux

- Radiation emitted by disk altered

- Significant gravitational power transmitted to corona

Dissipation vs generation

Standard model: Dissipation a direct result of turbulence

$$\text{Dissipation per unit area} \sim \frac{3}{8\pi}\frac{GM\dot{M}_a}{r^3}$$

This is fact the rate of generation of turbulence

Correct approach:

Rate of advection and diffusion of turbulence

= Generation - Dissipation

Standard model: Disspation = Generation

Poynting flux

When the condition for significant angular momentum transport by the azimuthal-vertical stress is satisfied there is also a significant energy transport

$$\text{Vertical Poynting flux} = S_z \approx \frac{\langle B'^2_\phi \rangle}{4\pi} \tilde{v}_z^+ - \frac{\langle B'_\phi B'_z \rangle}{4\pi} v_K$$

Second component likely to be the more important when

$$\frac{|B'_z|}{|B'_\phi|} > \left(\frac{h_{\rm av}}{r} \right) \left(\frac{\tilde{v}_z^+}{c_0} \right) \sim 10^{-2} \left(\frac{\tilde{v}_z^+}{c_0} \right)$$

Disk radiative luminosity

$$L_{\rm disk} \approx \frac{1}{2}\frac{GM\dot{M}_a(r_{\rm in})}{r_{\rm in}} - 2\pi r_i^2 T_{r\phi}(r_{\rm in})\Omega_K(r_{\rm in}) - P_{\rm wind}$$

Disk Luminosity reduced by power in wind:

$$P_{\rm wind} = -\int_{r_{\rm in}}^{\infty}\frac{GM}{2r}\frac{d\dot{M}_a}{dr}dr + 4\pi\int_{rin}^{\infty}\langle S_z\rangle r dr$$

- More complex expression for the power radiated per unit area (and consequently for spectrum) of disk.

- Poynting flux relevant when B ~ critical value

Comparison of critical magnetic fields

Critical field for angular momentum and energy transport

$$B_{\rm crit}^{\rm AM} \approx 3\times 10^4 \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{-1/2} \dot{m}^{1/2} \left(\frac{r}{r_g}\right)^{-5/4} \ {\rm Gauss}$$

Magnetic switch magnetic field

$$B^{\rm MS} \approx 3\times 10^5 \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{-1/2} \left(\frac{r}{r_g}\right)^{-5/4} \left(\frac{T_{\rm corona}}{10^9\ K}\right)^{-1/4} \tau_{\rm corona}^{1/2}{\rm Gauss}$$

$$\frac{B_{\rm crit}}{B_{\rm MS}} = 0.1\dot{m}^{1/2} T_{\rm corona,9}^{1/4} \tau^{-1/2}$$

Low and high powered AGN

$$\frac{B_{\rm crit}}{B_{\rm MS}} = 0.1\dot{m}^{1/2}T_{\rm corona,9}^{1/4}\tau^{-1/2}$$

- When the accretion rate is highly sub-Eddington then the critical magnetic field is well below the magnetic switch value.

- If the field is nearer the magnetic switch value then the disk will be largely non-radiative and most of the power will be either in the wind or the corona

- Applications to FR1 radio galaxies and Galactic Centre

Conclusions

- Defined the flow of energy in accretion disks and related wind and corona

- Determined the strength and configuration of the magnetic field that is important for diversion of energy into winds and the corona

- Main component of Poynting flux identified

- Existence of disk wind and corona inextricably linked

- Important to identify the relative importance of the various magnetic field estimates – magnetic switch etc.

- Possibly key to understanding the physics of low-powered AGN