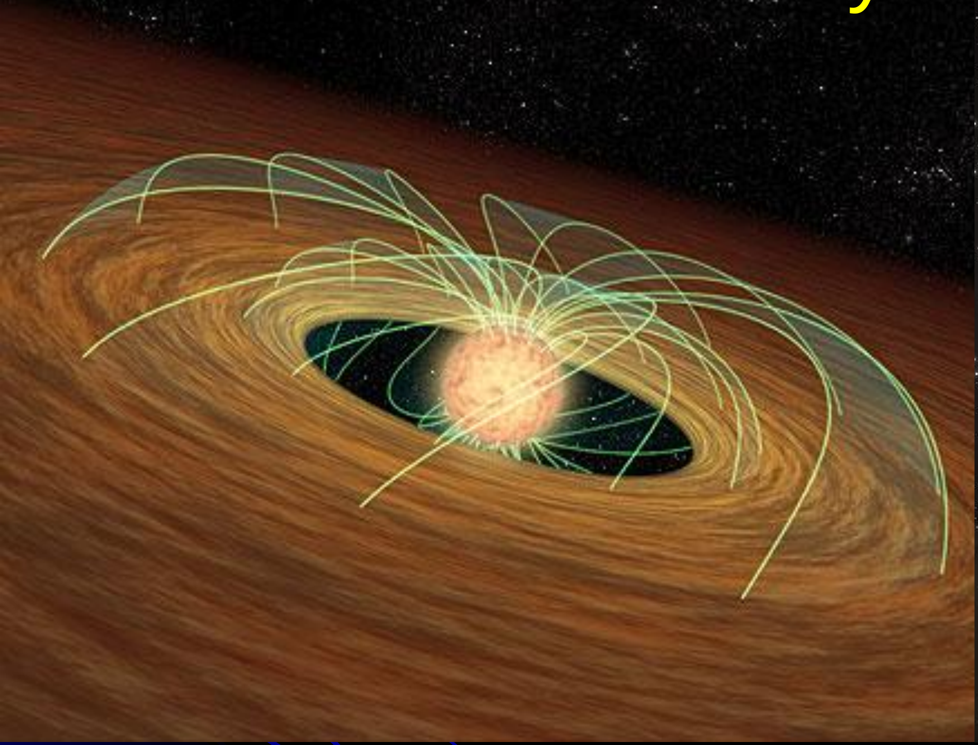
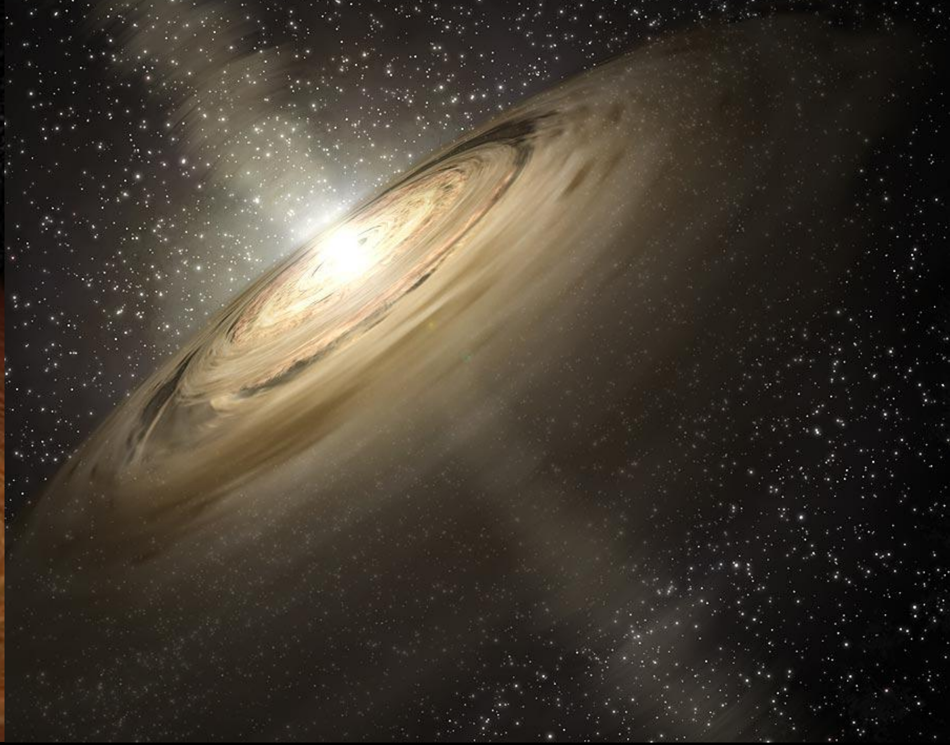
MHD Simulations of Star-disk Interactions in Young Stars & Related Systems





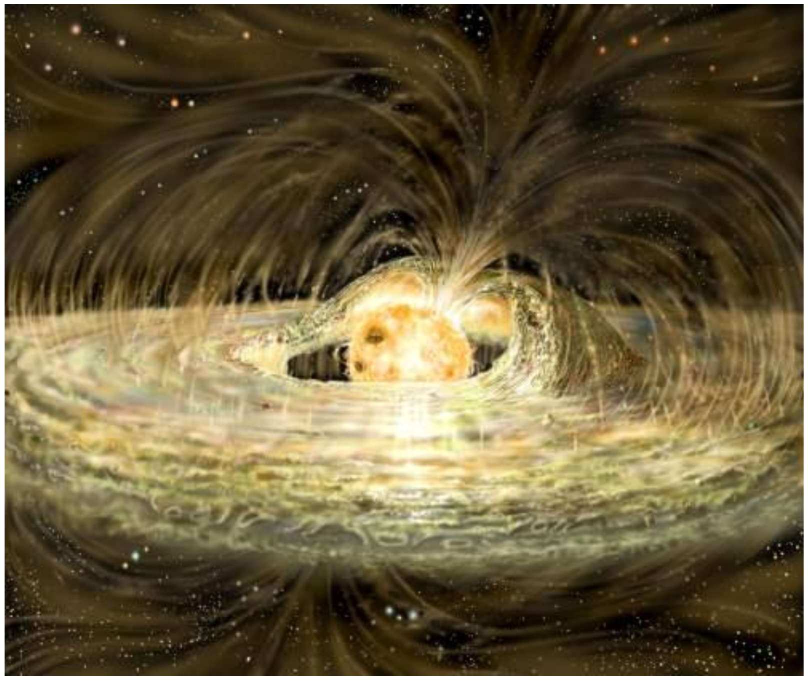
Marina Romanova, Cornell University

R. Kurosawa, P. Lii, G. Ustyugova , A. Koldoba, R. Lovelace

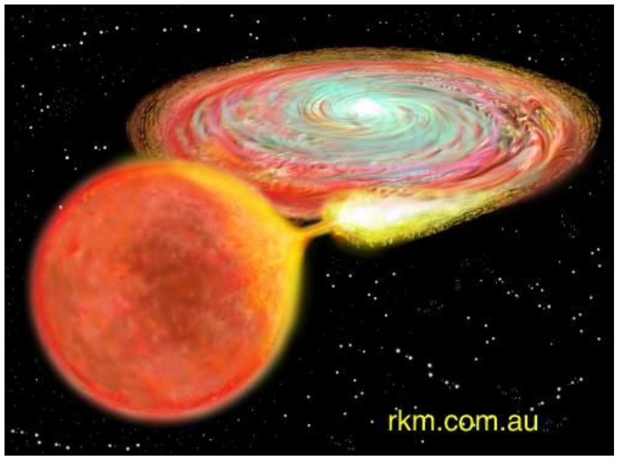
5 March 2012

Accreting Magnetized Objects

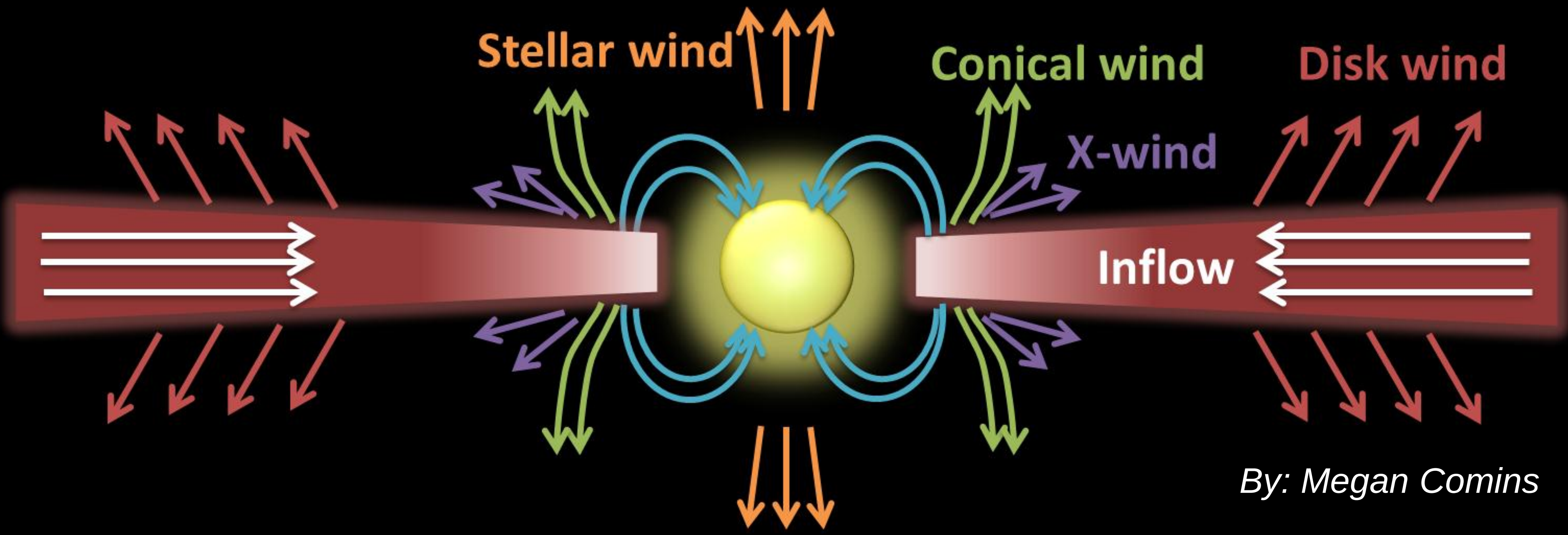
1. **Young stars**
2. Brown dwarfs
3. Neutron stars
4. White dwarfs
5. BH - possibly



Different scales, similar physics



Disk-magnetosphere interaction



By: Megan Comins

1. Accretion through funnel streams (*Ghosh & Lamb 1978*)
2. Disk wind (*Blandford & Payne 1982*) – centrifugally driven
3. X-wind (*Shu et al. 1994*) – centrifugally-driven
4. Conical winds (*Romanova et al. 2009; Lii et al. 2011) -* magnetically-driven (*Lovelace et al. 1991)*
5. Stellar winds (*Matt & Pudritz 2005*)

Outline:

1. Simulations of magnetospheric accretion
2. Simulations of outflows from the disk-magnetosphere boundary
3. Spectral analysis and comparisons with observations

Numerical Models:

Different MHD codes: 2.5D, 3D, ideal, non-ideal, Godunov-type (*Koldoba, Ustyugova 2002-2012*)

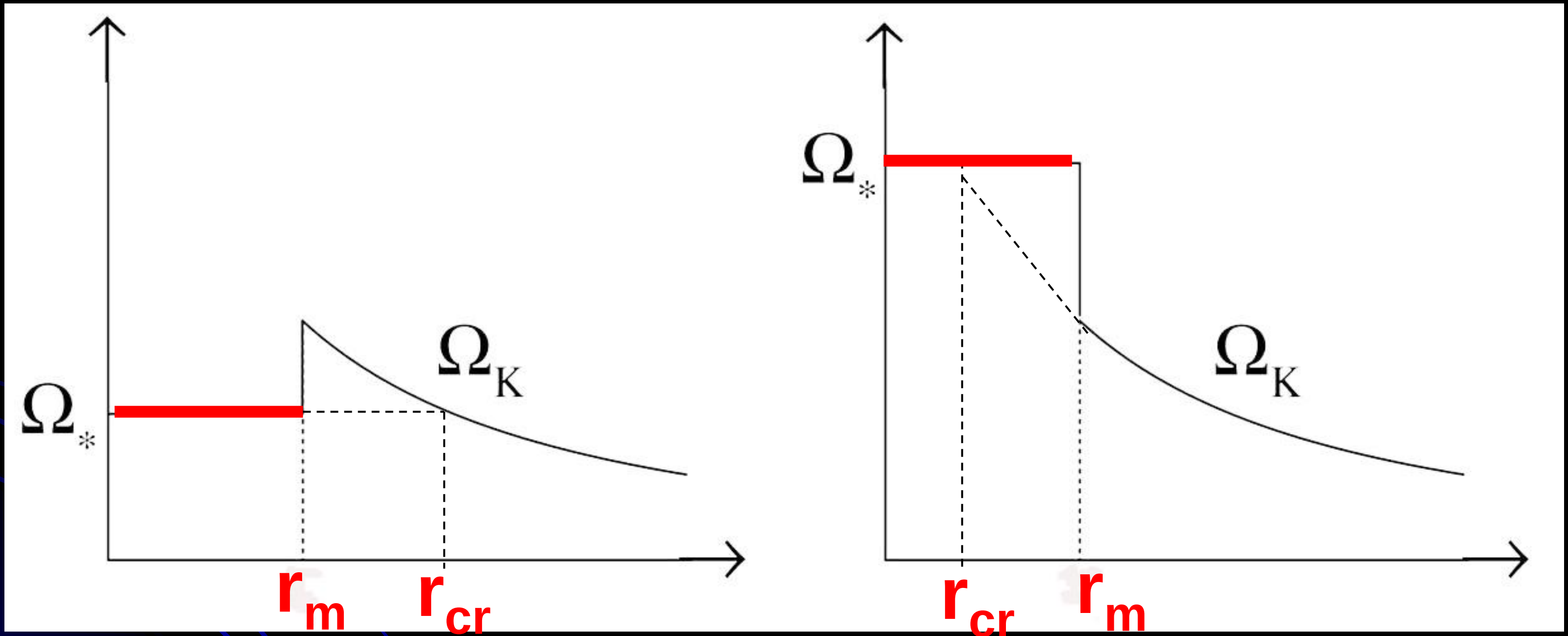
Grids: spherical, cylindrical, “cubed sphere”

Disk: α- disks (α_{vis} , α_{dif}) or MRI-driven disks

Spectrum calculations: 3D radiative transfer code TORUS with restructuring grid (*Harries et al. 2002)*, He – *Kurosawa et al. 2011*

Magnetospheric Accretion

Accretion / "Propeller" regime

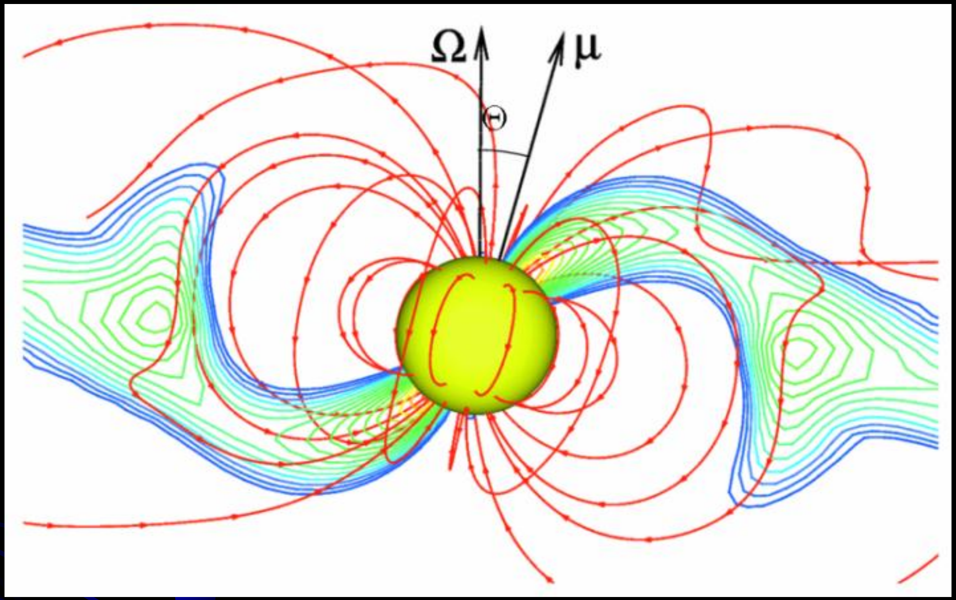


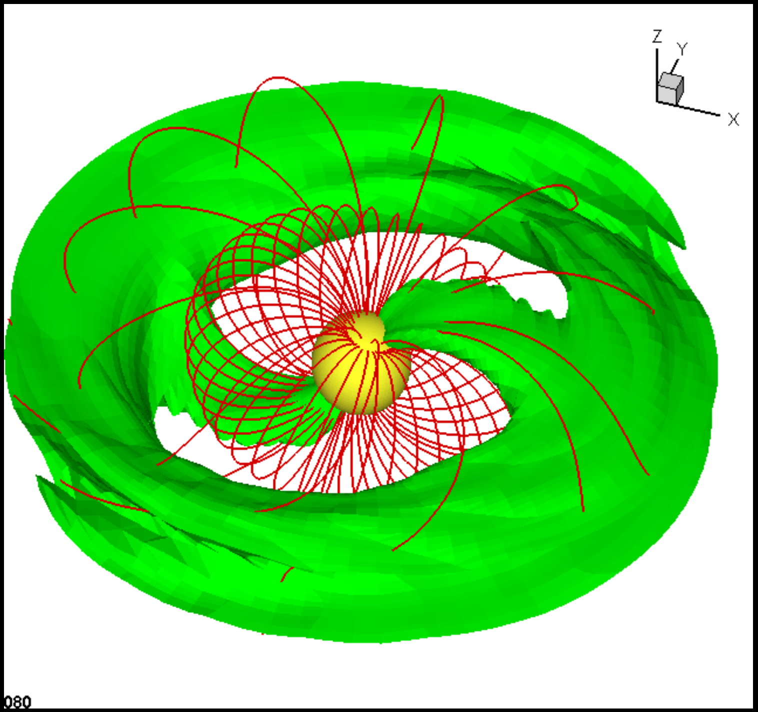
$r_{cr} > r_m$

$r_{cr} < r_m$

3D simulations of accretion onto tilted dipoles

Laminar, non-turbulent, α-type disk, , α=0.02



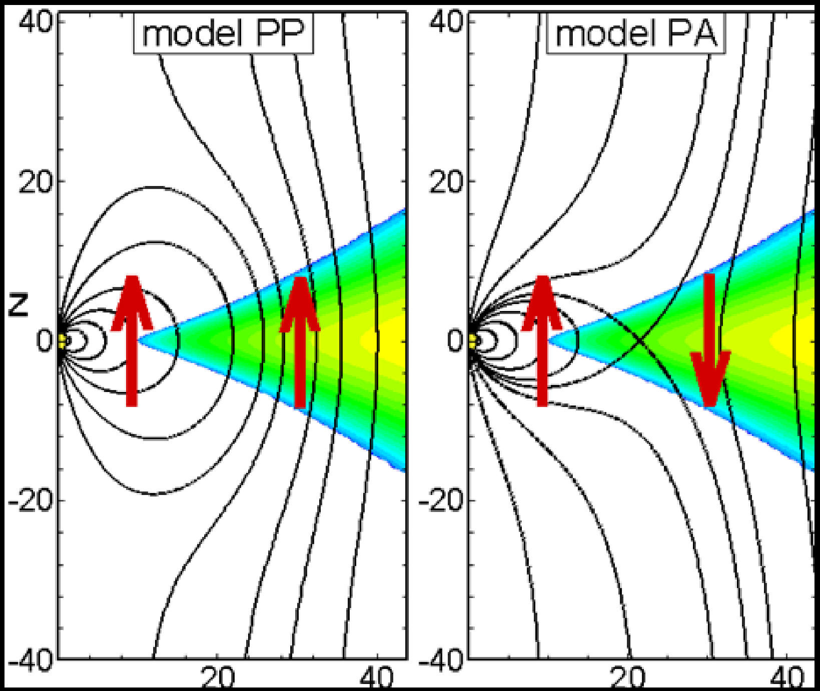


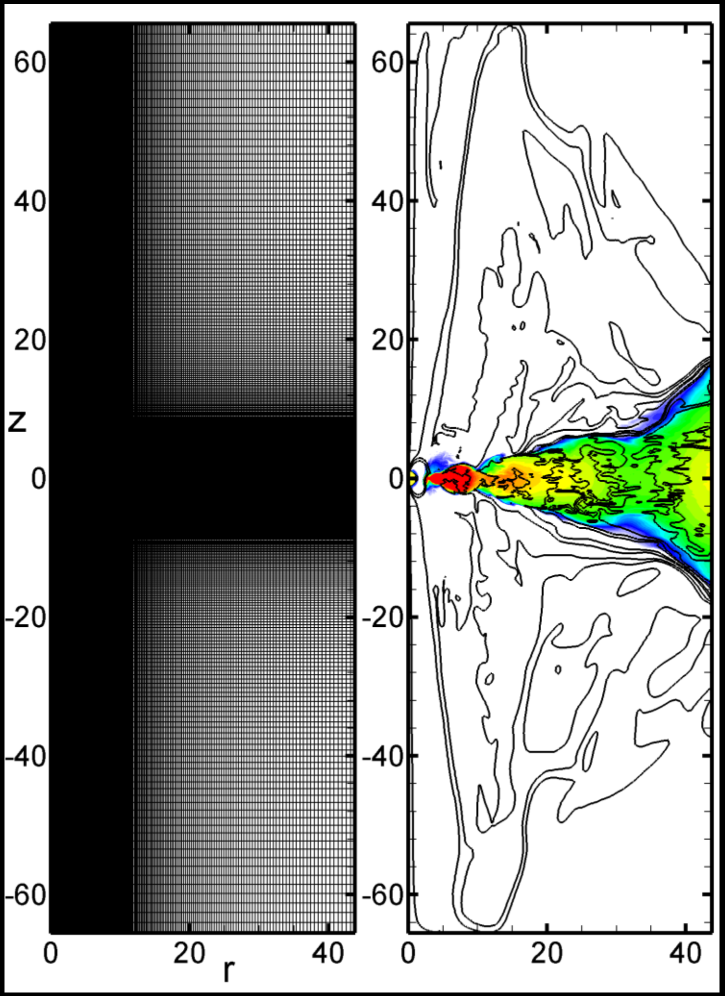
- Slice of density distribution
- Selected field lines

- Small part of the region
- One of density levels

Romanova, Ustyugova, Koldoba & Lovelace 2003,2004

MRI-driven Accretion onto Magnetized Stars



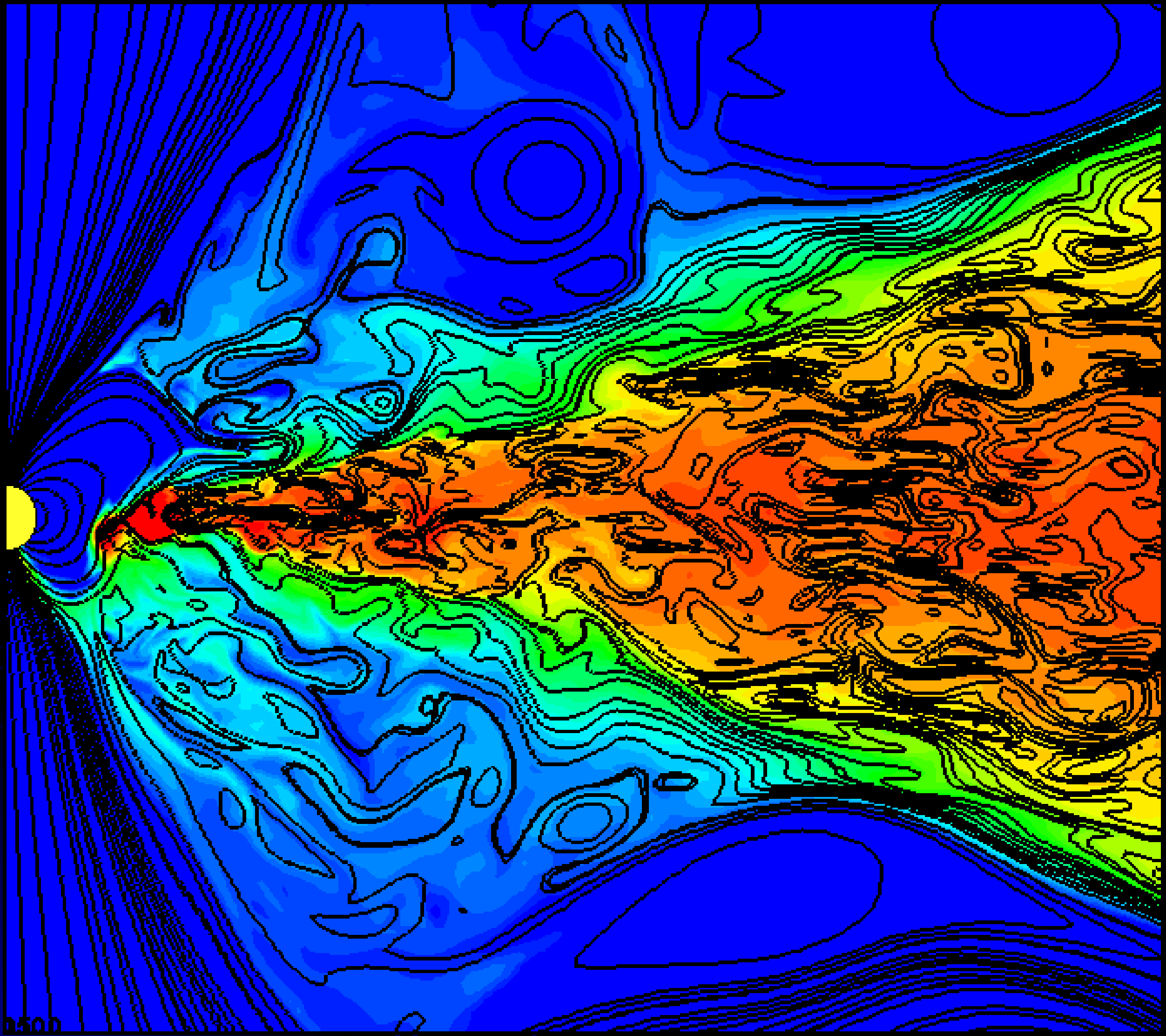


- Magnetized star
- High grid resolution: 270x432
- Axisymmetric & 3D MHD

MRI-driven accretion: *Balbus & Hawley 1991* + > 20 years of modeling
Hawley, Stone, Gammie – non-magnetized object

Romanova, Ustyugova, Koldoba, Lovelace 2011

2.5D simulations of MRI-driven accretion

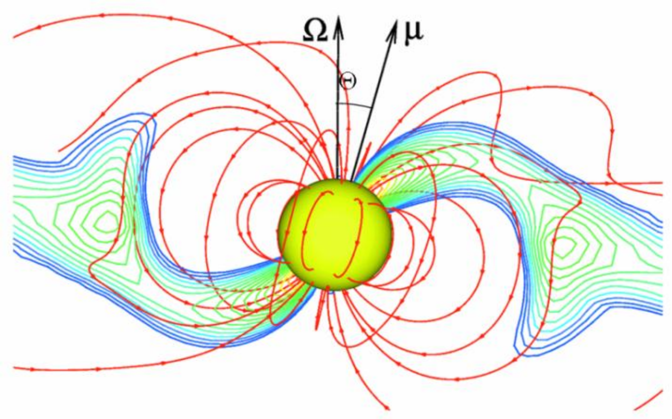


Long simulations.
For T Tauri stars:
----
1 min = 60 days

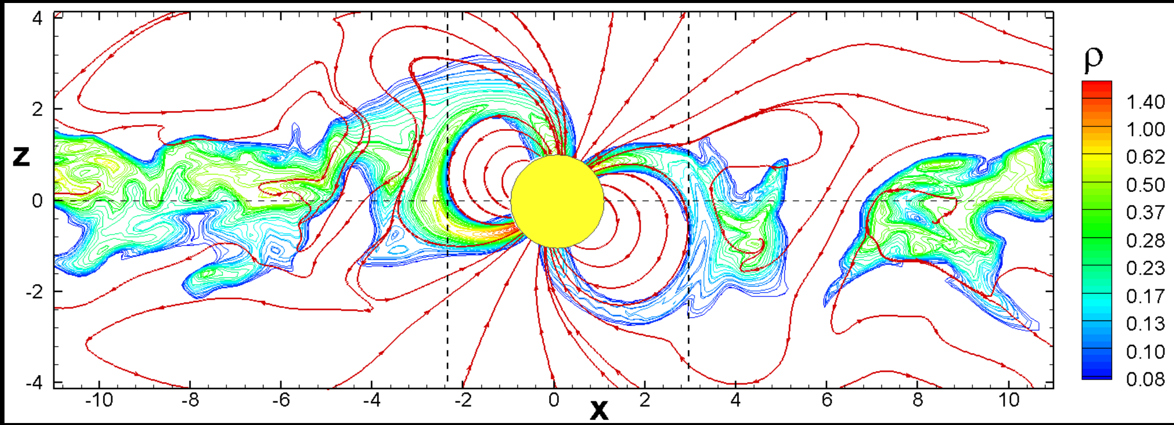
- No viscosity or diffusivity in the code
- MRI turbulence provides α_{vis}=0.02-0.06

Romanova et al. 2011

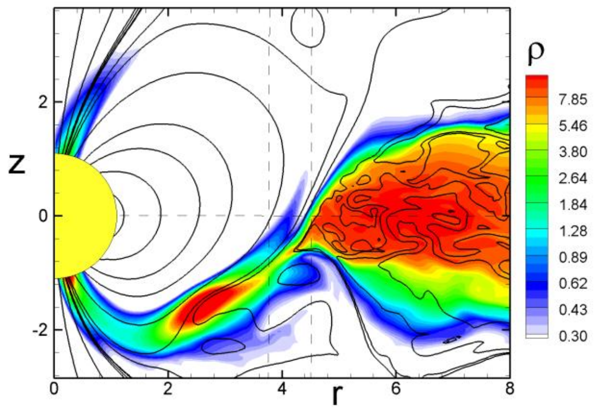
Summary of 2D and 3D Simulations :



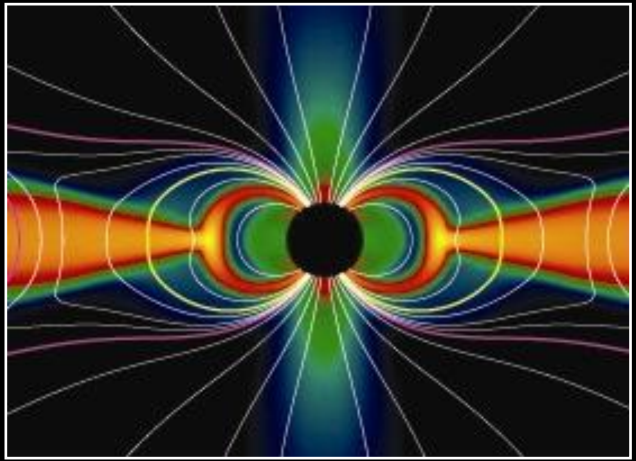
3D MHD, α-disk, Romanova et al. 2004



3D MHD, MRI disk, Romanova et al. 2012



2D, MRI disk Romanova et al. 2011

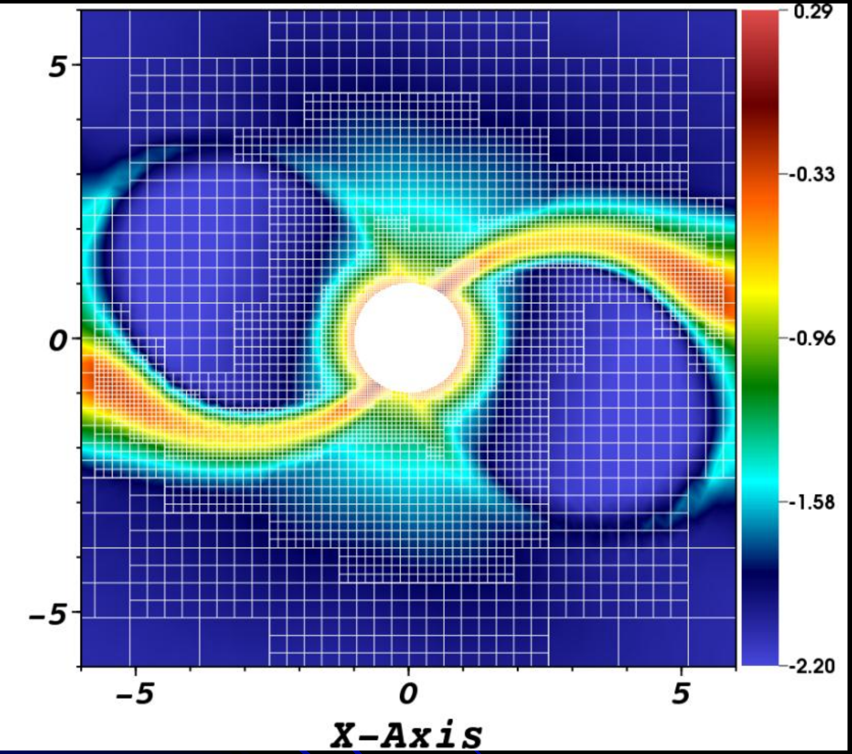


From : *Zanni et al. 2007*

The disk stops where stresses are equal: **$P+\rho v^2=B^2/8\pi$**

Romanova, Ustyugova, Koldoba, Lovelace 2002-2012

Testing the Magnetospheric Accretion



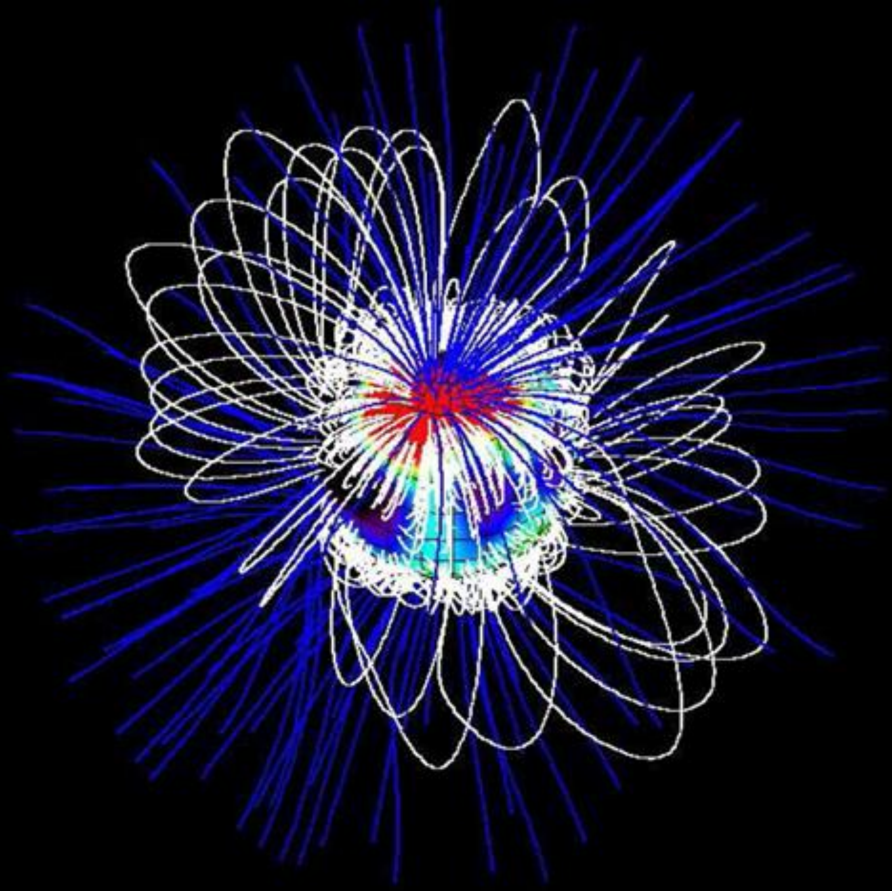
Ryuichi Kurosawa

1. Perform MHD simulations
2. Project our MHD data to the TORUS grid
3. Spectrum in H and He lines
4. Compare with observations

Kurosawa, Romanova, Harries 2008, 2011; TORUS -Tim Harries

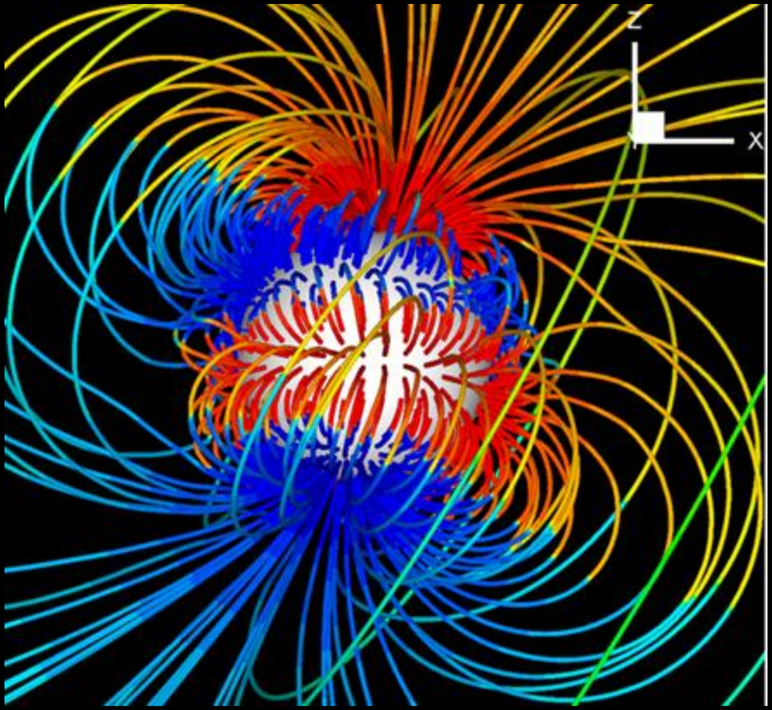
Magnetic Field of V2129 Oph

The magnetic field of the



Donati et al. 2007

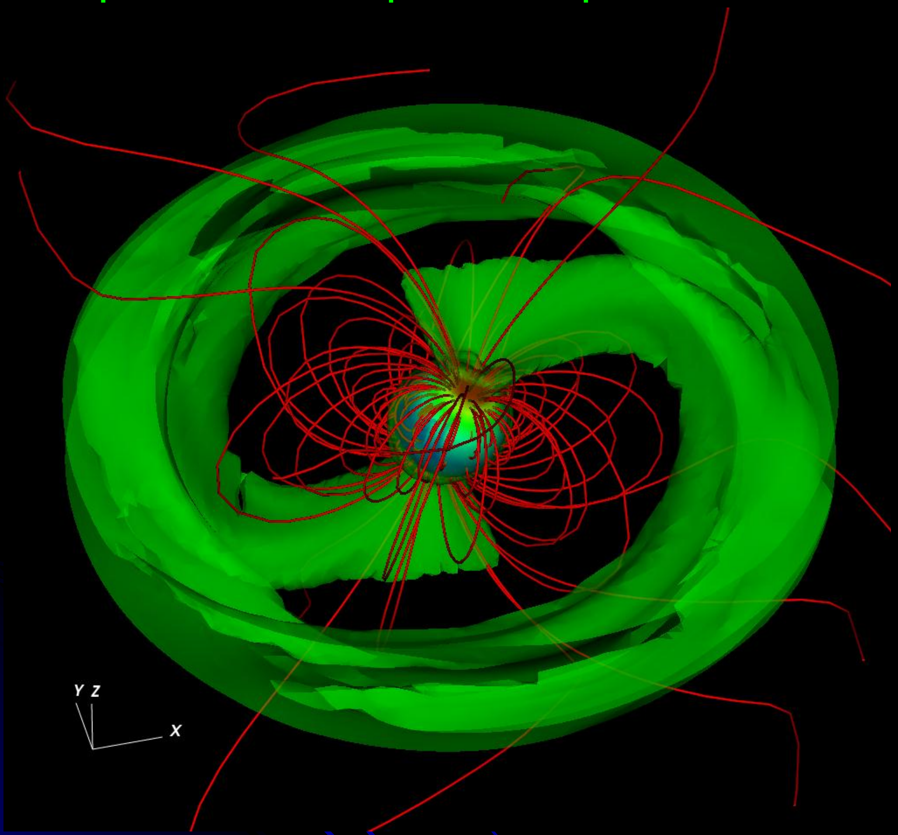
3D field of V2129 modeled with 1.2 kG octupole and 0.35 kG dipole fields



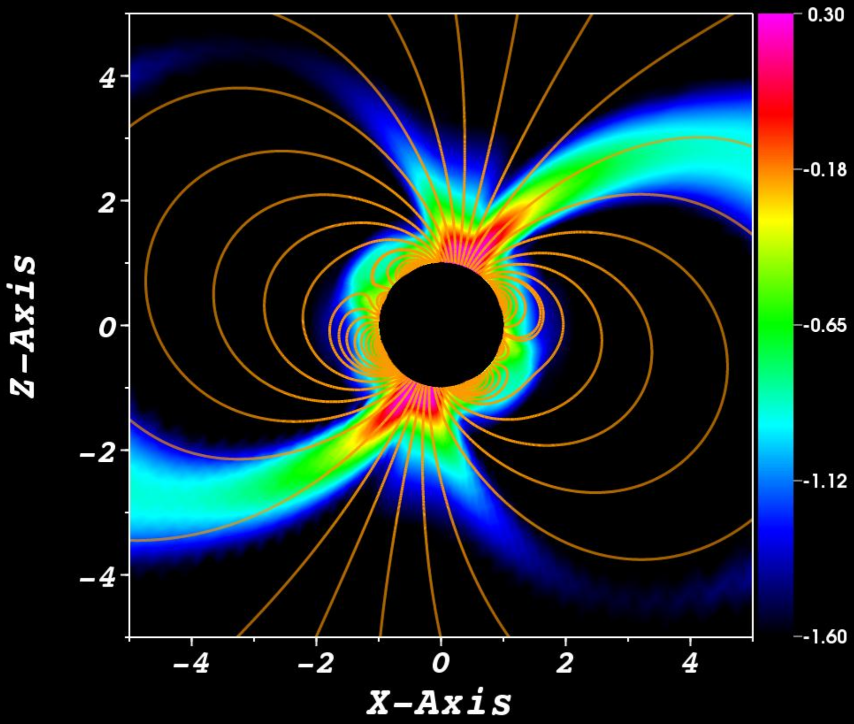
Long et al. 2010   Romanova et al. 2010

Application of model to T Tau star V2129 Oph

Dipole and octupole components

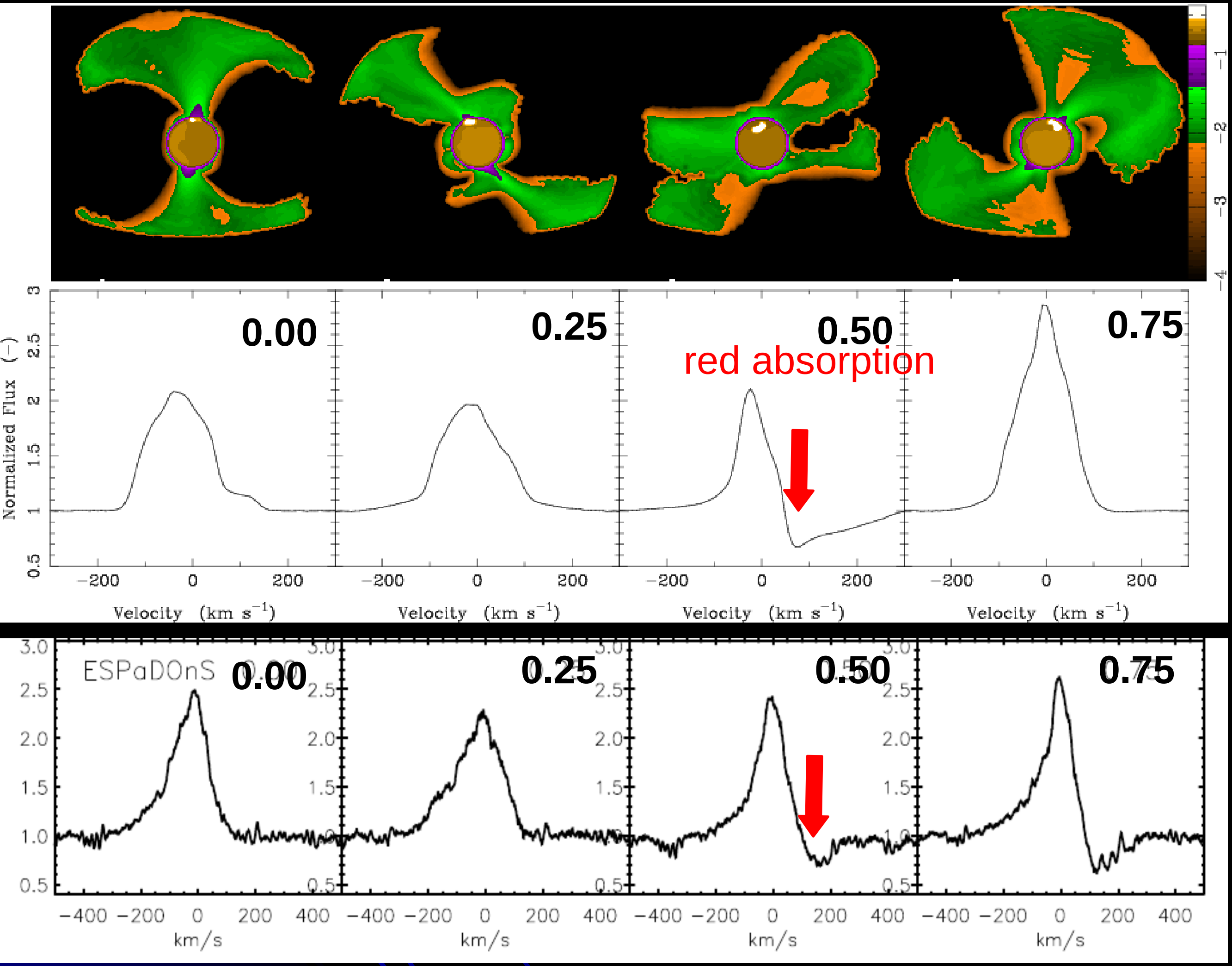


Density map and B field lines on X-Z plane



- Calculated 3D MHD flow
- Calculate spectrum in Hydrogen lines using 3D code TORUS
- Compared spectrum with observations

Modeling of T Tauri V2129 Oph: Spectrum



Flux map in Hβ

Calculated spectrum

Hβ Profiles

Observed spectrum

Hβ Profiles

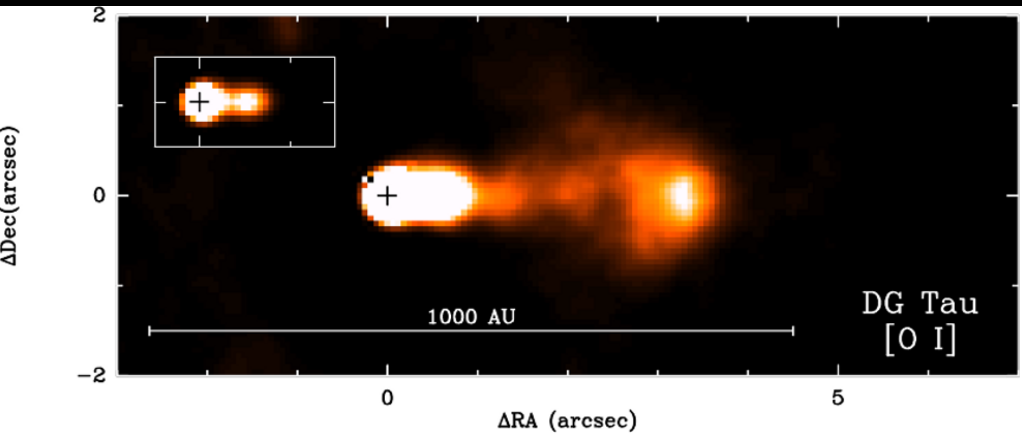
Alencar et al. 2011

We have a 3D+3D tool !

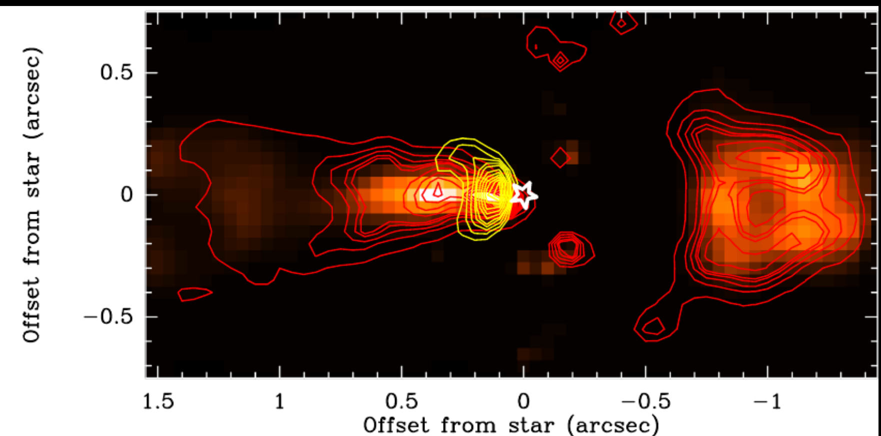
Kurosawa et al. 2008

Alencar et al. 2011

T Tauri Jets and Outflows: DG Tau



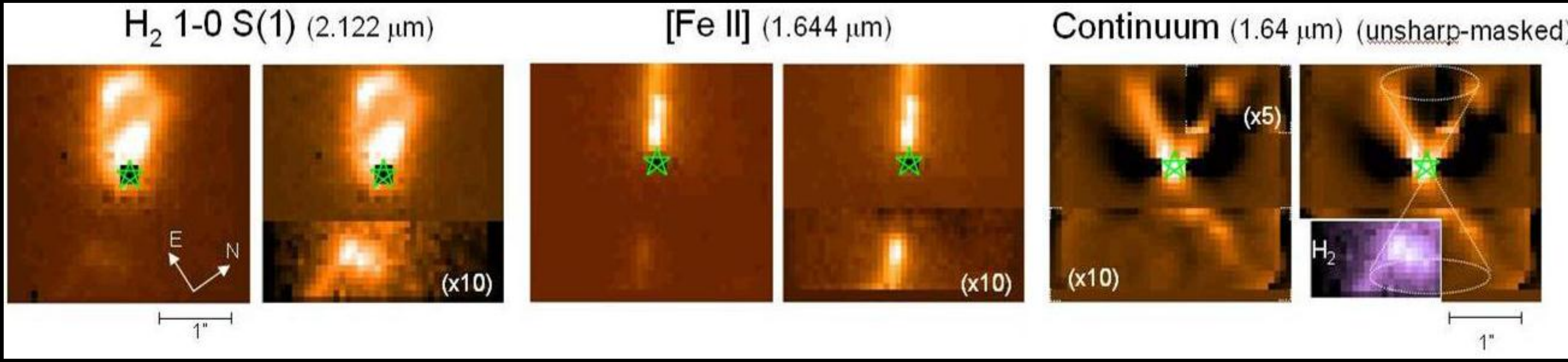
DG Tau in [O I] 6300 A line CFH telescope
(*Dougados et al. 2000*)



DG Tau in [Fe II] 1.64 μm VLT telescope
Resolution: 0.15" HV component –
200 km/s, low collimation component
traces H_2~2.212 μm, velocity 50 km/s

CTTS – a good laboratory to study launching of outflows

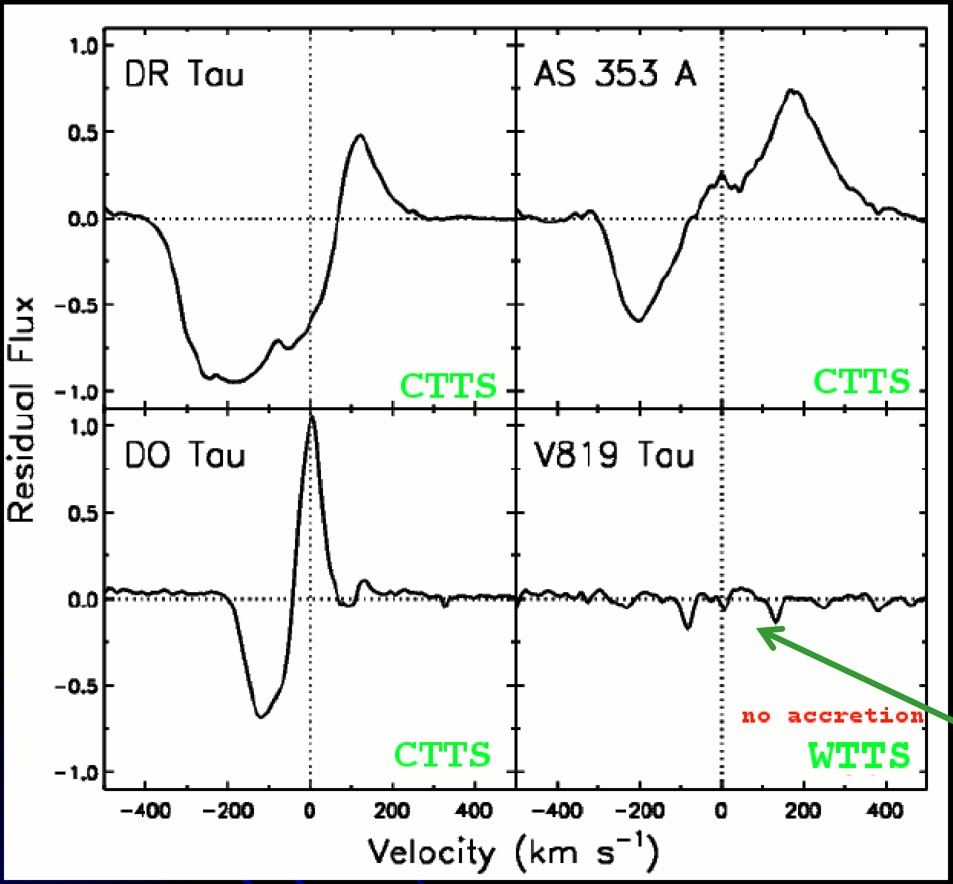
T Tauri Jets and Outflows: HL Tau



The high-resolution images of the CTTS HL Tau show that the outflow is well-collimated in the [Fe II] 1.64 μm line (two middle panels), and is less collimated H2 2.122 μm (two left panels). A conical shaped emission is observed in the continuum at 1.64 μm (two right panels). *Takami et al. (2007).*

- Fast component is collimated at R < 10AU
- 10AU – molecular gas
- Onion-skin structure at small distances

Evidence of Winds in He I λ10830 line



- Strong P-Cyg like profile – possibly stellar wind. Usually high accretion rate.

- Narrow blue-shifted feature – some type of disk wind

- No outflows – no disk

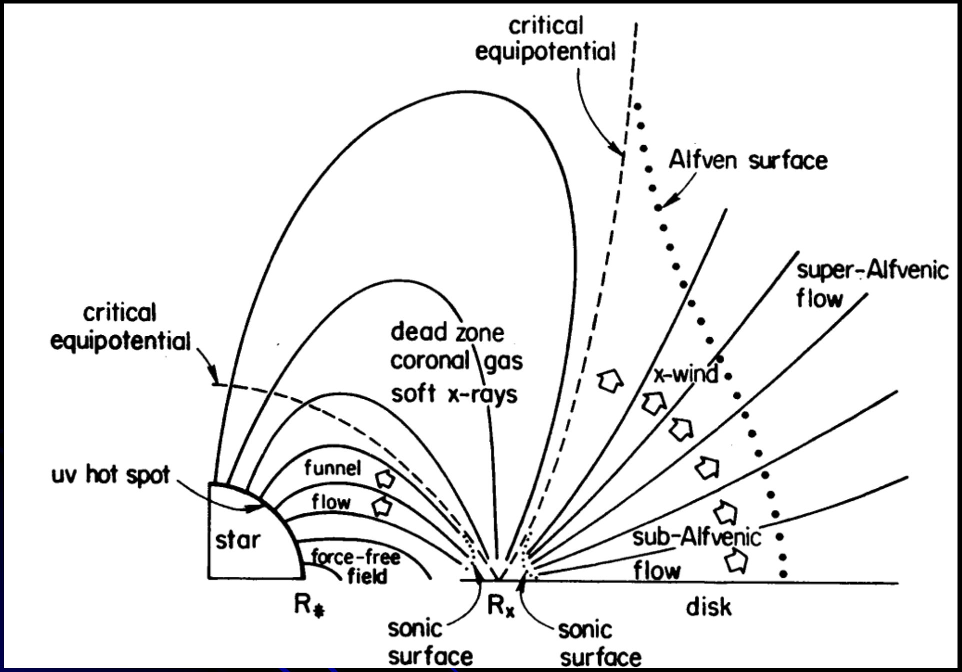
Diskless TTS
No accretion – no wind

- *Edwards et al. (2003, 2006); Kwan et al. (2007)*

- T Tau stars: can probe accretion very close to the star
- A good laboratory to investigate outflows

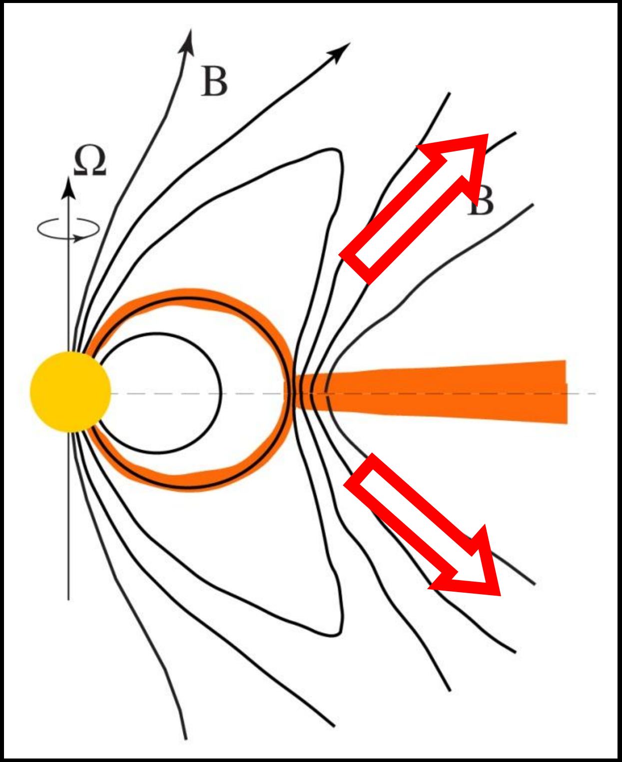
Formation of Winds: Conical Winds

Inspired by X-wind Model



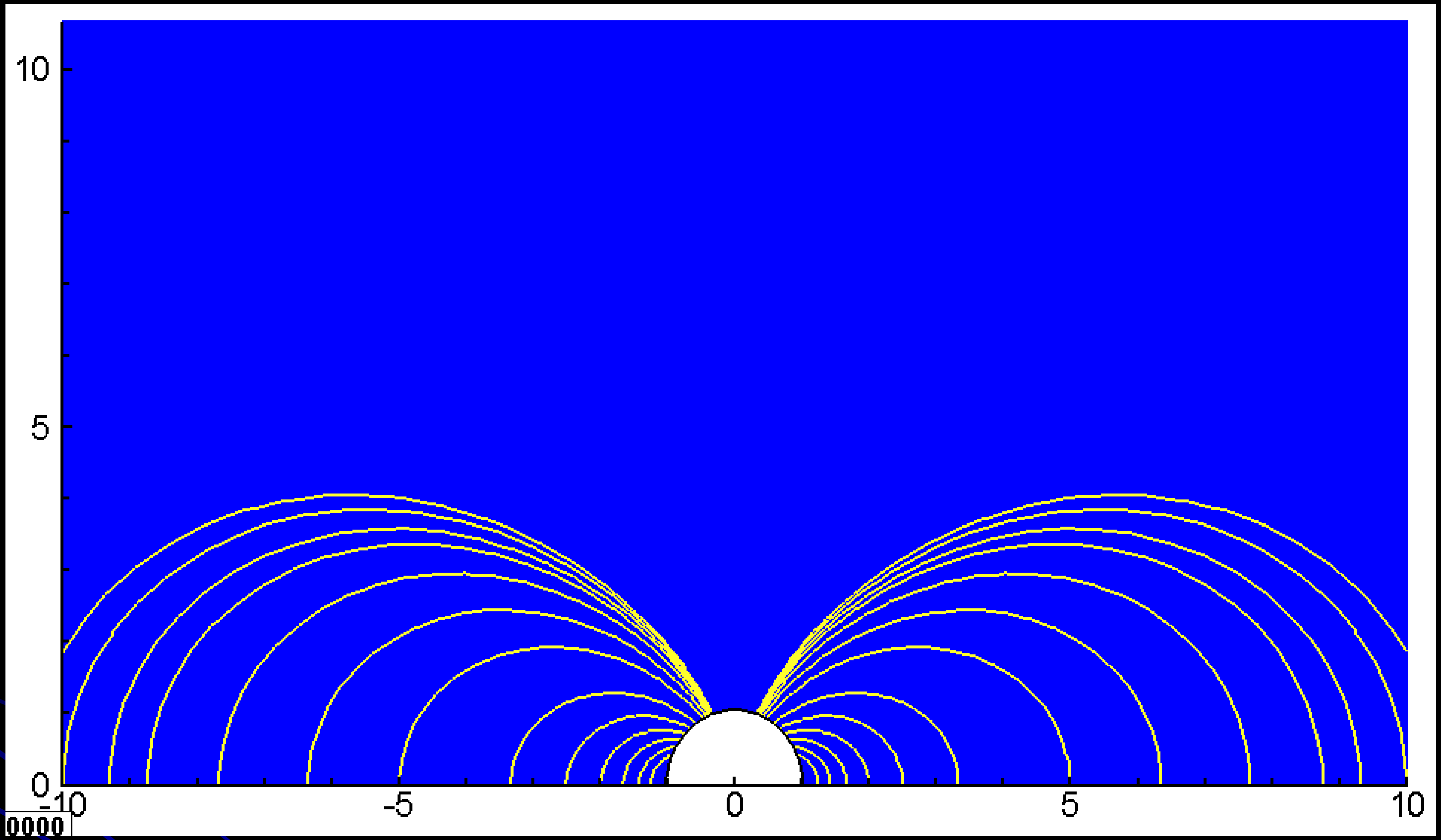
Shu et al. 1994

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



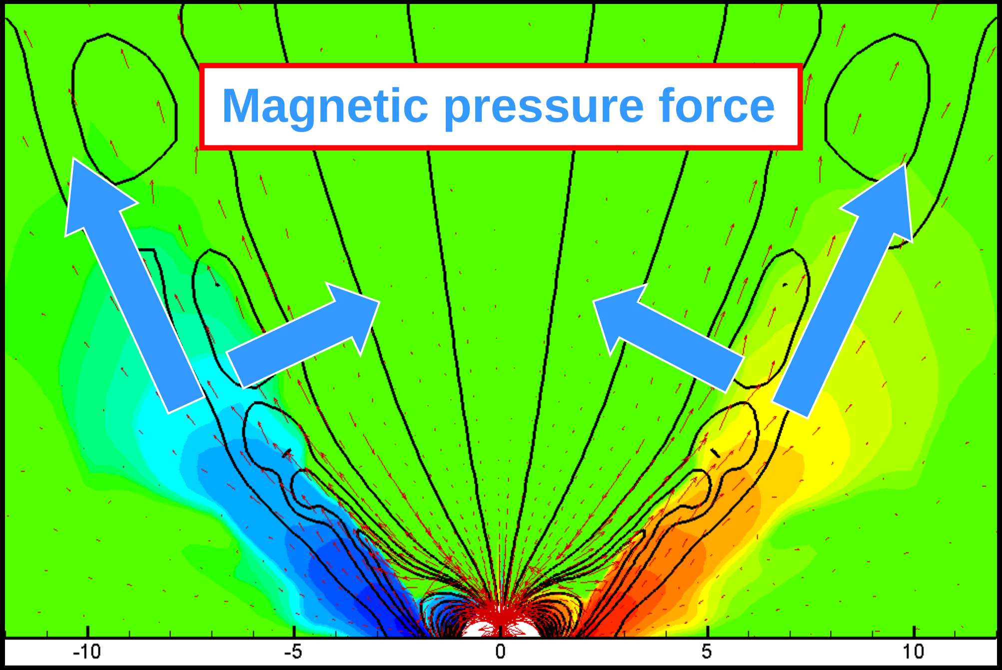
Matter inflows faster than the field diffuses out

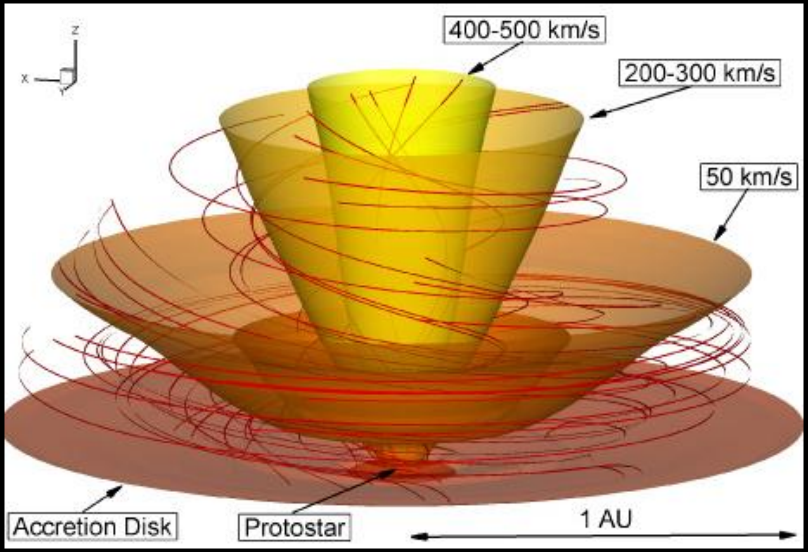
Conical Winds



- Compression of the magnetosphere – matter flows inward faster than the field lines diffuse outward
- 10-30 % of matter flows to the wind
- Somewhat similar to X-winds , but many differences

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





Magnetic force: *Lovelace et al. 1991*

3D rendering: azimuthal component

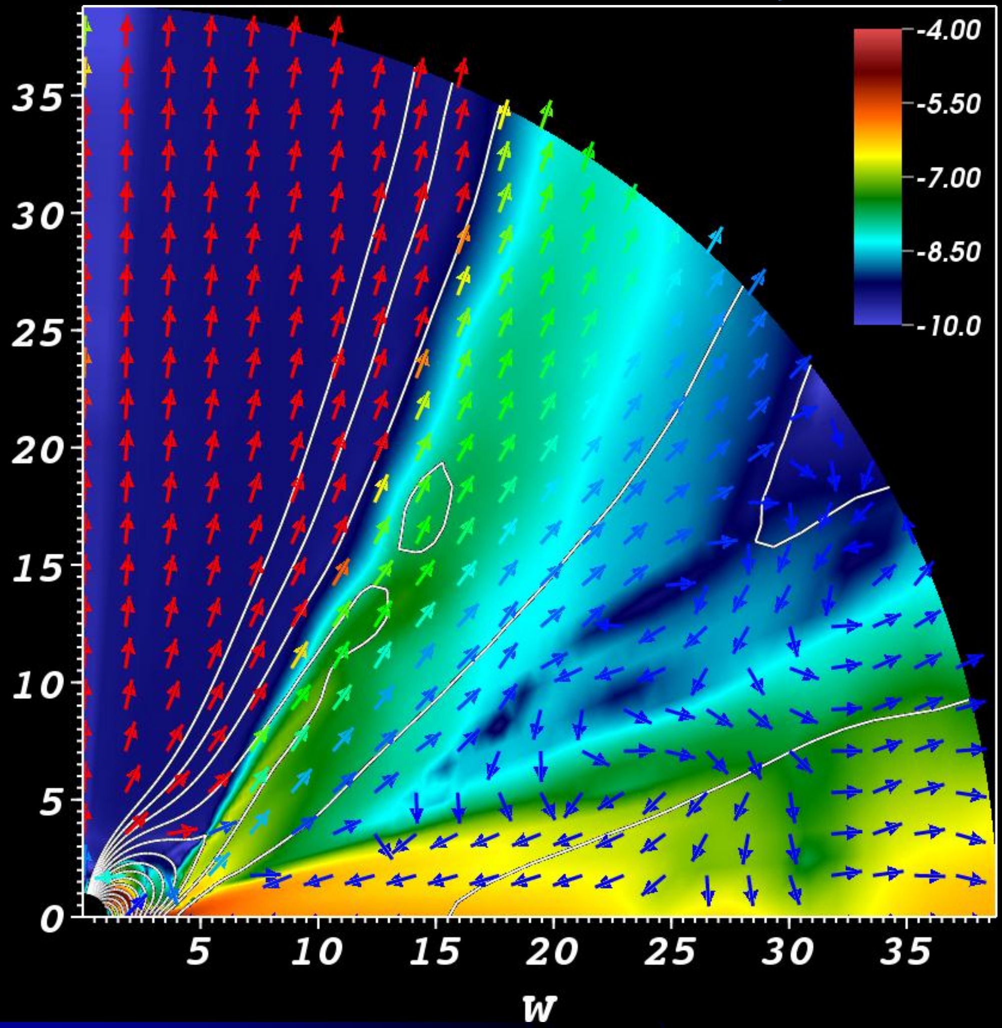
Driving force is the magnetic force:

$$F_m = k \nabla (rB_\phi)^2$$

Magnetic force determines both: acceleration and collimation

Modeling of Spectrum from Conical Winds

Poster # P23
R. Kurosawa

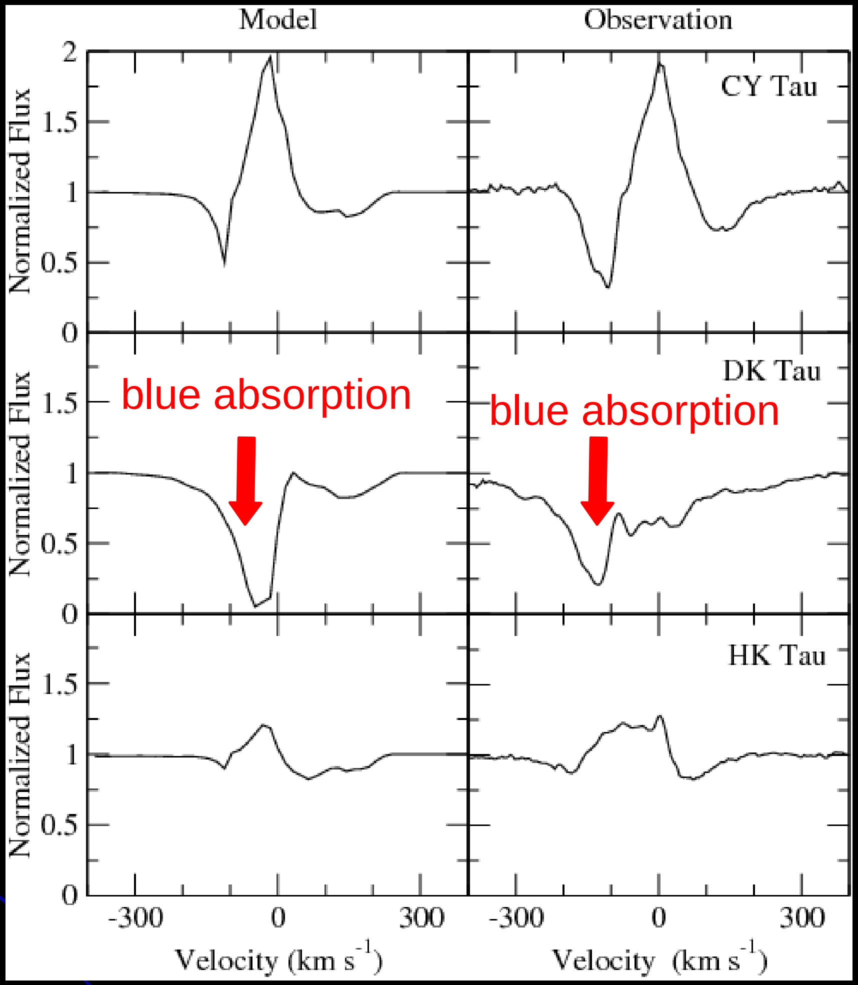


- Axisymmetric MHD simulations
- Both – funnel and winds
- Calculate He and H lines
- X-ray from the star, L_x

Kurosawa & Romanova (2012)

Comparison with Observations: He I λ10830

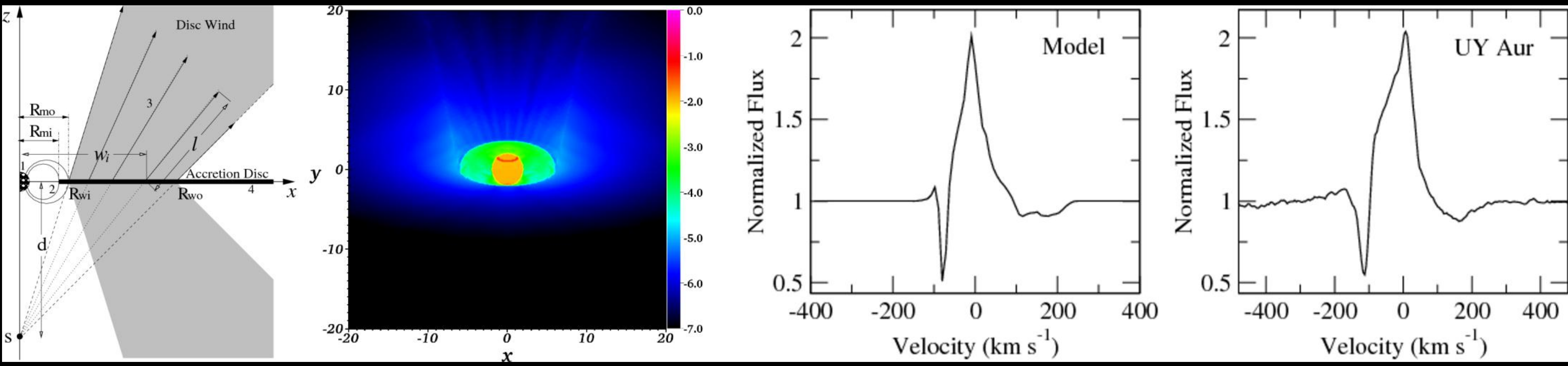
Model:



Observations
(Edwards et al. 2006)

- Examples for 3 T Tauri stars
- Varied inclination angles and L_x
- Blue absorption – conical winds

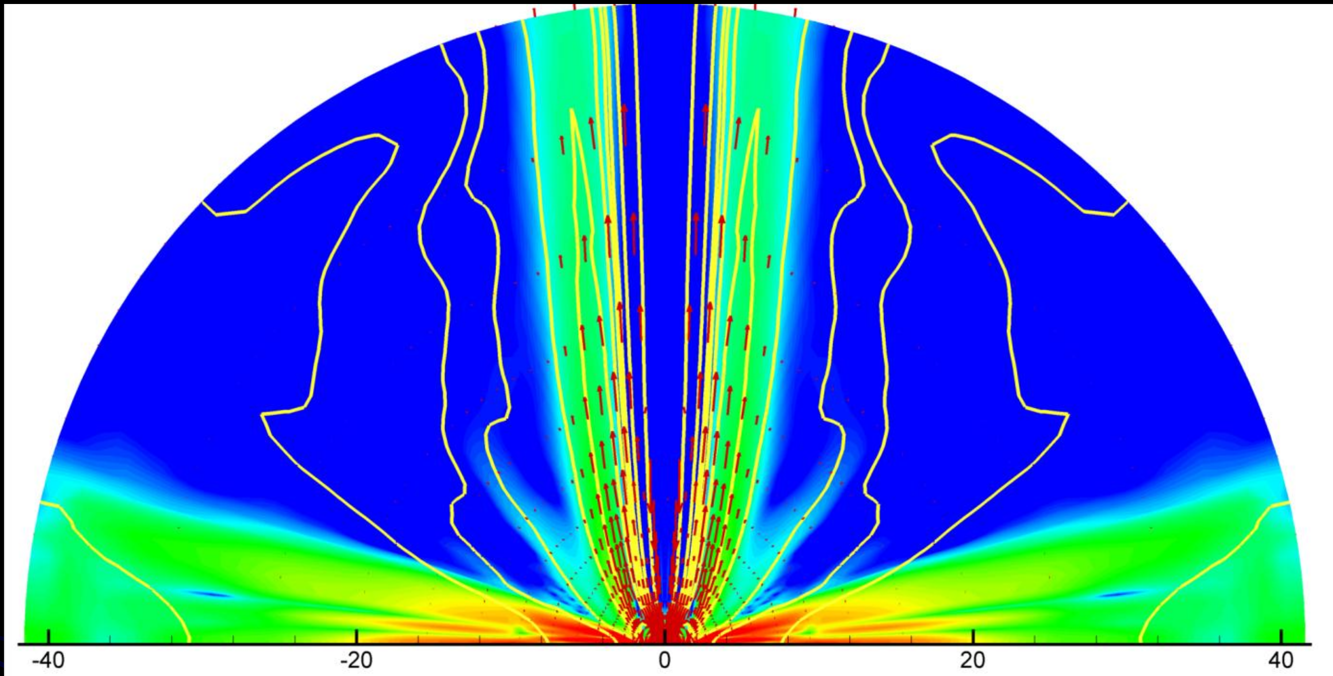
Modeling of Spectrum from Disk Winds

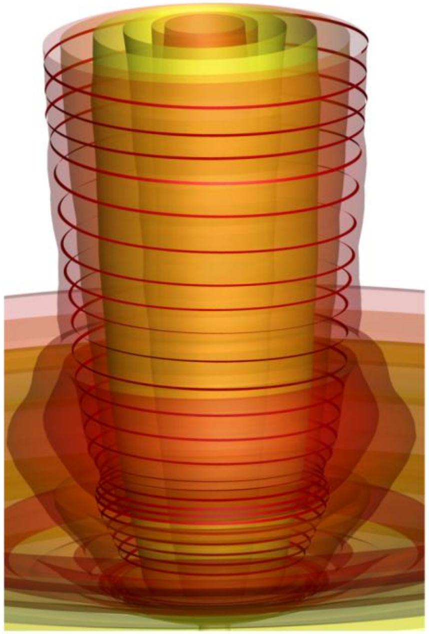


- Schematic disk wind
- Inner part of the disk is really important
- He I spectrum shows the disk feature like in conical winds

Kurosawa, Romanova Harries (2012)

Collimation – can be different



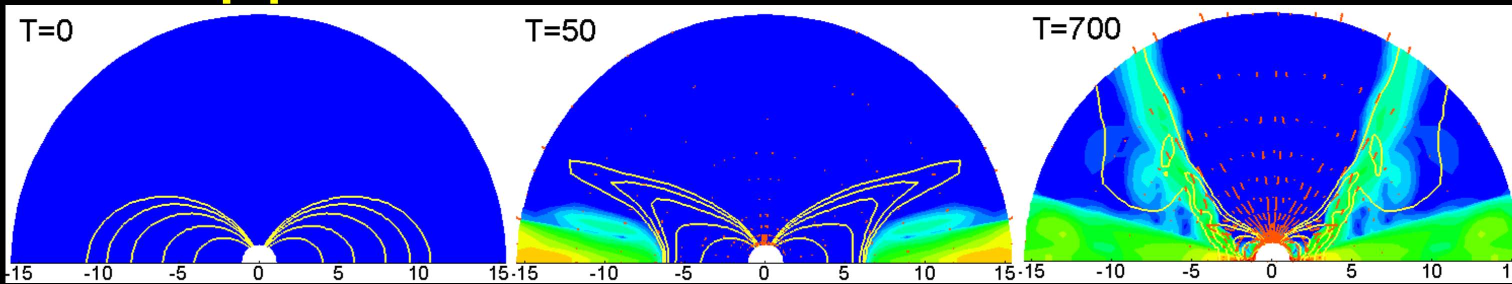


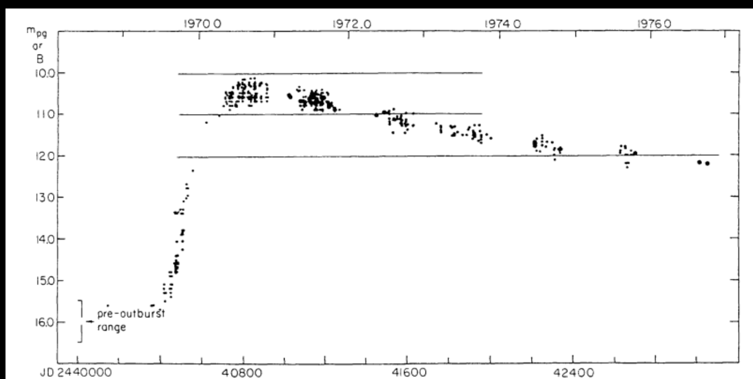
Patrick Lii, Romanova & Lovelace 2011

Analysis of forces – collimation by magnetic hoop-stress
Stronger compression – stronger collimation

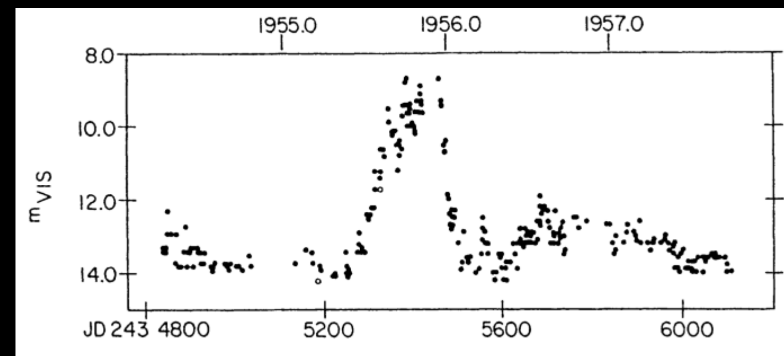
Lii, Romanova & Lovelace 2011; FU Ori: *Konigl, Romanova, Lovelace 2011*

Application to EXOrs & FUOri

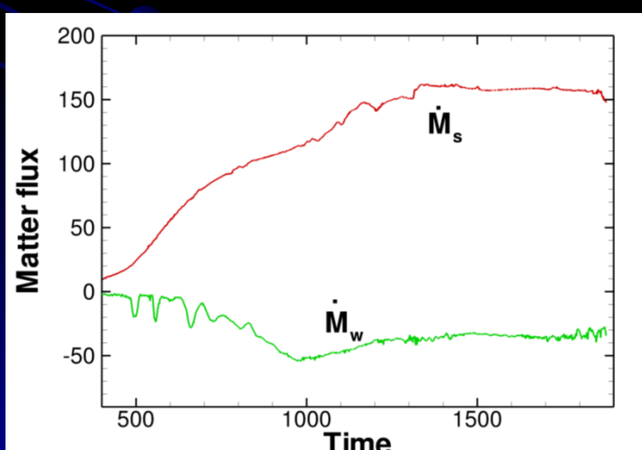


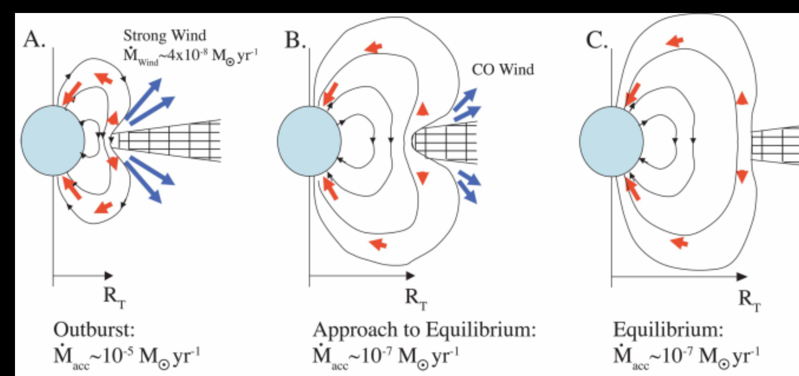


The B-light curve of V1057 Cyg (Herbig 1977)



Exor EX Lup (Herbig 1977)

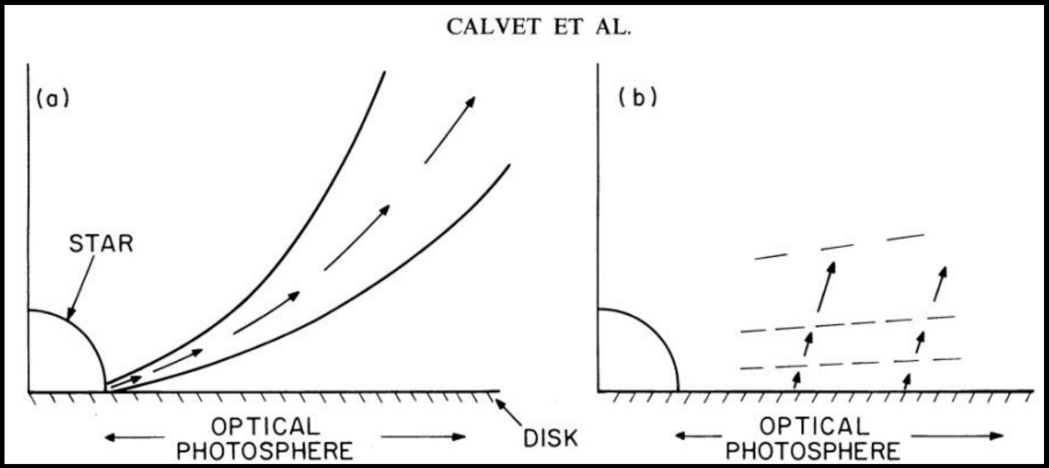




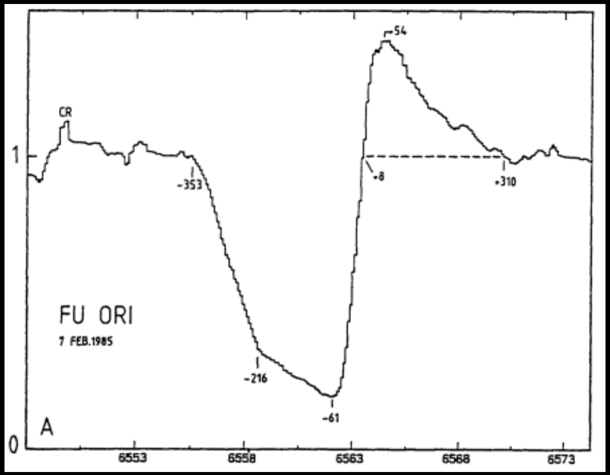
Brittain (2007)

Konigl, Romanova, Lovelace 2011

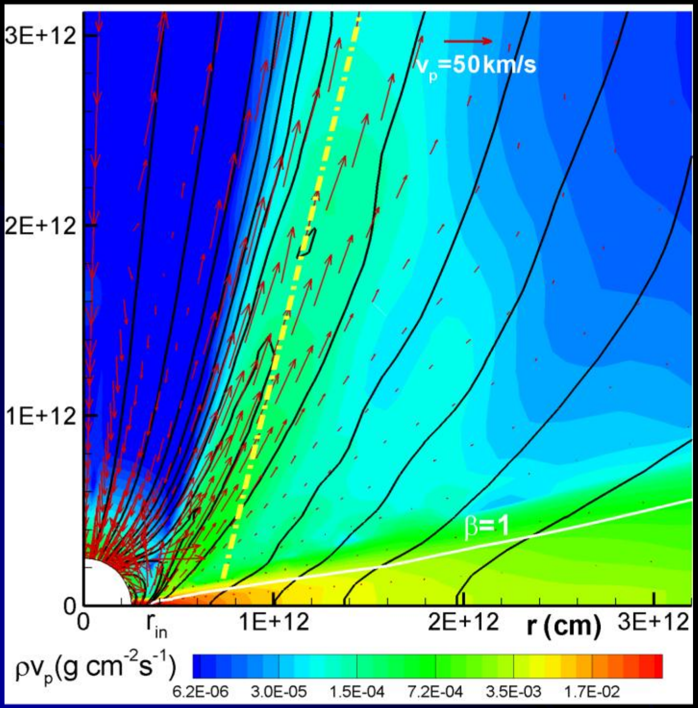
Modeling of Winds in FU Ori

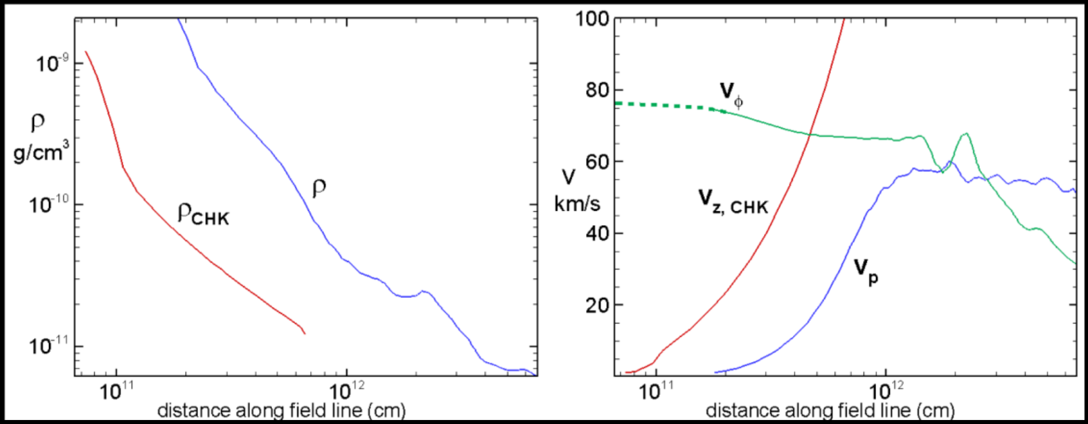


Calvet, Hartman, Kenyon 1995 – spectral model



Hα-line, Reipurth 1990

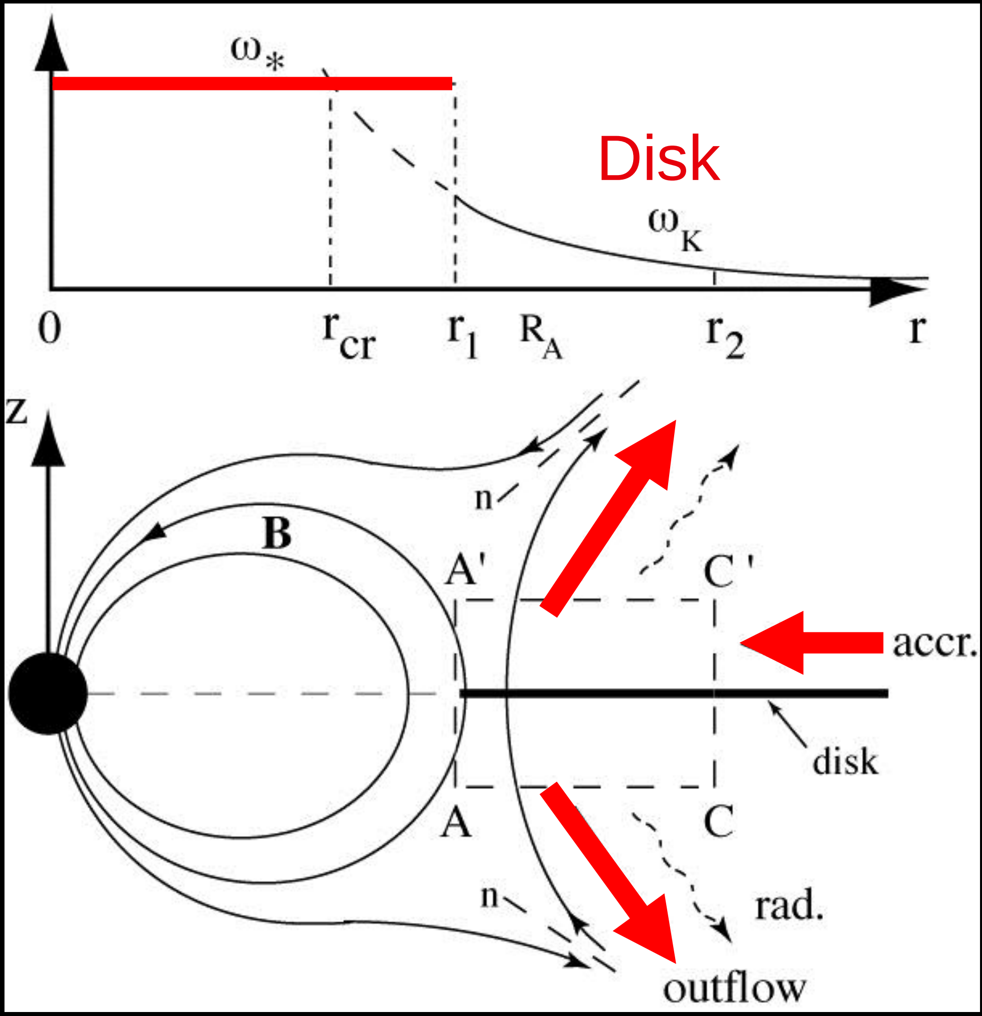




Konigl, Romanova, Lovelace 2011

Propeller Regime

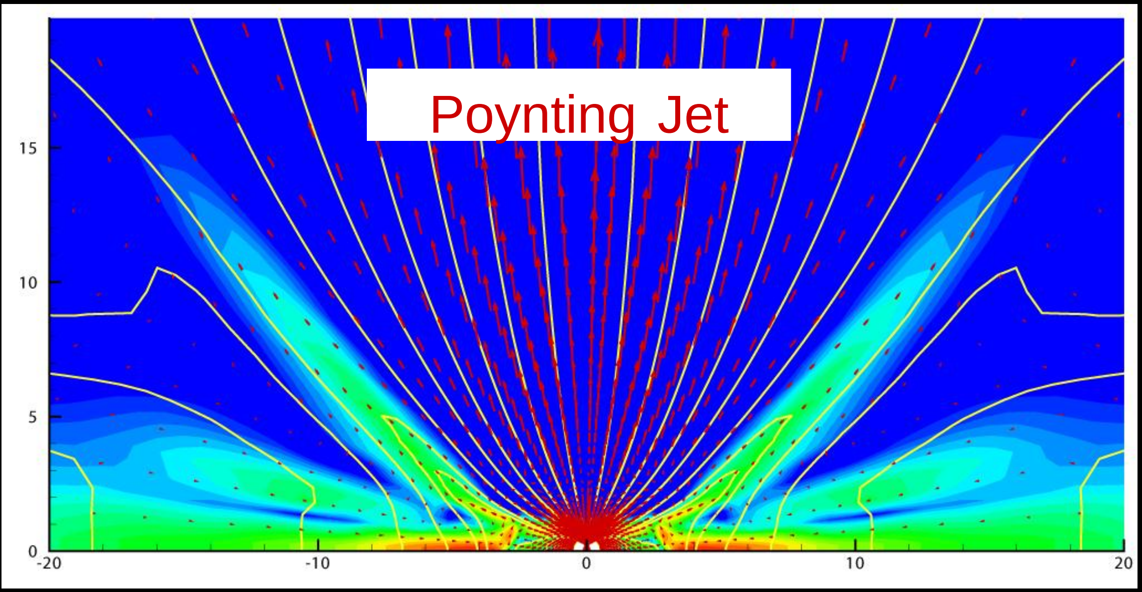
- Protostars –rotate rapidly
- Can be at the propeller regime
- Any other star can be when accretion rate decreases
- Most of matter may flow out



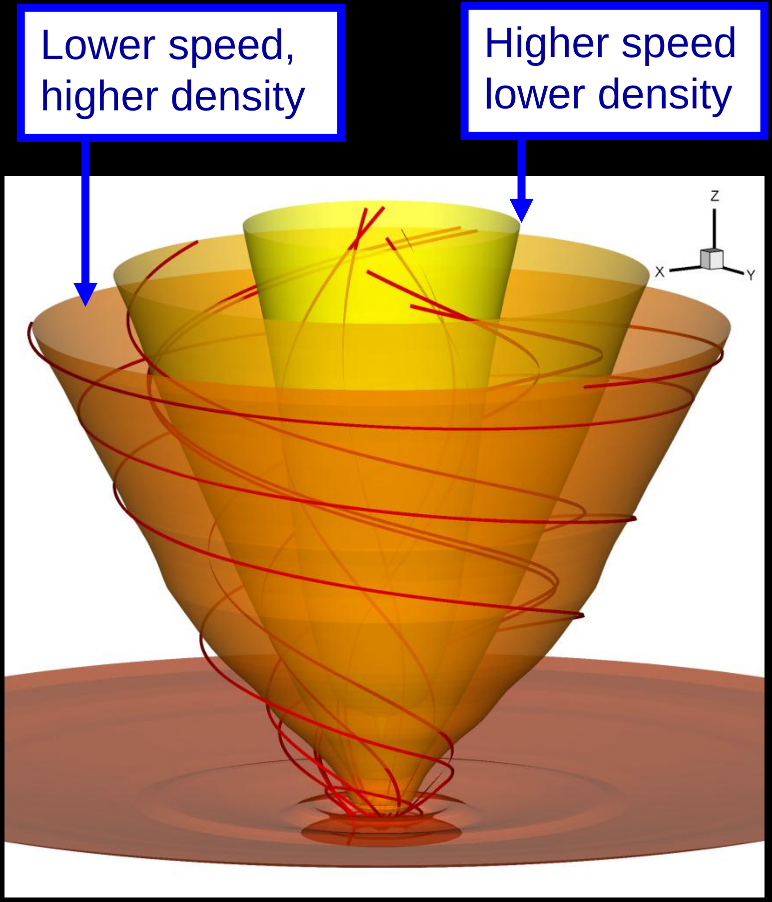
$F_c > F_G$

Illarionov & Sunyaev 1975;
Lovelace, Romanova and Bisnovatyi-Kogan (1999)

Propeller regime



- Conical Winds + Polar Jet
- Matter flows from the inner disk- centrifugally-driven
- Energy & angular momentum flow along stellar field lines
- Magnetically-driven
- Can spin-down protostar

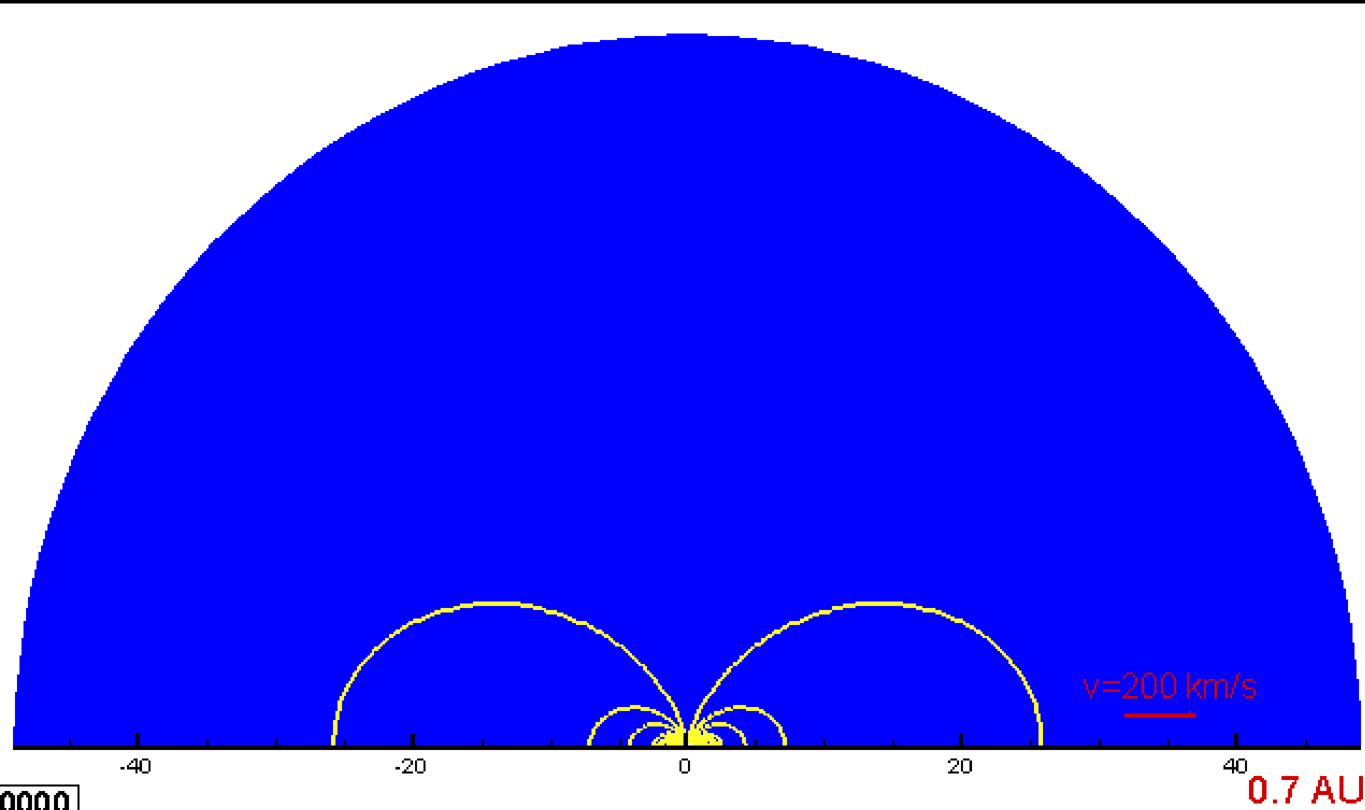


Onion-skin structure

Bacciotti et al. 2009

Romanova et al. 2005; Ustyugova et al. 2006

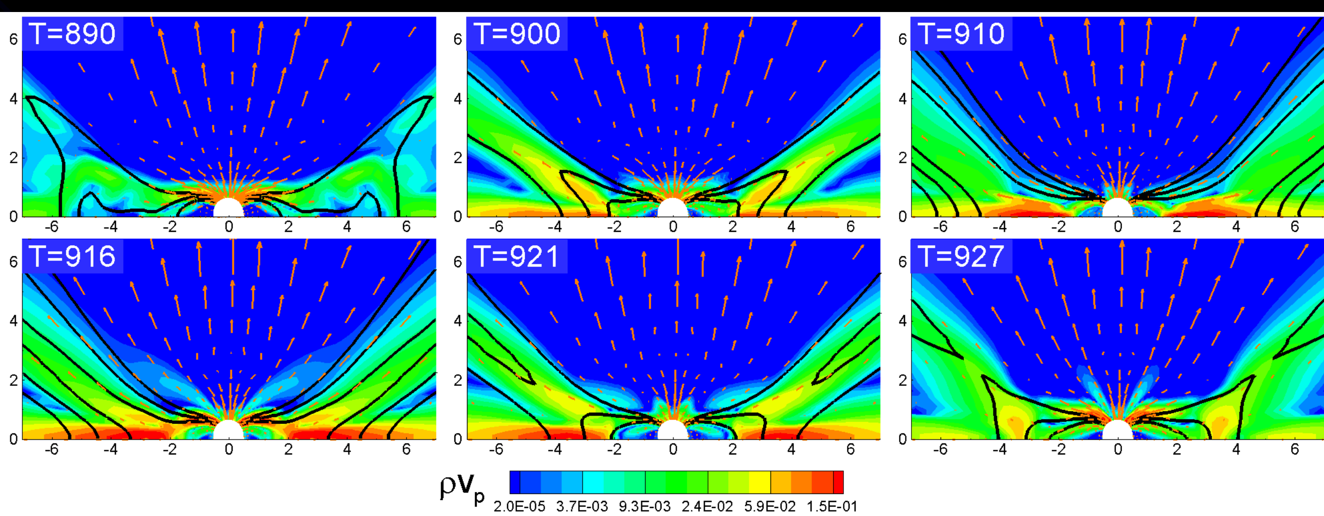
Propeller Case

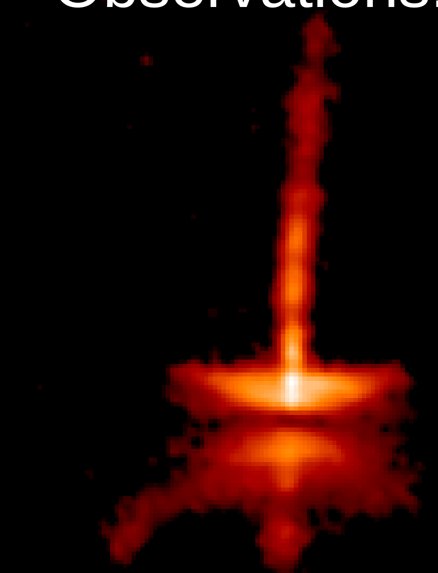


Simulations:
7 years

Major outbursts:
2 months

HST
Observations:



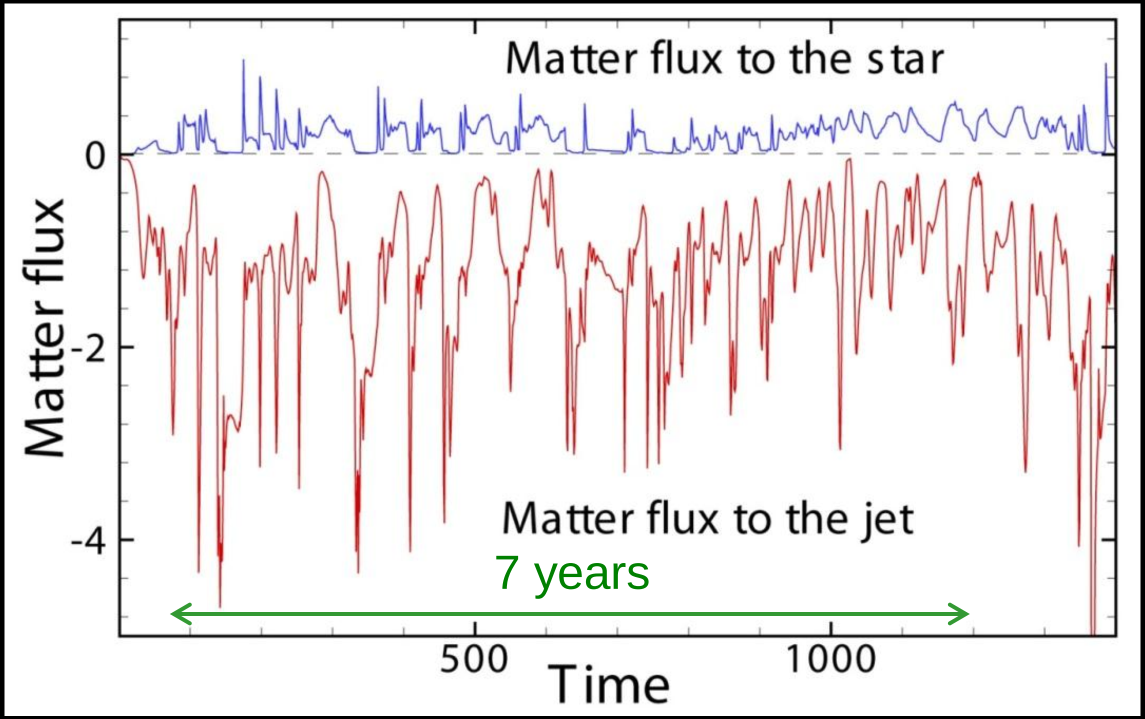


Cycle of inflation

Ustyugova et al. 2006

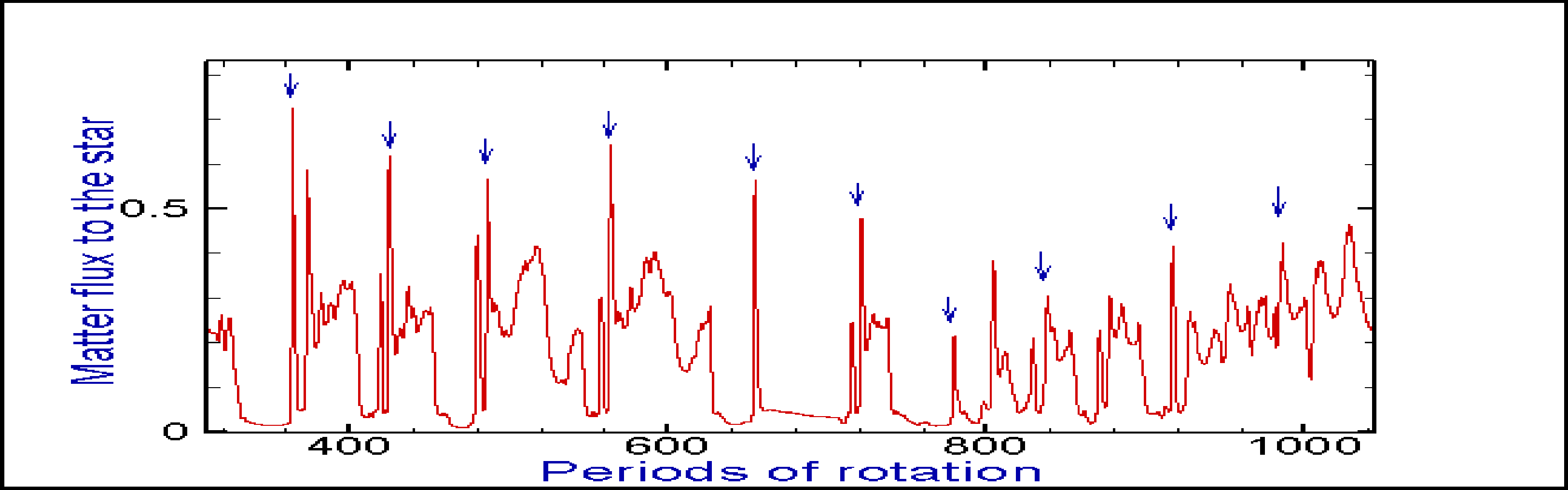
HH30

Outflows: Episodic

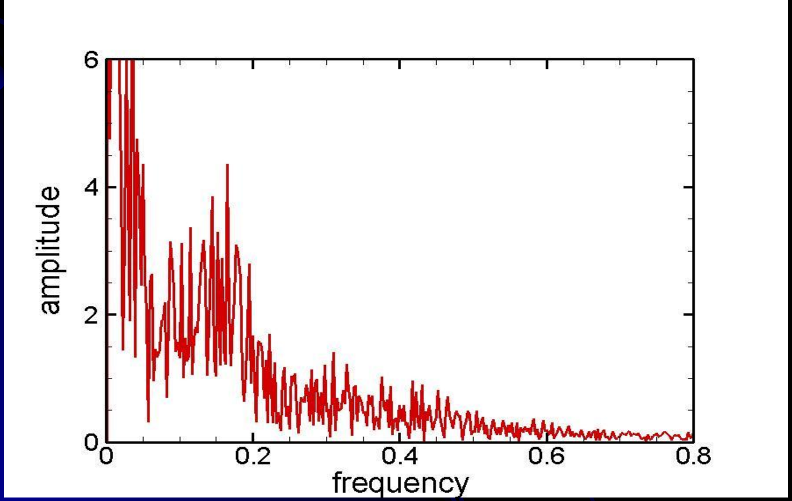


Most of matter can go to outflows

Accretion – Ejection, quasi-period



Fourier spectrum



$\nu_{QPO} = (0.02 - 0.2)\ \nu_*$

Example for CTTS:

P_{QPO} **= 10 - 100 days**

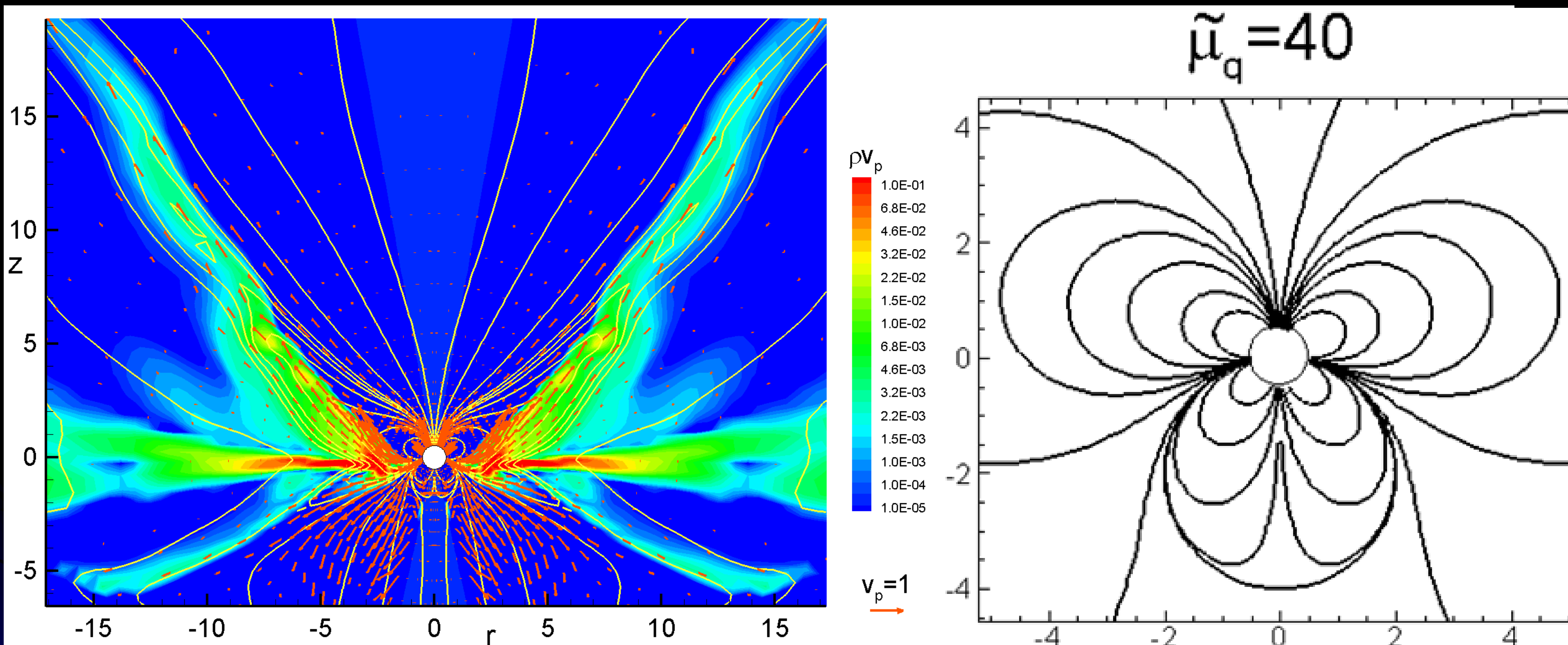
Propeller regime: 2D MRI simulations

Poster # P26
Patrick Lii

Outflows are observed!

Ustyugova, Lii, Romanova et al. 2012 (in prep)

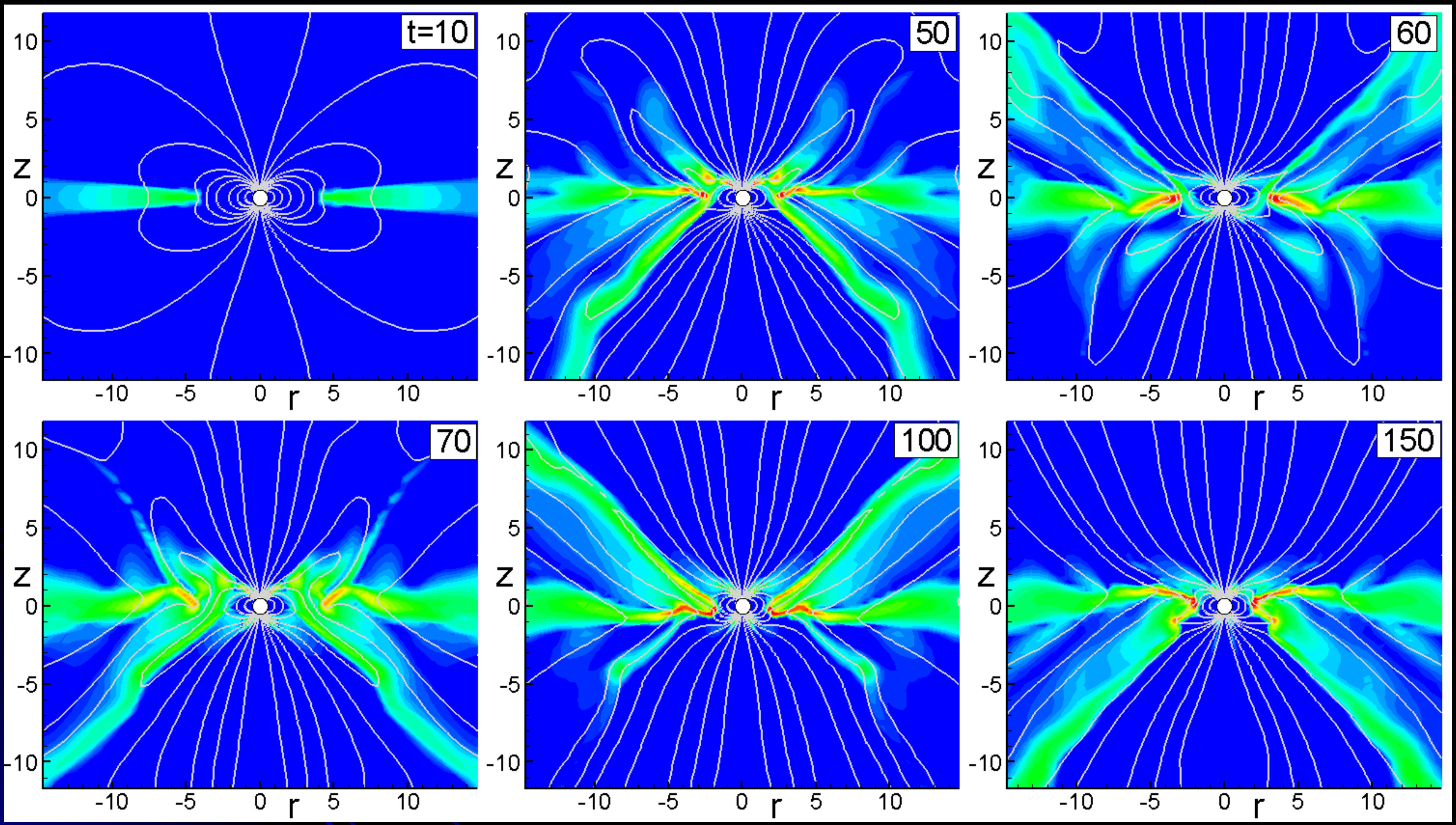
Winds from Stars with Complex Fields



- Example of dipole + quadrupole field
- Not symmetric about equatorial plane
- Wind can be persistently one-sided

Lovelace, Romanova, Ustyugova, Koldoba 2010

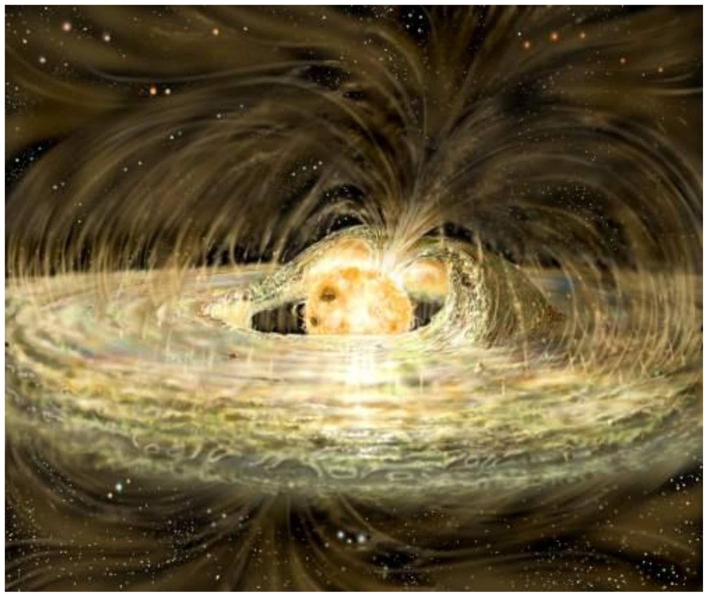
Flip-flop Outflows – Dipole Field



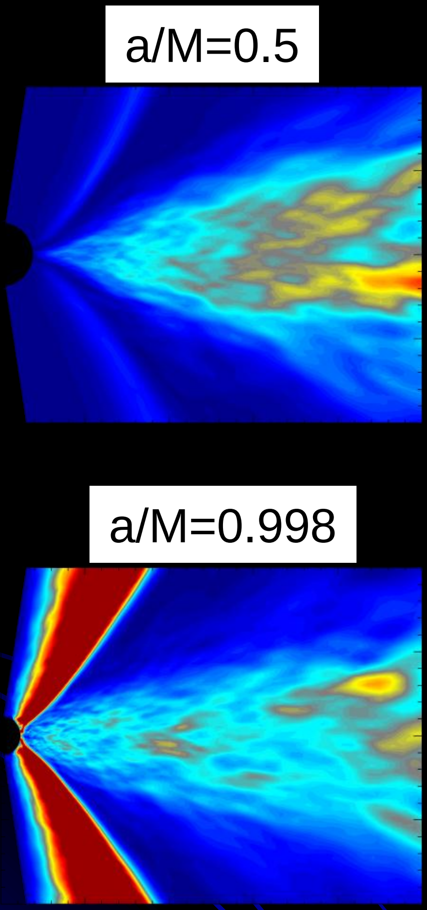
Lovelace, Romanova, Ustyugova, Koldoba 2010

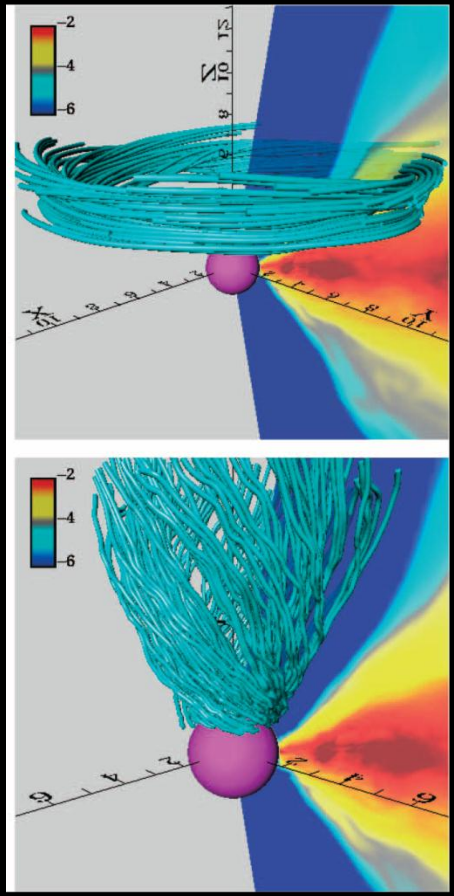
Accreting Magnetized Objects

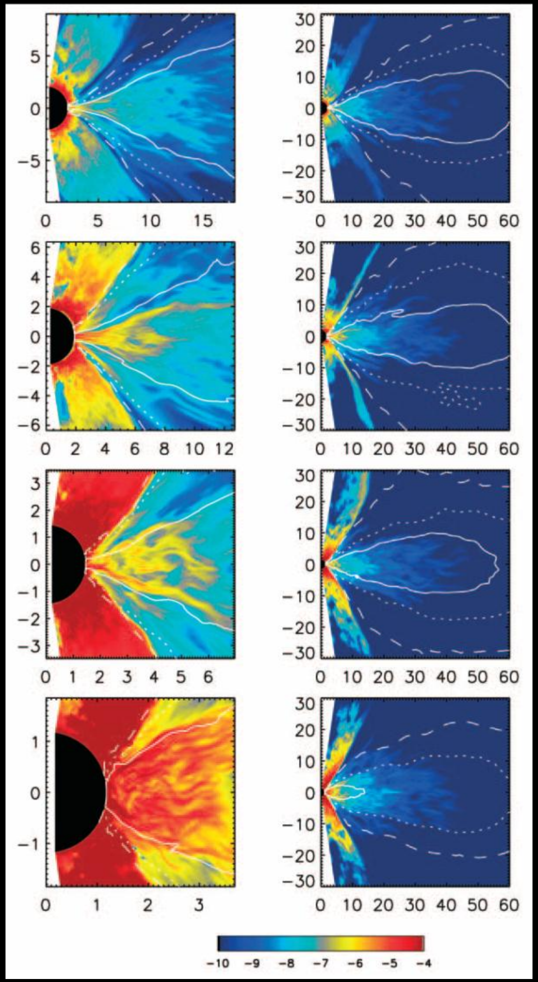
1. Young stars (T Tau) - Yes
2. Brown dwarfs -Yes
3. Neutron stars - Yes
4. White dwarfs -Yes
5. Black Holes – a number of similarities



Rapidly Spinning BHs: Analog of Propeller







The strength of Poynting flux jet increases with angular momentum of BH (a/M)

Poloidal current increases with a/M

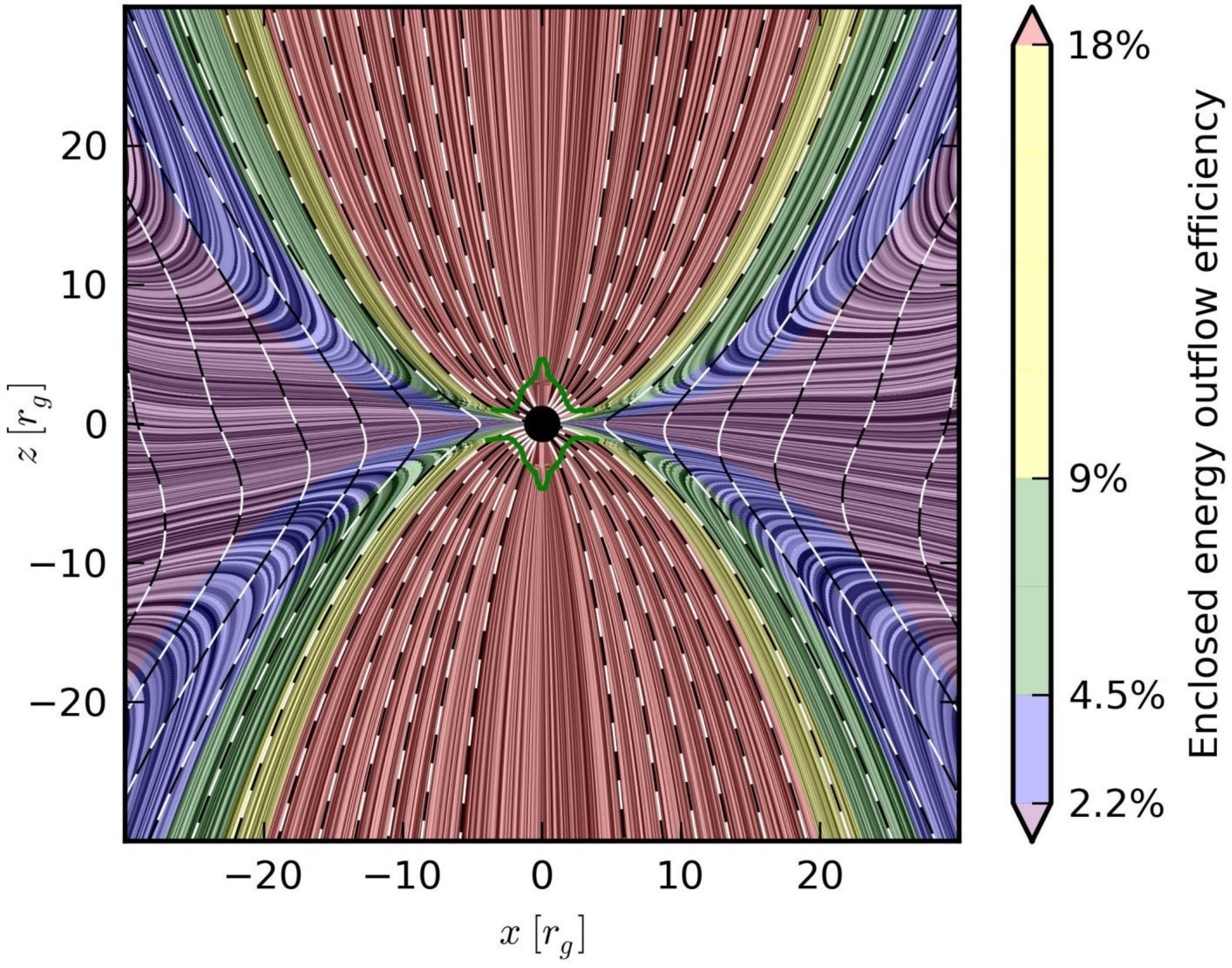
Krolik, Hawley, Hirose 2004

Hirose, Krolik, De Villiers, Hawley 2004

Conclusions:

- 3D MHD + 3D RT tool for probing magnetospheric flow and outflows. Tested – V2129 Oph
- Enhanced accretion leads to formation of Conical Winds which are magnetically-driven.
- Outbursts - viscouse time-scale of the inner disk replenishment – years to 100s of years (FU Ori)
- Propeller regime – centrifugally-driven
- Propeller regime – outbursts on the time-scale of the inner disk accretion/diffusion – weeks-years
- Angular momentum and energy flows from the star to corona – rapid spin-down of protostars
- Outflows can be systematically or episodically one-sided !

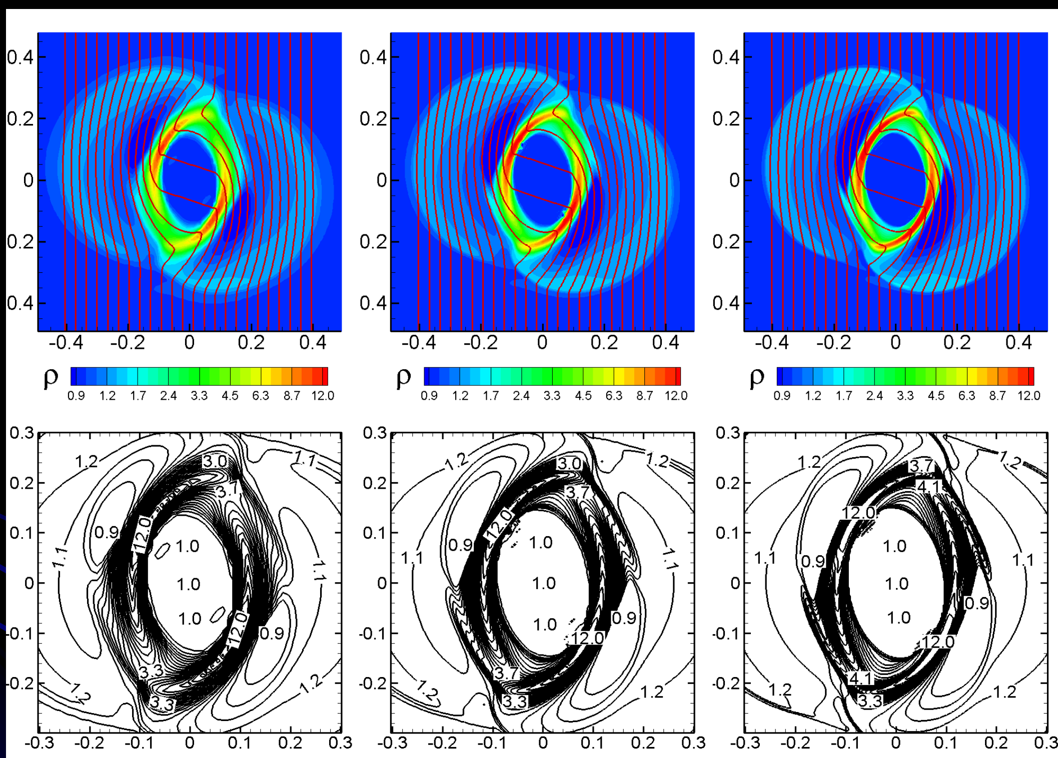
Rapidly Spinning BHs: Analog of Propeller



McKinney, Tchekhovskoi, Blandford 2012

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

Viscosity and diffusivity blocks are switched-off



100x100 200x200 400x400

Color background- density

Lines are the magnetic field lines

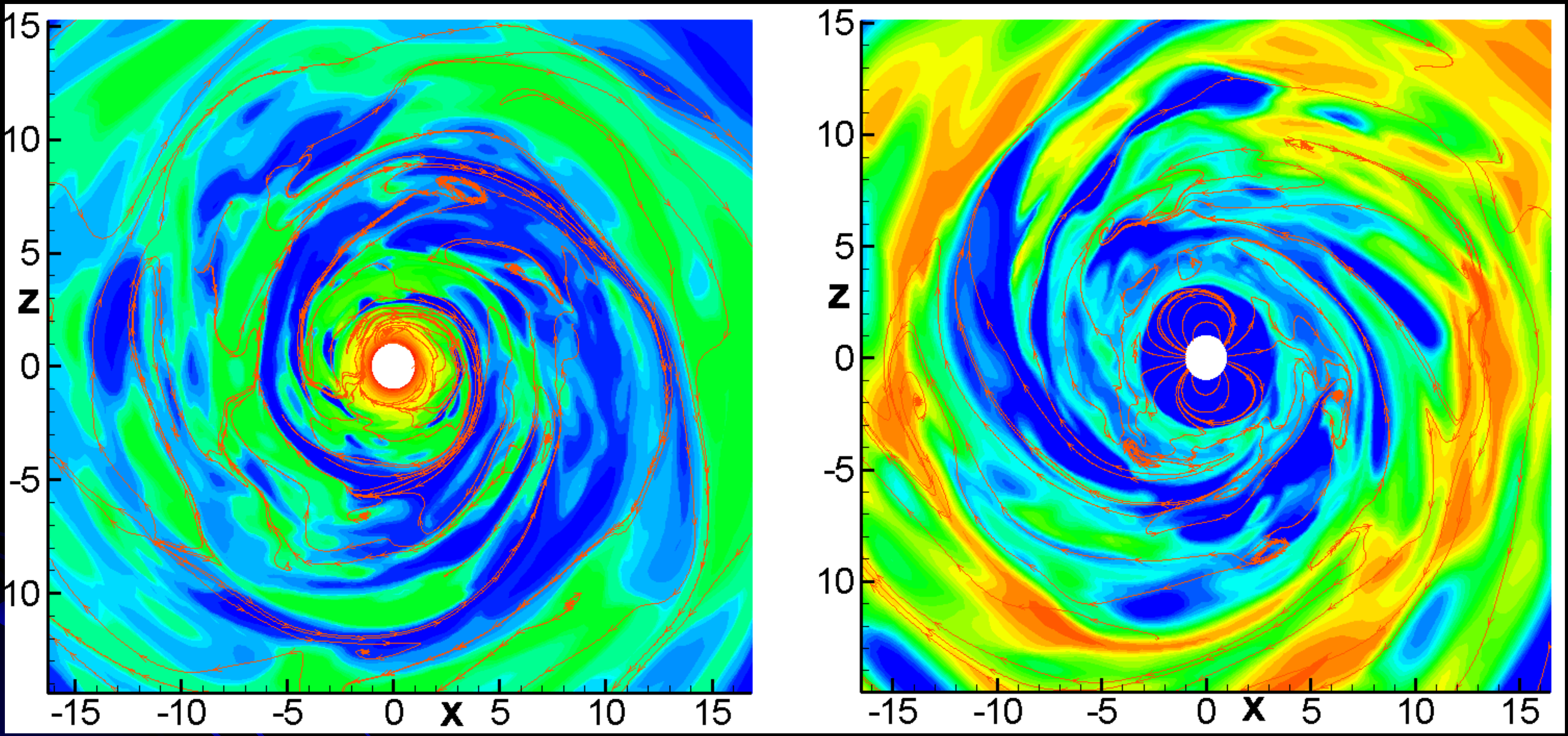
Lines are density contours

Comparisons show grid convergence

Romanova, Ustyugova, Koldoba, Lovelace 2009

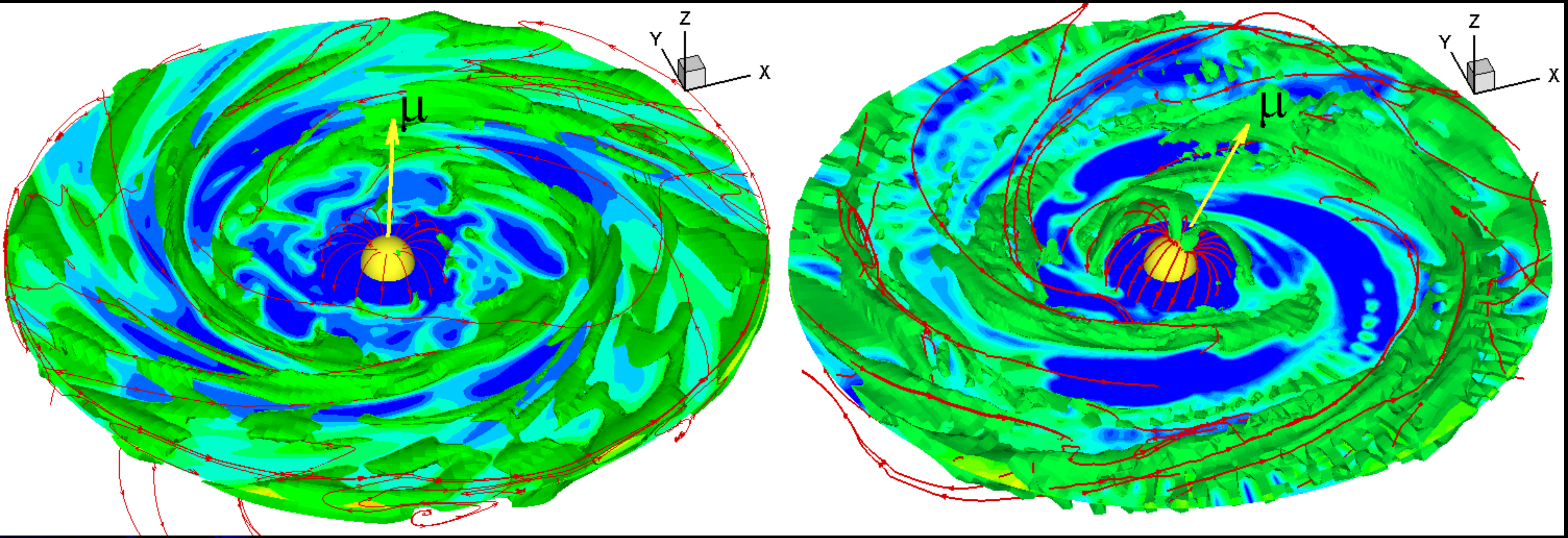
3D simulations of MRI-driven accretion, $\Theta=30^{o}$

B=0 B≠0



- Large-scale turbulence is observed like in case of non-magnetic star (e.g., Hawley 2000)
- Low-m spiral modes

3D view of MRI-driven Accretion



- Matter accretes in funnel streams
- Funnels form episodically
- Variability is higher than in case of the laminar flow