Massive-Star Magnetospheres

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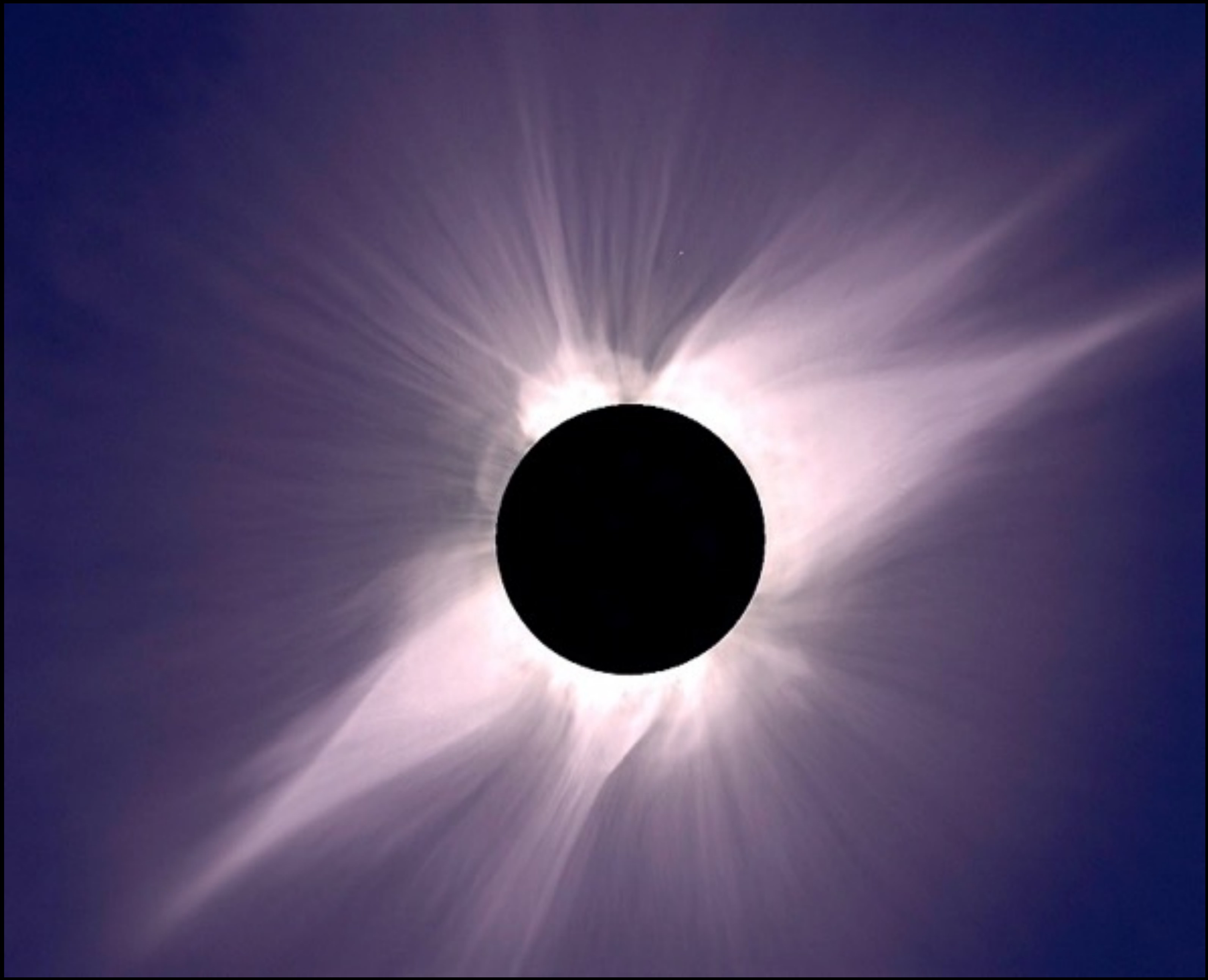
Collaborators

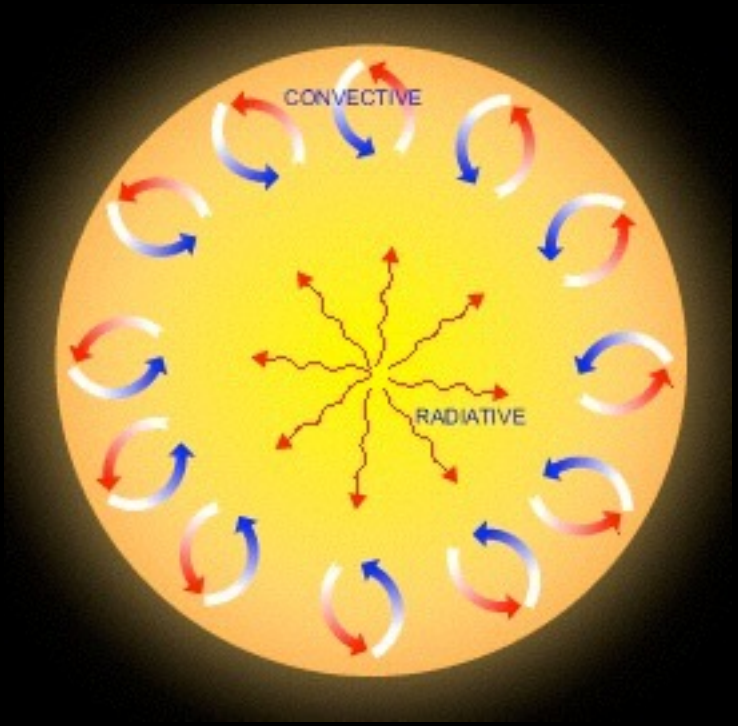
- Asif ud-Doula
- Rich Townsend
- Jon Sundqvist
- Vero Petit
- MiMeS collaboration

Corona during Solar Eclipse



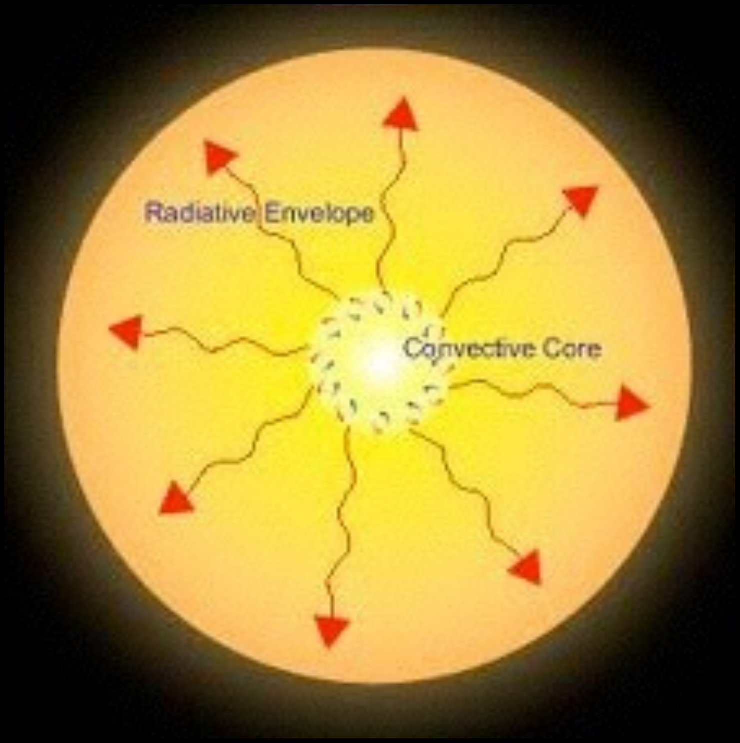
Convective vs. Radiative Envelopes

Solar mass stars

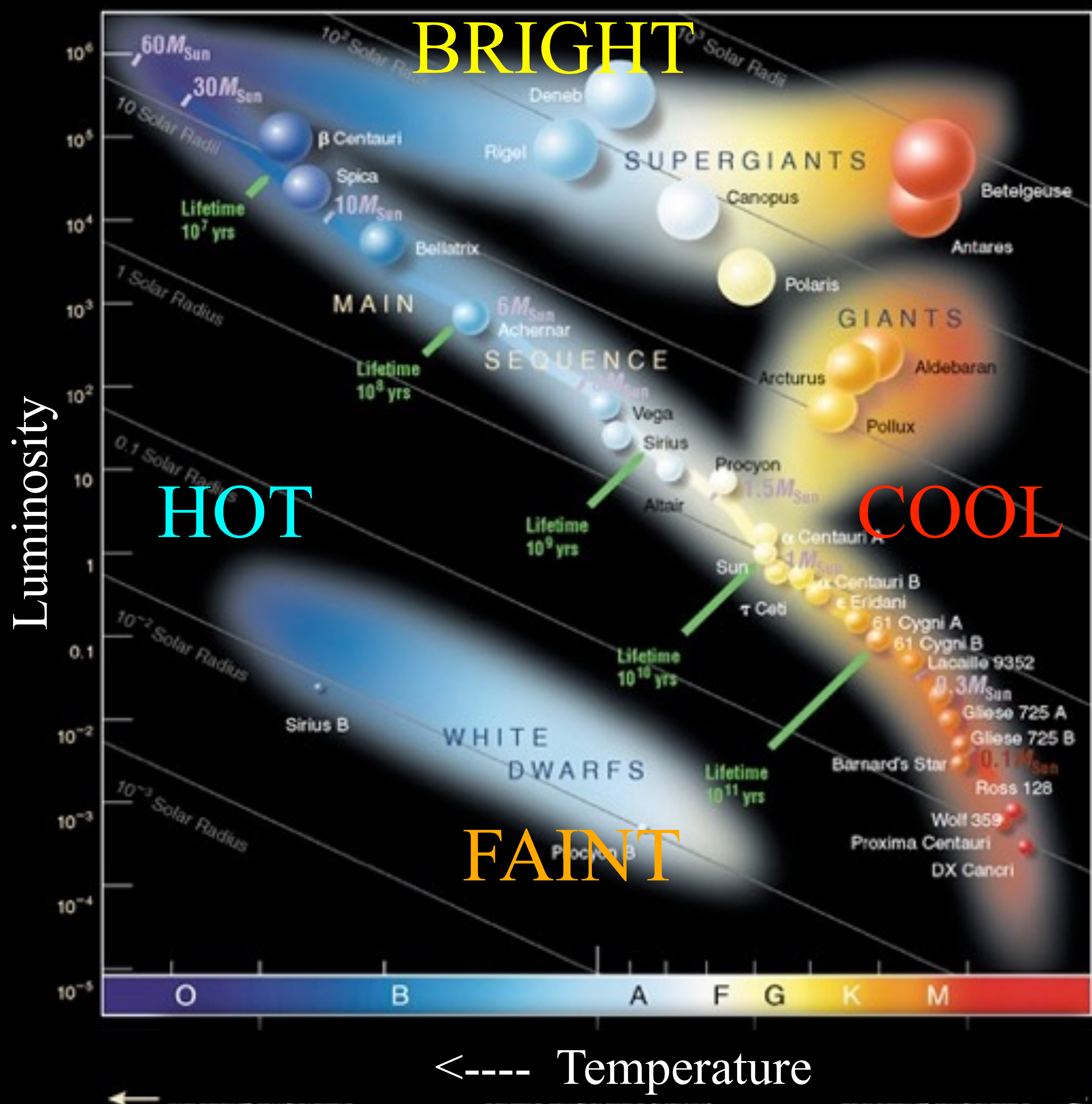


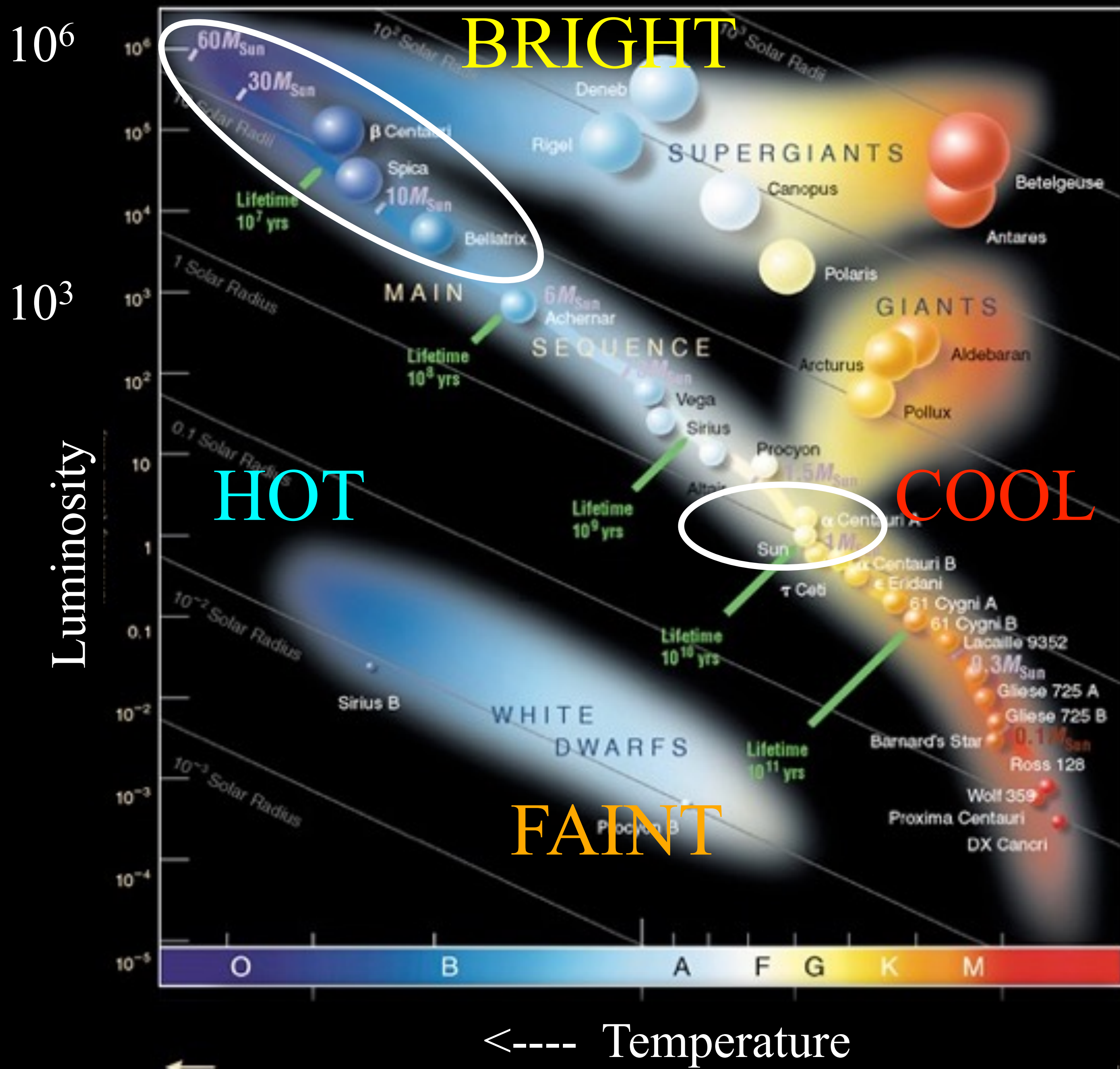
Rotation-Convection Dynamo

High-mass stars



No envelope Dynamo


BRIGHT
HOT
COOL
FAINT
Luminosity
<---- Temperature
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
$60 M_{Sun}$
$30 M_{Sun}$
$10 M_{Sun}$
$6 M_{Sun}$
$1.5 M_{Sun}$
$1 M_{Sun}$
$0.3 M_{Sun}$
$0.1 M_{Sun}$
10^3 Solar Radii
10^2 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Canopus
Betelgeuse
Antares
Polaris
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B



BRIGHT
HOT
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10^6
10^3
Luminosity
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O
B
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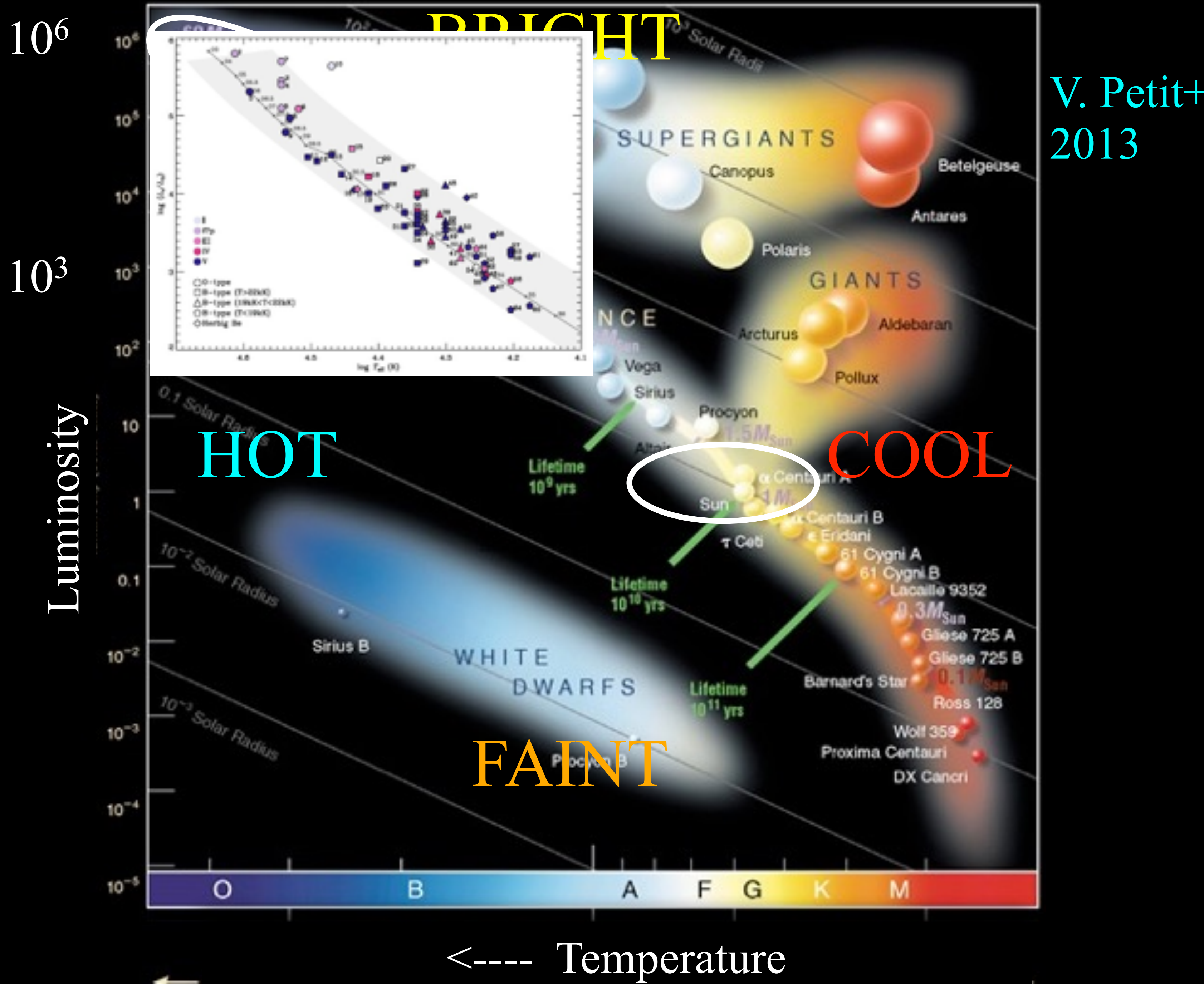
K
M



BRIGHT
V. Petit+ 2013
10^6
10^3
Luminosity
SUPERGIANTS
Canopus
Betelgeuse
Antares
Polaris
GIANTS
Aldebaran
Arcturus
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Lifetime 10^9 yrs
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0.1 Solar Radius
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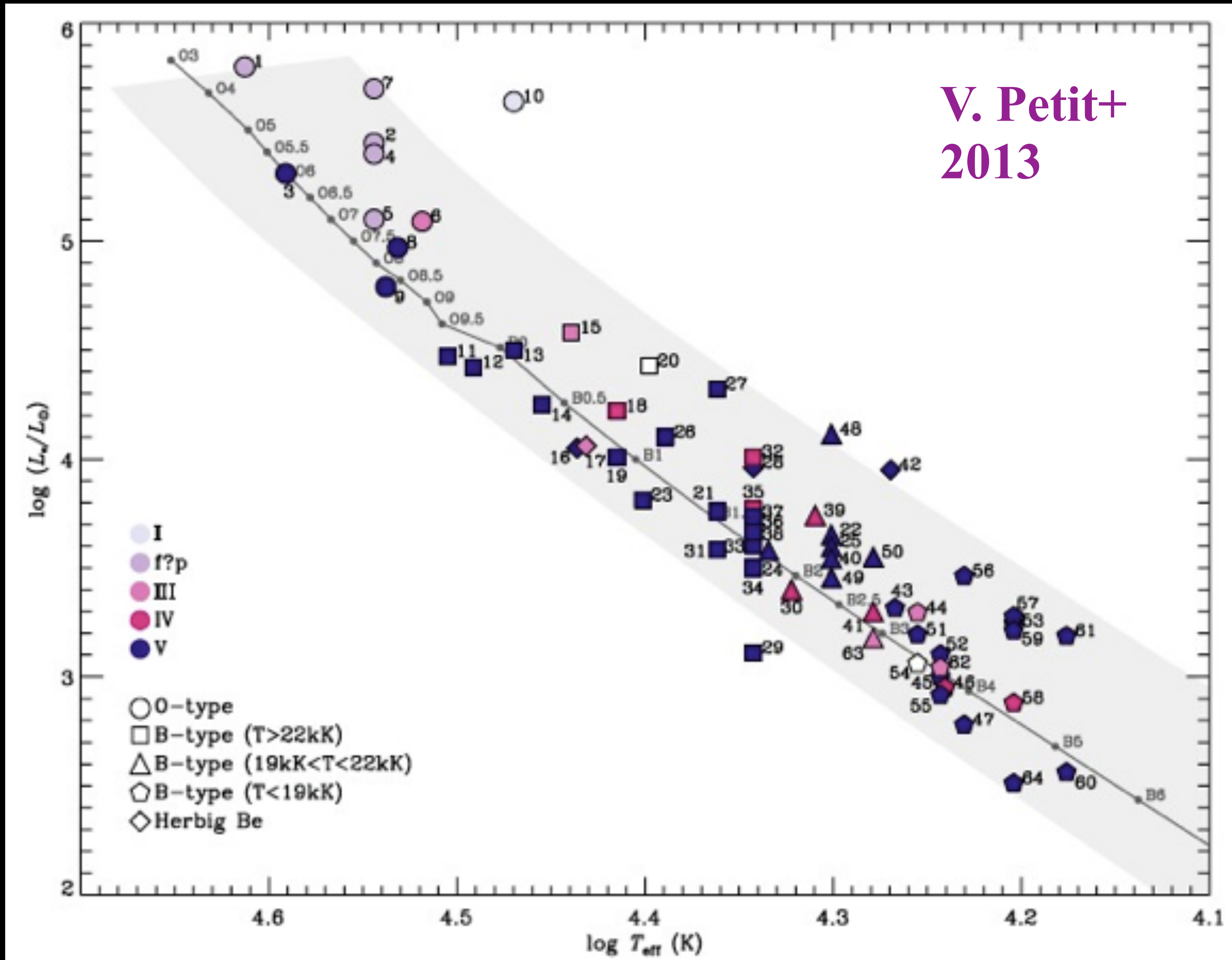
10^-3 Solar Radius
10^3 Solar Radii
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
O
B
A
F
G
K
M
<---- Temperature

64 Confirmed Magnetic Massive Stars

10^6

Luminosity

10^3



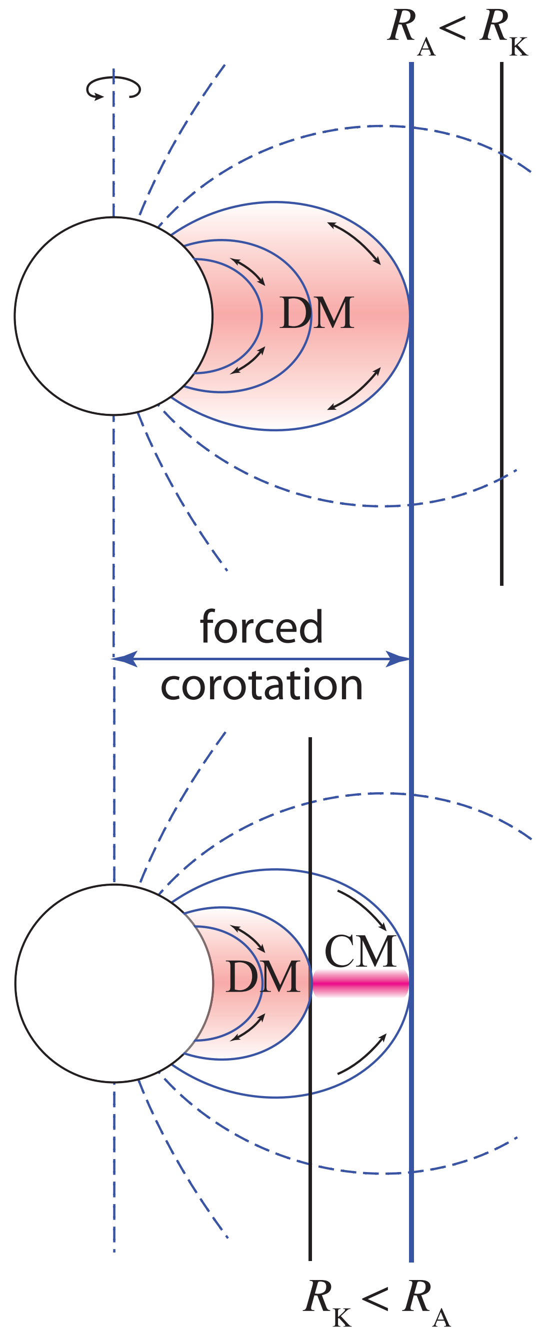
<---- Temperature

Key differences between hot vs. cool star winds and magnetospheres

- hot stars have cool winds, $T \sim T_{eff}$; no hot coronae
  - driven by radiation not gas pressure
  - become supersonic near surface R_*
  - closed loops not hydrostatic,
  - supersonic upflow leads to shocks near loop apex
- some hot stars have rapid rotation
  - lead to centrifugally supported magnetospheres
- field is large-scale, and stable
  - fossil, not from dynamo activity cycle

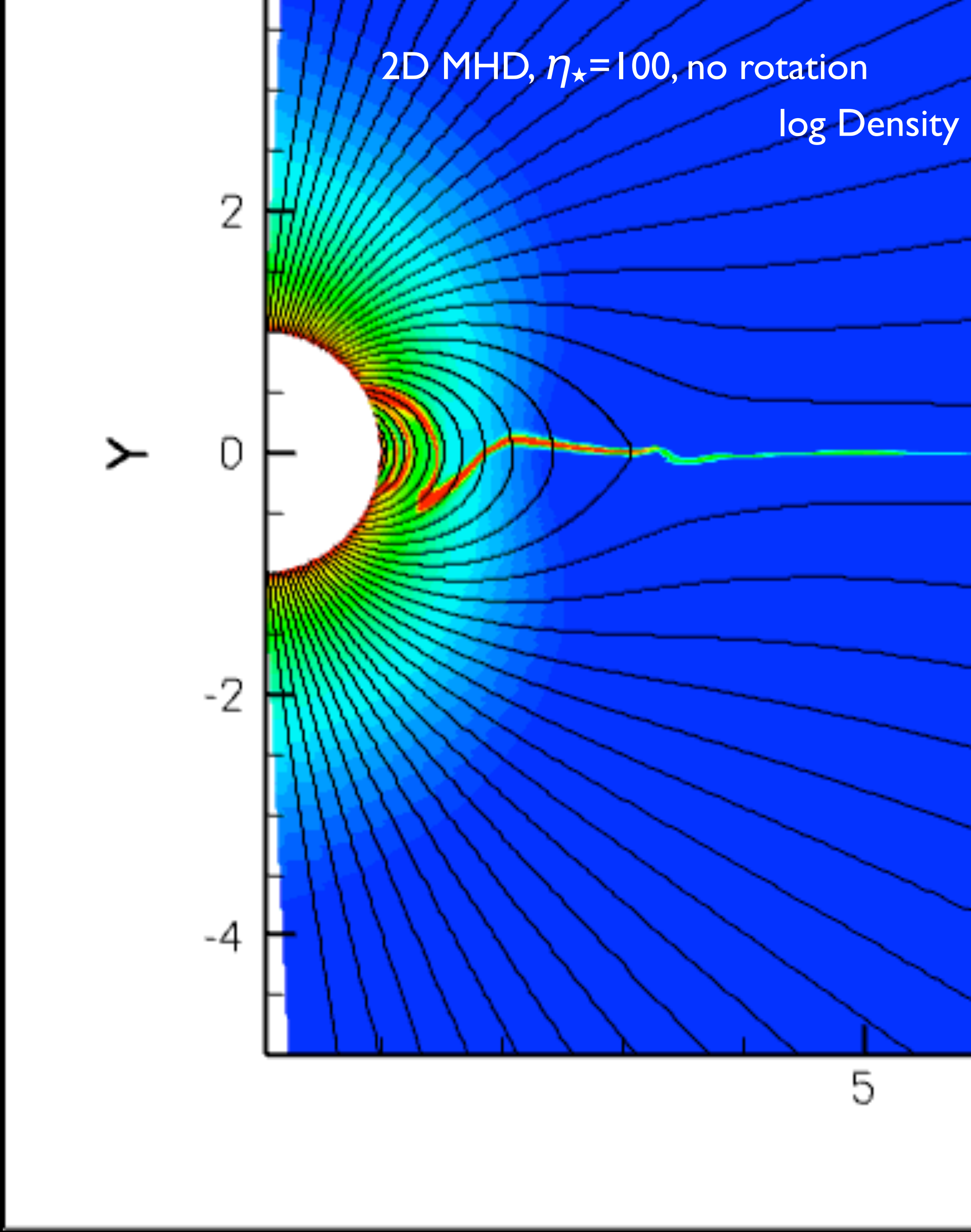
Dynamical Magnetospheres $R_A < R_K$

Centrifugal Magnetospheres $R_K < R_A$



Magnetic confinement

$$\eta = \frac{B^2/8\pi}{\rho v^2/2}$$



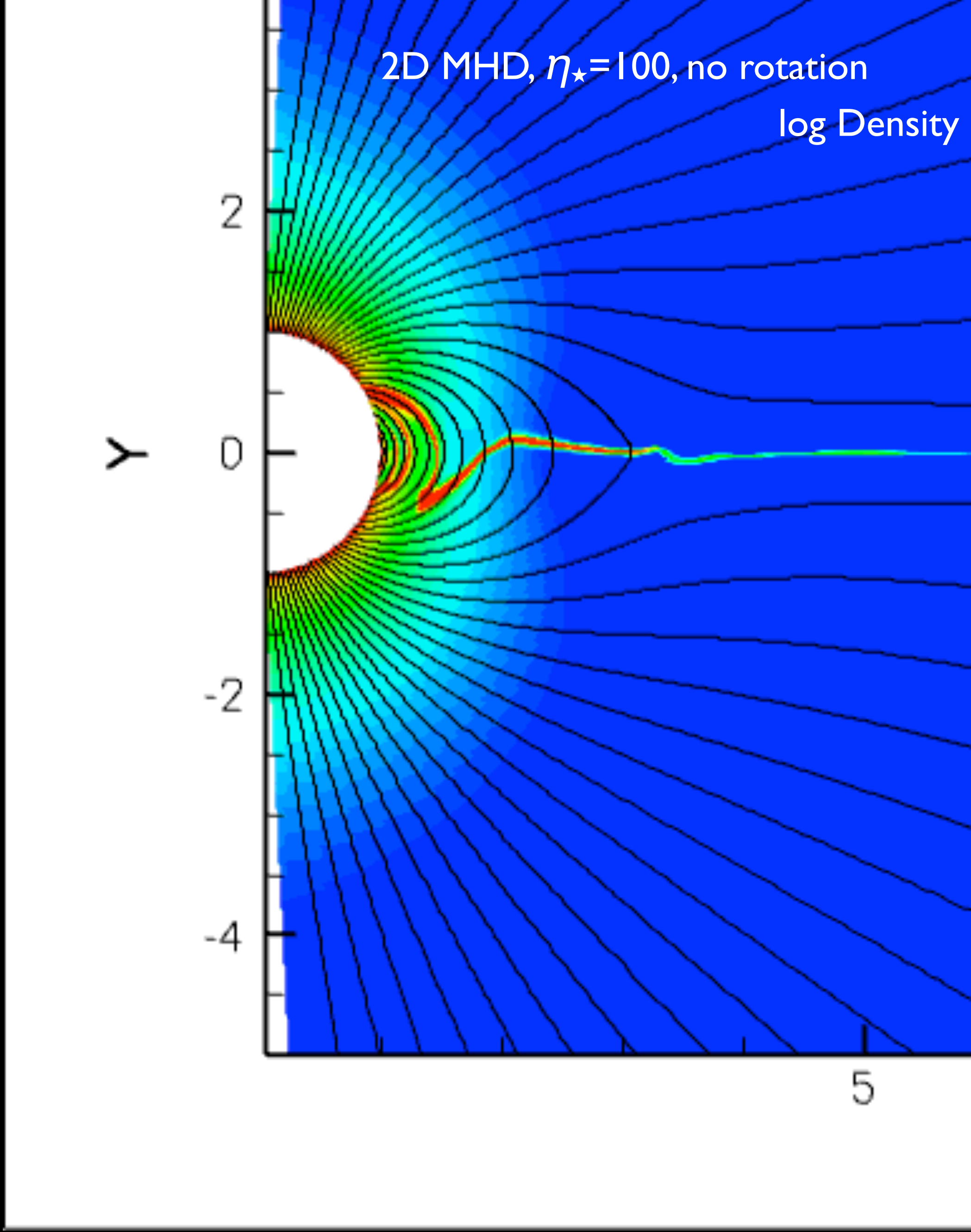
ud Doula+ 2008

Magnetic confinement

$$\eta = \frac{B^2/8\pi}{\rho v^2/2}$$

$$\eta(R_{\rm A}) \equiv 1$$

Alfven radius



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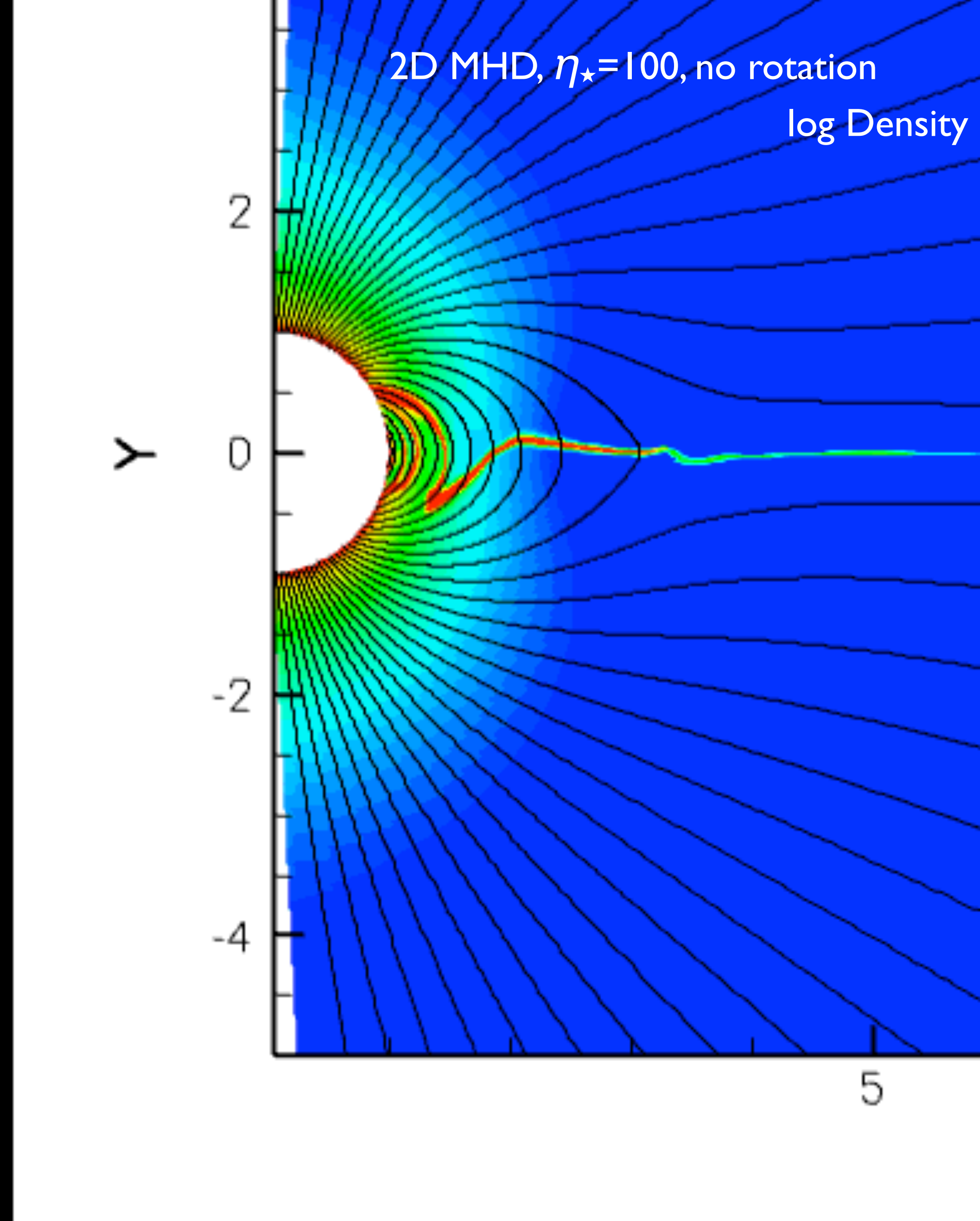
$$\eta_\star \equiv \frac{B_\star^2\, R_\star^2}{\dot{M}\, v_\infty}$$



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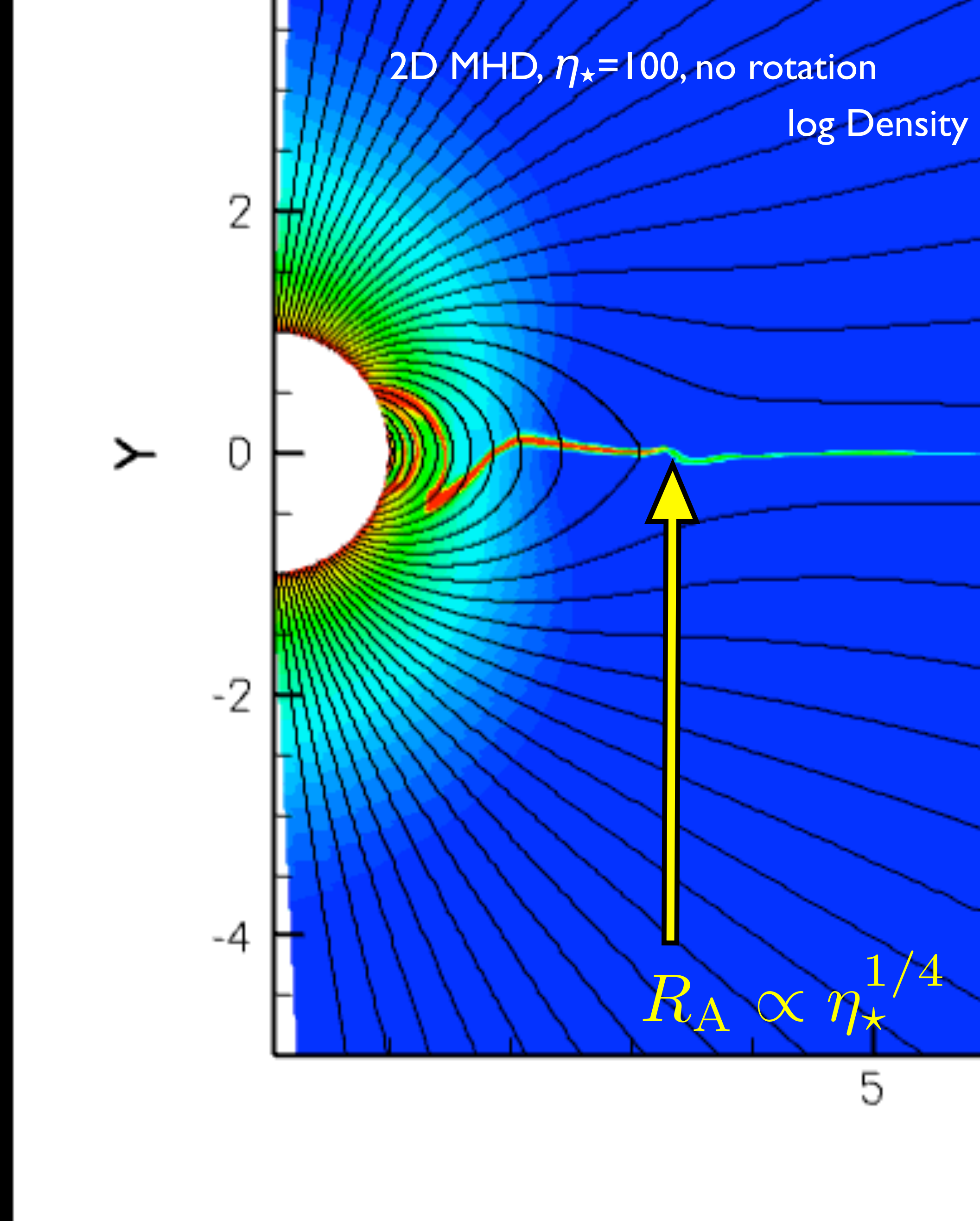

ud Doula+ 2008

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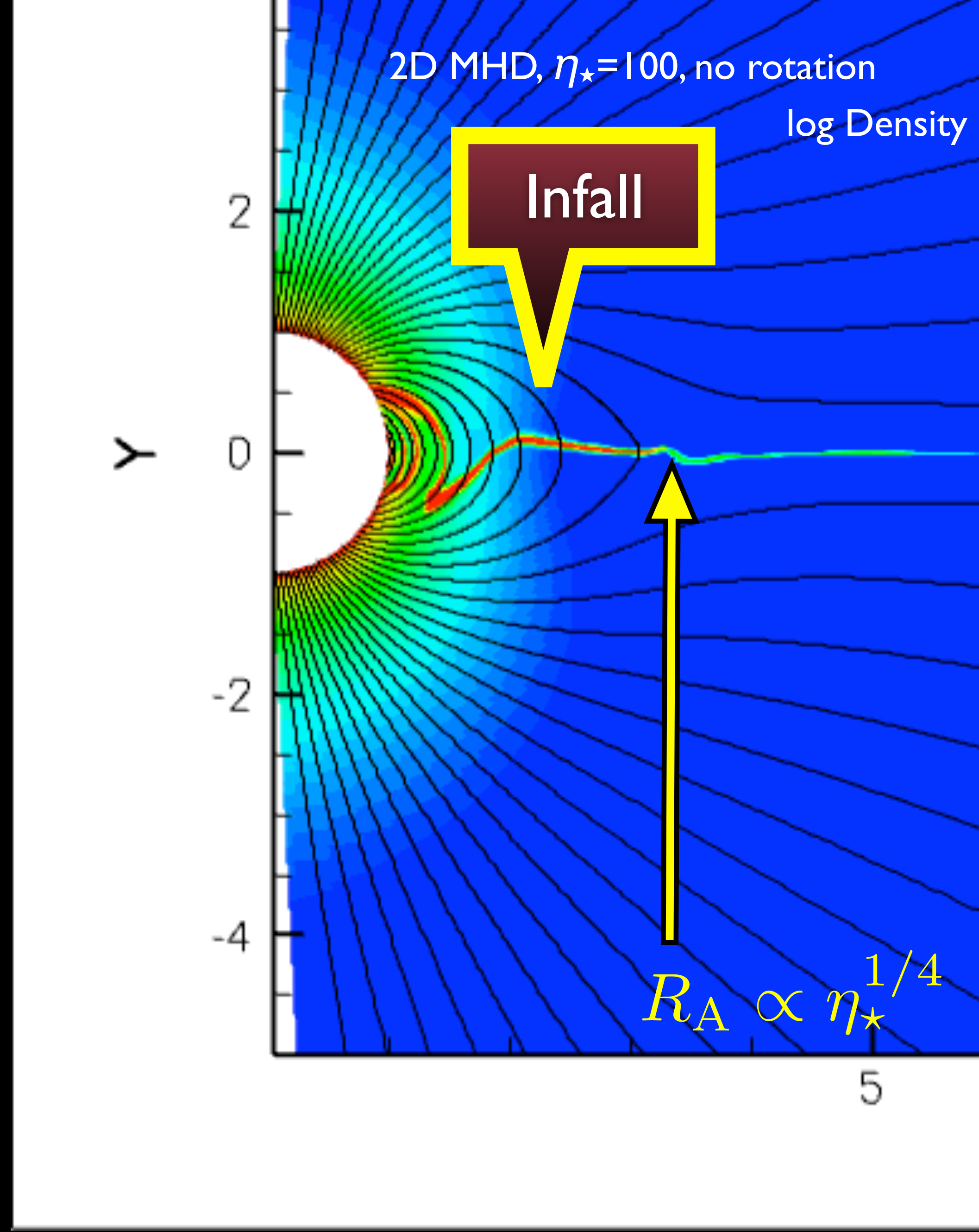
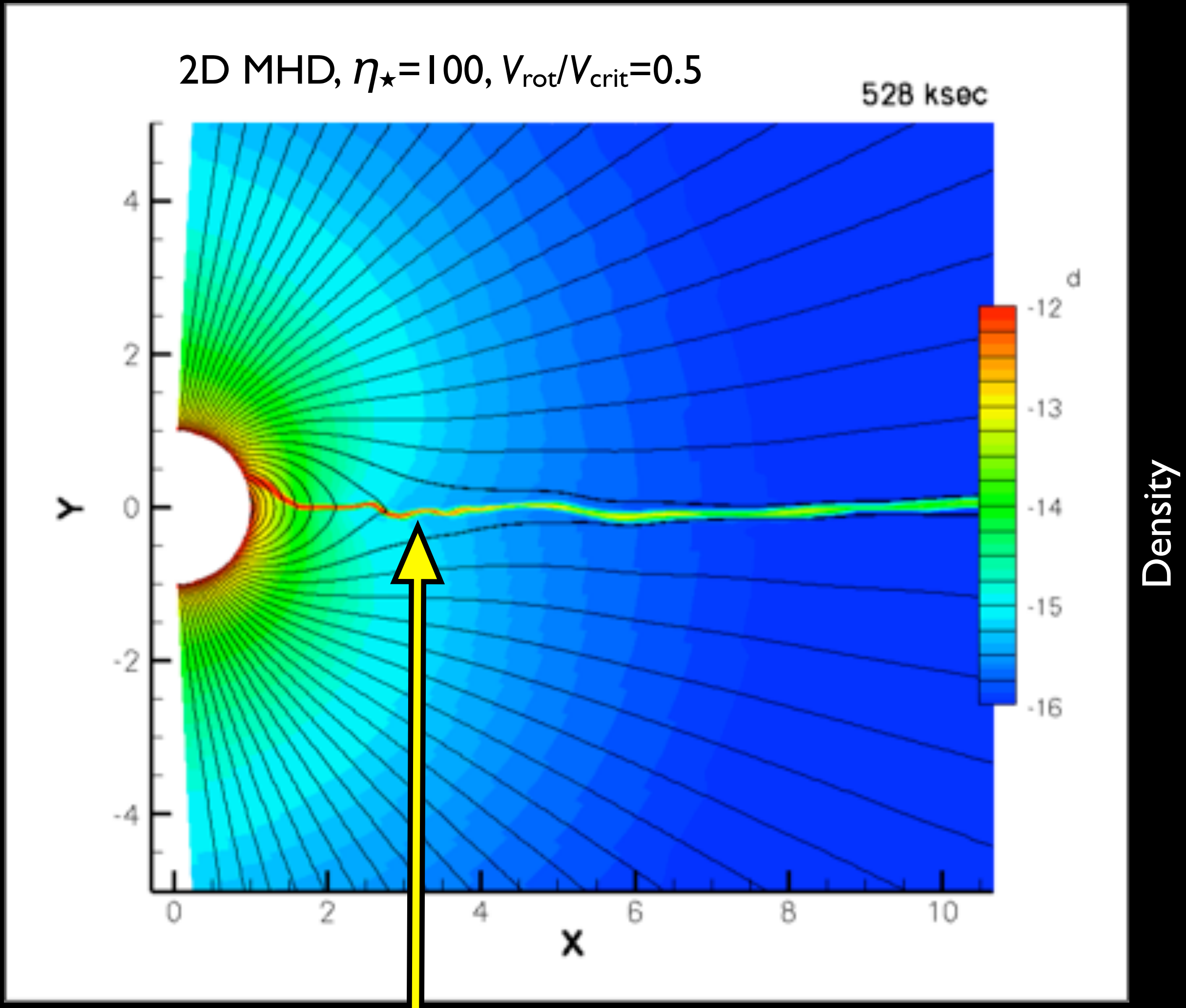


ud Doula+ 2008

Centrifugal support

$$W = \frac{V_{rot}}{V_{crit}}$$

$$\frac{R_K}{R_*} \equiv W^{-2/3}$$



$R_A \propto \eta_\star^{1/4}$

ud Doula+. 2008

Centrifugal support

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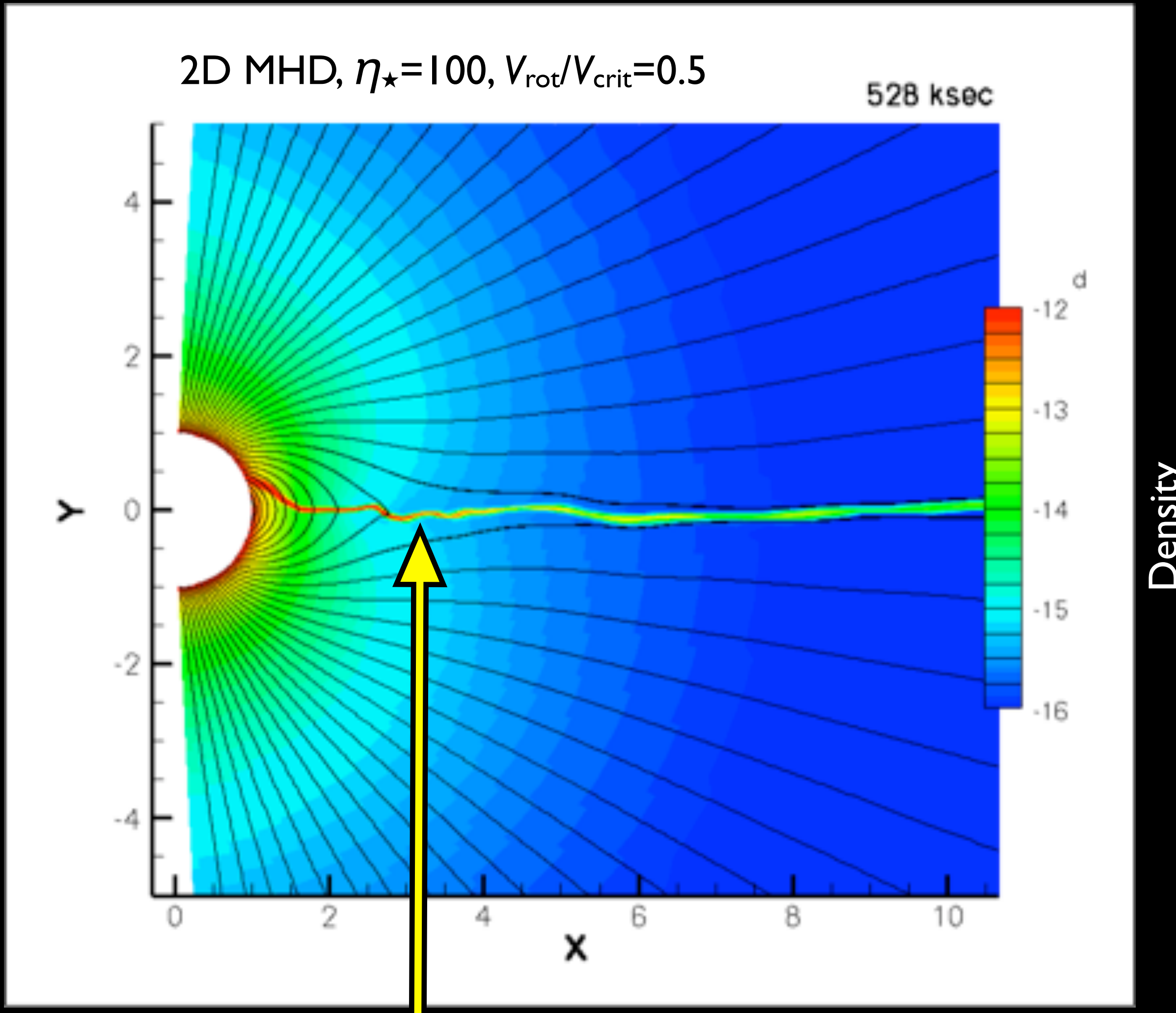
$$\frac{R_K}{R_*} \equiv W^{-2/3}$$

Kepler radius



$$R_{\rm A} \propto \eta_\star^{1/4}$$

ud Doula+. 2008

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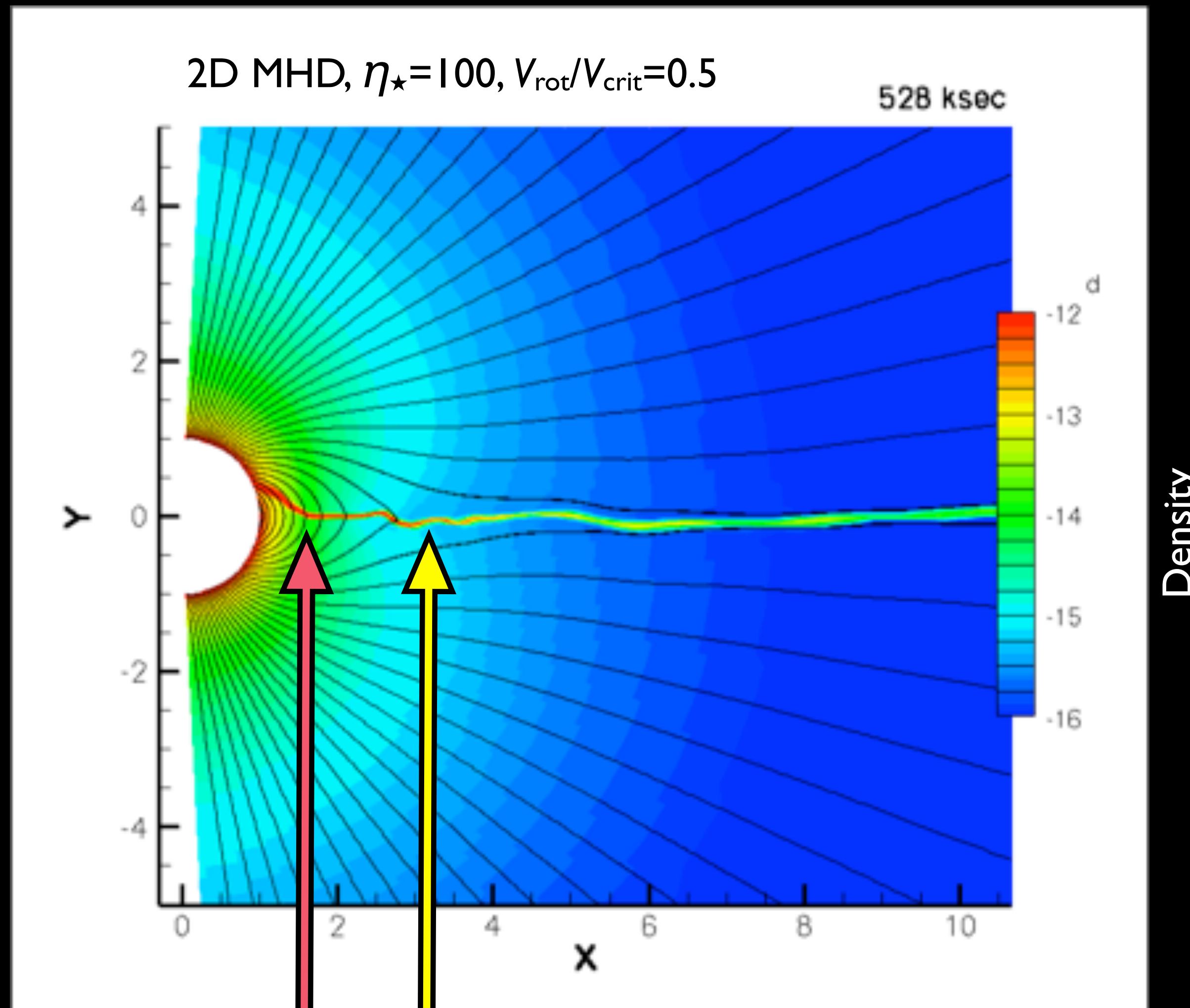

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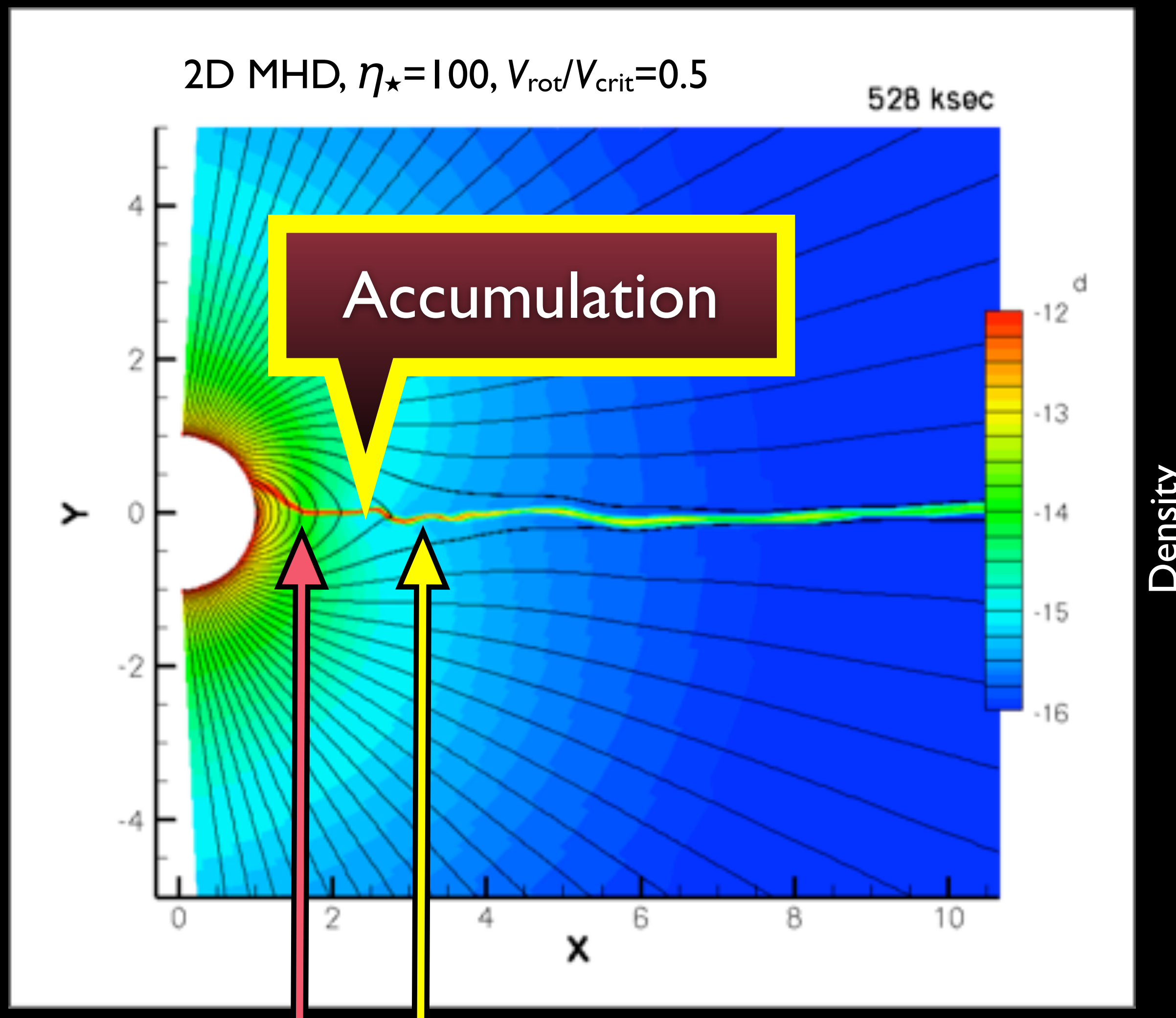

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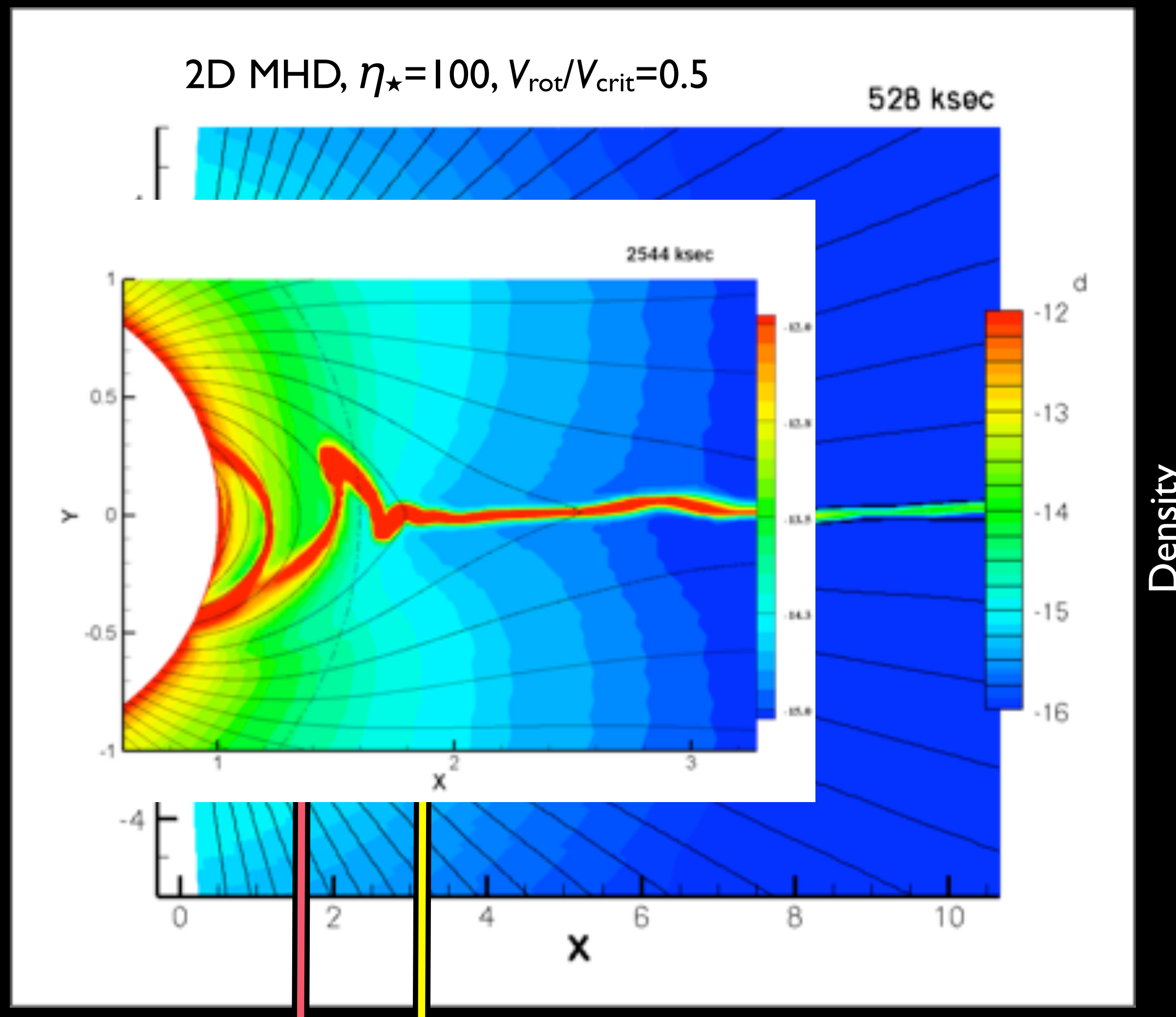
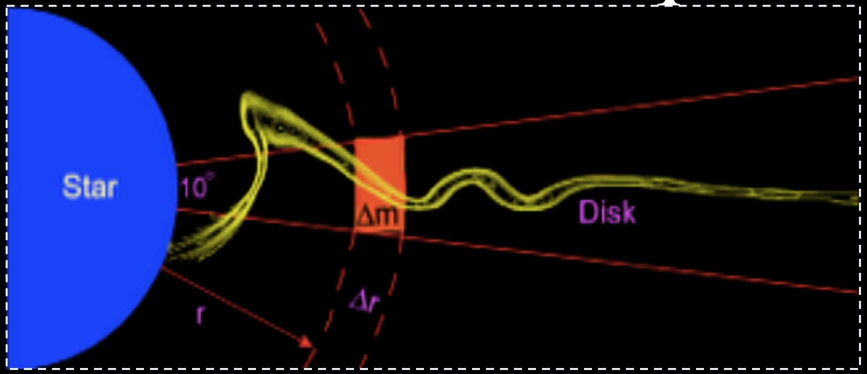


R_K $R_A \propto \eta_\star^{1/4}$

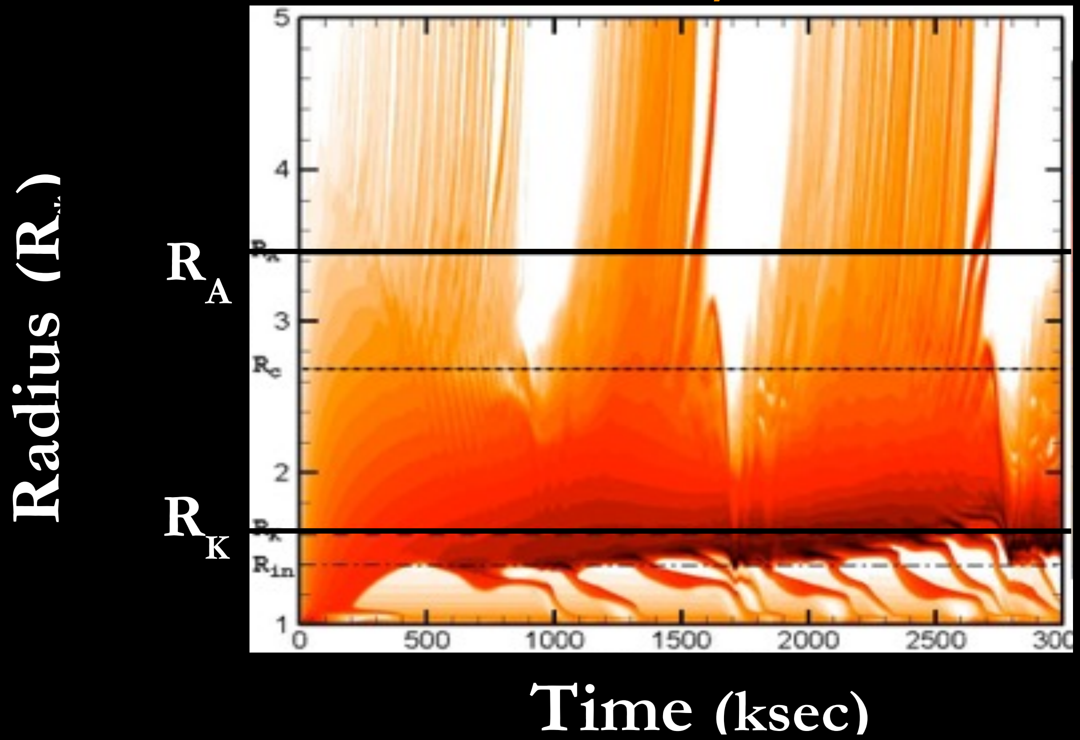
ud Doula+. 2008

Radial Distribution of Equatorial Mass



ud-Doula+ 2008

Δm/Δr



$\eta_* = 100$

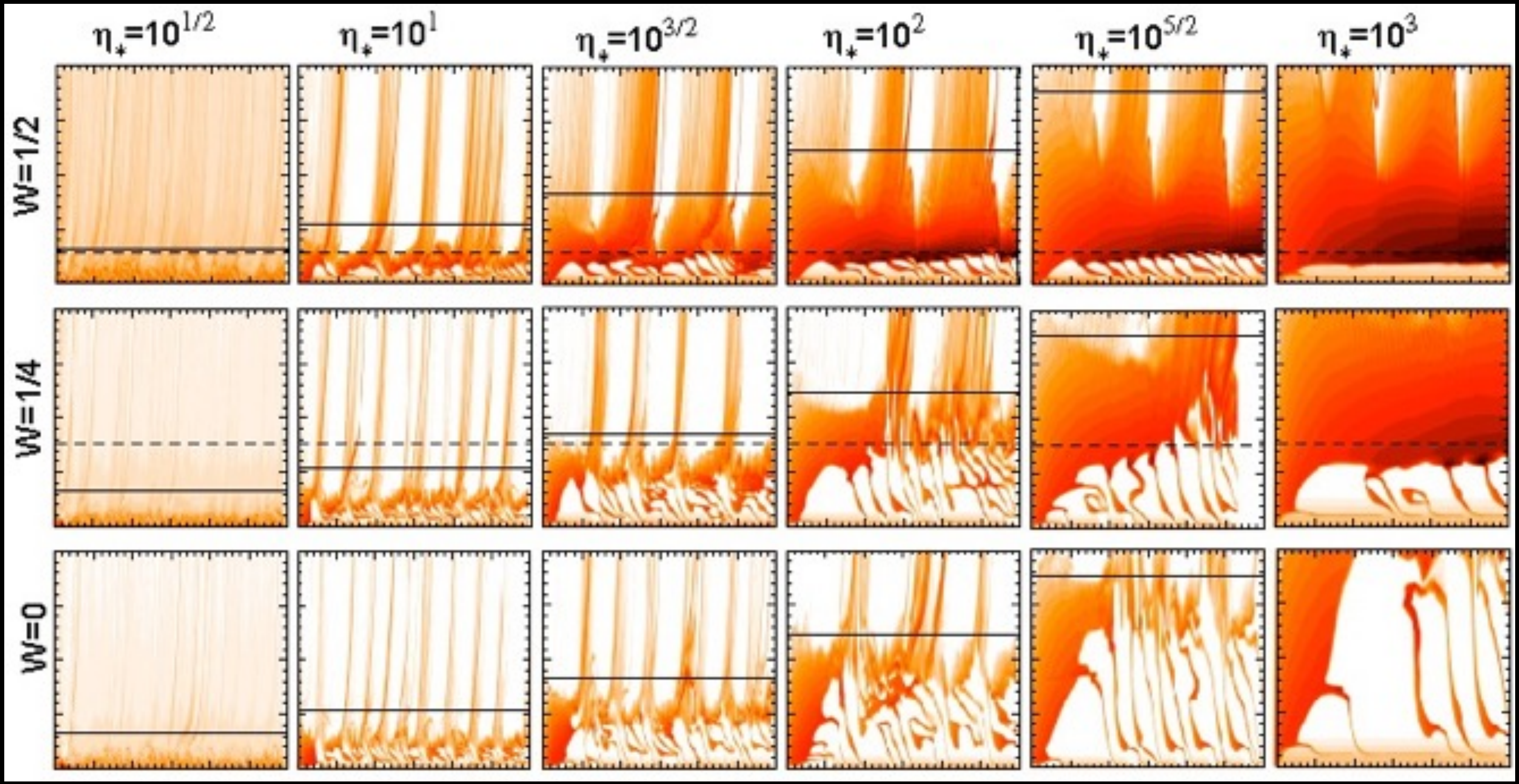
$V_{rot}/V_{crit} = 1/2$

ud-Doula+ 2008

Δm/Δr (r,t) for various W, η_*

r=1-5

More Rapid Rotation --->



t=0-3 Msec

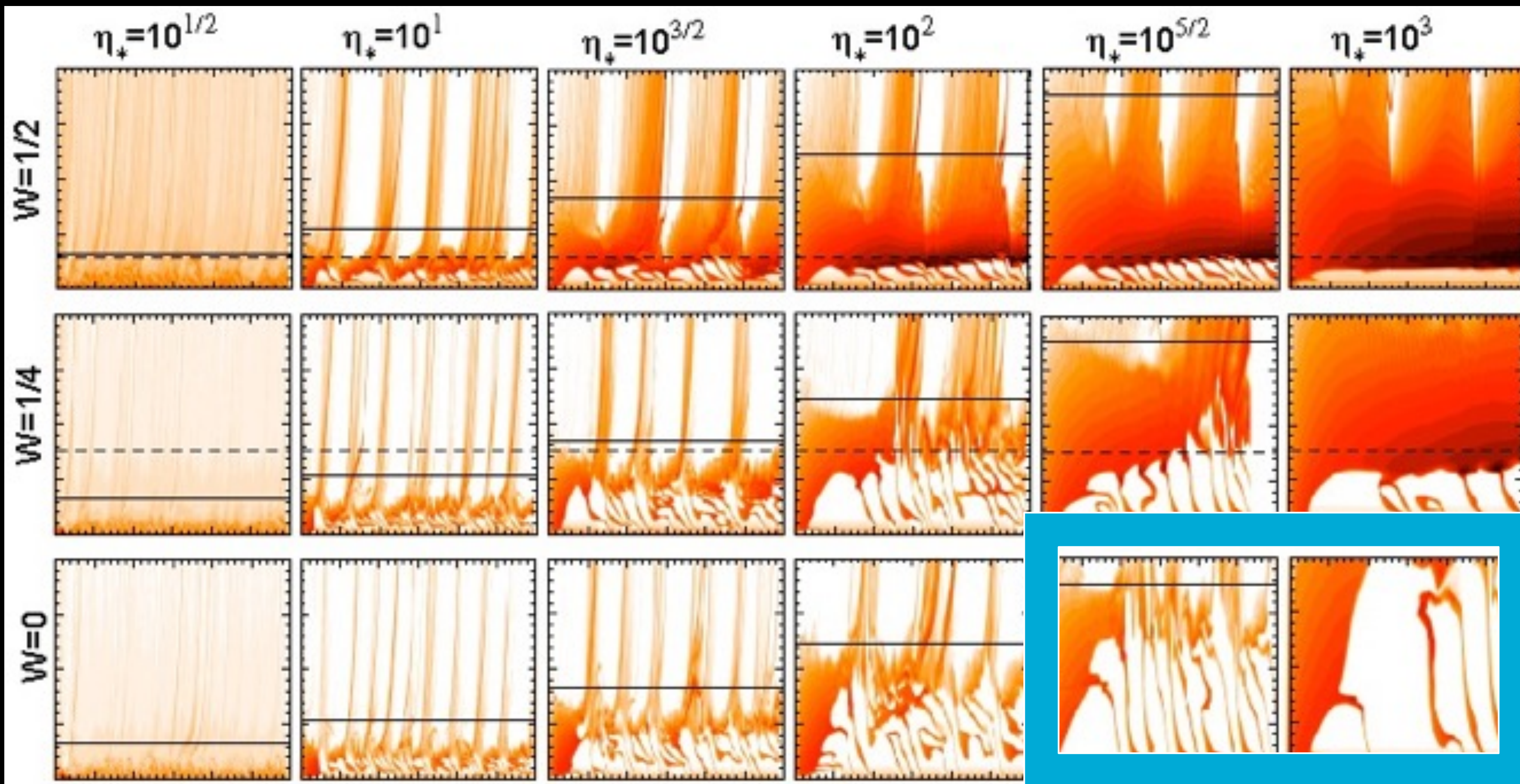
Stronger Magnetic Confinement --->

$\Delta m/\Delta r$ (r,t) for various W, η_*

ud-Doula+ 2008

More Rapid Rotation --->

r=1-5



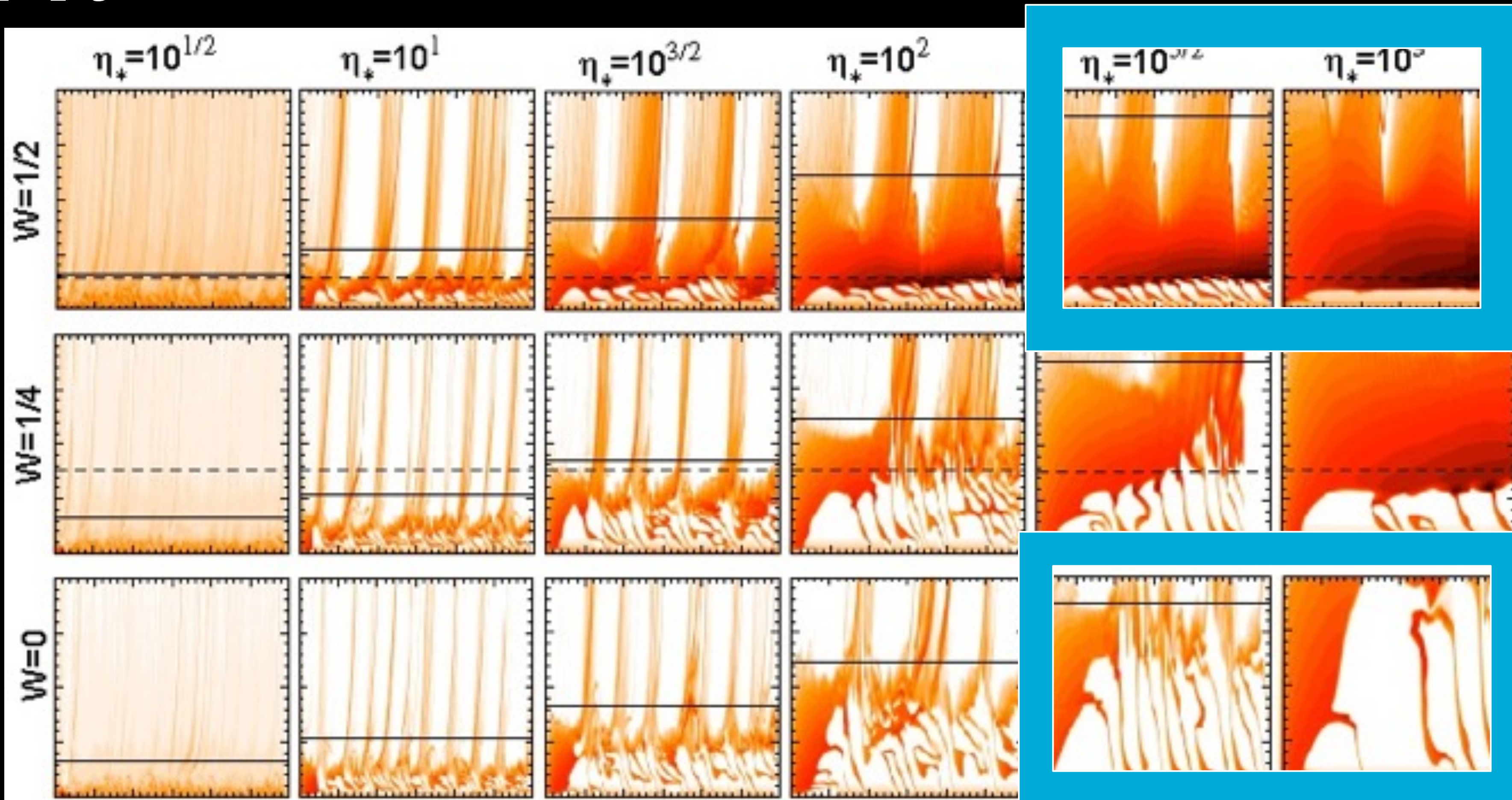
t=0-3 Msec

Dynamical

Stronger Magnetic Confinement --->

ud-Doula+ 2008

Δm/Δr (r,t) for various W, η_*

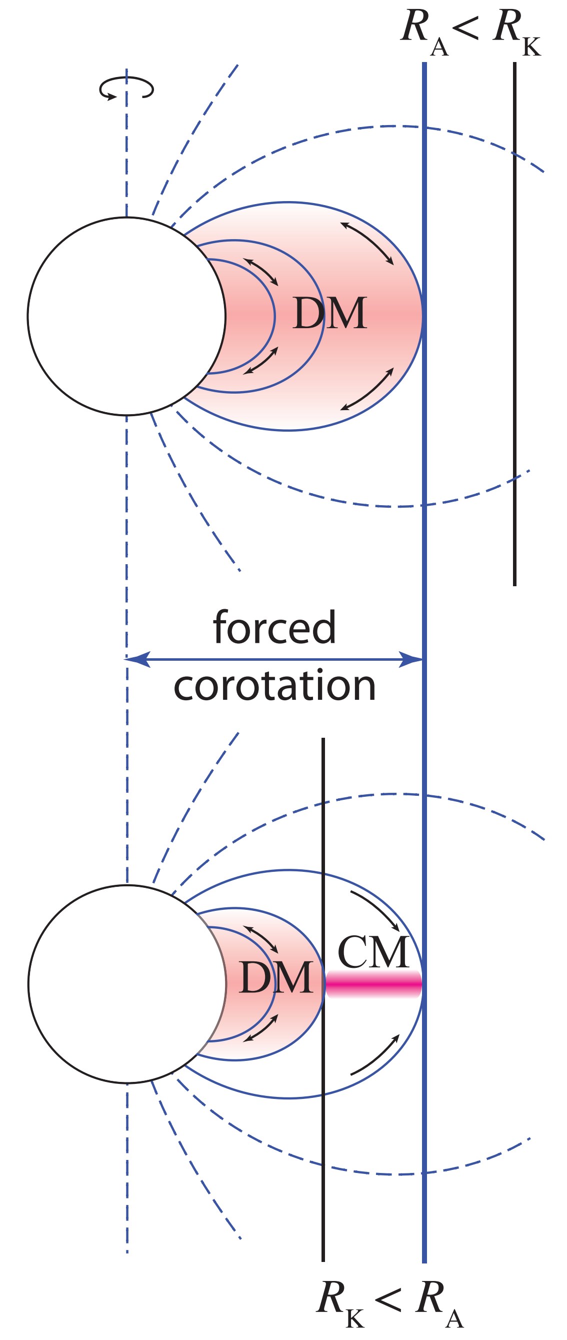


More Rapid Rotation --->

Stronger Magnetic Confinement --->

Dynamical Magnetospheres
$R_A < R_K$

Centrifugal Magnetospheres
$R_K < R_A$

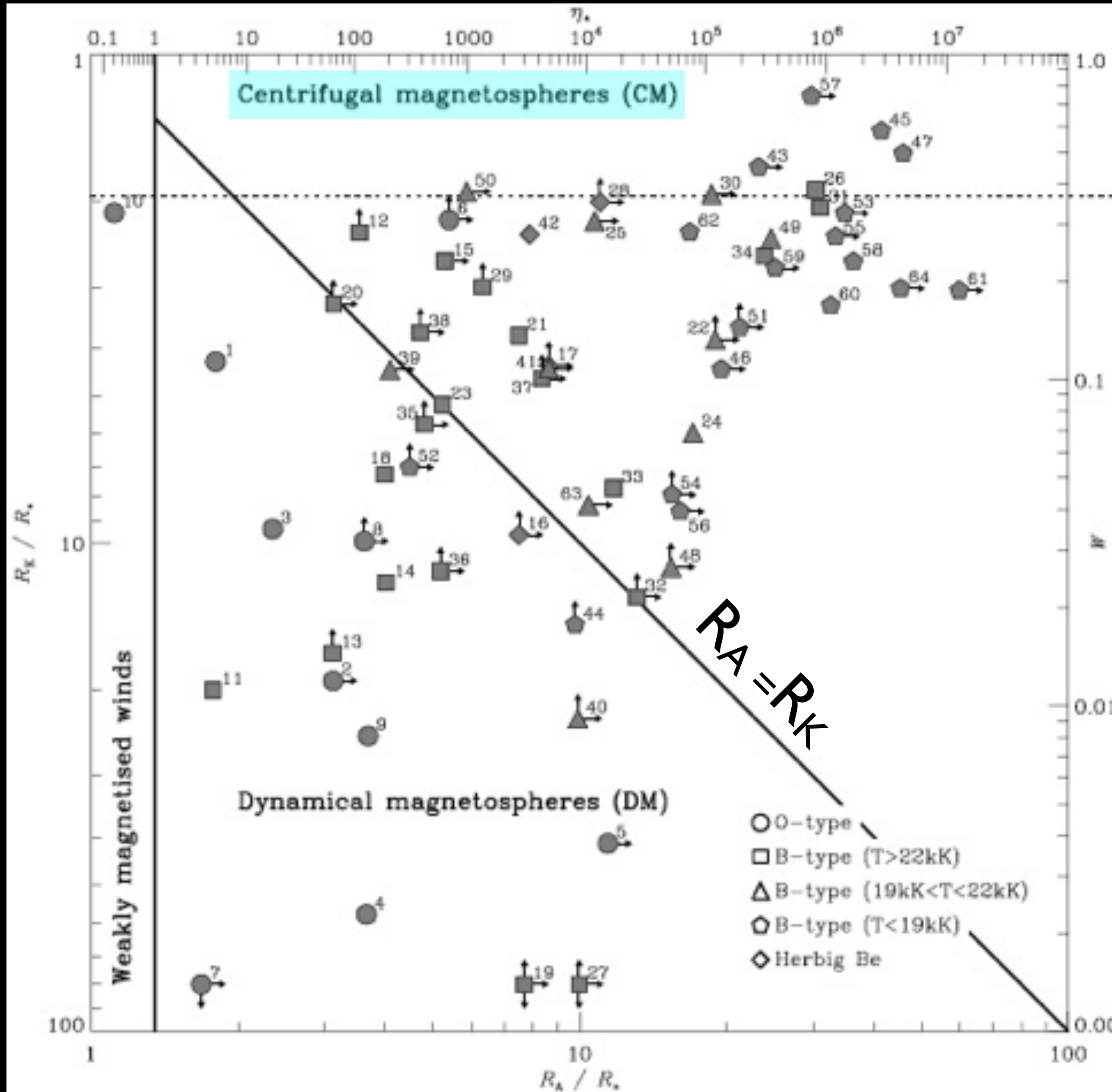


V. Petit+ 2013

Fast rot.

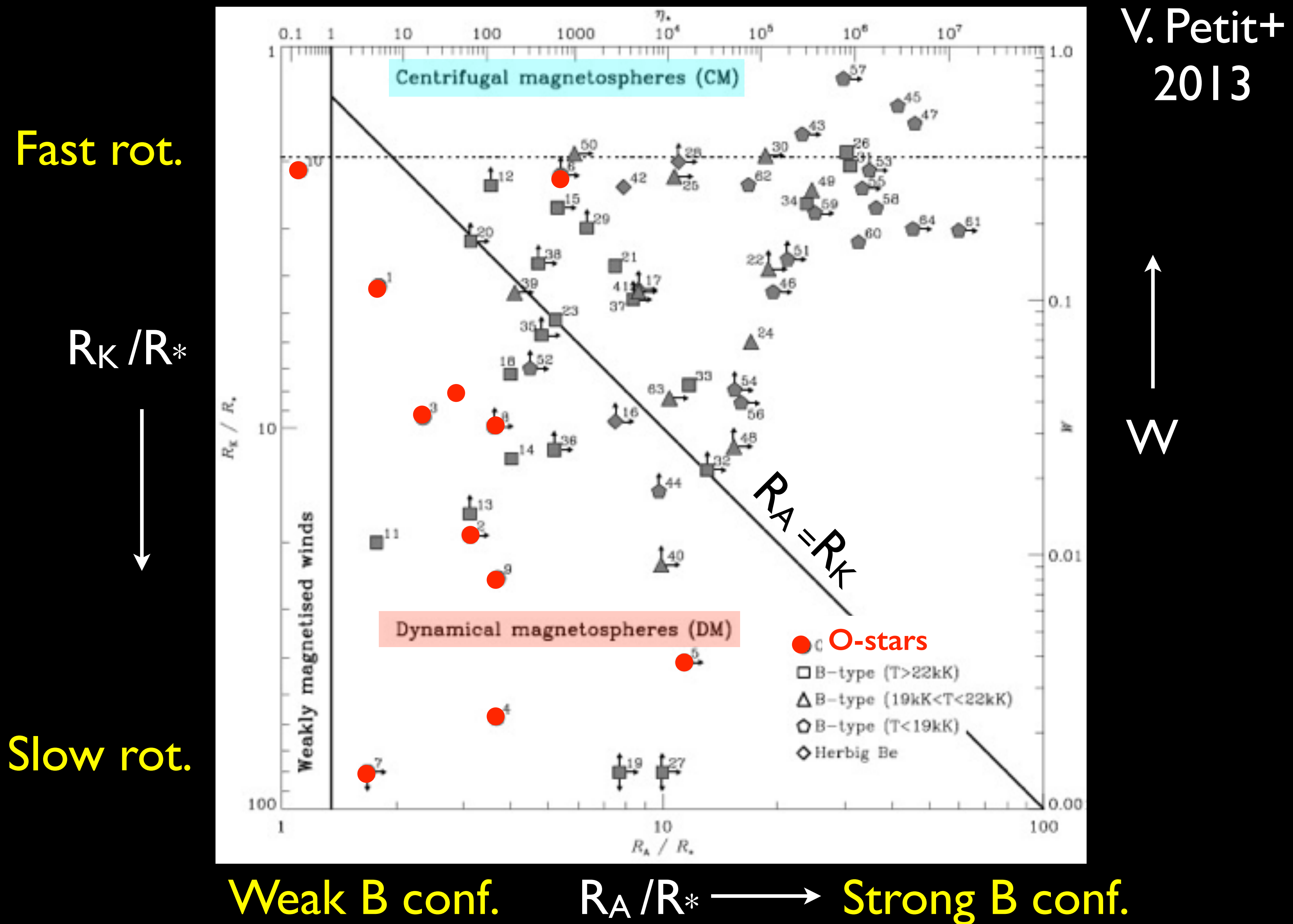
R_K / R_*

Slow rot.



W

Weak B conf. R_A / R_* → Strong B conf.

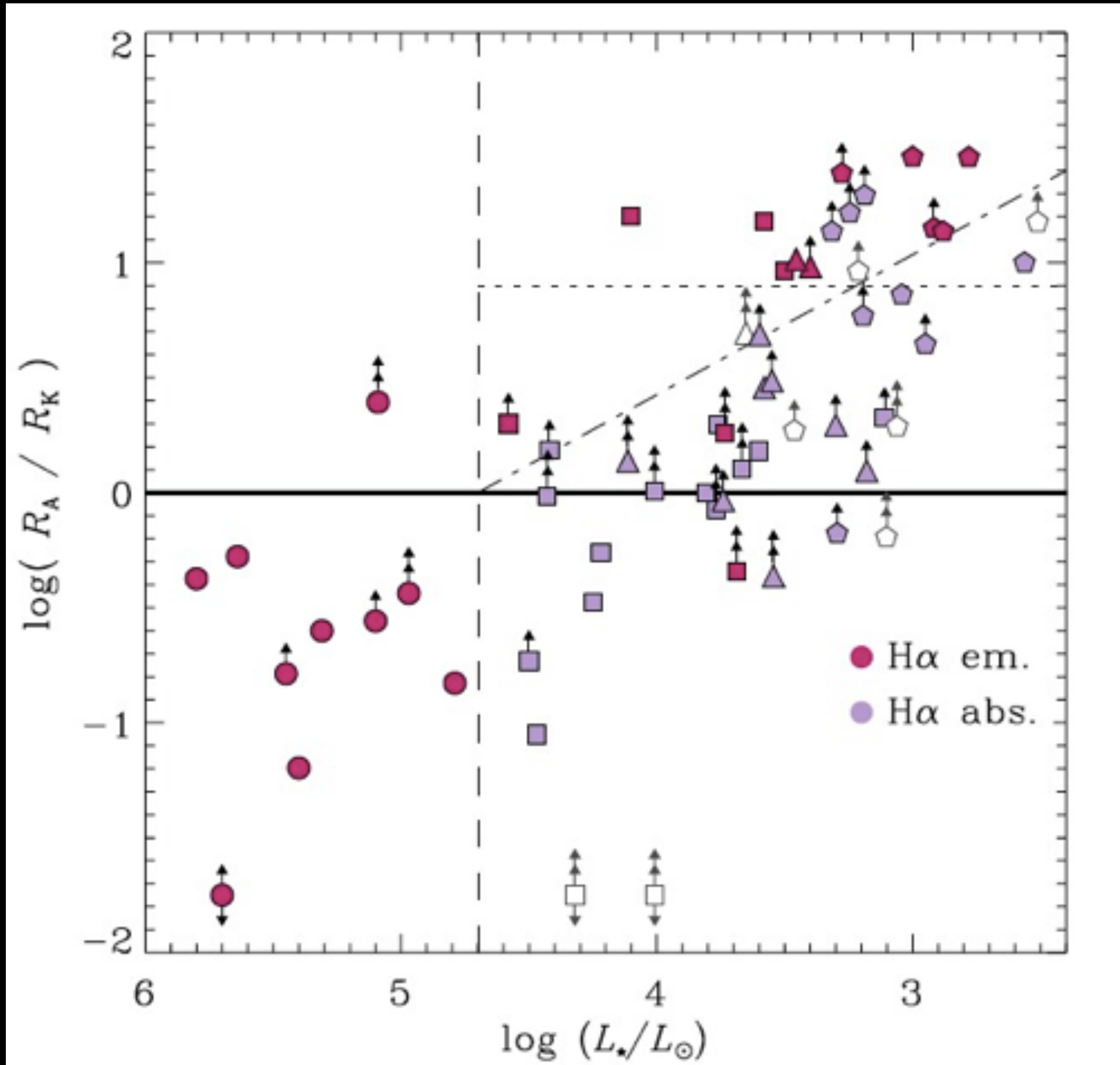

V. Petit+ 2013
Fast rot.
Slow rot.
RK /R*
W
Weak B conf.
RA /R*
Strong B conf.
Centrifugal magnetospheres (CM)
Dynamical magnetospheres (DM)
Weakly magnetised winds
RA =RK
O-stars
B-type (T>22kK)
B-type (19kK<T<22kK)
B-type (T<19kK)
Herbig Be

V. Petit+ 2013

Fast rot. CM's

Slow rot. DM's

R_A / R_K



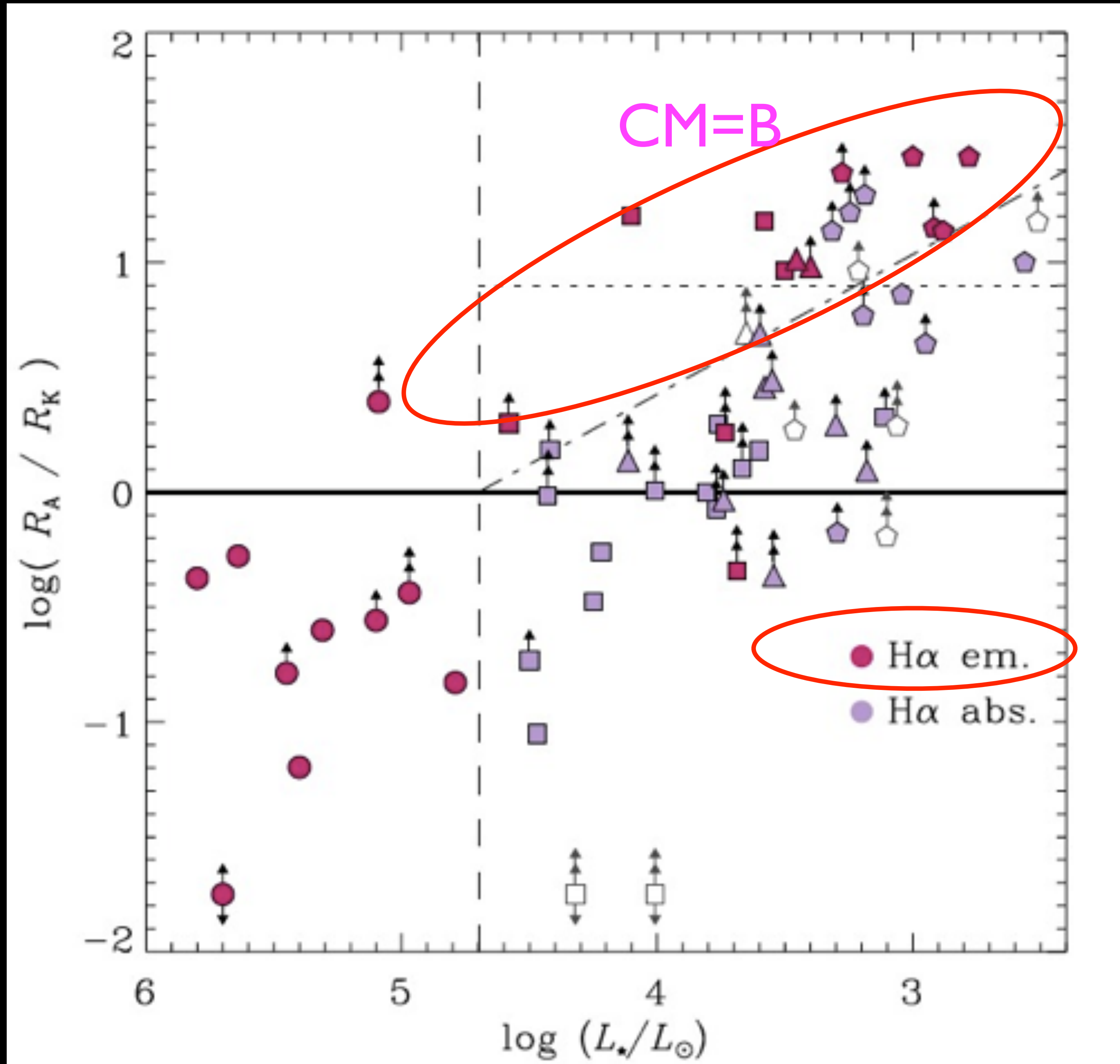
O-stars ← Luminosity Bstars

V. Petit+ 2013

Fast rot. CM's

R_A / R_K

Slow rot. DM's



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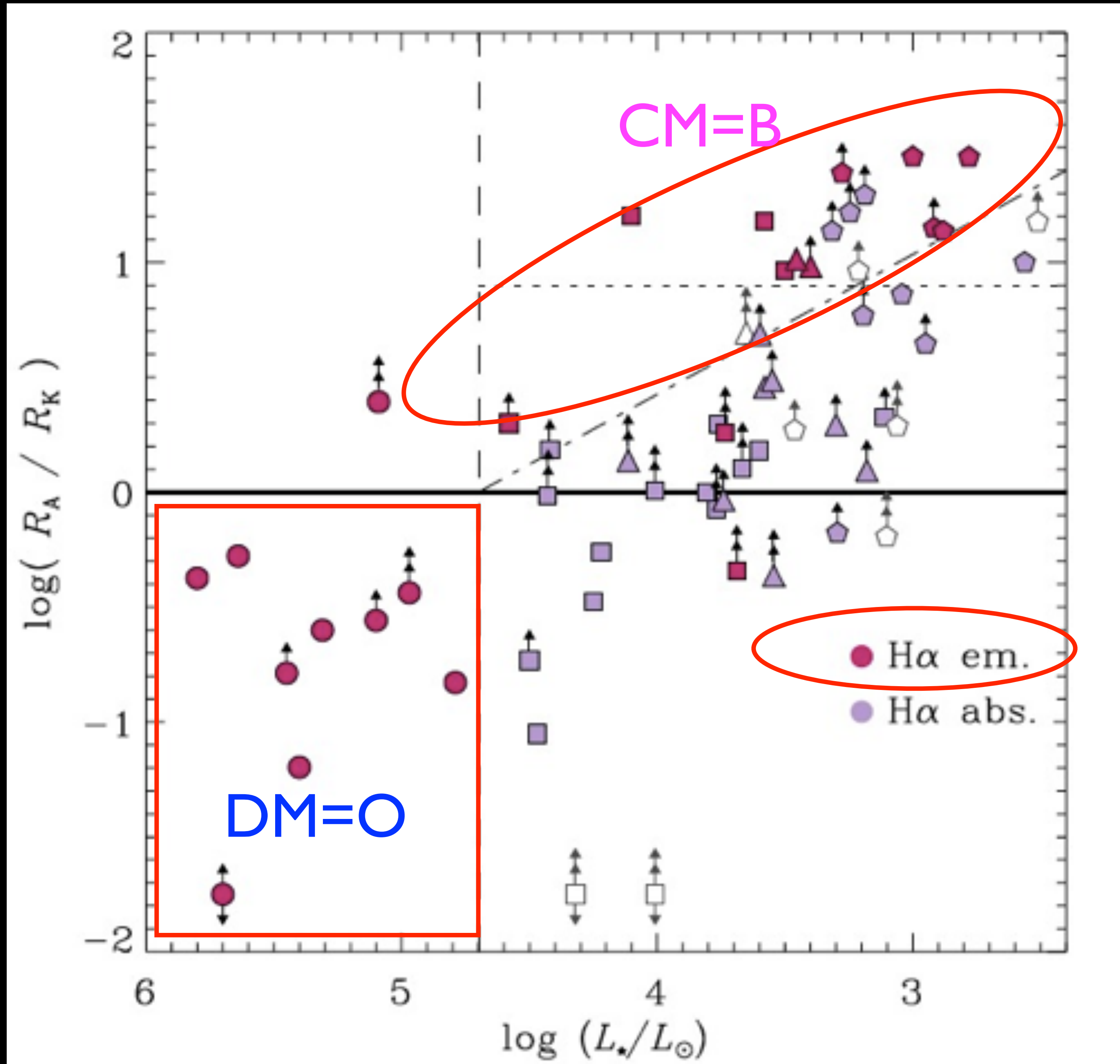
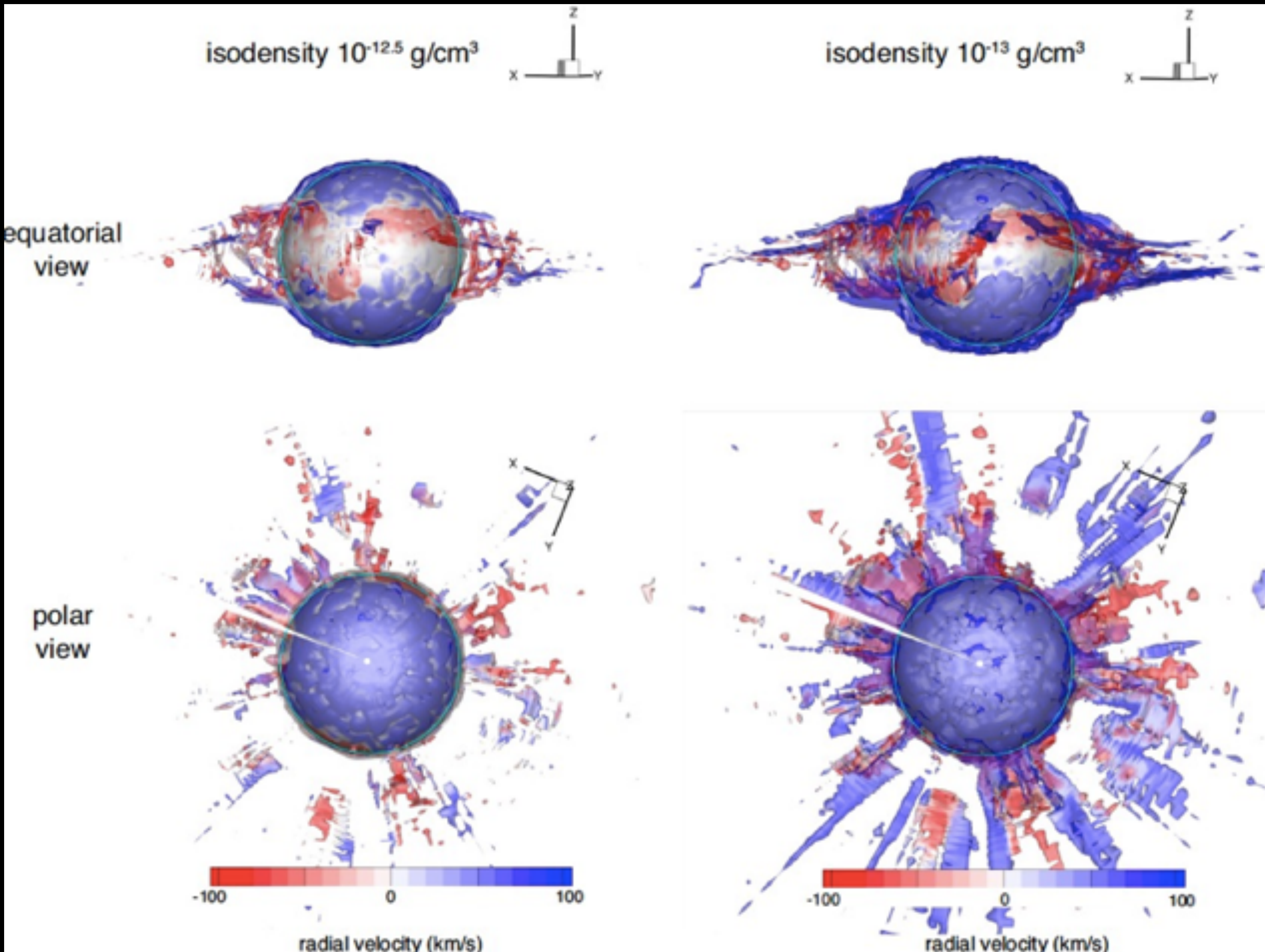
R_A / R_K

Slow rot. DM's

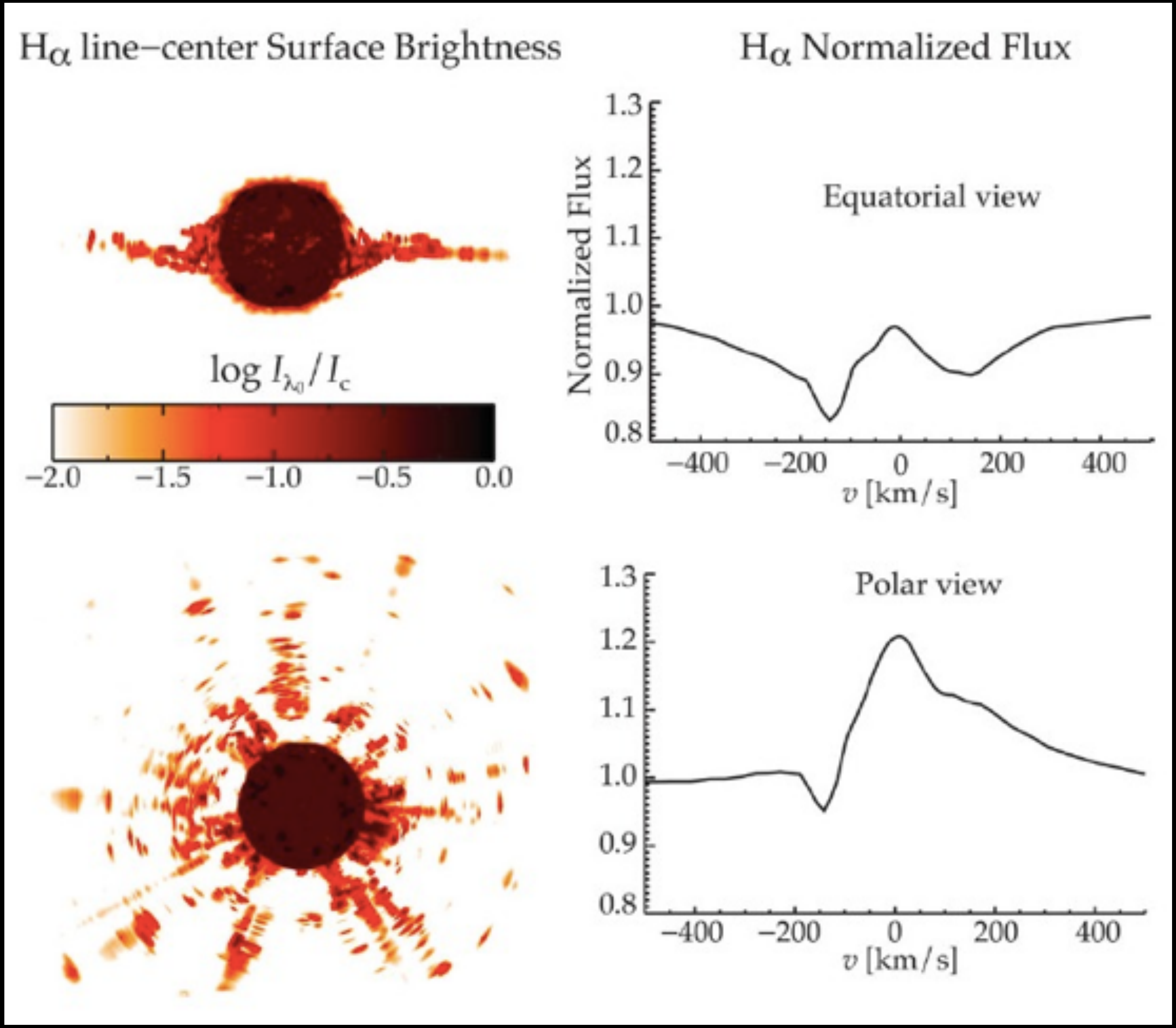


O-stars ← Luminosity Bstars

3D MHD sim of DM



3D sim of DM



H_α line−center Surface Brightness
H_α Normalized Flux
log I_{λ_0}/I_c
−2.0
−1.5
−1.0
−0.5
0.0
Equatorial view
Polar view
Normalized Flux
1.3
1.2
1.1
1.0
0.9
0.8
−400
−200
0
200
400
v [km/s]

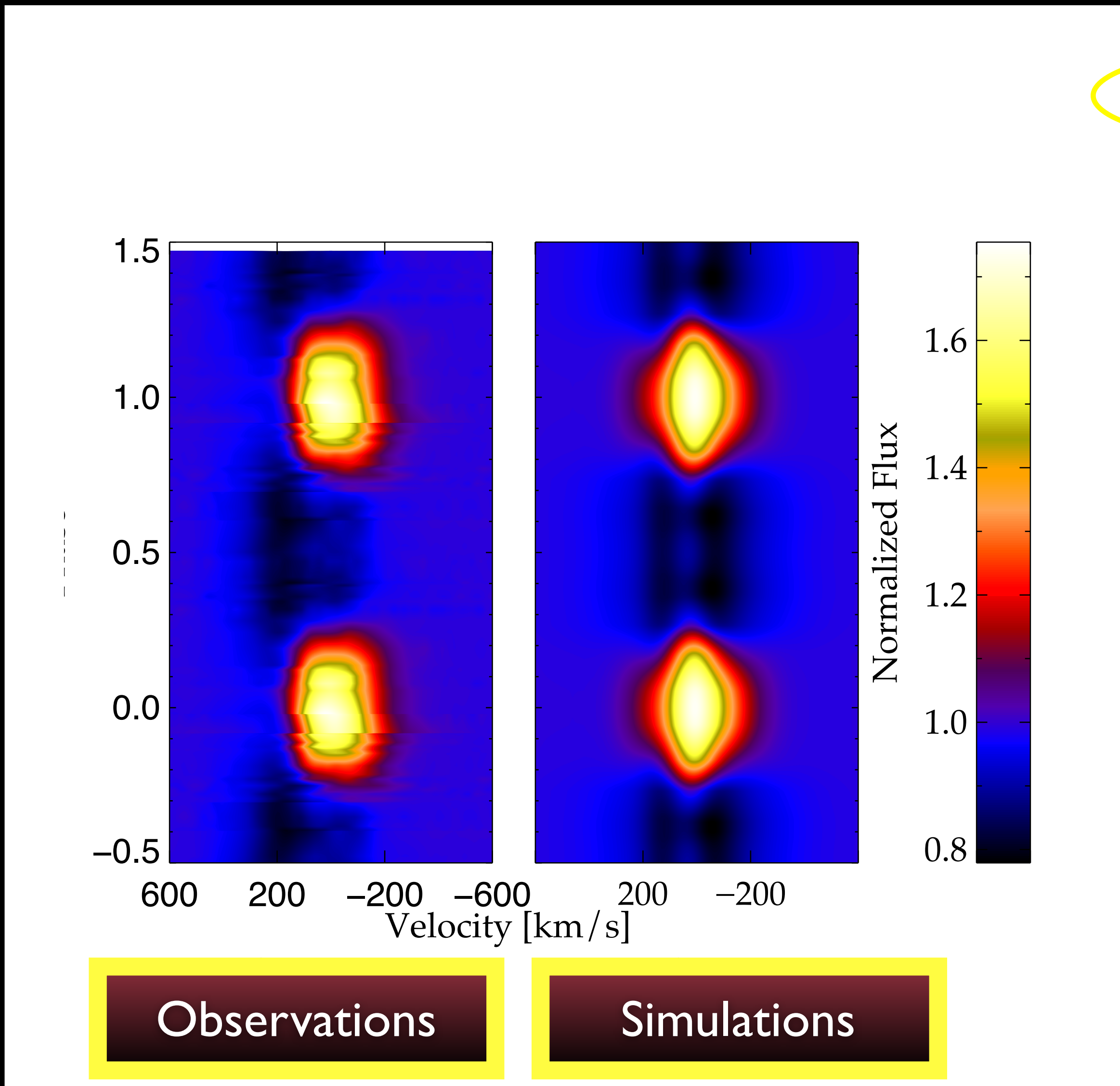
HD 191612 (Of?p)

vsini < 45 km/s

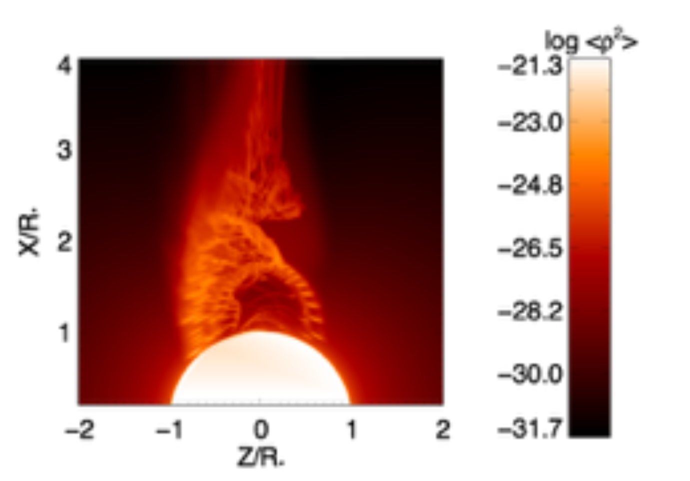
$\eta^* \sim 50$

$P_{rot} \sim 540$ d; $R_{Kep} \sim 50\ R^*$

$B_d \sim 2.5$ kG; $R_{Alf} \sim 3\ R^*$



“Dynamical” Magnetosphere



Sundqvist + 2012

RRM model for σ Ori E

$B_* \sim 10^4$ G

$\eta_* \sim 10^6$

$W \sim 0.5$

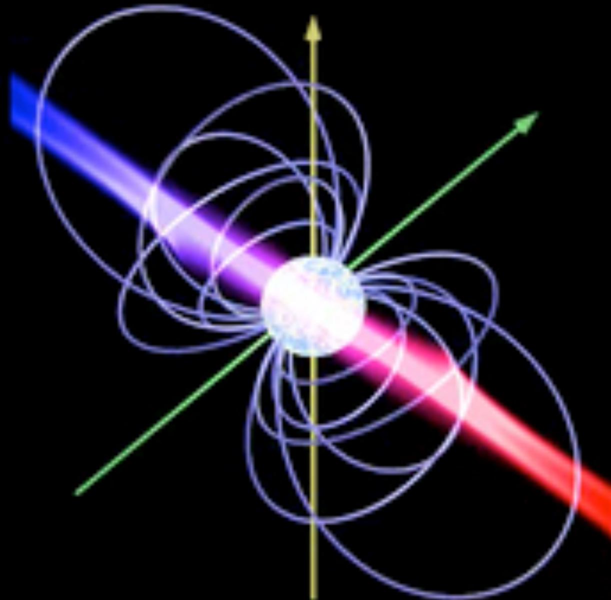
$R_K \sim 1.7 R_*$

<<

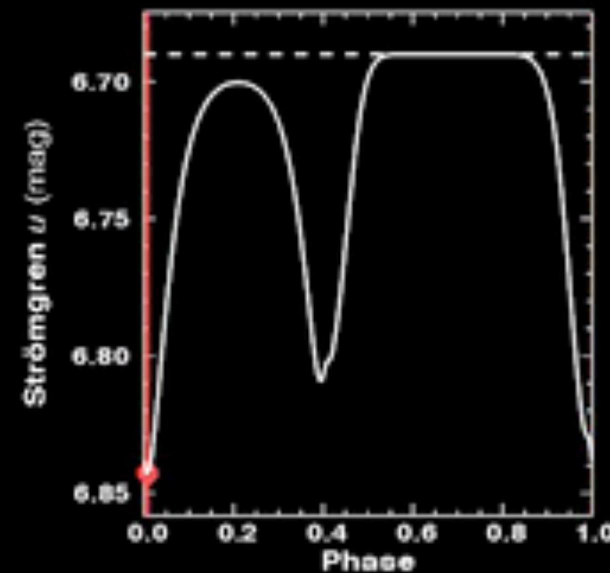
$R_A \sim 30 R_*$

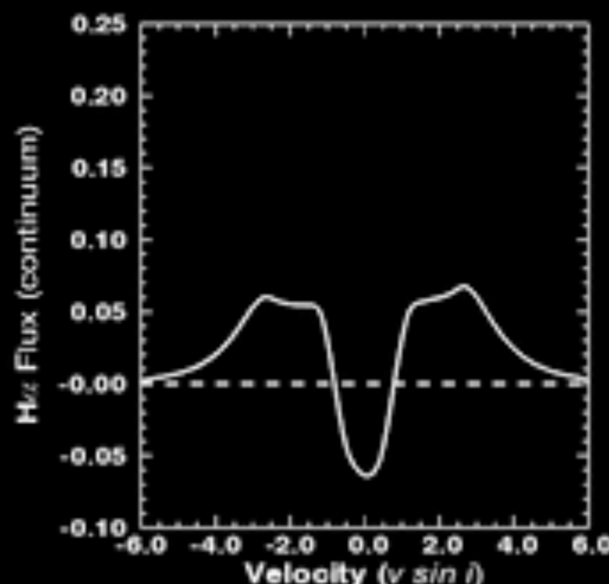
tilt ~ 55°

EM +B-field

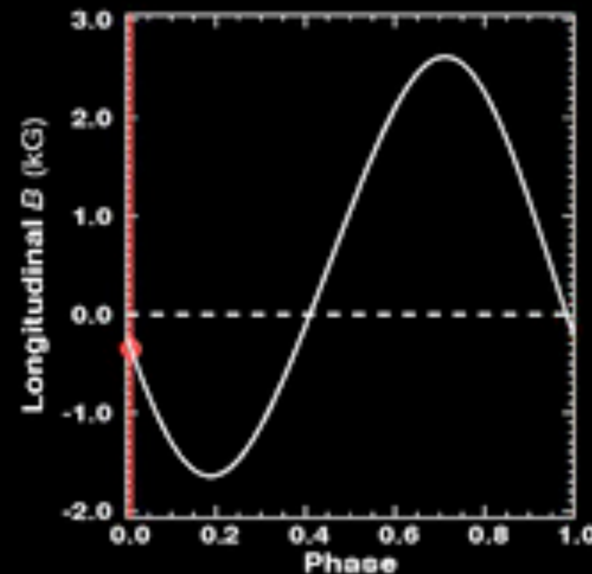


photometry





Hα



polarimetry

RRM model for σ Ori E

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$\eta_* \sim 10^6$

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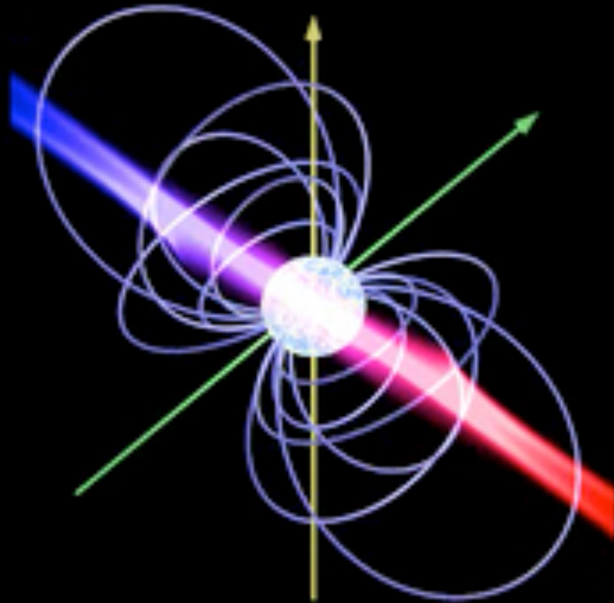
<<

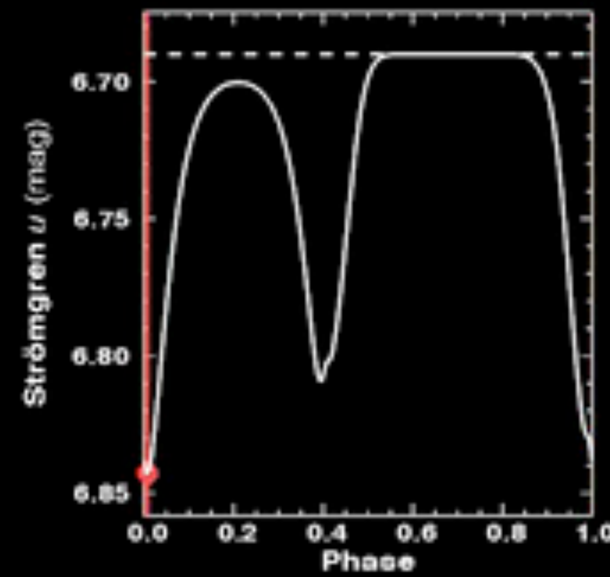
$R_A \sim 30 R_*$

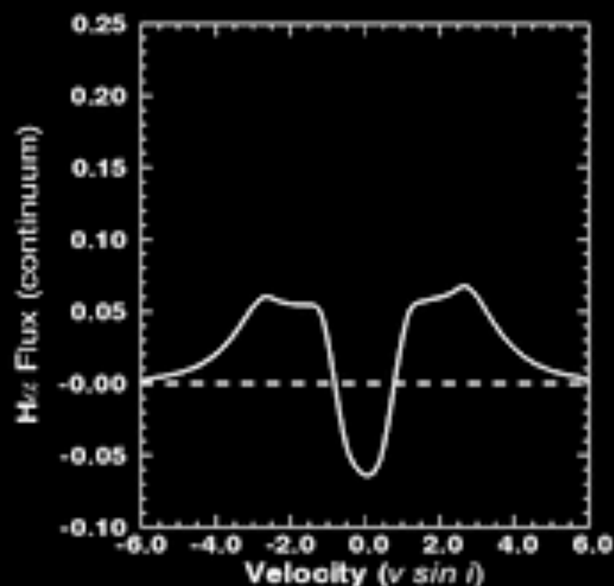
tilt ~ 55^o

EM +B-field

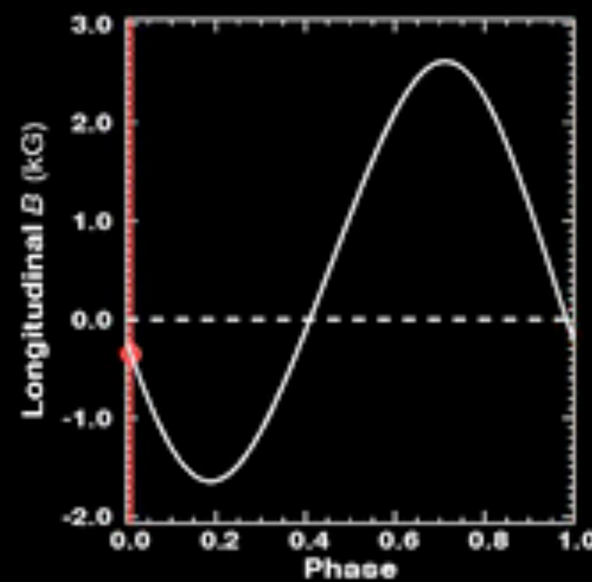


photometry





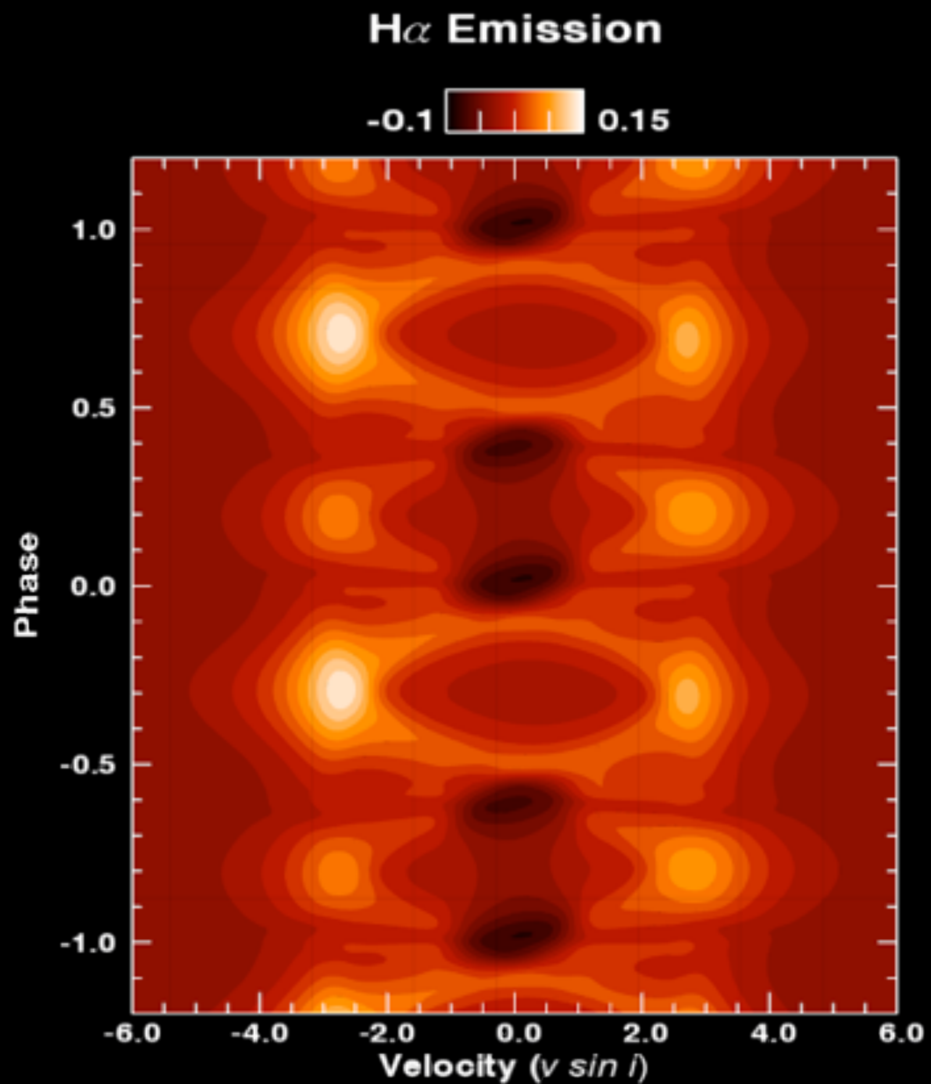
Hα



polarimetry

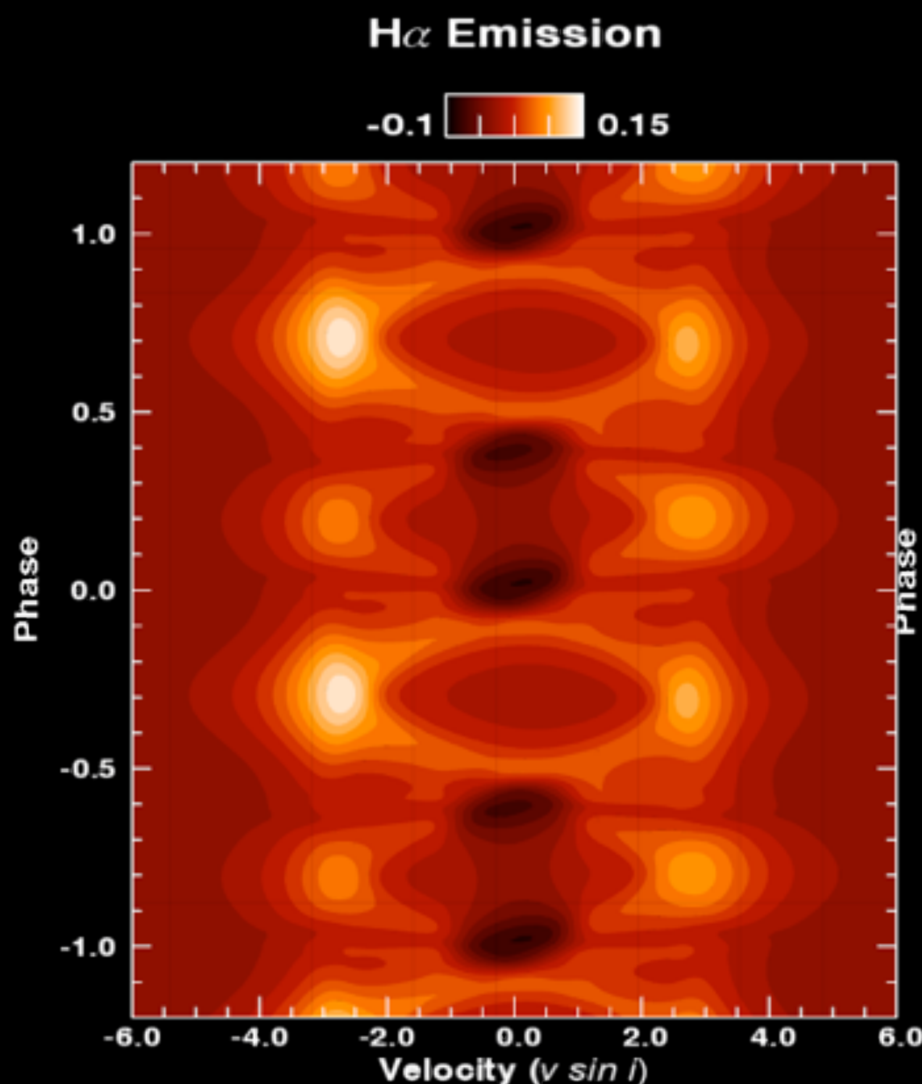
σ Ori E

RRM Model

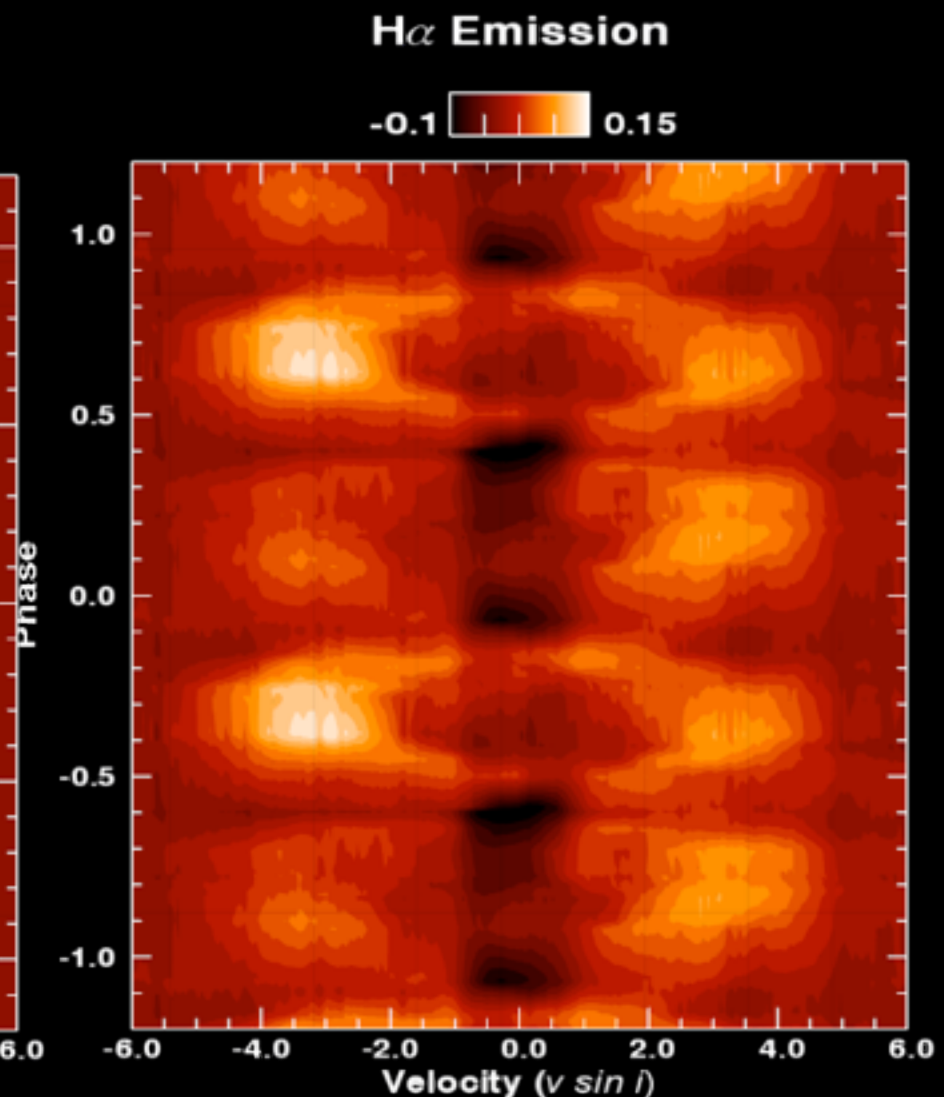


σ Ori E

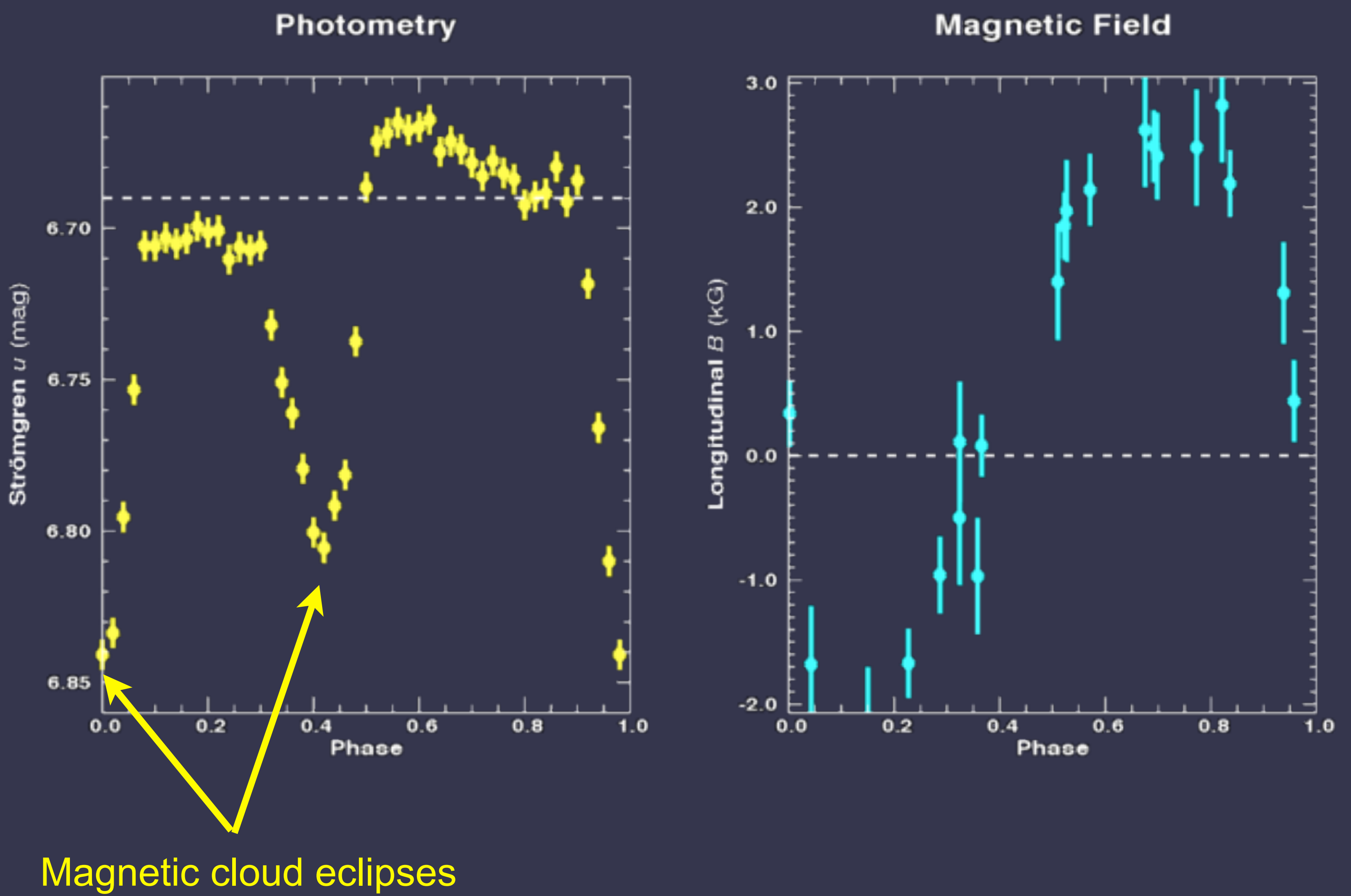
RRM Model



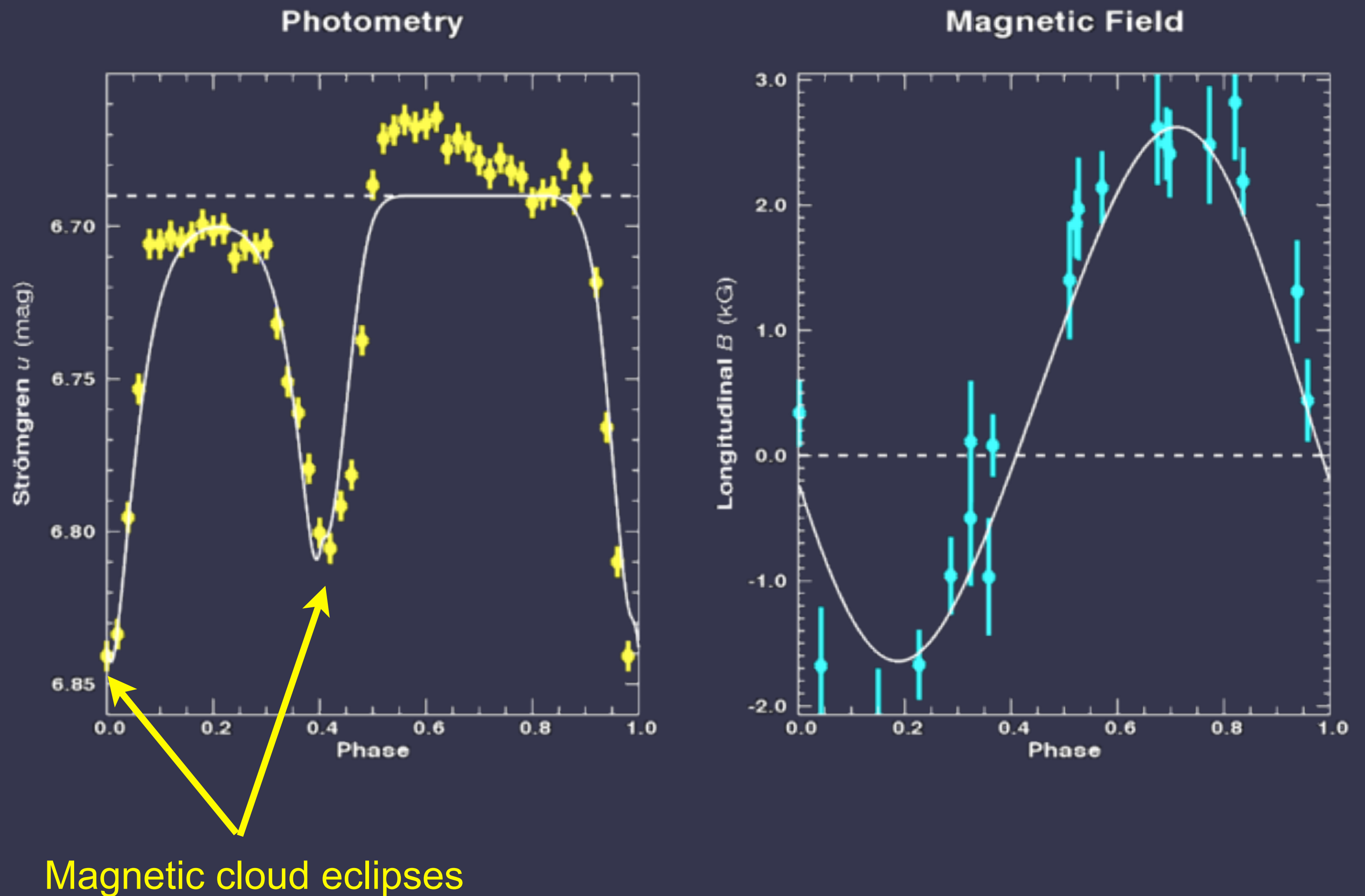
Hα Observations



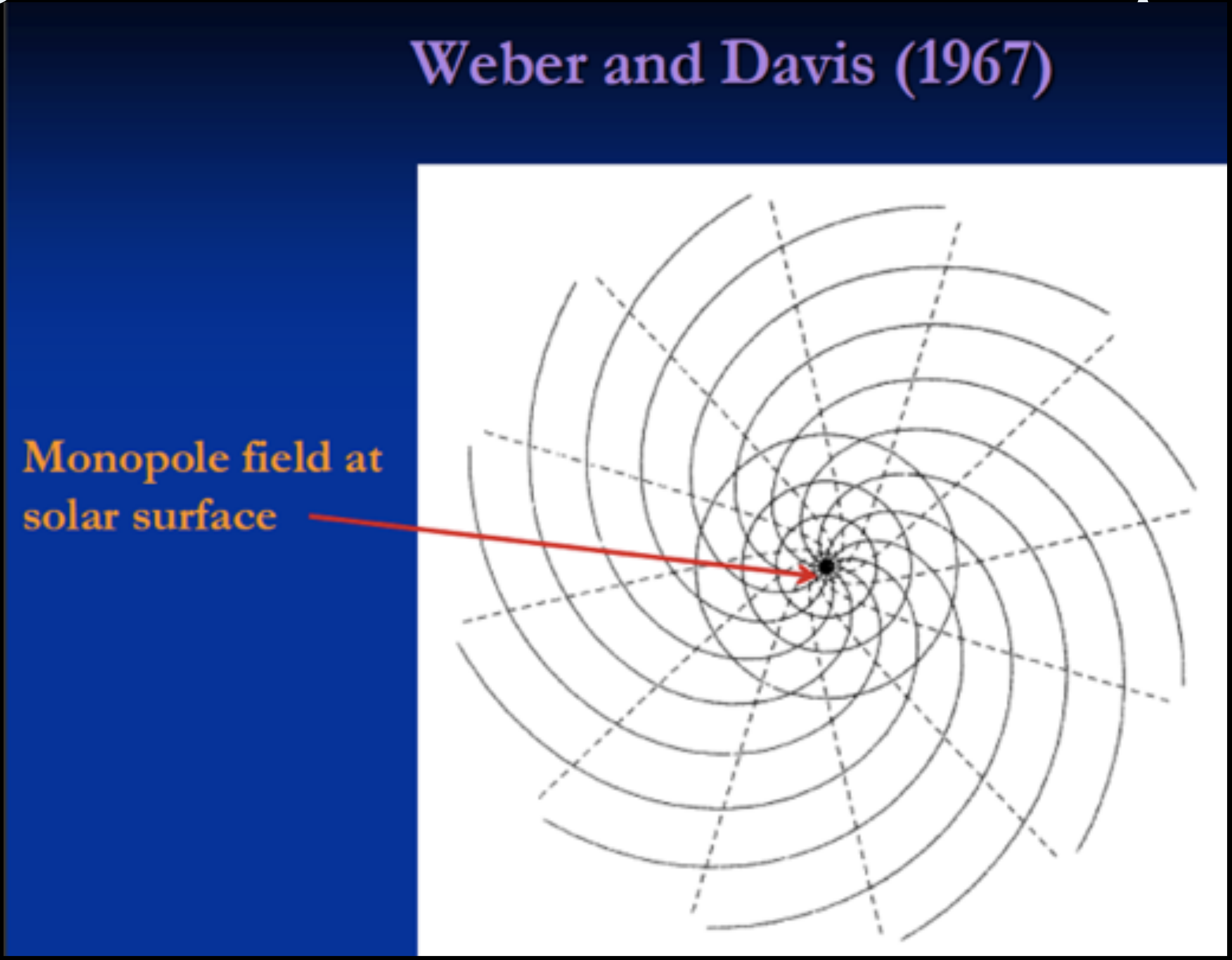
Photometric variation of σ Ori E



Photometric variation of σ Ori E



Angular Momentum Loss & Spindown



$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega R_A^2$$

Weber & Davis 1967

Total equatorial Angular mom/mass

gas field

$$j = V_\phi r + \frac{B_\phi B_r r}{4\pi\rho V_r}$$

Weber & Davis 1967

Total equatorial Angular mom/mass

Frozen flux

gas field

$$j = V_\phi r + \frac{B_\phi B_r r}{4\pi\rho V_r} \quad \& \quad \frac{B_\phi}{B_r} = \frac{\Omega r - V_\phi}{V_r}$$

Weber & Davis 1967

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=> $$j_{gas} \equiv V_\phi r = \frac{j M_A^2 - \Omega r^2}{M_A^2 - 1}$$

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At r= R_A,
M_A=1 implies

$$j = \Omega R_A^2$$

Spindown

contribution from both matter & field

$$\dot{J} = \frac{2}{3}\dot{M}\,\Omega R_A^2 \qquad \frac{R_A}{R} = \eta_*^{1/2n} \qquad \eta_* \equiv \frac{B_{eq}^2\,R^2}{\dot{M}\,V}$$

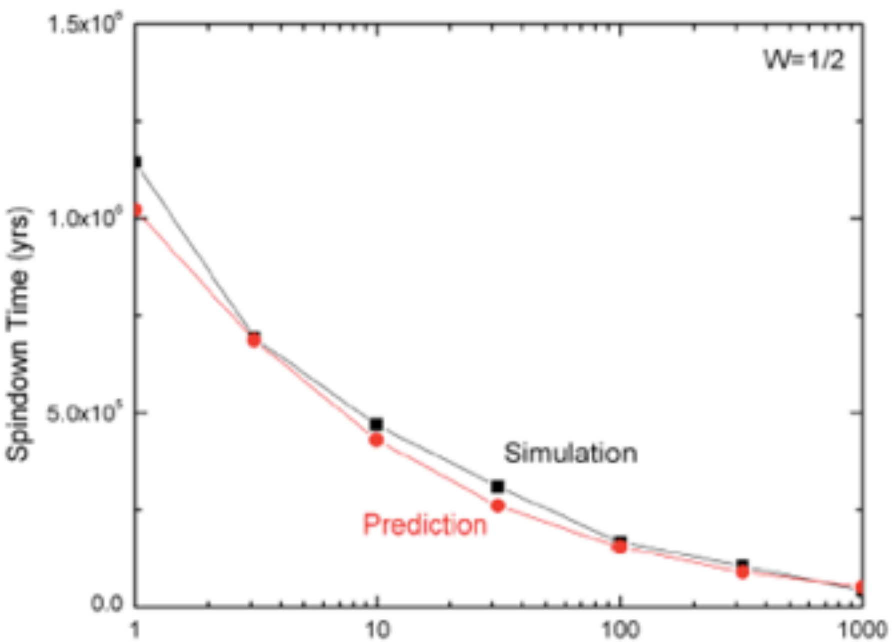
$$\tau_{spin} \equiv \frac{J}{\dot{J}} \approx \frac{\frac{3}{2}I}{MR^2}\,\frac{M}{\dot{M}}\,\frac{1}{\eta_*^{1/n}} = \tau_{mass}\,\frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

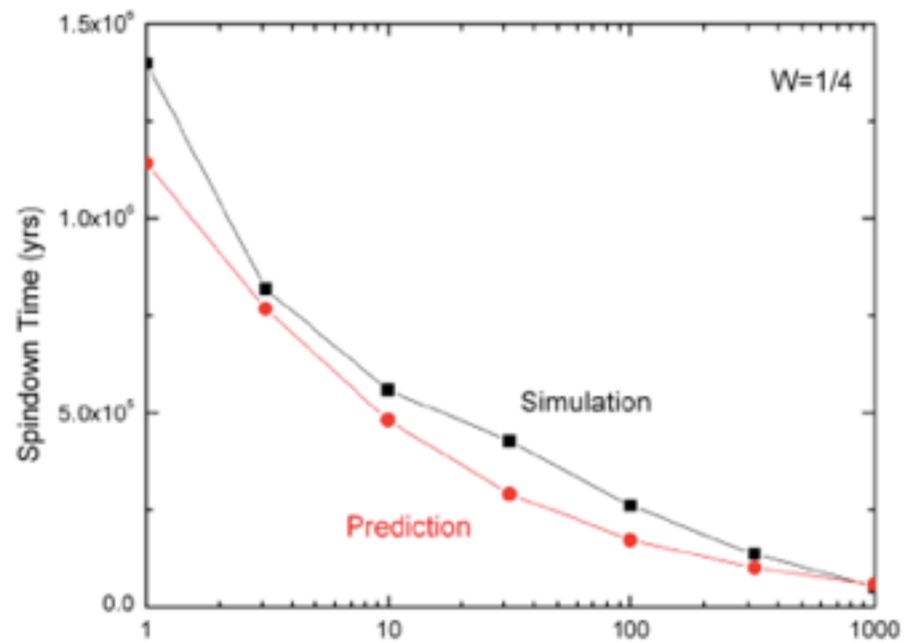
For dipole (n=2): $$\frac{\tau_{spin}}{\tau_{mass}} \approx \frac{0.15}{\sqrt{\eta_*}}$$

Spindown Time

Results from MHD sims for dipole field (n=2)

W=1/2 **W=1/4**

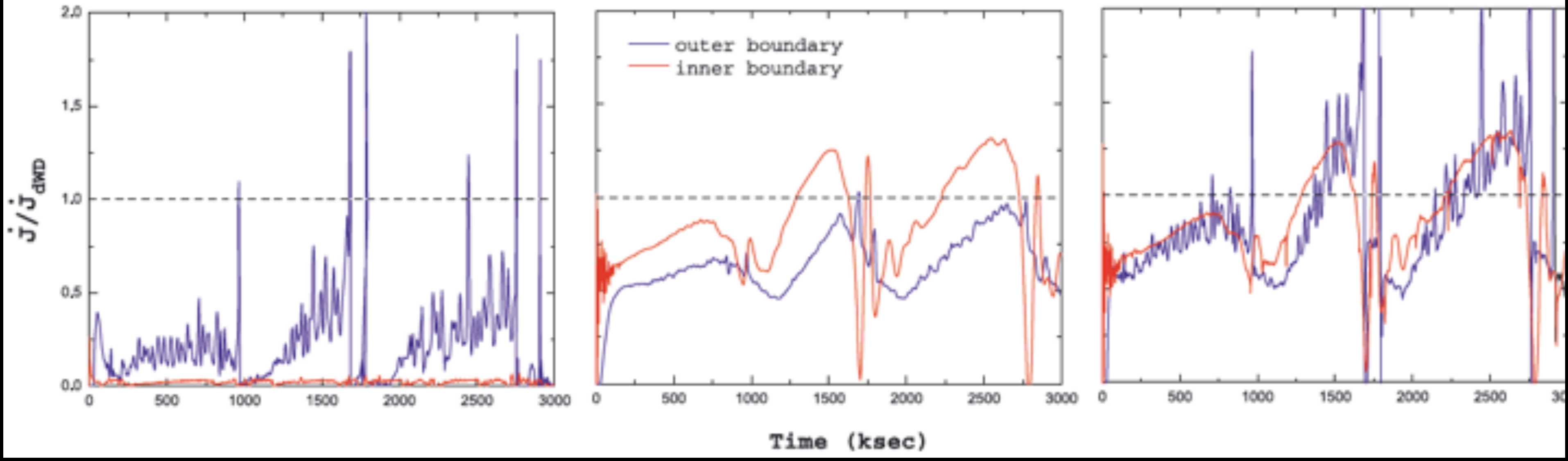




Magnetic confinement parameter =>

Time variation of total Angular Momentum Loss

Gas Field Total



Predicted spindown times

Table 1. Estimated spin-down time for selected known magnetic stars.

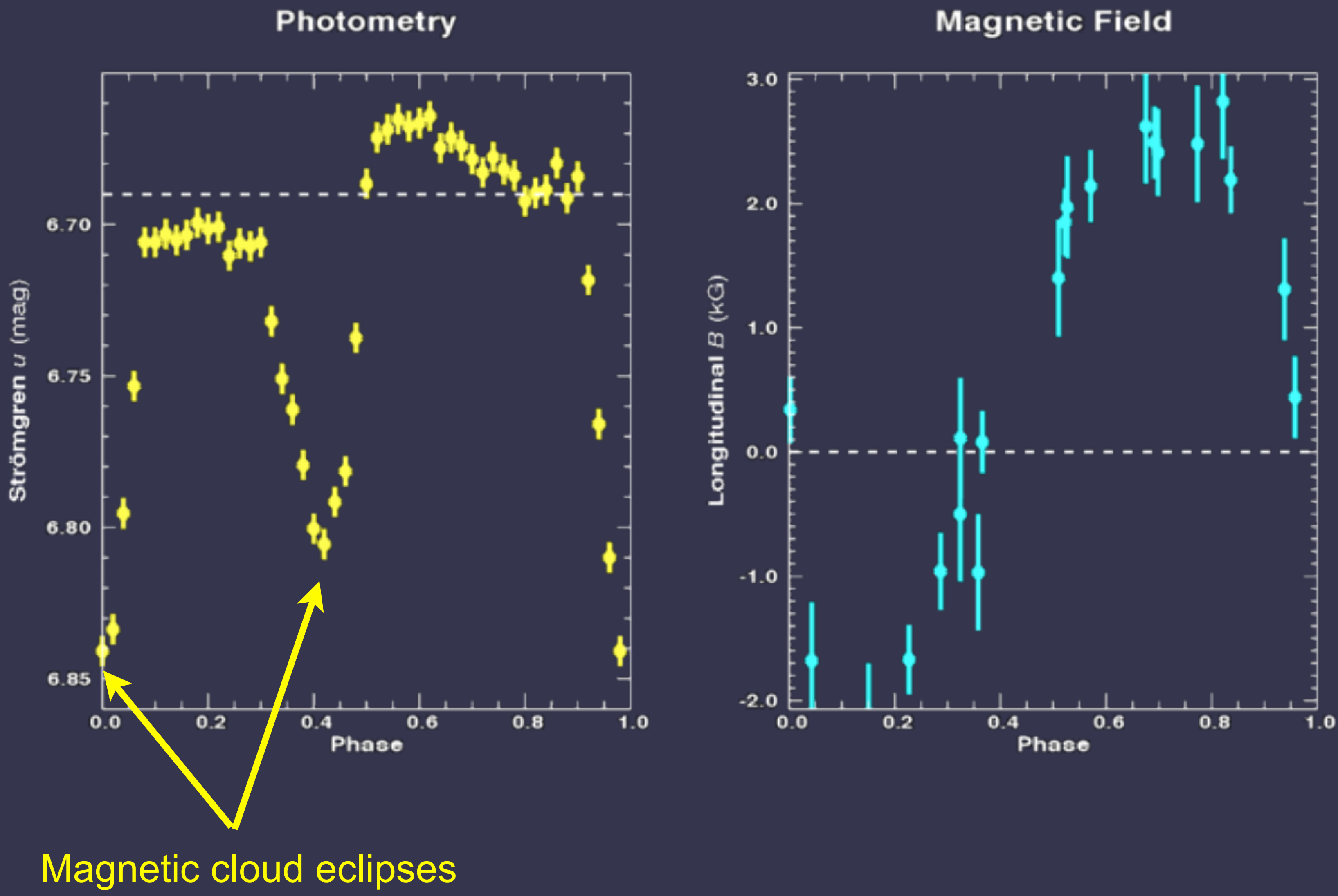
Star[a]	$M/M_\odot$	$R_*/R_\odot$	P (d)	k	$\dot{M}$ ($10^{-9}\,M_\odot\,yr^{-1}$)	v_∞ ($1000\,km\,s^{-1}$)	B_p (kG)	η_*	τ_{spin} (Myr)
θ^1 Ori C[1]	40	8	15.4	0.28	400	2.5	1.1	15.7	8
HD191612[2]	40	18	538	0.17	6100	2.5	1.6	7.6	0.4
ζ Cas[3]	8	5.9	5.37	0.1	0.3	0.8	0.34	3200	65.2
σ Ori E[4]	8.9	5.3	1.2	0.1	2.4	1.46	9.6	1.4×10^5	1.4
ρ Leo[5]	22	35	7-47	0.12	630	1.1	0.24	20	1.1

ud-Doula+ 2009

$$\tau_{spin} \approx \tau_{mass} \frac{\frac{3}{2}k}{\sqrt{\eta_*}}$$

$$\approx 11 Myr \; \frac{k_{-1}}{B_{kG}} \frac{M_*}{R_*} \sqrt{\frac{V_8}{\dot{M}_{-9}}}$$

Photometric variation of σ Ori E



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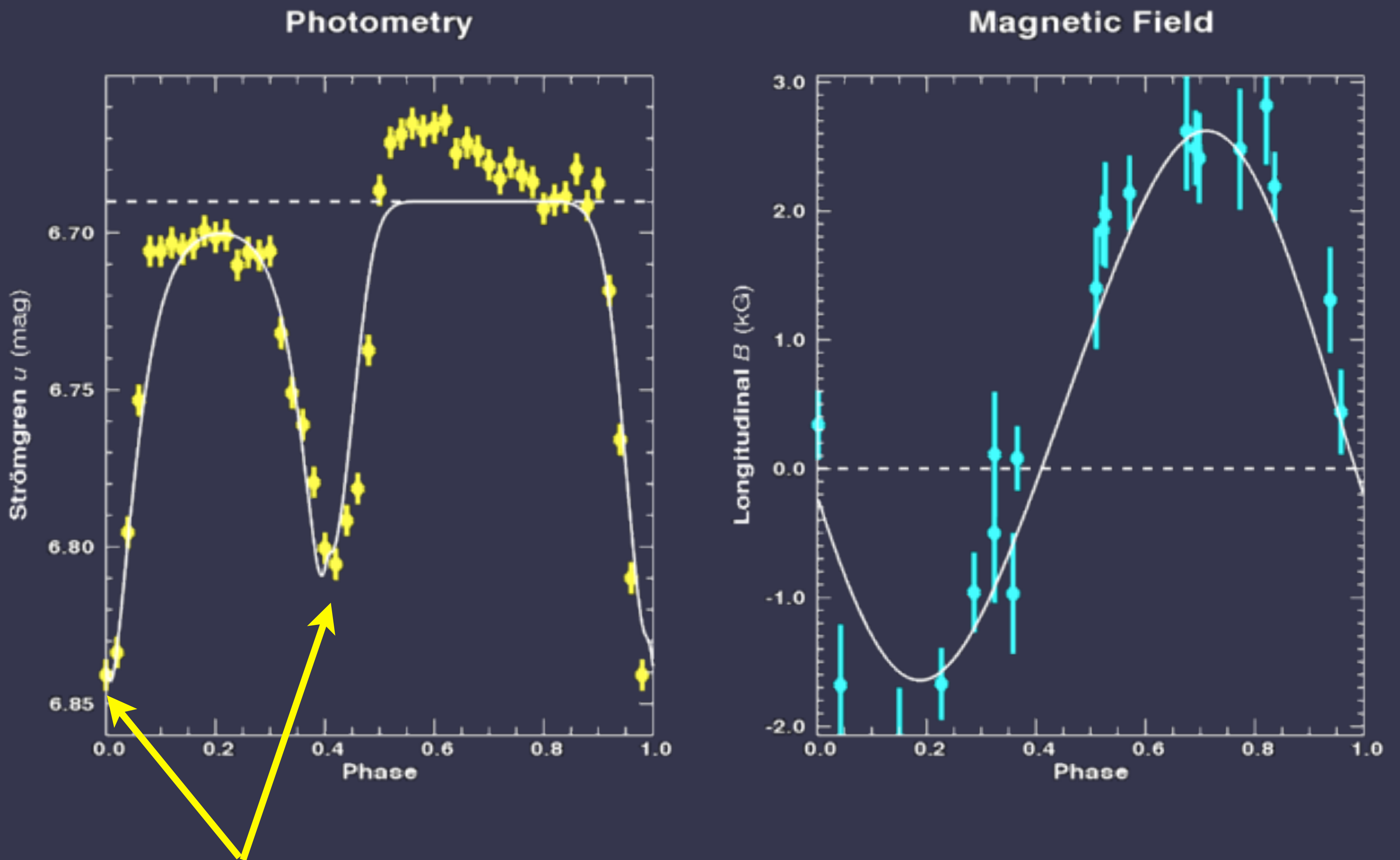

Magnetic cloud eclipses

The Astrophysical Journal Letters, 714:L318–L322, 2010 May 10 doi:10.1088/2041-8205/714/2/L318

DISCOVERY OF ROTATIONAL BRAKING IN THE MAGNETIC HELIUM-STRONG STAR SIGMA ORIONIS E

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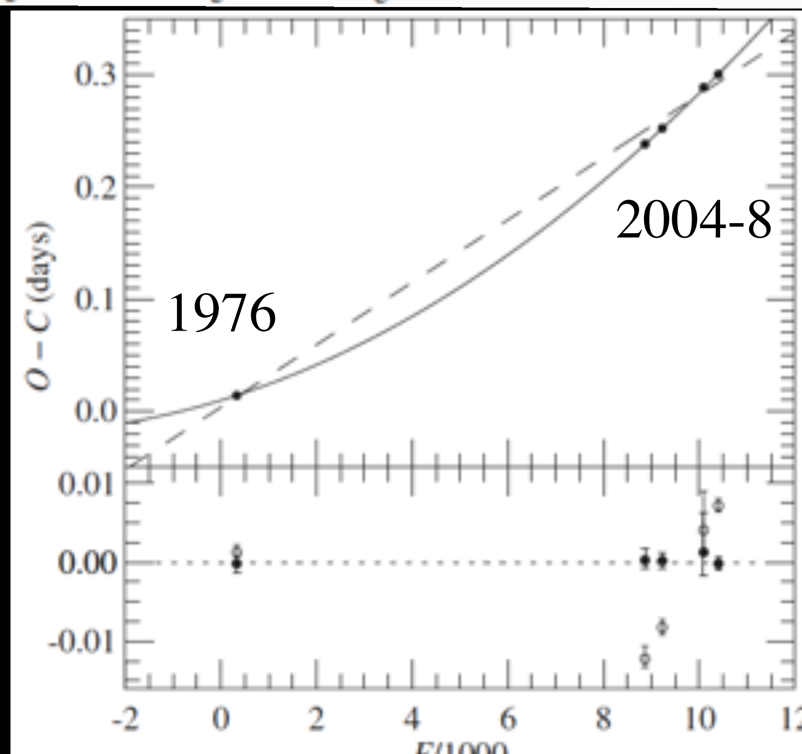
Received 2010 March 12; accepted 2010 April 14; published 2010 April 26

ABSTRACT

We present new *U*-band photometry of the magnetic helium-strong star σ Ori E, obtained over 2004–2009 using the SMARTS 0.9 m telescope at Cerro Tololo Inter-American Observatory. When combined with historical measurements, these data constrain the evolution of the star's 1.19 day rotation period over the past three decades. We are able to rule out a constant period at the $p_{null} = 0.05\%$ level, and instead find that the data are well described ($p_{null} = 99.3\%$) by a period increasing linearly at a rate of 77 ms per year. This corresponds to a characteristic spin-down time of 1.34 Myr, in good agreement with theoretical predictions based on magnetohydrodynamical simulations of angular momentum loss from magnetic massive stars. We therefore conclude that the observations are consistent with σ Ori E undergoing rotational braking due to its magnetized line-driven wind.



Spindown age

$$P = P_o e^{t/\tau_{spin}}$$

$$P_o \approx f P_c$$

Spindown age

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$$P_c = 0.21\, d\; R\sqrt{R/M} \qquad \Rightarrow\; P_o \sim day$$

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$$\tau_{age} = 2.3\,(\mathrm{Log}\,P_{day} - \mathrm{Log}\,P_{o,day})\,\tau_{spin}$$

e.g. HD191612, with $P_o = 0.5$ to 1 day:

$$\tau_{age} \approx 6.3 \rightarrow 6.9\ \tau_{spin} \approx 2.5 \rightarrow 2.9\ Myr$$

← Spindown time

Fast rot.

R_K / R_*

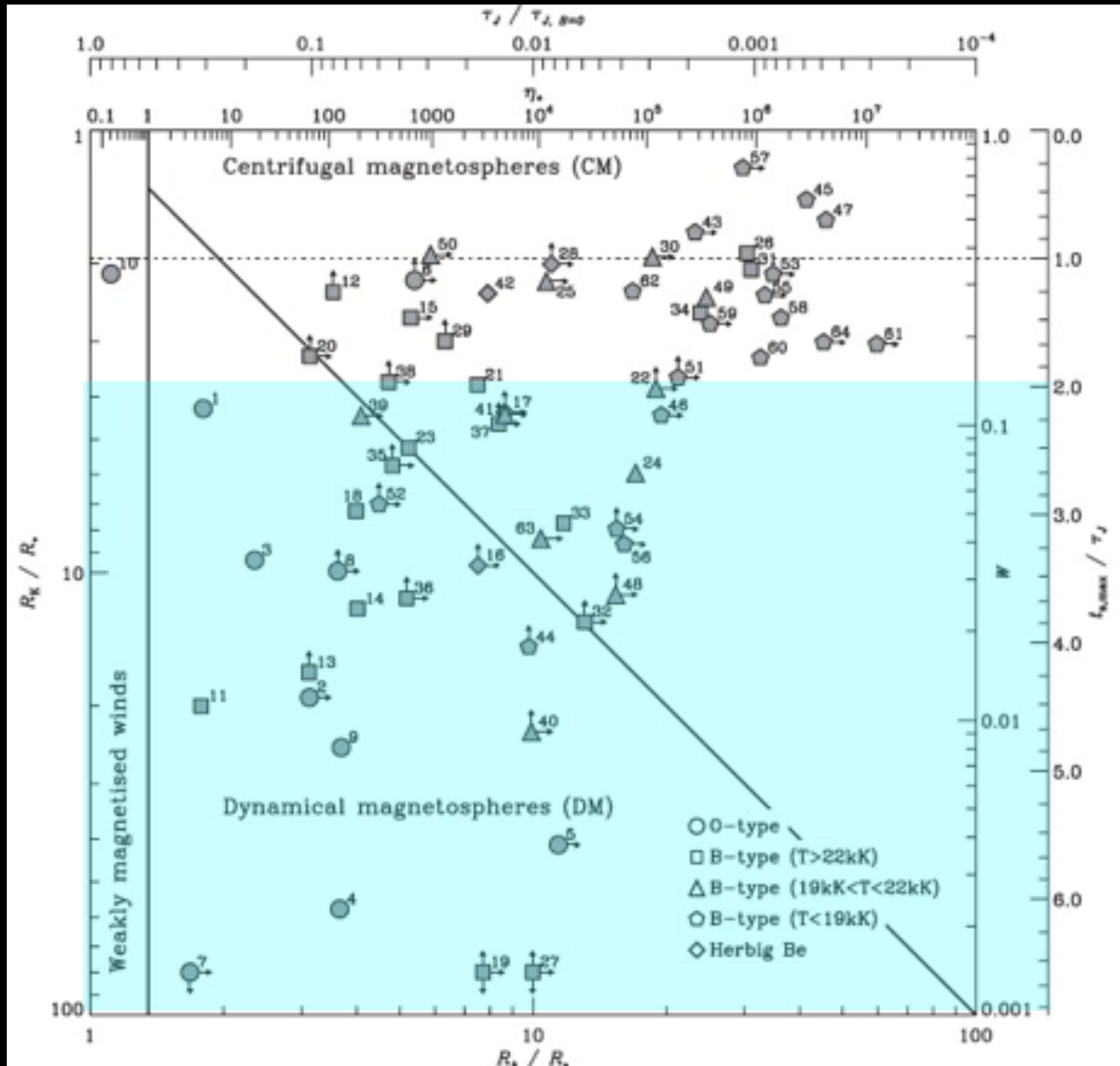
↓

Slow rot.

max Spindown Age

↓

Spundown



Weak B conf. R_A / R_* Strong B conf.

Extrapolated spindown law for higher order multipoles?

$$\frac{\tau_{spin}}{\tau_{mass}} = \frac{\frac{3}{2}k}{\eta_*^{1/n}}$$

n=1 monopole
=2 dipole
=3 quadrupole
... etc.

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=> Spindown weaker for more complex fields?

If so, hard to explain tau Sco by spindown??

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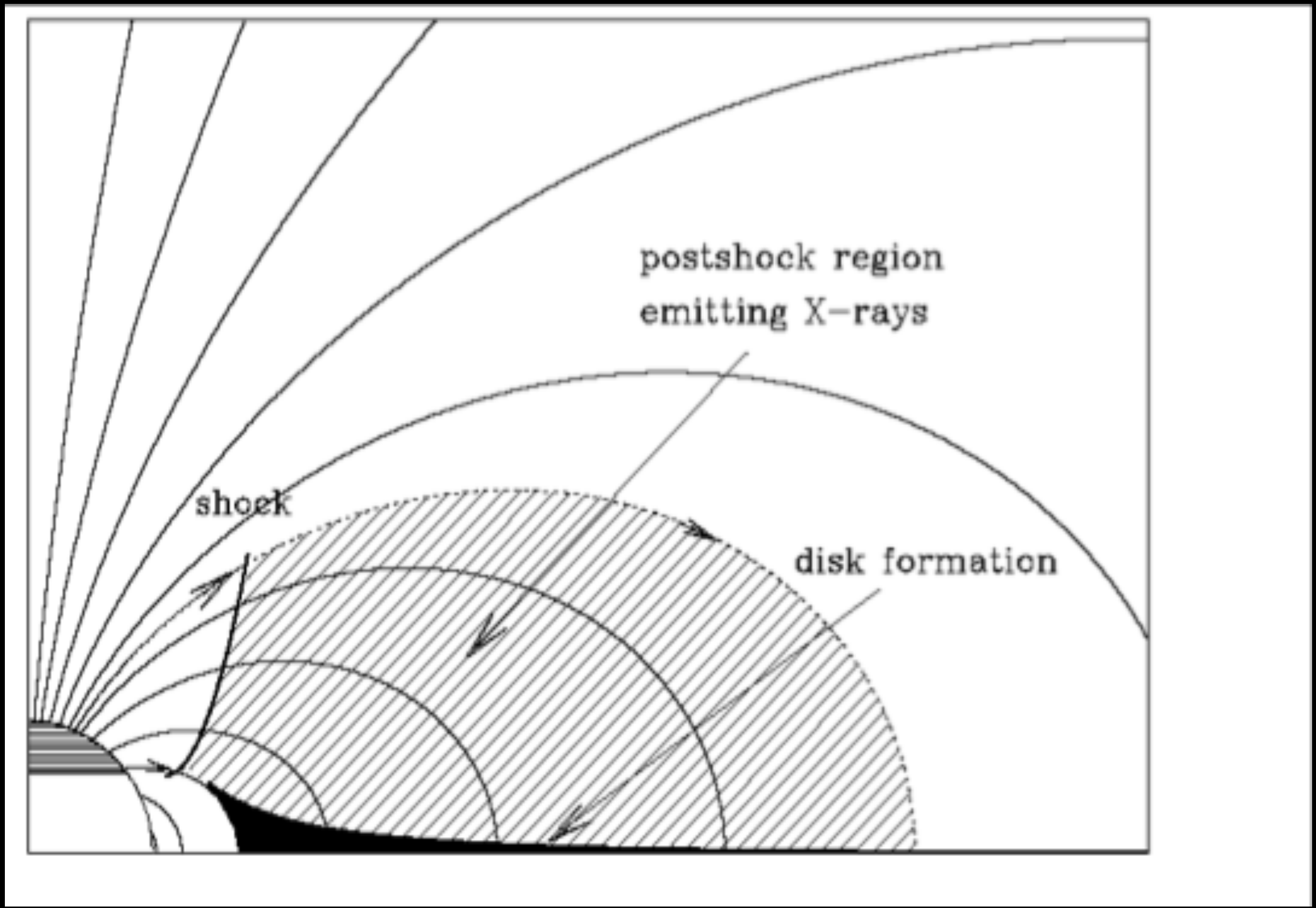
Need 3D MHD sims to test this!

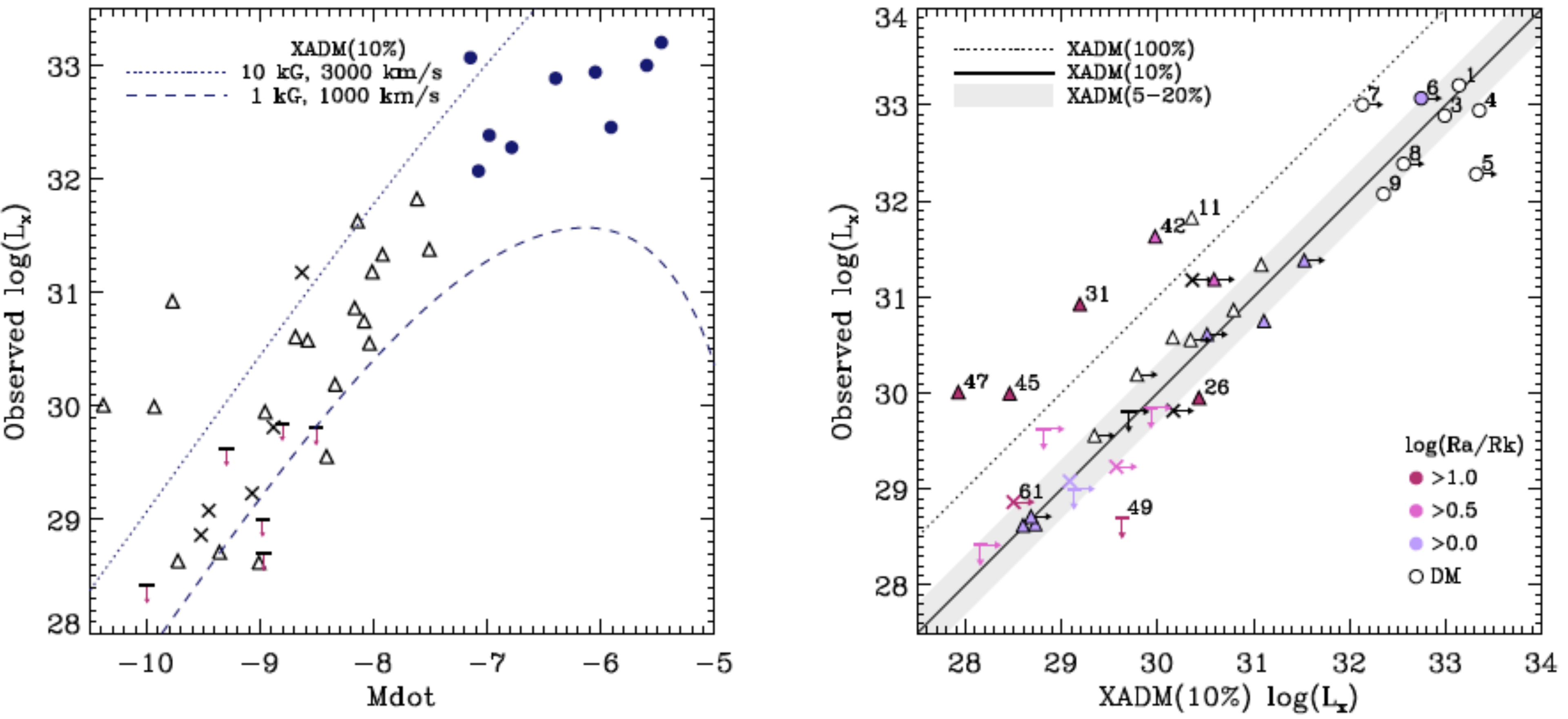
X-rays from Magnetically Confined Wind-Shocks

Babel & Montmerle 1997



Lx vs. Mdot
observations vs. XADM theory

Naze + 2014



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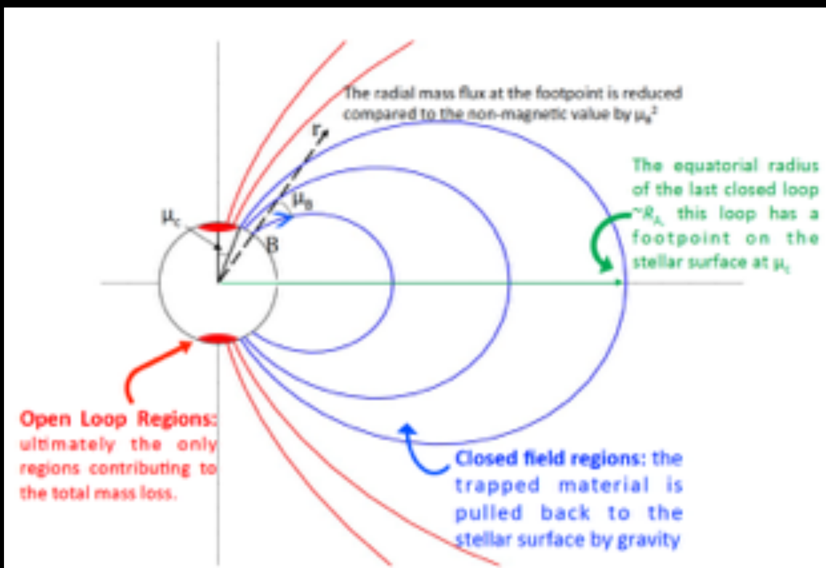
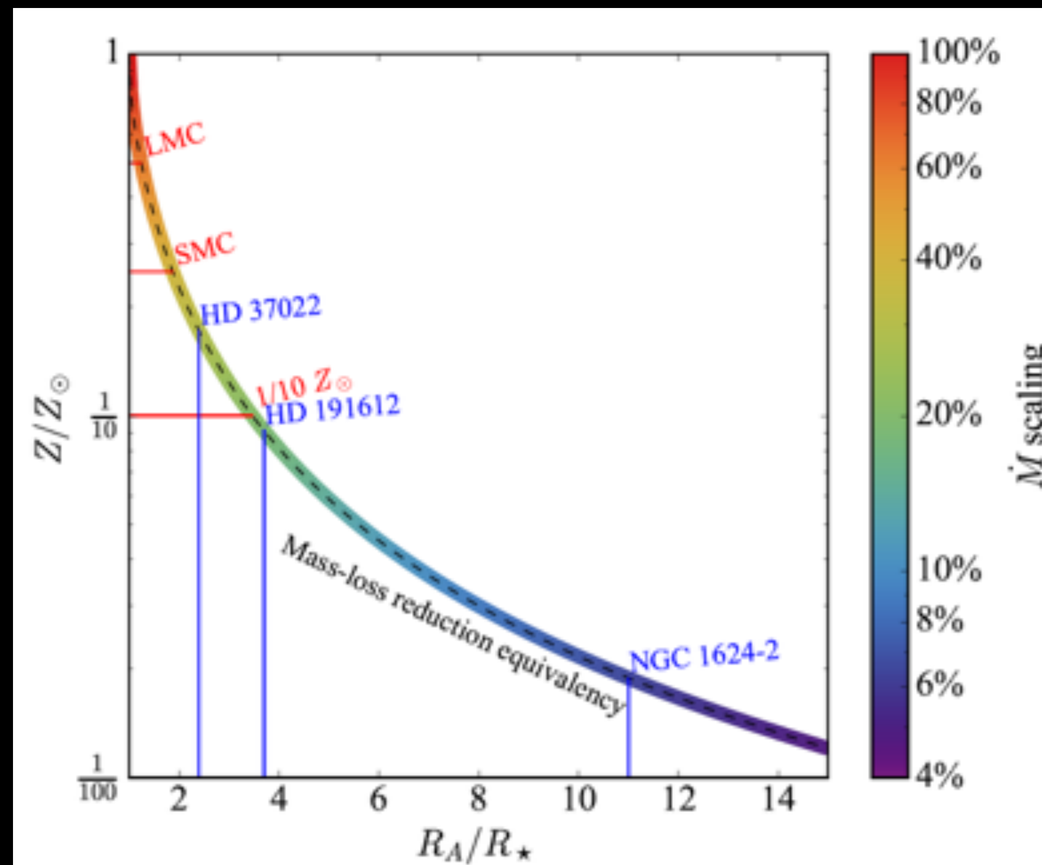
MNRAS 466, 1052–1060 (2017)
Advance Access publication 2016 December 2
doi:10.1093/mnras/stw3126

MNRAS 466, 1051

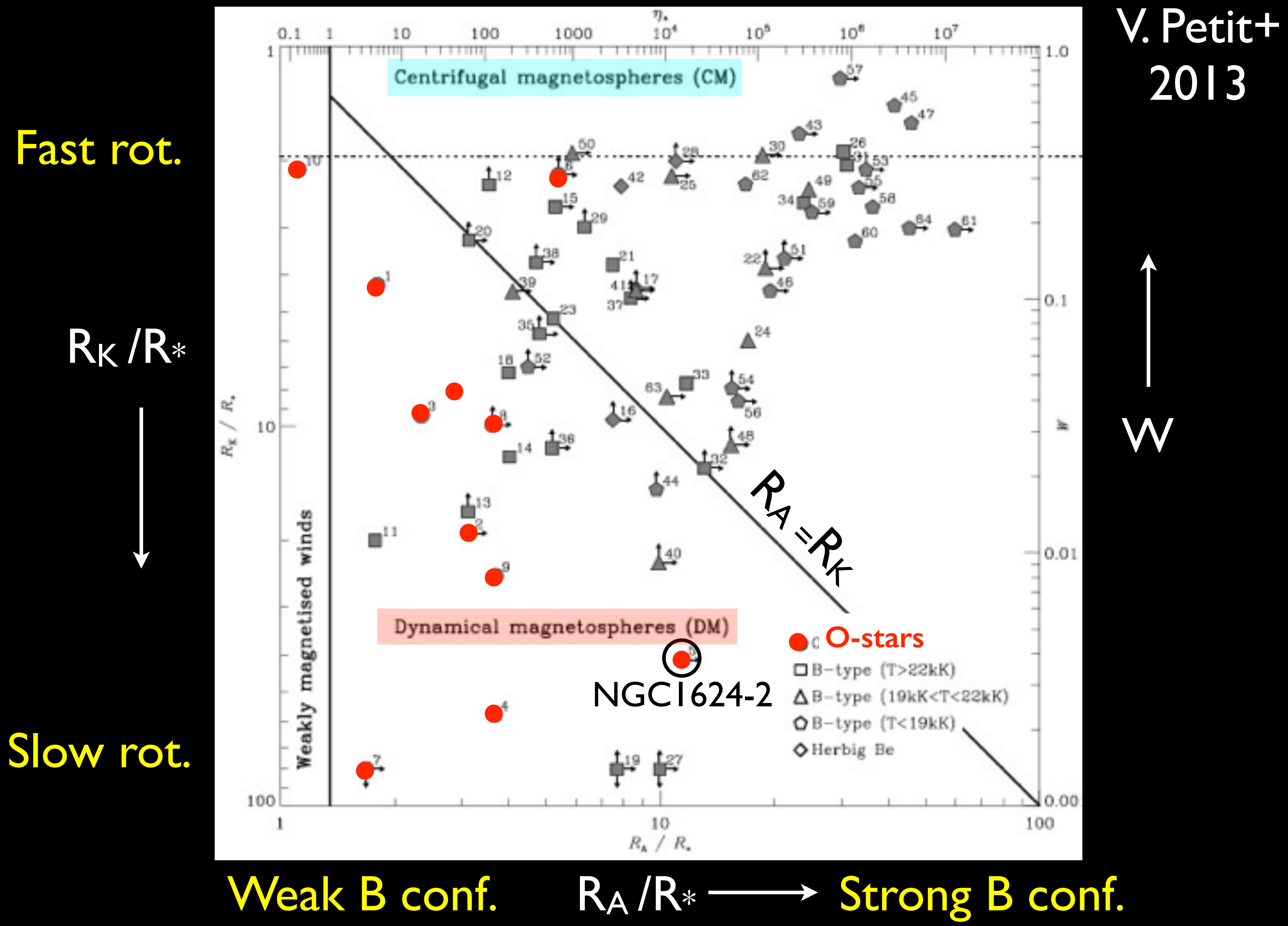
Magnetic massive stars as progenitors of 'heavy' stellar-mass black holes

V. Petit,[1★] Z. Keszthelyi,[2,3] R. MacInnis,[1] D. H. Cohen,[4] R. H. D. Townsend,[5] G. A. Wade,[2] S. L. Thomas,[1] S. P. Owocki,[6] J. Puls[7] and A. ud-Doula[8]





Magnetic trapping **reduces** net mass loss

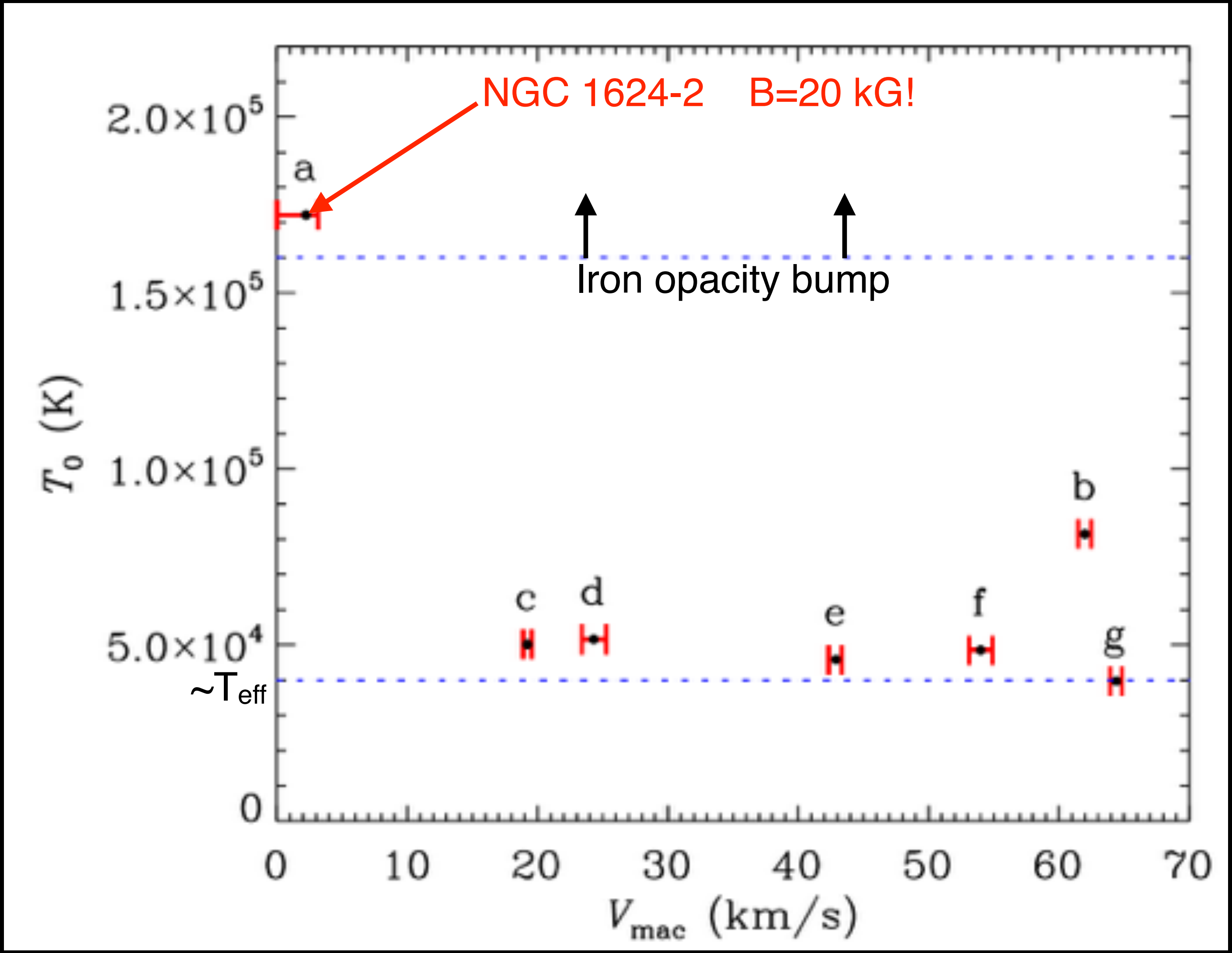


V. Petit+ 2013
Fast rot.
RK /R*
Slow rot.
W
Weak B conf.
RA /R*
Strong B conf.
Centrifugal magnetospheres (CM)
Dynamical magnetospheres (DM)
Weakly magnetised winds
RA =RK
O-stars
NGC1624-2
B−type (T>22kK)
B−type (19kK<T<22kK)
B−type (T<19kK)
Herbig Be

Magnetic inhibition of macroturbulence

Sundqvist+ 2013

T_0=
Equipartition temperature where
$P_{mag} = P_{gas}$



macroturbulent speed inferred from observed line broadening

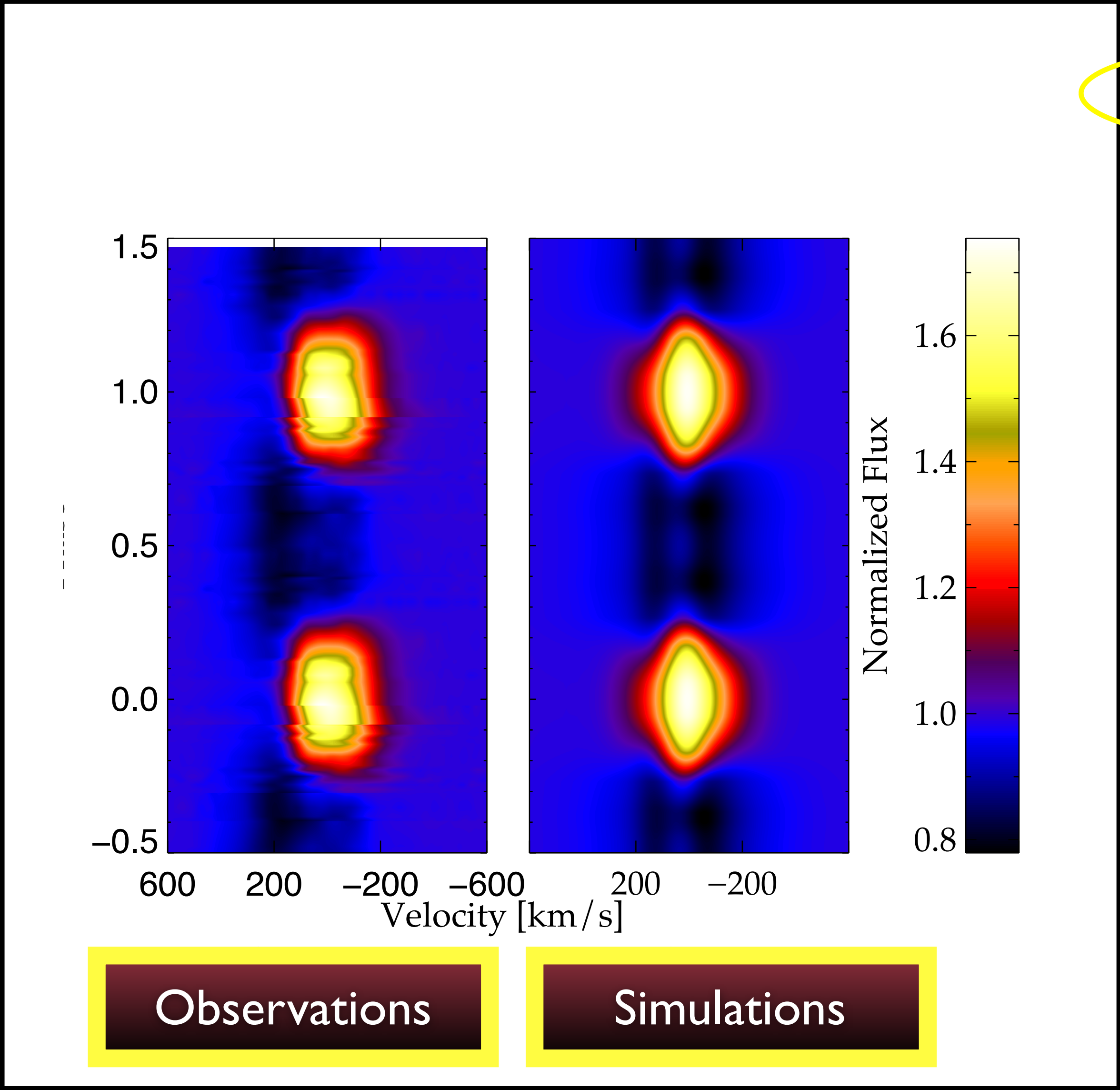
HD 191612 (Of?p)

vsini < 45 km/s

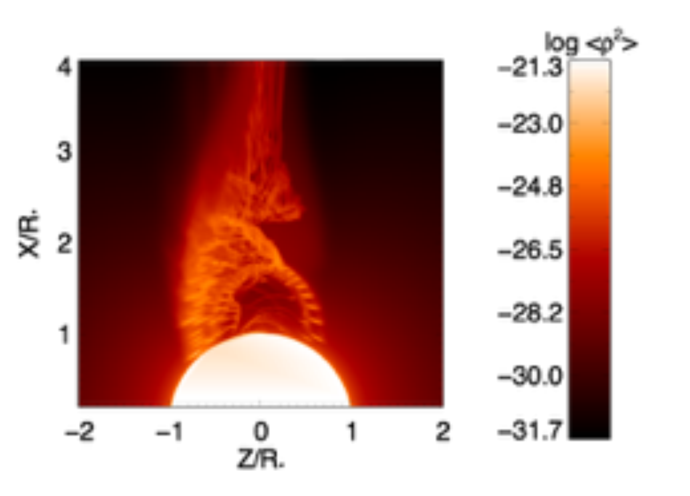
η^* ~ 50

P_{rot} ~ 540 d; R_{Kep} ~ 50 R*

B_d ~ 2.5 kG; R_{Alf} ~ 3 R*



"Dynamical" Magnetosphere



Sundqvist + 2012

Summary

Magnetic field + hot-star wind:

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Magnetic field + hot-star wind:

- Traps wind into magnetosphere
  - alt channel for high-mass b.h. detected by GW?
  - Centrifugally supported vs. Dynamically suspended
  - MHD vs. RFHD vs. RRM models
  - explains Hα emission vs. rot. phase
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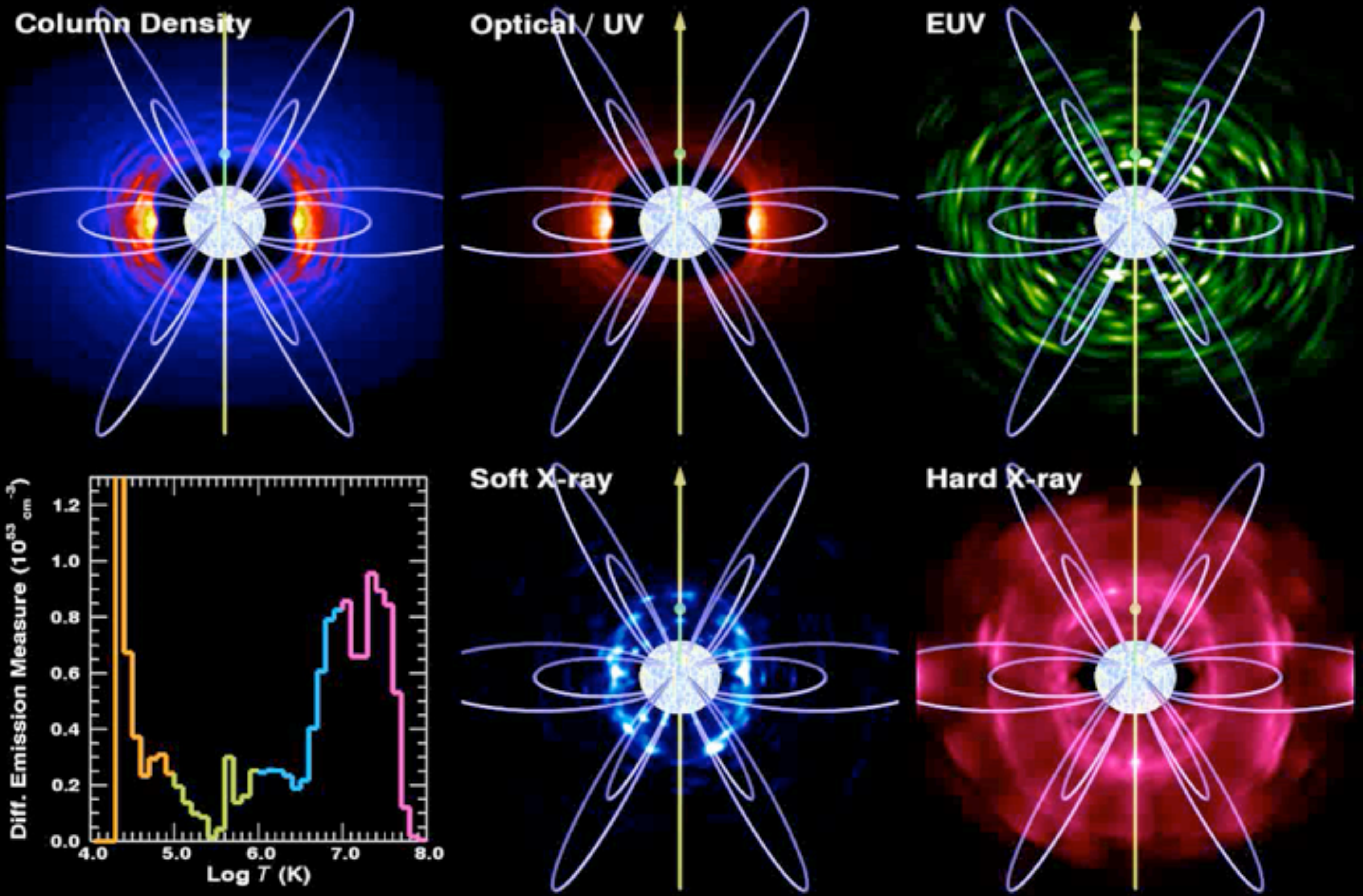
The MiMeS Project

Magnetism in Massive Stars

courtesy of Rich Townsend



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