Stellar Magnetospheres part deux: Magnetic Hot Stars

Stan Owocki

Key concepts from lec. 1

- MagRe# --> inf => "ideal" => frozen flux
- breaks down at small scales: reconnection
- Lorentz force ~ mag. pressure + tension
- plasma $\beta \sim P_{gas}/P_{mag} \sim (a/V_A)^2$
- press. scale ht. H << R (except in corona)
- wind mag. conf. $\eta \sim B^2R^2/\dot{M}V_\infty$

Wind Magnetic Confinement

Ratio of magnetic to kinetic energy density:

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2} = \frac{V_A^{\,2}}{v^2}$$

$$= \frac{B^2 r^2}{\dot{M} v} = \underbrace{\frac{B_*^{\,2} R_*^{\,2}}{\dot{M} v_\infty}}_{\eta_*} \frac{(r/R_*)^{2-2q}}{(1-R_*/r)^{\beta}}$$

e.g, for dipole field, q=3; $\eta \sim 1/r^4$

for OB SG, to get $\eta_* \sim 1$, need $B_* \sim 100$ G

Alfven Radius: $\eta(R_A) \equiv 1$

For dipole (q=3): $R_A = \eta_*^{1/4} R_*$

Hot Stars vs. Sun

- Luminous Radiative Envelope (not conv.)
- Radiatively Driven Wind (line scatt.)
  - $T_{wind} \sim= T_{eff}$
  - $M_{dot} \sim 10^{-7}\ M_O/yr \ >> \ M_{dot,sun}$
- Detected B-fields often steady, dipole
- Rotation can be rapid $V_{rot} \sim< V_{crit}$

$\Rightarrow$ NOT a (direct) solar Coronal analog!

Light's Momentum

- Light transports energy (& information)
- But it also has momentum, p=E/c
- Usually neglected, because c is so high
- But becomes significant for very bright stars,
- Key question: how big is force vs. gravity??
- $\Gamma_e = g_e/g < 1$ (near but below "Edd. limit")
- "CAK" wind model: $\Gamma_{lines} = g_{lines}/g > 1$

Aside: Radiation Pressure vs. Gas Pressure

- Force depends on **gradient** of Pressure
- grad P_{rad} comes from opacity κ
- Deep interior ($\tau >> 1$), P_{rad} nearly isotropic
  - $P_{rad} + P_{gas}$ act together => $H_\rho = a^2/g(1-\Gamma)$
- But near surface ($\tau \sim 1$) radiation "beamed"
- wind is not "Radiation Pressure Corona" $H \sim< R$

Radiative force

$$\vec{g}_{rad} = \int_0^\infty d\nu\, \kappa_\nu \left\langle \hat{n}\, I_\nu \right\rangle / c \qquad = \kappa F / c \quad \textbf{if } \kappa \textbf{ gray}$$

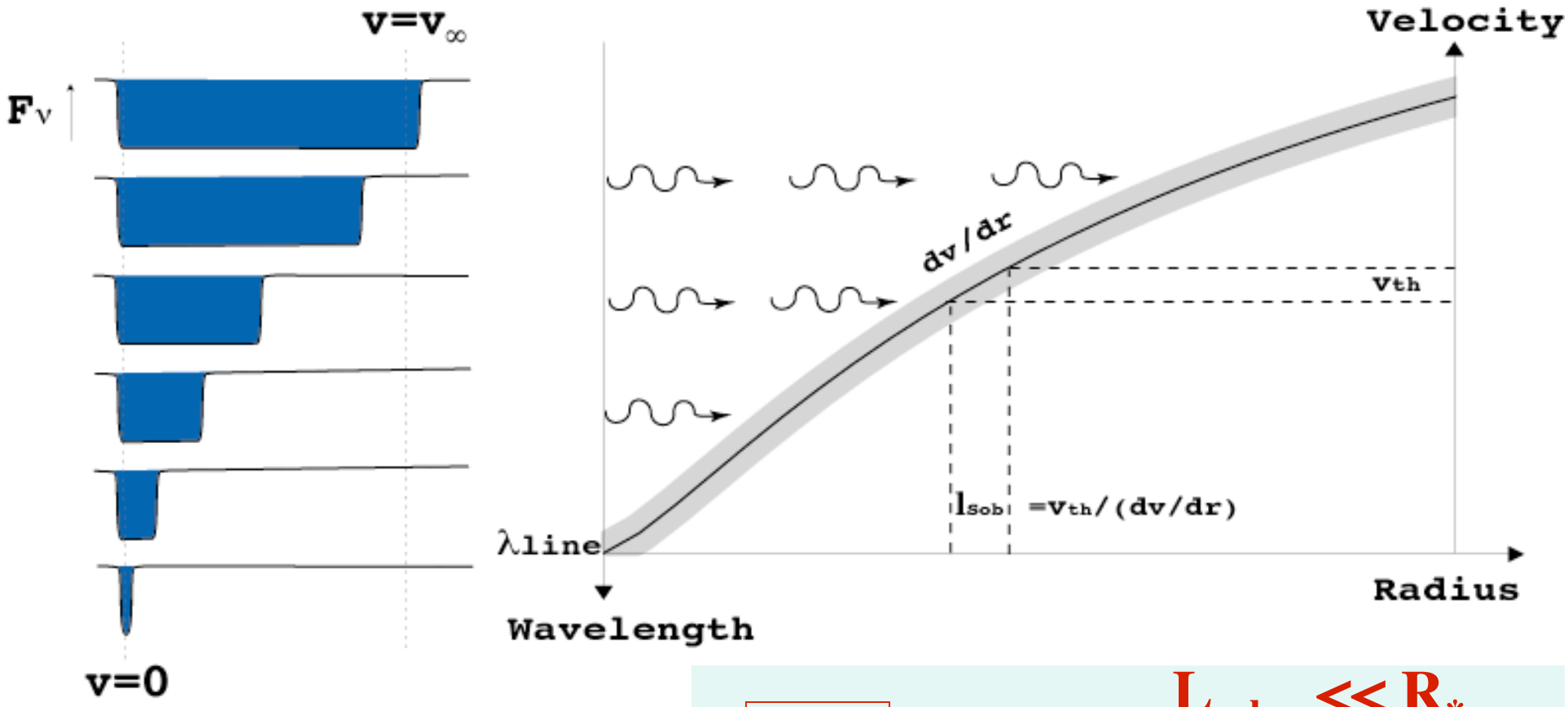
e.g., compare electron scattering force vs. gravity

$$\Gamma \equiv \frac{g_{el}}{g_{grav}} = \frac{\dfrac{L}{4\pi r^2 c}\dfrac{\sigma_{Th}}{\mu_e}}{\dfrac{GM}{r^2}} = \frac{\kappa_e L}{4\pi G M c}$$

- For sun, $\Gamma_\odot \sim 2 \times 10^{-5}$
- But for hot-stars with $L \sim 10^6\, L_\odot$; $M = 10\text{-}50\, M_\odot$

$$\Gamma \lesssim 1$$

Optically Thick Line-Absorption in an Accelerating Stellar Wind



For strong, optically thick lines:

$$g_{thick} \sim \frac{g_{thin}}{\tau} \sim \boxed{\frac{1}{\rho}\frac{dv}{dr}}$$

$$\tau \equiv \kappa\rho \boxed{\frac{v_{th}}{dv/dr}} \sim \frac{v_{th}}{v_\infty} R_*$$

$L_{sob} \ll R_*$

CAK force for power-law line ensemble

$$g_{lines} \sim \frac{g_{thin}}{\tau^{\alpha}} \sim \frac{L}{r^2}\left(\frac{1}{\rho}\frac{d\mathrm{v}}{dr}\right)^{\alpha}$$

CAK wind in zero-gas-pressure limit

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \cancel{\frac{a^2}{\rho}\frac{d\rho}{dr}} + g_{lines}$$

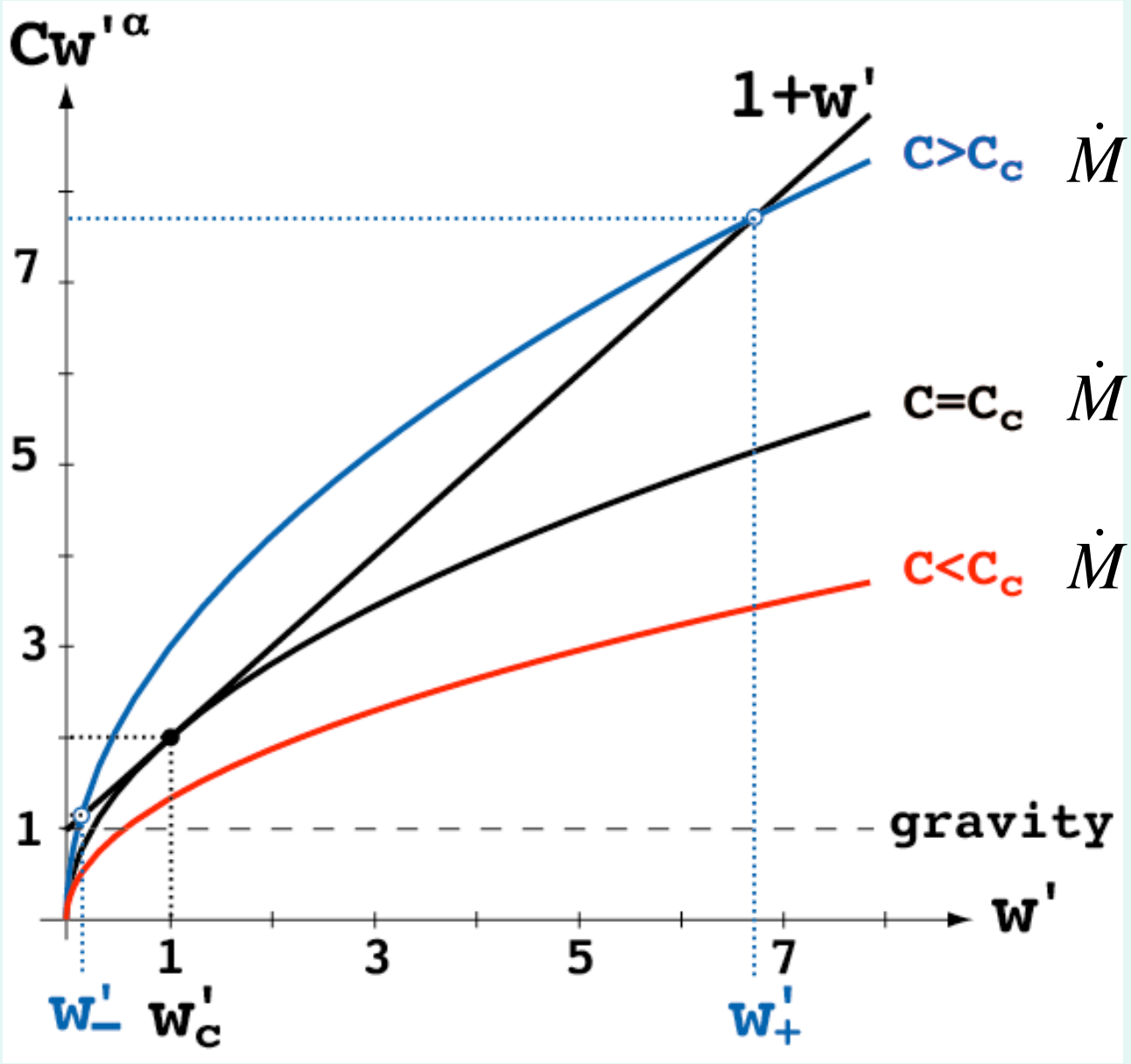
$$\frac{g_{thin}}{\tau^{\alpha}} \sim \frac{L}{r^2}\left(\frac{1}{\rho}\frac{dv}{dr}\right)^{\alpha}$$

$$w' \equiv \frac{r^2 v\, dv/dr}{GM}$$

$$\boxed{w' = -1 + C\, w'^{\alpha}}$$

$$C \sim \frac{1}{\dot{M}^{\alpha}}$$

Graphical solution



Magnetohydrodynamic (MHD) Equations

$$\frac{D\rho}{Dt} + \rho\nabla \bullet v = 0$$

Mass

$$\rho\frac{Dv}{Dt} = -\nabla p + \frac{1}{4\pi}(\nabla \times B) \times B + \rho(g_{lines} - g_{grav})$$

Momentum

$$\frac{\partial e}{\partial t} + \nabla \cdot e\mathbf{v} = -P\nabla \cdot \mathbf{v} + H_M - n^2\Lambda(T)$$

Energy

$$P = \rho a^2 = (\gamma - 1)e$$

Ideal Gas E.O.S.

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

mag Induction

$$\nabla \bullet B = 0$$

Divergence free B

Magnetohydrodynamic (MHD) Equations

$$\frac{D\rho}{Dt} + \rho\nabla \bullet v = 0$$

Mass

$$\rho\frac{Dv}{Dt} = -\nabla p + \frac{1}{4\pi}(\nabla \times B) \times B + \rho(g_{lines} - g_{grav})$$

Momentum

$$T = const.$$

Energy

$$P = \rho a^2$$

Ideal Gas E.O.S.

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

mag Induction

$$\nabla \bullet B = 0$$

Divergence free B

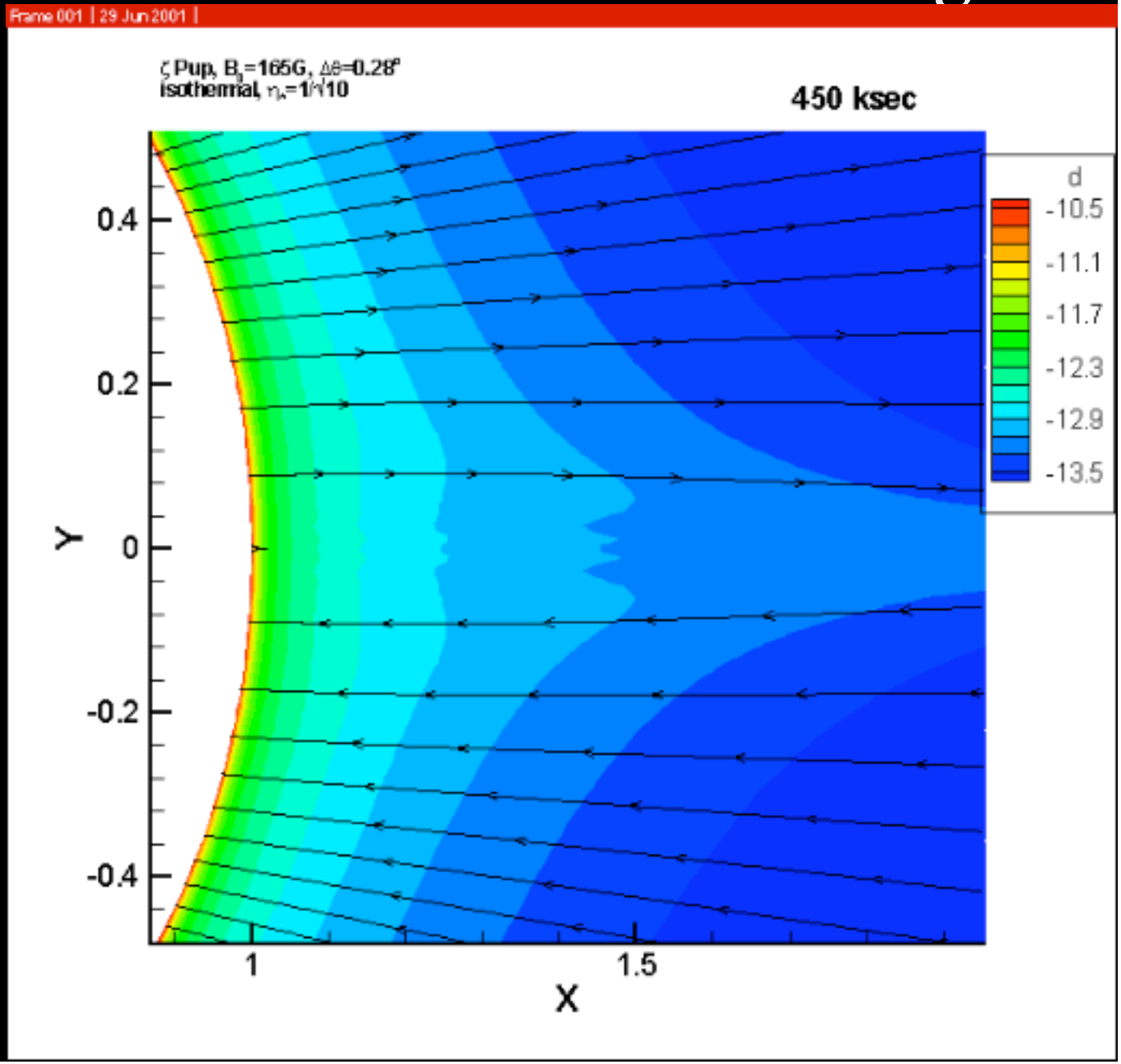
MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 1/3$

A. ud Doula
PhD thesis 2002

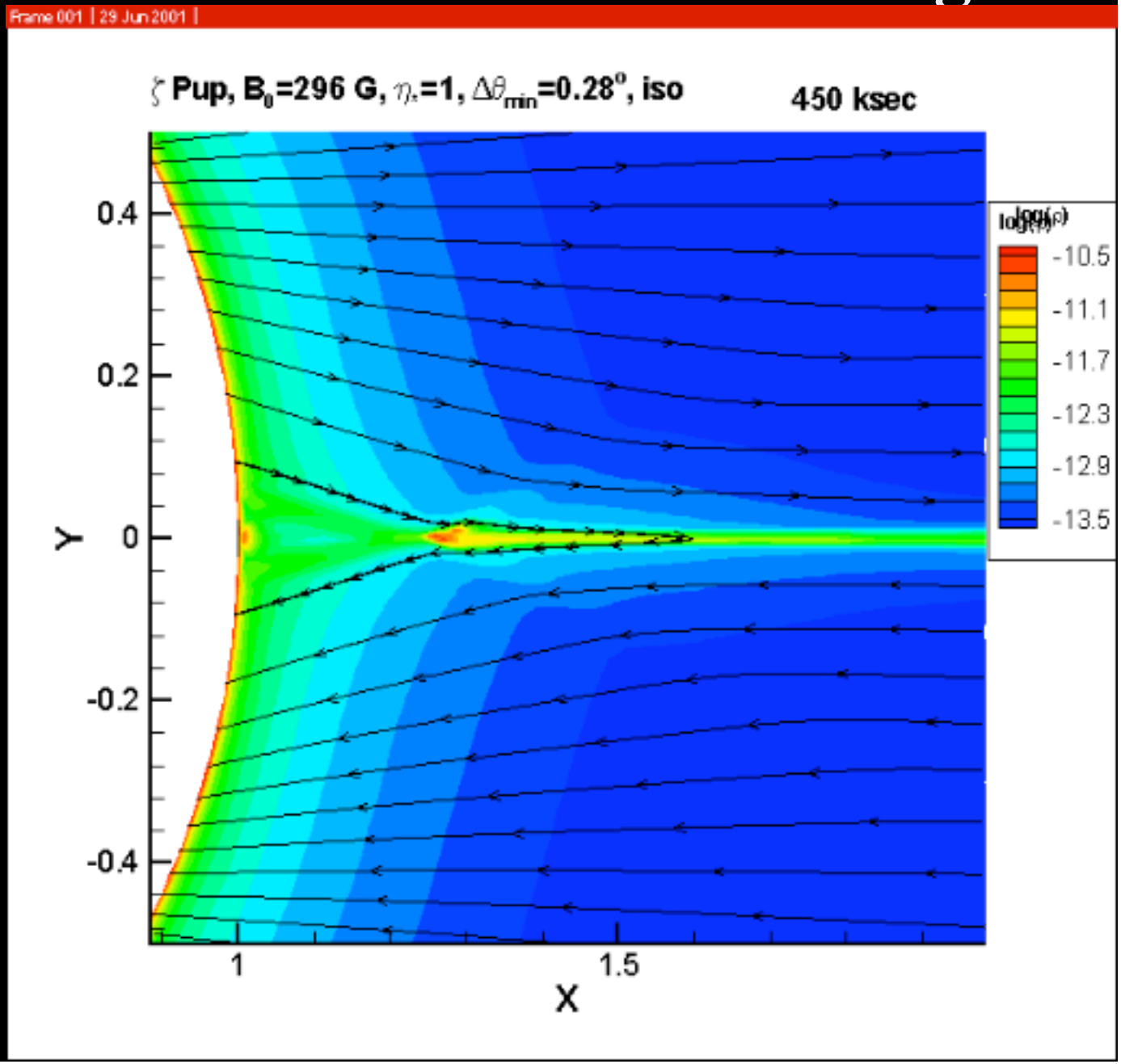


MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 1$

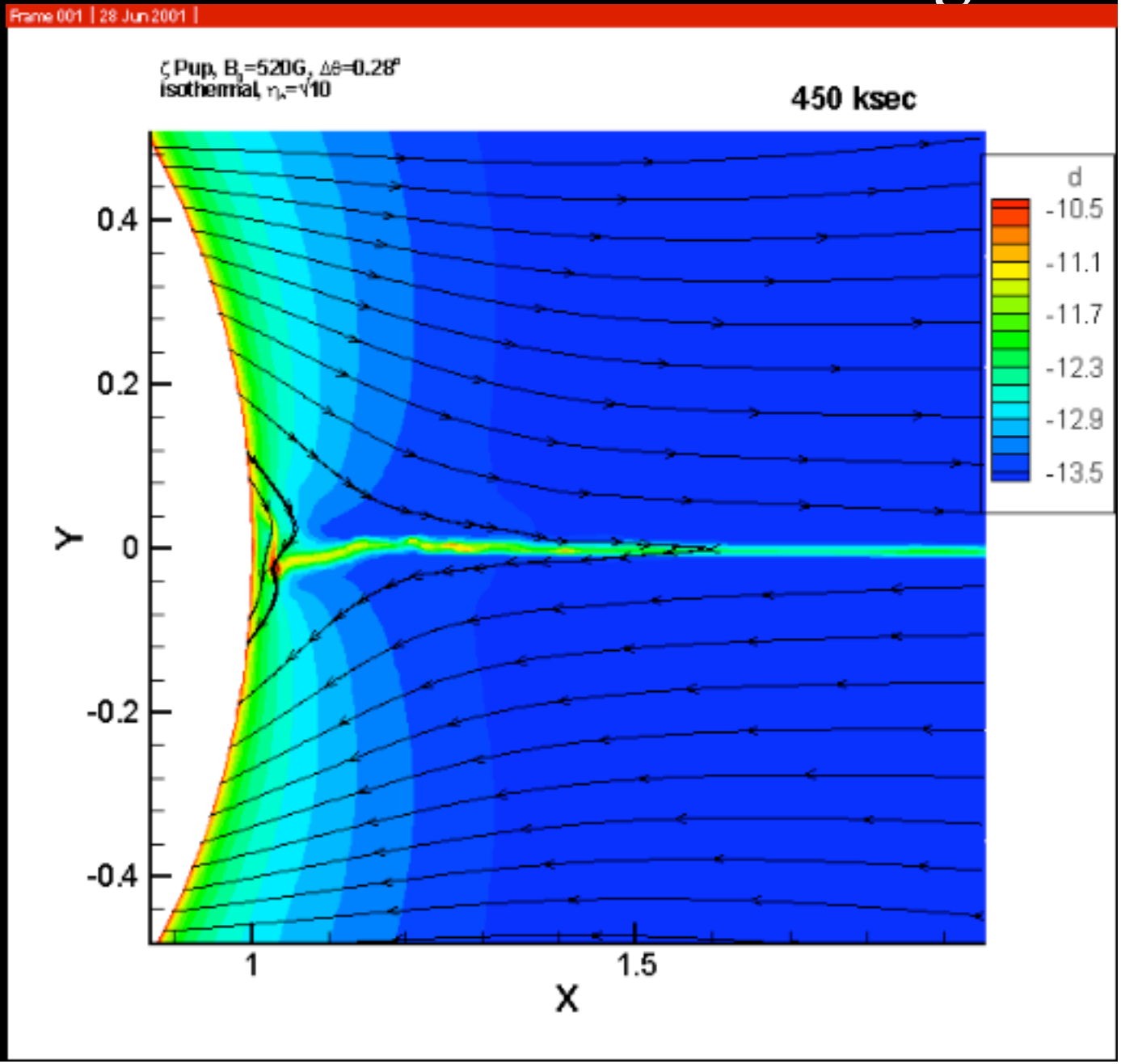


MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 3$

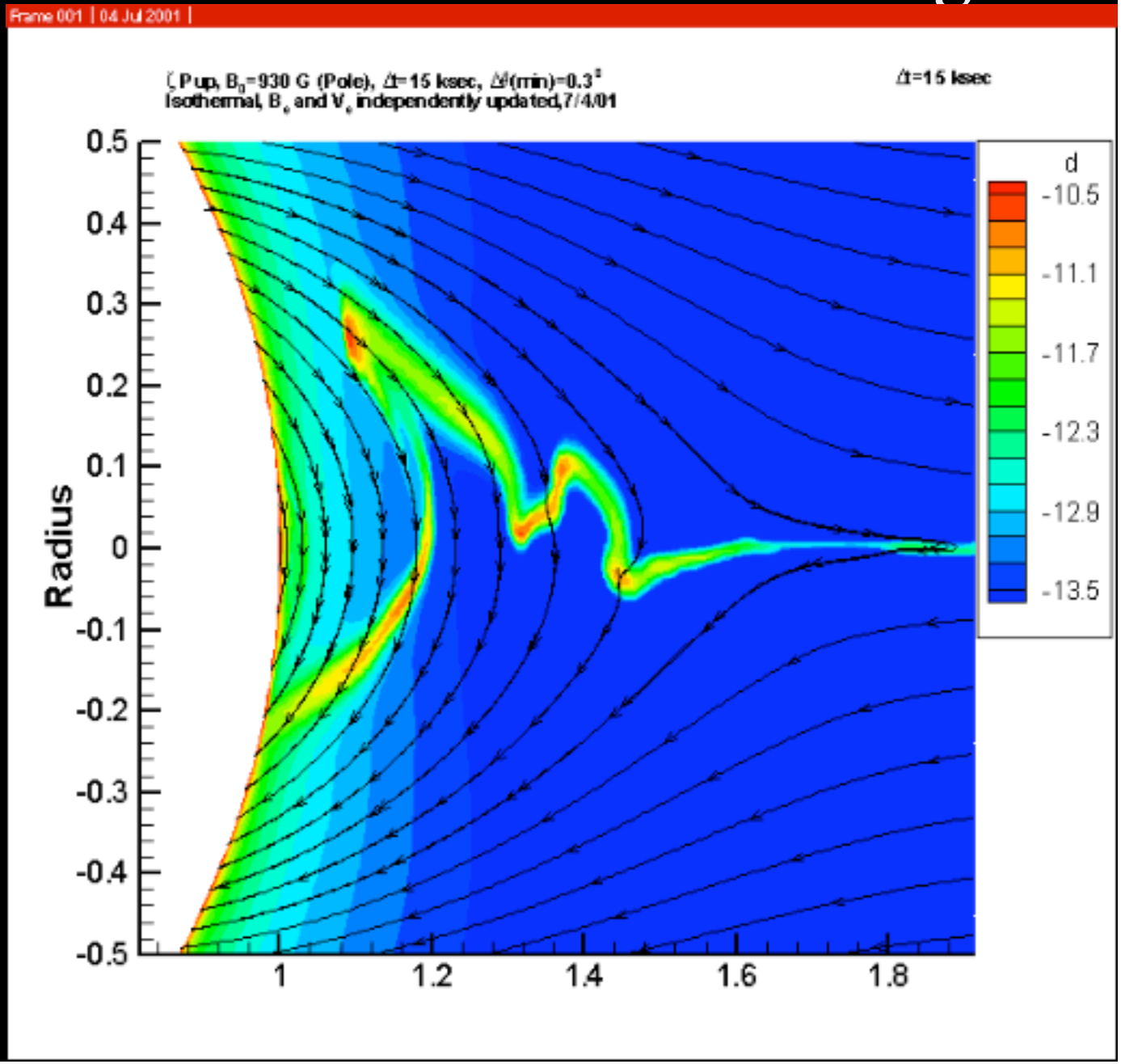


MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

$\eta_* = 10$

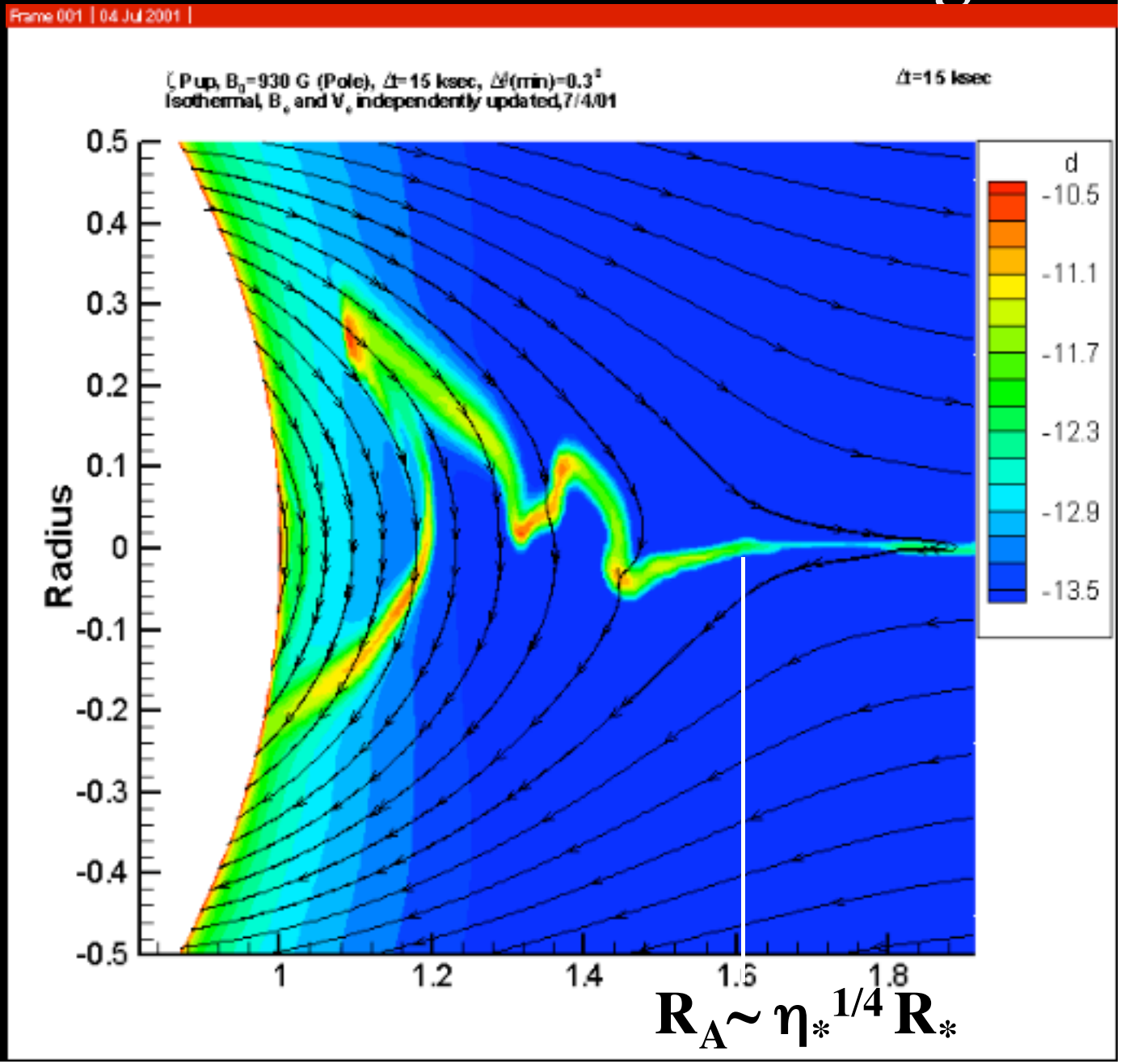


MHD Simulation of Wind Channeling

Isothermal
No Rotation

Confinement parameter

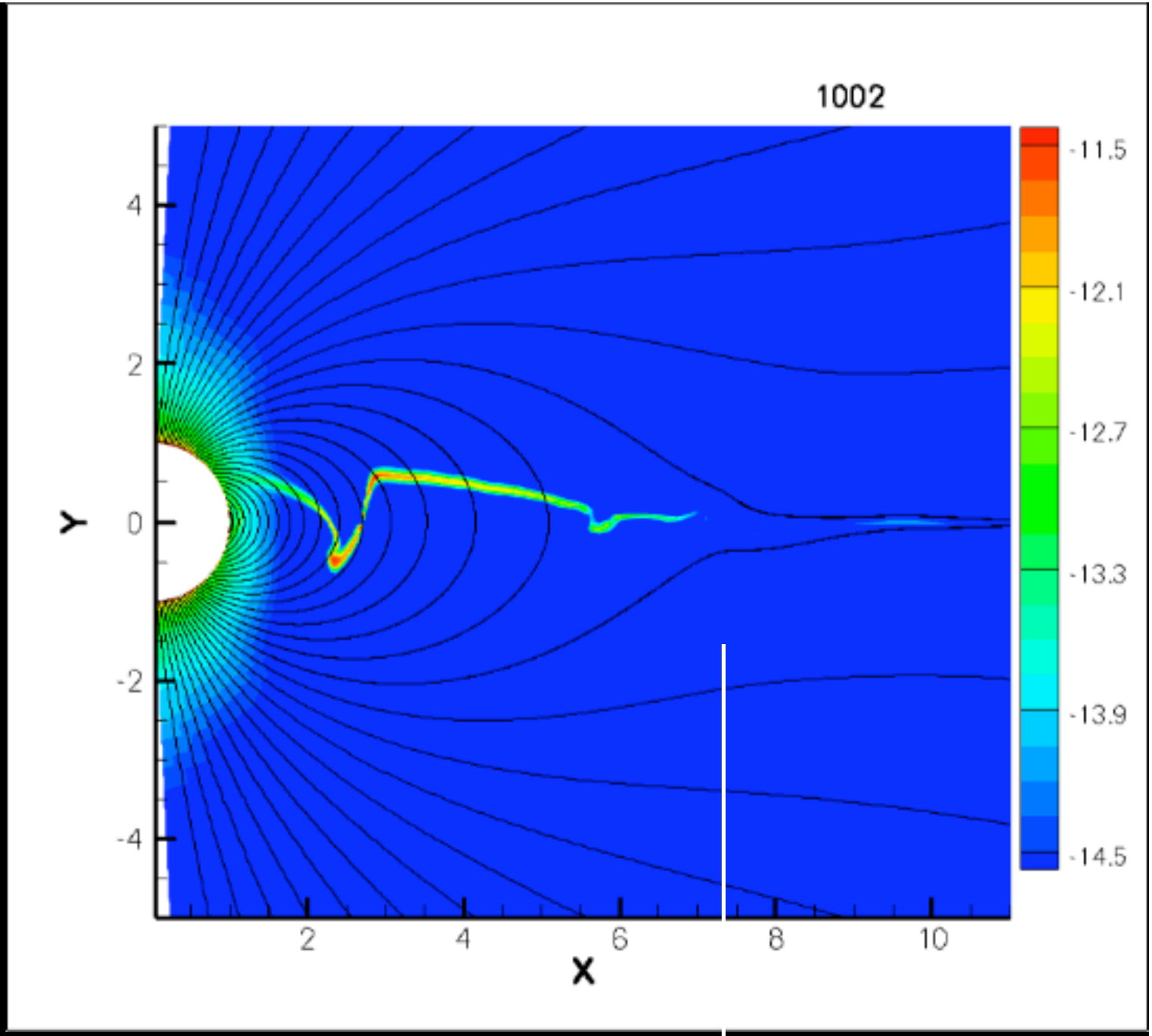
$\eta_* = 10$



Isothermal
No Rotation

Confinement parameter

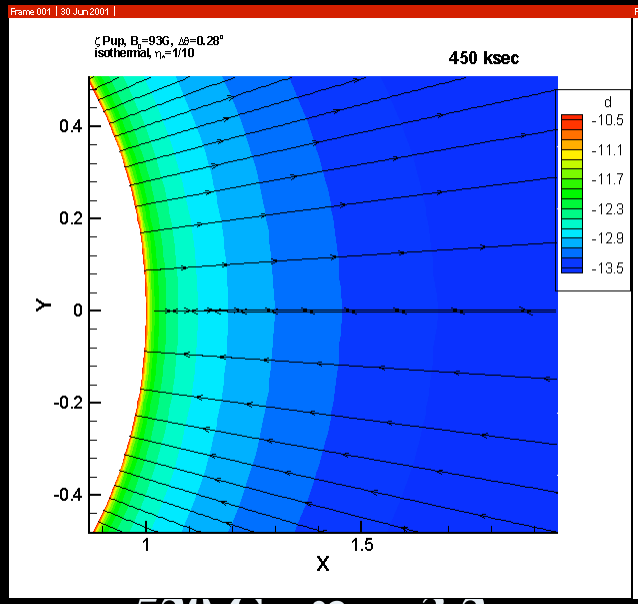
$\eta_* = 1000!!$



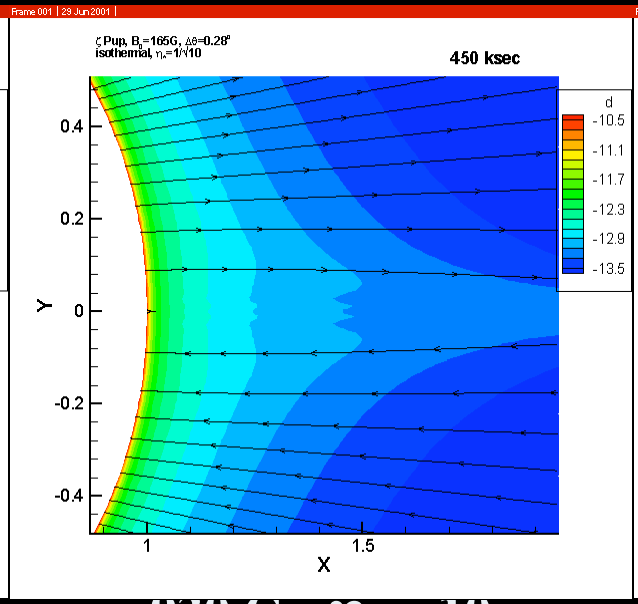
$R_A \sim \eta_*^{1/4} R_*$

Final state of isothermal models

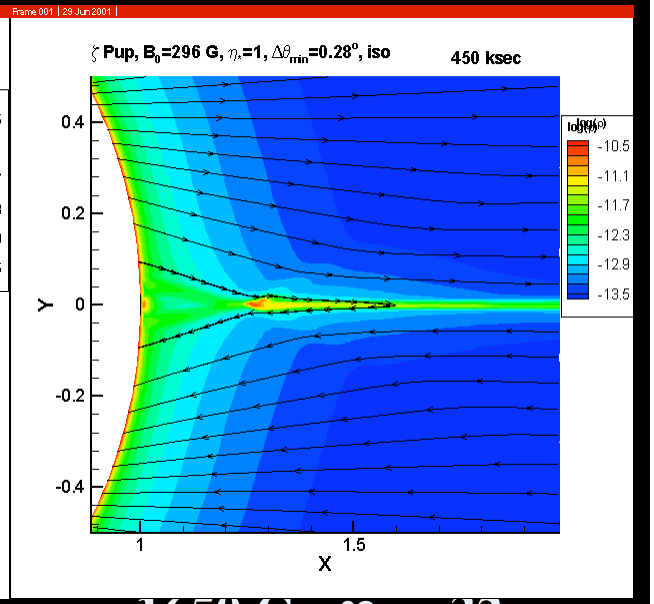
93 G ; $\eta_* = 0.1$



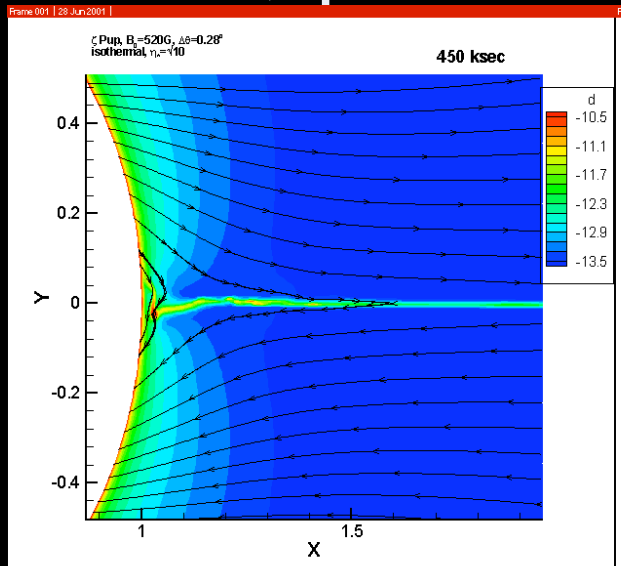
165 G ; $\eta_* = 0.32$



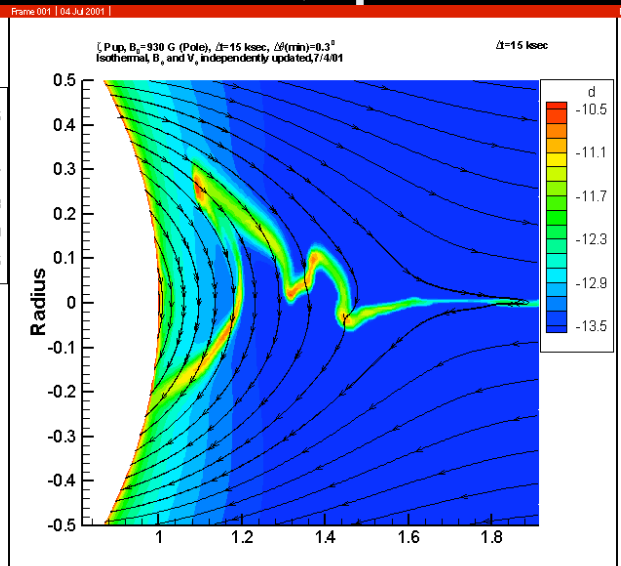
295 G ; $\eta_* = 1$



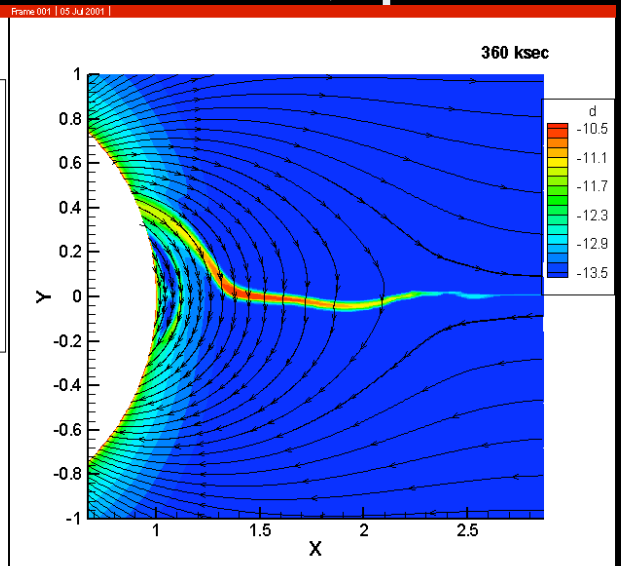
520 G ; $\eta_* = 3.2$



930 G ; $\eta_* = 10$



1650 G ; $\eta_* = 32$



Θ^1 Ori C

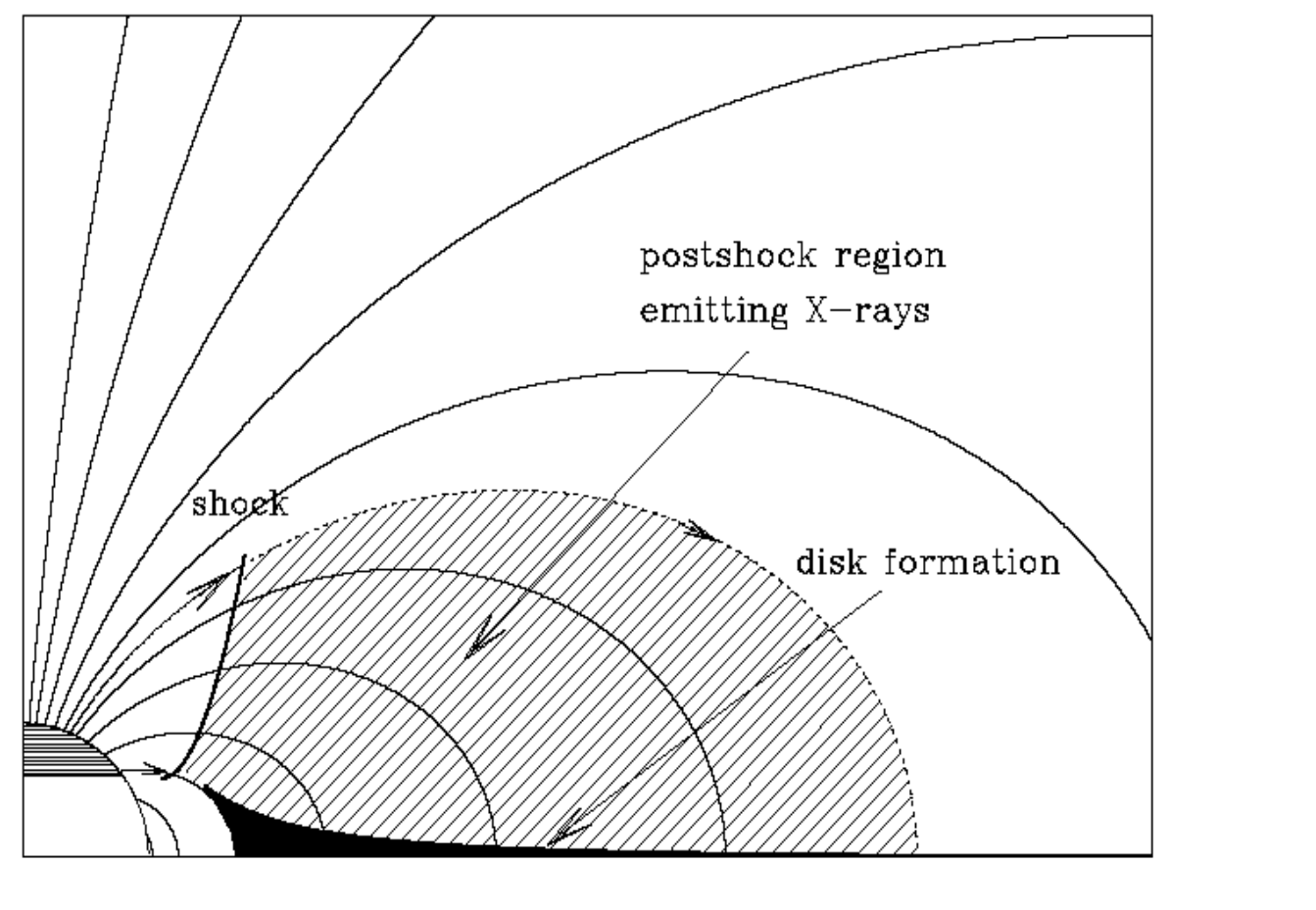
MHD simulation for Θ^1 Ori C (O7 V)

- $B_{obs} \sim 1100$ G + $P_{rot} = 14$ days
- $M_{dot} \sim 10^{-7} M_{sun}/yr$
- $\eta_* \sim = 14$
- **M**agnetic **C**onfined **W**ind **S**hock (**MCWS**)
- kev X-rays => match Chandra obs.

Magnetically Confined Wind-Shocks

Babel & Montmerle 1997

Magnetic A_p-B_p stars



Magnetically Confined Wind Shock

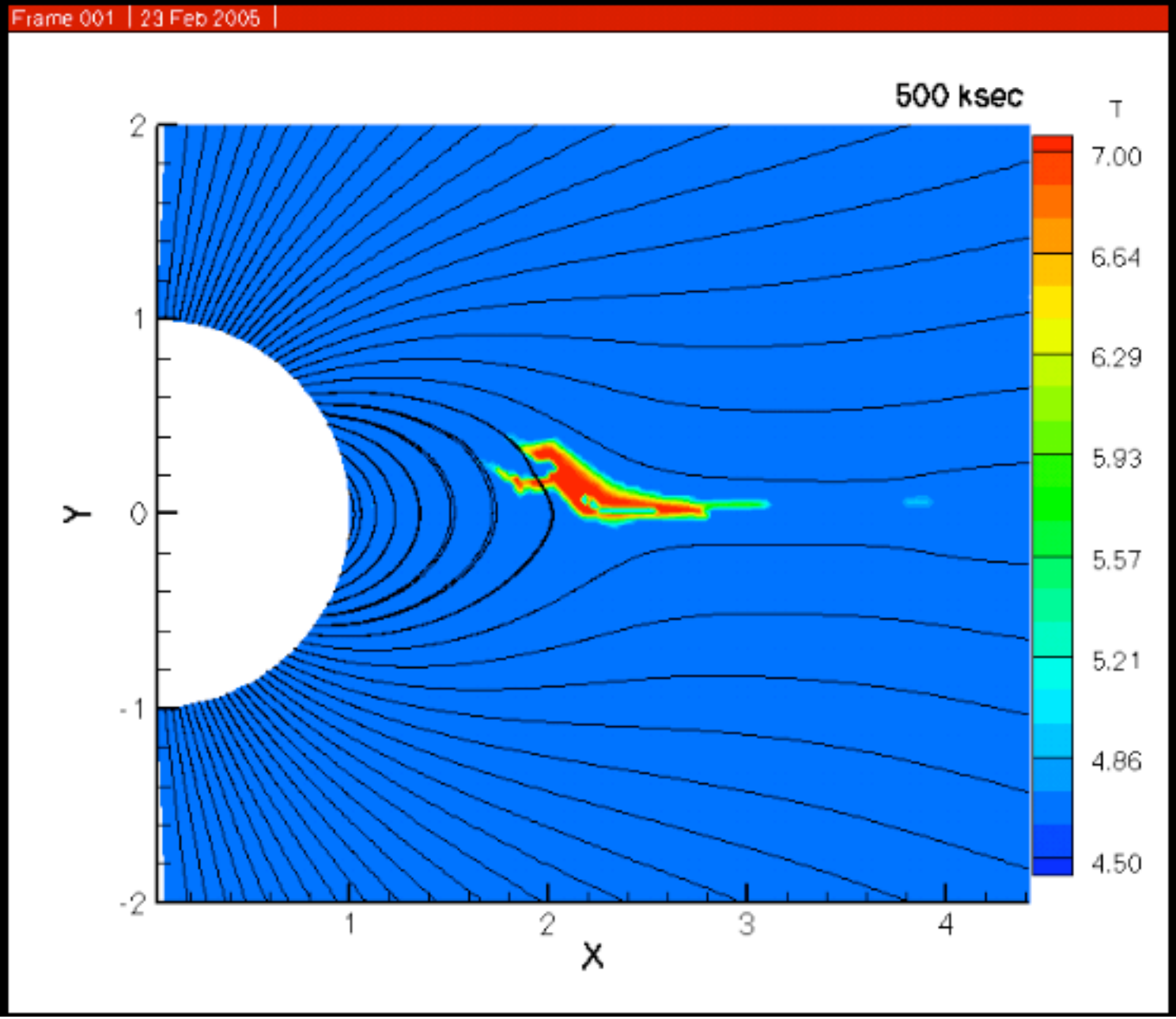
log T

still no rotation

but now with **Radiative Cooling**

~ 2 kev X-rays fit Chandra spectrum

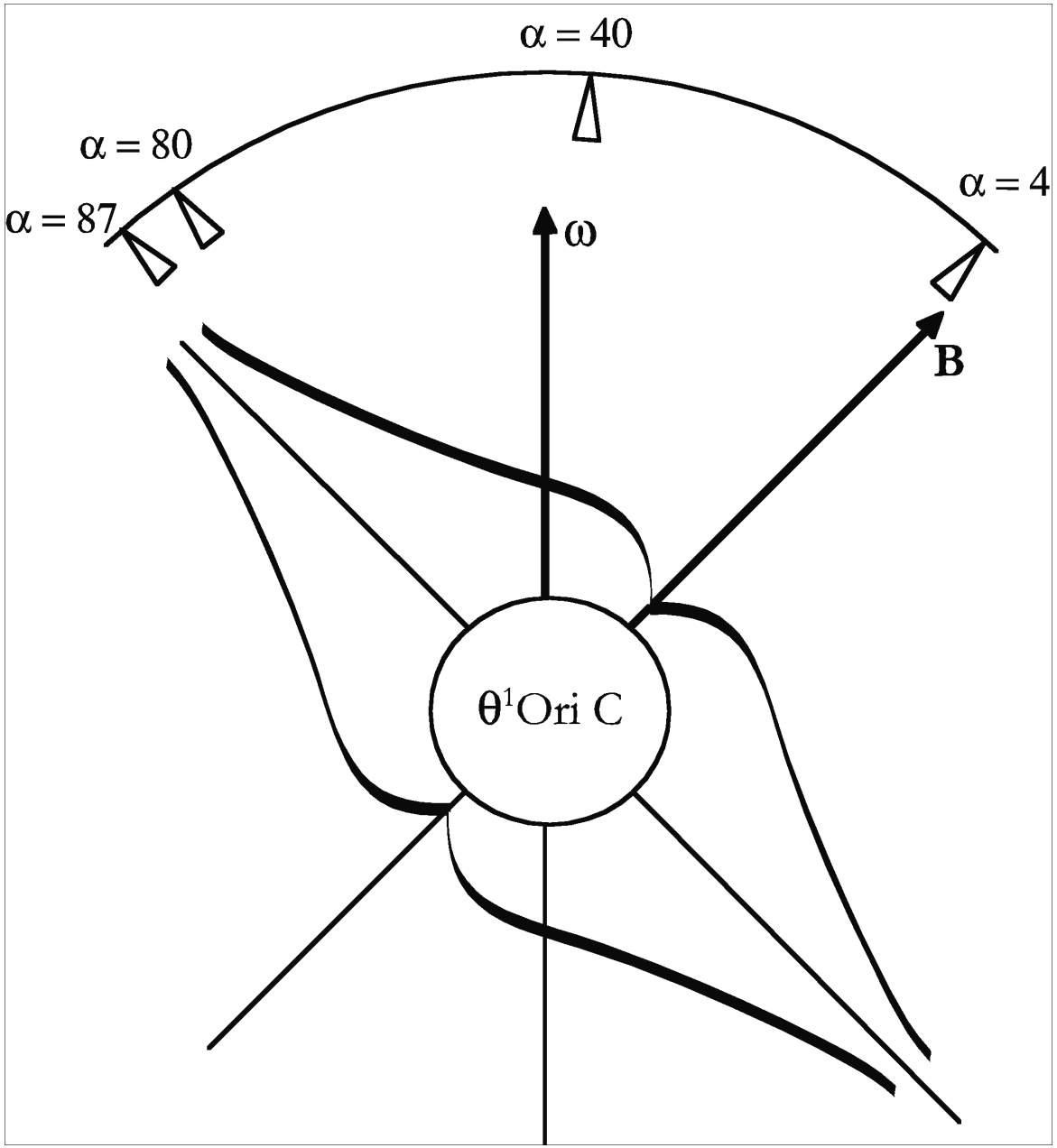
for Θ^1 Ori C



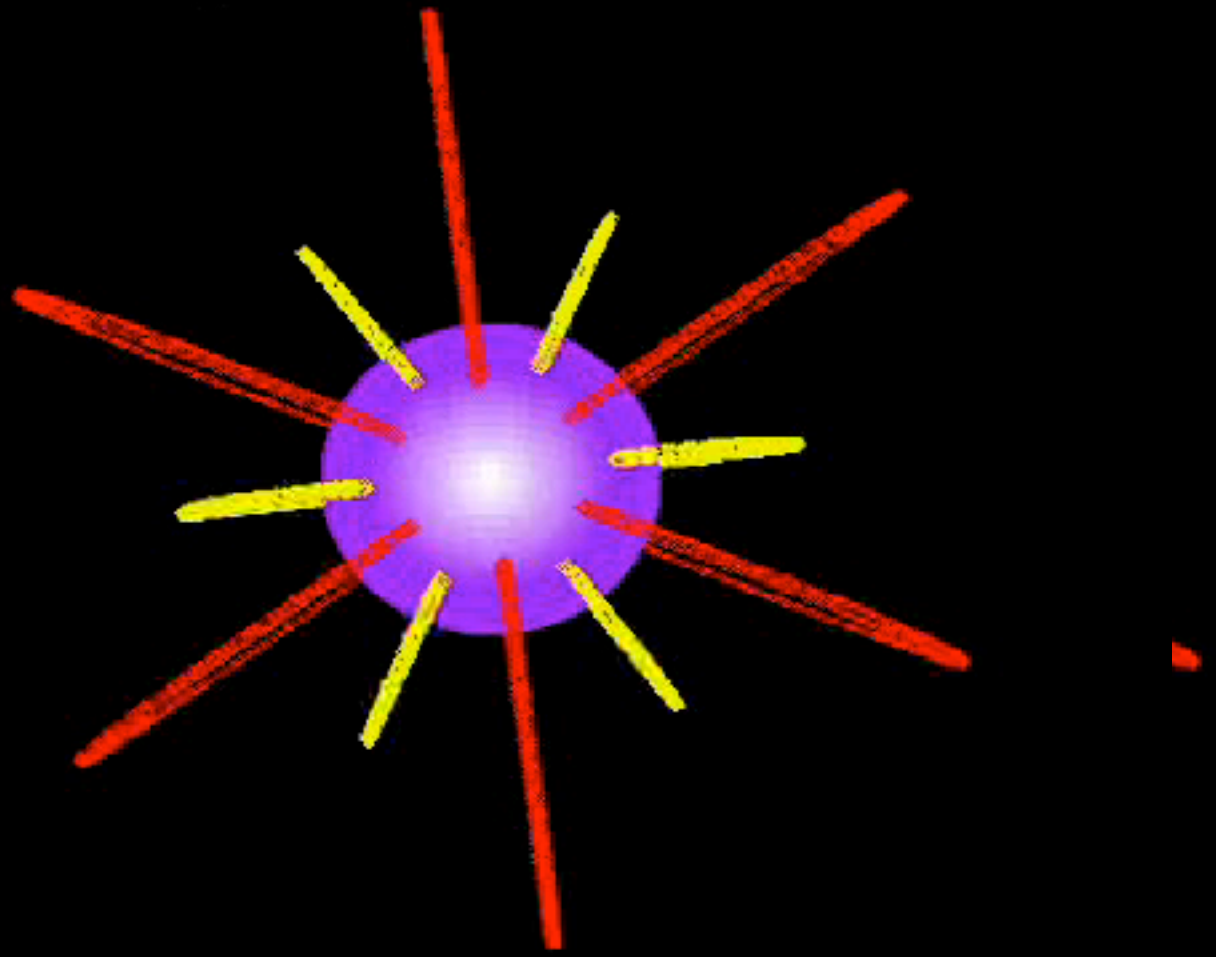
Θ-1 Ori C

Gagne et al. 2005, ApJ, 528, 986

P_{rot} = 13 days



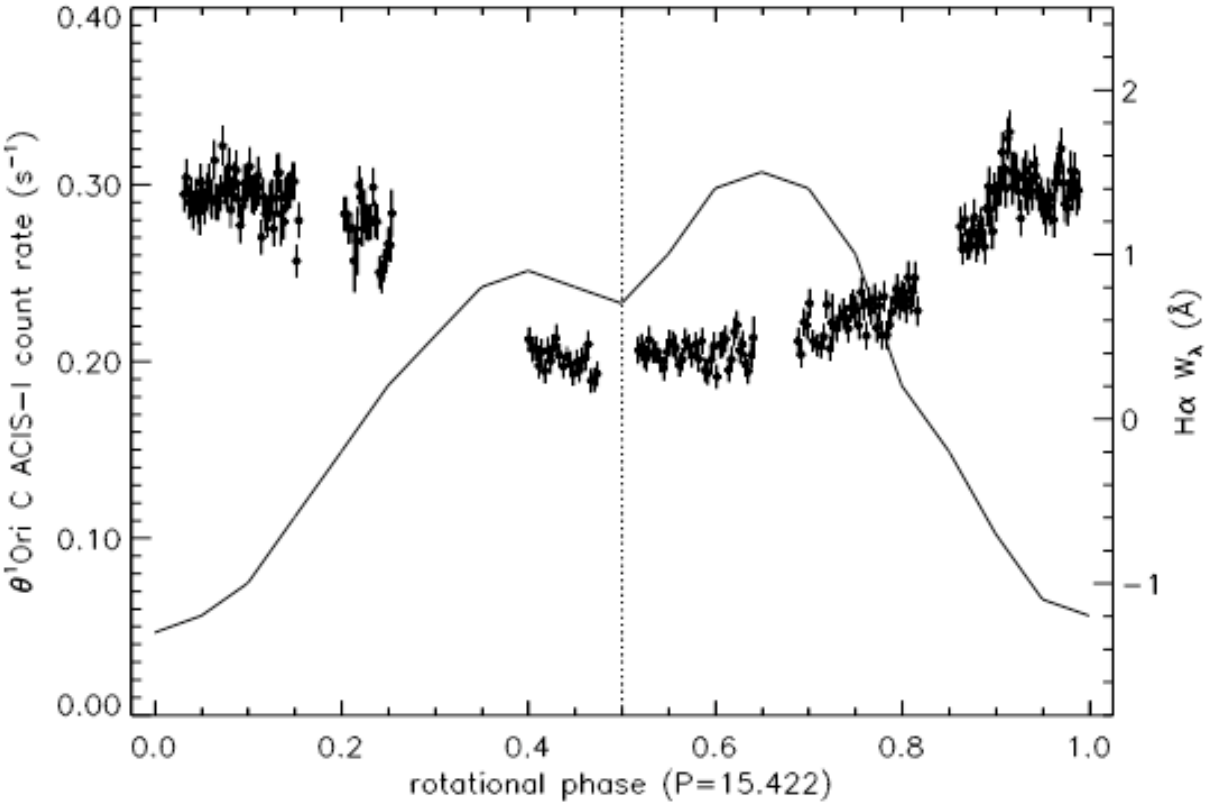
Θ1 Ori C



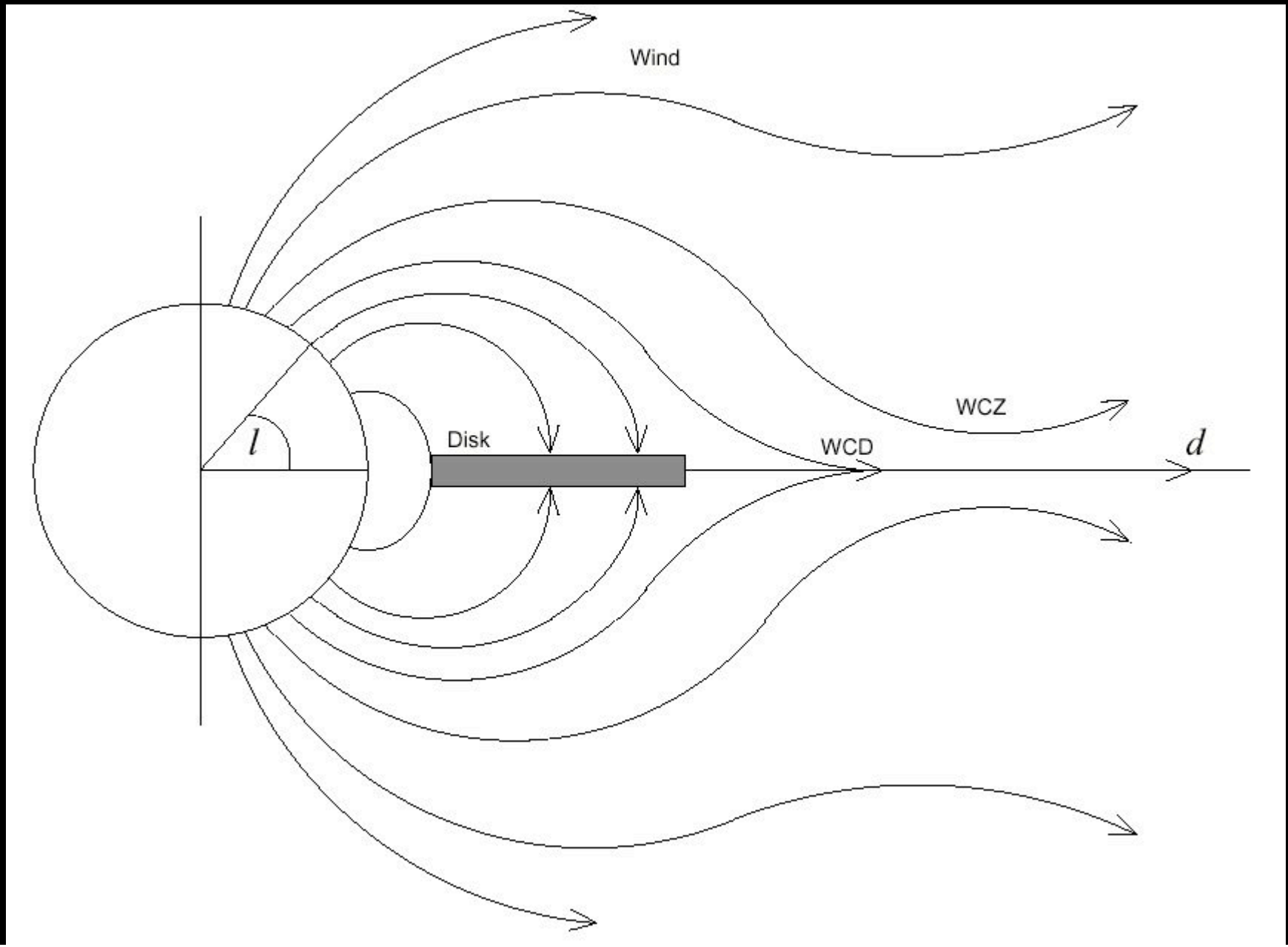
β ~ 45°

i ~ 45°

X-ray Light Curve for Θ1Ori C



Magnetically Torqued Disk (MTD)



Alfven vs. Kepler Radius

Kepler co-rotation Radius, R_K:

$$GM/R_K^2 = V_\phi^2/R_K = V_{rot}^2 R_K/R_*^2$$

$$R_K = w^{-2/3} R_* \qquad w = V_{rot}/V_{crit} \qquad V_{crit}^2 = GM/R_*$$

Alfven radius: $\eta(R_A)=1$

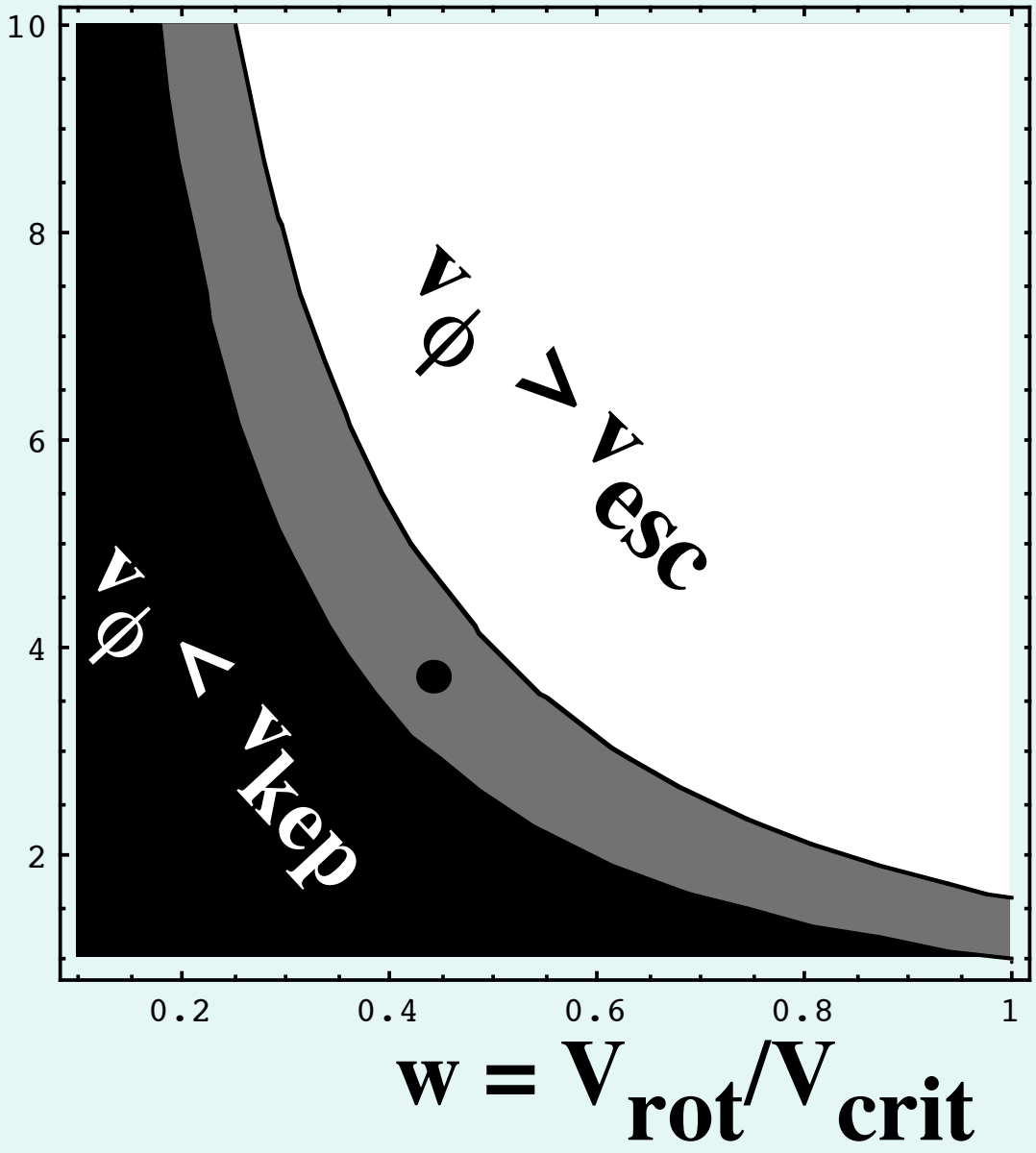
e.g, for dipole field,
$\eta \sim 1/r^4$

$$R_A = \eta_*^{1/4} R_*$$

when $R_A > R_K$:
Magnetic spin-up => centrifugal support & ejection

Keplerian spin-up vs. escape

$\mathrm{sqrt}(\eta_*) \sim \mathbf{B}$

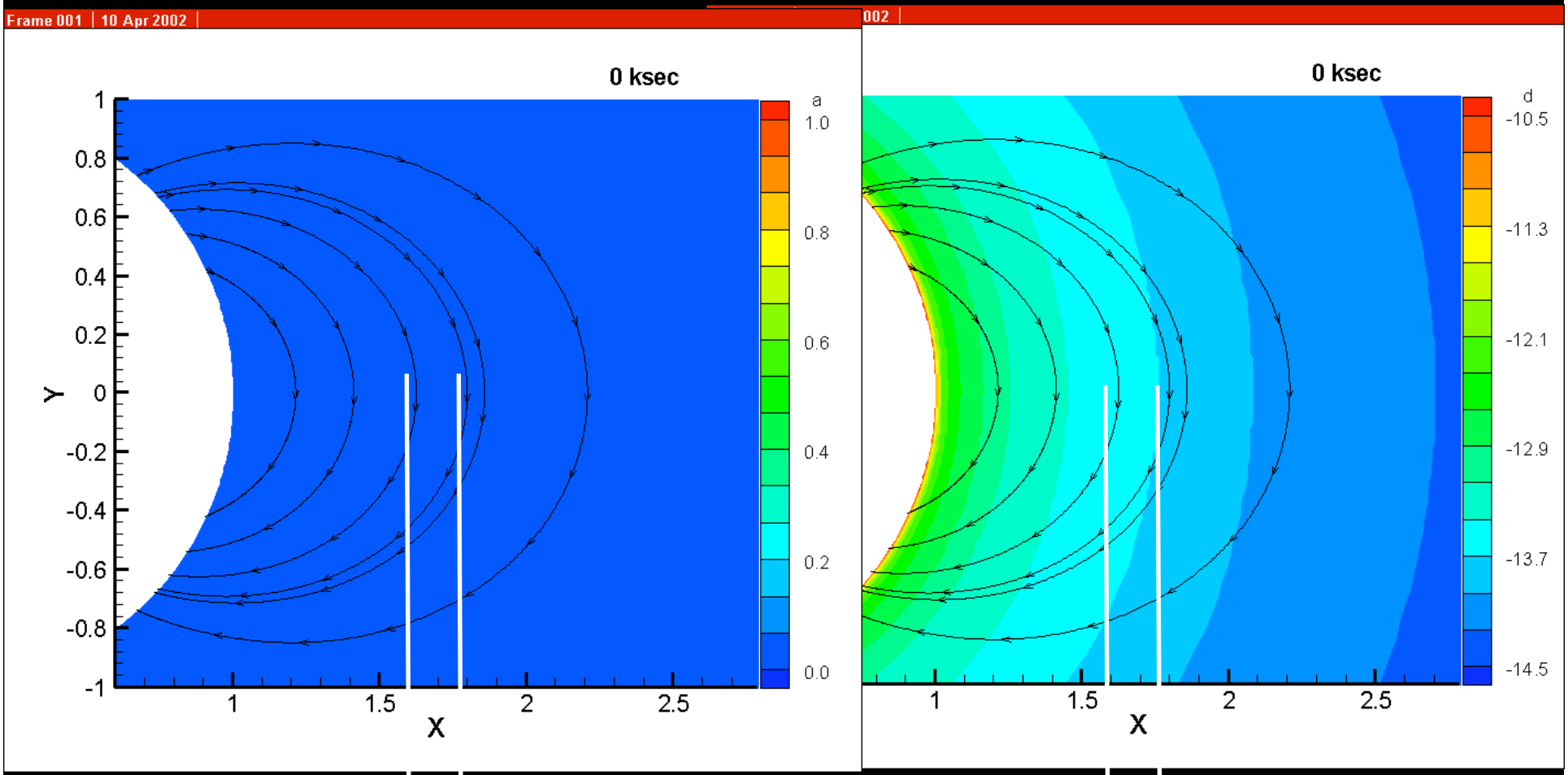


MHD Sims of Field-Aligned Rotation

$\eta_* = 10$; $v_{rot} = 250$ km/s (w=1/2)

V_ϕ / V_{rigid}

Density

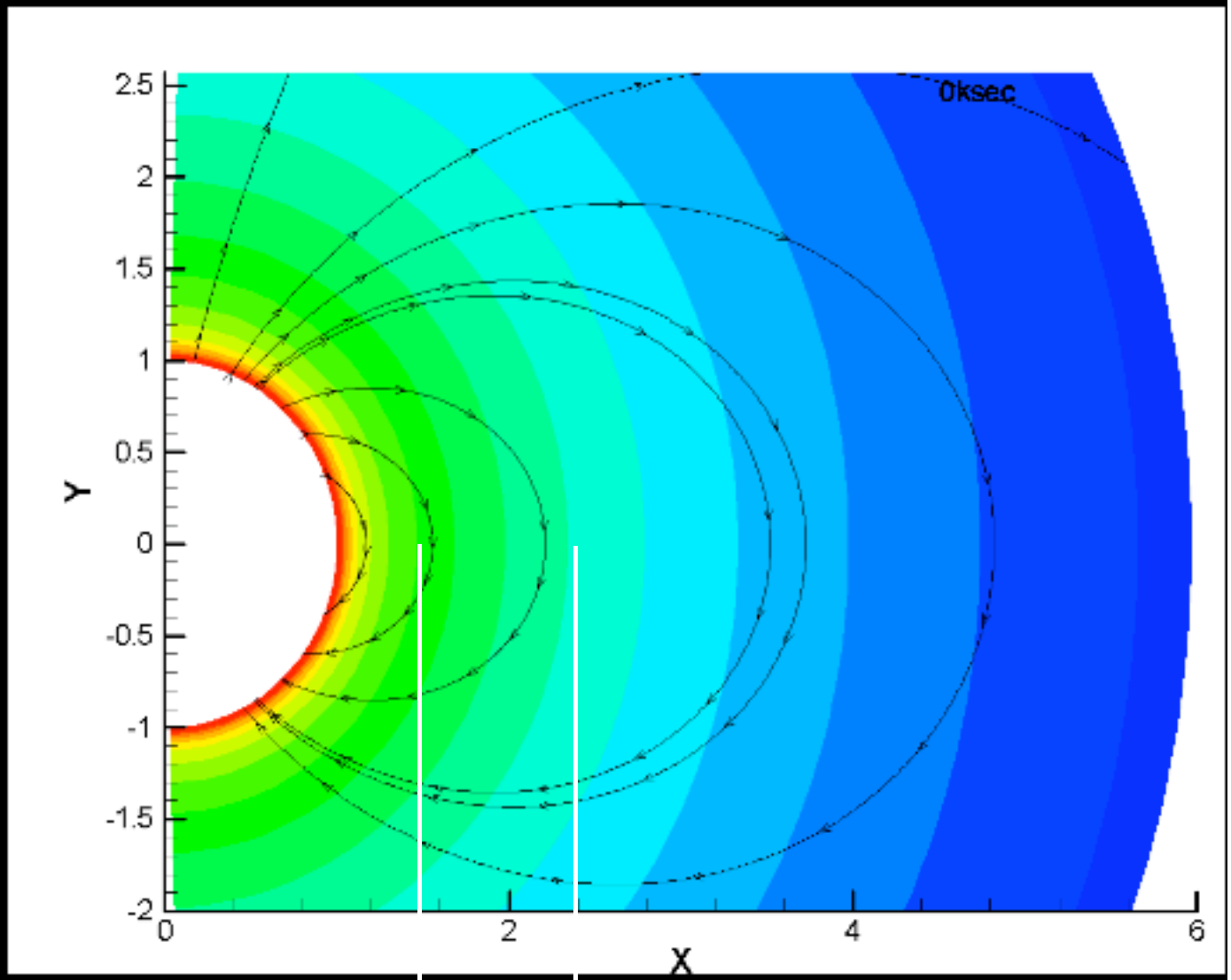


R_K R_A

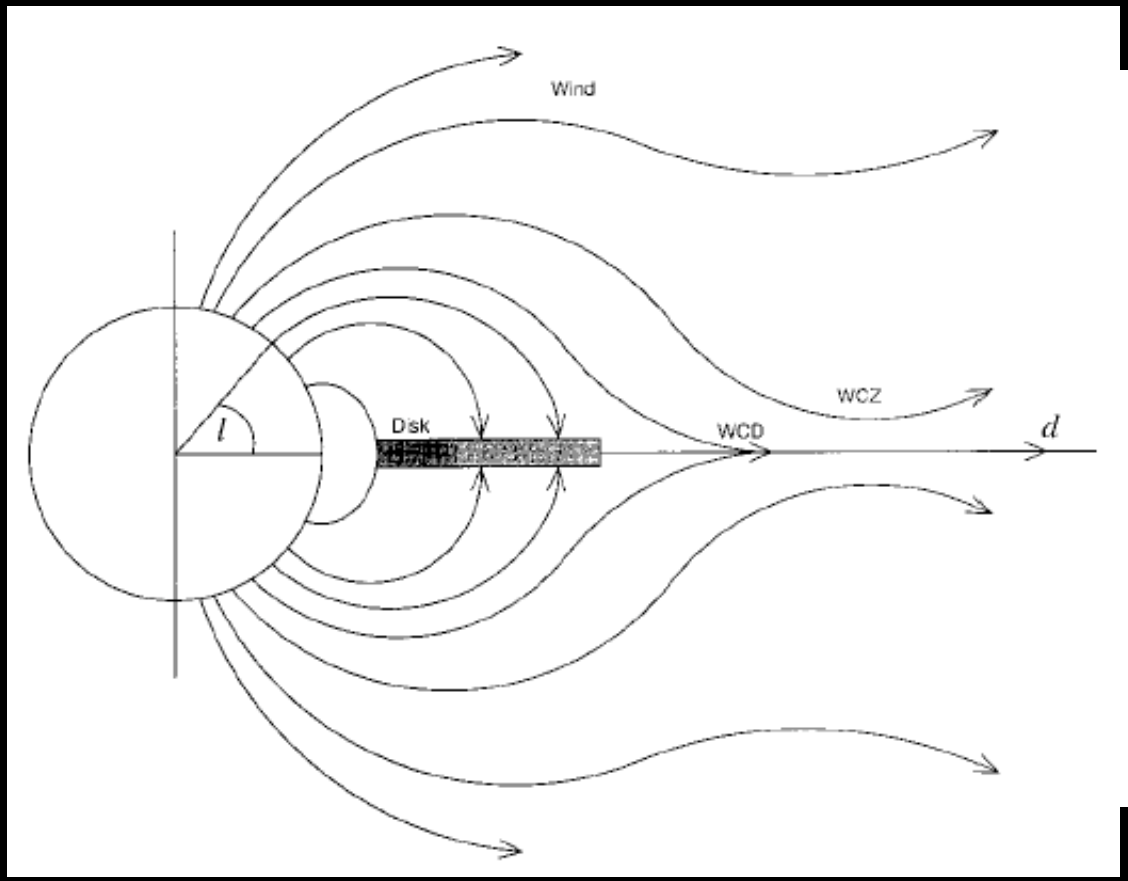
R_K R_A

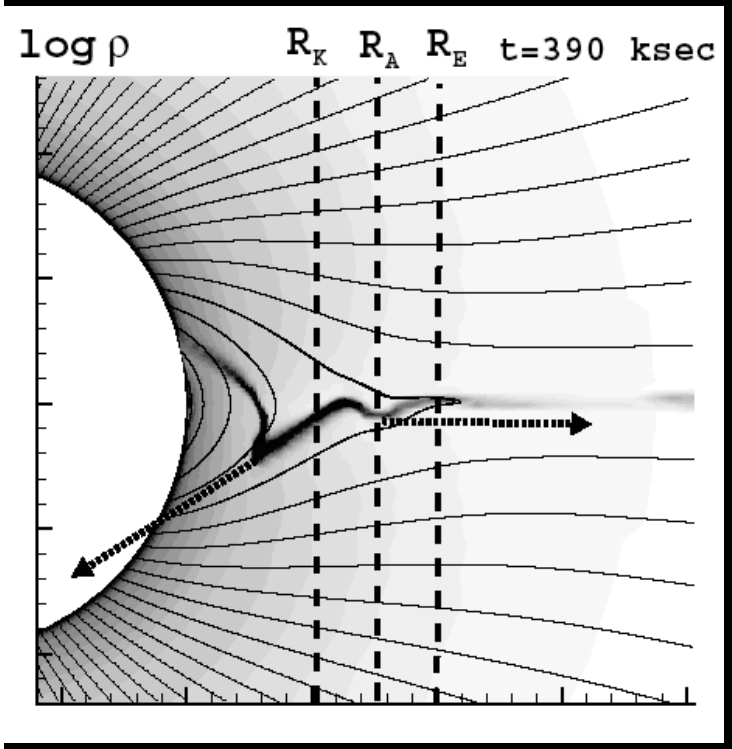
Field aligned rotation

again
isothermal,
but now with
V_{rot}=250 km/s
= V_{crit}/2



Magnetically Torqued Disk

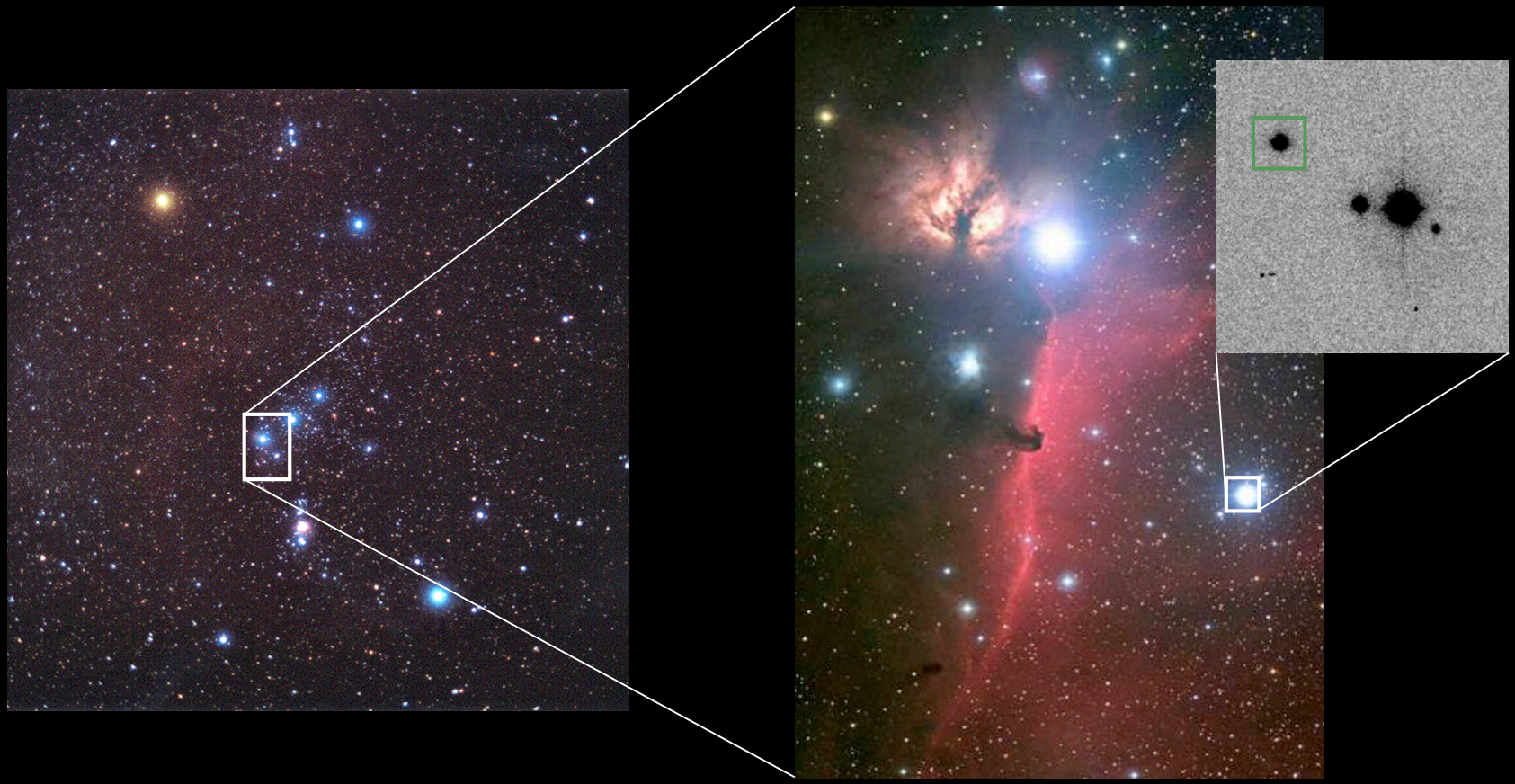




Cassinelli et al. 2002

Owocki & ud-Doula 2003

σ Ori E



Magnetic Bp Stars

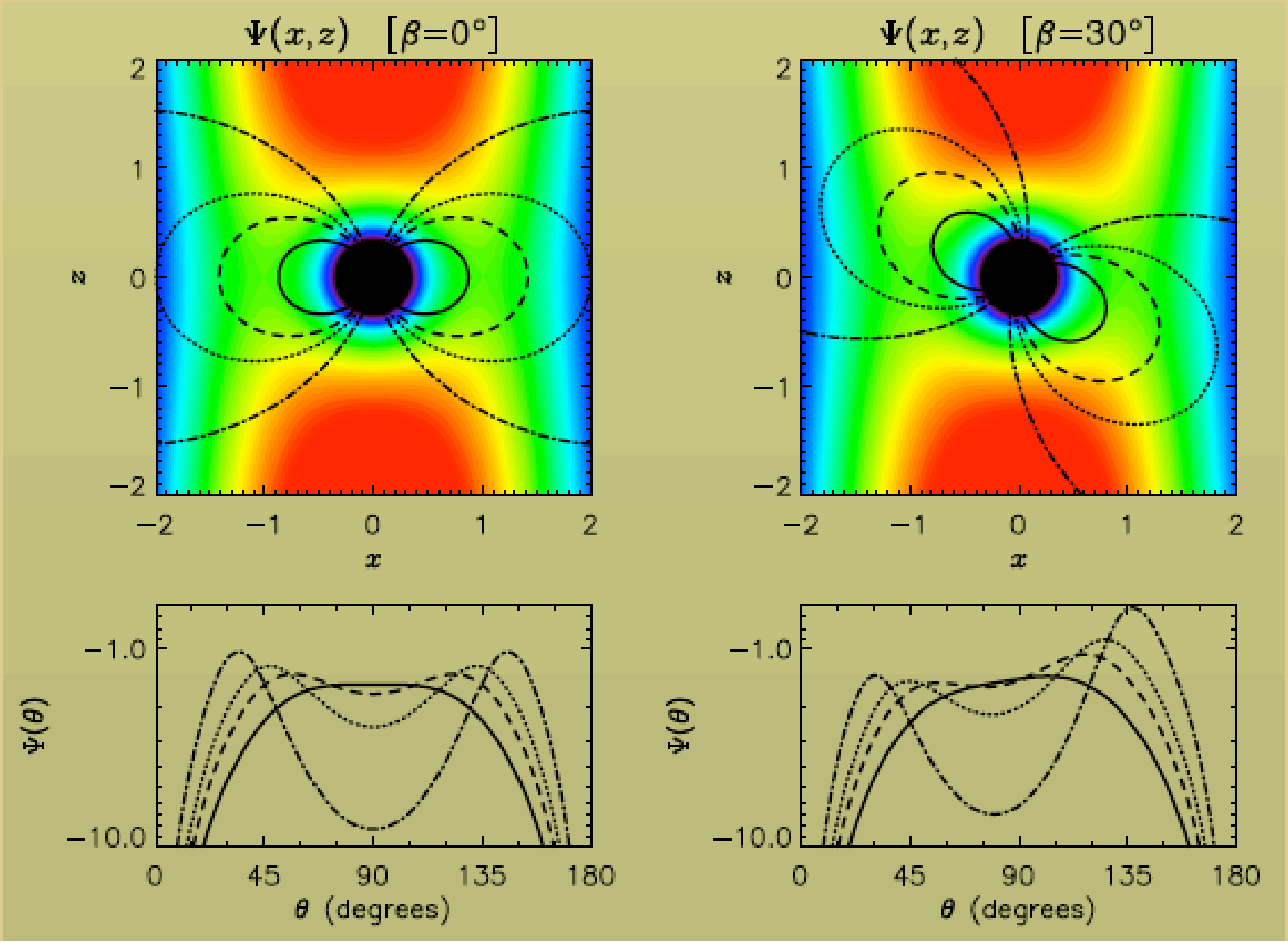
- σ Ori E (B2p V)
  - P_{rot} = 1.2 days => $v_{rot}/v_{crit} \sim 1/2$
  - $B_{obs} \sim 10^4$ G => $\eta_* \sim 10^7$!
  - => V_{Alfven} very large => Courant time very small
  - => Direct MHD impractical

- Instead treat fields lines as "Rigid"

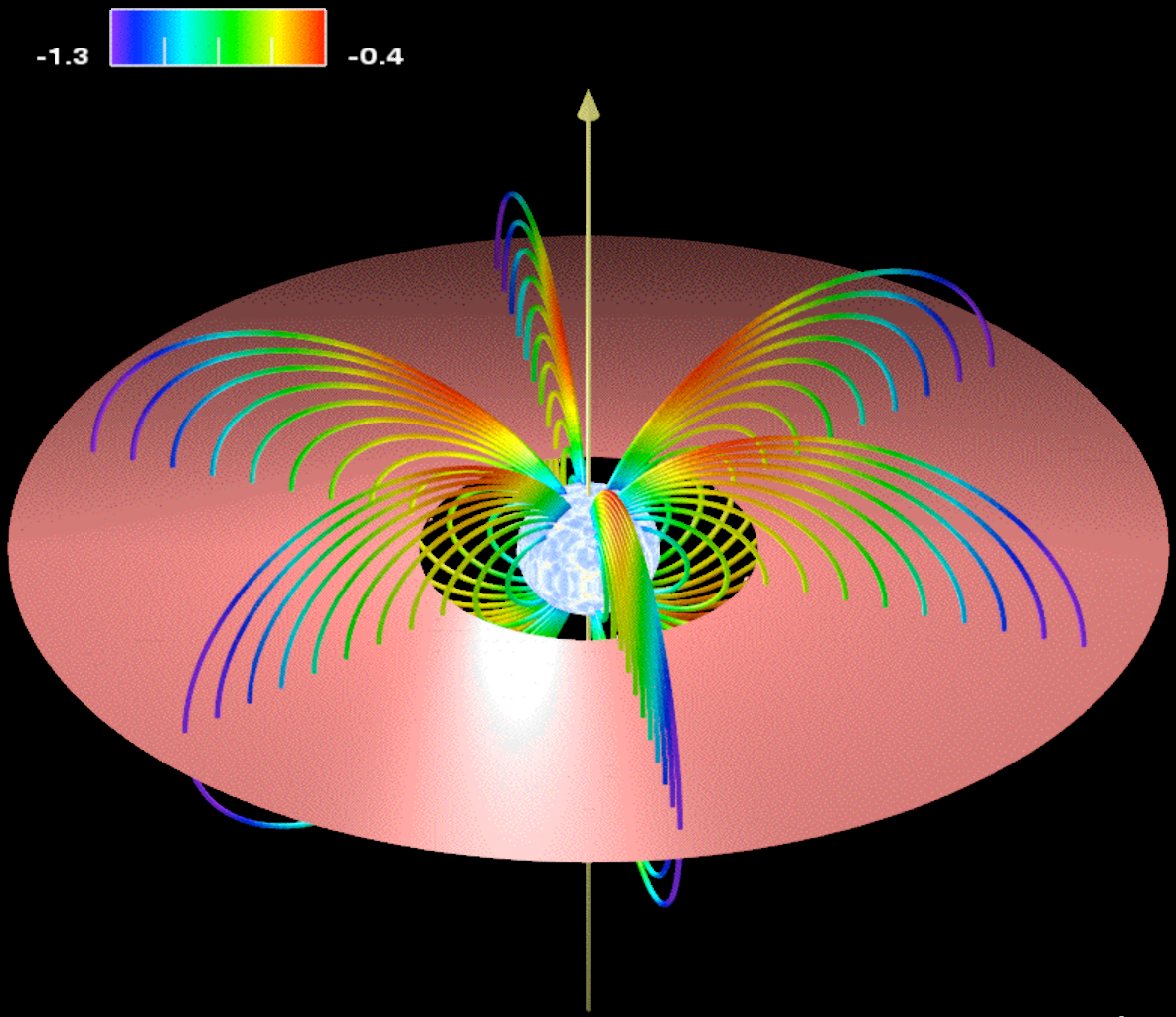
Strong field limit: $B_*, \eta_* \rightarrow \infty$

- Field lines act as rigid guides for wind outflow
  - Torque up wind outflow
  - **Hold down** disk material vs. centrifugal force
- Problem: $V_{Alfven} \rightarrow \infty$ => can't do MHD
- But can model semi-analytically
  - **R**igidly **R**otating **M**agnetosphere (RRM)
  - gas accumulates at minima in grav+cent. potential

Effective Gravitational+Centrifugal Potential

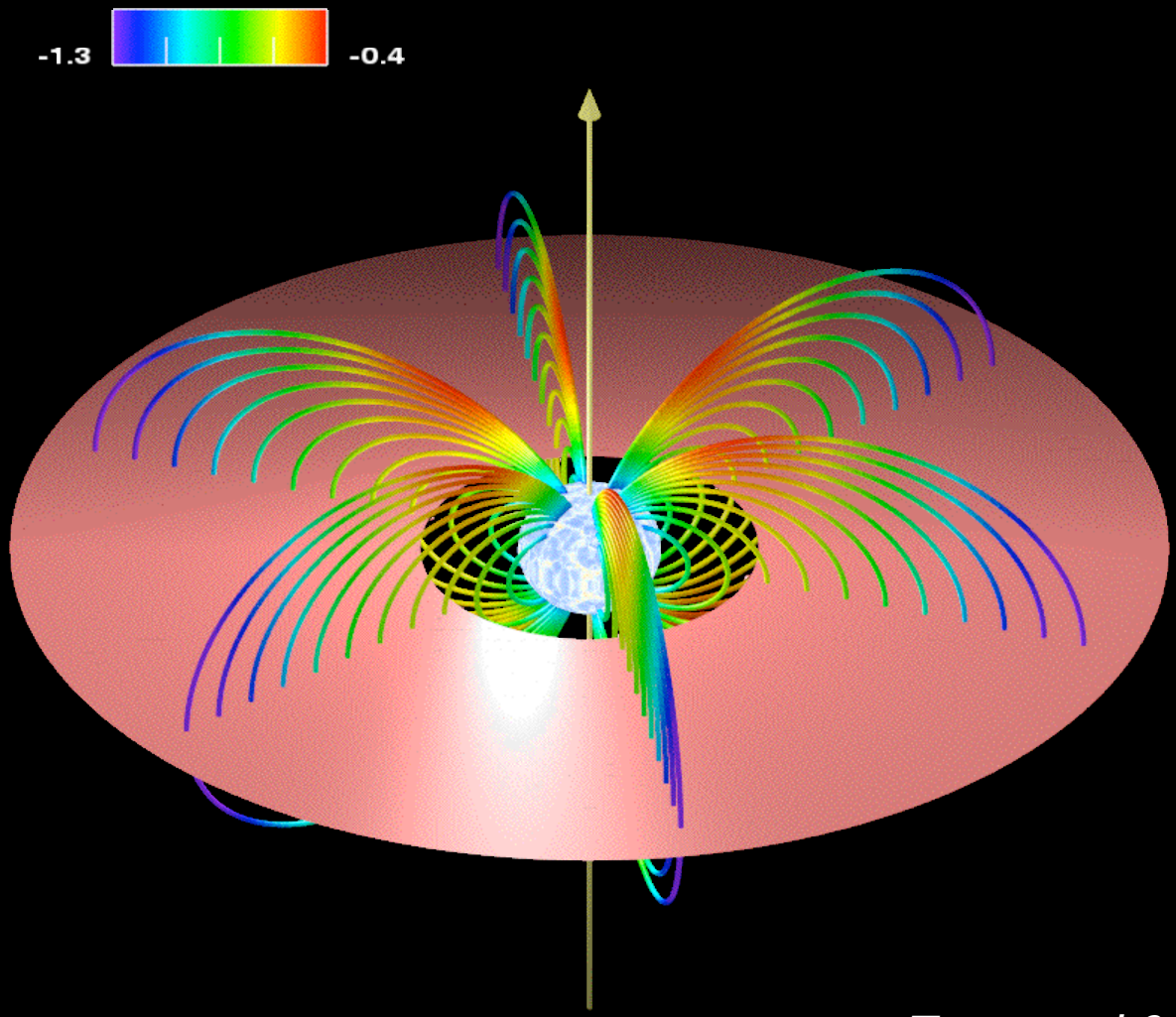


Rigidly Rotating Magnetosphere

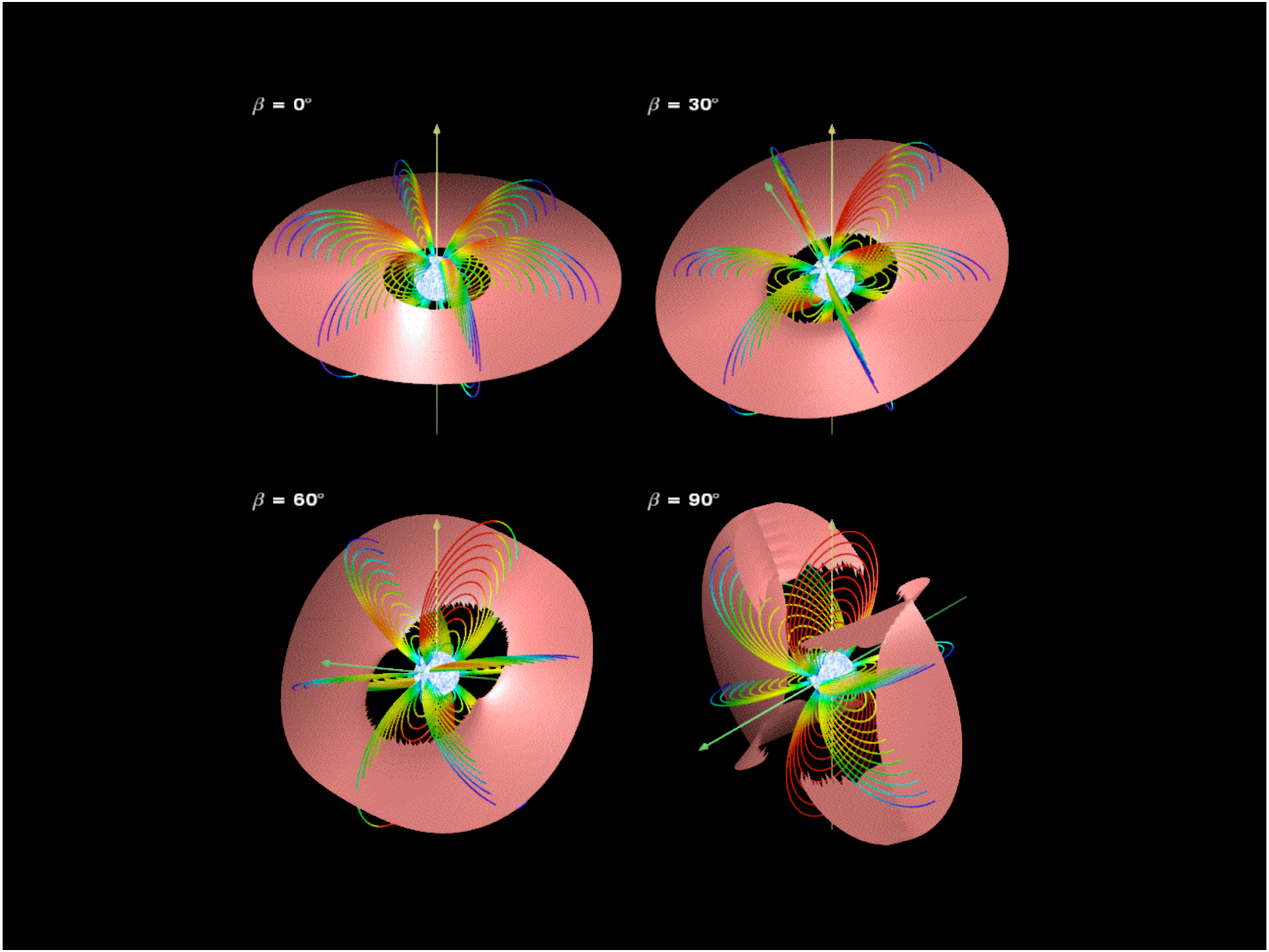


Townsend & Owocki (2005)

Accumulation Surface



Townsend & Owocki (2005)

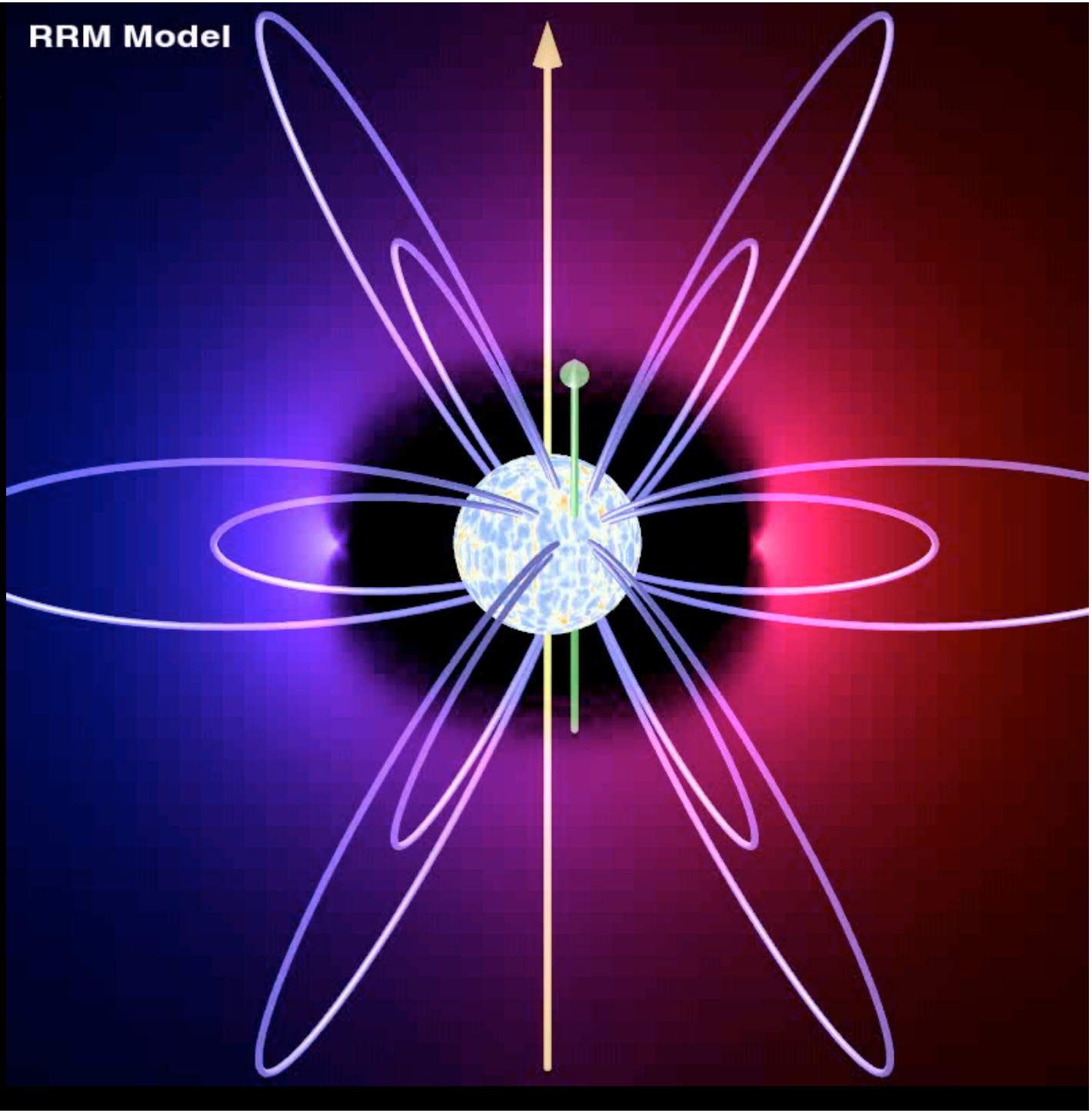

β = 0°
β = 30°
β = 60°
β = 90°

RRM model for σ Ori E

$B_* \sim 10^4$ G

$\eta_* \sim 10^6$!

tilt ~ 55°



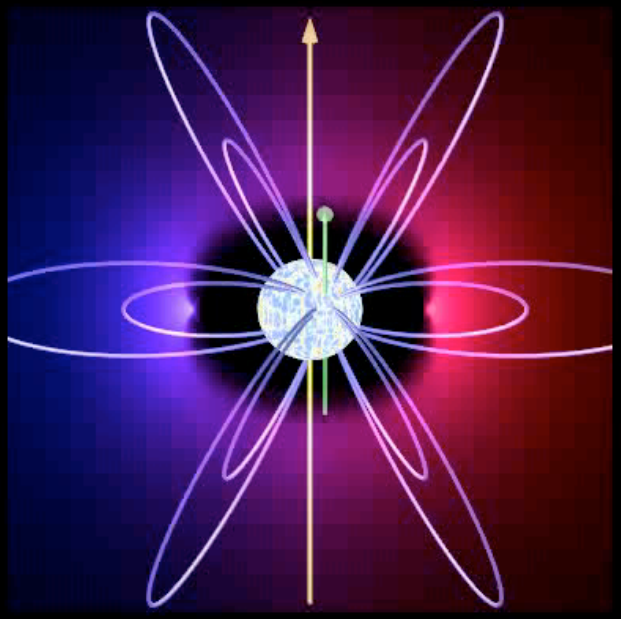
RRM model for σ Ori E

$B_* \sim 10^4$ G

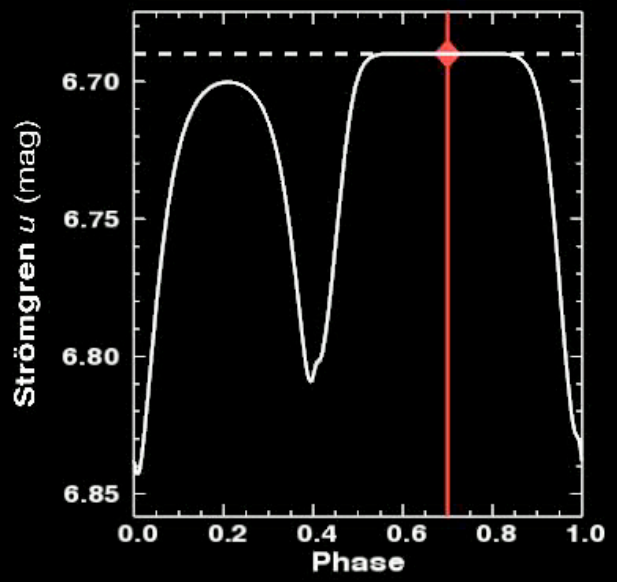
$\Rightarrow \eta_* \sim 10^6$!

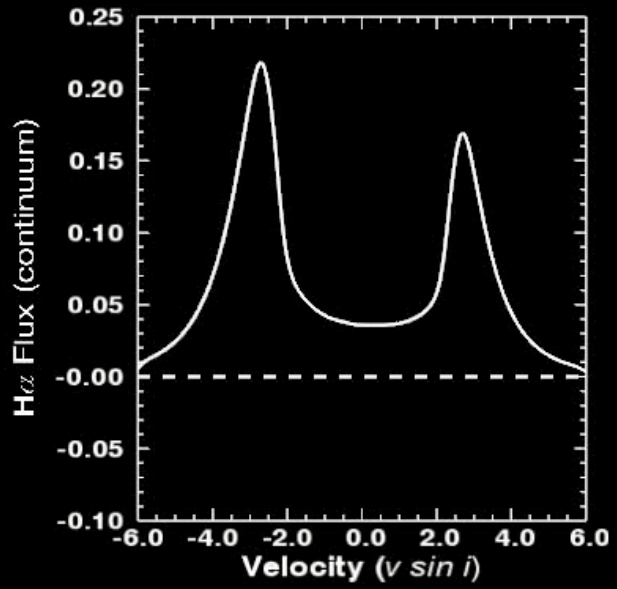
tilt ~ 55°

EM +B-field

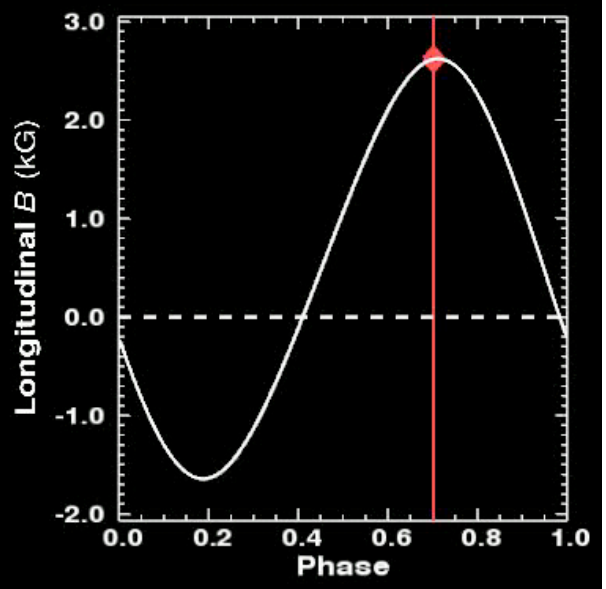


photometry

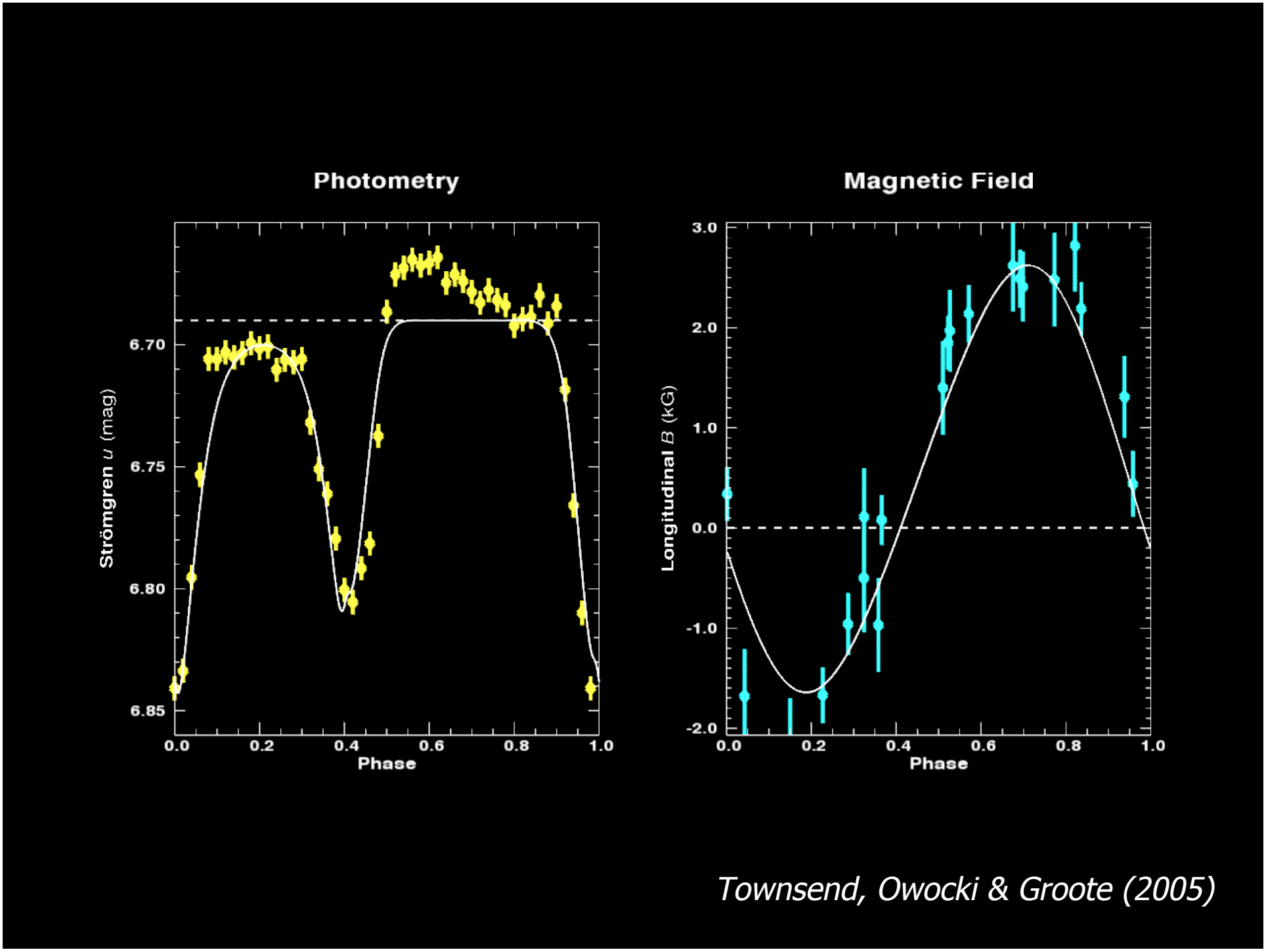




Hα



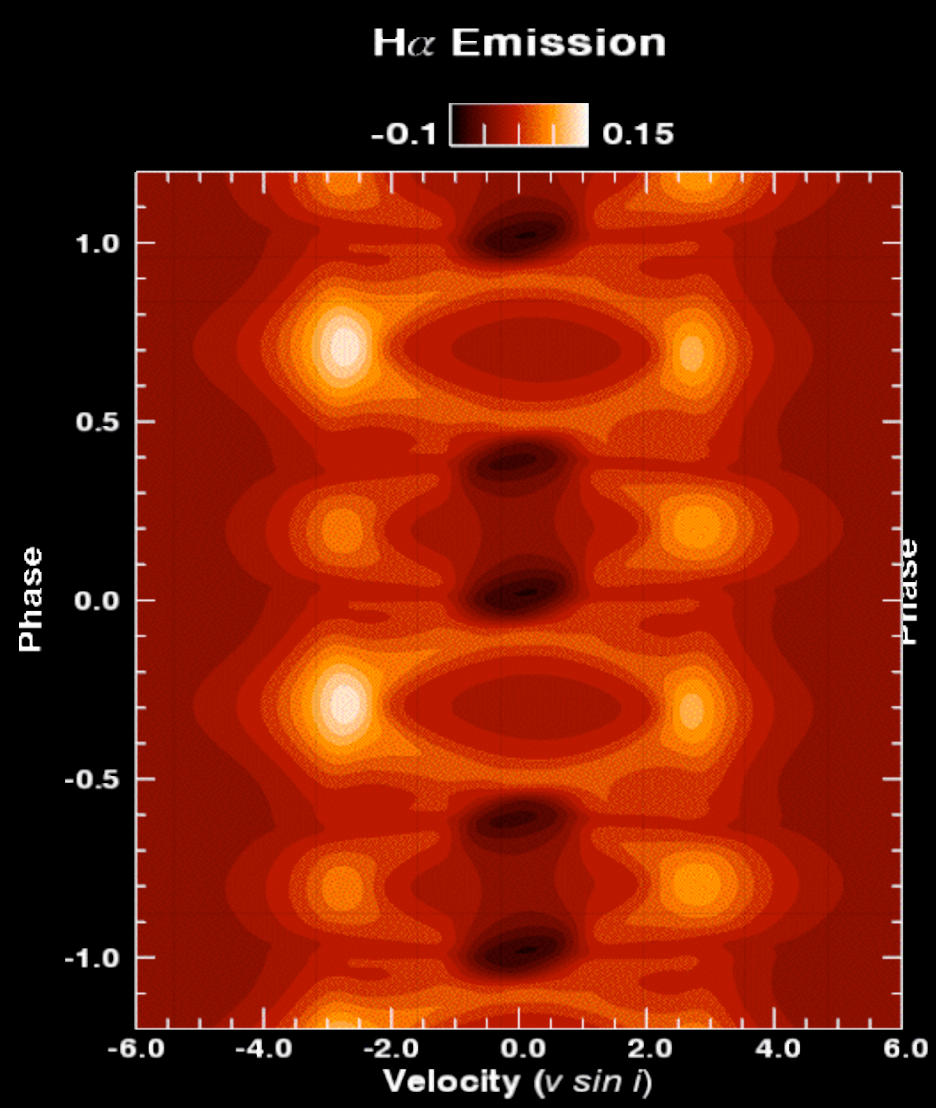
polarimetry



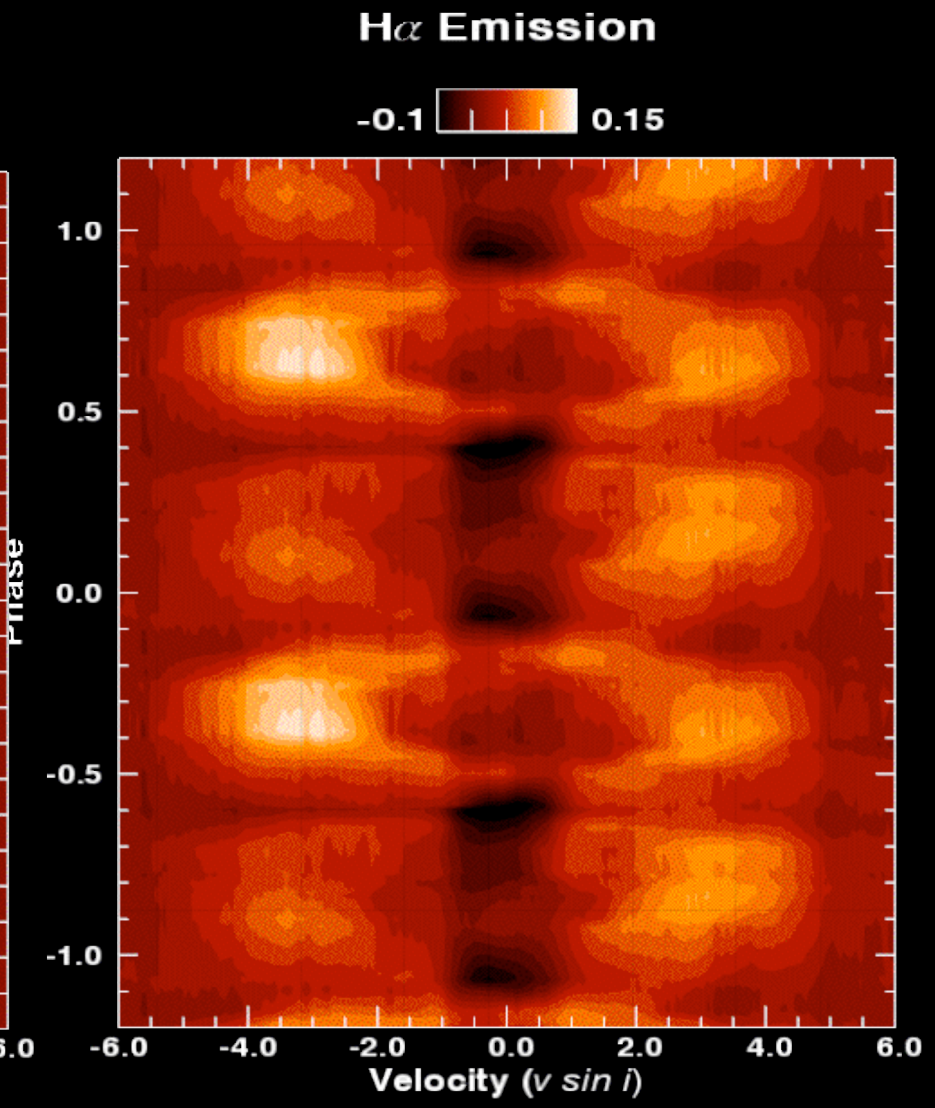
Townsend, Owocki & Groote (2005)

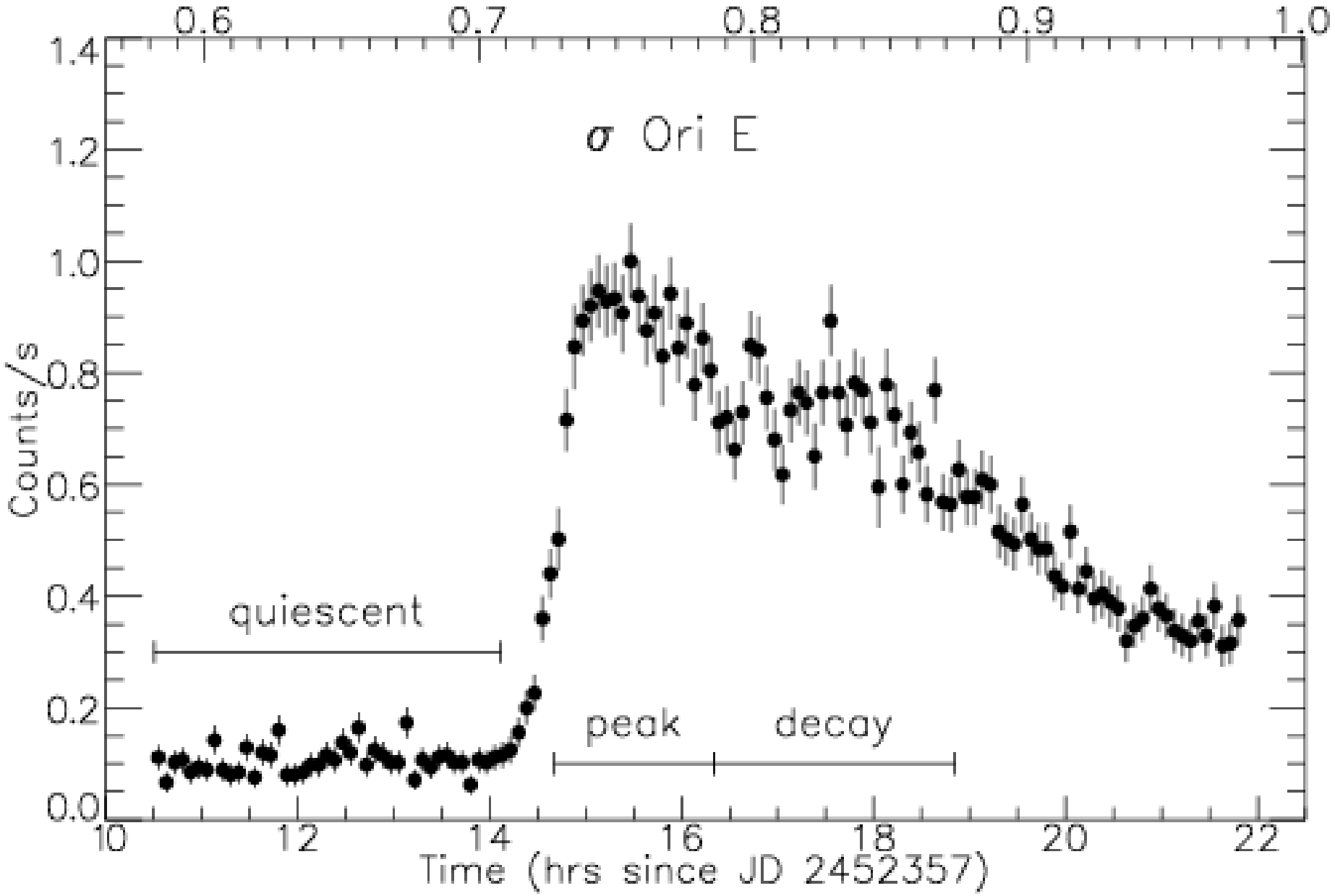
σ Ori E

RRM Model



Hα Observations





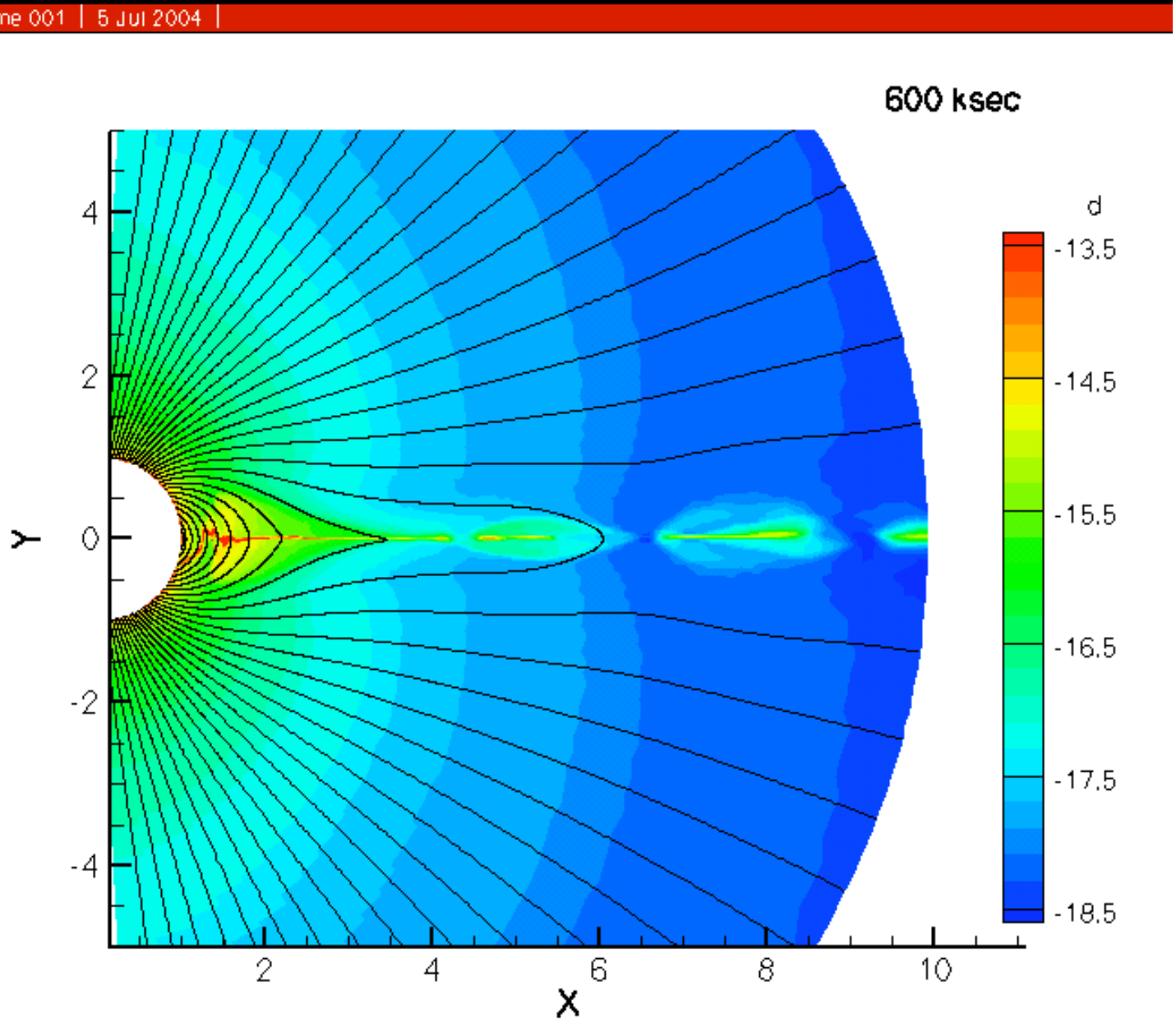
Sanz-Forcada et al. (2004)

MHD sim of centrifugal breakout

$\log(\rho)$

$\eta_* = 620$

$v_{rot} = v_{crit}/2$



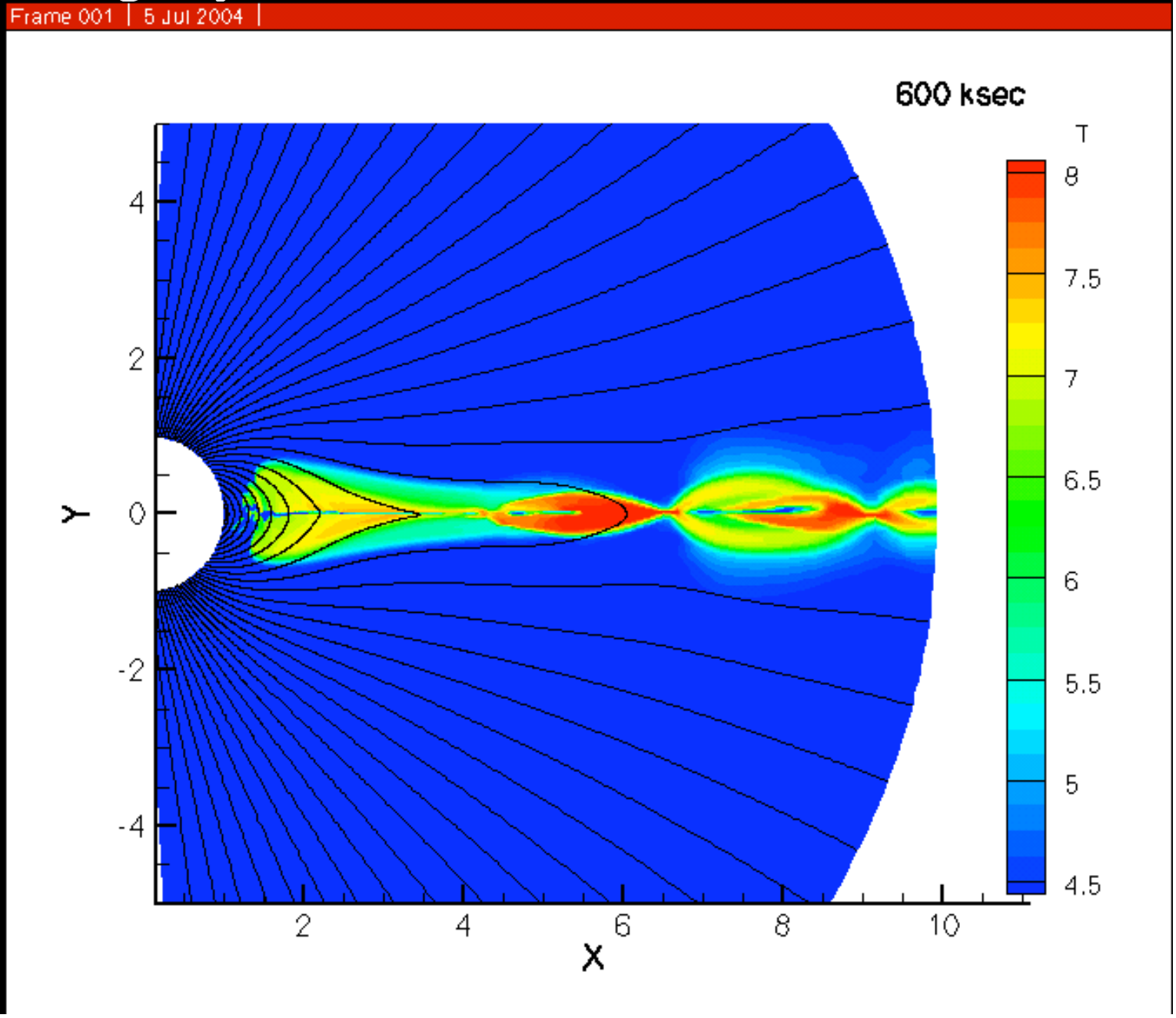
Centrifugally Driven Reconnection Flare

log T

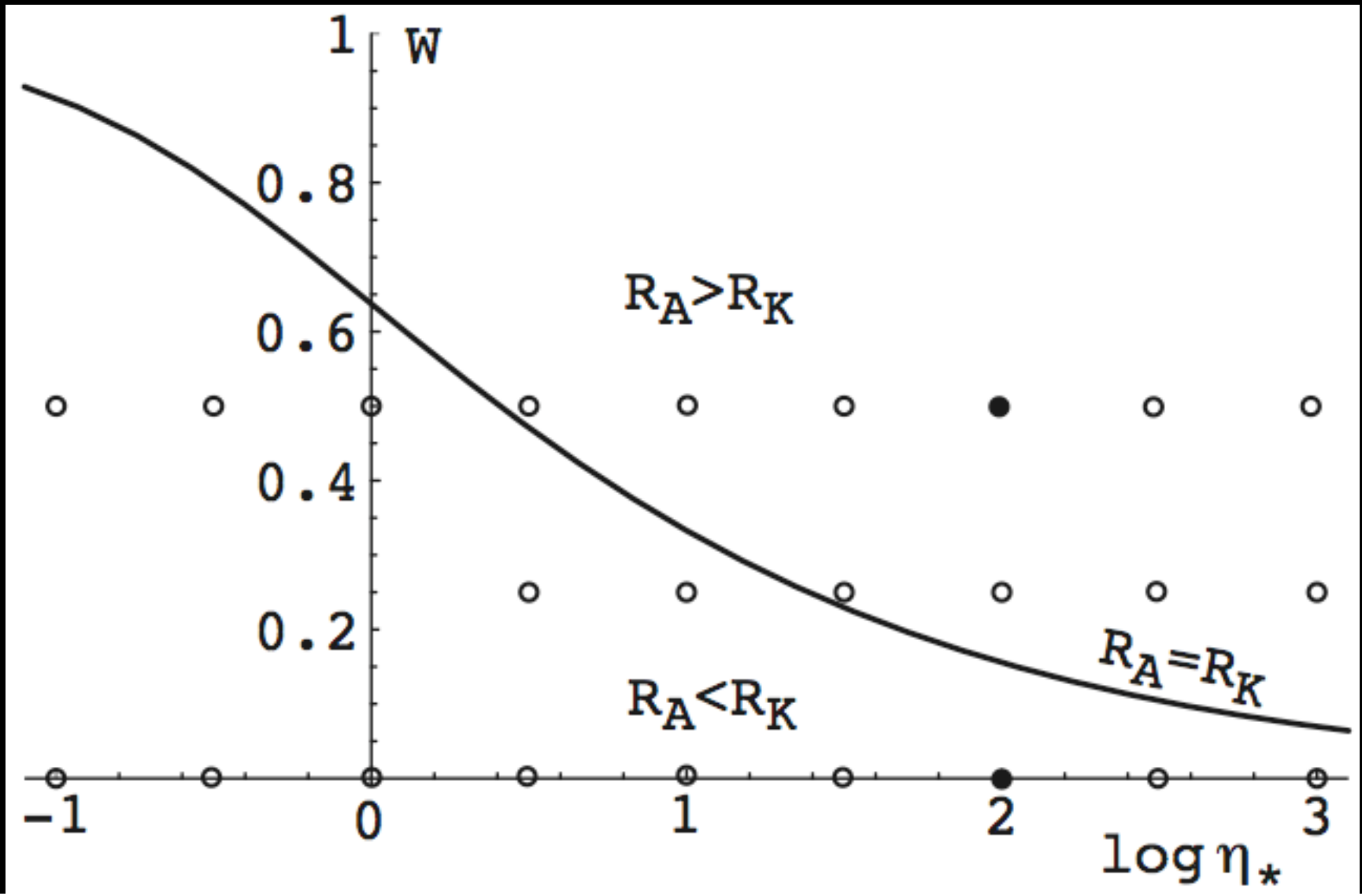
$\eta_* = 620$

$v_{rot} = v_{crit}/2$

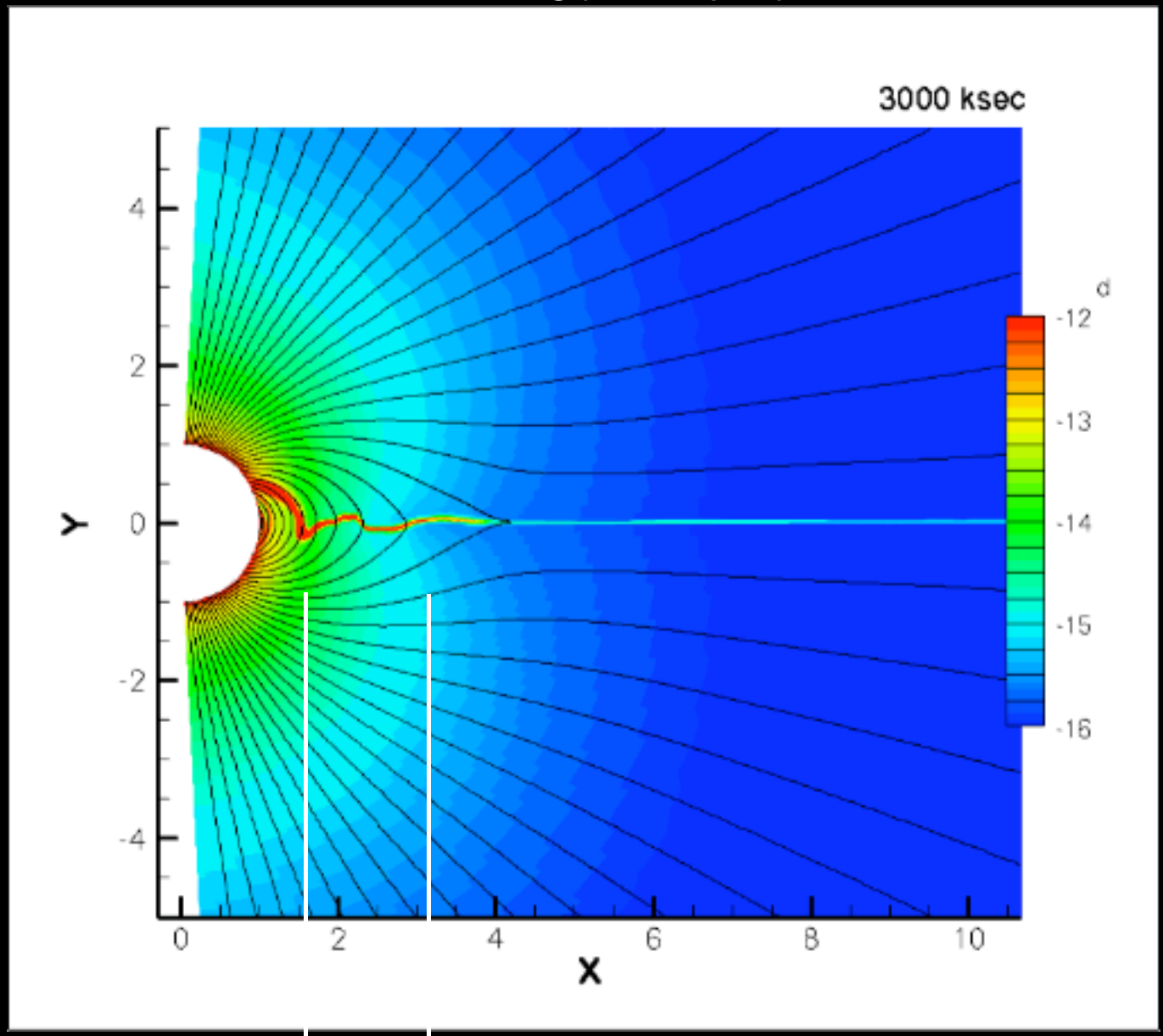
~ 4-5 kev X-ray flares, as seen in σ Ori E



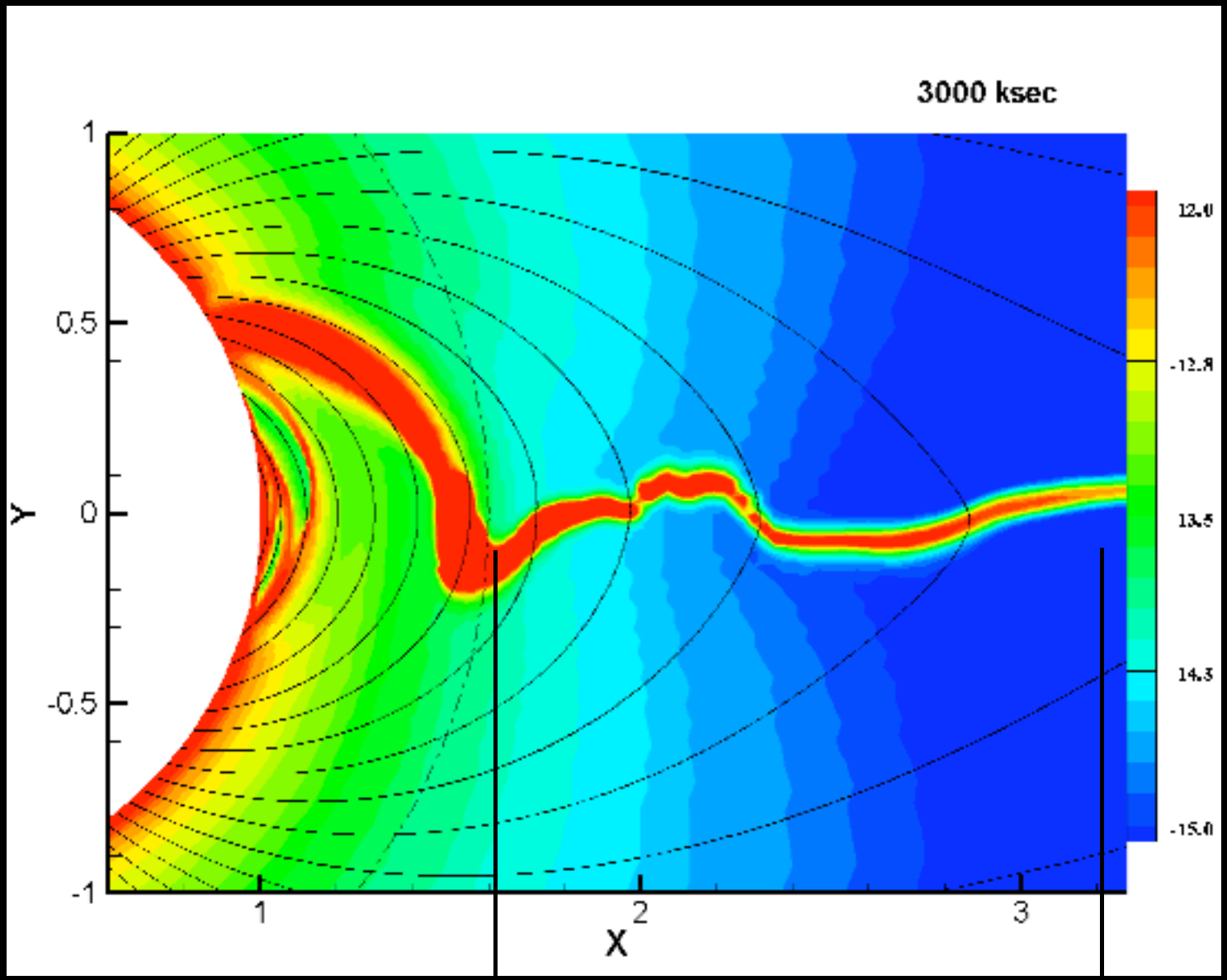
Model grid for 2-Parameter study: Rotation & Magnetic Confinement



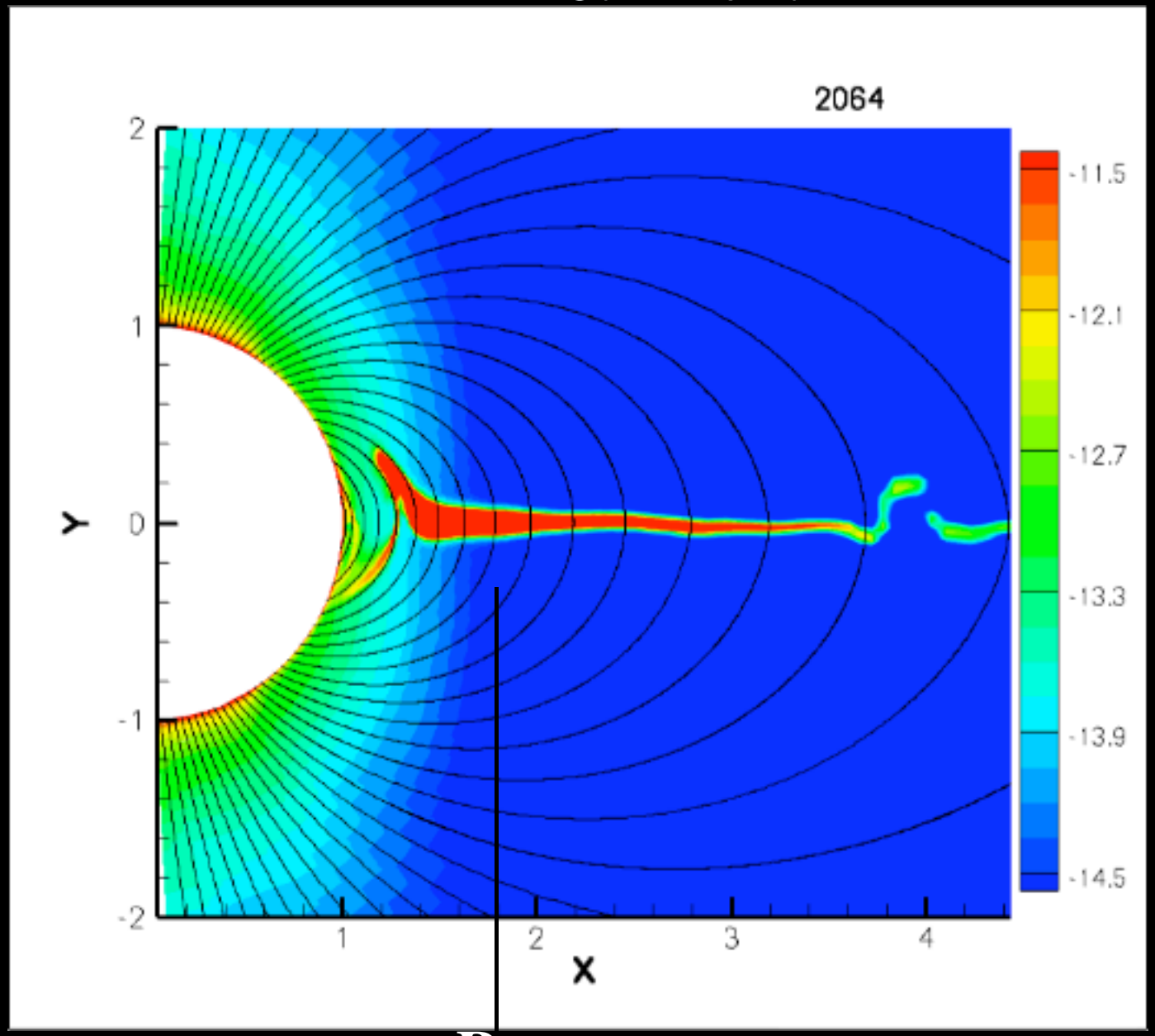
Isothermal, $v_{rot}=v_{crit}/2$, $\eta_*=100$



Isothermal, $v_{rot}=v_{crit}/2$, $\eta_*=100$



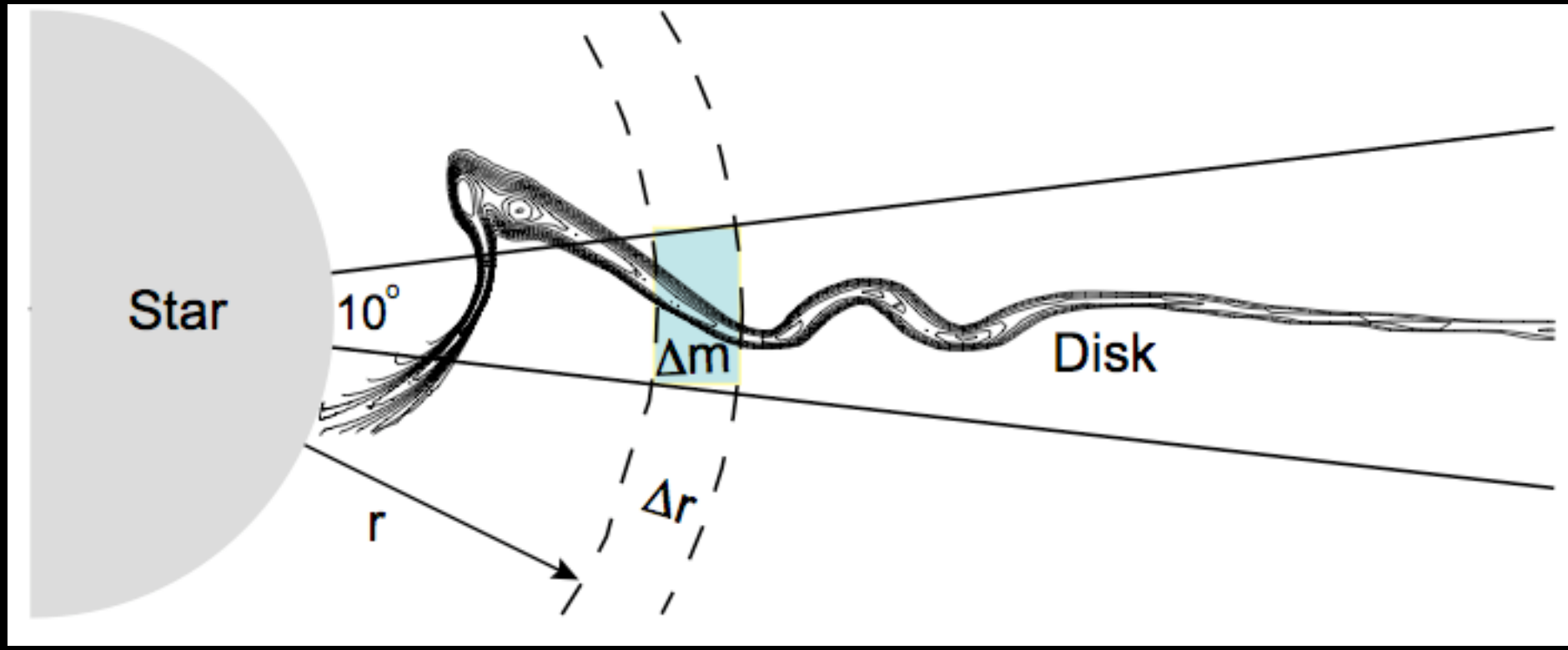
Isothermal, $v_{rot}=v_{crit}/2$, $\eta_*=1000$



R_K

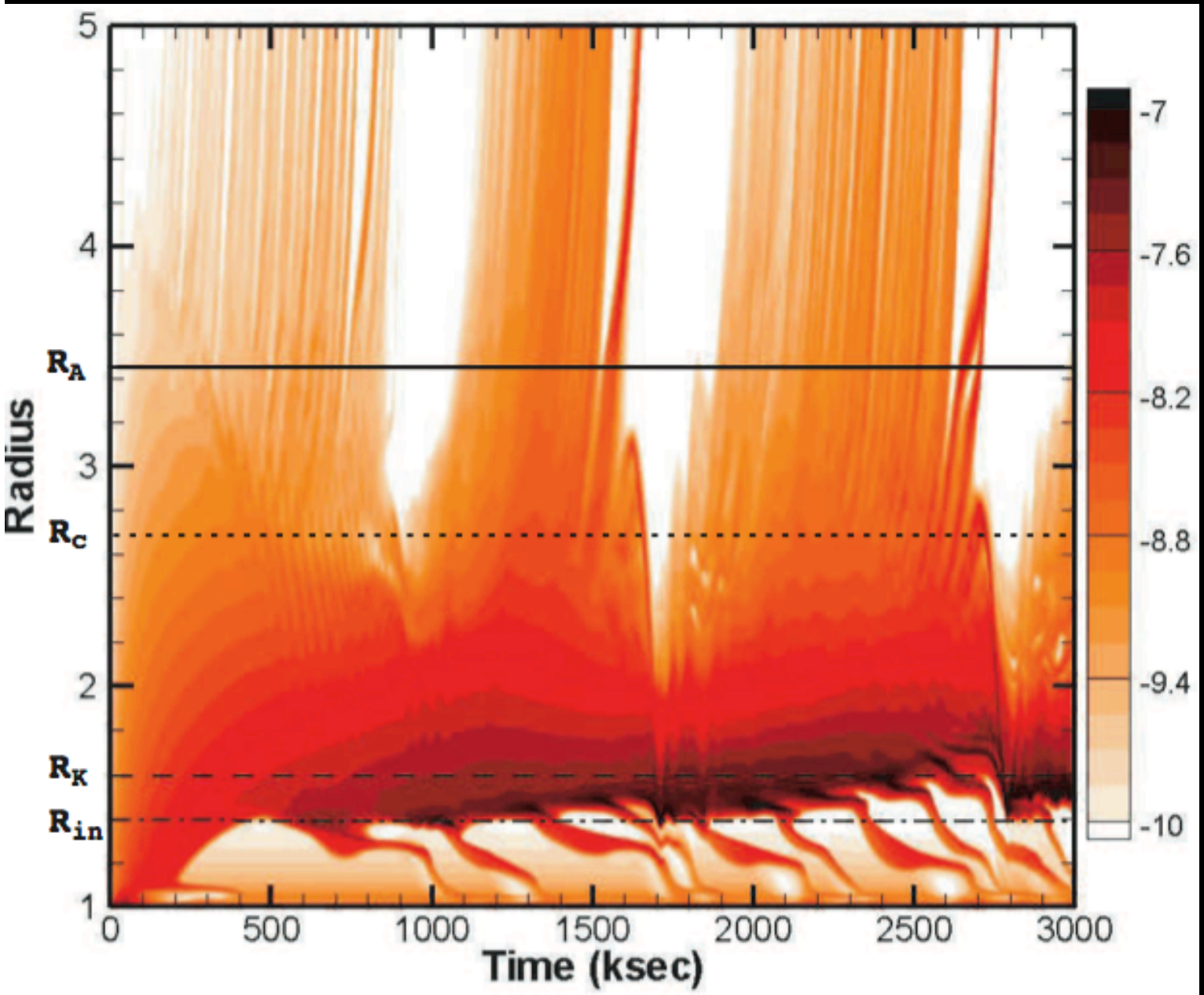
$R_A \sim 7R_*$

Radial disk mass: dm_e/dr



$$\frac{dm_e}{dr} \equiv 2\pi r^2 \int_{\pi/2-\Lambda\theta/2}^{\pi/2+\Lambda\theta/2} \rho \sin\theta d\theta$$

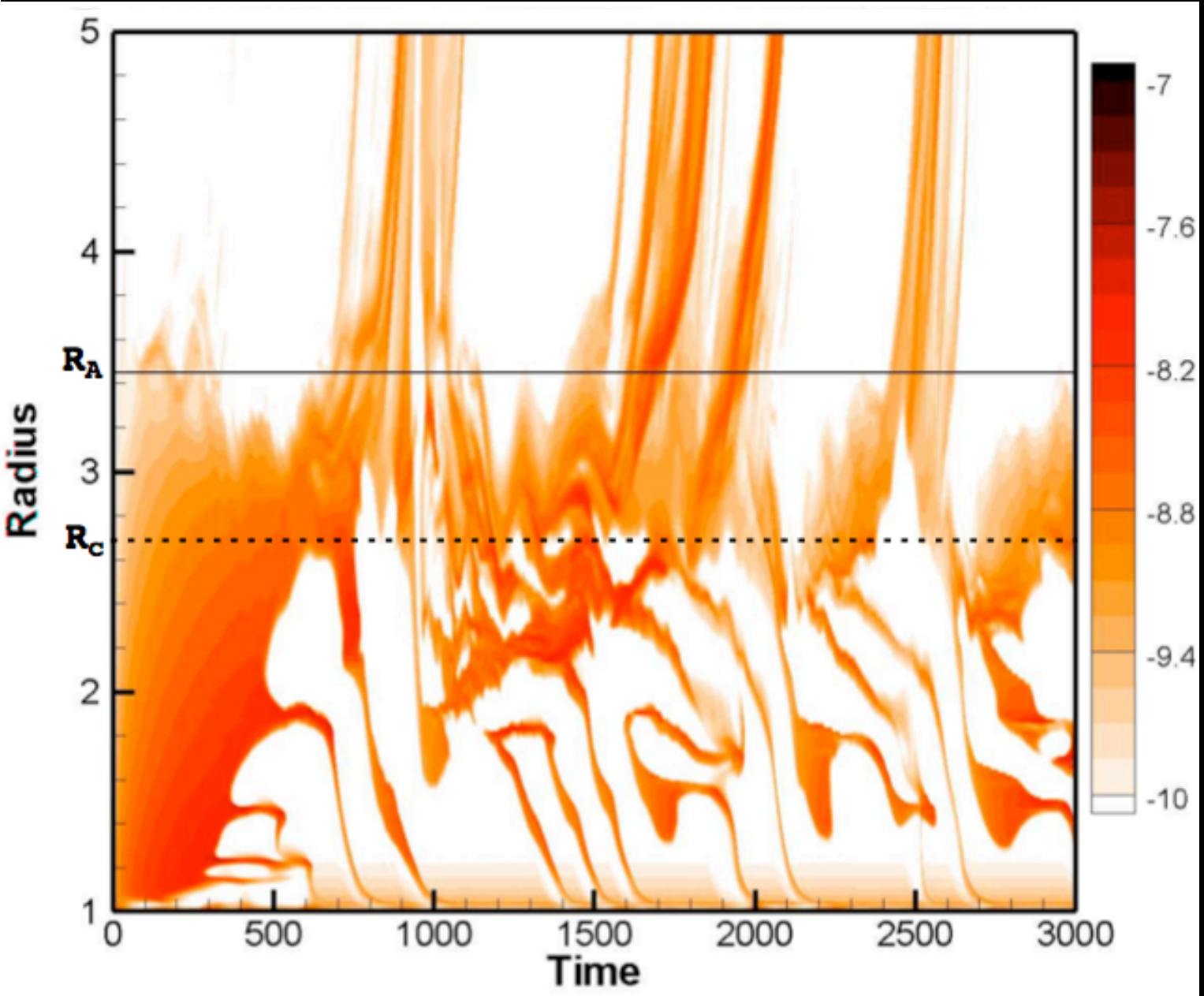
Equatorial mass distribution dm_e/dr



$\eta_*=100$

W=1/2

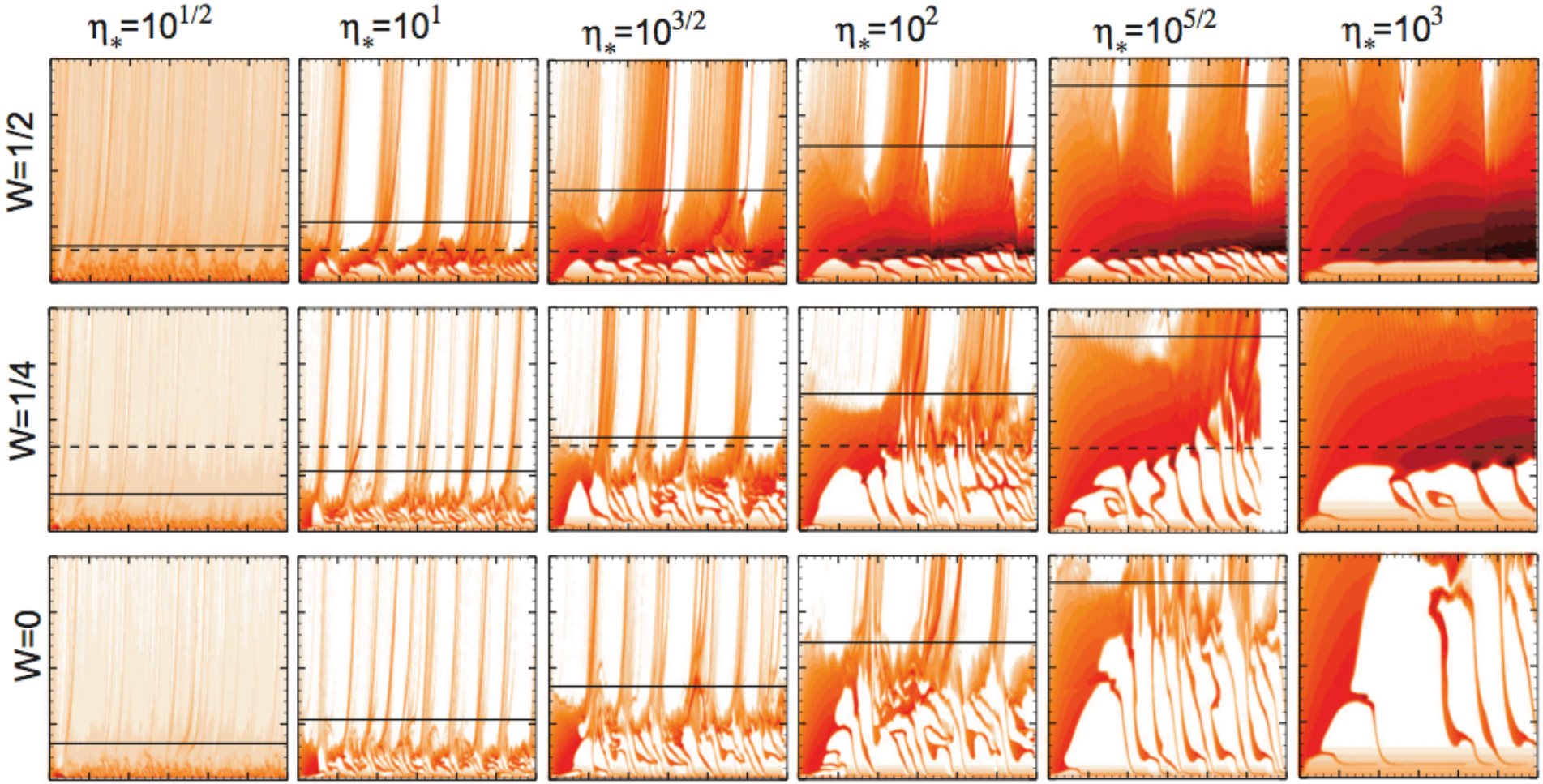
Equatorial mass distribution dm_e/dr



$\eta_*=100$

W=0

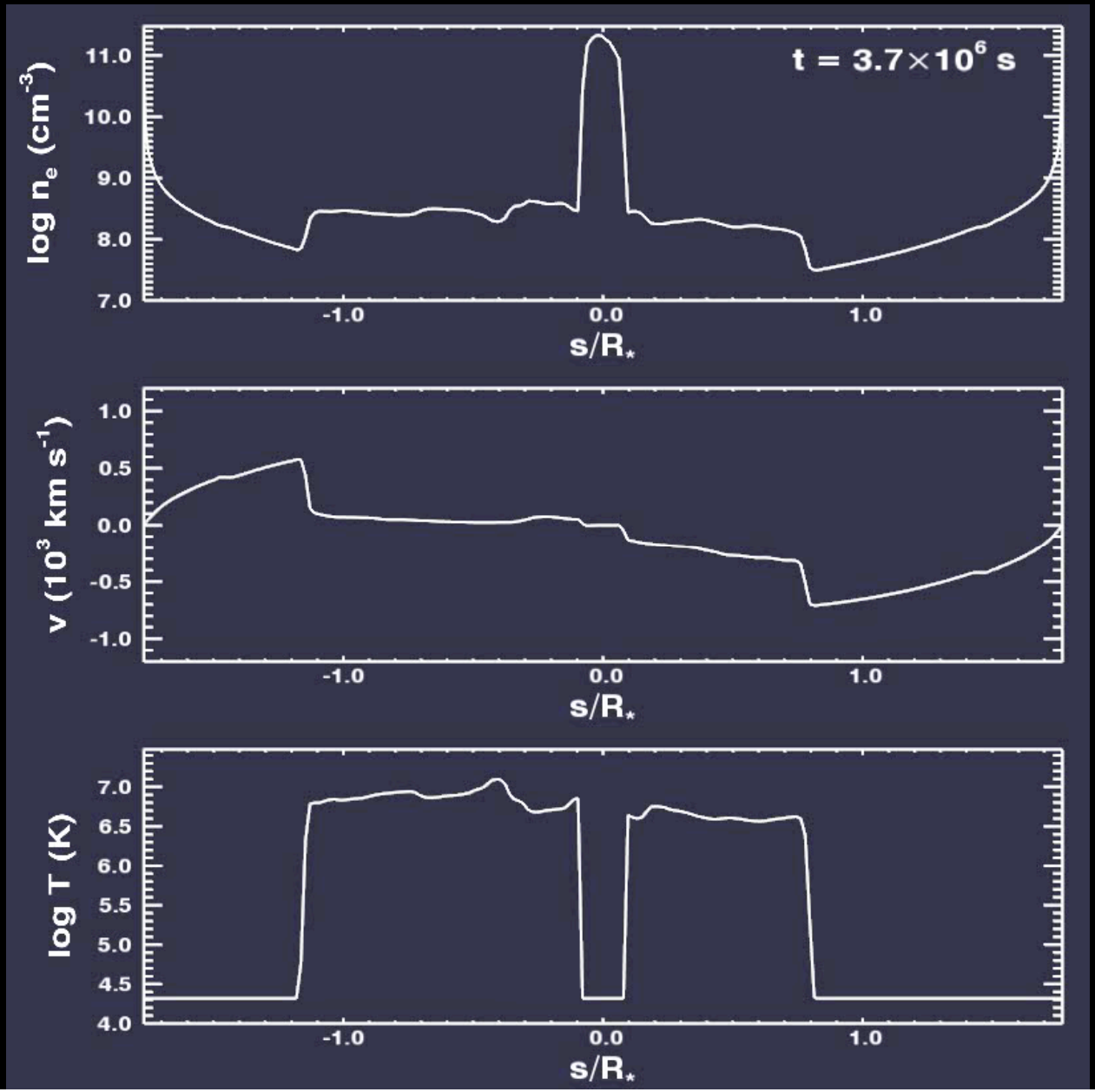
Parameter study: rotation & magnetic confinement



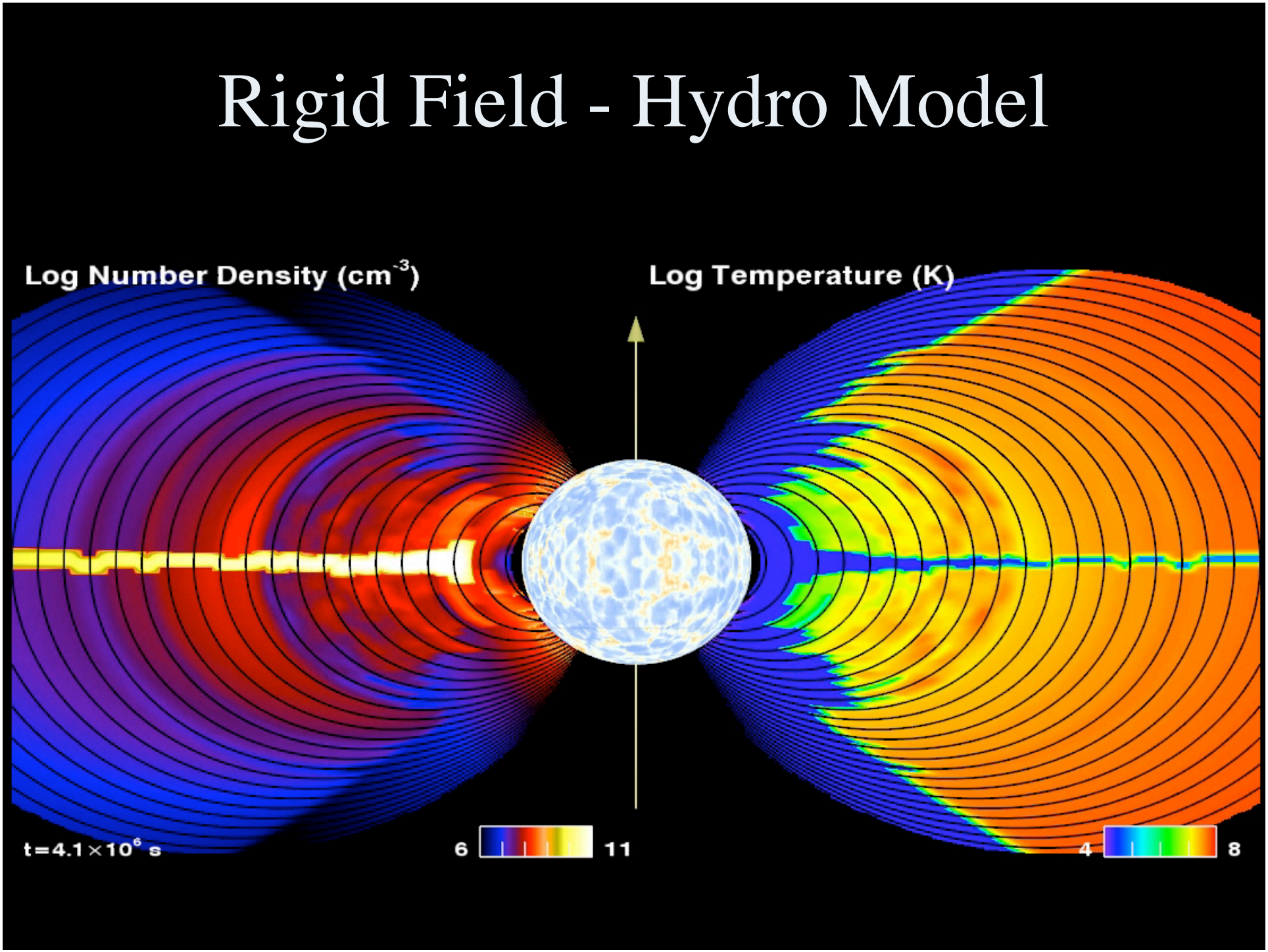
Between RRM and full MHD: "Rigid Field Hydro-Dynamics" RFHD

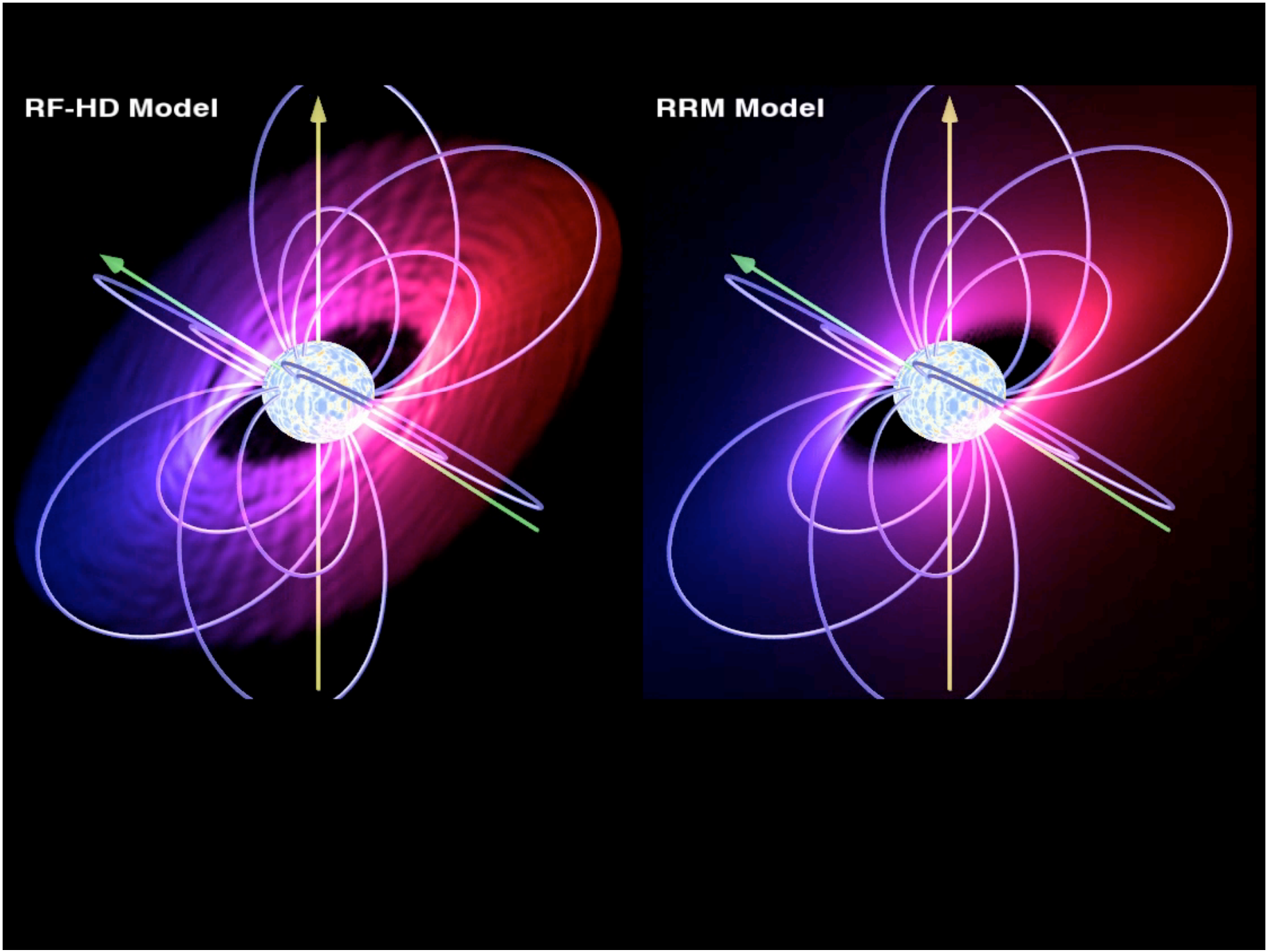
Solve time-dependent hydro along completely rigid individual field lines

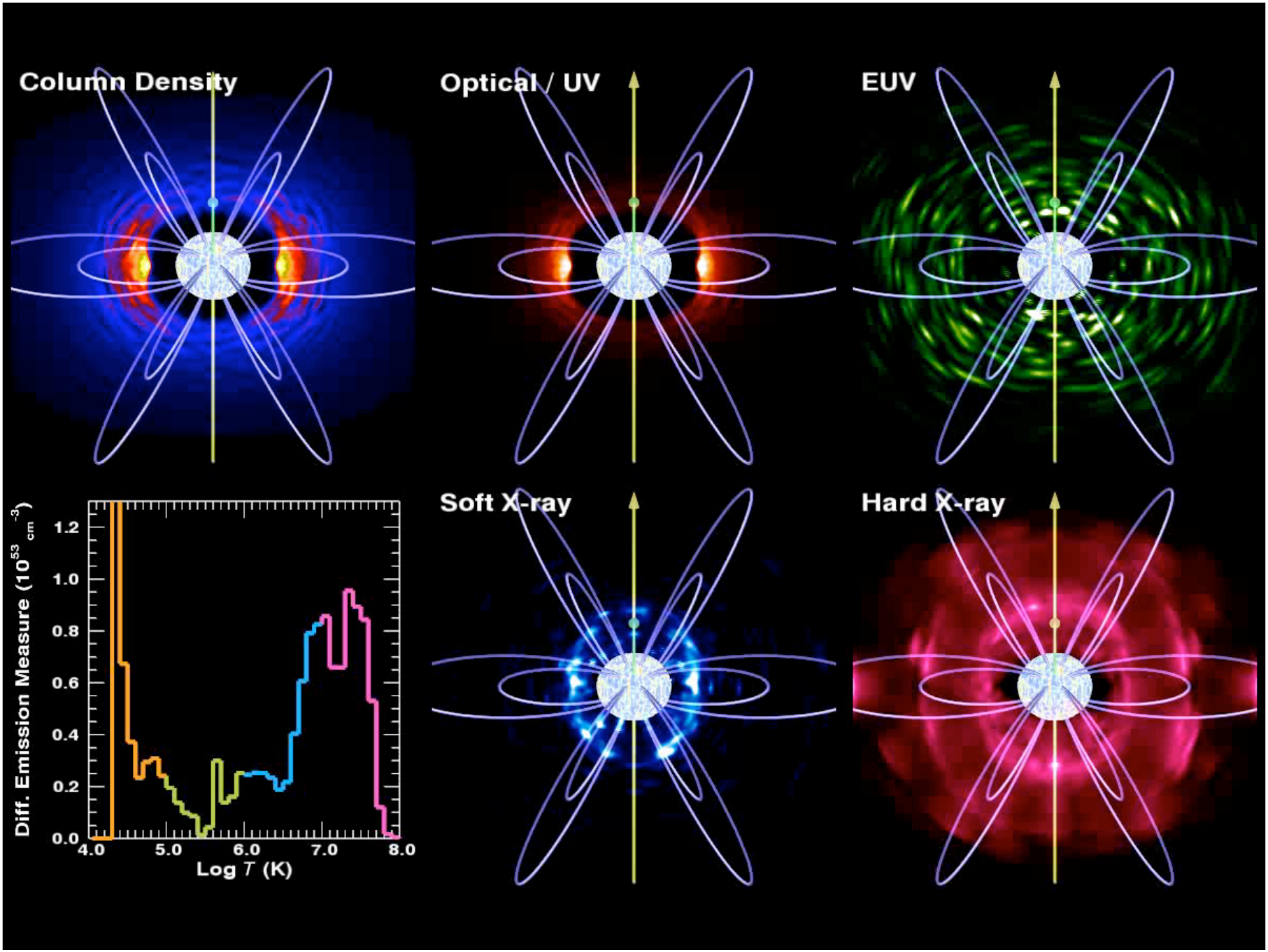
The flow along an individual field line



Rigid Field - Hydro Model




RF-HD Model
RRM Model


Column Density
Optical / UV
EUV
Soft X-ray
Hard X-ray
Diff. Emission Measure (10^{53} cm^{-3})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
4.0
5.0
6.0
7.0
8.0
Log T (K)

Summary

- Magnetic field + hot star wind:
  - $\eta_* > 10$: **channel** wind into shock (MCWS)
    - explains X-rays from Θ^1 Ori C
  - **spin up** wind past Kepler co-rotation radius
  - **confine** material against centrifugal
    - Rigidly Rotating Magnetosphere (RRM)
    - explains H-α vs. rot. phase in σ Ori E
  - mass build up => **centrifugal breakout**
    - reconnection => $T >\sim 10^8$ K
    - can explain hard X-ray **flares** in σ Ori E
    - "centrifugally driven reconnection"

Current & Future Work

- 3D MHD of MCWS
  - lateral structure scale, tilted field case
- Comparison with observations
  - Chandra & XMM
    - X-rays from shocks and flares
  - Optical photometry, spectroscopy, polarimetry
    - Rotation Spin-Down??
  - VLTI to resolve disk
- Application to other types of magnetospheres?
- RRM shock as site for Fermi acceleration??
  - Could produce up to TeV Gamma Rays!