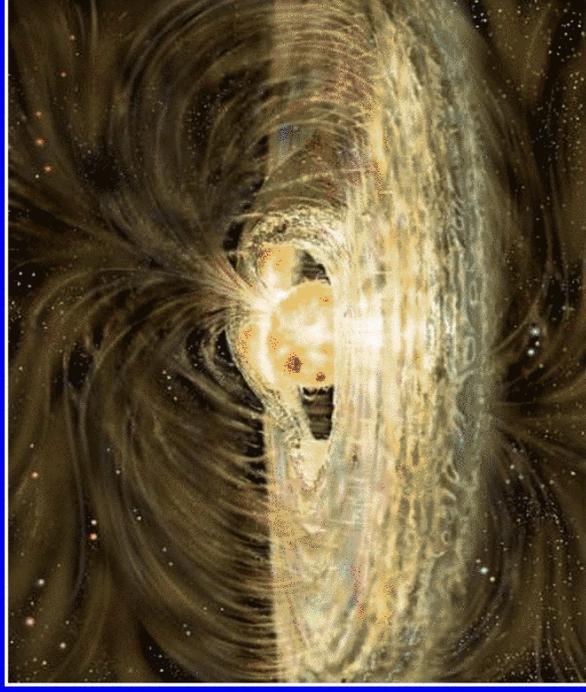


Accretion and Outflows from the Vicinity of Magnetized Stars



Marina Romanova
Cornell University

Collaborators:

Richard Lovelace – Cornell U.

Akshay Kulkarni – Cornell U.

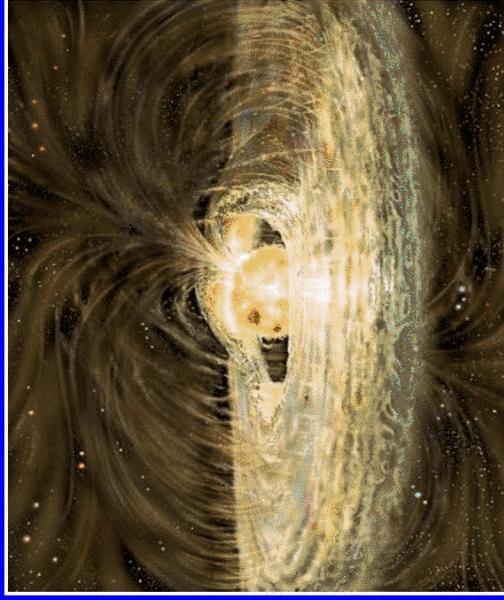
Min Long – Cornell U.

Galina Ustyugova – Moscow, Russia

Alexander Koldoba – Moscow, Russia

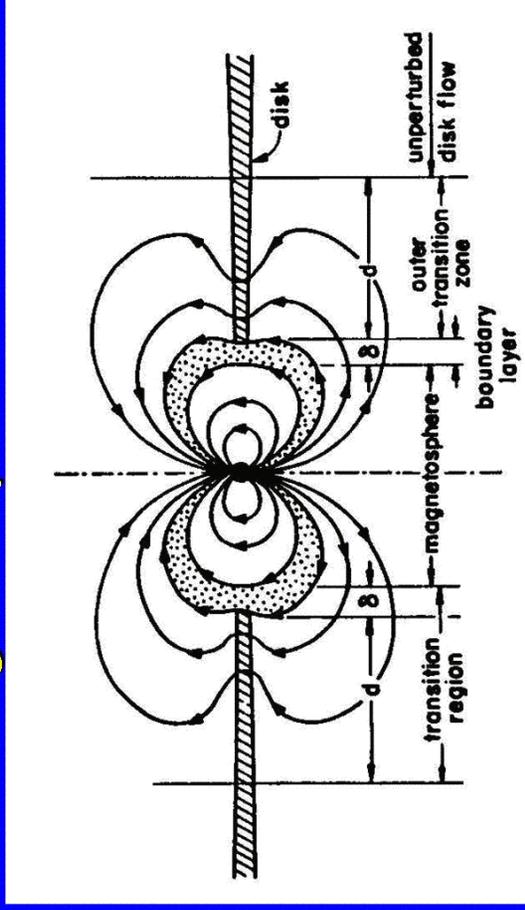
Stars with Magnetic Field:

- Young stars – classical T Tauri stars
- Neutron stars
- White dwarfs



- Disk Structure ?
- Outflows ?

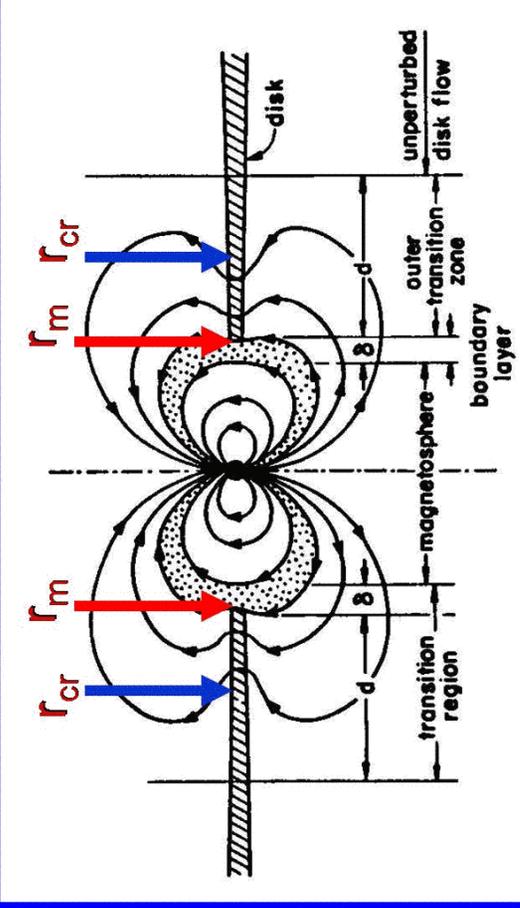
Disk-magnetosphere interaction



Pringle & Rees 1972; Ghosh and Lamb 1978-79, Konigl 1991

- Matter accretes through funnels to the star

Disk-magnetosphere interaction



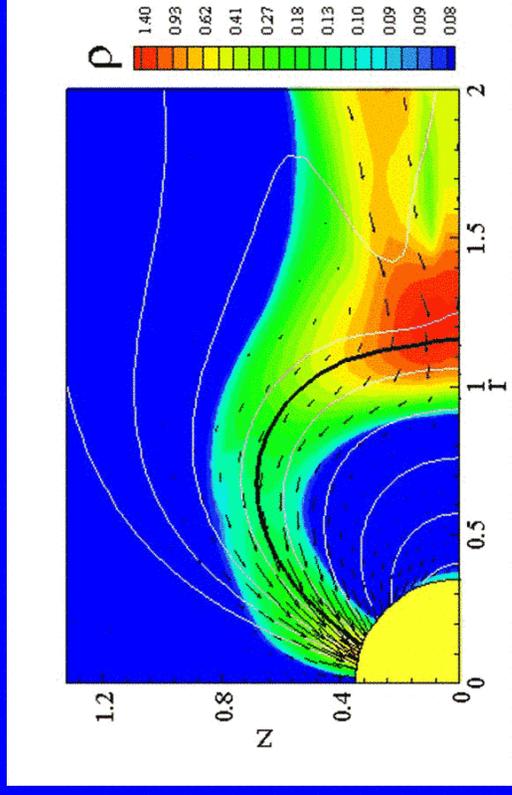
Pringle & Rees 1972; Ghosh and Lamb 1978-79, Konigl 1991

- Rotational equilibrium: Slowly rotating star

Numerical Model

- 2D (axisymmetric) and 3D
- Non-relativistic MHD
- Godunov-type numerical code
- α – viscosity and α – diffusivity:
 $\alpha_{\text{vis}} = 0.01-0.02$ $\alpha_{\text{dif}} = 0.01-0.02$
- 2D: Spherical coordinates: $N_r=50-100$,
 $N_\theta=30-70$, High resolution near the dipole
- Quasi-equilibrium initial conditions – viscous flow

Result of 2D Simulations

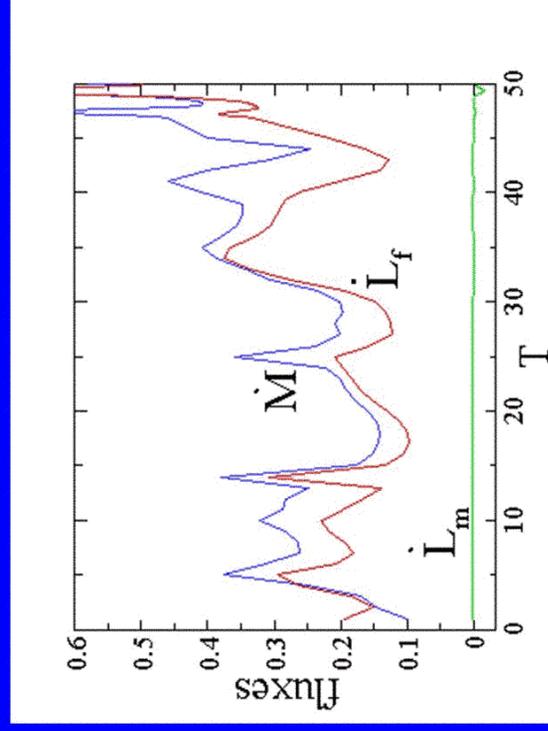


Romanova, Ustyugova, Koldoba, Lovelace 2002

- Matter stops at the magnetospheric radius
- Spin-up/spin-down

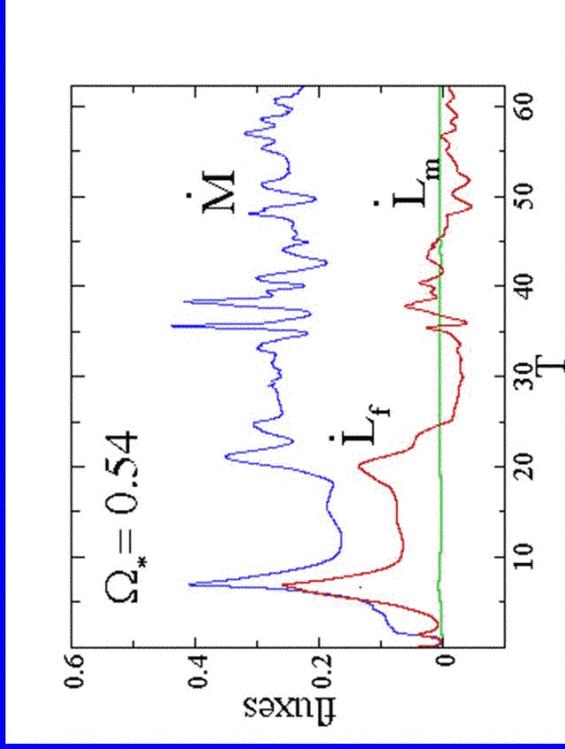
Variation of Fluxes with Time:

Spin-up:

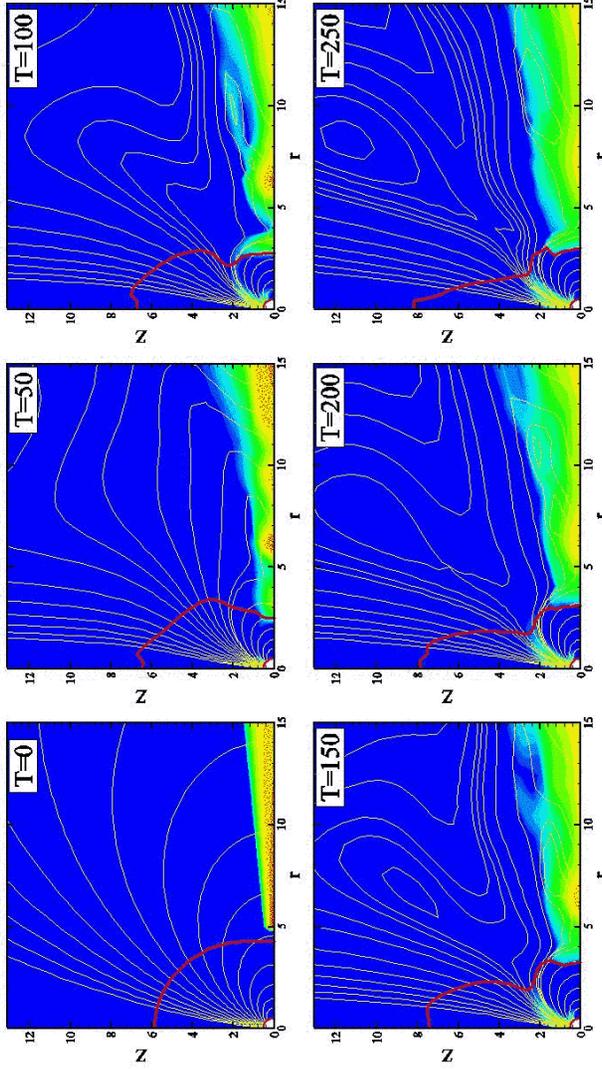


Matter flux \dot{M} and angular momentum fluxes associated with matter \dot{L}_m and magnetic field \dot{L}_f

Example of “Torqueless” Accretion

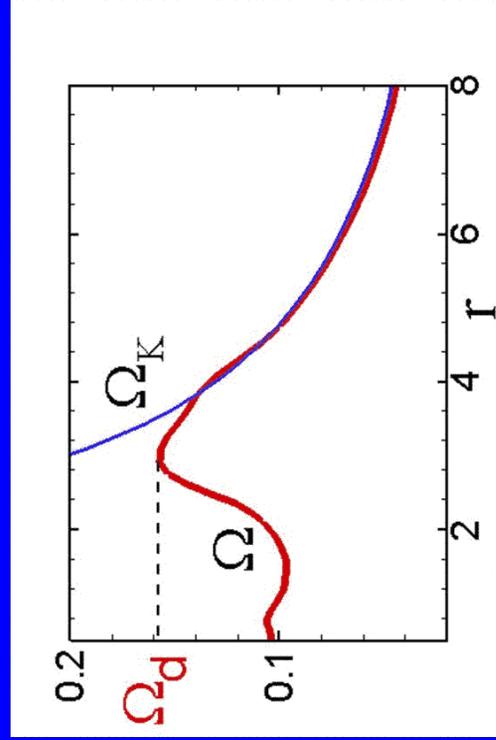


Rotational Equilibrium State



Long, Romanova, Lovelace 2005

Rotational equilibrium: rotation of the star is locked to rotation of the disk at $r=r_d$



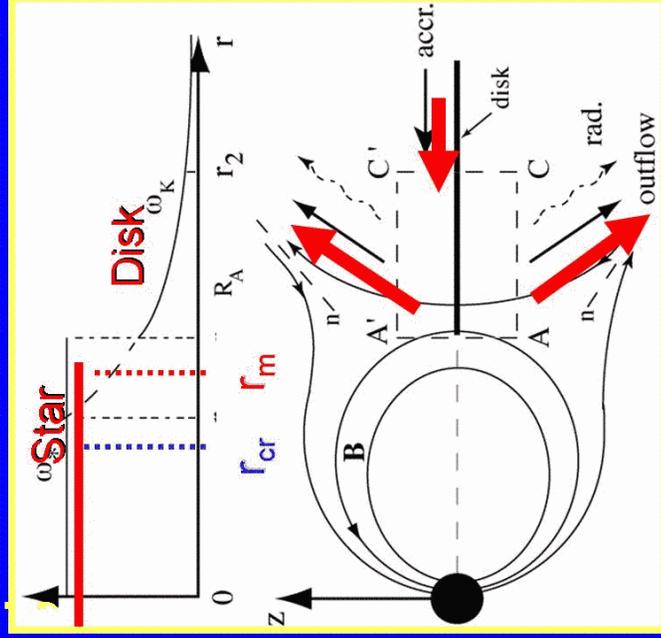
$$\Omega_d : \Omega_* = 1.3 - 1.6$$

Ghosh & Lamb 1978; Konigl 1991

“Propeller” Regime

Propeller Regime

- $r_{cr} < r_m$
- $F_c > F_G$

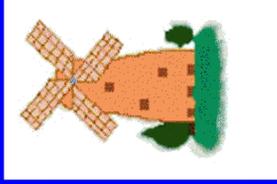


Illarionov & Sunyaev 1975;
 Lovelace, Romanova and Bisnovatyi-Kogan 1999; Spruit 2004

Two types of propellers:

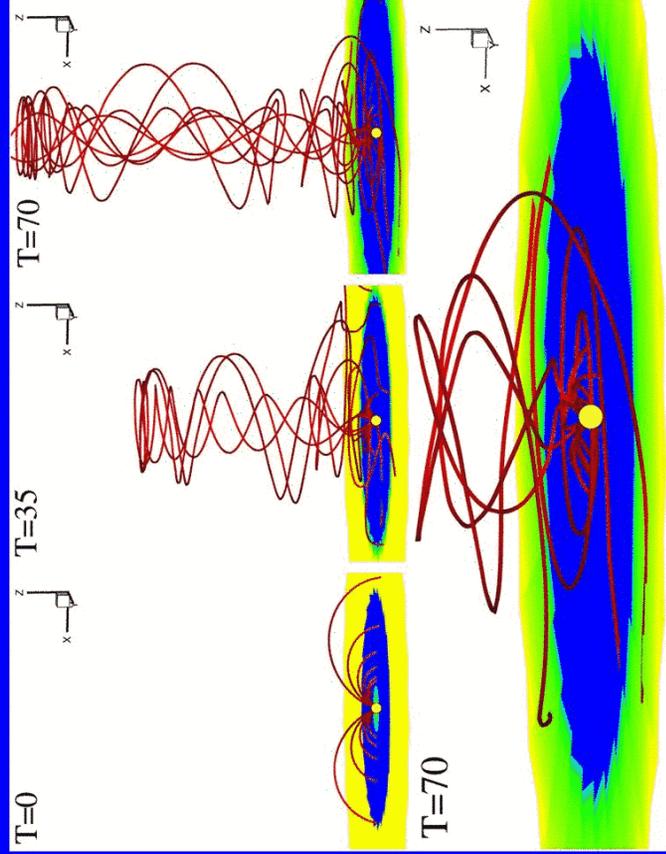


(1) "weak" propellers:
no outflows

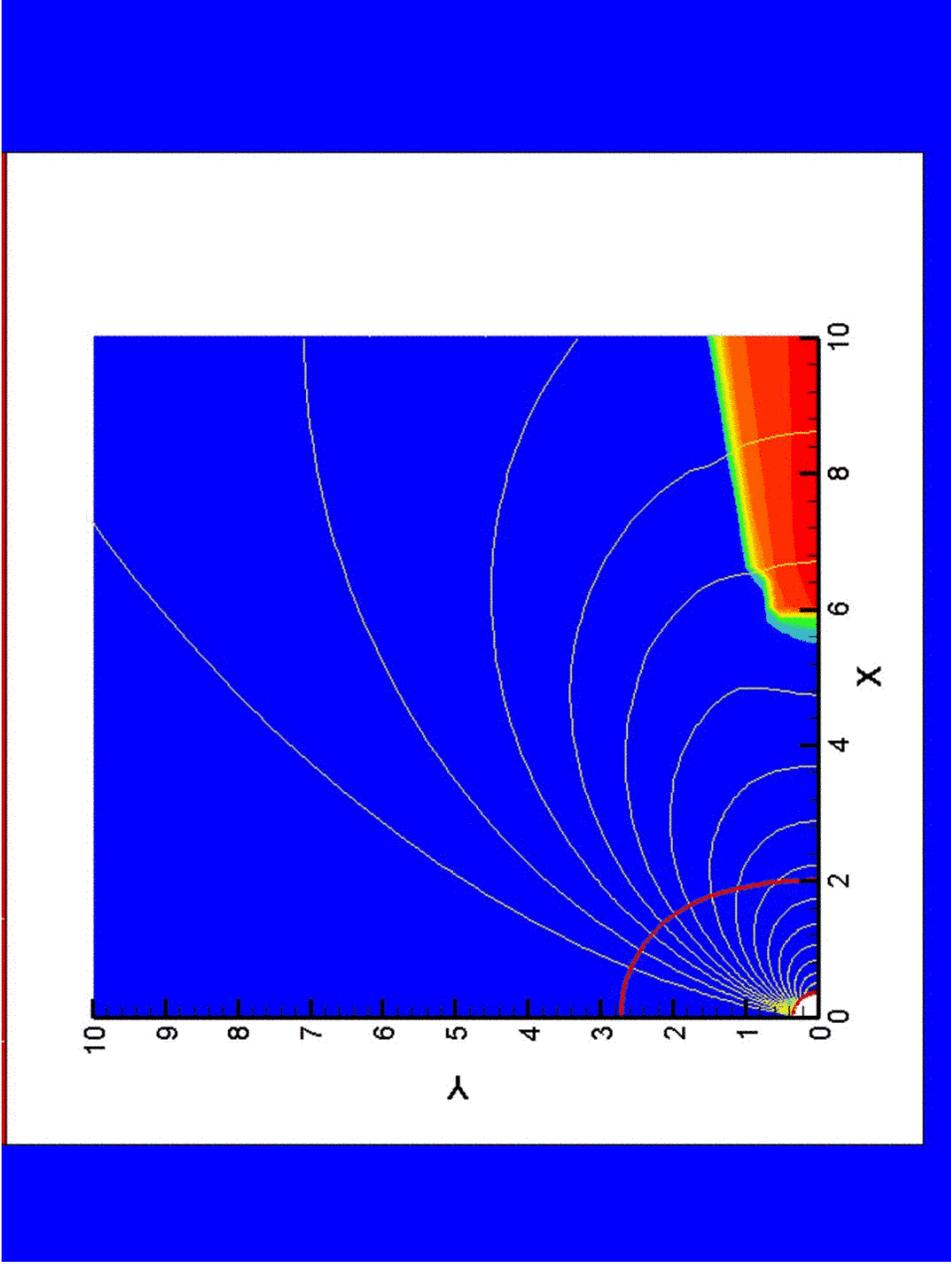


(2) "strong" propellers:
with outflows

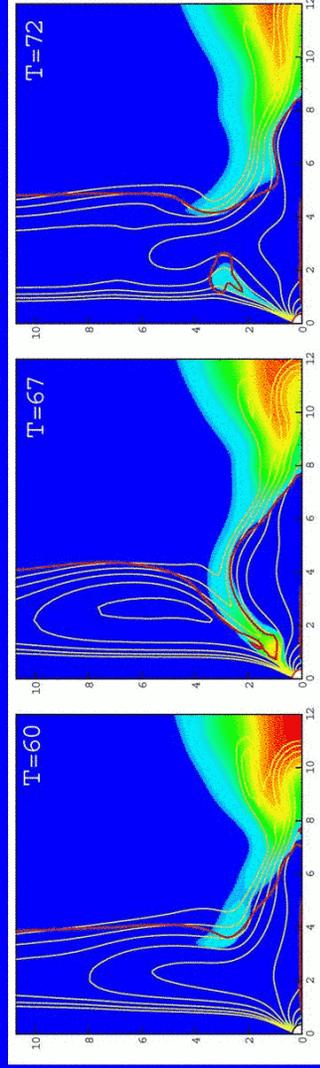
Magnetic "Tower"



Romanova, Ustyugova, Koldoba, Lovelace 2004, also Kato et al. 2004

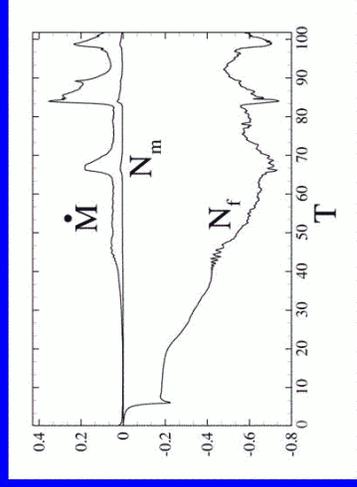


Matter accretes to the star quasi-periodically

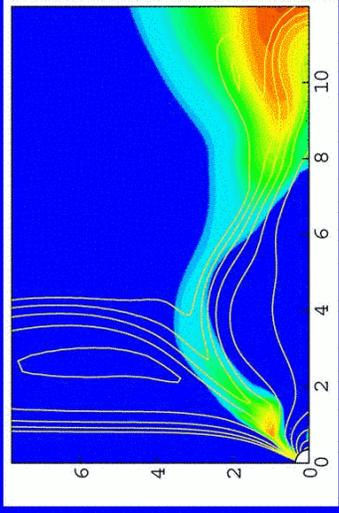


- Star strongly spins-down
- No outflows —

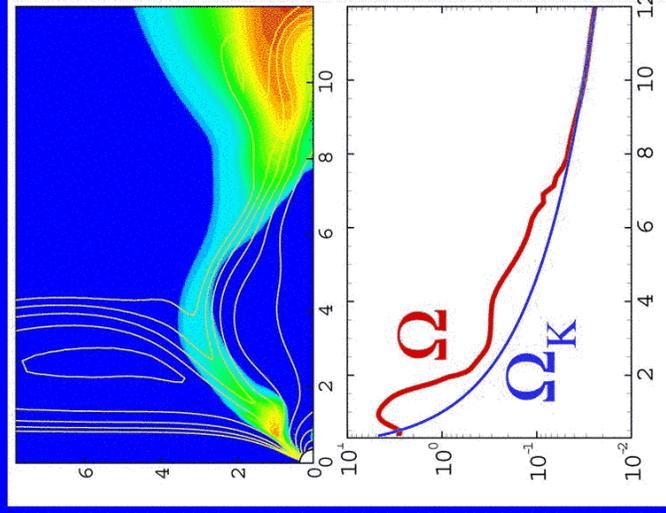
“Weak Propeller”



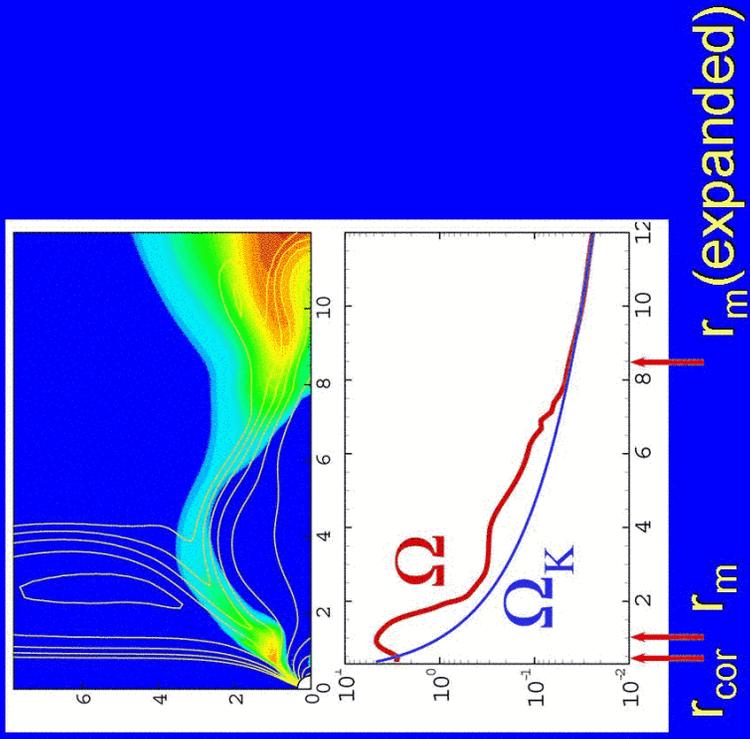
Physics of “Weak” Propellers



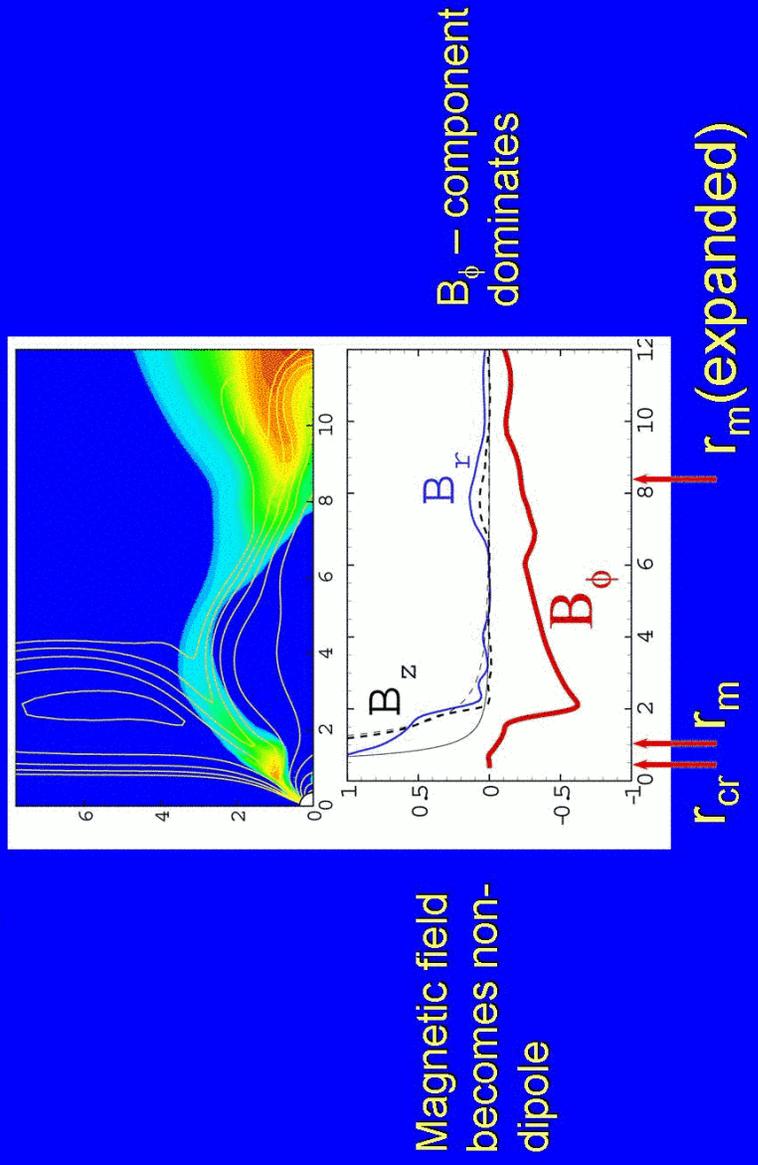
Physics of “Weak” Propellers



Physics of “Weak” Propellers



Physics of “Weak” Propellers

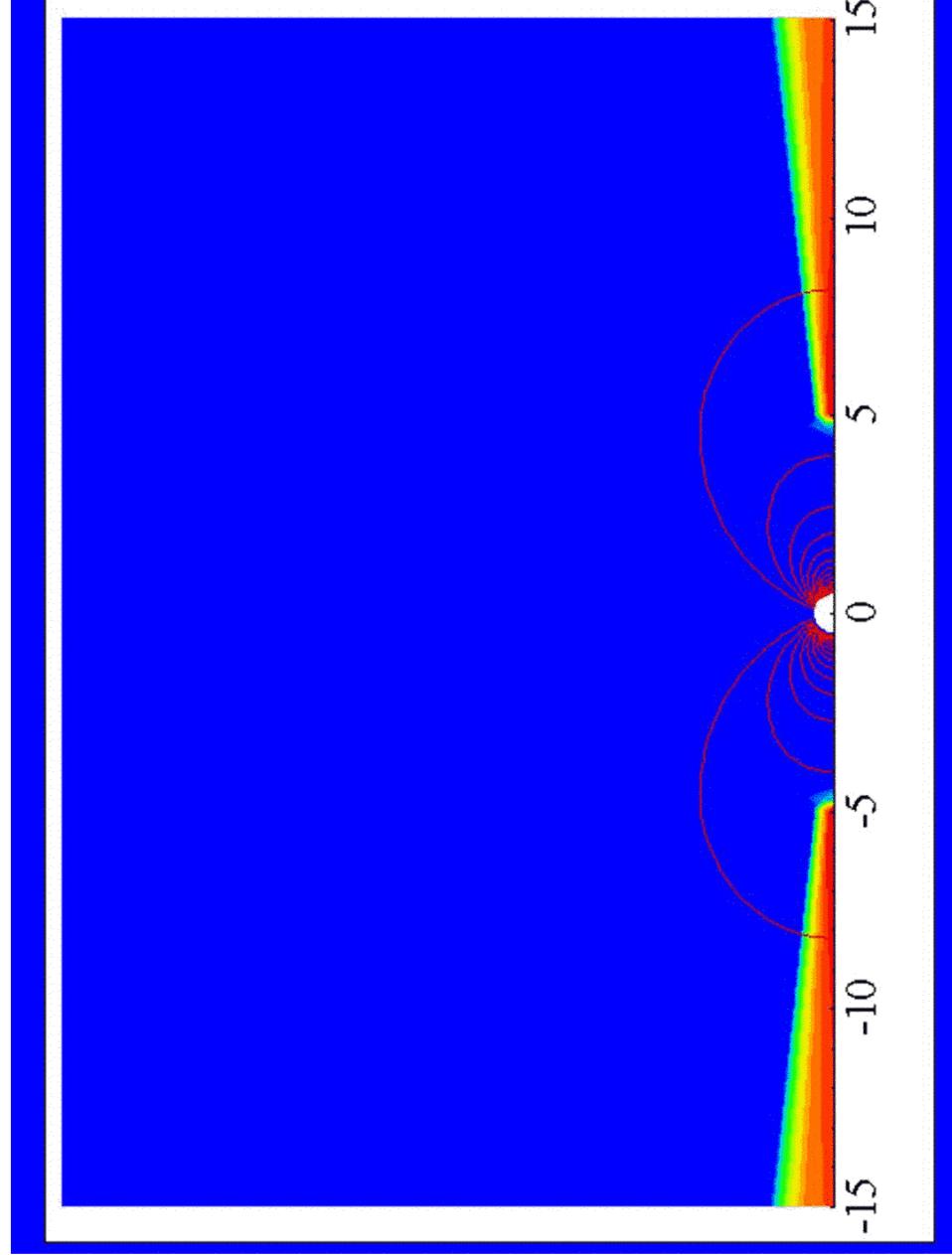


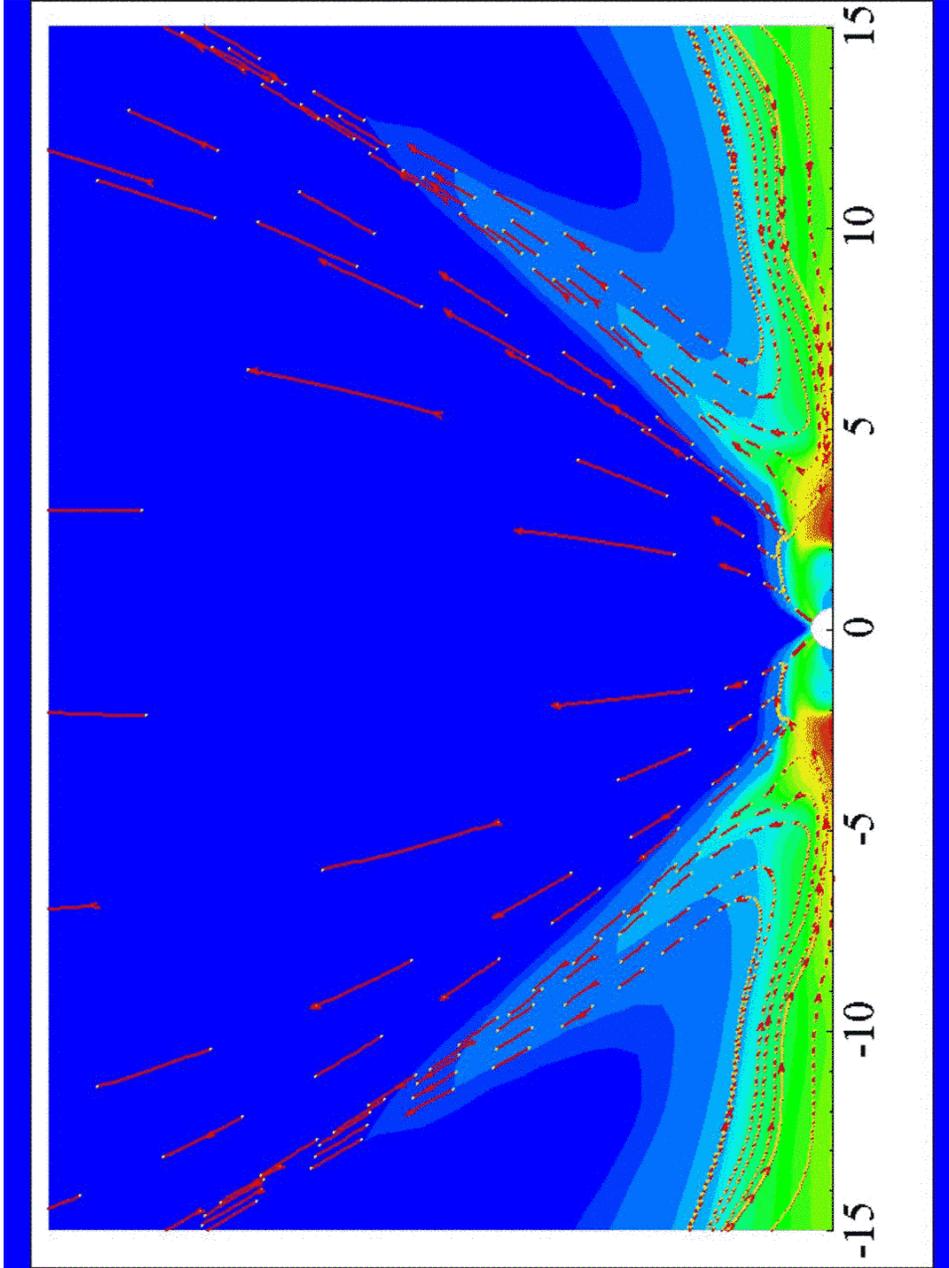
“Strong” Propeller: Outflows

Investigation of propeller stage at
different parameters: μ , Ω , α_{vis} , α_{dif}

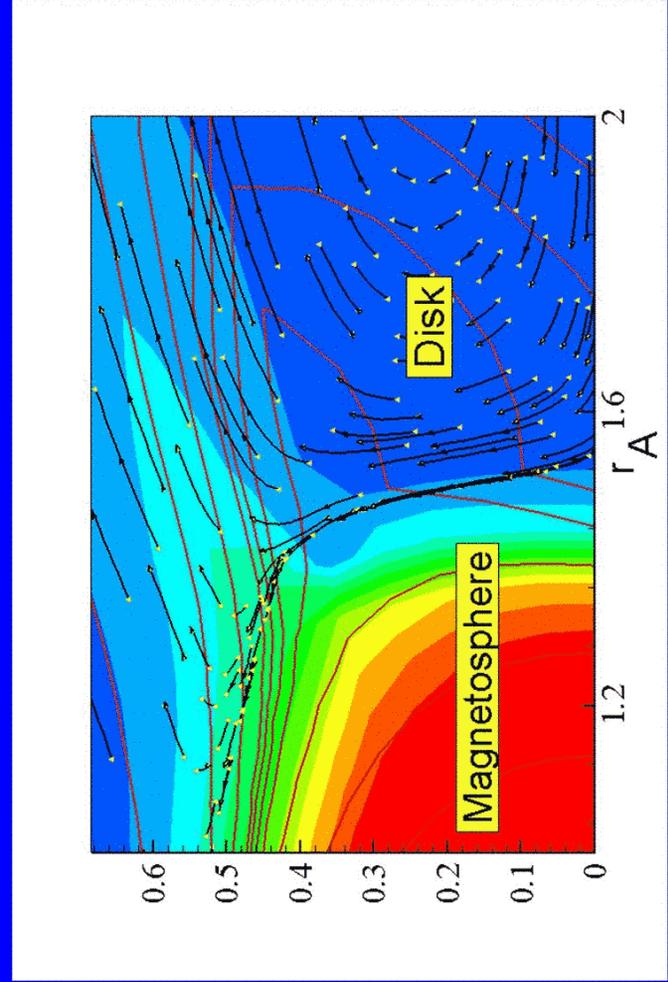
$\alpha_{\text{dif}} > 0.2$ – larger diffusivity

$\alpha_{\text{vis}} > 0.2$ – larger matter flux





Angular velocity is a background

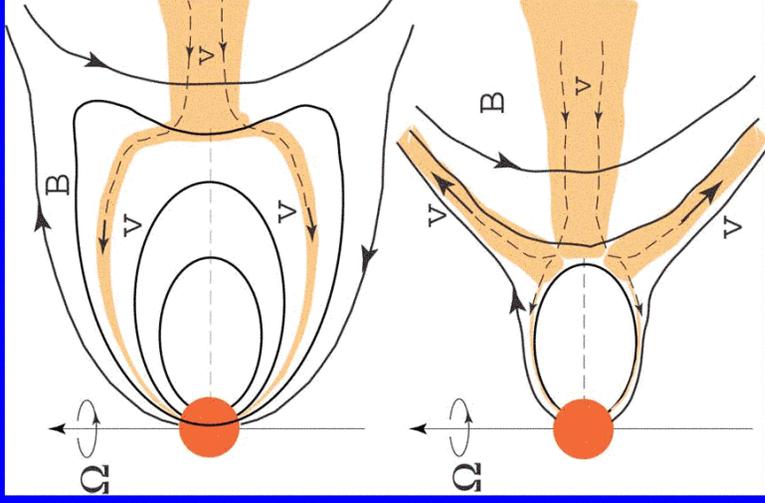


“Weak” propeller:

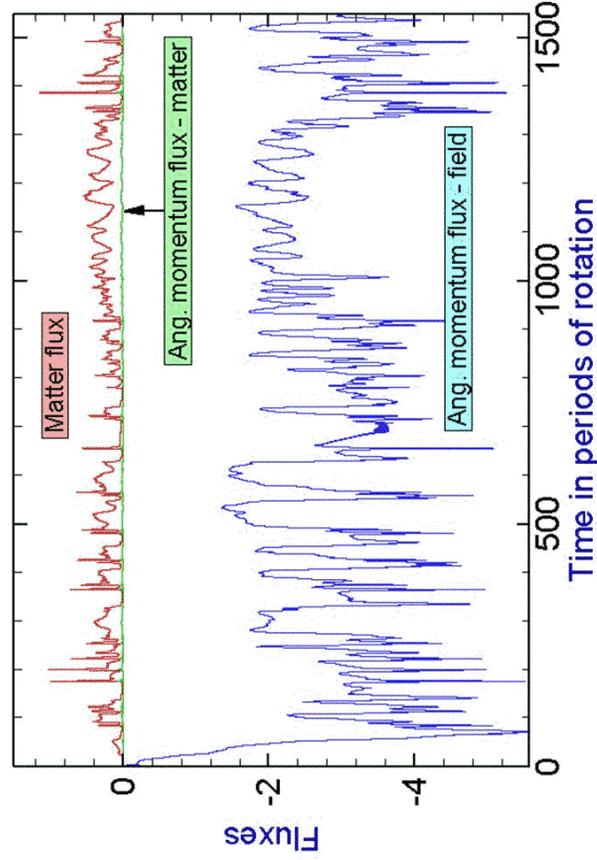
- Accretion disk is weak
- Disk is stopped by fast rotating magnetosphere

“Strong” propeller:

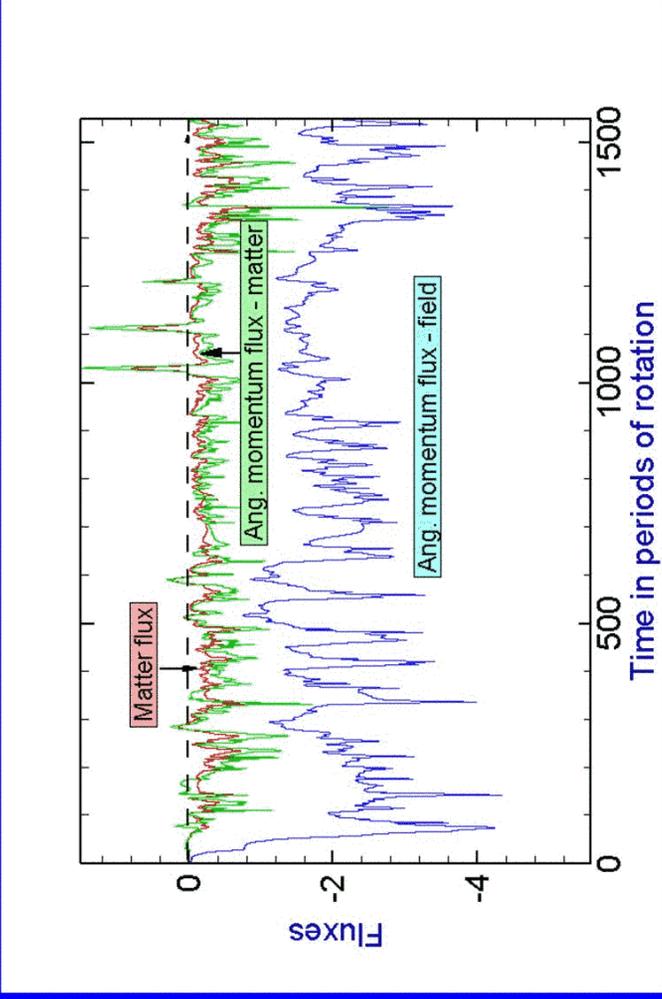
- Accretion disk is strong
- Matter penetrates to the region of fast rotating magnetosphere



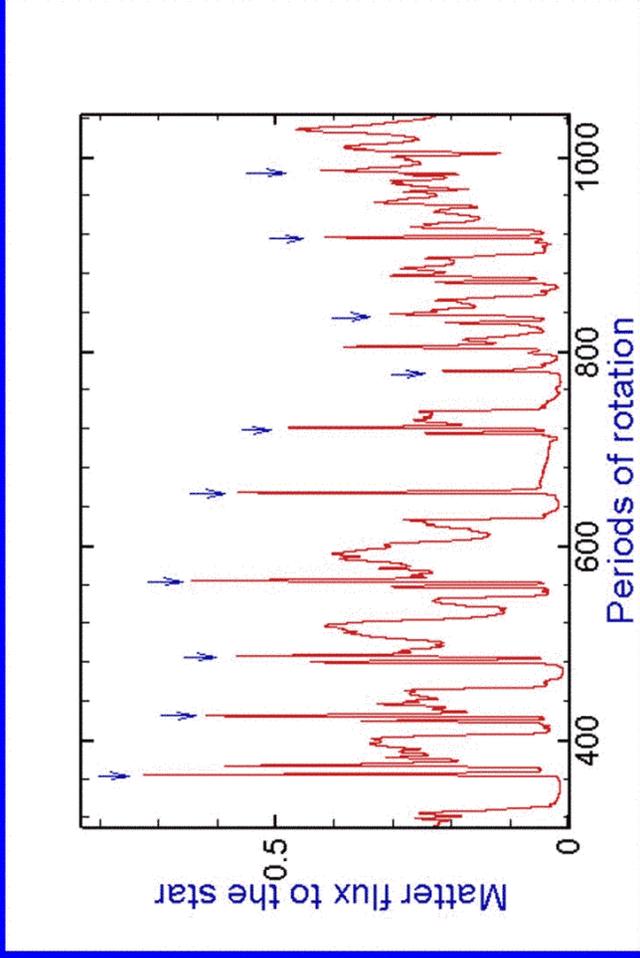
Fluxes to the star



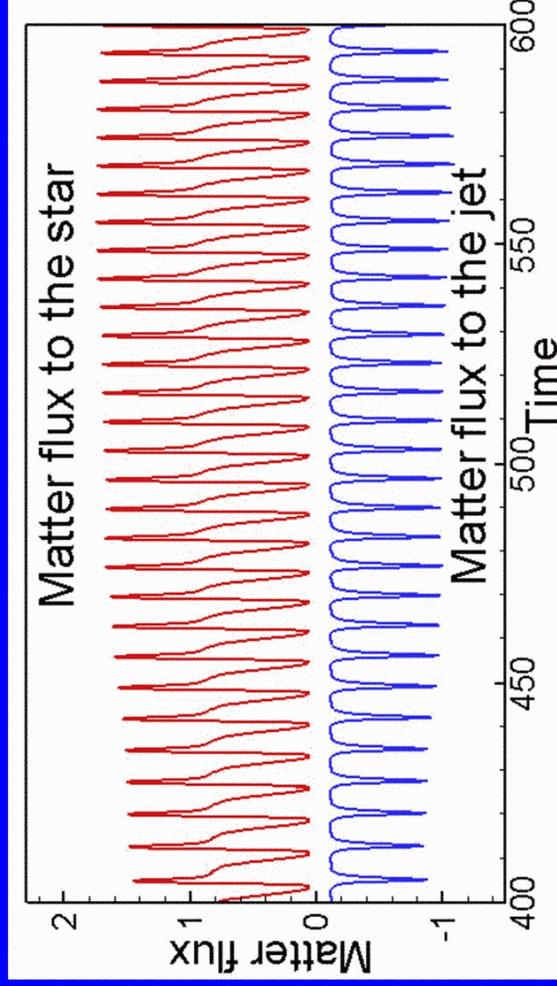
Fluxes to the jet



Quasi-periodic oscillations



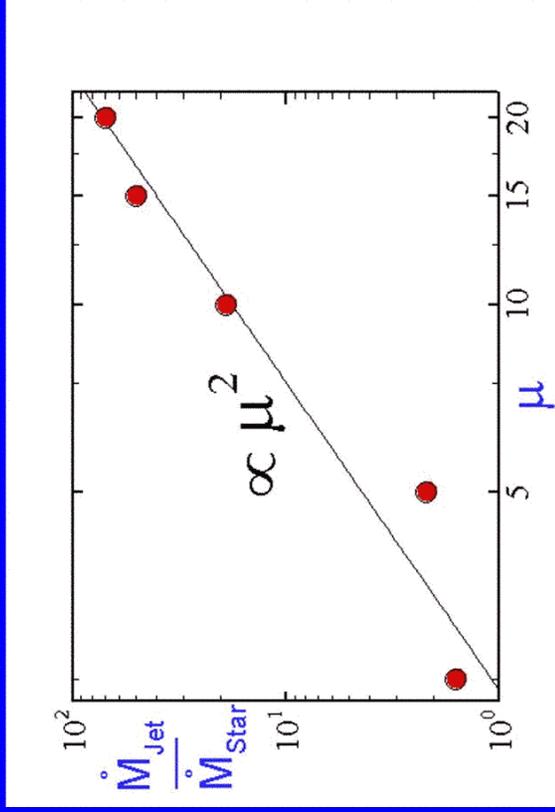
(Amazing) Case of larger matter
flux $\alpha_{\text{vis}} = 0.6$ ($\alpha_{\text{dif}} = 0.2$)



Time-scale for QPOs :

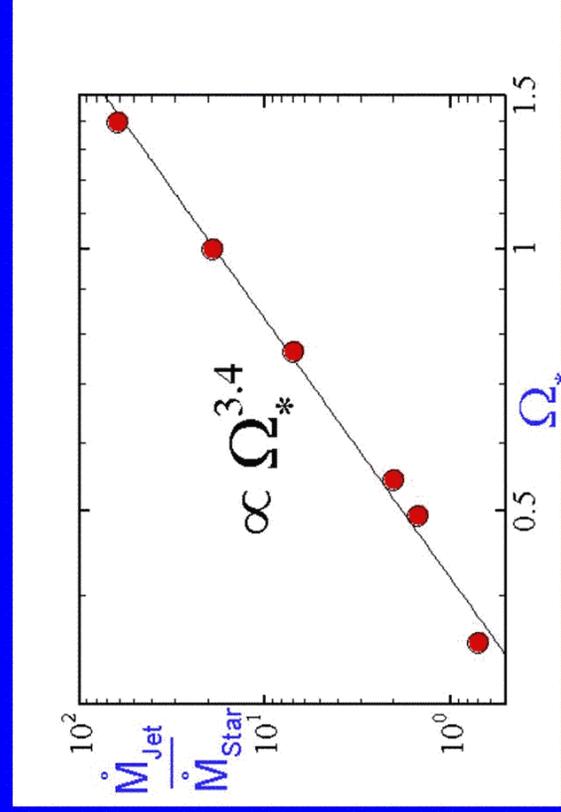
$$\Omega_{\text{QPO}} = (0.2 - 0.01) \Omega_*$$

Efficiency of Propeller



Efficiency increases with magnetic moment

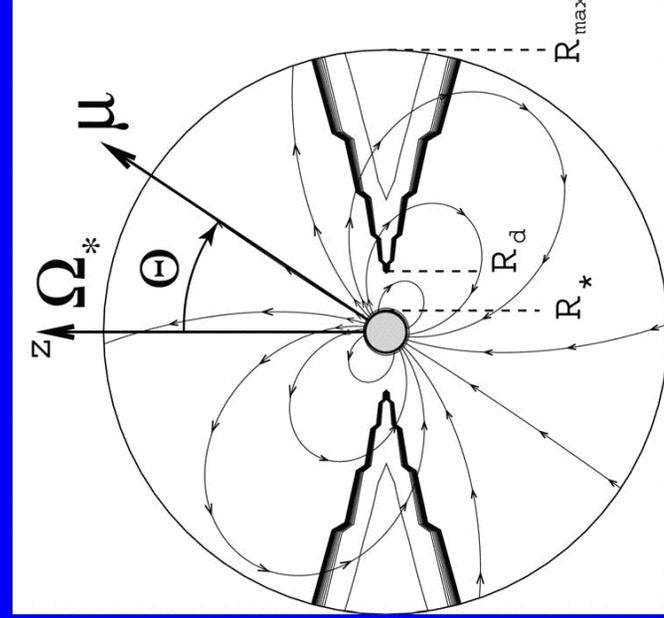
Efficiency of Propeller



Efficiency increases with spin of the star

3D Simulations

Sketch of the model:



$$\Omega_* \parallel \Omega_{\text{disk}}$$

$$\Theta = 0-90^\circ$$

“Cubed sphere” numerical grid

Typical grid:

$N_R=70$, 100

$N_\theta=29 \times 29$

Test cases:

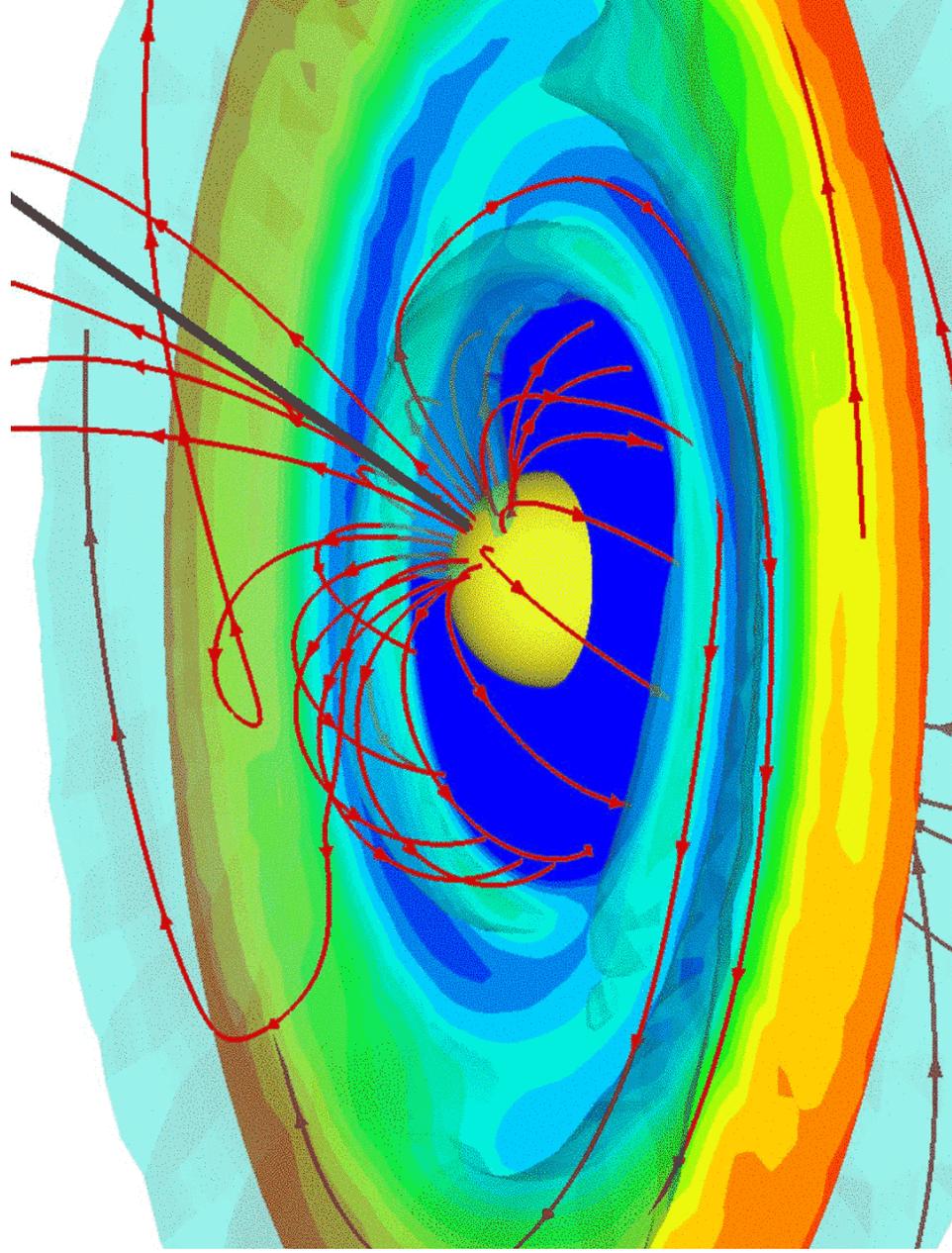
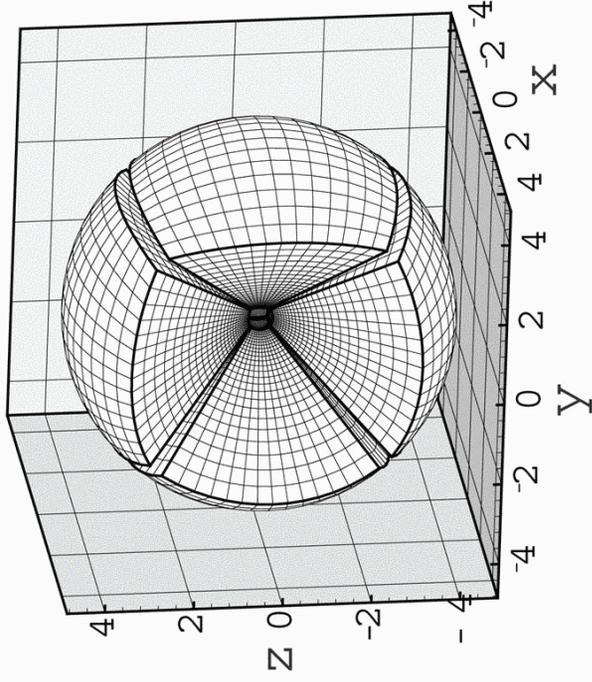
$N_\theta=41 \times 41$ and

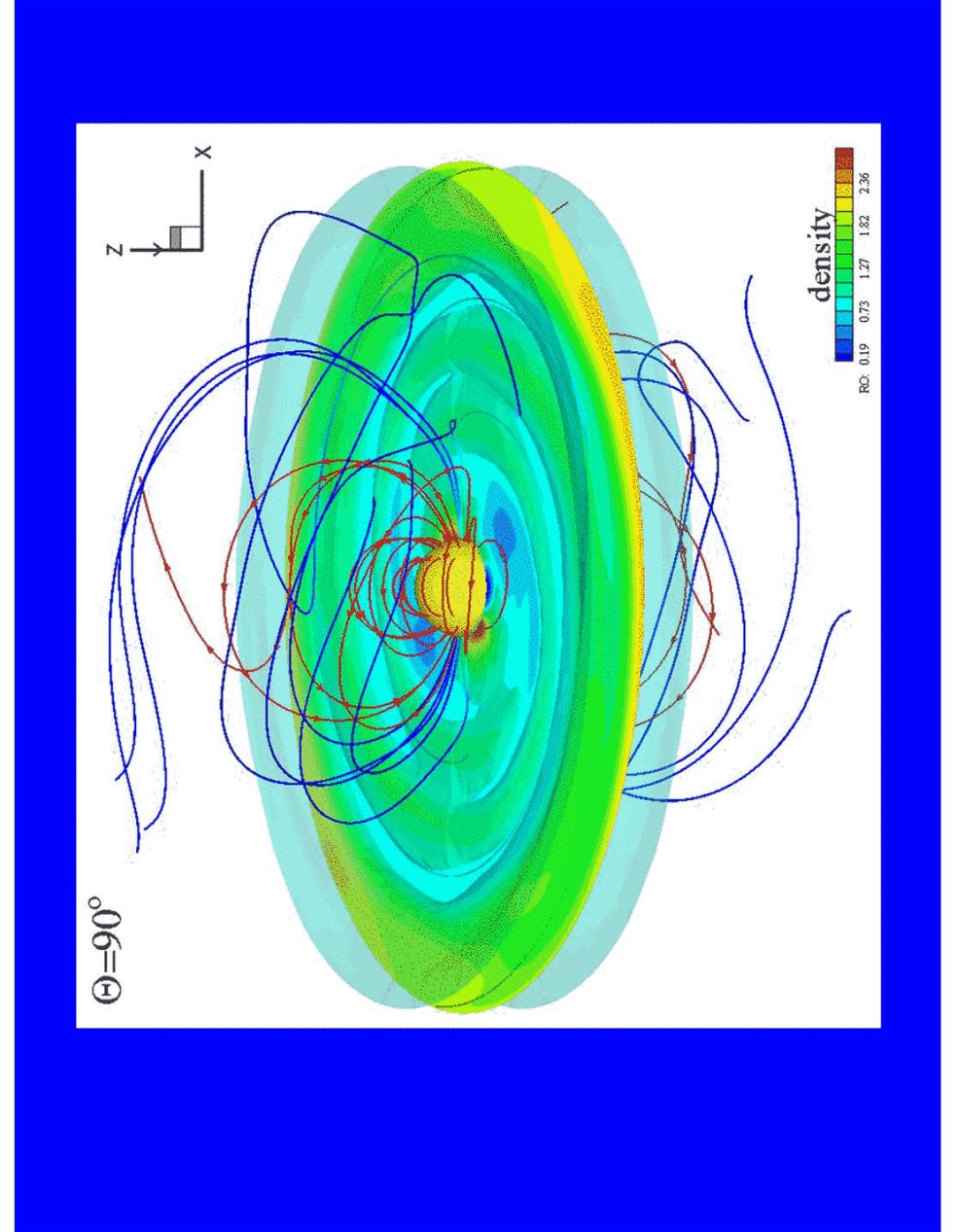
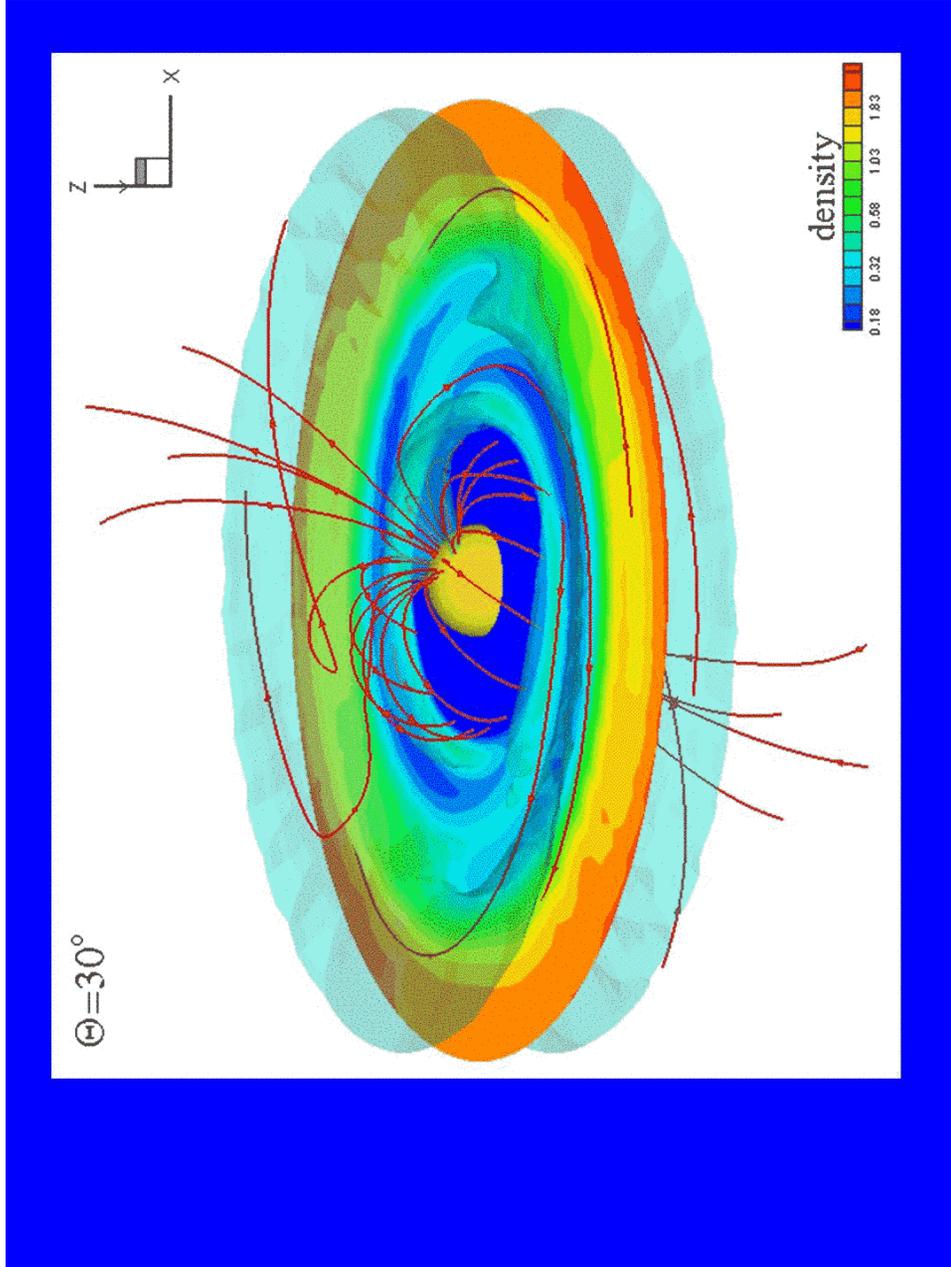
$N_\theta=51 \times 51$

Parallelization:

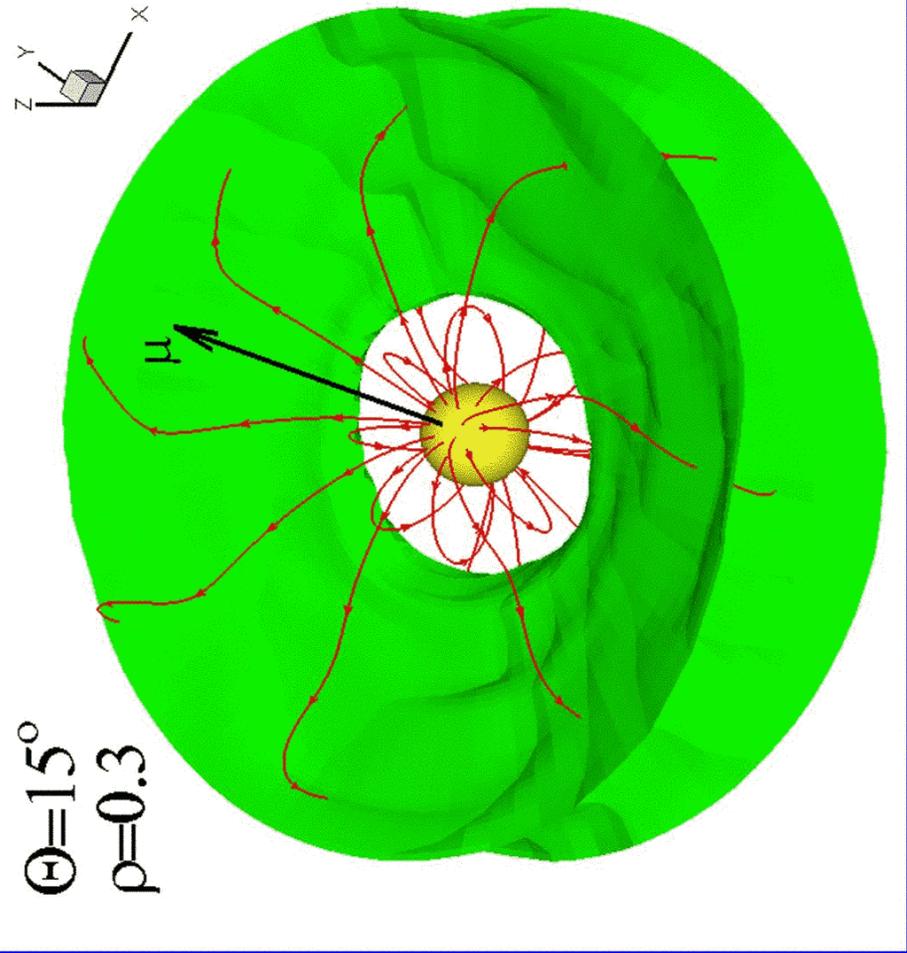
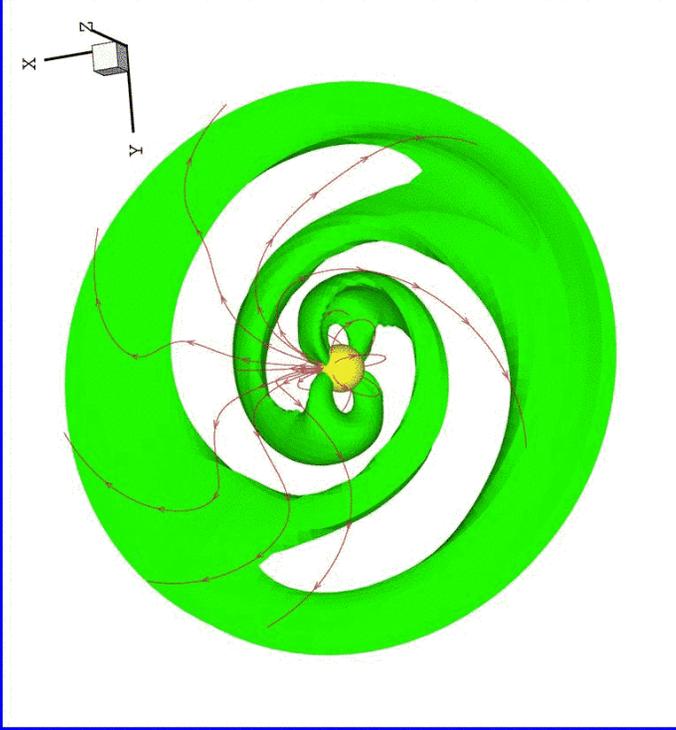
6-processors

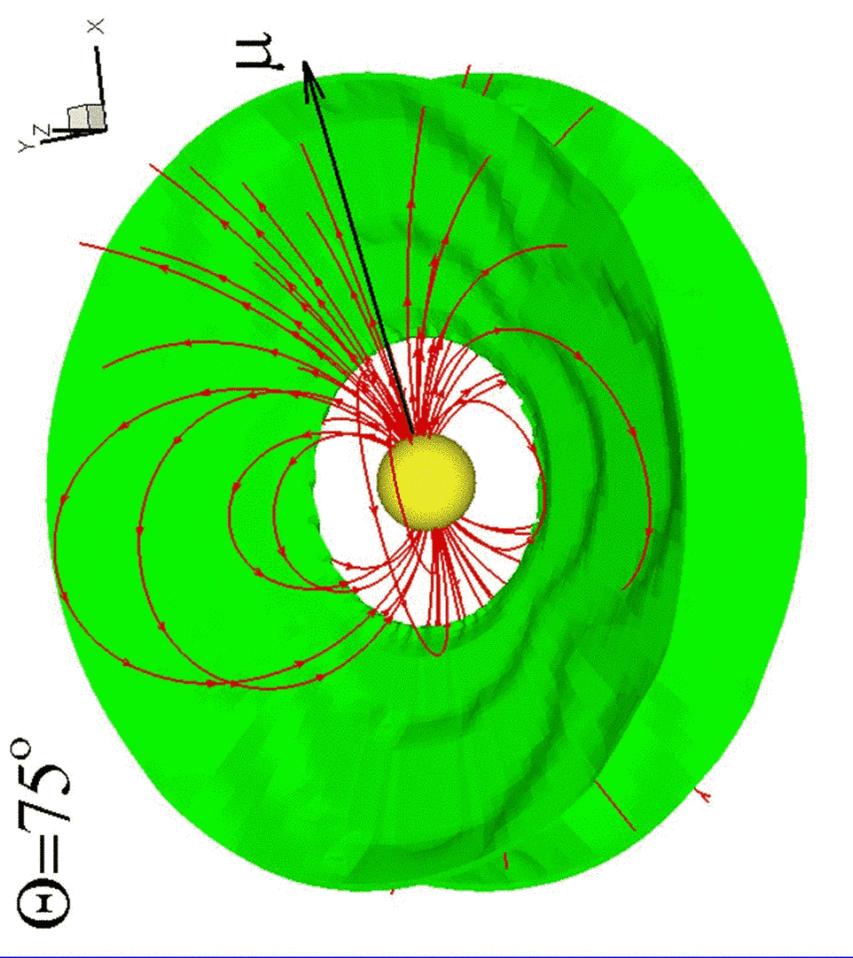
6xN -processors



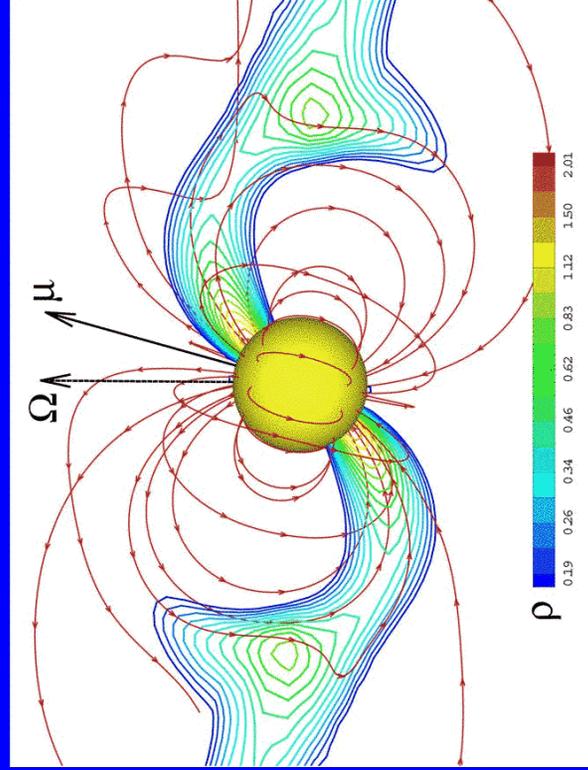


Accreting matter often forms a spiral structure



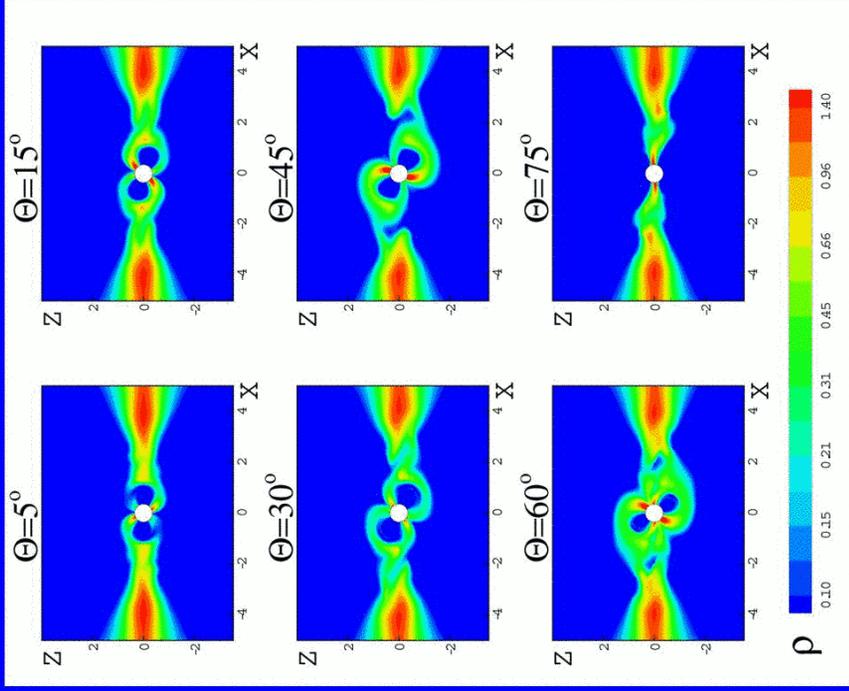


Slice of the density distribution in the funnel stream for $\Theta = 15^\circ$

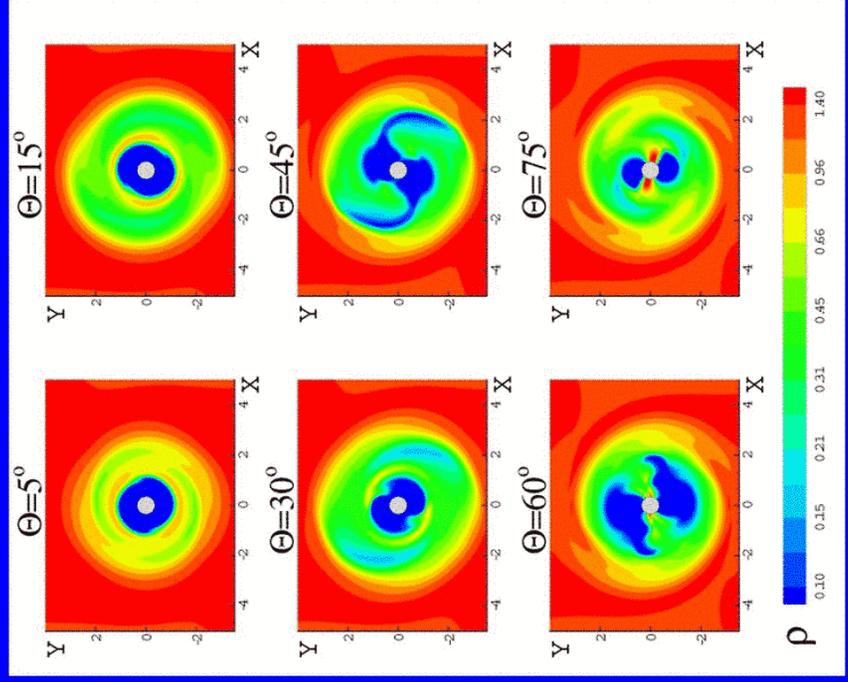


Density is enhanced near the funnel streams - QPOs

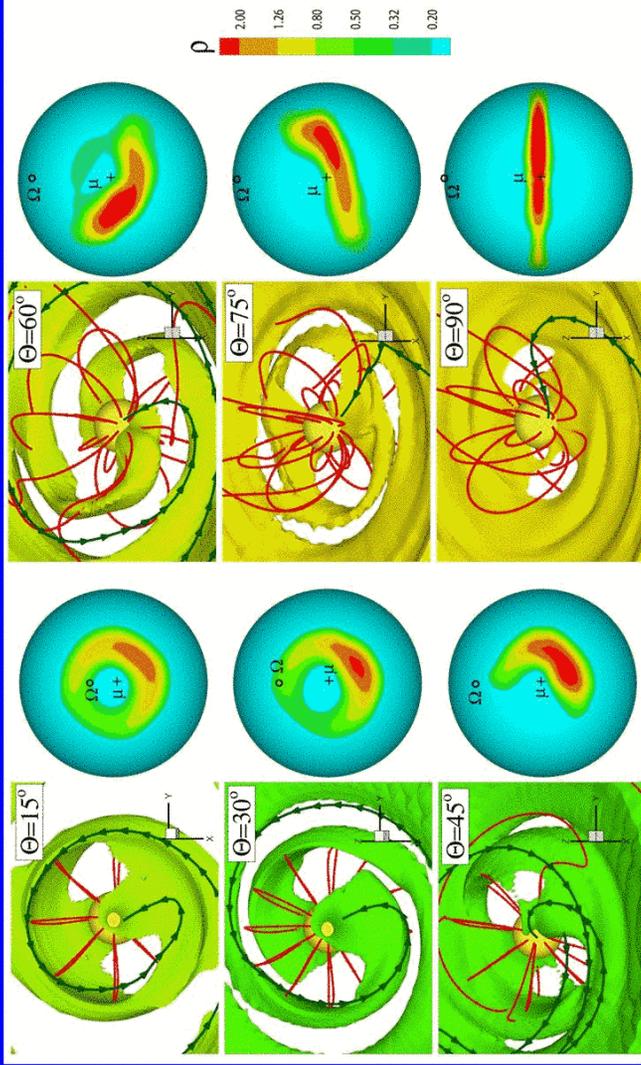
XZ-
plane
Time=5



XY-plane

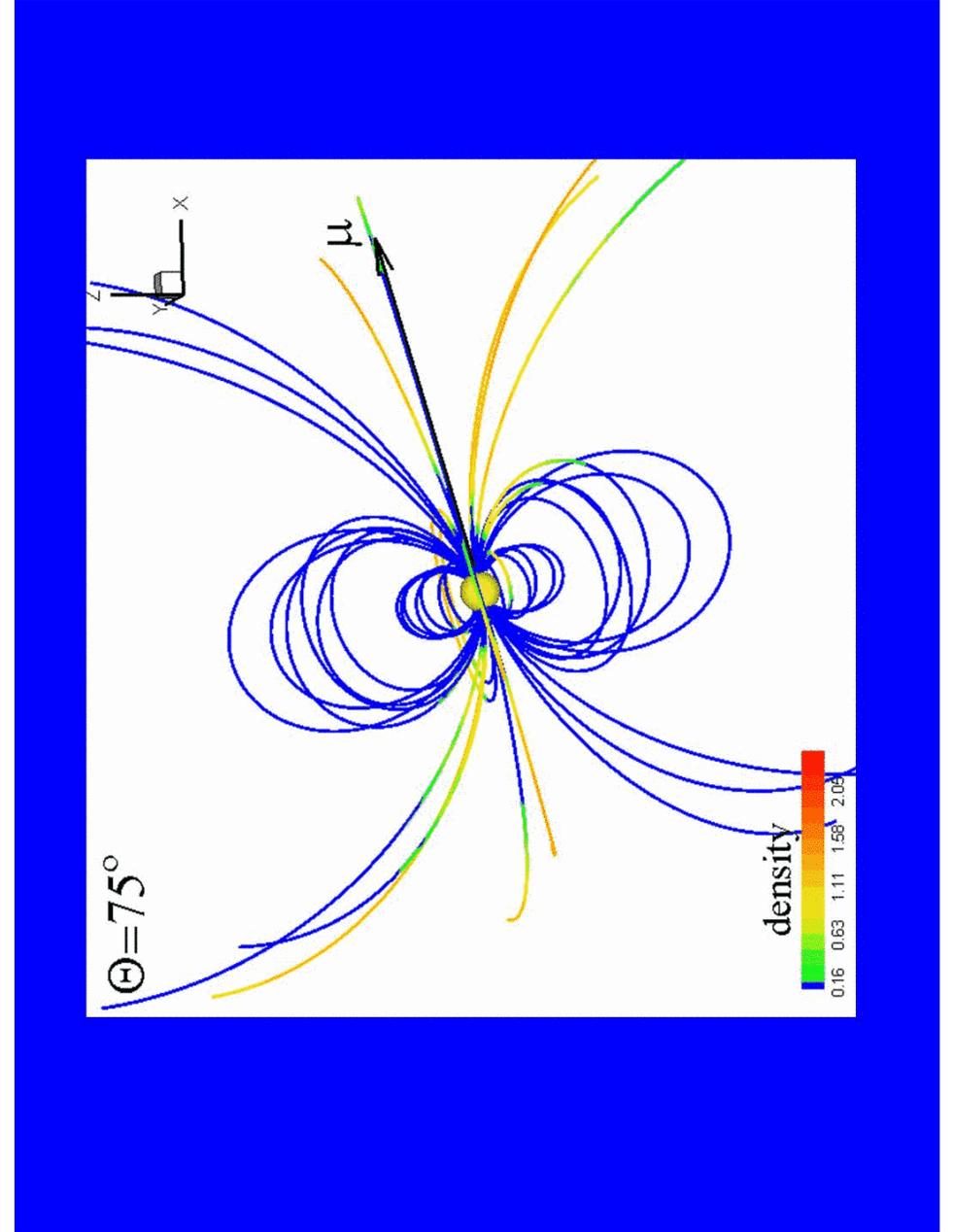
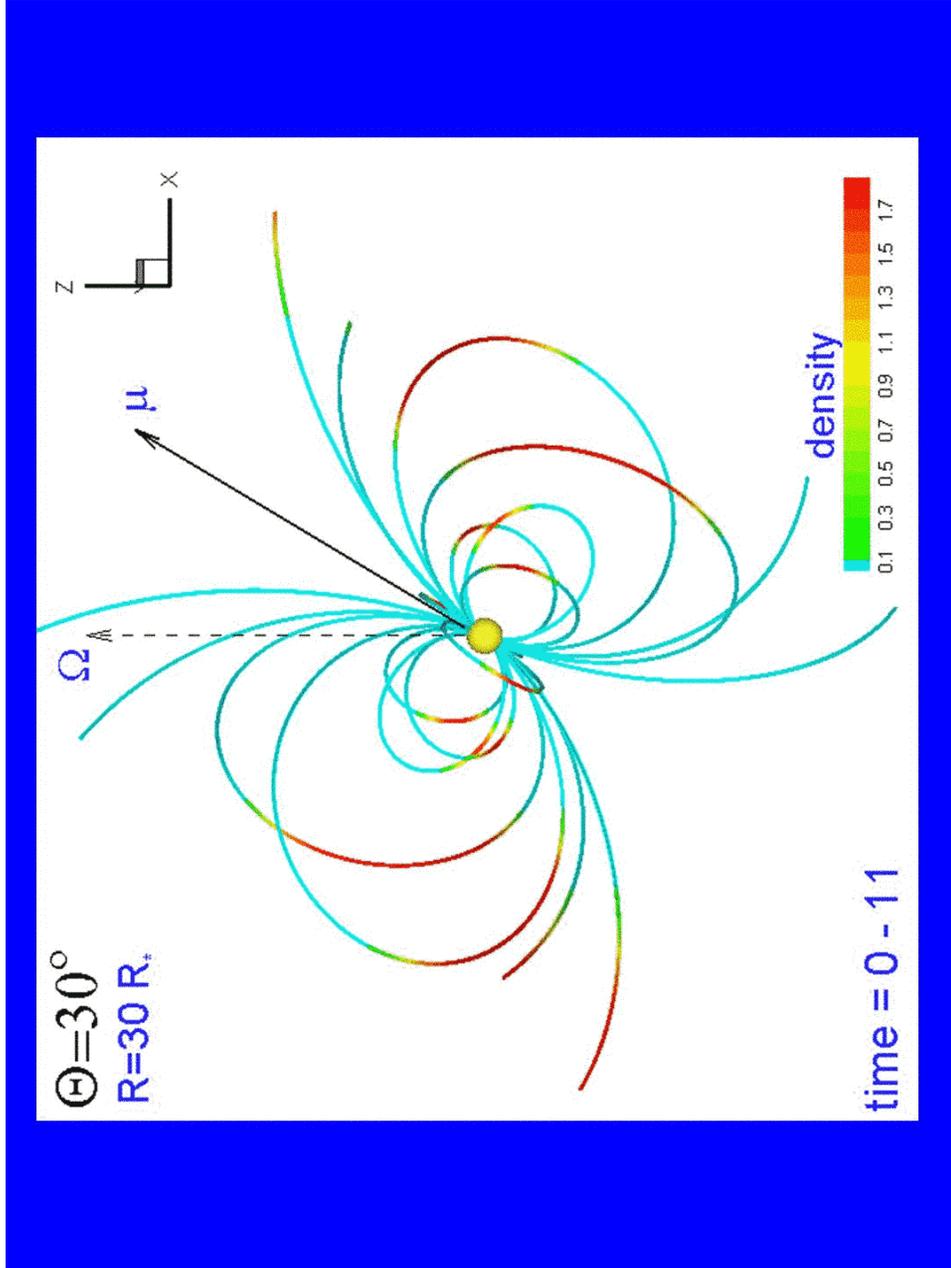


Magnetospheric Flow and Hot Spots at the Surface of the Star for Different Misalignment Angles Θ



Romanova, Ustyugova, Koldoba, Lovelace 2004

Magnetic Field Lines



Conclusions

- Slowly rotating stars – no outflows, disk changes structure
- “Propeller” – star strongly spins-down, disk oscillates, **OUTFLOWS**
- 3D: disk changes structure, magnetic tower forms, no outflows
- 3D “Propeller”: should to be done in the future