Modeling accretion-ejection processes in magnetized young star environments

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26 October 2007

Outline

- Young Stellar Objects:
  Observational clues and puzzles
- Magnetohydrodynamic modeling

  ⇒ *launching jets from accretion disks*

  ⇒ *wind-jet interactions*

  ⇒ *near-star accretion processes*
- Outlook: bringing all scales together

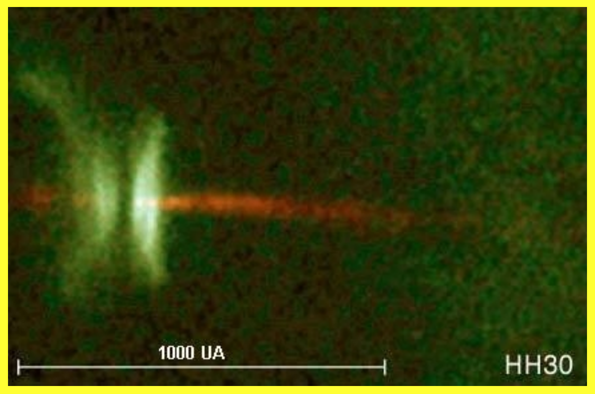
Astrophysical Jets: YSO

- Forming stars: T-Tauri with mass $M_* \leq M_\odot$

  $\Rightarrow$ bipolar jets, velocities up to 400 km/s

- accretion disk play role in launching process:

  $\Rightarrow$ proportionality between jet/disk luminosity



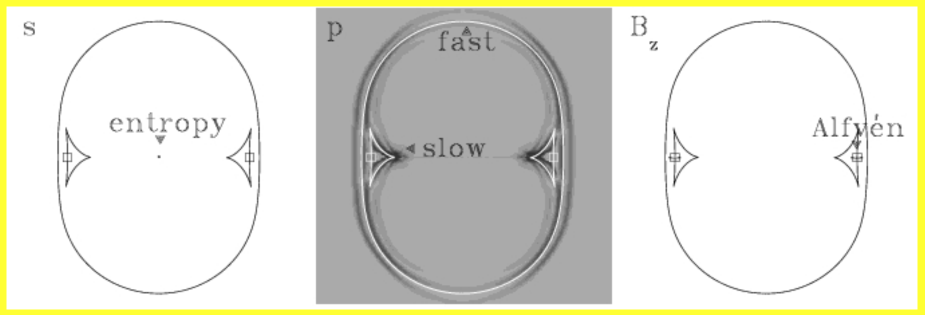
Astrophysical Jets

- astrophysical jets: ubiquitous in presence of accretion disks
  - ⇒ Young Stellar Objects (YSO)
  - ⇒ compact objects in binaries
  - ⇒ Active Galactic Nuclei (AGN)
- collimated, reach high velocities (up to c)
  - ⇒ mass source of the jet?
  - ⇒ how to collimate and keep collimated?
  - ⇒ how to launch and accelerate mass in jet?

MagnetoHydroDynamics

- Conserve MASS, MOMENTUM, ENERGY, MAGNETIC FLUX $\Rightarrow$ 8 non-linear PDE

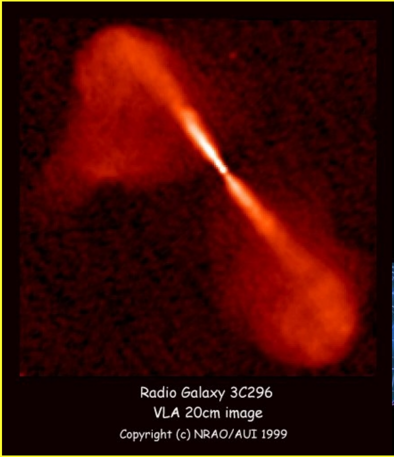
  $\Rightarrow \nabla \cdot \mathbf{B} = 0$: no magnetic monopoles
- 7 wavespeeds *entropy*, $\pm$ *slow*, $\pm$ *Alfvén*, $\pm$ *fast* [anisotropic!]

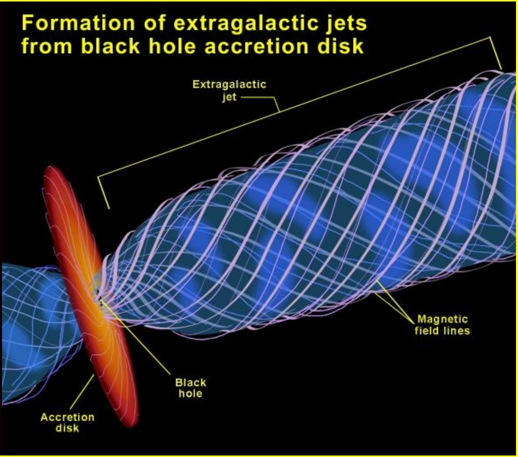


MHD waves animation

Magnetic Accretion-Ejection structure

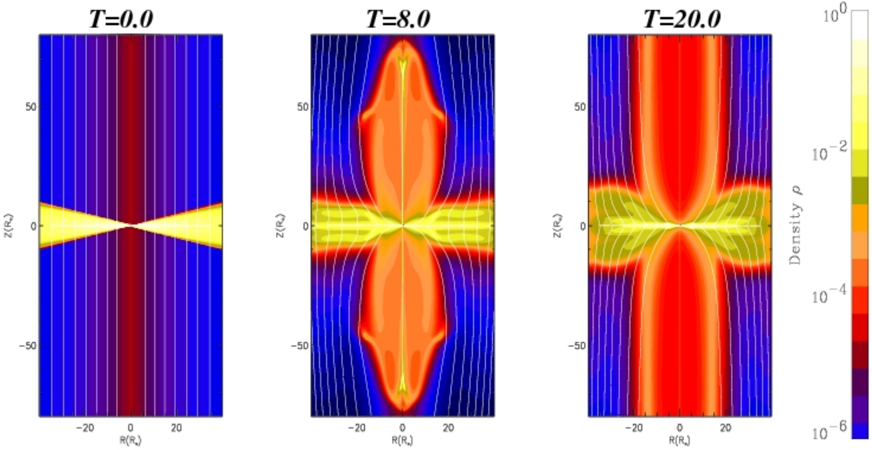
- key ingredients are: presence of accretion disk + **B**
  - ⇒ observed versus 'artist impression' (for AGN)





Casse & Keppens, ApJ **581**, 988 (2002)

- perform axially symmetric 2.5D MHD simulations
  - ⇒ disk with initial vertical **B**: self-consistently forms collimated jet
  - ⇒ 15 % of accreted mass persistently ejected

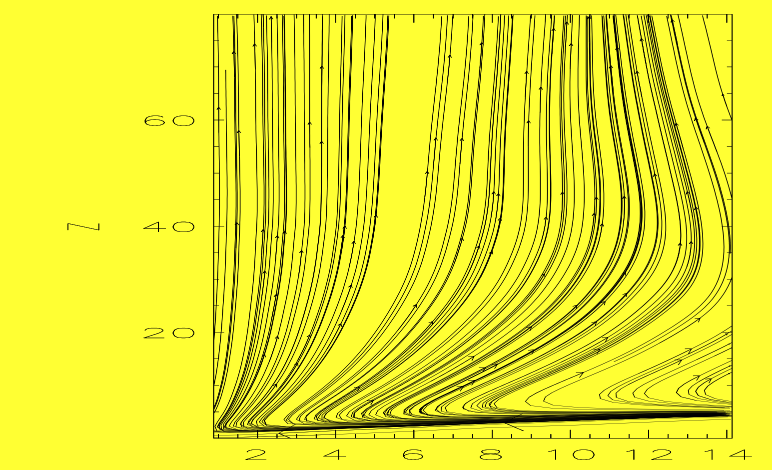


MAES

- mechanism for jet launch and acceleration
  - $\Rightarrow$ mass source: accretion disk
  - $\Rightarrow$ collimation and acceleration of jet: $\mathbf{B}$
- identical for YSO, compact objects, AGN:
  - $\Rightarrow$ MAES model relies on its gravitational influence on disk material
  - $\Rightarrow$ does not require specific disk/magnetosphere interaction
  - $\Rightarrow$ object (plus magnetosphere or event horizon): point source
  - $\Rightarrow$ consistent with observed jet radii at 'origin'

MAES: Streamlines

- in jet launch region: accretion and ejection

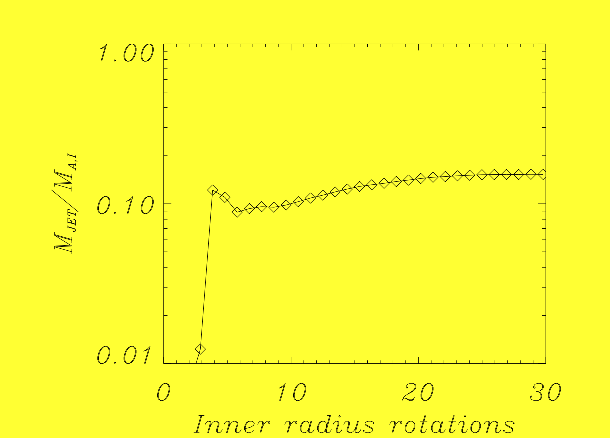


⇒ resistive disk treatment allows accretion

⇒ accretion rate as BC: mimics outer regions

MAES: persistent launch

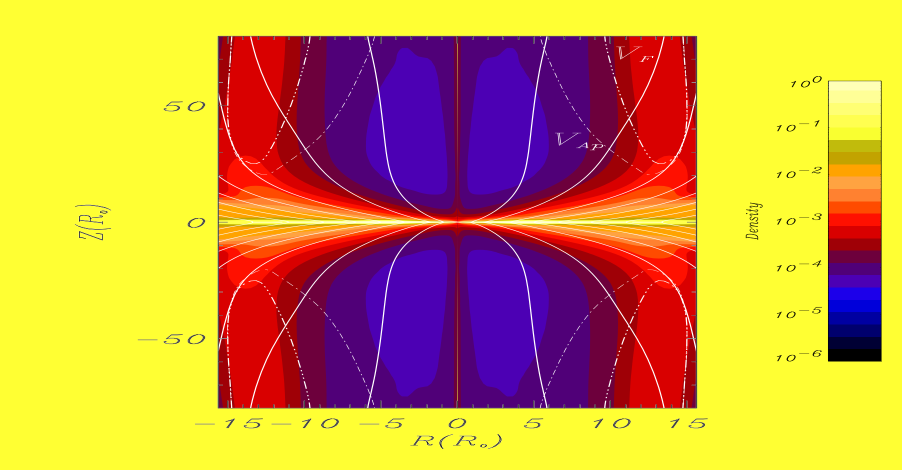
- spatio-temporal resistivity only in disk
  - $\Rightarrow$ accretion flow slips across vertical **B**
  - $\Rightarrow$ region above disk: ideal MHD (frozen-in)
- jet launch, once initiated, persists:
  - $\Rightarrow$ material ejected from disk: 15 % of $\dot{M}_A$



MAES: hollow jets

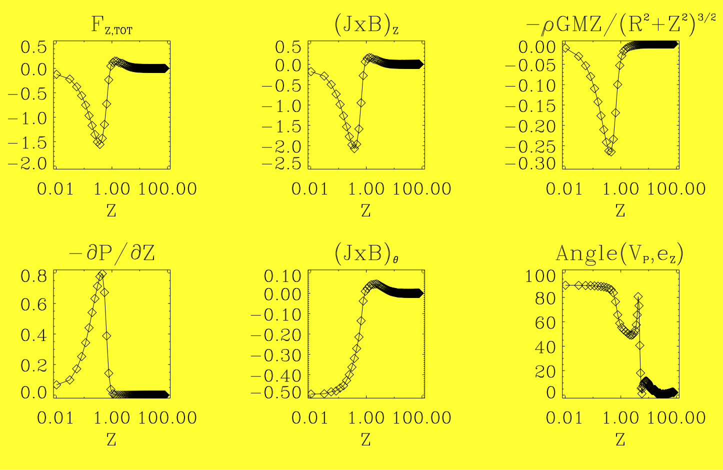
- since jet launched from disk: hollow jet

  ⇒ reaches super-fastmagnetosonic speeds: accelerated while ejected



MAES: Force analysis

- Jet ejection mechanism: axial force analysis



⇒ thermal pressure gradient lifts matter

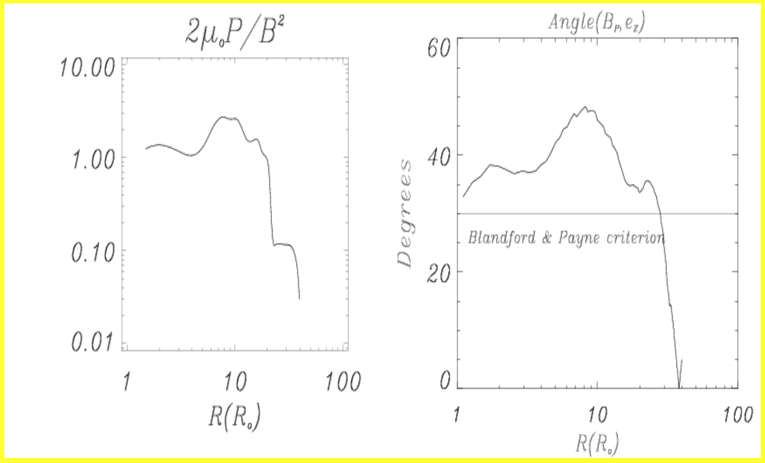
⇒ magnetic torque brakes in disk, spins up jet

MAES: Angular Momentum

- Angular Momentum: channeled by $\mathbf{B}$
  - $\Rightarrow$ in disk: magnetic torque brakes azimuthally
  - $\Rightarrow$ gravity wins from centrifugal: accretion
  - $\Rightarrow$ AM flux parallel to poloidal flow/$\mathbf{B}_p$
- torque $(\mathbf{J} \times \mathbf{B})_\varphi$ changes sign at disk surface:
  - $\Rightarrow$ magnetocentrifugal acceleration of jet
- starts and stays collimated by magnetic hoop force
  - $\Rightarrow$ B_φ created by rotating disk

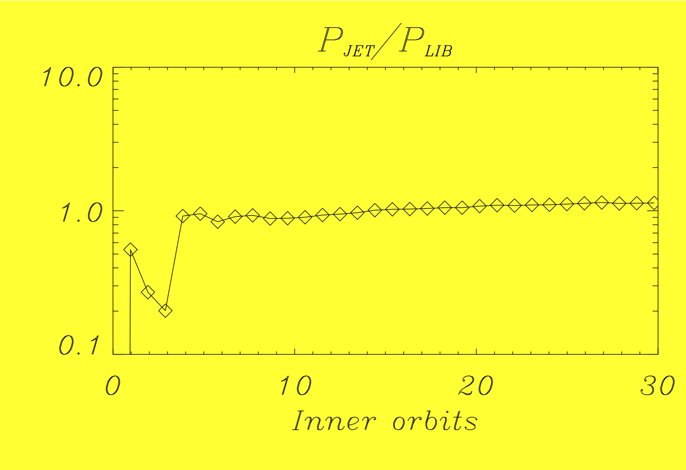
MAES Jet extent

- radial extension of jet launching region
  - ⇒ equipartition field region
  - ⇒ sufficiently bent poloidal **B**(cold jet)

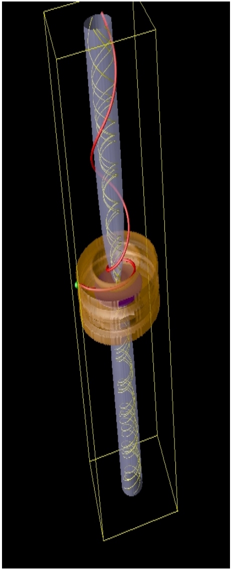


MAES Energetics

- Jet energetics
  - $\Rightarrow$ disk material heats: compression & Ohmic
  - $\Rightarrow$ hot jet emerges
- jet luminosity $\propto$ energy liberated by accretion $GM_* \dot{M}_A / 2R_I$



MAES Summary



Escaping accretion

- mechanism for launch

  ⇒ magnetic torque brakes disk material azimuthally and spins up jet matter

  ⇒ mass source for jet: disk

  ⇒ **B** collimates, accelerates

  ⇒ Jet formation animation
- accretor can be very different

  ⇒ YSO, compact object, AGN

Jet launching: improving the models

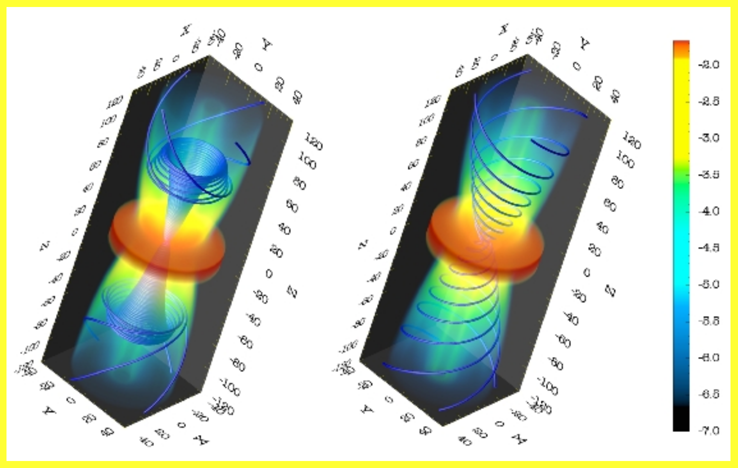
- Numerical 'proof of principle' (2.5D VAC code simulations)
  - ⇒ Jet Launch: ApJ **581**, 988 (2002)
  - ⇒ Energetics: ApJ **601**, 90 (2004)
- MAES model explains
  - ⇒ how jets are launched and accelerated
  - ⇒ why start and remain collimated
  - ⇒ underluminous disks and hot jets
- Recent improvements:
  - ⇒ higher resolution (grid-adaptive) studies

  Zanni et al., A&A 469, 811 (2007)
  - ⇒ including stellar outflows, viscosity in the disk

  Meliani et al., A&A 460, 1 (2006)

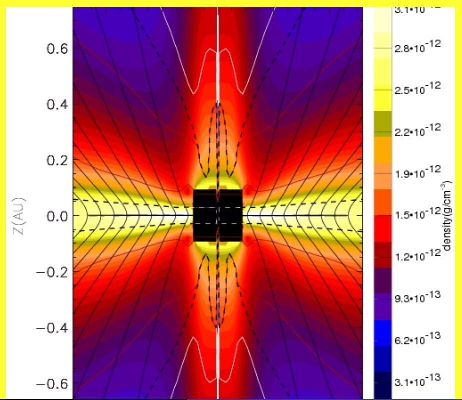
Zanni et al., A&A 469, 811 (2007)

- FLASH code (with AMR); emphasize role of anomalous resistivity prescription



Two-component outflows

- Meliani et al.: A&A 460, 1 (2006)
  - $\Rightarrow$ disk 'turbulence' by enhanced visco-resistive α-prescription
  - $\Rightarrow$ MHD Poynting flux of disc-jet: removes most AM from thin disc
  - $\Rightarrow$ $\mathbf{B}_\varphi$ zero to $\beta \sim 1$ in disc scale height $\Rightarrow$ effective magnetic torque
- wind region: hot corona (turbulent heating near axis)
  - $\Rightarrow$ numerical trick: sink (0.1 AU) $\rightarrow$ mass source along polar axis



Two-component outflows

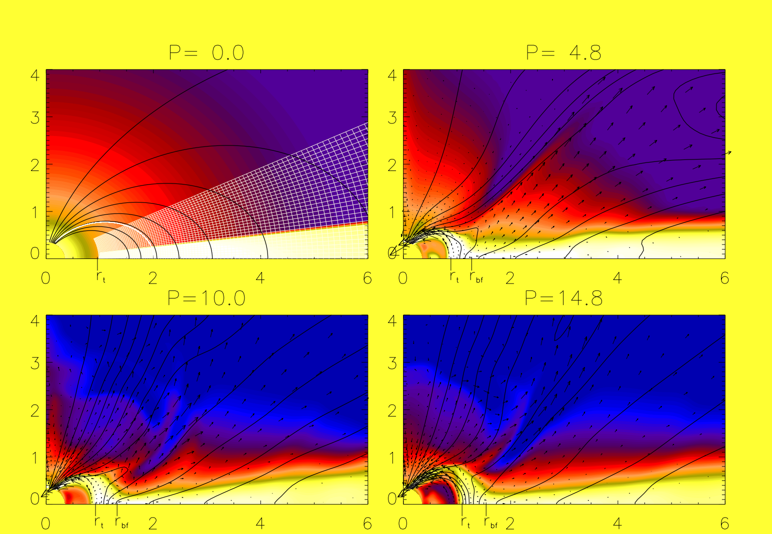
- collimation differs for wind versus jet
  - ⇒ wind region forces: thermal + Lorentz (pinch)
  - ⇒ in turn collimated by disc-driven jet
- all axisymmetric, aimed at stationary endstates, unanswered:
  - ⇒ 3D jet stability and termination
  - ⇒ multi-component jets: interface dynamics?
  - ⇒ near star accretion dynamics

Near-star accretion

- Seminal work done by Romanova et al. (ApJ 578, 420, 2002)
  - ⇒ axisymmetric studies of 'stationary' accretion on magnetized stars
  - ⇒ relevant for T-Tauri stars with kG (aligned) dipole fields
  - ⇒ funnel flows connect disk to star, AM transport by magnetic torque
  - ⇒ meanwhile progressed to 3D unaligned dipoles
- Recent independent confirmation: Bessolaz et al (A&A, submitted)
  - ⇒ VAC simulations, using resistive disk and 2.5D
  - ⇒ Funnel flows are robust features, even down to 140 G fields
  - ⇒ However, realistic $\dot{M} \sim 10^{-8} M_{\circ} yr^{-1}$: need kG fields!

Bessolaz et al.

- uses split into static dipole and solve for $\mathbf{B}_1$ (Tanaka 1994)
- Temporal evolution and grid:



Bessolaz et al.

- Aim of the study: relative position of truncation radius r_t, corotation radius r_{co}, equipartition between poloidal magnetic pressure and disc poloidal ram r_{bf}, disc thermal pressure

  $\Rightarrow$ Analytic criterion for a-priori determination of steady funnels

$$\beta \sim 1, \quad and \quad m_s = \frac{u_r}{C_s} \simeq 1$$

  $\Rightarrow$ express truncation radius (where accretion halts) in basic parameters

$$\frac{r_t}{R_*} \simeq 2\,(m_s)^{2/7} B_*^{4/7} \dot{M}_a^{-2/7} M_*^{-1/7} R_*^{5/7}$$

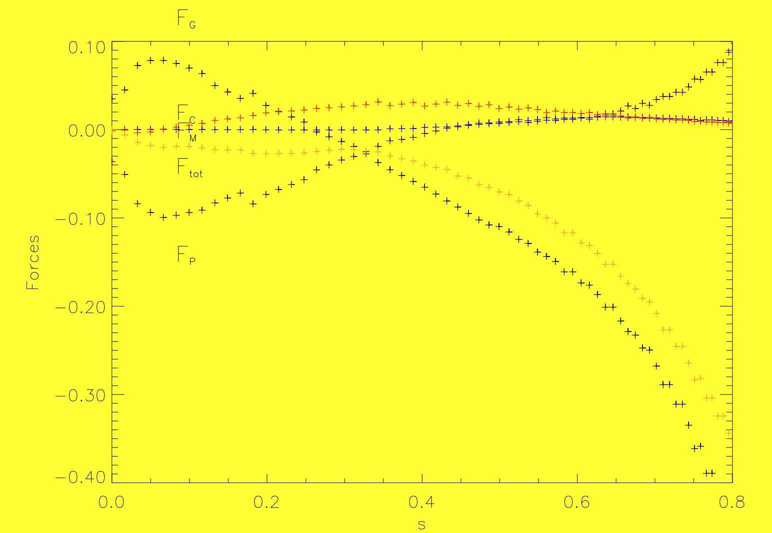
- for realistic CTTS values: truncation radius smaller than co-rotation

  $\Rightarrow$ CTTS must always spin-up due to star-disc interaction!

  $\Rightarrow$ unless other processes effective (stellar and disc jets again...)

Bessolaz et al.

- forces in funnel flow: first pressure gradient
  - $\Rightarrow$ eventually gravity wins, free-fall velocity (surface at $s \sim 1.2$)



Outlook I

- Model lacks as yet
  - $\Rightarrow$ stellar outflows, disc outflows (X-winds?)
  - $\Rightarrow$ all models treat disc with anomalous transport prescriptions
  - $\Rightarrow$ source of turbulence? MRI? Still compatible with large-scale field?
- near-Keplerian, thin disks versus strongly magnetized, thick disks
  - $\Rightarrow$ garantueed many, different instabilities at play in real disks
  - $\Rightarrow$ e.g. Convective Continuum Instability *(Blokland et al, A&A 467, 21, 2007)*
- 3D effects, stability of (multi-component) outflows?
  - $\Rightarrow$ twisted fields $\rightarrow$ kink instabilities
  - $\Rightarrow$ shear flow interfaces: Kelvin-Helmholtz

Outlook II

- stability issue also for relativistic jets (AGN)
  - ⇒ Meliani & Keppens, *arXiv:0709.3838*
  - ⇒ cross-cut in fast inner, slow outer jet, AMR simulation
  - ⇒ different launch mechanism → different rotation profile
  - ⇒ interacting body-surface KH, Rayleigh-Taylor (centrifugal force)