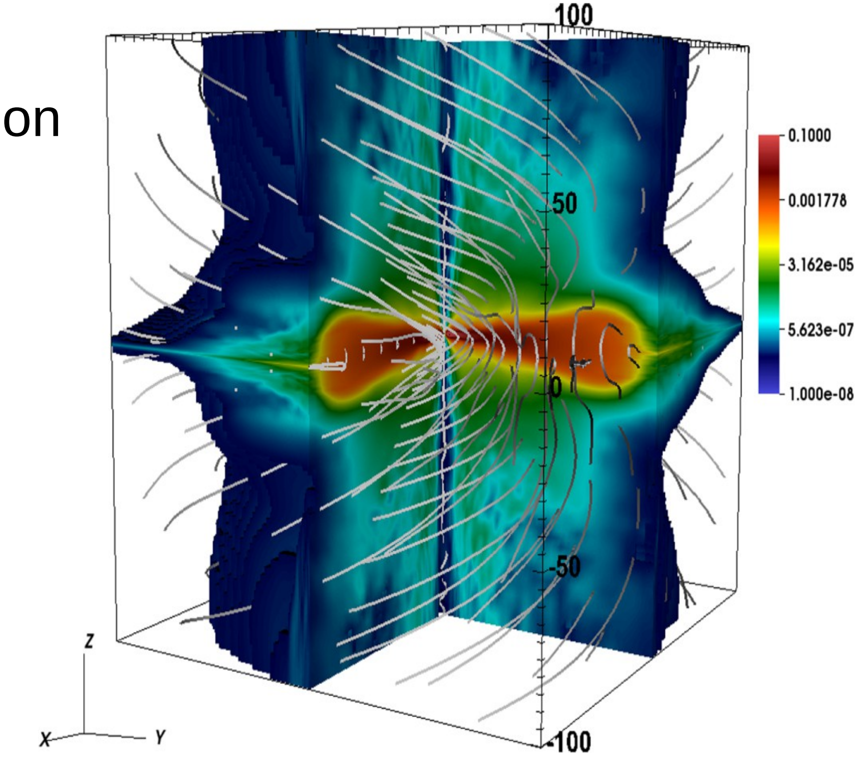
Modeling the magnetized accretion & outflow in young stellar objects

***Stars with a stable magnetic field*, Brno, Aug. 28, 2017**

Christian Fendt

Contents:

- Background: jet sources, MHD
- Jet launching: mass fluxes, disk magnetization
- Jets from a mean-field disk dynamo
- 3D launching: jets from disks in binaries



Collaborators:

Somayeh Sheikhnezami, Deniss Stepanovs,
Dennis Gassmann, Bhargav Vaidya, Oliver Porth

Jets - observational overview

Protostellar (YSO) jets & outflows

→ "micro jets" ↔ pc-scale jets

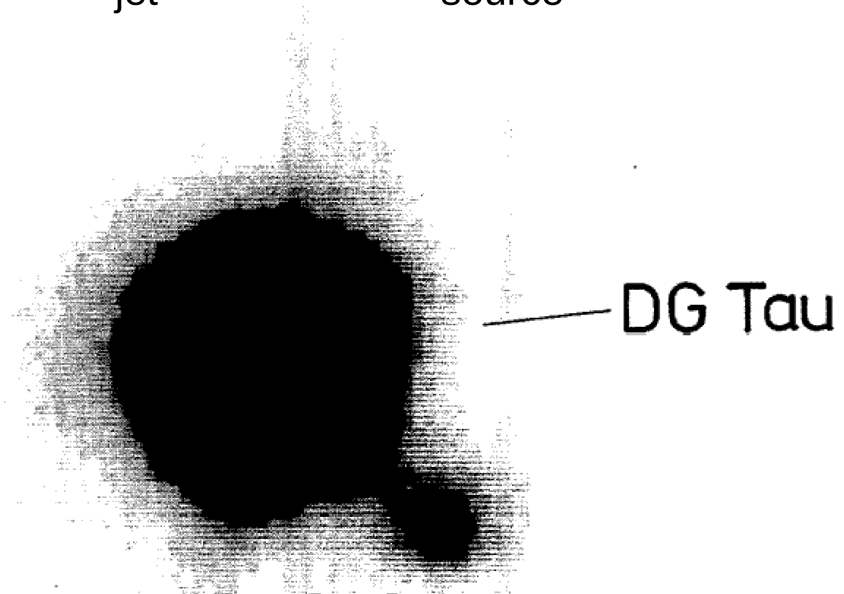
→ one-sided / two-sided, knotty structure

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

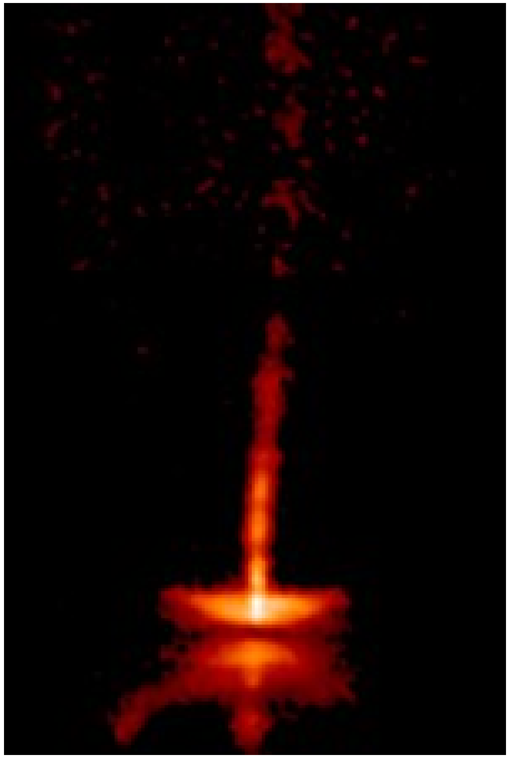
→ densities $< 10^4 \ cm^{-3}$ (from line ratios)

→ accretion disk

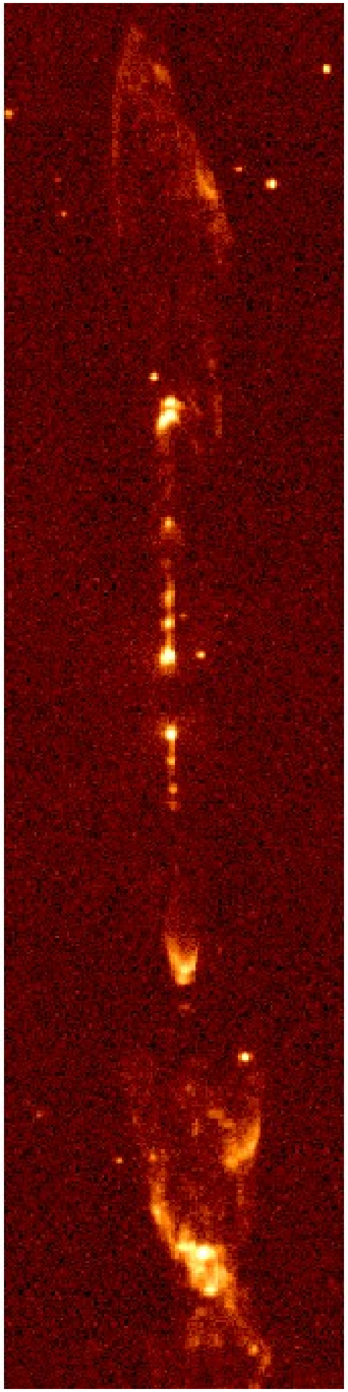
→ $B_{jet} \sim \mu G$ $B_{source} \sim kG$



DG Tau [SII]
(Mundt & Fried 1983)



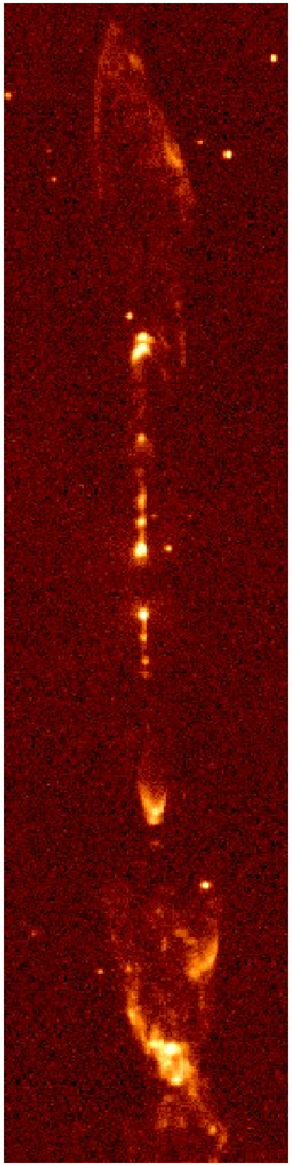
HH 30 [SII] (HST)



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

Jets: a common astrophysical phenomenon

Protostellar jets | **Extragalactic jets** | **Micro quasars (μQ)**



HH 212 H_2, 2.12 μm
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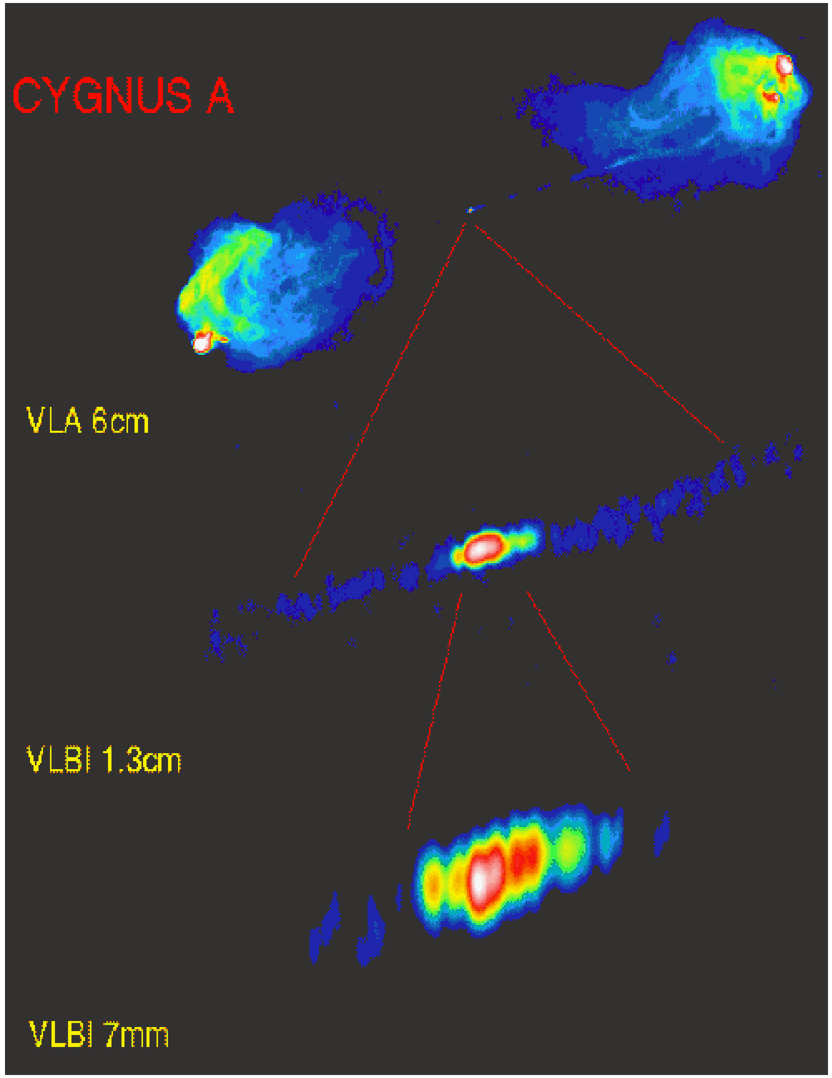
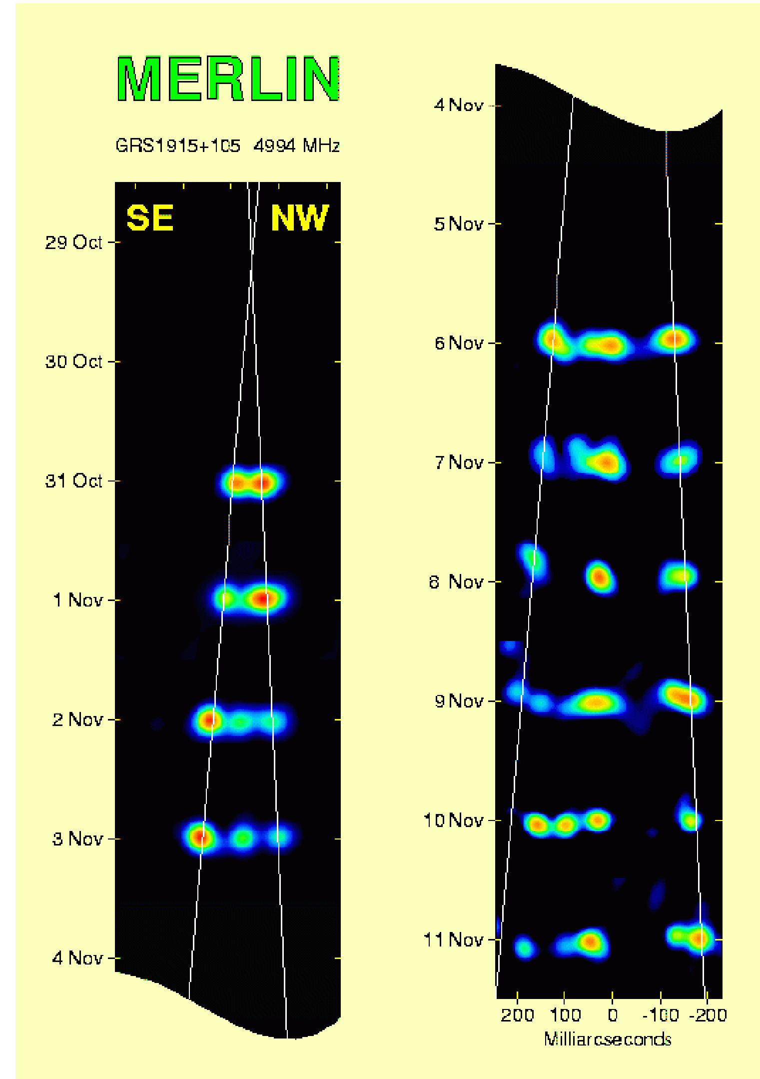
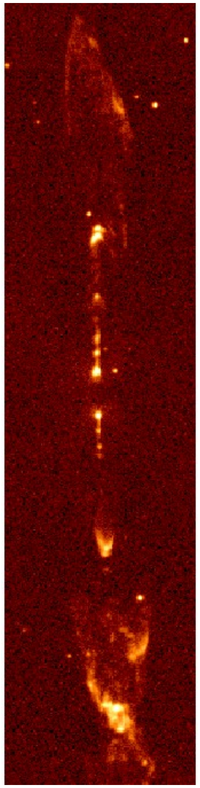


Cyg A radio map, resolution 0.1pc = 130 light days (Krichbaum+)



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+ '02)

Jets - observational overview



What is a jet?

→ collimated beam of <u>matter</u> of high velocity

- sources: **young stars (YSO)**, AGN, μ-Quasars,
  pulsars (?), GRBs (?)

- jet speed > escape speed → launching close to central object

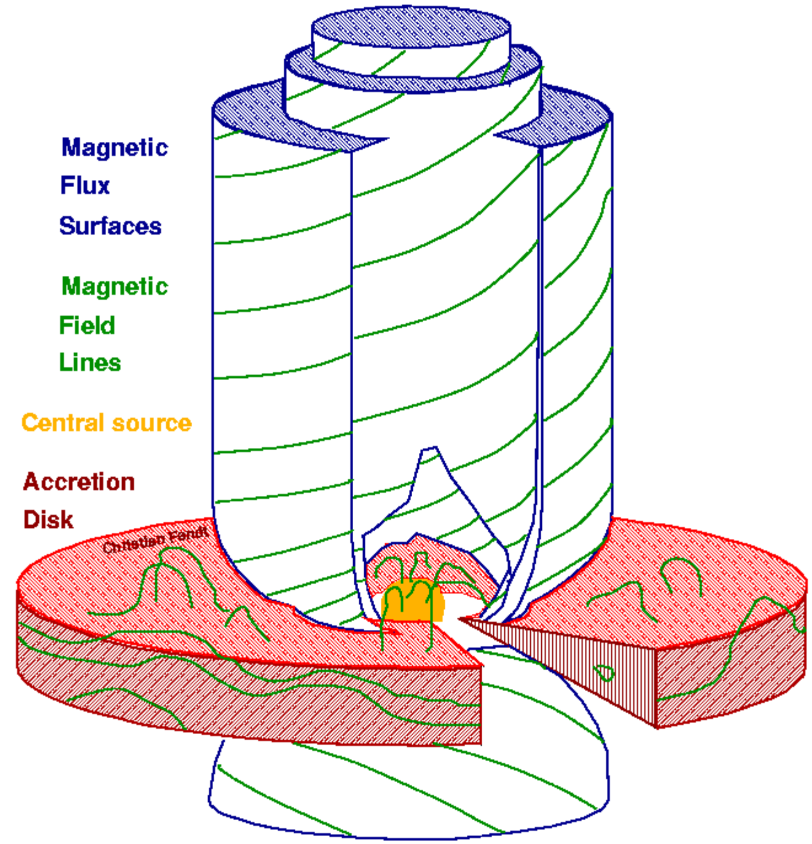
- (most) jets appear asymmetric

- jets are structured → knots: generated intrinsically or externally ?

- **jet sources host accretion disks**

- **jet sources / jets are magnetized**

Jets - observational overview



Conclusion:

same jet driving mechanism (?):

i) **magnetic** phenomenon

ii) launched from **accretion disks**

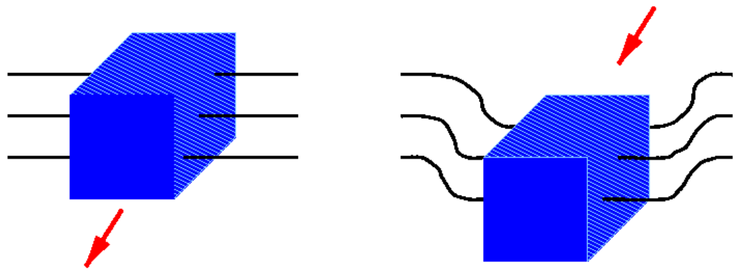
Jets:

collimated disk (+ "stellar") winds:

launched, accelerated,

collimated by magnetic forces

MHD model of jets



MHD jet formation from disks:

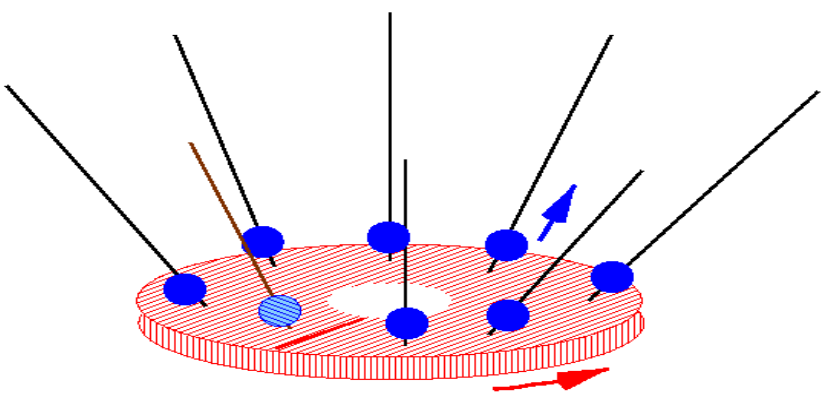
→ magnetic field lines act like wires / rubber band, loaded with beads

→ **three mechanisms at work:**

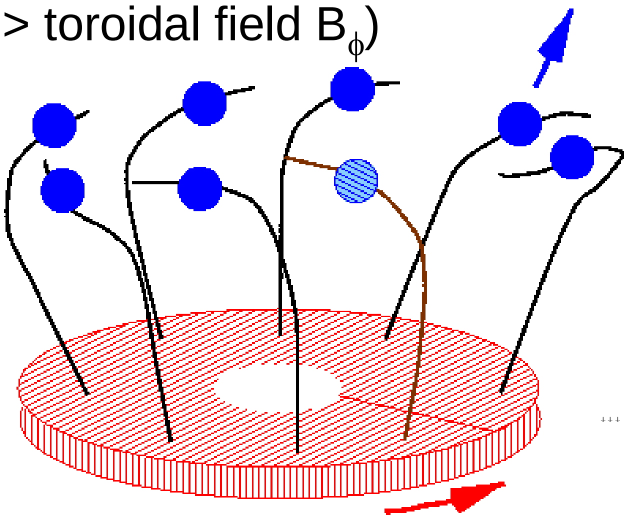
1. "rotating" field lines:
radial ejection of material
(along poloidal field Bp)

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

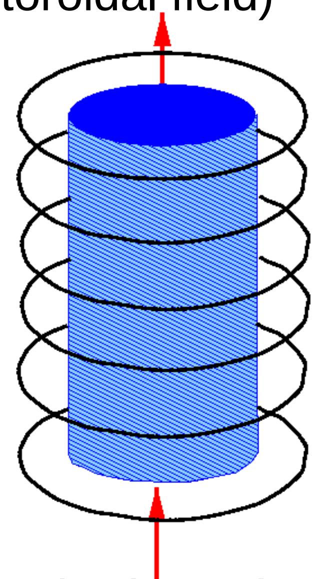
3. collimation
of outflow:
(by toroidal field)



centrifugal force



inertial forces



field tension

Blandford & Payne (1982): **magneto-centrifugal driving of jets**

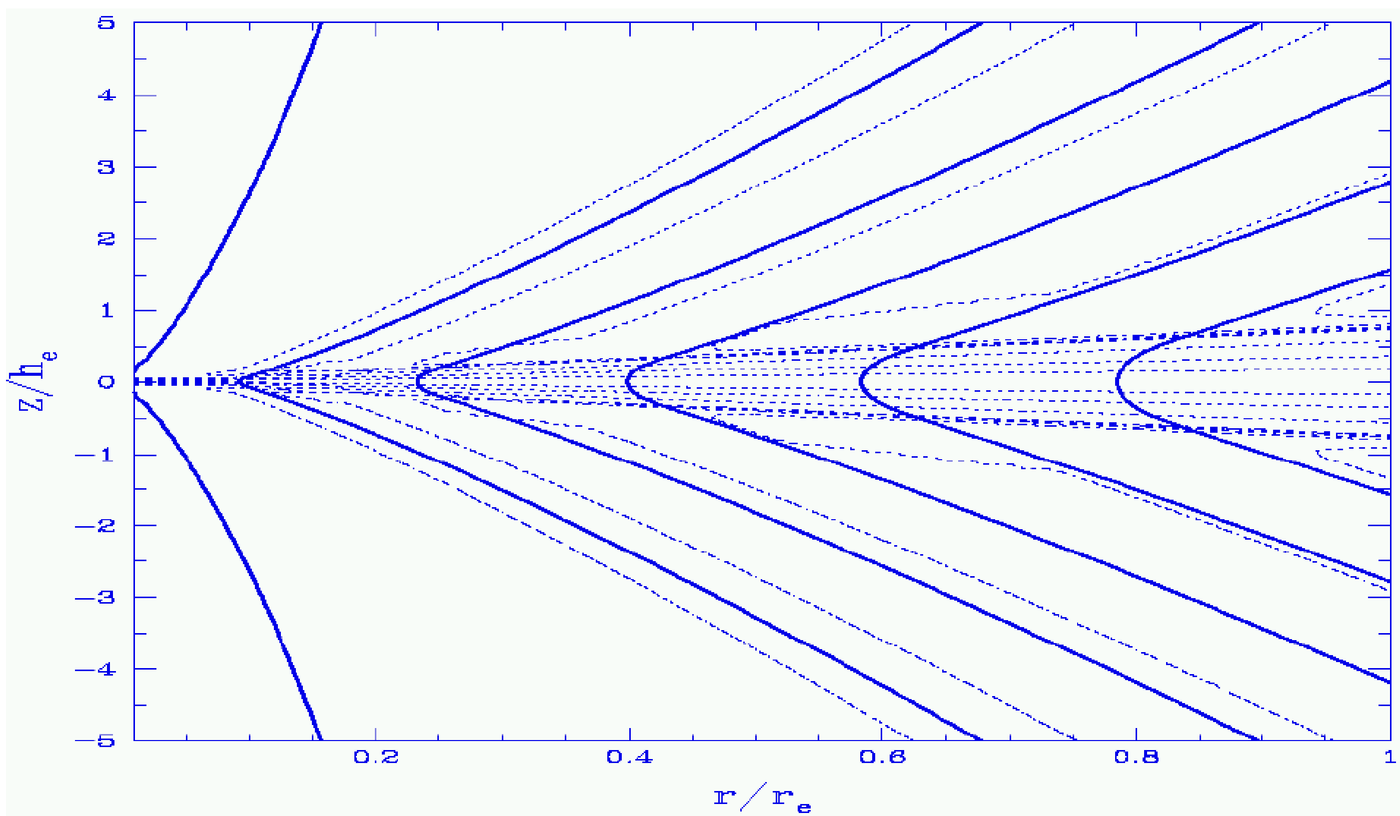
Jet launching: disk - jet connection

Mass loading: accretion to ejection, <u>resistive</u> (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



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 simulations

→ 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)

MHD launching: disk - jet connection

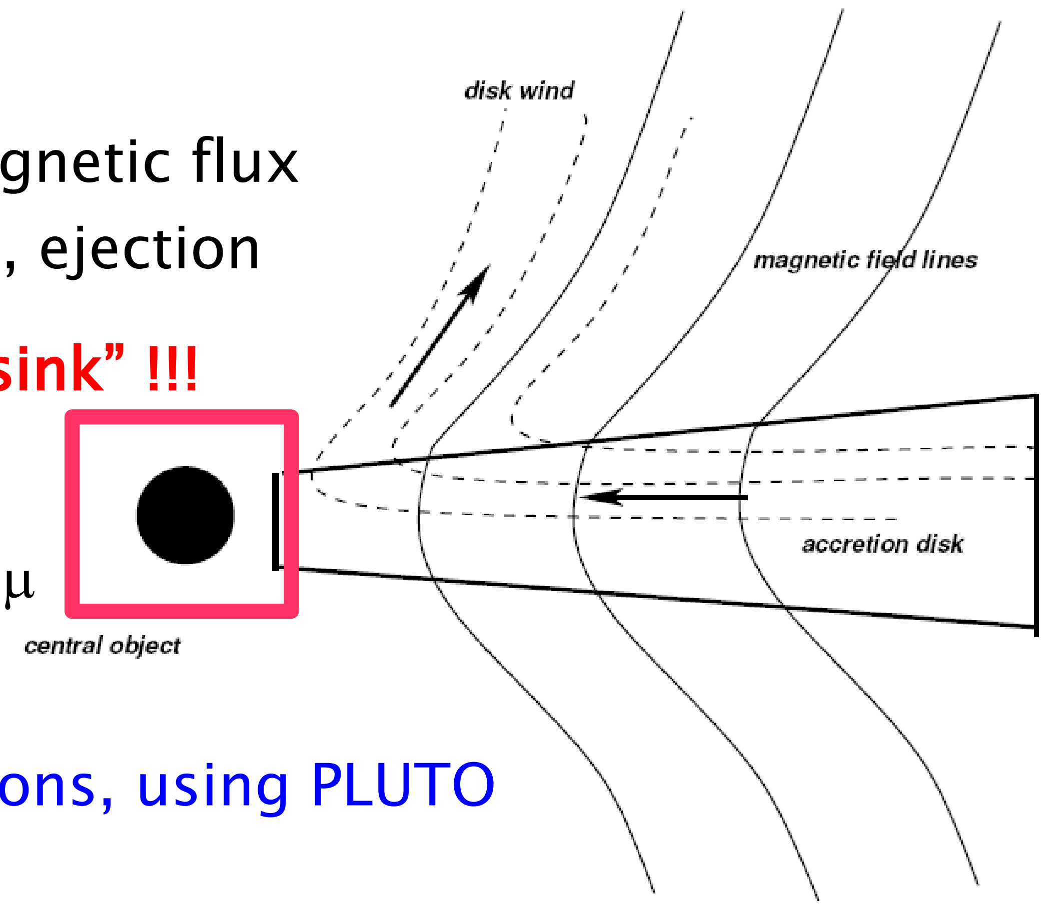
Simulation setup: (Fendt et al.)

→ initially Keplerian disk (no advection)

→ **"resolve" disk physics (!!!) :**
- advection/diffusion of magnetic flux
- launching: mass accretion, ejection

→ physical definition of mass **"sink" !!!**

→ main parameter:
- plasma-β / magnetization μ
- magnetic diffusivity η

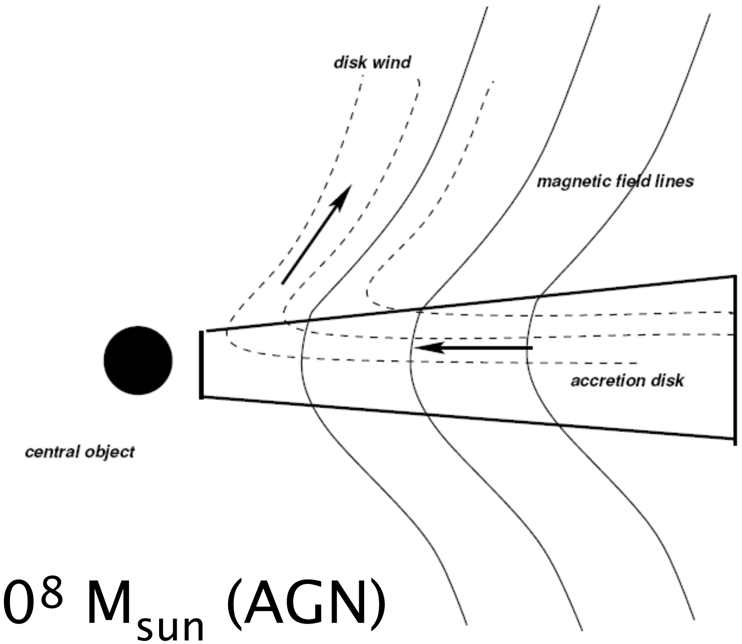


→ solving resistive MHD equations, using PLUTO

→ here: **no viscosity**

→ angular momentum transfer by magnetic field

MHD launching: disk - jet connection



Simulation setup: physical scaling:

→ Normalized to

Central mass: $M = 1\ M_{sun}$ (YSO) ... $10^8\ M_{sun}$ (AGN)

Inner disk radius (and Keplerian velocity there):

$R_0 \sim 3\ R_{mass} = 0.1$ AU (YSO) ... 1 AU (AGN)

Plasma beta: $\beta = P_G / P_B = 0.1 \ldots 1000$

Entropy: $K = P_G / \varrho^{\gamma}$

→ **Simulations can be scaled to**

YSO, BDs, planets (also to AGN, MQ but $v << c$)

MHD launching: disk - jet connection

Movie 1:   Launching of bipolar jets

Movie 2:   Diffusion – advection

Simulation movies: www.mpia.de/homes/fendt/

www.mpia.de/homes/fendt/movies.html

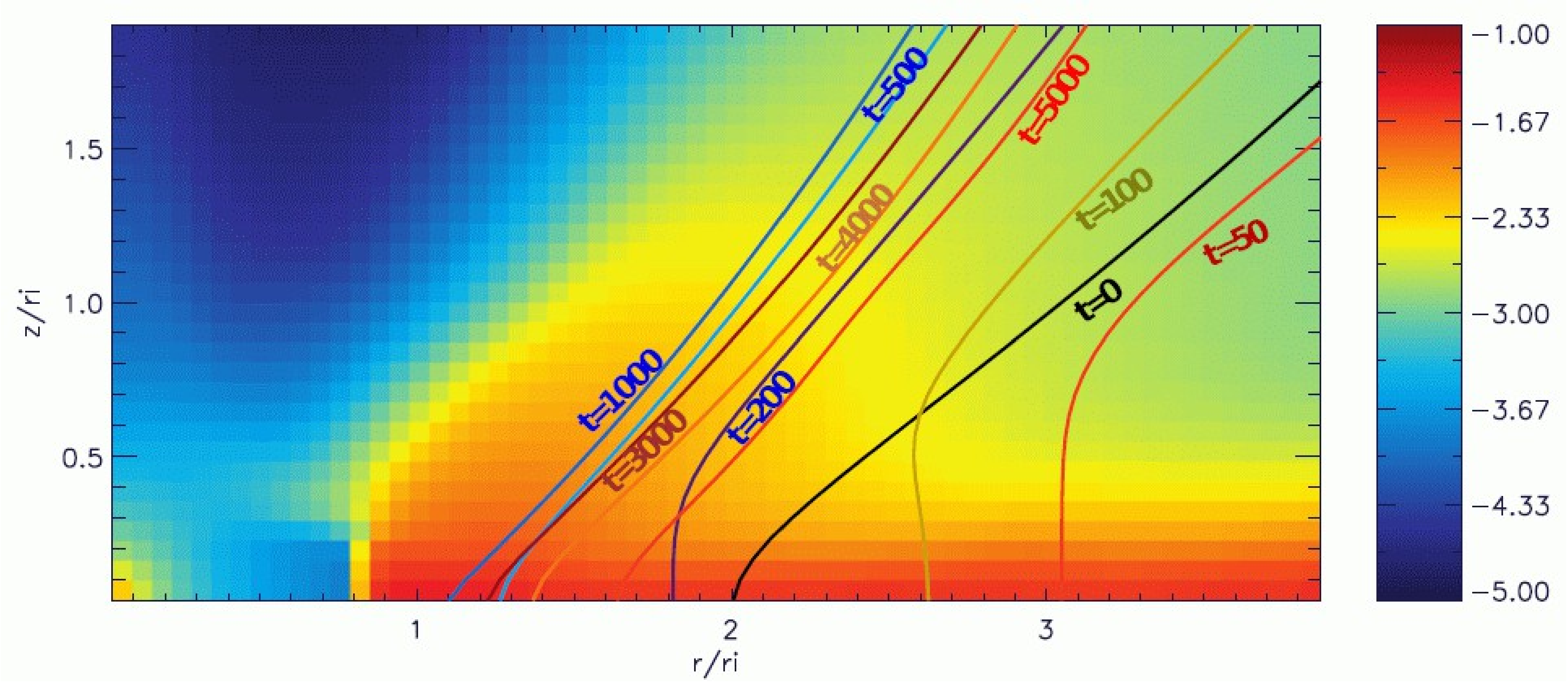
MHD launching: disk - jet connection

→ Re-configuration of magnetic flux by advection & diffusion:

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

→ estimate: magnetic flux conservation: $\Psi \sim B_p r^2 = \mathrm{const}$

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



Sheikhnezami, Fendt, et al. 2012

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

MHD launching: forces

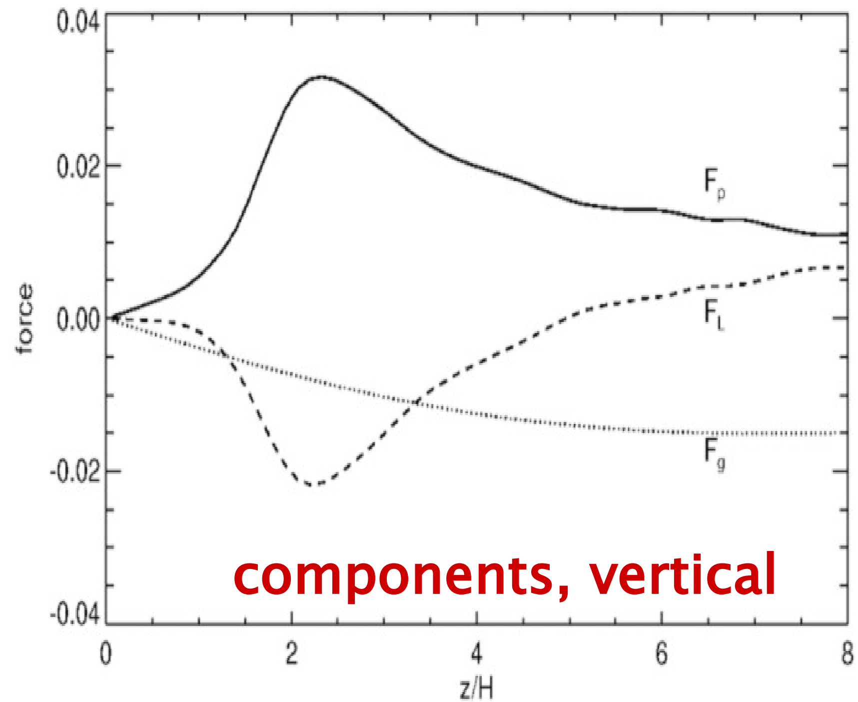
Accretion–ejection: launching forces

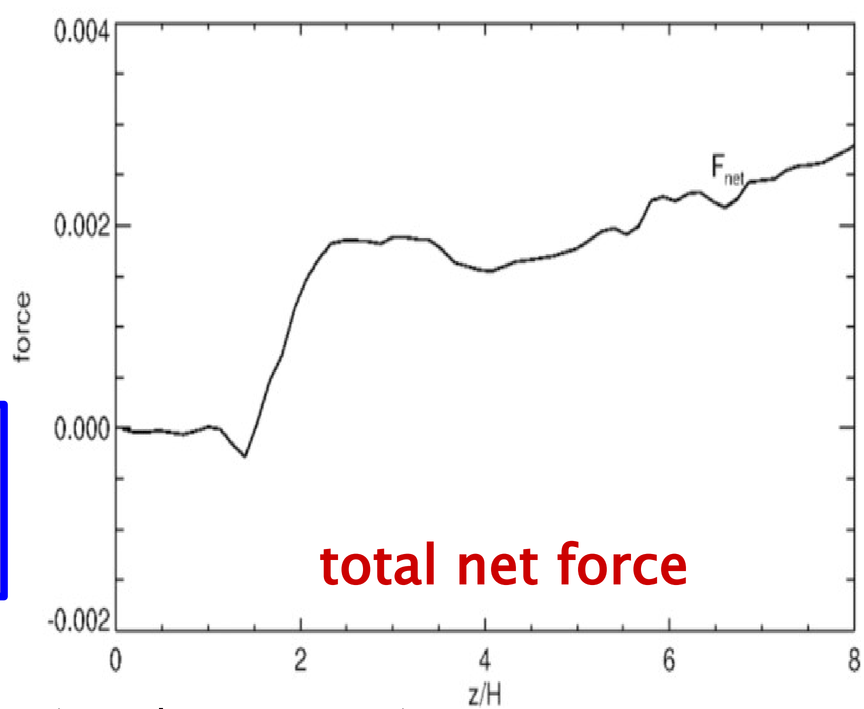
Vertical profile
of vertical forces

at radius r=5, at t=1000,
z in scales of disk pressure scale height H:

- gravity F_G
- Lorentz force F_L
- gas pressure F_P

→ net force positive for $z/H > 1.5$
→ upper disk layers loaded into outflow





(simulation case 1)

MHD launching: forces

Accelerating & collimating forces

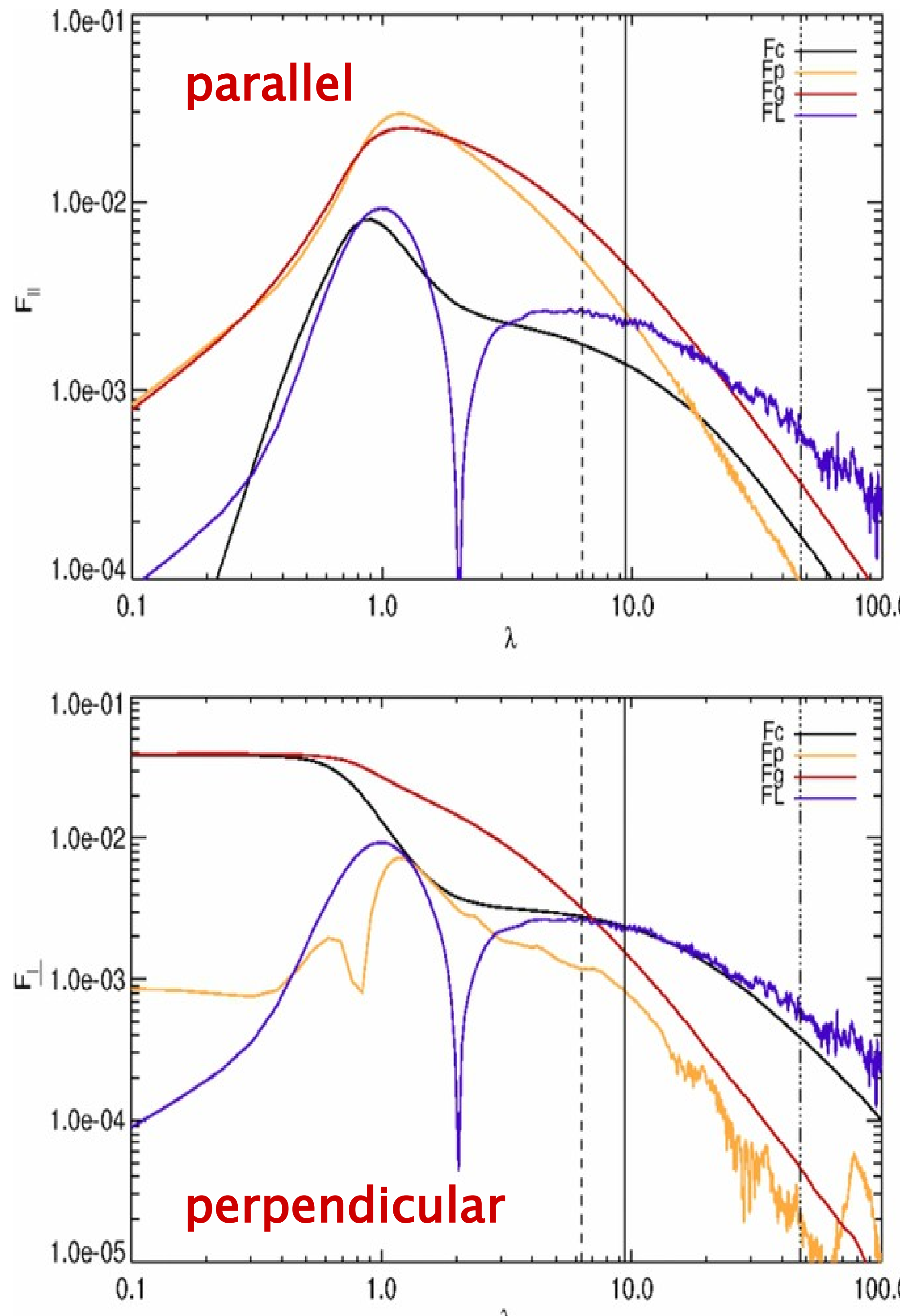
Specific forces (log scale)

along the distance λ of,
and projected on
field line rooted at (5,0) at t=1000:

- centrifugal force F_C
- gravity F_G
- Lorentz force F_L
- gas pressure F_P

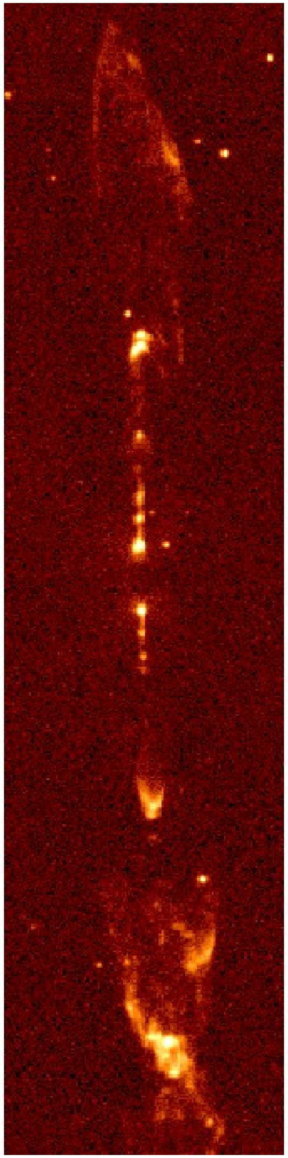
Critical MHD points:

- slow-magnetosonic (dashed)
- Alfvén (solid)
- fast-magnetosonic (dot-dashed)



(simulation case 1)

MHD launching: disk - jet connection



Bipolar jet launching

→ Evolve bipolar jets into both hemispheres
→ Check for signatures of jet / counter jet asymmetry
→ Asymmetry triggered intrisincally - in the disk, or externally

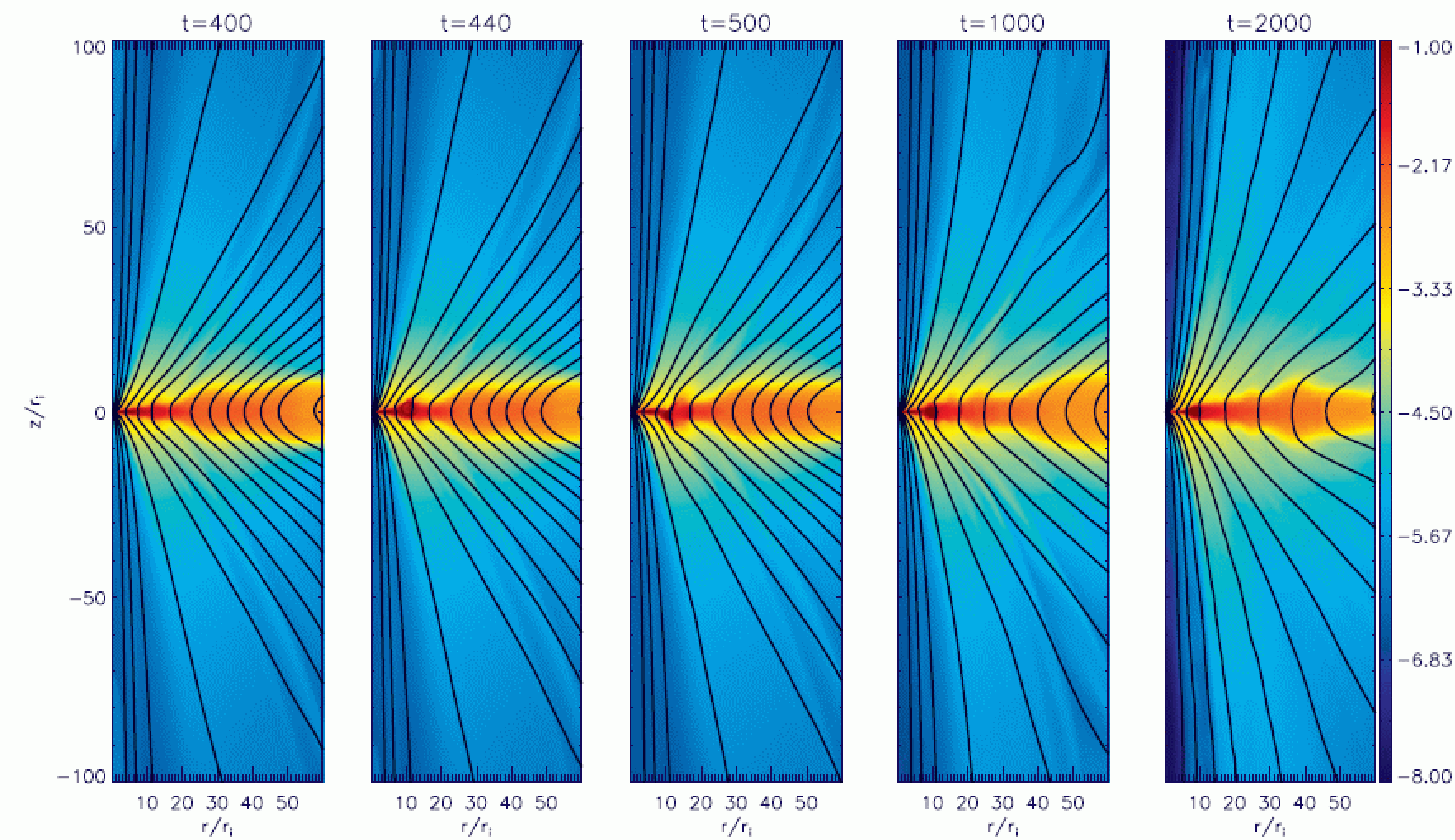
Example simulation 2:

symmetric disk with localized energy injection
→ local disk asymmetry
→ advected inwards
→ asymmetric jet launching
→ jet asymmetry (delayed from localized energy injection)

Jet launching: bipolar jets

Expl. 1: symmetric disk with localized energy injection (at t=400)

→ local disk asymmetry → advected inwards → outflow asymmetry



colors: density, lines: magnetic flux surfaces

Jet launching: bipolar jets

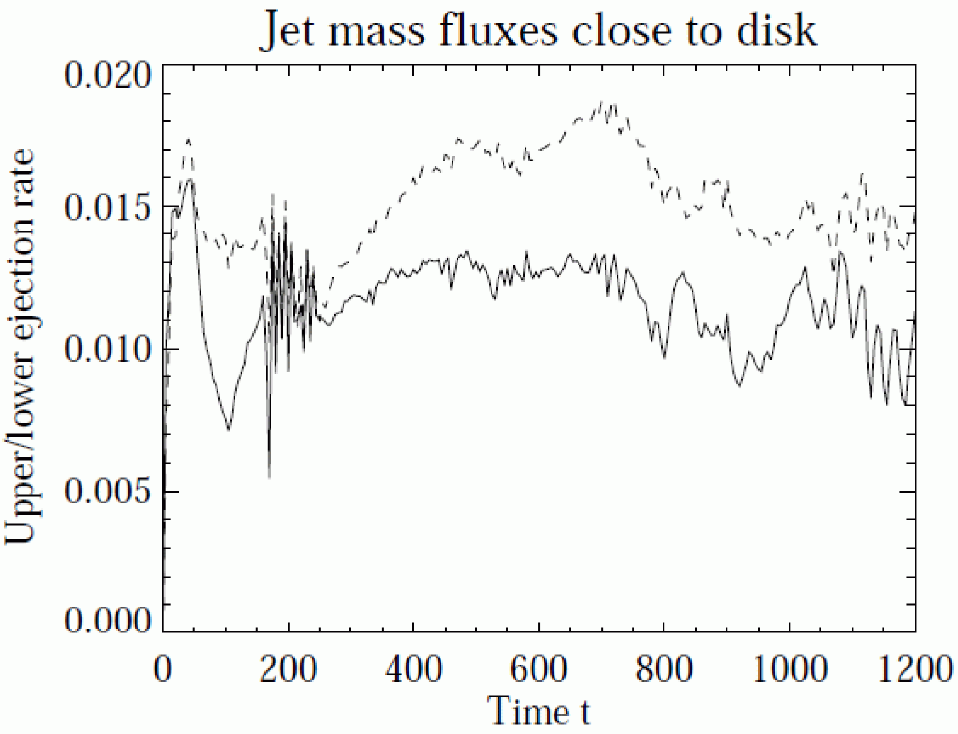
Example 3:

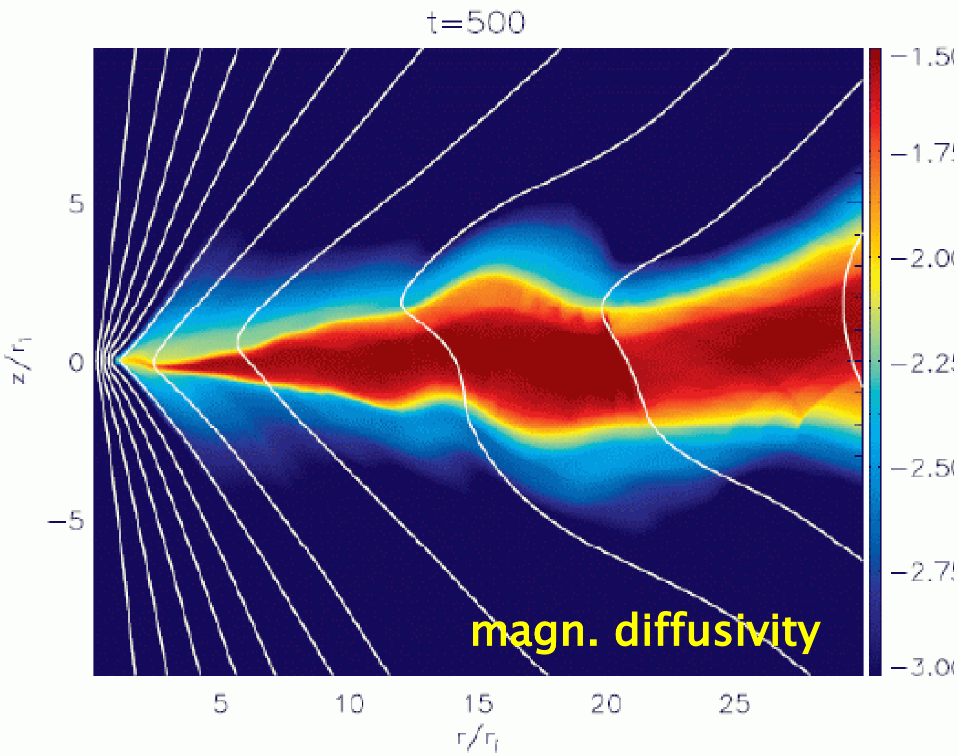
local description of

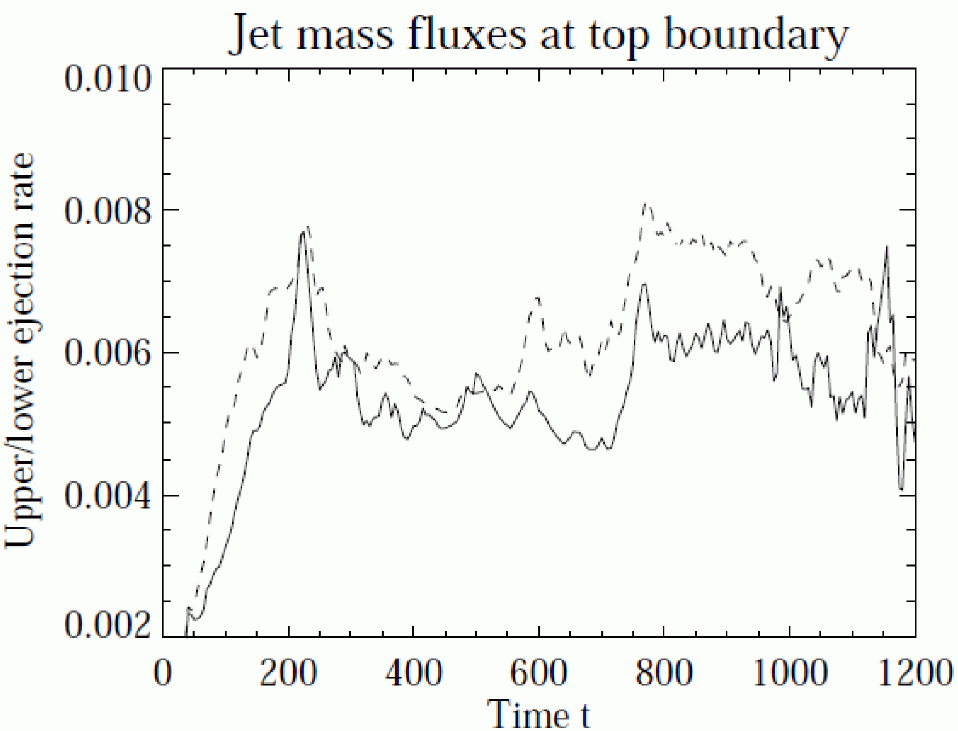
magnetic diffusivity

→ long-living disk &

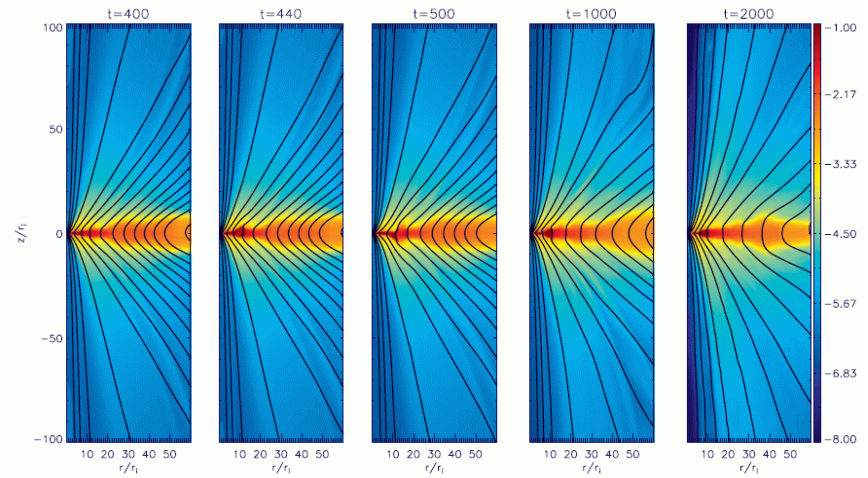
jet asymmetry !







Jet launching: bipolar jets



Results in general:

- ejection rate ~20–40% of accretion rate

- jet velocity ~ 0.8–1.3 Keplerian velocity at launching radius

- asymmetric jets may be triggered by disk asymmetries:
  - 20–30% mass flux difference for jet & counter jet, also in velocity
  - localized asymmetry advected to inner disk & ejected into jets
  - asymmetric ambient medium → embeded jets asymmetric

MHD launching: disk - jet connection

→ Re-configuration of magnetic flux by advection & diffusion:

→ **magnetization (relative field strength) changes, and thus local jet launching conditions**

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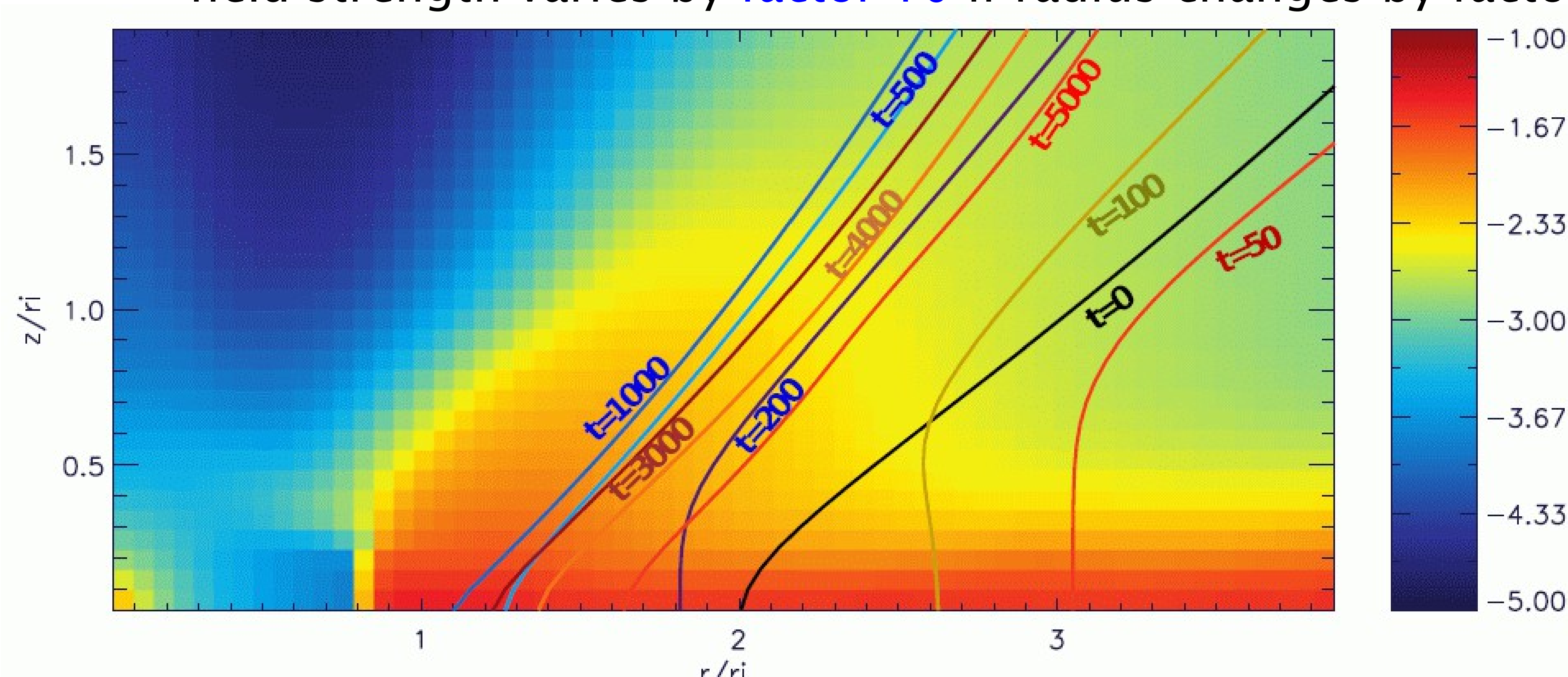
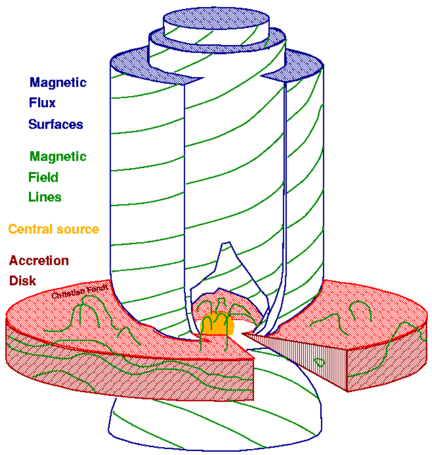


Sheikhnezami, Fendt, et al. 2012

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

MHD launching: disk - jet connection



Parameter survey of jet launching conditions (Stepanovs & Fendt, ApJ, 2016)

1) Apply certain disk initial conditions:
   disk density, magnetic field, magnetic diffusivity, ...

2) Let the disk & jet evolve:
   advection & diffusion of magnetic flux, outflow generation

3) Relax simulation for quasi-steady state dynamical equilibrium
   (jet evolves faster than disk)

4) Compare leading disk & jet parameters → disentangle interrelation

→ **result: disk magnetisation μ_D governs jet dynamics**

MHD launching: disk - jet connection

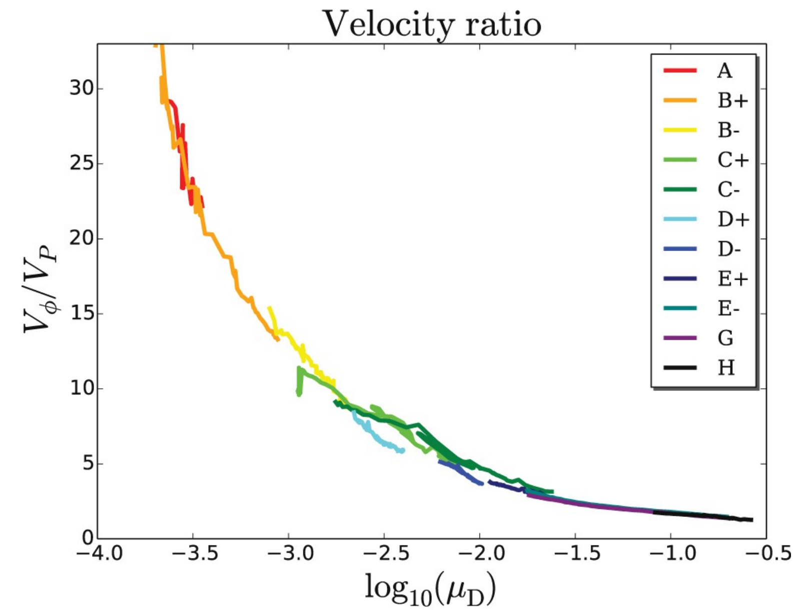
Disk **magnetization**
is the
leading parameter
that
governs jet dynamics

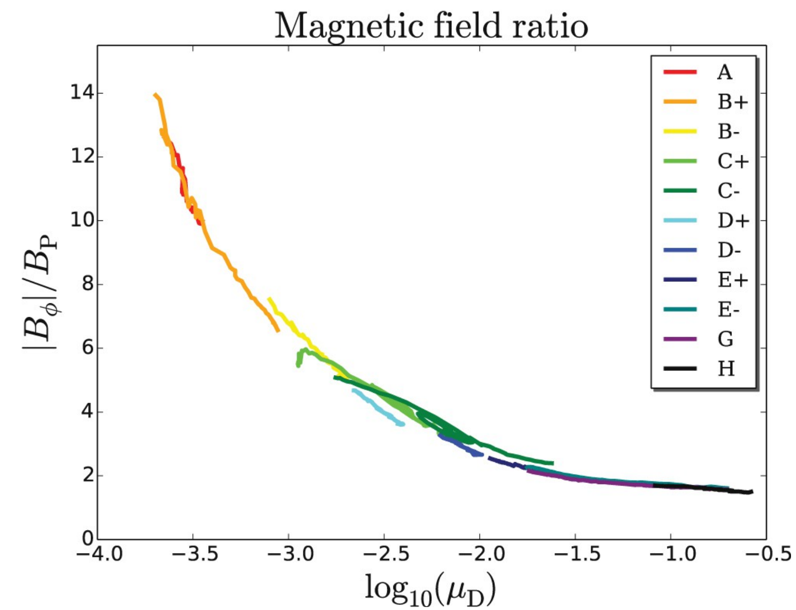
$\mu_D = B_D^{\ 2} / P_D$

Disk magnetization **profile**
provides
profile of jet dynamics:

$\mu_D\ (r, z=0) \rightarrow\ v_{jet}(r, z=z_{obs})$

Jet parameters “far” from the disk

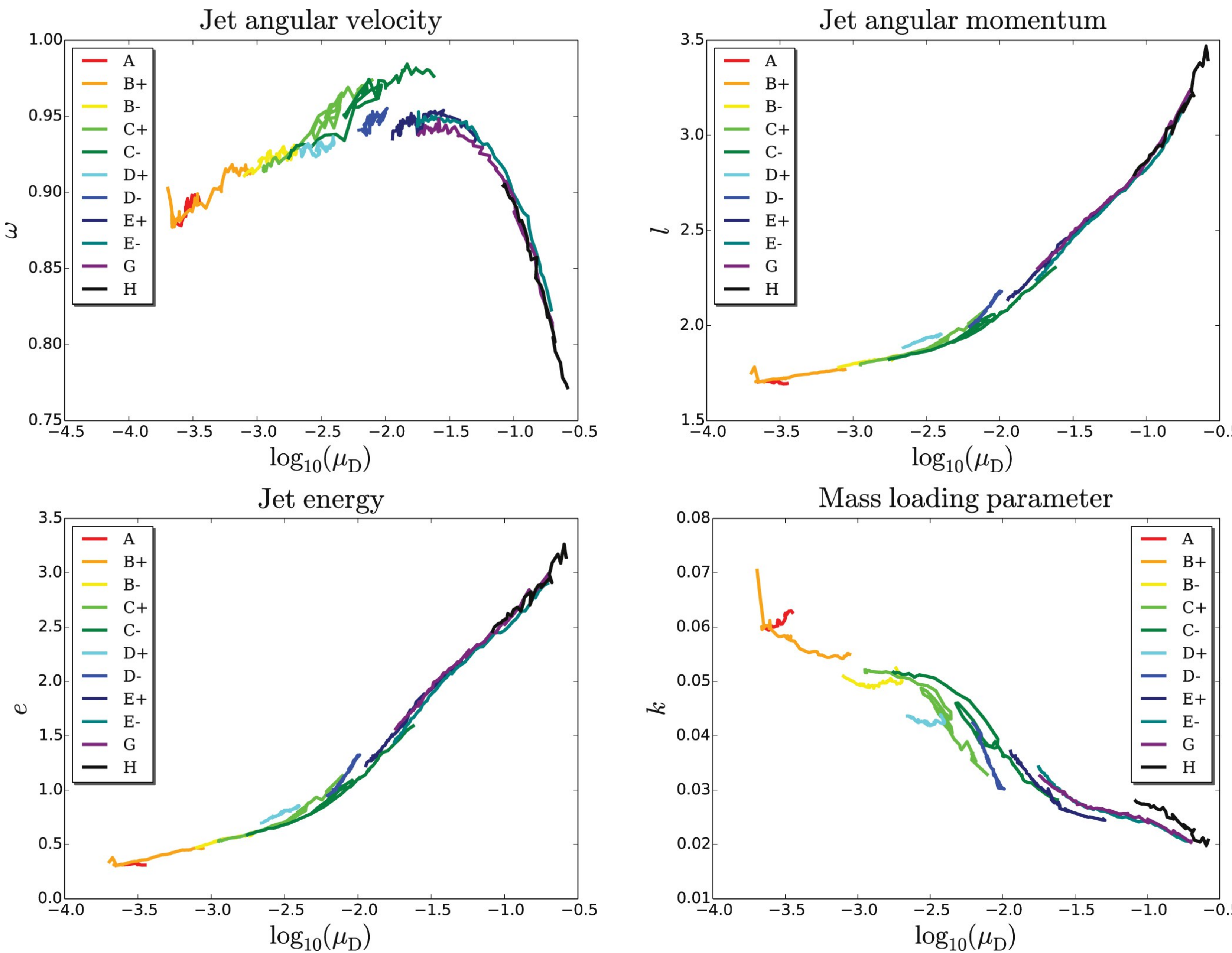




Disk magnetization at jet launching radius

MHD launching: disk - jet connection

Jet parameters “far” from the disk



Disk magnetization at jet launching radius

A mean-field disk dynamo

→ consider “self-generated” disk magnetic field

→ mean-field α^2 / α-Ω dynamo added to induction equation of PLUTO code

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

Stepanovs, Fendt & Sheikhnezami, ApJ 796, 29 (2014)

Jet launching: disk dynamo

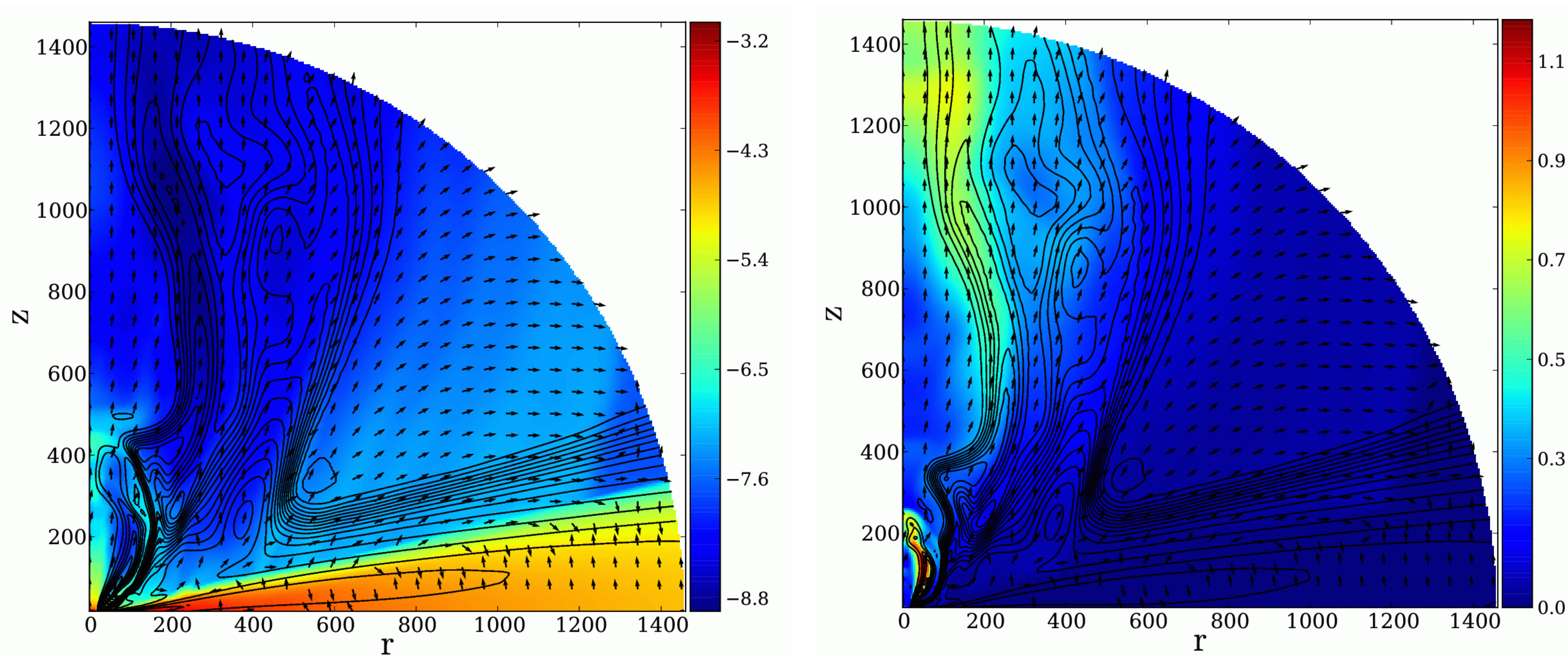
Long time scales: 100,000 rotations & more;   large size: ~ 140 AU

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

Dynamo-generated loops of poloidal field break up into open field lines:

→ Blandford-Payne magneto-centrifugal driving for $r < 50$

→ fast narrow jet & slow disk wind



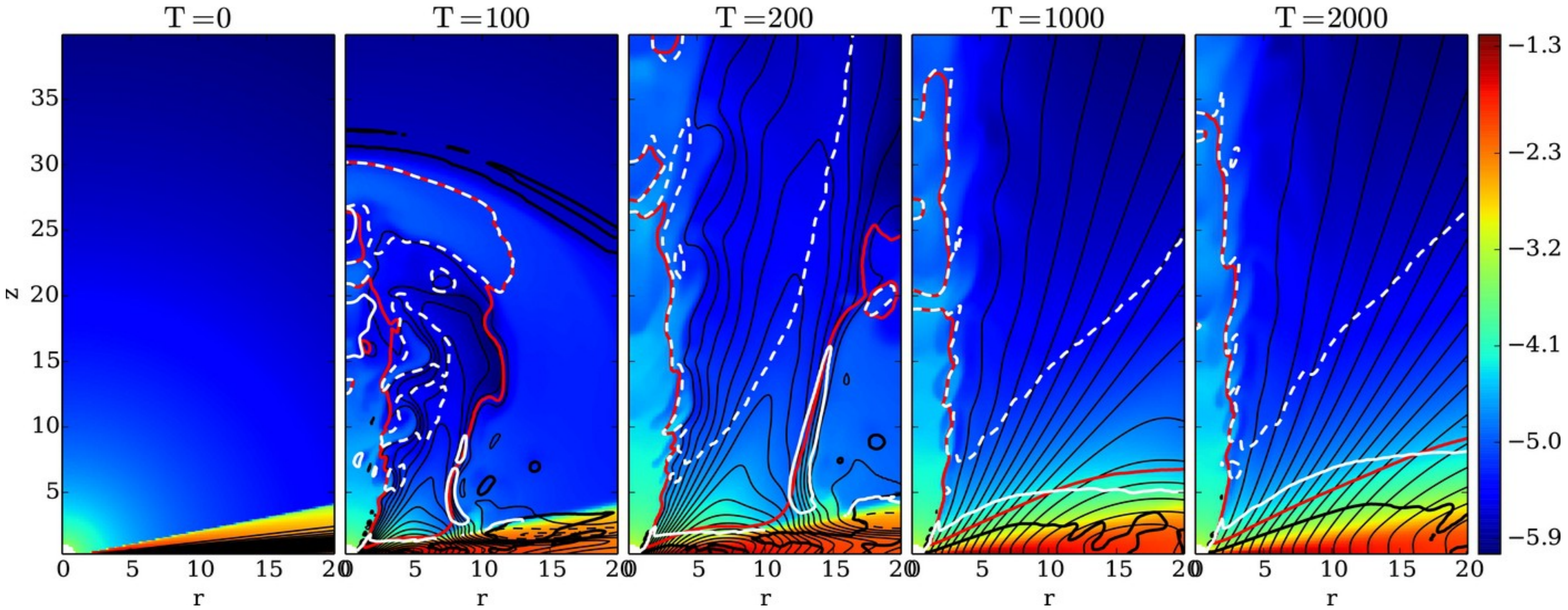
Jet launching: disk dynamo

Inner launching region taken from large grid ~ 140 AU

Initial magnetic field: pure B_R or B_ϕ ,   initial magnetization $\mu \sim 10^{-6}$

Dynamo-generated loops of poloidal field break up into open field lines:

→ **Blandford-Payne magneto-centrifugal driving for $r < 50$**



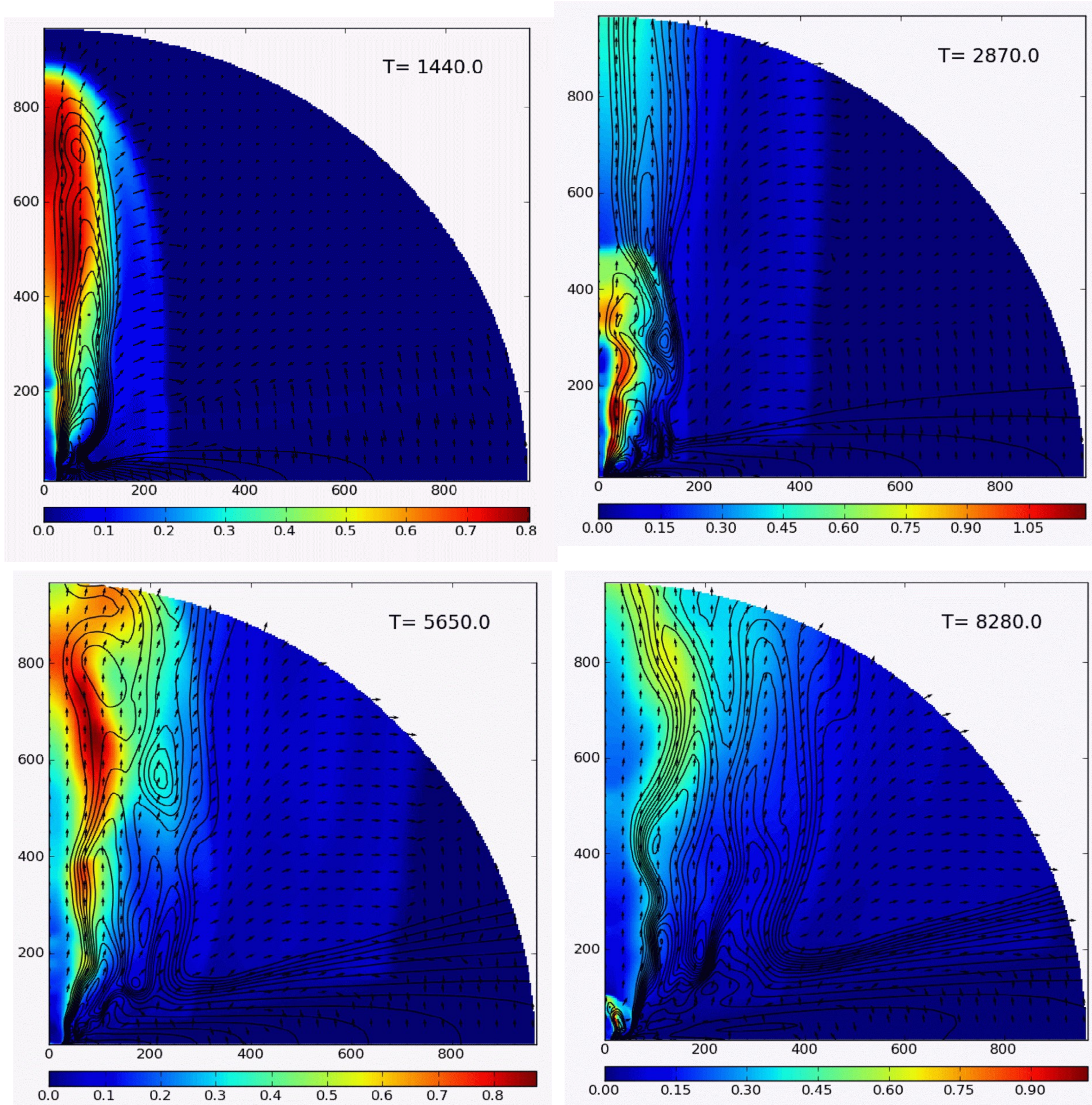
density (log, colors); magnetic field lines (thin); disk surface (thick);
critical surfaces: Alfven (white), sonic (red), fast (dashed)

Jet launching: disk dynamo

Time variable dynamo:

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

Time-dependent ejection of jet → "knots"



Jet launching: disk dynamo

Movie 3: Dynamo-active inner disk

Movie 4: Toy dynamo for modeling jet knots

3D jet launching simulations

→ 3D evolution: jet symmetry & stability

3D effects: 1) intrinsic 3D structure

2) global 3D structure:

tidal forces from a binary

→ disk warping ?

→ disk & jet precession ?

Sheikhnezami & Fendt, ApJ 814, 113 (2015)

3D jet launching

Simulation setup:

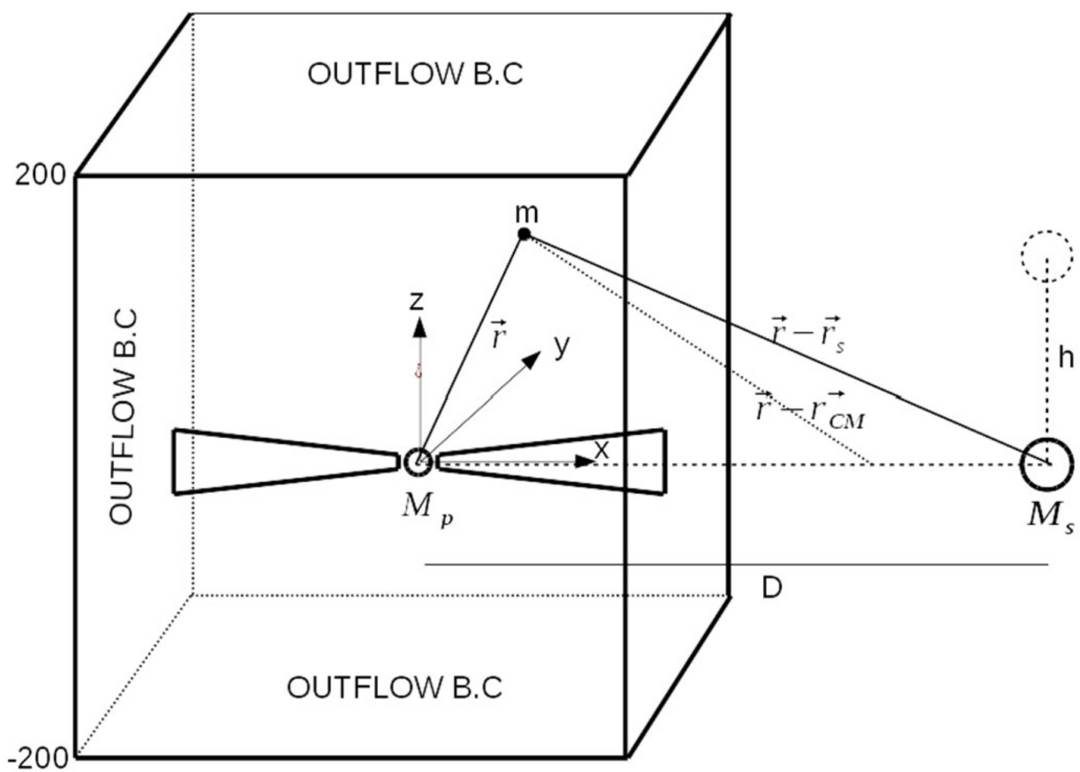
→ same as in axisymmetry (test case):

initial Keplerian disk, "resolve" disk physics, mass "sink"

→ **NEW:** – "long-term" simulation $<$ 3000 dynamical time steps

– 3D gravitational potential (Roche potential)

– Cartesian grid



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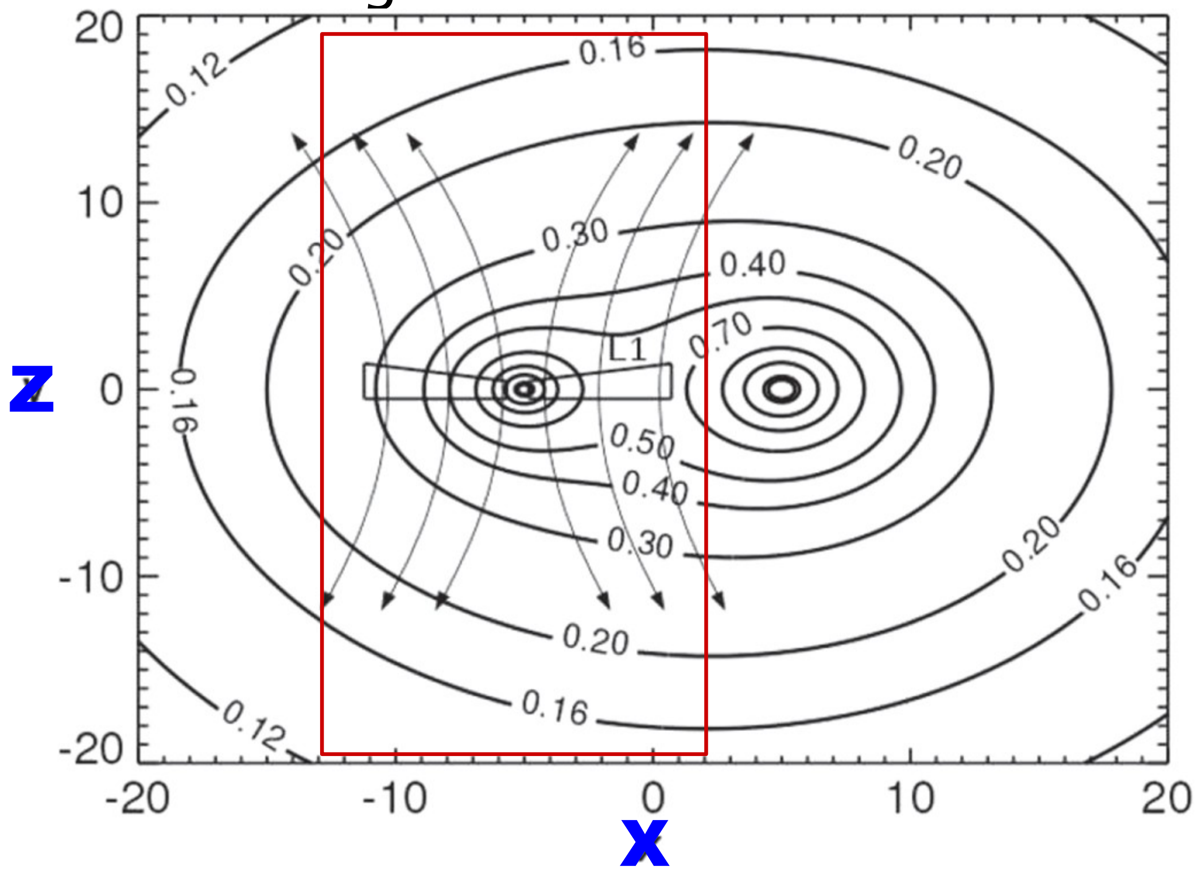


3D jet launching

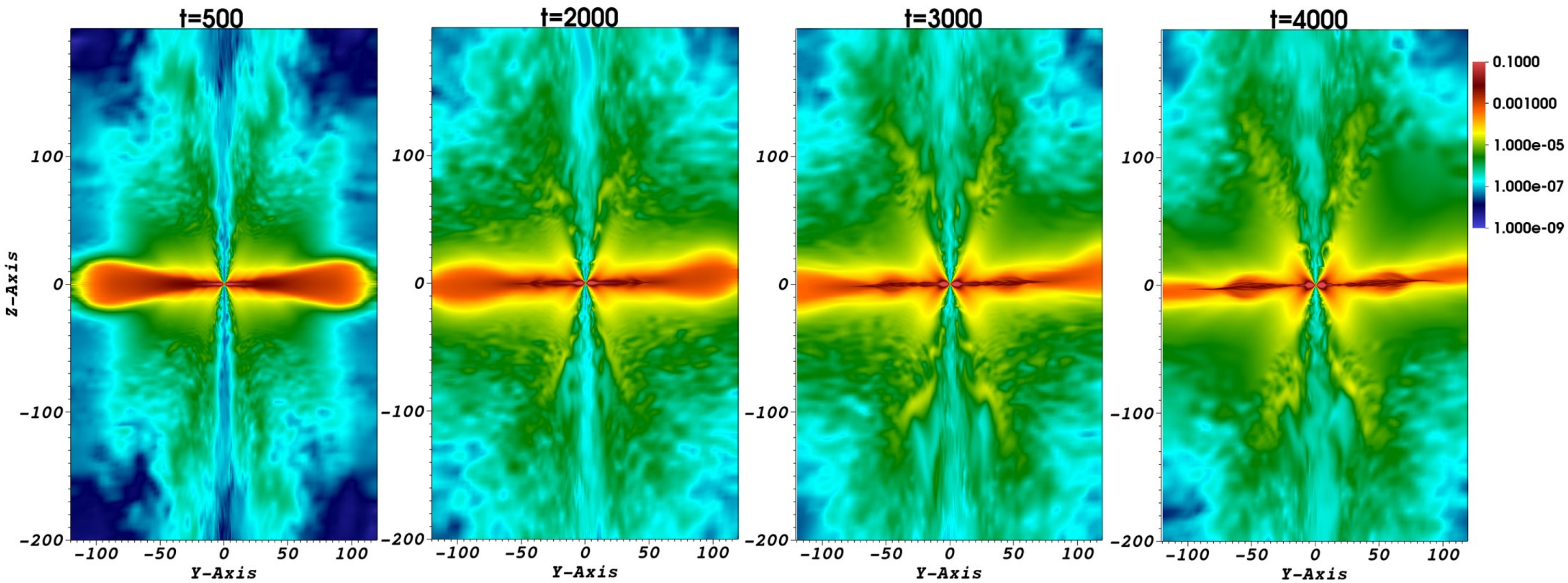
Fully 3D, applying Roche potential with different stellar separation

→ orbital time scales >> disk rotation time scale:

→ small binary separation to enhance tidal effects:

secondary located at $r \sim 200\ R_{in}$, $z = 60\ R_{in}$

→ **result: disk plane re-aligns to orbital plane, jet axis re-aligns**



3D jet launching

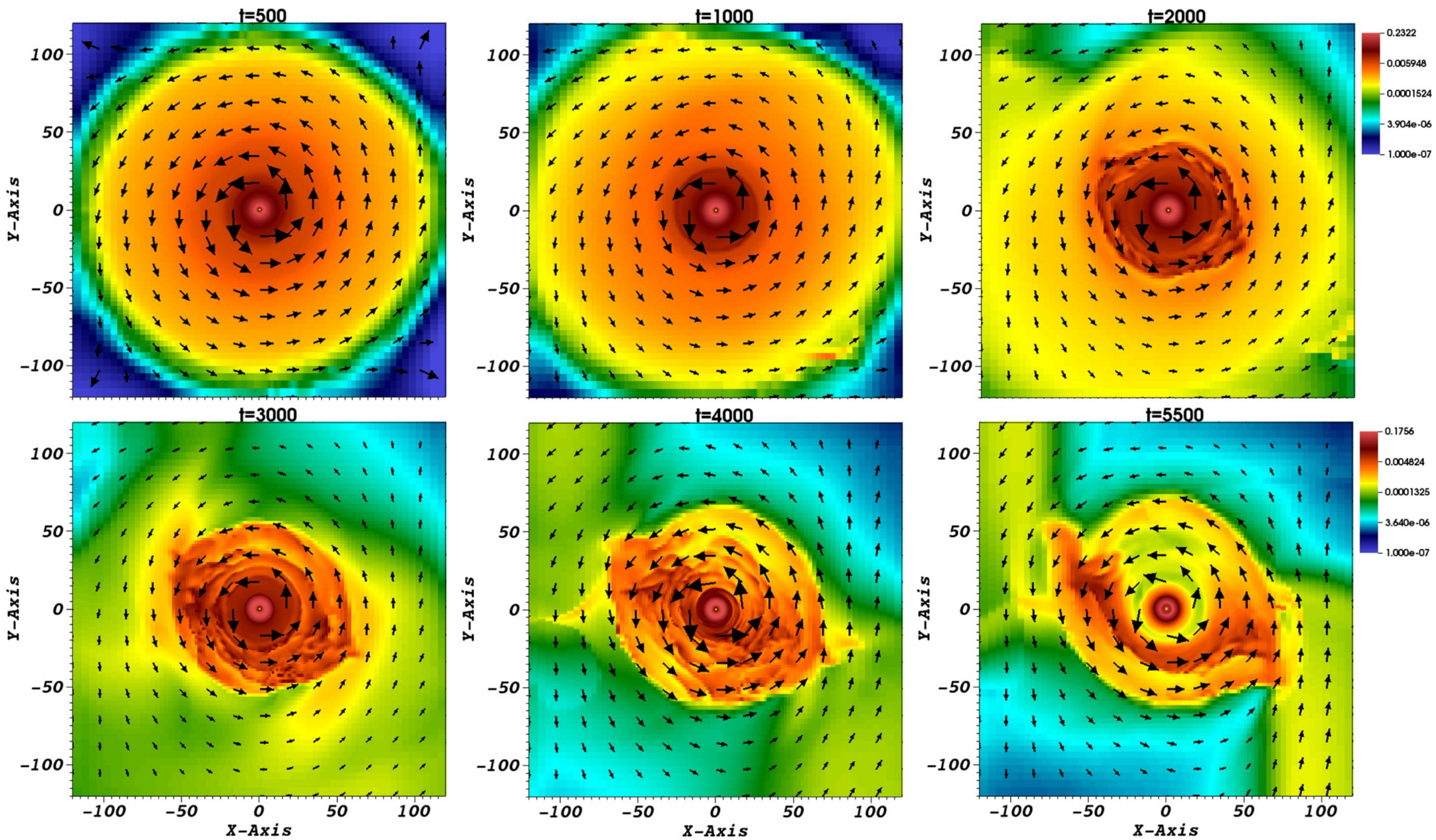
Fully 3D, applying Roche potential with different stellar separation

→ orbital time scales >> disk rotation time scale:

→ small binary separation to enhance tidal effects:

secondary located at $r \sim 200\ R_{in}$, $z = 60\ R_{in}$

→ **disk expands across inner Lagrange point L1 → disk mass loss**

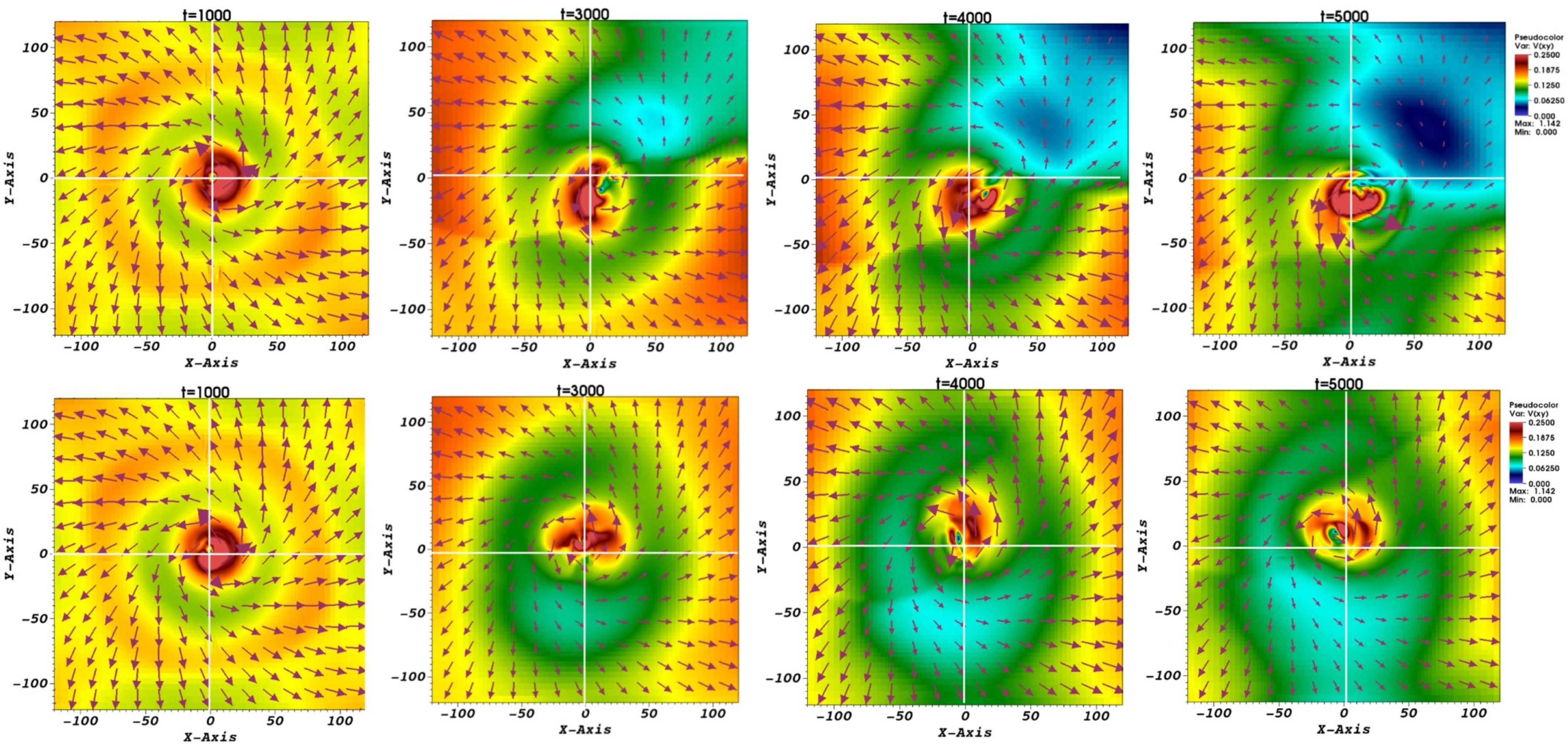


3D jet launching

Fully 3D, applying Roche potential with different stellar separation

→ jet precession (?), precession cone opening angle~ 4°

Note: expected precession time scale ~ 10 orbital time scale ~ t=100,000 (!!)



Jet (top) & counter jet (bottom) cross section (x-y projected velocity)

Modeling the magnetized accretion & outflow in young stellar objects

Summary:

- outflow mass loss $<$ 30 – 50% of accretion rate
- outflow velocity ~ 0.8 – 1.3 Keplerian speed at launching
- disk magnetization changes substantially during disk evolution

  → main parameter that governs jet dynamics
  (numerically derived interrelations)
- asymmetric jet/counter jet ~30% difference in mass flux/speed;
  can be triggered by disk-internal asymmetries
- magneto-centrifugally driven jet from a disk-dynamo B field,
  episodic ejections triggered by toy-dynamo variability
- 3D launching: jets from disks in binary systems:
  disk warping, re-alignment, precession disk & jet (??)