Jet launching: MHD simulations of the accretion-ejection structure

Christian Fendt [1, *, @]

1 : Max Planck Institut für Astronomie (MPIA) - ***Website***

Königstuhl 17, 69117 Heidelberg Tel.: (++49|0) 6221 – 528-0 Fax: (++49|0) 6221 – 528-246 E-mail: sekretariat@mpia.de - Germany

* : Corresponding author

I will present our recent MHD simulations treating the accretion-ejection structure. Our setup considers various approaches for a physical magnetic diffusivity that is essential for loading the accretion material onto the outflow. We find relatively high mass fluxes in the outflow, of the order of 20-40% of the accretion rate. We also consider simulations treating jet launching in a truly bipolar setup, thereby investigating the origin of an intrinsic jet-conter jet asymmetry. Simulations including a mean-field disk dynamo and launching outflows by a self-generated magnetic field will also be discussed.

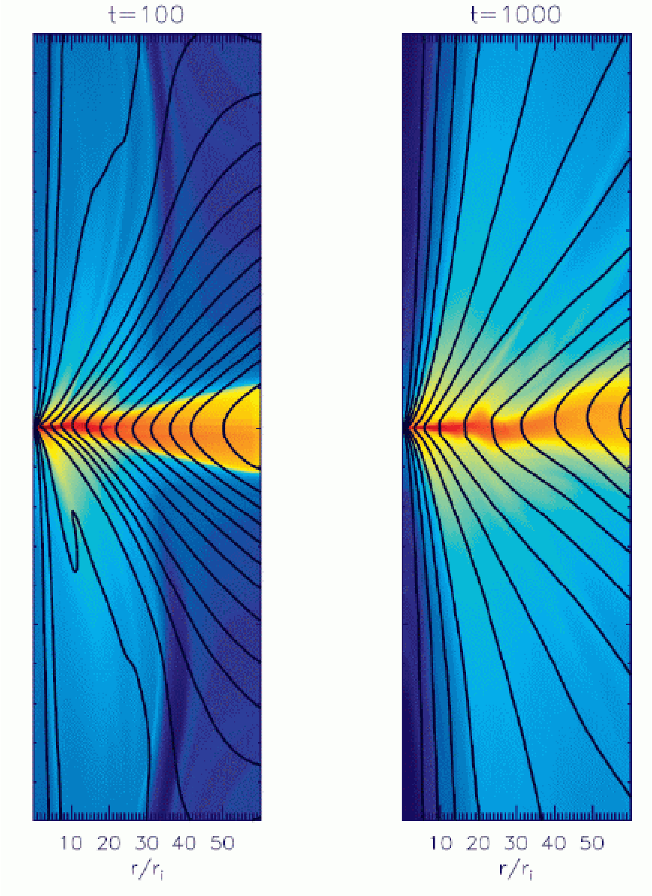
Subject : : oral
Topics : Astrophysics

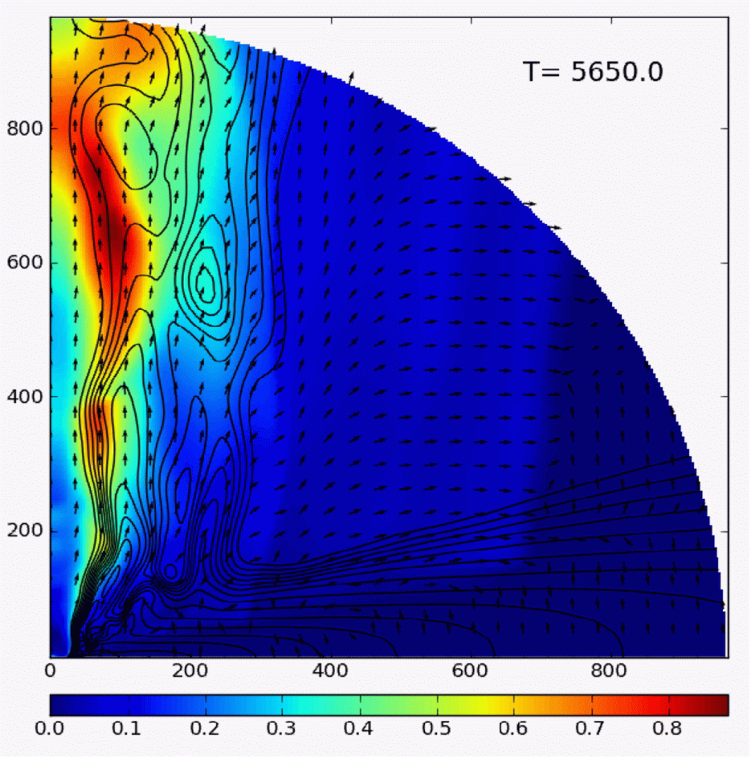
Jet launching - MHD simulations of the accretion-ejection structure

Accretion & outflows throughout the scales

Lyon, 2014, October 1

Christian Fendt





Jet launching - MHD simulations of the accretion-ejection structure

Contents:

1) Background I: Observational summary

2) Background II: MHD jets, formation & launching, relativistic effects

3) Simulations of jet launching: Fluxes, bipolar asymmetry

4) Jets from a mean-field disk dynamo

A) Jet rotation by helical MHD shocks

B) Relativistic jets: MHD & radiation:

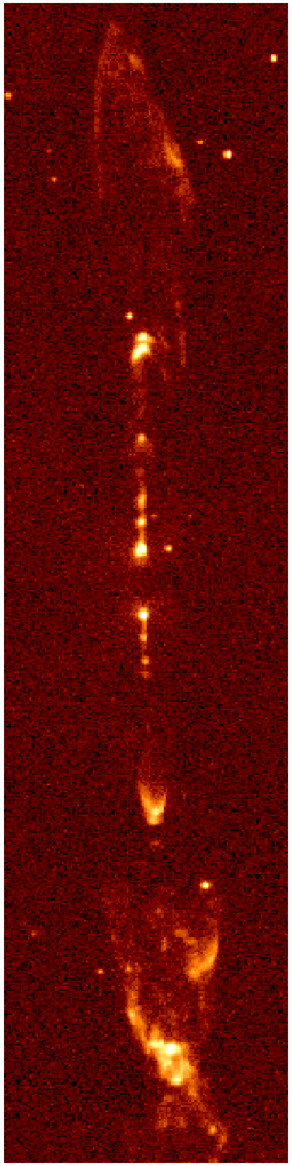
jet formation (simulations), synchrotron mock observations

Collaborators:

Deniss Stepanovs, Somayeh Sheikhnezami, Qian Qian,
Bhargav Vaidya, Oliver Porth

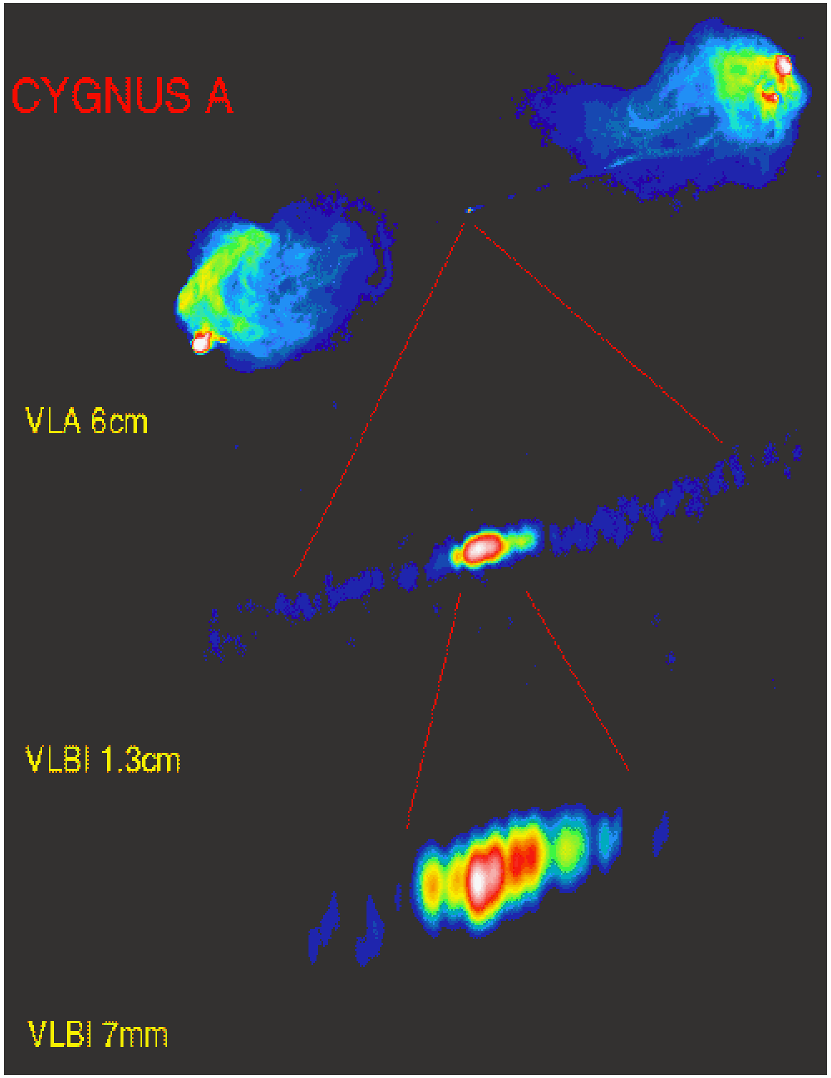
Jets: a common astrophysical phenomenon

Protostellar jets



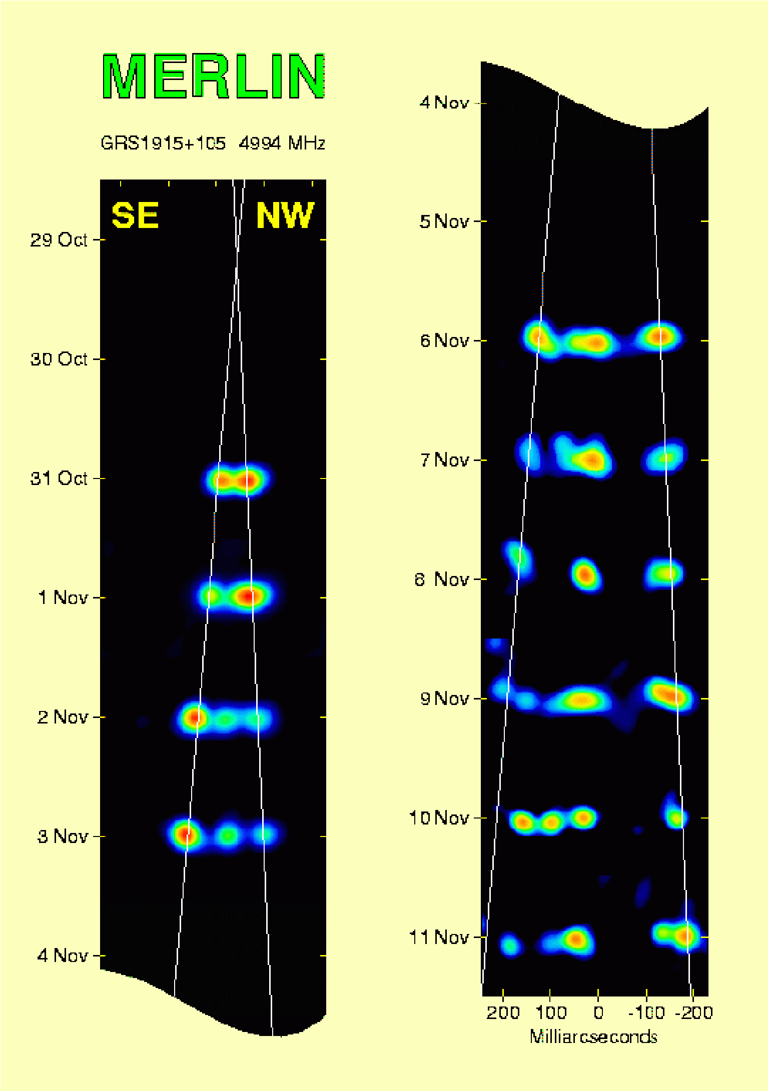
HH 212 H_2, 2.12 μm
(McCaughrean etal '98)

Extragalactic jets



Cyg A radio map, resolution 0.1pc = 130 light days (Krichbaum etal)

Micro quasars (μQ)



GRS 1915+105 D=12kpc, M_{BH}=14M_{O}
v=0.92c, $v_{j,app}$=1.25c, $v_{cj,app}$=0.65c
(Fender '99, Greiner etal '02)

Jets - observational overview

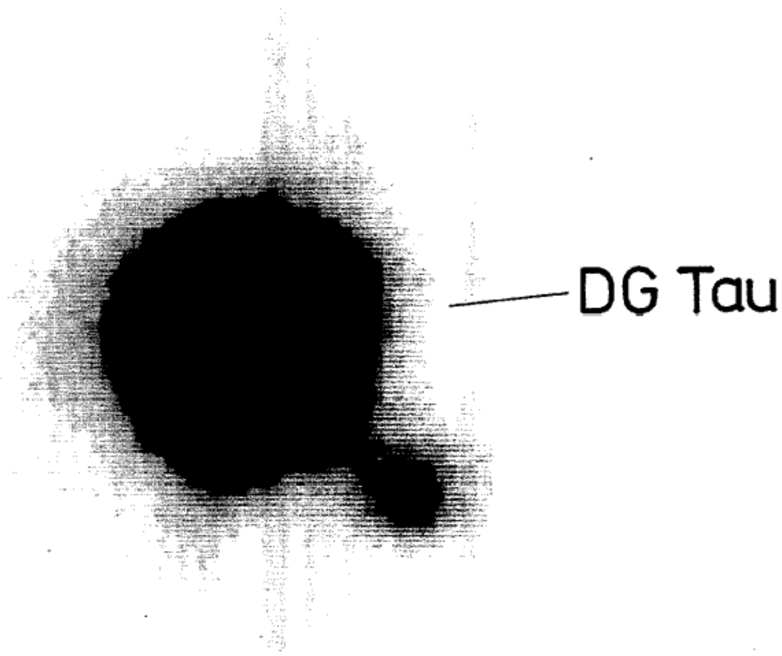
Protostellar (YSO) jets & outflows

-> “micro jets” / pc-scale jets

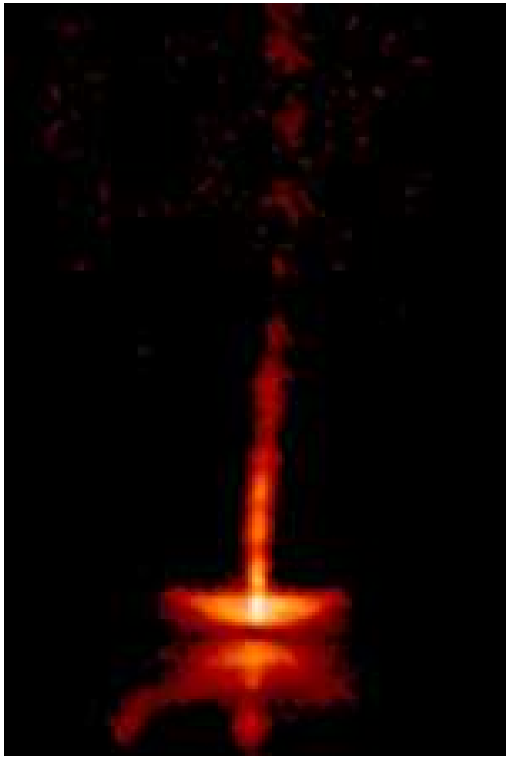
-> one-sided / two-sided

-> velocity < 500 km/s (proper motion, Doppler shift)

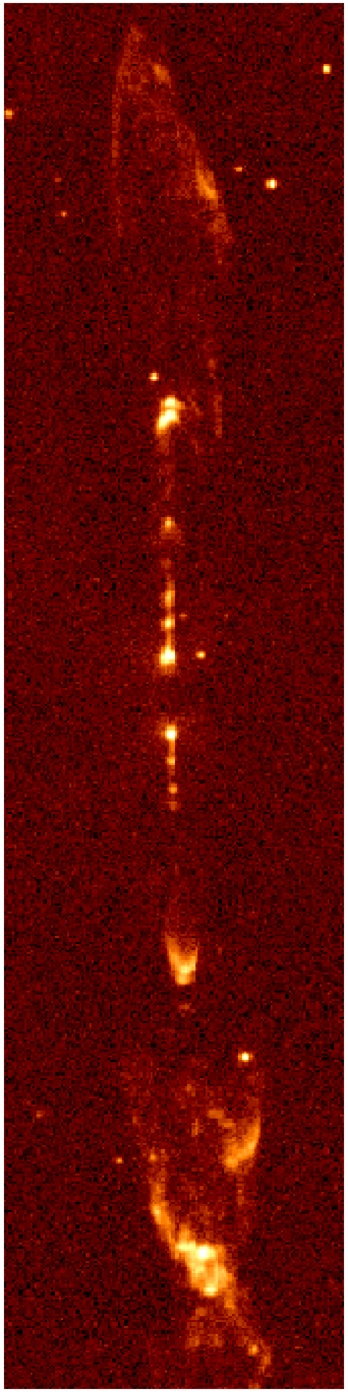
-> densities < 10^4 cm^{-3} (line ratios)



DG Tau **[SII]**
(Mundt & Fried 1983)



HH 30 [SII] (HST)



HH 212 H_2, 2.12 μm
(McCaughrean et al. '98)

Jets - observational overview

AGN jets are magnetized

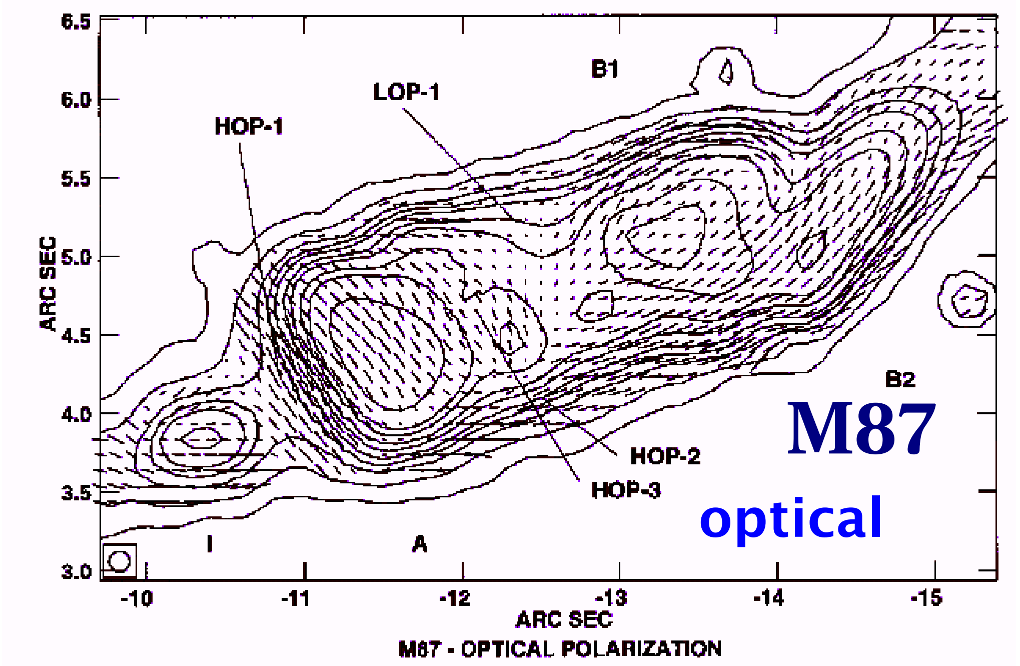
Polarisation maps

(HST & VLA Perlman et al 1999,
resolution 0."2 =15 pc):

-> polarisation degree 40 – 50%

-> synchrotron radiation
of highly relativistic electrons

-> **ordered µG magnetic field
on kpc-scales**

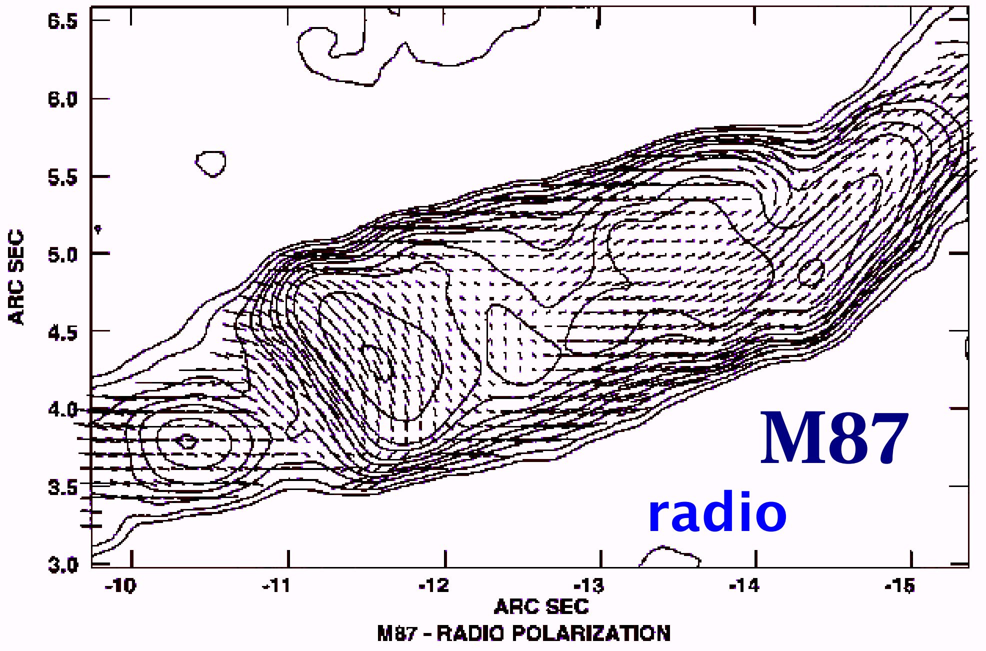


AGN jets are relativistic:

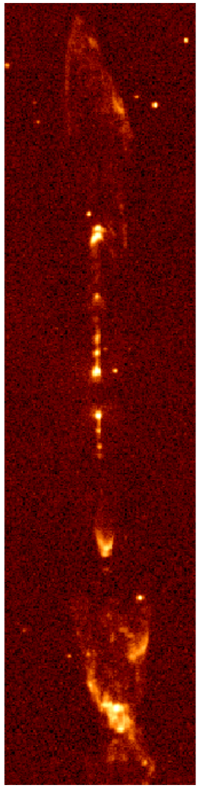
-> superluminal ejection of knots
from AGN cores

<u>However:</u> exact velocity unknown,
no direct detection

-> mass fluxes unknown, matter content
(leptonic/hadronic) not yet clear



Jets - observational overview



What is a jet?

-> **Collimated beam of matter of high velocity**

- Sources: AGN, YSO, μ-quasars, pulsars, GRBs

  -> wide range of central mass & energy output:

  $M_{source} \sim 1 \dots 10^8\ M_O$, $P_{jet} \sim 10^{33} \dots 10^{43}$ erg/s

- Jet sources host accretion disks
- Jet speed > escape speed: -> jets launched close to central object
- Jet sources / jets are magnetized:

  $B_{jet} \sim \mu G$ (YSO) ... mG (AGN), $B_{source} \sim$ kG (YSO) ... GG (μQ)

- Jets appear asymmetric (most of them)
- Knots: generated intrinsically or externally?

Jets - observational overview

Conclusion:

same jet driving mechanism (?):

i) not an intrinsically relativistic, but **magnetic** phenomenon

ii) launched from **accretion disks**

-> time scale of physical processes scale with central mass:

example: orbital period at inner disk radius $R_{in} = 3\ R_{source}$

$$\tau_{Kep,Rin} = \sqrt{\frac{27 R^3_{YSO}}{G M_{YSO}}} \simeq 10^d \simeq \sqrt{\frac{27 R^3_{SMBH}}{G M_{SMBH}}} \simeq 10^7 \sqrt{\frac{27 R^3_{\mu Q}}{G M_{\mu Q}}}$$

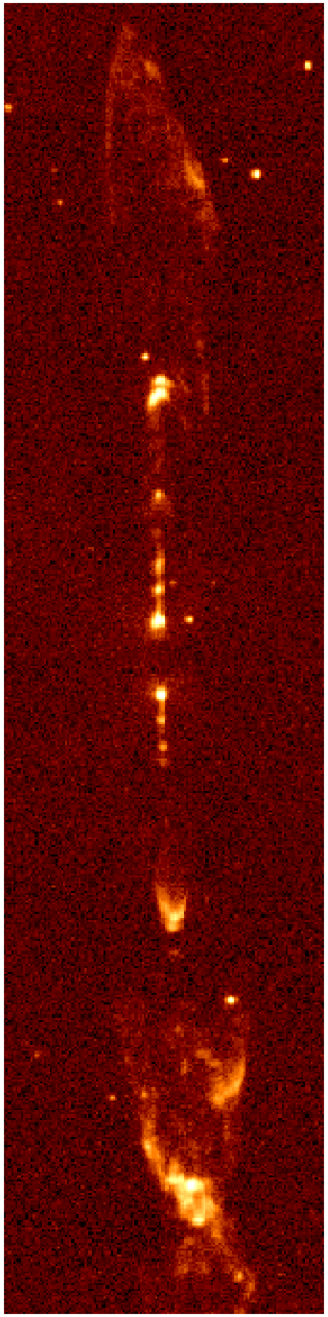
Jet launching - MHD simulations of the accretion-ejection structure

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

-> accretion-ejection structure

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

HH 212



Zinnecker et al. 1998

Jet time scales: (young stars)

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

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

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

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

-> compare to disk life time ~ 10^6 yrs

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

Jet launching - MHD simulations of the accretion-ejection structure

Feedback ?

Transfer rates for mass, energy, angular momentum?

-> accretion-ejection structure

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 ?

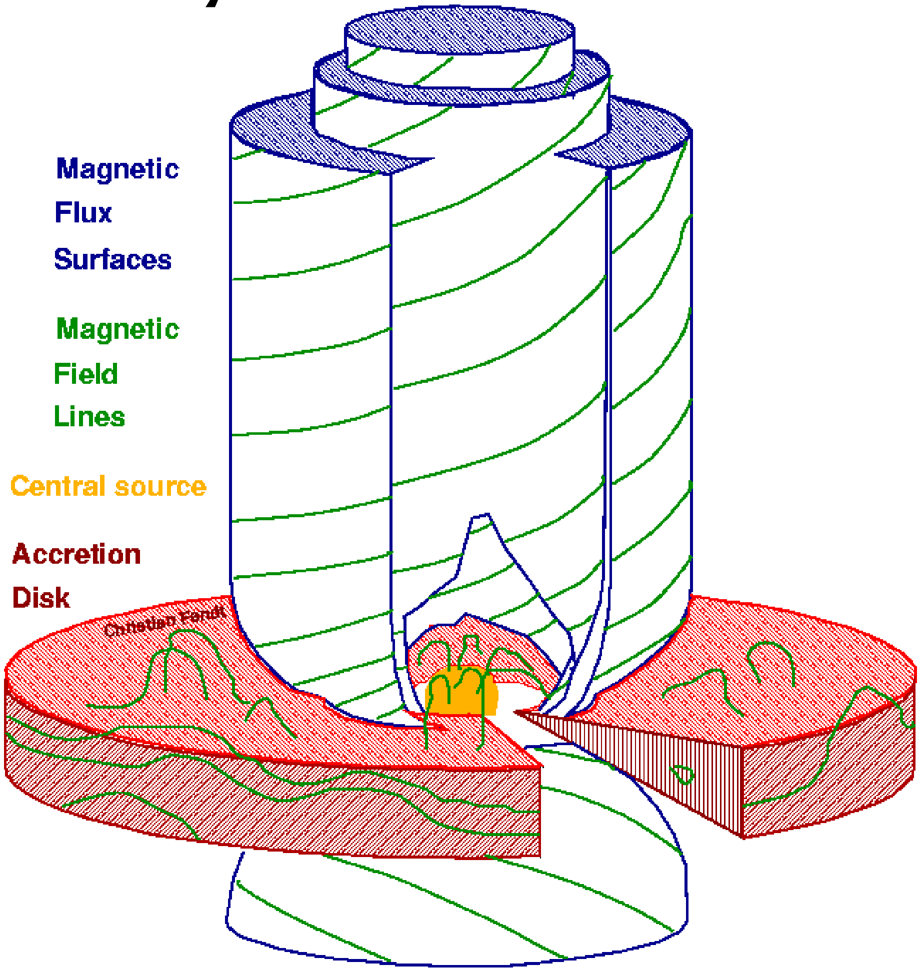
2) Ejection of disk / stellar material
into wind?

3) Accretion disk structure ?

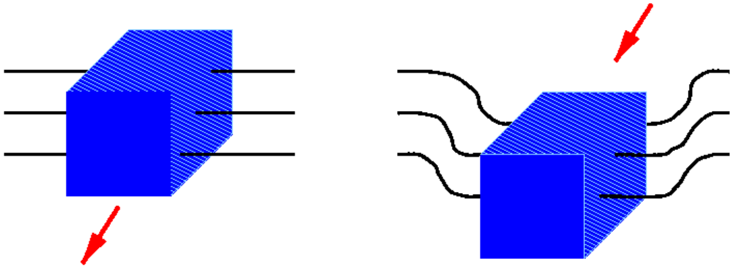
4) Origin of magnetic field ?

5) Jet propagation / interaction
with ambient medium ?

6) Impact of central spine jet
(stellar wind / black hole jet) ?



1) MHD model of jets

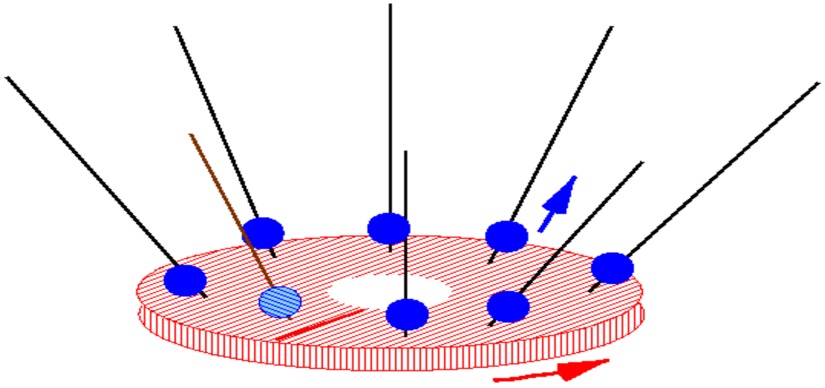


MHD jet formation:

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

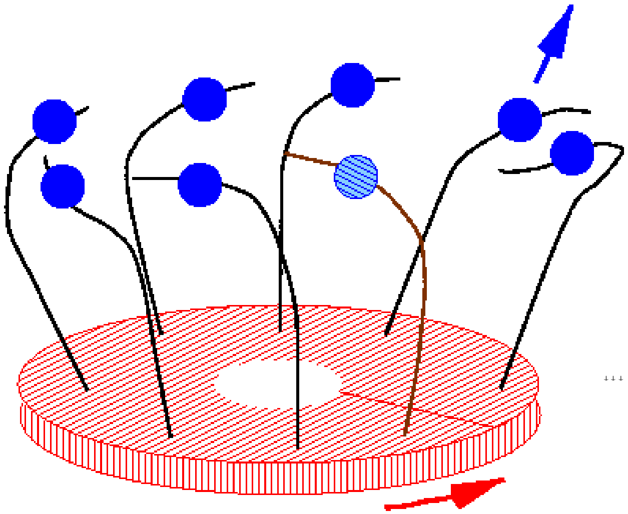
-> three mechanisms at work for MHD jet formation:

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



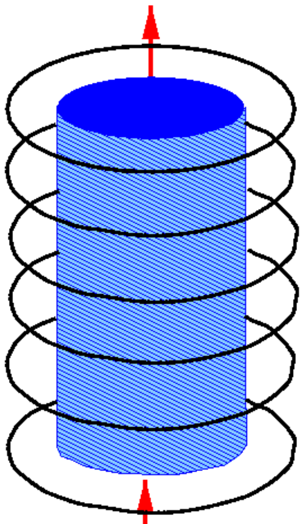
centrifugal force

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

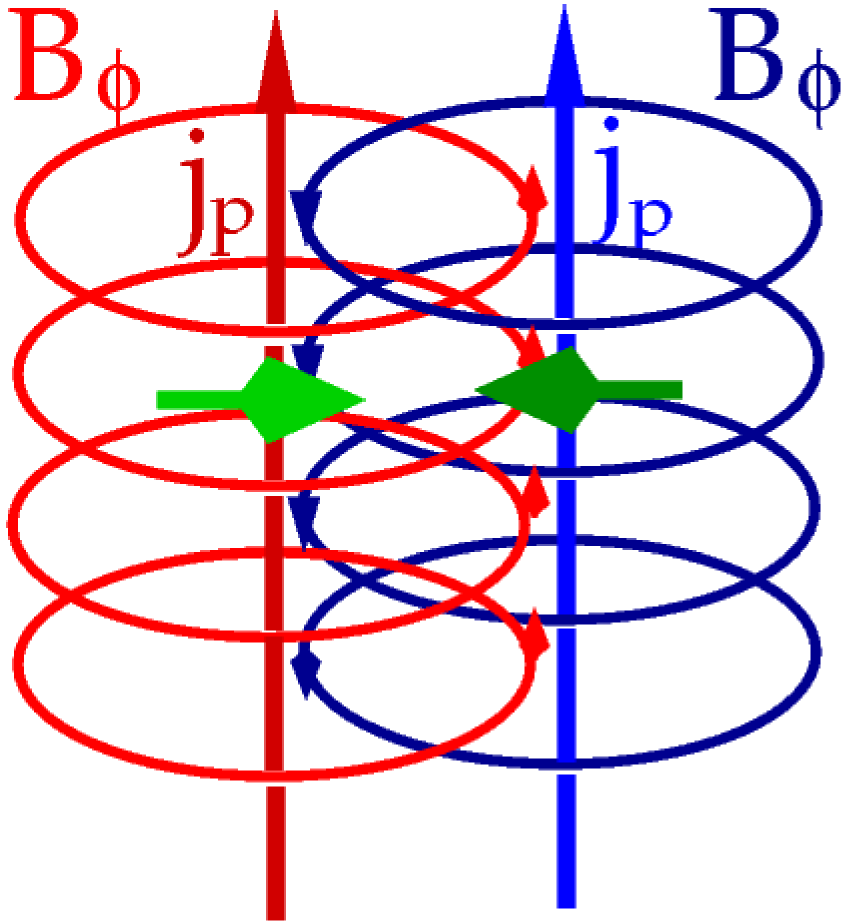
Simple explanation:

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**



$F_L = j_p B_\phi$ $F_L = j_p B_\phi$

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 ...

Self-collimation of MHD jets

Proposed by general analytic considerations by

Heyvaerts & Norman (1989) for non-relativistic jets, and

Chiueh, Li & Begelman (1991) for relativistic jets:

> " ... we find that all flux surfaces generally converge to either cylinders or paraboloids that are nested around the rotational axis."

-> current-carrying jets self-collimate to cylindrical configuration

-> but:

be aware of the "globality" of the magnetic field / electric current system:

- -> field lines/ electric current must close
  - -> return currents, boundary effects

Self-collimation of (non-relativistic) MHD jets

Numerical proof of MHD self-collimation by simulations

(Ustyugova etal. 1995; Ouyed & Pudritz 1997)

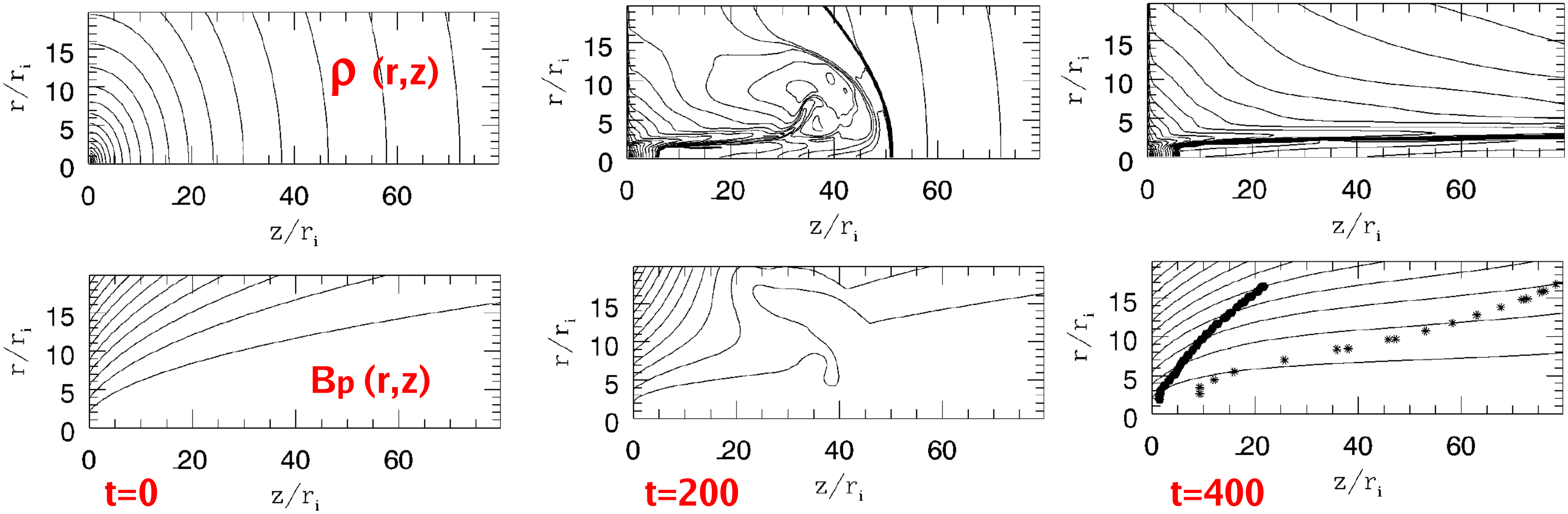
Model assumptions (OP 97):

-> ideal MHD, axisymmetry, Keplerian disk as boundary condition

-> mass injection <u>from disk surface</u> (mass / maagnetic flux prescribed)

-> asymptotic jet speed ~ Keplerian speed at foot point (along each field line)

-> inner jet collimates to cylindrical shape



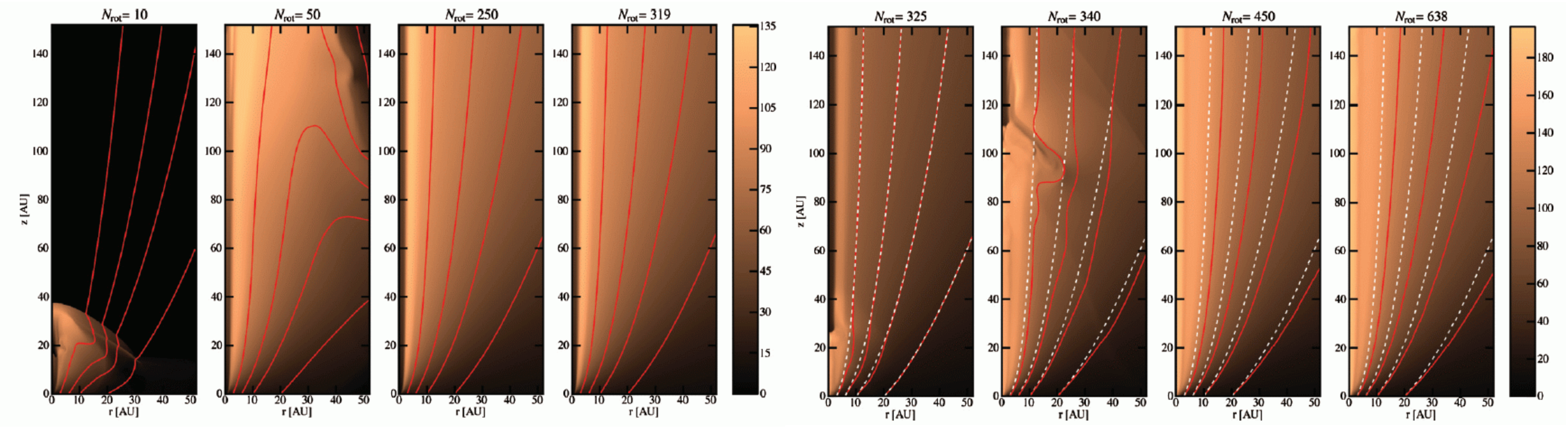
Self-collimation of (non-relativistic) MHD jets

Numerical proof of MHD self-collimation by simulations

Model extensions:

-> influence of mass loading disk surface (Ouyed & Pudritz 1999)
-> central dipolar field (Fendt & Elstner 1999, 2000)
-> magnetic diffusivity weakens collimation (Fendt & Cemeljic 2002)
-> disk magnetic field distribution (Fendt 2006, Pudritz et al. 2006)
-> flares and ejection events of anti-aligned disk and stellar field (Fendt 2009)
-> relativistic MHD jets (Porth et al. 2010, 2011)

-> **radiation pressure of central star & inner disk (Vaidya et al. 2011):**
field lines (red, white) & poloidal velocity (colors, km/s)



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),

Stepanovs & Fendt, ApJ 793, 31 (2014)

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

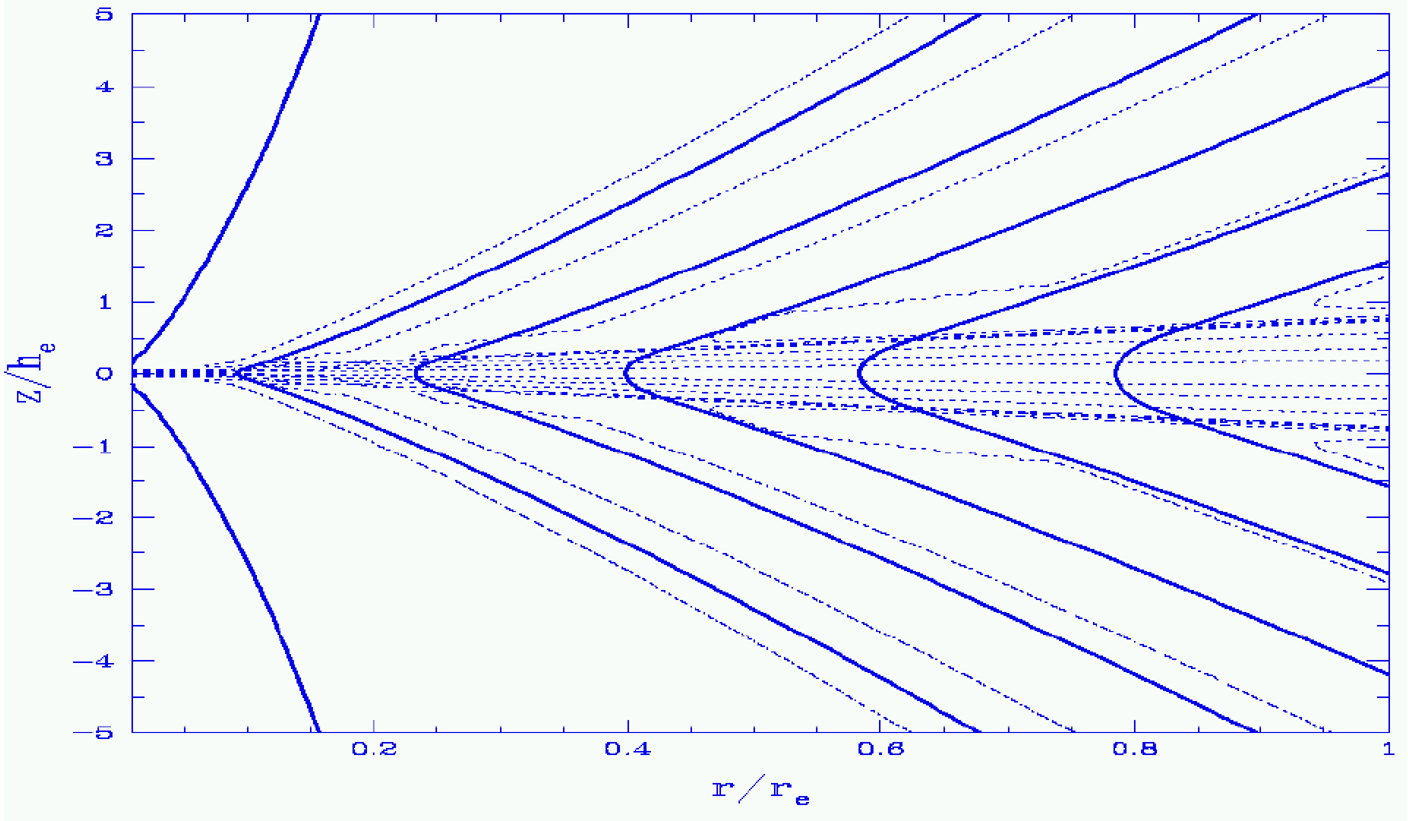
1) Jet launching: disk - jet connection

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

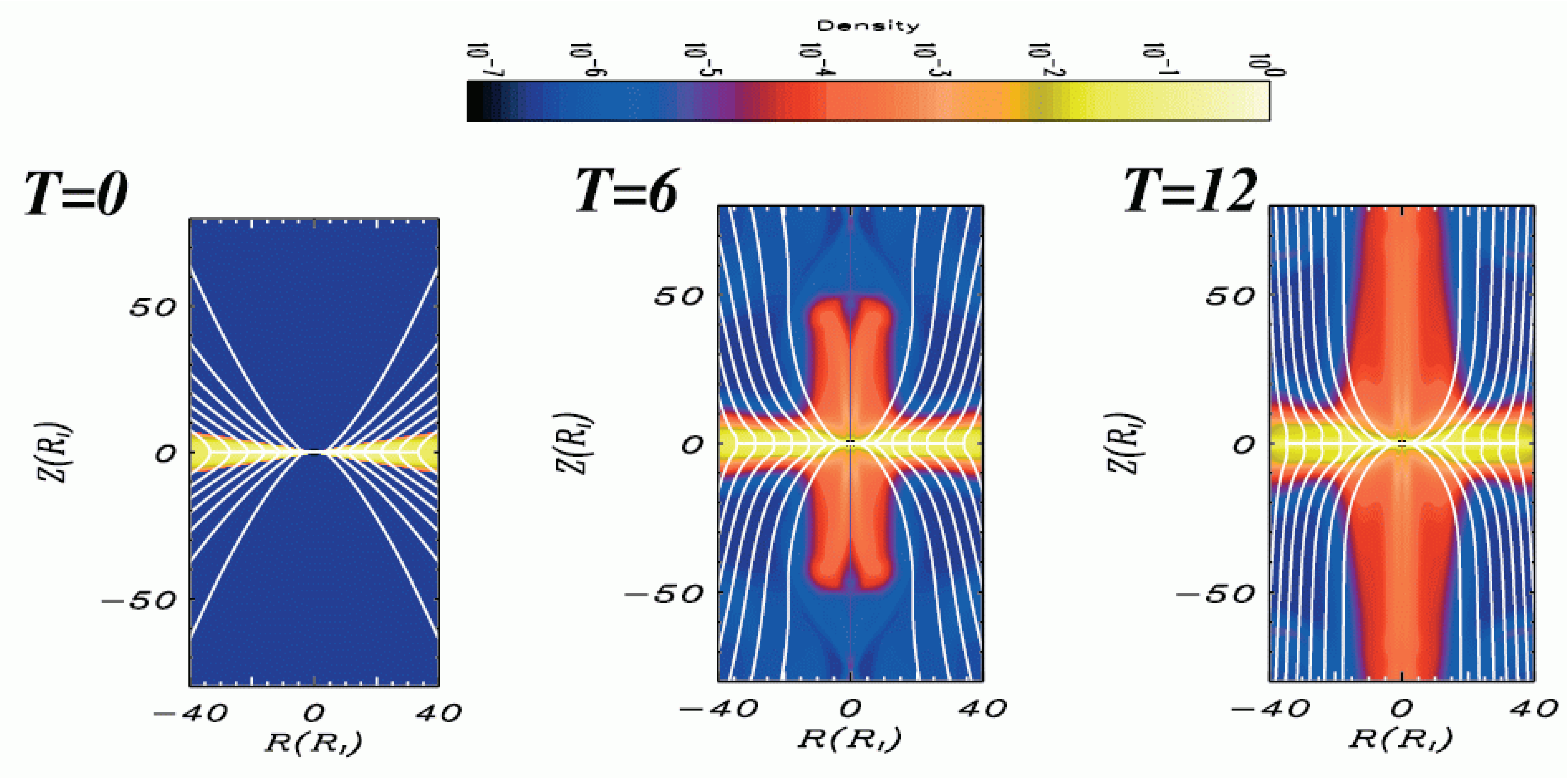
Jet launching: disk - jet connection

Magnetic accretion-ejection structures

Casse & Keppens (2002, 2004) :

first “long-term” simulations, resistive MHD, 50 rotations

Note the early, seminal simulations of disk-jets by Uchida & Shibata (1983)



Density and poloidal magnetic field lines

2) MHD launching: disk - jet connection

Simulation setup:

-> initial Keplerian disk (no advection)

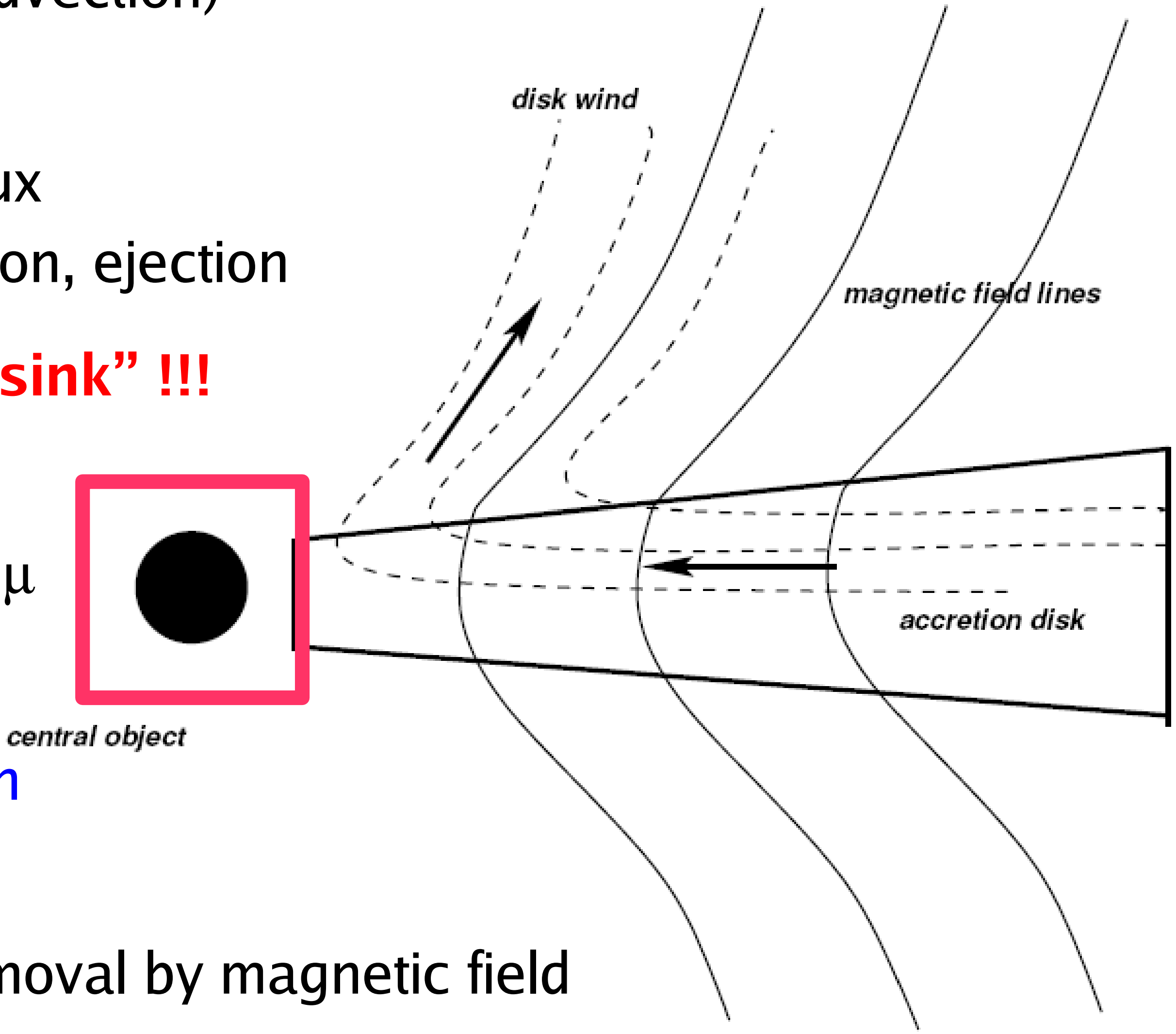
-> **“resolve”** **disk physics:**
  - advection/diffusion of flux
  - launching: mass accretion, ejection

-> 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



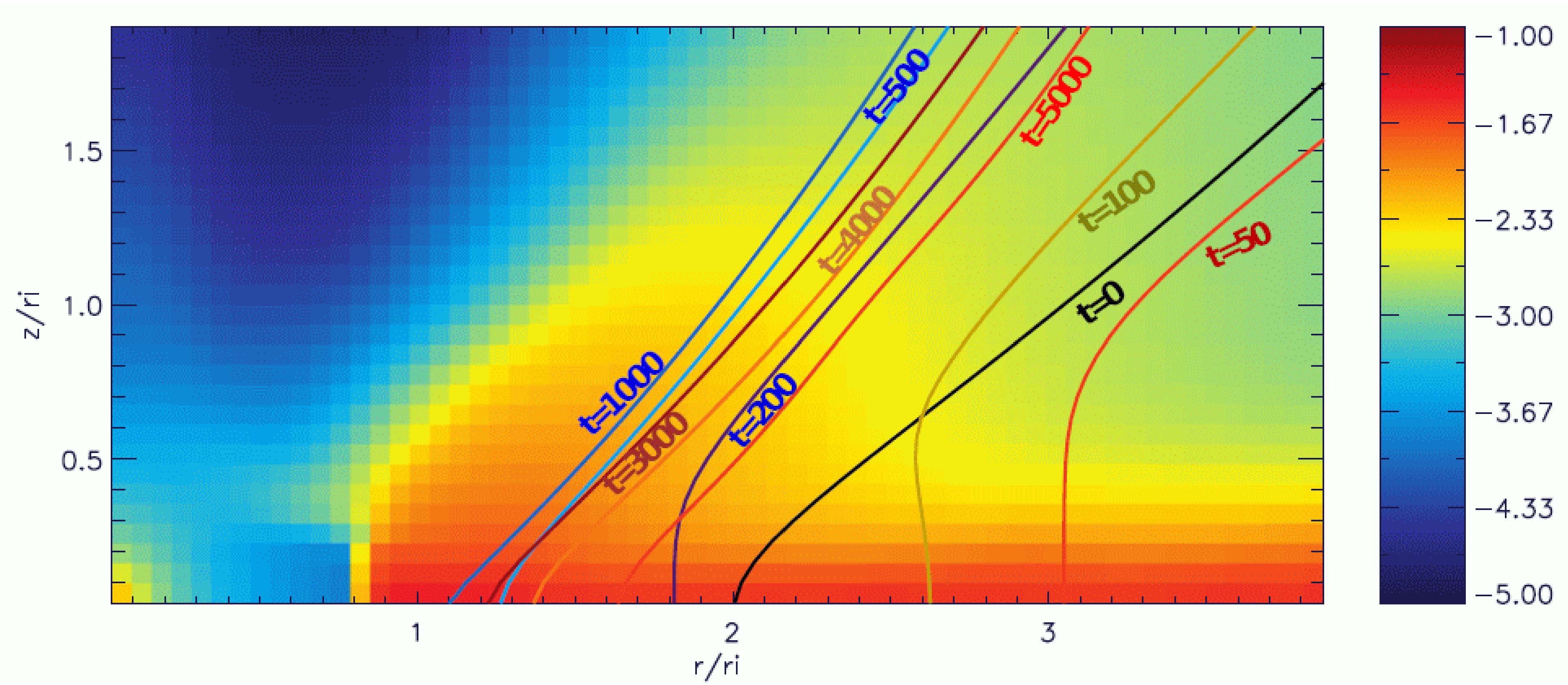
2) MHD launching: disk - jet connection

-> 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

colors: density at t=5000, lines: **one** magn. flux surface at different times

2) MHD launching: disk - jet connection

Movie 1:   Diffusion - advection

Movie 2:   Launching in one hemisphere

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:

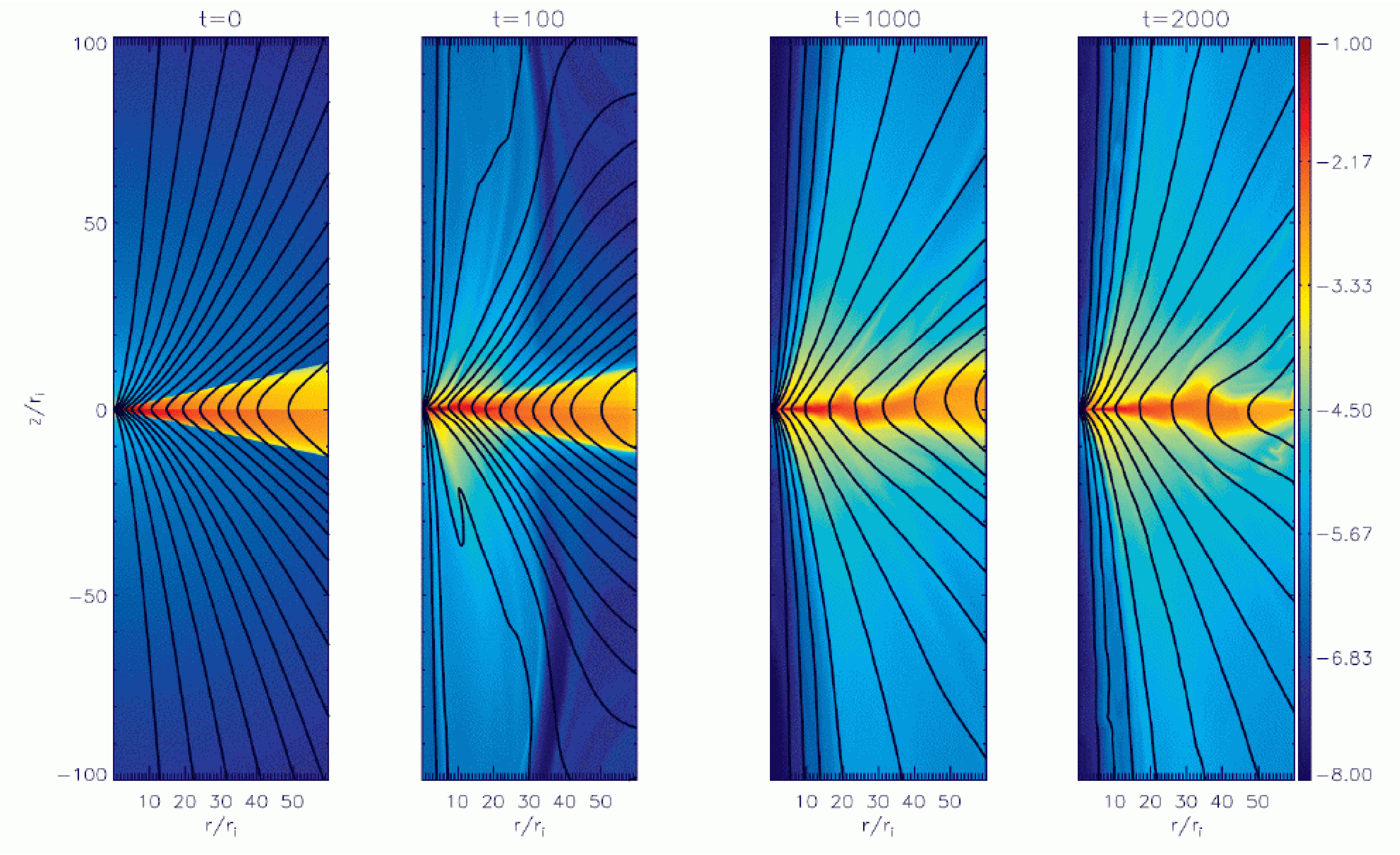
v5 local description for $\eta=\eta(\rho(r,z),t)$

2) MHD launching: disk - jet connection

Movie 3: Bipolar launching simulation

2) Jet launching: bipolar jets

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

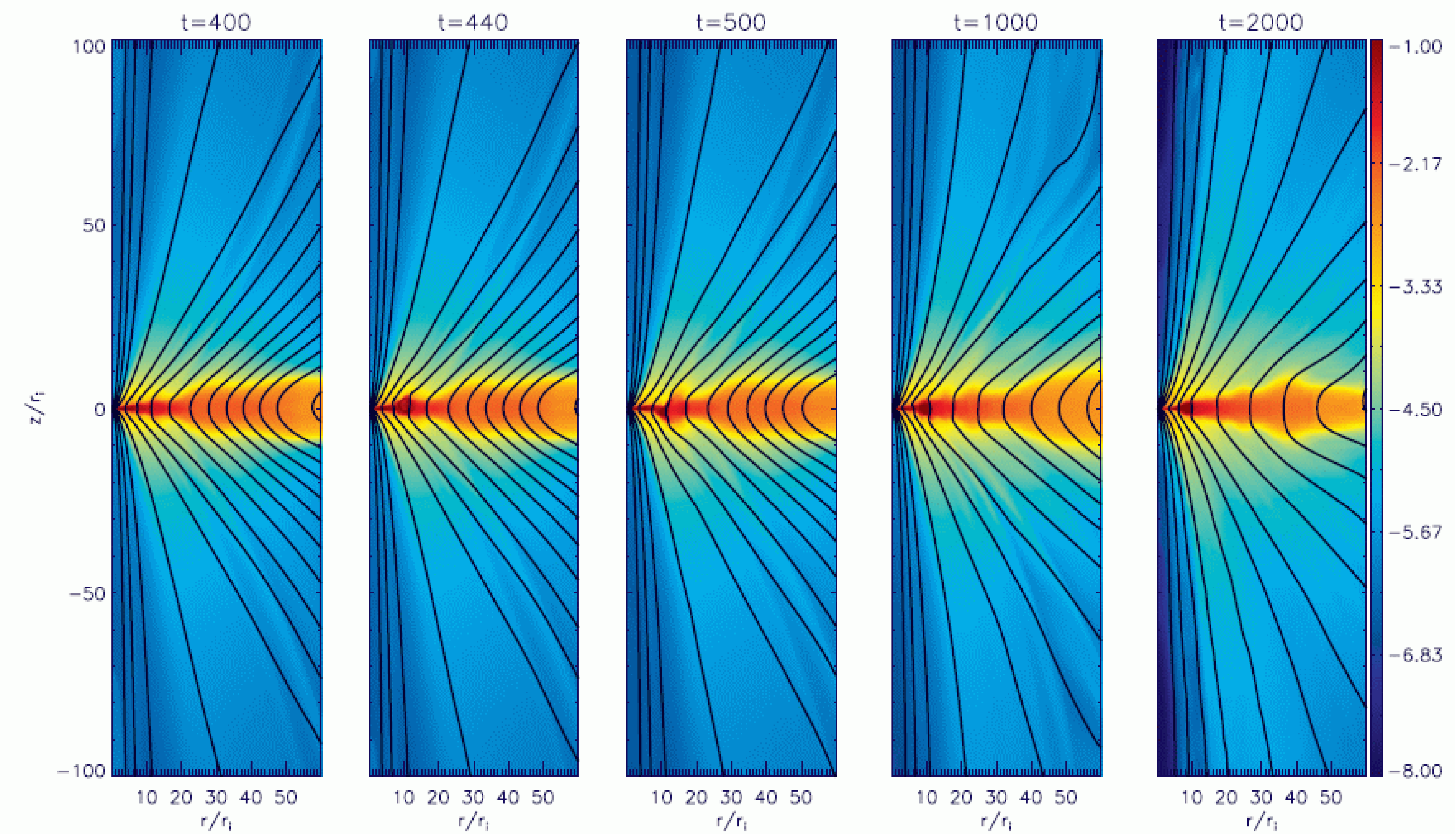


colors: density, lines: magnetic flux surfaces

2) Jet launching: bipolar jets

case v3): symmetric disk with localized energy injection

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



colors: density, lines: magnetic flux surfaces

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 (time delay)
-> asymmetry propagated along outflow

v4: asymmetric ambient medium:

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

v5: local diffusivity model: asymmetries live longer

2) Jet launching: bipolar jets

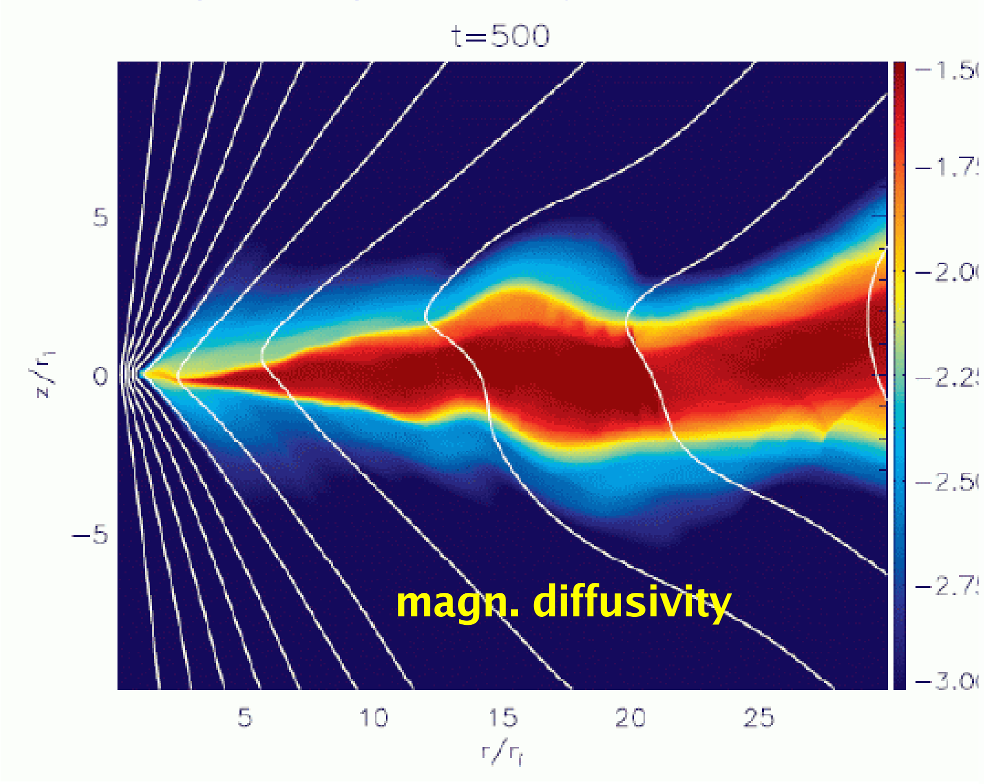
v5): local description of diffusivity:

density-weighted “local disk height H_L”

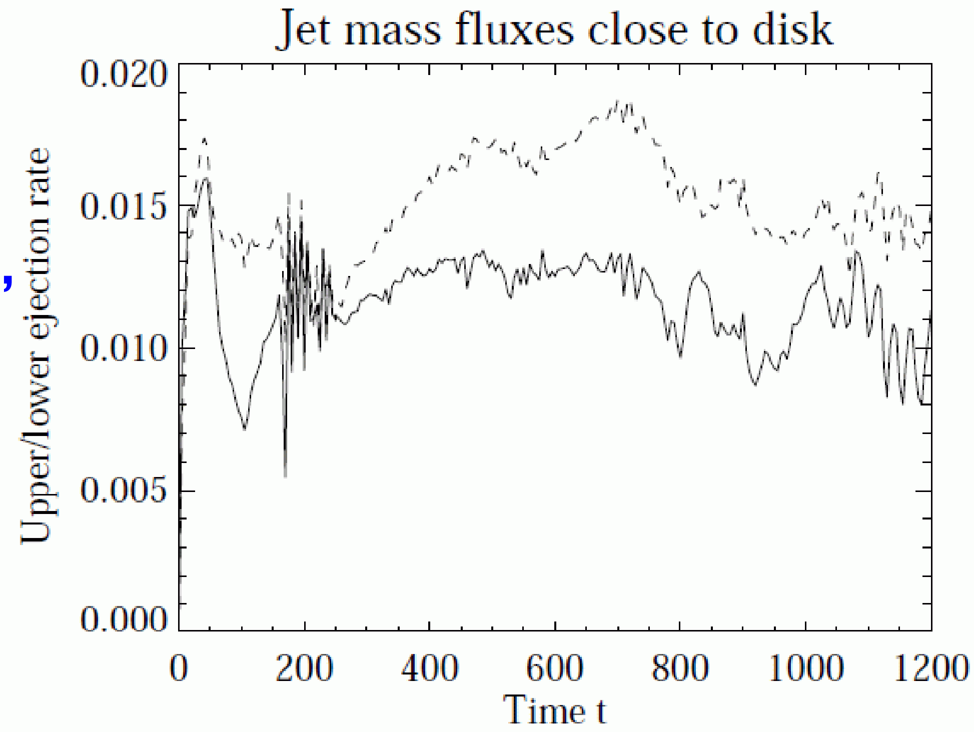
$$\eta(r,z)=\alpha_M H_L(r,z)\left[1-\frac{H_L(r,z)}{H_0}\right]^{-1}$$

$$H_L(r,z)\equiv\rho^{\sigma_\rho}(r,z)\sqrt{\gamma\frac{P(r,z)}{\rho(r,z)}}\frac{1}{v_{Kep}(r)}r^{\sigma_r}$$

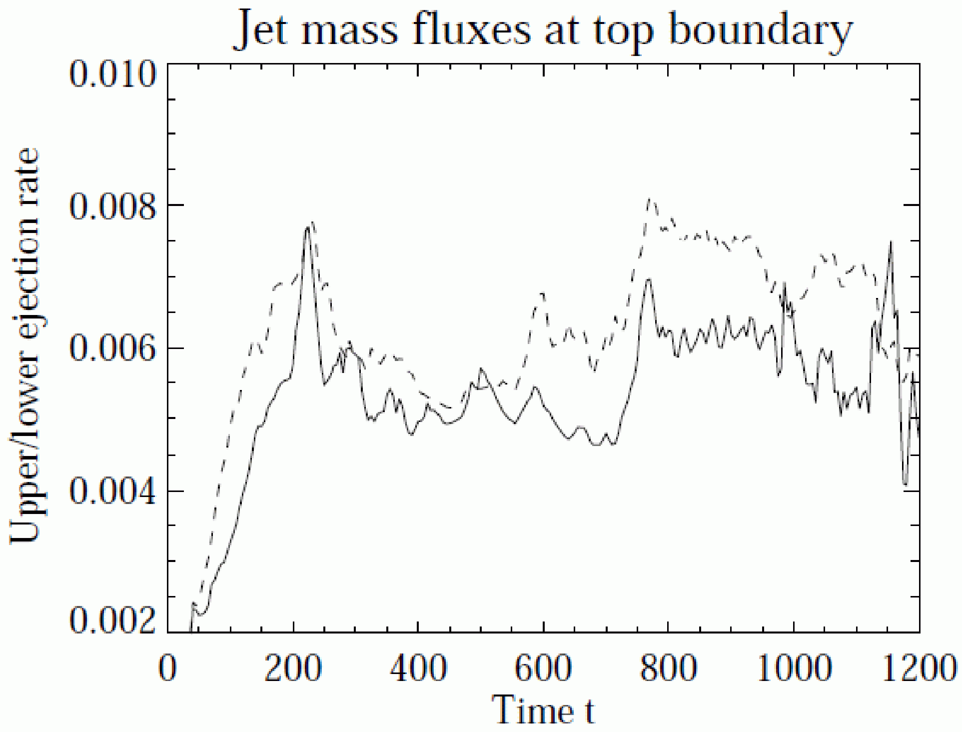
-> long-living disk & jet asymmetry !



magn. diffusivity



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 (time delay)
-> asymmetry propagated along outflow

v4: asymmetric ambient medium:

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

v5: local diffusivity model: asymmetries live longer

3) A mean-field disk dynamo

-> further investigate launching time scales

-> extend numerical grid to observational scales

-> consider “self-generated” disk magnetic field

    -> added dynamo equations to PLUTO code

Stepanovs & Fendt, ApJ 793, 31 (2014), Stepanovs & Fendt (2014), revised

Stepanovs, Fendt & Sheikhnezami (2014), in press

3) Jet launching: jets from disk dynamos

Stepanovs, Fendt et al, 2014 a,b,c:

-> 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 reaching observational time scales
    -> model setup allows for more than 100,000 inner disk orbits ~ 28 yrs

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

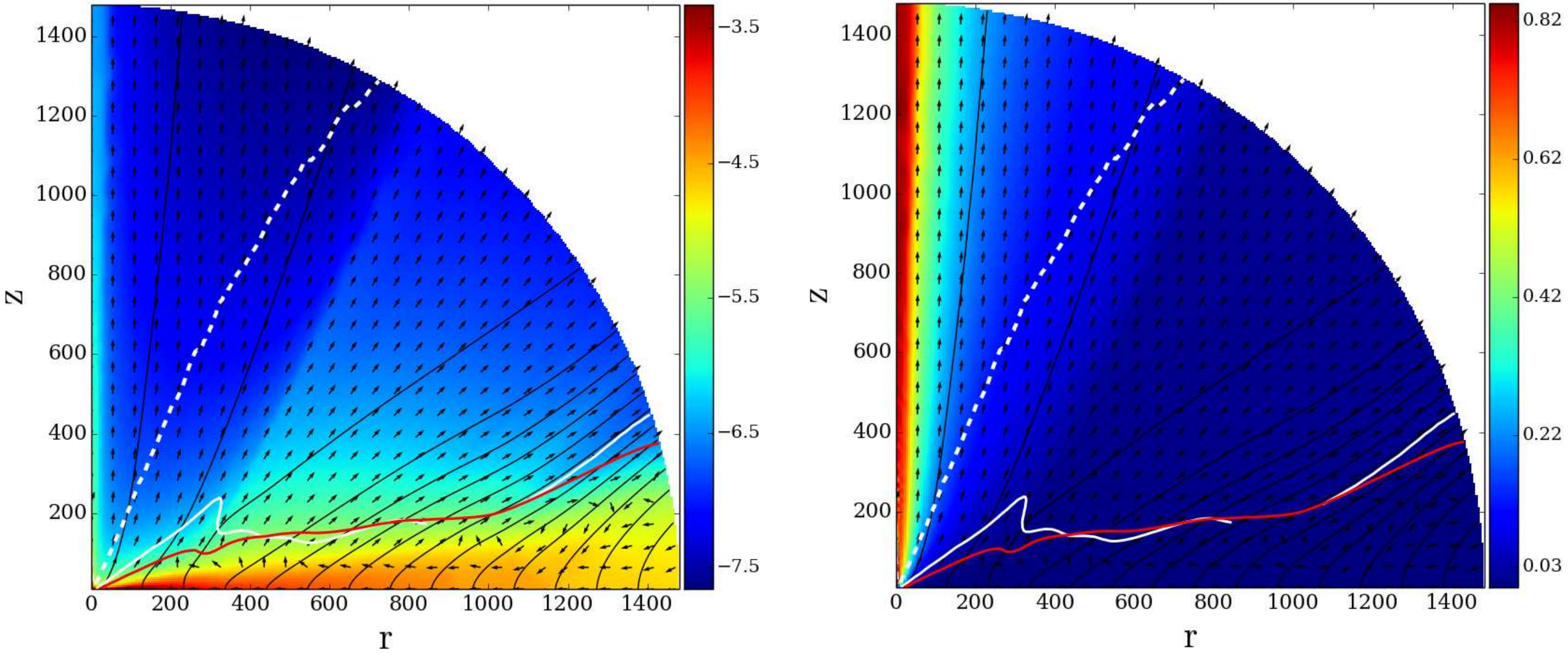
-> revise model for resistivity / magnetic diffusivity
    -> allow for mass supply from outer disk to inner disk

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)

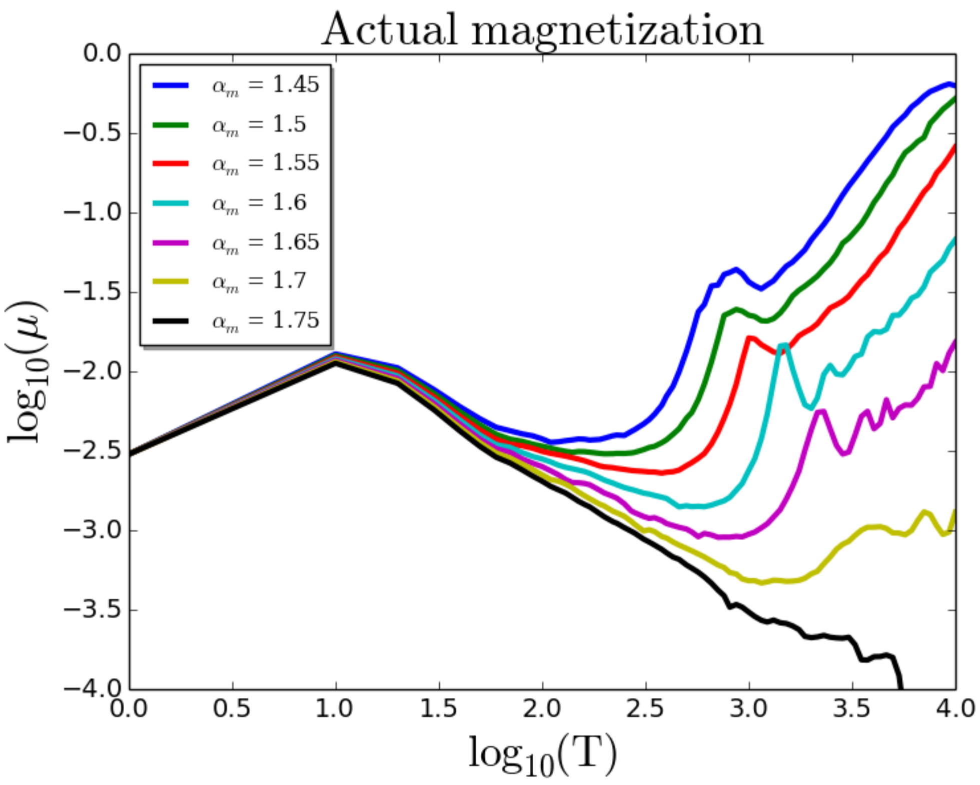
3) Jet launching: large numerical grid

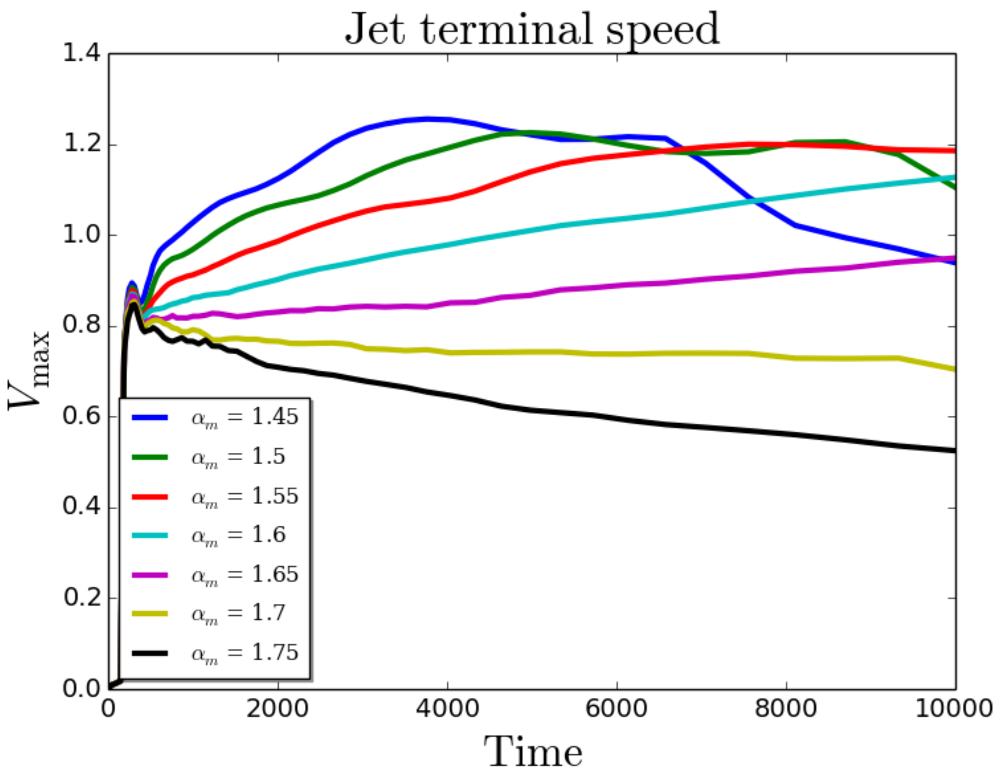
Movie 4: Jet launching on a large scale grid

3) Jet launching: large numerical grid

Question: What disk properties govern the outflow properties?

-> consider small part of jet launching area of the disk
-> calculate average disk properties, actual values (i.e. at 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)





3) Jet launching: large numerical grid

Question: What disk properties govern the outflow properties?

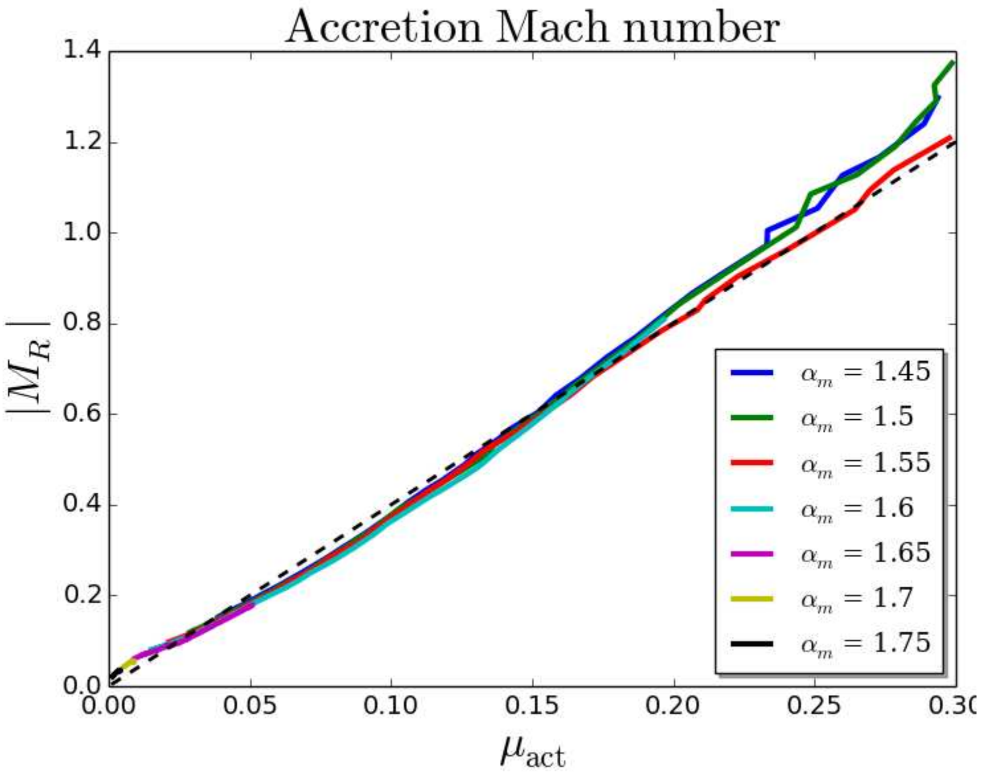
-> consider small part of jet launching area of the disk

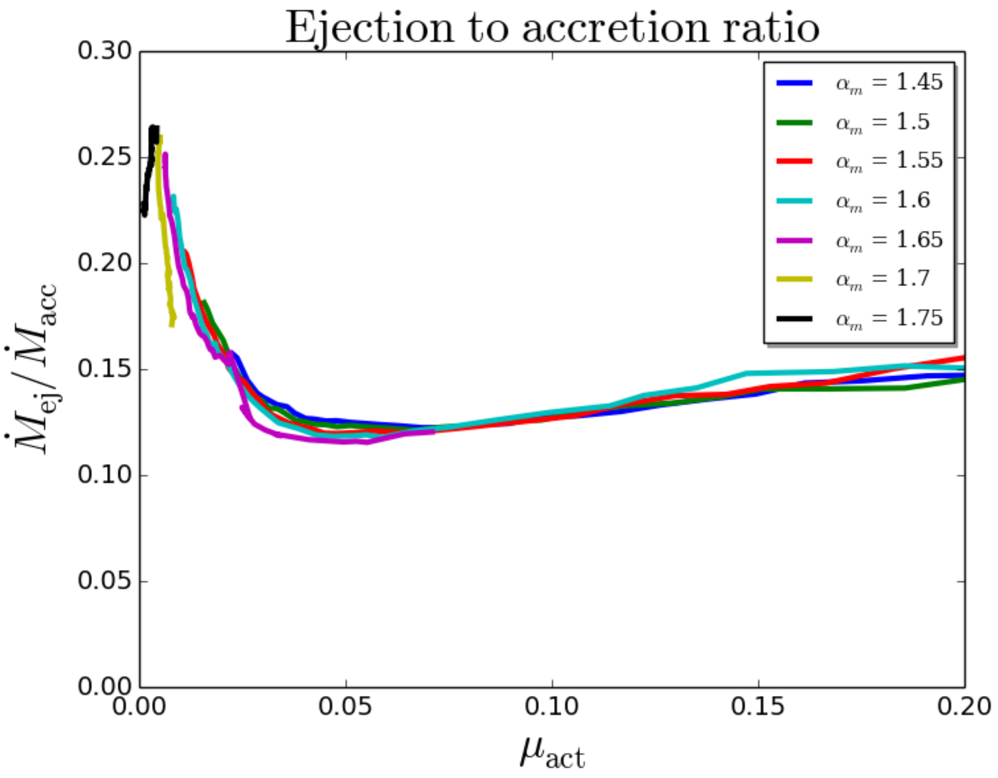
-> calculate average disk properties, actual values (i.e. a time):

-> 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)


Accretion Mach number


Ejection to accretion ratio

3) Jet launching: disk dynamo

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

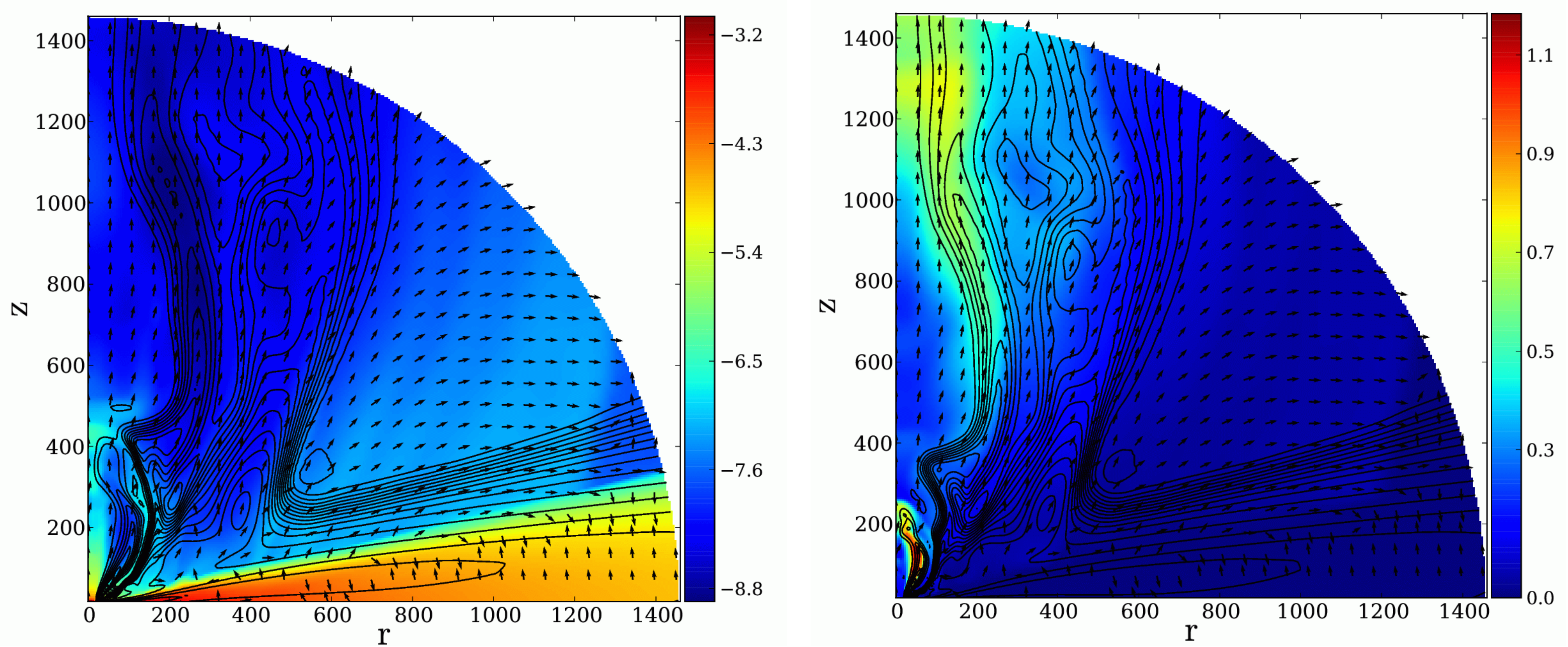
α^2-Ω-dynamo

Initial magnetic field: B_R, or B_ϕ , magnetization **$\mu \sim 10^{-4}$** ,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

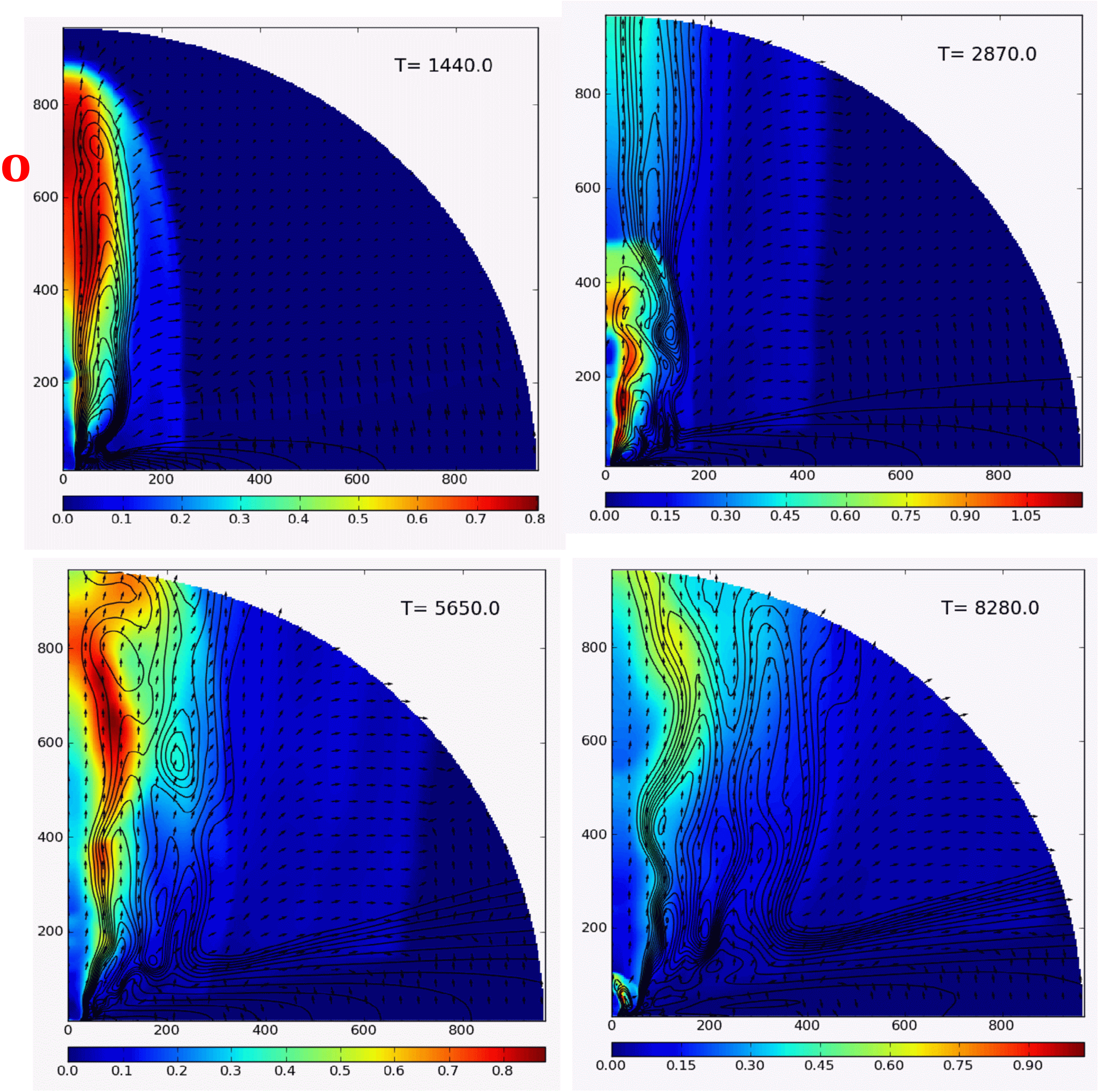
Movie 5: Dynamo action, inner disk

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

Movie6: Toy dynamo for modeling 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