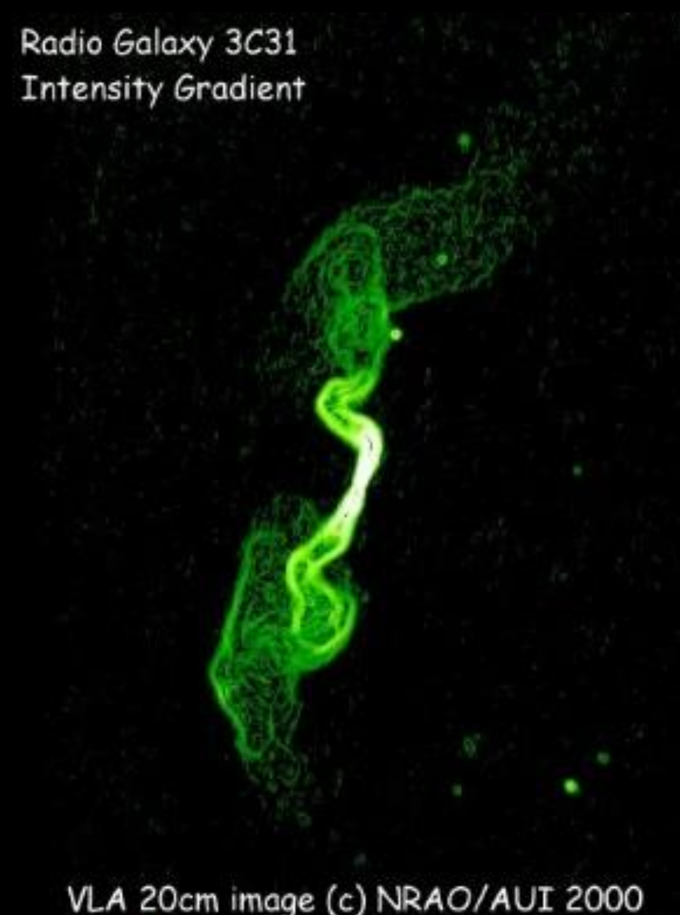
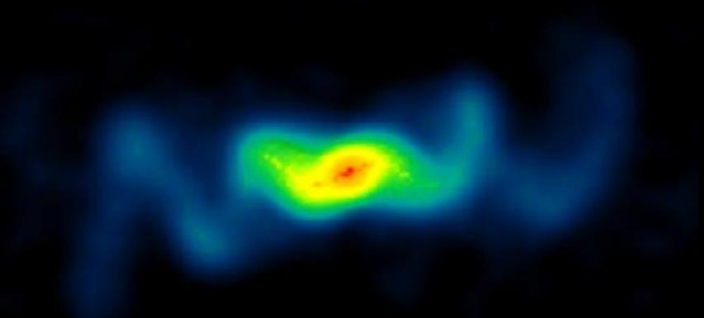
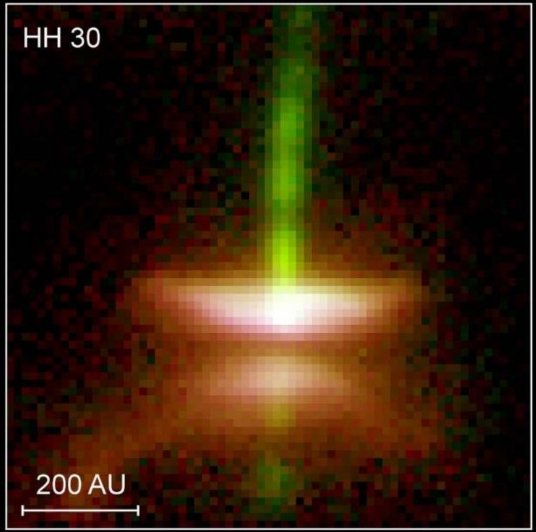
MHD Simulations of jet-disk structure at different astrophysical objects



Somayeh Sheikhnezami
Institute for Research in Fundamental Sciences

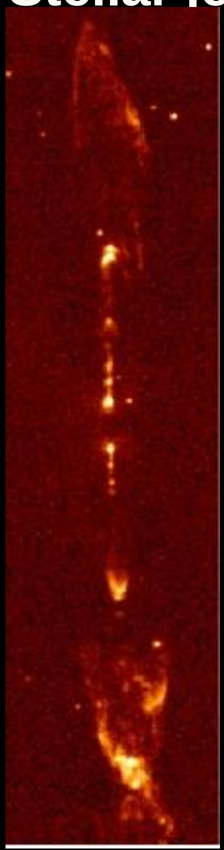




Astrophysical jets

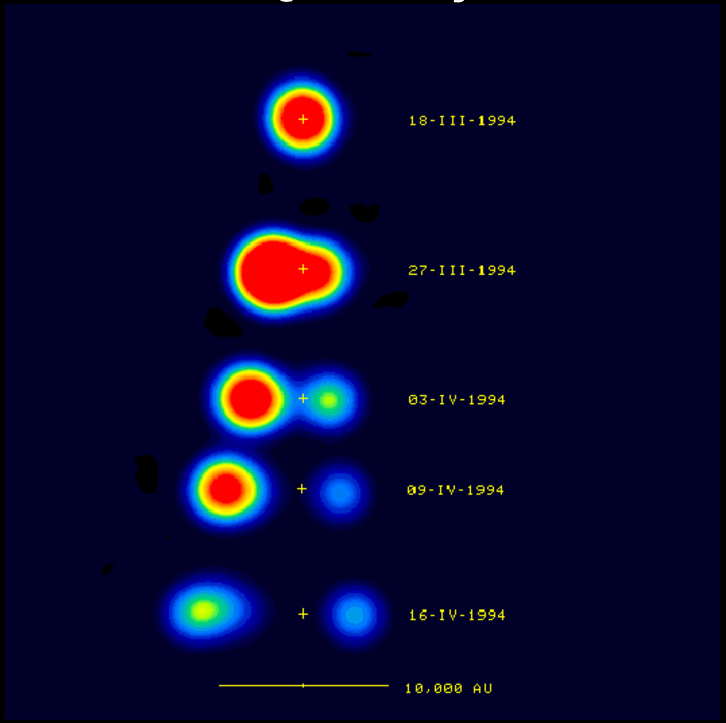
- Collimated beam of matter with higher velocity than outer medium
- Transport mass, momentum, energy and magnetic
- Sources: young stars, active galactic nuclei, micro quasars, gamma ray bursts, planetary nebulae, pulsars

Stellar jet



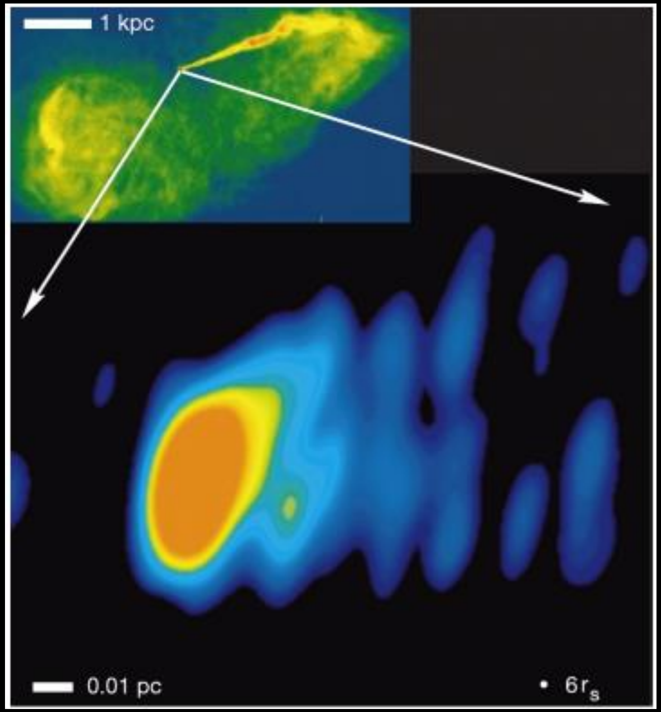
HH 212 , H2, 2.12 μm
(McCaughrean et al. '98)

Micro Quasar jet



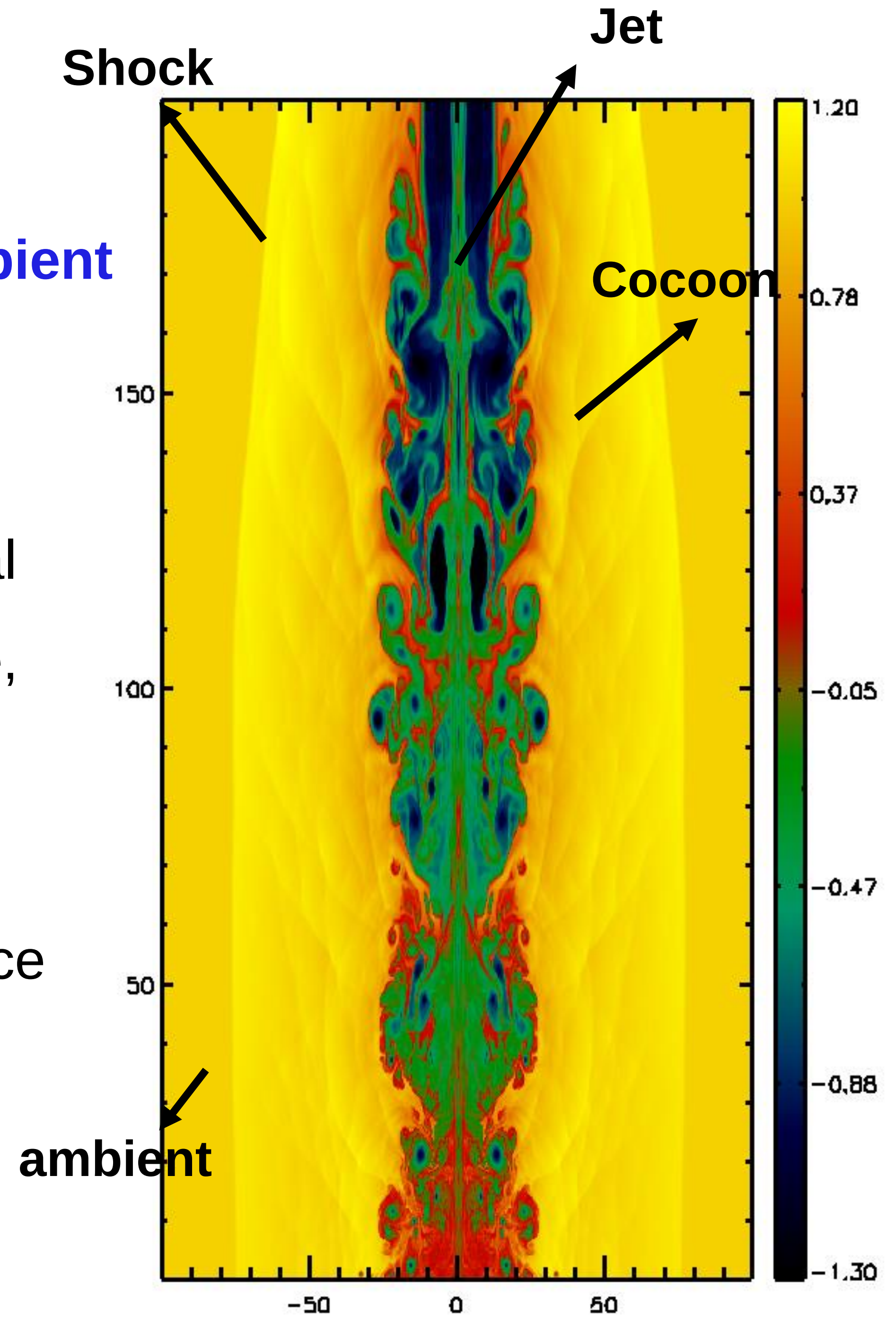
arcsec-scale radio jets from the superluminal Galactic jet source
GRS~1915+105. (VLA)
Mirabel & Rodriguez (1994)

extragalactic jet (AGN jet)



M87 central region
(Biretta et al, 1999)

Studying jets / outflows ??



Sheikhnezami 2017

Jet propagation and interaction with ambient

- Interesting astrophysical phenomena (Physic lab)
- Important for angular momentum removal
- Impact on ISM/IGM : Driving **Turbulence**, energy (work in progress)
- Constraining on star formation
- Shock chemistry -> ambient and jet source compositions

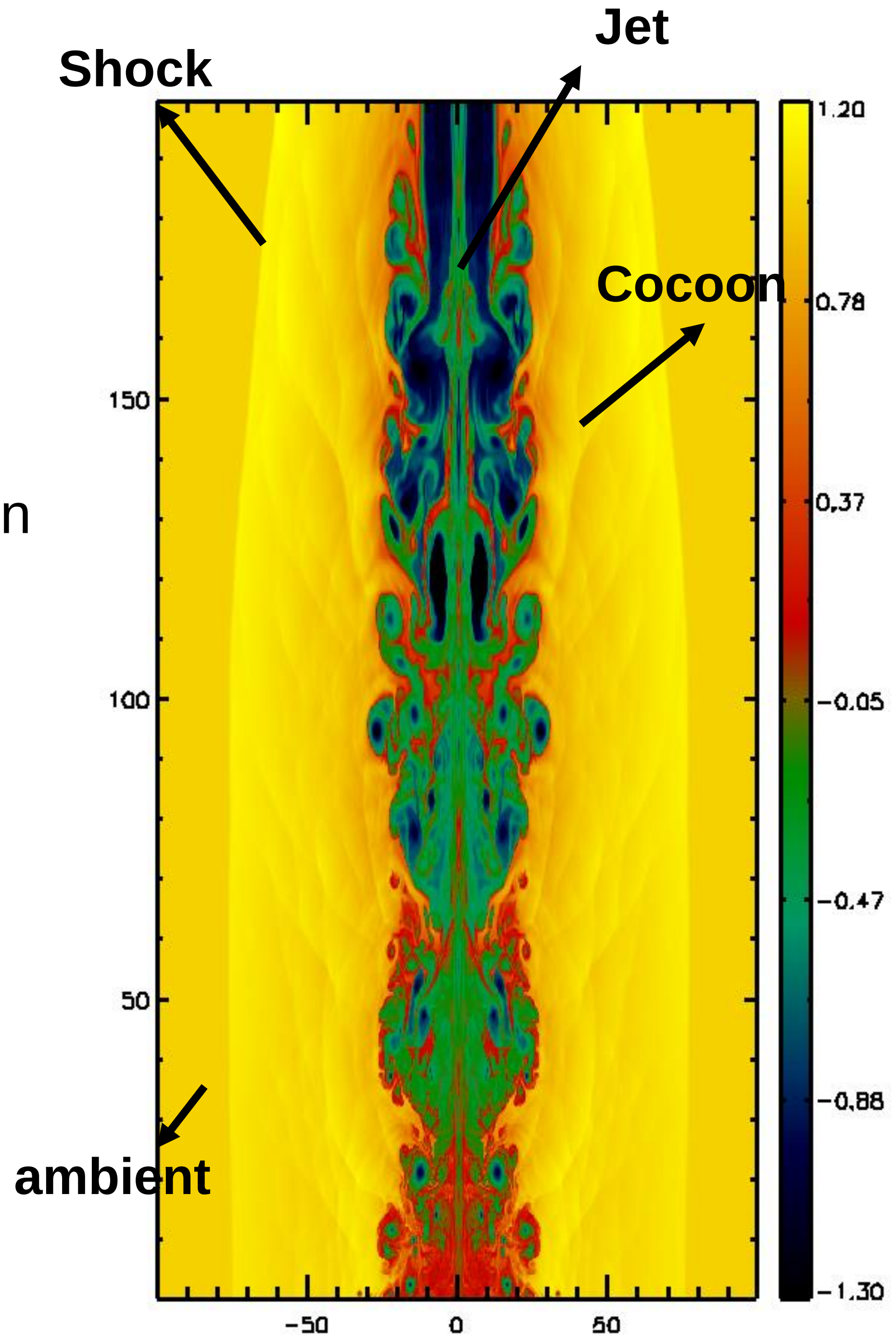
Studying jets / outflows ??

Internal structure

- Internal structure of jet/internal heating
- Matter contents !?
- **Instability inside the jet**, (MRI?! Work In progress)

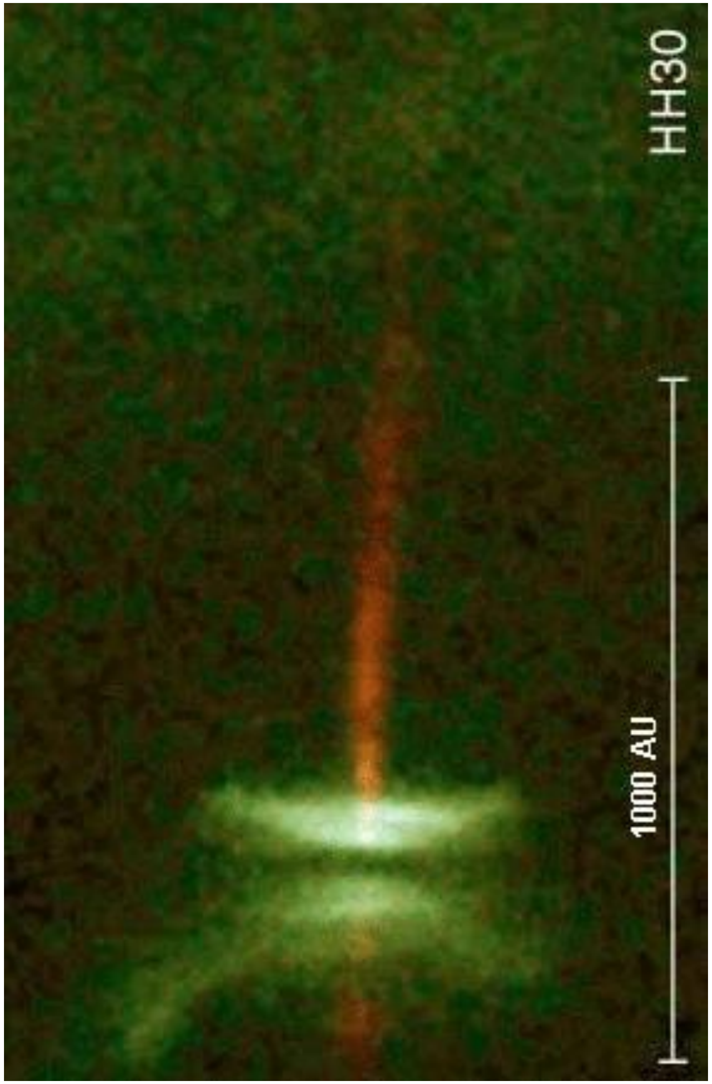
Jet formation

- What are deriving mechanisms of jets?
- Which system can have jet?
- Launching area, physical conditions
- Disk-jet connection? Source properties?

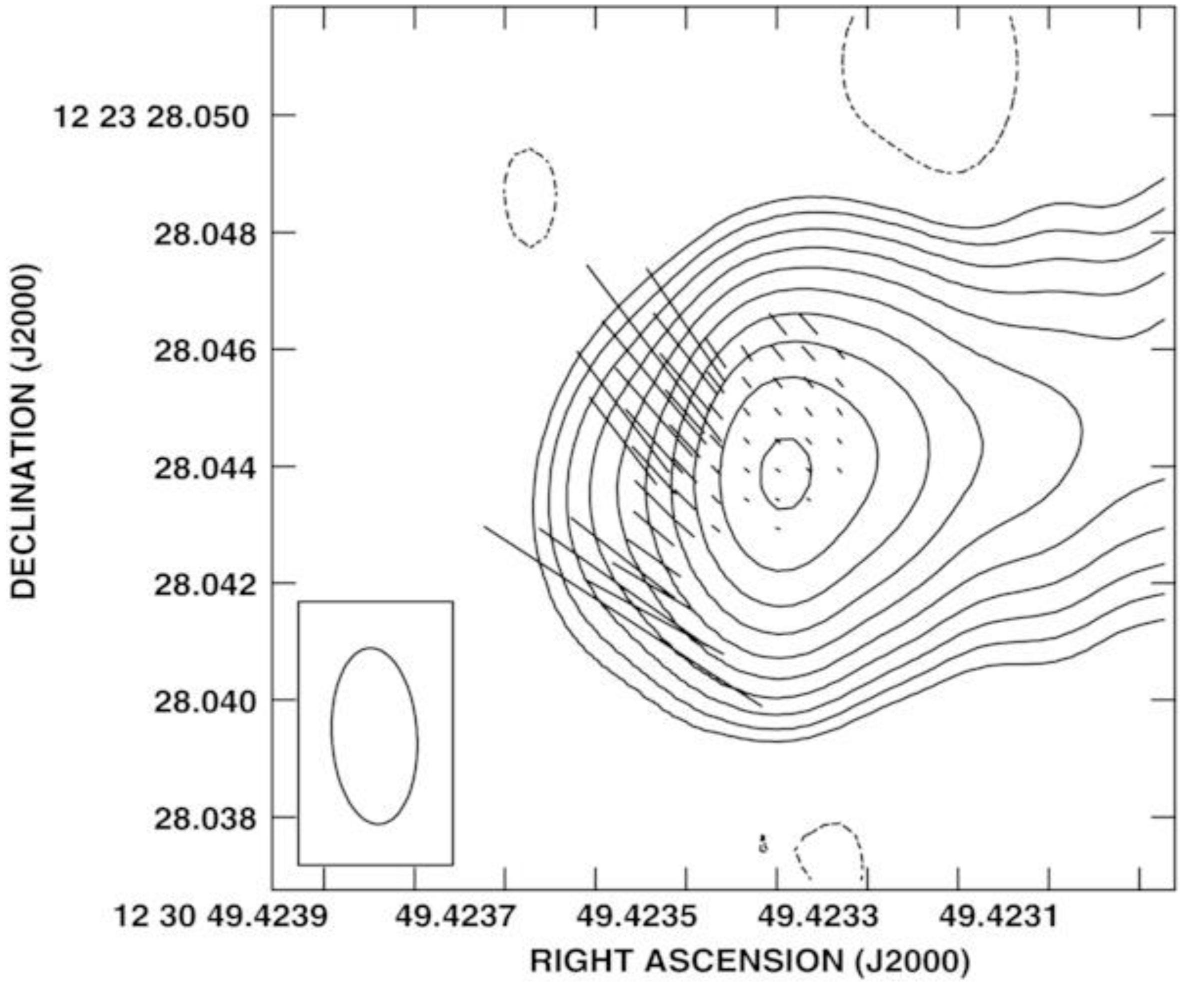


Sheikhnezami 2017

Jet properties in general:



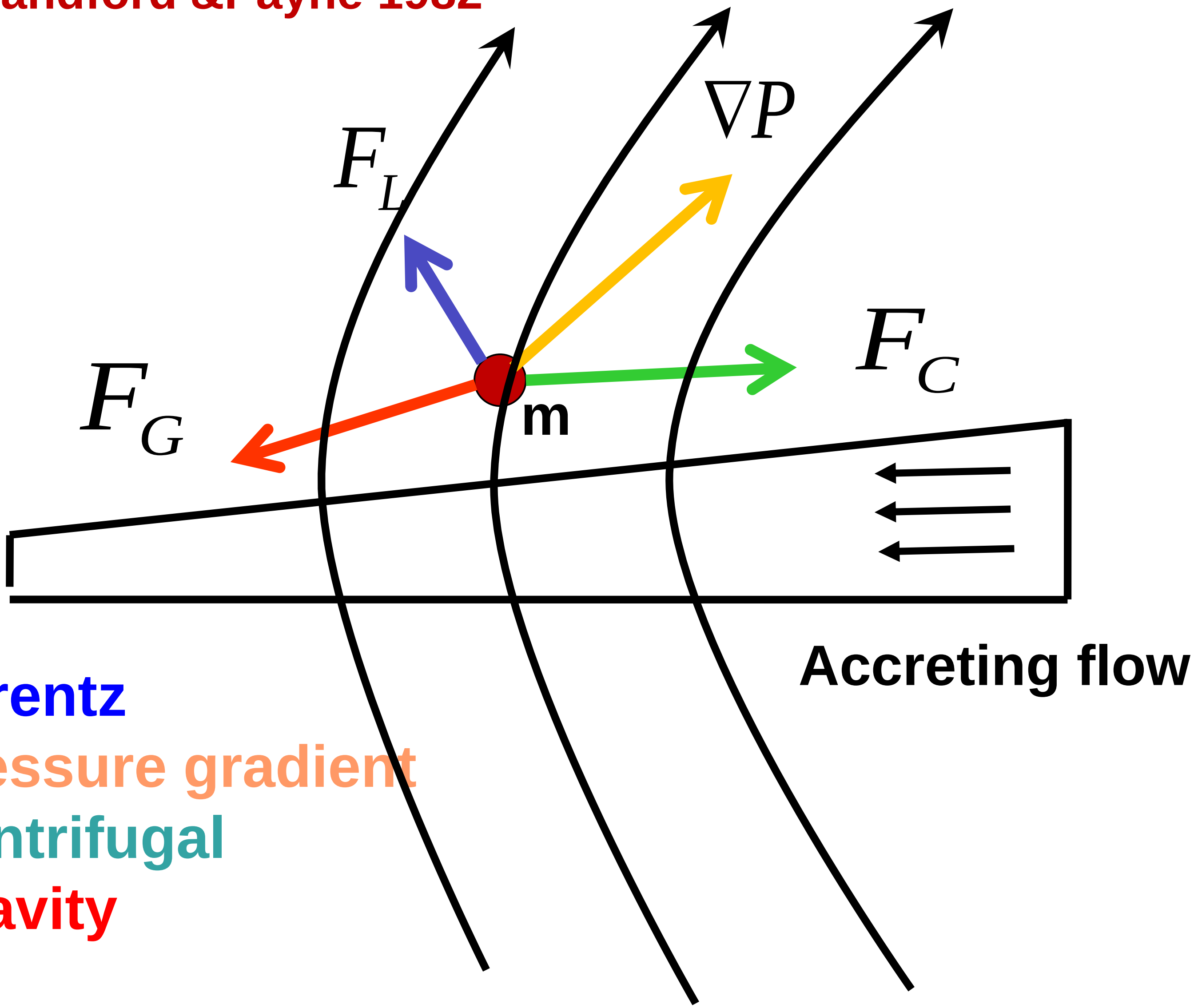
Accretion disk and jet in a proto-star HH30 (HST)



5 GHz VLBA image of the core in M87 with fractional polarization electric vectors superposed.
(P. Kharb et al. 2012 ApJ 754)

Jet Launching

Disk wind - Blandford &Payne 1982



Forces

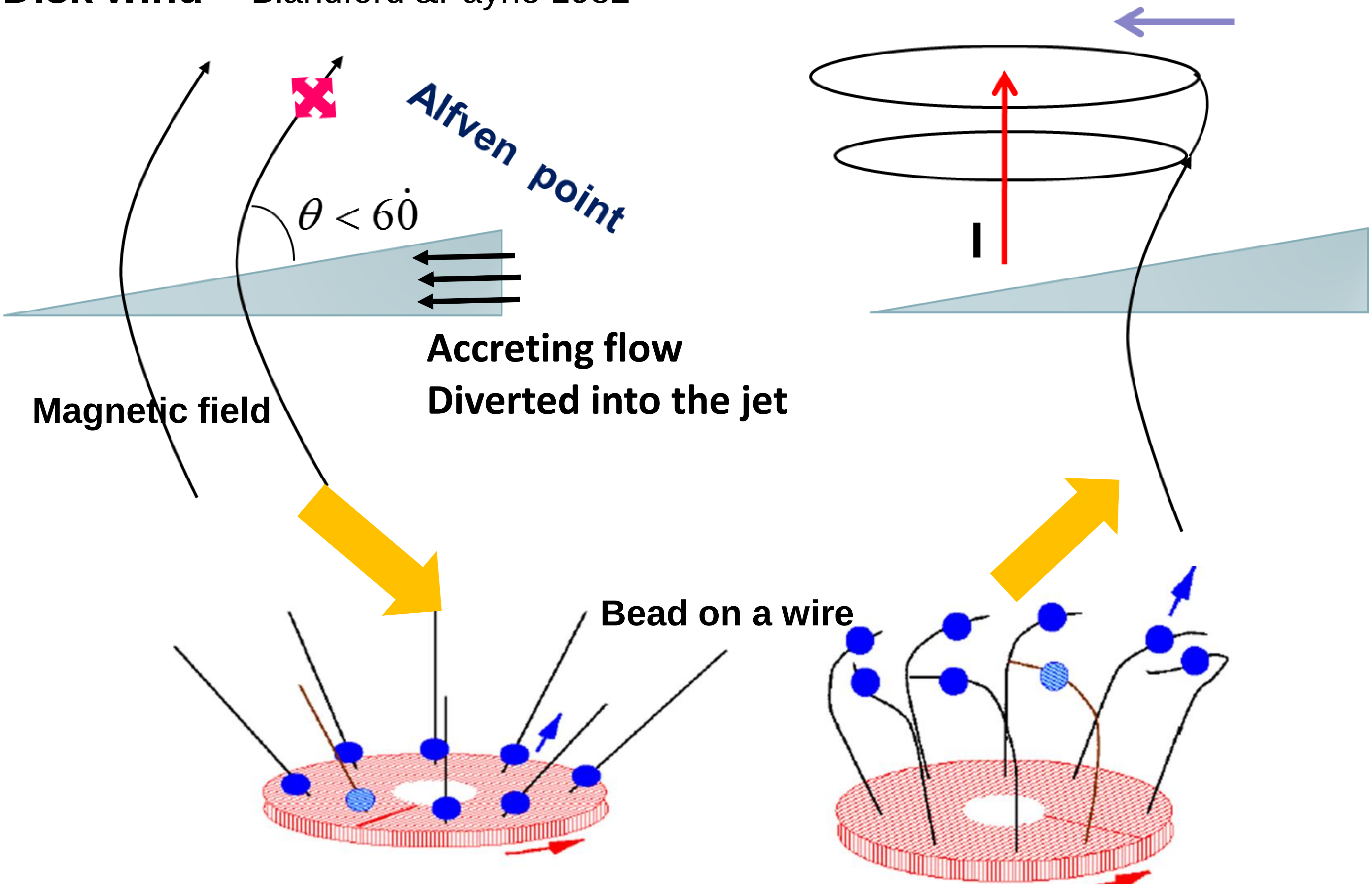
Lorentz
Pressure gradient
Centrifugal
Gravity

B: Large sale Magnetic field

Jet formation : Launching and acceleration

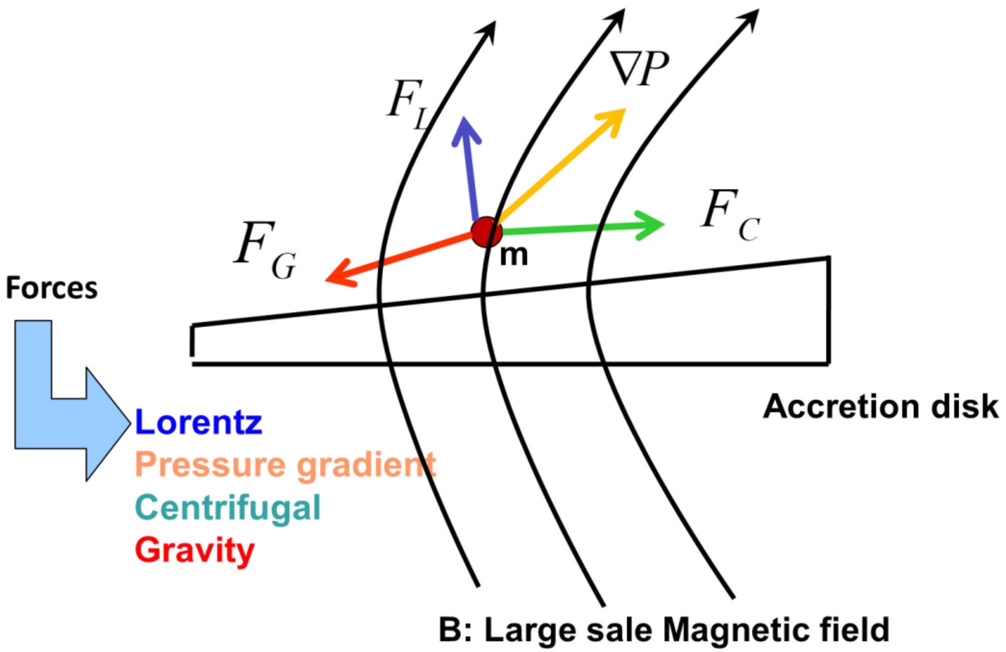
Disk wind Blandford &Payne 1982

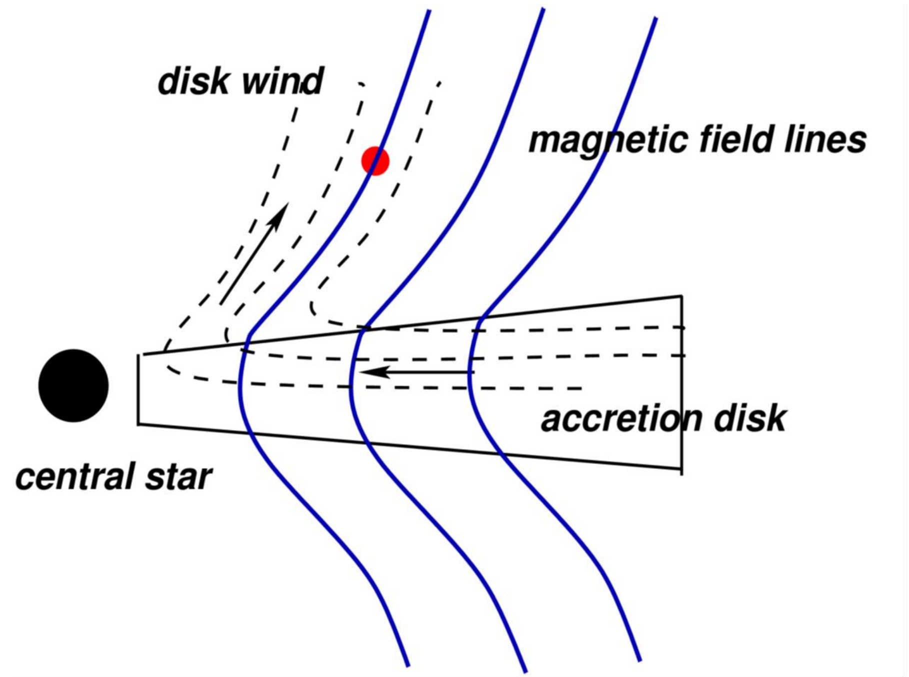
Bφ: Hoop stress



Jet formation : Launching and acceleration

Disk wind   Blandford &Payne 1982

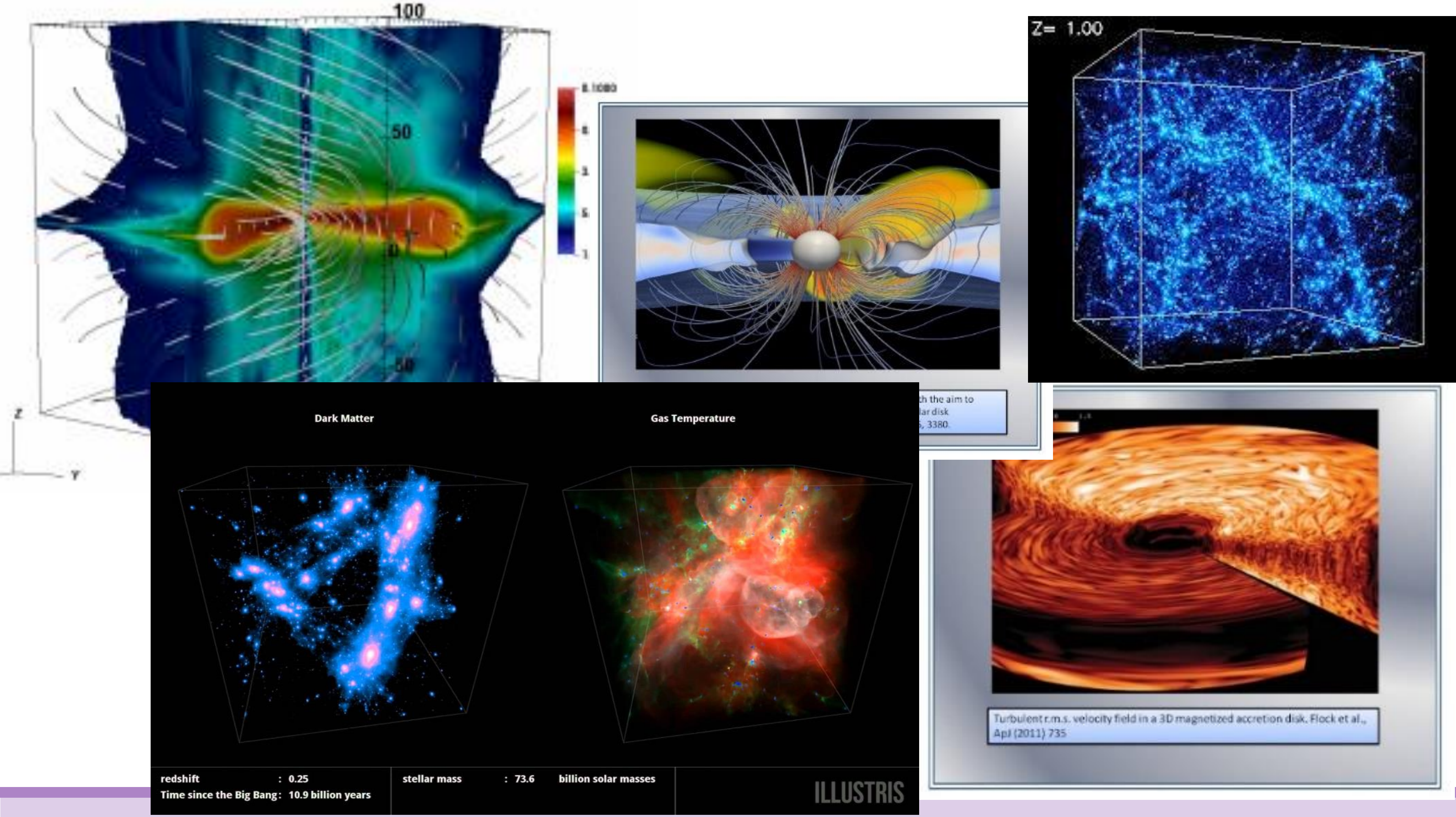




Sheikhnezami, S., et.al 2012, ApJ, 757, 65
Fendt & Sheikhnezami 2013 APJ
Stepanovs, D., Fendt, C., Sheikhnezami, S. 2014, APJ
Sheikhnezami & Fendt , 2015 , APJ
Sheikhnezami & Fendt , 2018 , APJ

Numerical approach

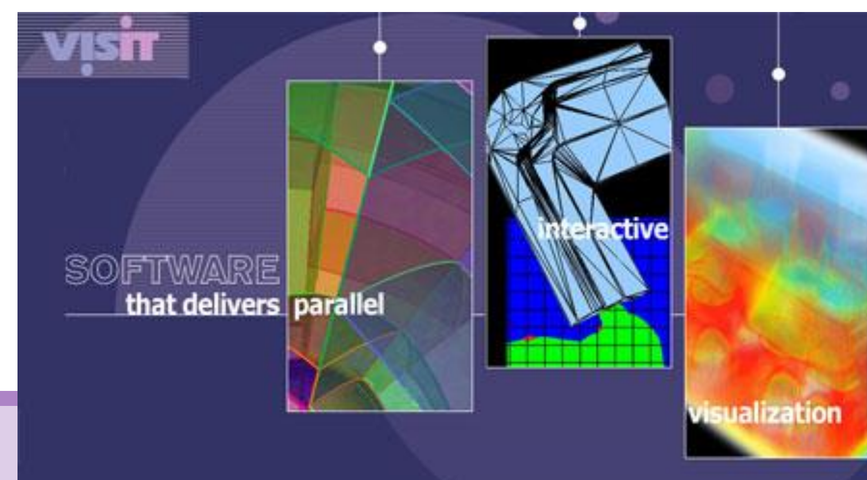
- Non-observable Physical processes.
- Limited information by dynamical parameters
- Nonlinear system of hyperbolic conservation laws



Numerical approach

- PLUTO code, MHD module
- Parallel processing in Large Cluster , THEO, HYDRA, DRACO, ISAAC

- Post Processing
- Analyzing the outputs
- Visualization IDL, PYTHON, VISIT….



Initial Conditions

Hydrostatic corona and thin sub Keplerian disk

Axisymmetric $\varepsilon = \dfrac{H}{r} = 0.1$

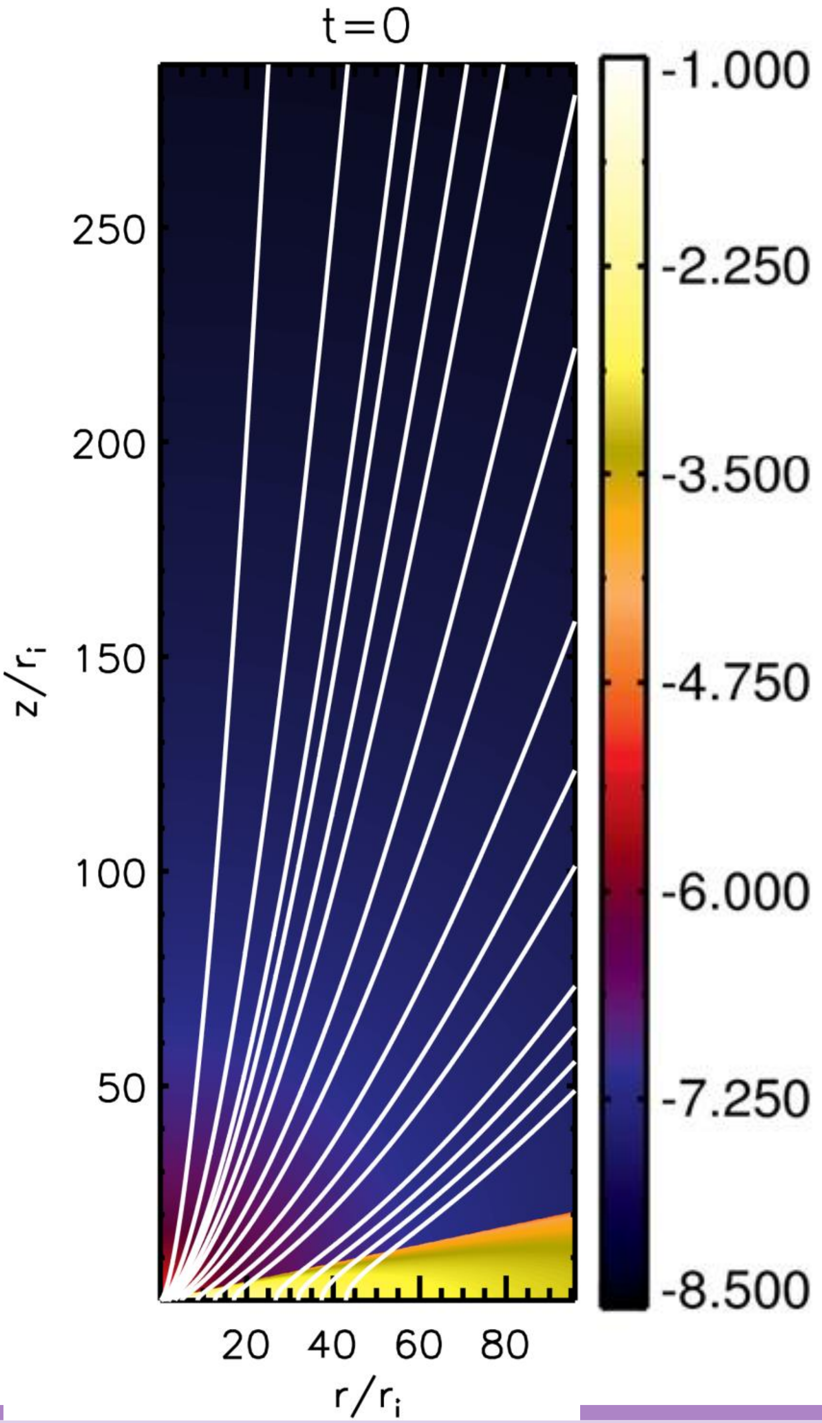
Density contrast $\sim 10^{-4}$

Field distribution (Zanni et al.2007)

$$\vec{B} = \vec{B}_p + B_\varphi \ \hat{e}_\varphi$$

$$\vec{B}_p = \frac{1}{r}\vec{\nabla}\psi \times \hat{e}_\varphi \ , B_\varphi = \frac{\psi(r,z)}{r}$$

$$\psi = \frac{4}{3} B_{z0} r_0^2 \left(\frac{r}{r_0}\right)^{3/4} \frac{m^{5/4}}{\left[m^2 + \frac{z^2}{r^2}\right]^{5/8}}$$



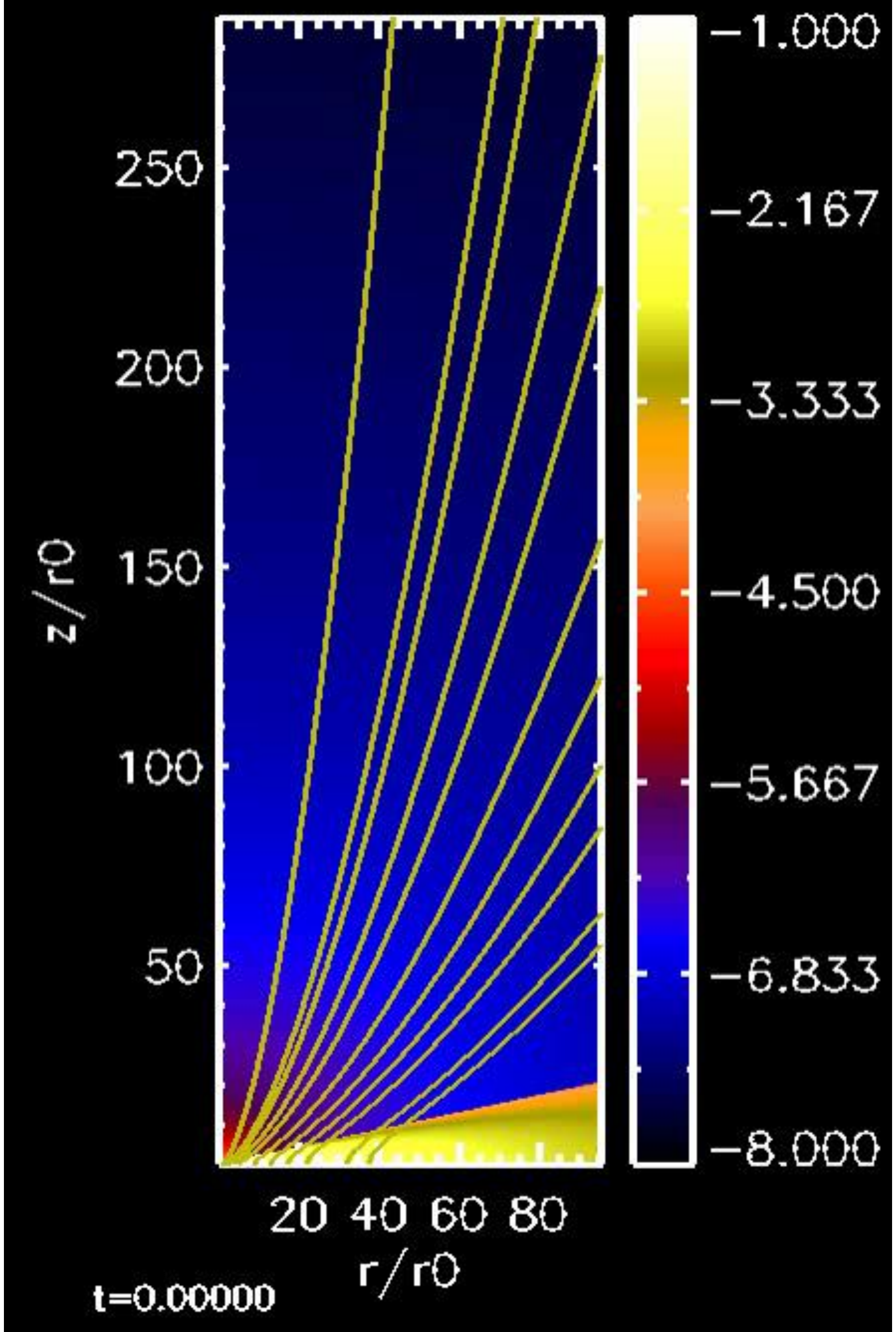
Axisymmetric jet launching:

- Reference run in 2D
- Hydrostatic corona in equilibrium with thin sub Keplerian disk
- Density distribiution in color
- Density contrast $\sim 10^{-4}$
- Magnetic field lines in orange
- Including disk and jet evolution

Bipolar Jets Launched from Magnetically Diffusive Accretion Disks

Sheikhnezami, S., Fendt, C., Porth, O., Vaidya, B., & Ghanbari, J. 2012, **ApJ**, 757, 65

Sheikhnezami et.al 2012



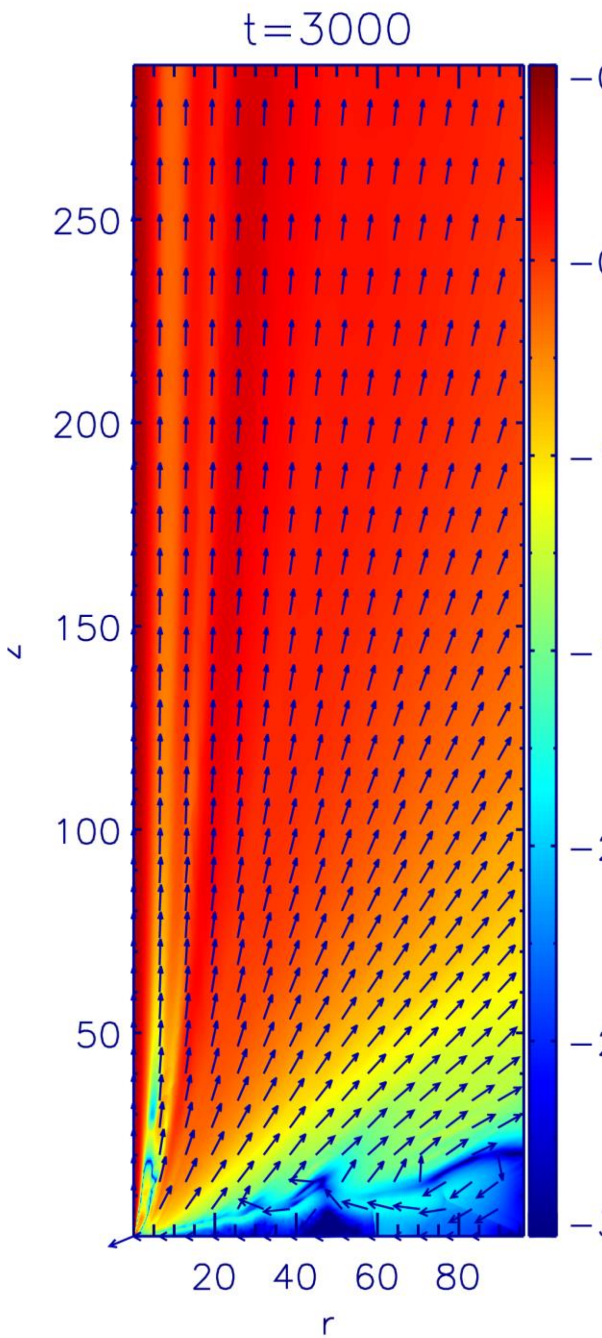
Our previous works

- **Axisymmetric launching:**

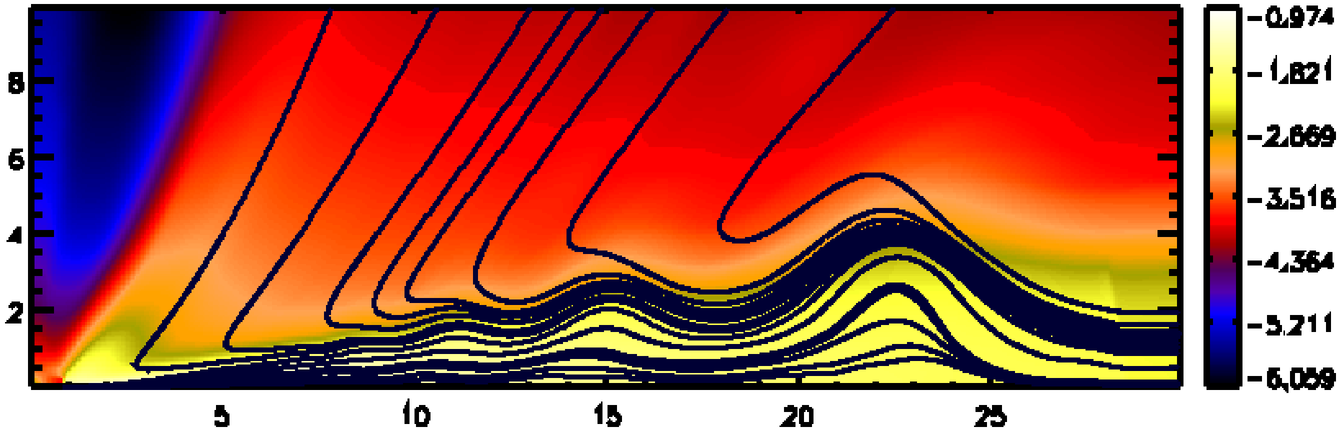
  Bipolar Jets Launched from Magnetically Diffusive Accretion Disks.

  I. Ejection Efficiency versus Field Strength and Diffusivity,

  Sheikhnezami, S., et.al 2012, **ApJ**, 757, 65

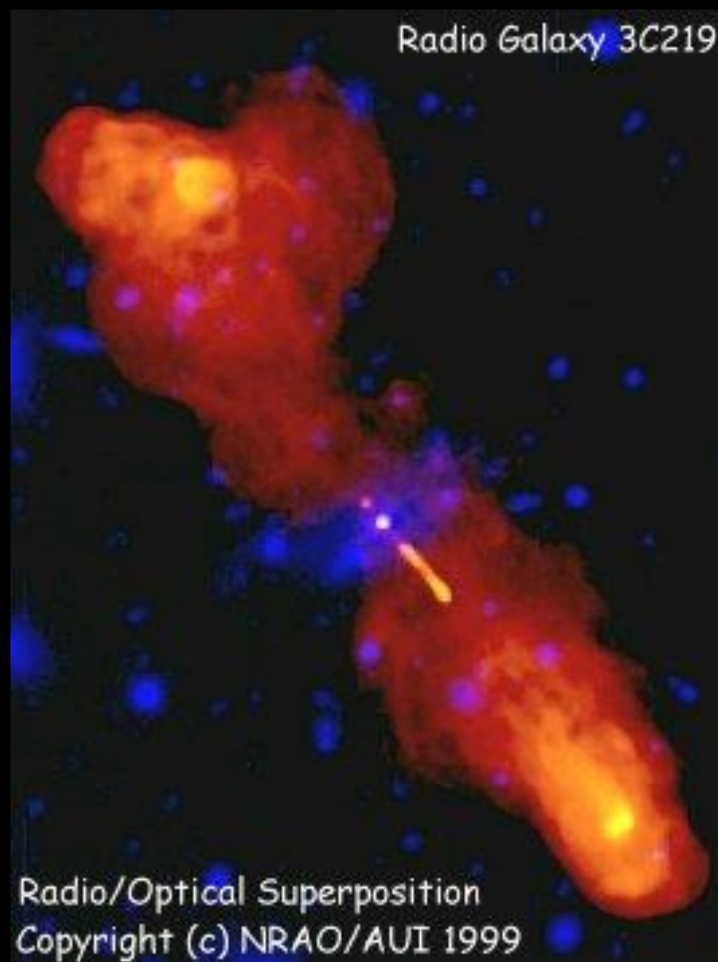


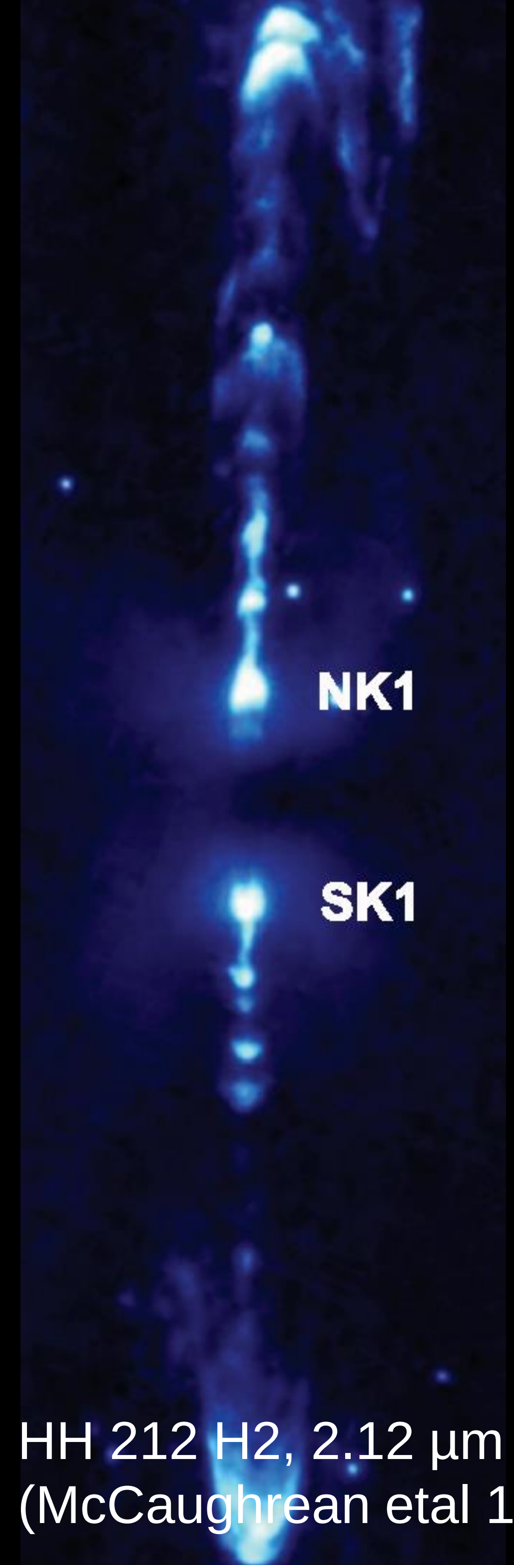
Accretion –ejection connection
Mass stream line



Bipolar jets launched from asymmetric disks

- Co-existence of jet and counter jet
- Typically asymmetric in shape with very few exceptions, HH212



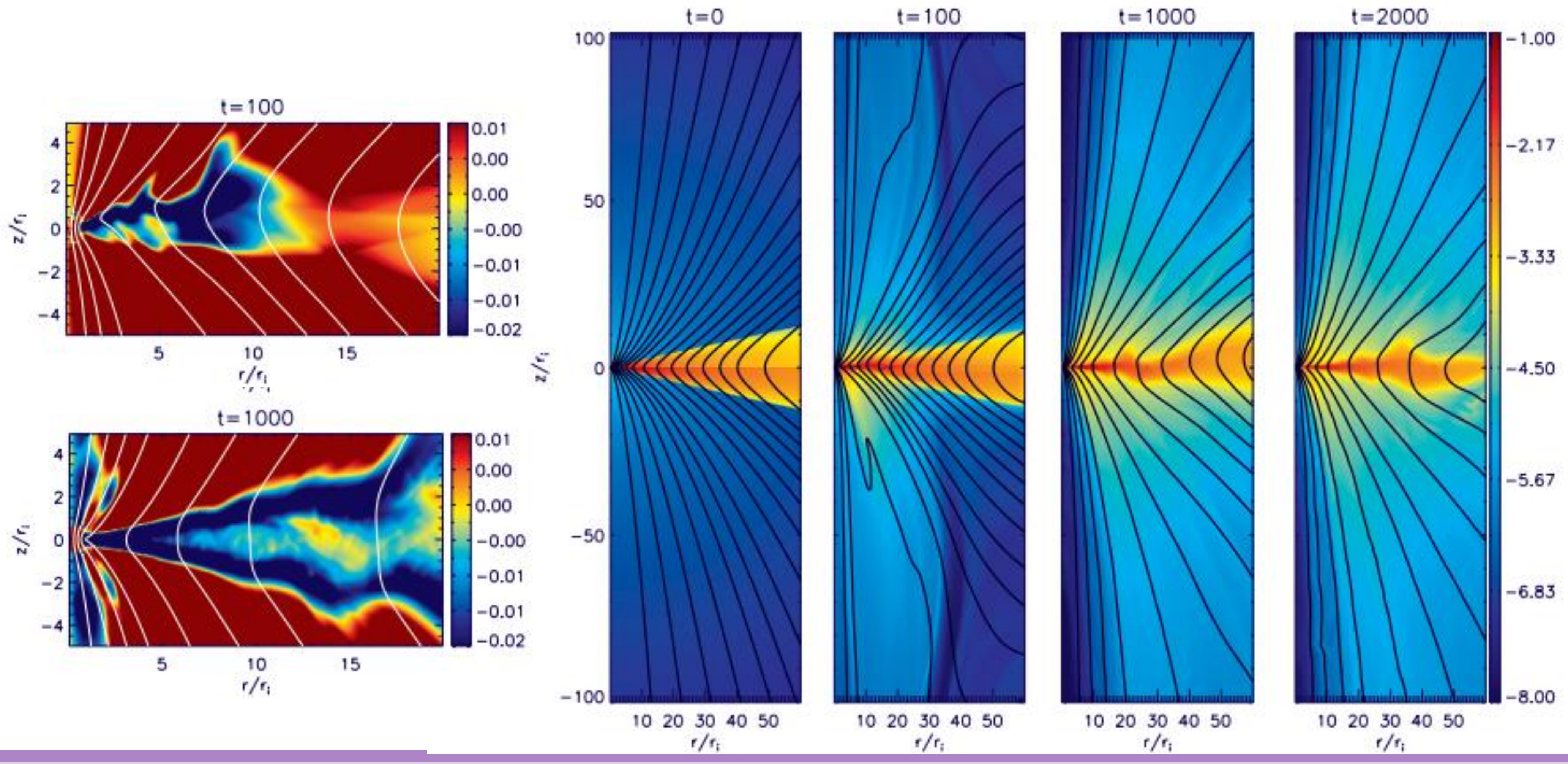


HH 212 H2, 2.12 µm
(McCaughrean etal 1

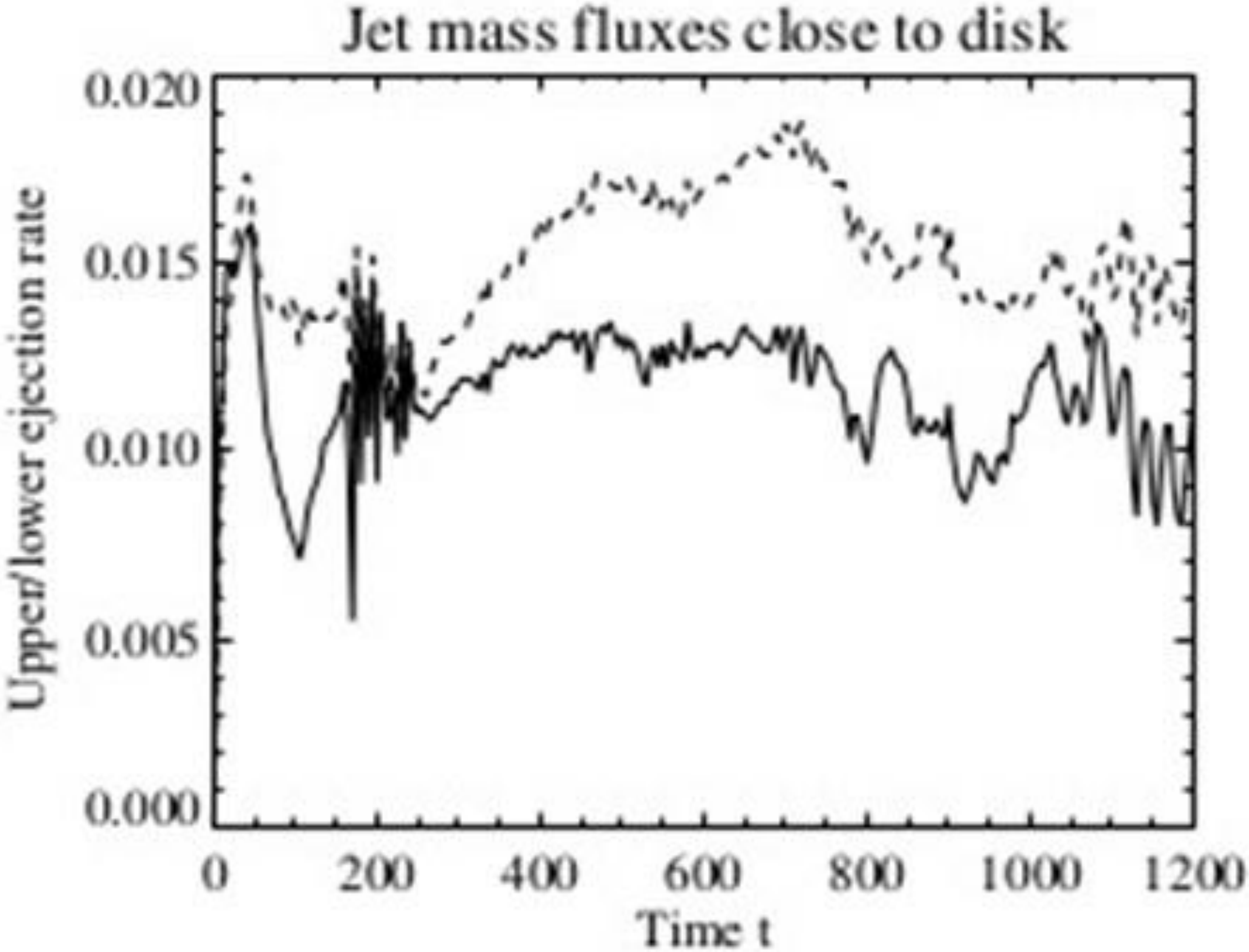
Our previous works

- **Bipolar jet asymmetry :**

Bipolar Jets Launched from Accretion Disks. II. The Formation of Asymmetric Jets and Counter Jets,
Fendt, C. & Sheikhnezami, S. 2013, **ApJ**, 774, 12

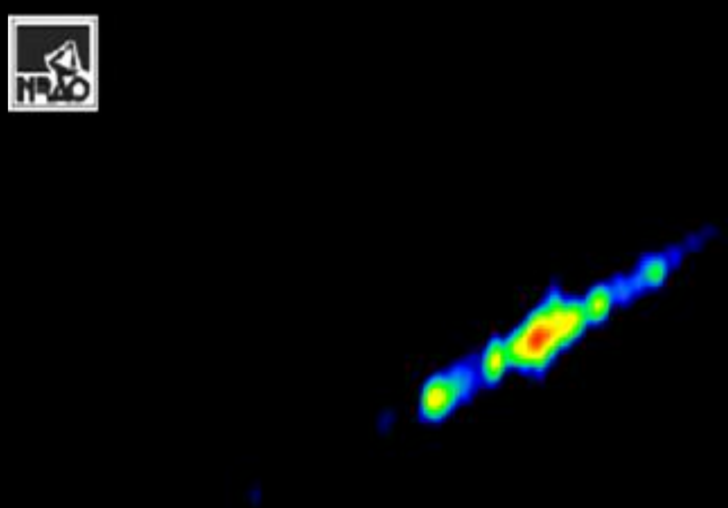


20 -30% differenes in mass fluxes for the jet and counter jet

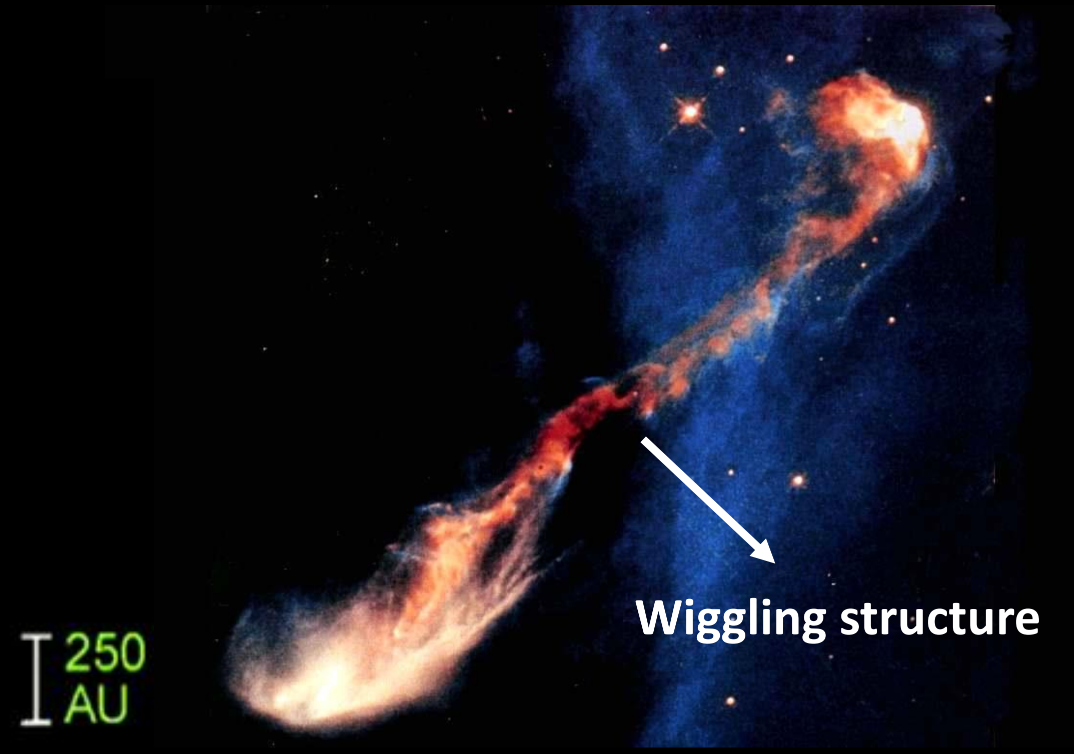


Fendt, C. & Sheikhnezami .S, 2013, ApJ, 774, 12

Jet precession and wiggling in observation



HH-47 (HST)



VLBA observations of the X-ray binary SS 433

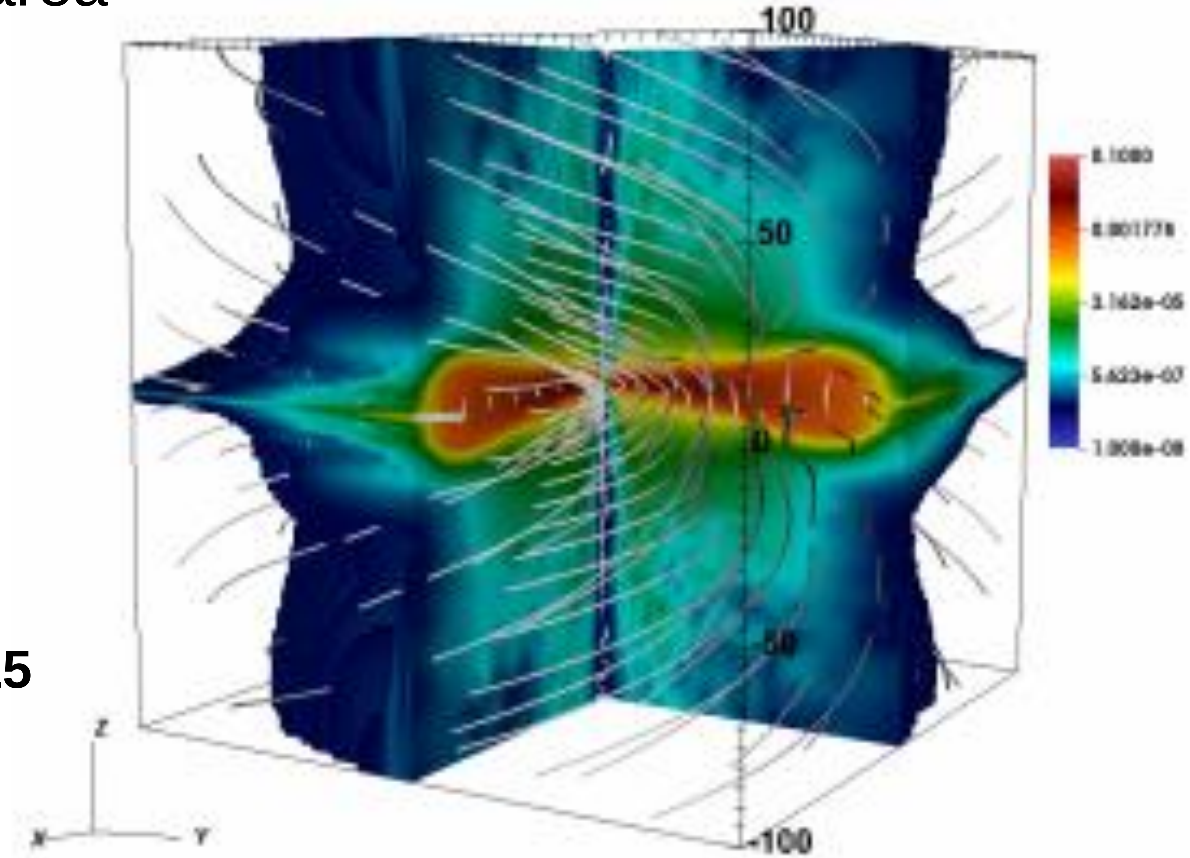
CREDIT: A. Mioduszewski et al., NRAO/AUI/NSF

HH-47 1,500 light-years away,

at the edge of the Gum Nebula (HST)

3D MHD simulations of Jet formation / why!!?

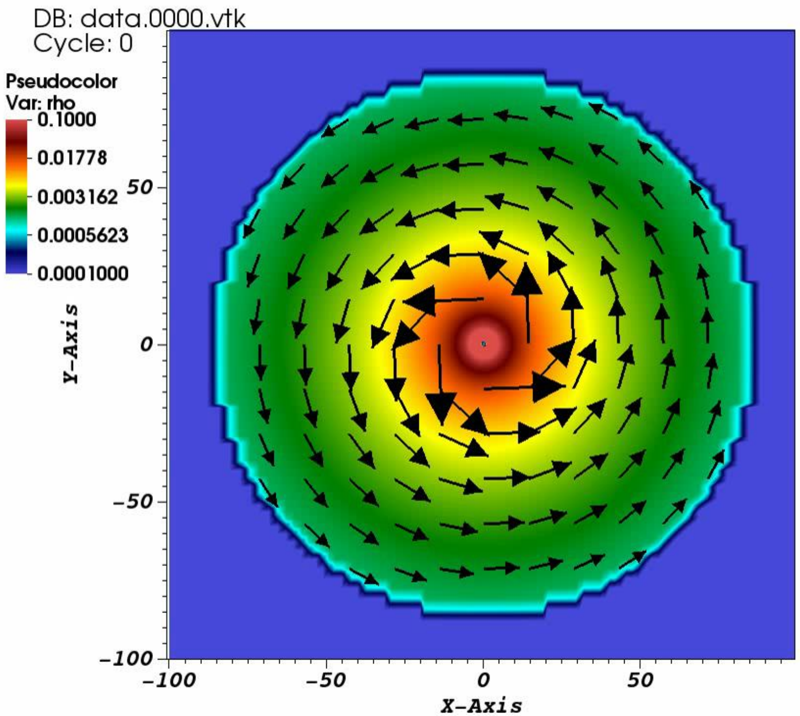
- Jets are not smooth but locally structured
- Typical asymmetry seen between jet and counter jet
- Asymmetry seen in disk/ jet system (C shape, S shape, warp)
- 3D evolution of launching area



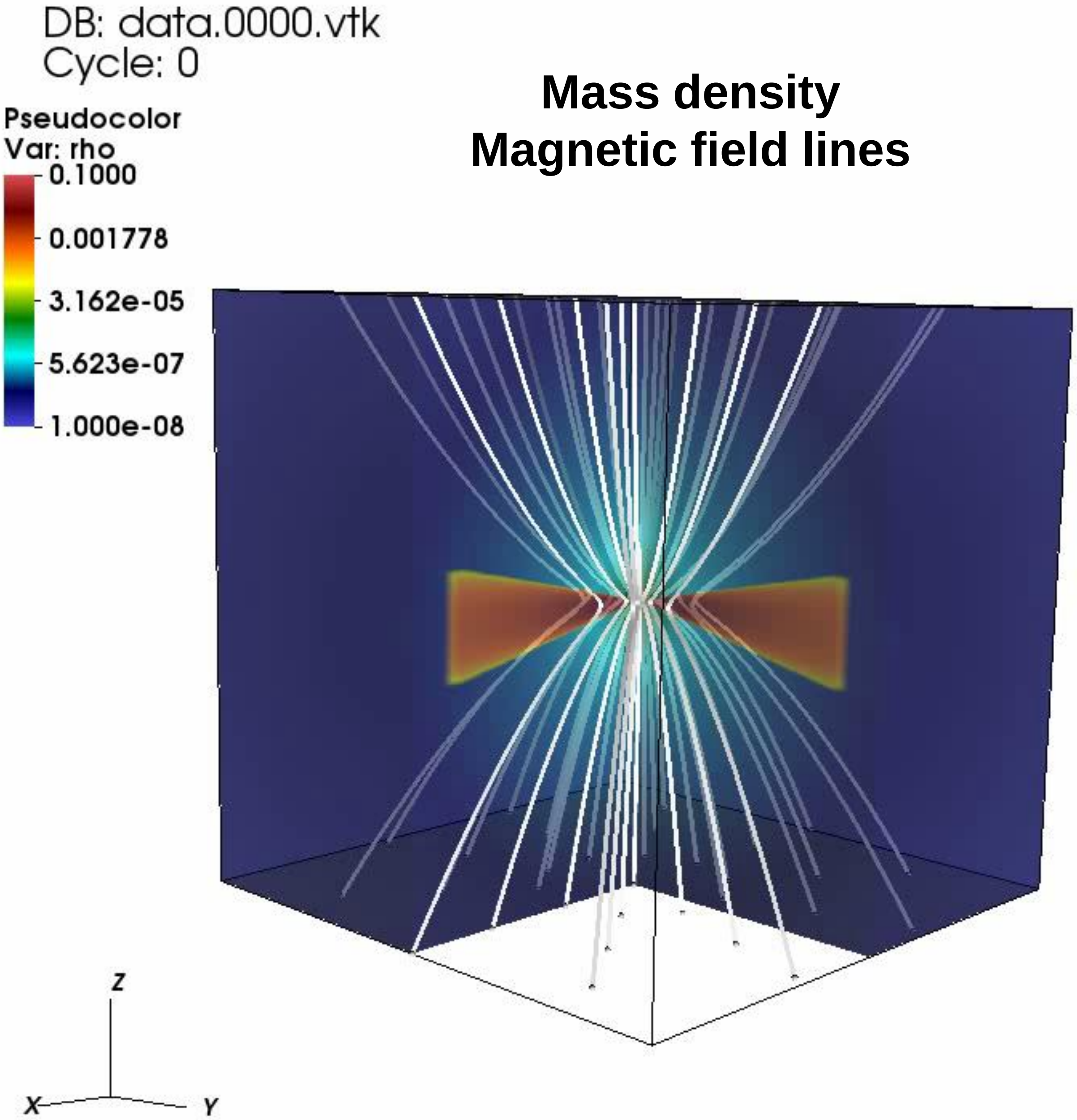
Sheikhnezami & Fendt ApJ 2015

3D MHD simulation of single star/disk /jet

Mass density
Velocity vectors
Z=0



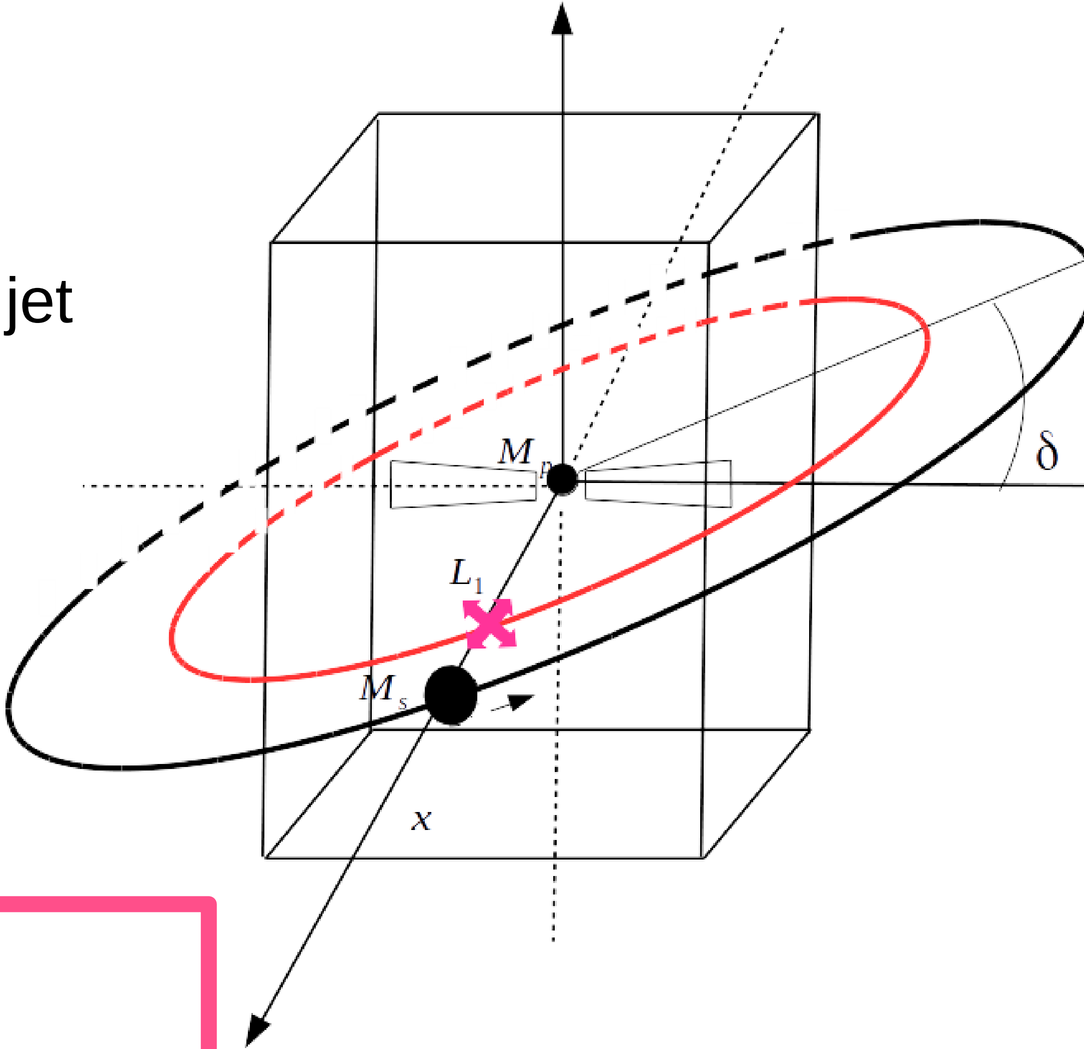
Mass density
Magnetic field lines



Sheikhnezami & Fendt , APJ 2015

Recent study:

- Long term 3D MHD simulation of jet formed from binary system
- Including the time dependent potential of the binary



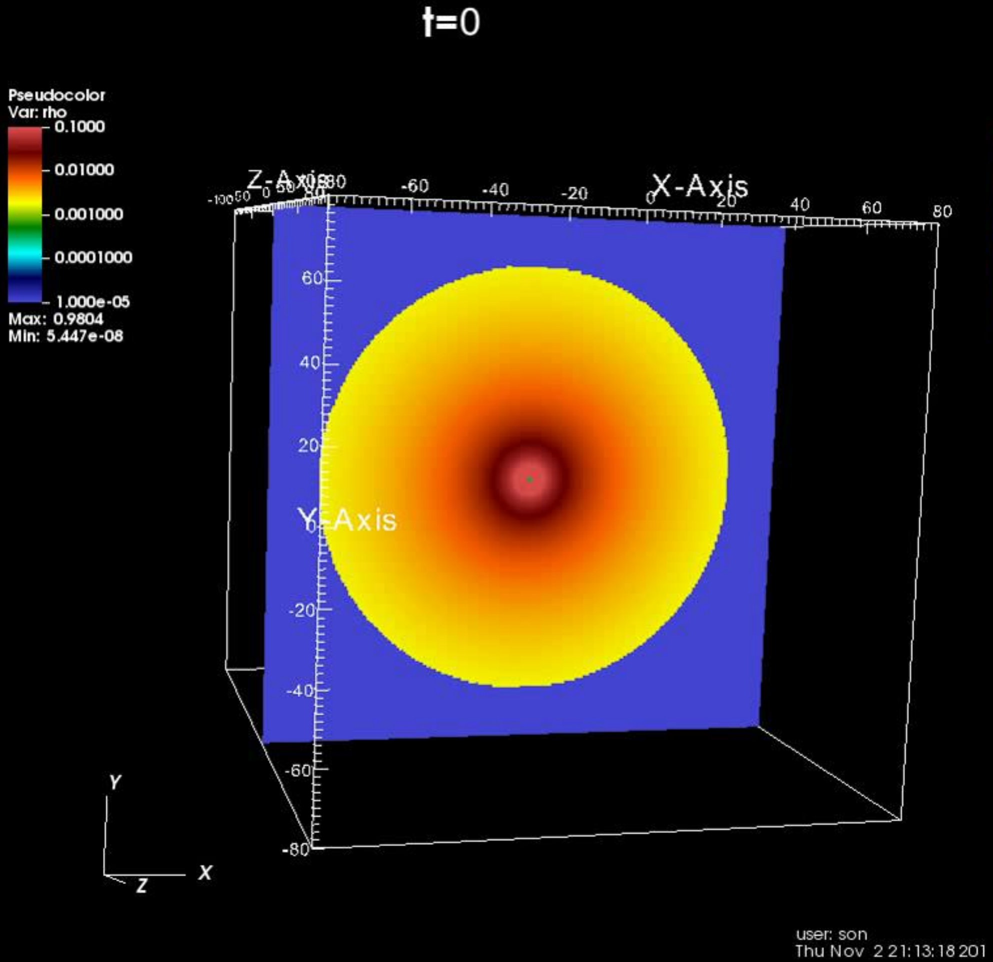
$$\Psi_{ext} = -\frac{GM_p}{\mid \mathbf{r} \mid} - \frac{GM_s}{\mid \mathbf{r} - \mathbf{D} \mid} + \frac{GM_s \mathbf{r} \cdot \mathbf{D}}{D^3}$$

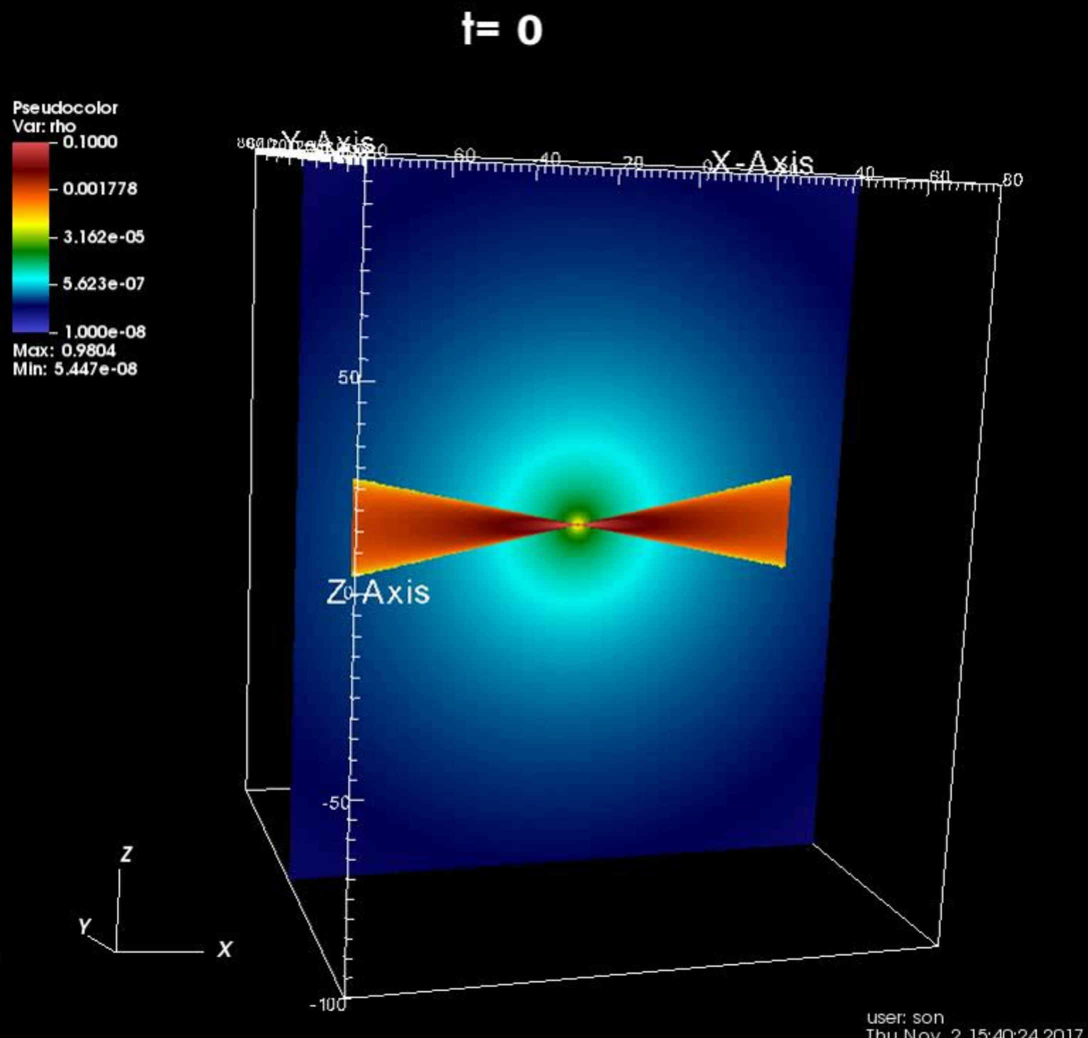
$$\mathbf{D} = D \cos \omega t \, \hat{\mathbf{i}} + D \sin \omega t \cos \delta \, \hat{\mathbf{j}} + D \sin \omega t \sin \delta \, \hat{\mathbf{k}}$$

Sheikhnezami & Fendt APJ 2018

Inclined orbital planes

Mass density
Moderate case $\delta = 10$



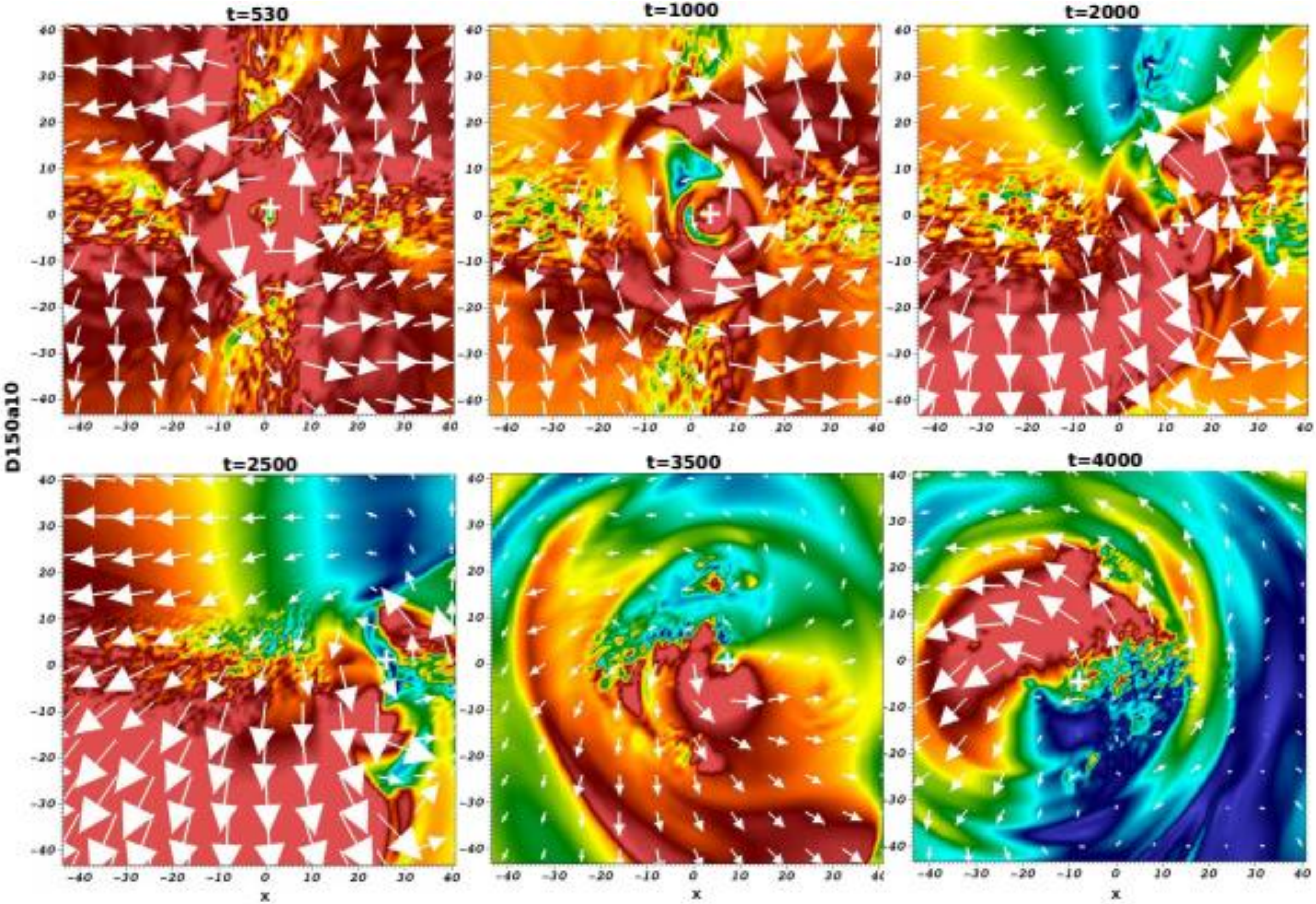


Sheikhnezami & Fendt APJ 2018

Indication of Jet precession

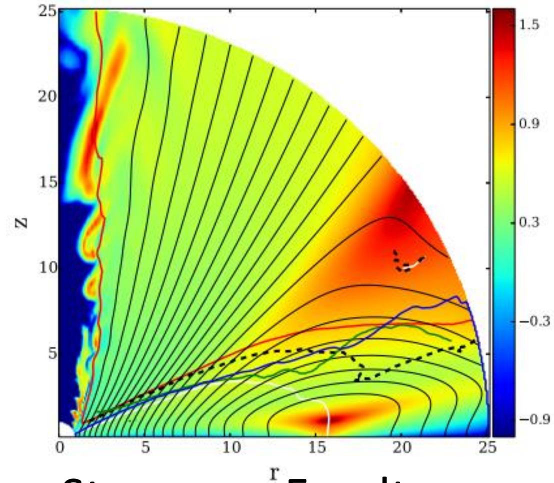
Color Bar : $\sqrt{V_x^2 + V_y^2}$

Arrows : Velocity field

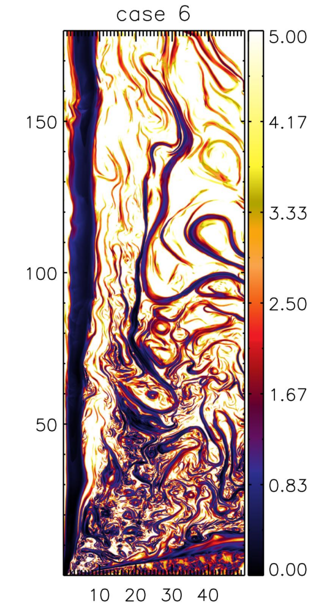


Take home message

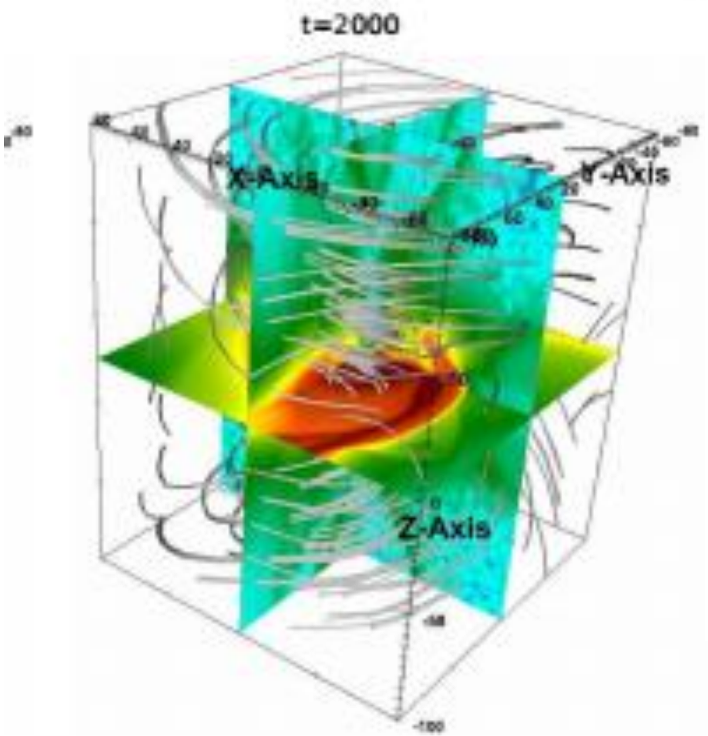
Simulation is a useful tool to expose nice picture predictions of very complex models



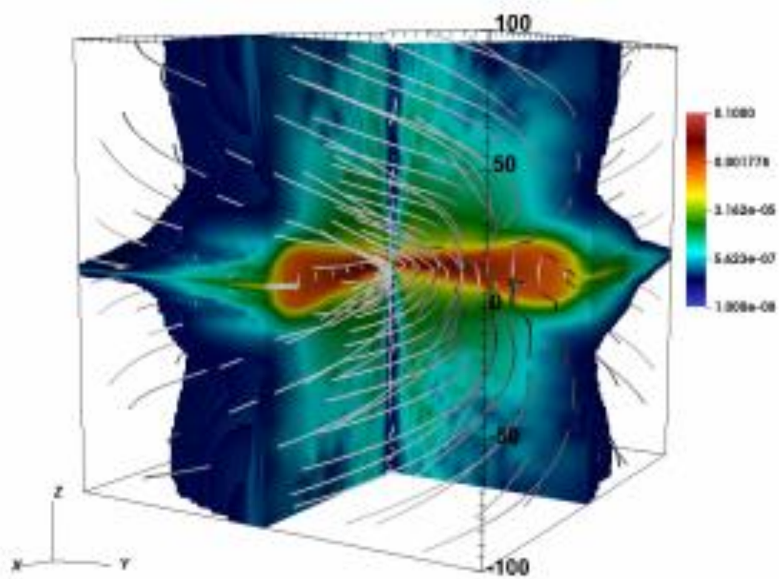
Stepanov, Fendt
sheikhnezami 2014



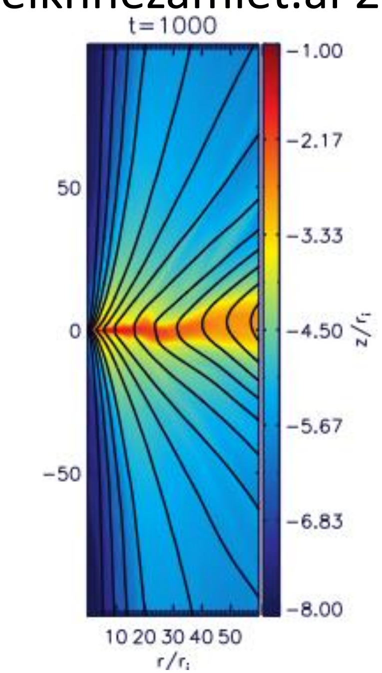
Sheikhnezamiet.al 2012



Sheikhnezami et.al 2018

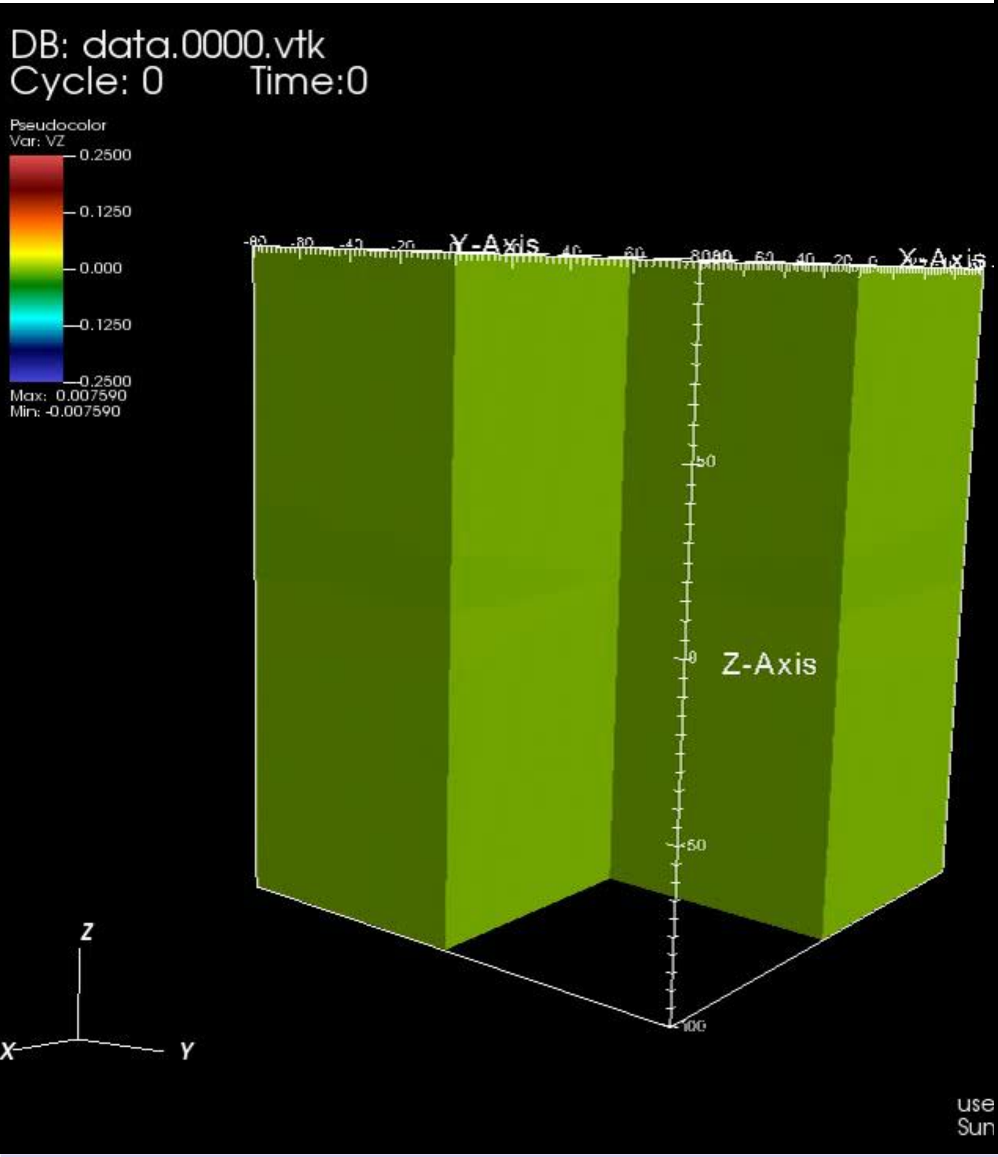


Sheikhnezami et.al 2015



Fendt & Seikhnezami 2013

Thanks For Your Attention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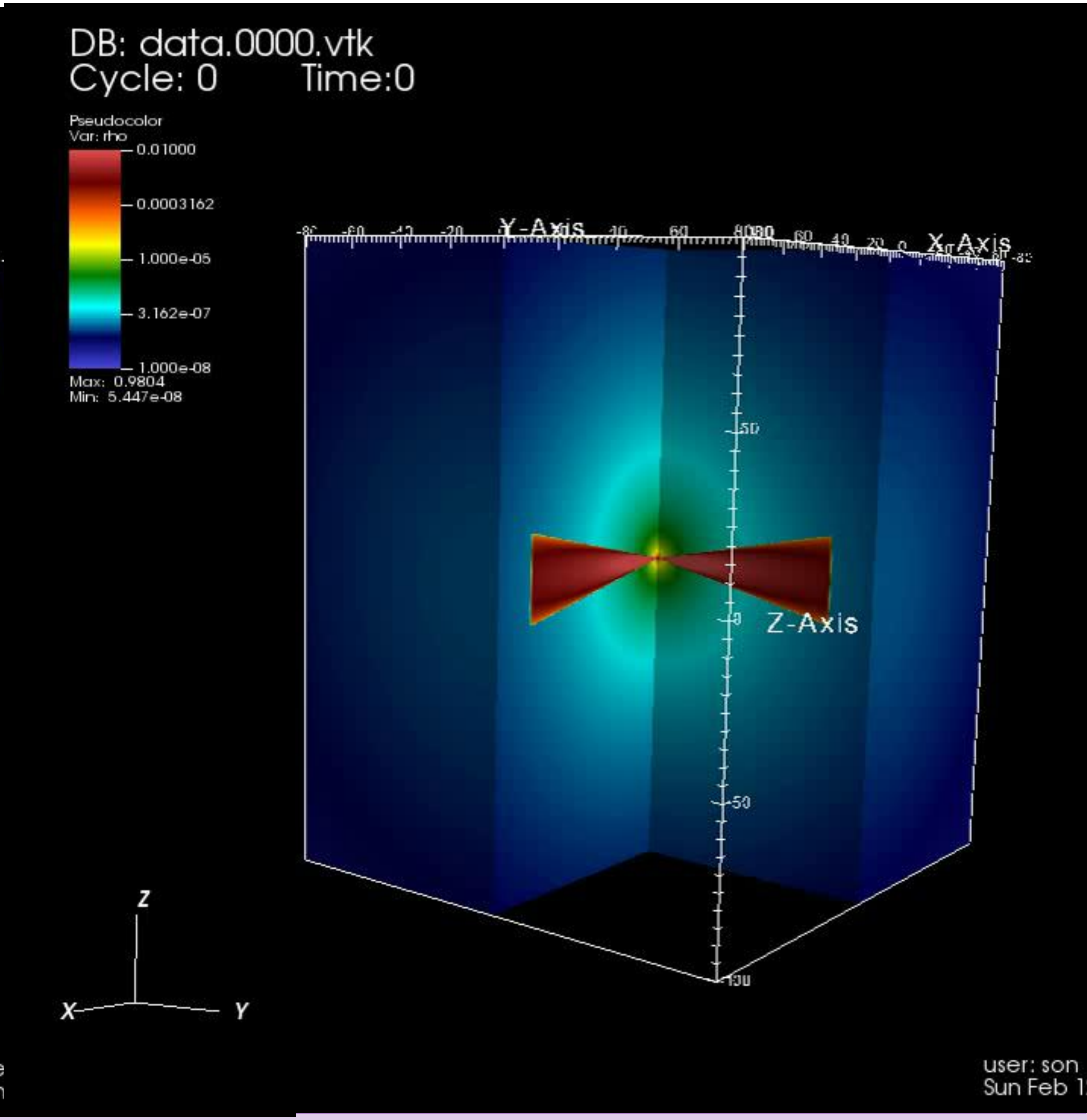
Cycle: 0 Time:0
Pseudocolor
Var: VZ
0.2500
0.1250
0.000
-0.1250
-0.2500
Max: 0.007590
Min: -0.007590
Y-Axis
X-Axis
Z-Axis
Z
X
Y


DB: data.0000.vtk
Cycle: 0 Time:0
Pseudocolor
Var: rho
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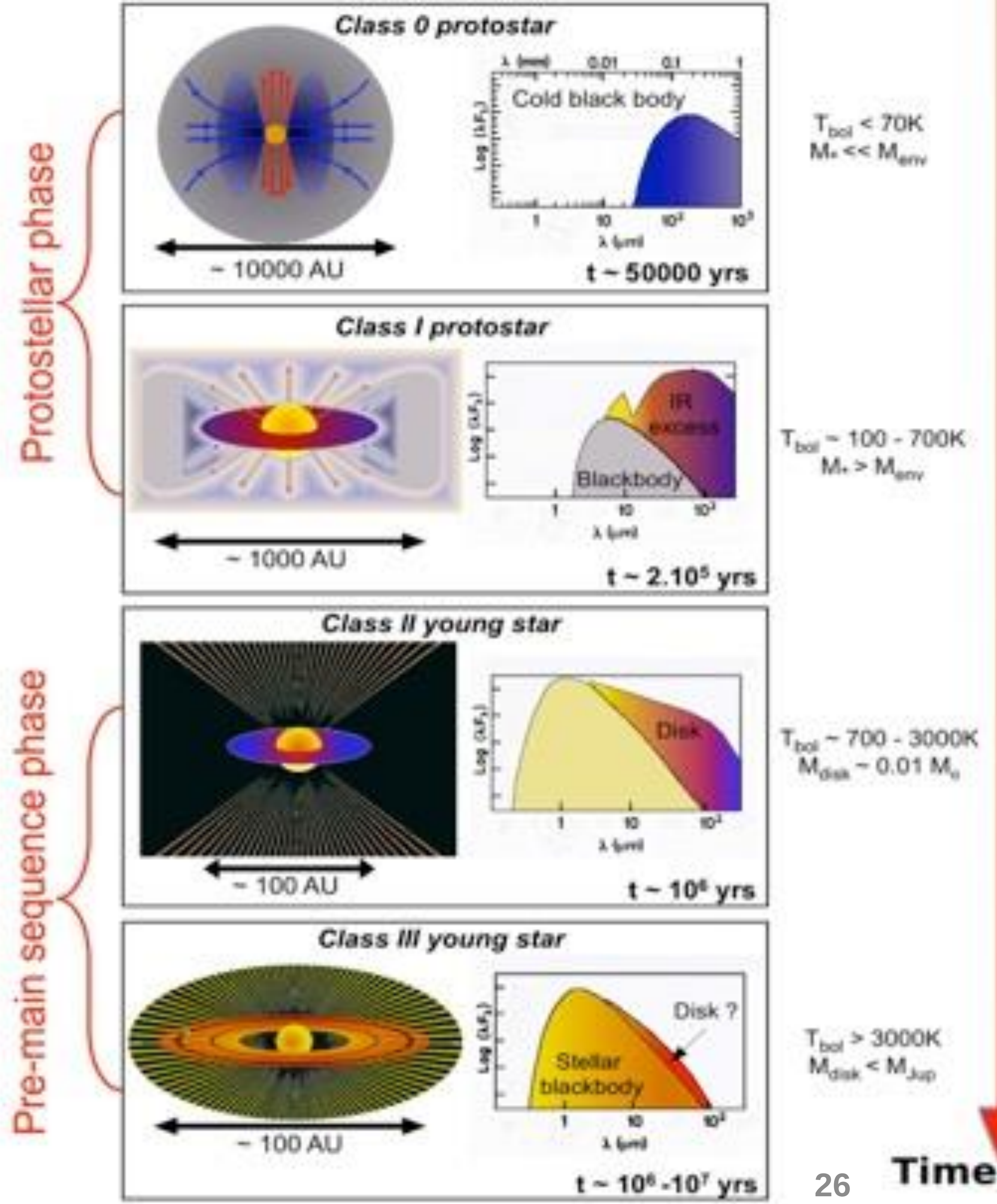
0.0003162
1.000e-05
3.162e-07
1.000e-08
Max: 0.9804
Min: 5.447e-08
Y-Axis
X-Axis
Z-Axis
Z
X
Y
user: son

Stellar jets

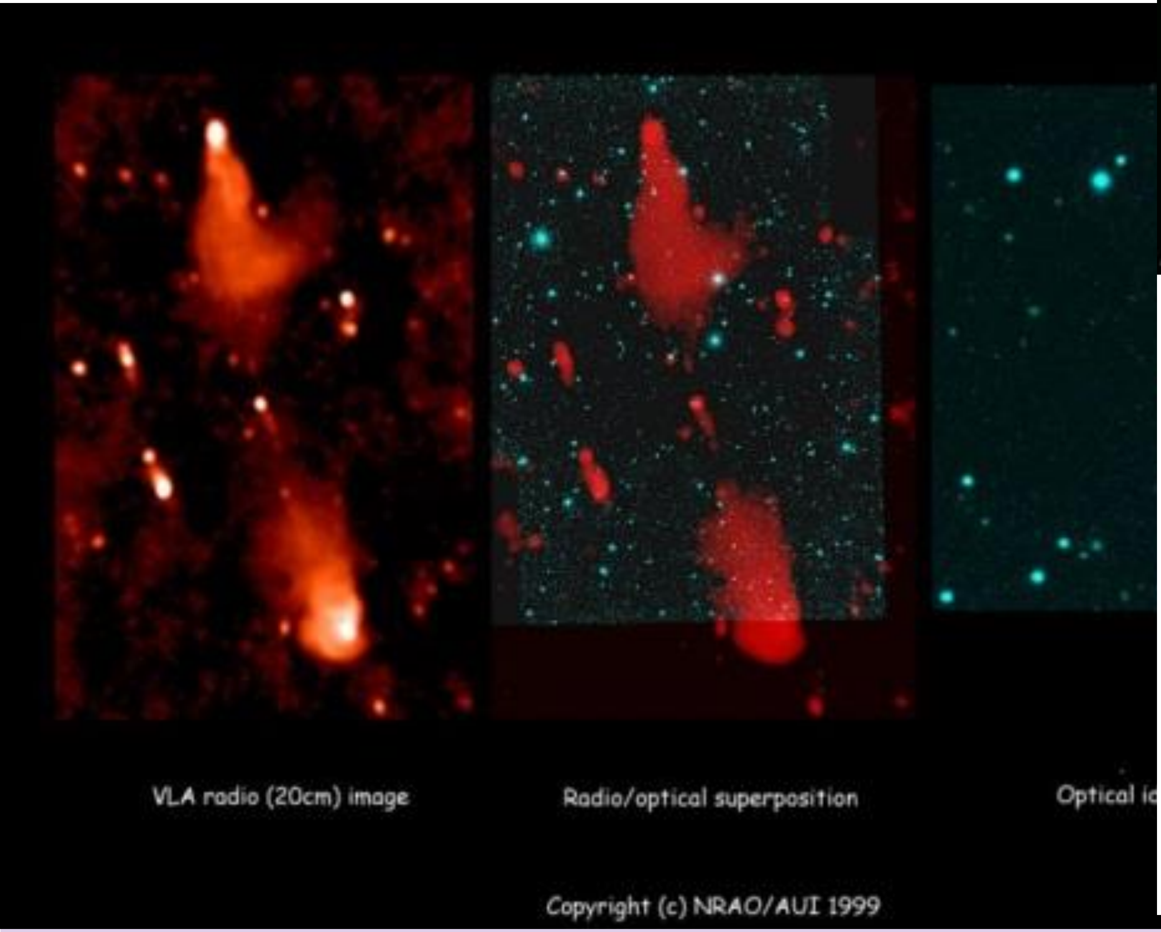
Young stellar objects

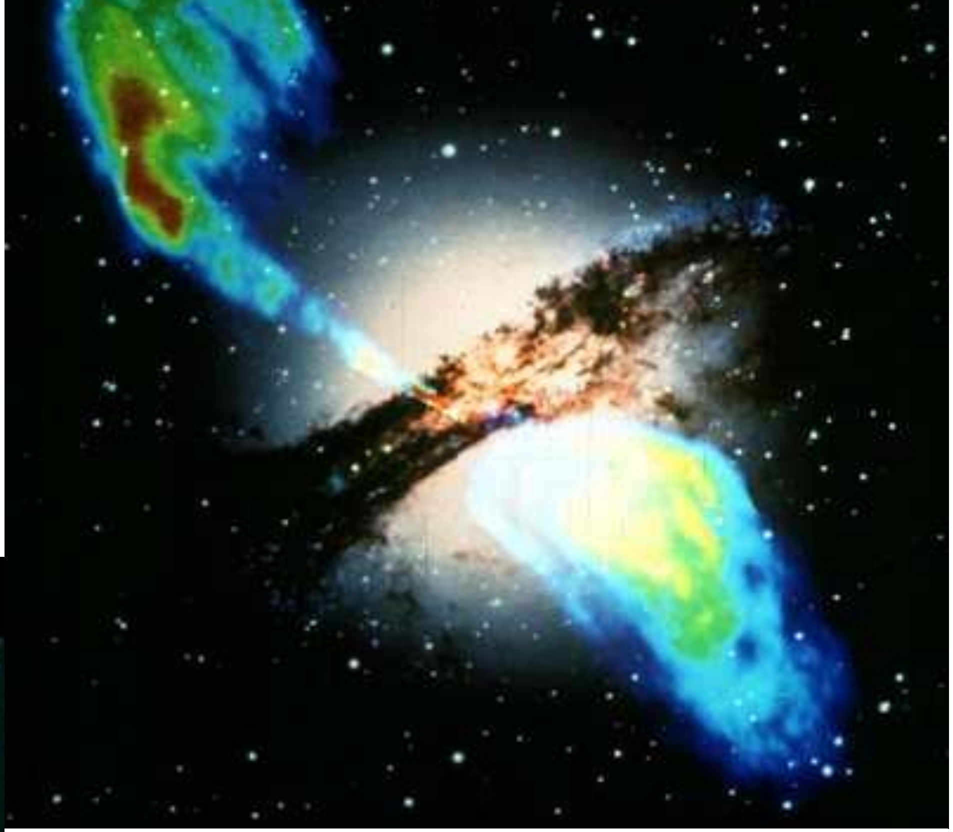
- **Class 0** :just after collapse has started
- **Class** I: Completely embedded objects have SEDs with positive spectral index in the far-IR
- **Class II (T Tauri) :** YSOs with SEDs from a reddened stellar component and an IR excess
- **Class III** : The IR excess has disappeared; circumstellar gas still observable in atomic lines



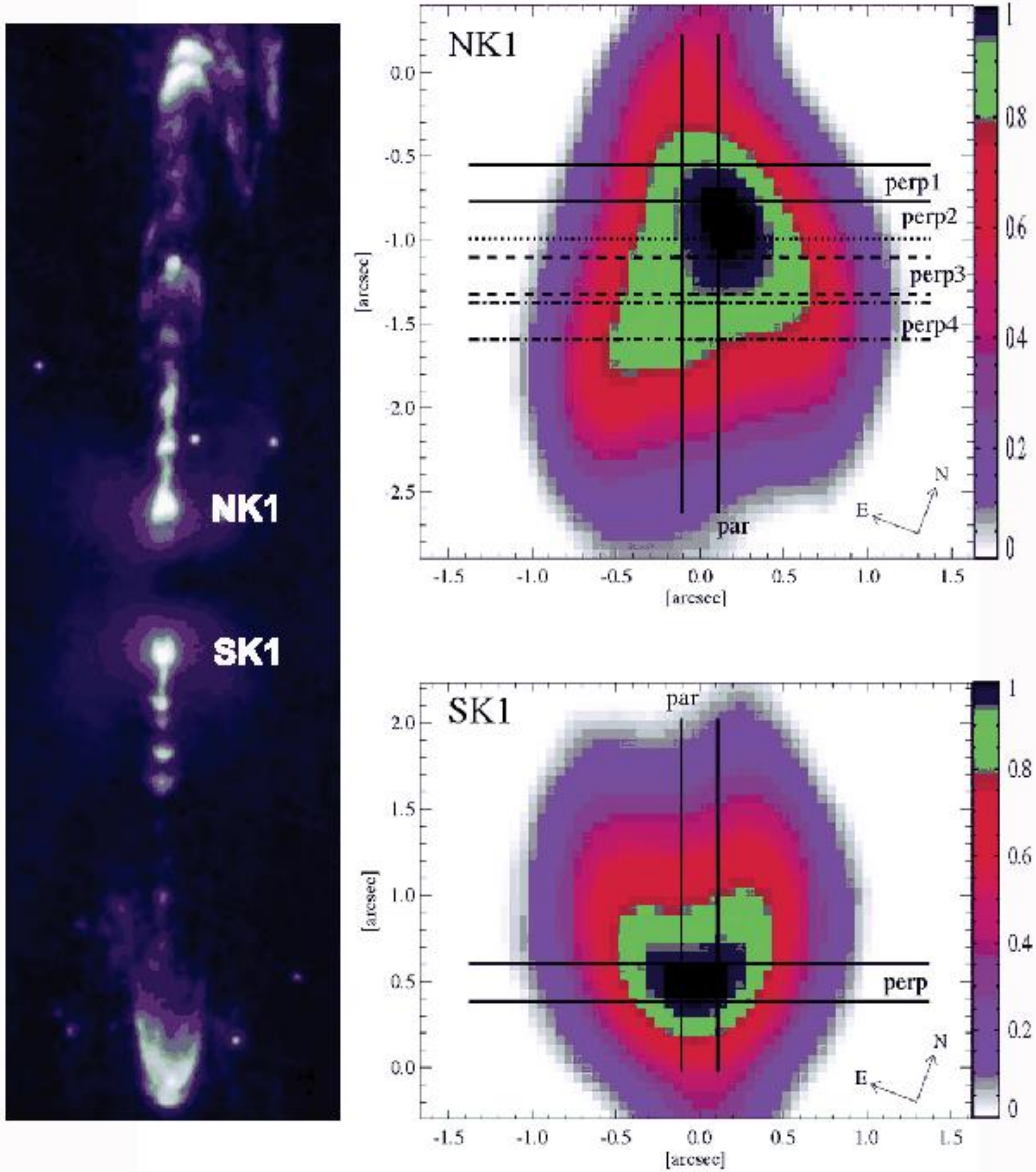
Extragalactic jet

DRAGNs : large-scale double radio sources produced by outflows (jets) in active galactic nuclei (AGN).
Overall radio size: 4.5 Mpc

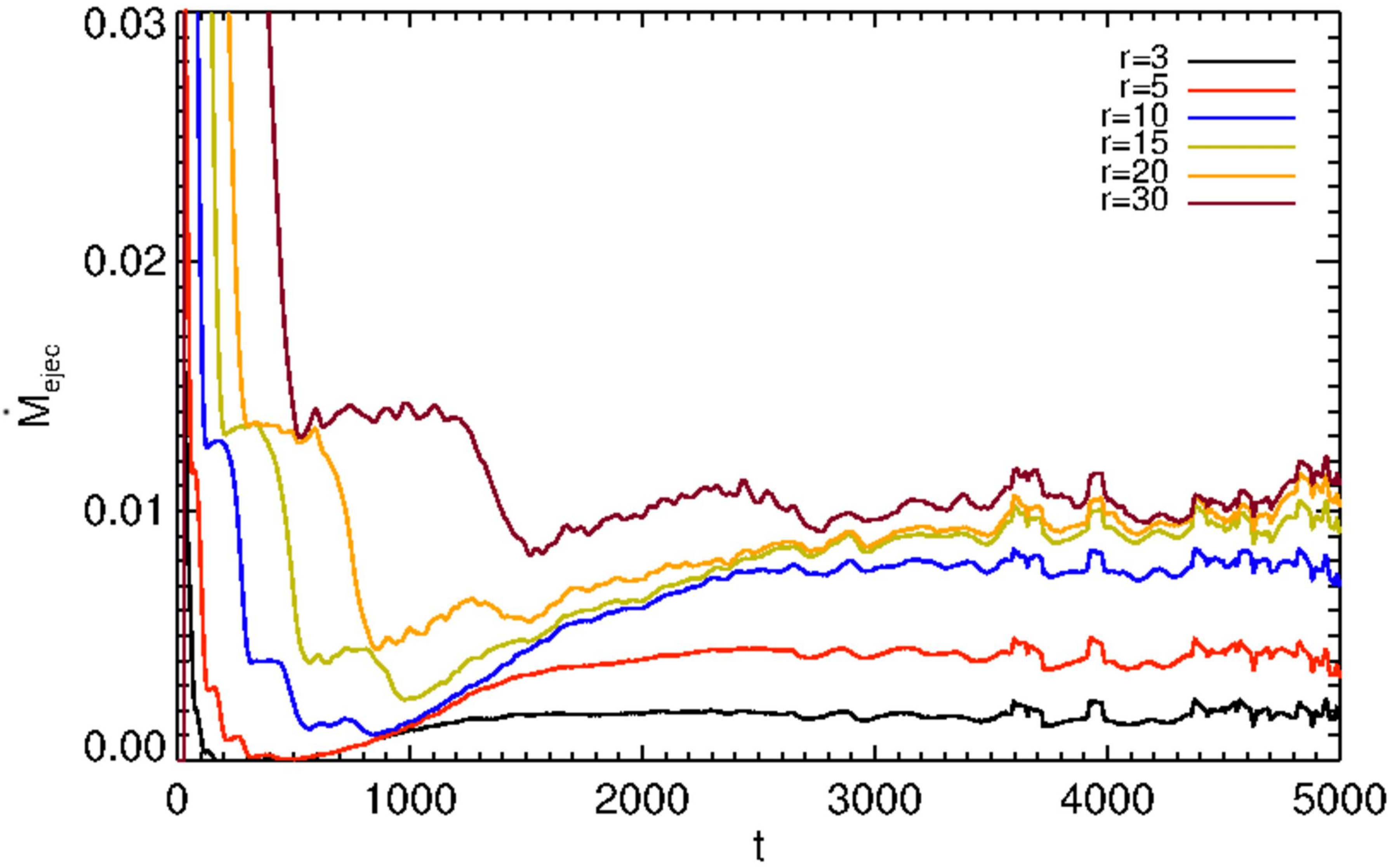




Centaurus A
brightest and nearest of giant radio galaxies
- size ~ 10 degrees!!
- distance 3.5 Mpc
- (optical and radio image
- (VLA 6 cm), STScI/NASA)


NK1
SK1
NK1
perp1
perp2
perp3
perp4
par
[arcsec]
N
E
SK1
par
perp
[arcsec]
N
E

Ejection rate evolution

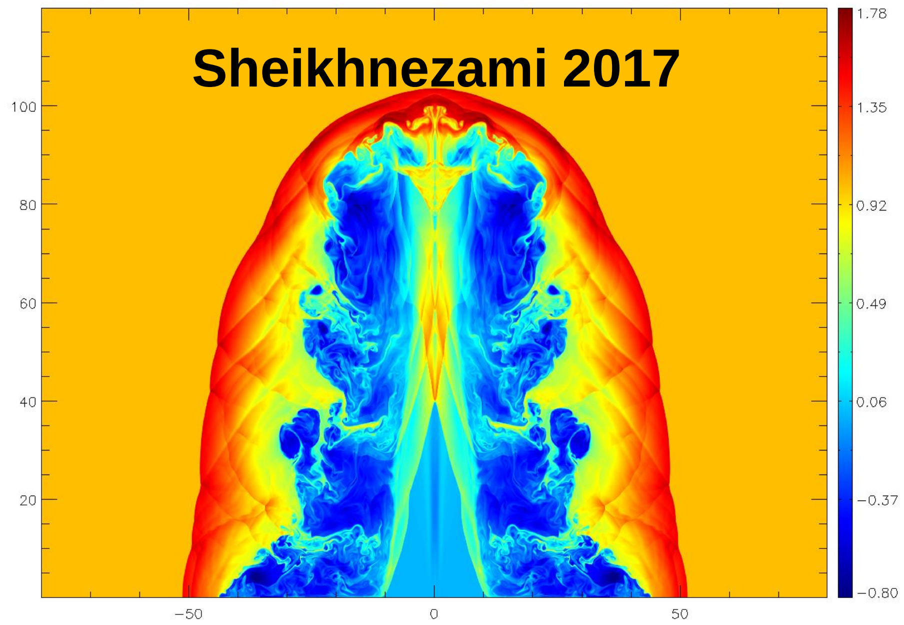


Current and future projects

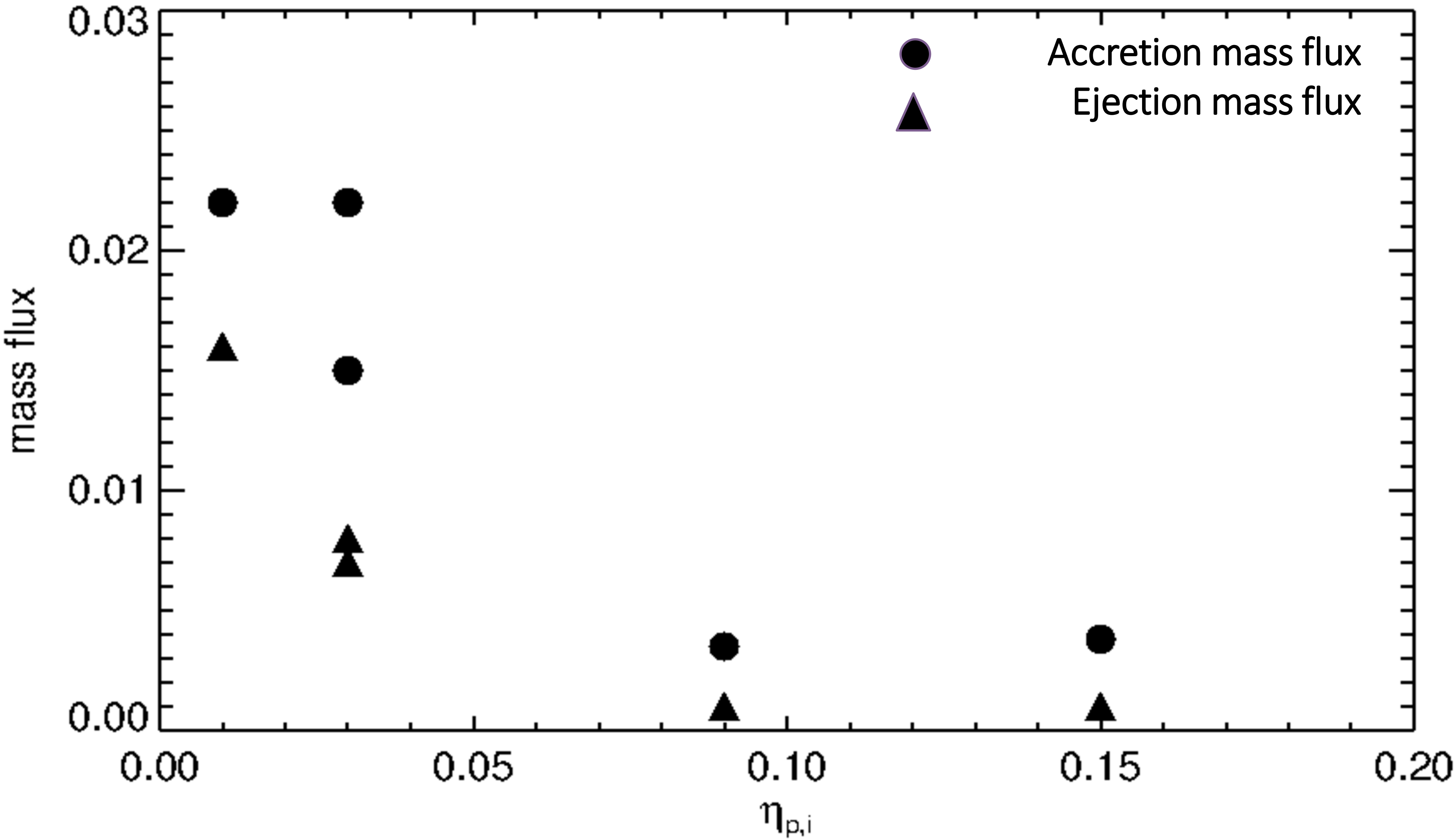
- Launching area :
- Including the physic of the disk in the model like thermal cooling

- Jet feedback : Studying the Jet interaction with the ambient
- Including the energy equation cooling in the jet model
- Turbulence inside the jet/ heating

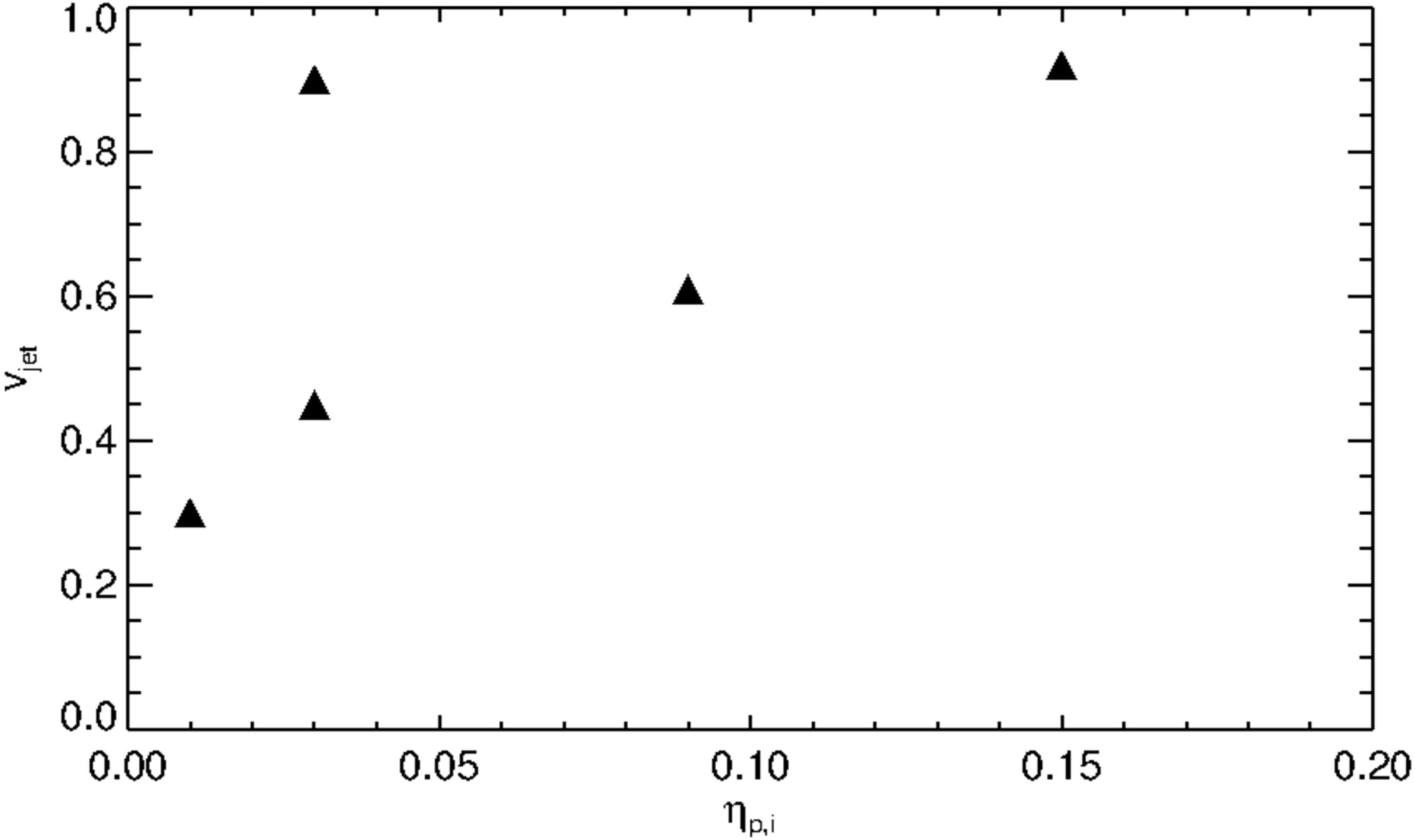
- Studying the protoplanetary disk
- Planet formation/ gap formation



Poloidal diffusivity governs the mass loading into the outflow.

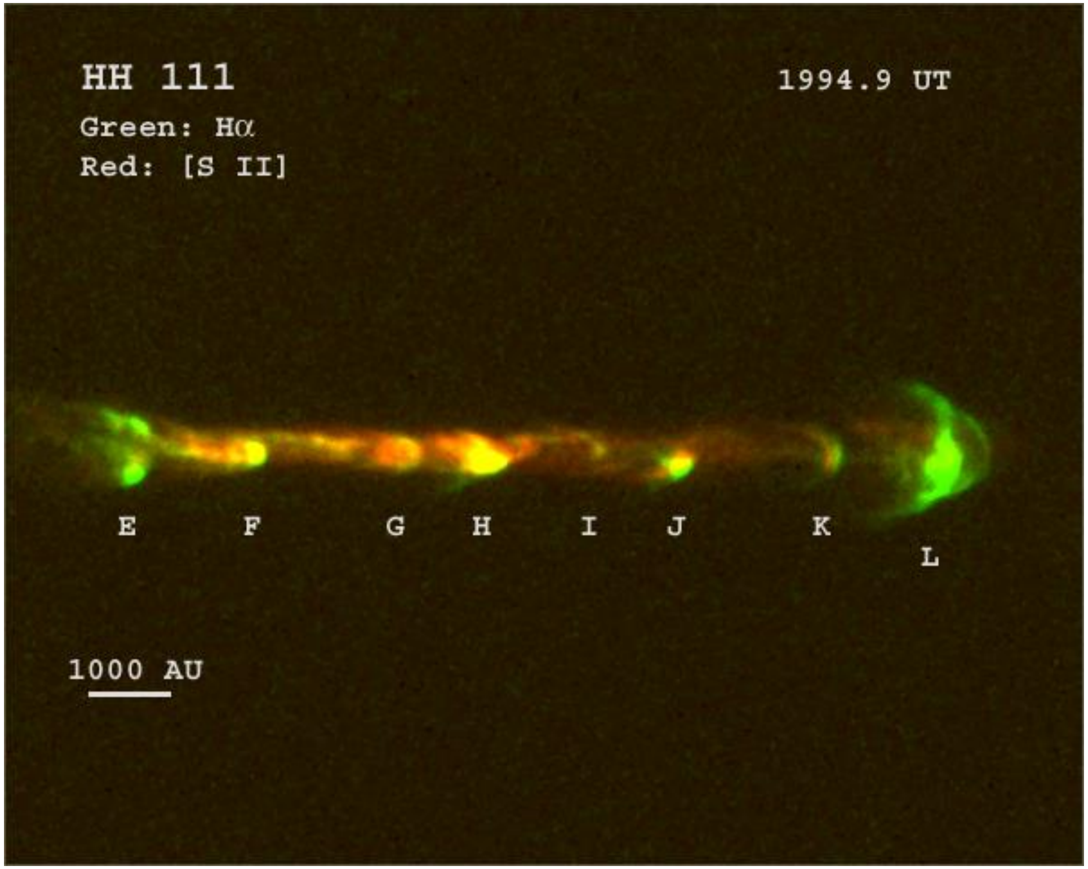


higher ejection rates result in a lower asymptotic outflow velocities



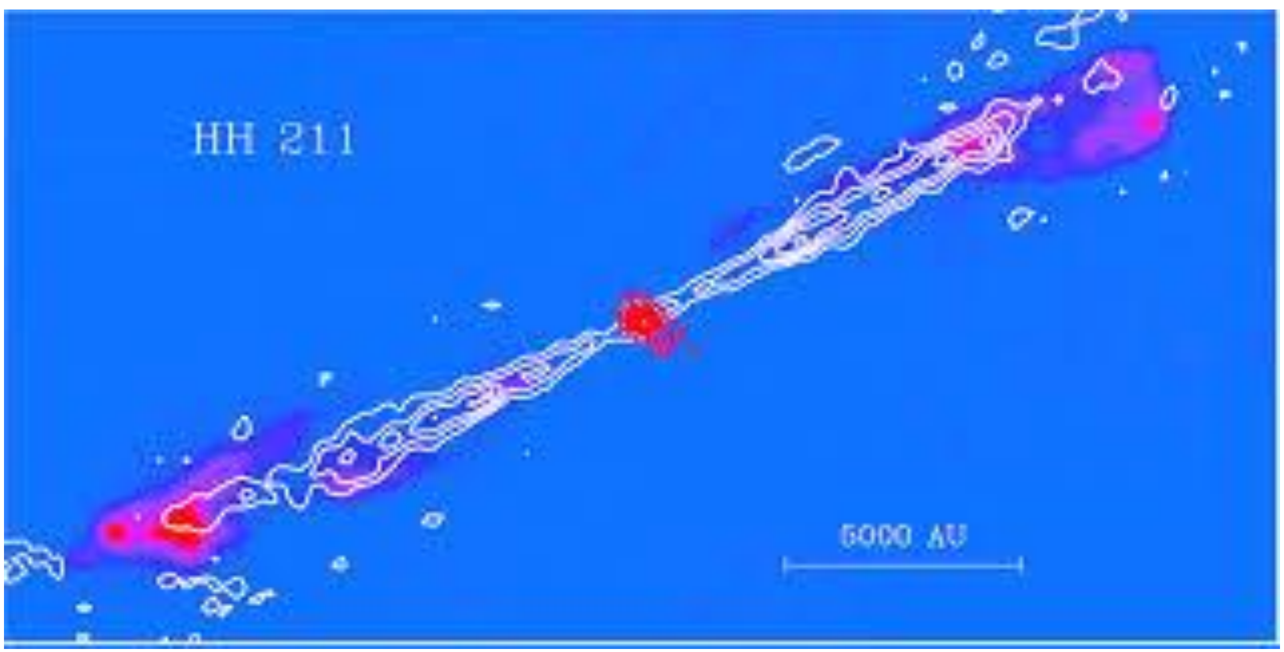
Stellar jets

- Discovery : Herbig/ Haro objects (1940's)
- Scale: up to pc-scale jets
- Velocity < 500 km/s (proper motion, Doppler shift)
- source mass ~ M_{sun},
- L ~ 10^{35} erg/s
- one-sided/ two-sided
- onion-like layering of velocities, the largest inside and the smallest on the larger scales

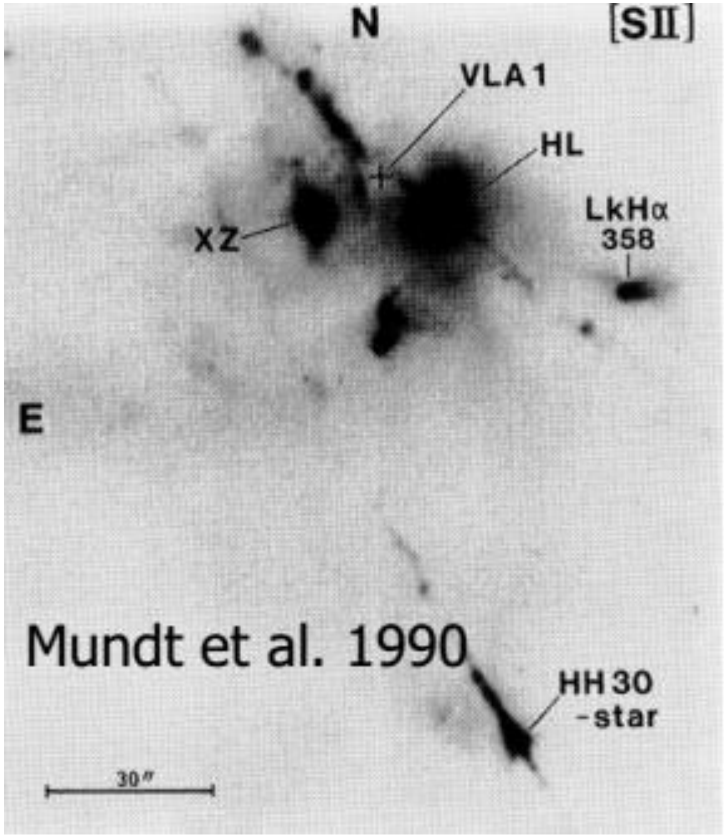


Stellar jet and outflow tracers:

- Millimeter molecular emission (Co, Sio): 1-10 km/s
- Near-IR H2 (2.12μm) and [Fe II] (1.644μm) :10's km/s
- Forbidden Emission Line , [SII], [Ni], [NII], [OII], [OIII], [FeI] :100 Km/s
- X-ray : > 300 Km/s

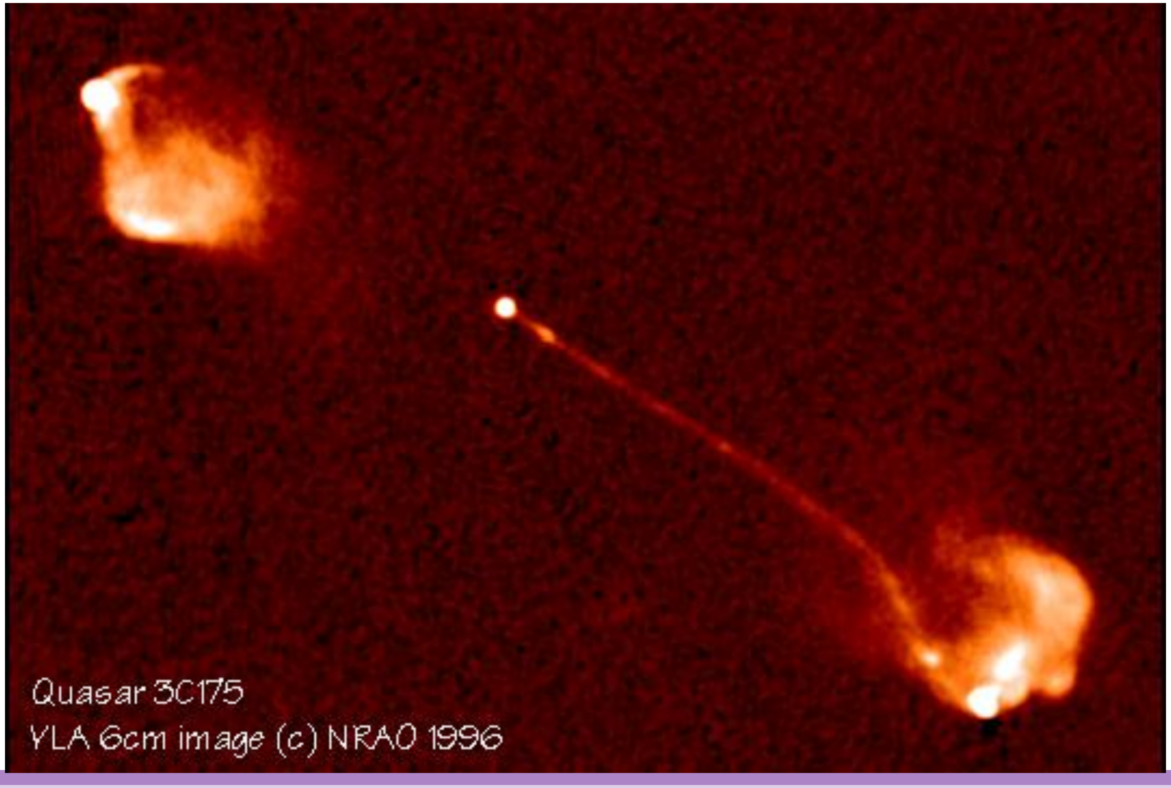


HH211, CO emission, Gueth et.al 1999



Extragalactic jet

- AGN: Scale: 10^6 pc,
- AGN jets are relativistic: velocities ~ c,
- source mass ~$10^{8-10} M_{sun}$,
- L ~ 10^{43} -10^{48} erg/s
- AGN jet radiation -> Synchrotron / inverse Compton
- exact velocity unknown, no direct detection
- mass fluxes unknown, matter content (leptonic/hadronic) not yet clear

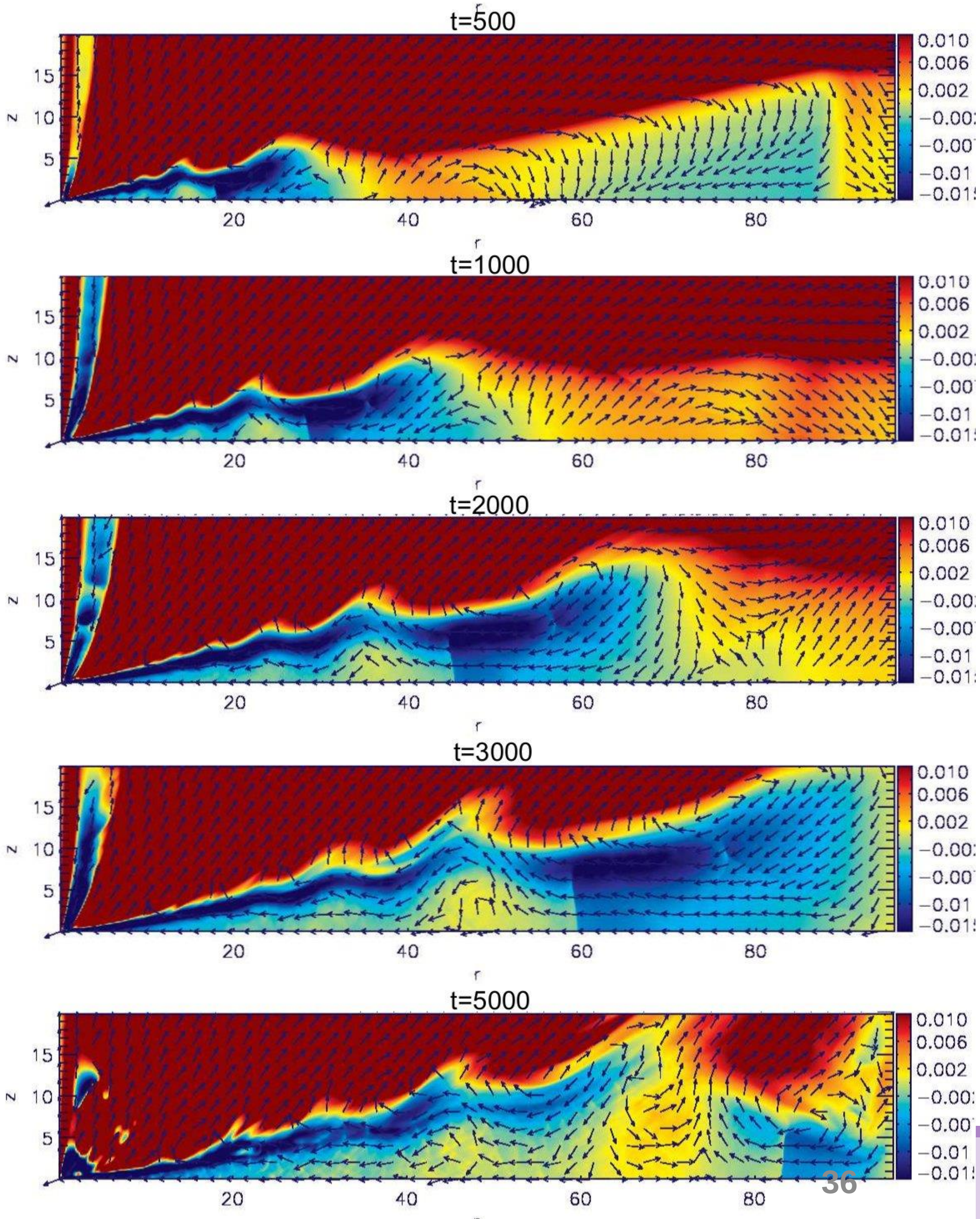


Classic double-lobed radio source.
The overall linear size is of the radio structure is **212 kpc**.

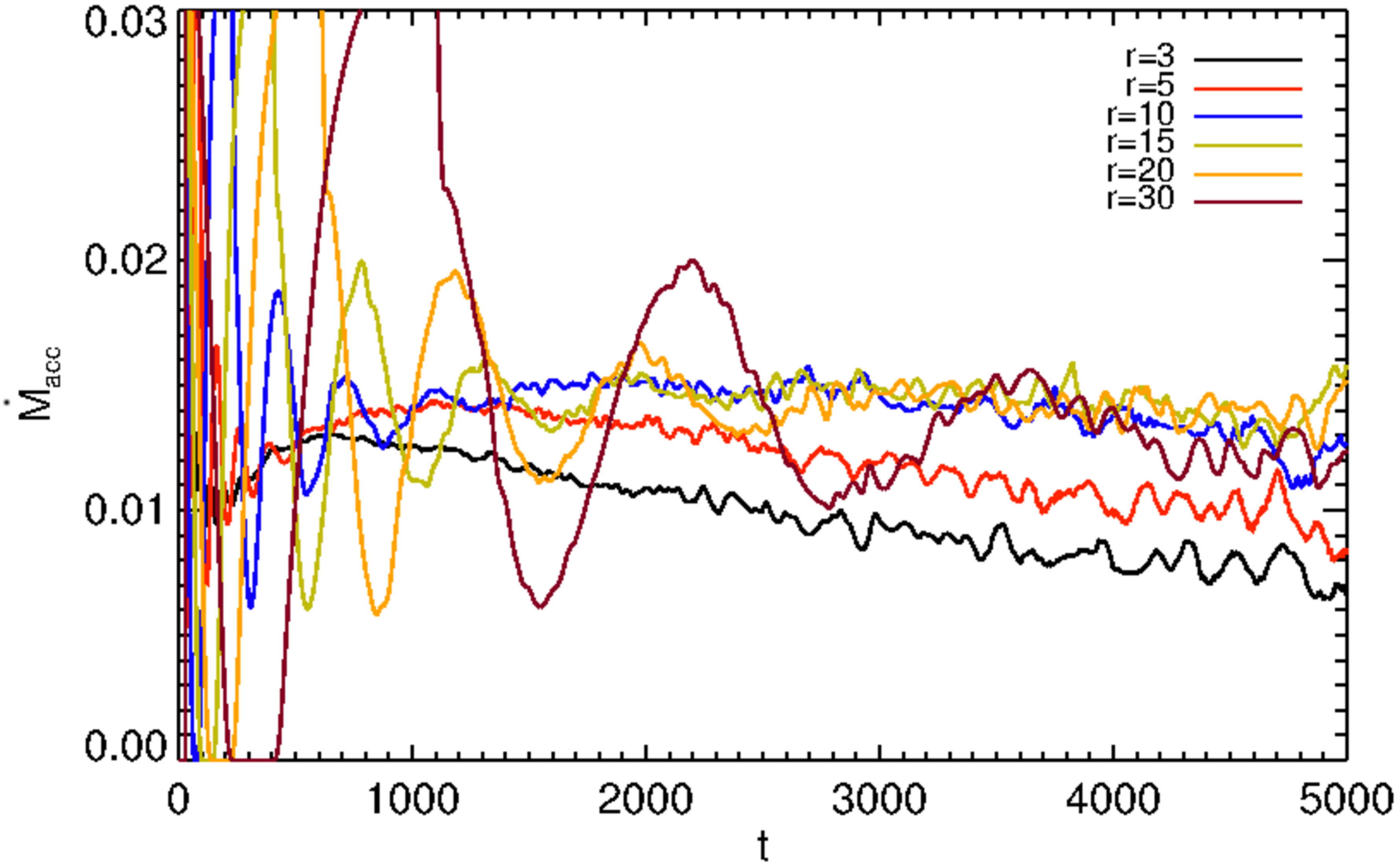
Disk evolution

Radial velocity map for reference run

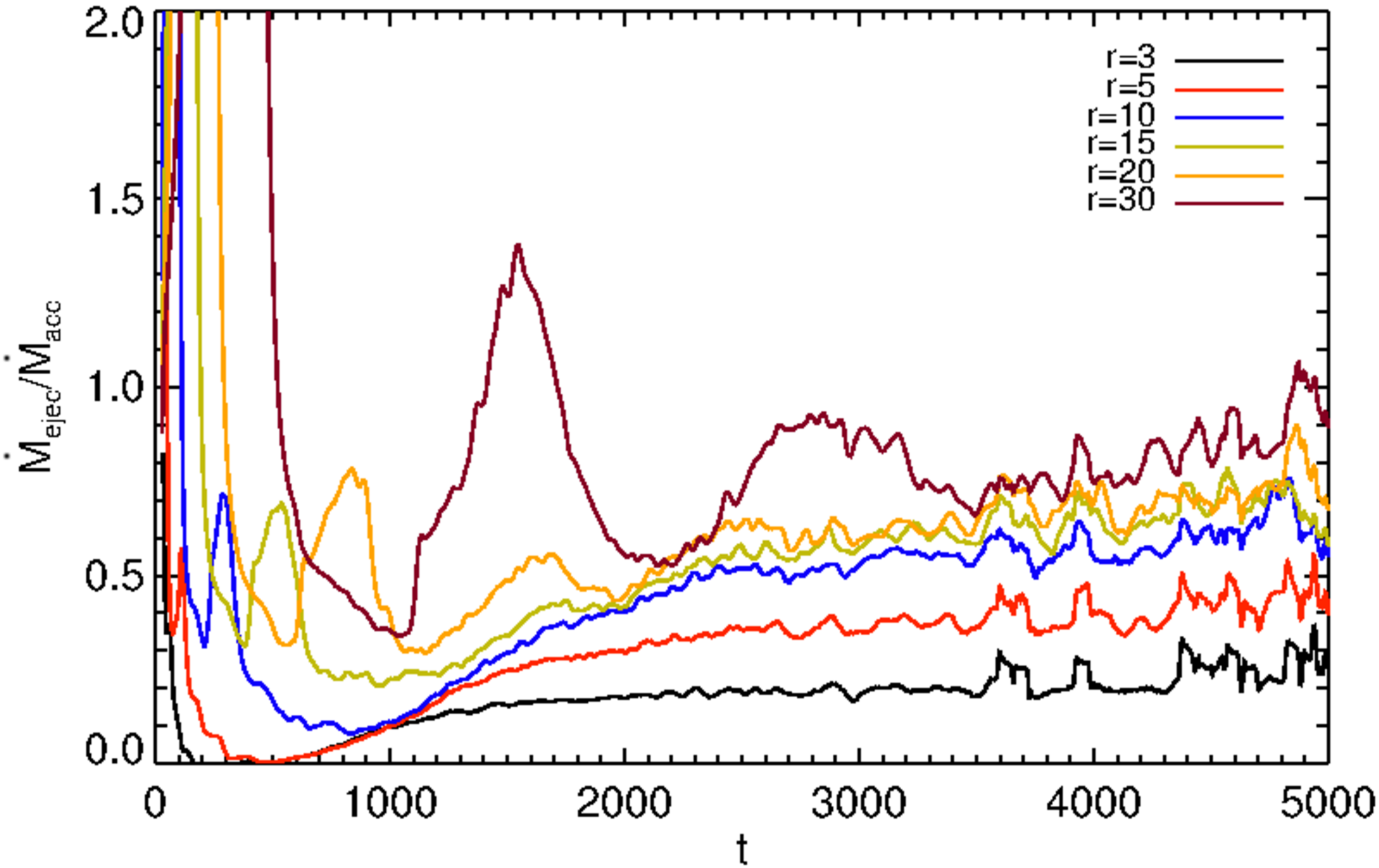
Arrows :V_R direction



Accretion rate evolution



Ejection to accretion rates ratio



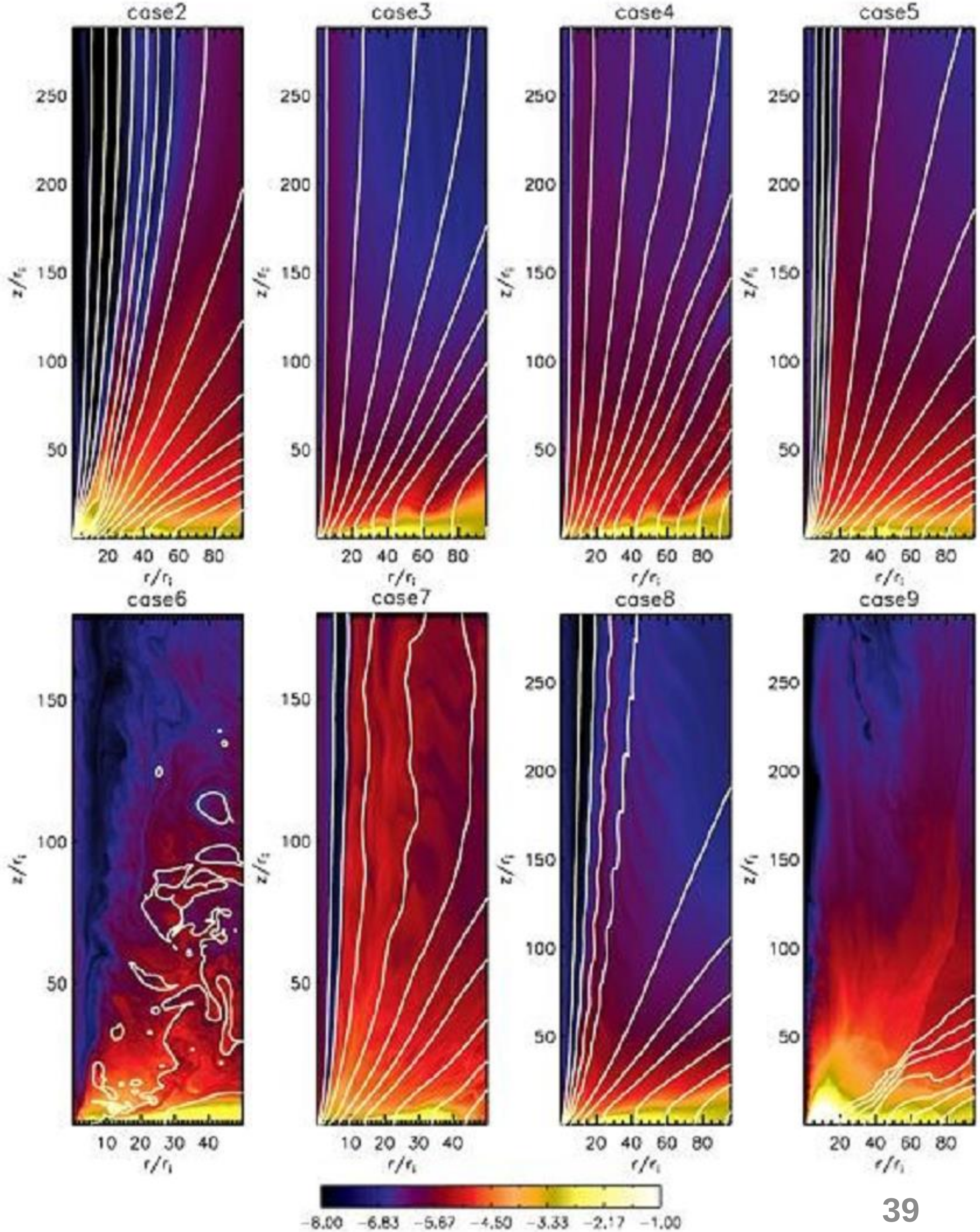
Parameters runs

$$\eta_p = 0.01 - 0.15$$

$$\beta = 10 - 5000$$

$$res = 0.025 - 0.066$$

$$\beta = \frac{P_g}{P_{mag}} = \frac{8\pi p}{B^2}$$

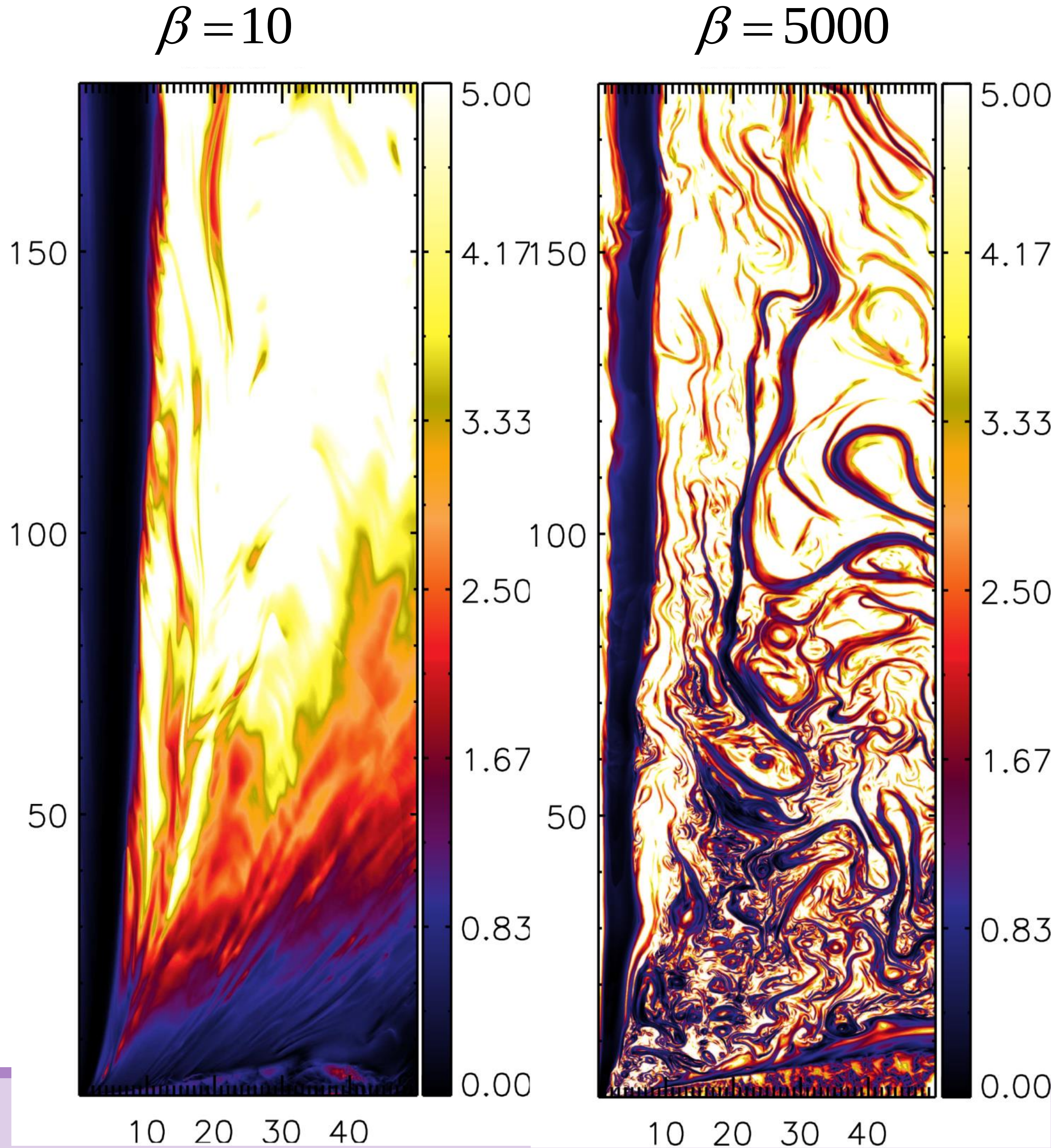


Alfven Mach Number

$$M_A = \frac{V}{V_A}$$

Plasma beta

$$\beta = \frac{P_g}{P_{mag}} = \frac{8\pi p}{B^2}$$



Jet radius and launching area :

Radius corresponding to the bulk of the mass flux at Zm

$$r_{jet} = \frac{\left[\int_0^{rm} r\rho v_z dr\right]_{zm}}{\left[\int_0^{rm} \rho v_z dr\right]_{zm}}$$

For reference run:

R_jet = 44r0   at   z= 180 r0

Launching area : 4 r0

YSO :   Launching area   0.4AU

AGN :   Launching area   40 Rs

Ellerbroek et.al 2014 :

Herbig Ae star HD 163296 -> Launching region <0.5 AU

Bipolar jets/ main goals :

- The evolution of the bipolar jets into both hemispheres
- Check for signatures of jet / counter jet asymmetry
- Asymmetry triggered intrinsically - in the disk, or externally

Numerical approach - Simulations

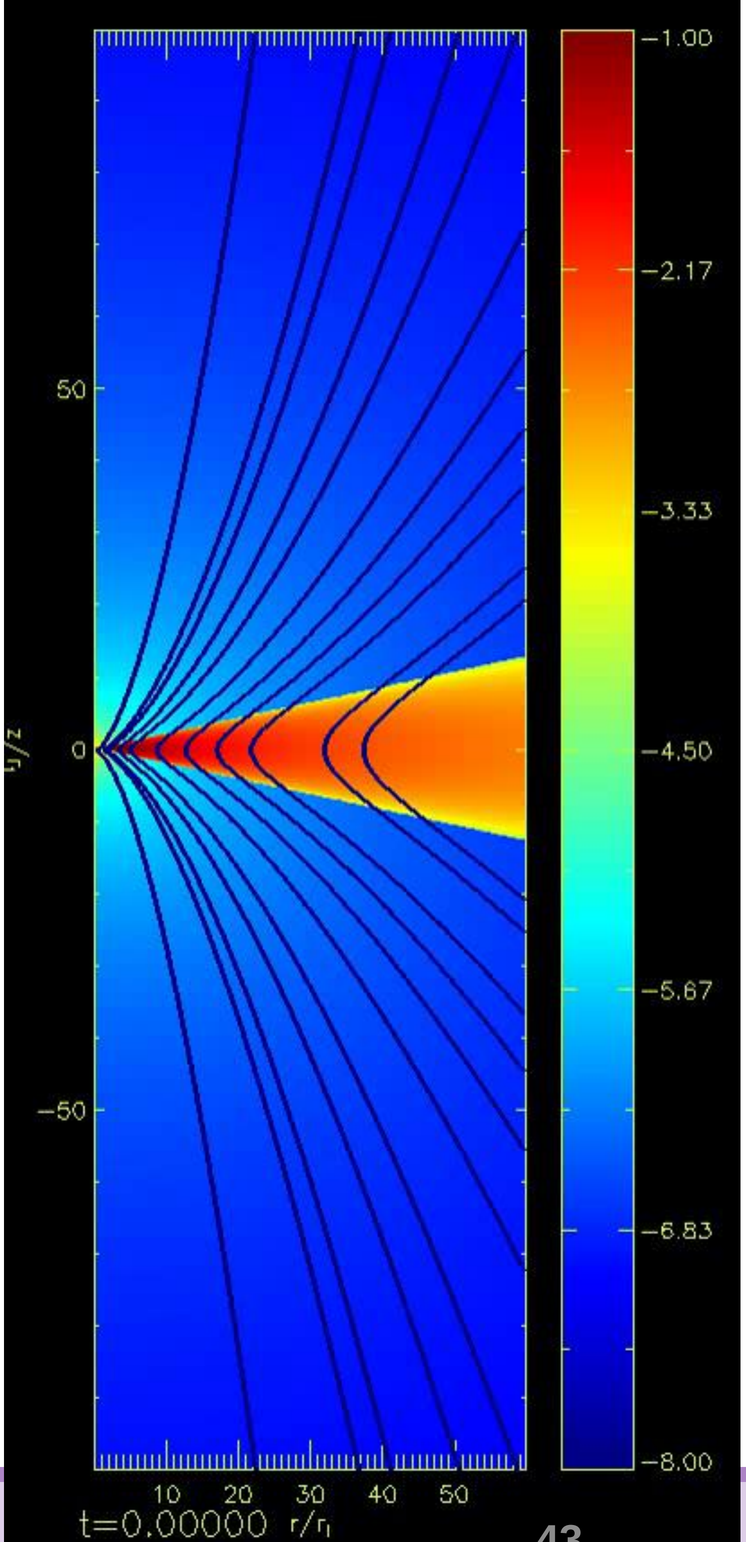
- Symmetric accretion disk -> symmetric bipolar jet
- Asymmetric disk -> disk warping
- Symmetric disk with localized energy injection -> local disk asymmetry

Bipolar jet – Symmetric run

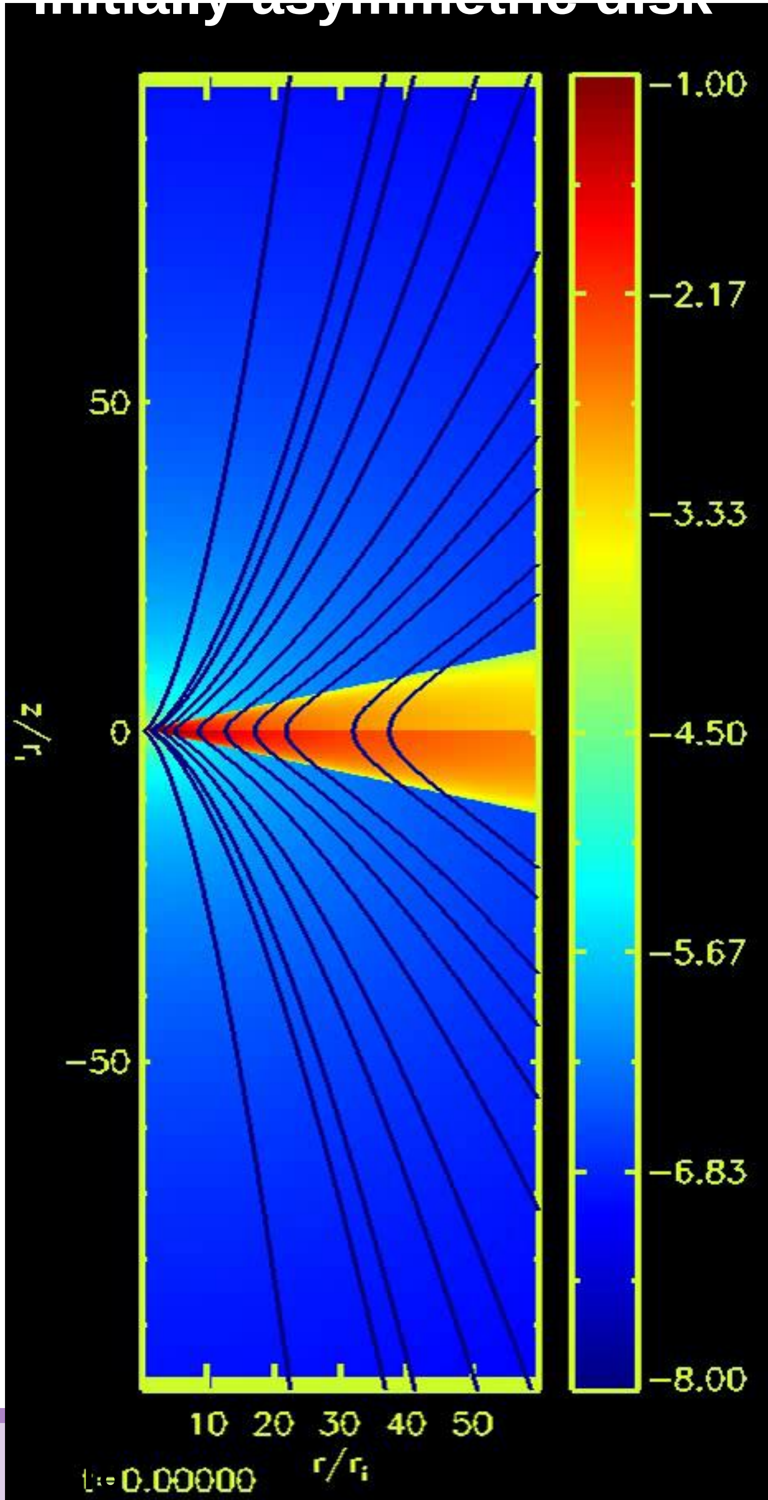
- Perfectly symmetric run
- Mass density in colot
- Magnetic field lines

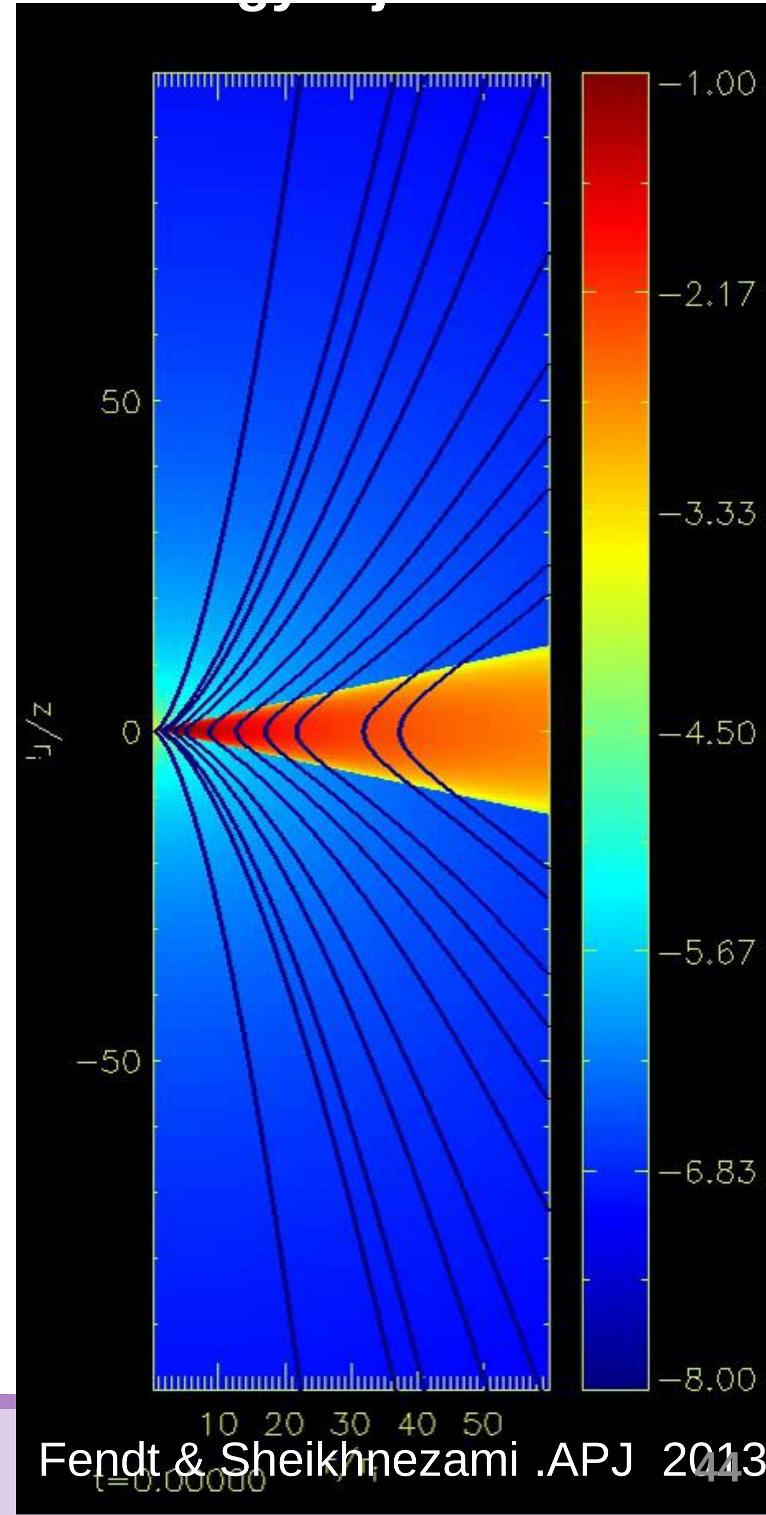
Bipolar Jets Launched from Accretion Disks. II. The Formation of Asymmetric Jets and

Counter Jets, Fendt, C. & Sheikhnezami, S. 2013, **ApJ**, 774, 12



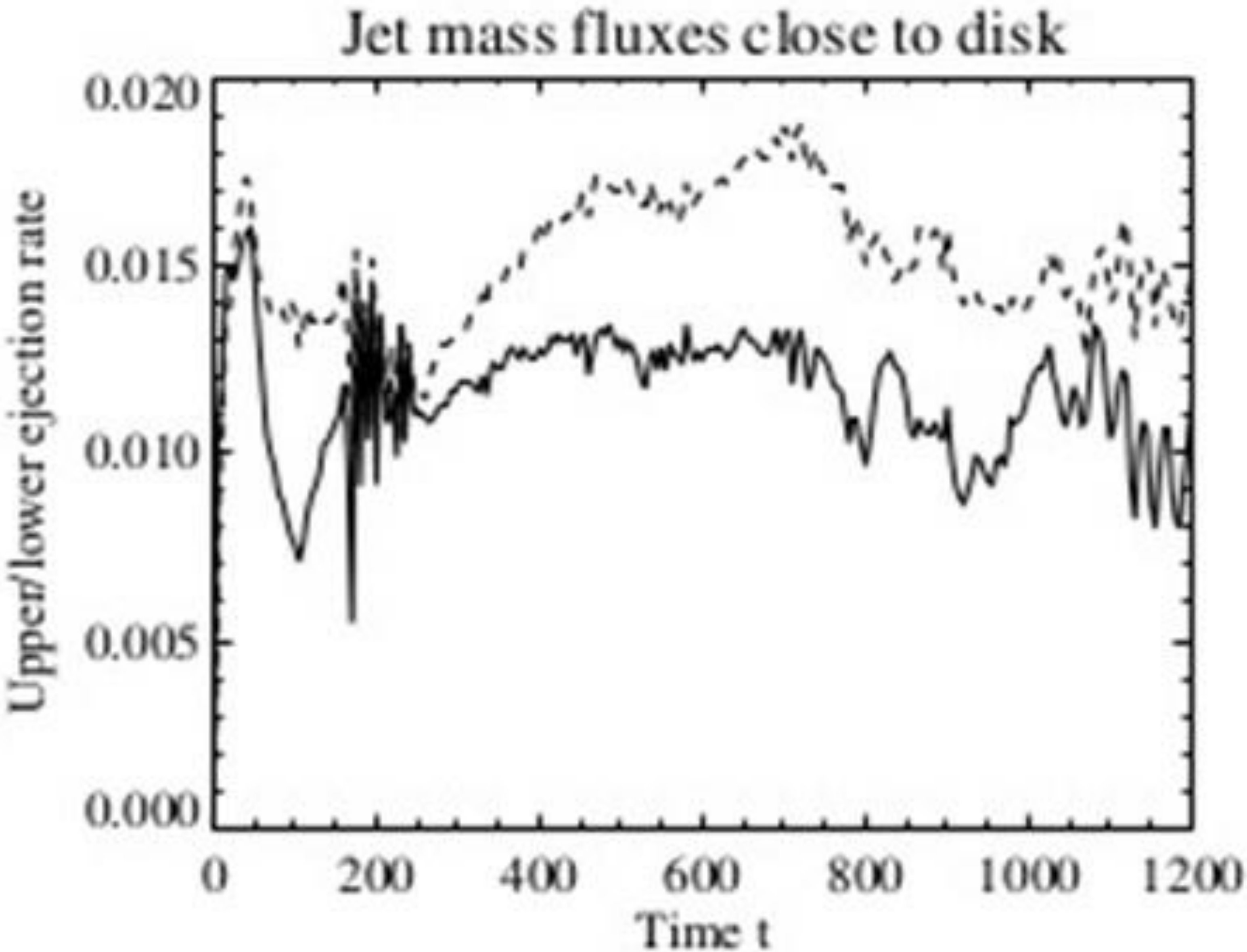
Initially asymmetric disk





Fendt & Sheikhnezami .APJ 2013

20 -30% differenes in mass fluxes for the jet and counter jet



Fendt, C. & Sheikhnezami .S, 2013, ApJ, 774, 12

Equations of the system:

The conservative, time-dependent, resistive, inviscous MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\boldsymbol{v} \rho \boldsymbol{v} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \right] + \nabla \left[P + \frac{B^2}{8\pi} \right] + \rho \nabla \Phi = 0,$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(e + P + \frac{B^2}{8\pi} \right) \boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B}) \frac{\boldsymbol{B}}{4\pi} + (\bar{\bar{\eta}} : \boldsymbol{j}) \times \frac{\boldsymbol{B}}{4\pi} \right]$$
$$= -\Lambda_{\text{cool}}.$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B} - \bar{\bar{\eta}} : \boldsymbol{j}) = 0 \qquad \boldsymbol{j} = (\nabla \times \boldsymbol{B})/4\pi$$

Jet properties in general:

- Highly collimated and originate in compact objects
- Show a chain of knots
- Often terminate in emission lobes
- Jet sources host accretion disks
- Jet speed > escape speed: -> jets launched close to central object
- Indication of the magnetic field:
- B jet~ µG (YSO) ... mG (AGN),
- B source~ kG (YSO) ... GG (µQ)