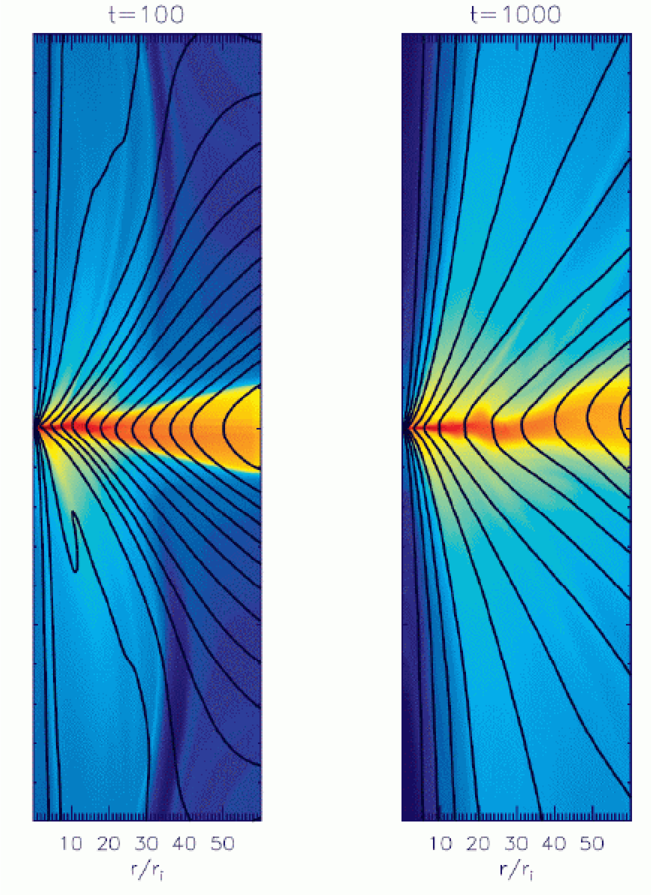
Jet launching - MHD simulations of the accretion-ejection structure

EpoS 2014, Ringberg , June 3



Christian Fendt

Contents:

1) MHD jets - model setup
2) Simulations of jet launching:
   fluxes, bipolar asymmetry
3) Jets from a mean-field disk dynamo
A) Jet rotation: helical MHD shocks

Collaborators:
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Jet launching - MHD simulations of the accretion-ejection structure

What kind of disks
form jets,
what kinds of disks
do not ?

What kind of disks form jets and what kinds of disks do not ?

Jet time scales:

Jet formation: $\tau_{jet} \sim 10,000$ yrs

from L_{jet} / V_{jet} and $\#_{jets} / \#_{disks}$

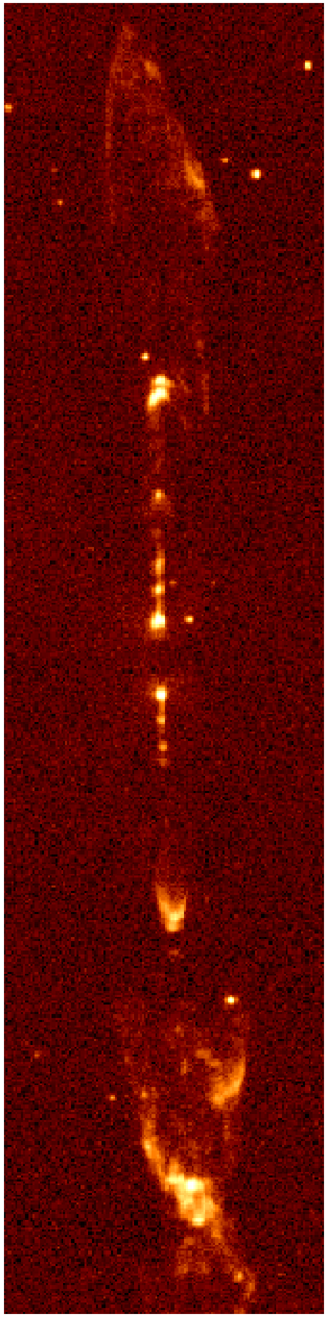
Origin of knots: $\tau_{knot} \sim 100\text{-}1000$ yrs

from $\Delta L_{knot} / V_{knot}$

-> compare to disk life time $\sim 10^6$ yrs

-> compare to time scale of jet launching area:
orbital period of inner disk ~ 10-20 days

HH 212



Zinnecker et al. 1998

Jet launching - MHD simulations of the accretion-ejection structure

Feedback ?

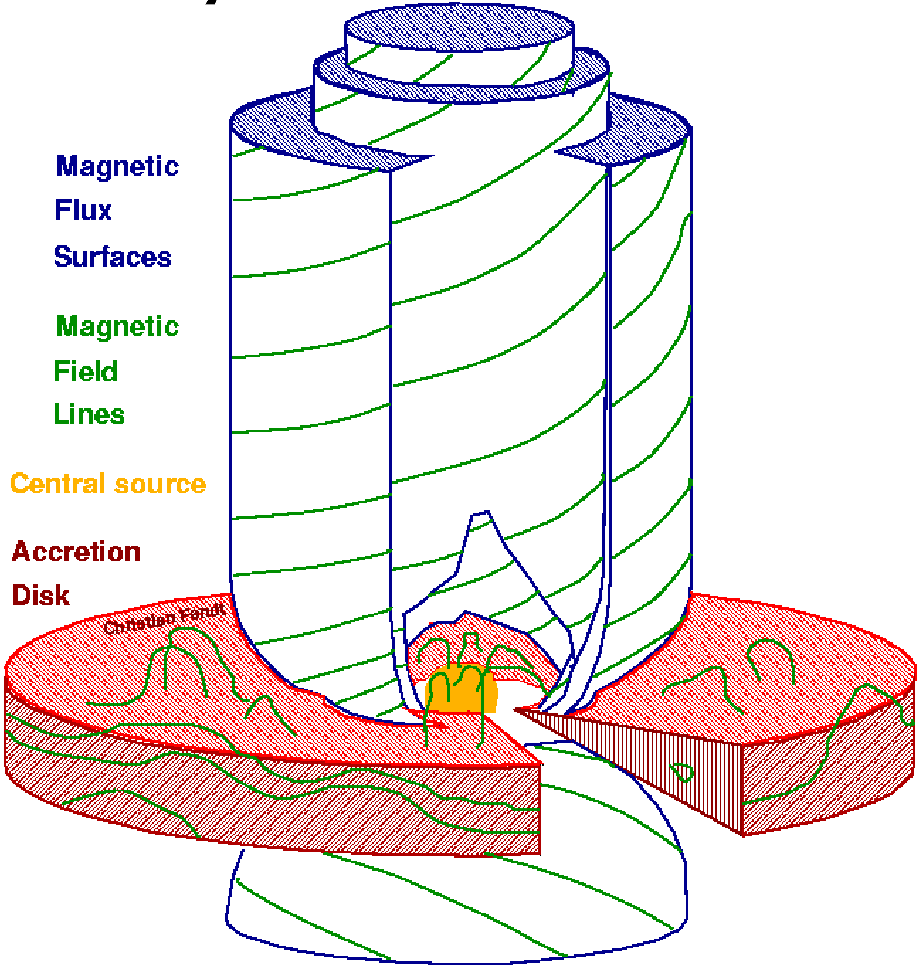
Transfer rates for mass, energy, angular momentum?

1) MHD model of jets

**Jets: collimated disk / "stellar" winds,
launched, accelerated, collimated by magnetic forces**

Fundamental questions of MHD jet theory:

1) Collimation & acceleration of disk winds into jets ?
2) Ejection of disk / stellar material into wind?
3) Accretion disk structure ?
4) Origin of magnetic field ?
5) Jet propagation / interaction with ambient medium ?
6) Impact of central spine jet (stellar wind / black hole jet) ?



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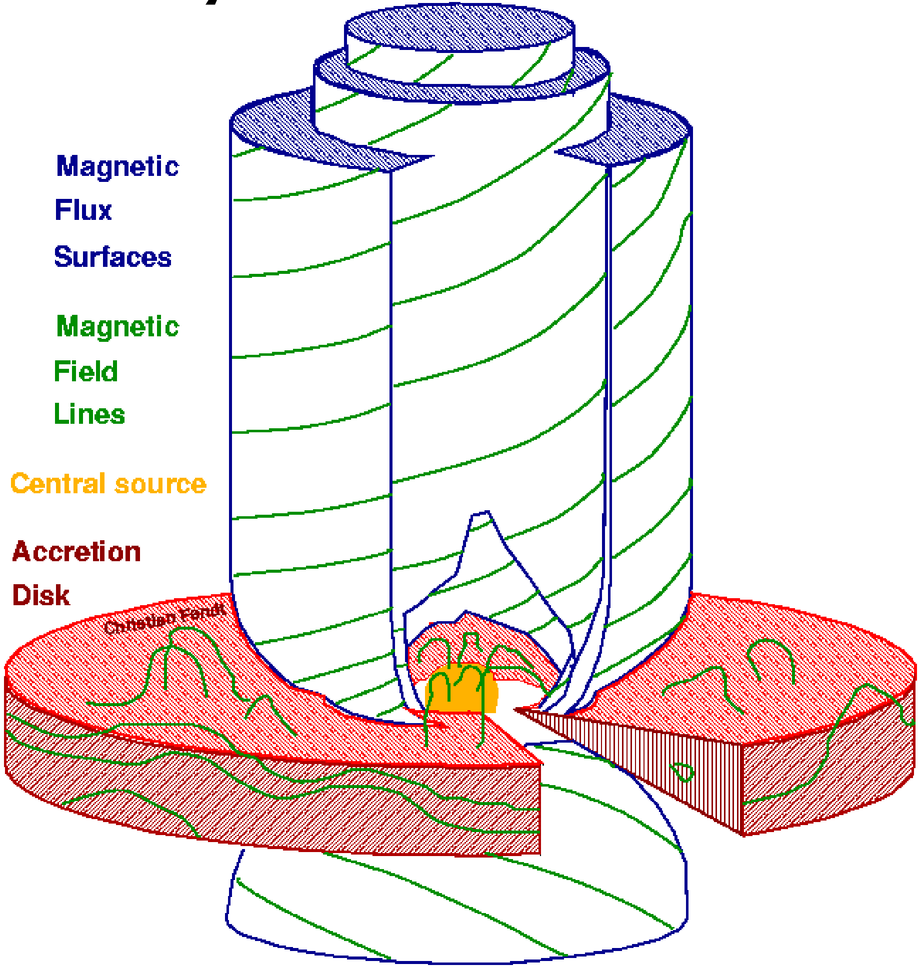
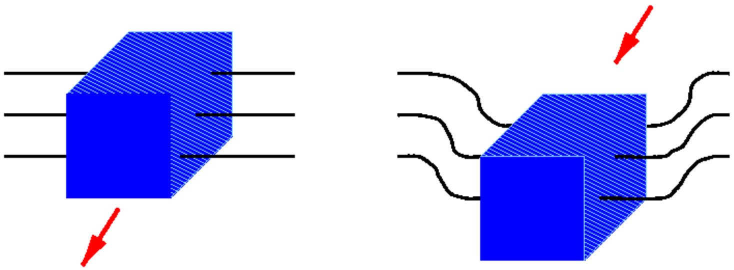


1) MHD model of jets

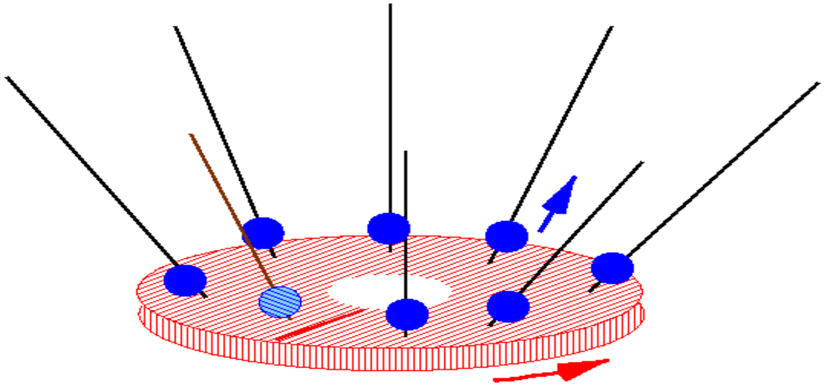


MHD jet formation:

-> magnetic field lines are like wires / rubber band, loaded with beads:

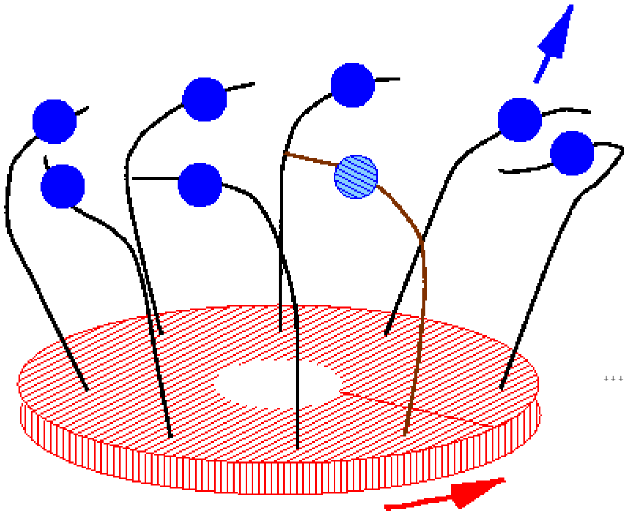
-> three mechanisms at work for MHD jet formation:

1) “rotating” field lines:
ejection of matter
radially outwards
(along poloidal field B_p)



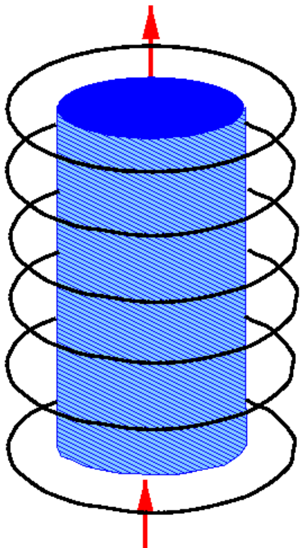
centrifugal force

2) “bending" of
magnetic field:
(-> toroidal field B_ϕ)



inertial forces

3) collimation
of outflow:
(by toroidal field)



field tension

Blandford & Payne (1982): self-similar steady-state solutions of jet formation

1) MHD jet self-collimation

Simple explanation:

by high school experiment:

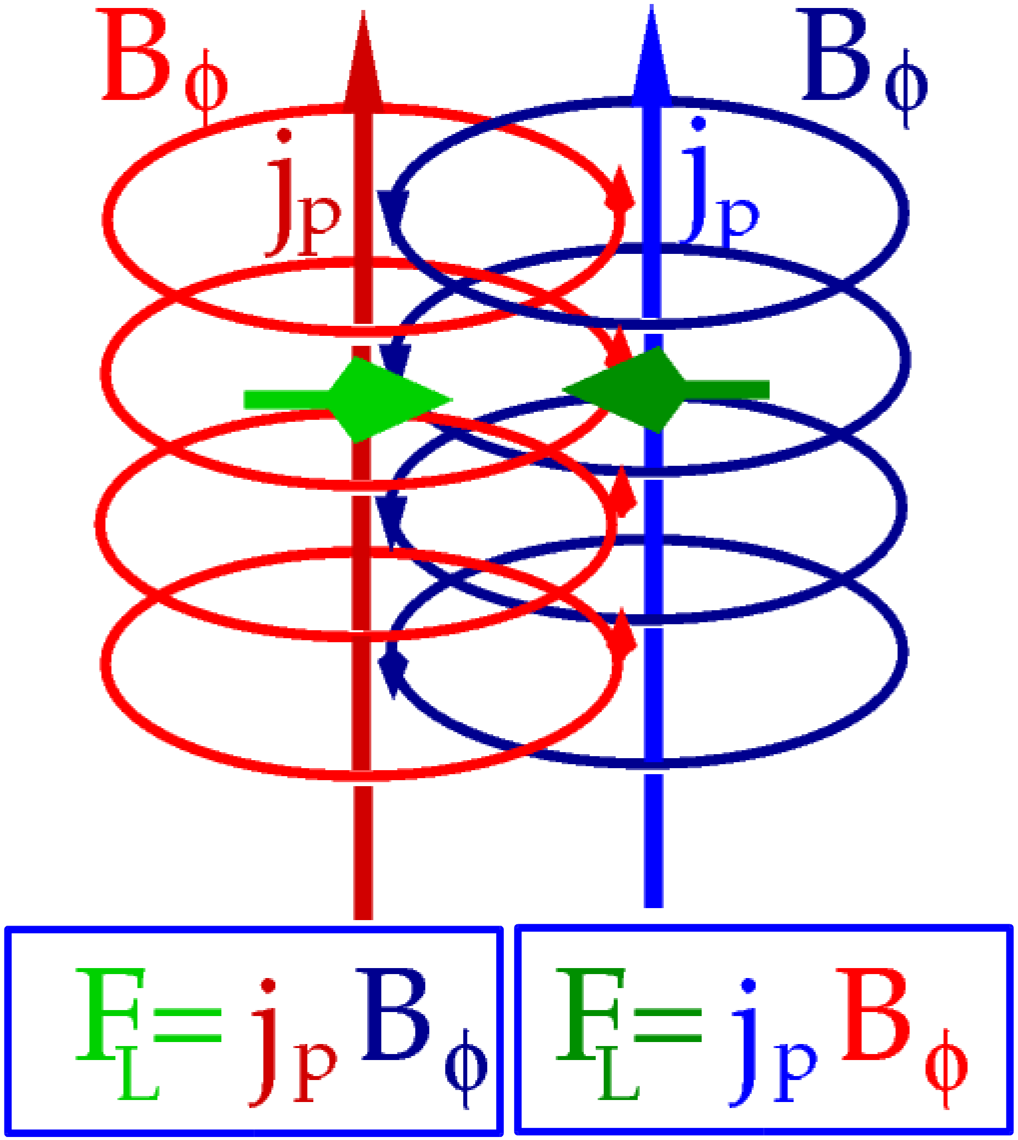
- current-carrying wires attract / push off each other
- attractive Lorentz force between two wires, if electric currents are aligned

-> **collimation** if jet carries net electric current

Remember:

Ampere's law: $j_p \sim \mathrm{rot}\ B_\phi$

Lorentz force: $F_L = q\ v \times B$



Note of caution: you need to close the electric current somewhere ...

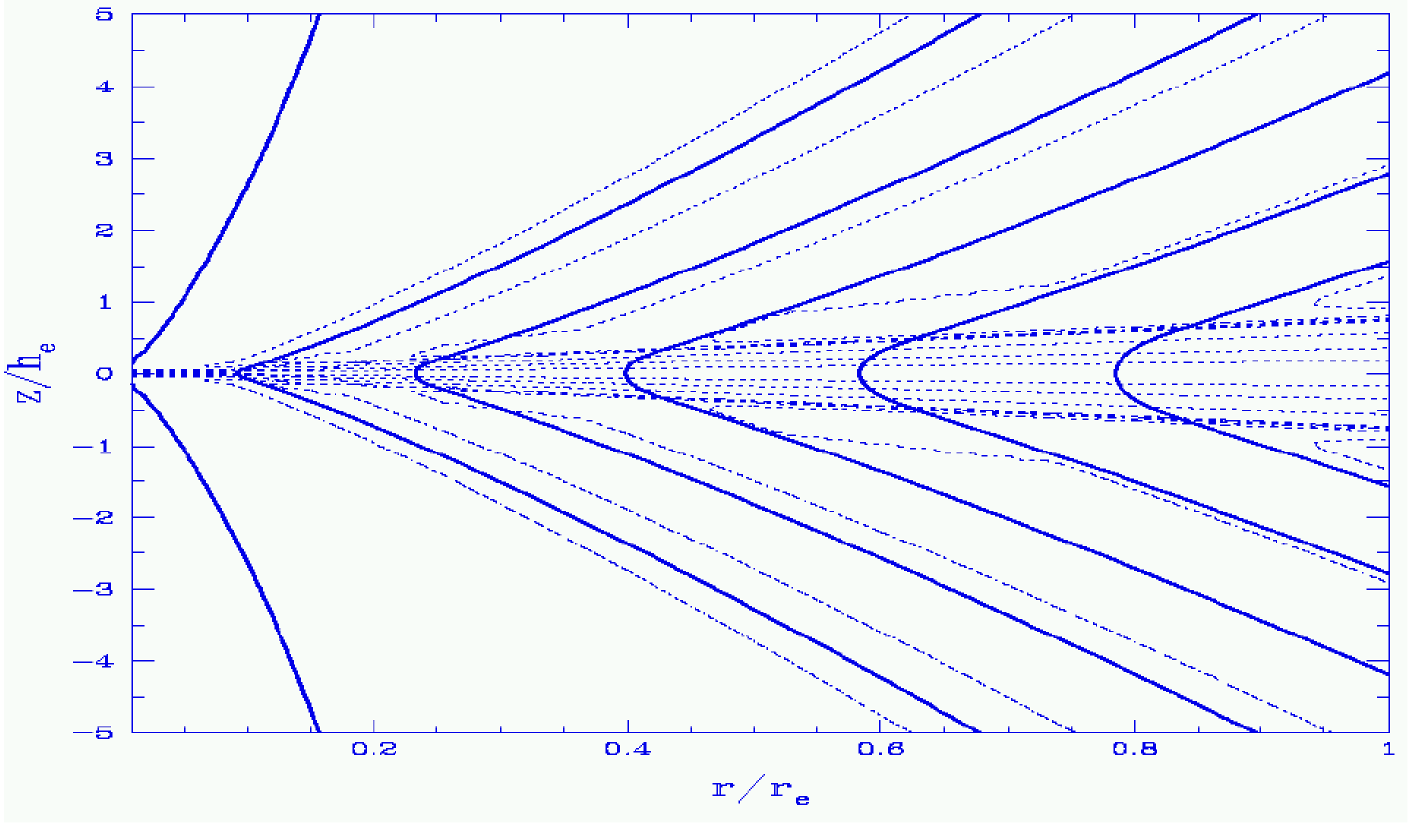
1) Jet launching: disk - jet connection

Mass loading: **accretion to ejection,** **resistive (diffusive) MHD**

-> **Jet launching is MHD effect:**

if $F_{L,\perp}$ decreases -> gas pressure gradient lifts plasma

if $F_{L,\phi}$ increases -> centrifugal acceleration of plasma (BP82)



Ferreira 1997: **field lines (solid), mass streamlines (dashed)**

-> Self-similar, steady-state MHD solutions (Ferreira et al. 1997):

Main result: **1-10% ejection-accretion efficiency in mass flux**

2) Jet launching

-> transition accretion -> ejection

-> mass fluxes for accretion and outflow

-> bipolar simulations considering both hemispheres:

asymmety in jet & counter jet

Sheikhnezami, Fendt, et al., ApJ 757, 65 (2012),

Fendt & Sheikhnezami, ApJ 774, 12 (2013)

See also: Casse & Keppens (2002, 2004), Zanni et al. (2007)

2) MHD launching: disk - jet connection

Simulation setup:

-> initial Keplerian disk (no advection)

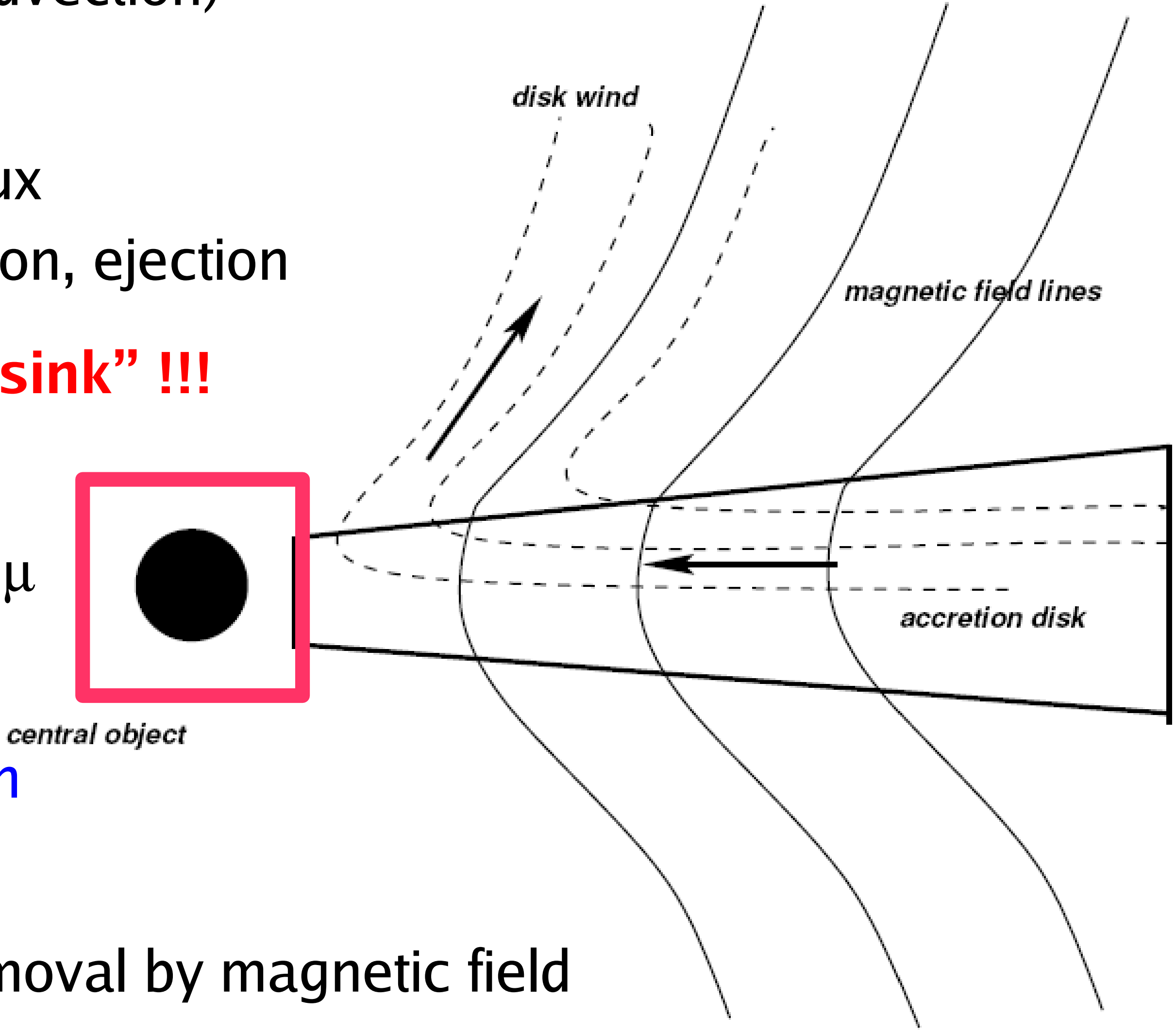
-> **“resolve” disk physics:**
  - advection/diffusion of flux
  - launching: mass accretion, ejection

-> careful definition of mass **“sink” !!!**

-> parameter runs:

plasma-β / magnetization μ

α – magnetic diffusivity



-> stable, long-term simulation

-> here: no viscosity

-> angular momentum removal by magnetic field

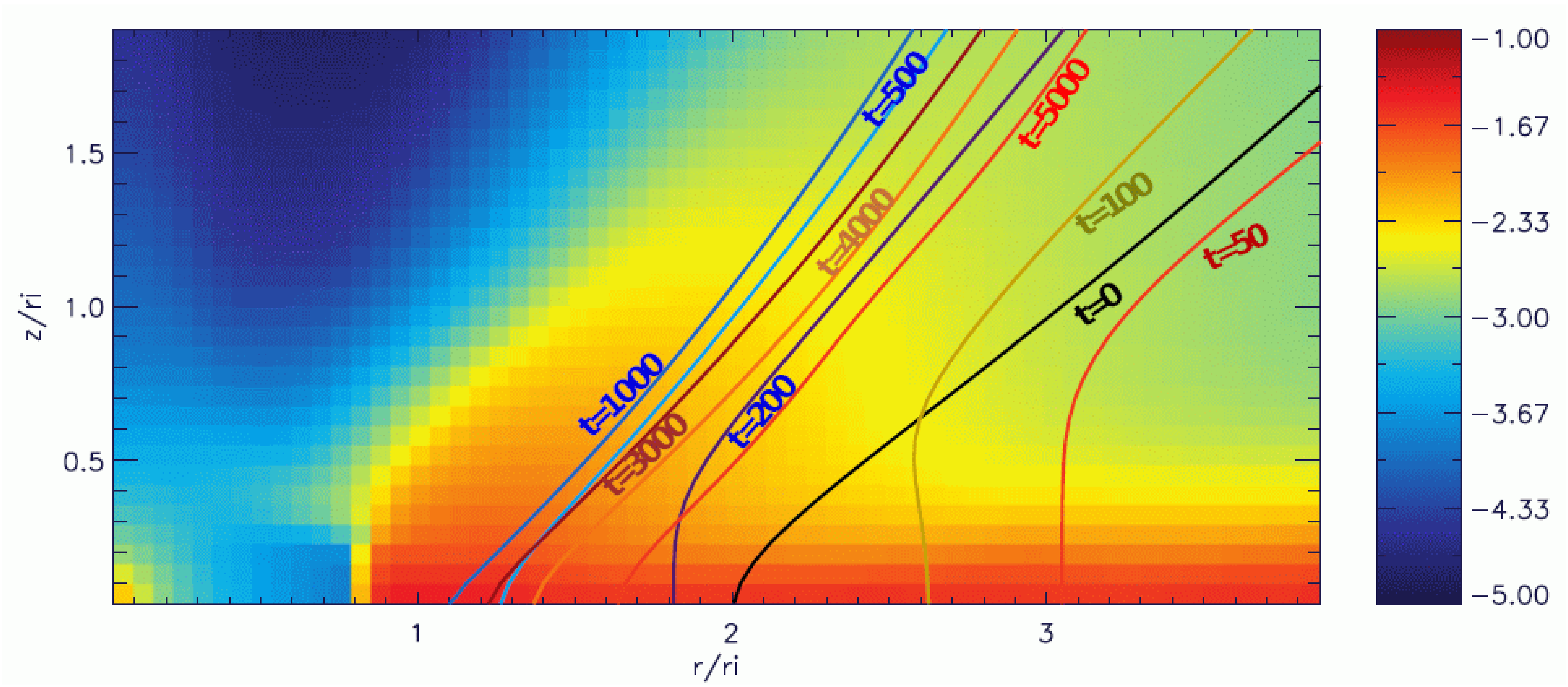
2) MHD launching: disk - jet connection

-> Re-configuration of magnetic flux by advection and diffusion:

  -> magnetization (relative field strength) changes, and thus local jet launching conditions

  -> estimate: magnetic flux conservation: $\Psi \sim B_p r^2 = \text{const}$

  field strength changes by factor 10 if radius changes by factor 3



Sheikhnezami, Fendt, Vaidya, et al. 2012

2) MHD launching: disk - jet connection

Movie : 1 diffusion - advection

`http://www.mpia-hd.mpg.de/homes/fendt/movies.html`

2) MHD launching: disk - jet connection

Bipolar jet launching

-> Evolve bipolar jets into both hemispheres

-> Check for signatures of jet / counter jet asymmetry

-> Asymmetry triggered intrinsically - in the disk, or externally

Numerical setup:

v1 symmetric accretion disk -> symmetric bipolar outflow/ jet

v2 asymmetric disk -> disk warping -> outflow asymmetry

v3 symmetric disk with localized energy injection

-> local disk asymmetry -> advected inwards -> outflow asymmetry

v4 symmetry / asymmetry of ambient medium

Model of magnetic diffusivity η essential:

for local description, $\eta=\eta(\rho(r,z),t)$, asymmetry much longer sustained

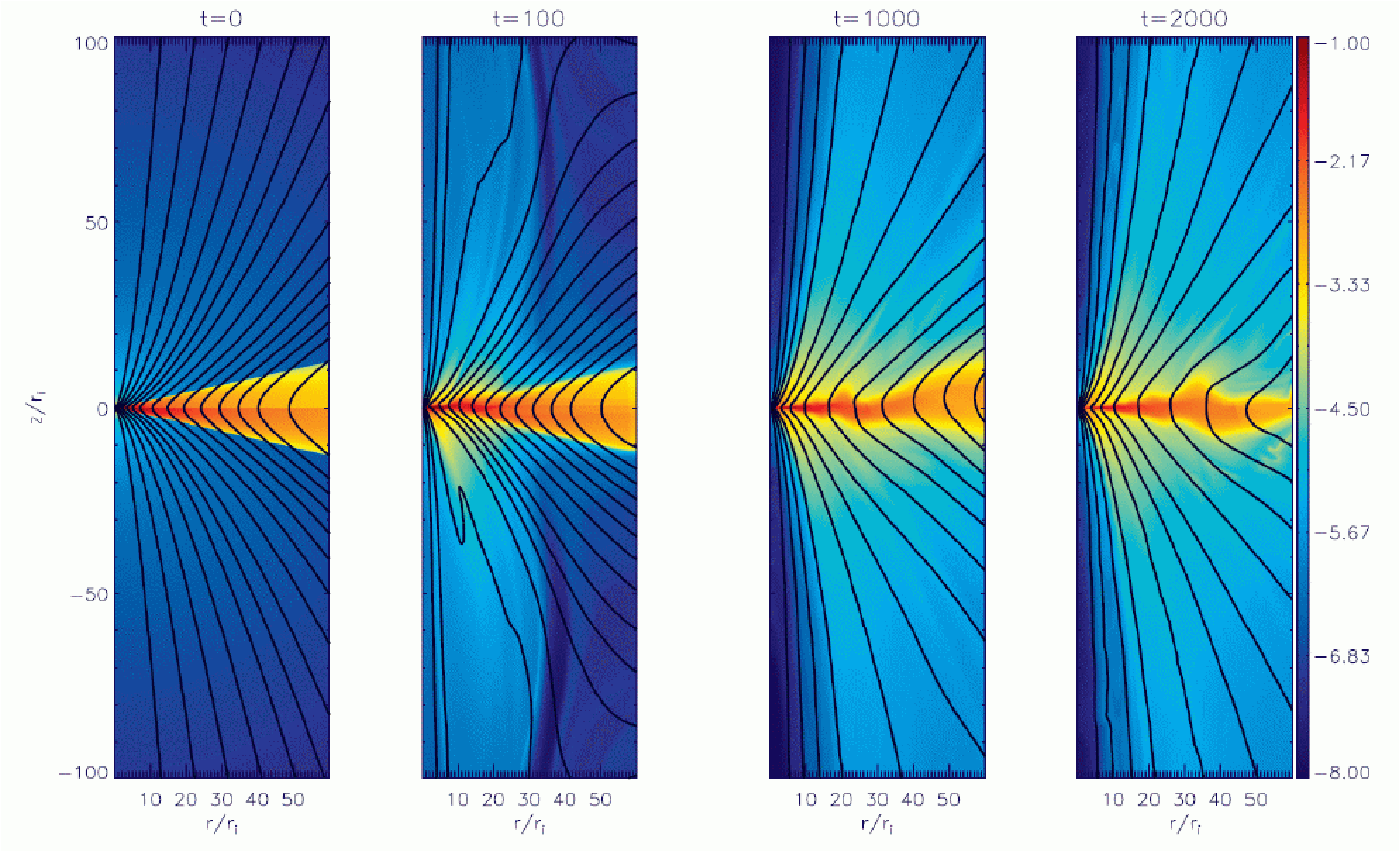
2) MHD launching: disk - jet connection

Movie 2: bipolar simulation

`http://www.mpia-hd.mpg.de/homes/fendt/movies.html`

2) Jet launching: bipolar jets

case v2) asymmetric disk -> disk warping -> outflow asymmetry



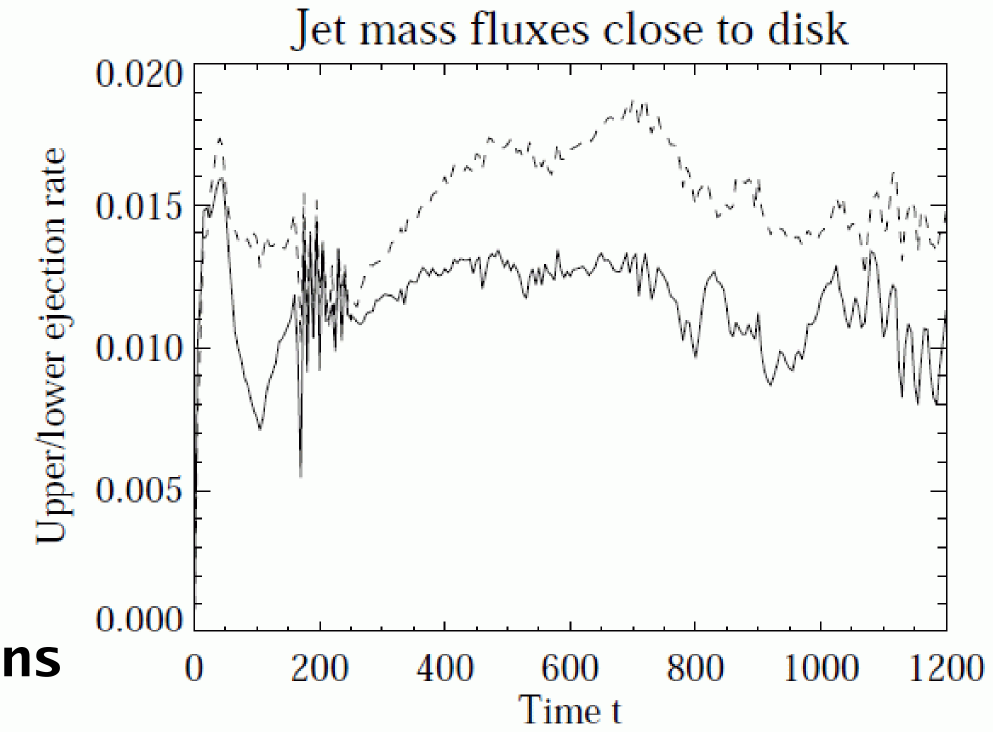
2) Jet launching: bipolar jets

v2) asymmetric disk

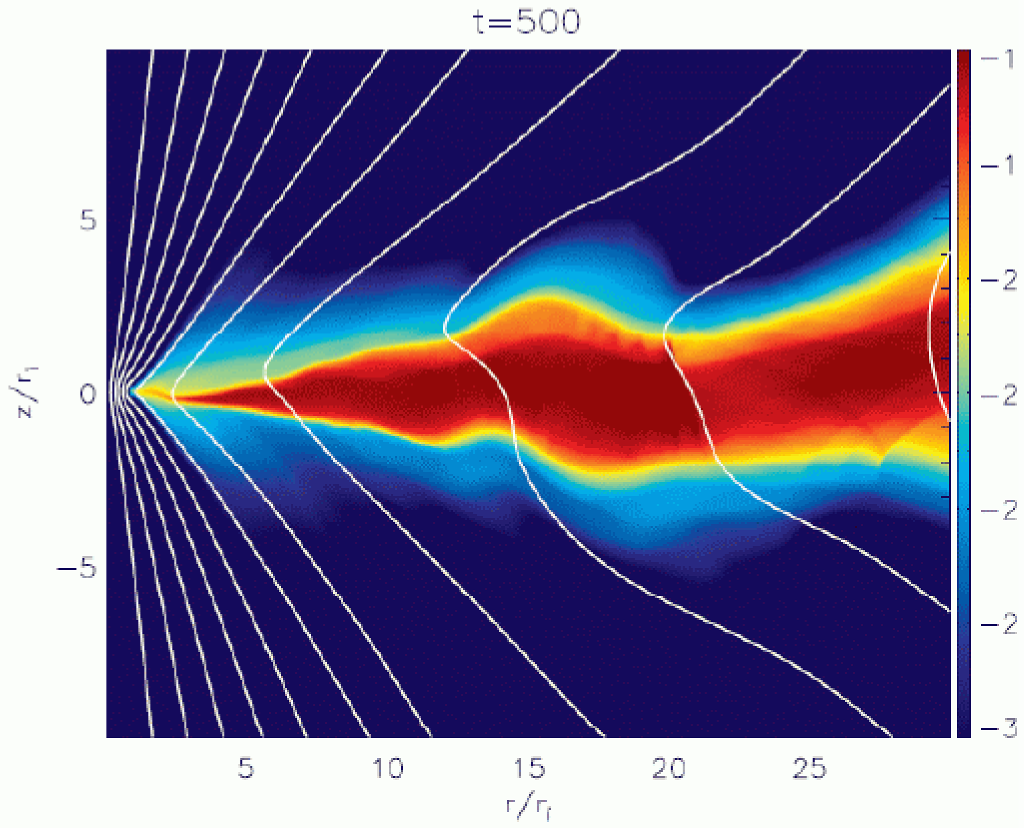
-> disk warping

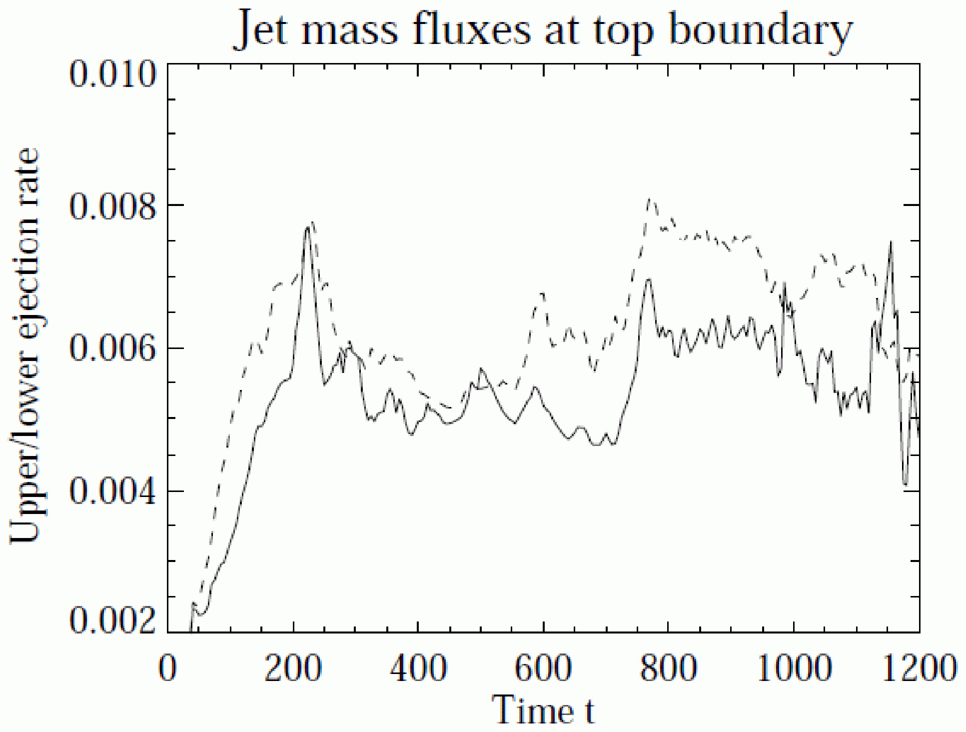
-> outflow asymmetry

- **20-30% mass flux difference**
- **in jet / counter jet, similar in velocity**
- **accretion rate 2-3x ejection rate**
- **time scale of variation ~ 1000 rotations**



Jet mass fluxes close to disk





Jet mass fluxes at top boundary

2) Jet launching: bipolar jets

Main results:

v1: global diffusivity model, constant in time:
disk returns to Keplerian rotation, (jet) asymmetry decays

v2: asymmetric disk -> disk warping -> outflow asymmetry

- **20-30% mass flux difference in jet / counter jet, similar in velocity**
- **ejection rate ~20-40% of accretion rate**
- **time scale of variations ~ 1000 rotations = 10-100 yrs (?), depending on diffusivity model**

v3: localized asymmetry:

advection to inner disk
-> asymmetric launching of outflows (time delay)
-> asymmetry further propagated along outflow

v4: asymmetric ambient medium:

(overdense) jet slightly asymmetric (when embedded ambient medium)

3) A mean-field disk dynamo

-> further investigate launching time scales

-> extend numerical grid to observational scales

-> consider “self-generated” disk magnetic field

  -> add dynamo equations to PLUTO code

Stepanovs & Fendt, ApJ, revised (2014)

Stepanovs & Fendt, to be submitted (2014)

3) Jet launching: jets from disk dynamos

Stepanovs & Fendt (2014a revised; 2014b to be submitted):

-> consider large grid to follow outflow from launching to propagation
  -> spherical grid of up to $R < 5000\ R_{in} \sim 500$ AU

-> run long simulations to reach observed time scales
  -> model setup allows for more than 100,000 inner disk orbits ~ 28 yrs

-> introduce longer physical time scales on disk-jet evolution
  -> mean-field α^2 / α-Ω-dynamo, initial magnetization $\sim 10^{-4}$
  -> toy model: switch on/off dynamo

-> model for resistivity / magnetic diffusivity -> allow for mass supply from outer disk to inner disk

3) Jet launching: large numerical grid

Movie Jet

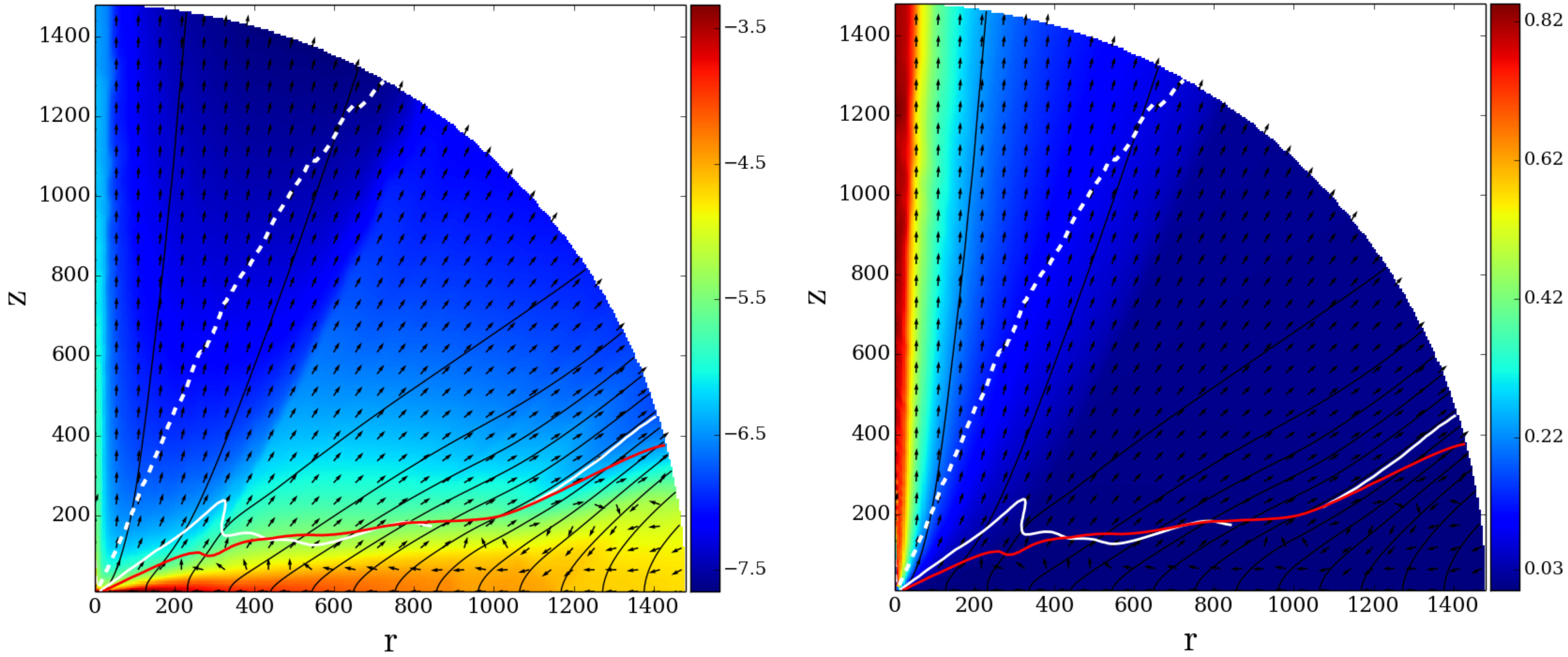
http://www.mpia-hd.mpg.de/homes/fendt/movies.html

3) Jet launching: large numerical grid

Time ~ 150,000 rotations at R_{in}, grid size ~ 140 AU

Narrow, “fast” axial jet: V_{jet} ~ 0.9 $V_{Kep}(R_{in})$ ~ 100km/h for R_{in} ~0.1 AU

R_{jet} ~ 50-100 R_{in} ~ 5-10 AU for R_{in} ~0.1 AU



density,

poloidal velocity,

magnetic field lines, normalized velocity vectors;
Surfaces: Alfven (white line), sonic (red line), fast (dashed)

3) Jet launching: large numerical grid

Question: What disk properties govern the outflow properties?

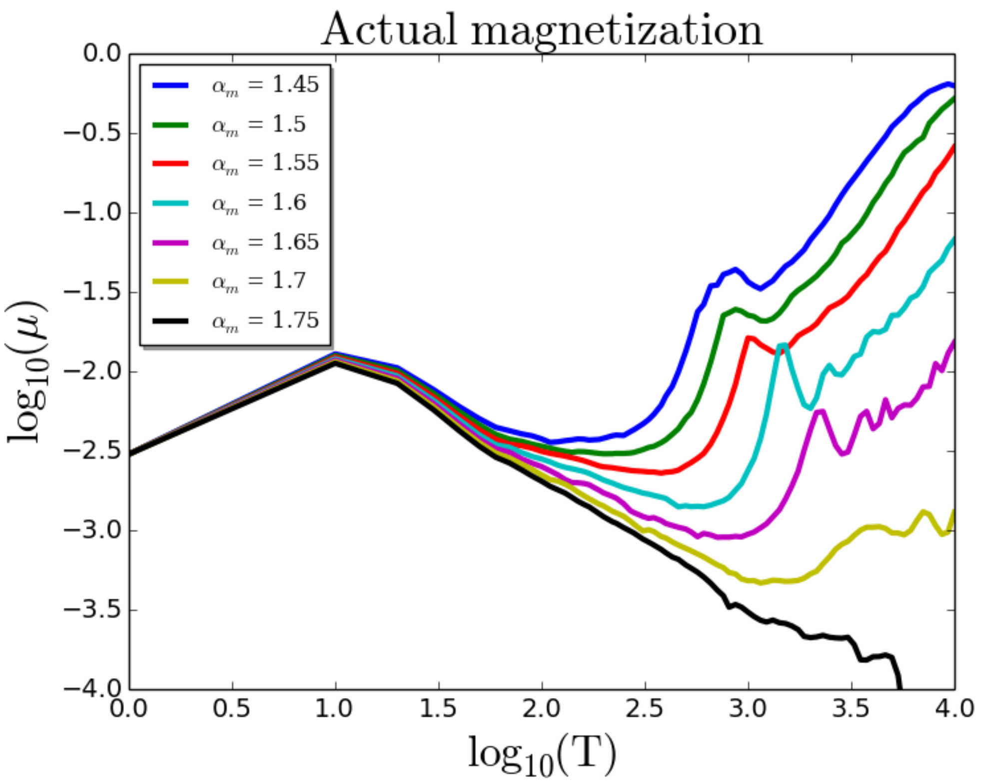
-> take a small jet launching area of the disk

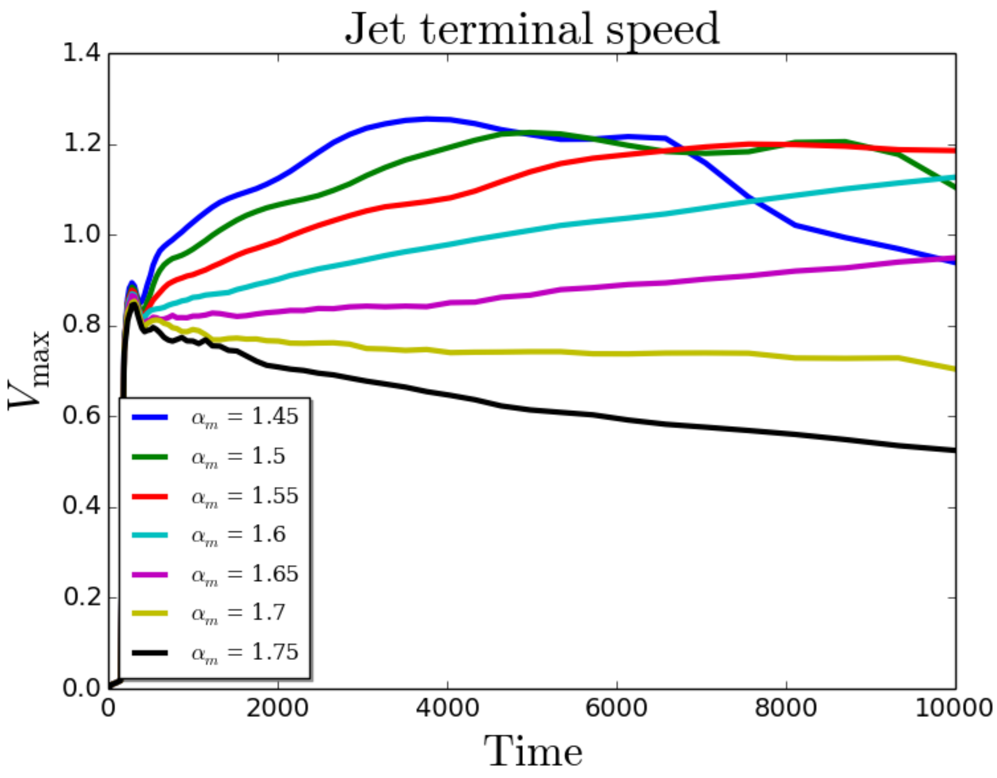
-> calculate average disk properties, actual values (i.e. a time):

-> e.g. **actual disk magnetization μ**

-> slight time variation due to change in disk mass (evolving quasi steady state)

-> **relate disk properties** (variation of μ) **to jet properties** (mass flux, velocity)


Actual magnetization


Jet terminal speed

3) Jet launching: large numerical grid

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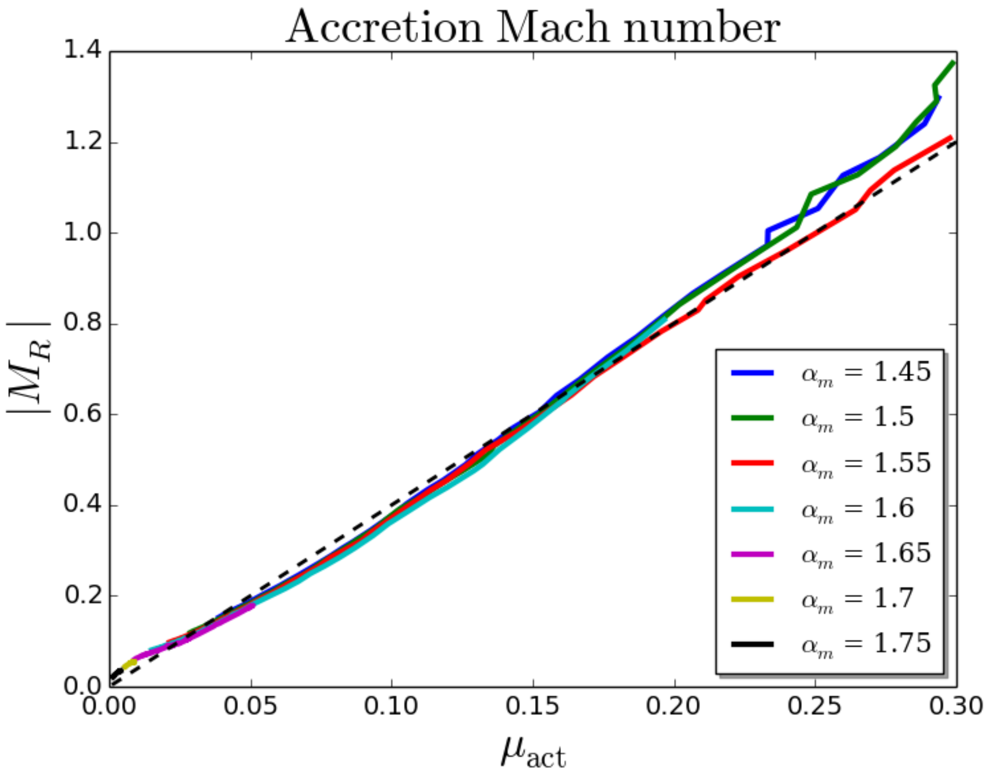
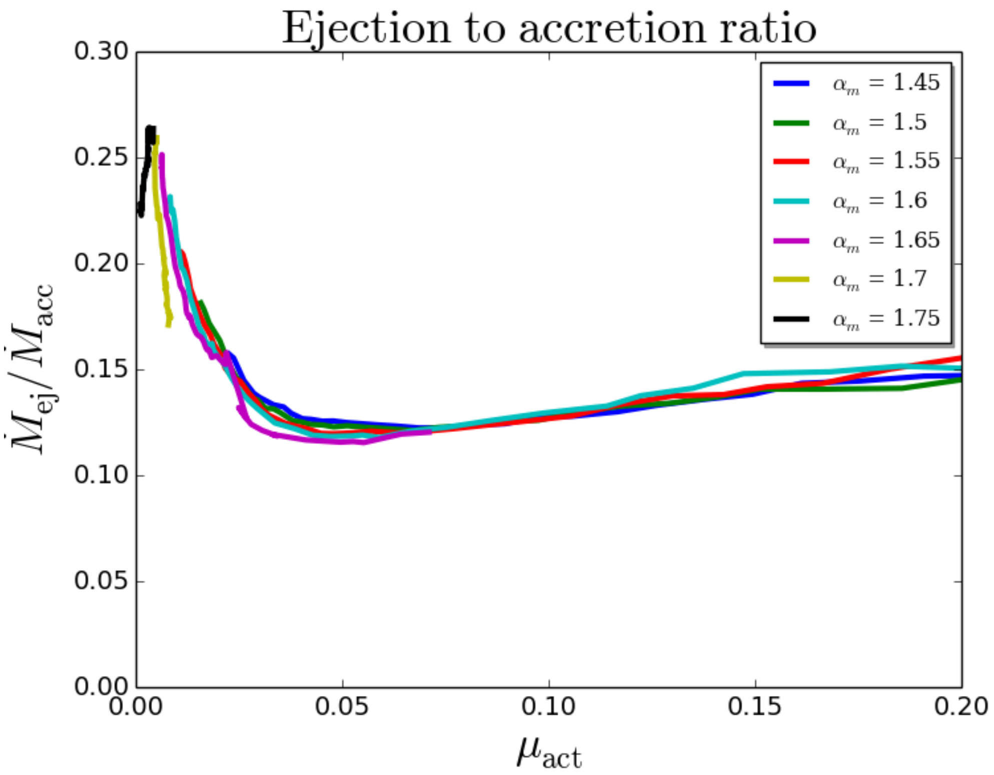




3) Jet launching: disk dynamo

Long times ~ 10,000 rotations & more; large size ~ 140 AU

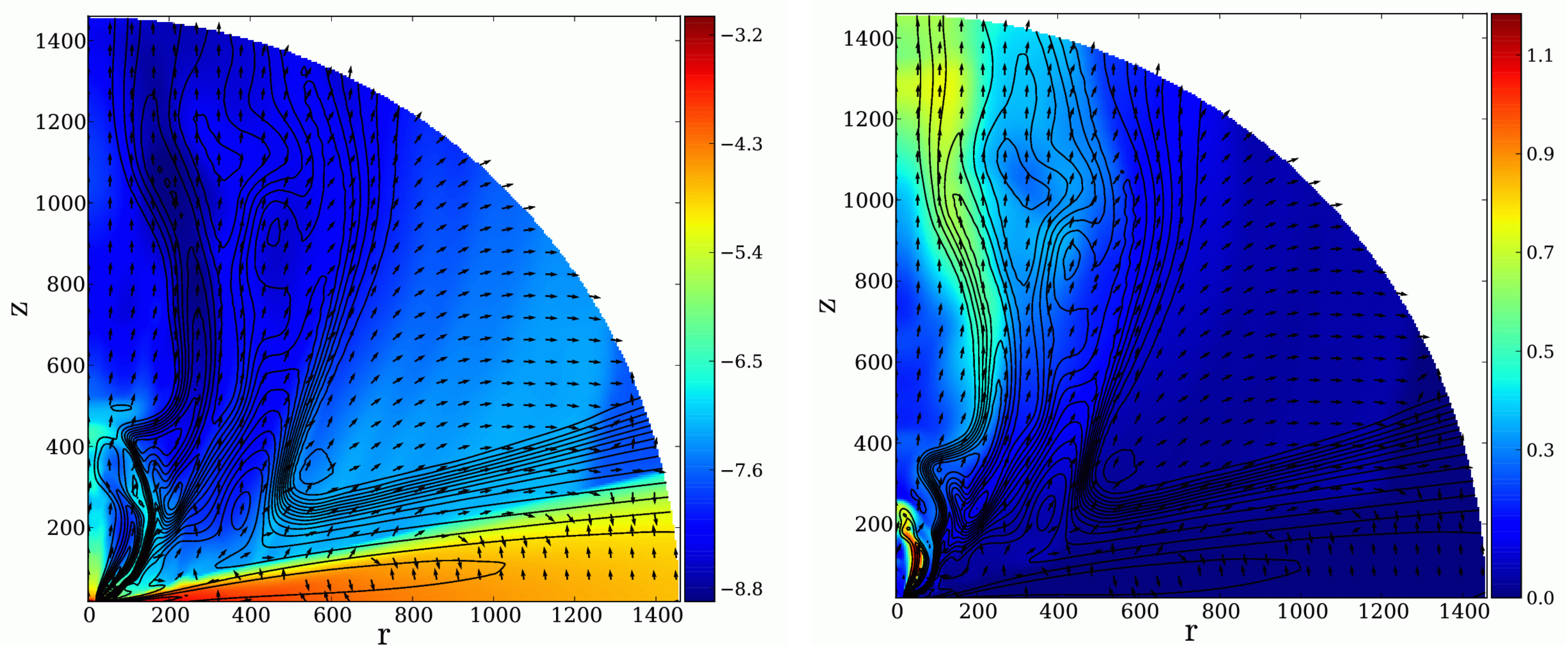
α^2-Ω-dynamo

Initial magnetic field: B_R, or B_ϕ , magnetization μ ~10^{-4} ,quenching for high $\mu \sim 0.1$

Dynamo-generated loops of poloidal field break up

-> open field lines Blandford-Payne magneto-centrifugal driving for r>20

-> fast jet, slow disk wind



3) Jet launching: disk dynamo

Movie Dynamo, inner part

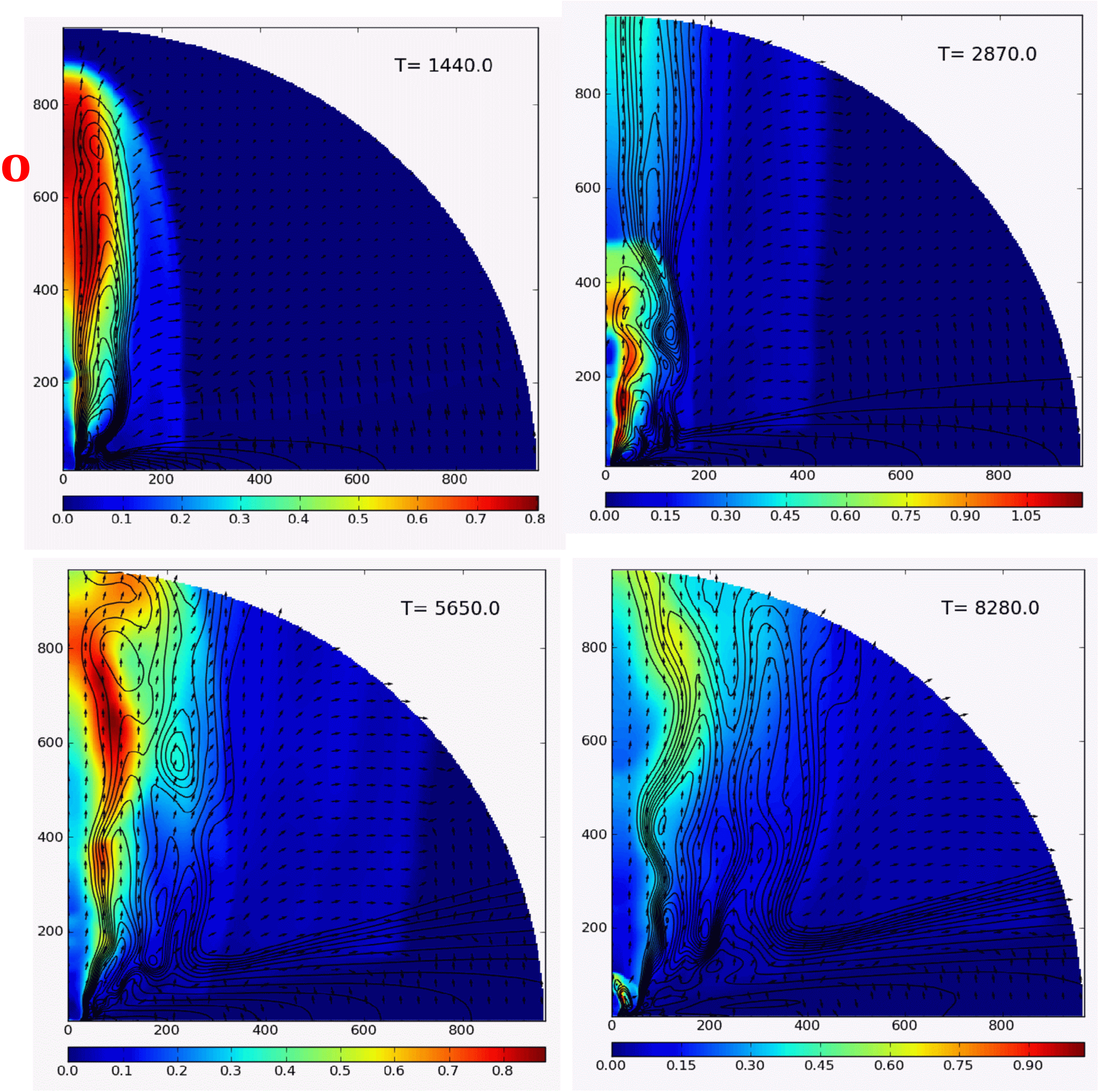
`http://www.mpia-hd.mpg.de/homes/fendt/movies.html`

3) Jet launching: disk dynamo

Time variable dynamo:

Toy model: switch on/off dynamo at $\Delta t = 1000$

Time-dependent ejection of jet



3) Jet launching: disk dynamo

Movie toy model of knots

MHD simulations of disk-jet transition (i.e. launching)

Summary:

- outflow mass loss ~ 50% of accretion rate
- disk magnetization changes substantially during disk evolution
- asymmetric jet / counter jet, ~30% difference in mass flux / speed;
  can be triggered by disk-internal asymmetries
- runs for ~100,000 disk rotations, grid of 5000 inner disk radii (500AU)
- magneto-centrifugally driven jet from disk-dynamo magnetic field,
  episodic ejections triggered by toy dynamo variability

Outlook:

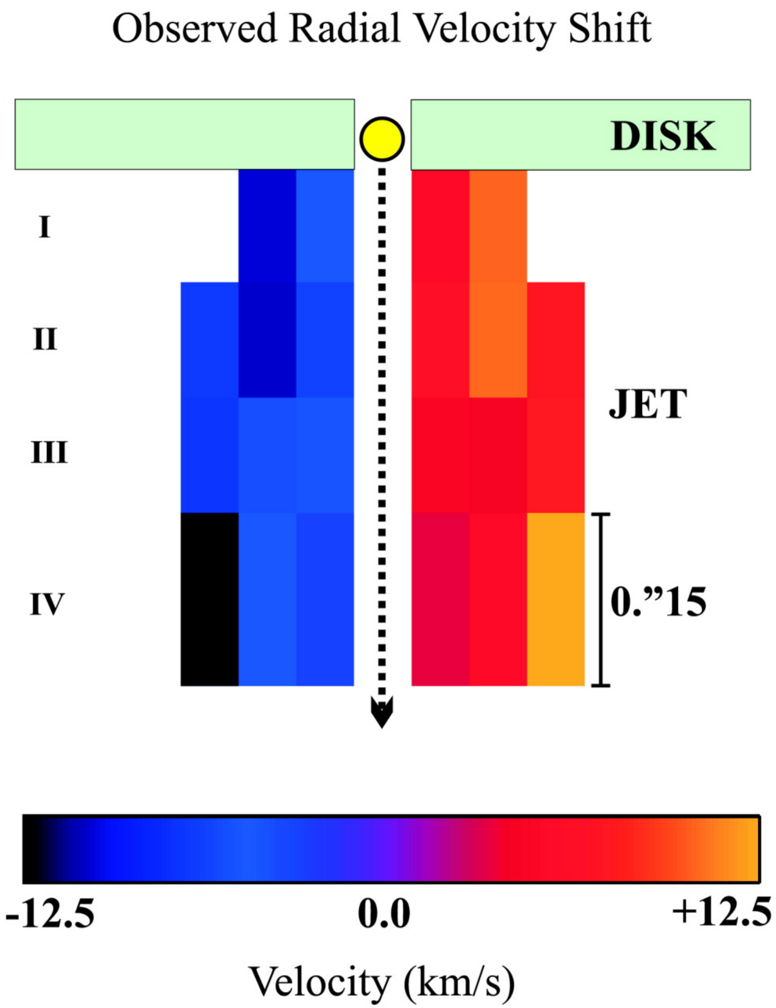
- improve disk model: visosity, heating, cooling -> new time scales?
- increase disk resolution -> jet launching under MRI (??)
- improve jet physics on large scales: cooling, radiation -> observations
- 3D simulations: stability & launching -> disk warping, binary system

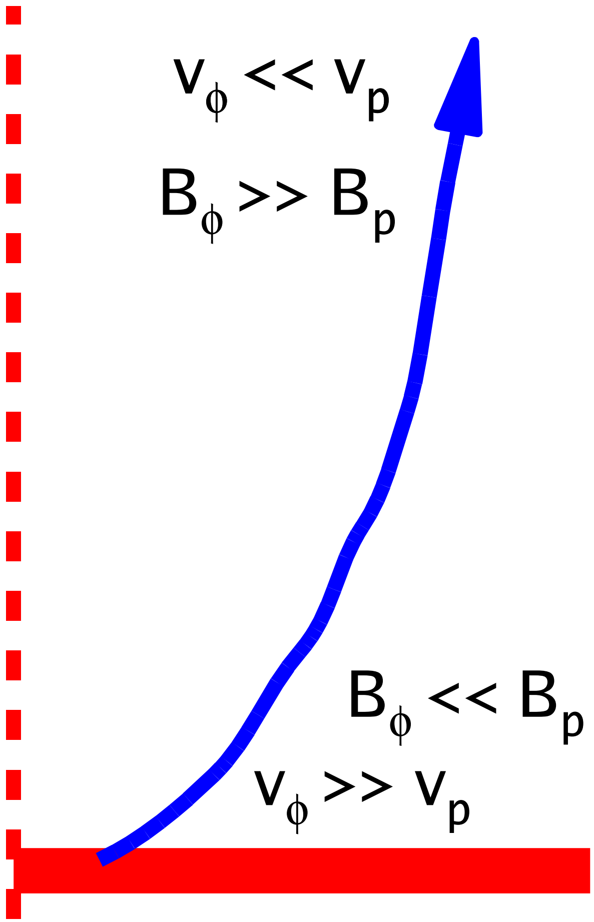
A) Rotation from helical MHD shocks

Fendt, ApJ 737, 43 (2011)

Jet rotation

- shocks in helical magnetic fields compress the toroidal magnetic

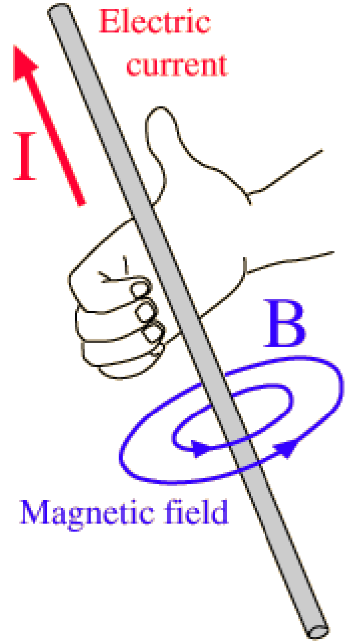




Observations: Bacciotti et al 2003

Theory: Anderson et al. 2003

MHD Lorentz force



Ampere's law: $\vec{J} \sim \nabla \times \vec{B}$

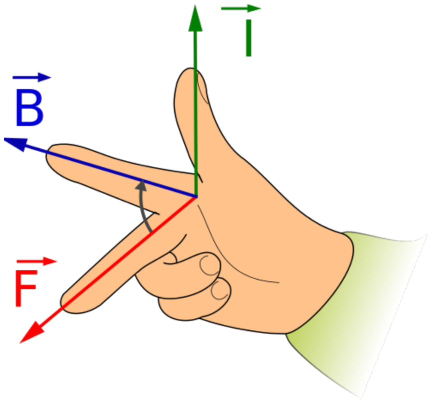
Lorentz force in MHD:

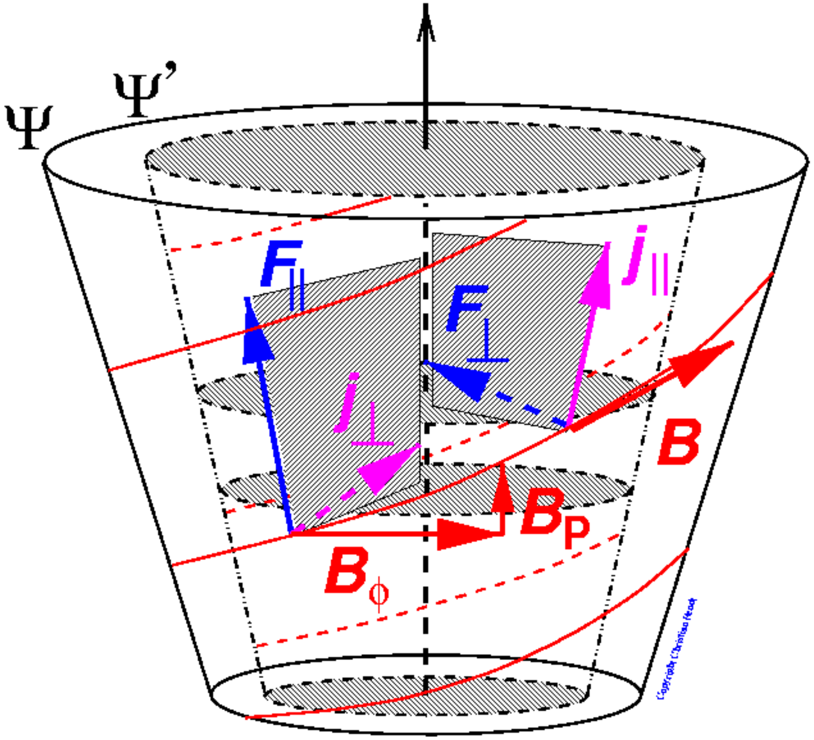
particle motion -> electric current:

$$\vec{F}_L \sim \vec{J} \times \vec{B} \sim \left(\nabla \times \vec{B} \right) \times \vec{B}$$

Component in ϕ-direction will accelerate in ϕ-direction -> rotation:

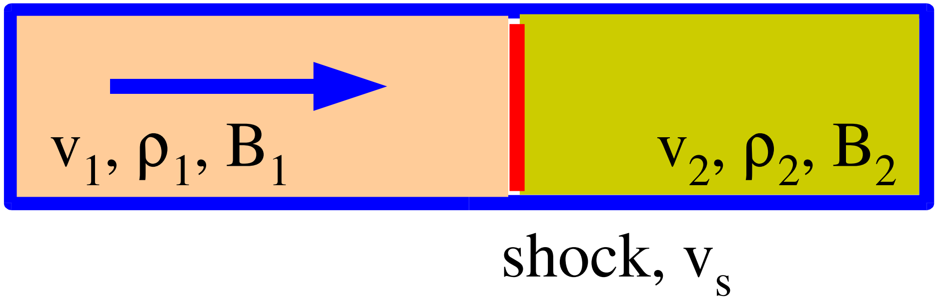
$$\vec{F}_{L,\phi} \sim \vec{J}_P \times \vec{B}_P \sim \left(\nabla \times \vec{B}_\phi \right) \times \vec{B}_P$$



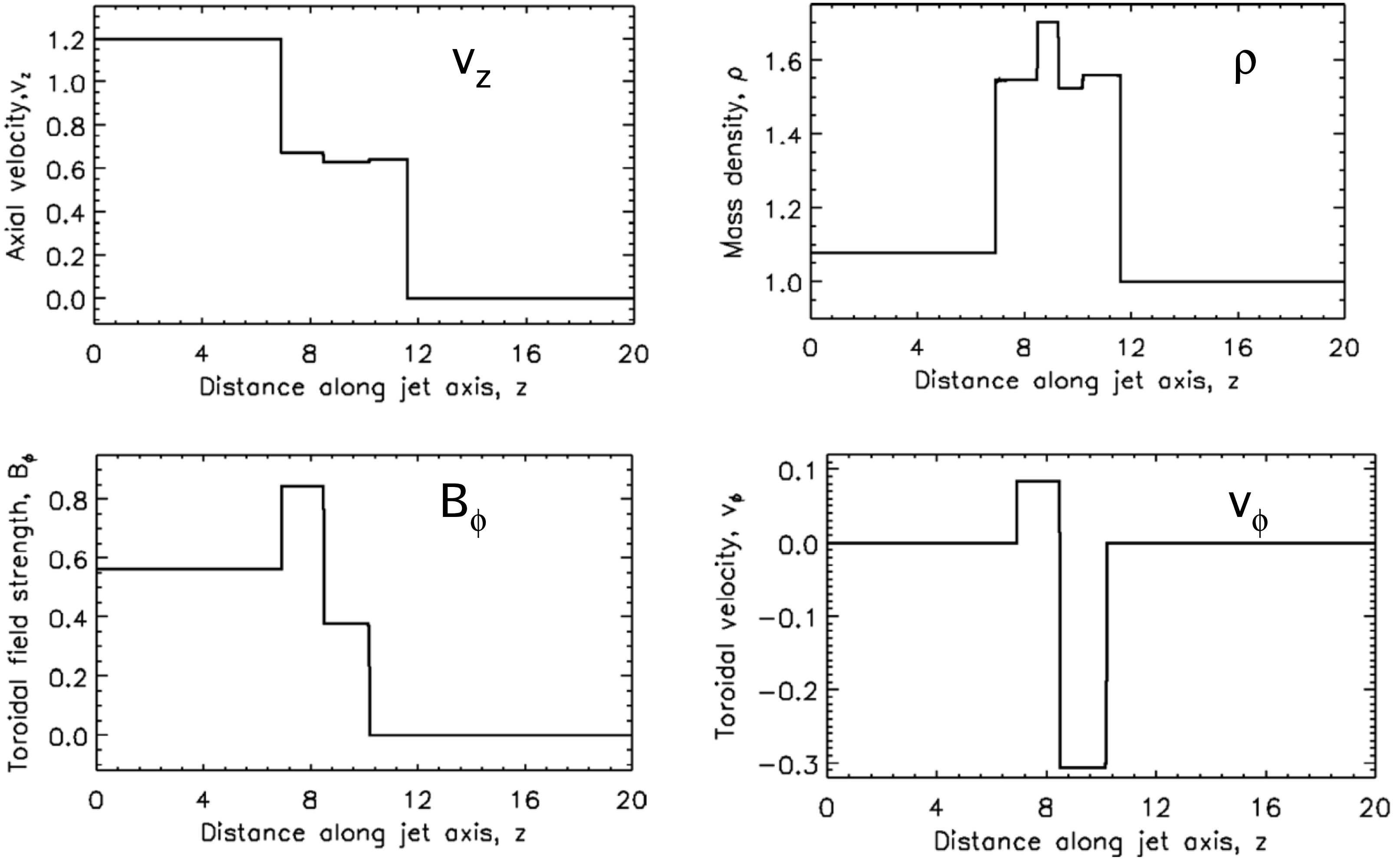


MHD shocks

Push gas against another gas:



-> **compression:** increase of density, pressure,
and perpendicular magnetic field (= B_ϕ-component in jet)

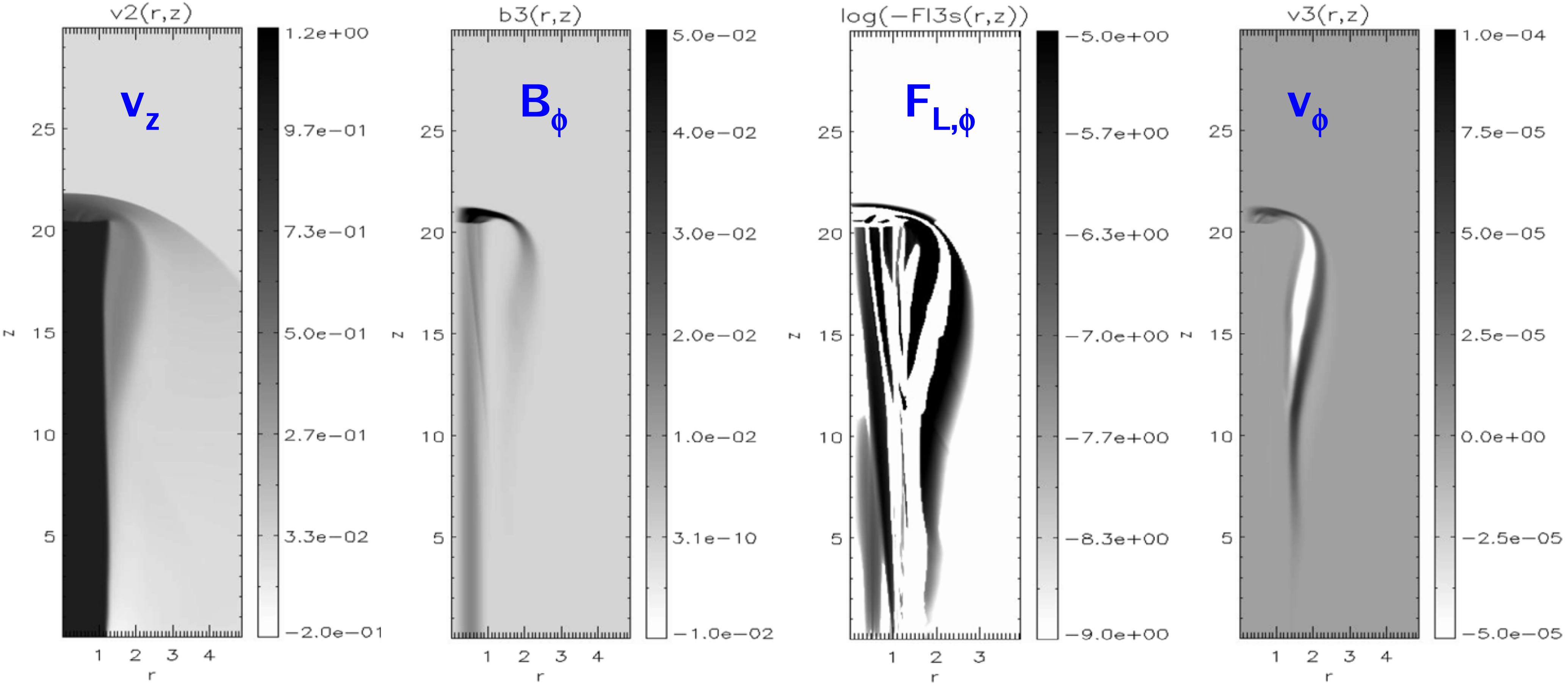


1D MHD simulation in cylindrical coordinates (z,r,ϕ), Fendt 1011

Jet rotation by MHD shocks

Axisymmetric jet simulations:

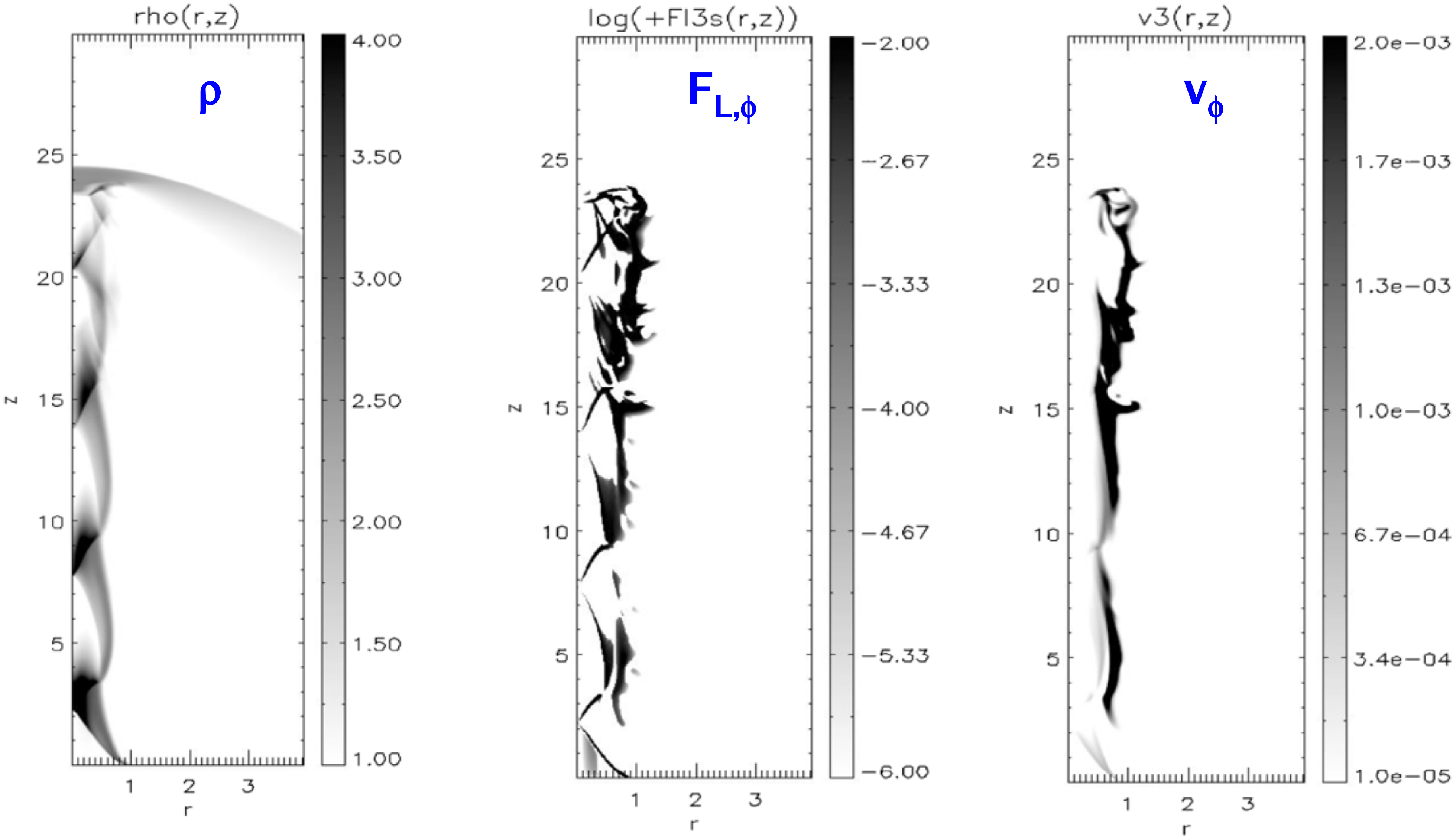
Complex rotational structure, sheets of opposite rotation,
rotation velocity ~ 1% of propagation speed



Jet rotation by MHD shocks

Axisymmetric jet simulations with unsteady injection:

-> multiple shocks lead to multiple rotation signatures



Jet rotation by MHD shocks

- shocks in helical magnetic fields compress the toroidal magnetic field component, leding to a toroidal Lorentz force enforcing rotation of the jet material

- derived rotational velocity is 0.1 - 1% of the jet propagation speed

- consistent with observed jet "rotation" in stellar jets, not yet observed in extragalactic jets