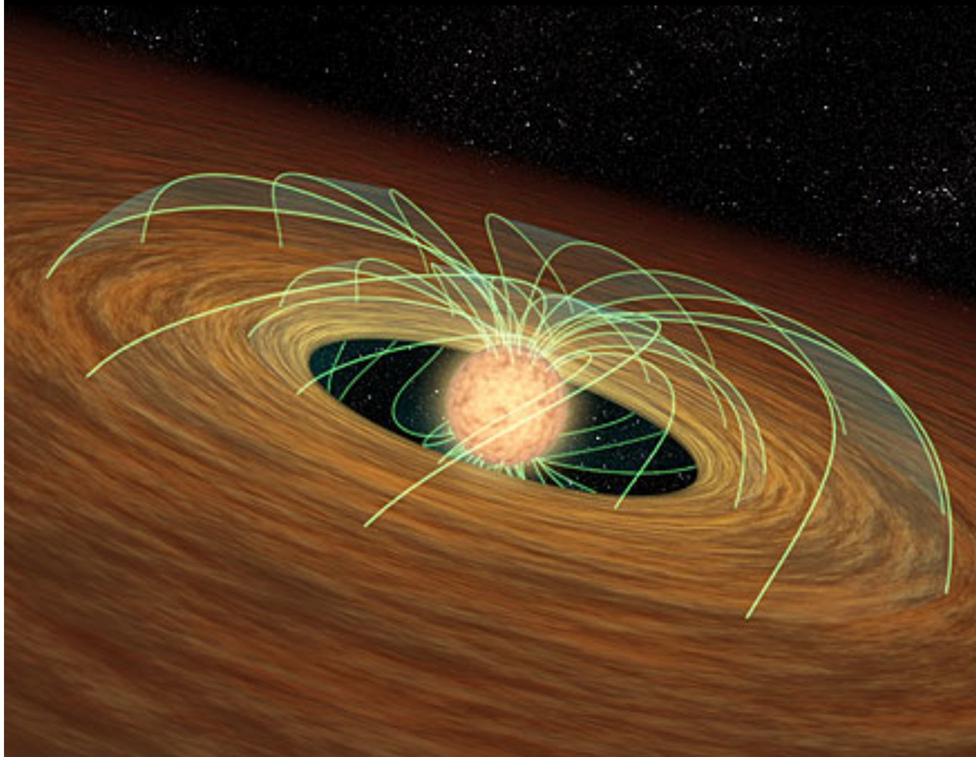
MHD Simulations of Disk-Star Interaction




Marina Romanova, Cornell University

Collaborators: A. Kulkarni (Harvard), M. Long (U. of Illinois), R. Lovelace (Cornell U.), A. Koldoba, G. Ustyugova (Moscow, Russia), M. Bachetti (U. of Calgary)

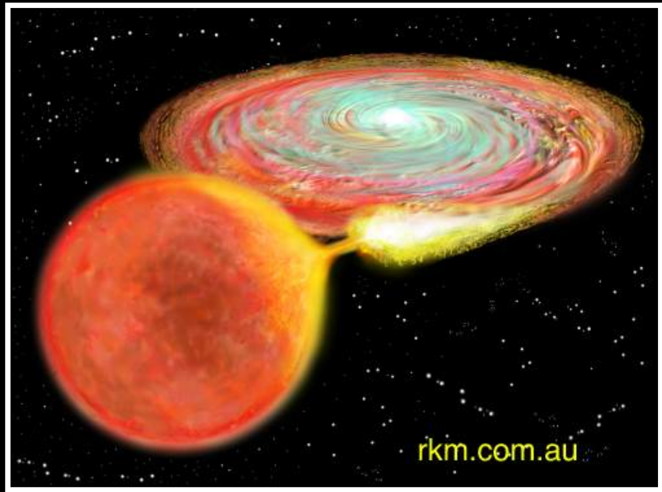
13 Jan. 2010

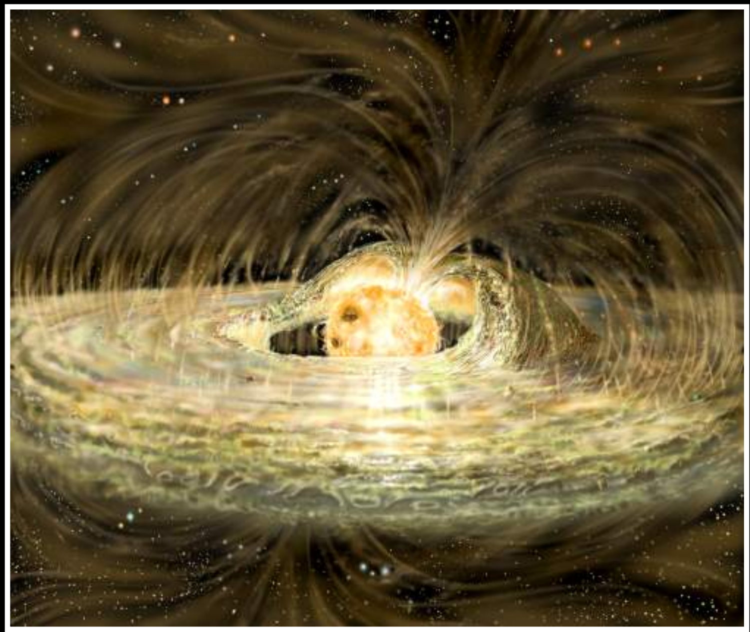
Accreting Magnetized Stars

Neutron stars: accreting millisecond pulsars, $B=10^8$-10^9 G, $R=10^6$ cm

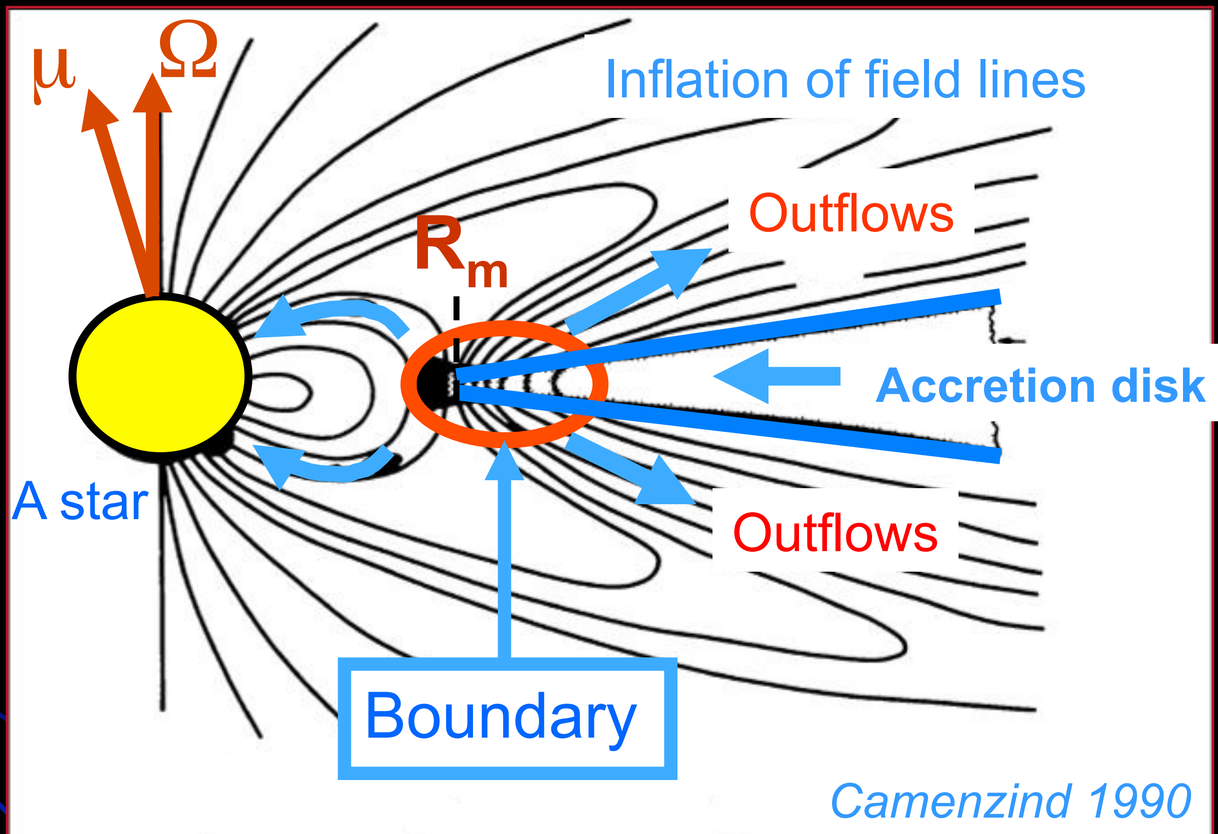
White dwarfs: cataclysmic variables –Intermediate polars $B=10^6$-10^8 G, $R=5\times10^8$ cm

Young stars: like our Sun in the past $B=10^3$ G, $R=10^{12}$ cm





Disk-Magnetosphere Interaction



- Magnetospheric radius, R_m: $B^2/8\pi=\rho v_\phi^2$
- Corotation radius, R_{cor}: $\Omega_{star}=\Omega_{disk}$

2D and 3D simulations

3D and 2D Simulations

- Non-relativistic MHD (PW in case of NSs)
- Godunov-type numerical codes

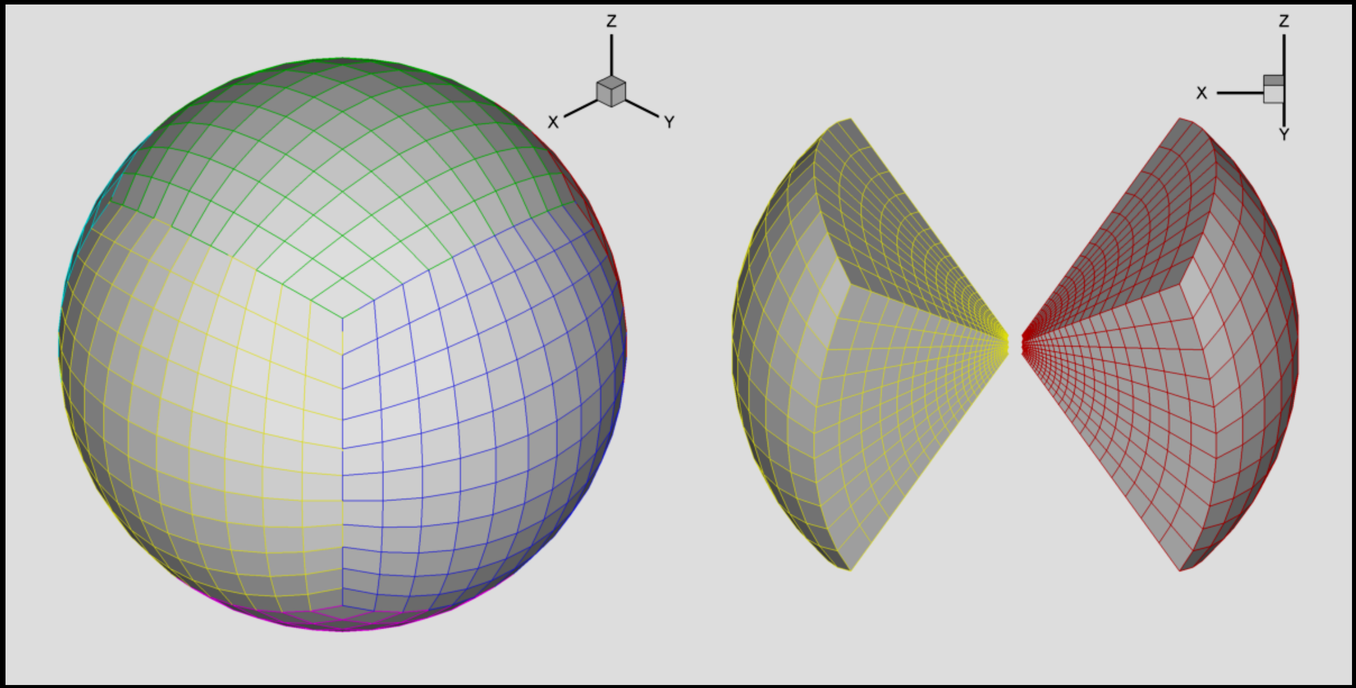
Transport coefficients:

- Viscosity (both 2D and 3D)
- Diffusivity only in 2D code

α_{vis}=0.01-0.5 α_{dif}=0.01-0.5

- MRI – experiments

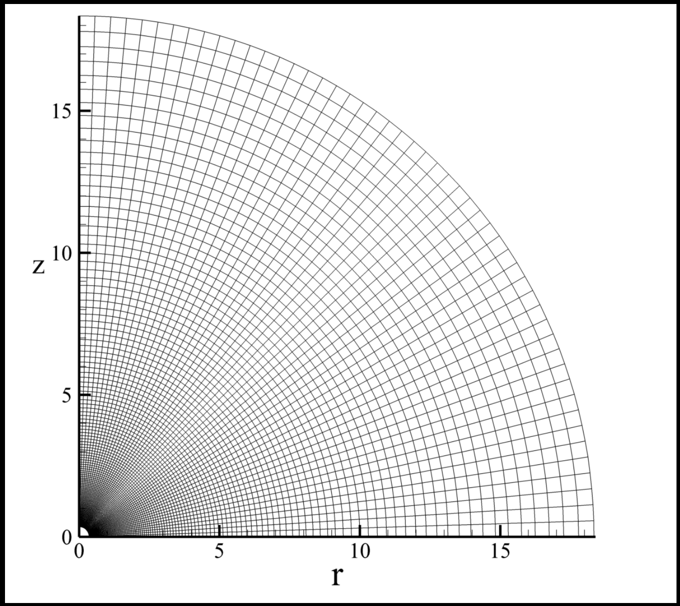
3D "Cubed Sphere" grid



- Each sphere represents an inflated cube
- Set of cubed spheres (*Koldoba et al. 2002*)

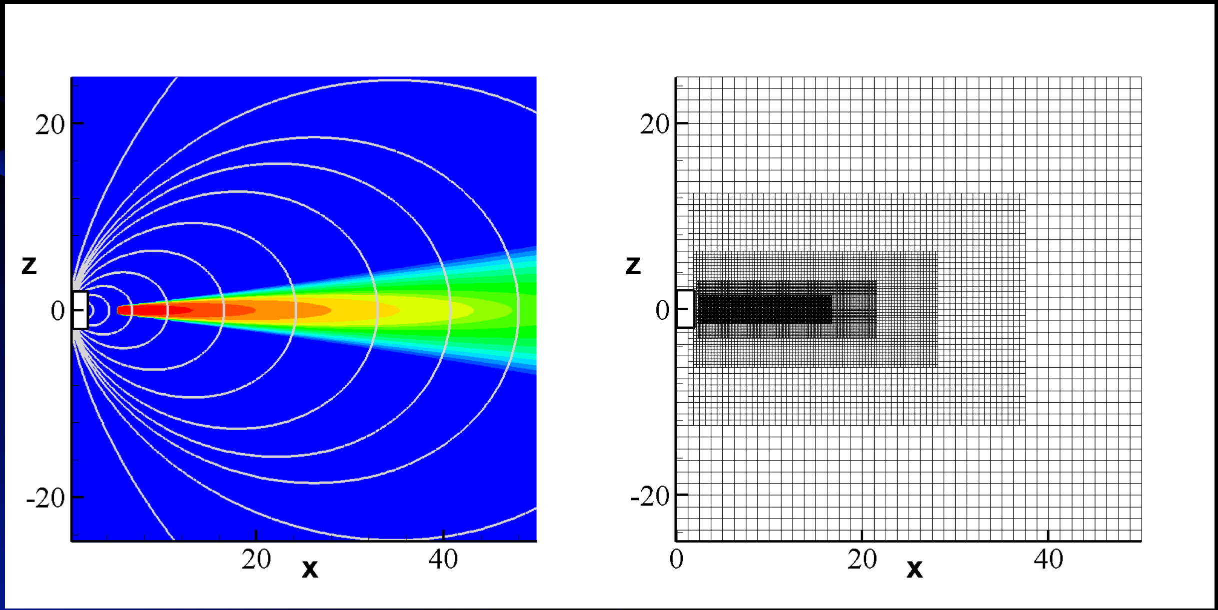
The grid has been used earlier in geophysics: *Sadourny 1972, Ronchi et al. 1996; More recently: Putman 2007; Fragile 2009*

2.5D, axisymmetric grids



Spherical grids – if need to resolve processes near the star

Angular resolution: N_θ= 30 – 140



Cyllindrical grids

Fixed mesh refinement

Resolution: N= 100-400

3D - Ideal MHD Equations, 2D (non-ideal)

- Written in the coordinate system rotating with a star
- Splitting of the field: $B = B_0 + B_1$ (*Tanaka 1994*)

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

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = -\nabla \mathcal{T} + \rho\, \boldsymbol{g} + \underline{2\rho \boldsymbol{v} \times \boldsymbol{\Omega} - \rho \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{R})}$$

Corotating frame

Stress tensor

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

No shocks

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{v}) = 0$$

Ideal

$$\nabla \cdot \boldsymbol{B} = 0, \qquad p = S\rho^{\gamma} \qquad \gamma=5/3$$

Adiabatic

Full set of equations

$$\frac{\partial \boldsymbol{U}}{\partial t} + \nabla \cdot \boldsymbol{F}(\boldsymbol{U}) = Q$$

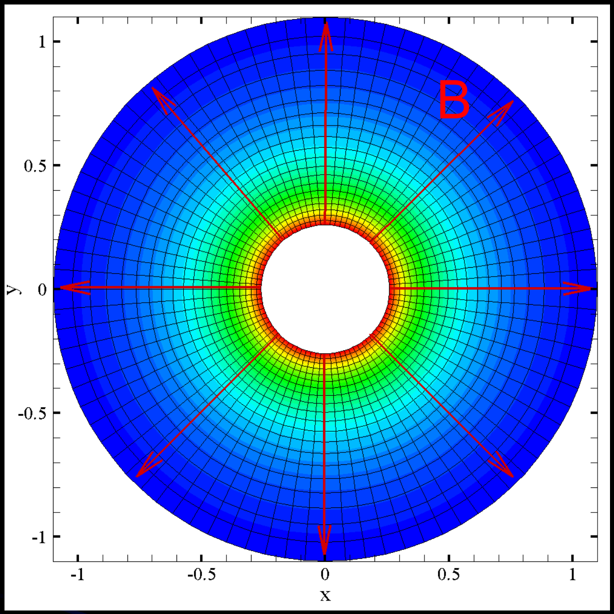
$$\boldsymbol{U} = \Big(\rho, \rho u, \rho v, \rho w, \rho S, B_x, B_y, B_z\Big)$$

$$\boldsymbol{F} = \begin{pmatrix} \rho u \\ \rho u^2 + p + \frac{B^2}{8\pi} - \frac{B_x^2}{4\pi} \\ \rho uv - \frac{B_x B_y}{4\pi} \\ \rho uw - \frac{B_x B_z}{4\pi} \\ \rho S u \\ 0 \\ uB_y - vB_x \\ -(wB_x - uB_z) \end{pmatrix}, \begin{pmatrix} \rho v \\ \rho uv - \frac{B_x B_y}{4\pi} \\ \rho v^2 + p + \frac{B^2}{8\pi} - \frac{B_y^2}{4\pi} \\ \rho vw - \frac{B_y B_z}{4\pi} \\ \rho S v \\ -(uB_y - vB_x) \\ 0 \\ vB_z - wB_y \end{pmatrix}, \begin{pmatrix} \rho w \\ \rho uw - \frac{B_x B_z}{4\pi} \\ \rho vw - \frac{B_y B_z}{4\pi} \\ \rho w^2 + p + \frac{B^2}{8\pi} - \frac{B_z^2}{4\pi} \\ \rho S w \\ wB_x - uB_z \\ -(vB_z - wB_y) \\ 0 \end{pmatrix}$$

Developed Godunov-type code (*Koldoba et al. 2002)*
2-nd order

Similar to: *Powell, Roe, Linde, Gombosi, De Zeeuw 1999*
Described e.g. in the book: Kulikovskii, Pogorelov, Semenov 2001

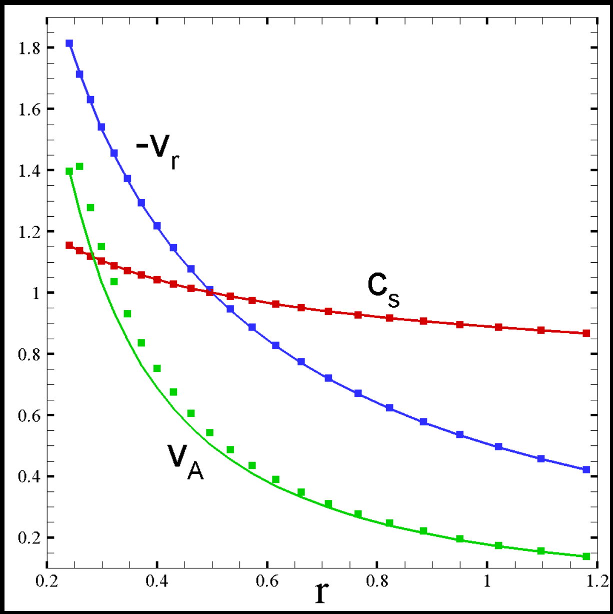
Test of the 3d Cubed Sphere code: Bondi accretion in case of monopole magnetic field



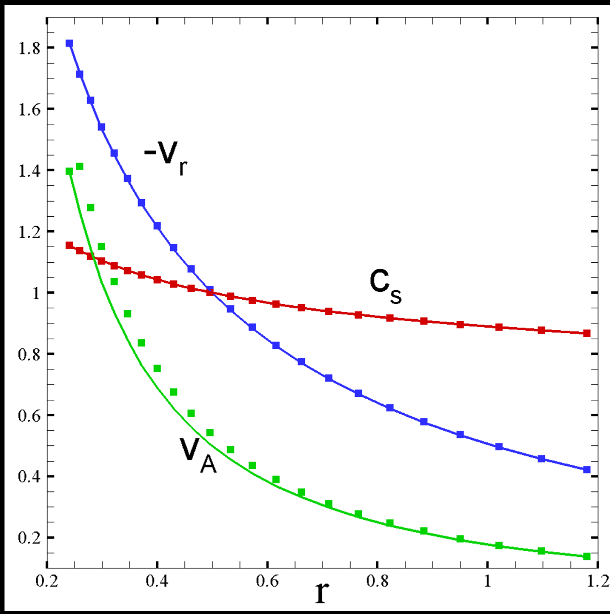
Grid: 1 of 6 blocks: $N_r x N x N = 30x21x21$

v_r – radial velocity of the flow
c_s – sound speed
v_A – Alfv'en velocity

Side of the block

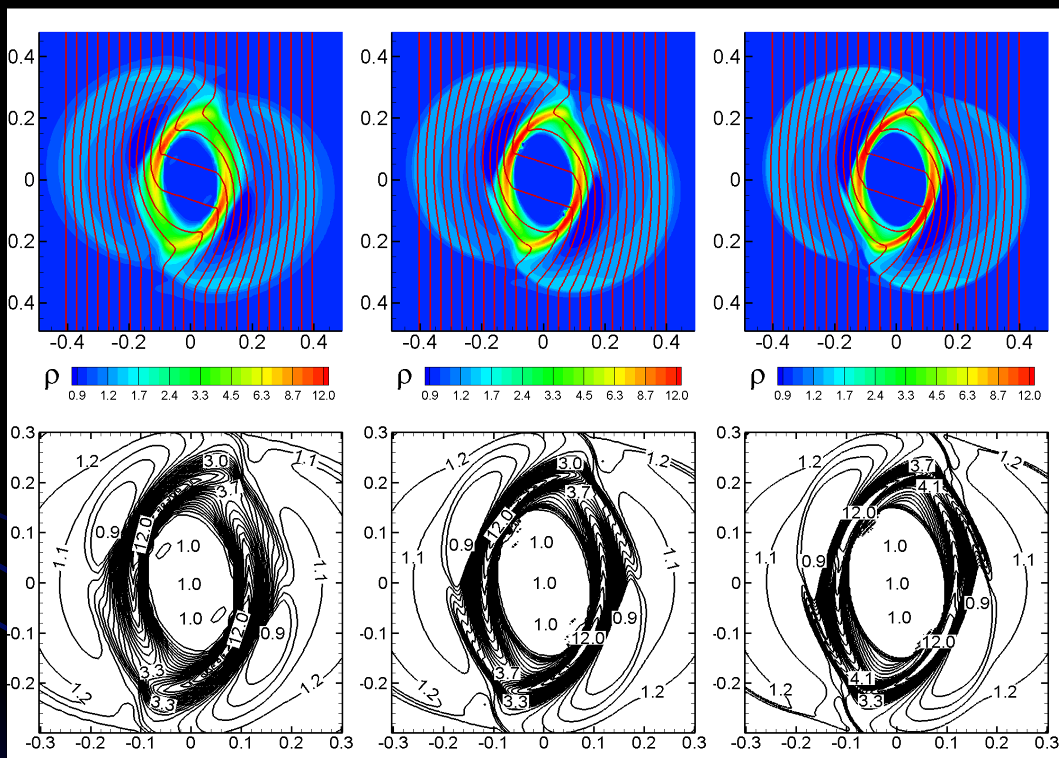


Center of the block



The "rotor problem" test for the ideal block of the 2D MHD Godunov code

Viscosity and diffusivity blocks are switched-off



Color background- density

Lines are the magnetic field lines

Lines are density contours

100x100 200x200 400x400

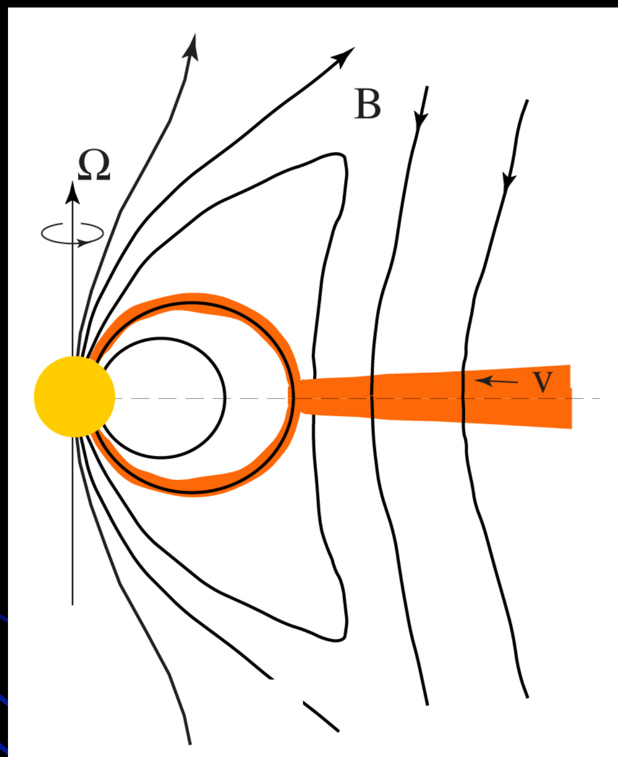
Comparisons show grid convergence

Romanova, Ustyugova, Koldoba, Lovelace 2009

Two important situations:

$\alpha_{vis} = \alpha_{dif}$

I.

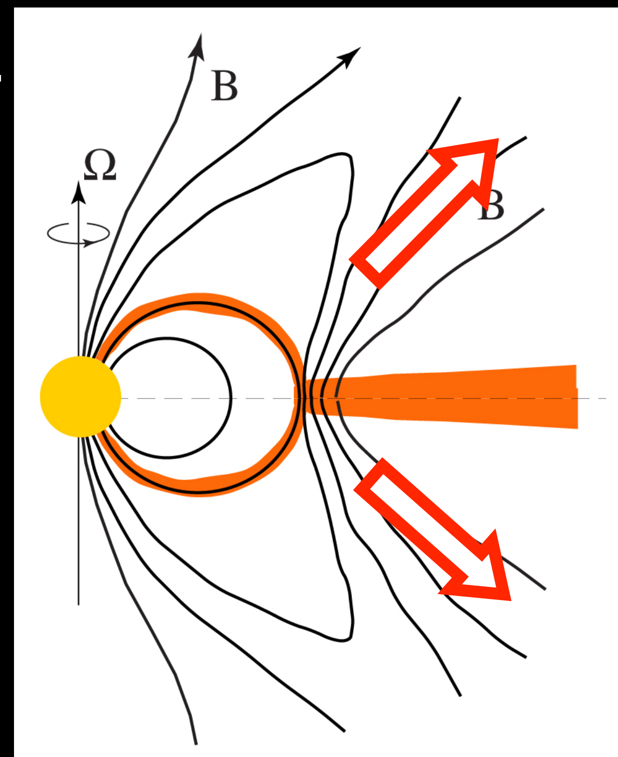


Matter inflows with the same rate as the magnetic field diffuses out

Accretion, no outflows

$\alpha_{vis} >> \alpha_{dif}$

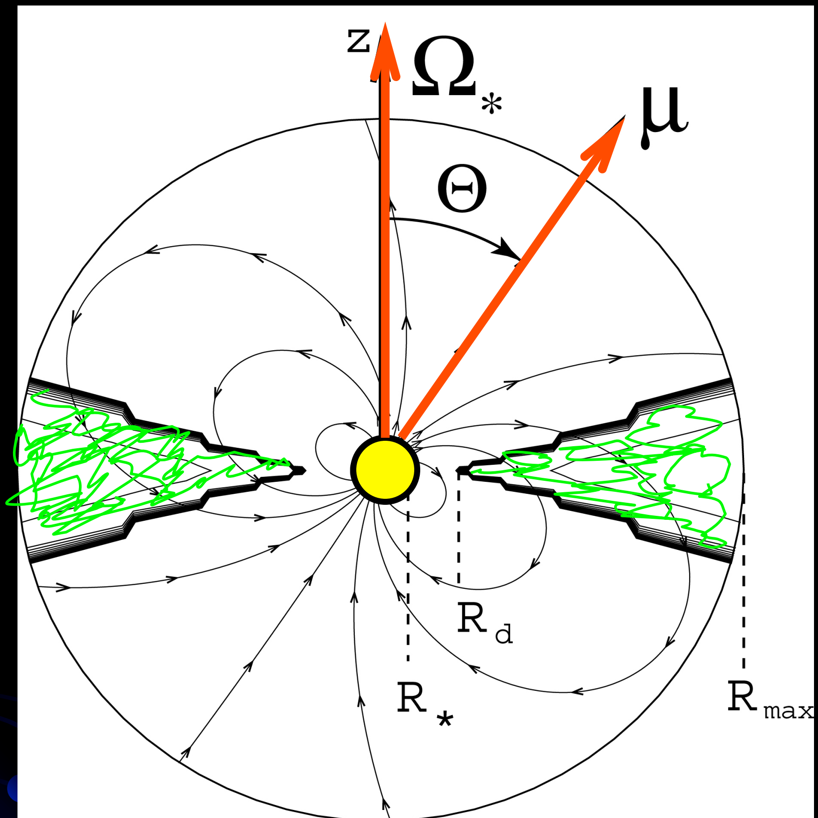
II.



Matter inflows faster than the field diffuses out

Accretion and outflows

Initial and boundary conditions



INITIAL CONDITIONS:

- Dipole or more complex field frozen to the star, inclined

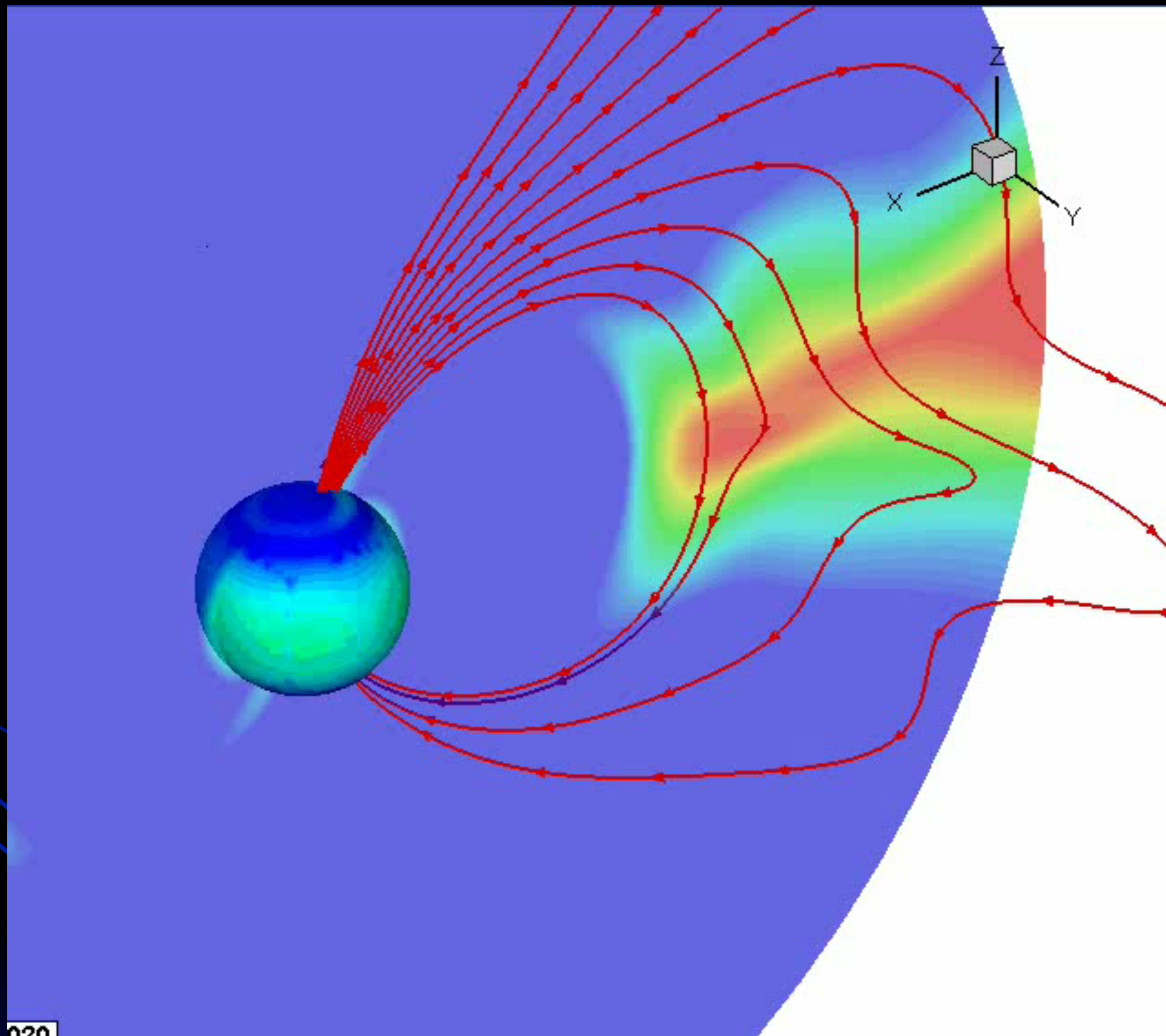
- Aligned rotation

- Disk is cold, corona is hot

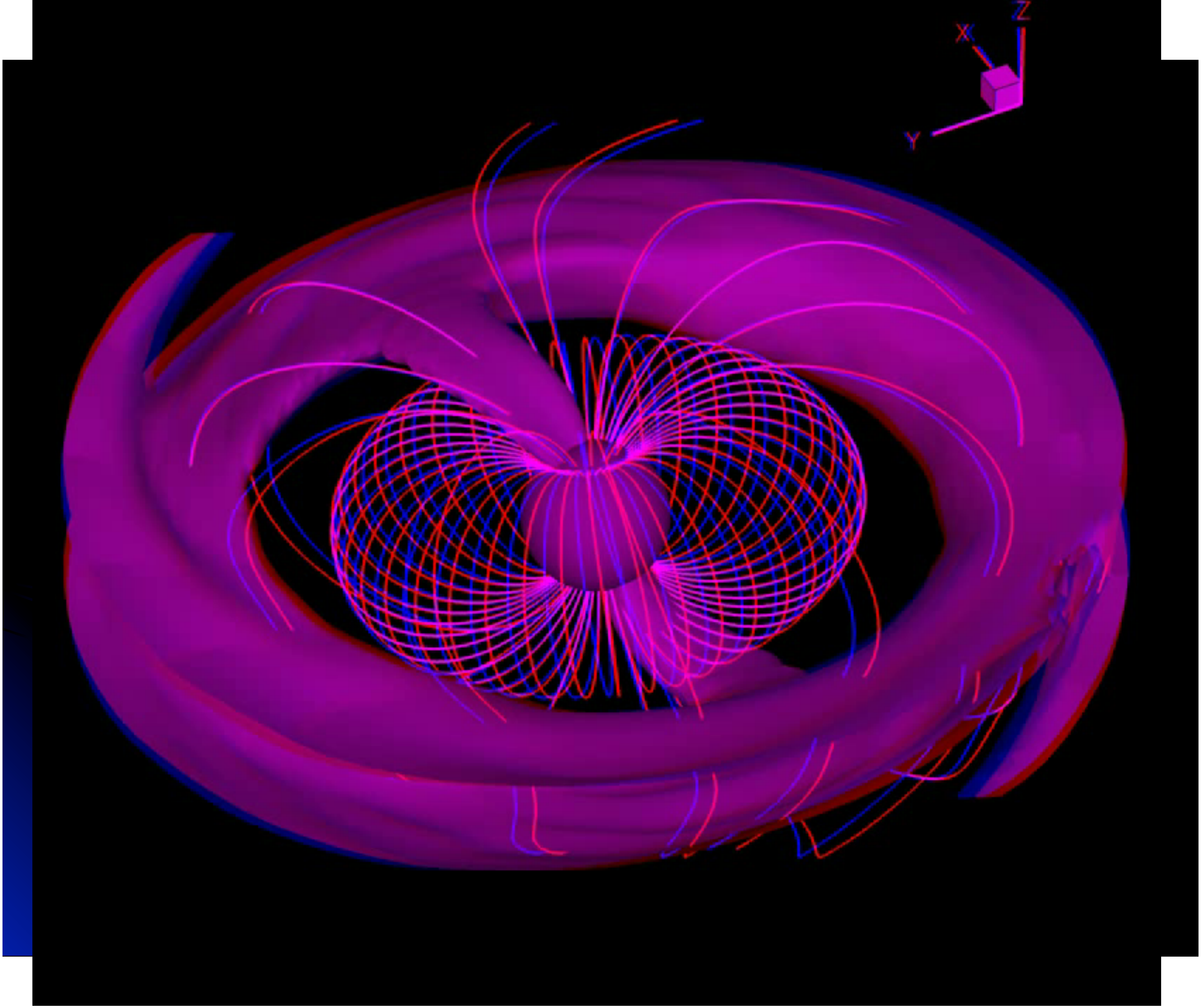
- Initially, disk and corona are in the rotational equilibrium

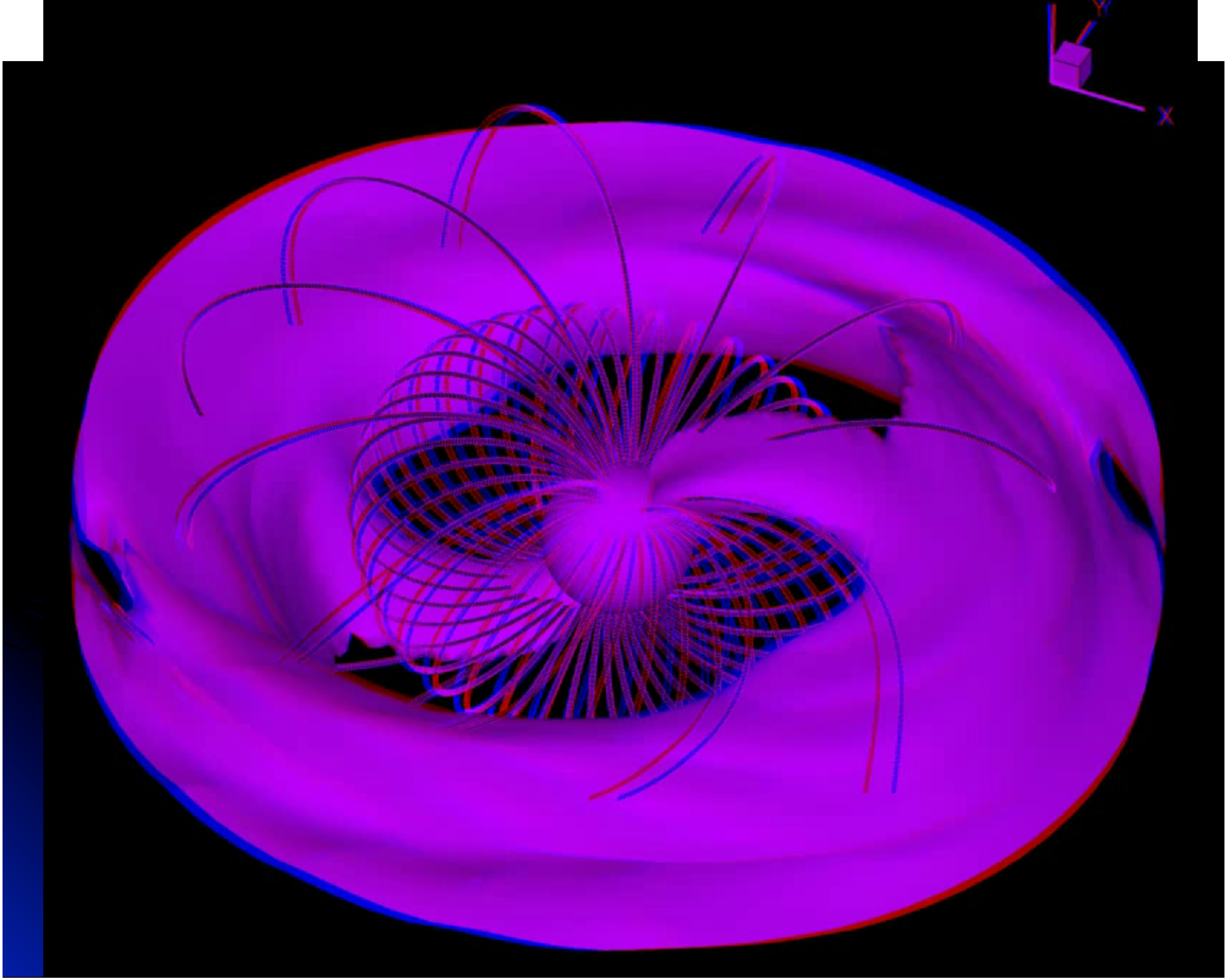
BOUNDARY CONDITIONS:

Free boundary conditions on the star $\delta A/\delta R=0$ for all hydro variables and B_ϕ,
Fixed normal component of the field (frozen-in conditions), also v II B
Free external boundary conditions + non-precipitation

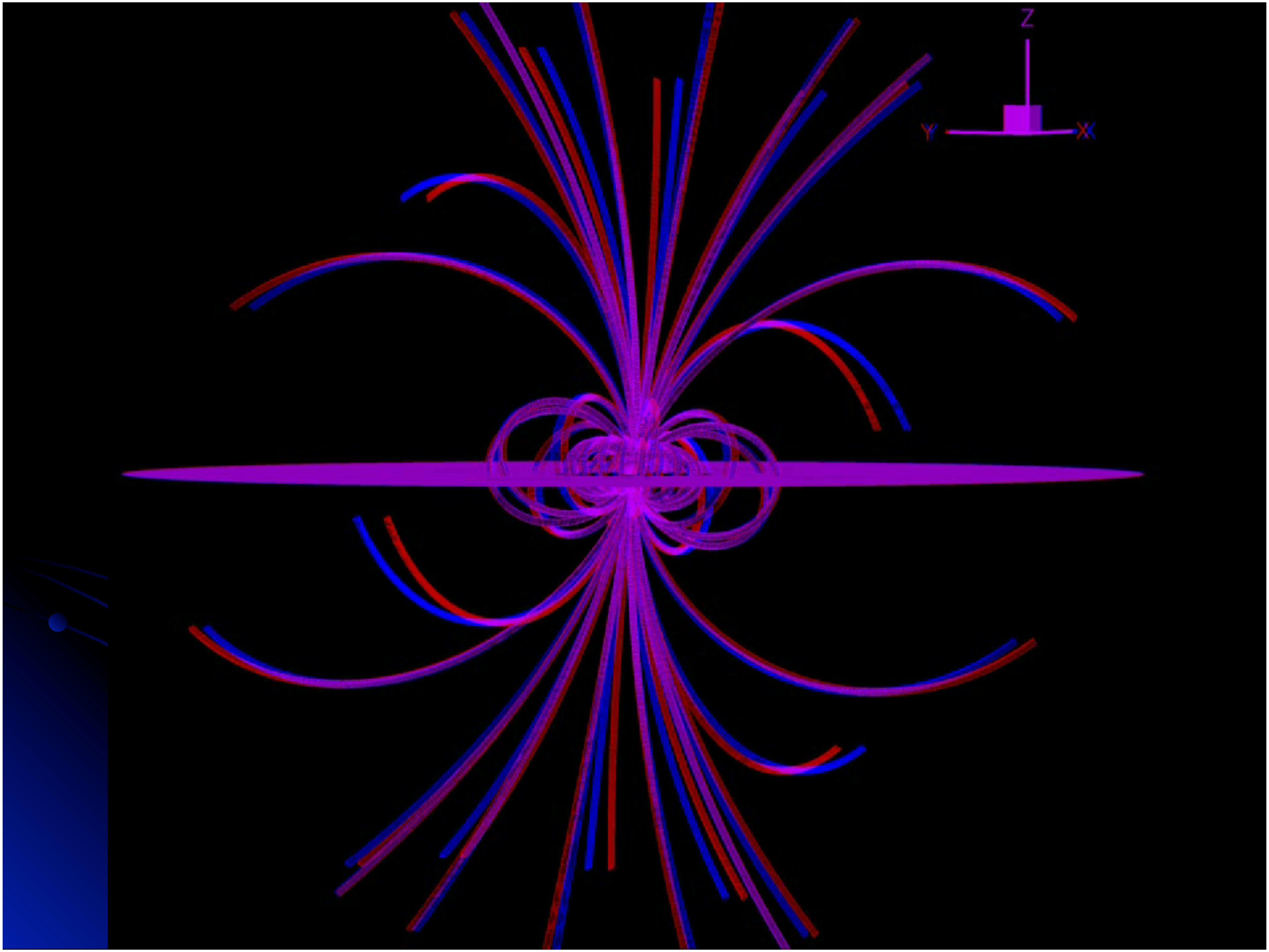


Z
X
Y
020


X
Y
Z

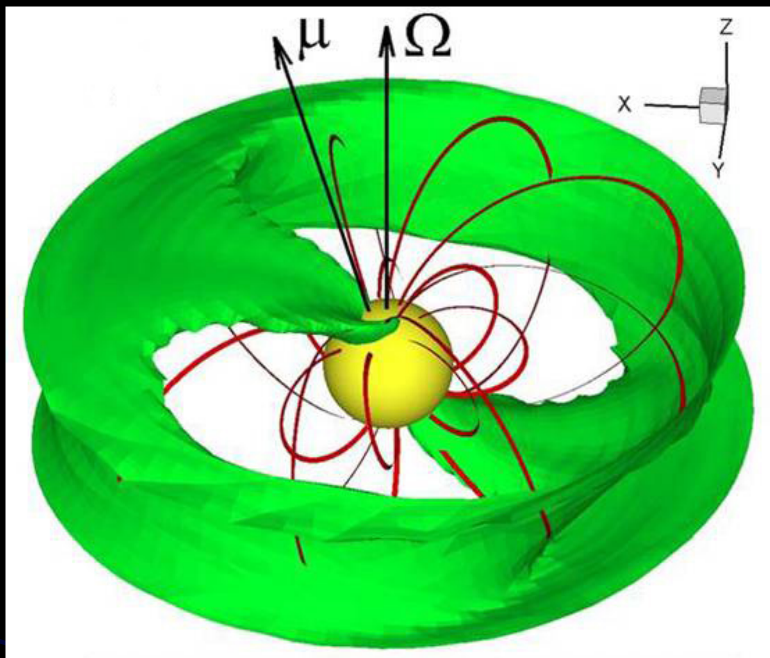


Y
X

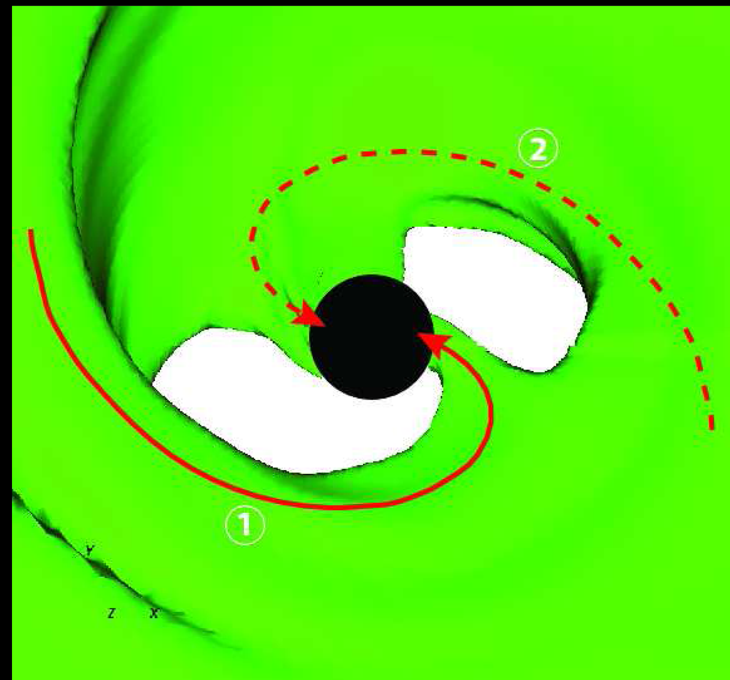

Z
Y
X


Z
X
Y
Ω

Comparisons with accreting tilted BHs



Matter flow around tilted rotating magnetized star *Romanova et al. 2003*

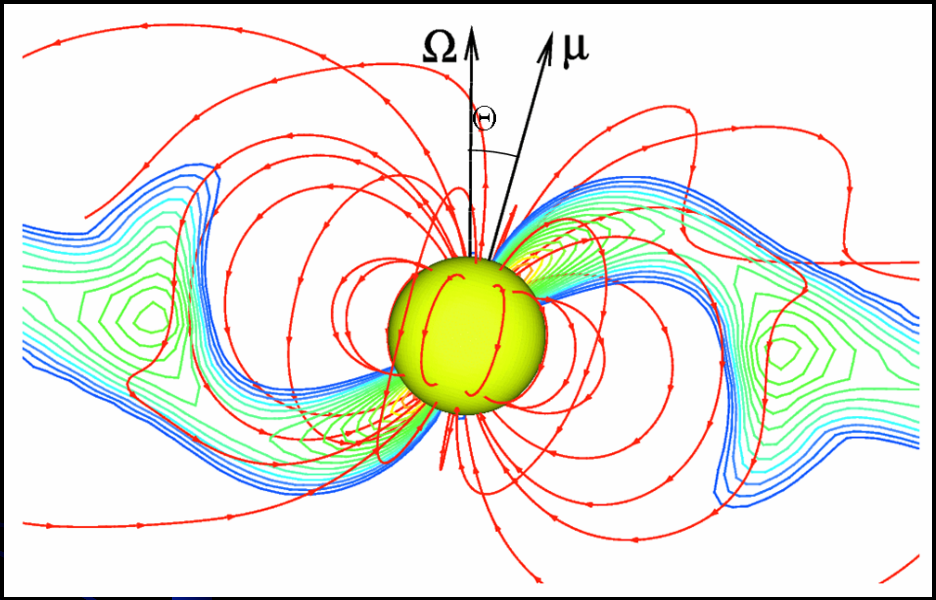


Matter flow around tilted rotating BH *Fragile et al. 2007*

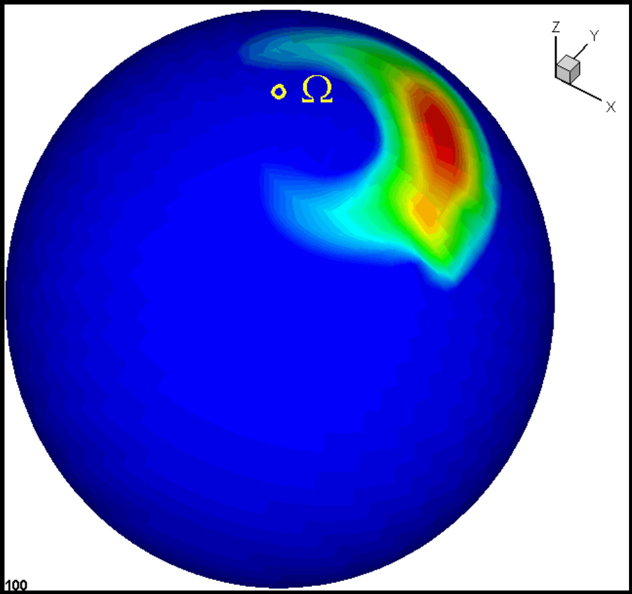
- In both cases matter chooses energetically favorable path
- Matter has tendency to flow in magnetic/BH equator (disk is warped)

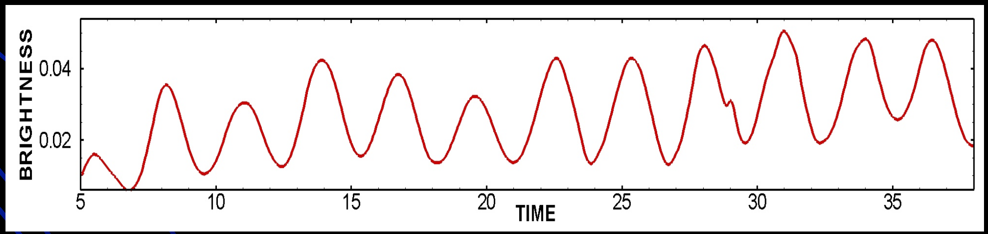
Funnel Streams, Hot Spots - ν_{star}

Funnel streams



Hot Spot

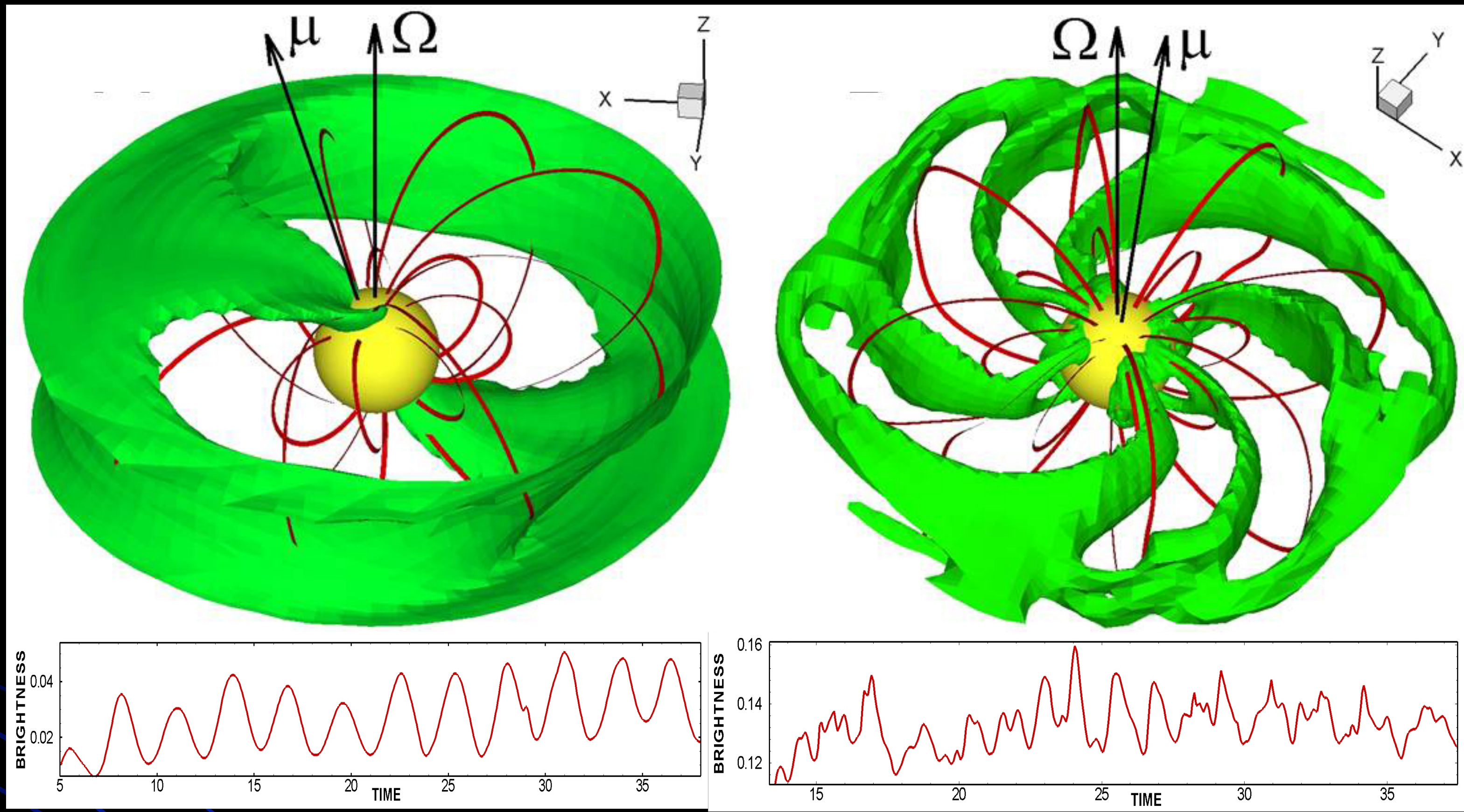




Light Curve

Romanova, Ustyugova, Koldoba, Lovelace 2004

Stable or unstable regimes:

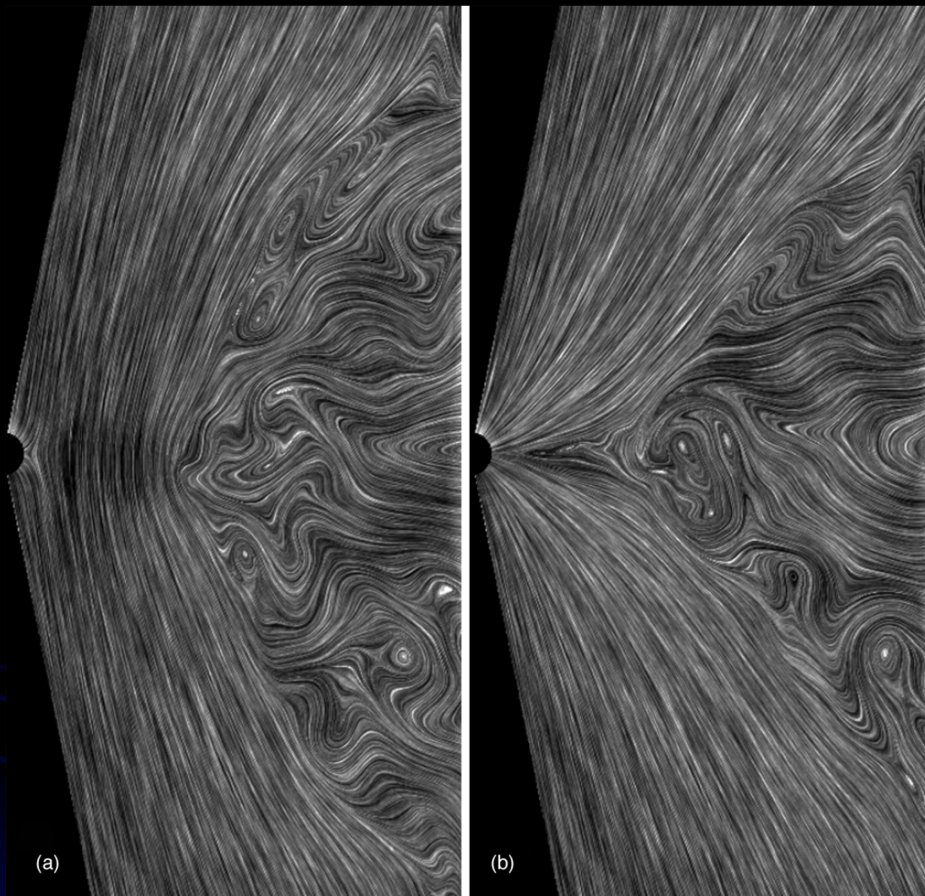


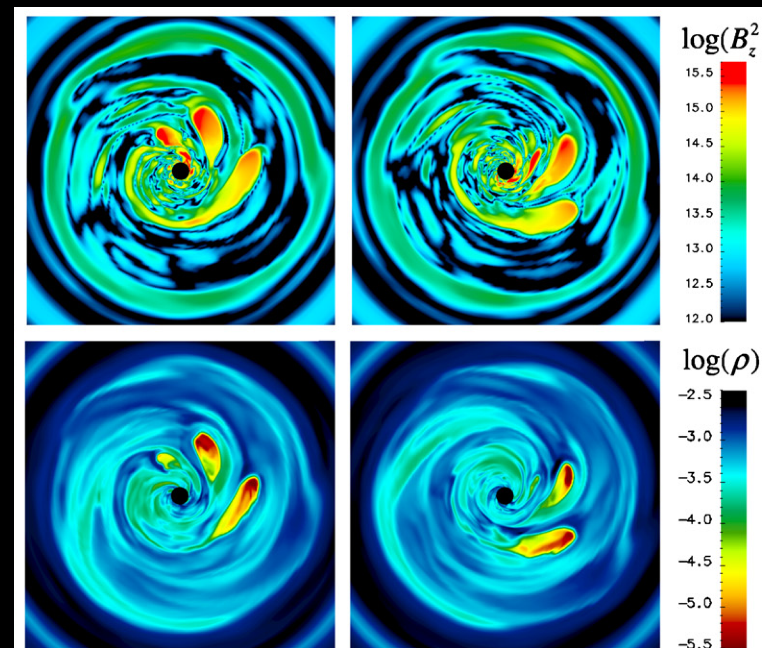
- Chaotic light-curve
- QPO oscillations with the frequency of the inner disk

Predicted: *Arons & Lea 1976; Lamb 1976*

Global simulations: *Kulkarni & Romanova 2008; Romanova, Kulkarni, Lovelace 2008*

It seems that RT (interchange) instability near BH

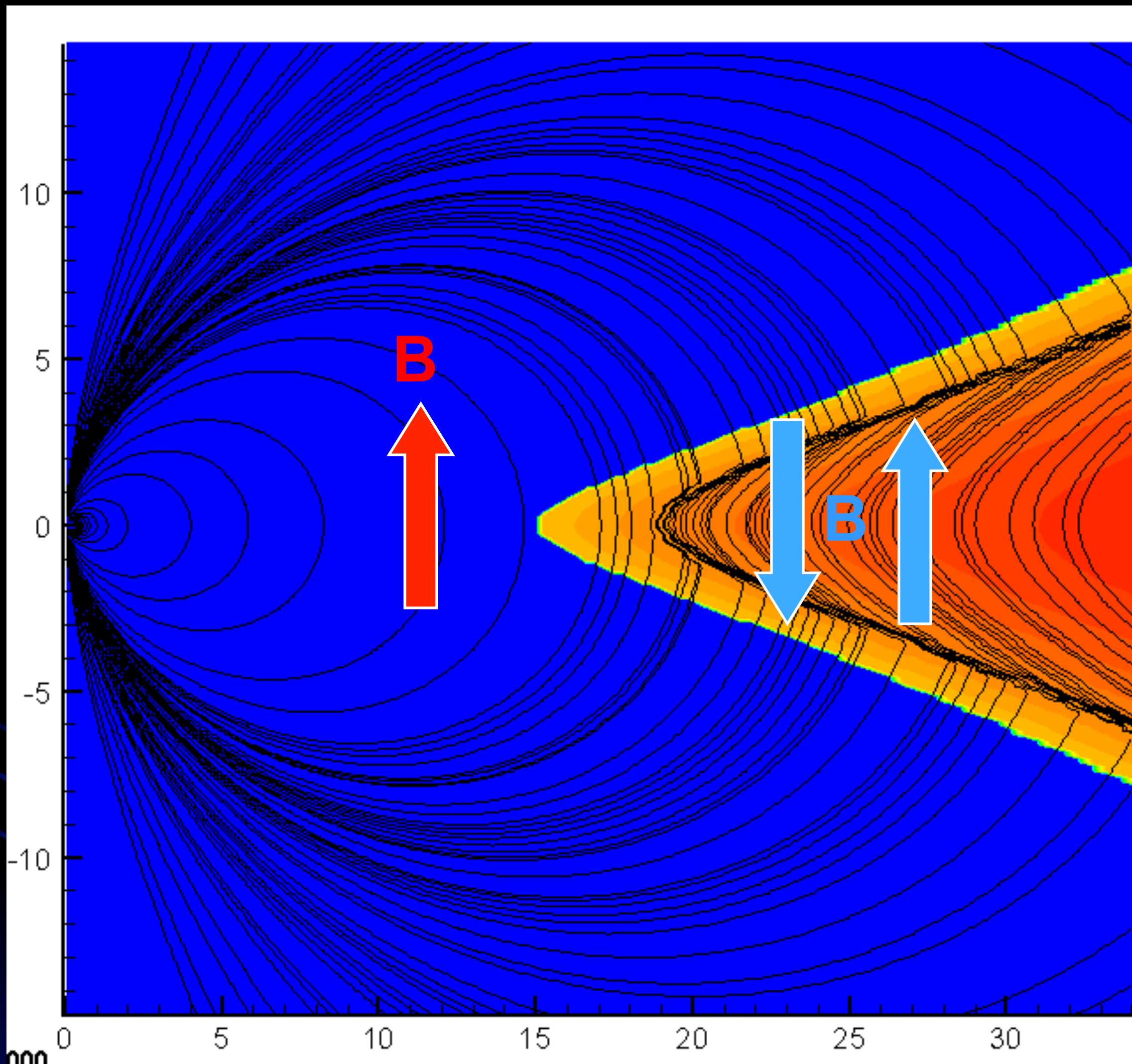




Punsly, Igumenshchev, Hirose 2009

Interchange instability in accretion disks*: Lovelace et al. 1992; Spruit & Taam 1990*

MRI-driven Accretion onto magnetized star (2.5D)

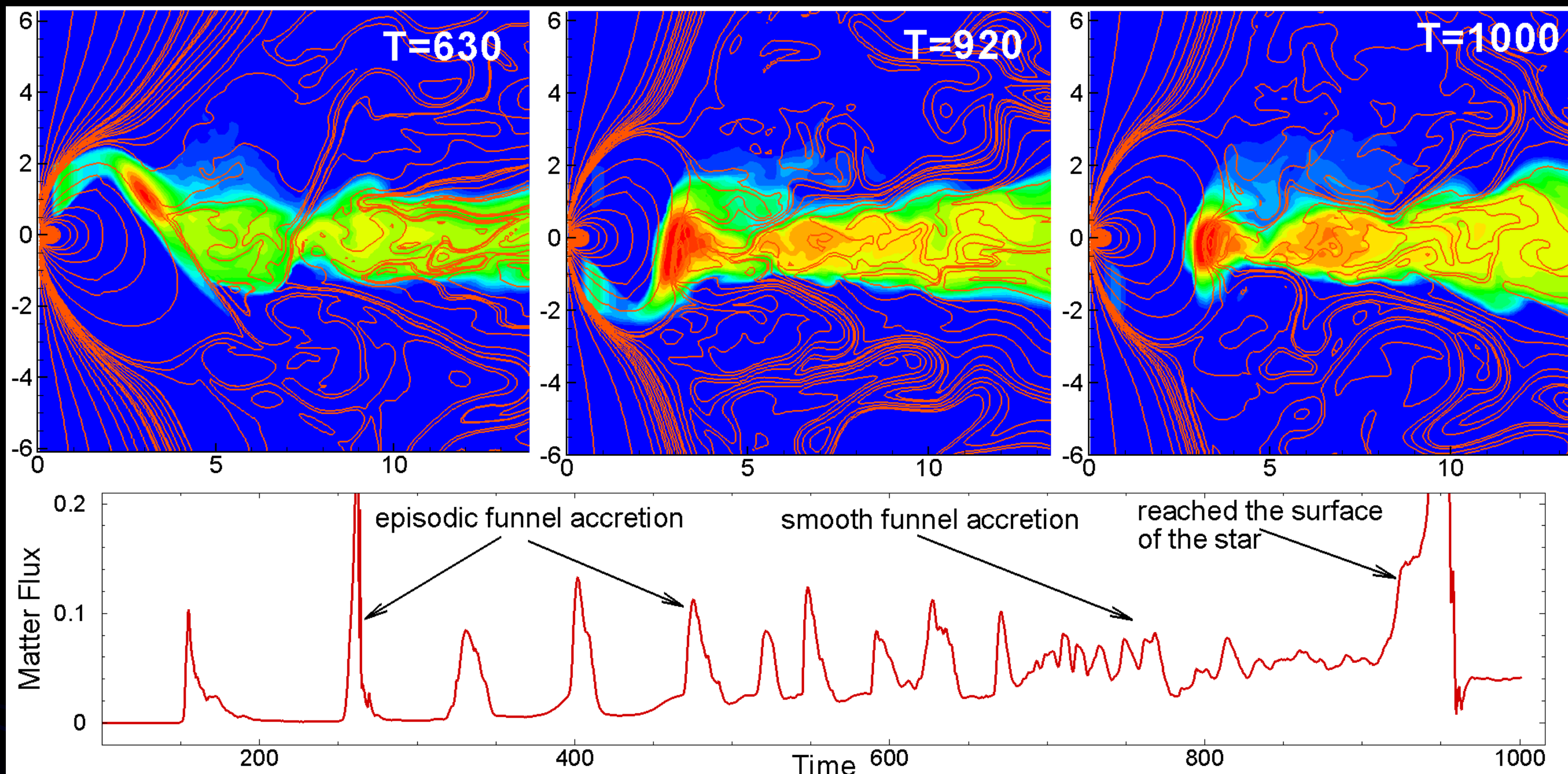


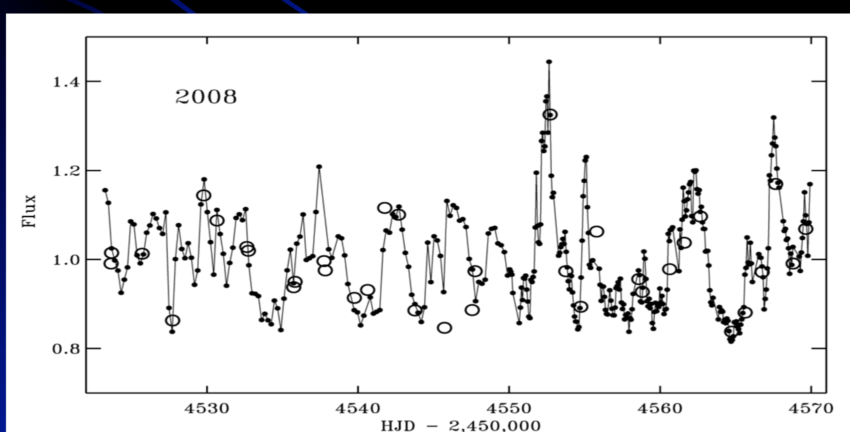
- $R_{cor}=6$
- T=15 rotations at r=30
- Different configurations of the seed poloidal field in the disk:
  - Parallel field
  - Parallel with cut
  - Different orientation
  - Loops

Romanova et al. (in prep.)

MRI-driven accretion: *Balbus & Hawley 1991, 1998; Hawley & Balbus 1999; Stone, Howley, Gammie, Balbus 1995; Hawley & Krolik 2001, and more*

MRI-driven Accretion onto a magnetized star (2.5D)



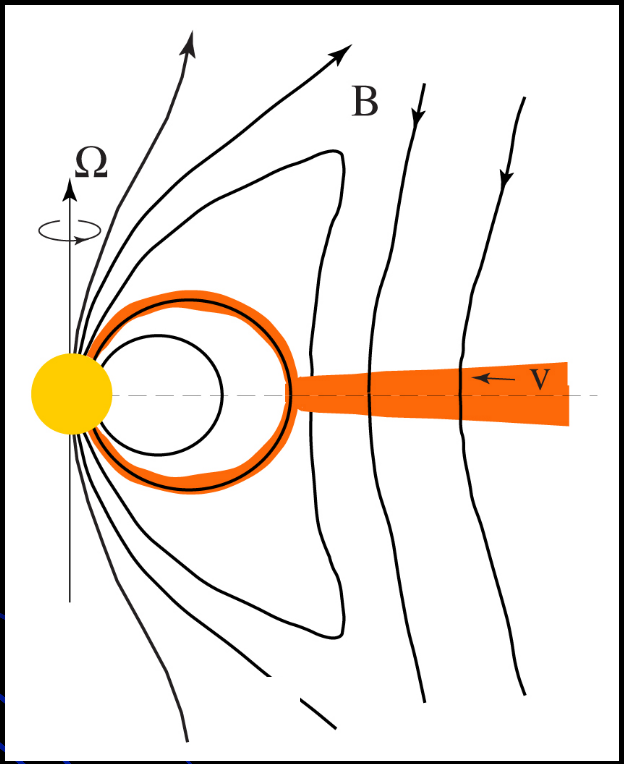


- MRI is not suppressed by B-field
- Funnel accretion from one side or another
- Or matter is accumulated
- High flux variation in simulations

Two important situations:

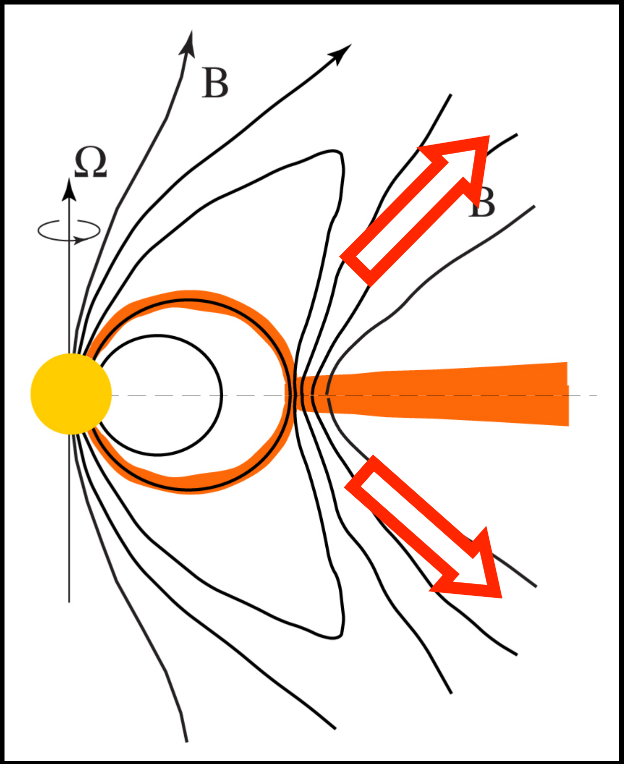
$\alpha_{vis} = \alpha_{dif}$

I.



$\alpha_{vis} >> \alpha_{dif}$

II.



Matter inflows with the same rate as the magnetic field diffuses out

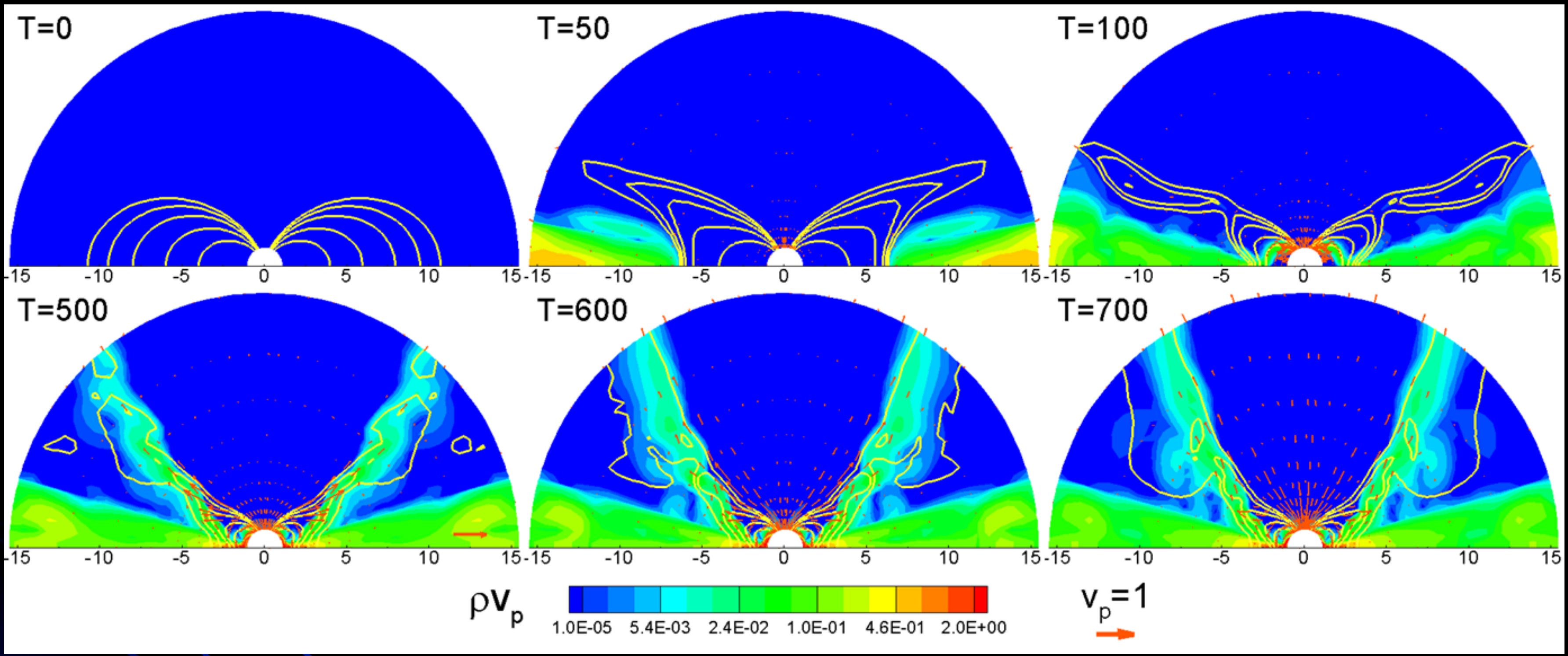
Accretion, no outflows

Matter inflows faster than the field diffuses out

Accretion and outflows

Conical Winds from Slowly Rotating Stars

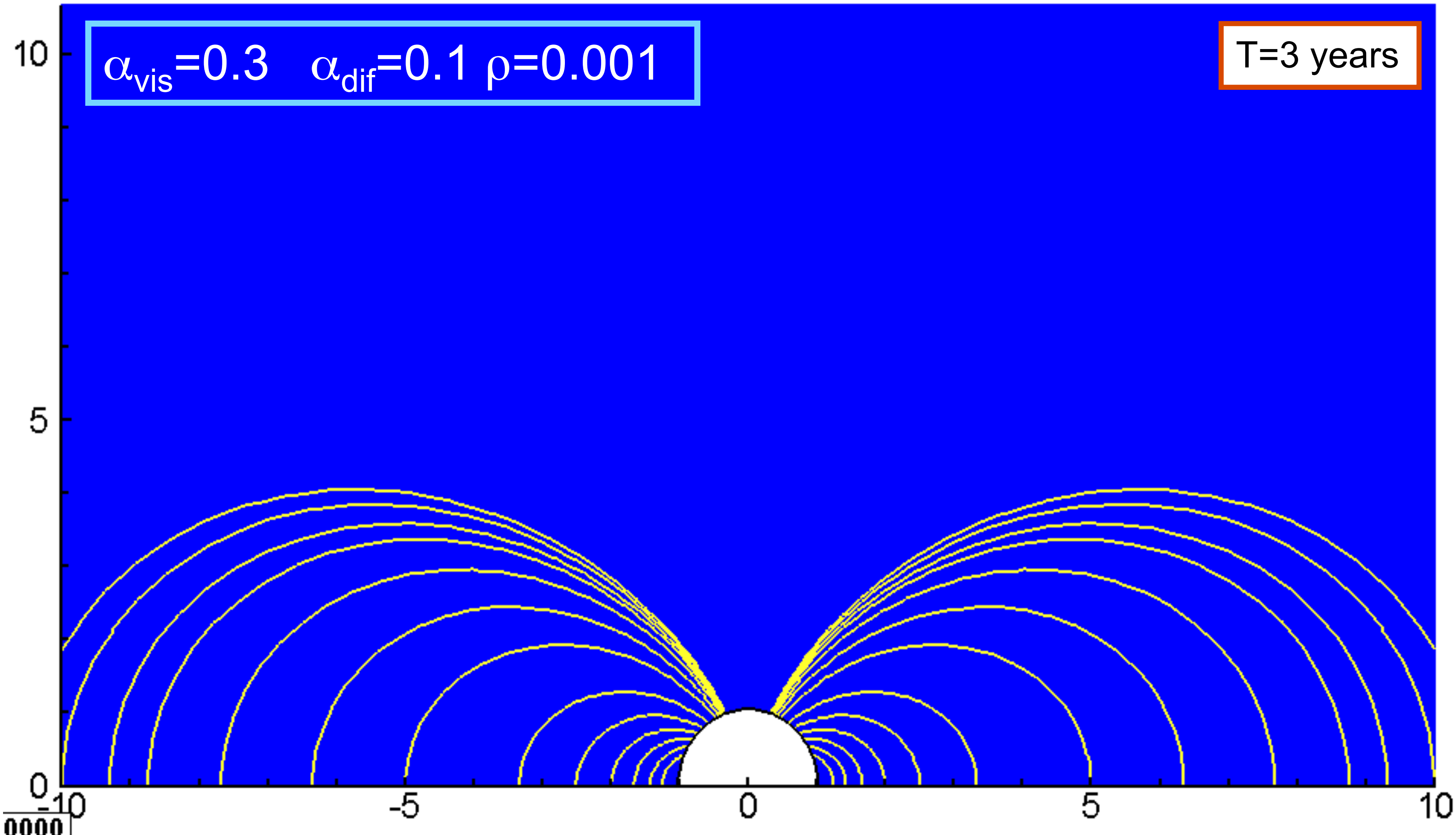
$\alpha_{vis}=0.3 \quad \alpha_{dif}=0.1$



Matter flux, velocity, field lines

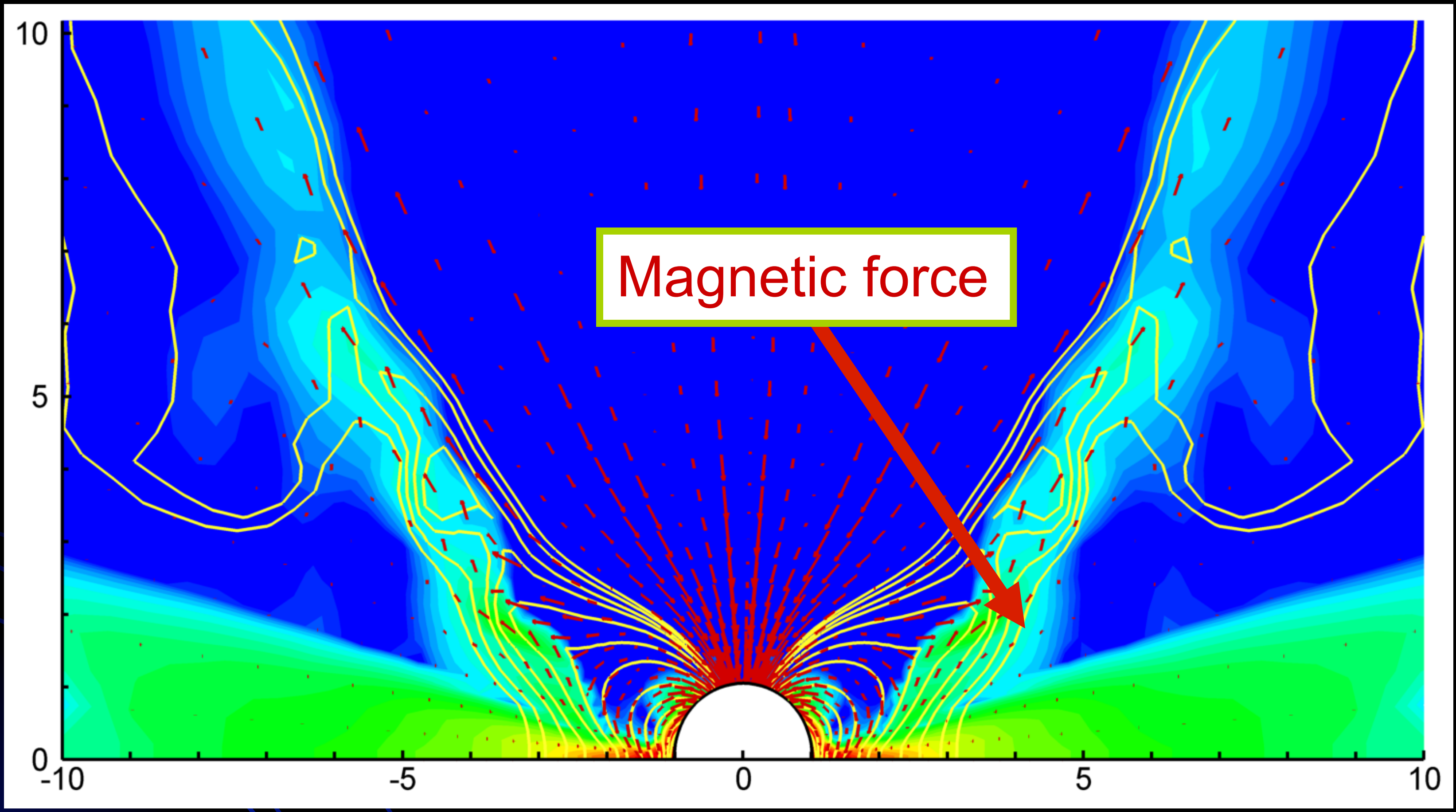
- Inflation of the field lines (*Lovelace et al. 1995; Uzdensky et al. 2002*)
- Compression of the magnetosphere (*Shu et al. 1994*)

Conical Winds from Slowly Rotating Stars



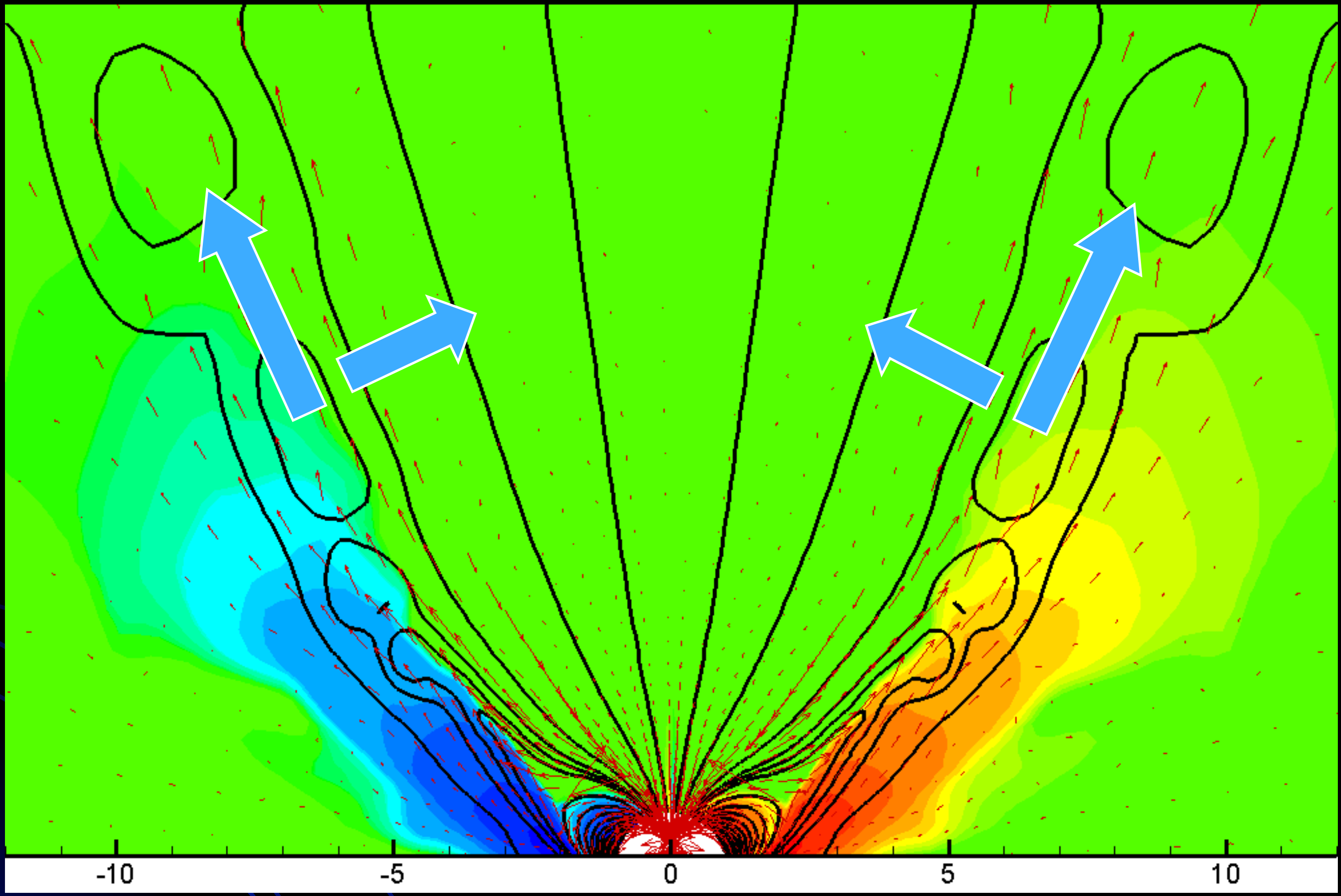
Matter flux, velocity, field lines

$V = V_{Keplerian}$



α_{vis}=0.3, α_{dif}=0.1

Magnetic force and poloidal current: $J_p = rB_\phi$

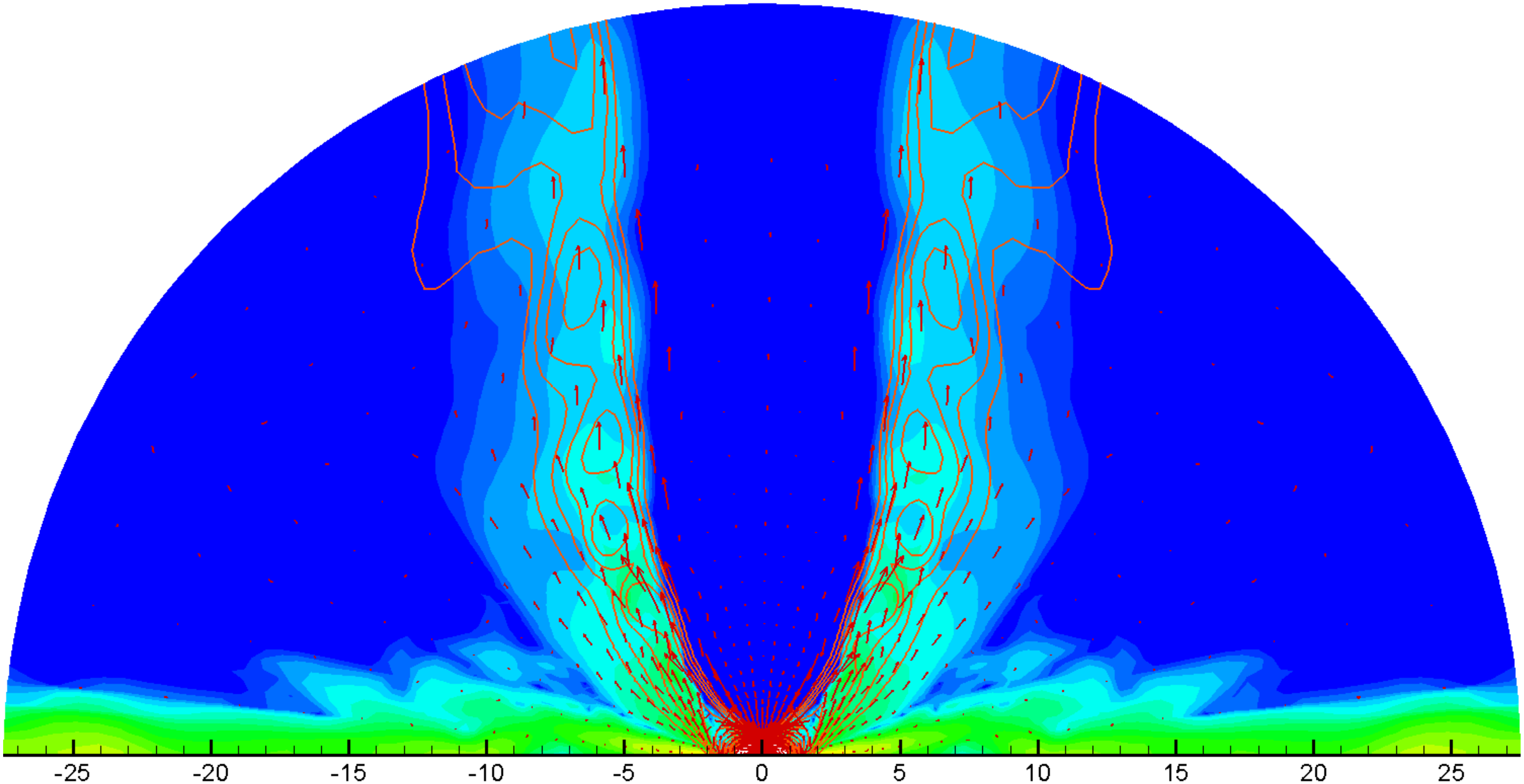


Driving force is the magnetic force: $F_m = k \text{ grad } (rB_\phi)^2$:

- Acceleration
- Collimation

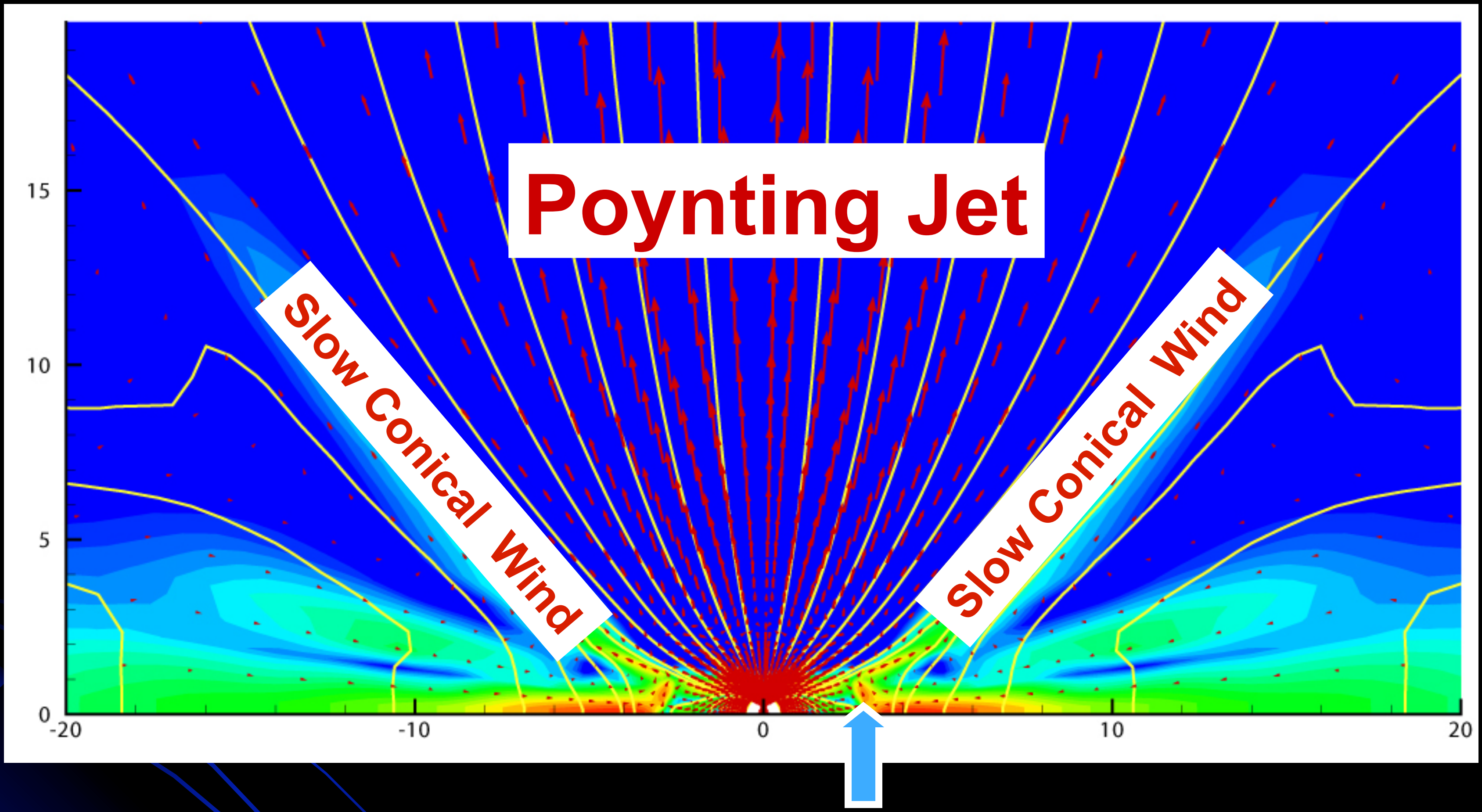
Lower-density corona, larger region

ρ_{cor}=0.0003 ρ_{disk}



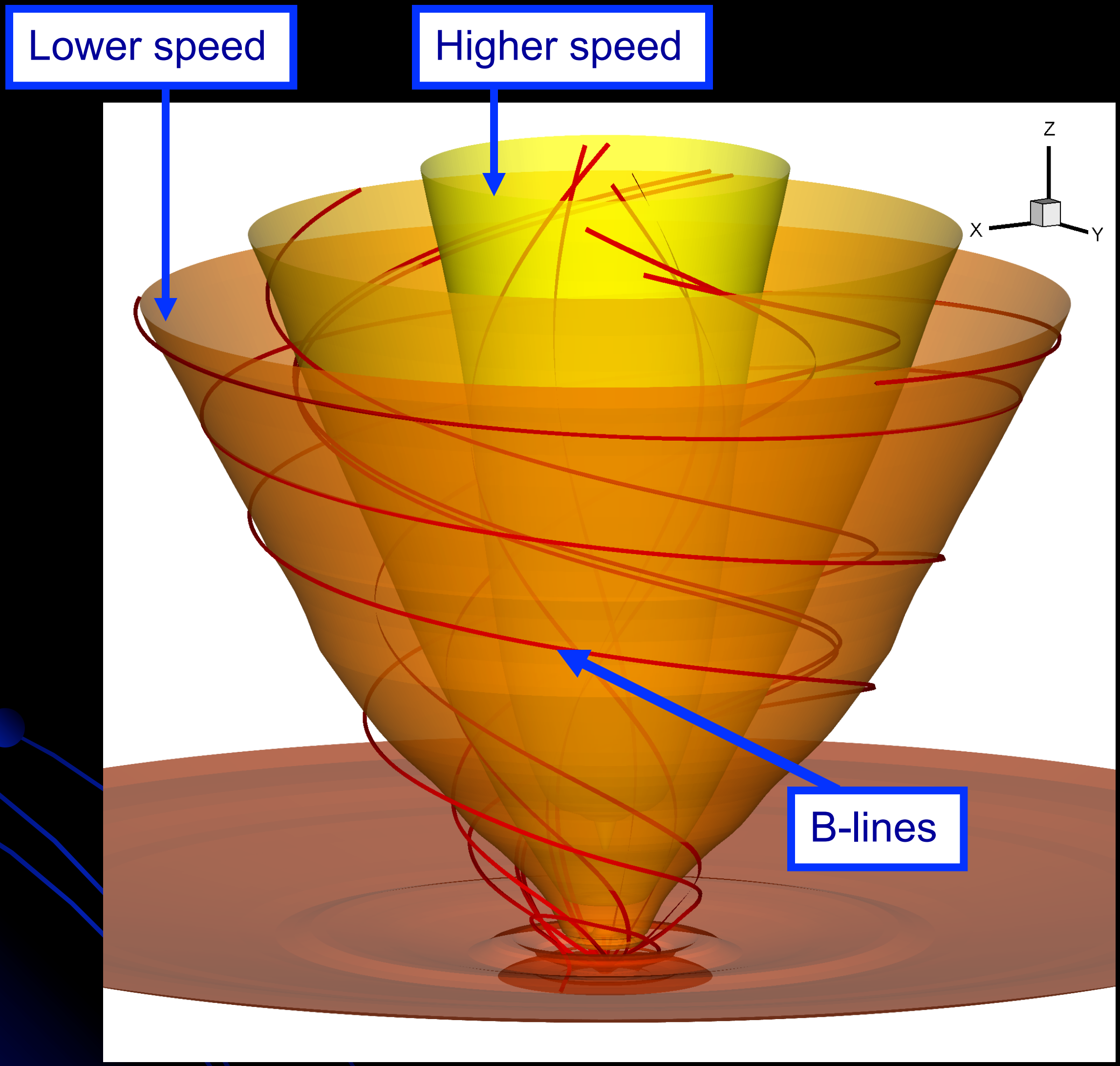
Stronger collimation by the magnetic hoop-stress

Rapidly rotating stars: Propeller regime

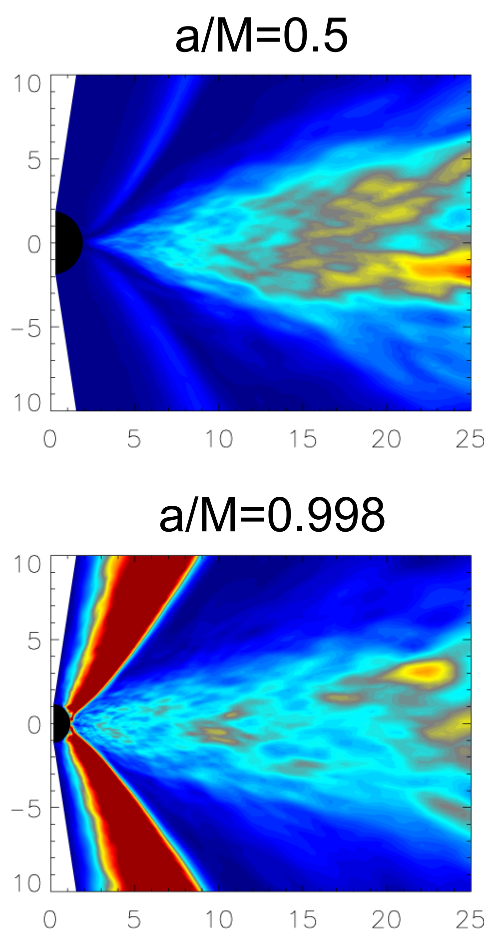


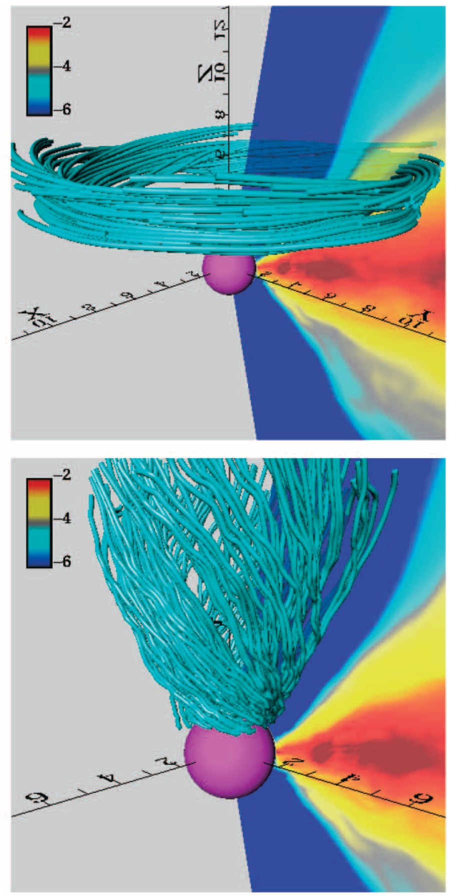
- Magnetosphere rotates faster than the inner disk
- Two-component outflow forms
- Conical winds carry most of matter outwards
- Poynting jet carries energy and ang. momentum

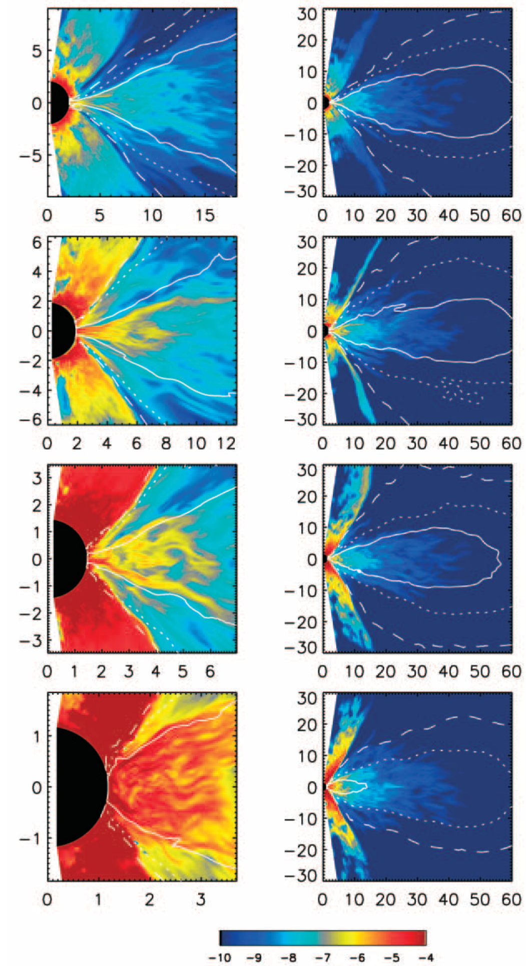
3D rendering



GR simulations of outflows from BHs





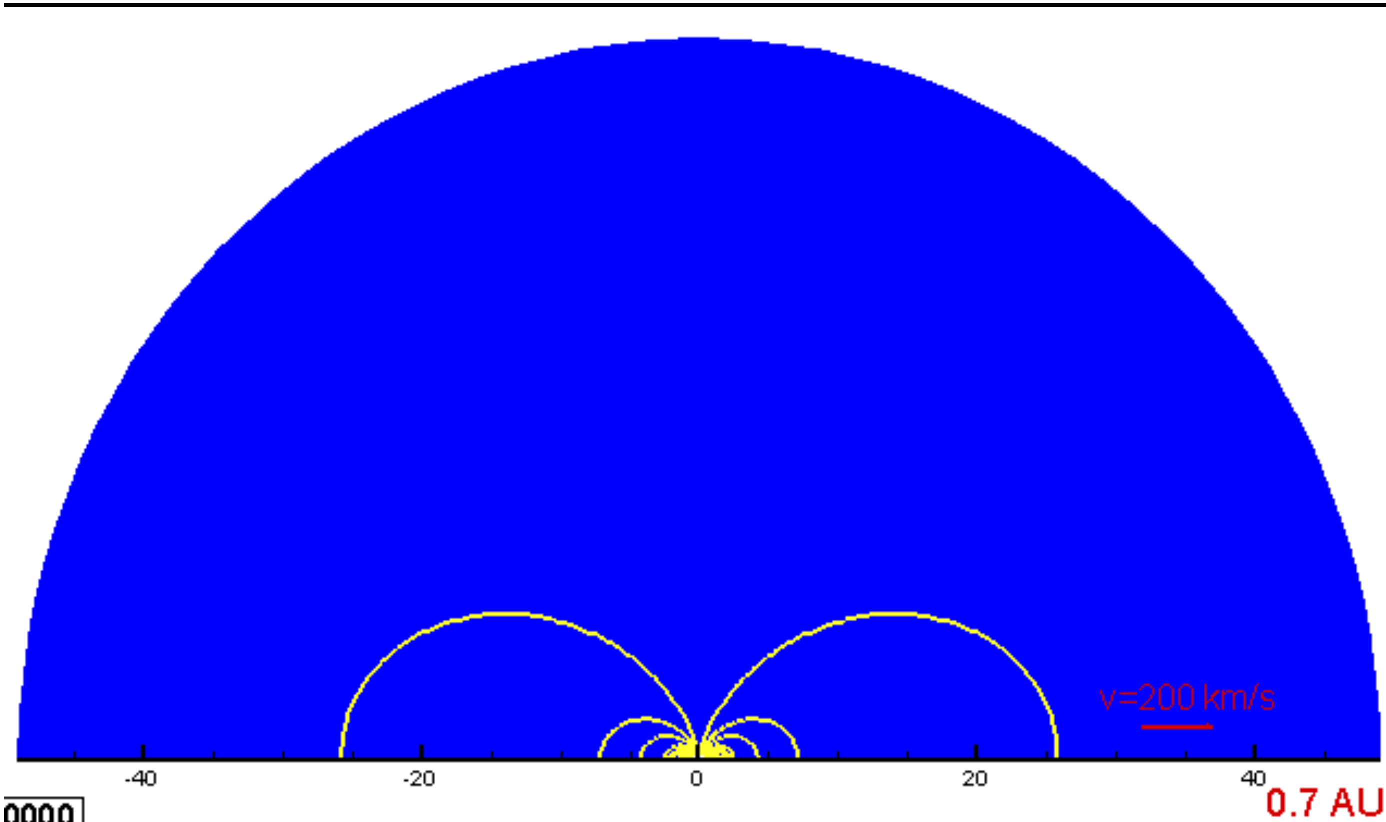


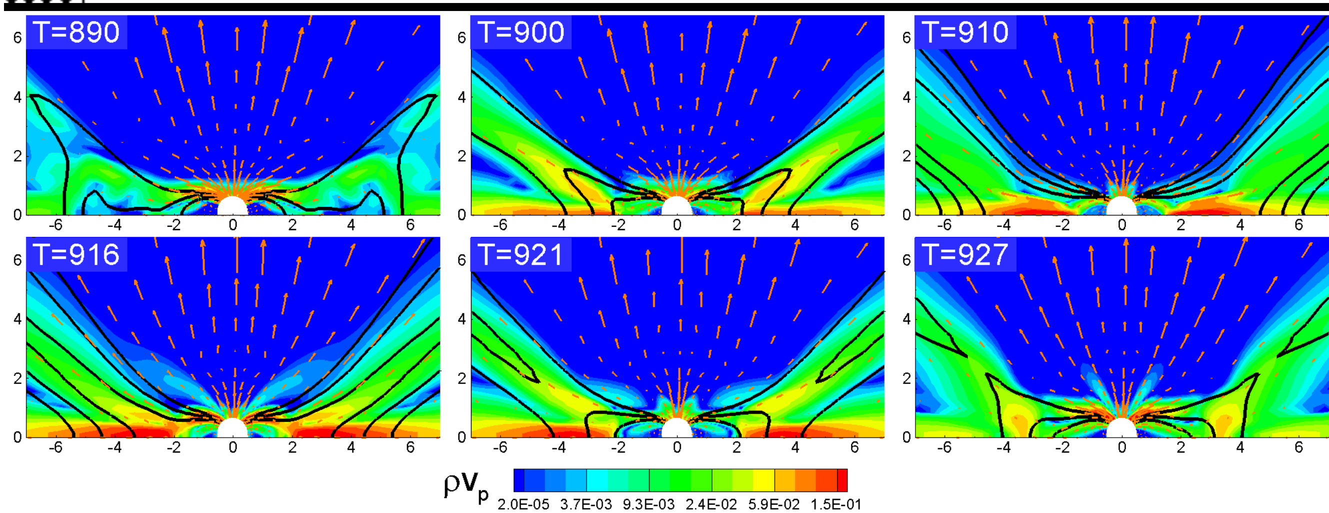
Poynting flux jet increases with a/M

Poloidal current increases with a/M

Krolik, Hawley, Hirose 2004

Hirose, Krolik, De Villiers, Hawley 2004





Simulations:
7 years

Major outbursts:
2 months

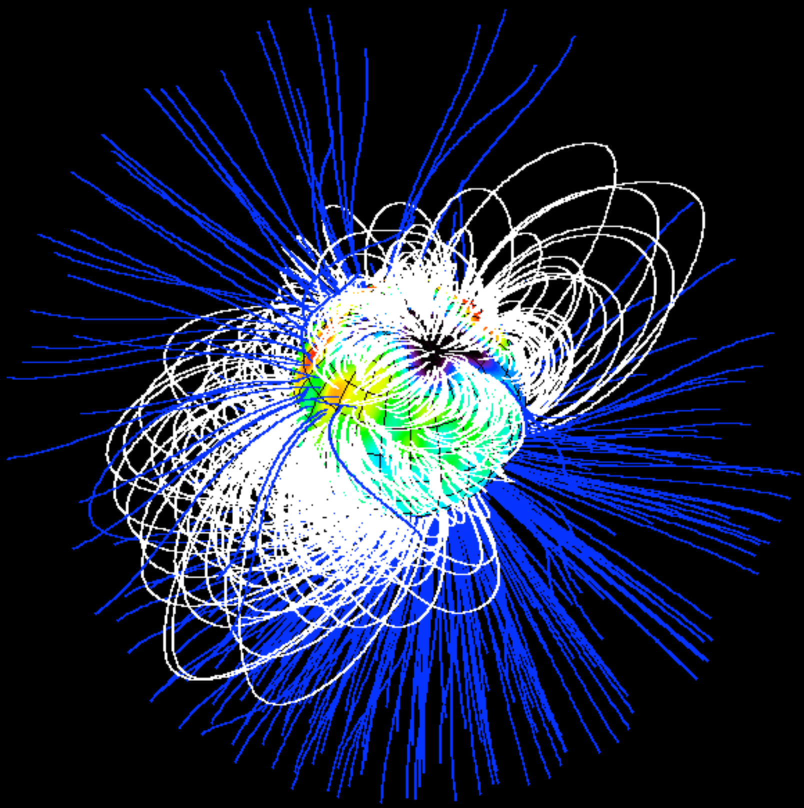
HST

Observations:

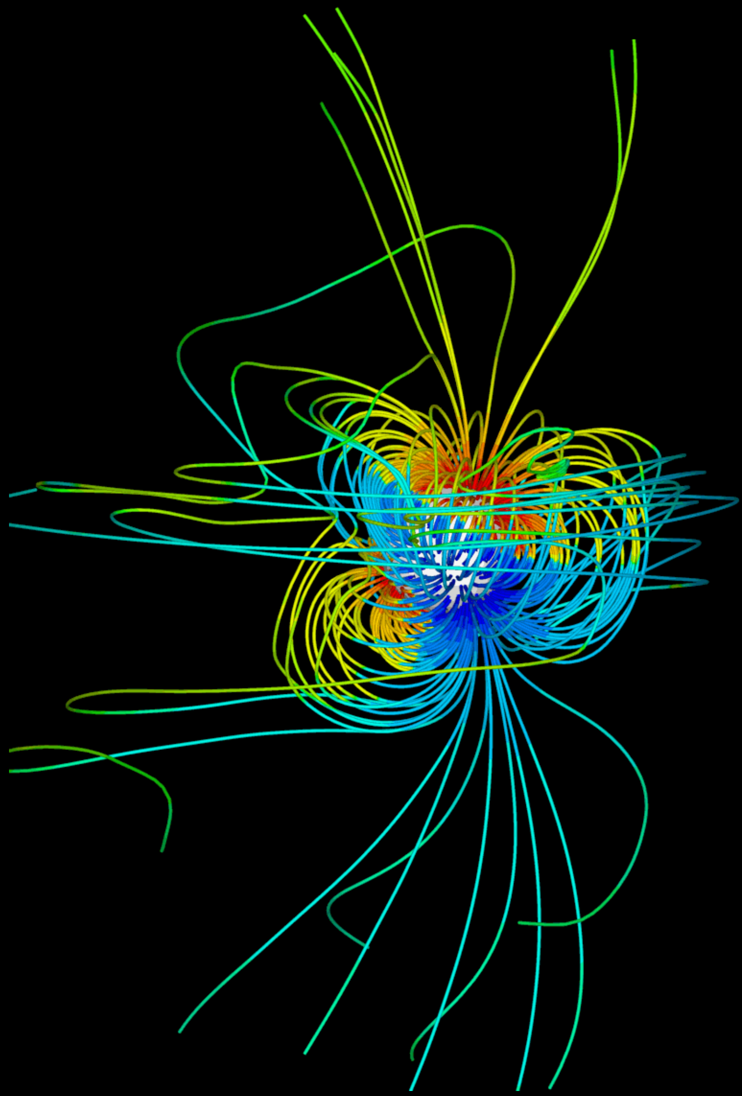
HH30

Cycle of inflation

Stars with Complex Magnetic Field



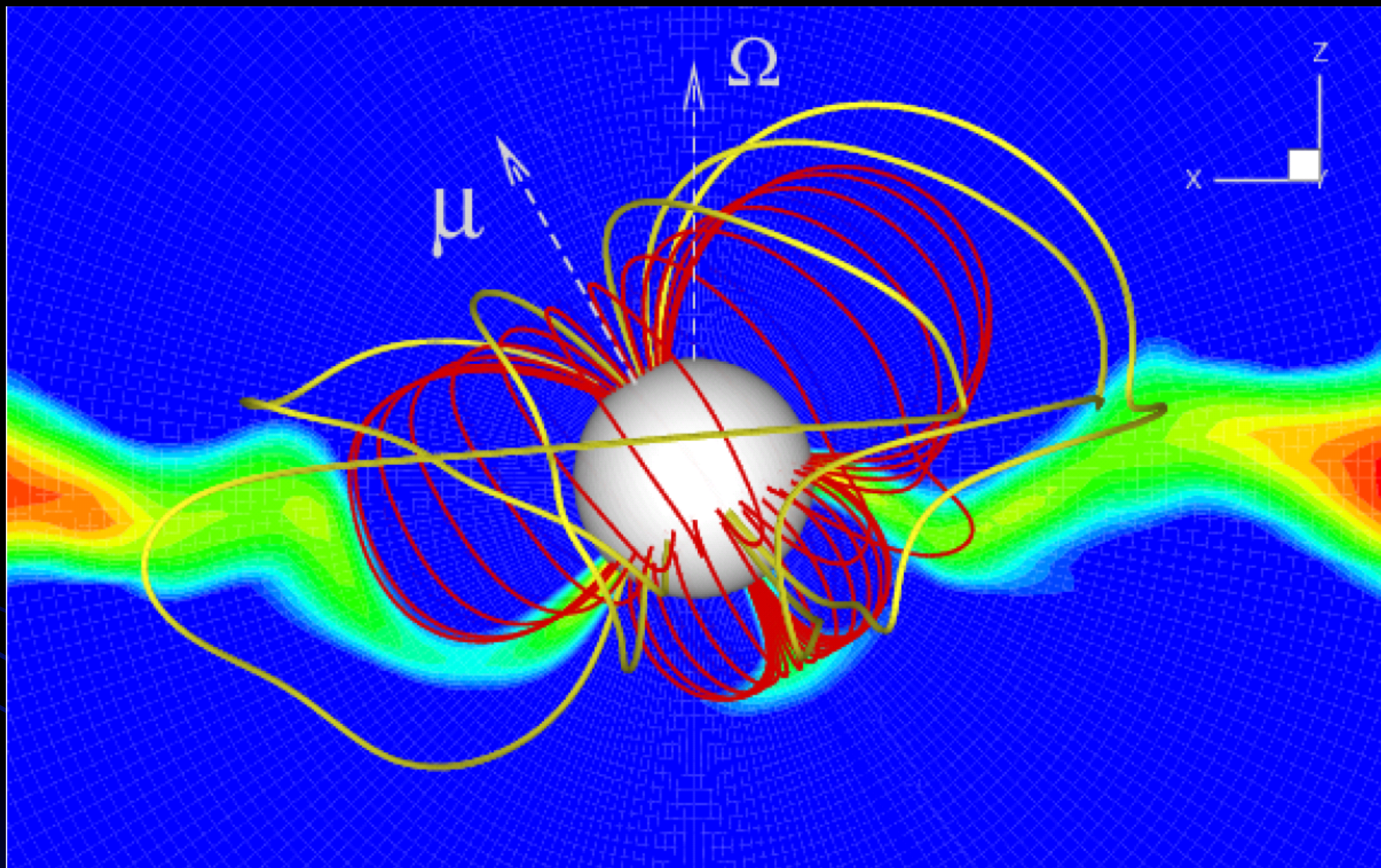
Extrapolated Magnetosphere of SU Auriga (G2 CTTS), (Donati, J. –F. et al., 2007)



3D model: dipole + quadrupole

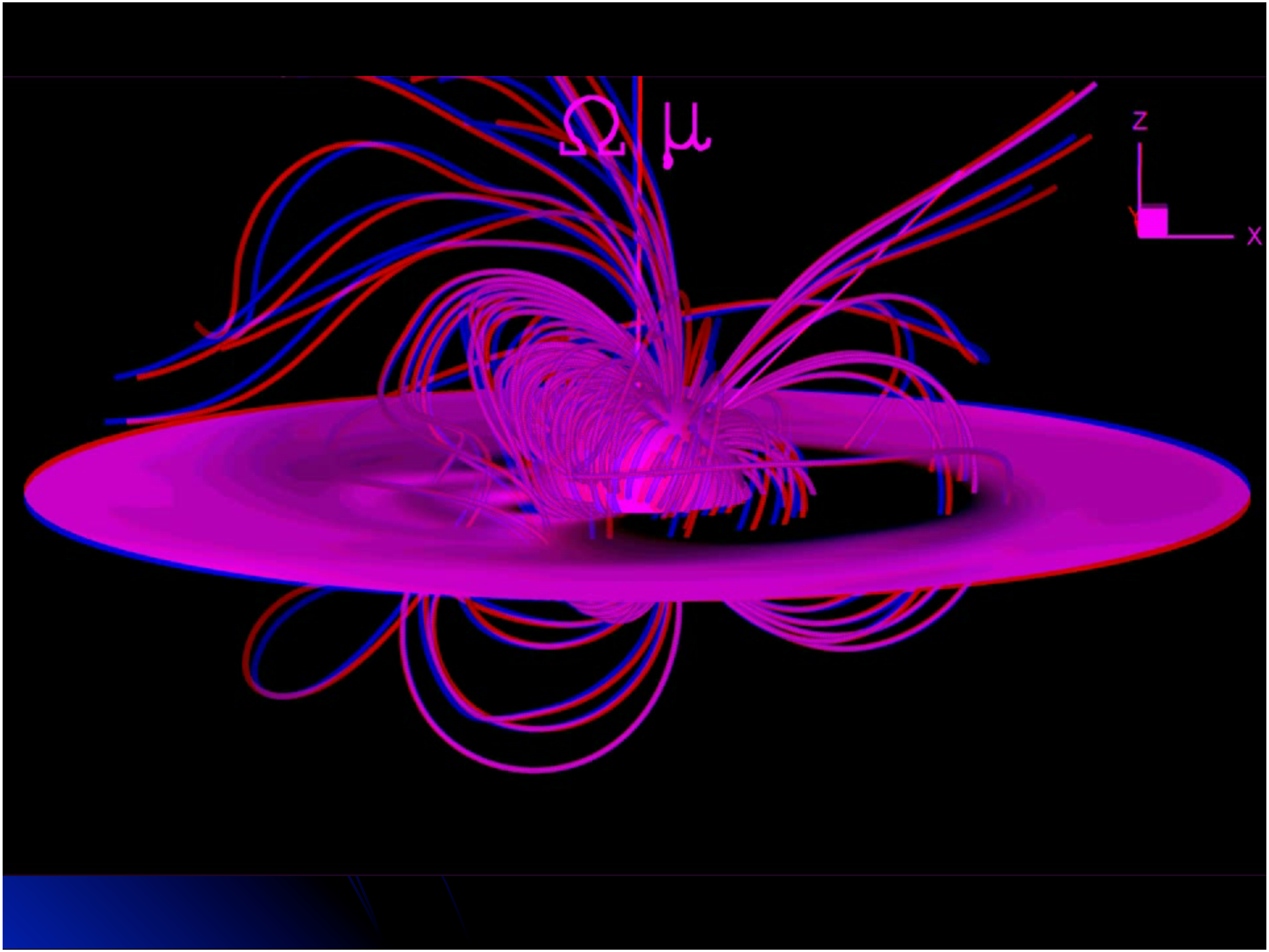
Long, Romanova & Lovelace 2008

Accretion to stars with non-dipole B

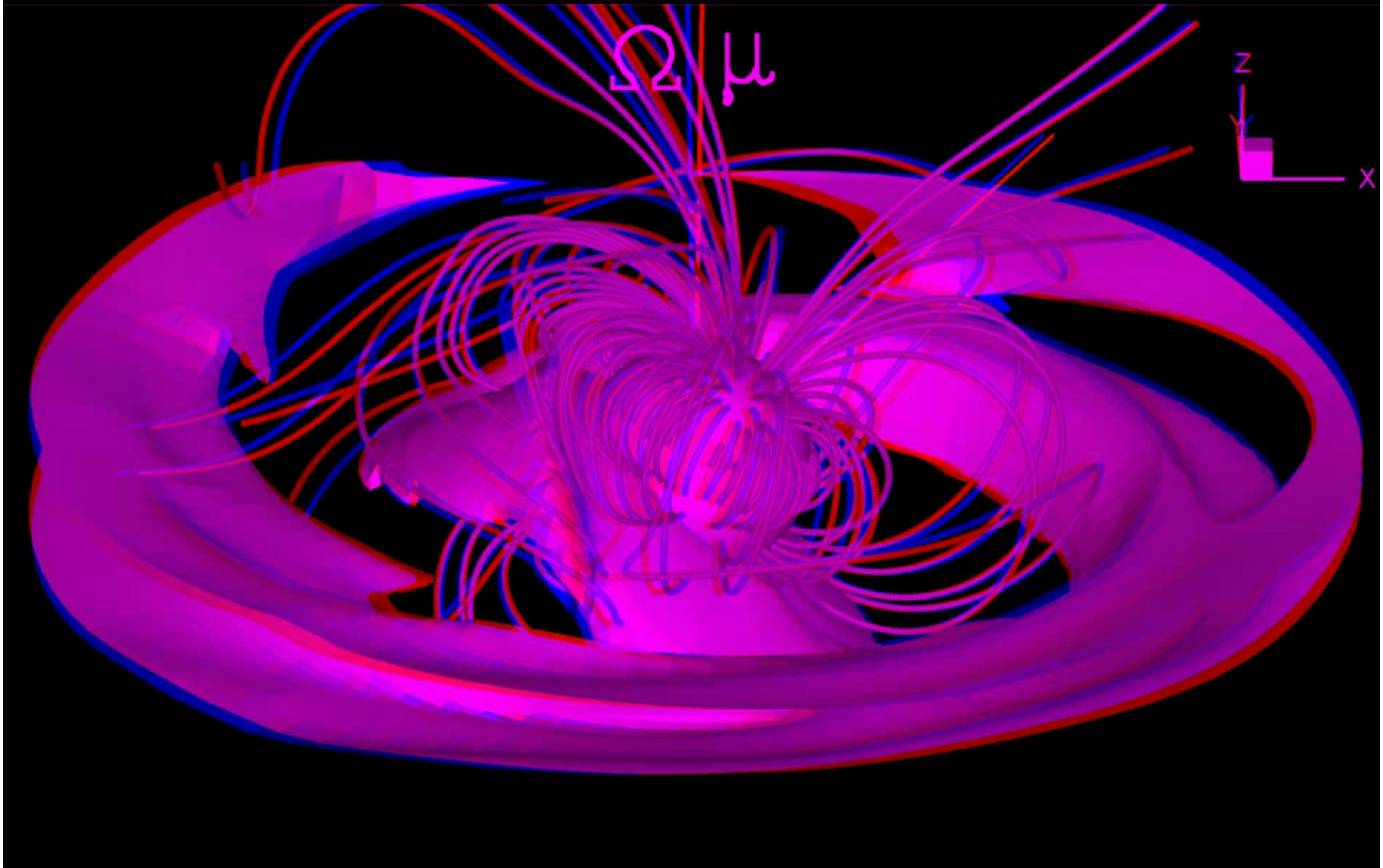


Combination of aligned dipole and quadrupole fields

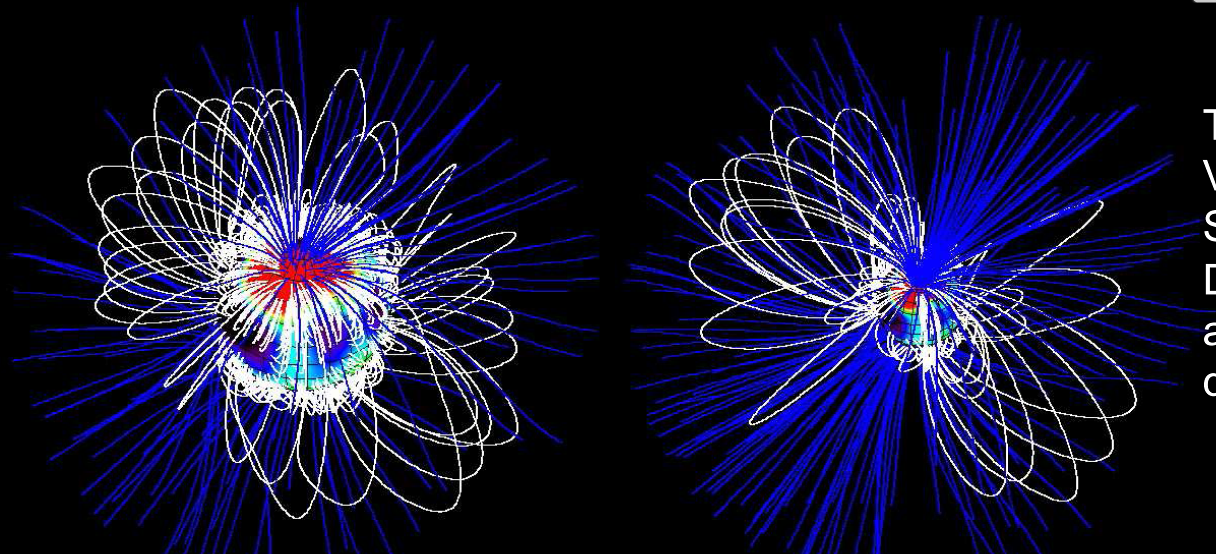
Long, Romanova, Lovelace 2007



Ω
μ
z
x

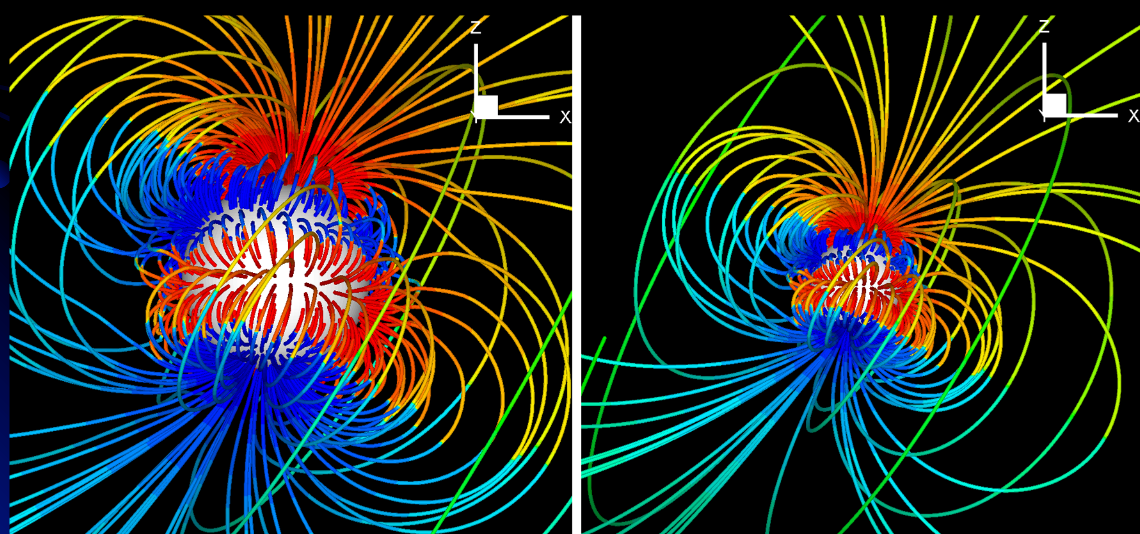

Ω μ
z
x

Games with Realistic Magnetic Fields



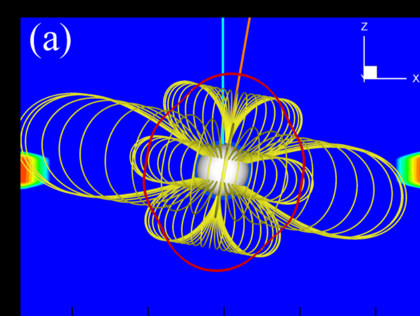
Donati et al. 2007

The magnetic field of the young star V2129 Oph is measured on the Surface of the star with the Doppler-Zeeman technique and extrapolated to the larger distances in force-free approximation



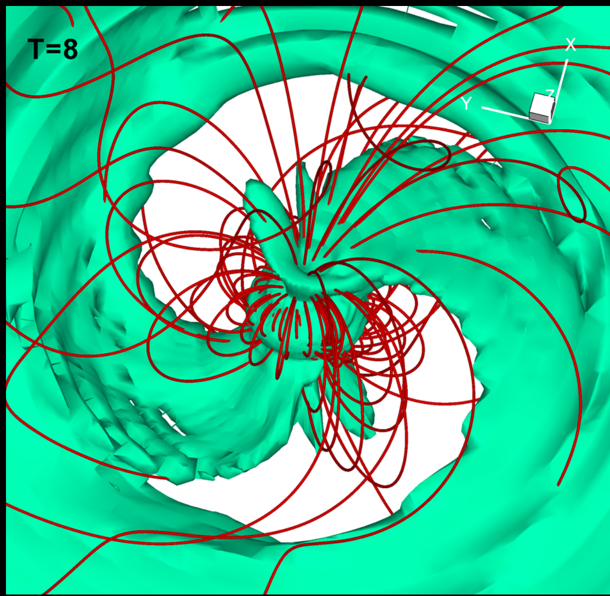
3D field of V2129 modeled with 1.2 kG octupole and 0.35 kG dipole fields

Romanova, Long, Lamb, Kulkarni, Donati 2009

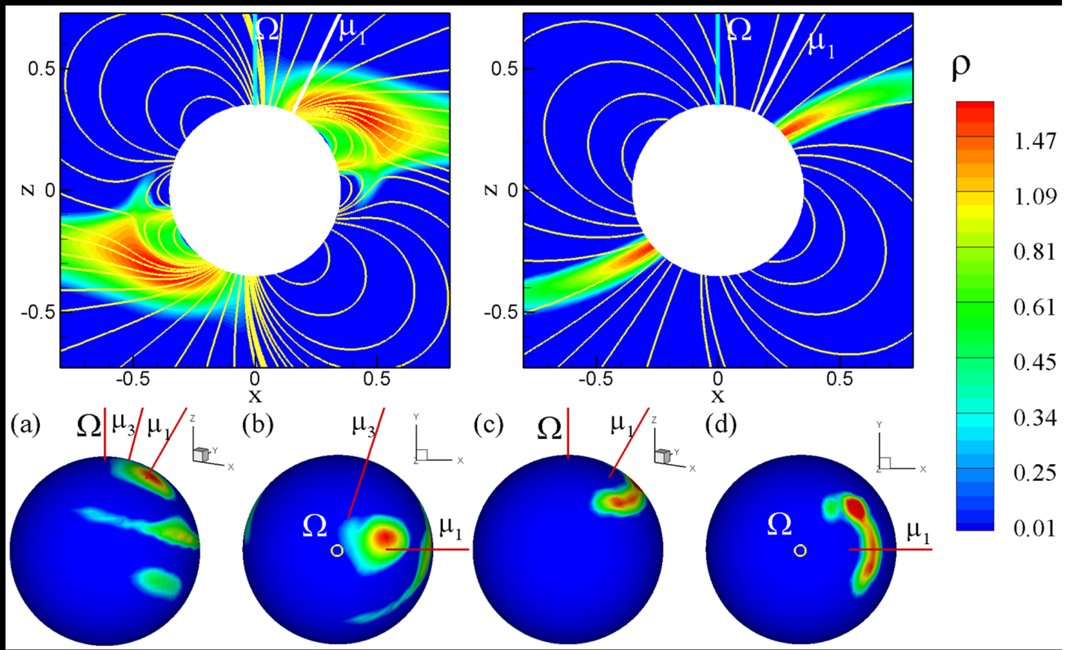


Pure octupole field

Games with Realistic Magnetic Fields



Dipole component disrupts the disk and determines most of observational properties



Dipole+Octupole

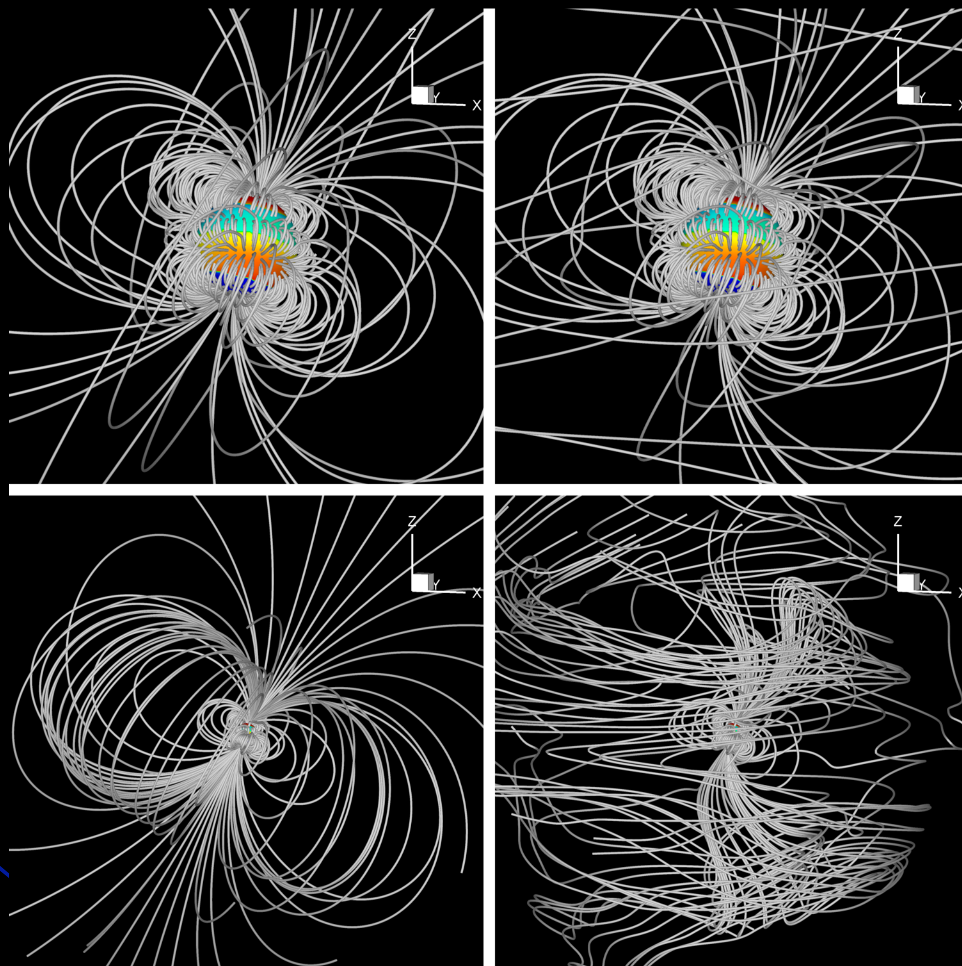
Dipole

Matter flow is adjusted by the octupole component close to the star

Long, Romanova, Lamb 2009

Romanova, Long, Lamb, Kulkarni, Donati 2009

Magnetic field distribution

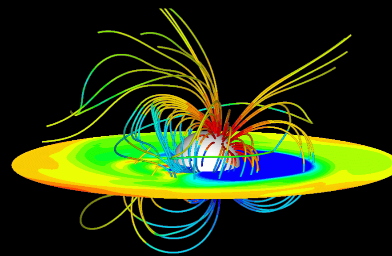


Initial field

Final field

Potential approximation (no external currents) does not work outside the magnetosphere

Conclusions :



- A star may be in the regime of stable or unstable accretion with different observational properties
- Bunching of field lines during period of enhanced accretion leads to persistent conical outflows
- Propeller-driven outflows have two components: slow heavy conical winds and fast Poynting jet
- Accretion in MRI-regime also shows funnels
- Magnetic field of stars may be complex

Thank you !