MHD Models of Jets & Winds

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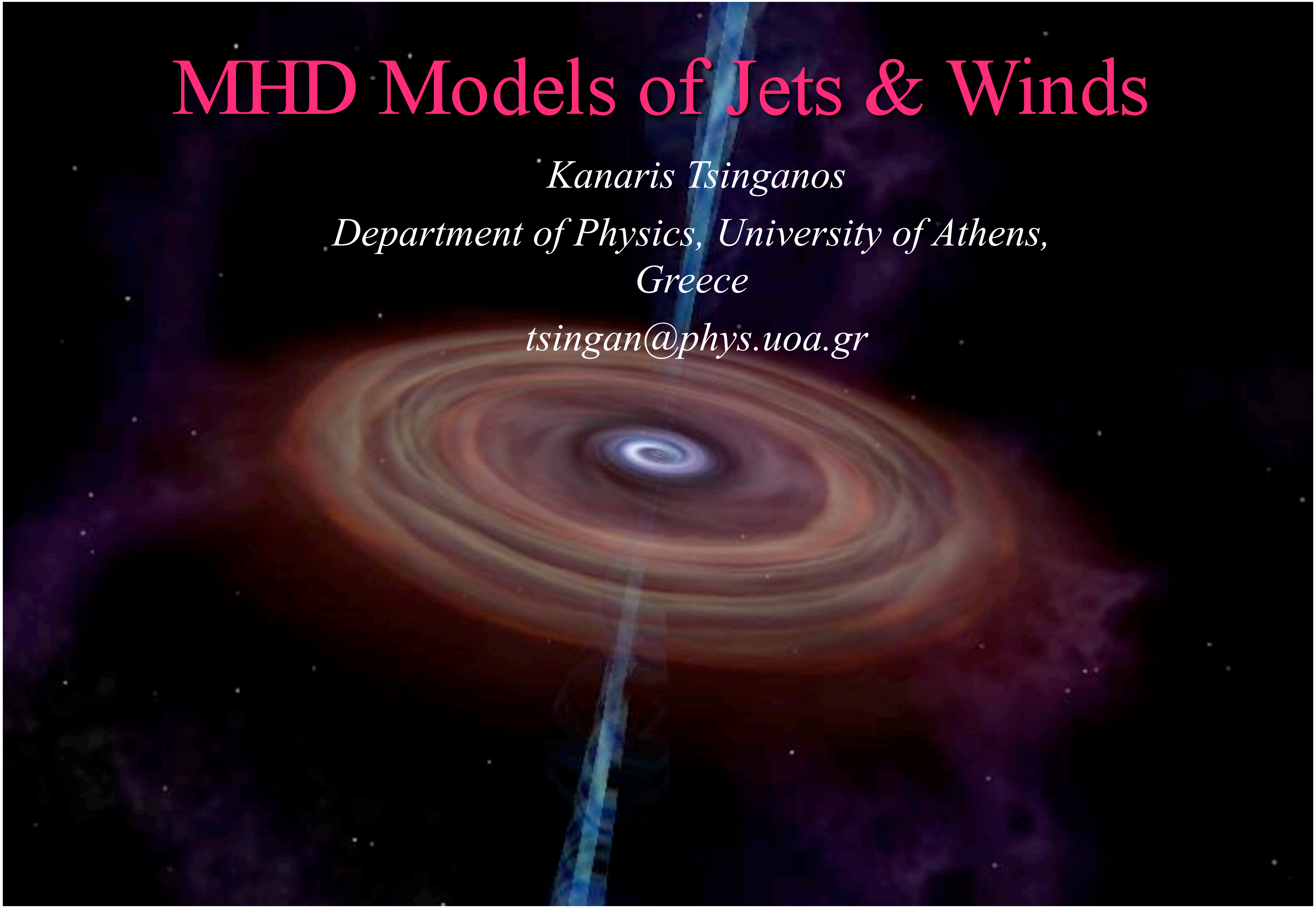
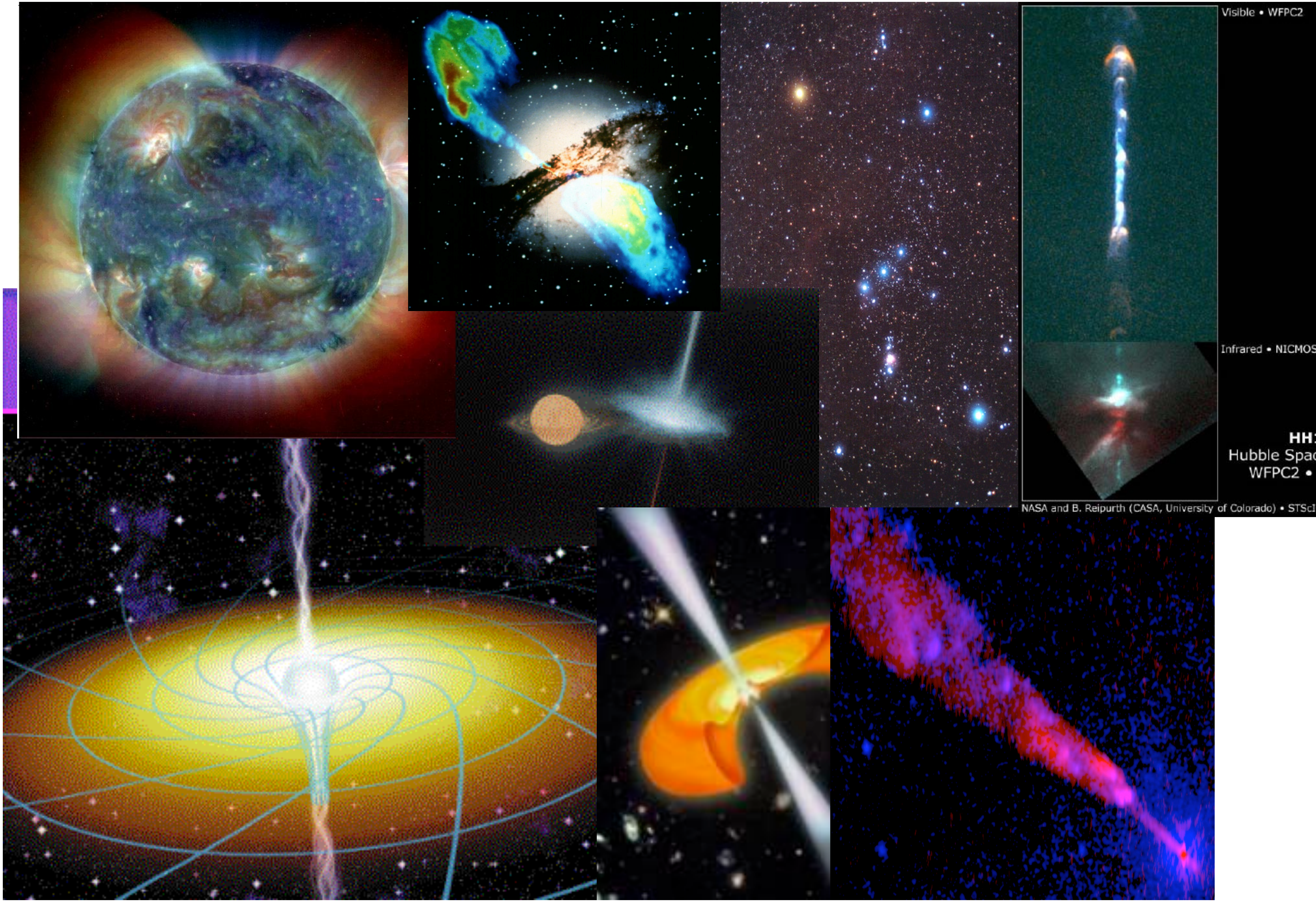


Classes of Astrophysical Objects with Highly Collimated Jets

- Active Galactic Nuclei & Quasars, e.g., M87, 3C273, etc
- X-Ray Binaries, e.g., SS433, etc
- Symbiotic Stars, e.g., R Aquarii, etc
- Young Stellar Objects, e.g., HH30, HH34, etc
- Black Hole X-Ray Transients, e.g., GRS 1915+105, etc
- Cataclysmic Variables, e.g., T Pyxidis
- Super Soft X-Ray Sources, e.g., CAL 83, 84
- Planetary Nebulae Nuclei, e.g., Egg Nebula, etc
- Pulsars, e.g., Crab and Vela Pulsars

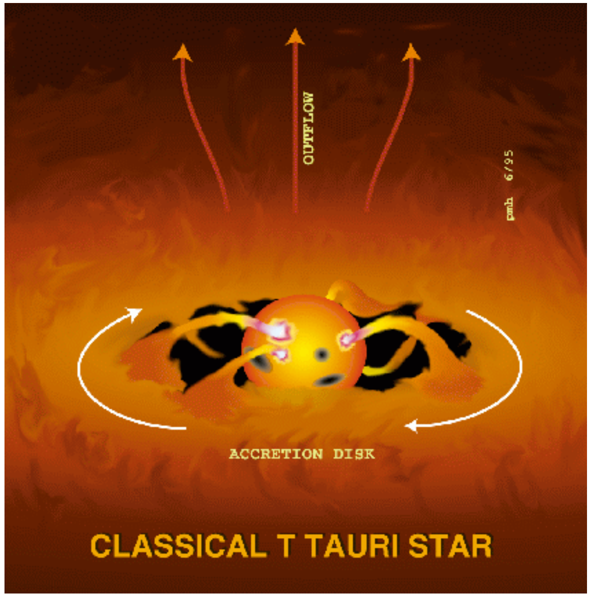


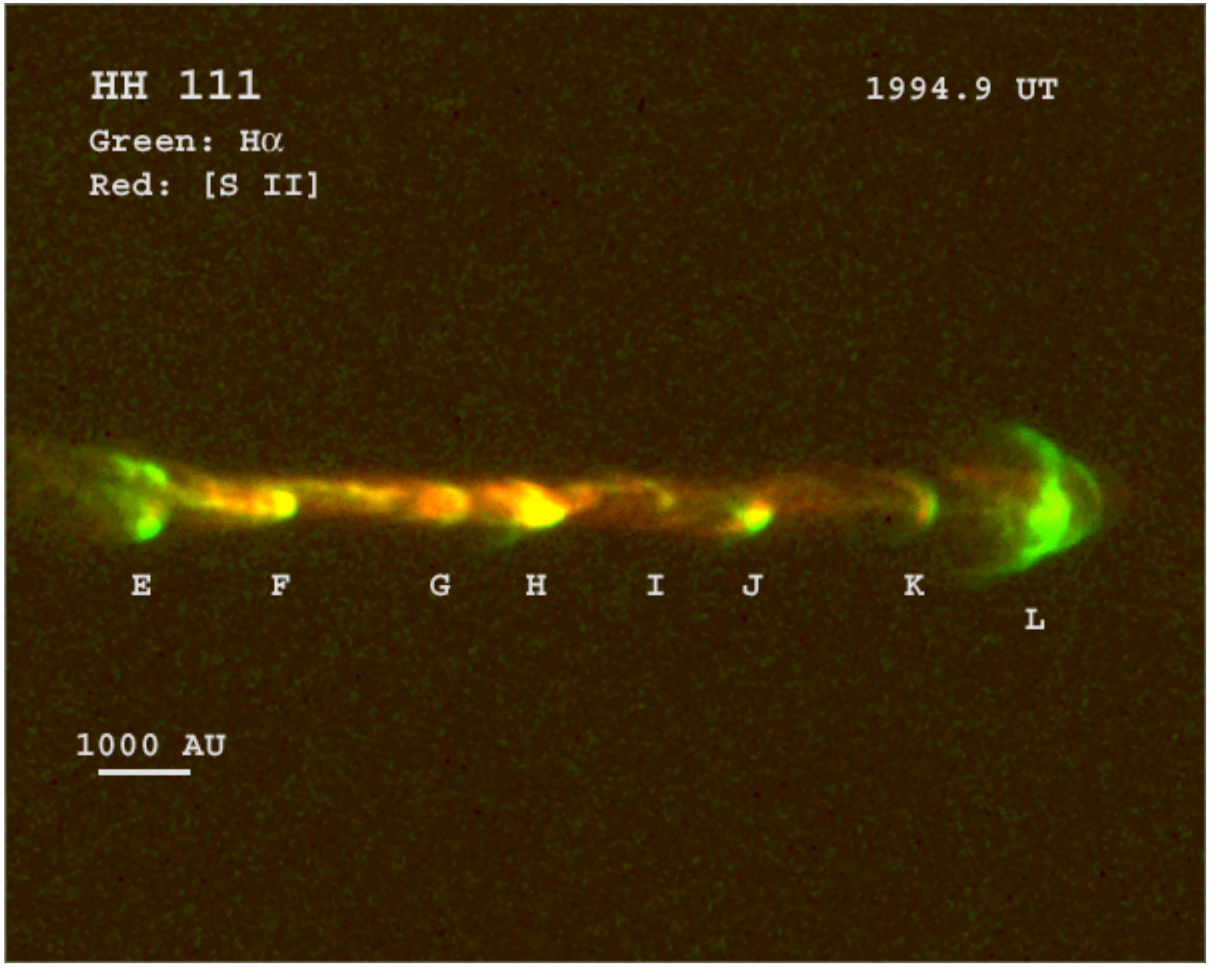
Visible • WFPC2
Infrared • NICMOS
NASA and B. Reipurth (CASA, University of Colorado) • STScI

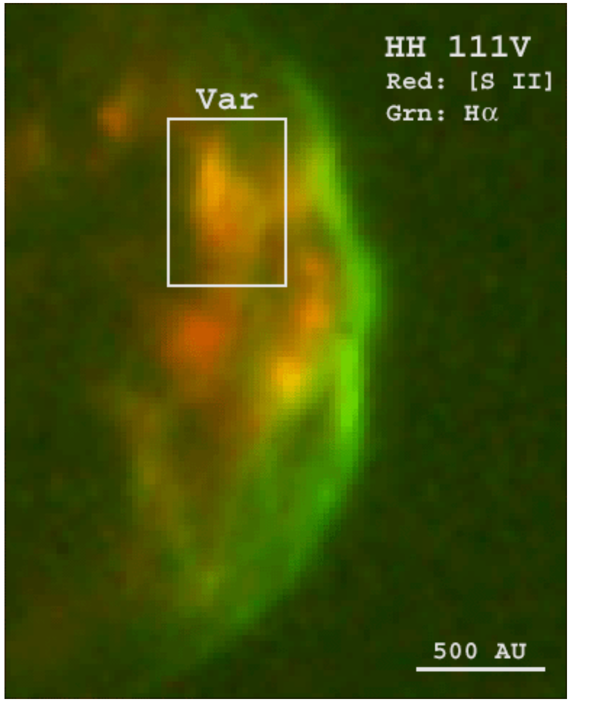

Jets appear at the end of the life of a star
The Cat's Eye Nebula — NGC 6543
HUBBLESITE.org

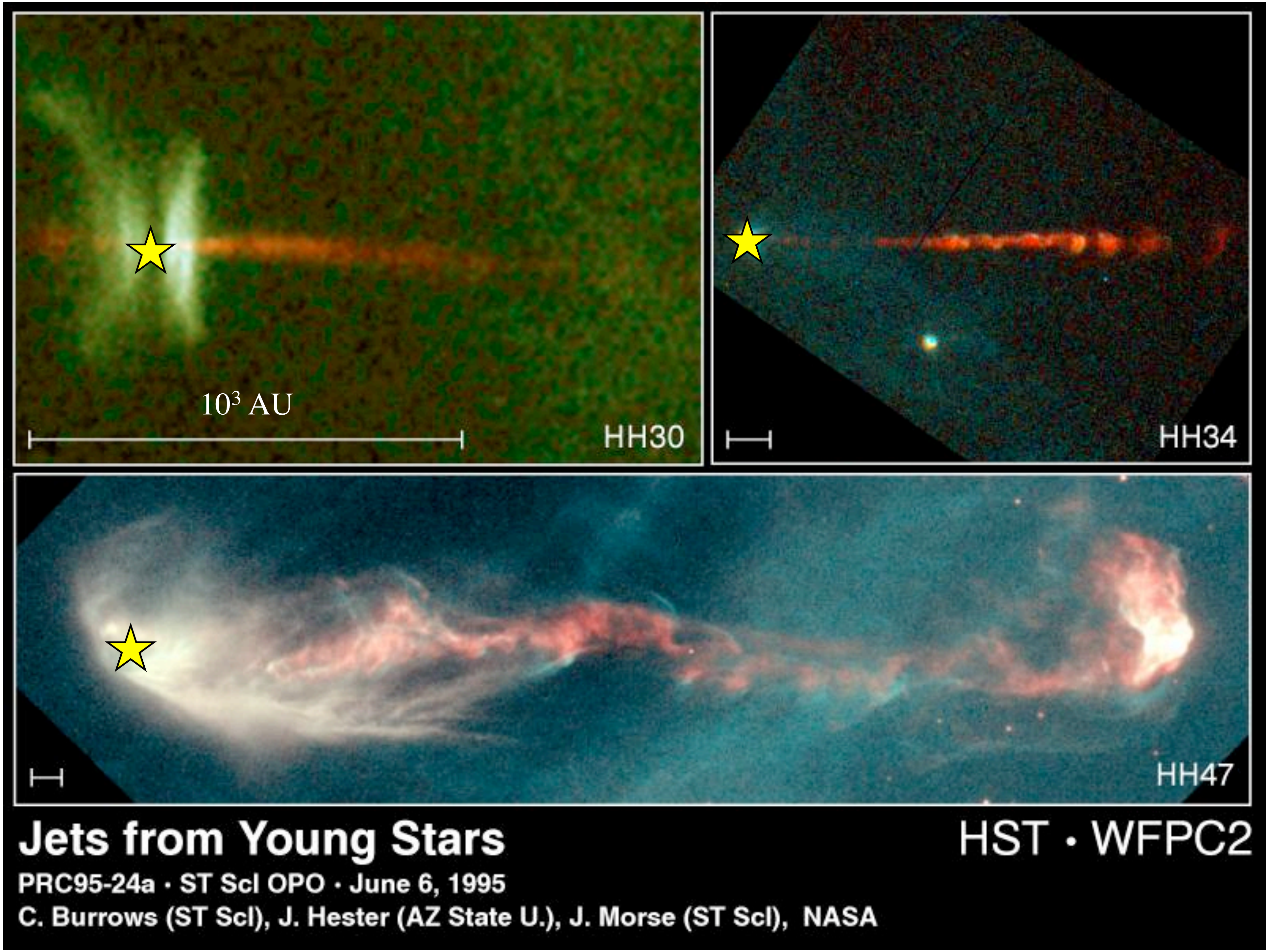

..and also at the beginning of the life of a star

Jets are useful – for example in young stellar objects jets remove angular momentum and thus allow the the disk to collapse and the star to form



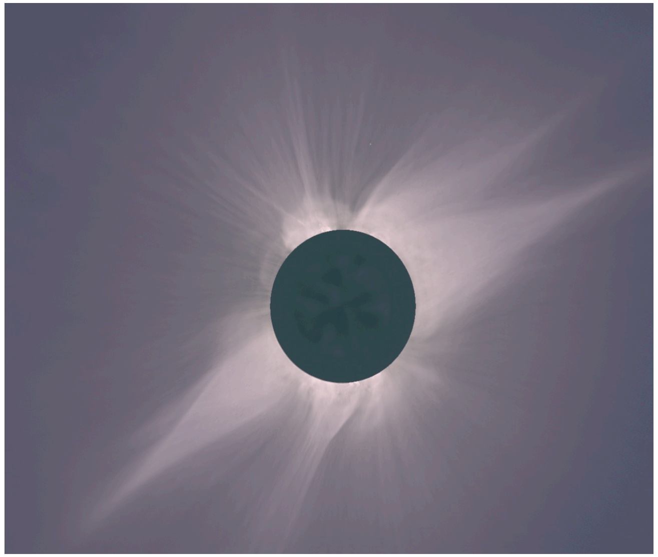




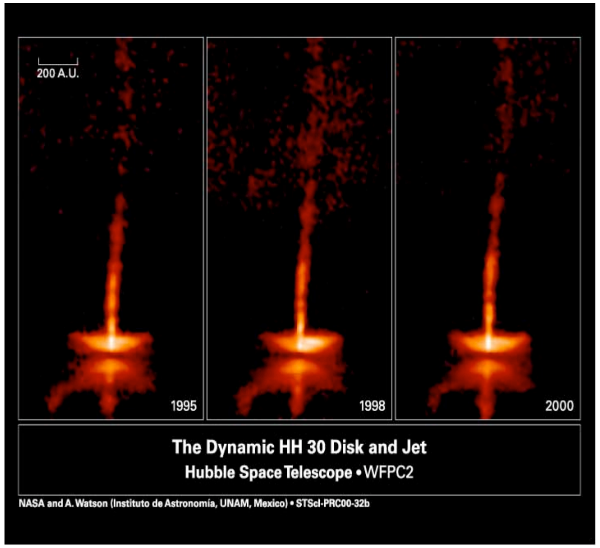

10³ AU
HH30
HH34
HH47
Jets from Young Stars
HST · WFPC2
PRC95-24a · ST ScI OPO · June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

The Dichotomy of Winds and Jets

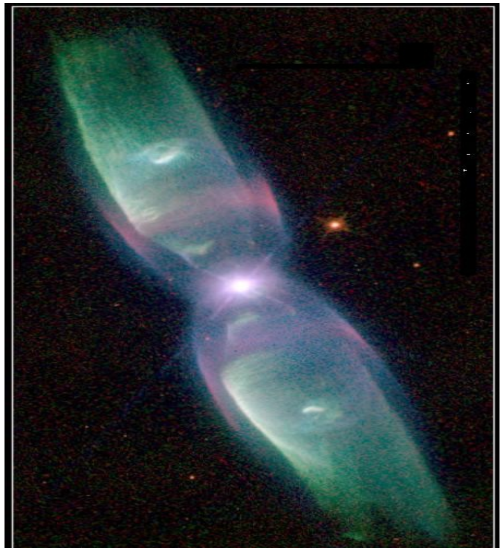
- Winds = no collimation
- Jets = tight collimation



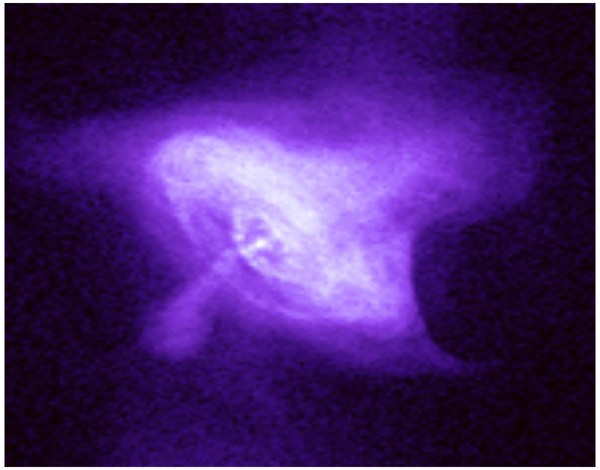
Solar Wind



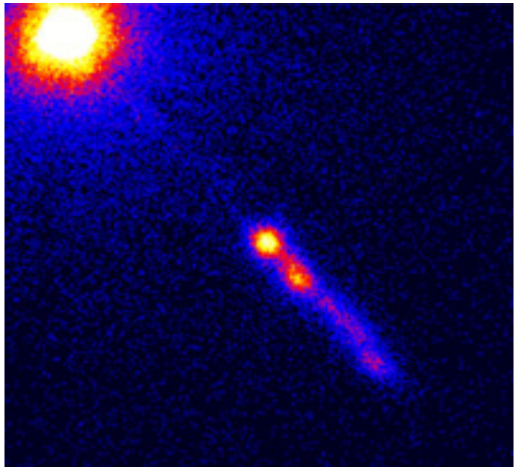
1. Star-birth



2. Star-death



3. Pulsars



4. AGN

Questions still open+under study

- Jet source: accretion, or, *
  central engine *
- Jet composition: electron-proton, or, *
  electron-positron plasma *
- Jet acceleration: thermal or radiation pressure, MHD Waves, *
  magnetocentrifugal acceleration *
- Jet confinement: thermal pressure, or, *
  magnetic hoop stress *
- Jet stability: hydrodynamic, or,
  hydromagnetic stability
- Jet speed: nonrelativistic, or, *
  relativistic*
- Jet radiation: shocks, magnetic fields, etc

Origin, Acceleration, Collimation

Origin

- Accretion disk
- Central object
- Accretion disk-central object interface

Acceleration

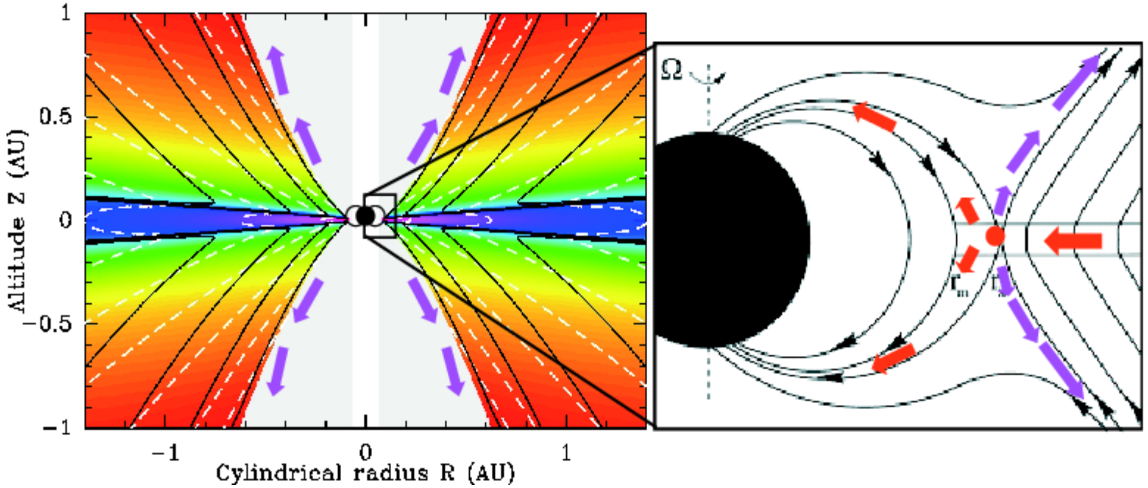
- Pressure gradient driving (thermal, radiation, waves, etc)
- Magnetocentrifugal driving

Collimation

- Pressure gradient confinement (thermal, radiation, waves, etc)
- Magnetic confinement (magnetic hoop stress)

Jet source :

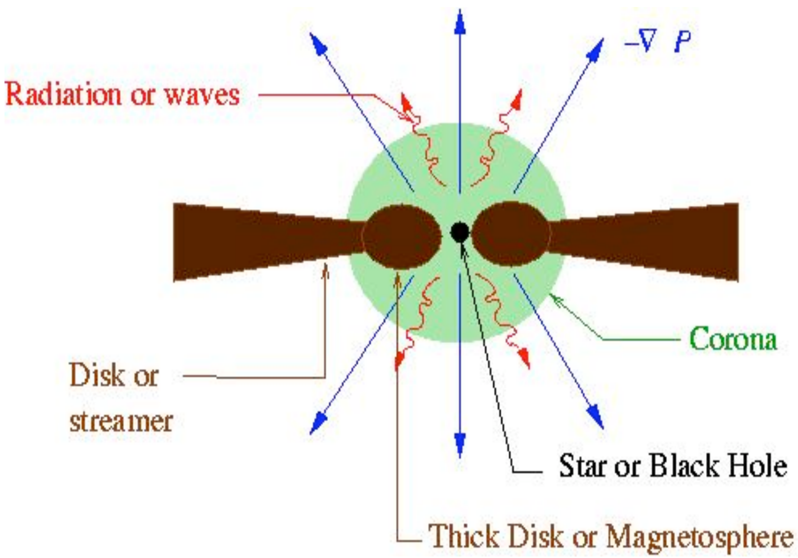
- Accretion disk
- Central object
- Accretion disk-central object interface



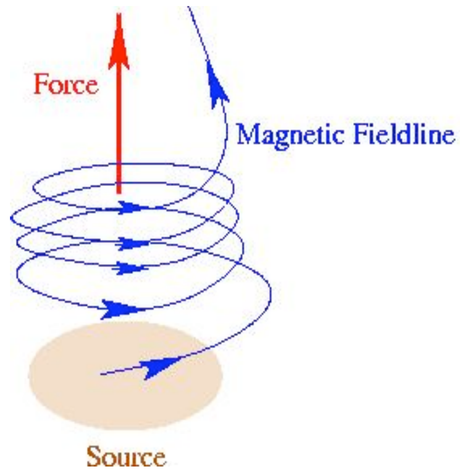
Disk-Winds, X-winds, Star-Winds (Shu, Ferreira, Sauty, et al)

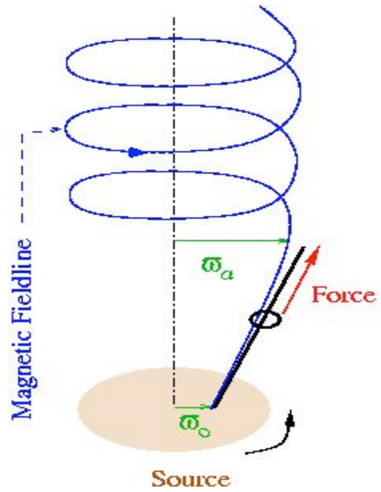
Plasma acceleration :

- Pressure gradient driving (thermal, radiation, waves, etc)



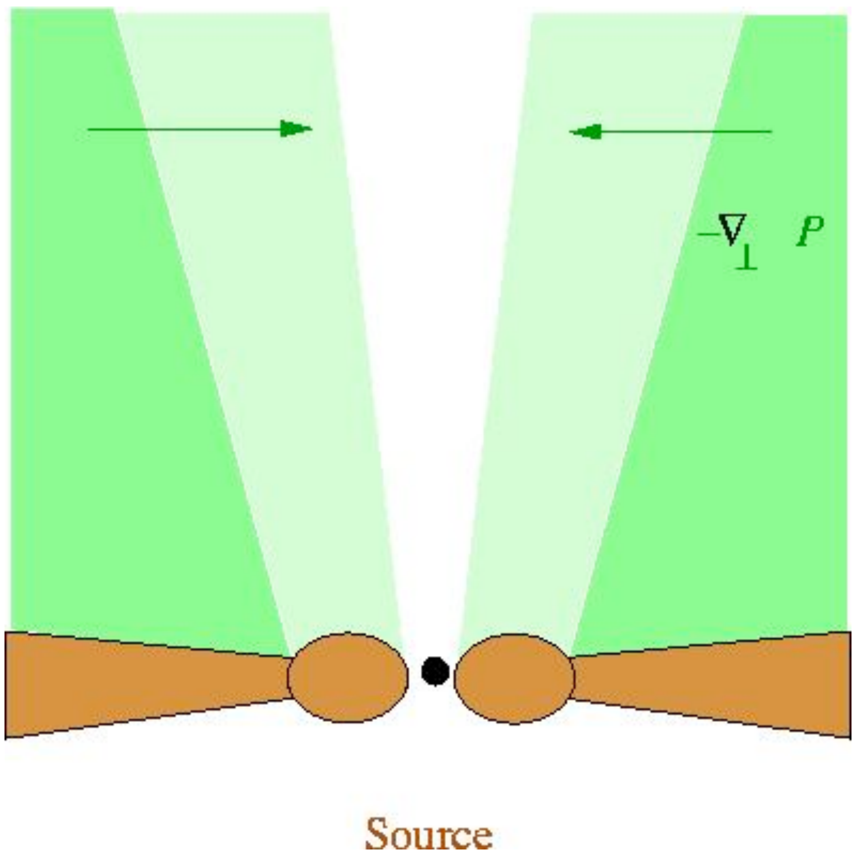
- Magnetocentrifugal driving



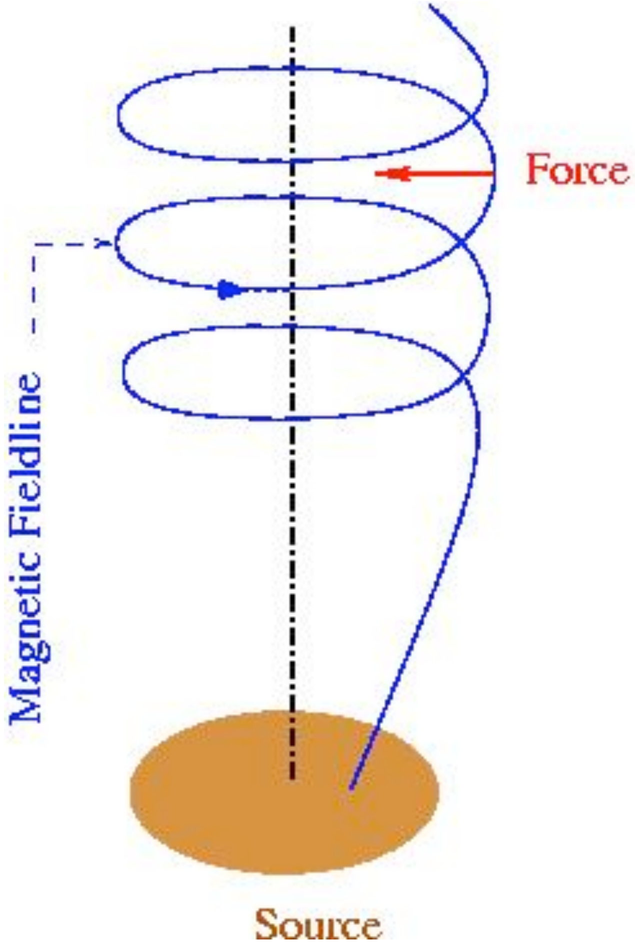


Plasma collimation :

- pressure gradient confinement (thermal, radiation, waves, etc)



- magnetic confinement (magnetic hoop stress)



MHD modelling of cosmical outflows

- I. *Steady models*

Advantages:

- analytical treatment
- parametric study
- physical picture
- cheap method

Difficulties:

- Nonlinearity (MHD set !)
- 2-dimensionality (PDEs !)
- Causality (unknown critical surfaces !)

- II. *Time-dependent models*

- temporal evolution
- nonideal MHD effects

- 3D MHD code (magnetic flux conservation !)
- large grid space (large lengths of jets !)
- correct boundary conds (boundary effects !)
- expensive method !

Basic Equations of the MHD Problem

$$\vec{\nabla}\cdot\vec{\mathbf{B}} = 0, \qquad \vec{\nabla}\cdot\vec{\mathbf{E}} = 4\pi\delta \approx 0\,,$$

$$\vec{\nabla}\times\vec{\mathbf{E}} = -\frac{1}{c}\frac{\partial\vec{\mathbf{B}}}{\partial t}, \qquad \vec{\mathbf{E}} + \frac{\vec{\mathbf{V}}\times\vec{\mathbf{B}}}{c} = \frac{\vec{\mathbf{J}}}{\sigma} \simeq 0\,, \qquad \underline{\textit{Maxwell}}$$

$$\vec{\nabla}\times\vec{\mathbf{B}} = \frac{4\pi}{c}\vec{\mathbf{J}} + \frac{1}{c}\frac{\partial\vec{\mathbf{E}}}{\partial t} \simeq \frac{4\pi}{c}\vec{\mathbf{J}}\,,$$

. . . .

$$\rho\frac{\partial\vec{\mathbf{V}}}{\partial t} + (\rho\vec{\mathbf{V}}\cdot\vec{\nabla})\vec{\mathbf{V}} = -\vec{\nabla}P + \frac{\vec{\mathbf{J}}\times\vec{\mathbf{B}}}{c} - \rho\vec{\mathbf{G}}\,, \qquad \underline{\textit{Newton}}$$

. . . .

$$\vec{\nabla}\cdot\rho\vec{\mathbf{V}} + \frac{\partial\rho}{\partial t} = 0\,, \qquad \underline{\text{mass conservation}}$$

. . . .

$$\rho\left[P\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{\rho}\right) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{P}{\rho(\Gamma-1)}\right)\right] = \rho\frac{\partial h}{\partial t} - \frac{\partial P}{\partial t} + \rho\vec{\mathbf{V}}\cdot\left[\nabla h - \frac{\nabla P}{\rho}\right] = q\,.$$

$\vec{\mathbf{V}}(x_1, x_2, x_3)$: Bulk Flow Speed of Plasma

$\vec{\mathbf{B}}(x_1, x_2, x_3)$: Magnetic Field in Plasma

$\vec{\mathbf{J}}(x_1, x_2, x_3)$: Electric Current Density in Plasma

$\vec{\mathbf{G}}(x_1, x_2, x_3)$: External (gravitational) Field in Plasma

$\rho(x_1, x_2, x_3)$: Plasma Density

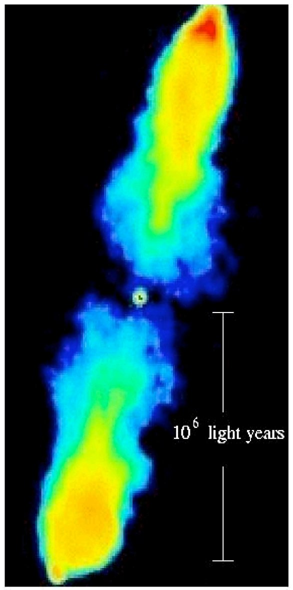
$P(x_1, x_2, x_3)$: Plasma Pressure

$h(x_1, x_2, x_3)$: Enthalpy $(= \frac{\Gamma}{\Gamma-1}\frac{P}{\rho})$

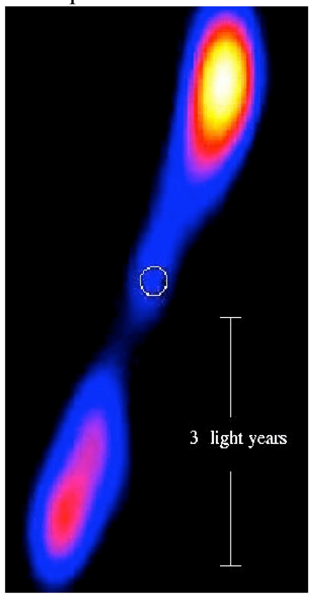
$q(x_1, x_2, x_3)$: Volumetric Rate of Energy Addition in System in general curvilinear coordinates (x_1, x_2, x_3).

Analytical Solutions: Self-similarity

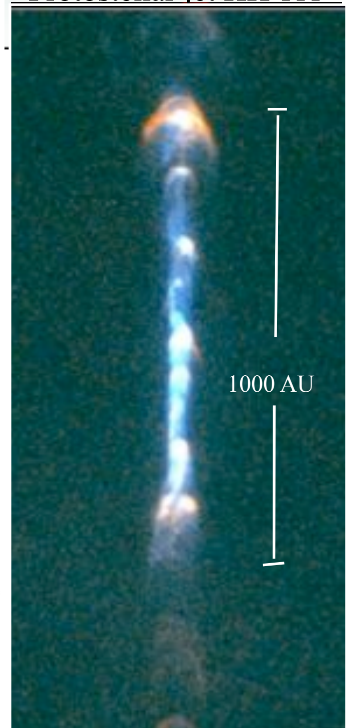
Quasar/radio galaxy



Microquasar 1E1740.7-2942

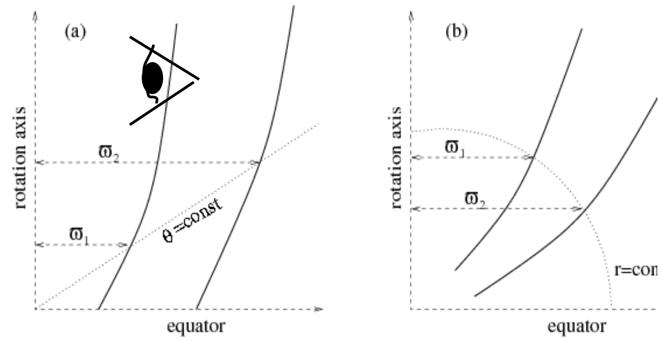


Protostellar jet HH 111



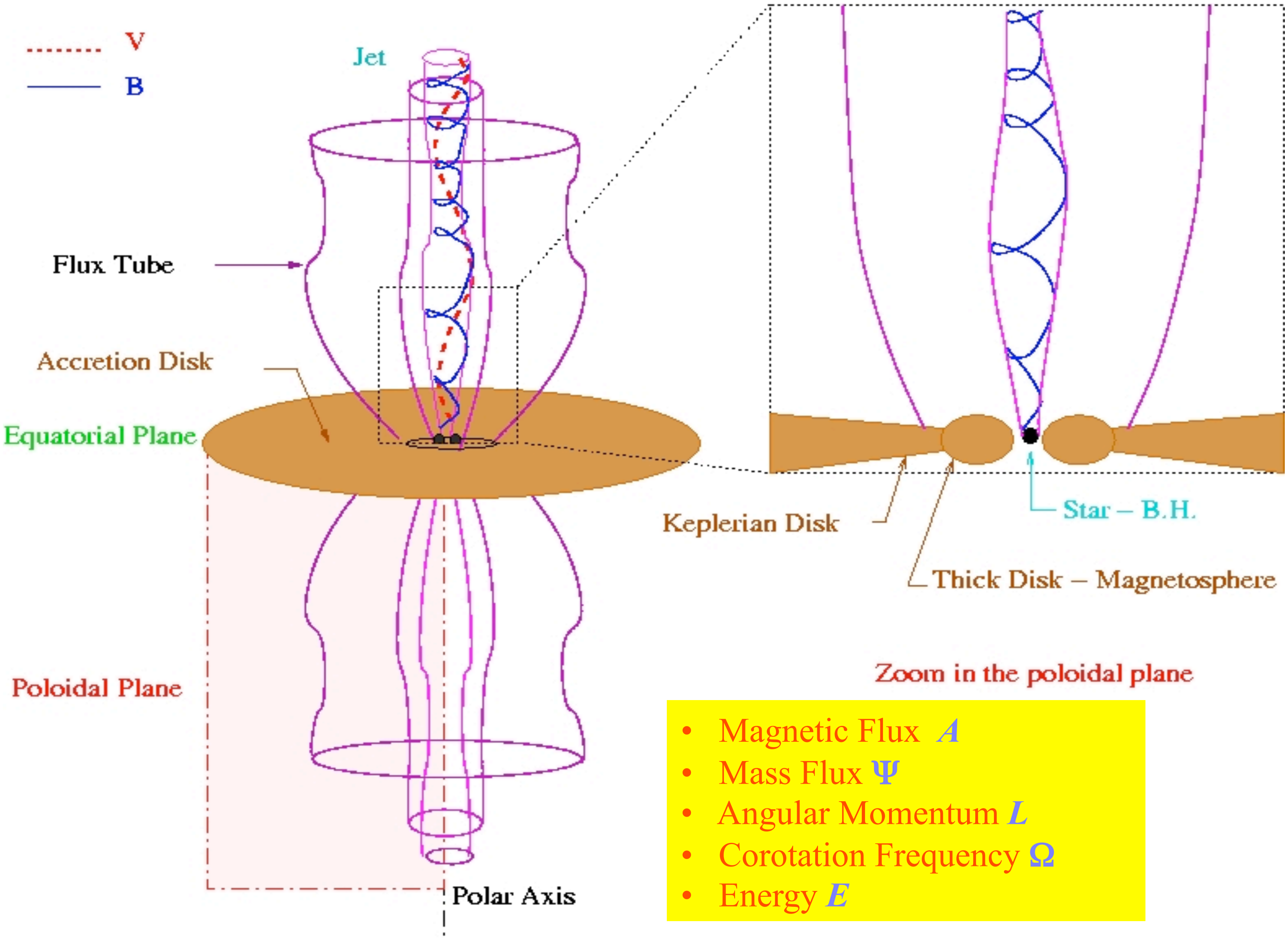
Analytical solutions

- In steady states, the axisymmetric ideal MHD equations that describe plasma outflows can be analytically solved by a non linear separation of the variables
- By a systematic way there have been found[1] two general families of solutions
  - Radially Self Similar
  - Meridionally Self Similar



- These two classes of models are the ONLY 2D analytical solutions available today for MHD outflows, Vlahakis & Tsinganos, MNRAS, 1998

I. STEADY and AXISYMMETRIC MHD MODELS



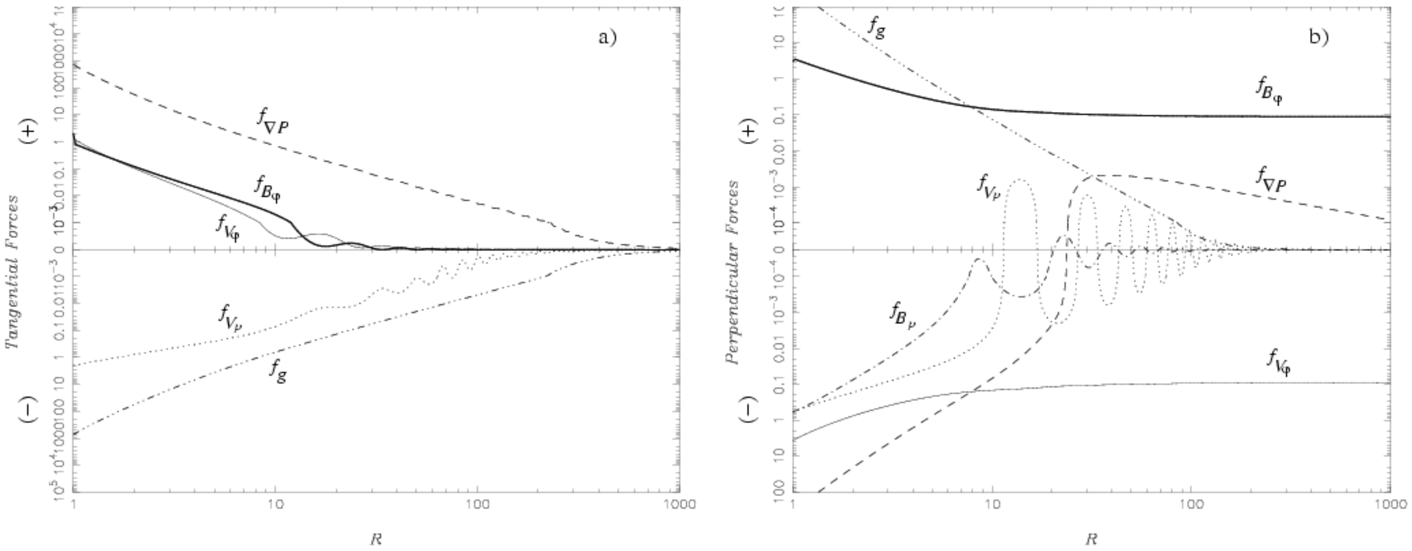
- Magnetic Flux A
- Mass Flux Ψ
- Angular Momentum L
- Corotation Frequency Ω
- Energy E

The problem of causality:

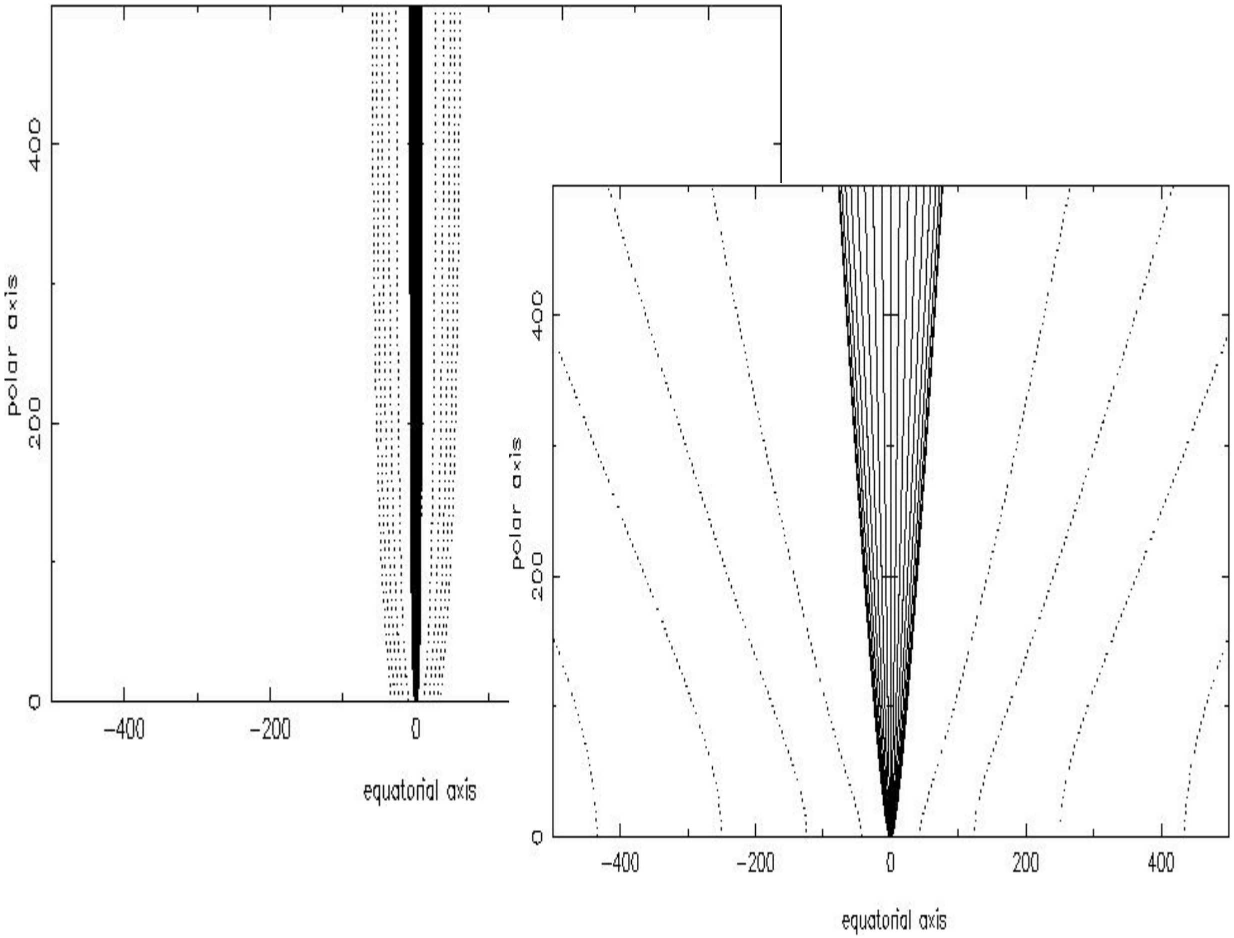
The MHD equations are of mixed elliptic/hyperbolic character and in hyperbolic regimes exist separatrices separating causally areas which cannot communicate with each other via an MHD signal.
They are the analog of the limiting cycles in Van der Pol's nonlinear differential equation, or, the event horizon in relativity.

The MHD critical points appear on these separatrices which do not coincide in general with the fast/slow MHD surfaces.
To construct a correct solution we need to know the limiting characteristics, but this requires a knowledge of the solution !

Balance of various MHD forces along and across the jet from base to infinity



Families of solutions



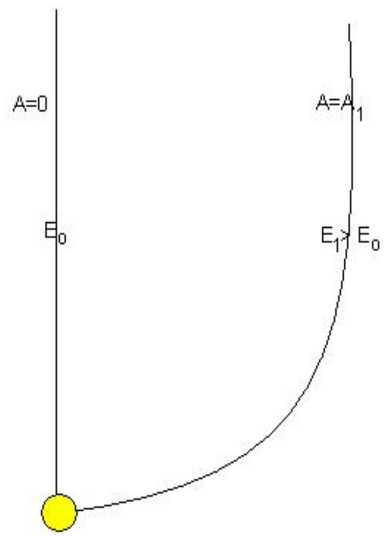
- Cylindrical (jets)
- Radial or Conical (Winds)

A criterion for cylindrical collimation:

$$\varepsilon' = \frac{\Delta(\rho E)}{\rho L \Omega}$$

$\Delta f = f$(non polar streamline) - f(polar axis)

- $\varepsilon' < 0$ --> No collimation
- $\varepsilon' > 0$ --> Collimation



$$\varepsilon' = \mu + \varepsilon$$

Efficiency of Pressure Confinement

$$\mu \sim \frac{\Delta P}{P} = \kappa$$

Efficiency of the Magnetic Rotator

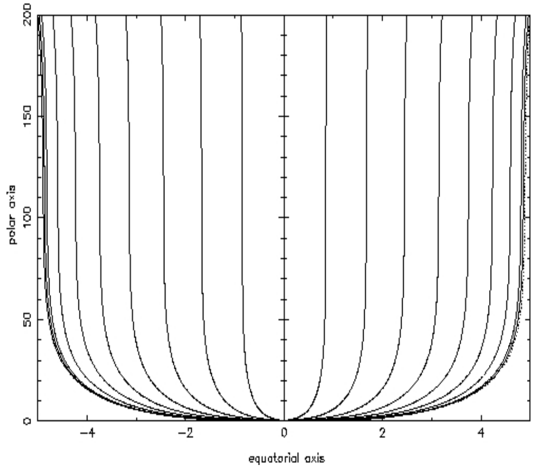
$$\varepsilon = \frac{L\Omega - E_{R,o} + \Delta E_G^*}{L\Omega}$$

where

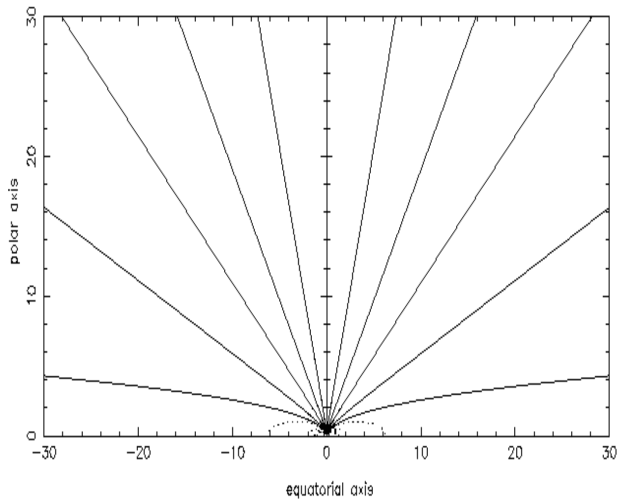
$$\Delta E_G^* = -\frac{GM}{r_0}\left(\frac{-\Delta T}{T_0}\right)$$

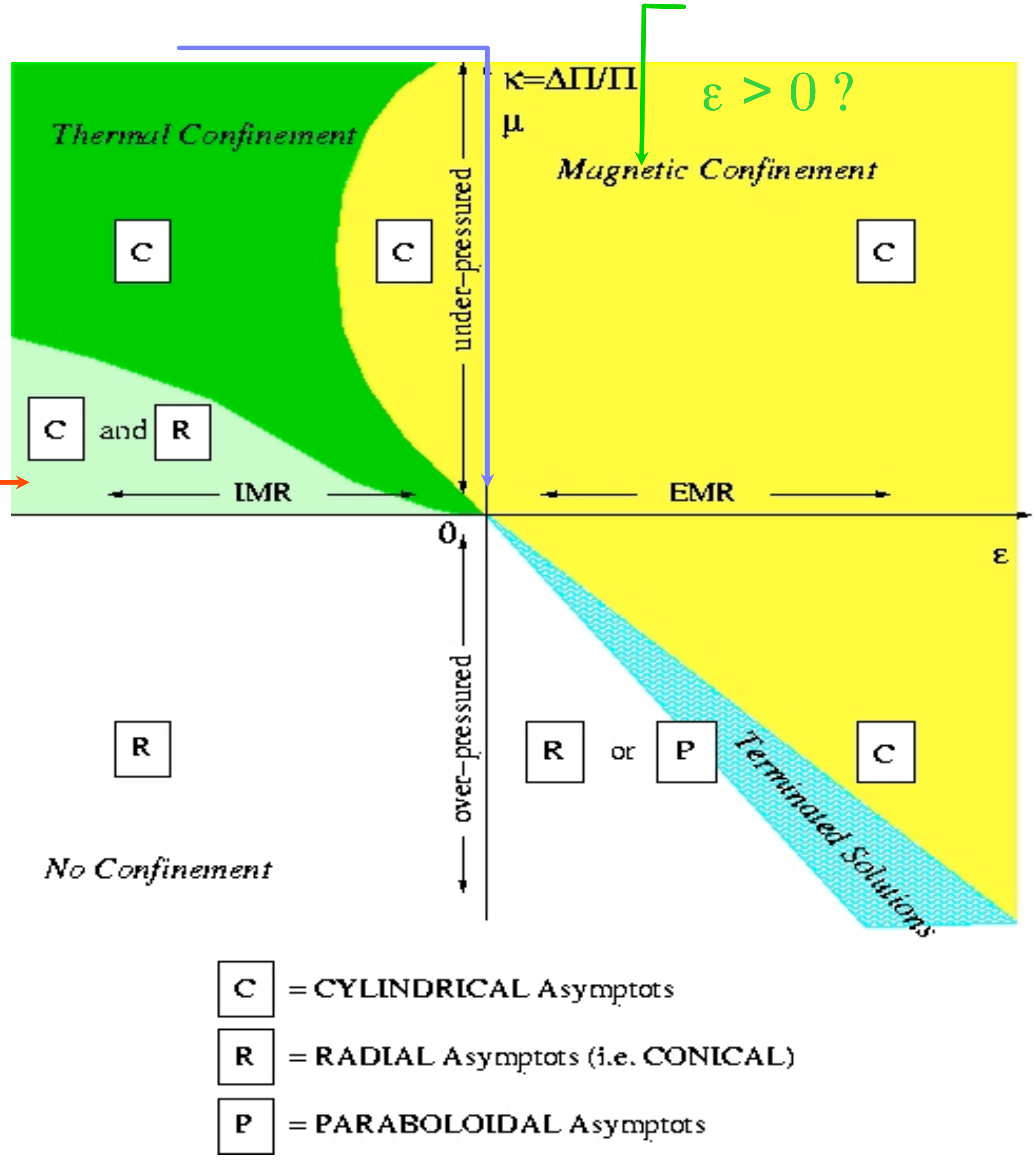
- $\varepsilon > 0$ --> Efficient Magnetic Rotator (EMR)
- $\varepsilon < 0$ --> Inefficient Magnetic Rotator (IMR)

A classification of outflows

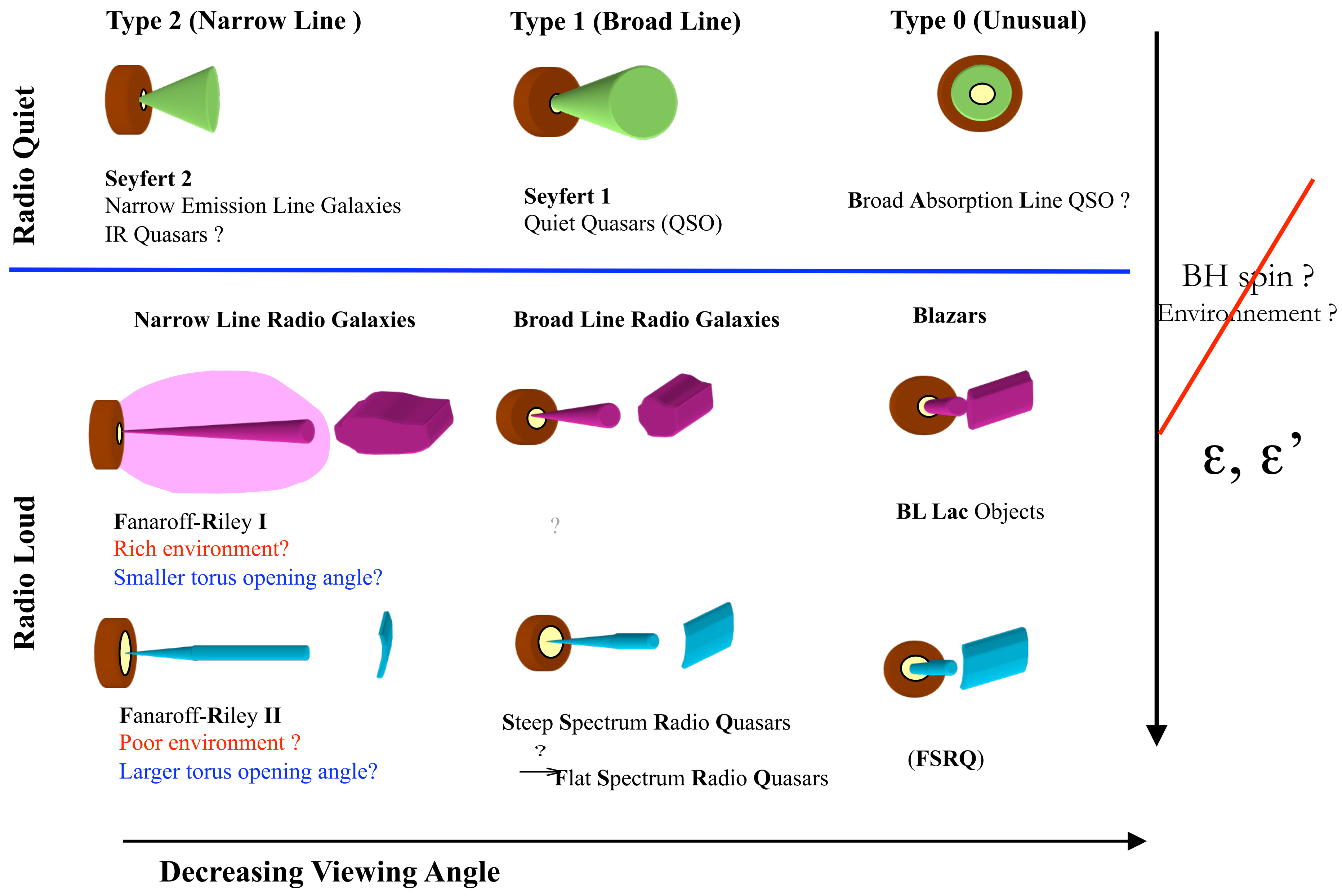


Solar Wind $\varepsilon = -50$



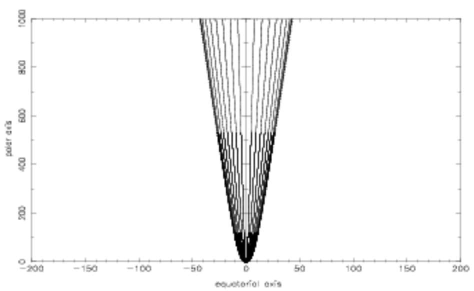


Unified Scheme for AGNs

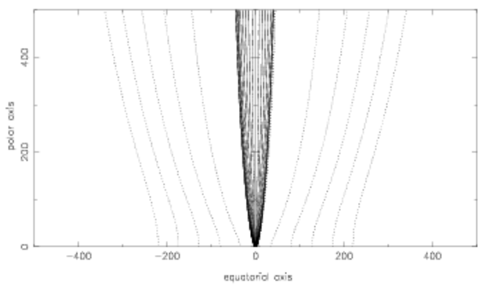


- Inefficient Magnetic Rotators (wide-angle outflows)
- Efficient Magnetic Rotators (Narrow jets)

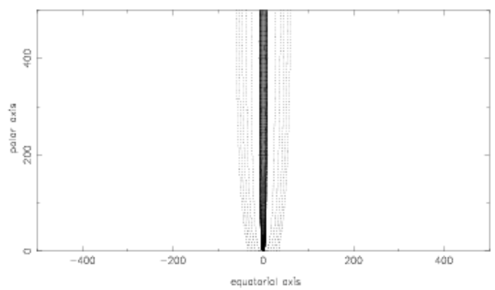
a) Sey2,Sey1, QSO,BAL



b) FRI, BLac



c) FRII,SSRQ,FSRQ



II. Time-dependent studies

– Time-dependent **simulations**: Governing MHD equations –

$$\mathbf{B_p} = \frac{\nabla A \times \hat{\varphi}}{\varpi}.$$

$$\frac{\partial A}{\partial t} = -V_\varpi \frac{\partial A}{\partial \varpi} - V_z \frac{\partial A}{\partial z},$$

$$\frac{\partial \rho}{\partial t} = -\frac{1}{\varpi}\frac{\partial}{\partial \varpi}(\rho \varpi V_\varpi) - \frac{\partial}{\partial z}(\rho V_z),$$

$$\frac{\partial B_\varphi}{\partial t} = \frac{\partial}{\partial z}(V_\varphi B_z - V_z B_\varphi) - \frac{\partial}{\partial \varpi}(V_\varpi B_\varphi - V_\varphi B_\varpi),$$

$$\frac{\partial V_\varphi}{\partial t} = -\frac{V_\varpi}{\varpi}\frac{\partial}{\partial \varpi}(\varpi V_\varphi) - V_z \frac{\partial V_\varphi}{\partial z} + \frac{1}{4\pi\rho}\left(B_\varpi \frac{\partial}{\varpi \partial \varpi}(\varpi B_\varphi) + B_z \frac{\partial B_\varphi}{\partial z}\right),$$

$$\frac{\partial V_z}{\partial t} = -V_\varpi \frac{\partial V_z}{\partial \varpi} - V_z \frac{\partial V_z}{\partial z} - \frac{1}{\rho}\frac{\partial P}{\partial z} - \frac{GMz}{r^3} - \frac{1}{8\pi\rho\varpi^2}\frac{\partial}{\partial z}(\varpi B_\varphi)^2 - \frac{B_\varpi}{4\pi\rho}\left(\frac{\partial B_\varpi}{\partial z} - \frac{\partial B_z}{\partial \varpi}\right),$$

$$\frac{\partial V_\varpi}{\partial t} = -V_\varpi \frac{\partial V_\varpi}{\partial \varpi} - V_z \frac{\partial V_\varpi}{\partial z} - \frac{1}{\rho}\frac{\partial P}{\partial \varpi} - \frac{GM\varpi}{r^3} - \frac{1}{8\pi\rho\varpi^2}\frac{\partial}{\partial \varpi}(\varpi B_\varphi)^2 + \frac{V_\varphi^2}{\varpi} + \frac{B_z}{4\pi\rho}\left(\frac{\partial B_\varpi}{\partial z} - \frac{\partial B_z}{\partial \varpi}\right),$$

$(z, \varpi, \varphi) \Longrightarrow$ cylindrical coordinates,
$\rho \Longrightarrow$ density,
$\vec{V} \Longrightarrow$ flow speed,
$\vec{B} \Longrightarrow$ magnetic field,
$A(z, \varpi) \Longrightarrow$ poloidal magnetic flux.

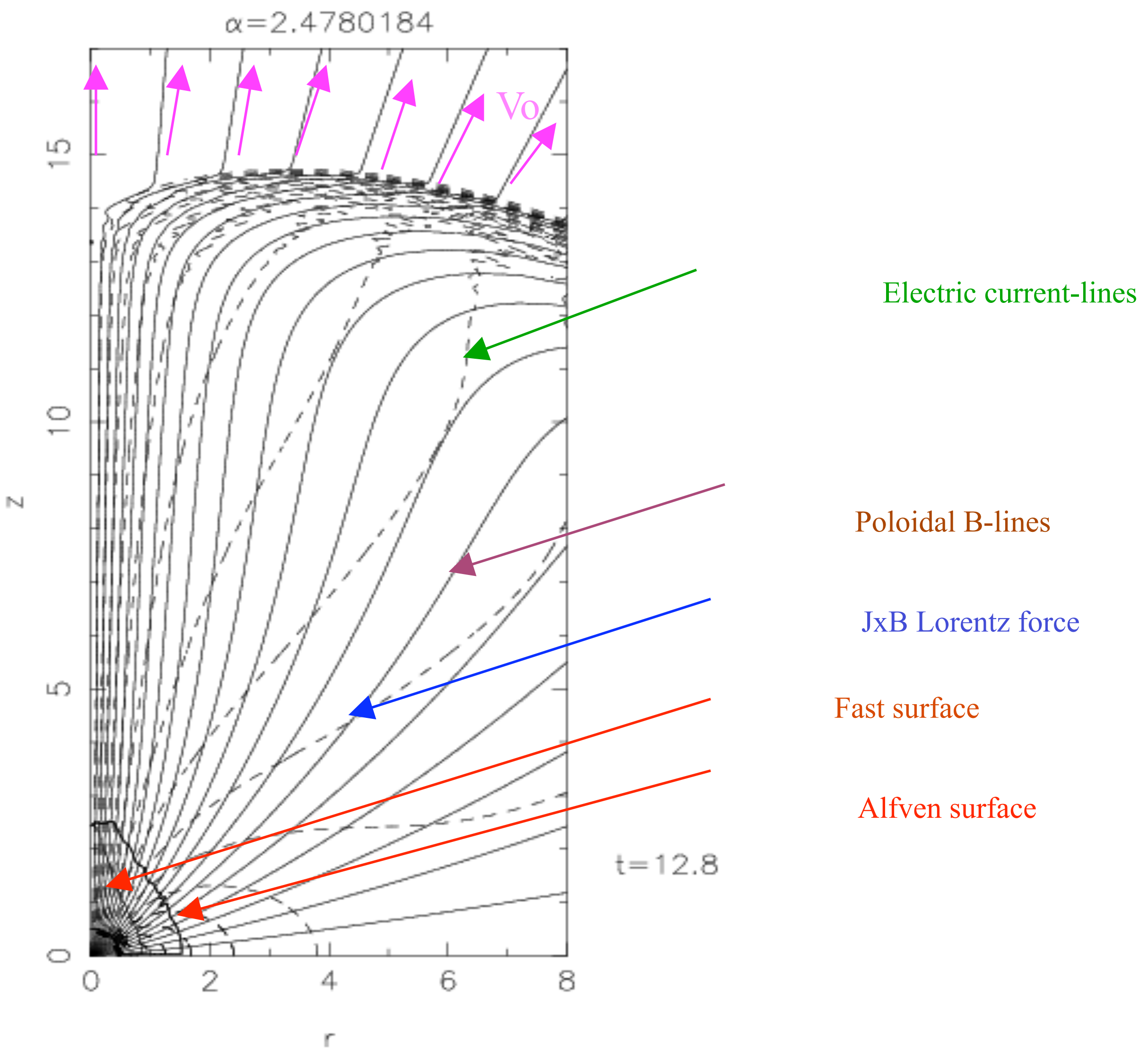
Magnetic self-collimation (numerically)

A near zone snapshot on the poloidal plane showing the change of shape of the poloidal magnetic field from an initially uniform with latitude radial monopole (before a stationary state is reached).

$\alpha = \Omega R_a / V_o = 2\pi T_{travel} / T_{rotation}$

α < 1: Slow magnetic rotators

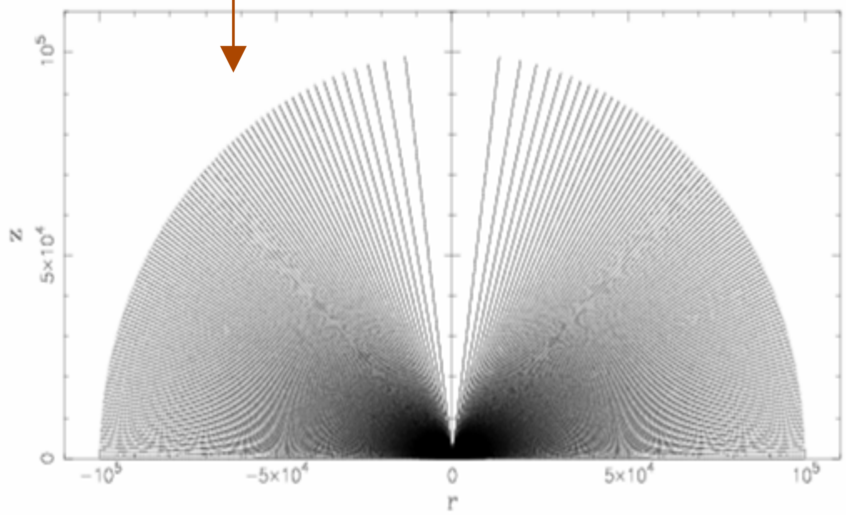
α > 1: Fast magnetic rotators

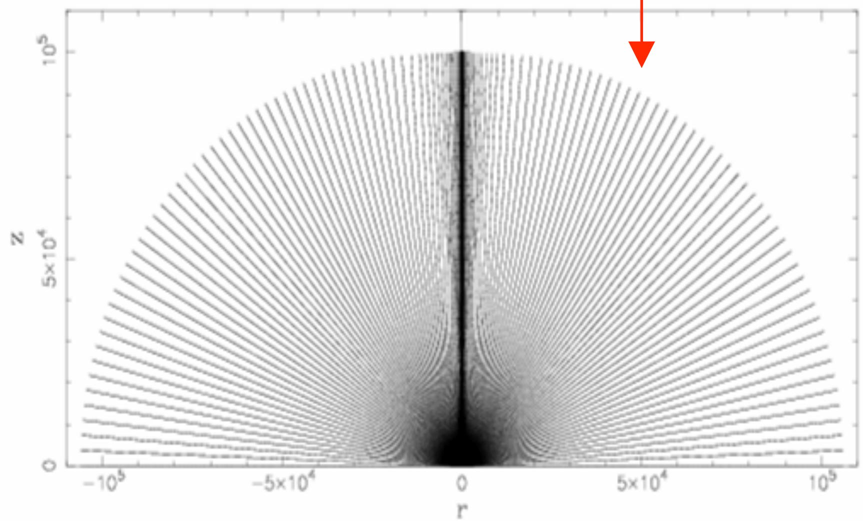


Magnetic self-collimation (numerically)

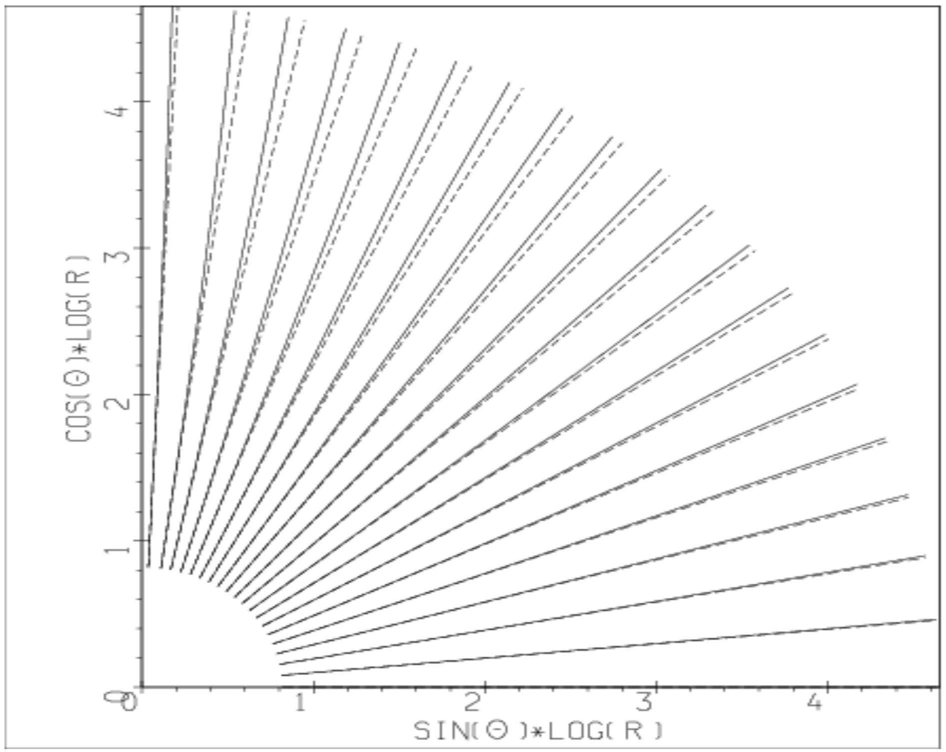
Far Zone : Poloidal magnetic lines of outflow at intervals of equal magnetic flux.

Before rotation starts – After rotation started

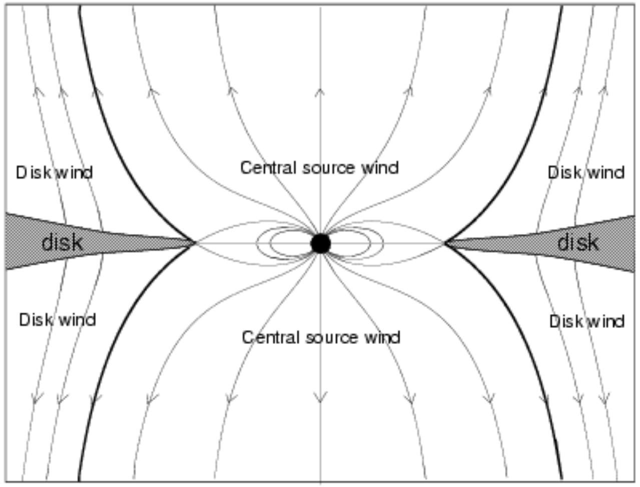




Very weak direct collimation of relativistic plasma



A two-compenent model for jets from a system of a central source+disk

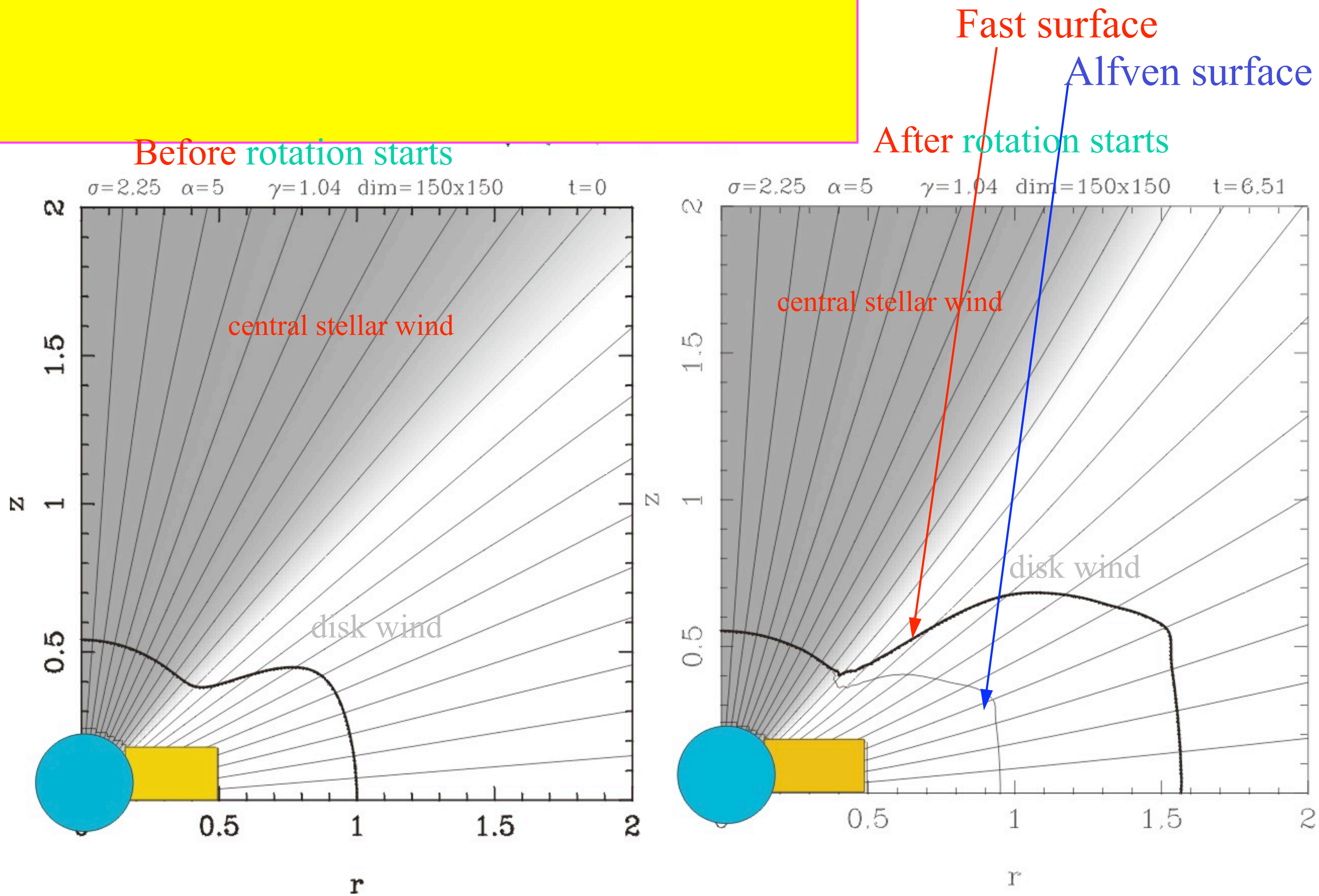


Recent numerical simulations and analytical models of magnetically collimated plasma outflows from a uniformly rotating central gravitating object and/or a Keplerian accretion disk have shown that relatively low mass and magnetic fluxes reside in the produced jet. Observations however indicate that in some cases, as in jets of YSO's, the collimated outflow carries higher fluxes than these simulations predict. A solution to this problem is proposed by the above model where jets with high mass flux originate in a central source which produces a noncollimated outflow provided that this source is surrounded by a rapidly rotating accretion disk. The relatively faster rotating disk produces a collimated wind which then forces all the enclosed outflow from the central source to be collimated too. This conclusion is confirmed by self-consistent numerical solutions of the full set of the MHD equations.

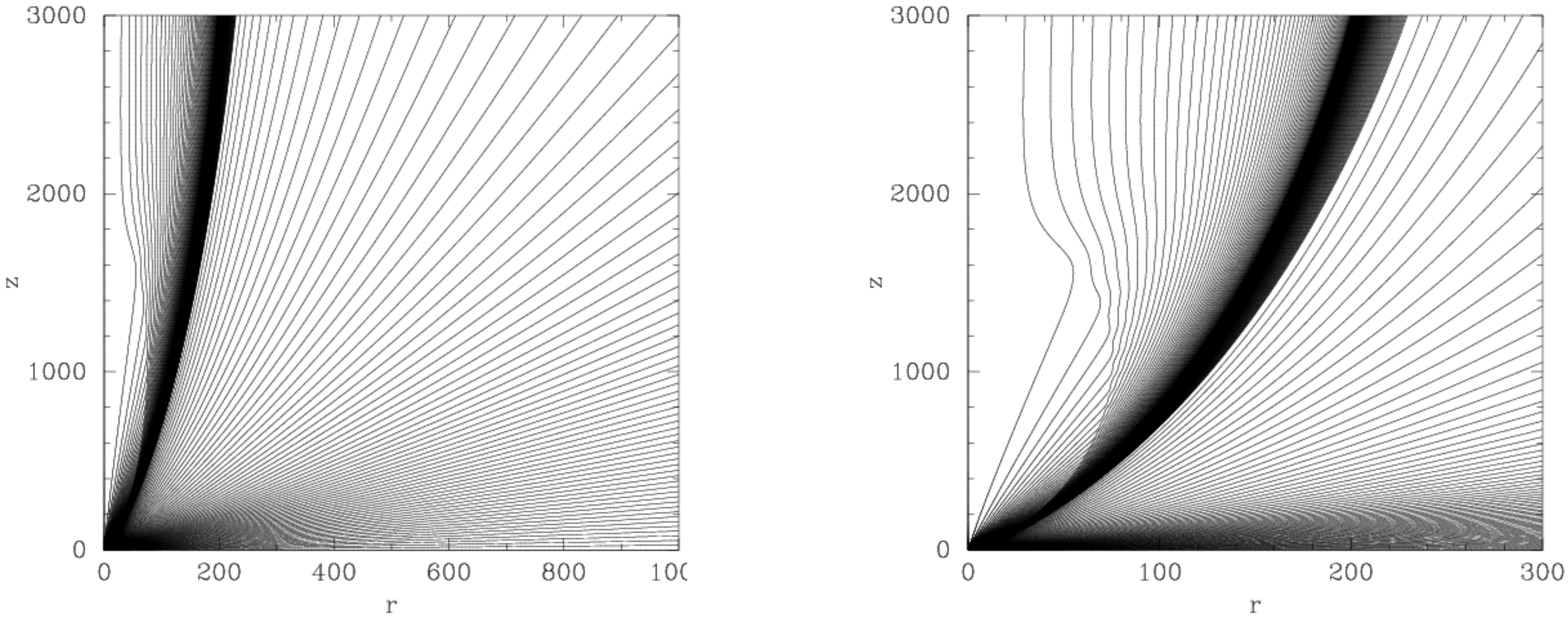
A two-component outflow model with :

a) a central stellar wind

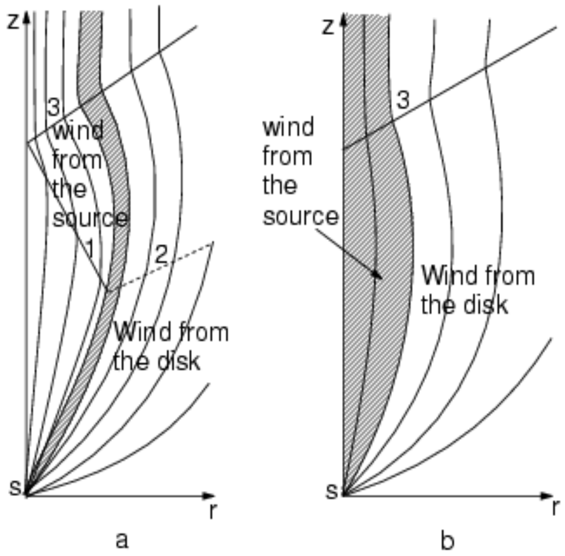
b) a disk-wind



Collimation of stellar outflow by surrounding disk-wind



Shock formation in a 2-component outflow by a rotating disk-wind



In panel (a) a sketch of the shock waves and singular surfaces which are expected to be formed in the general case of a two-component outflow is presented. The oblique shock front marked by '1' is formed at the collision of the two parts of the collimated and still uncollimated flows. An outgoing weak discontinuity from the one end of this shock is marked by '2'. The shock front marked by '3' is formed at the self reflection of the collimated flow at the axis of rotation. Under special conditions this collision shock may not be formed. In this case, the structure a shock as the one shown in panel (b) is expected

Conclusions

MHD outflows can be modelled via a combination of analytical + numerical means. In particular, we can answer the question of the observed dichoromy of winds/jets as a result of the central engine beeing an efficient (jets) or inefficient (winds) magnetic rotator. In the sam espirit we may understand the FRI (winds or loosely collimated jets)/FR I tightly collimated jets) dichotomy.