BEYOND DIPOLES:

GENERALIZED MULTIPOLE X-WIND MODEL

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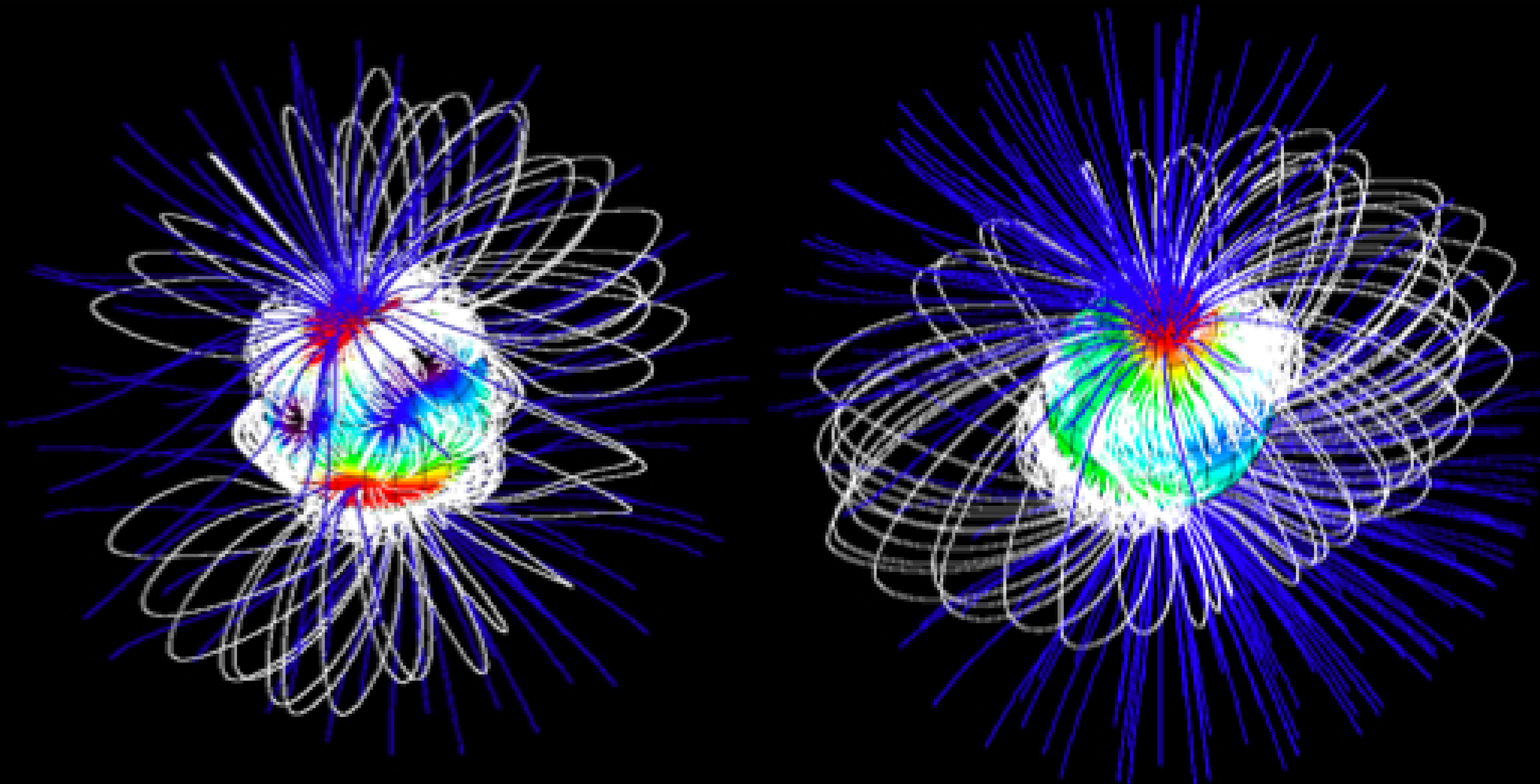
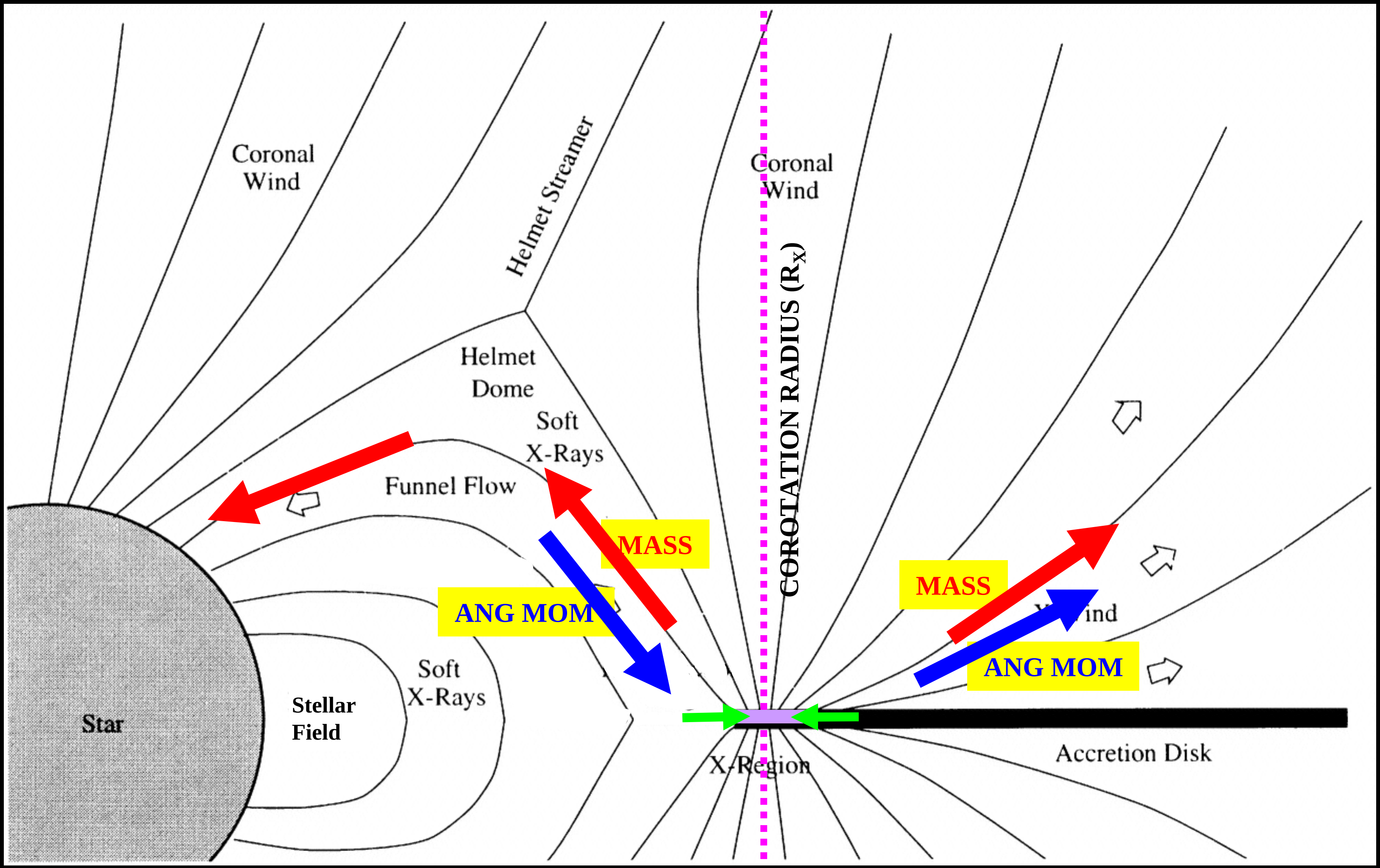
General Problem



- Accretion hot spots cover 0.1-5% of stellar surface
- Net surface polarization ~ 0

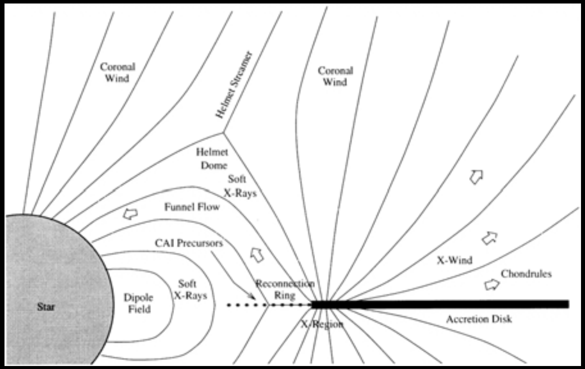
⇒ Complex multipolar surface fields

X-WIND MODEL: GENERAL STEADY-STATE SCHEMATIC



Shu et al. (1997)

GENERALIZED X-WIND MODEL



- **Trapped Flux at X-point:** Φ_t

- **Fraction of trapped flux involved in accretion (funnel flow):** Φ_t **/ 3**

- **Same field lines flow into hot spot:** $(2\pi R_*^2)\, F_h B_h = \Phi_t / 3$

- **Angular momentum removed by trapped flux from funnel flow gas:**

$$(1\text{-}f)\, \dot{M}_D\, (1\text{-}J_*)\, R_X^2 \Omega_X = \Box[\mathbf{r} \times (\mathbf{T} \bullet \mathbf{n})\, \hat{d}S] \propto (\Phi_t^2 / R_X)$$

- **Disk-locking:** $\Omega_X = \Omega_* = (GM_*/R_X^3)^{1/2}$

$\Rightarrow$ **general:** $F_h R_*^2 B_h \propto (G M_* \dot{M}_D / \Omega_*)^{1/2}$

dipole: $R_*^3 B_h \propto (G M_*^{5/3} \dot{M}_D / \Omega_*^{7/3})^{1/2}$

Mohanty & Shu (2008)

CONSTANT of PROPORTIONALITY

- **With:** $f \equiv \dot{M}_W / \dot{M}_D$ **and** $\beta \equiv \int_0^1 \beta(\psi) d\psi$, where $\mathbf{B} = \beta(\psi) \rho \mathbf{u}$

  (i.e., β=mean magnetic field to mass flux ratio in X-wind)

- **Wind dynamics:** $\Phi_t / 3 = 2\pi \beta f^{1/2} (G M_* \dot{M}_D^2 R_X^3)^{1/4}$

- **Recall:** $(2\pi R_*^2) F_h B_h = \Phi_t / 3$ and $\Omega_X = \Omega_* = [GM_*/R_X^3]^{1/2}$

- $F_h B_h = \beta f^{1/2} B_{norm} (R_X / R_*)^{3/4}$ where $B_{norm} \equiv (G M_* \dot{M}_D^2 / R_*^5)^{1/4}$
- $F_h R_*^2 B_h = \Phi_t = \beta f^{1/2} (G M_* \dot{M}_D / \Omega_*)^{1/2}$

- **Angular momentum balance in X-region (entering = leaving):**

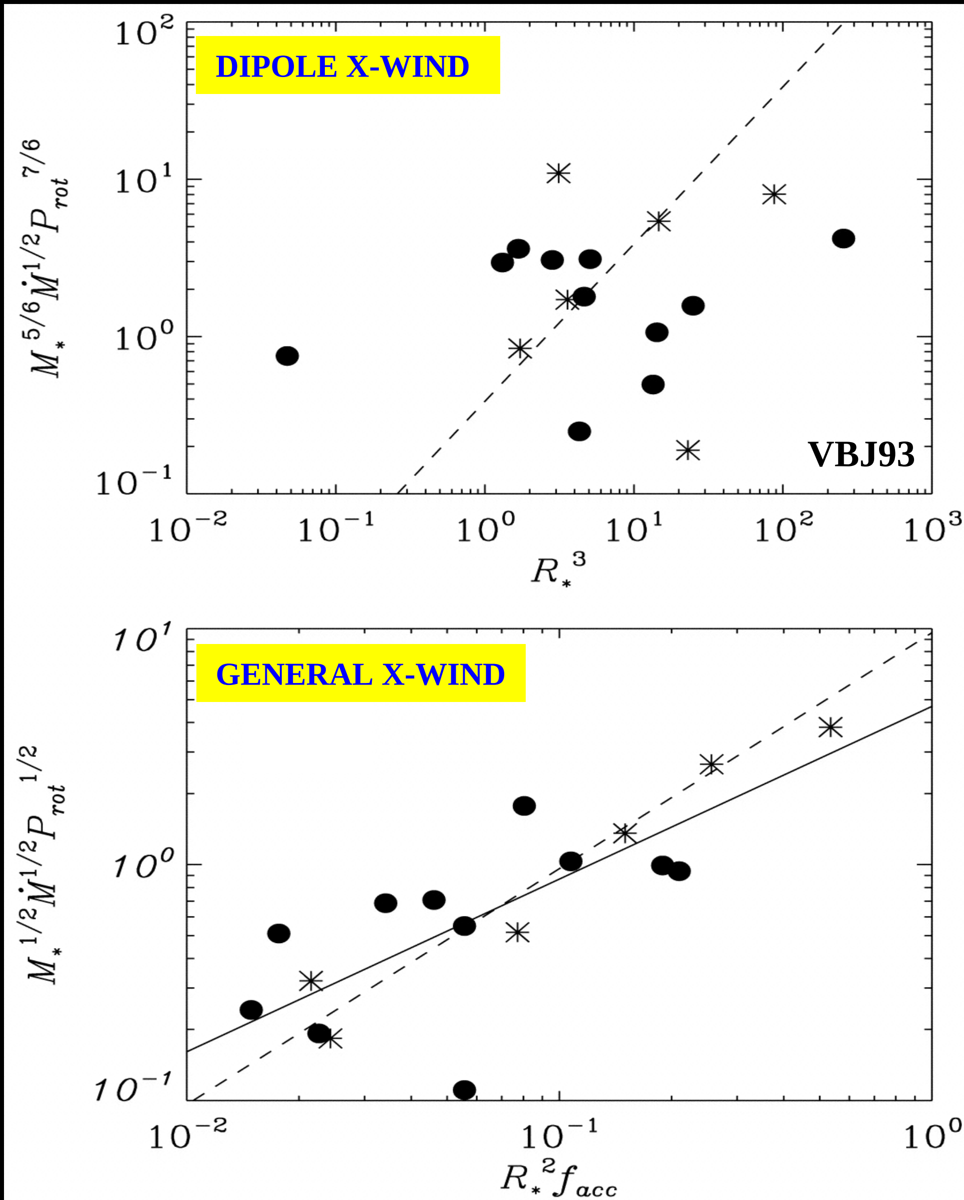
$$\dot{M}_D R_X^2 \Omega_X = (1-f) \dot{M}_D J_* R_X^2 \Omega_X + f \dot{M}_D J_W R_X^2 \Omega_X + T$$

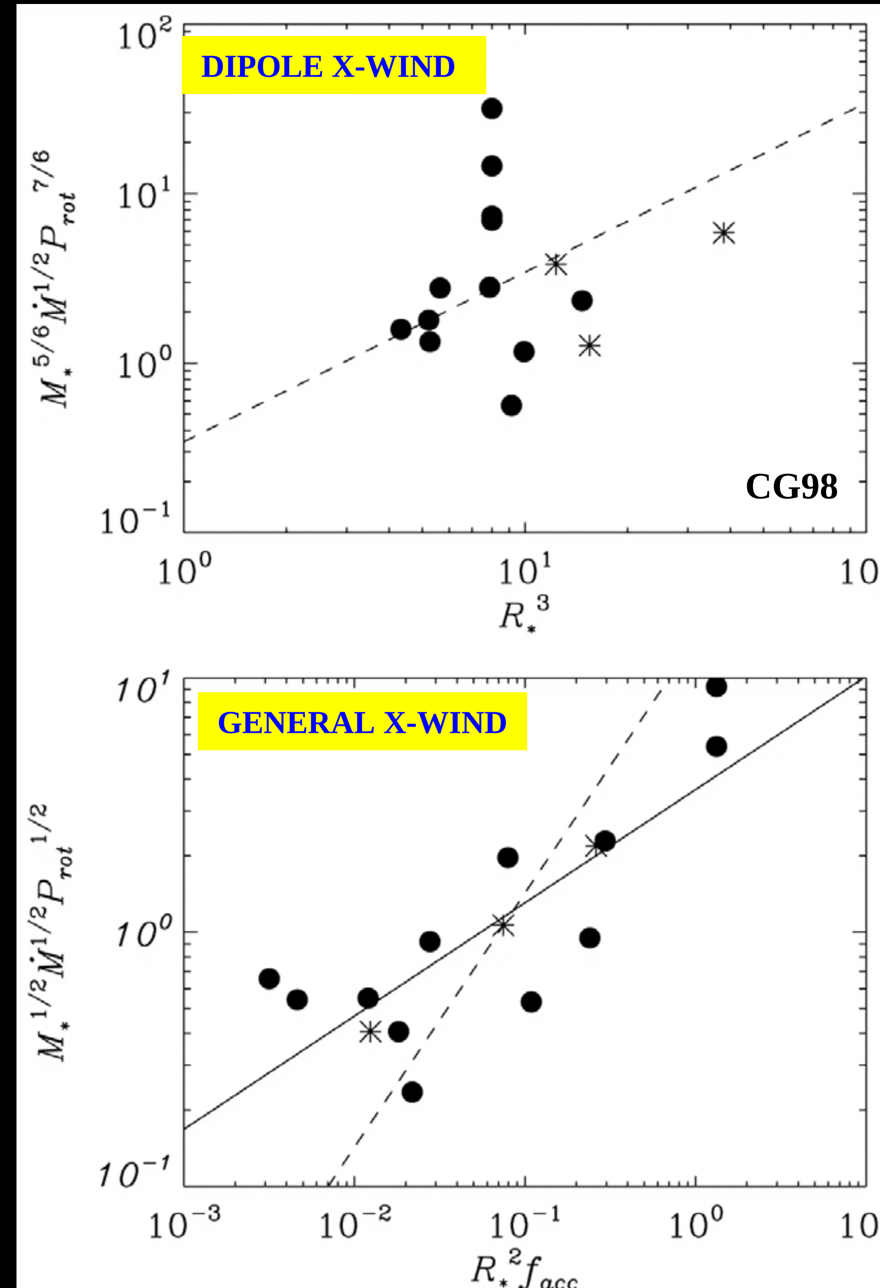
$$\Rightarrow f = (1 - J_* - \tau) / (J_W - J_*)$$

- Assume: $J_* \approx 0$, $\tau \approx 0 \Rightarrow J_W \approx 1 / f$; $f = 1/3 \Rightarrow \beta = 1.21$ **(Cai et al. 2008/talk)**

Mohanty & Shu (2008)

Checking the Generalized Model...





Johns-Krull & Gaffford (2002)

The Cases of V2129 Oph & BP Tau

(Mdot, F_h, B_h directly measured simultaneously)

V2129 Oph:

- $M_* = 1.35\ M_\odot$, $R_* = 2.4\ R_\odot$, Mdot = $1 \times 10^{-8}\ M_\odot$/yr
- $P_* = 6.53$ day $\Rightarrow R_{COROTATION}\ (=R_X) = 6.67\ R_*$
- $B_h = 2$ kG, $F_h = 5\%$ $\Rightarrow$ measured $F_hB_h = 100$ G (Donati et al. 2007)
- *Multipole X-wind equation (with f = 1/3, ß = 1.21):*

$\Rightarrow$ predicted $F_hB_h = 79$ G

BP Tau:

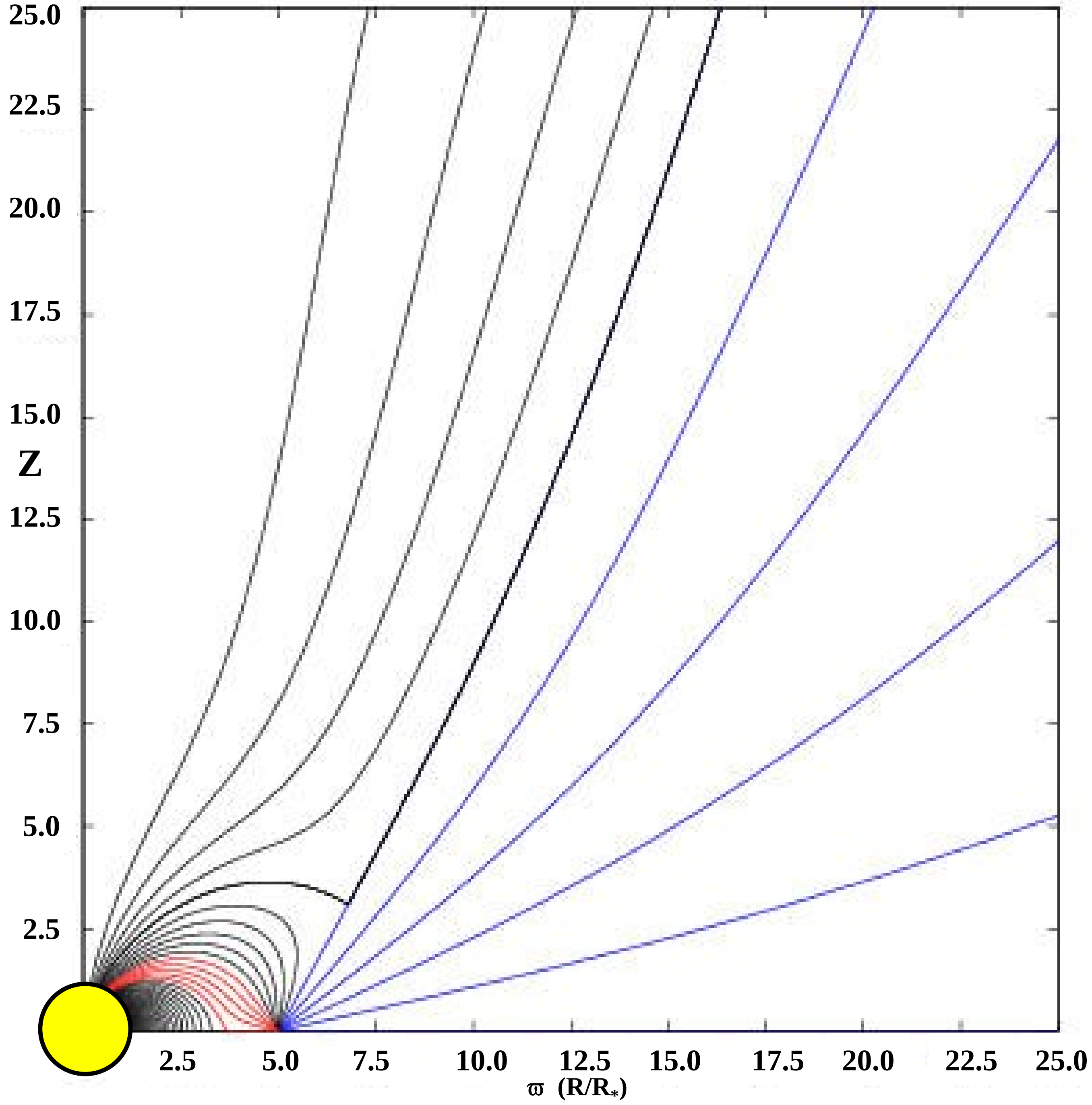
- $M_* = 0.8\ M_\odot$, $R_* = 1.95\ R_\odot$, Mdot = $3 \times 10^{-8}\ M_\odot$/yr
- $P_* = 7.6$ day $\Rightarrow R_{COROTATION}\ (=R_X) = 7.5\ R_*$
- $B_h = 9$ kG, $F_h = 2\%$ $\Rightarrow$ measured $F_hB_h = 180$ G (Donati et al. 2008)
- *Multipole X-wind equation (with f = 1/3, ß = 1.21):*

$\Rightarrow$ predicted $F_hB_h = 170$ G

Ostriker & Shu (1995)

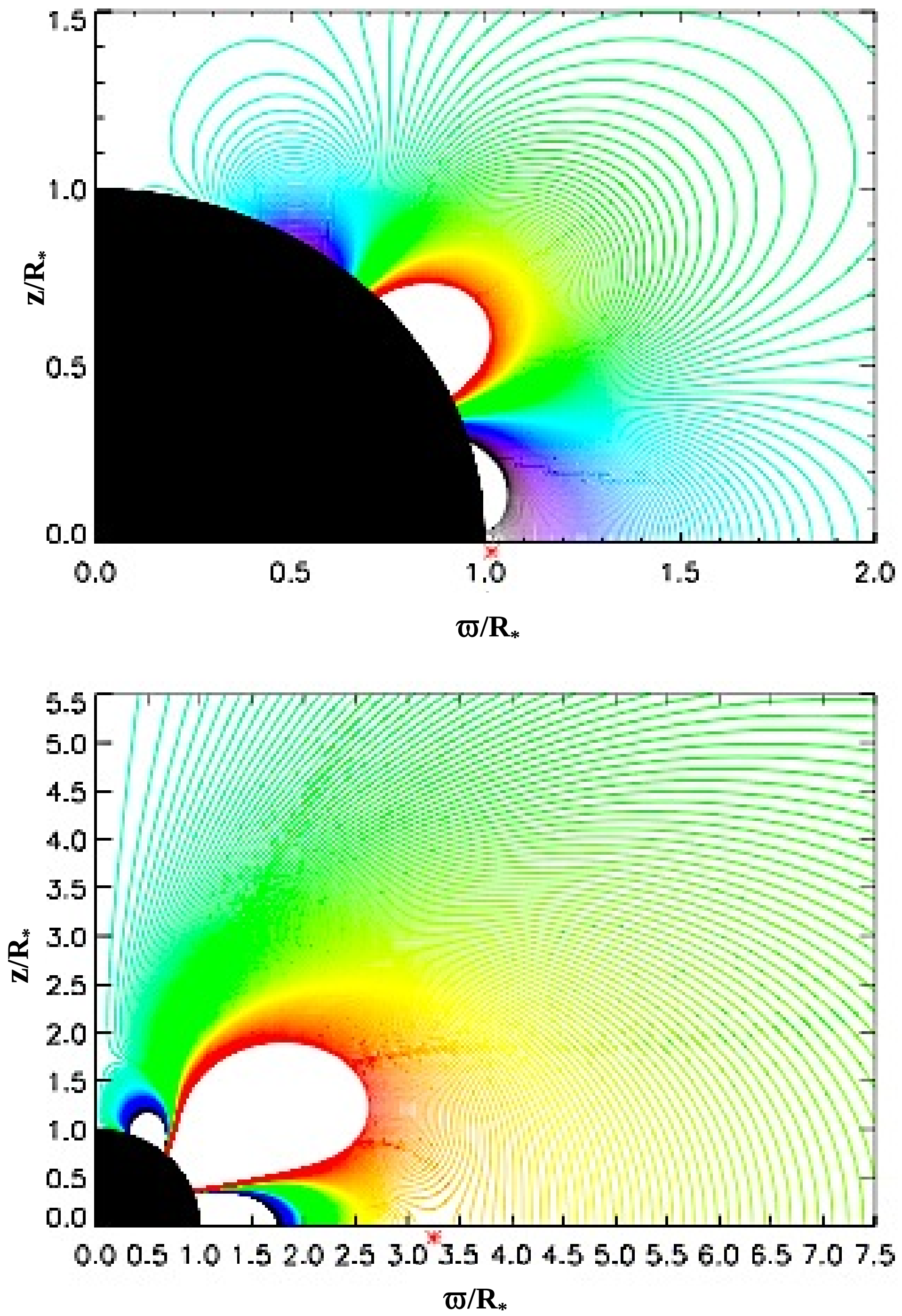
X-WIND MODEL:
DIPOLE FIELD

(R_X = 5 R_*)

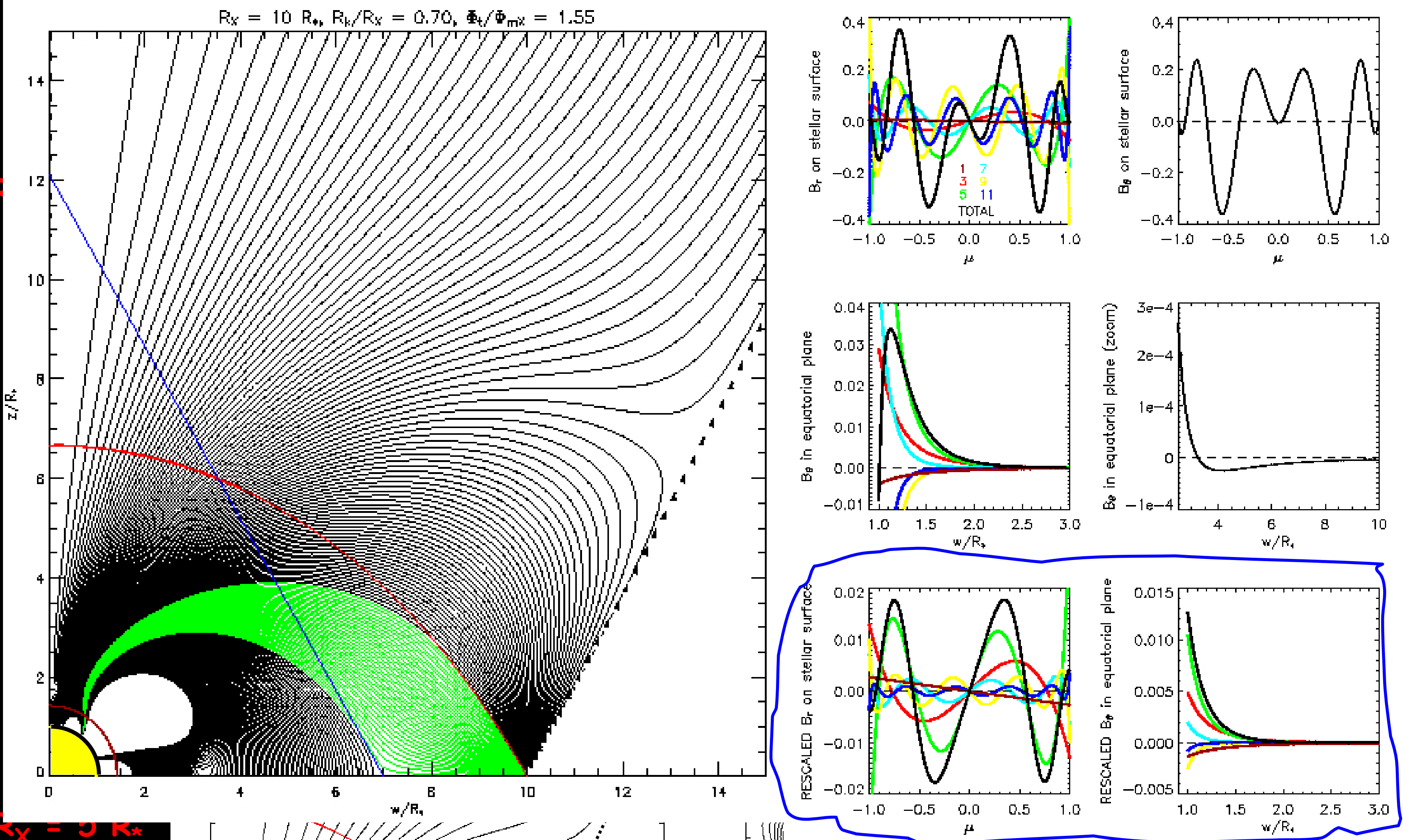


Observational Constraints on Surface Field

- Low Net Surface Polarization
- High Polarization within Accretion Flow
- Small Hot-Spot Covering Fraction (~few %)



Mohanty & Shu (2008)



Rescaled solution: $R_X = 7R_*$, hot spot latitude = 55°, dominant surface B: l = 1, 3, 5

F_h = 1% ⇒ B_h (with fiducial parameters $M_* = 0.5M_\odot$, $R_* = 2R_\odot$, Mdot = $10^{-8}M_\odot$/yr) = 8.8 kG

V2129 Oph & BP Tau: $R_X \sim 6.7 - 7.5R_*$, hot spot latitude ~ 70°, dominant surface B: l = 1, 3, 5

F_h = 2 - 5%, B_h = 2 - 9 kG

Conclusions

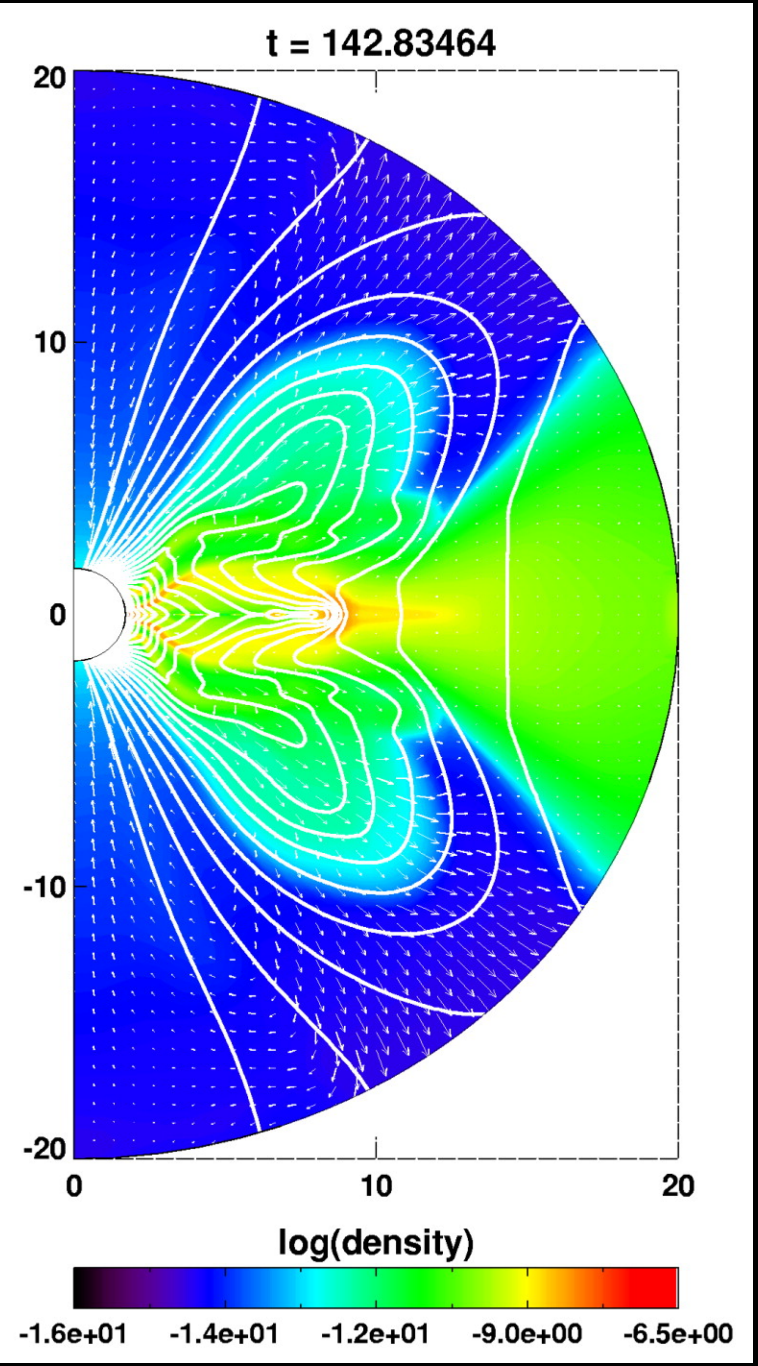
- X-Wind theory: Main ingredient is trapped flux;

- Dipole field not necessary;
makes general unique prediction consistent with obs.

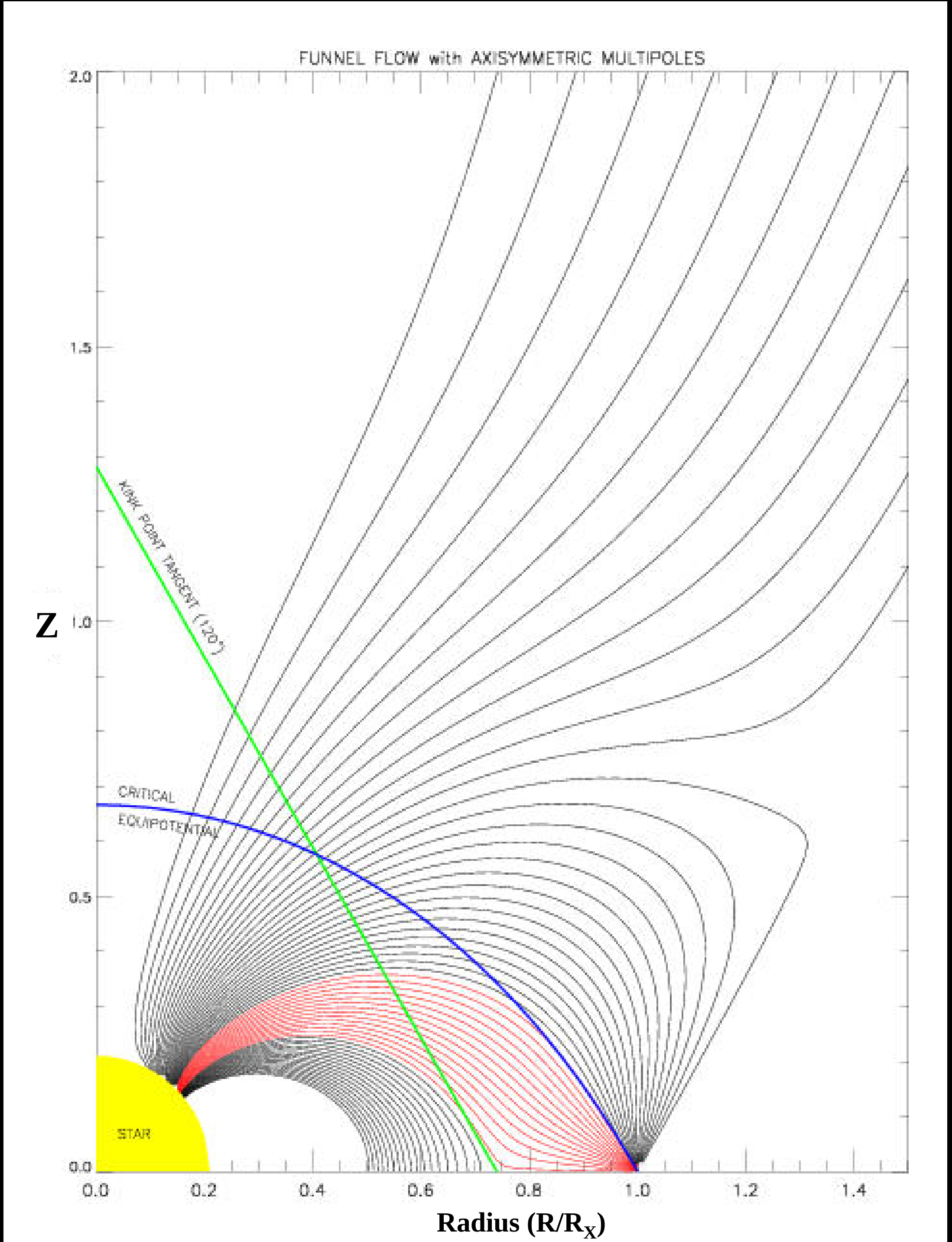
- Multipole fields can match both the observational constraints on surface field and the X-point geometry

- Future: include viscous torque (if disk fields present);
Tilted Fields; Non-Axisymmetry;
Theory: understand disk viscosity vs. resistivity better;
Simulations: non-dipole fields with flux-trapping
(a la Romanova et al. 2008 with dipole fields)

THE END



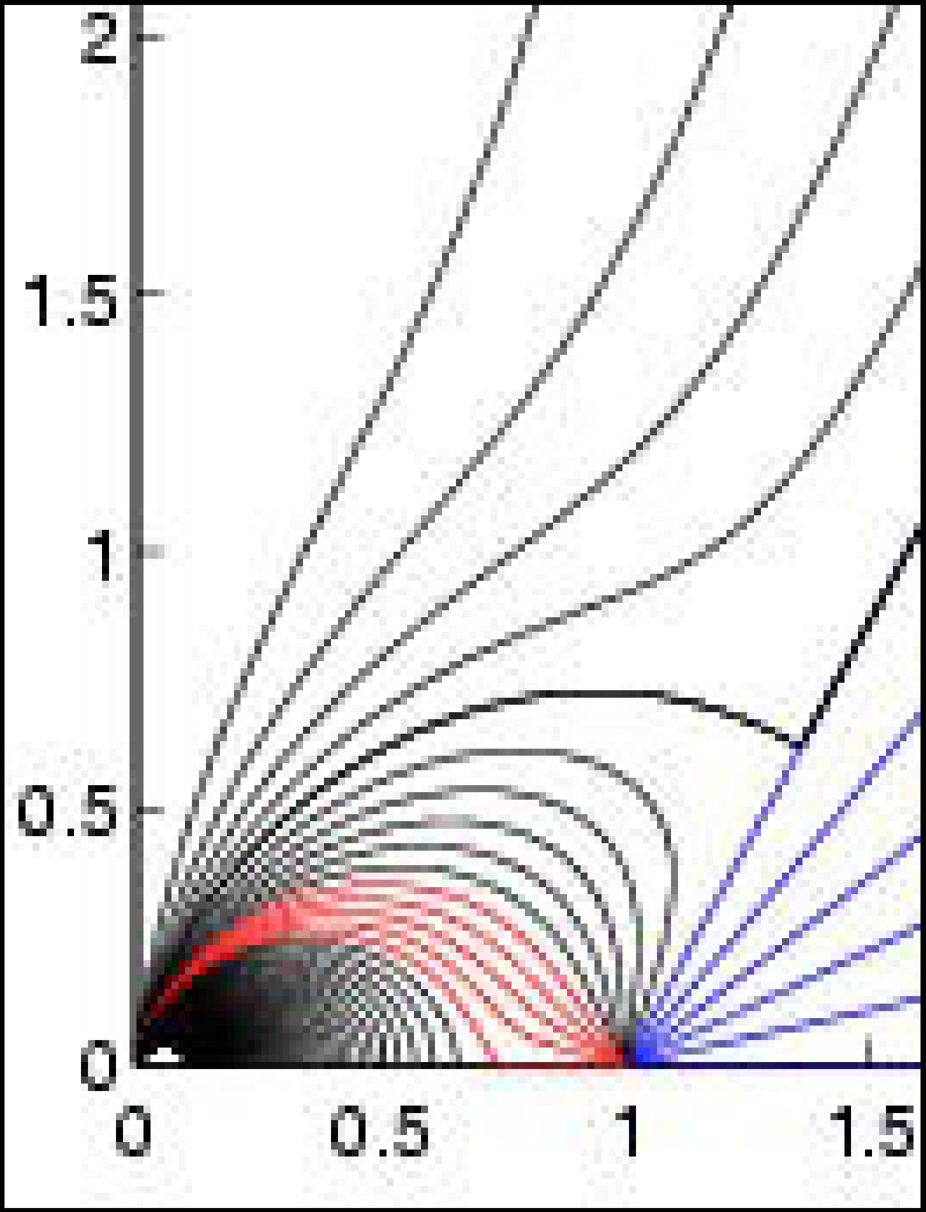
t = 142.83464
20
10
0
-10
-20
0
10
20
log(density)
-1.6e+01
-1.4e+01
-1.2e+01
-9.0e+00
-6.5e+00



X-WIND MODEL: MULTIPOLE FIELD

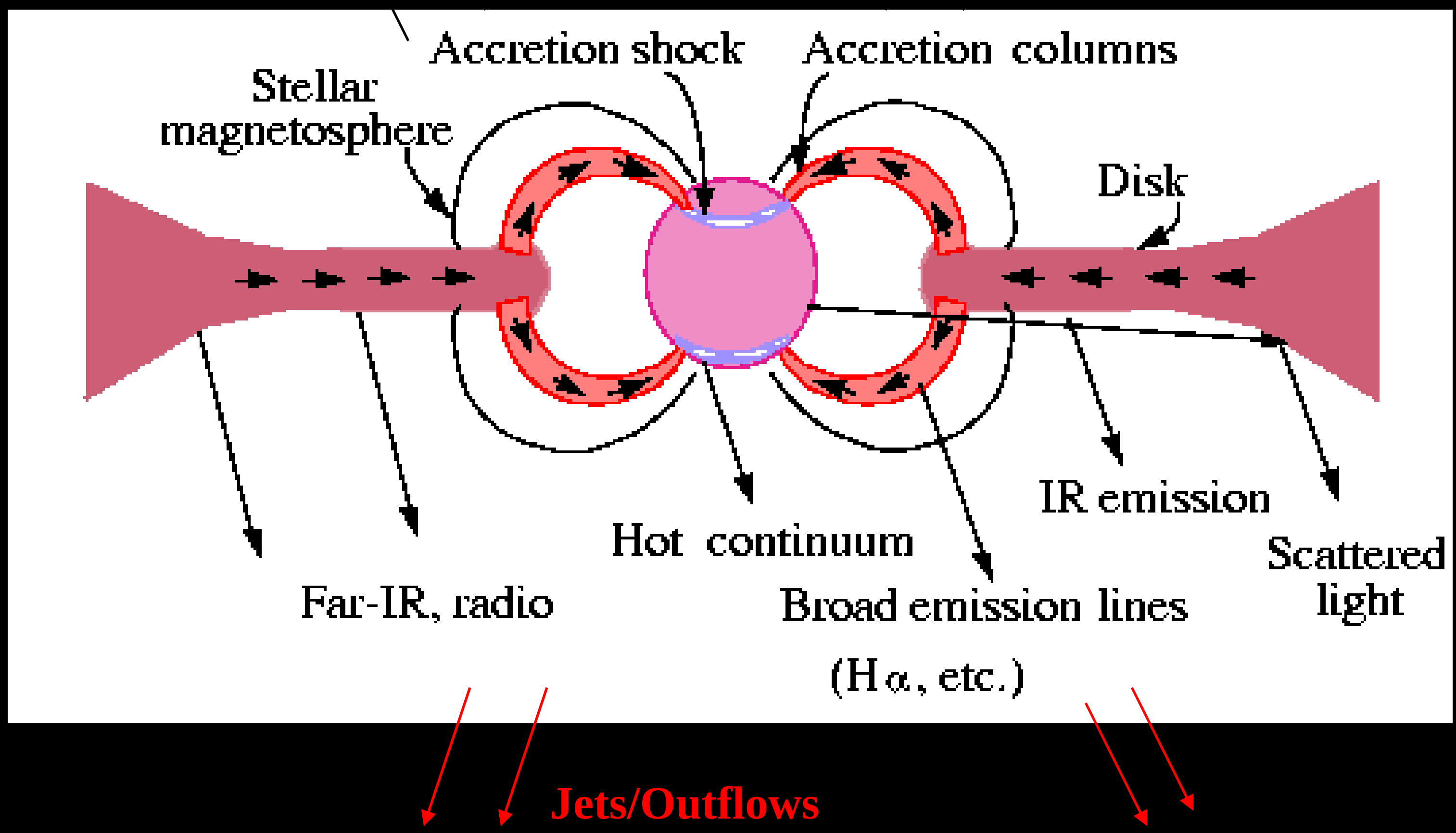
(R_X = 5 $R_\star$)

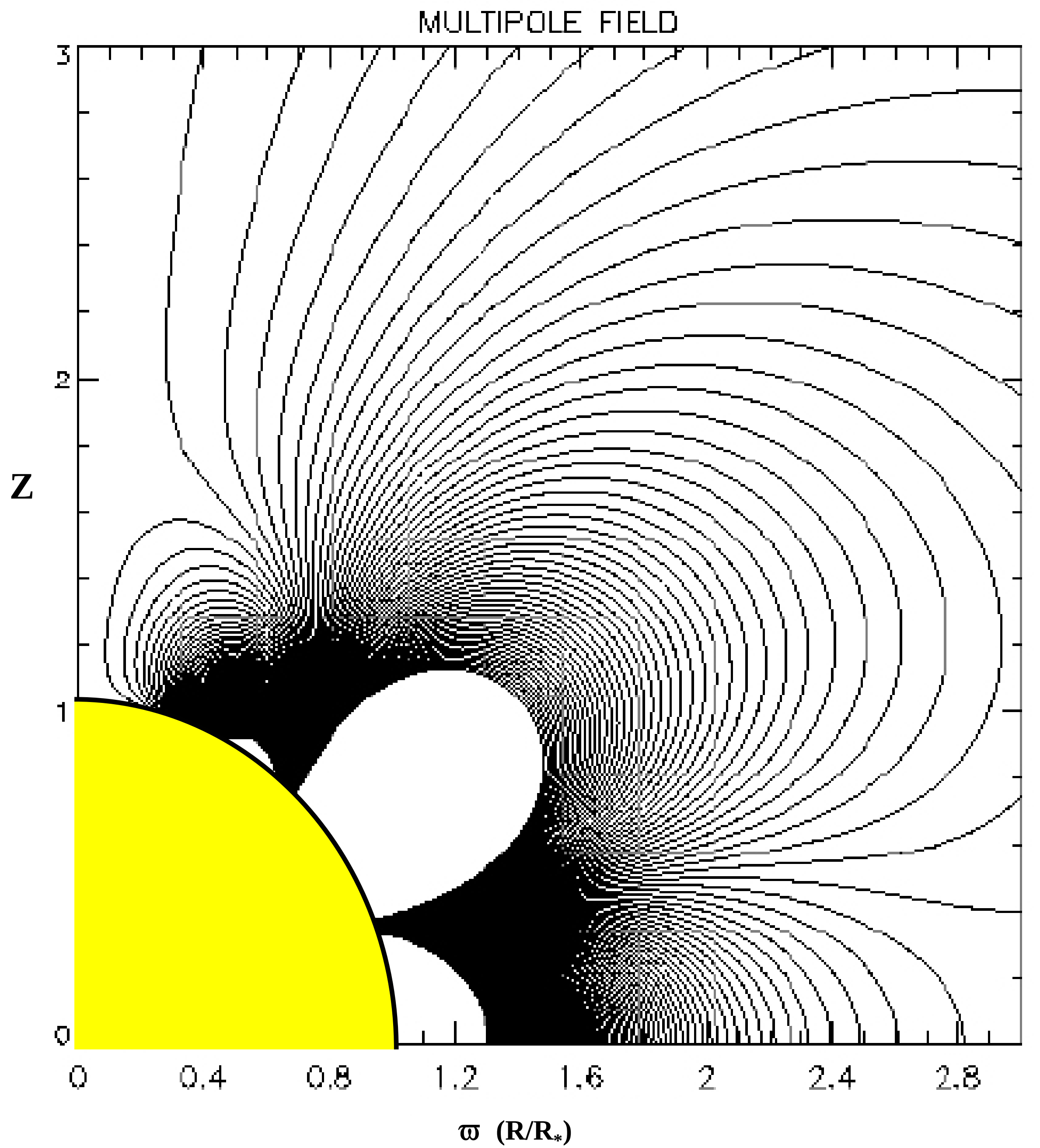
Mohanty & Shu (2005)



2
1.5
1
0.5
0
0
0.5
1
1.5

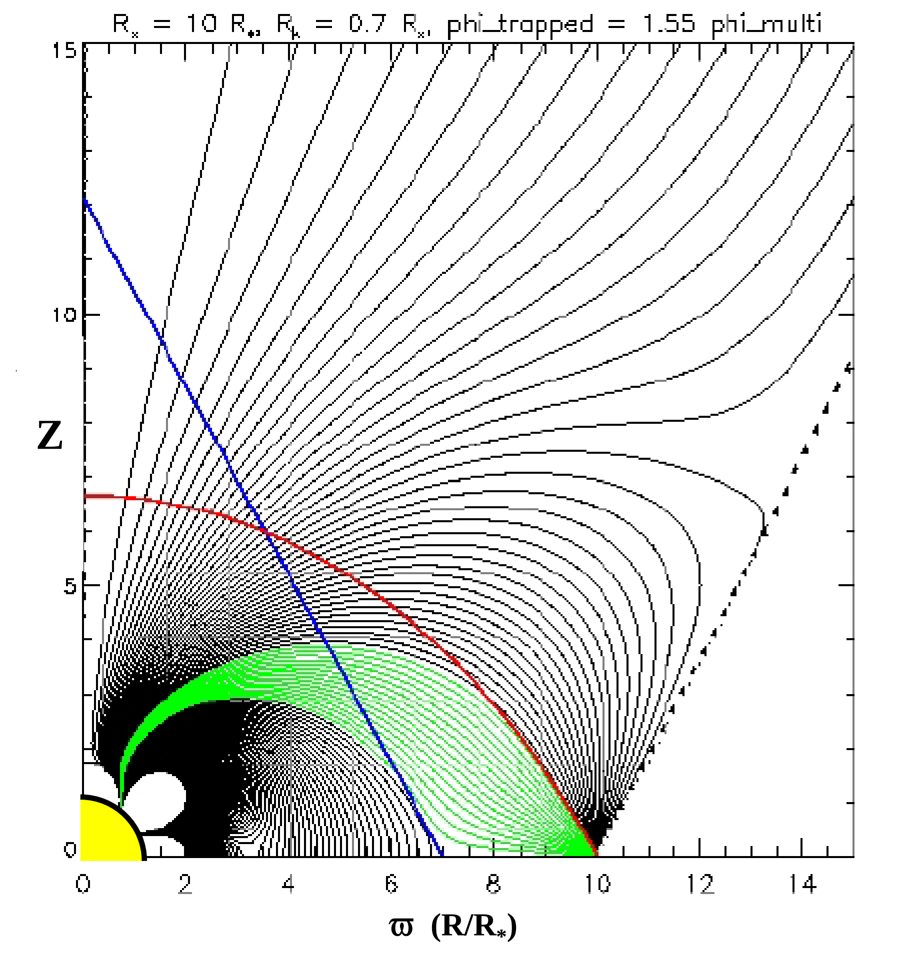
Disk-Locking in Accreting Stars



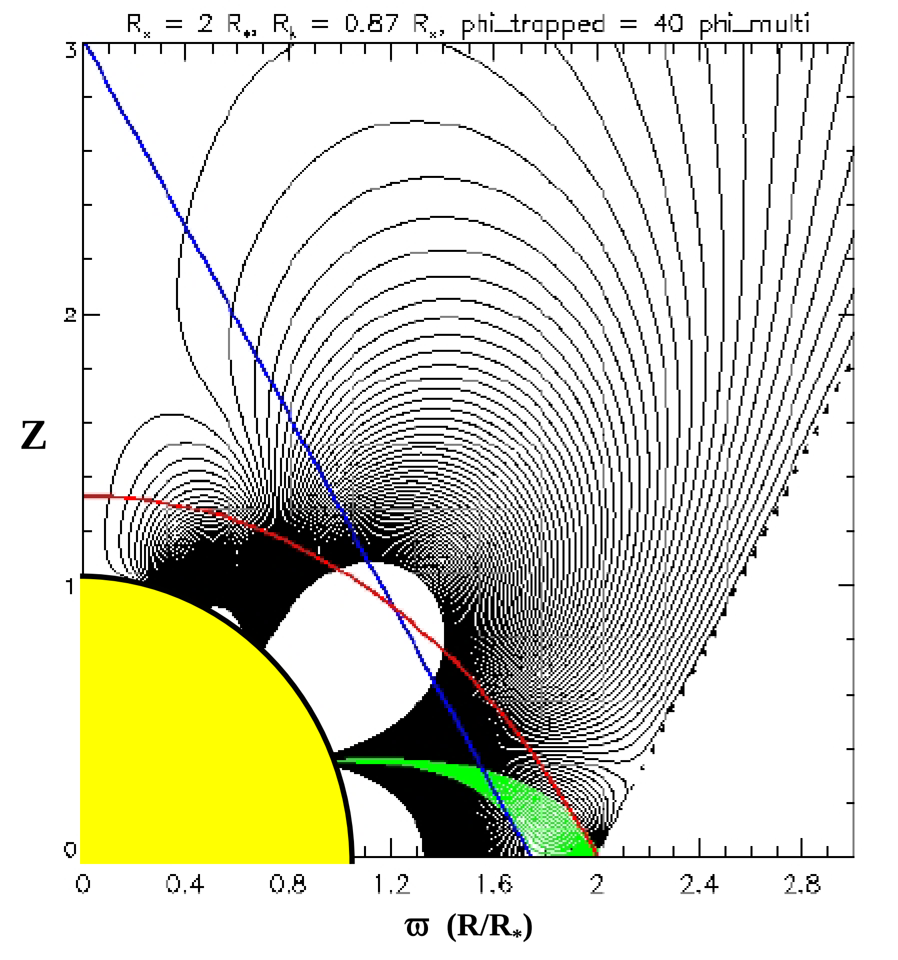

MULTIPOLE FIELD
Z
0
1
2
3
0
0.4
0.8
1.2
1.6
2
2.4
2.8
ϖ (R/R*)

MULTIPLE FLOWS with MULTIPOLE FIELD

$R_X = 10\ R_*$



$R_X = 2\ R_*$



Mohanty & Shu (2006)

Outline

- X-Wind Model:

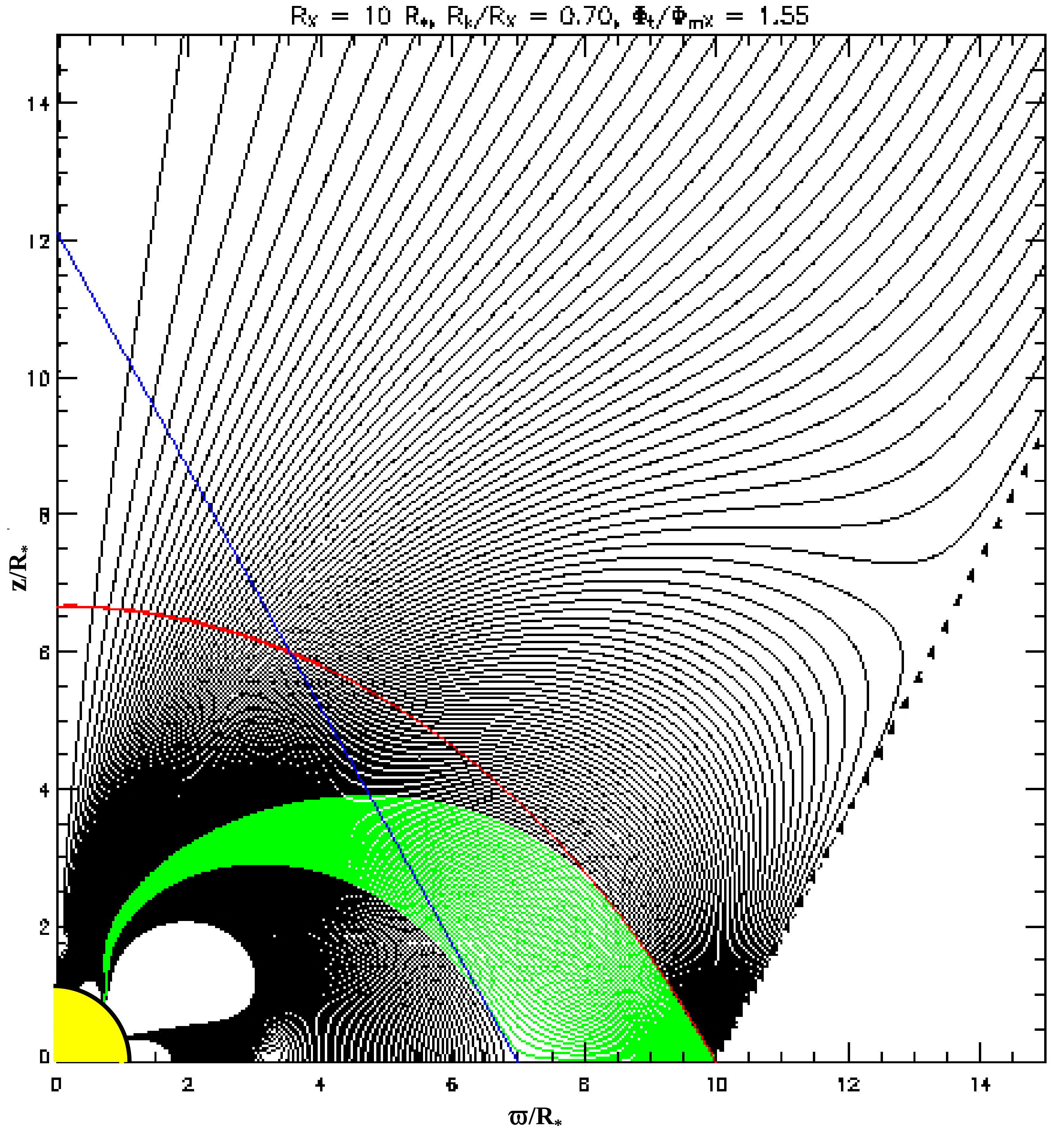
  Qualitative description

- Necessary Conditions for X-Wind Model:

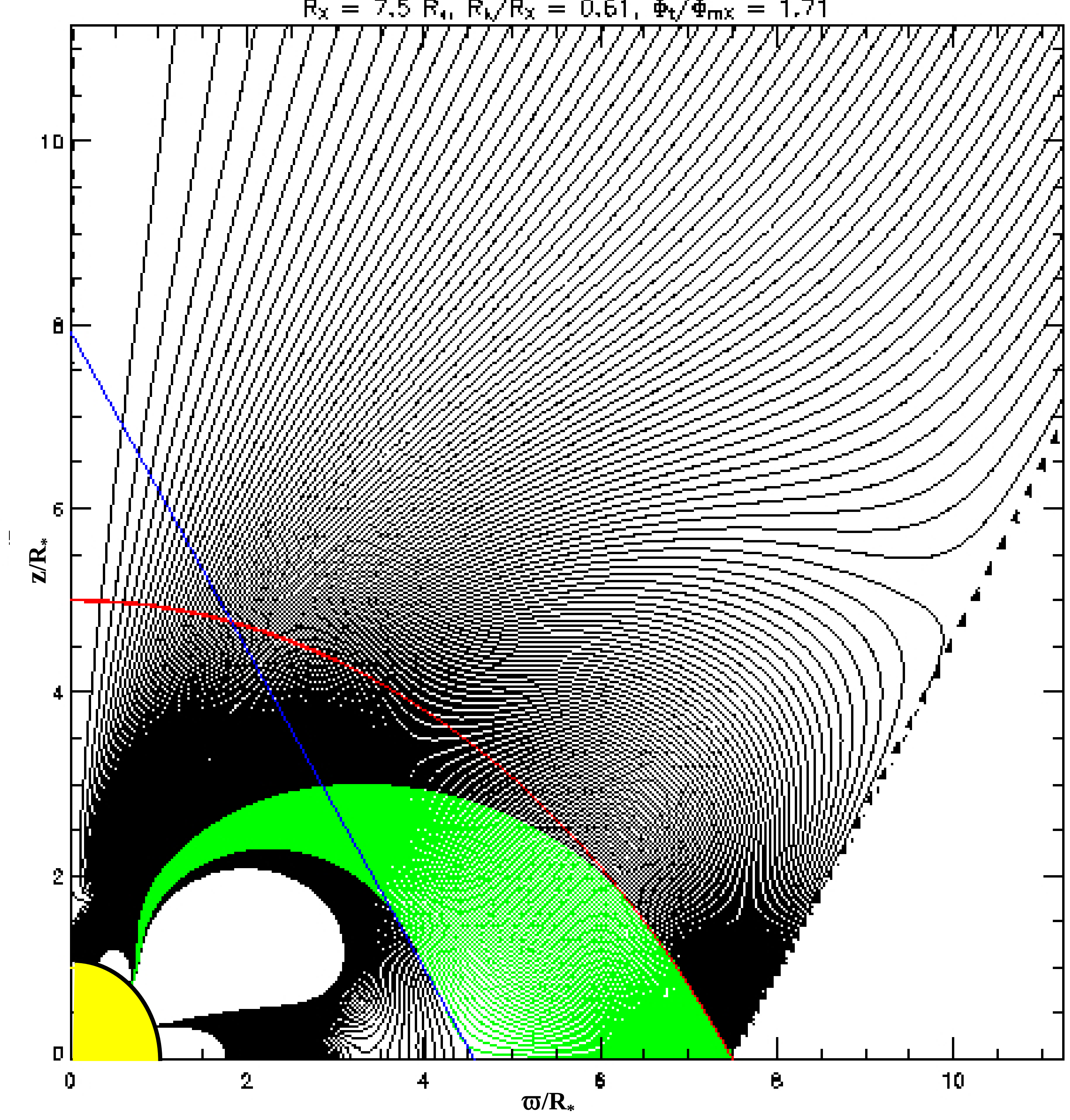
  Generalization; Unique prediction

- Comparison of prediction to Observations

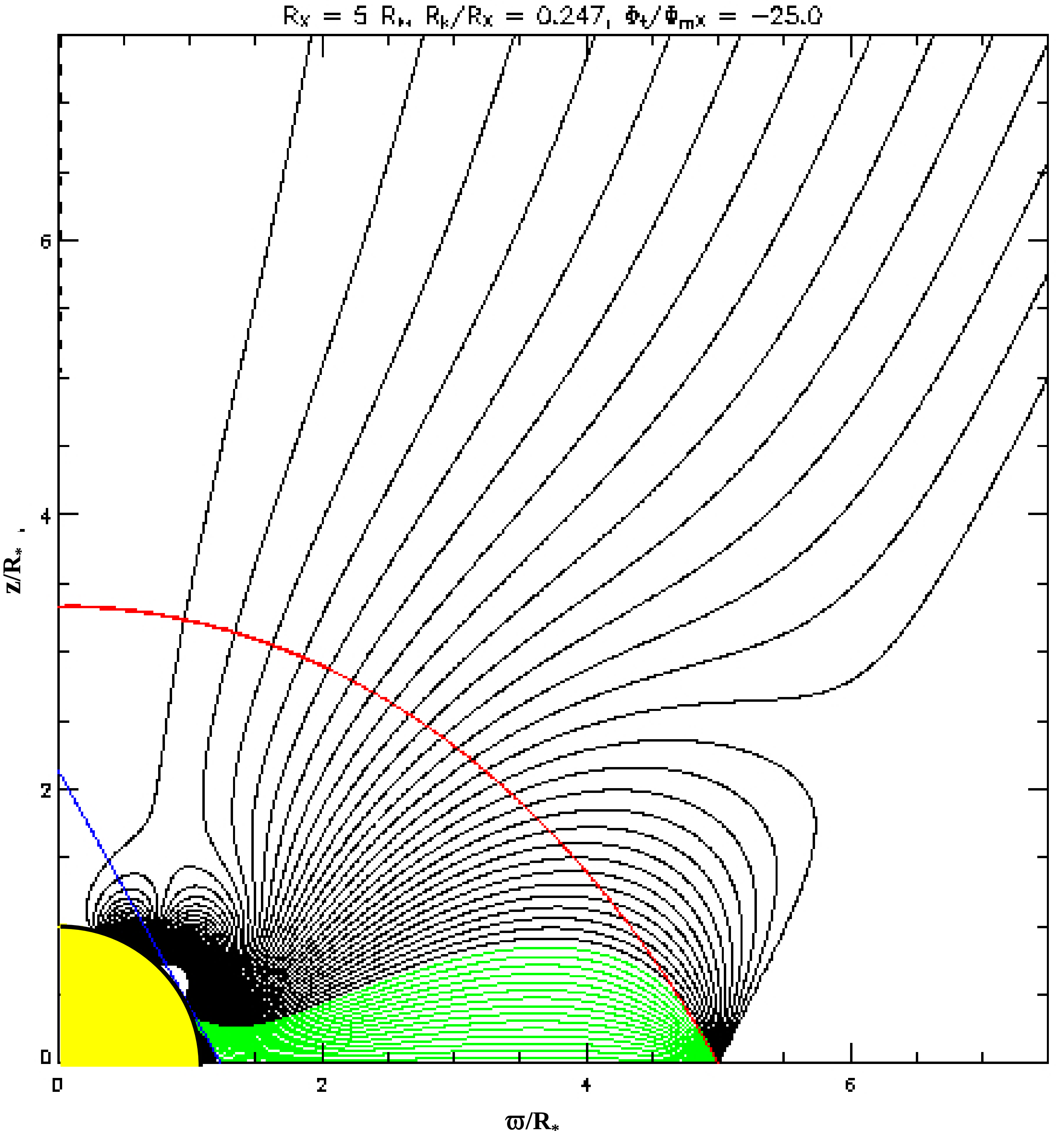
- Illustrative Multipole Simulations



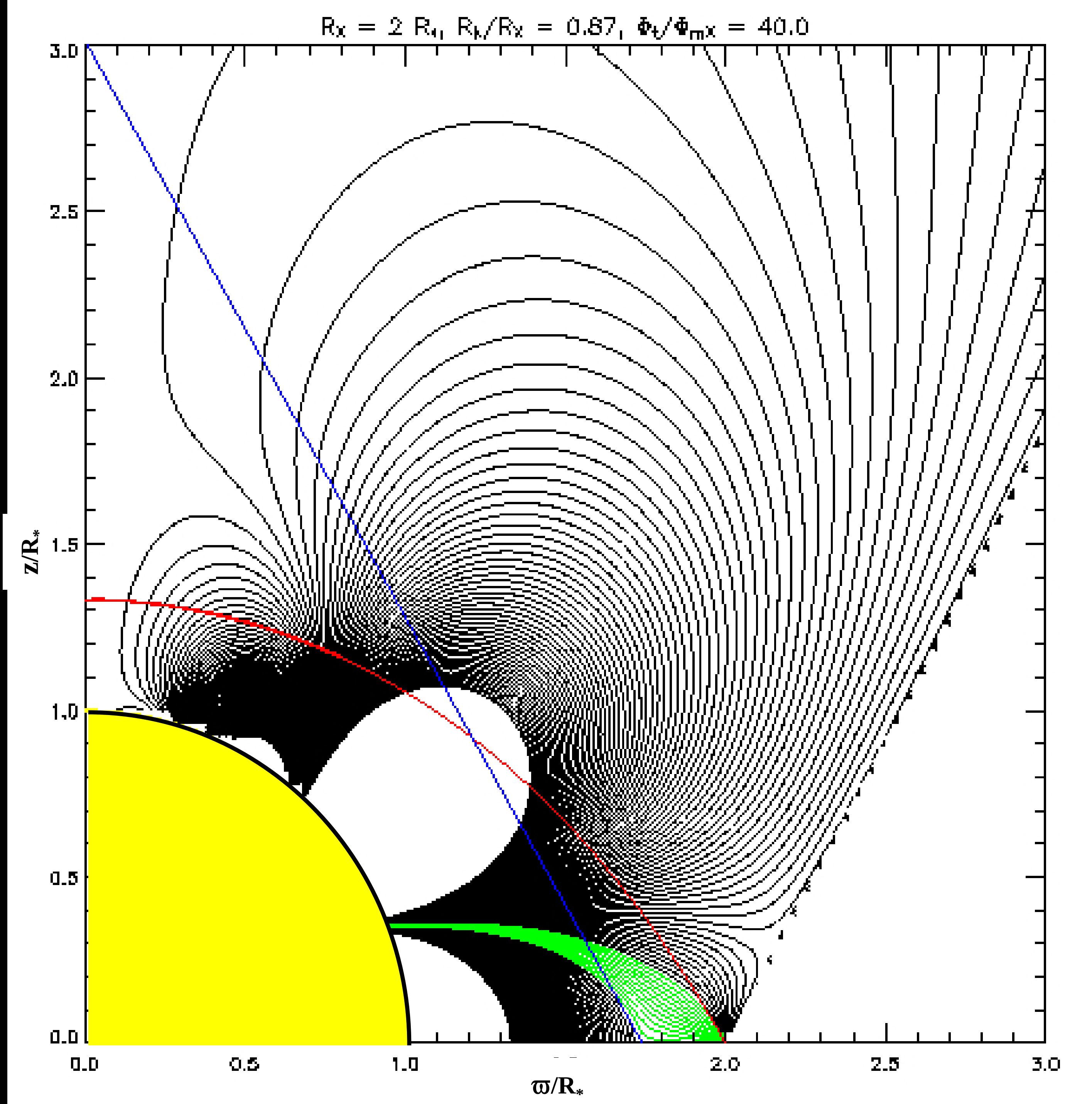
R_X = 10 R_*, R_k/R_X = 0.70, Φ_t/Φ_{mx} = 1.55
z/R*
ϖ/R*



$R_x = 7.5\ R_*,\ R_k/R_x = 0.61,\ \Phi_t/\Phi_{mx} = 1.71$
z/R*
ϖ/R*
0
2
4
6
8
10



Rx = 5 R*, Rk/Rx = 0.247, Φt/Φmx = −25.0
z/R*
ϖ/R*
0
2
4
6



Rx = 2 R*, Rk/Rx = 0.87, Φt/Φmx = 40.0
z/R*
ϖ/R*
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Which Movie Does Frank Love?

- The Golden Compass
- Conan the Barbarian
- Gone With the (X-)Wind
- Inebriated Wombats

Which Movie Does Frank Love?

- The Golden Compass
- Conan the Barbarian √!!!
- Gone With the (X-)Wind
- ~~Inebriated Wombats~~

Overview

- Classical T Tauri stars: accreted ~90% of their final mass, but continue to accrete from surrounding disk

- Magnetospheric accretion: stellar field truncates disk at some inner radius > stellar radius; incoming disk material climbs onto field lines and lands on star at nearly free-fall velocities:
  - Magnetic braking explains slow rotation of CTTs
  - Line profiles, variability, excess emission (e.g., UV) from accretion shock consistent with magnetospheric accretion at free-fall velocities