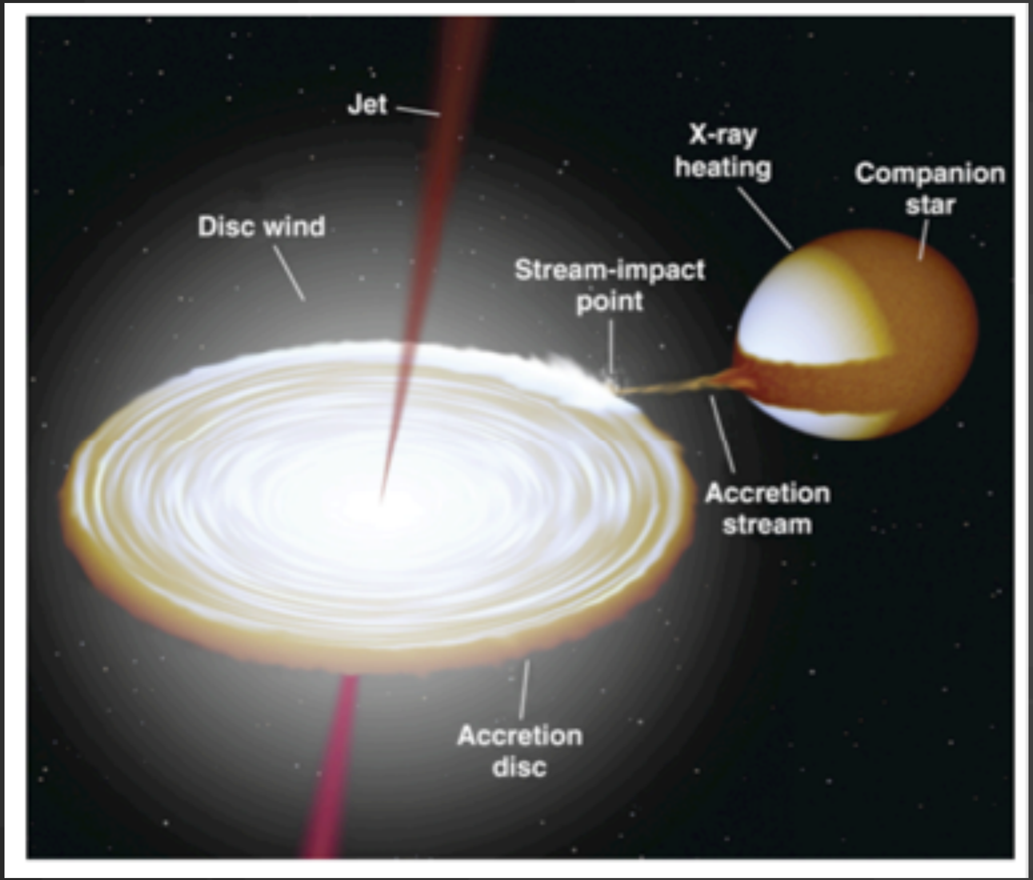

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Magnetothermal disk wind solutions applied to low mass X-ray binaries

Chandra Science Workshop: Accretion in Stellar Systems

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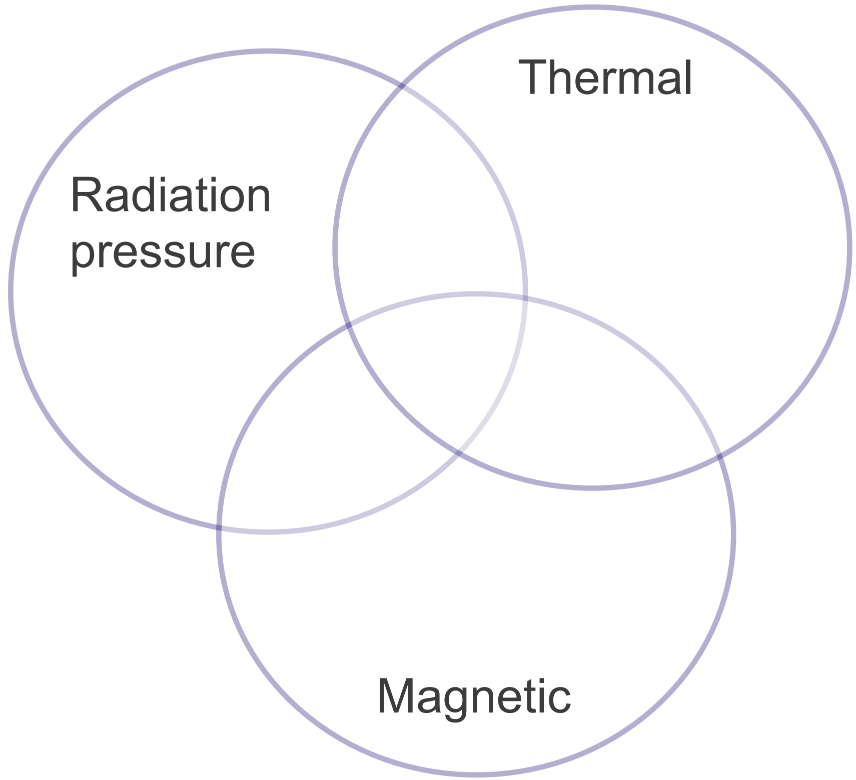
Outline

- **Summary of thermal, magnetic, & magnetothermal driving mechanisms**
- **Simulations using Athena++**
- **Conclusions**

Combining wind launching mechanisms



- Do we understand the intersections?

$$\rho \frac{D\mathbf{v}}{Dt} = -\rho \nabla \Phi - \nabla p + \mathbf{f}_{\rm rad} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

Thermal driving

In LMXBs, the source of thermal driving is Compton heating (Begelman, McKee, & Shields 1983).

Intuition may tell you that given a high enough radiation flux, thermal winds can be driven arbitrarily close to the black hole - this is not so!

$$n^2\Lambda_{IC} = n_e \sigma_T \frac{4kT}{m_e c^2} \frac{L}{4\pi R^2} . \quad (2.3b)$$

where

In t... until inverse Com... dominates, balances Comp... gives an equilibrium temperature

$$kT_{IC} = \tfrac{1}{4}\langle\epsilon\rangle , \quad (2.4)$$

which allows us to reexpress the heating rate as

$$\Gamma = \frac{kT_{IC}}{m_e c^2} \frac{\sigma_T L}{\pi R^2} . \quad (2.5)$$

Compton temperature depends on the spectrum of radiation, not on its intensity!

T_IC = T_escape sets the critical radius: R_IC = GM mbar/k T_IC

$$R_{IC} = \frac{1}{2} \frac{c^2}{kT_{IC}/\bar{m}} R_S = 5.45 \times 10^5 \frac{\bar{m}}{m_p} \left(\frac{T_{IC}}{10^7 \mathrm{K}}\right)^{-1} R_S.$$

Magnetic driving

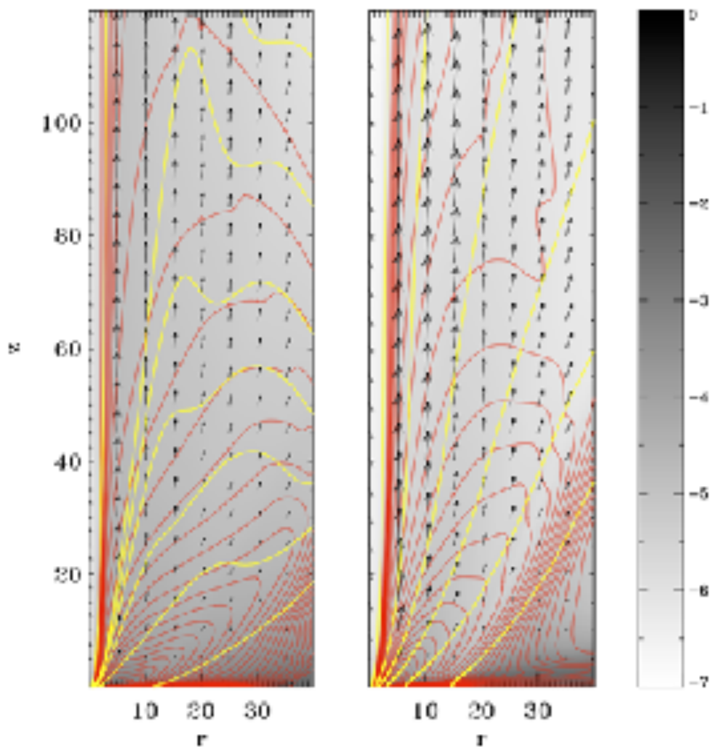
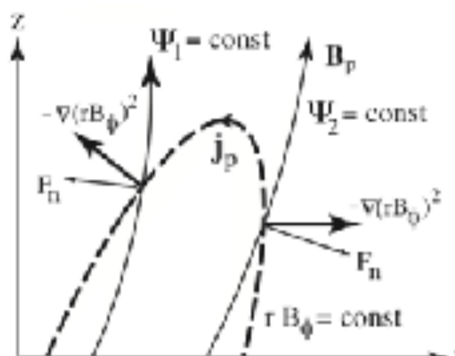


Fig. 6. Poloidal current circuits (*solid thin red lines*) at $t = 400$ of the cases ($\alpha_m = 0.1$, $\chi_m = 1$, $f = 1$, *left panel*) and ($\alpha_m = 1$, $\chi_m = 3$, $f = 1$, *right line*). Plotted are also sample poloidal field lines (*solid thick yellow lines*) and the poloidal speed vectors. In the background density maps in logarithmic grayscale are shown.

From Zanni et al. (2007)

$$F_\phi = \frac{B_p}{2\pi r}\nabla_{\|} I,$$
$$F_{\|} = -\frac{B_\phi}{2\pi r}\nabla_{\|} I. \quad (2)$$

Here, $I = 2\pi r B_\phi$ is the total current flowing within a given magnetic surface, and the projected gradient is defined by $\nabla_{\|} \equiv B_p^{-1}(\mathbf{B}_p \cdot \nabla)$. Notice that the current leakage through a flux suface, $\nabla_{\|} I$, is not relevant for assessing the relative importance of these forces, as their ratio is simply $F_\phi / F_{\|} = -B_p/B_\phi$. Since F_ϕ provides additional centrifugal force that will make the Blandford-Payne mechanism more important than acceleration from the parallel Lorentz force, magneto-centrifugal launching requires $B_p >> |B_\phi|$, while winds can be purely magnetically driven in the opposite limit.



Magnetothermal driving

The generalized Bernoulli integral can be written as:

$$\mathcal{E} = \frac{1}{2}V^2 + h - \frac{GM}{r} - \frac{rB_\phi \Omega}{\Psi_A} = \underbrace{\frac{1}{2}V_o^2 + h_o - \frac{GM}{r_o}}_{\mathcal{E}_o} - \underbrace{\frac{r_o B_\phi^o \Omega}{\Psi_A}}_{\approx \Omega L} \approx \mathcal{E}_o + \Omega L \quad (22)$$

where $\mathcal{E}_o$ is the specific energy of the thermally driven Parker wind and ΩL is the Poynting energy of the magnetic rotat… …pending on which of these two terms dominates we have two po…

1. $\mathcal{E}_o \gg \Omega L$: **Slow mag…** …n this case we have a thermally driven P…
2. $\mathcal{E}_o \ll \Omega L$: **I… …ator, FMR.** In this case we have a magnetorotation… …wind.

Equivalently, compare the Michel velocity with the outflow velocity!

See Tsinganos (2007)

$$V_M = V_A \left(\frac{V_\varphi}{V_A} \right)^{\frac{1}{3}}$$

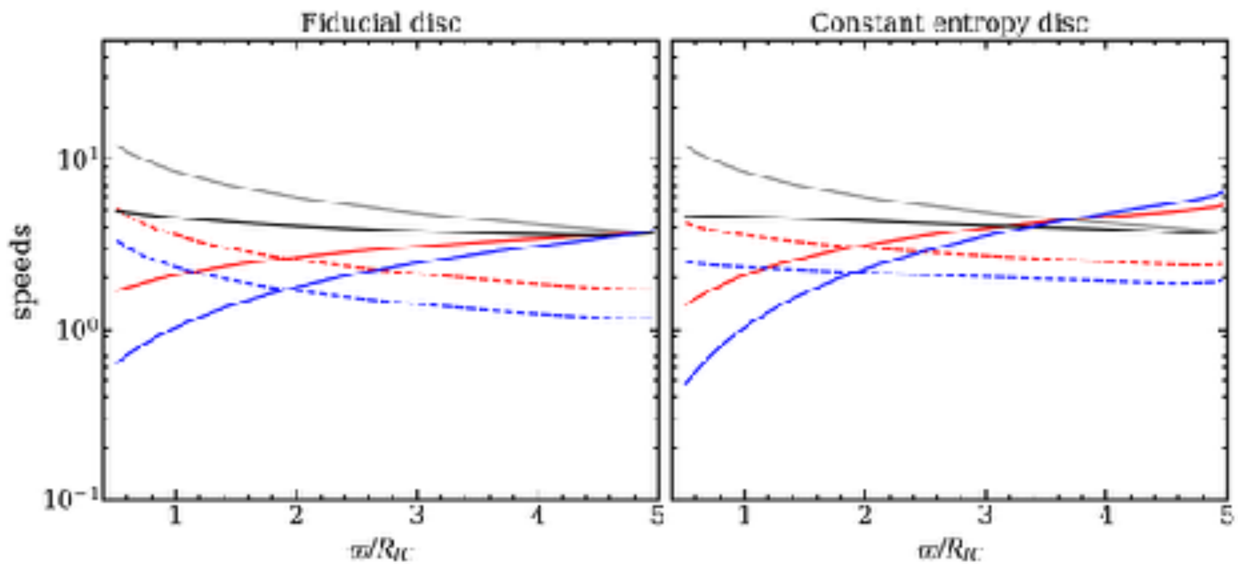
(FMR if V_M >> V_w)

Basic constraints for MHD disk winds

Lower limit on field strength:
Magnetic energy must be comparable to thermal energy

Upper limit on field strength:
Disk must be capable of supporting the magnetic field: magnetic energy must be significantly less than the rotational energy

Disk surface (instead of midplane) quantities



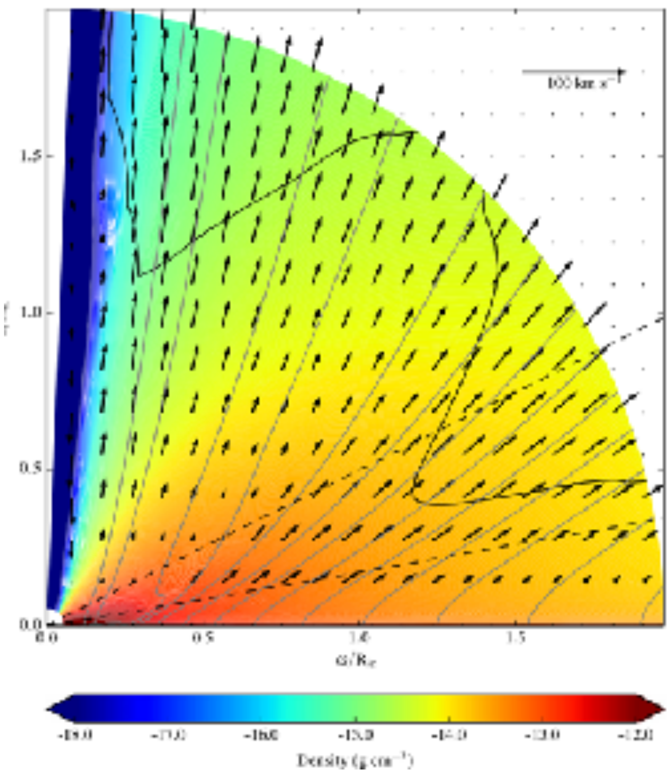
Red line:

$$V_M = V_A \left(\frac{V_{Kep}}{V_A} \right)^{\frac{1}{3}}$$

FMR if
V_M >> V_Kep

Combining thermal and MHD wind models

In a nutshell: Thermal winds struggle to produce velocities > 200km/s.



From Higginbottom & Proga (2015)

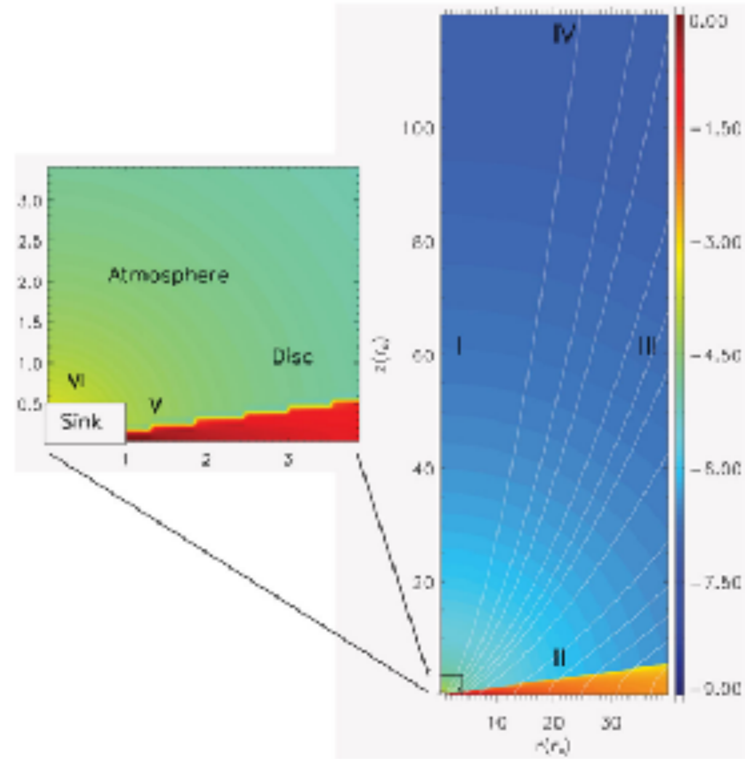


Figure 1. The initial condition, $t = 0$, displaying density logarithm along with sample field lines. The sink/internal boundary region is included as a magnification on the left. Roman numerals denote the six boundary regions, four (I–IV) for the computational domain and two more (V, VI) for the sink.

From Tzeferacos et al. (2013)

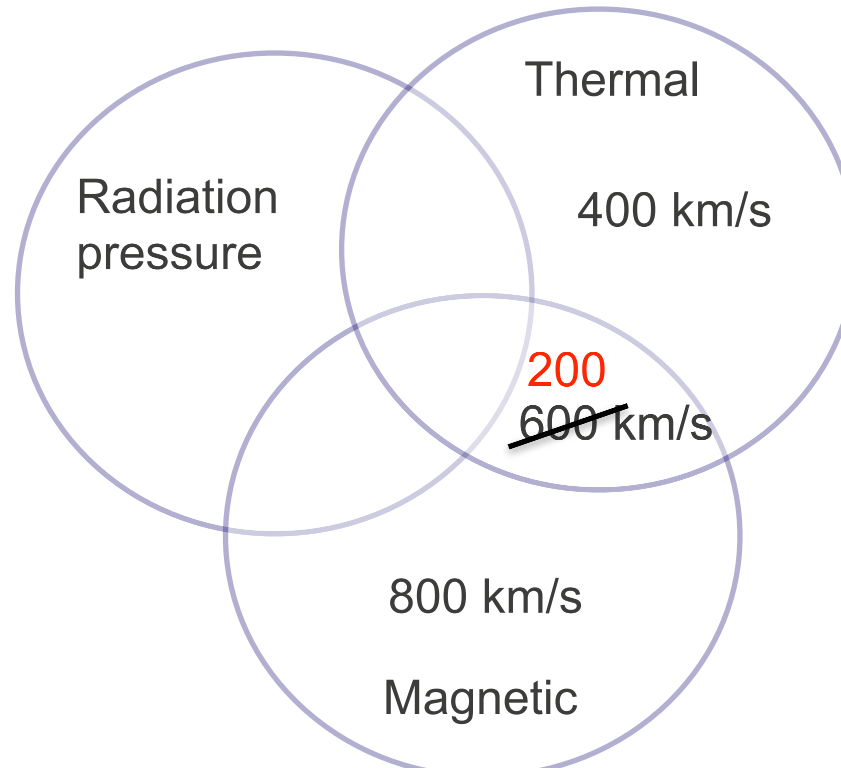
Magnetothermal wind models: expectations vs. findings

Based on previous studies, one would expect the addition of a strong poloidal magnetic field to provide a boost to the velocity.

It turns out that the 'primary' thermal disk wind is instead suppressed upon adding magnetic fields.

The potential for suppression is easy to understand in hindsight:

If the magnetic fields are strong enough to reshape the streamlines, the conditions may no longer be optimal to acceleration.
- mainly, the flow tube area is reduced



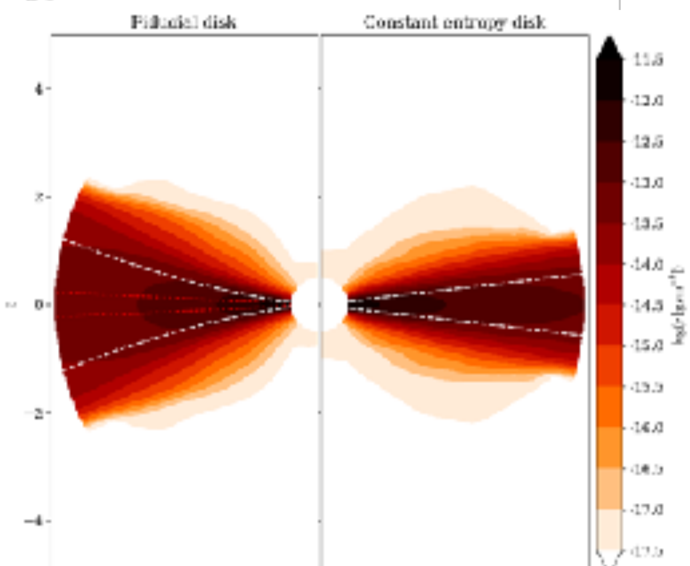
Magnetothermal wind models: setup

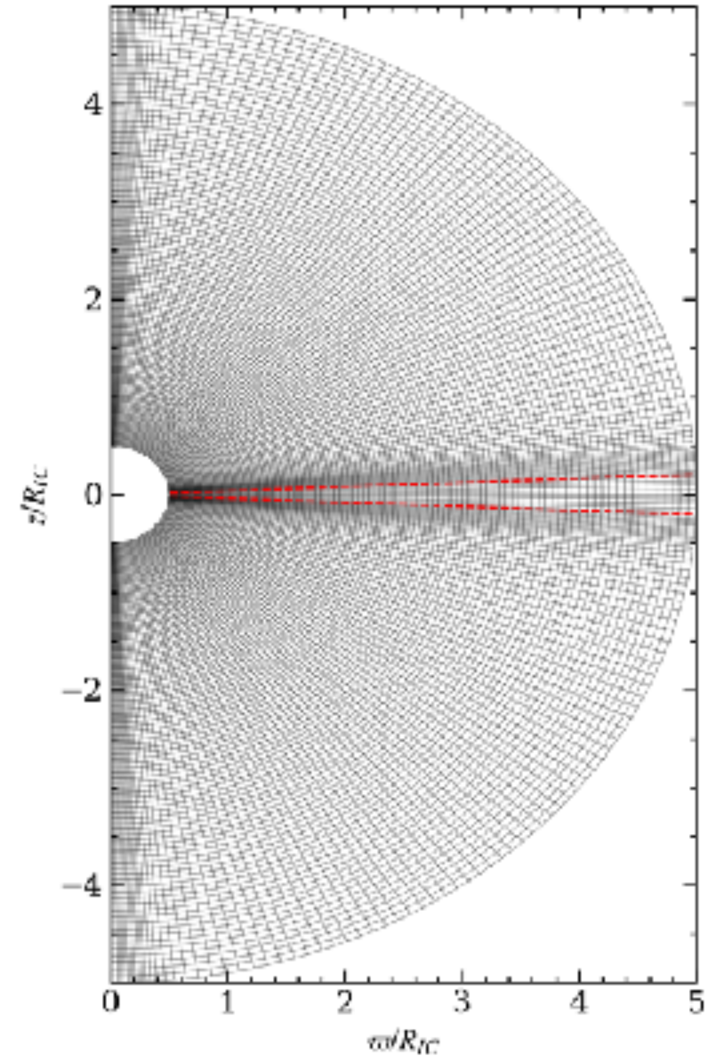
$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{v} = 0,$$

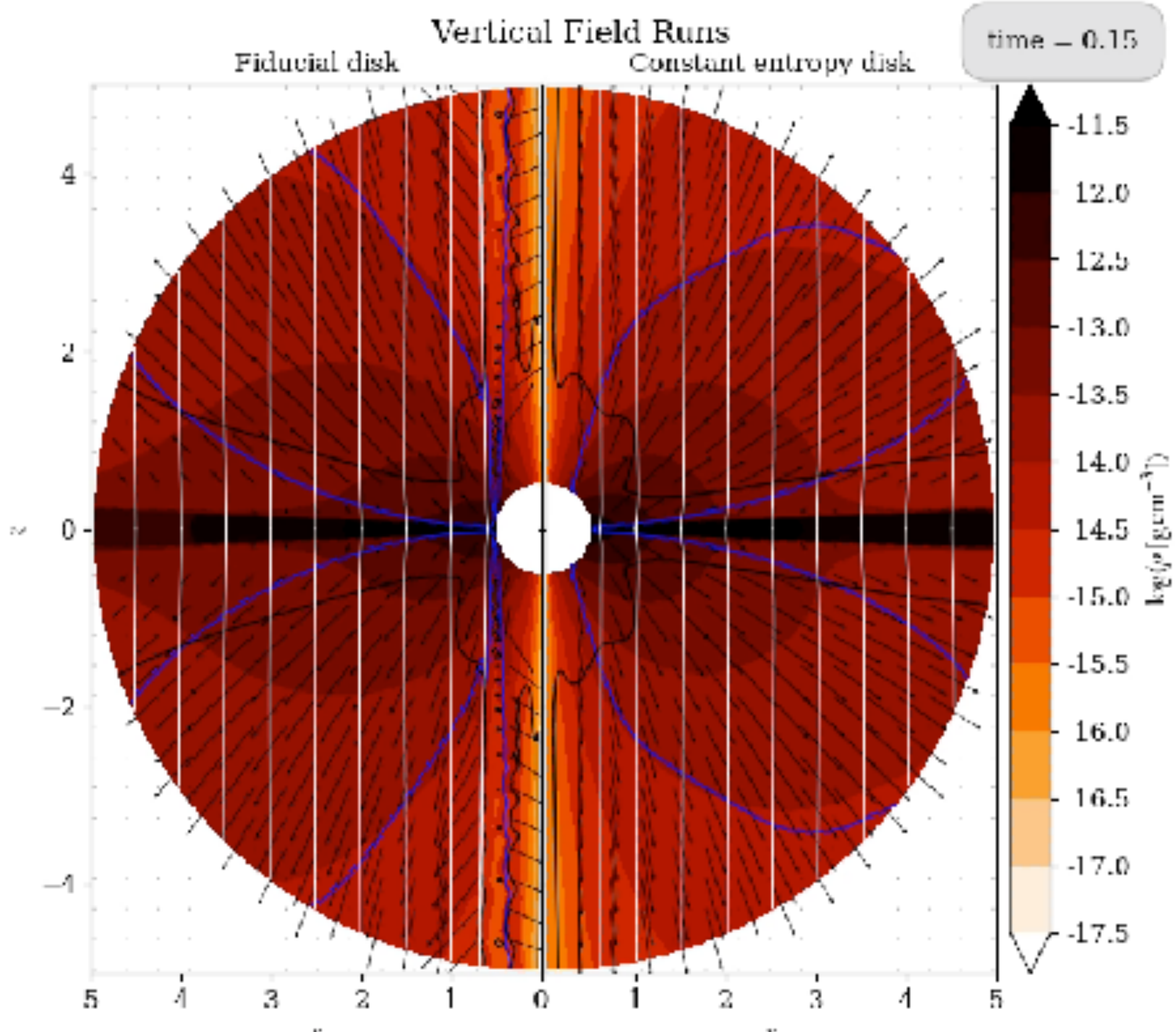
$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p - \rho\nabla\Phi + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B},$$

$$\rho\frac{D\mathcal{E}}{Dt} = -p\nabla\cdot\mathbf{v} - \rho\mathcal{L},$$

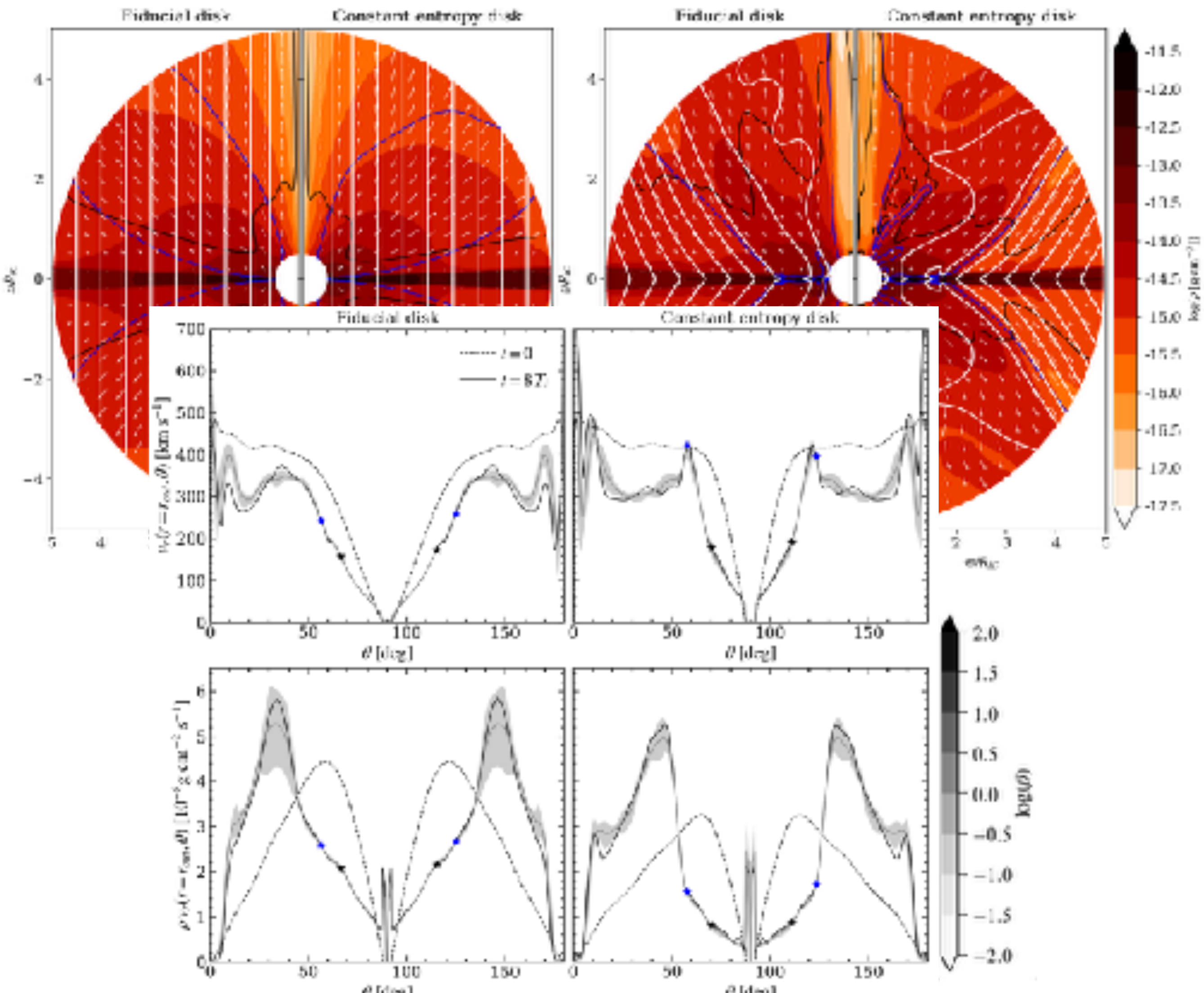
$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}).$$

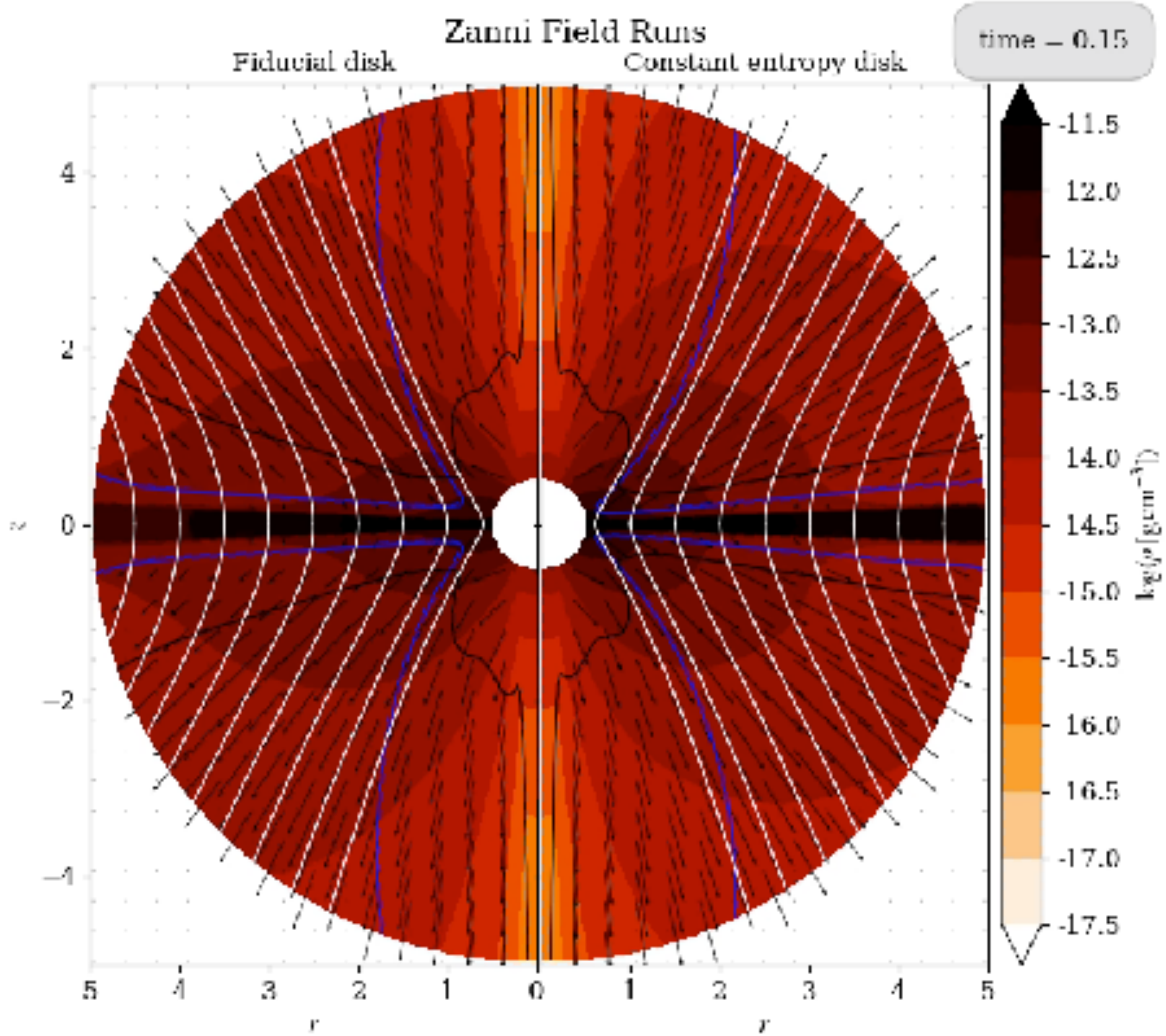





Vertical Field Runs
time = 0.15
Fiducial disk
Constant entropy disk
z
r
r
-11.5
-12.0
-12.5
-13.0
-13.5
-14.0
-14.5
-15.0
-15.5
-16.0
-16.5
-17.0
-17.5
log(ρ [g cm^{-3}])

Main result: suppression of the thermal wind in low beta regions





Zanni Field Runs
time = 0.15
Fiducial disk
Constant entropy disk
4
2
0
−2
−4
z
5
4
3
2
1
0
1
2
3
4
5
r
r
-11.5
-12.0
-12.5
-13.0
-13.5
-14.0
-14.5
-15.0
-15.5
-16.0
-16.5
-17.0
-17.5
log(ρ [g cm^-3])

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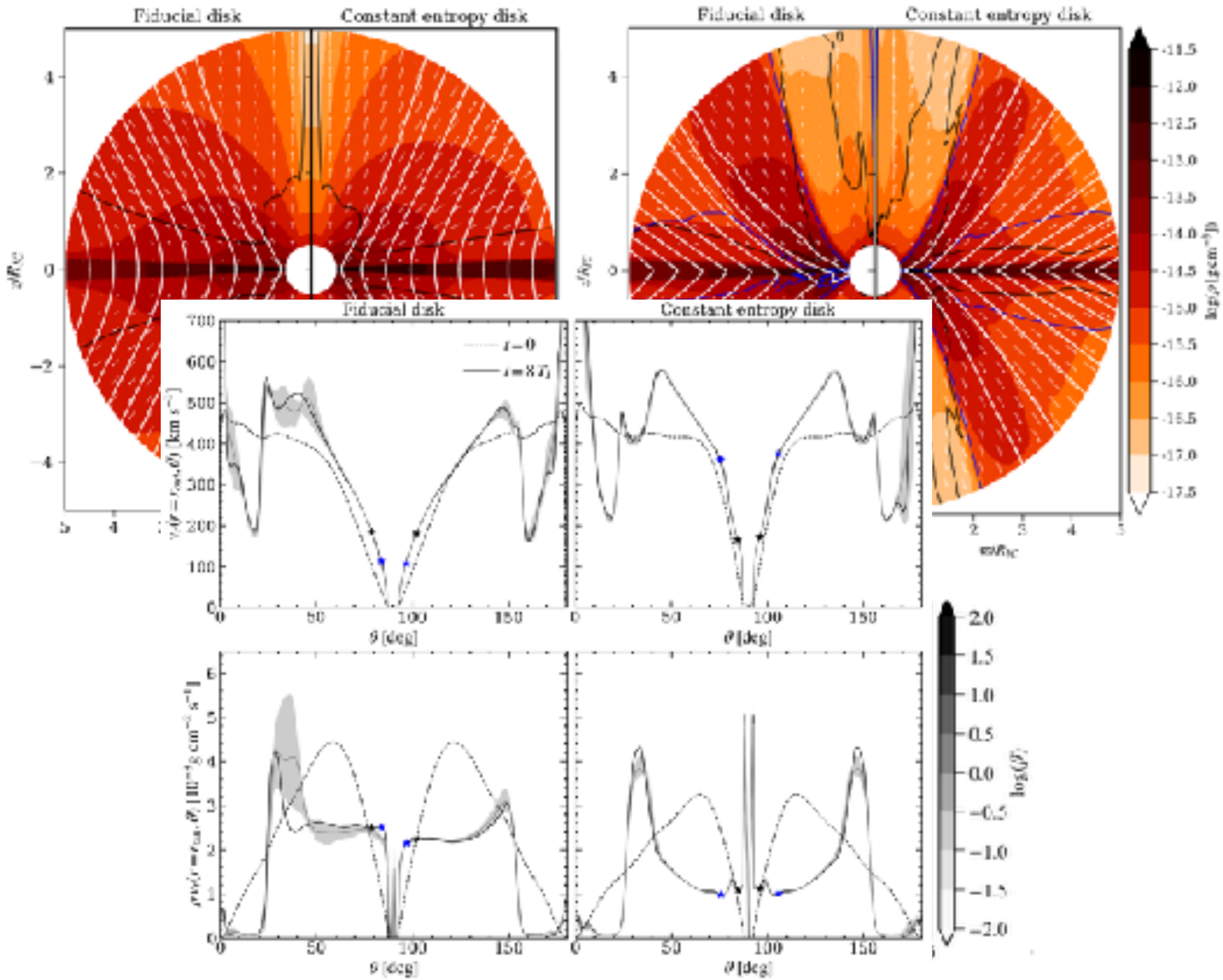

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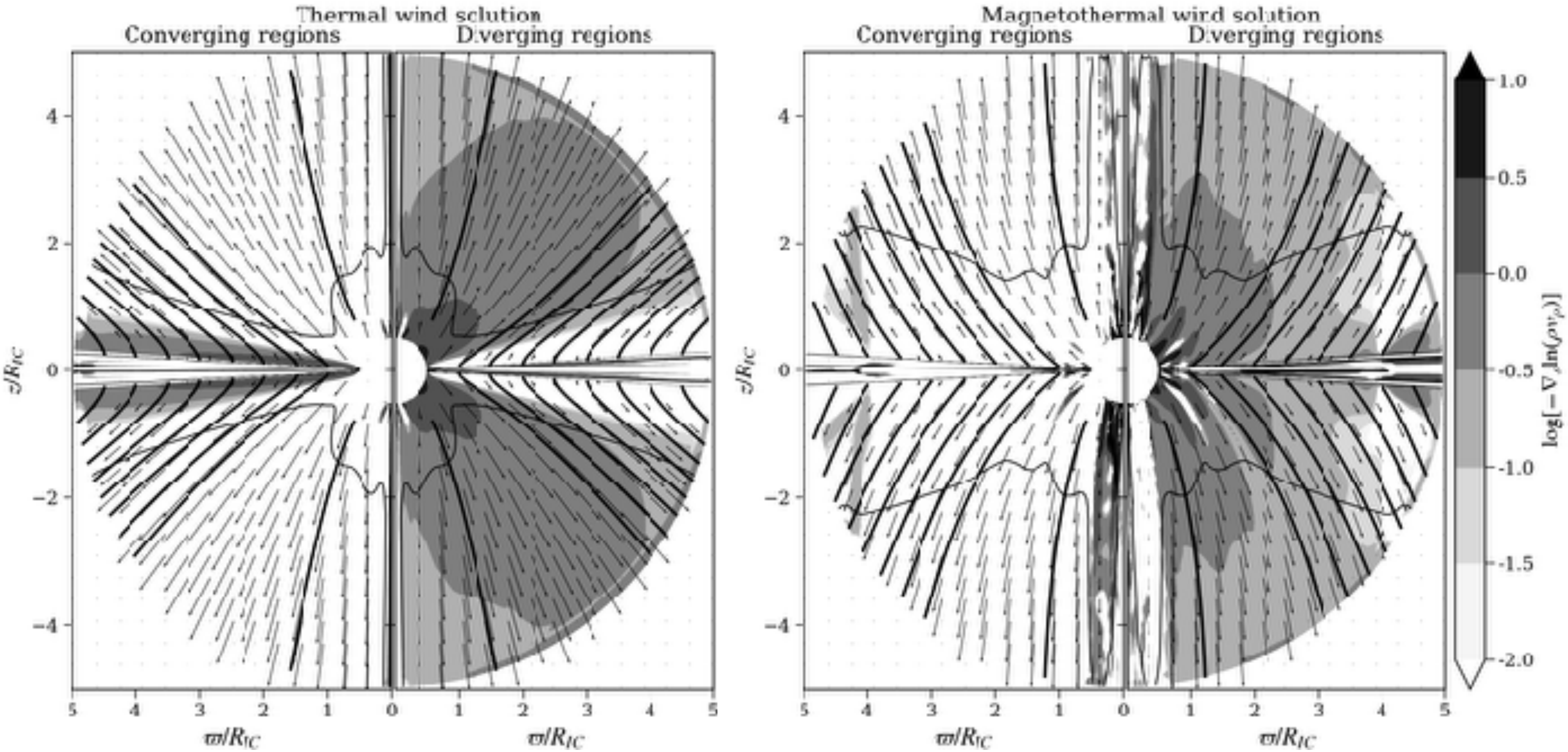

$$\nabla_s \ln(A) = -\nabla_s \ln(\rho v)$$

Conclusions

Magnetothermal winds at R_IC are slower than purely thermal winds near the Compton radius. The velocity suppression is a flow area effect.

However, the kinetic luminosities can still be higher at mid-latitudes. The details depend on the radial distribution of the B-field.

A viable model for many LMXBs is likely to be found well within the Compton radius, where the FMR regime can be reached.