FAST ROTATORS IN 3D MHD WIND SIMULATIONS

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ANR Toupies, BCool consortium

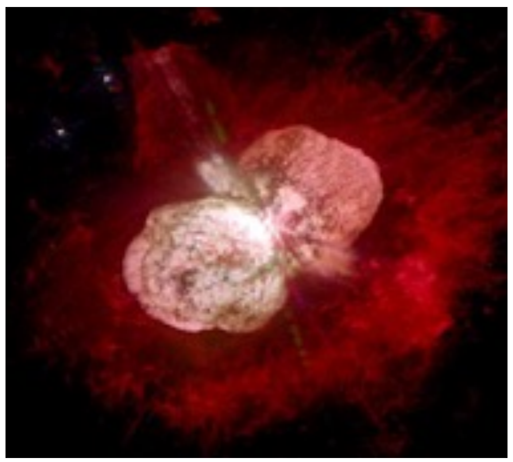
June 16th 2016

ATELIER SIMULATIONS

SF2A 2016

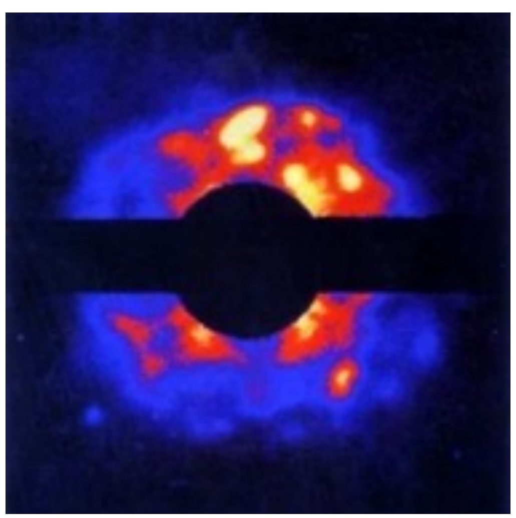
STELLAR WINDS: UBIQUITOUS IN THE HR DIAGRAM

Red Giants/Massive stars

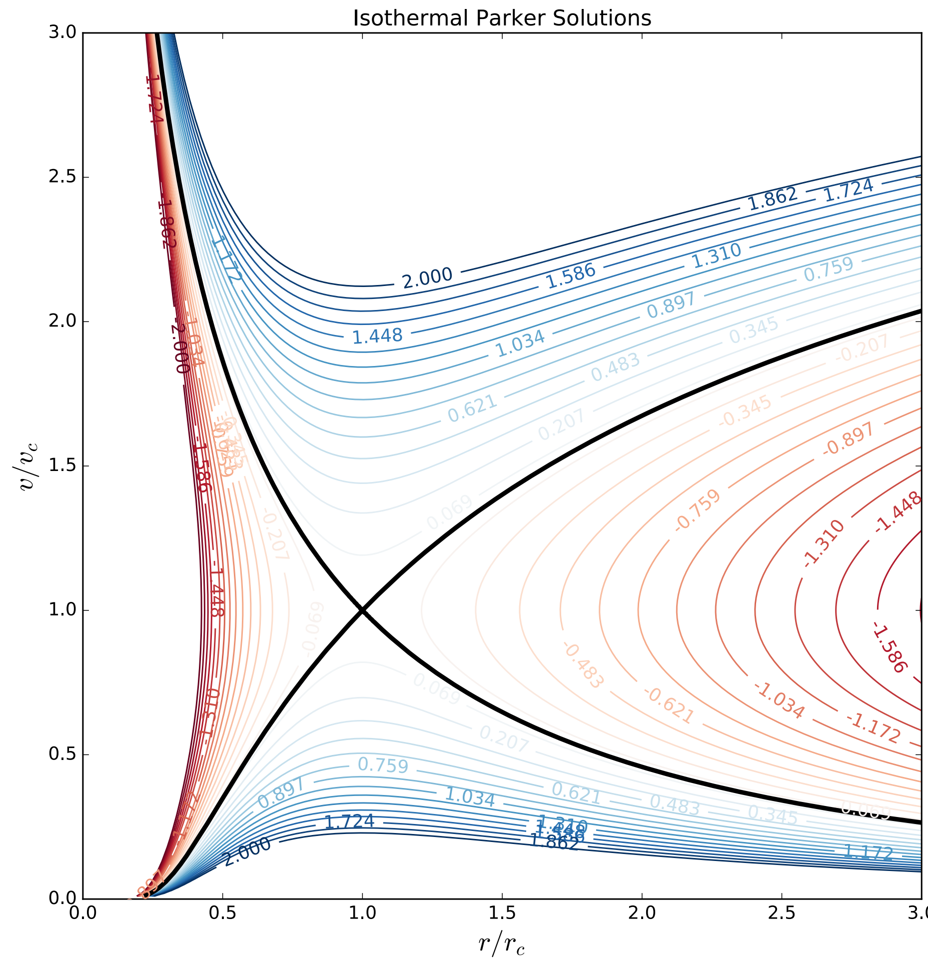


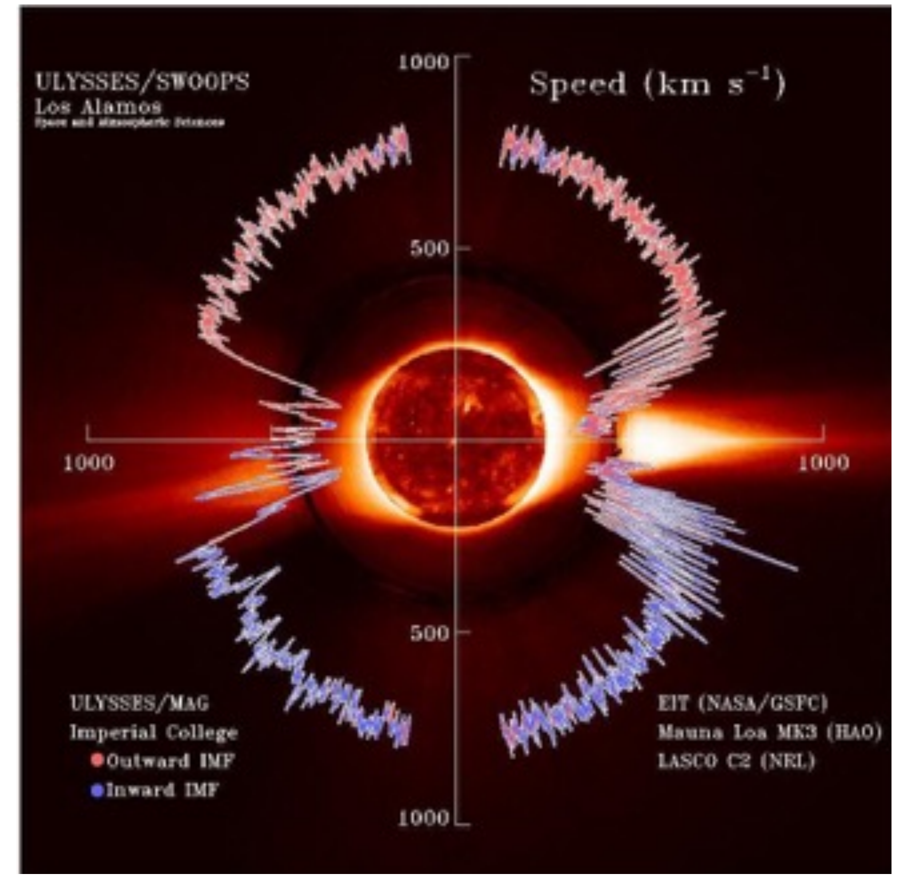
η Car

P-Cygni



Cool stars on the MS





Theory + *in-situ measurements of the Solar Wind*

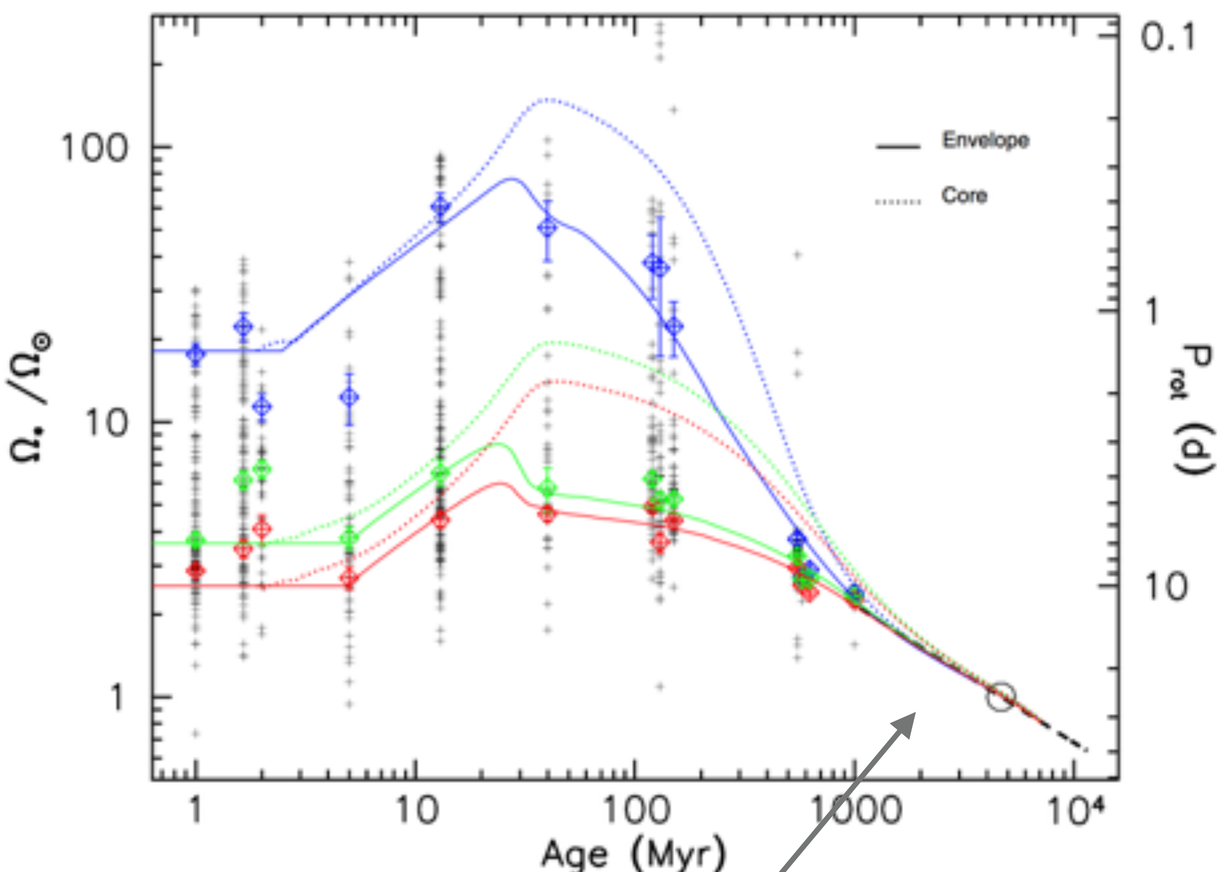
[Parker 1958] + *Lyman Alpha absorption spectrum*
[Velli 1994]

[Linsky & Wood 1996]
[Wood et al. 2004]

STELLAR WIND BRAKING

Rotation Models

[Gallet & Bouvier 2013]



Skumanich's law:

$$\Omega_* \propto t^{-1/2}$$

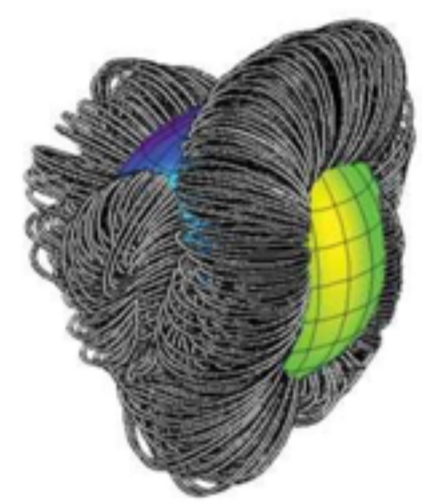
dynamo

wind

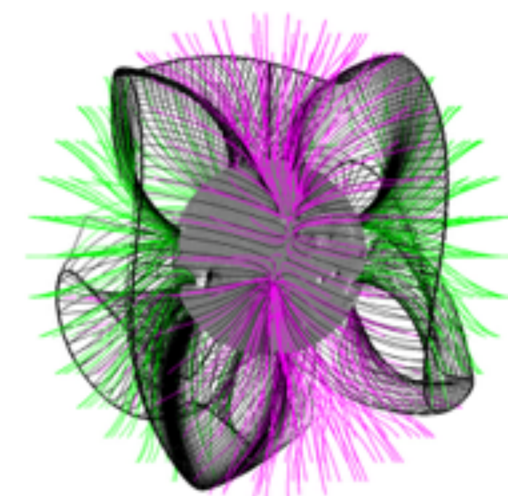
Magnetic Activity

[Donati et al. 2009]

[De Rosa et al. 2012]

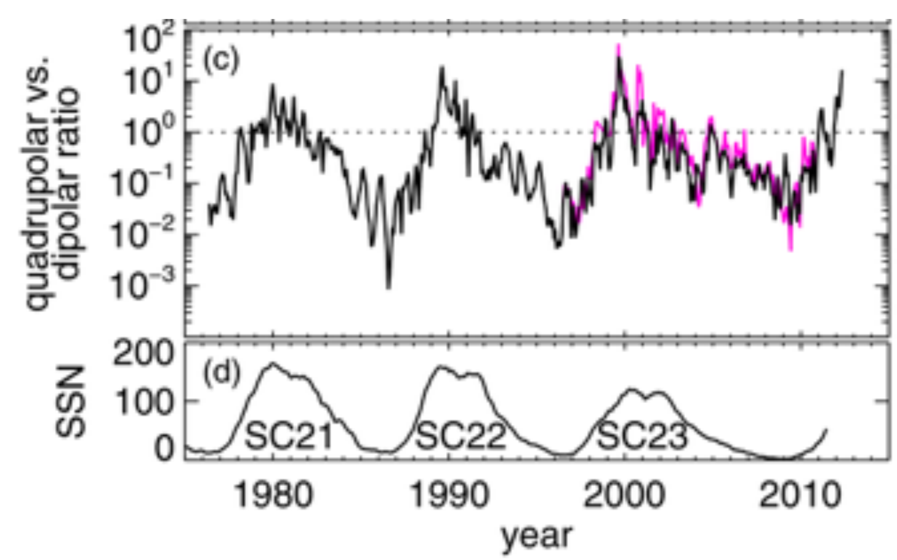


τ Sco



the Sun

Cycles ?



STELLAR WIND BRAKING

Empirical braking law

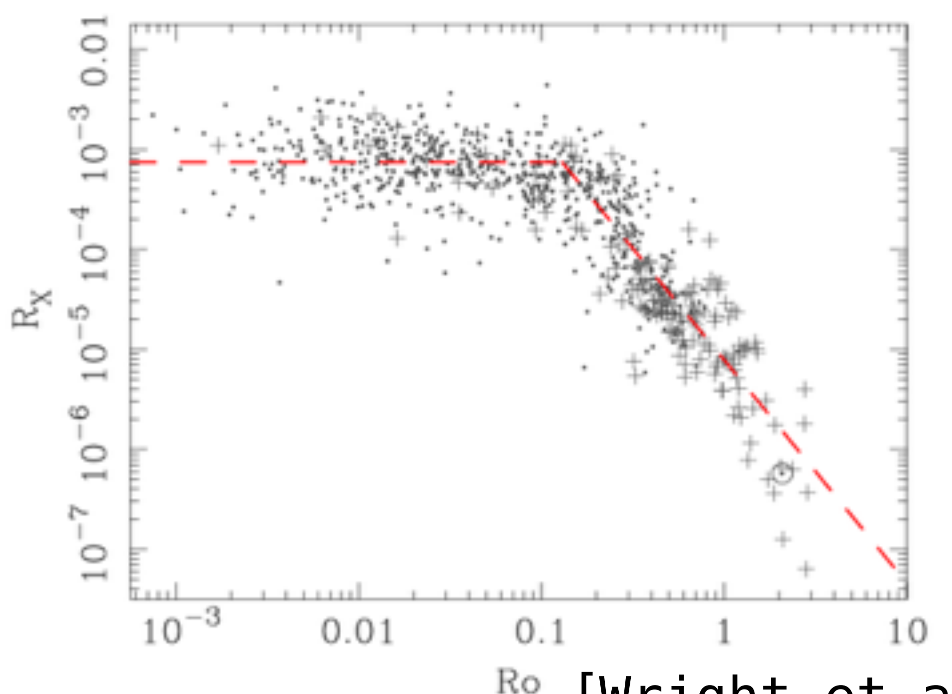
[Kawaler 1988]

[Bouvier et al 1997]

$$\frac{dJ}{dt} = K\min(\Omega_\star, \Omega_{\rm sat})^2\Omega_\star$$

What is the role of the magnetic field ?

$$R_X \propto B^2 \propto \Omega_\star^2 \propto R_o^{-2} \ ?$$



[Wright et al. 2011]

Theory

[Schatzmann 1962]

[Weber & Davis 1968]

$$\frac{dJ}{dt} = \frac{dM}{dt}\Omega_\star r_A^2$$

$$v(r_A) = v_A \qquad v_A = \frac{B}{\sqrt{4\pi\rho}}$$

Angular momentum transport by the wind = braking !

3D SIMULATIONS

PLUTO

A modular code for computational astrophysics

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

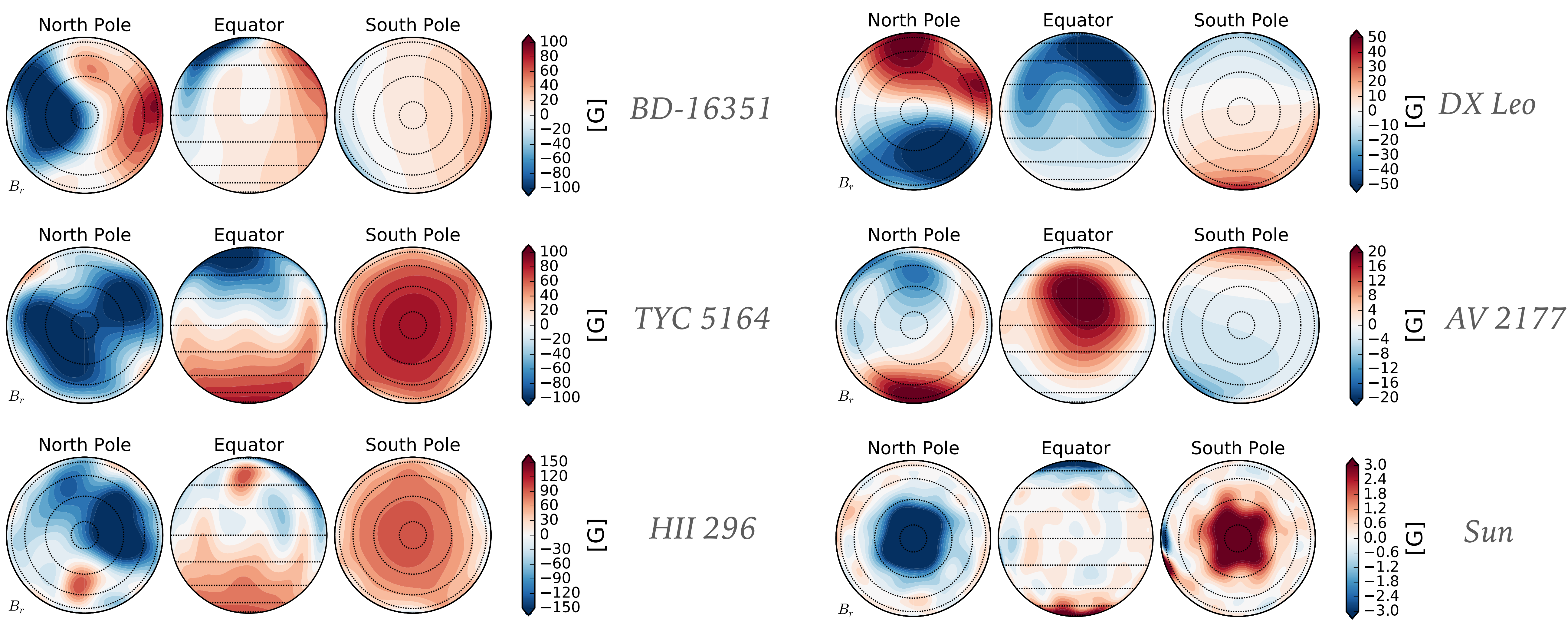
+

- *Ideal MHD / Polytropic EoS*
- *HLL Riemann Solver*
- *Constrained transport w/ background field*
- *RK2 Time stepping*
- *Cartesian grid uniform / stretched* $[-30R_\star, 30R_\star]$

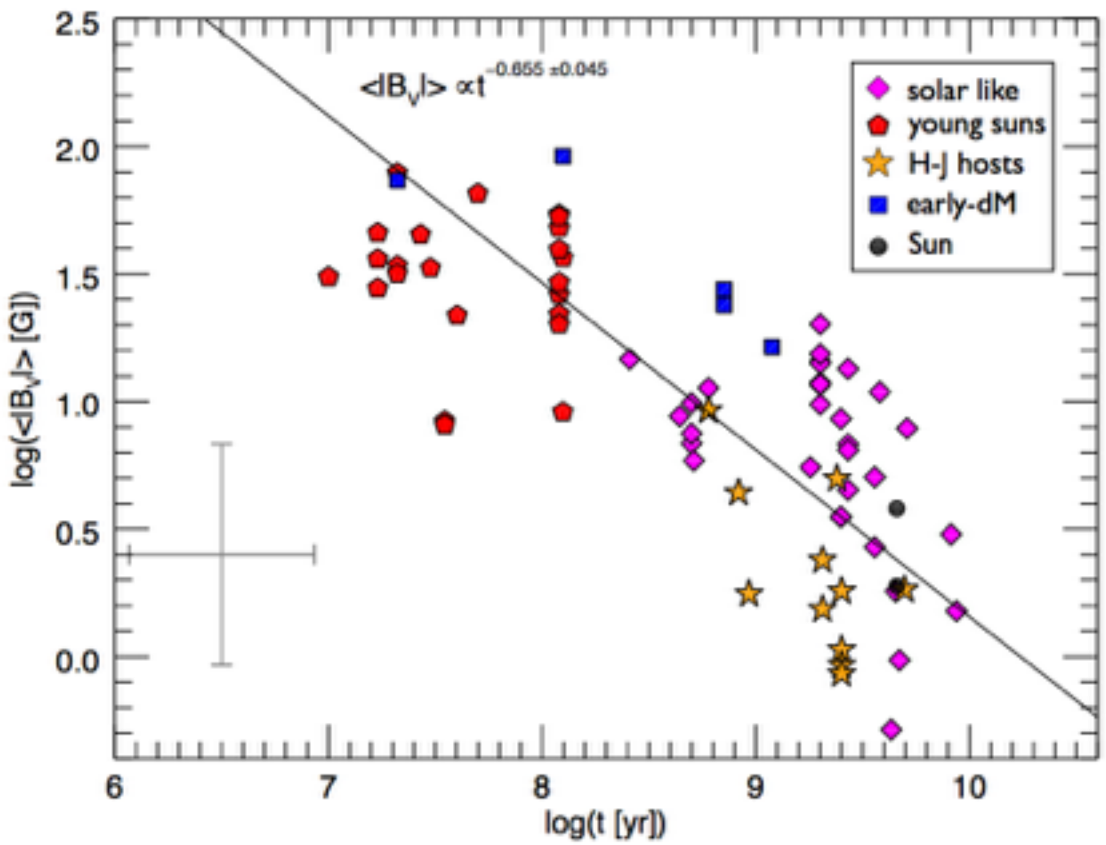
6 ZDI MAPS OF SOLAR TYPE STARS

[Folsom et al. 2016]

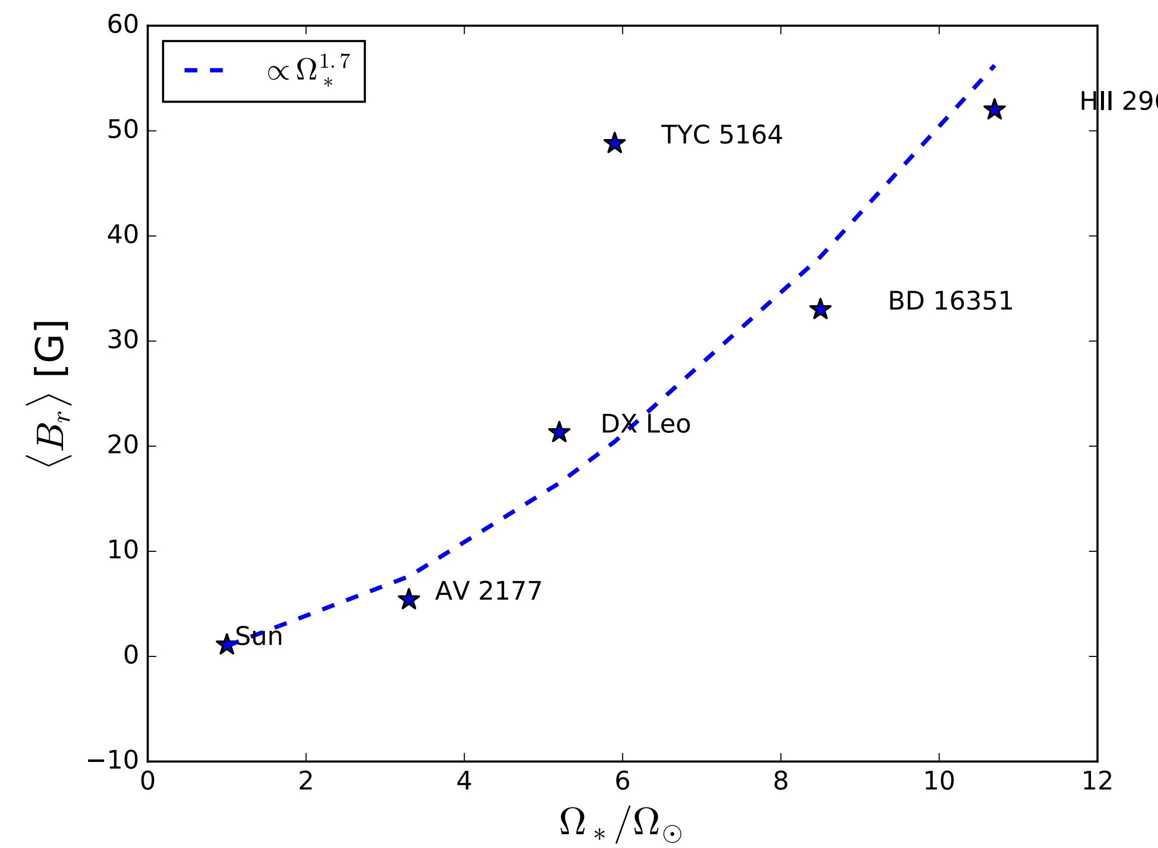
Name	Age (Myr)	Period (days)	Mass ($M_\odot$)	Radius ($R_\odot$)	$T_{\rm eff}$ (K)	$\langle B_r \rangle$ (G)	% dipole	% axis.
BD- 16351	42 ± 6	3.3	0.9	0.9	5243	33.0	60	5
TYC 5164-567-1	120 ± 10	4.7	0.9	0.9	5130	48.8	78	78
HII 296	125 ± 8	2.6	0.9	0.9	5322	52.0	57	50
DX Leo	257 ± 47	5.4	0.9	0.9	5354	21.3	69	1
AV 2177	584 ± 10	8.4	0.9	0.9	5316	5.4	57	4
Sun 1996	4570	28	1.0	1.0	5778	1.1	35	75



B VS AGE



[Vidotto 2014]



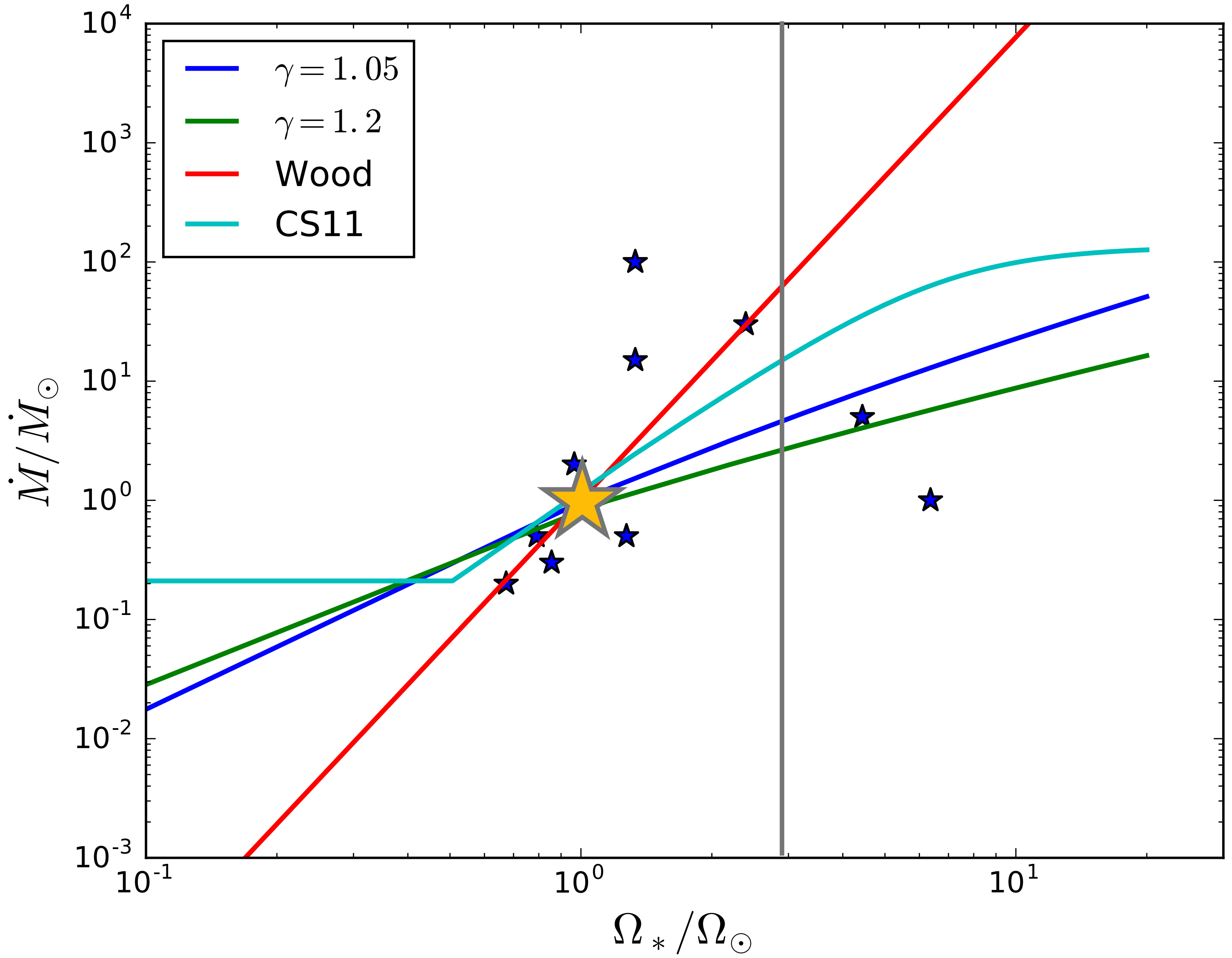
[This study]

$$\langle B \rangle \propto \Omega_\star^{1.3}$$

(reversed skumanich)

$$\langle B \rangle \propto \Omega_\star^{1.7}$$

CORONAL RECIPES



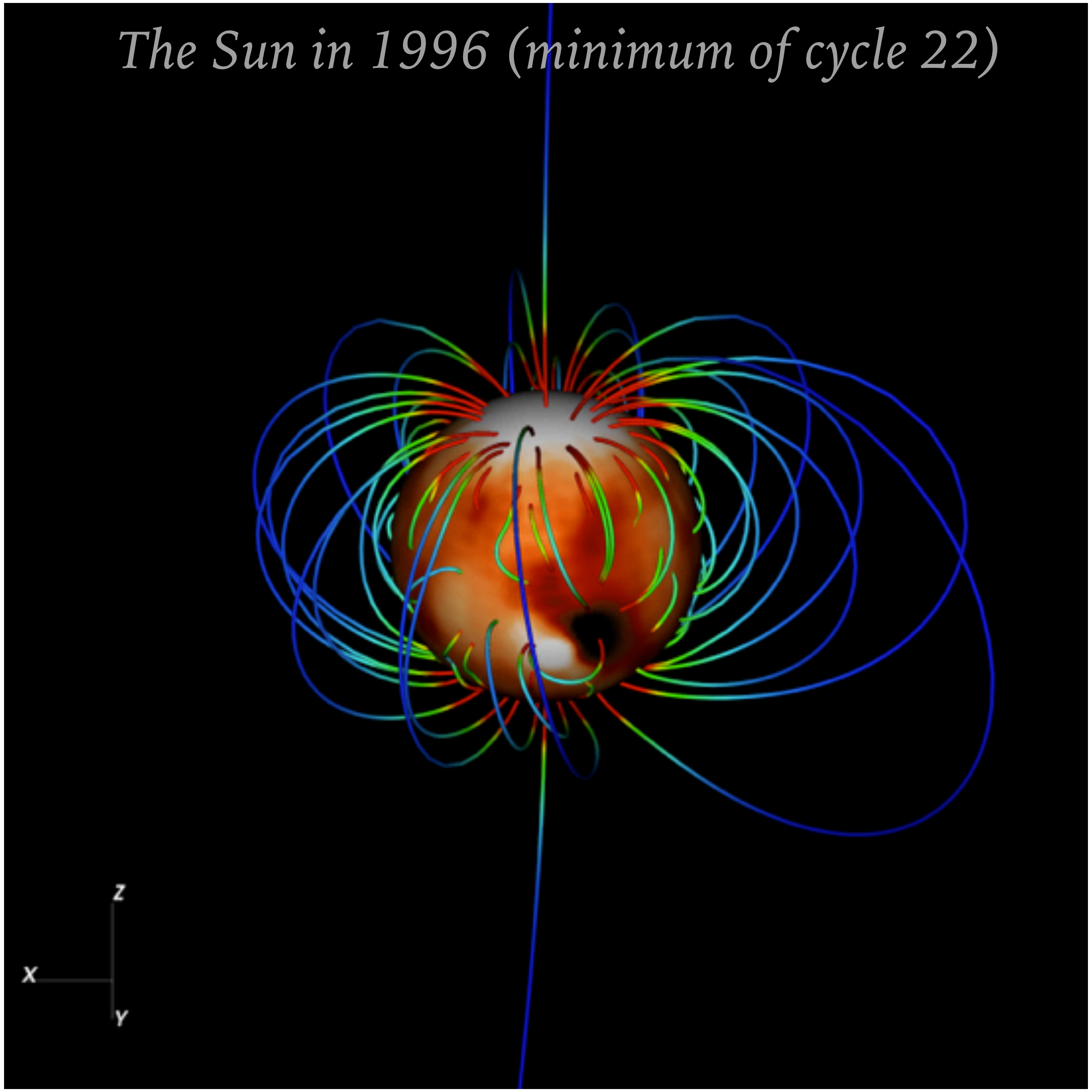
Transition below the Fx usual sat

[Wood 2005]
[Suzuki 2013]
[Vidotto 2016]

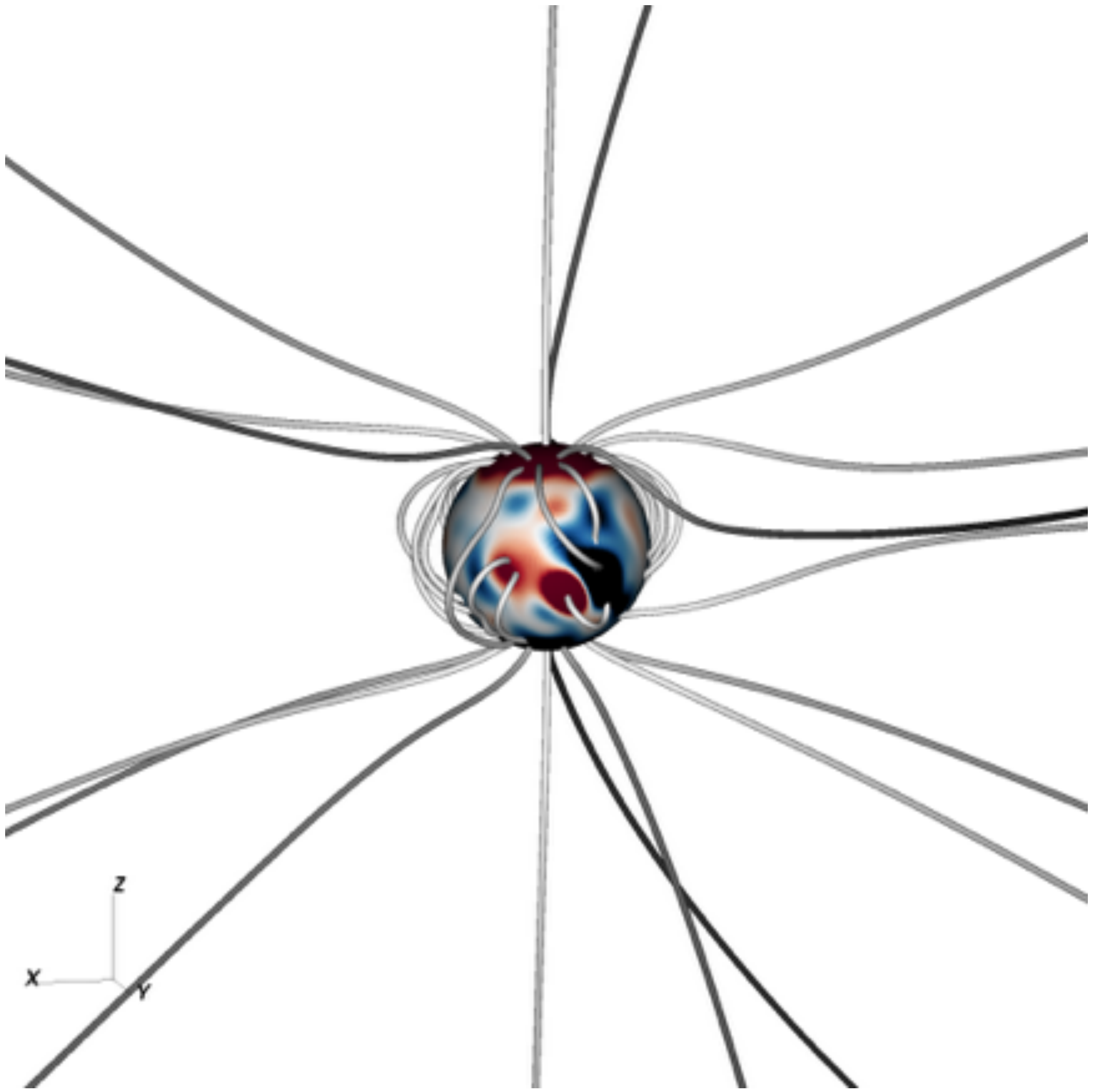
$$T = T_\odot \left(\frac{\Omega_*}{\Omega_\odot}\right)^{0.1} \quad n = n_\odot \left(\frac{\Omega_*}{\Omega_\odot}\right)^{0.6}$$

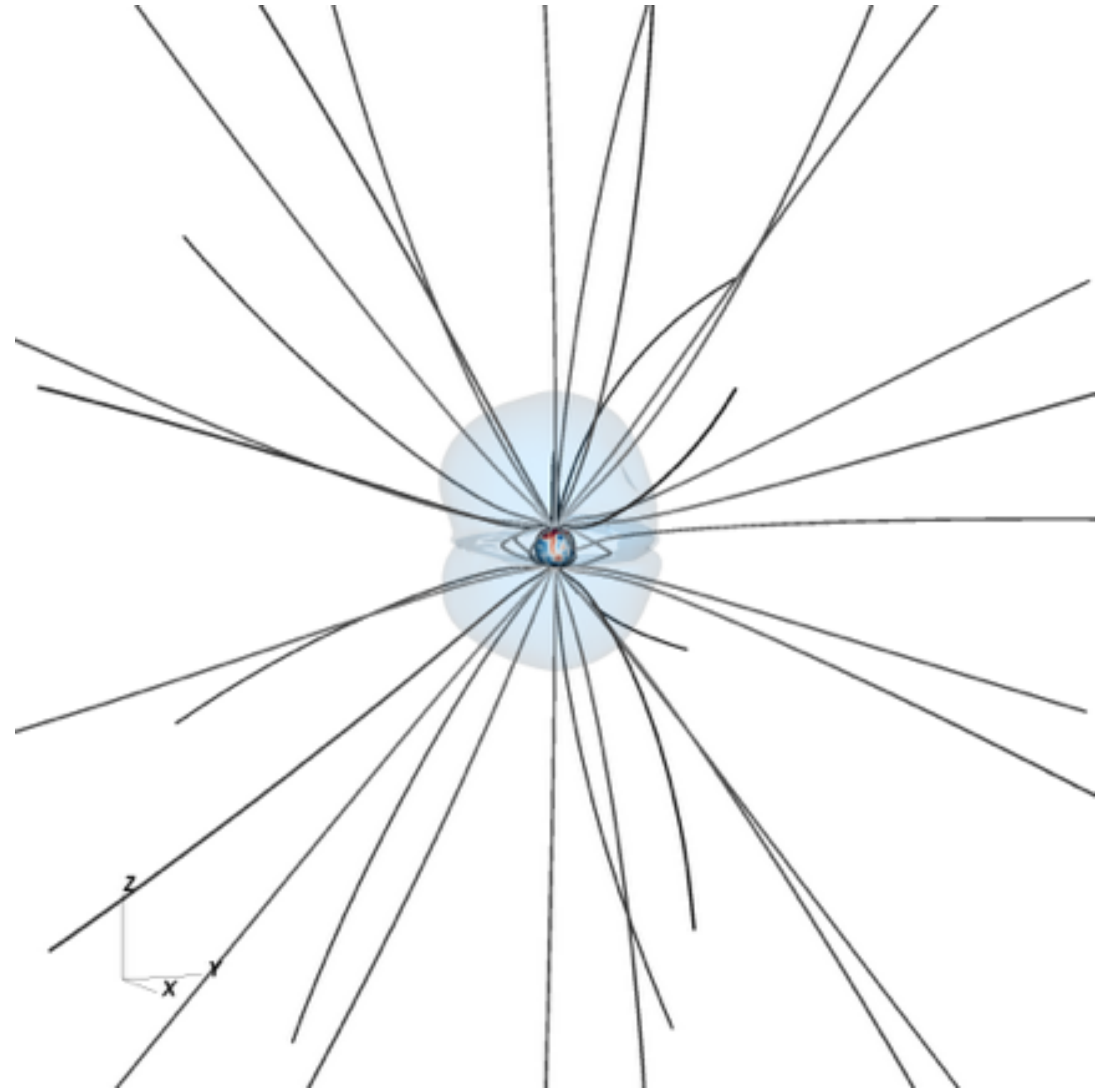
[Holzwarth & Jardine 2007]
[Réville et al. in prep]

REACHING A STEADY STATE

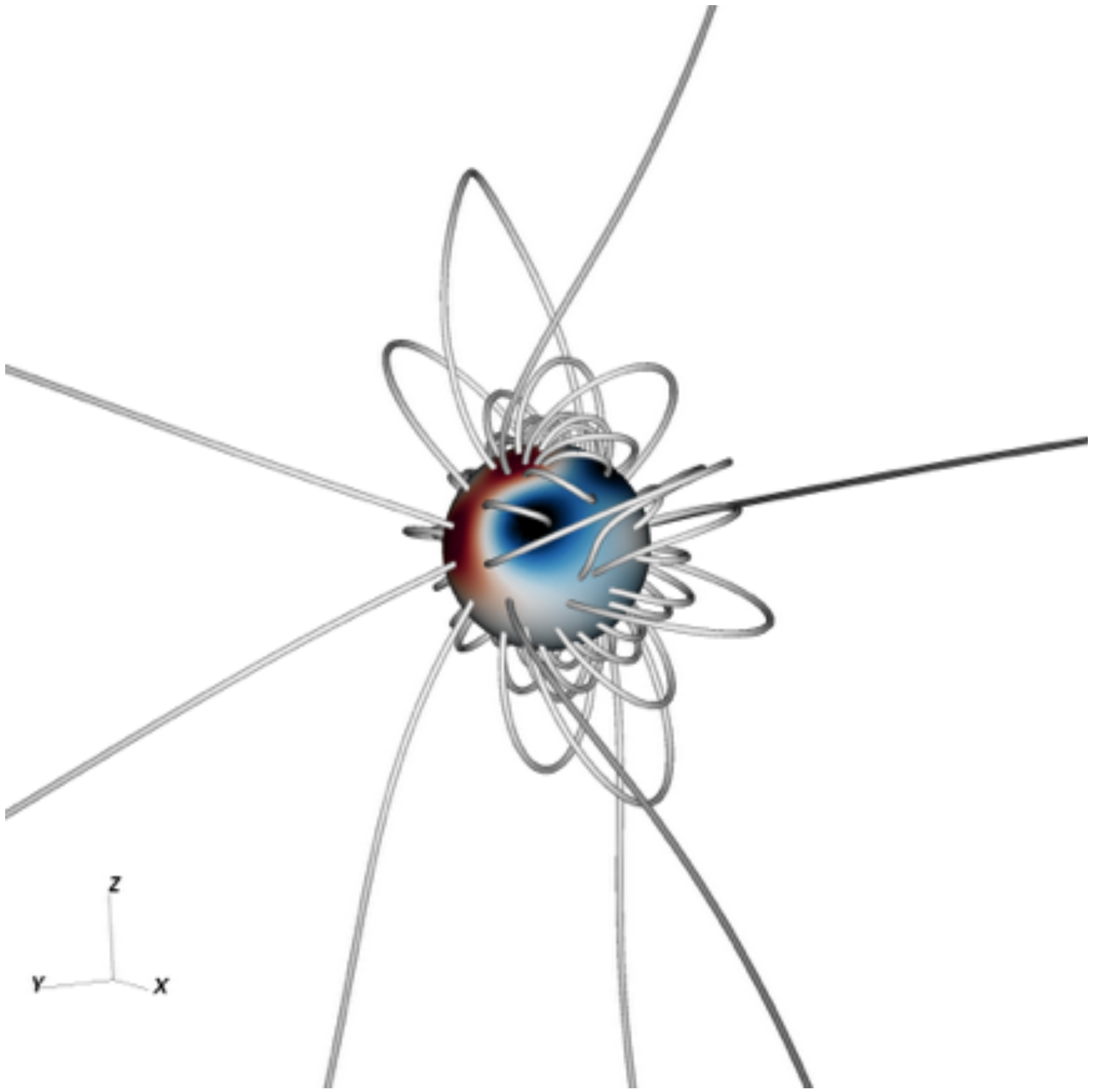


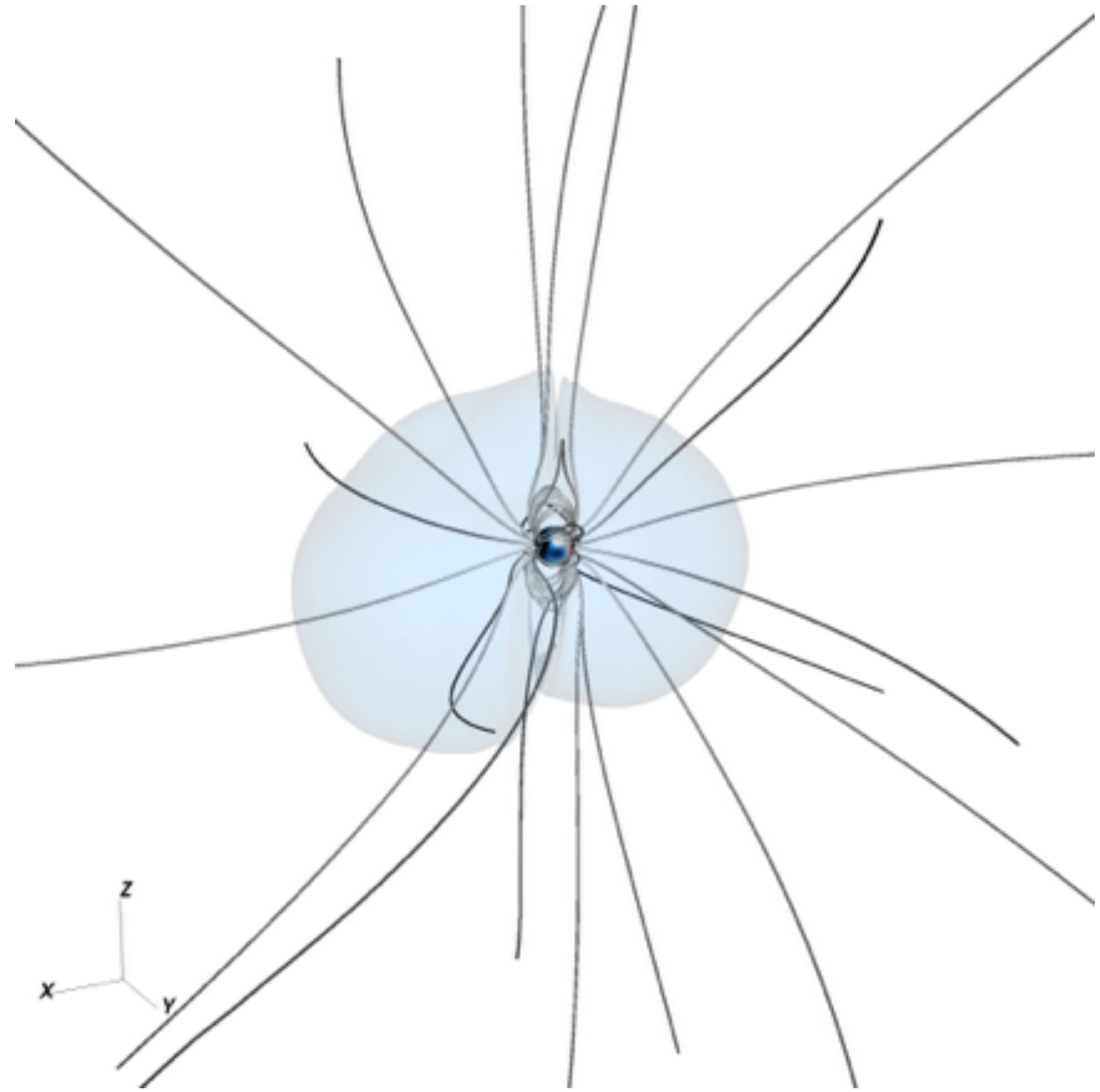
SUN



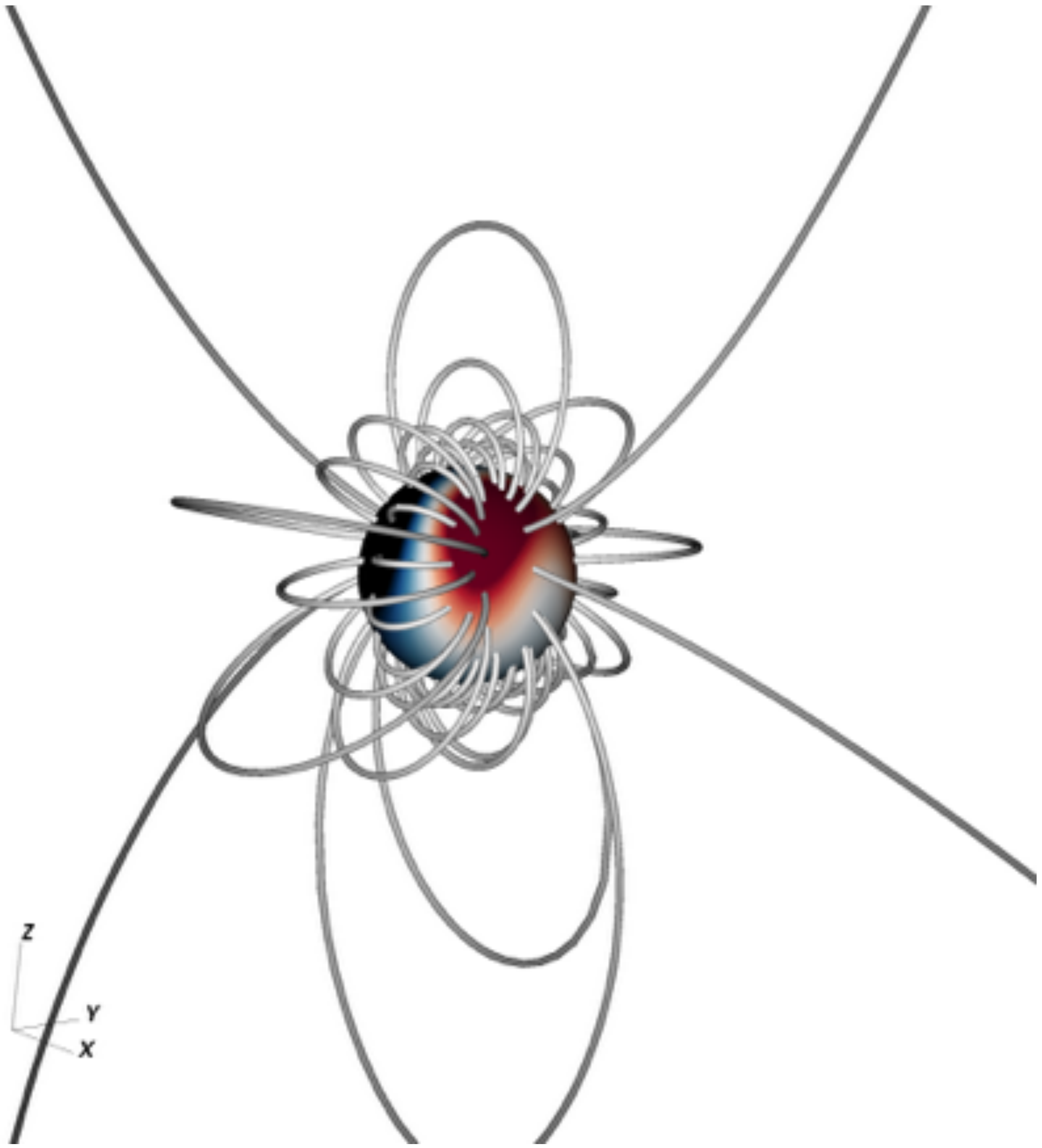


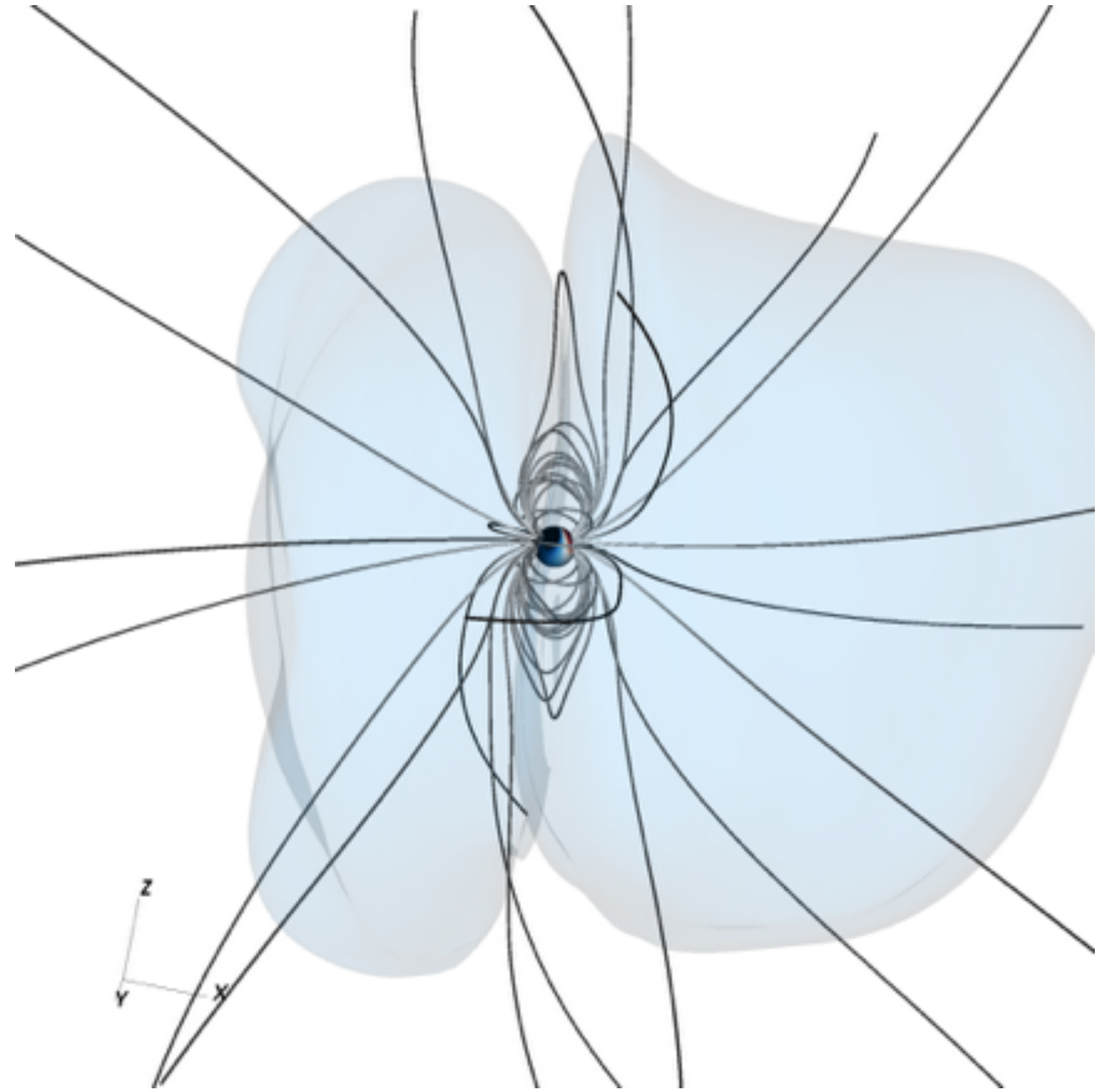
AV 2177



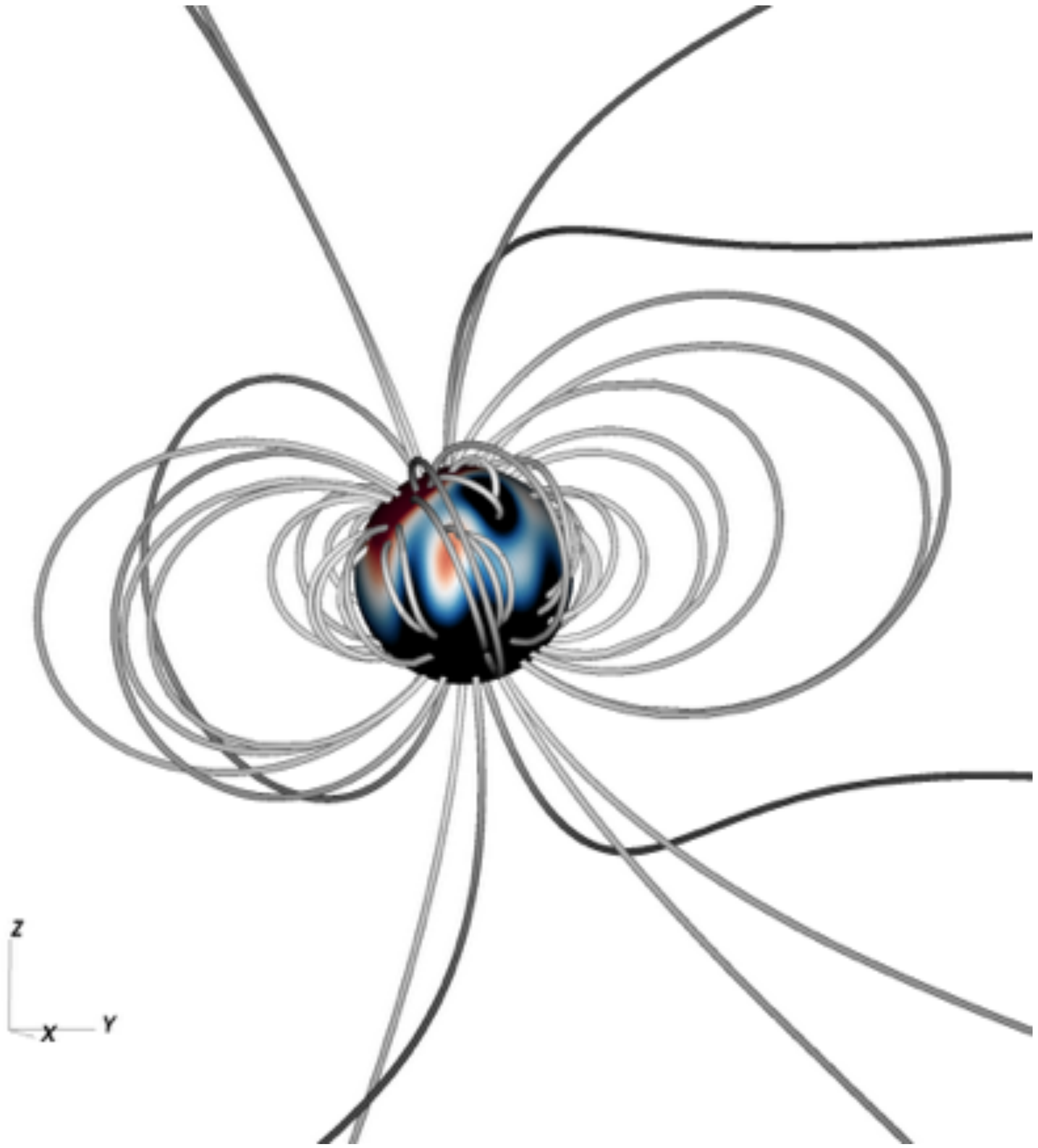


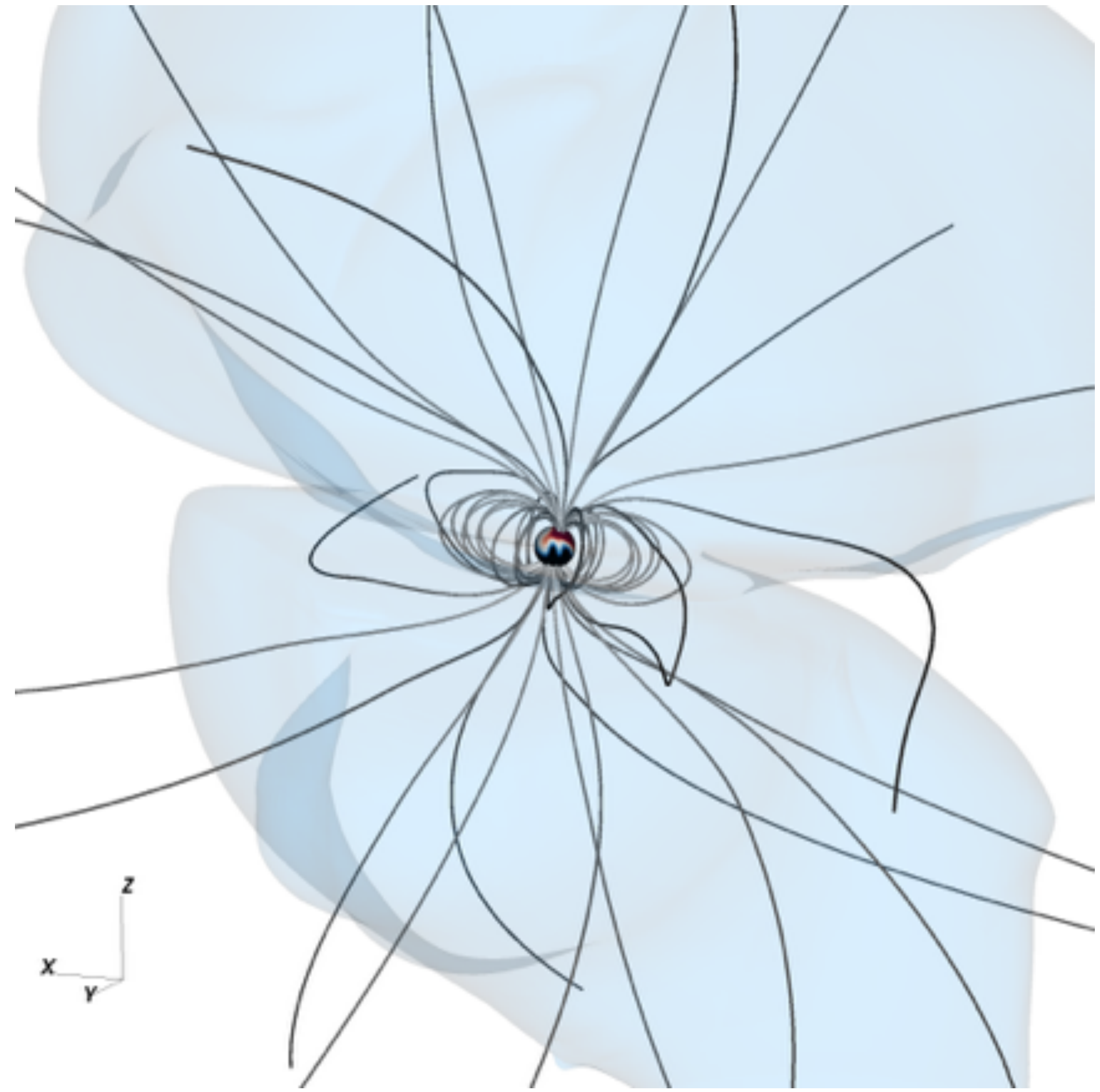
DX LEO



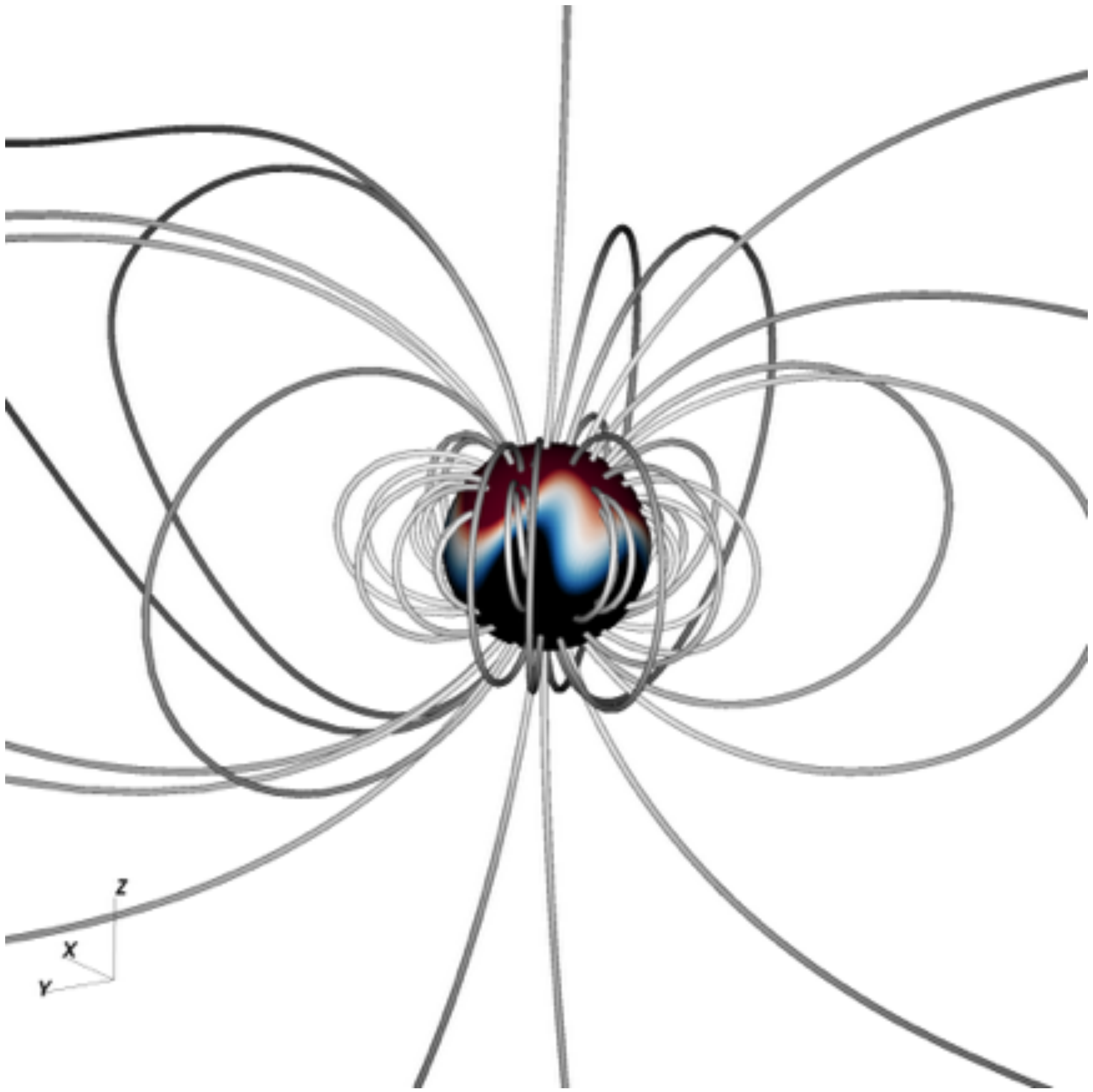


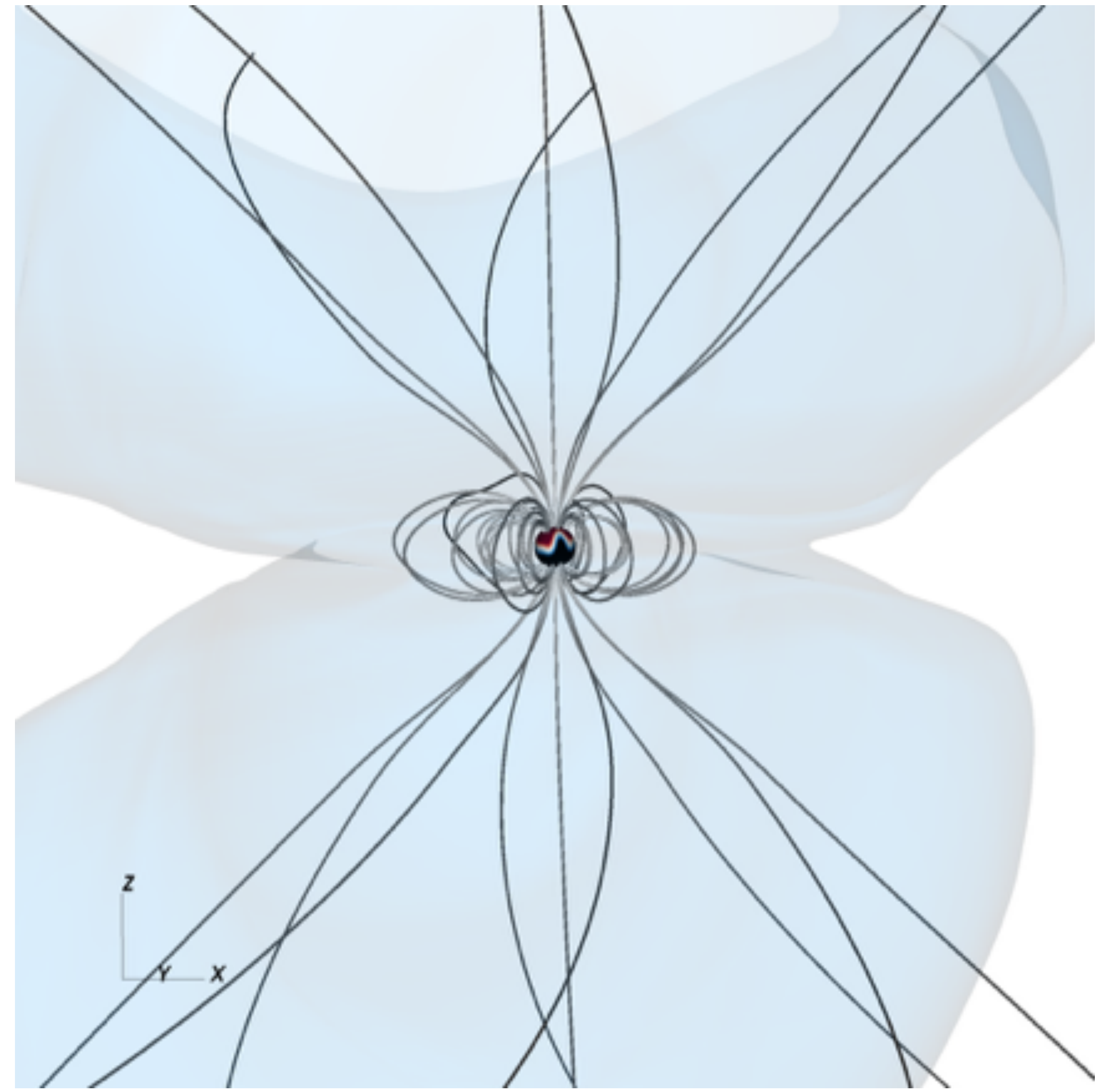
HII 296



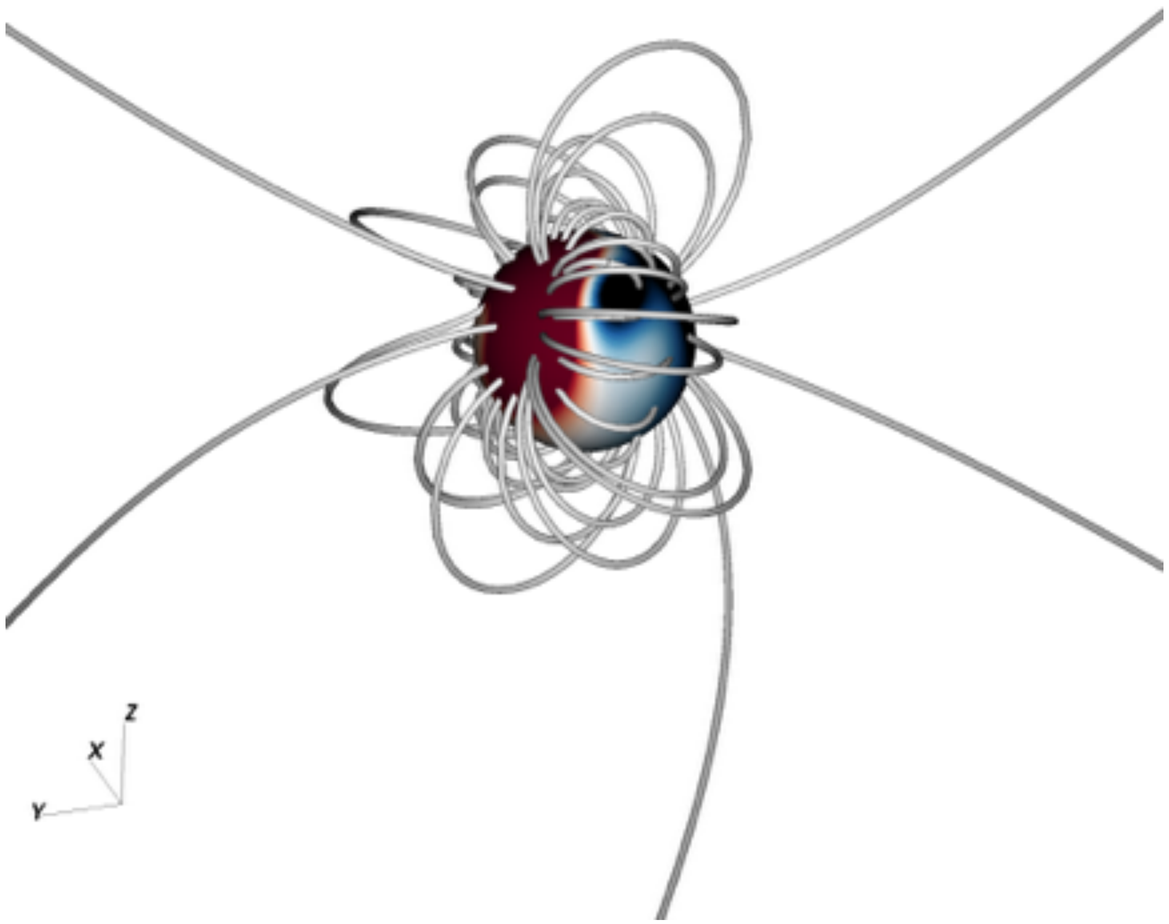


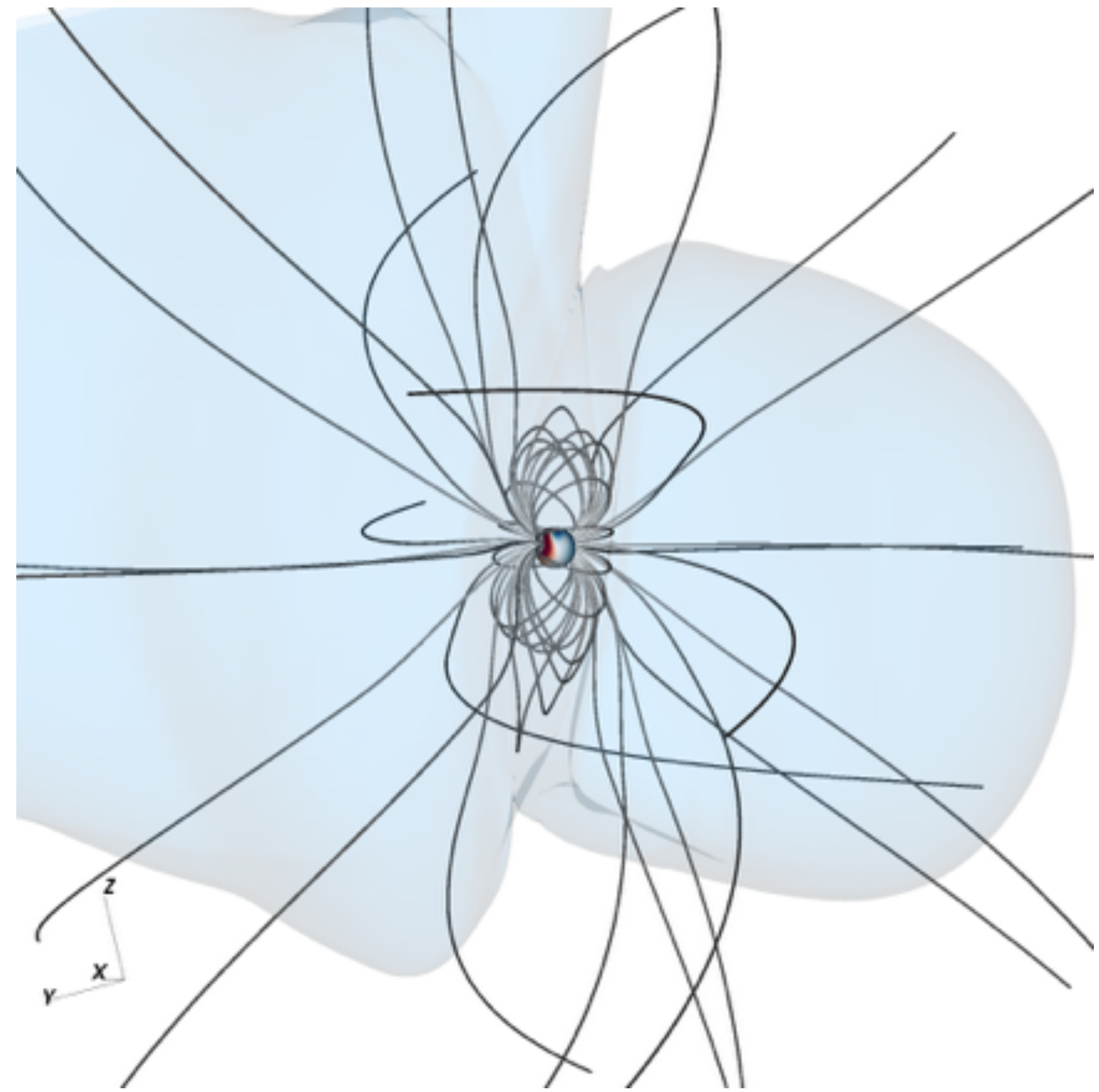
TIC 5164



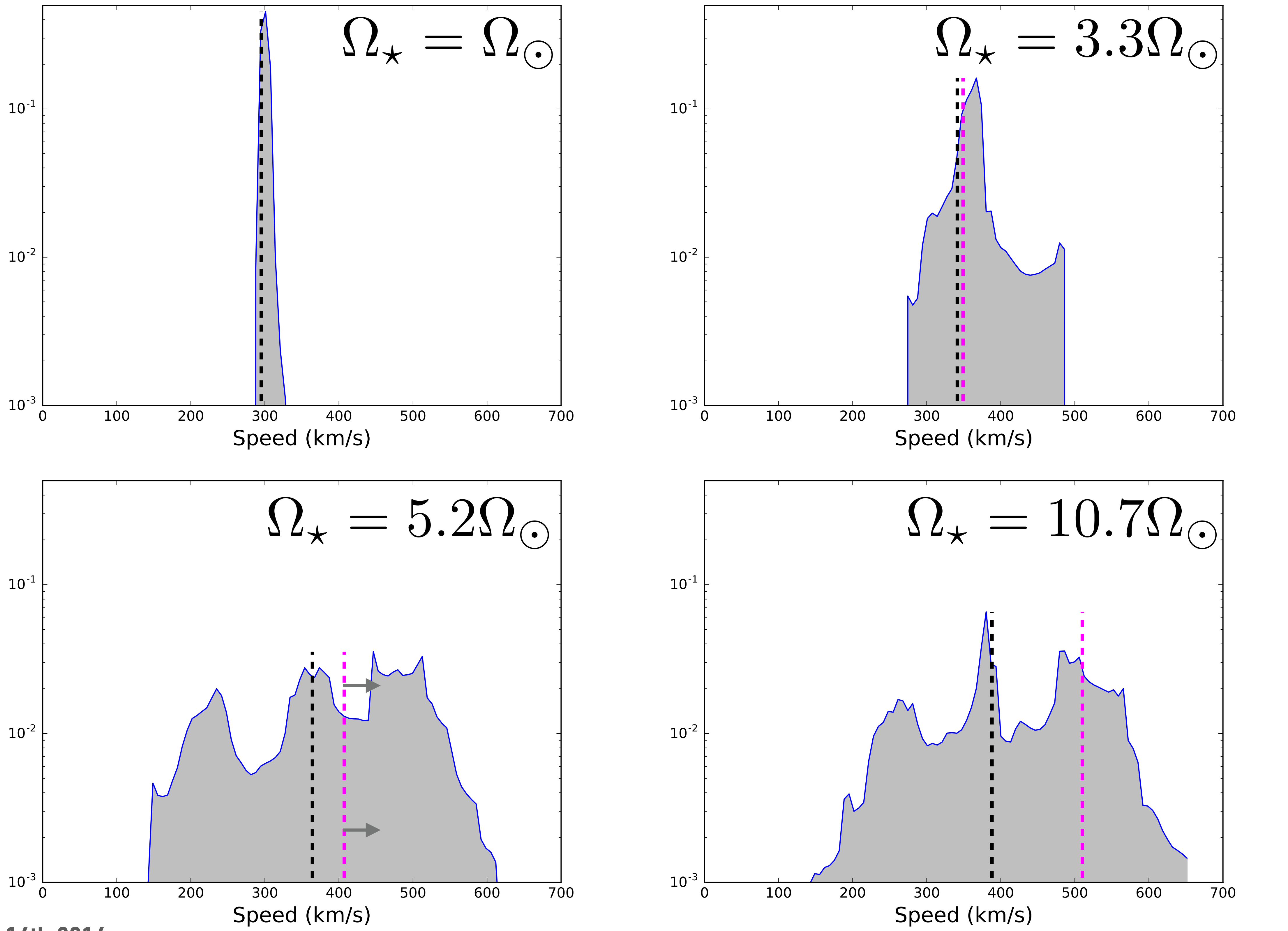


BD- 16351

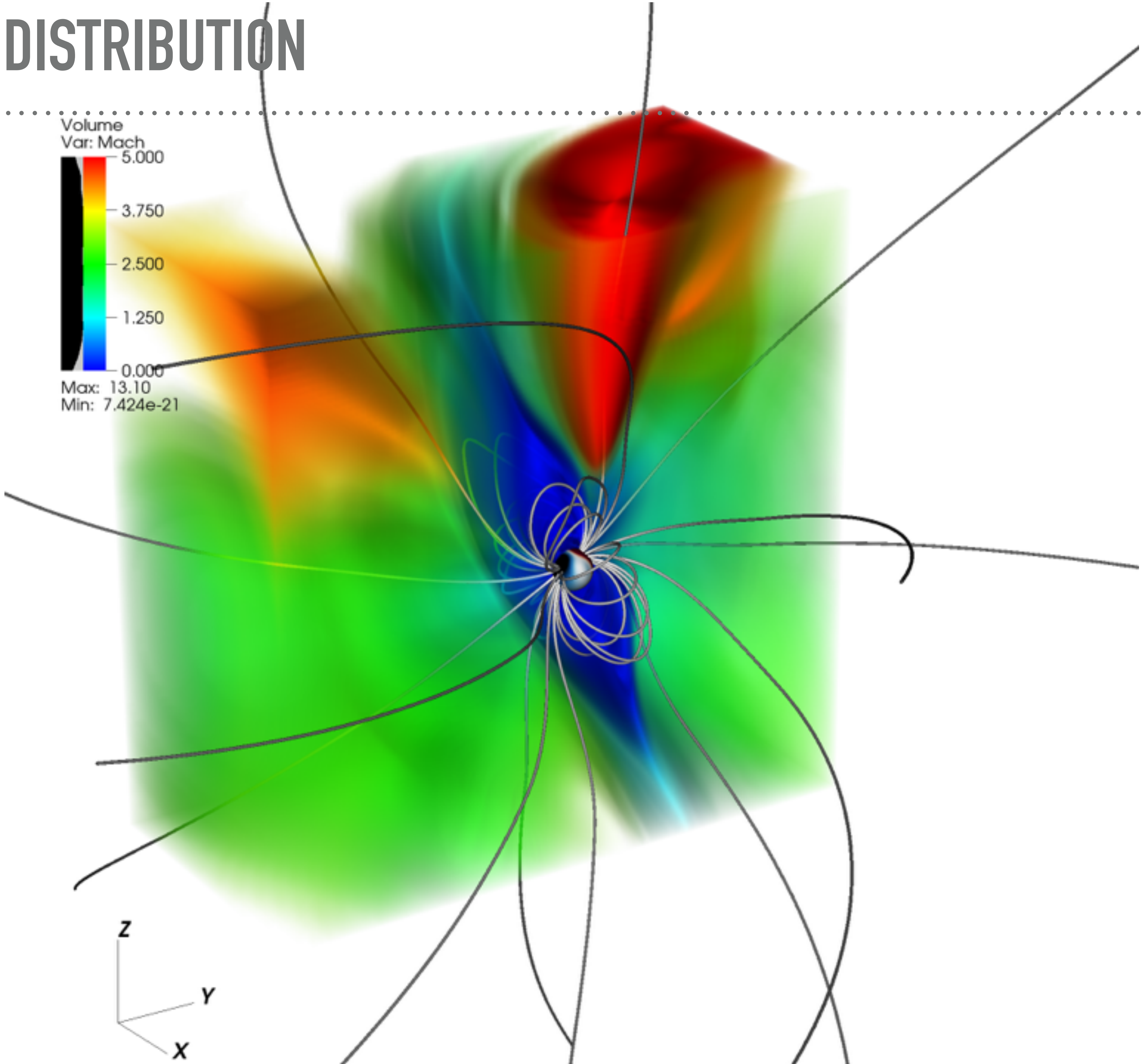




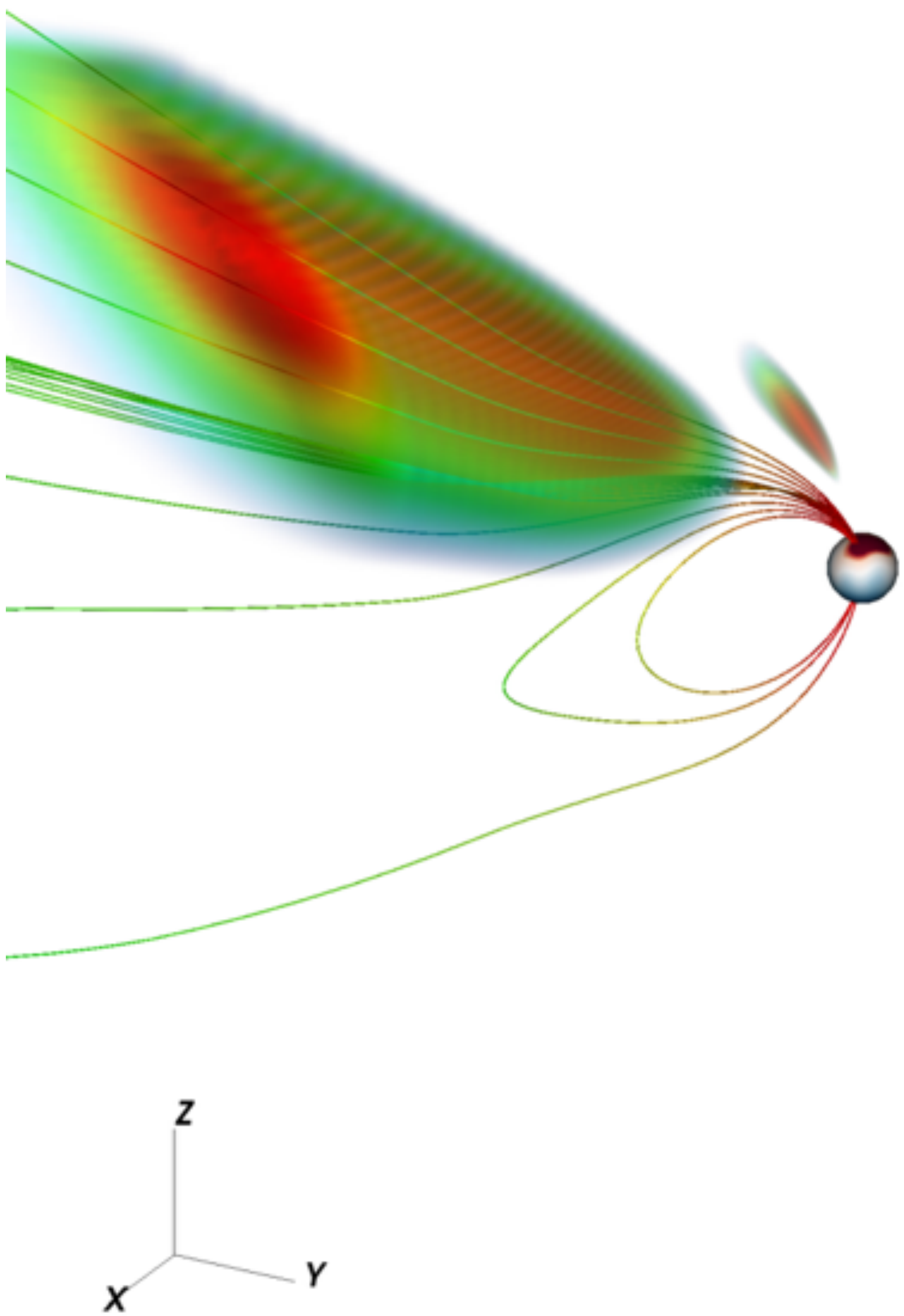
VELOCITY DISTRIBUTION AT 25 R

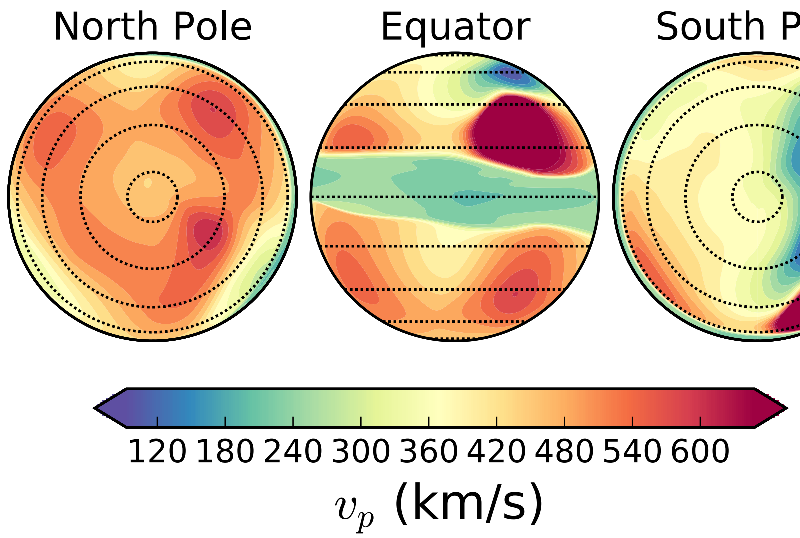


SPATIAL DISTRIBUTION

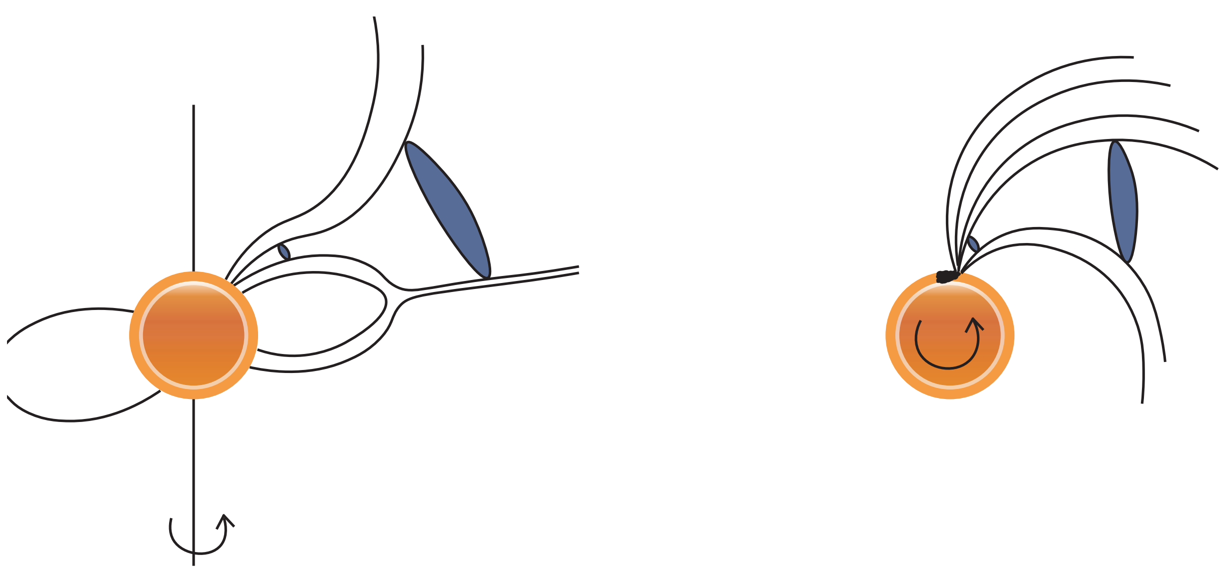


‘SUPER’ FAST STREAMS



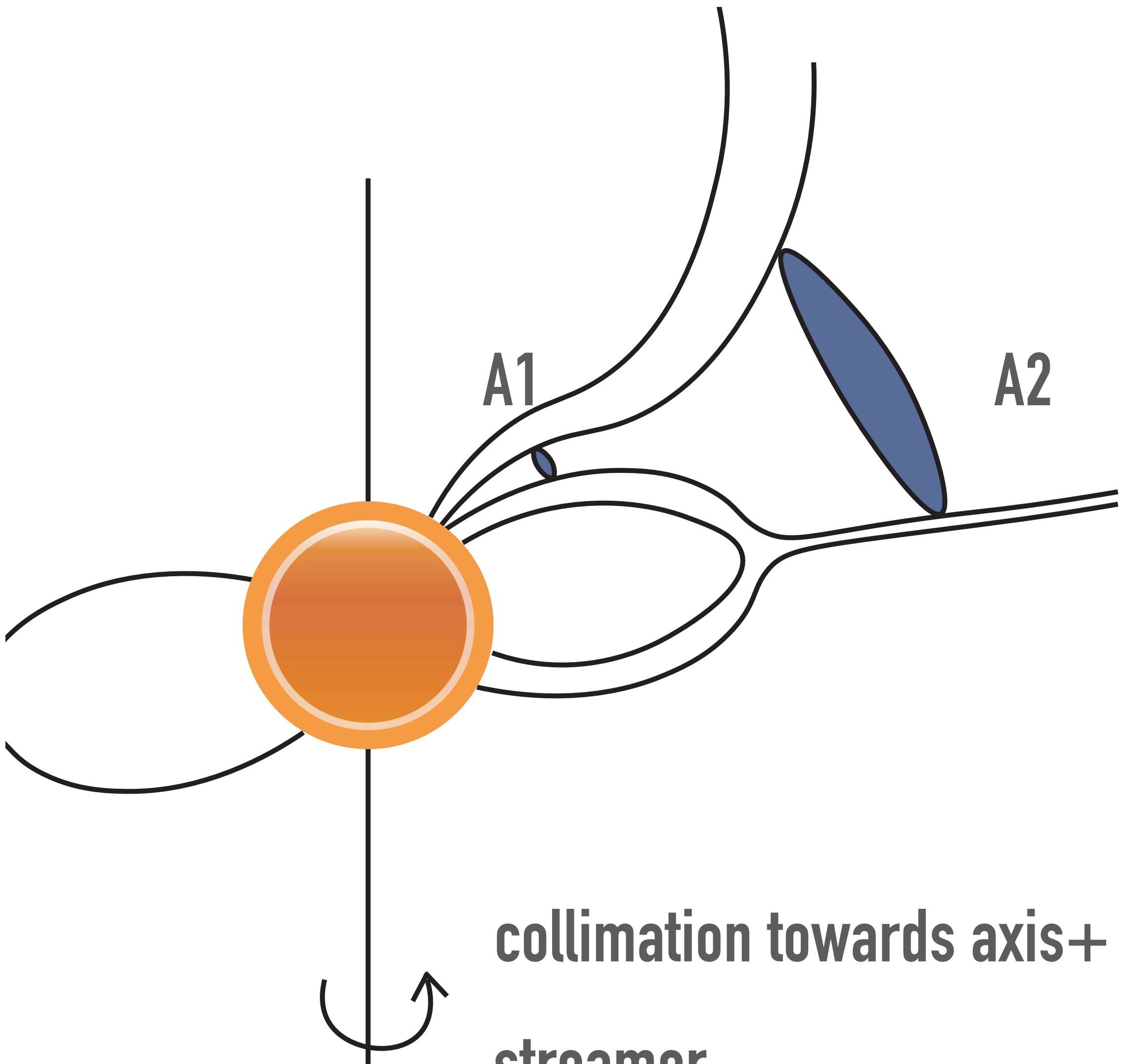


Velocity peak 1300 km/s (25R)



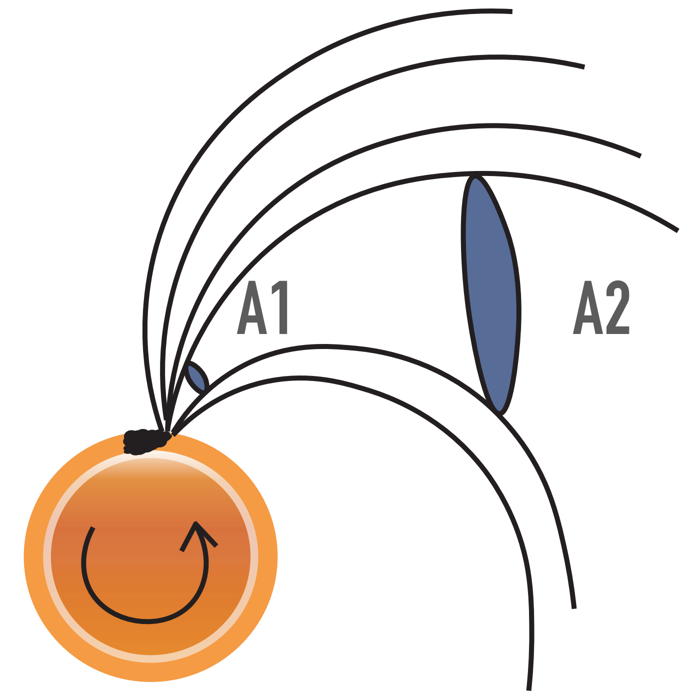
Superradial expansion: 2 causes

SUPERRADIAL EXPANSION



collimation towards axis+

streamer

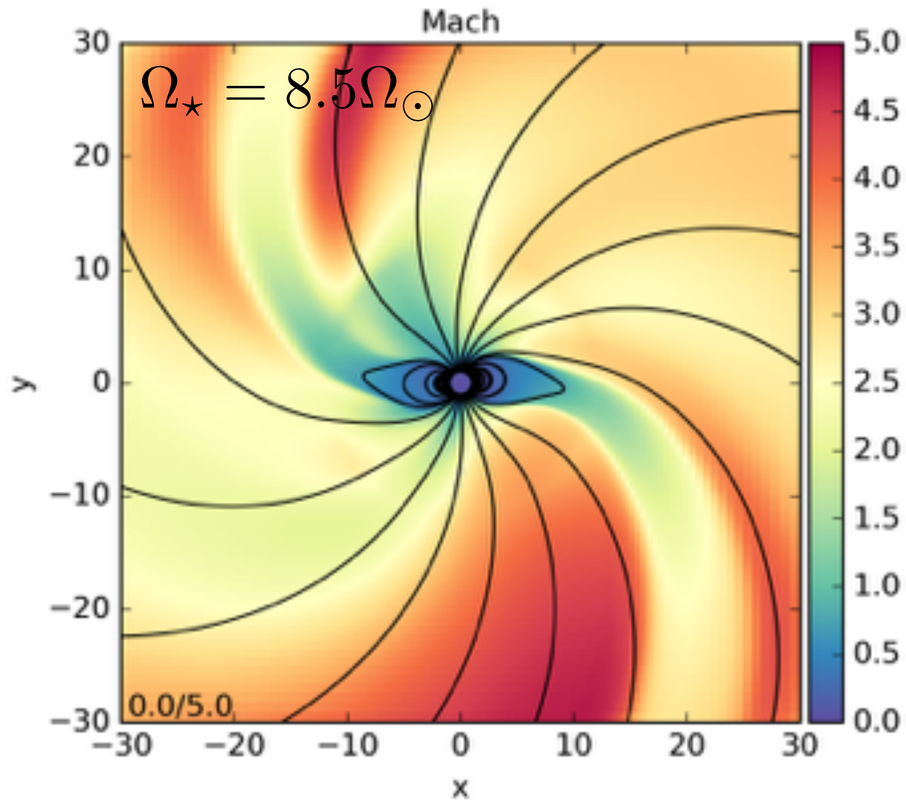


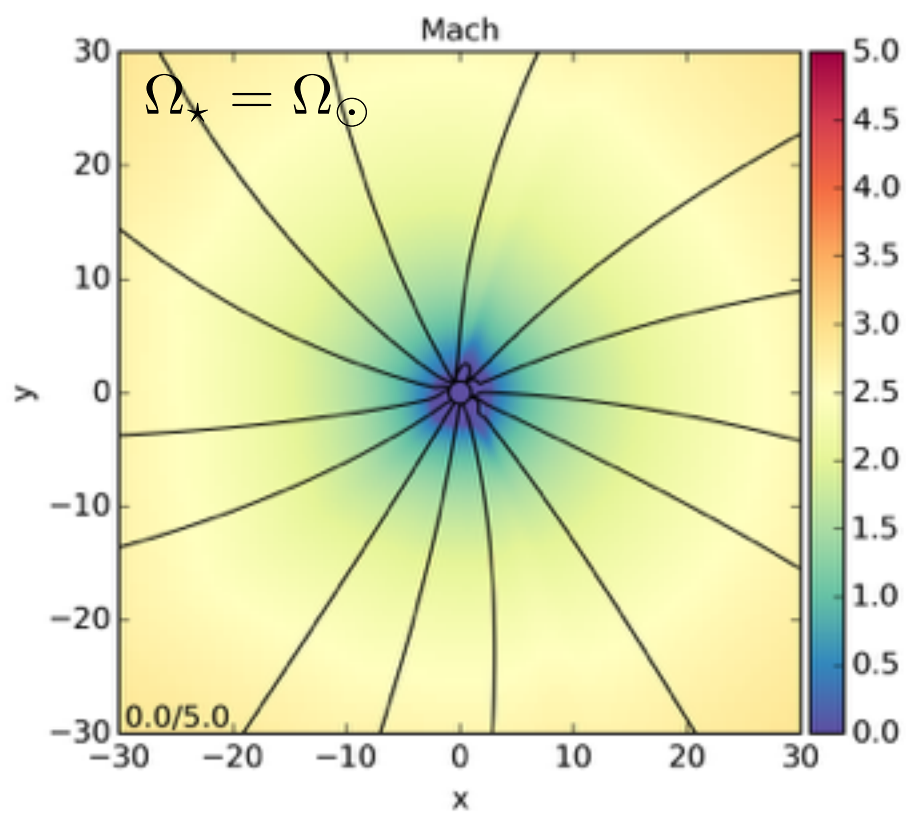
high flux concentration/differential

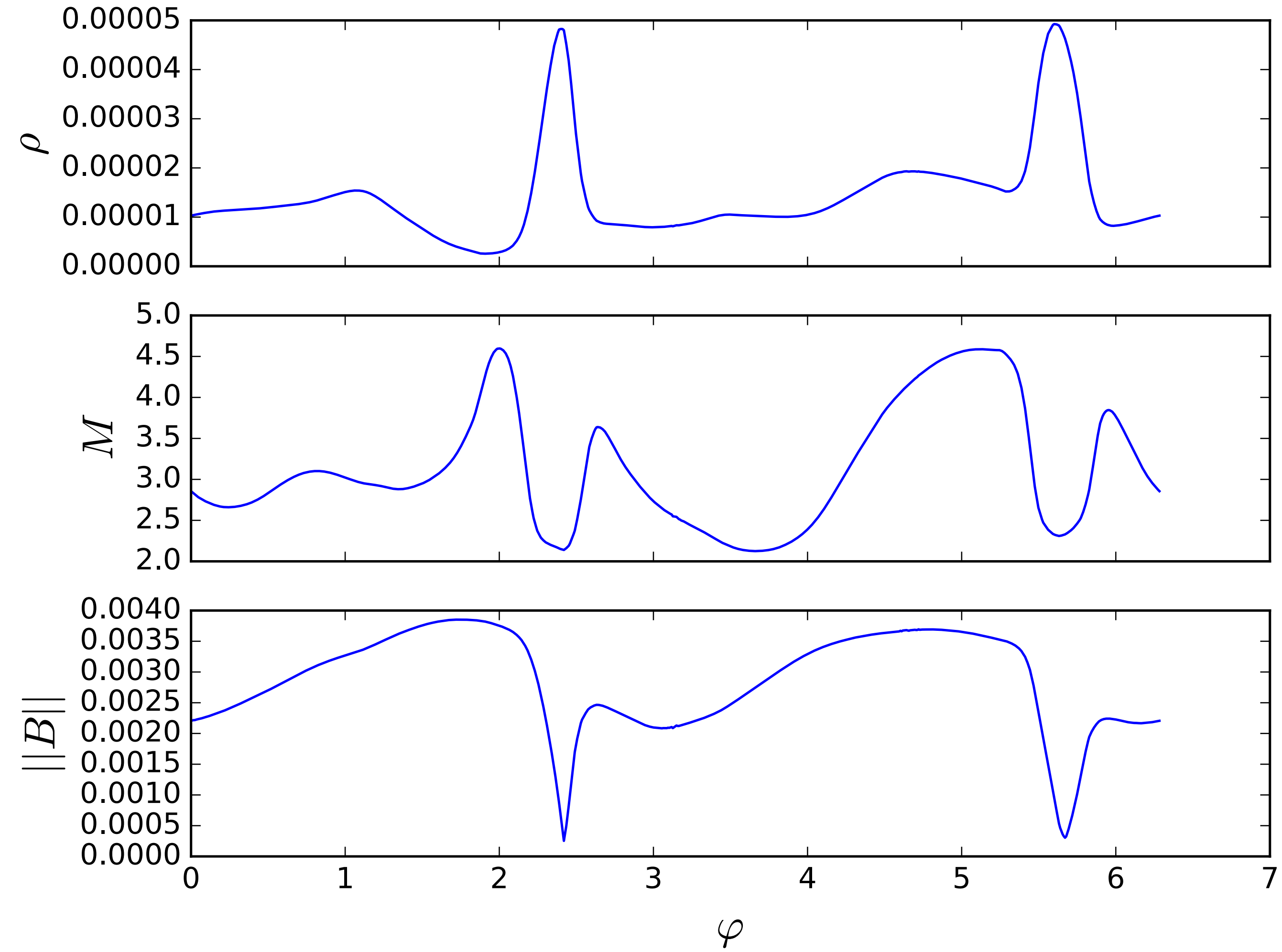
magnetic stress

$$f_{\exp} = \frac{A_2}{A_1}\frac{r_1^2}{r_2^2} \sim 100 - 1000$$

CIRS IN THE EQUATORIAL PLANE ?







- *Parker spiral*
- *Fast wind vs slow streams*
- *Corotation Interaction Regions*
- *Current sheet and polarity reversals*

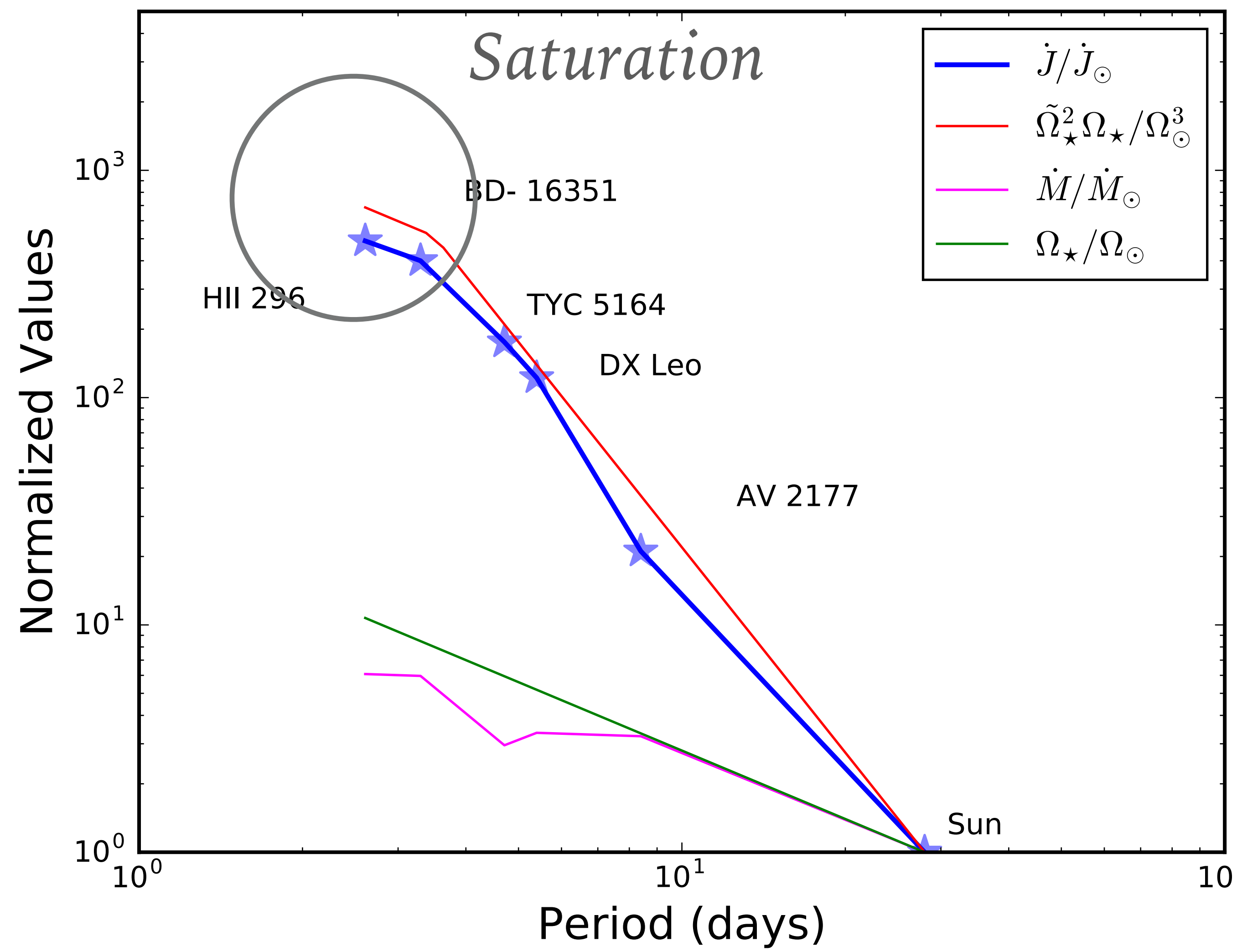
DEPENDENCE ON ROTATION RATE

$\Omega_{\rm sat} \sim 8\Omega_\odot$ *(Coherent for* $0.9M_\odot$ *)*

[Gallet & Bouvier 2015]
[Matt et al. 2015]

[Réville et al. in prep]

Name	$\Omega_\star/\Omega_\odot$	n (10^8 g/cm^3)	T (10^6 K)
BD- 16351	8.5	3.6	1.85
TYC 5164-567-1	5.9	2.9	1.8
HII 296	10.7	4.15	1.9
DX Leo	5.2	2.7	1.76
AV 2177	3.3	2.06	1.7
Sun	1.0	1.0	1.5



$$\dot J = \dot M \Omega_\star R_A^2$$

~one order of magnitude each

CONCLUSIONS

- *Slow, intermediate and fast wind components appears for fast rotators with intense magnetic fields*
- *Superradial expansion in the supersonic regime with non-axisymmetry and fast rotation !*
- *Slow and fast wind can encounter in the equatorial plane and form CIRs.*

- *3D simulations of stellar winds follow Réville et al. 2015a formulation*
- *Angular momentum and mass loss vary approximately like* $\Omega_\star^3$ *and* $\Omega_\star$

OPEN FLUX