Global MHD Simulations of Star-Disk Interaction

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In the final phase of star formation processes, gas accretes through circumstellar disks onto protostars, and the disk and the protostar interact each other via magnetic fields in the innermost region. The structure of the accretion flow in this region is determined by the strength of the stellar magnetic fields and the accretion rate, which depends on angular momentum transport by turbulence driven by the Magneto-Rotational Instability (MRI). Therefore, high resolution MHD simulations are required to study the structure of the accretion flow.

For this purpose, we have extended Athena MHD simulation code (Stone et al. 2008) by implementing a new MHD solver for spherical polar coordinates. We performed MHD simulations similar to Romanova et al. (2012) with sufficient resolution to resolve MRI within the disk. The properties of turbulent accretion disks with weak magnetic fields are similar to those obtained in local shearing box simulations. On the other hand, the magnetic interchange instability always persists in the visinity of the central star. When the stellar magnetic field is weak, the gas accretes directly onto the stellar surface through the disk. As the field strength increases, the interaction between the stellar field and disk makes the accretion strongly non-uniform.

Subject :	:	oral
Topics	:	Astrophysics
Topics	:	Numerical simulations

Accretion and Outflows throughout the scales
Oct 1-3, 2014

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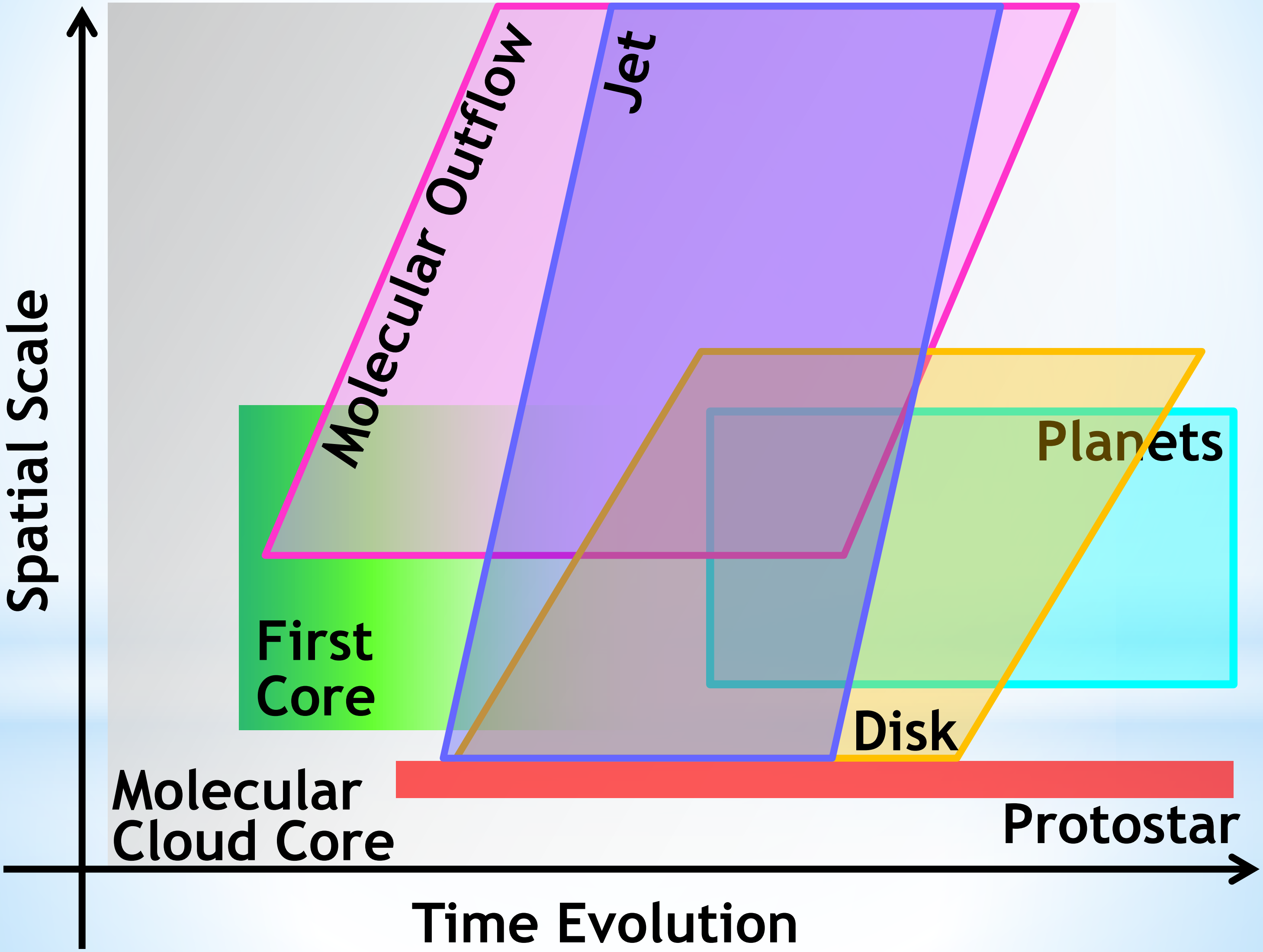
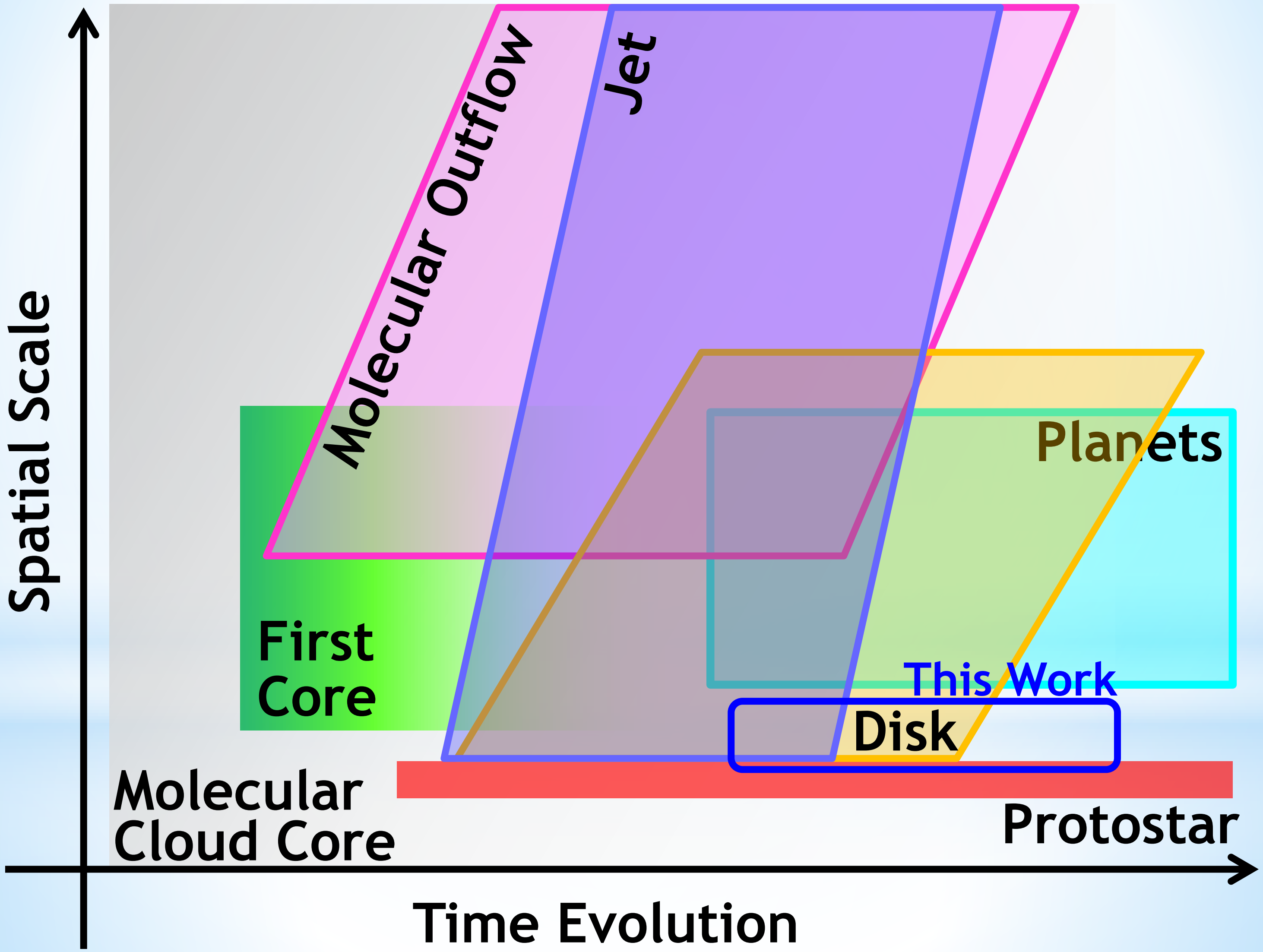
Kengo TOMIDA (Princeton / U. of Tokyo, JSPS Fellow)
James M. Stone (Princeton)

Context: Late Phase of Star Formation



Context: Late Phase of Star Formation



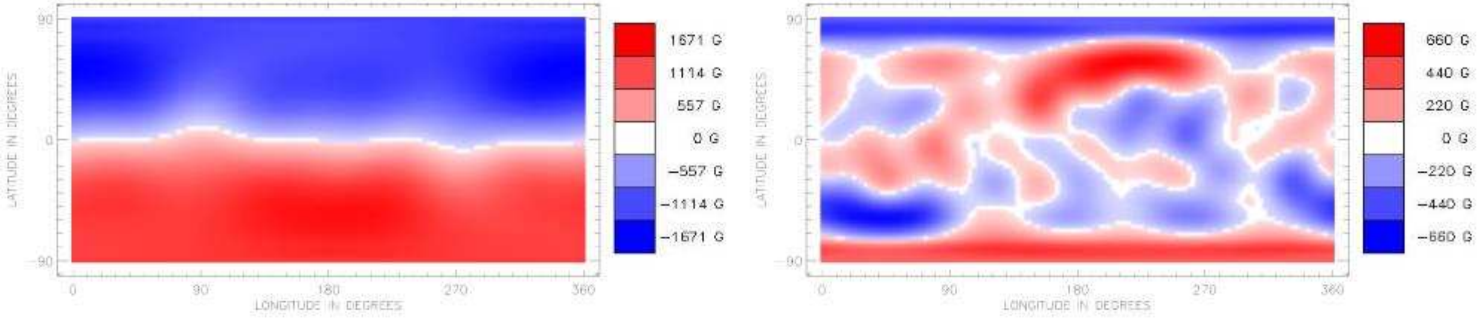
Backgrounds

- Toward understanding the main accretion phase of star formation
- Small scale structure around a protostar is crucial
- Modeling the accretion flow interacting with a protostar

Questions:

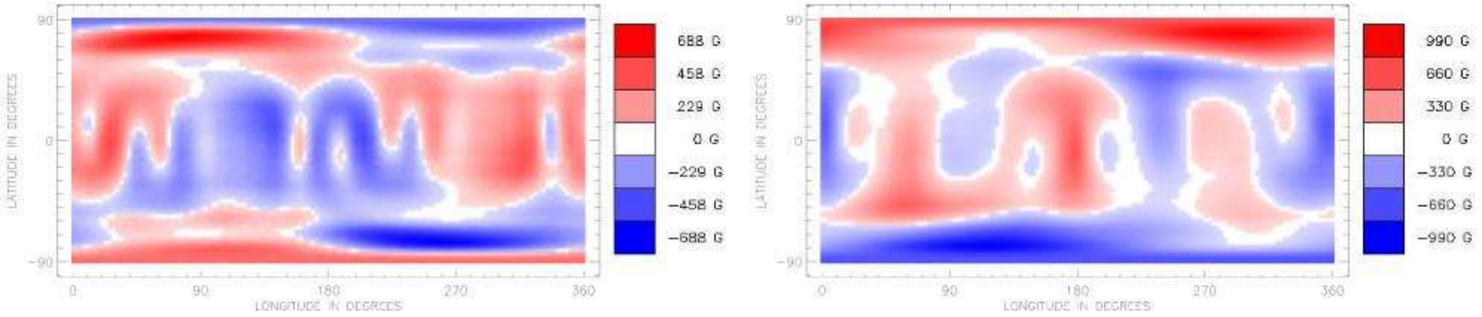
1. **How does the gas in the disk accrete onto the protostar?**
   a. MRI-driven turbulence in the presence of global magnetic fields (shearing-box simulations cannot be realistic enough)
   b. Interaction between the accretion flow and stellar B-fields
2. How does the stellar spin evolve?
3. How does the mass ejection process (outflow) occur?
4. How can transitional disks (disk with an inner hole) form?
   a. Accretion?
   b. Wind / Outflow?
5. Observations of T Tauri stars, especially variability

Observations



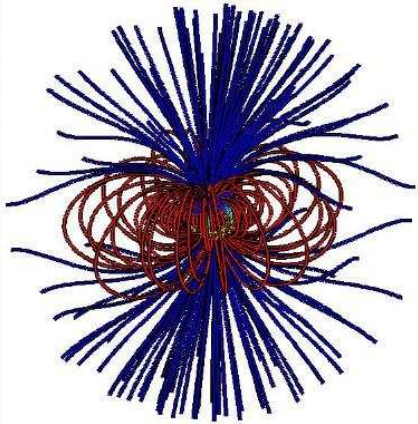
(a) AA Tau 2009

(b) V2247 Oph



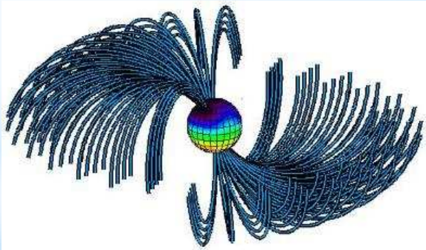
(c) CR Cha

(d) CV Cha



↑ Magnetic fields (AA Tau 2009)

↓ Accretion flow



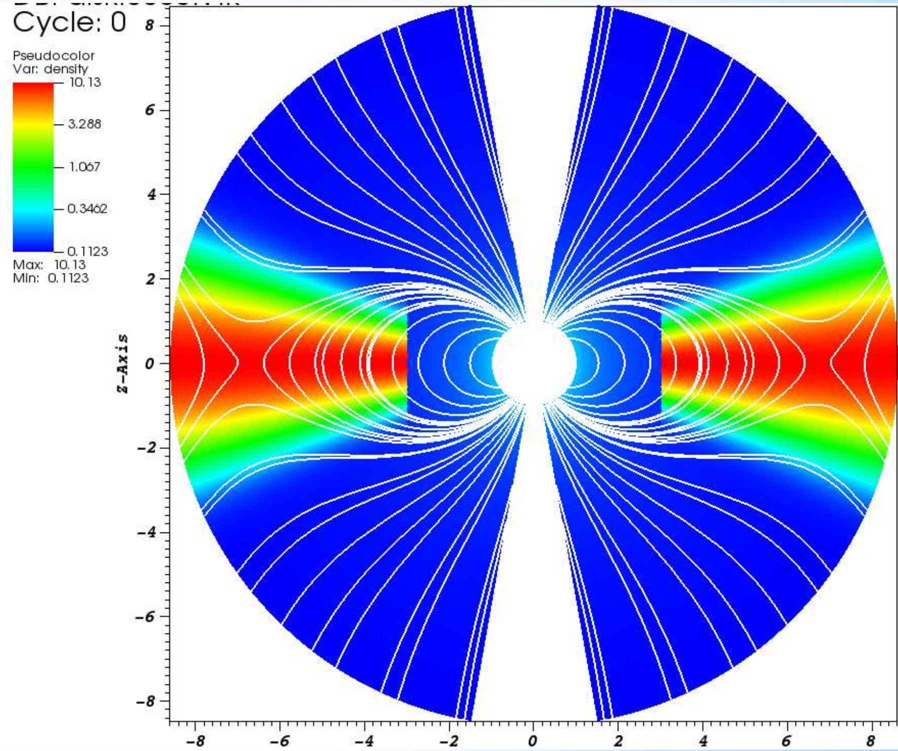
Johnstone et al. 2014

Surface field reconstruction by Zeeman-Doppler Imaging

Relation between the field structure, dipole strength, disk truncation, magnetic and accretion activities are inferred.

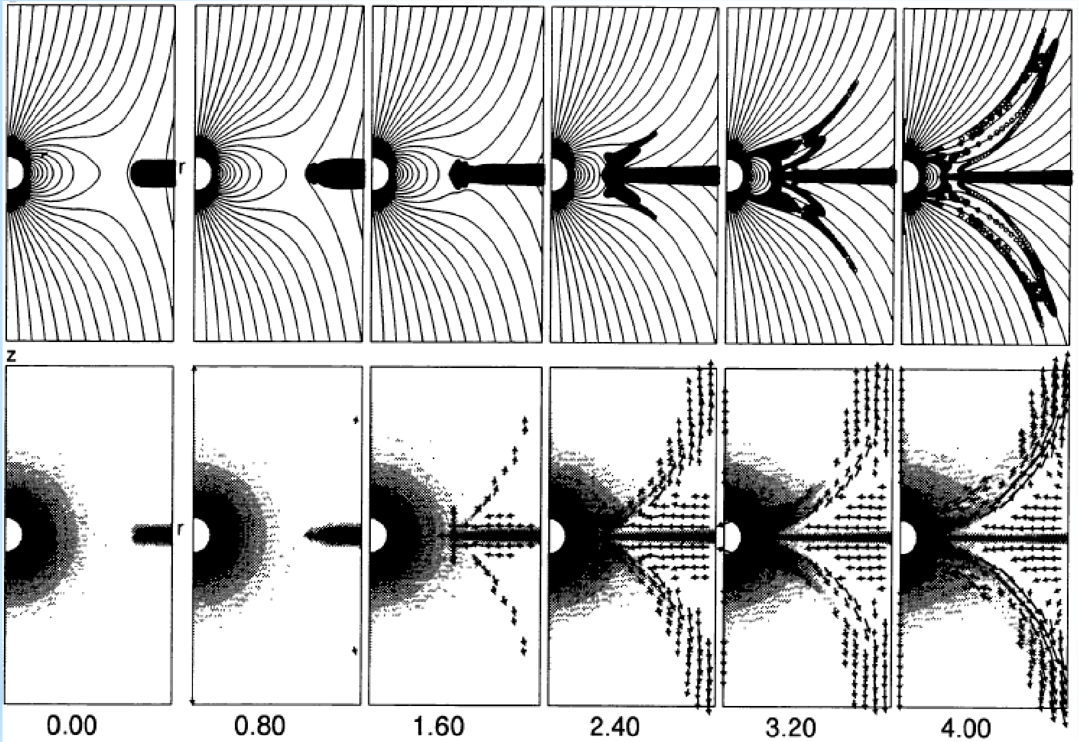
Magnetic Fields vs Accretion

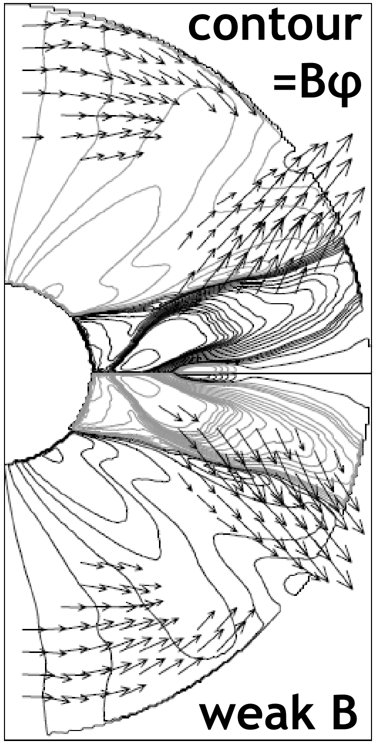
- Weak field cases:
  Turbulence driven by MRI will control the accretion
  Stellar fields cannot stop the accretion flow
  ⇒**Boundary-layer accretion**
- Strong field cases:
  Gas accretes along stellar fields
  ⇒**Magnetospheric accretion**
  Field **reconnection** is required,
  possibly by MRI turbulence
- In both cases:
  Magnetic braking / acceleration
  by stellar fields are important



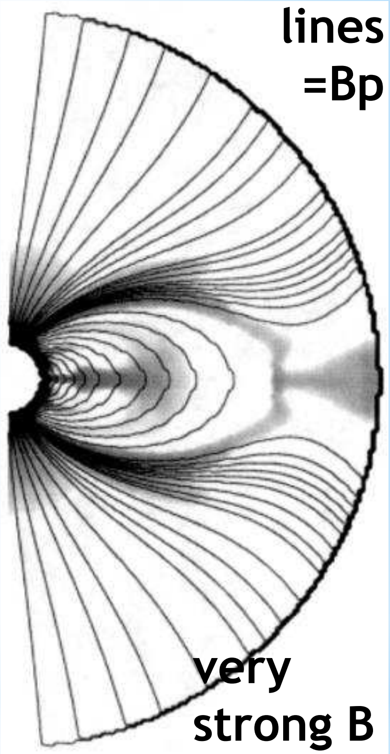
⇒High-resolution MHD simulations are of critical importance.

Early Works




contour =Bφ

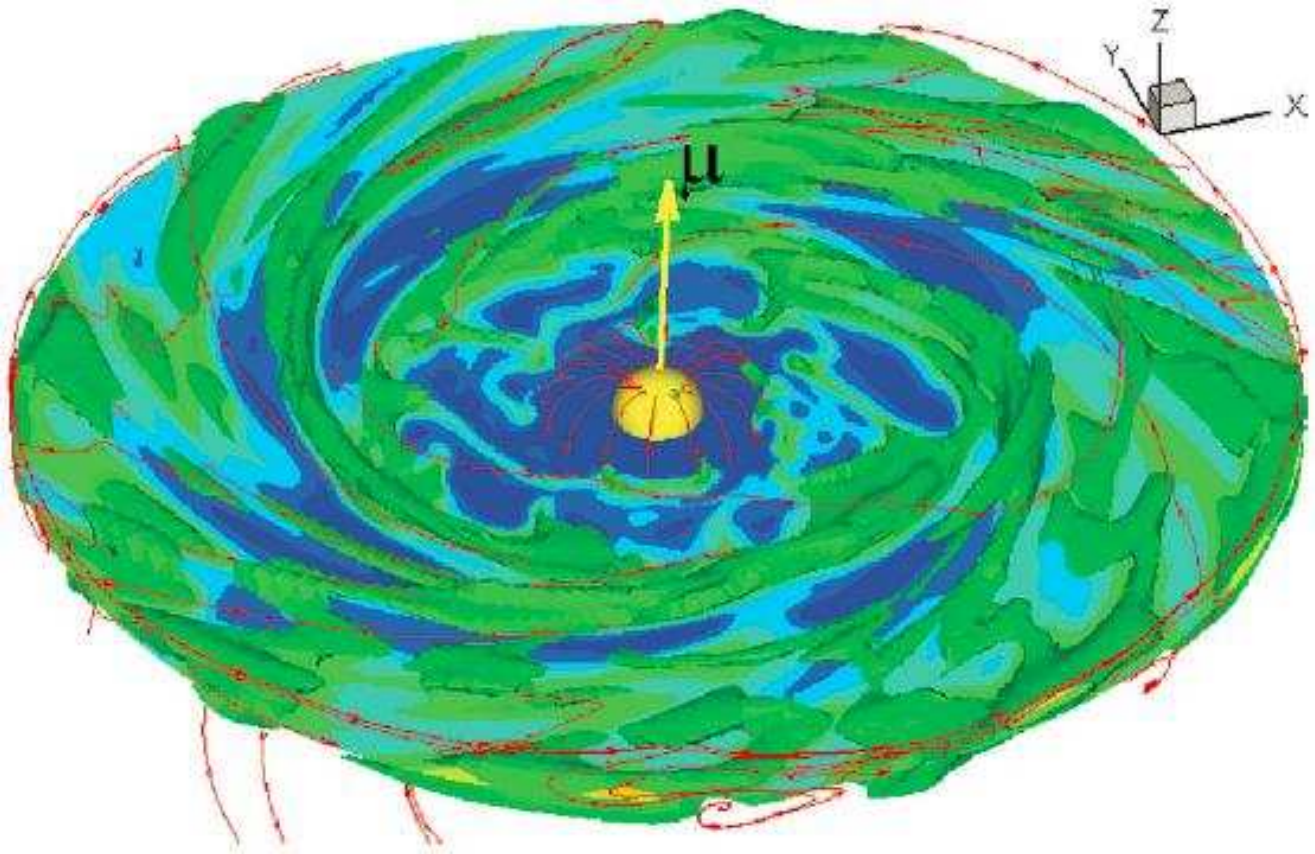
weak B

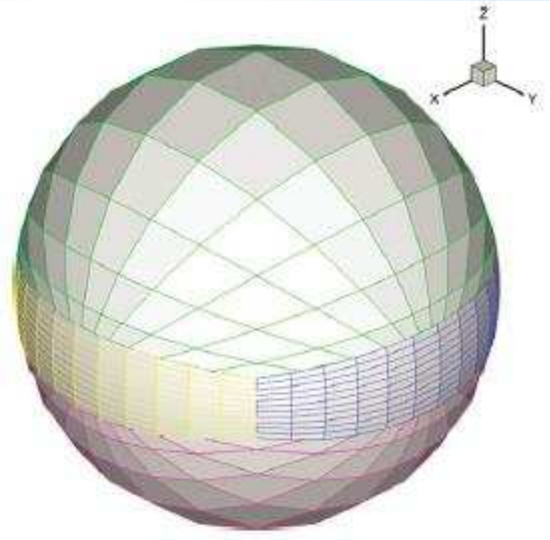

lines =Bp

very strong B

More than 15 years ago: 2D MHD simulations, short term (<10 orbits)
(Hirose et al. 1997 (left), Miller & Stone 1997(right), Fendt & Elstner 1999)
MRI does not develop well because of short simulation time.
Strong magnetic braking due to the I.C. might dominate the evolution.

Recent Work



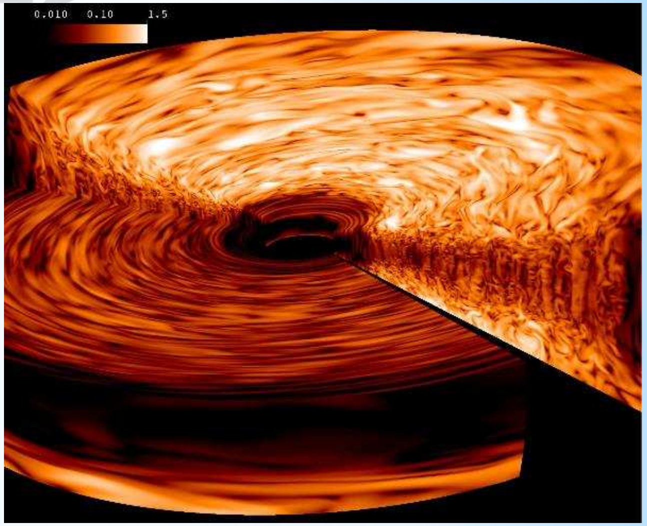


Romanova et al. 2012

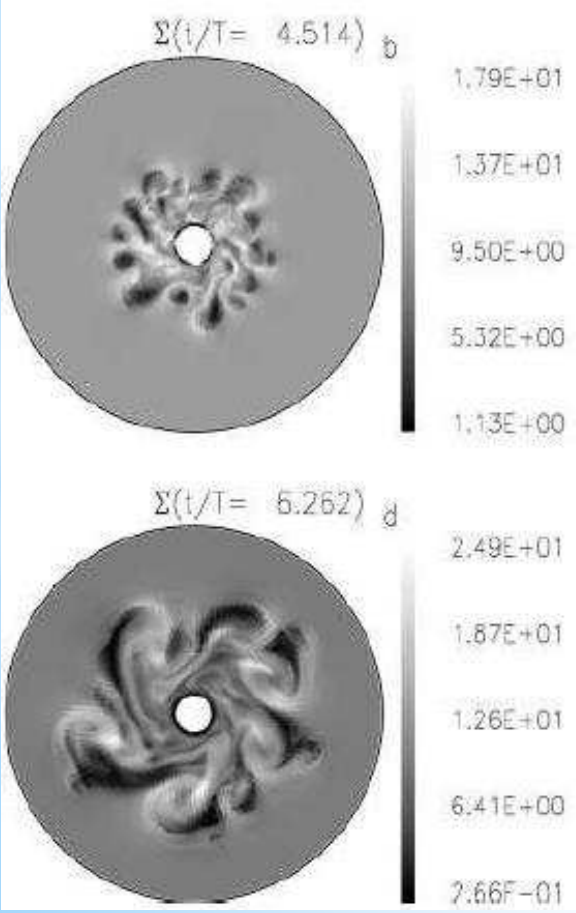
3D cubed-sphere MHD simulations by Romanova et al. @ Cornell
Weak fields: Boundary-Layer accretion through the disk
Strong fields: Magnetospheric accretion through the funnel-flow
Key: Interaction between stellar fields and accretion driven by MRI.

Key Processes

1. **Magneto-Rotational Instability**
   Fast and robust, transports angular momentum & triggers reconnection



Flock et al. 2011→



←Stehle & Spruit 2001

2. **Magnetic Interchange Instability**
   Disks with strong fields are unstable against RT-like interchange modes

$$\frac{d}{dr}\left(\frac{B}{\Sigma}\right) < 0$$

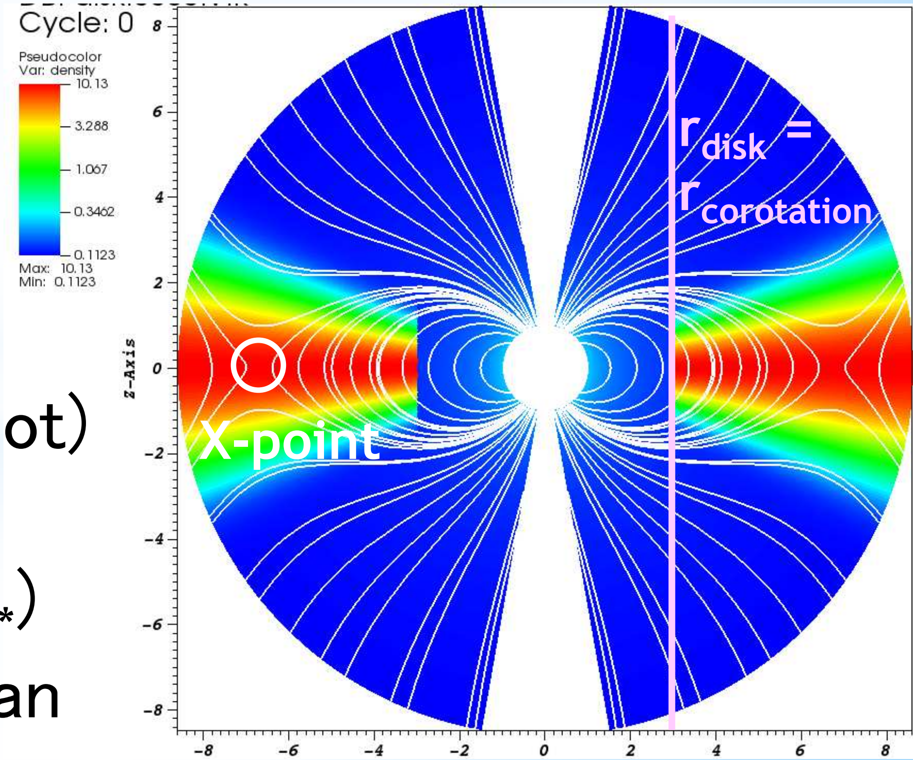
Note: dipole $B \propto r^{-3}$

   Essentially 3D. Occurs near the star.

3. **Magnetic Braking / Acceleration**
   Ang. Mom. exchange via global fields

Methods and Models

- New CT-MHD solver in **Spherical Coordinates** for Athena
  - Second-order Piecewise Linear Method + HLLD flux
  - Limitation: VL integrator, **uniform mesh-spacing**
  - Adiabatic EOS with $\gamma = 5/3$
  - Point-source gravity
  - Star: fixed + density ceiling
  - Other boundaries: outflow
  - $r < 30$ (strong), $r < 15$ (else)



- Cold disk + Hot corona(x100 hot)
- Stellar dipole B + uniform Bz
- Interior: rigid-body rotation (Ω_*)
- Disk / outer envelope: Keplerian

Model Parameters

	Weak Field	**Moderate**	**Strong**
μ (stellar dipole)	0.32	0.32	0.32
B_z (uniform field)	0.001	0.001	0.001
r_X (“X-point”)	6.84	6.84	6.84
r_d (disk = corot.)	3	3	3
R_T (T_{corona} / T_{disk})	100	100	100
Θ_d (c_s/v_K)	0.175 (10°)	0.175 (10°)	0.175 (10°)
ρ_d	10	1	0.1
β_i (plasma β at r_d)	～1400	～140	～14
R_F (F_{mag} / F_{grav} @ r=1)	**～0.03**	**～0.3**	**～3**

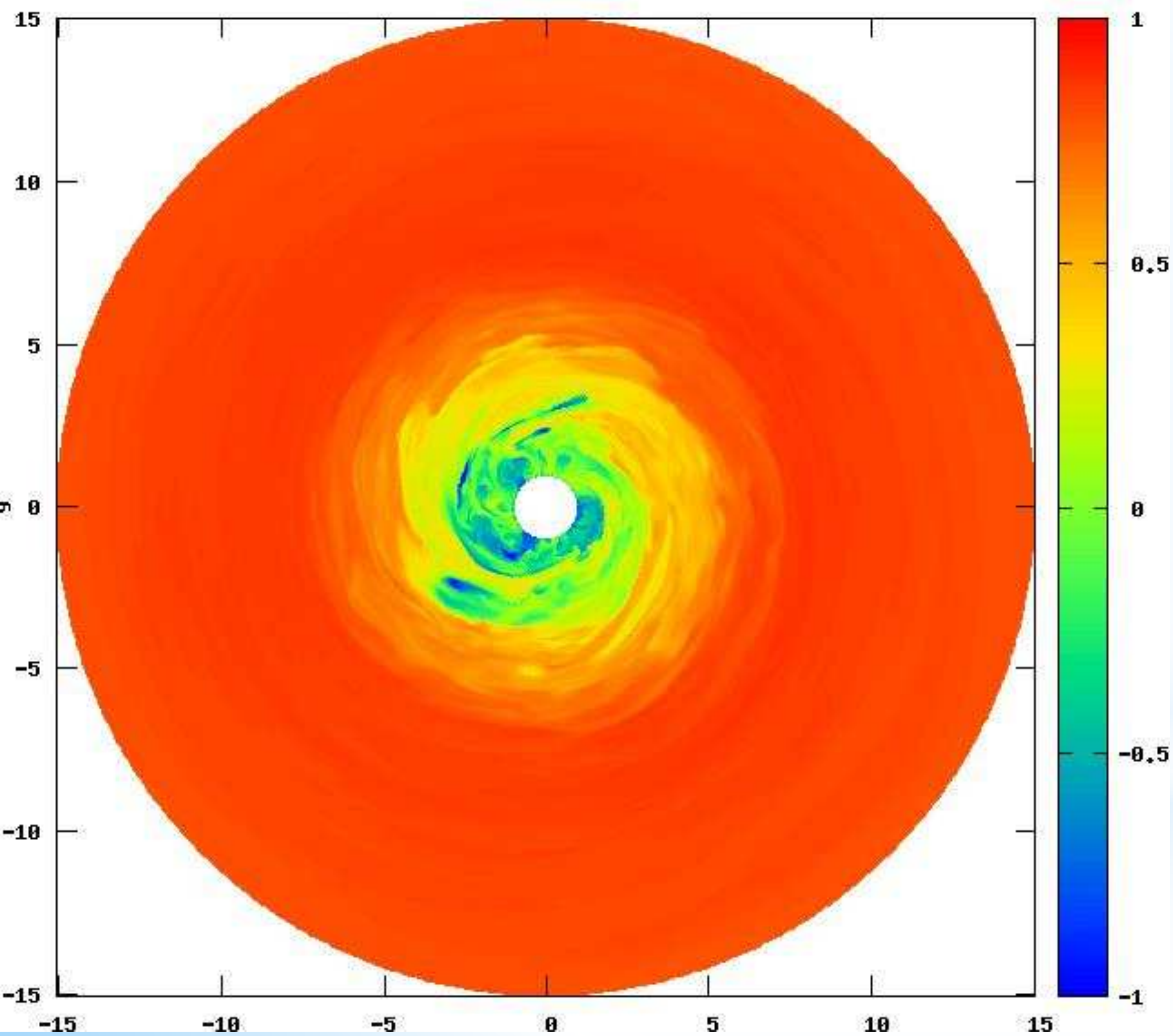
Based on Miller & Stone 1997 (Models Ia-c) and Romanova+ 2002

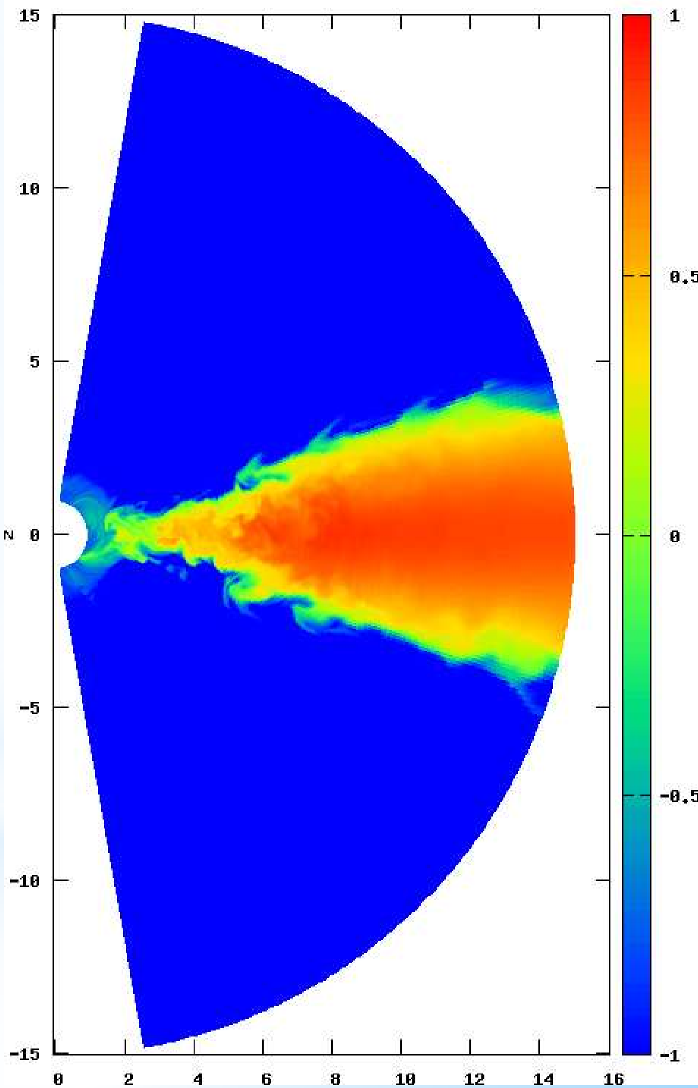
Resolution: N_r x N_θ x N_φ =800 x 320 x 640 ($\boldsymbol{H/\Delta x} \gtrsim$ **20** at r ～ 5)

Qualitative difference is expected between the strong case and others

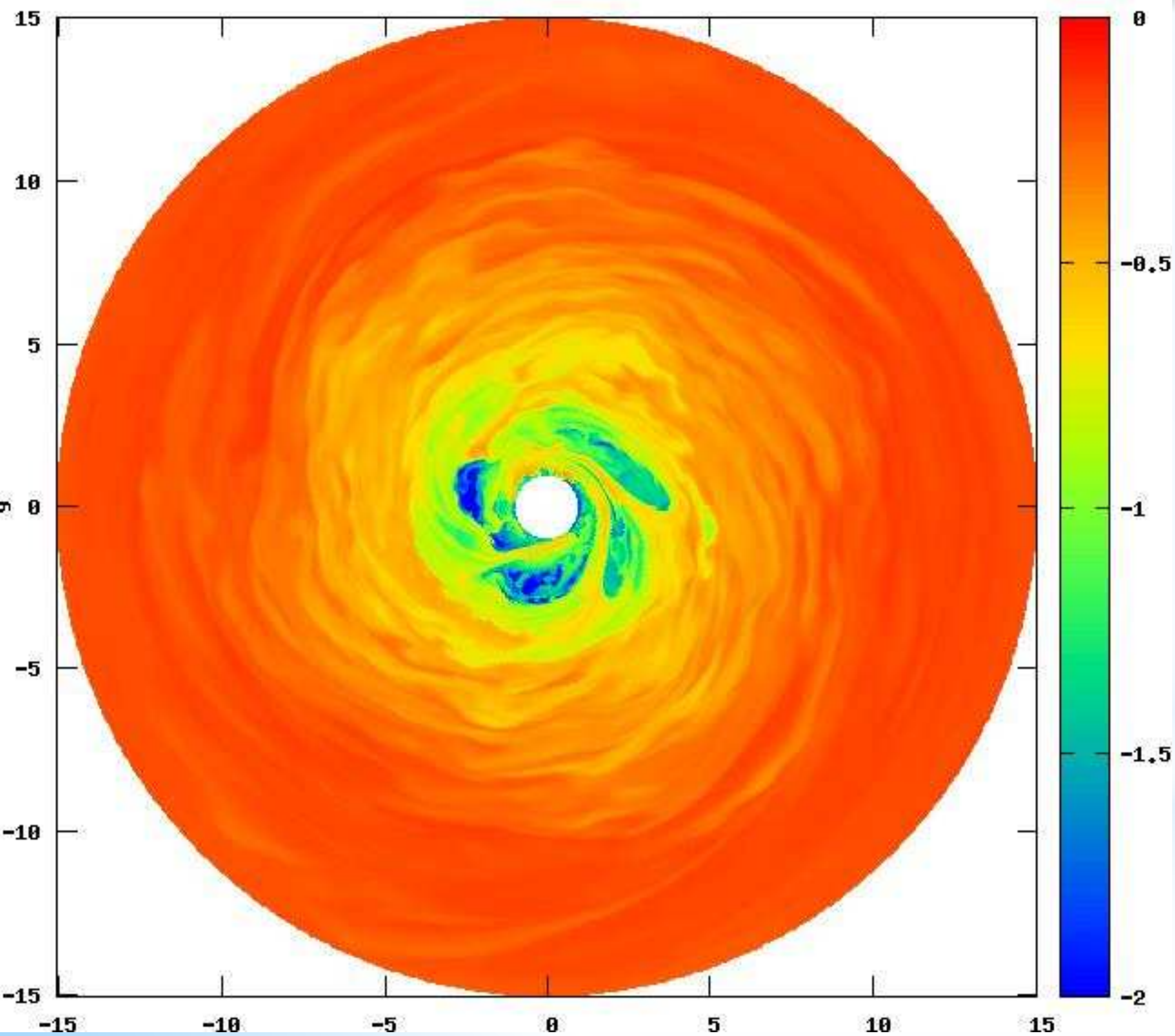
Note: this system is scale-free (B～160G for typical T-Tauri params)

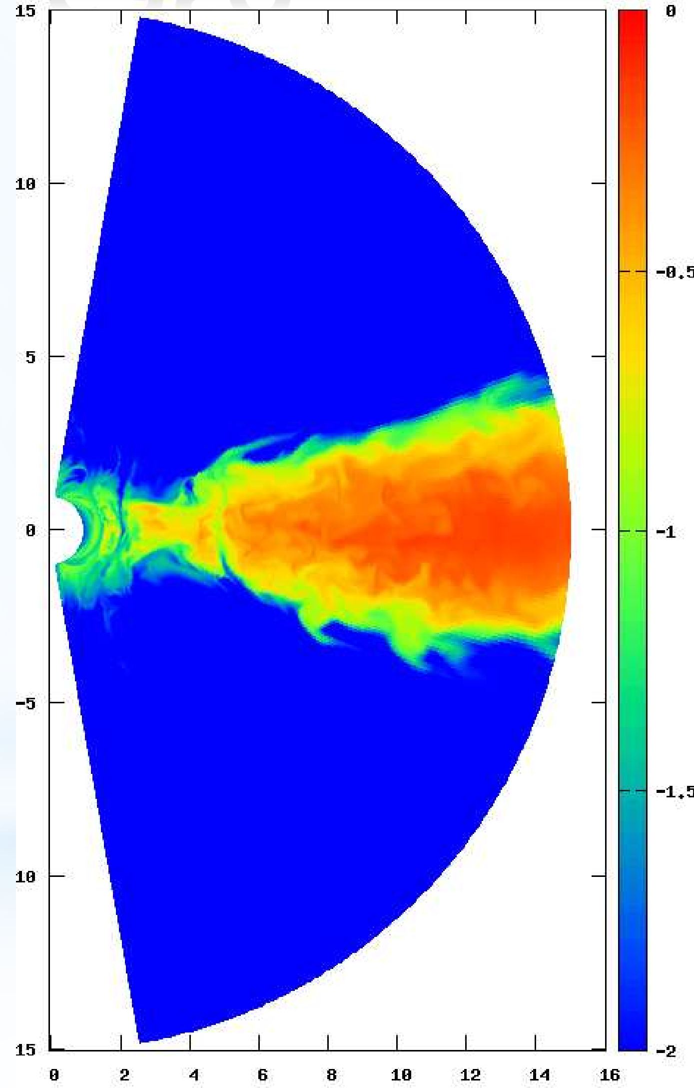
Weak field case



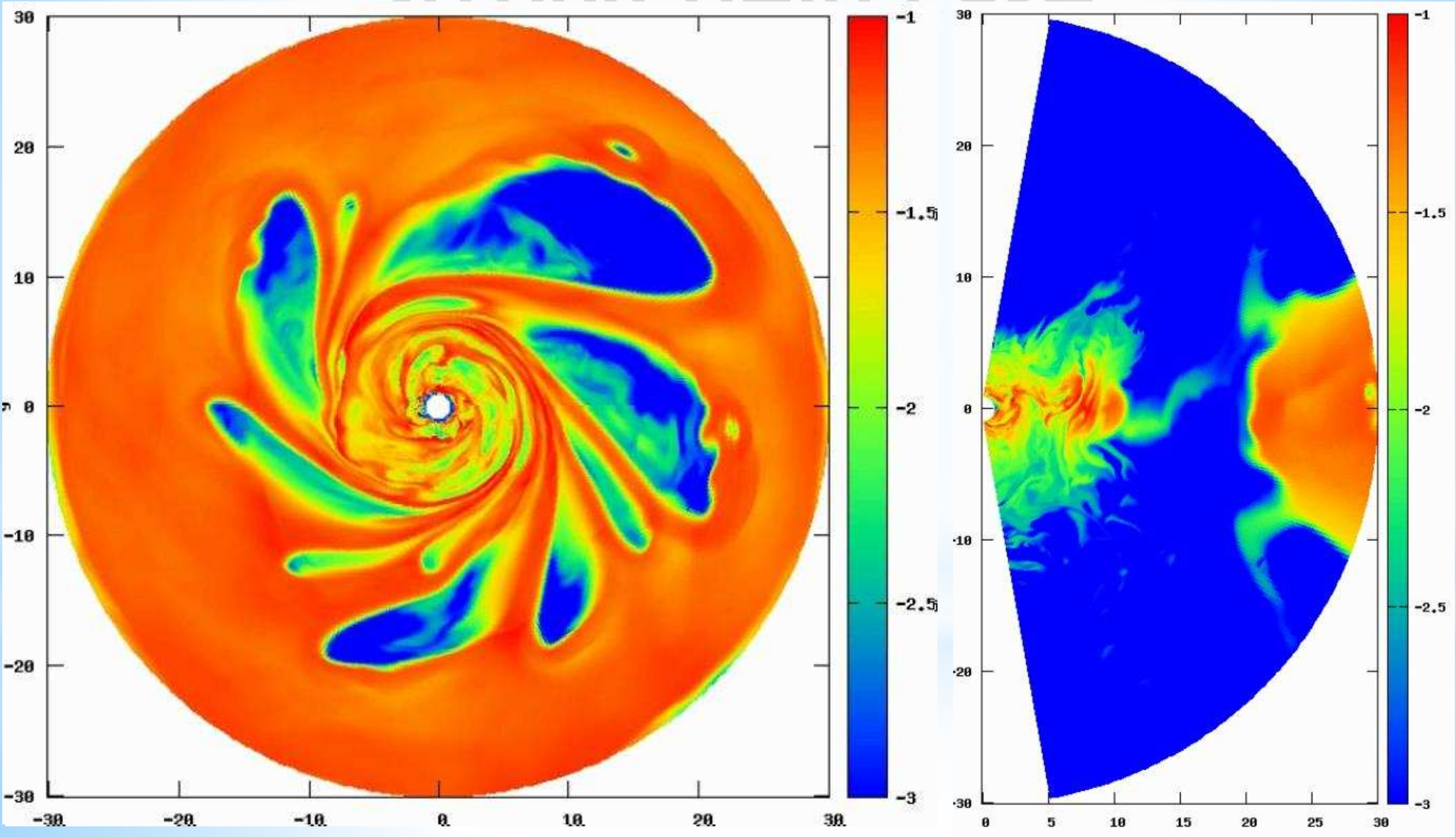


Moderate field case

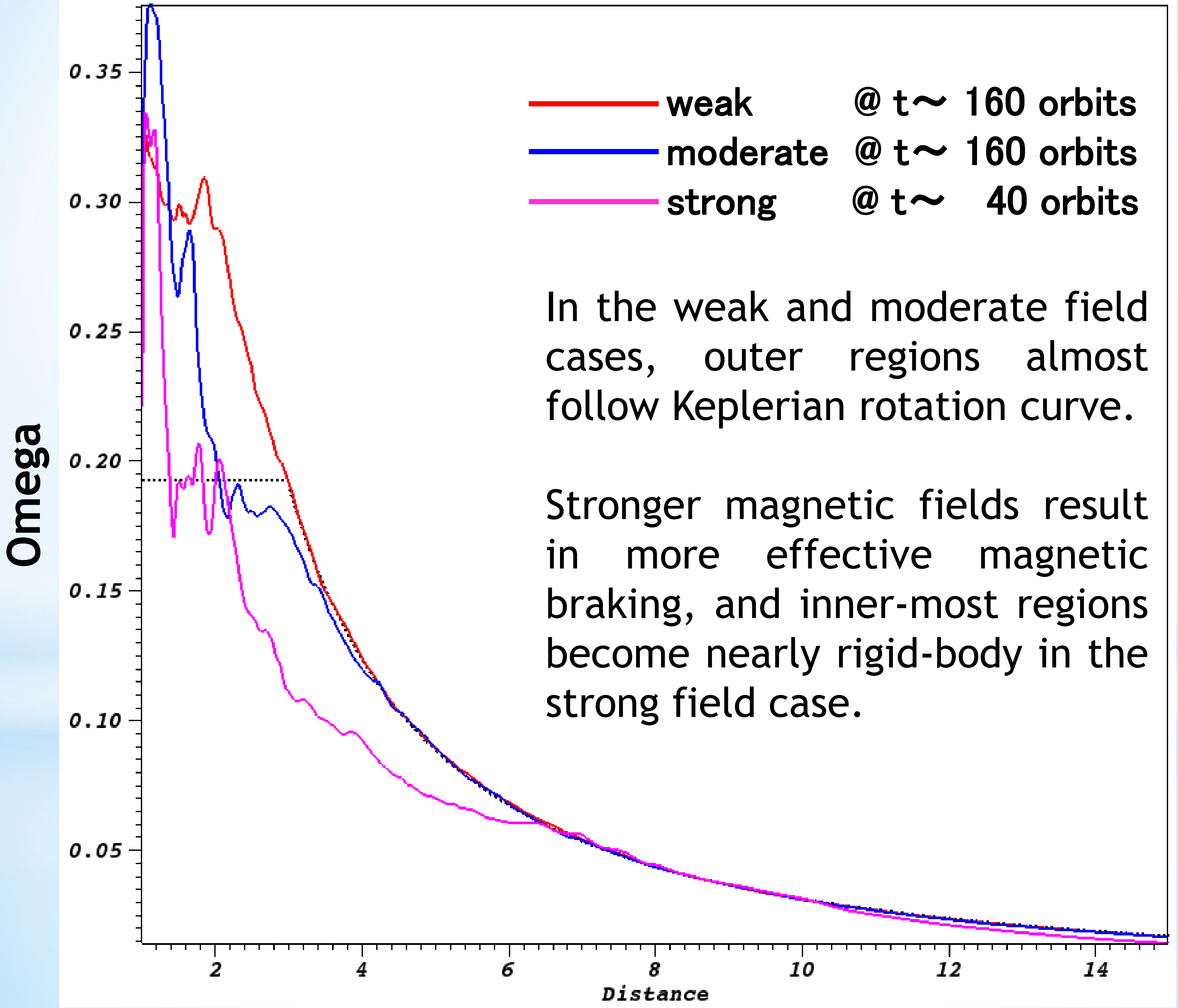




Strong field case



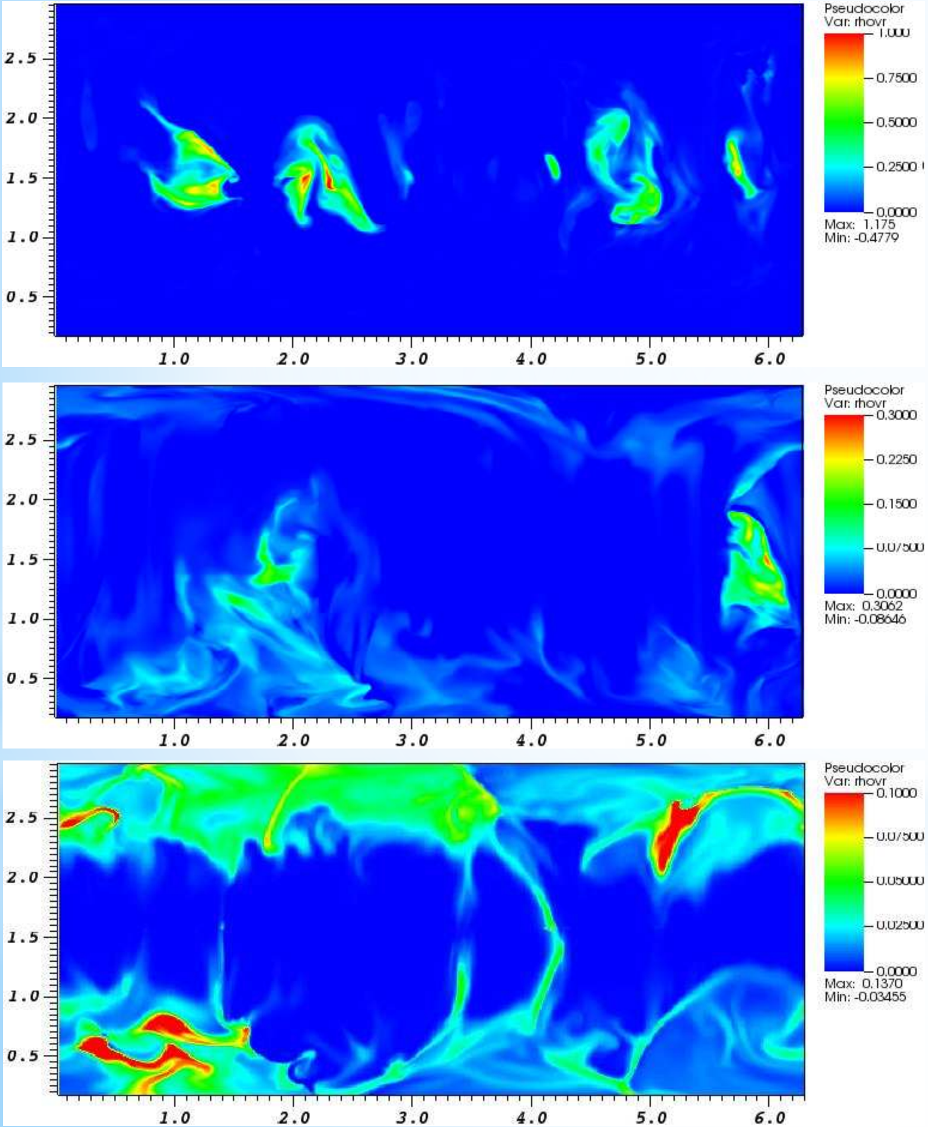
Rotation Profile



In the weak and moderate field cases, outer regions almost follow Keplerian rotation curve.

Stronger magnetic fields result in more effective magnetic braking, and inner-most regions become nearly rigid-body in the strong field case.

Accretion Geometry



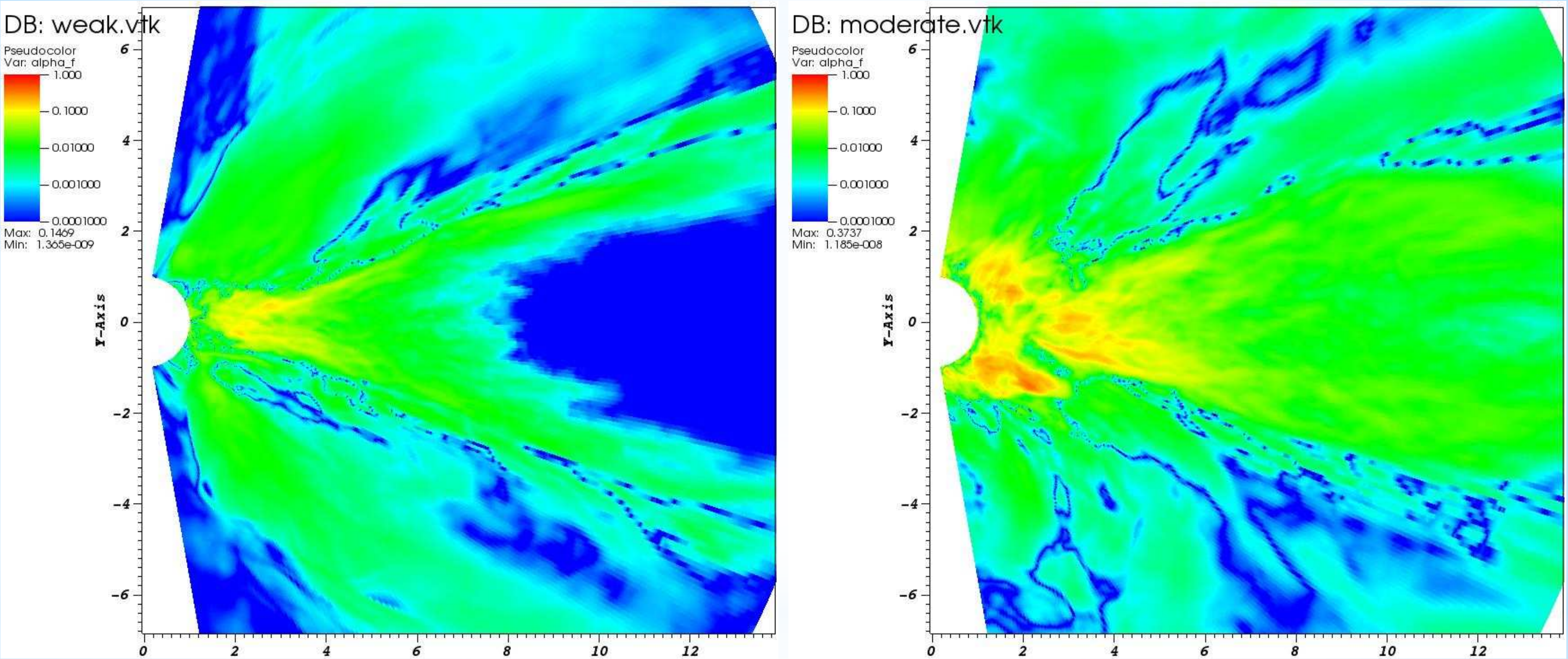
From top: Weak -> Strong
ρv_r at the stellar surface

In weak and moderate field models, the accretion flow has low m modes
→ the inner region is affected by the interchange instability

As the field strength increases, the accretion flow shifts toward polar regions.

Although the accretion flow piles up around the central star, small magnetosphere is formed in the strong field model.

Alpha (=$T_{r\varphi}/P$)



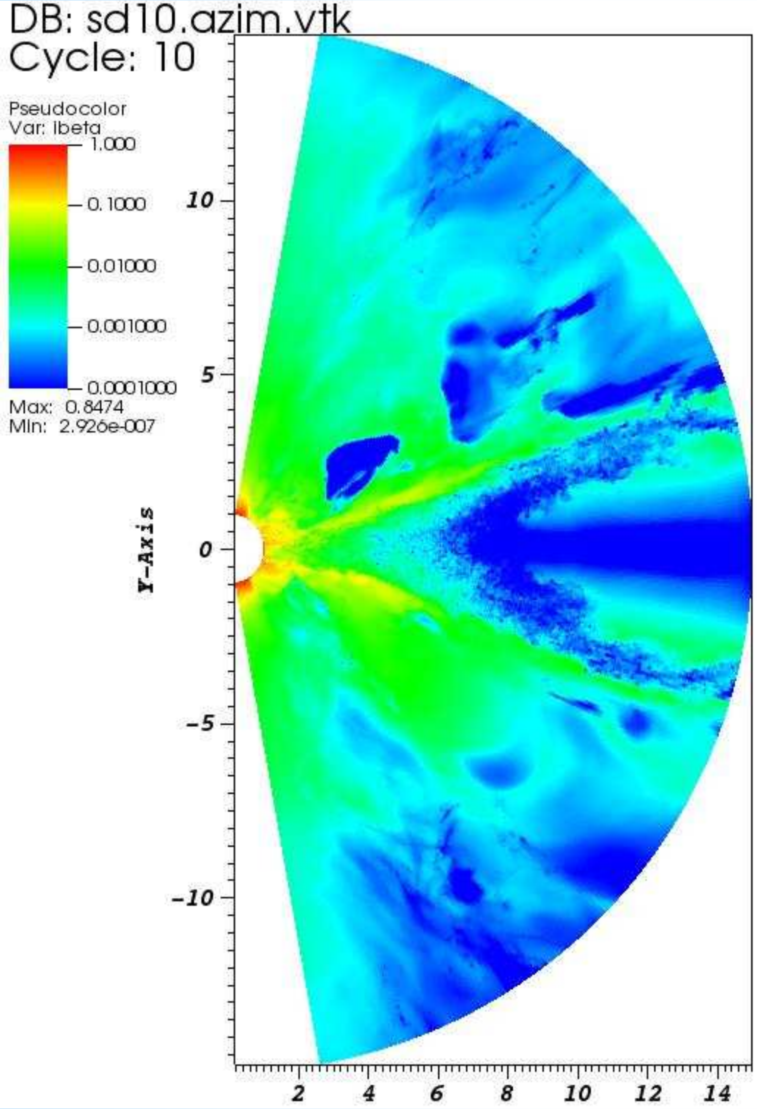
Weak (φ-averaged) Moderate

"Traditional indicator" of viscosity (Shakura & Sunyaev 1973)

Typical MRI turbulence results in $\alpha \sim 0.01$ (e.g. Flock et al. 2011)

The inner region and the surface layer exceeds $\alpha \sim 0.1$, indicating the effect of the global (stellar) magnetic fields.

1/Beta



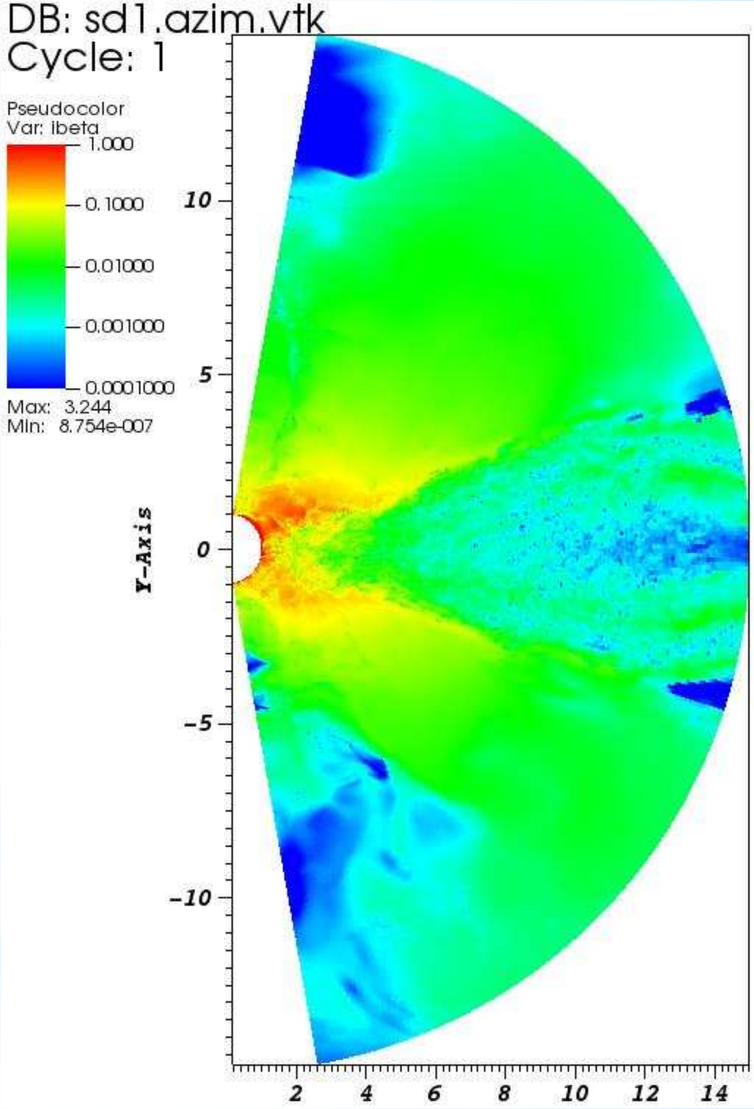
←

Weak

→

Moderate

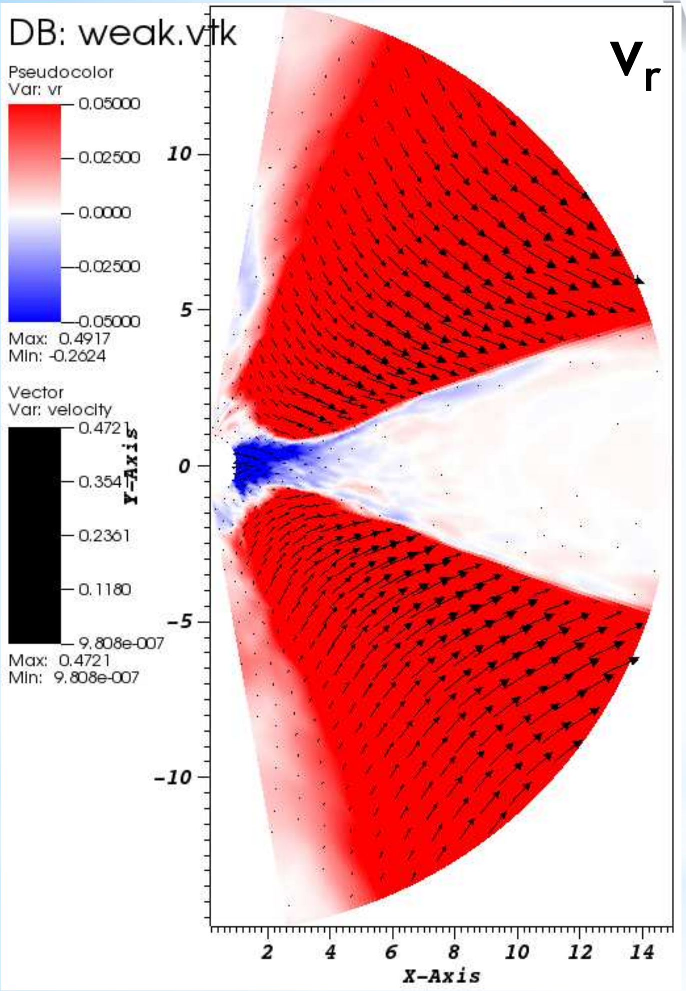
(φ-averaged)



$\beta = P_{gas}/P_{mag} \sim 10 - 100$ (green-yellow) in the turbulent disks

Note: MRI has not developed yet enough in $r > 6$

Accretion



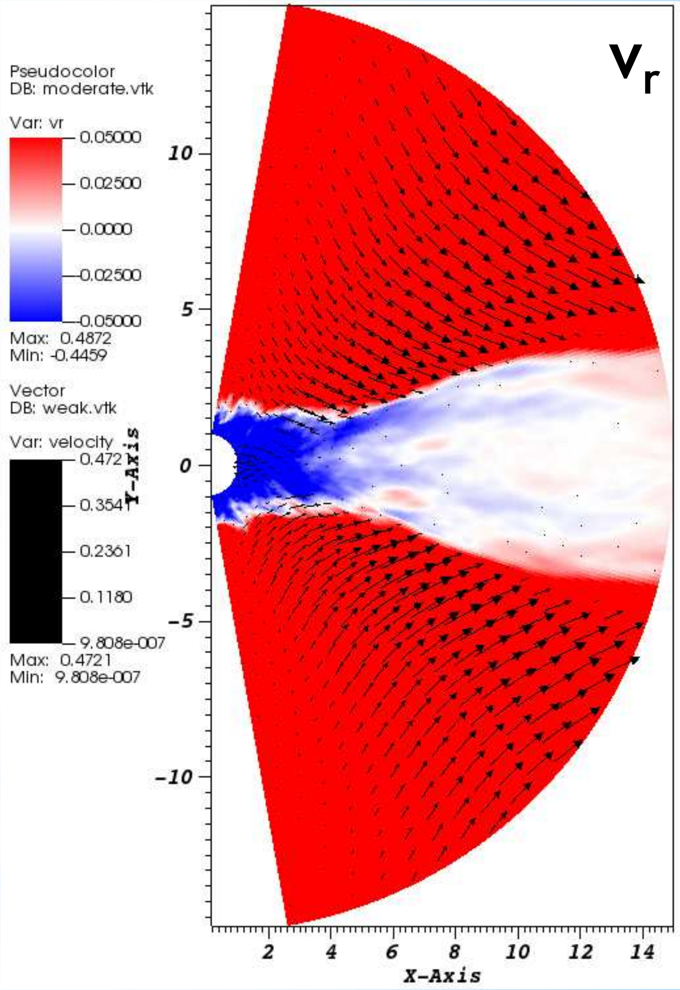
←

Weak

→

Moderate

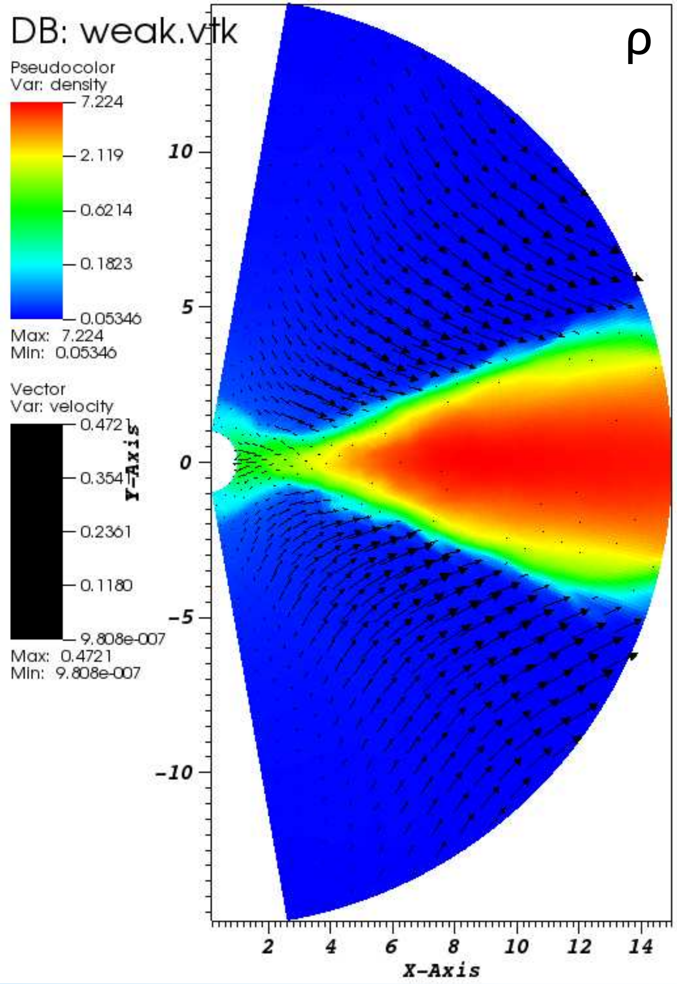
(φ-averaged)

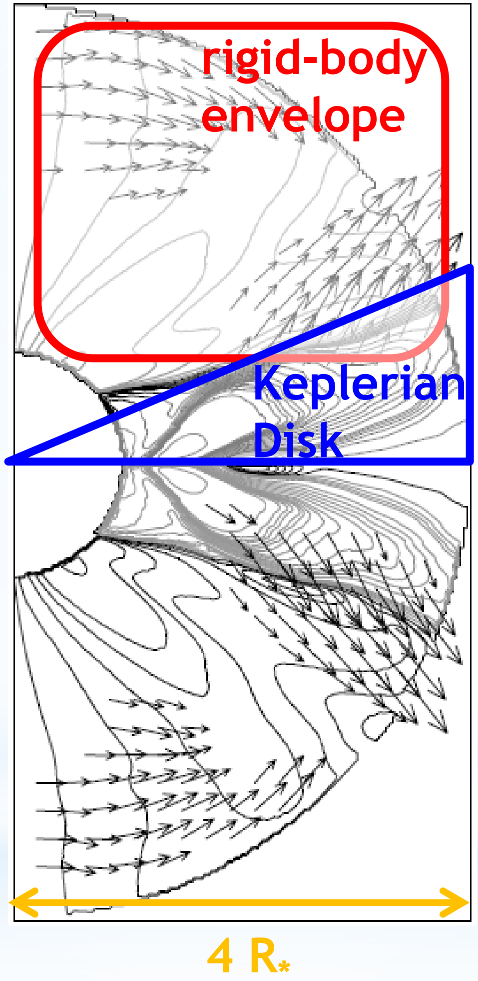


The accretion velocity is slightly higher in the surface layer, due to stronger magnetization and the global (stellar) magnetic fields.

Miller & Stone 1997

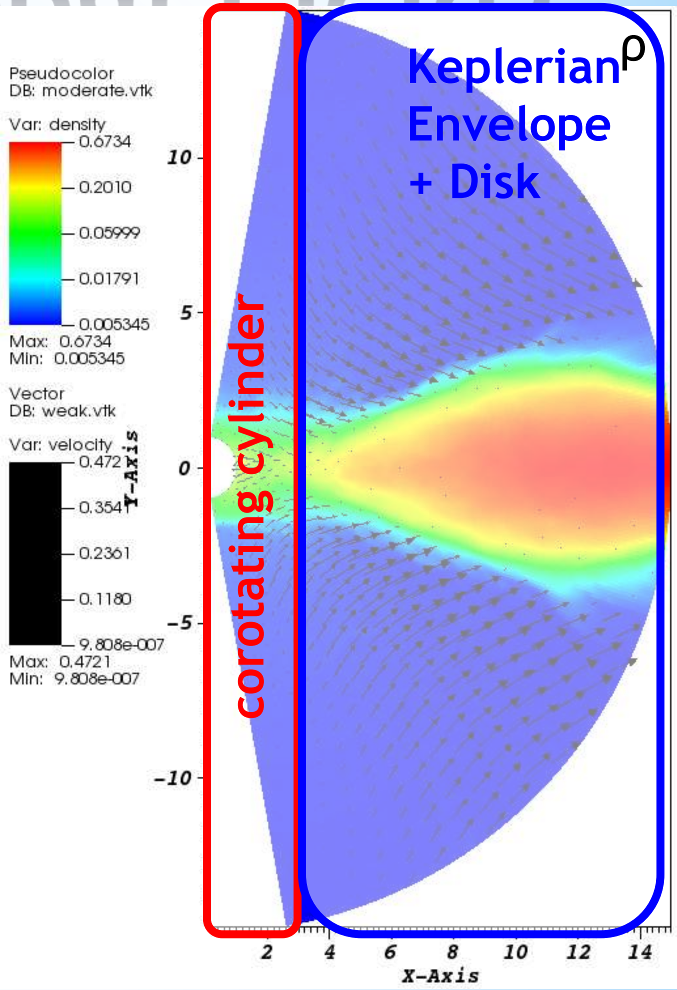
(No) Outflow 1. Global Fields




rigid-body envelope

Keplerian Disk

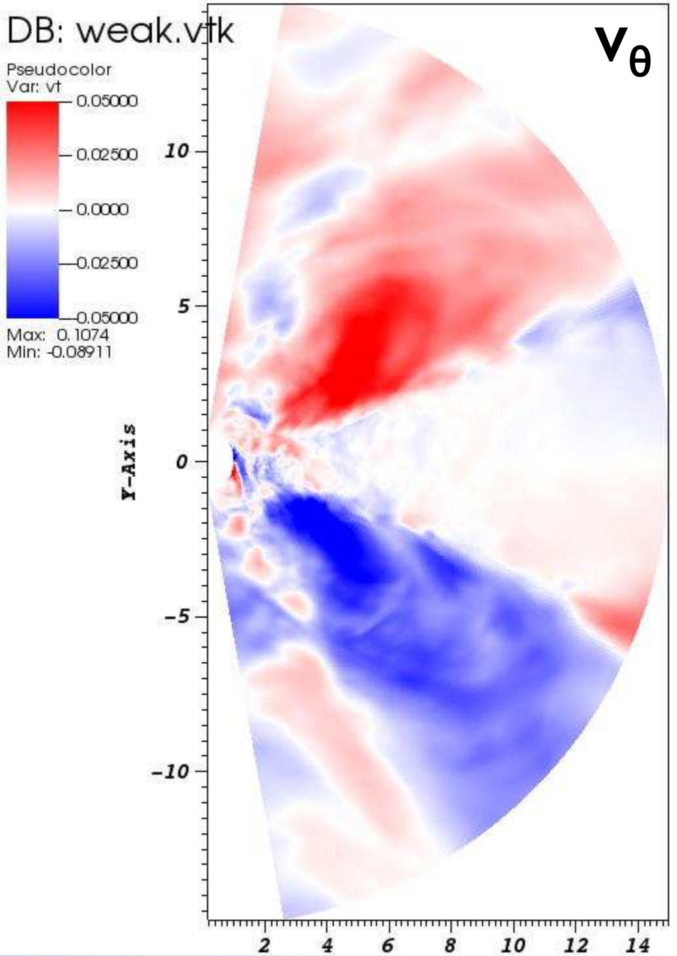
$4 R_*$

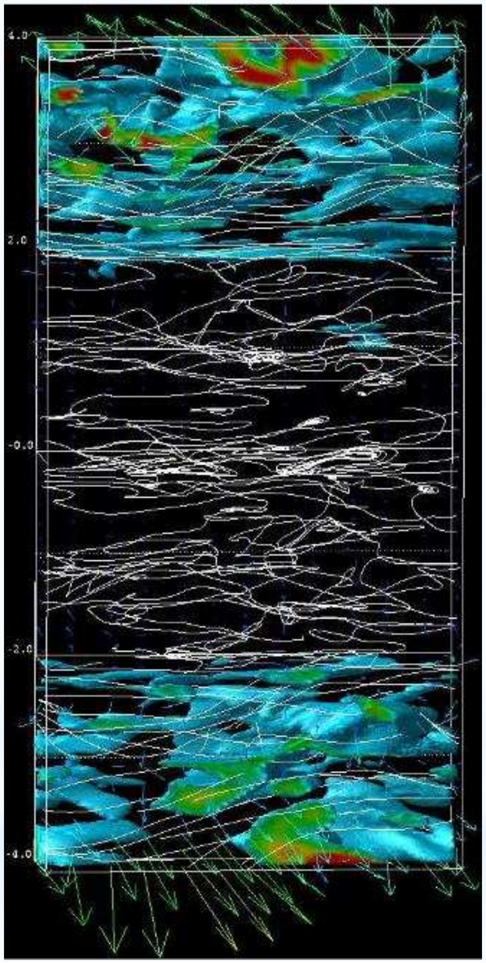

corotating cylinder

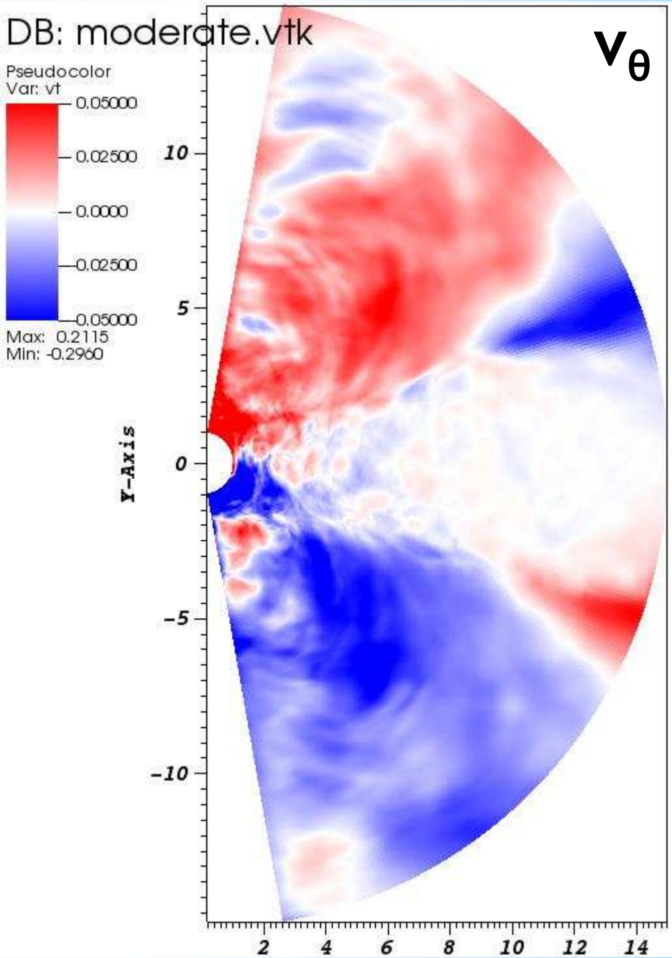
Keplerian Envelope + Disk

No significant outflows (like Blandford & Payne 1982) found.
Strong outflows in MS97 are probably due to unrealistic ICs.

(No) Outflow 2. MRI Driven Wind







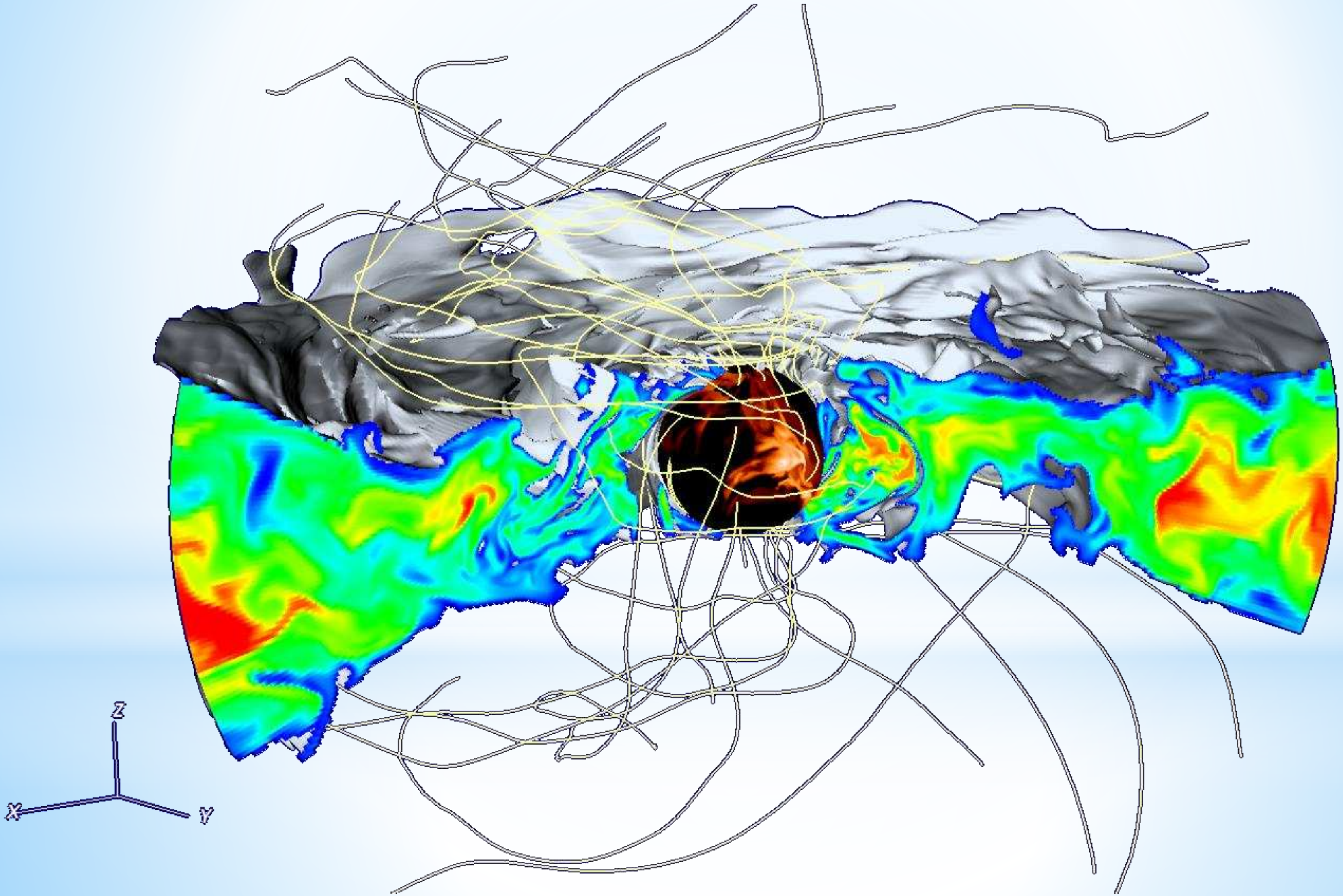
MRI turbulence can drive (weak) winds (e.g. ↑ Suzuki & Inutsuka 2009), but not significant in our simulations, possibly due to the dense corona? (disk height ∼2H, while outflow is launched ∼2H, or just larger inertia)

Summary

High-resolution MHD simulations of Star-Disk interaction

- In 15 years: 2D (100x50x1) -> 3D (800x320x640), 5 -> 160 orbits
- Possibly a new regime? (or just a transient phenomenon?)
  - ➢ Weak fields: direct accretion by MRI through boundary-layer
  - ➢ **Marginally Strong fields**: interchange + magnetic braking
    The magnetosphere collapses (or very small)
  - ➢ (Strong fields: Magnetospheric accretion)
- Outflows in old 2D simulations may be due to the initial conditions and possibly just transient phenomena for short duration
- Interchange instabilities, which are essentially 3D phenomena, are more important than previously thought as they occur almost always
- Long-term simulations + Time-dependent analyses on the way: Accretion rate, Stellar Spin, radial profile, etc.

Thanks!



Supplements