# Global Simulations of Accretion onto Magnetized Stars: Results of 3D MHD Simulations and 3D Radiative Transfer

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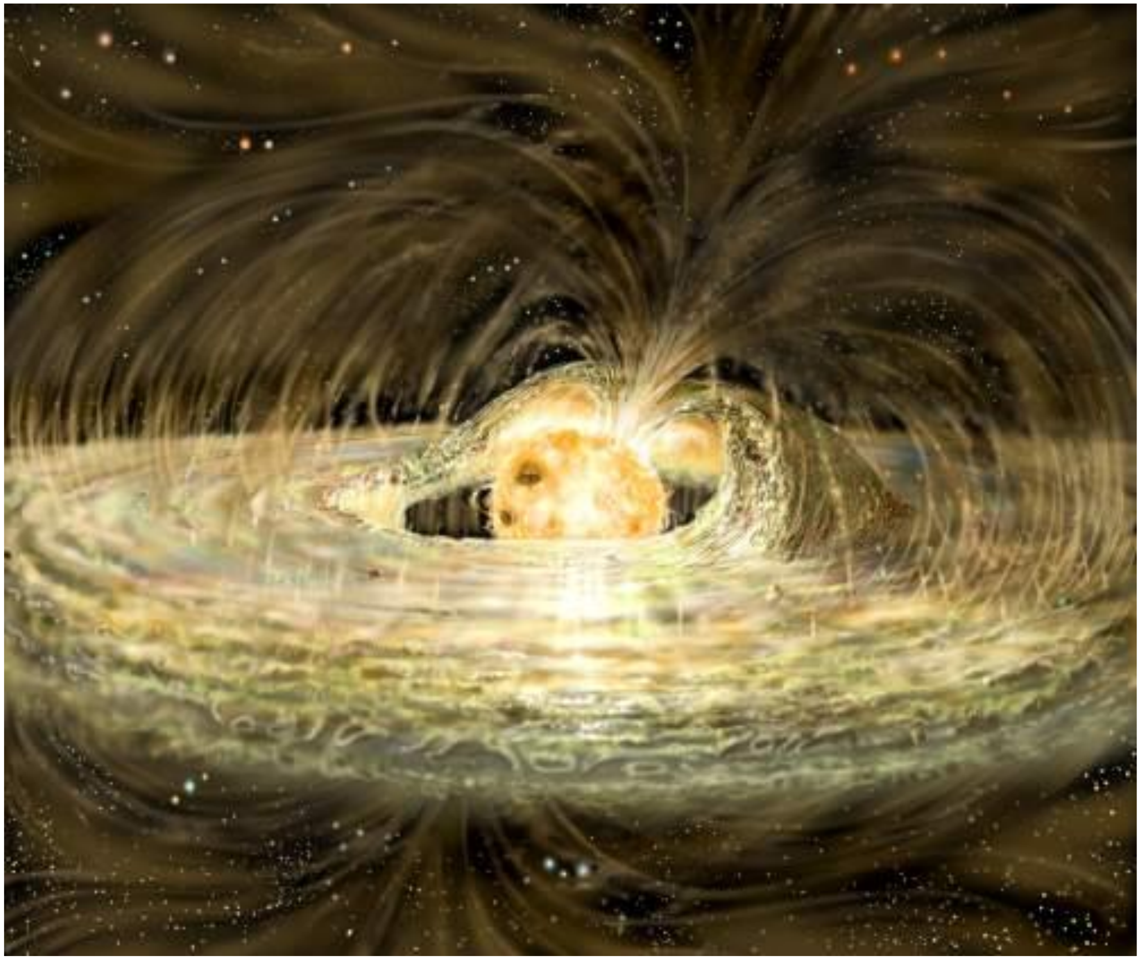
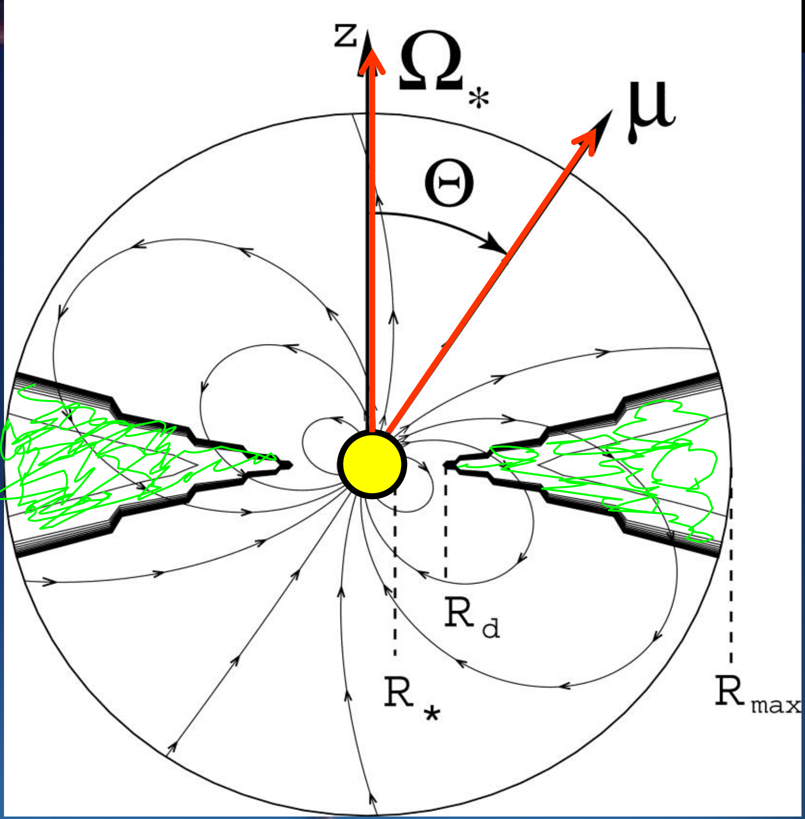
# Young, classical T Tauri Stars (CTTS)



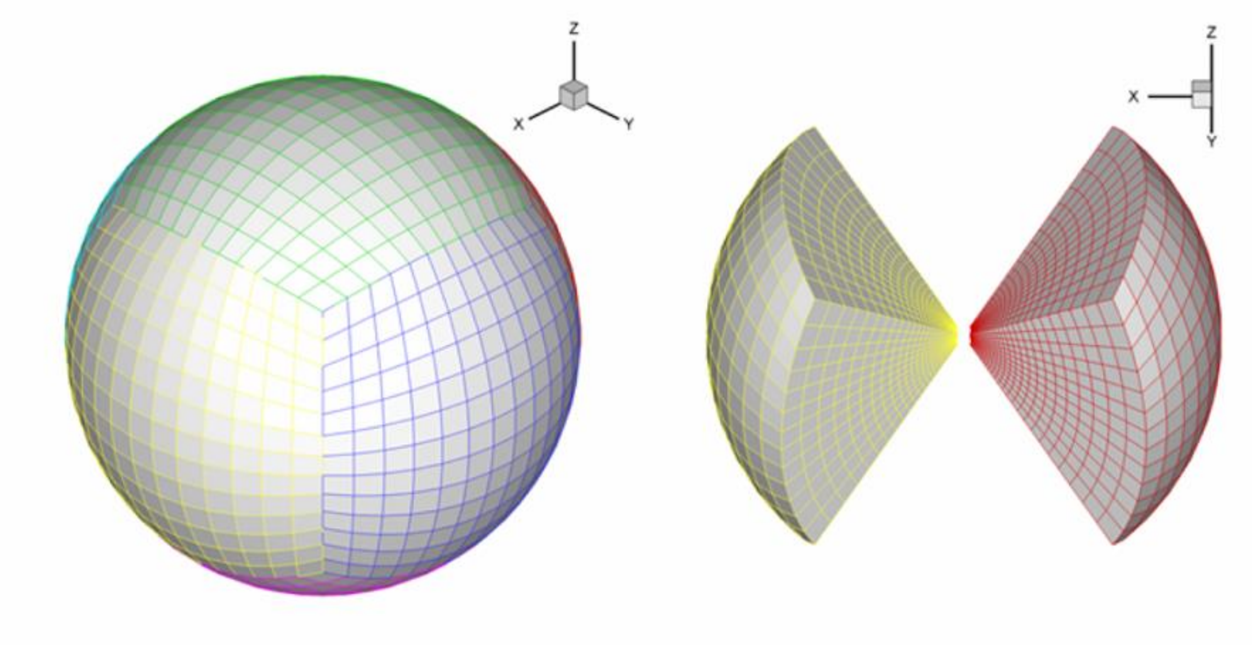
- Young stars, like our Sun in the past, 1-10 Myr
- Magnetic field is  1000 times larger than the Sun’s field
- The magnetic field opens a gap in the disk
- Matter falls to polar regions forming the hot spots
- Observational properties – disk-magnetosphere interaction

# Numerical Model

- 3D, 2nd order Godunov-type (*Koldoba et al. 2002*)
- Cubed sphere grid, 61x61x140
- Disk $\alpha$- disk ($\alpha_{vis}$=0.02)
- Initial equilibrium, disk and corona
- Dipole or more complex field



Cubed Sphere Grid



# Ideal MHD Equations:

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

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

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

Corotatin
frame

Stress
tensor

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

No shocks

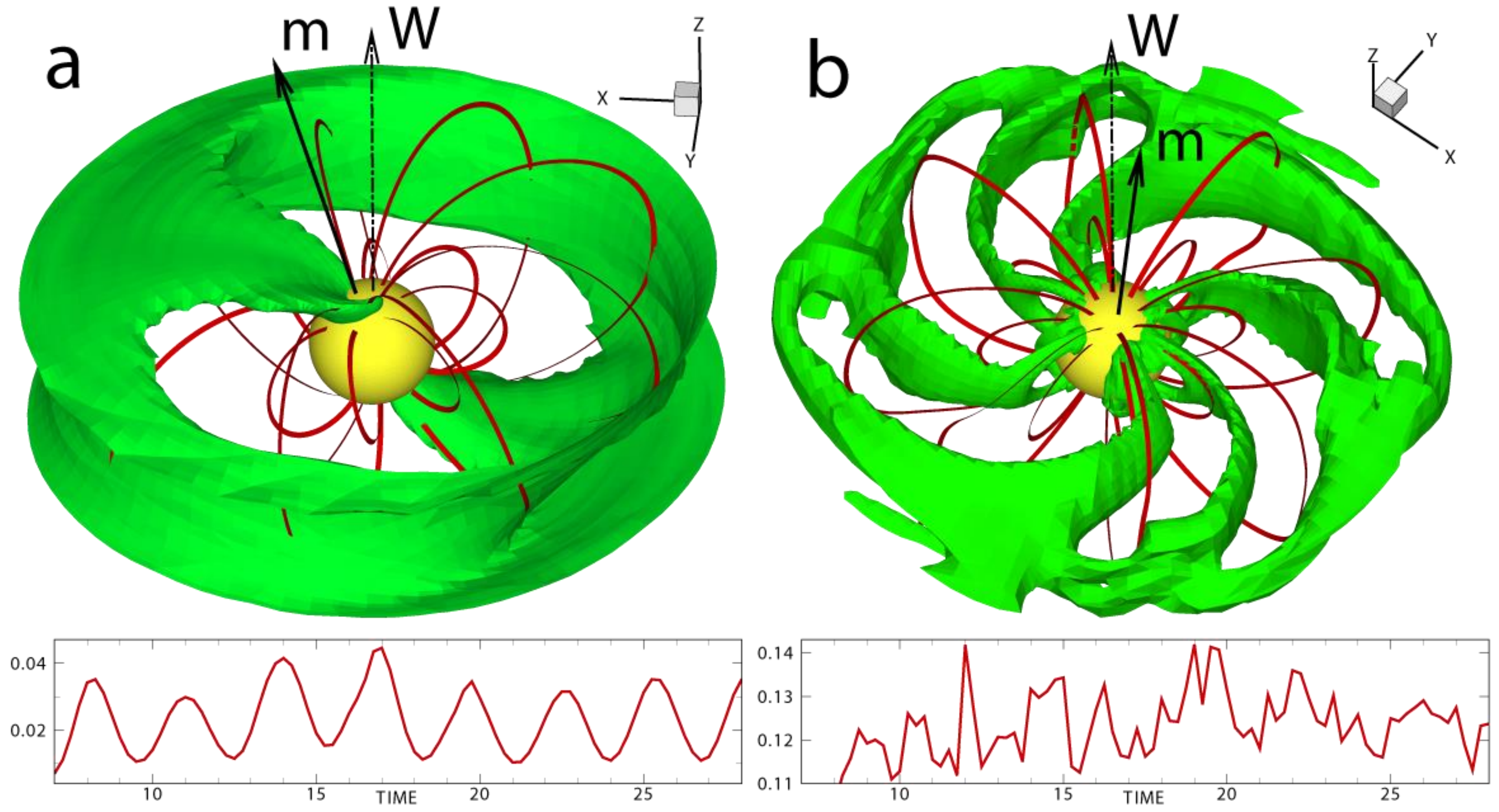
$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{v}) = 0$$

Ideal

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

Adiabatic

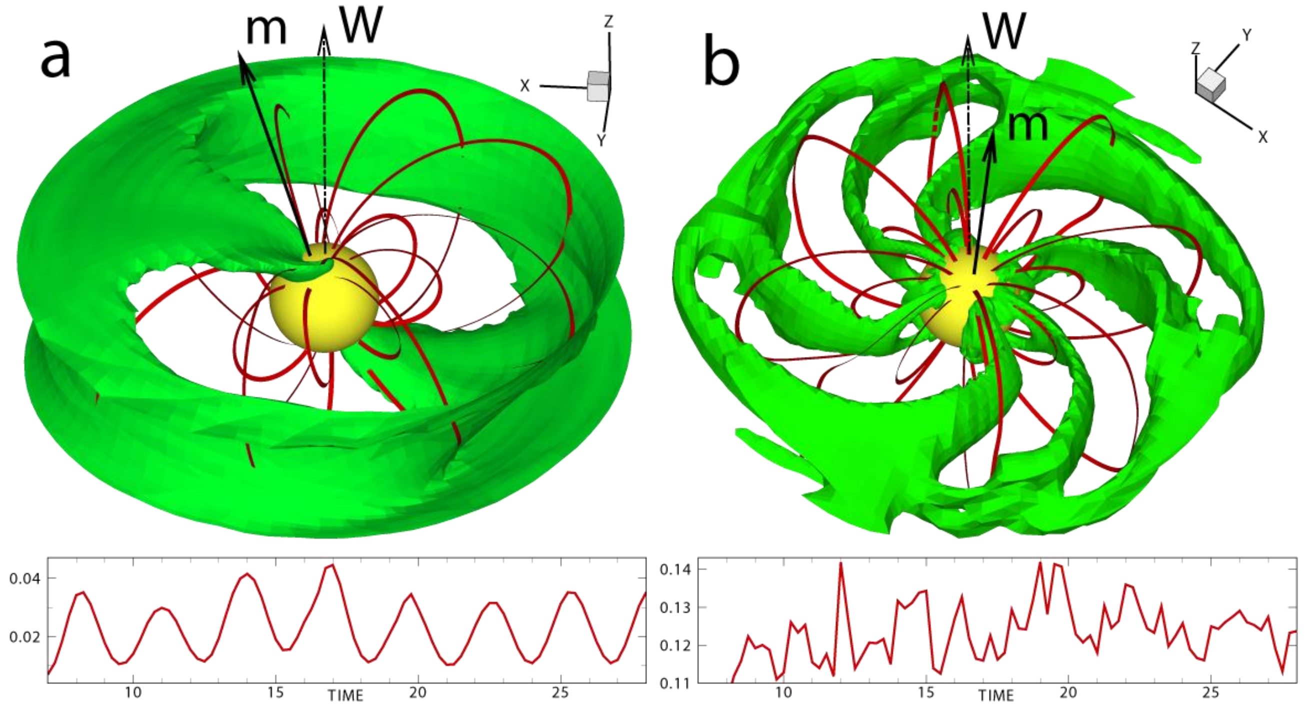
# Stable and Unstable Regimes

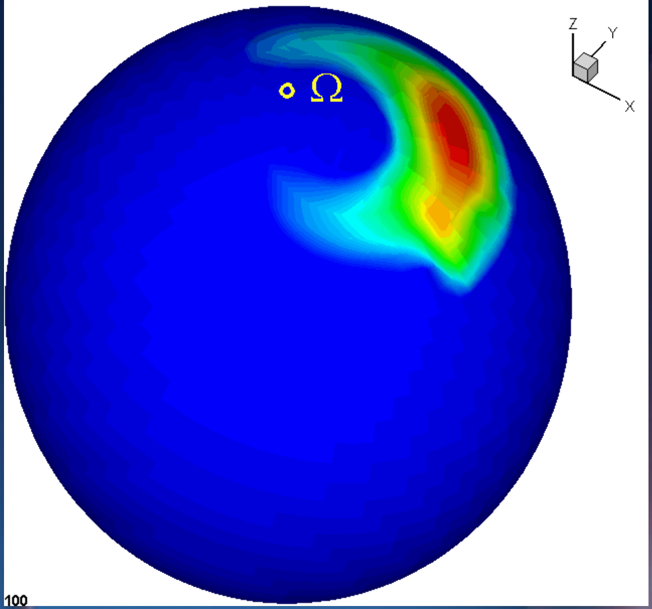


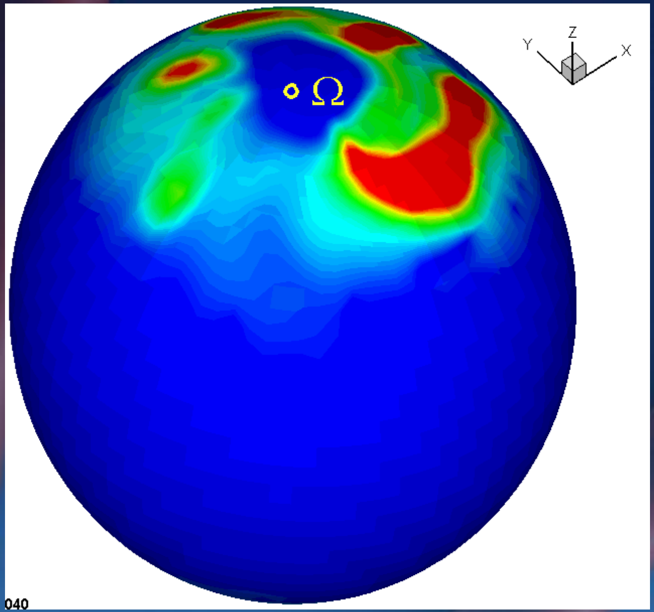
- **Stable**: accretion in two ordered funnel streams
- **Unstable**: matter accretes in chaotic tongues, Rayleigh-Taylor instability

Kulkarni & Romanova 2008; R., Kulkarni & Lovelace 2008; Arons & Lea (1976)

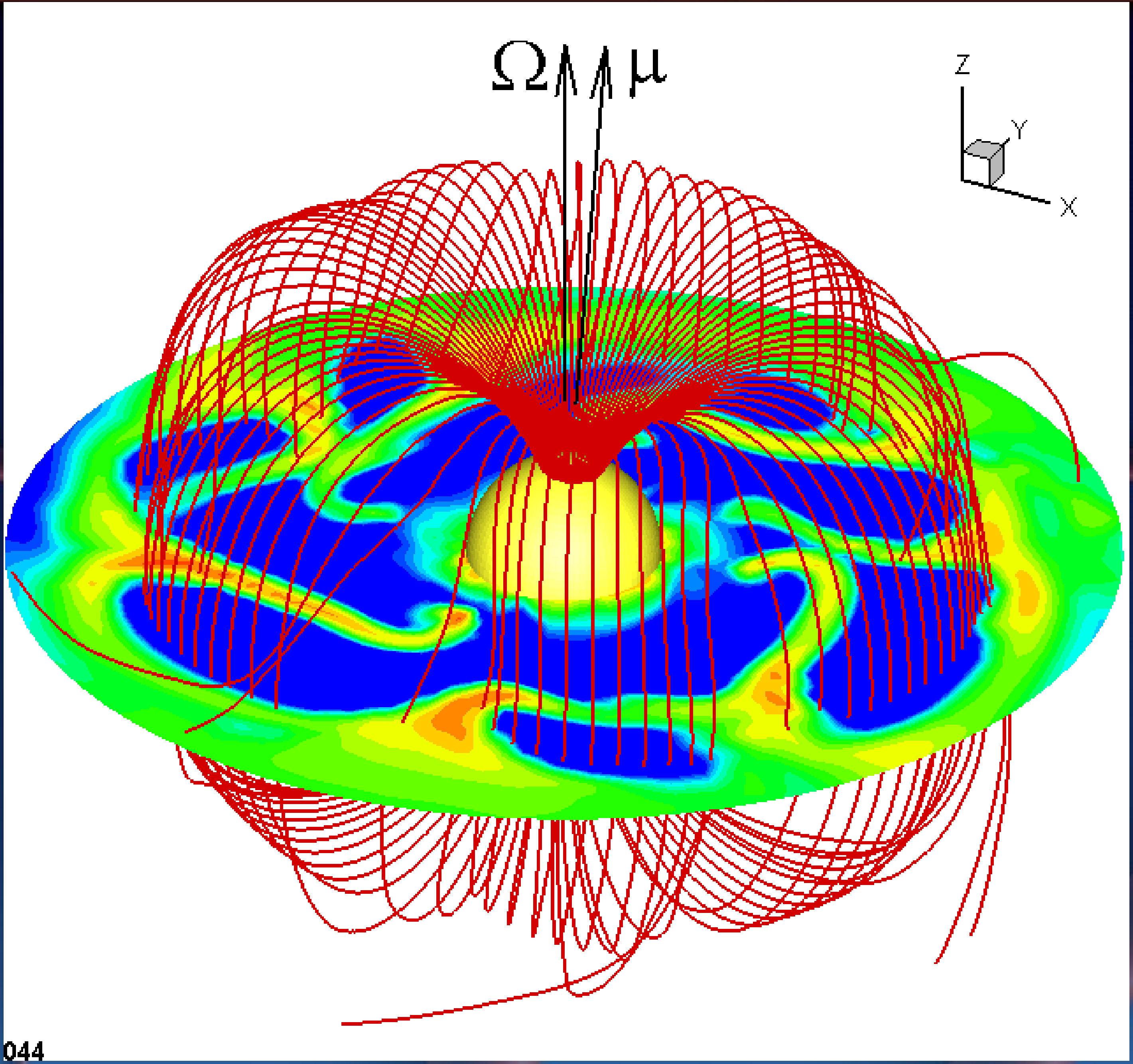
# Stable and Unstable Regimes





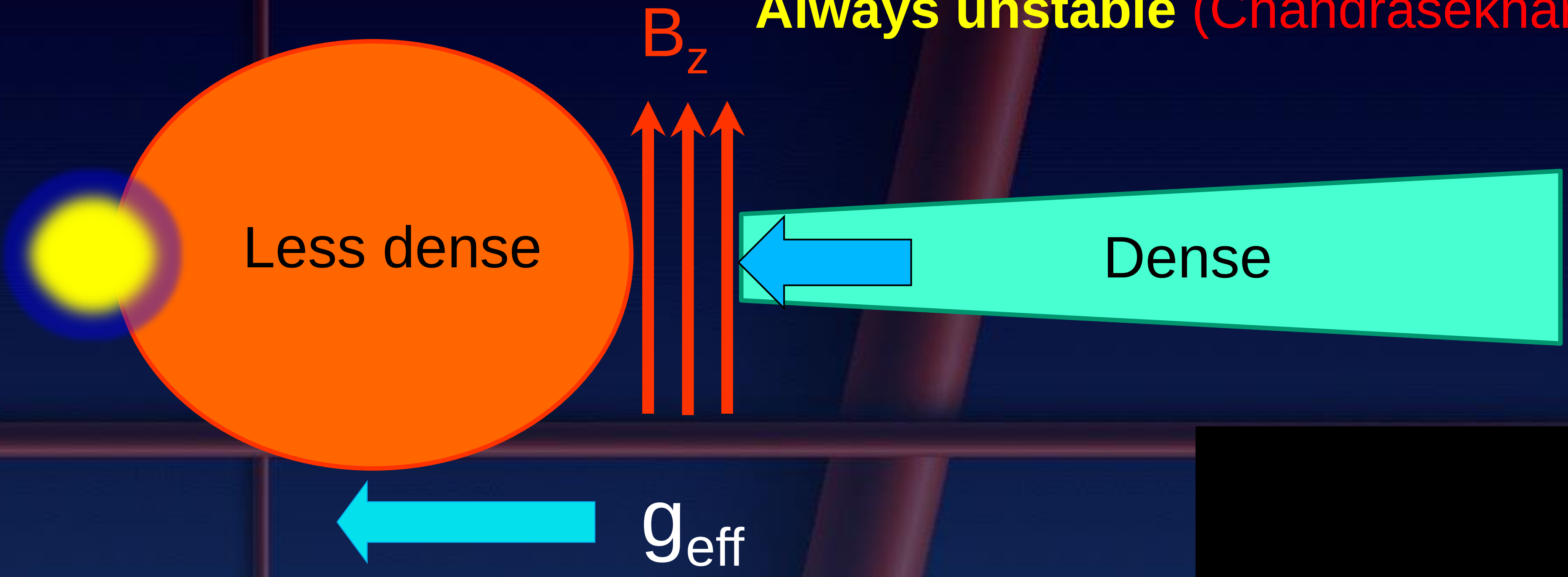


# An Example of Unstable Accretion



# What determines the regime?

**Always unstable** (Chandrasekhar 1960)



$$\gamma_{B\Sigma}^2 \equiv g_{eff}\left|\frac{d}{dr}\ln\frac{\Sigma}{B_z}\right| > 2\left(r\frac{d\Omega}{dr}\right)^2 \equiv \gamma_\Omega^2$$

$$g_m = \frac{B_r^+ B_z}{2\pi\Sigma}$$

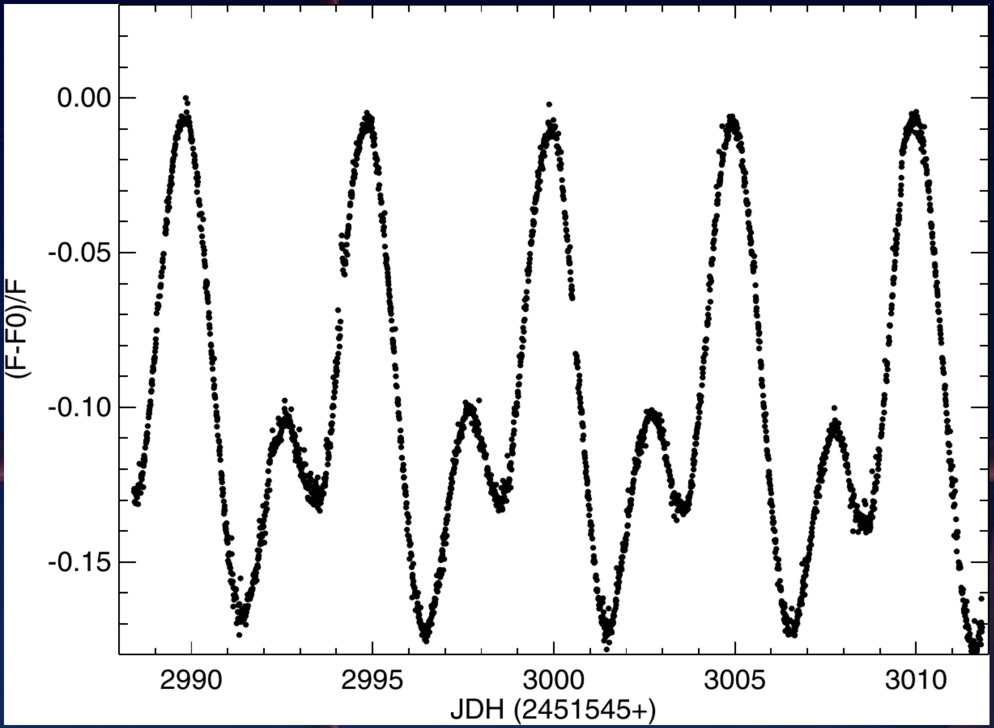
$g_{eff} = g - \Omega^2 r$

$r\frac{d\Omega}{dr}$ Shear in the disk acts to suppress the instability

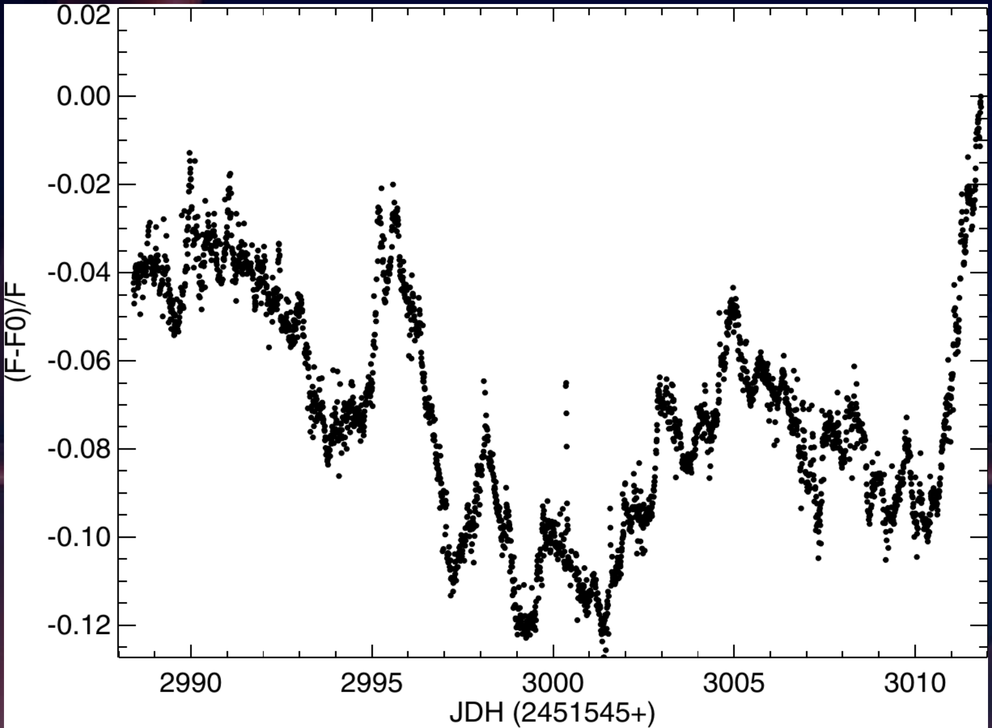
Spruit et al. 1995; Lubow & Spruit 1993; Kaisig, Tajima, Lovelace 1992

# Observations: Variability of T Tauri stars

Periodic



Non-Periodic

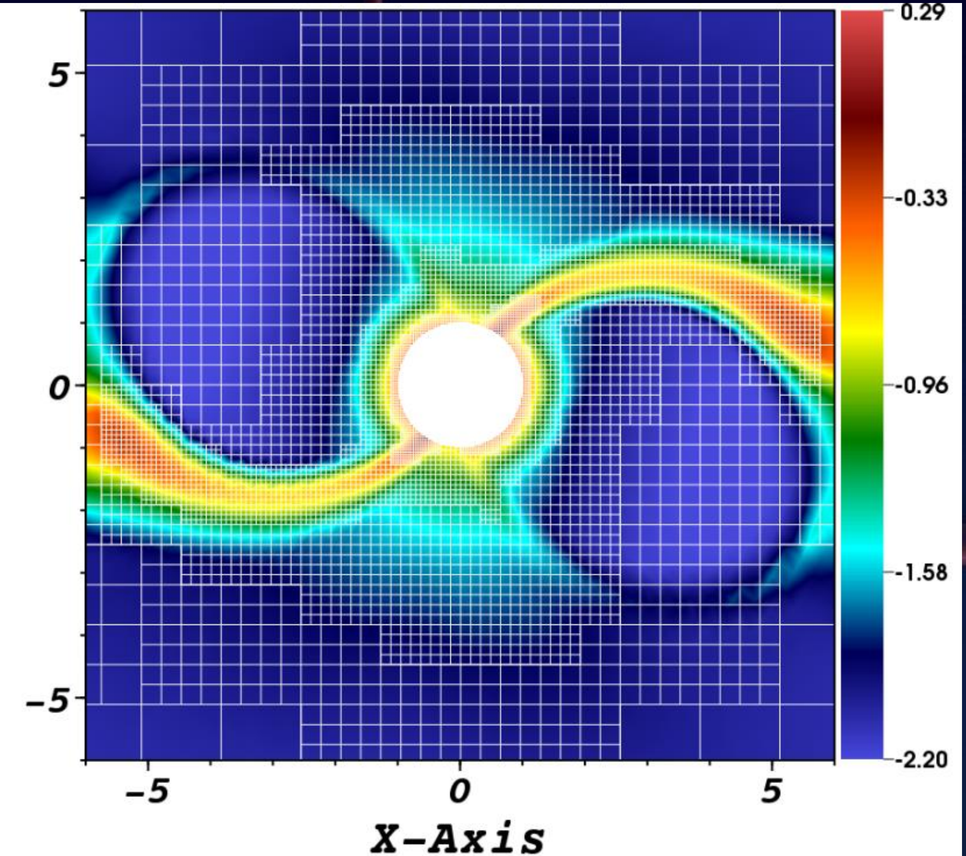


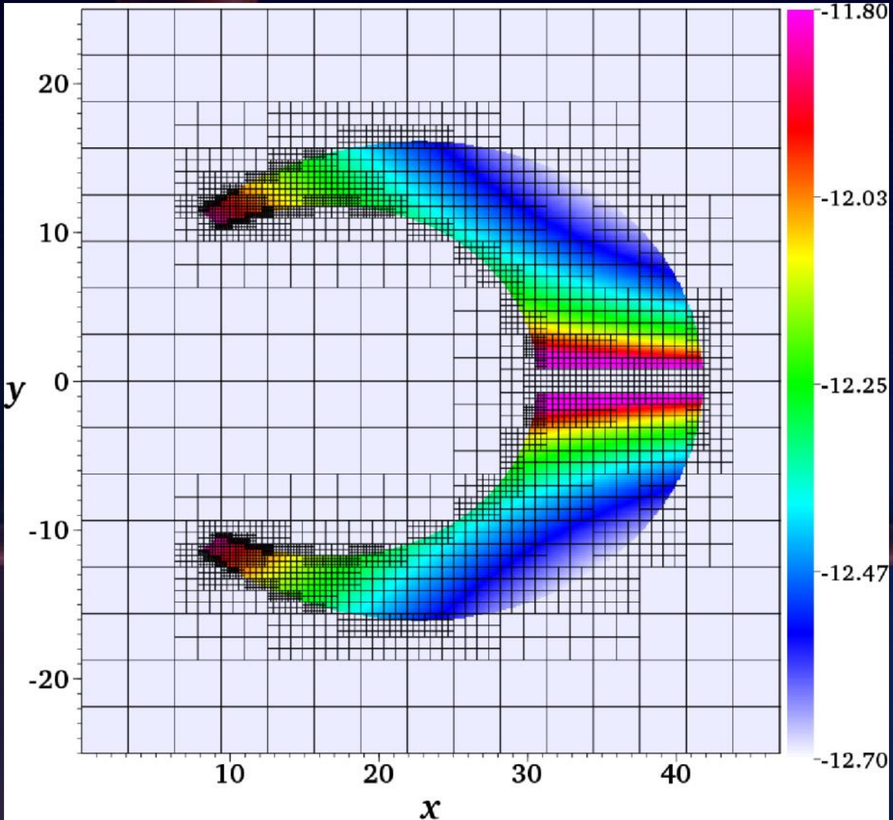
PERIODIC: Spots + Stellar Rotation

APERIODIC: Origin ? Stars have strong B-field. Period ?

- CoRoT observations of 83 CTTSs in NGC 2264,
- Alencar, Bouvier et al. (2010)
- About 40% of CTTSs show irregular light curves!

# Testing the Magnetospheric Accretion





Project our MHD data to the *TORUS* grid (velocity, density)
Adaptive Mesh refinement of *TORUS* code
Spectrum in H and He lines and images in lines

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

# Radiative Transfer Code *TORUS*

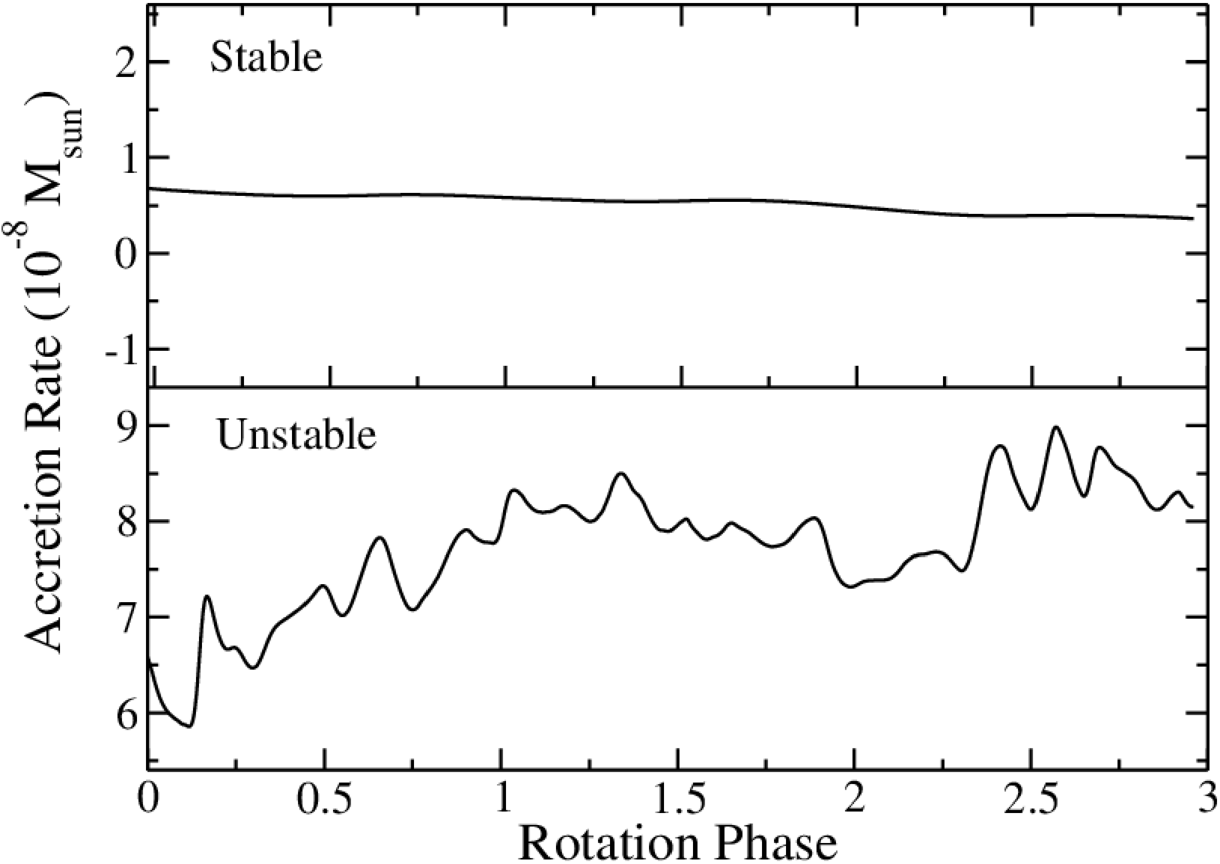
Non-LTE population of H and He atoms obtained by using the method described in Klein & Castor (1978) – originally developed for O star wind model.

*Main assumptions:*

1. Core-Halo approach: Continuum radiation is dominated by the “core”, but not by accretion flows.
2. Sobolev approximation: assumes the velocity gradient is large in the wind/accretion.
    - e.g. the mean intensity ($J_{ij}$) is expressed in terms of “escape probabilities ($\beta_{ij}$, $\beta_{c,ij}$) (e.g. Castor 1970)

$$\mathcal{J}_{ij} = (1-\beta_{ij})\frac{2h\nu_{ij}^3}{c^2}\left(\frac{g_j}{g_i}\frac{n_j}{n_i}-1\right)^{-1} + \beta_{c,ij} I_{c,ij}$$

# Mass-Accretion Rate



Almost constant

Smooth

Variable

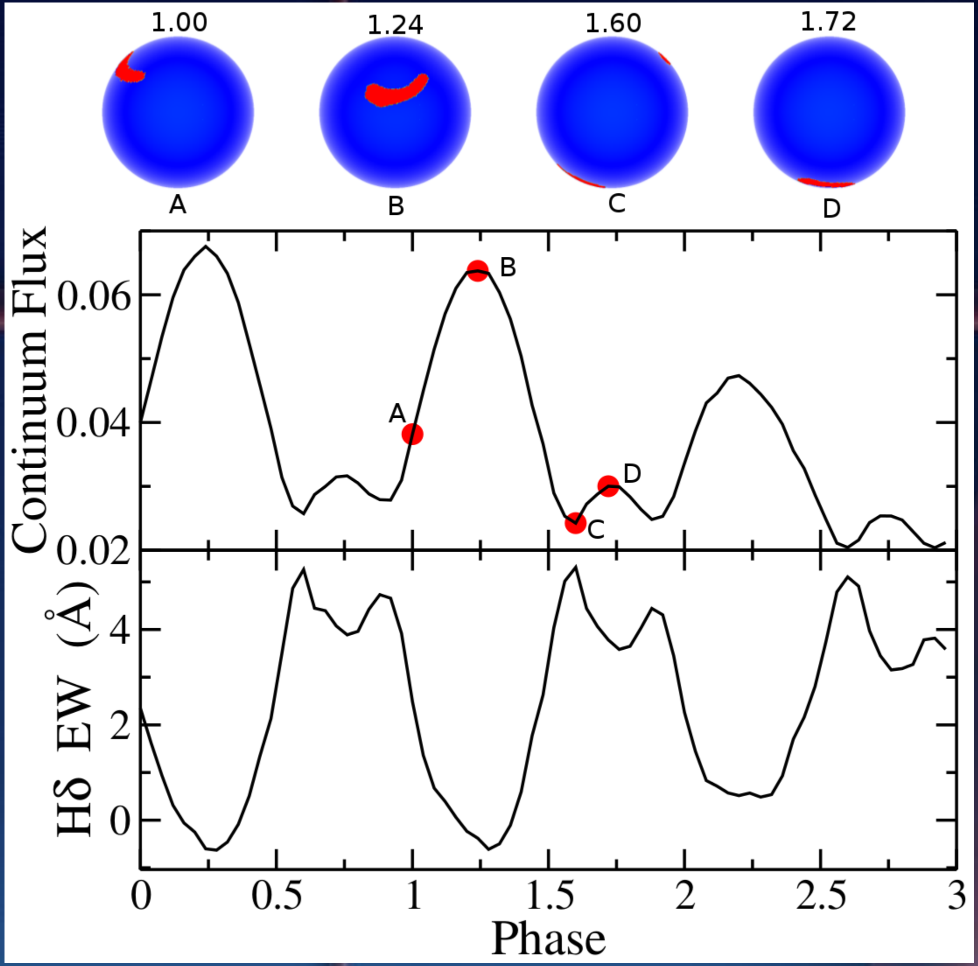
Irregular

- Took 25 slices per rotation, 3 periods of rotation
- Use the density and velocity fields and compute the corresponding line profiles and continuum flux
- Model includes the effect of hot spot radiation (variable size and shapes)

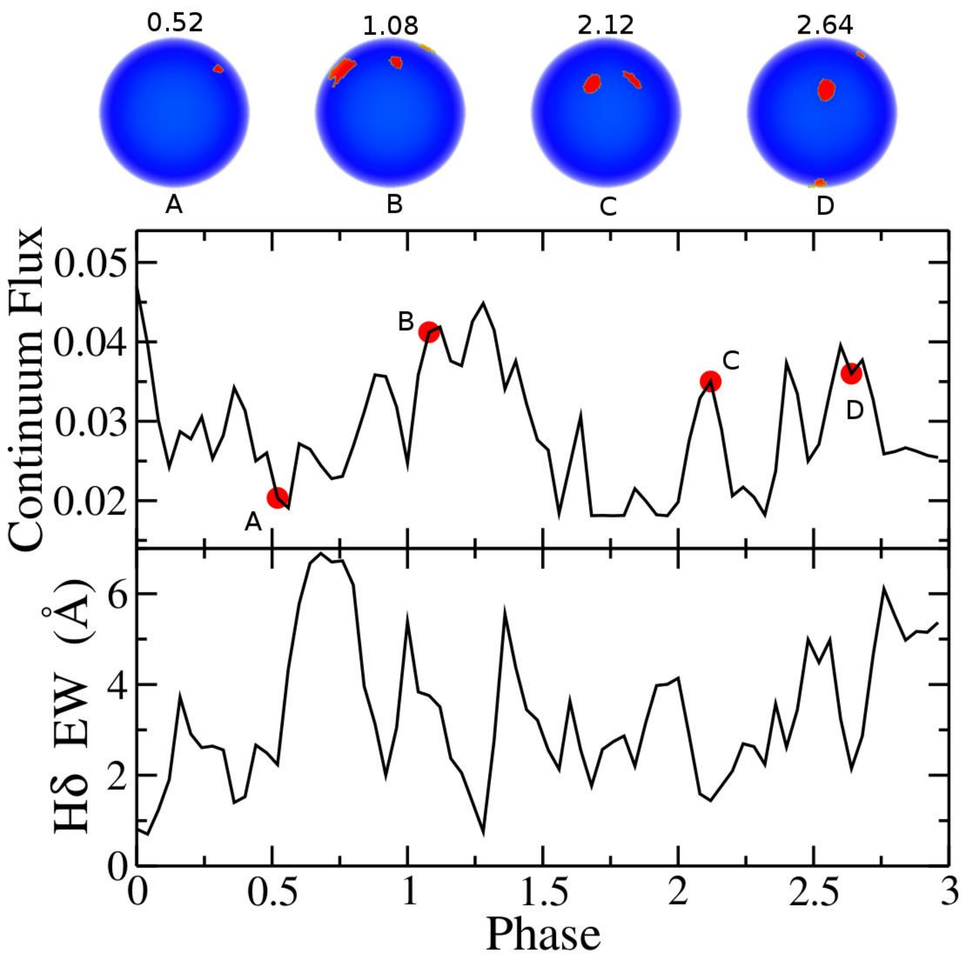
# Simulations: Light Curves

- Unstable case: irregular light curves due to stochastic formations of “tongues” and hotspots.

Stable



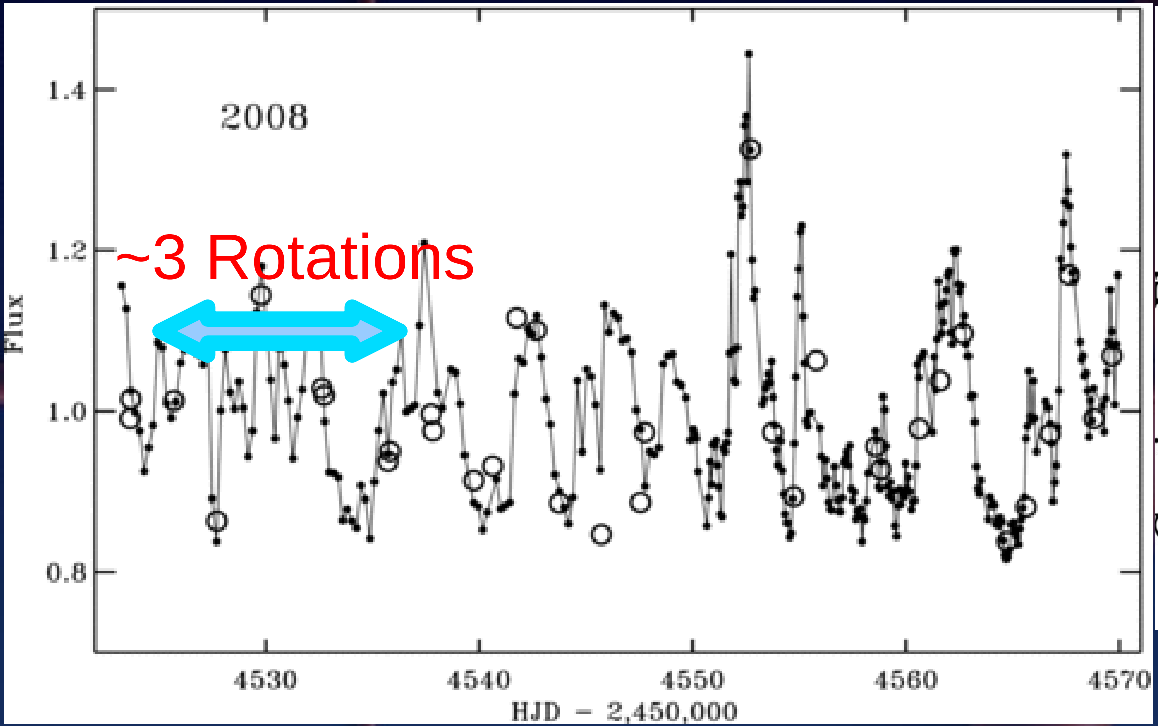
Unstable



# Lightcurve: CTTS TW Hya

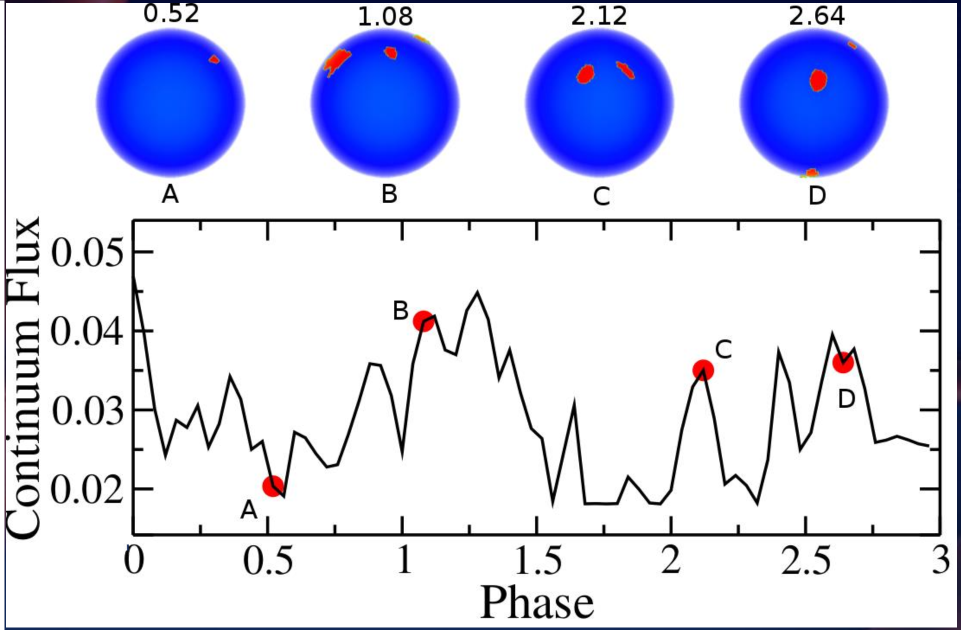
## Observation

*Stochastic Light curve* of TW Hya



## Unstable Model

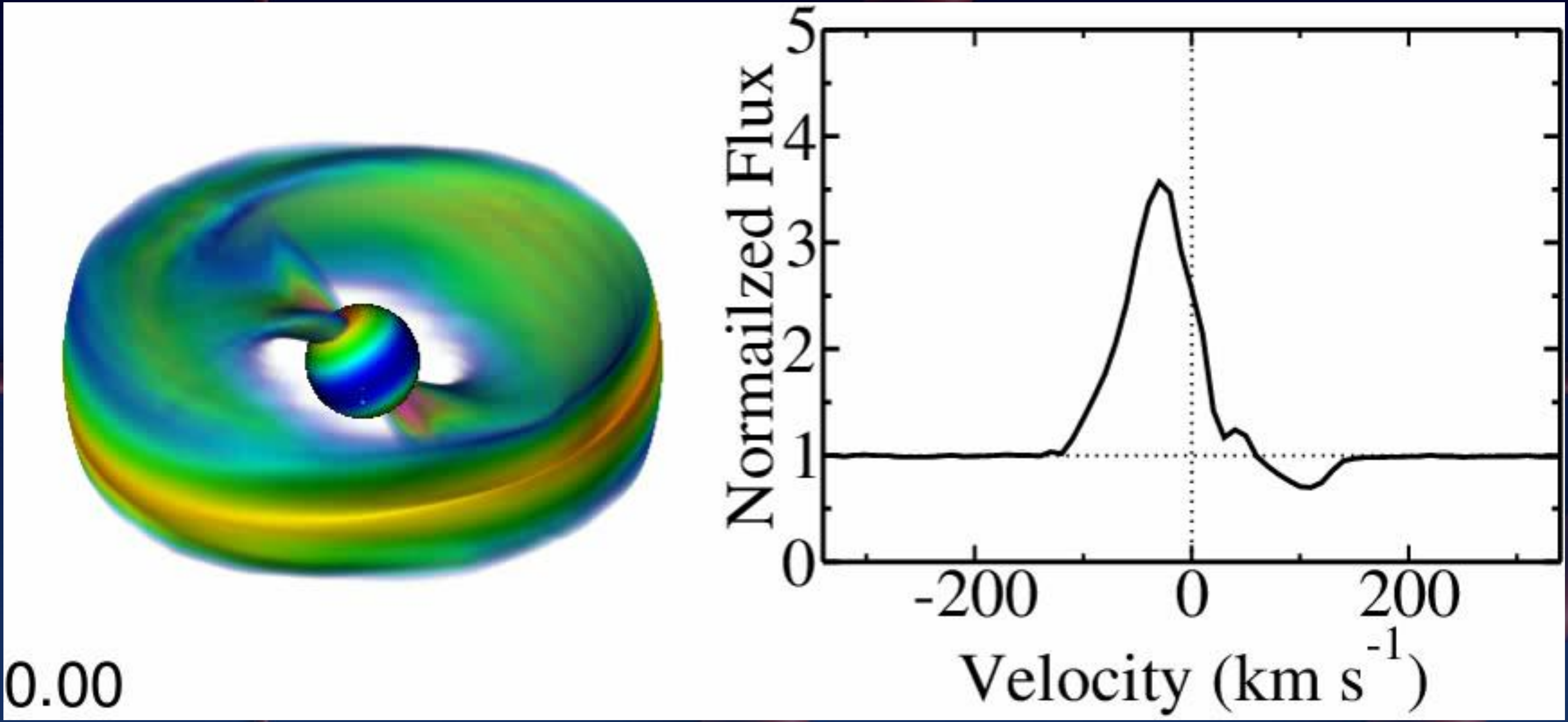
*Flux at 410.1 nm (Hδ)*



- *Left*: *MOST's* observation – lightcurve by Rucinski et al (2008)
- Model shows a similar number of random peaks per stellar rotation.
- The amplitudes of variations are also similar.
- Need more analysis - - **SPECTRUM !**

Kurosawa & Romanova 2013

# Time-Evolution of Hδ line profile

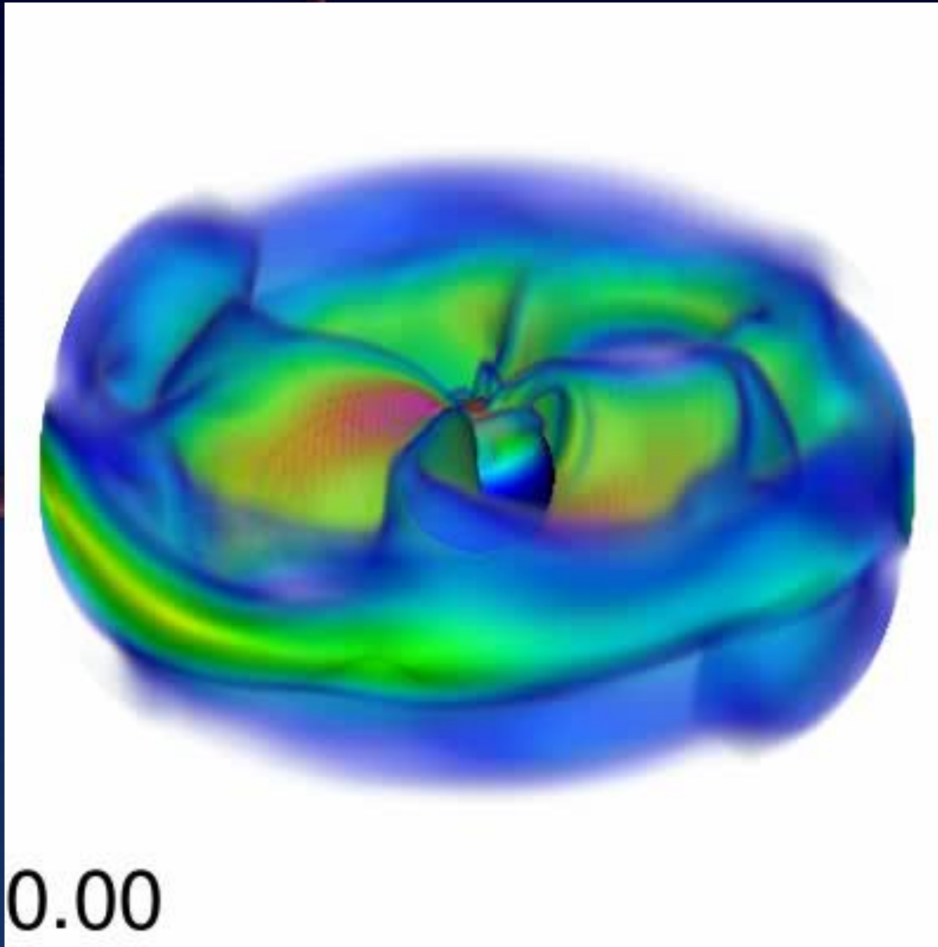


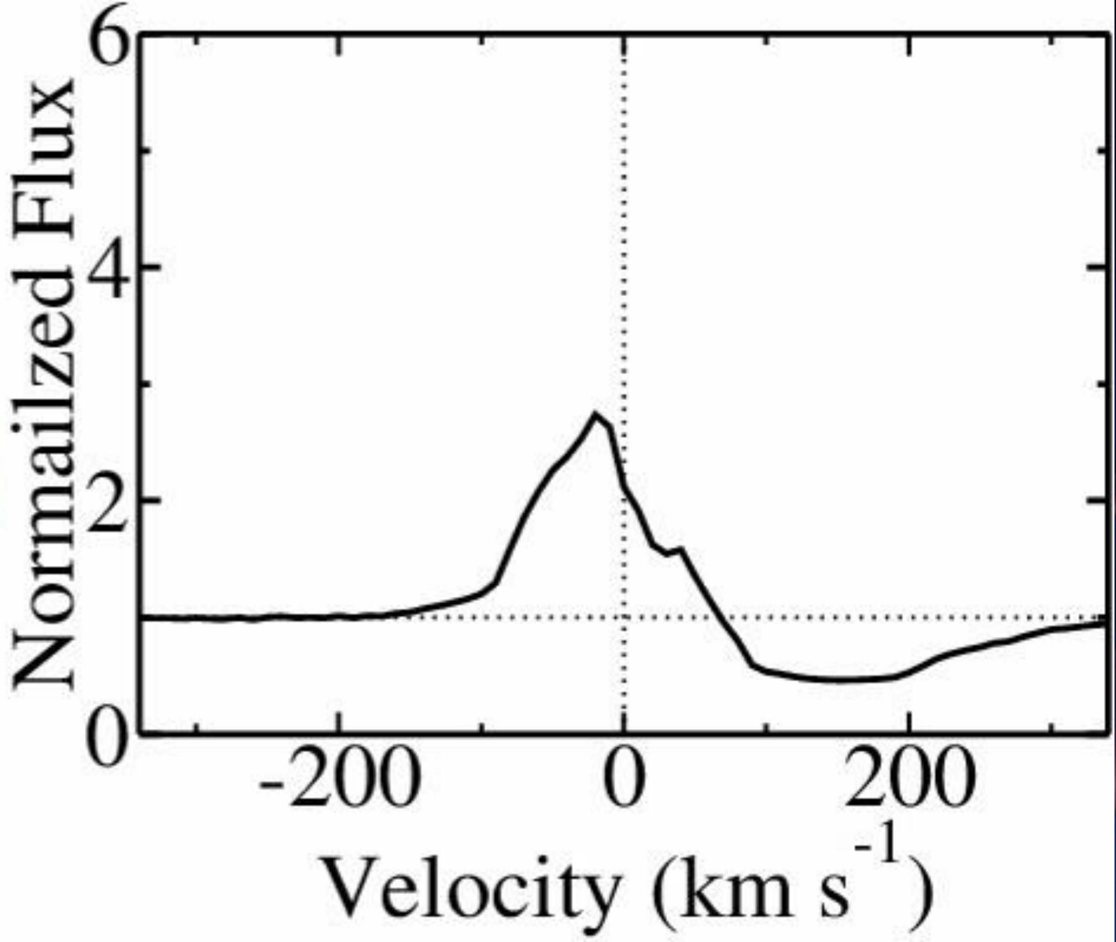
Stable regime

Periodic redshifted absorption

Kurosawa & Romanova 2013

# Time-Evolution of Hδ line profile





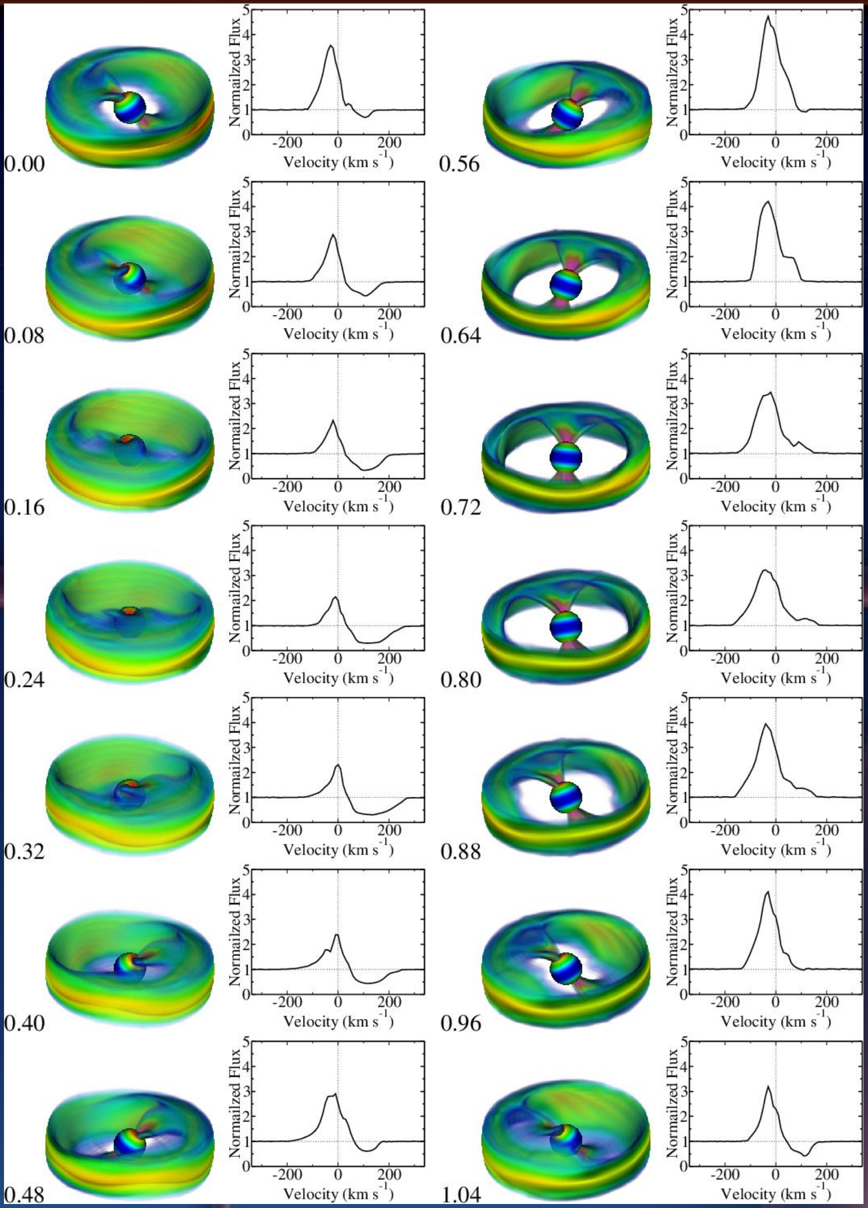
Unstable regime

Redshifted absorption is seen more frequently

Kurosawa & Romanova 2013

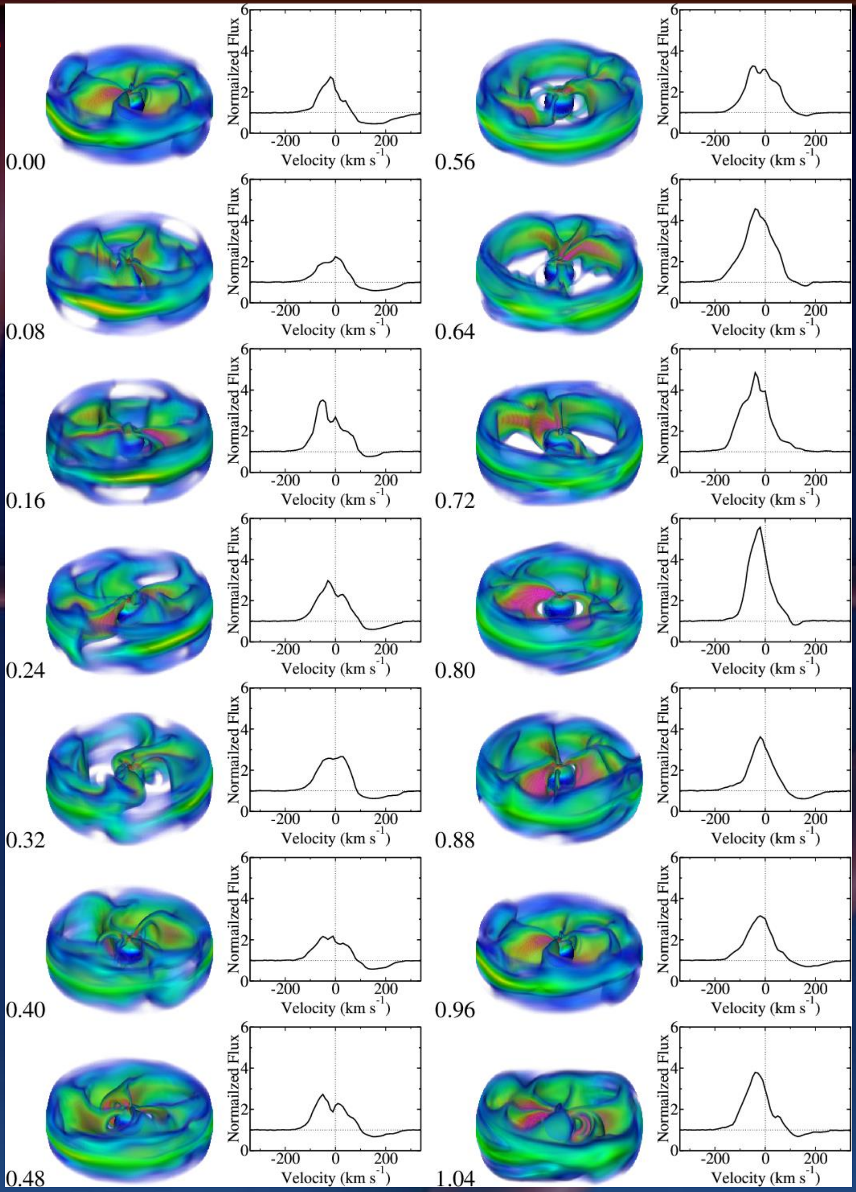
# Persistent Redshifted Absorption

Stable



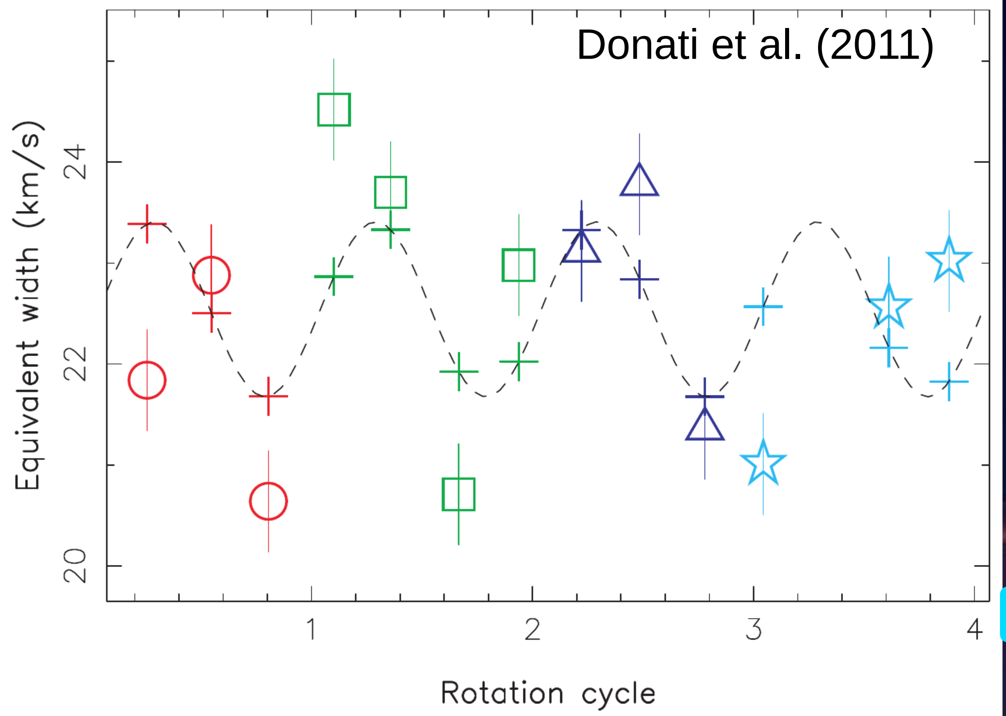
Redshifted absorption component appears once per rotation.

Unstable

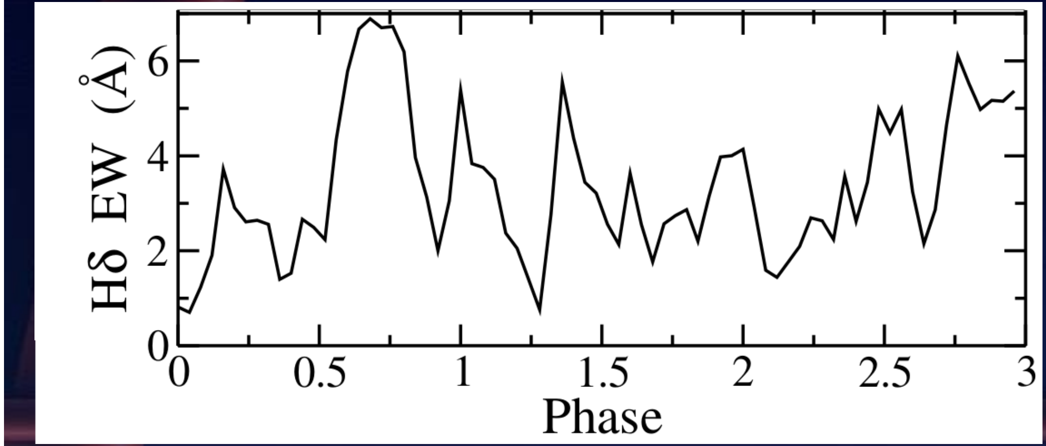


Variable but persistent redshifted absorption component

# Comparison with Observations: Line Variability



TW Hya Observation: EW of Ca II



Unstable Model: Hδ

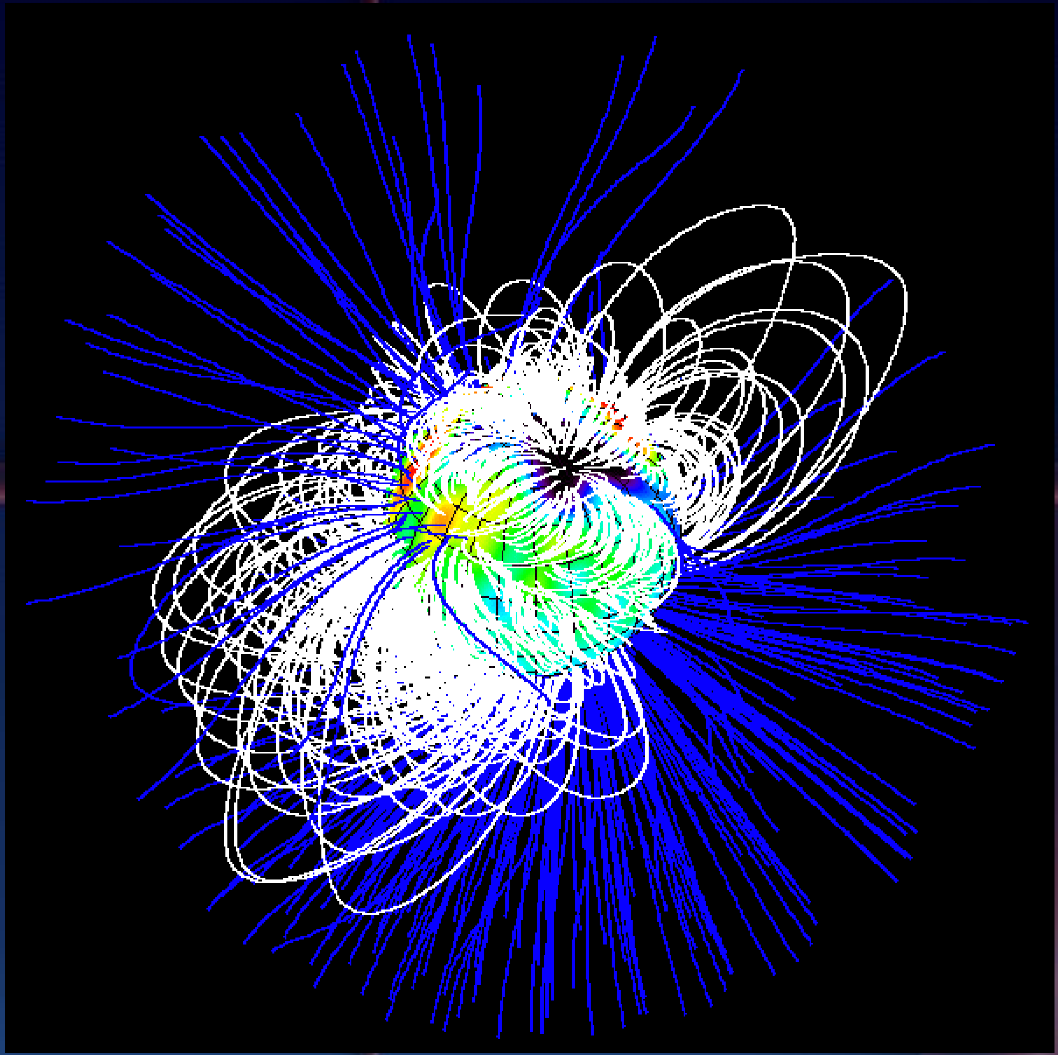
Significant intrinsic variability (stochastic) as in our model.

Non-Periodic Line Variability:

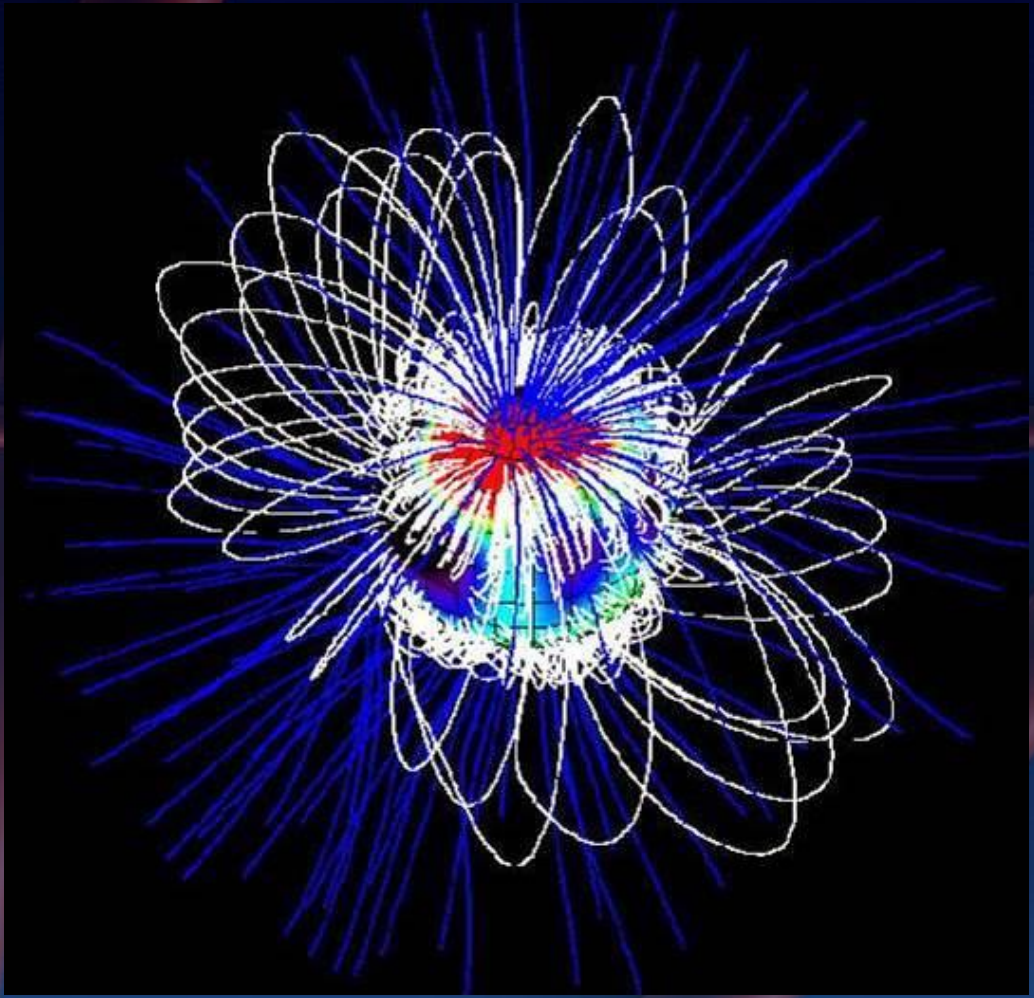
- TW Hya (Donati et al. 2011), DR Tau (Alencar et al. 2001) etc.

**PREDICTION**: Variable spectra, redshifted absorption – signs of accretion through R-T INSTABILITY. There are candidates CTTSs.

# Magnetic Field in CTTSs is Complex



SU Auriga



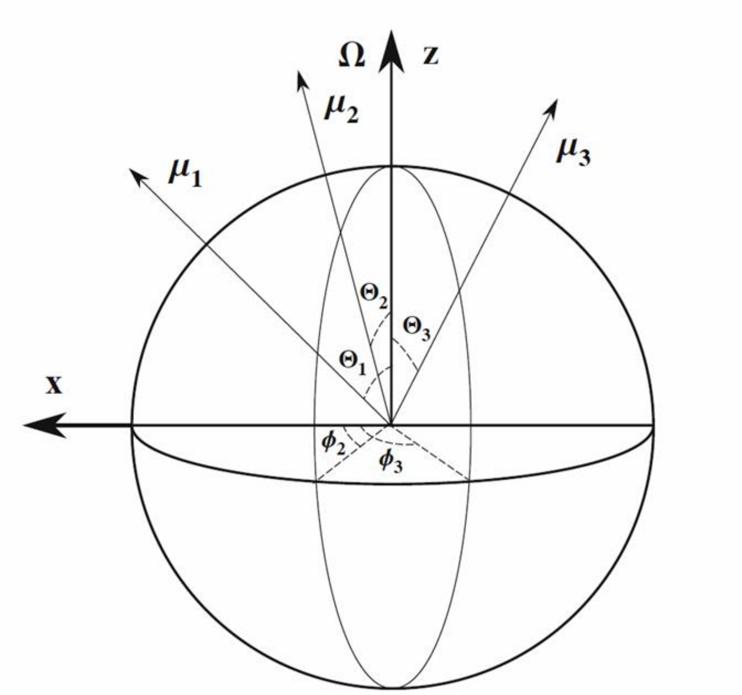
V 2129 Oph

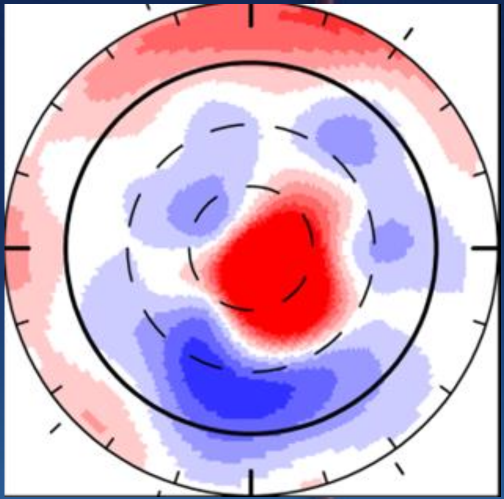
Donati, Jardine, Gregory et al., 2007, 2010

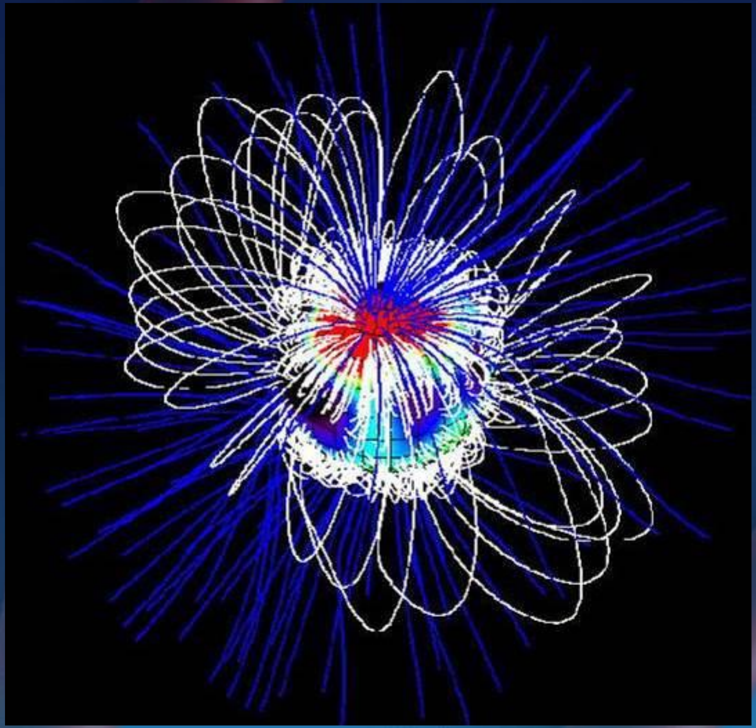
# Accretion onto Stars with Complex Fields

$$B=B_{dip}+B_{quad}+B_{oct}+\ldots$$

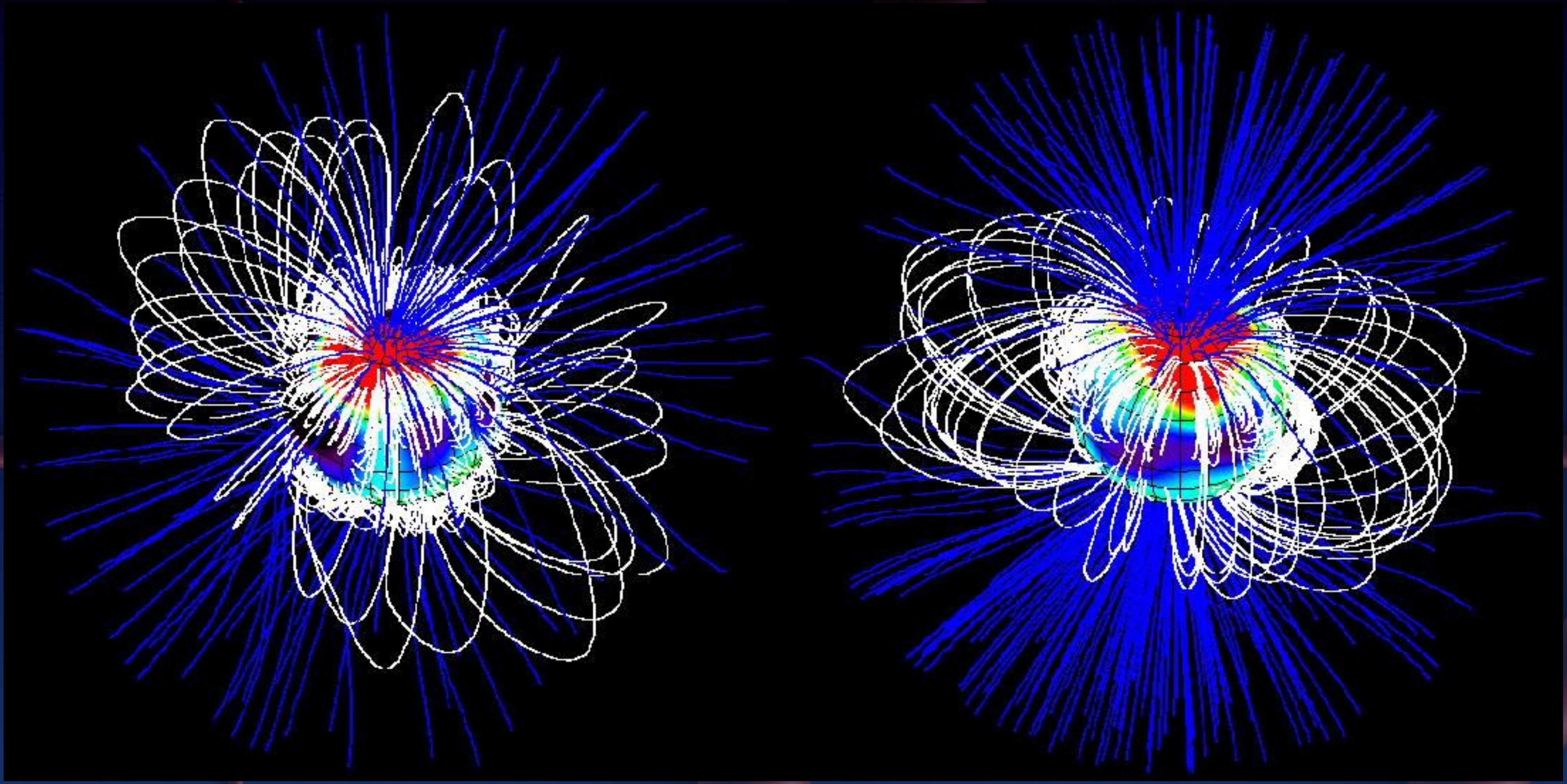
$$\mathbf{B}(\mathbf{r}) \sim \frac{\mu_1}{r^3}+\frac{\mu_2}{r^4}+\frac{\mu_3}{r^5}+\ldots$$







# Magnetic field of V2129 Oph & BP Tau

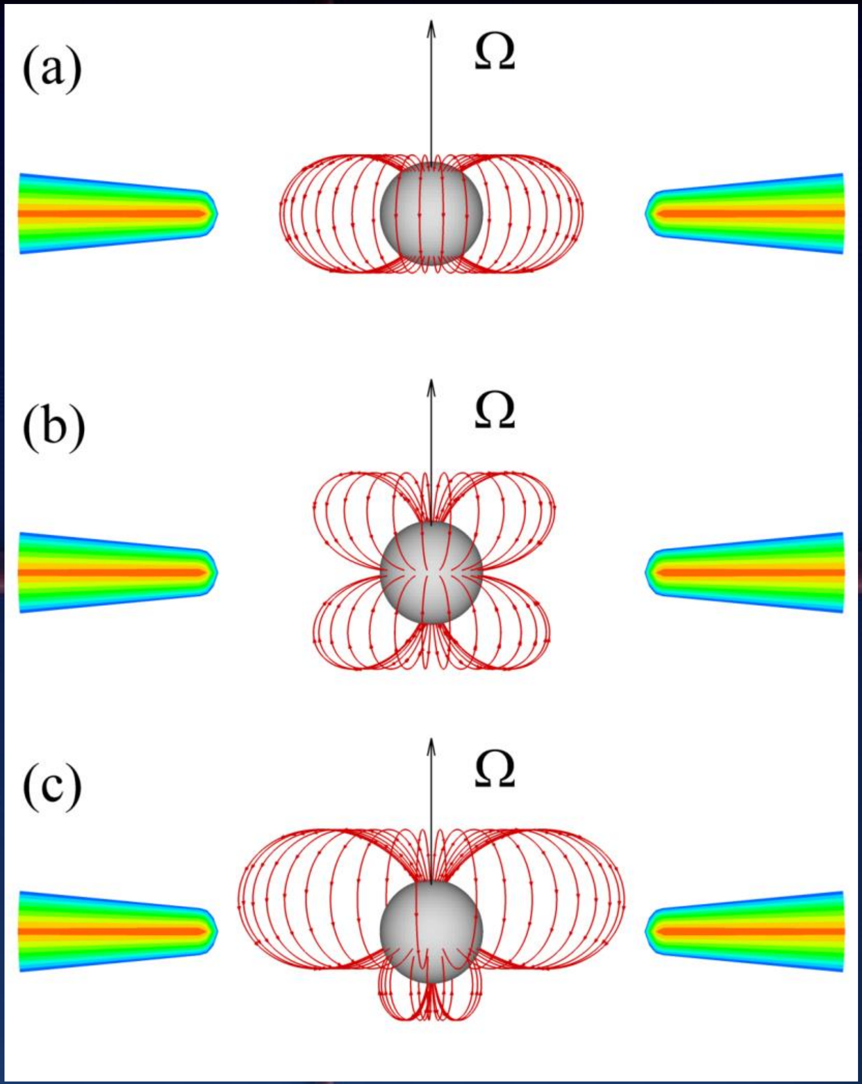


Dipole: 0.35 kG (0.9 kG)
Octupole: 1.2 kG (2.1 kG)

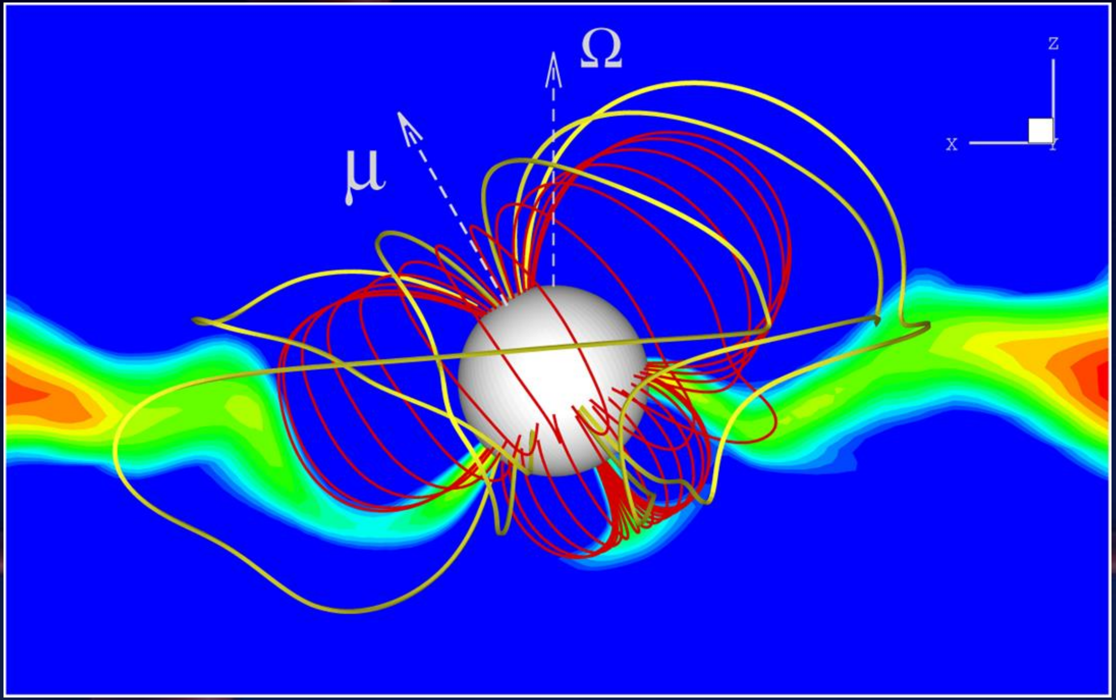
Dipole: 1.2 kG
Octupole: 1.6 kG

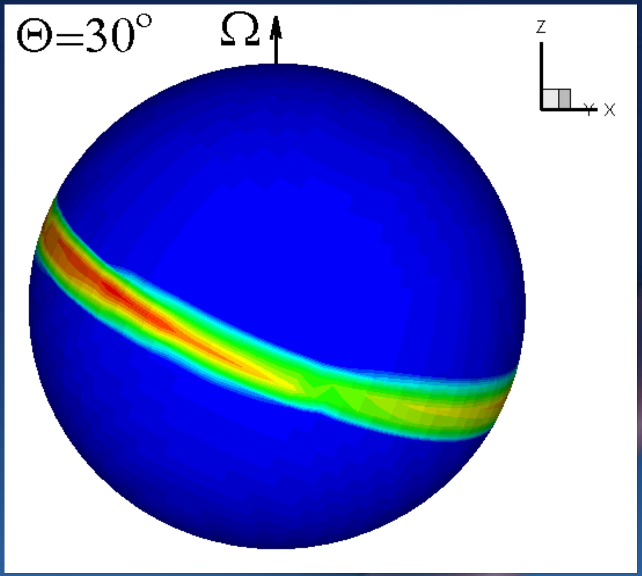
*Donati, Jardine, Gregory et al., 2007-2013*

# Aligned Quadrupole and Dipole Fields

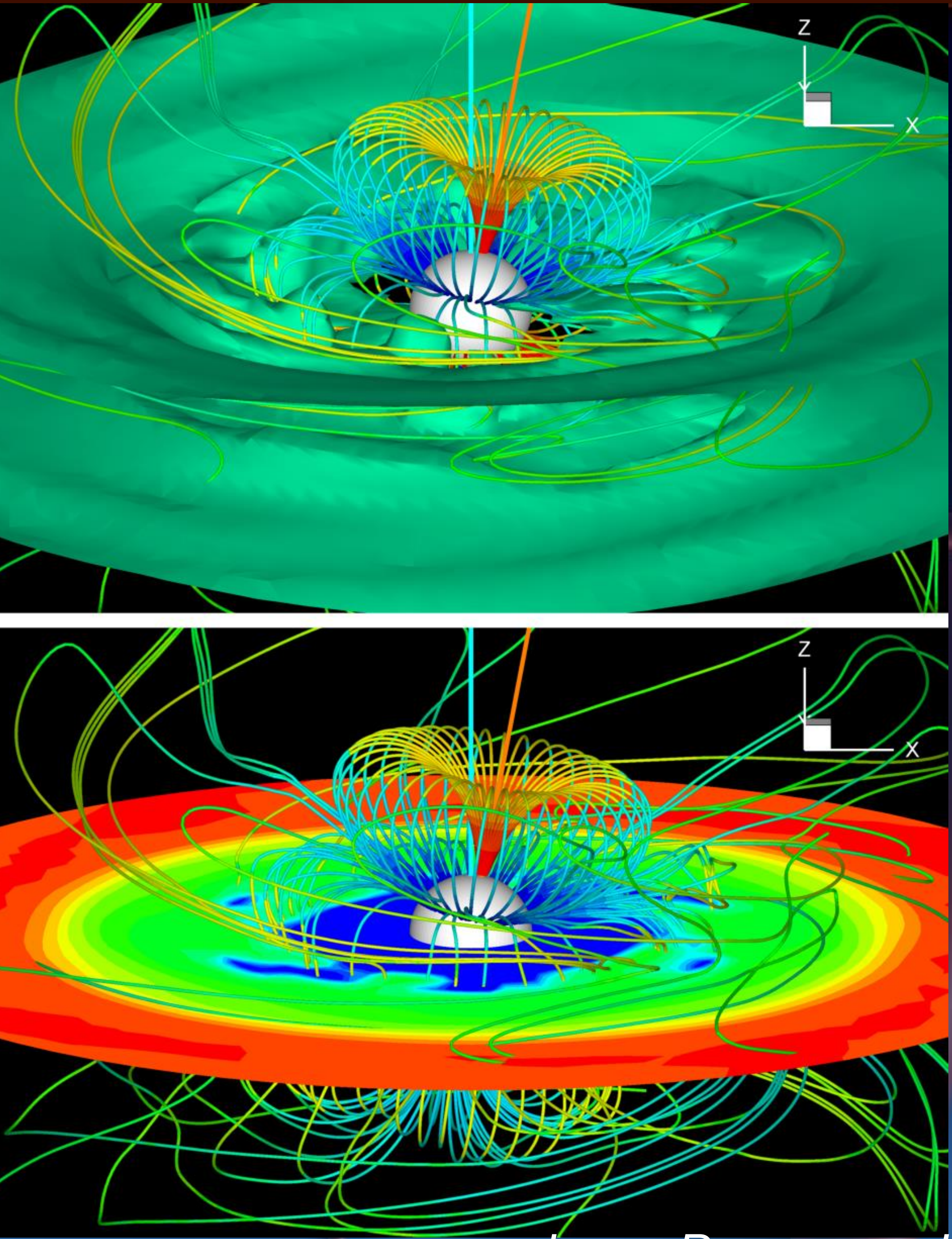


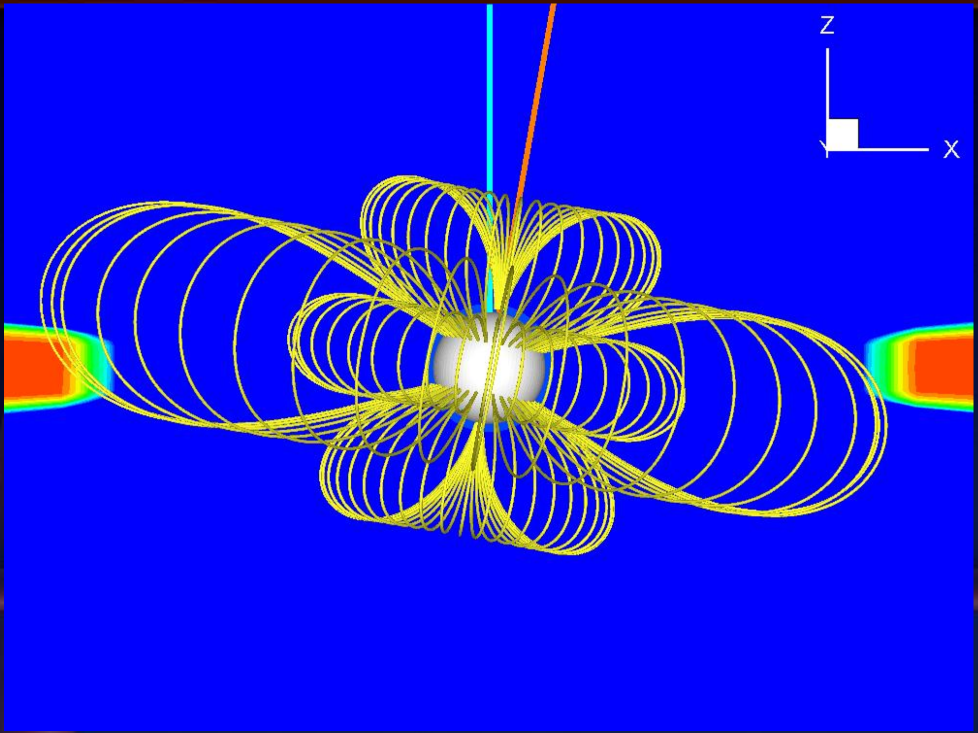
Dipole + Quadrupole



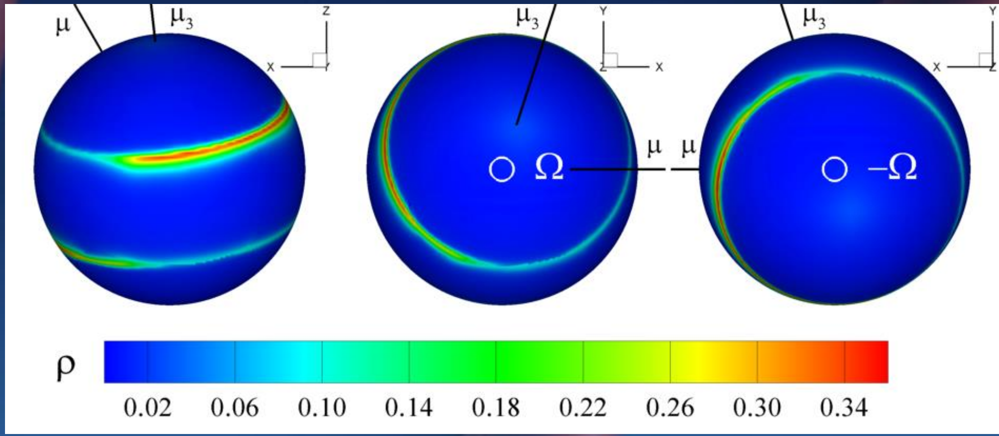


# Octupole Field



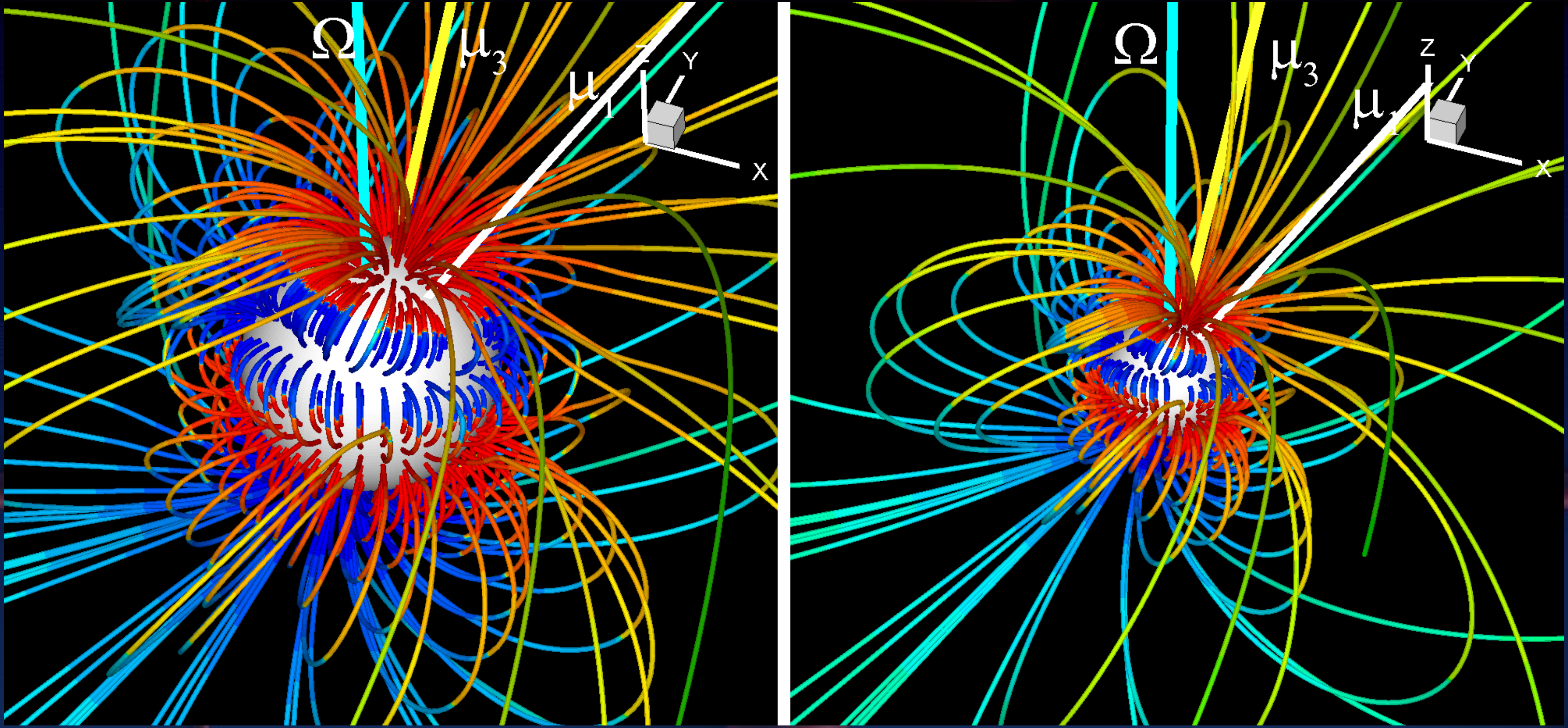


Hot spots – 2 rings



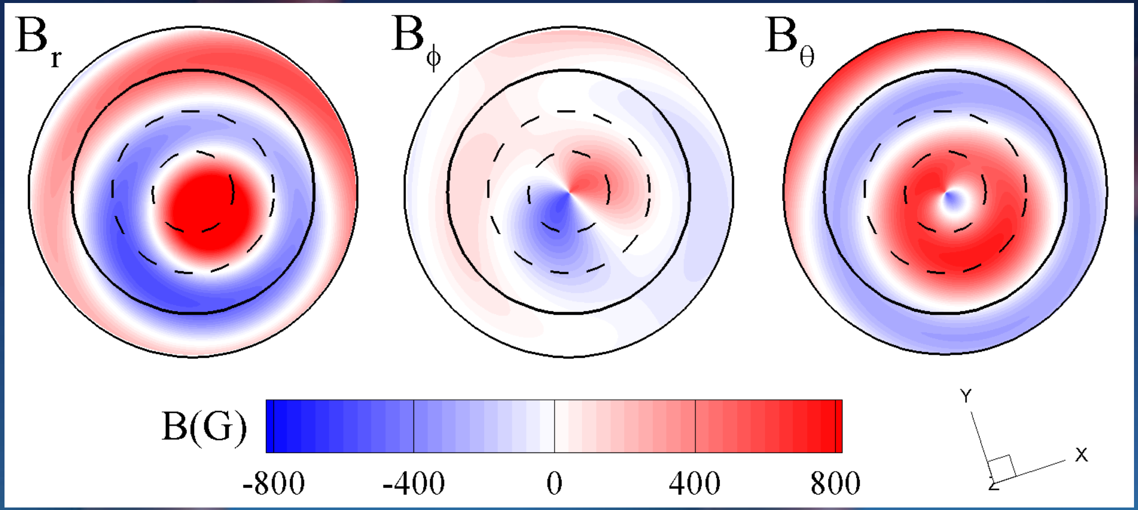
*Long, Romanova, Lamb, Kulkarni, Donati 2009*

# Initial field of V2129 Oph in our Model

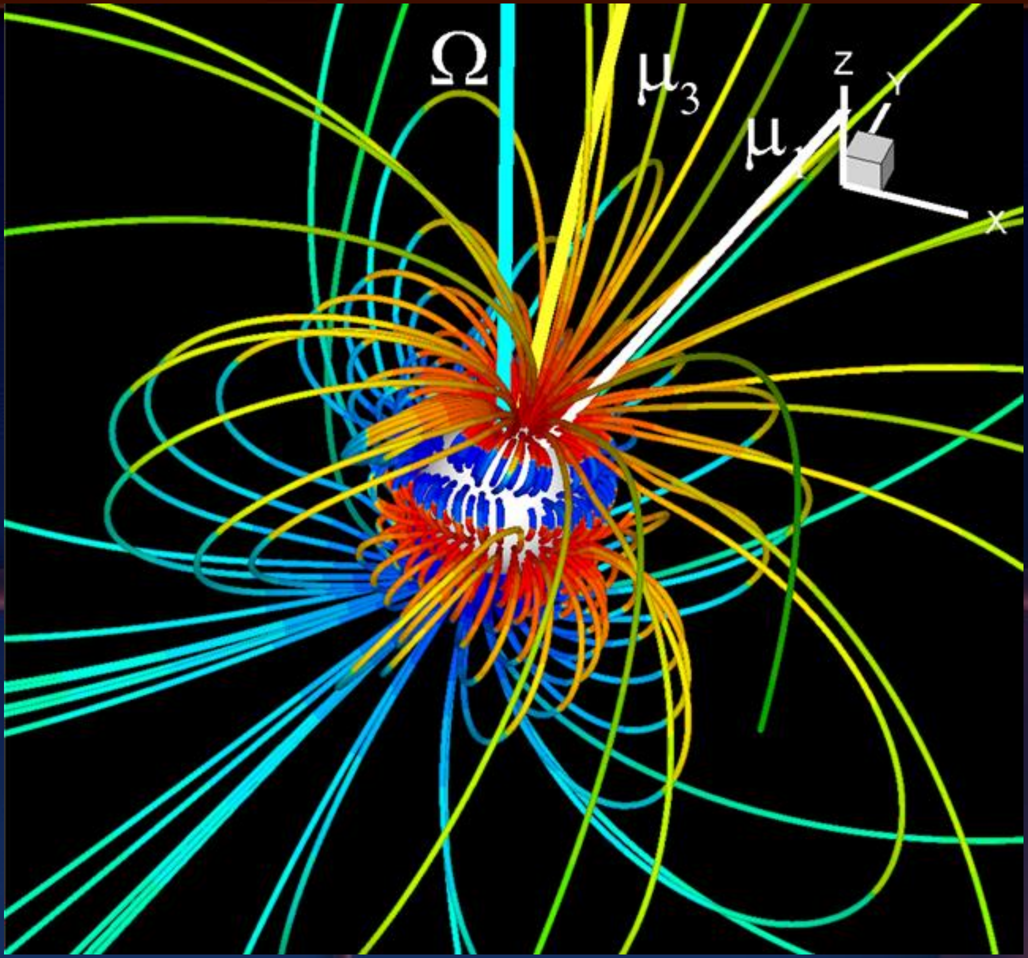


M=1.35 M_Sun
R=2.4 R_Sun
P=6.35 days
Rcor=6.8 R_star
M_dot=6.3 $10^{10}$

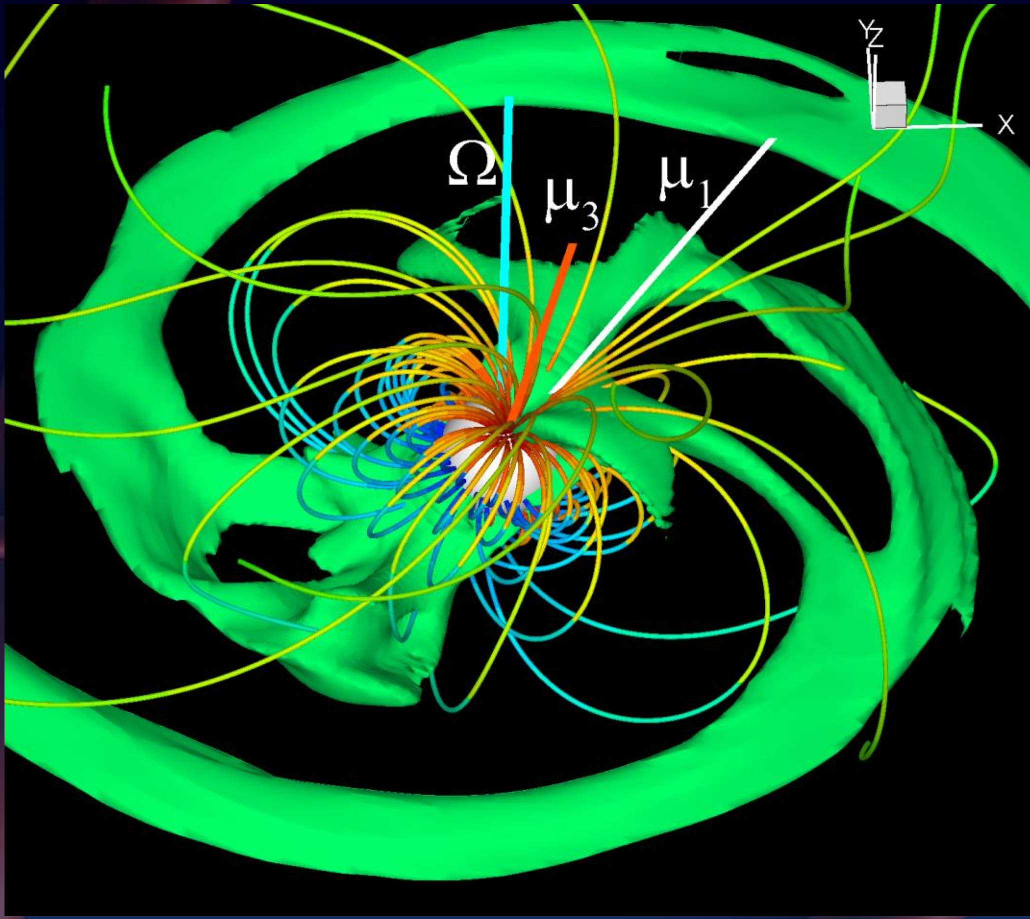
*Donati et al., 2007*



# Application of model to T Tau star V2129 Oph



Initial field

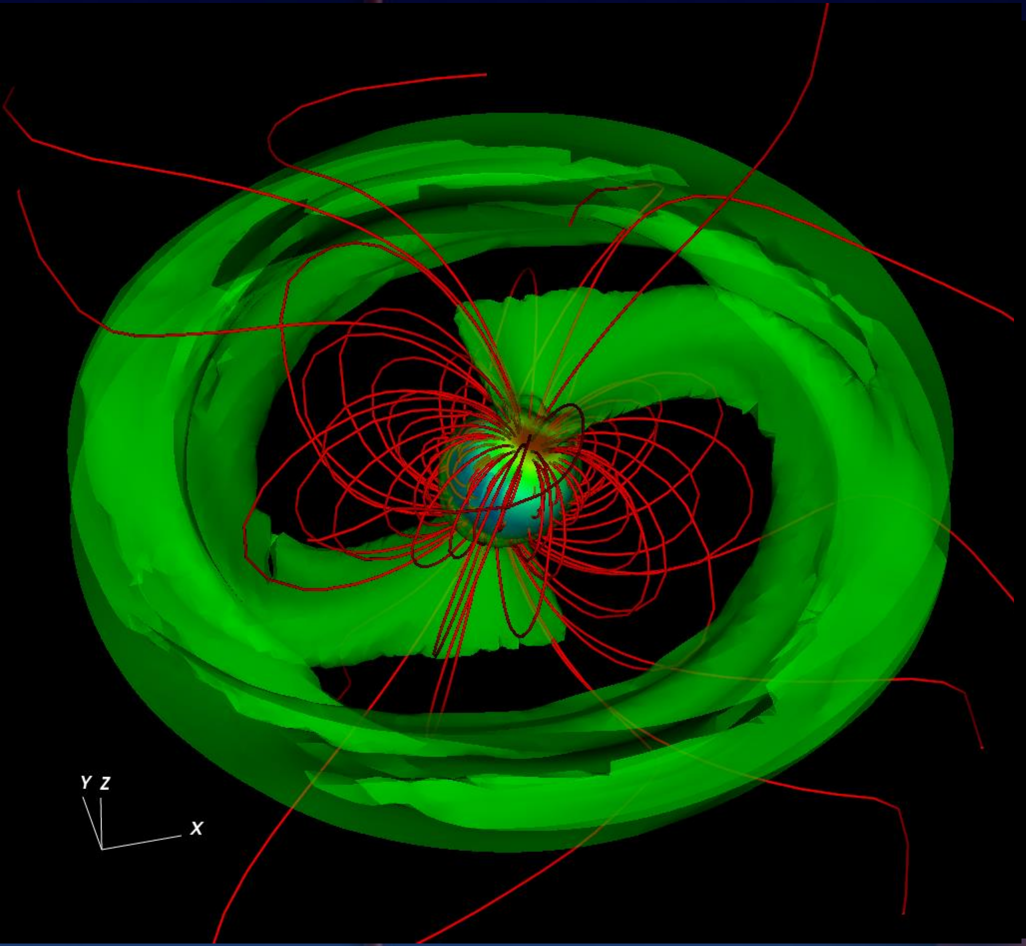


3D simulations

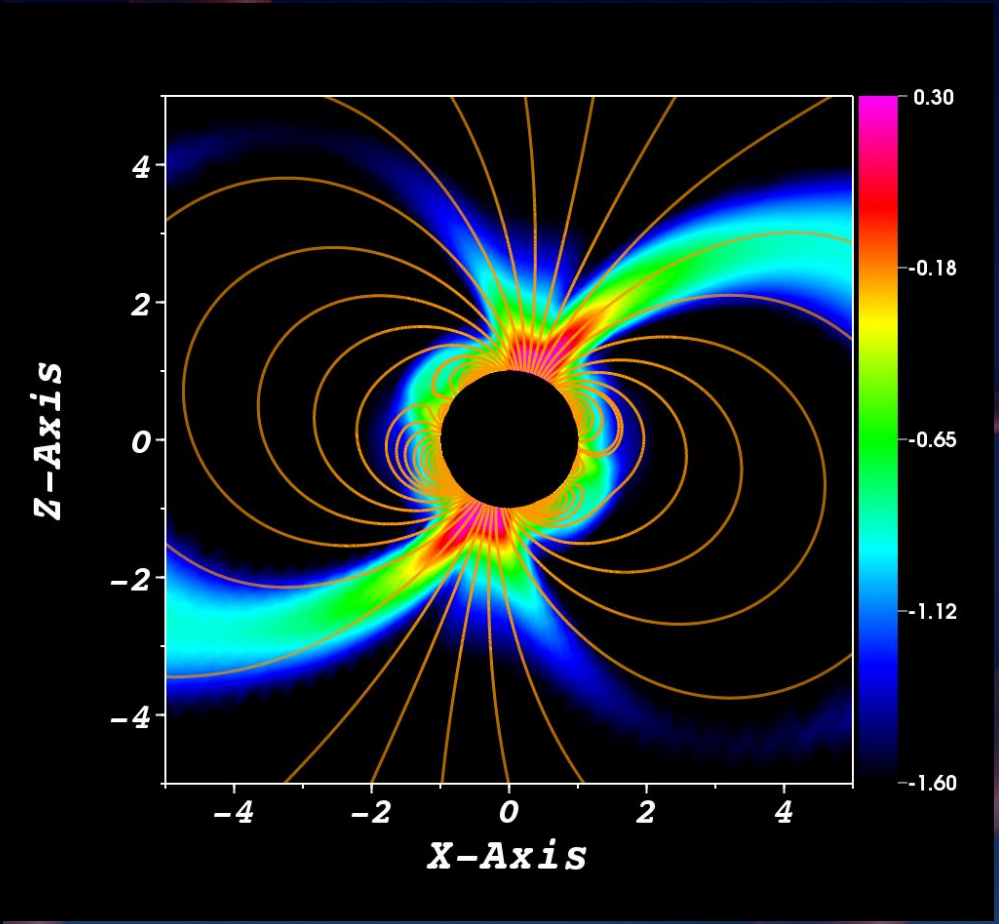
*Romanova, Long, Lamb, Kulkarni, Donati 2009*

# Application of model to T Tau star V2129 Oph

Dipole and octupole components

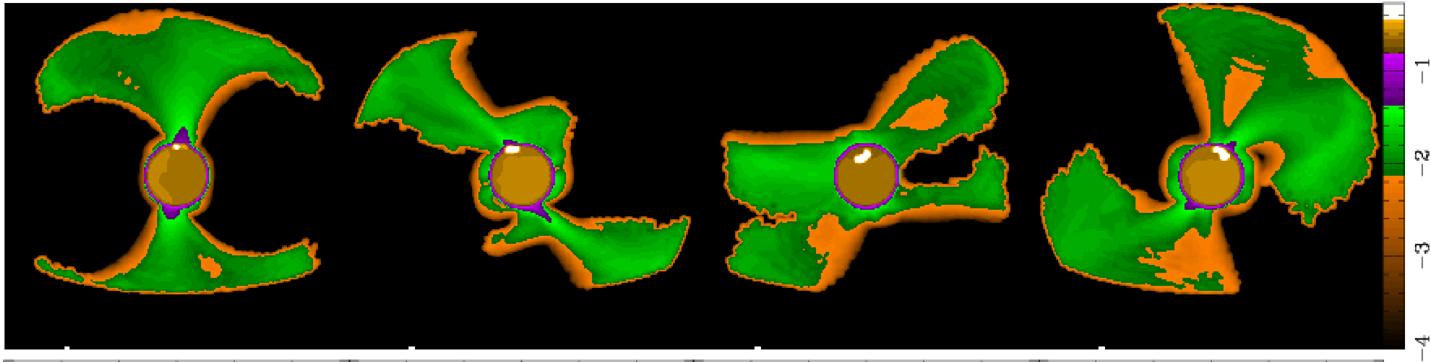


Density map and B field lines on X-Z plane



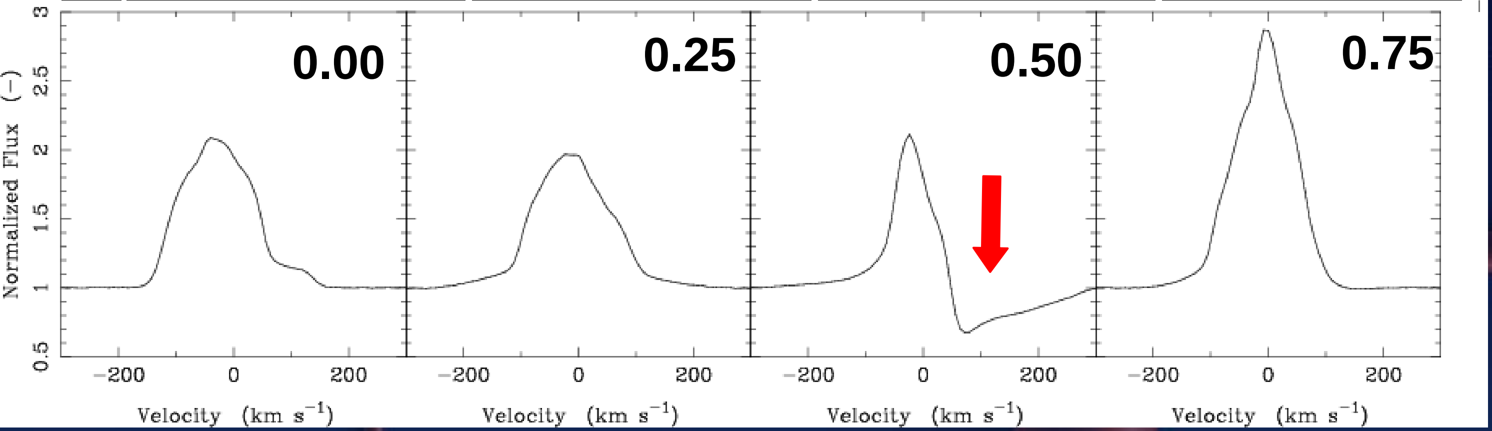
- Calculated 3D MHD flow
- Calculate spectrum in Hydrogen lines using 3D code TORUS
- Compared spectrum with observations

# Hβ Profiles and Images



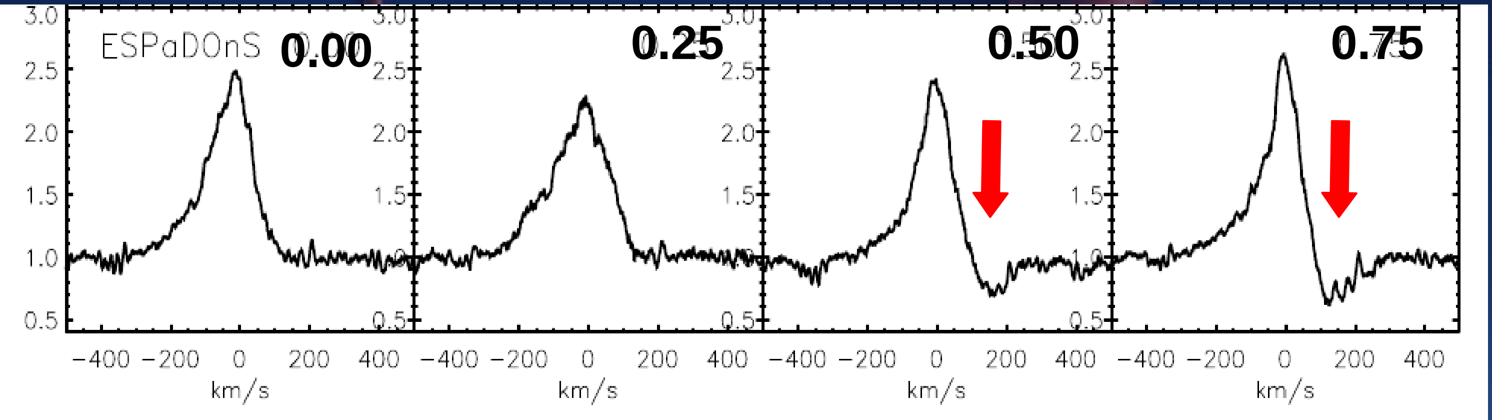
Model:

Flux map in Hβ



Model:

Hβ Profiles



Observation:

Alencar et al. (2011)

- Good agreement between 3D MHD + 3D RT simulations and observations
- This is a new tool for testing models and confronting them with observations

# Conclusions

- Developed 3D MHD + 3D radiative transfer tool for analysis of young stars
- Can compare photometric and spectral variations in observed and modeled stars, can validate MHD models
- Can predict new phenomena such as accretion through instabilities – persistent redshifted absorption