3D SIMULATIONS OF YOUNG STARS CONSTRAINED BY ZDI MAPS

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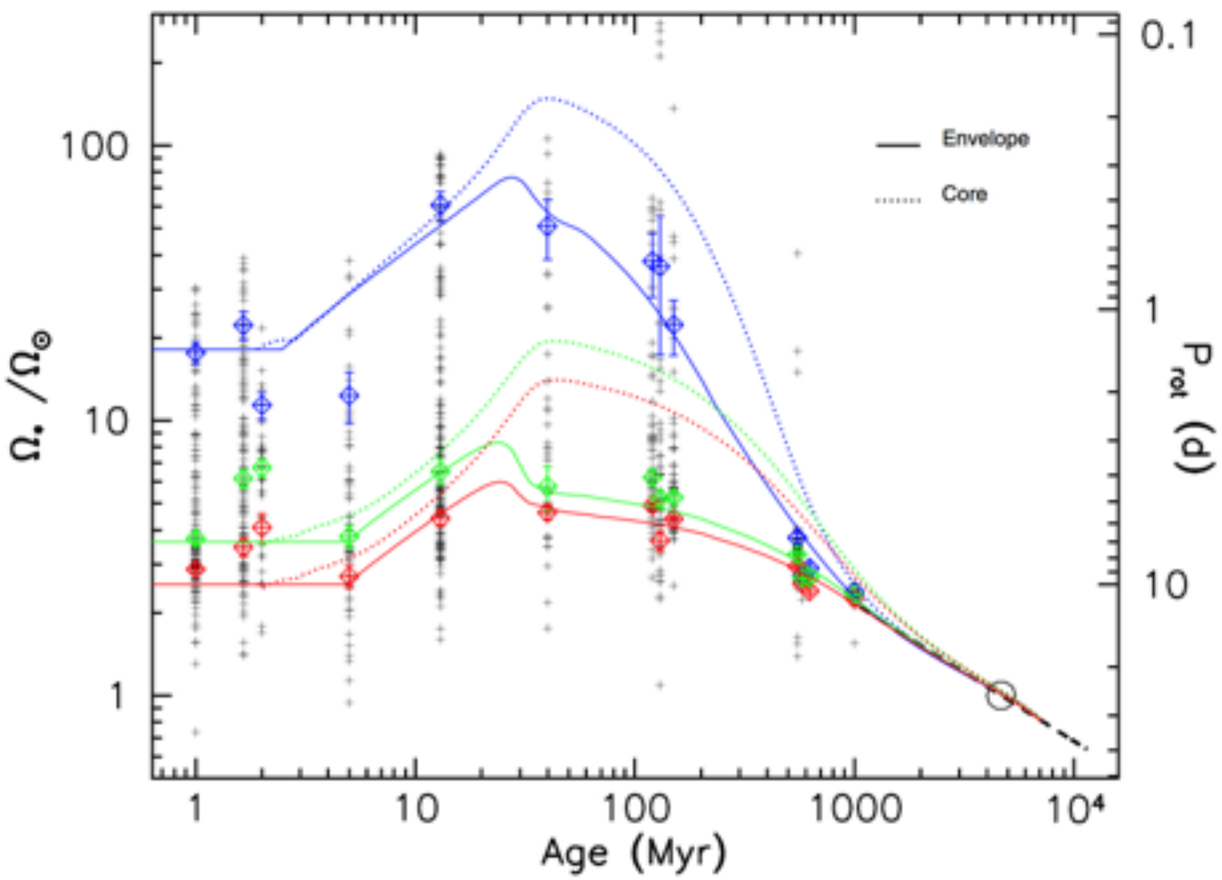
STELLAR WIND BRAKING

Rotation Models
[Gallet & Bouvier 2013]



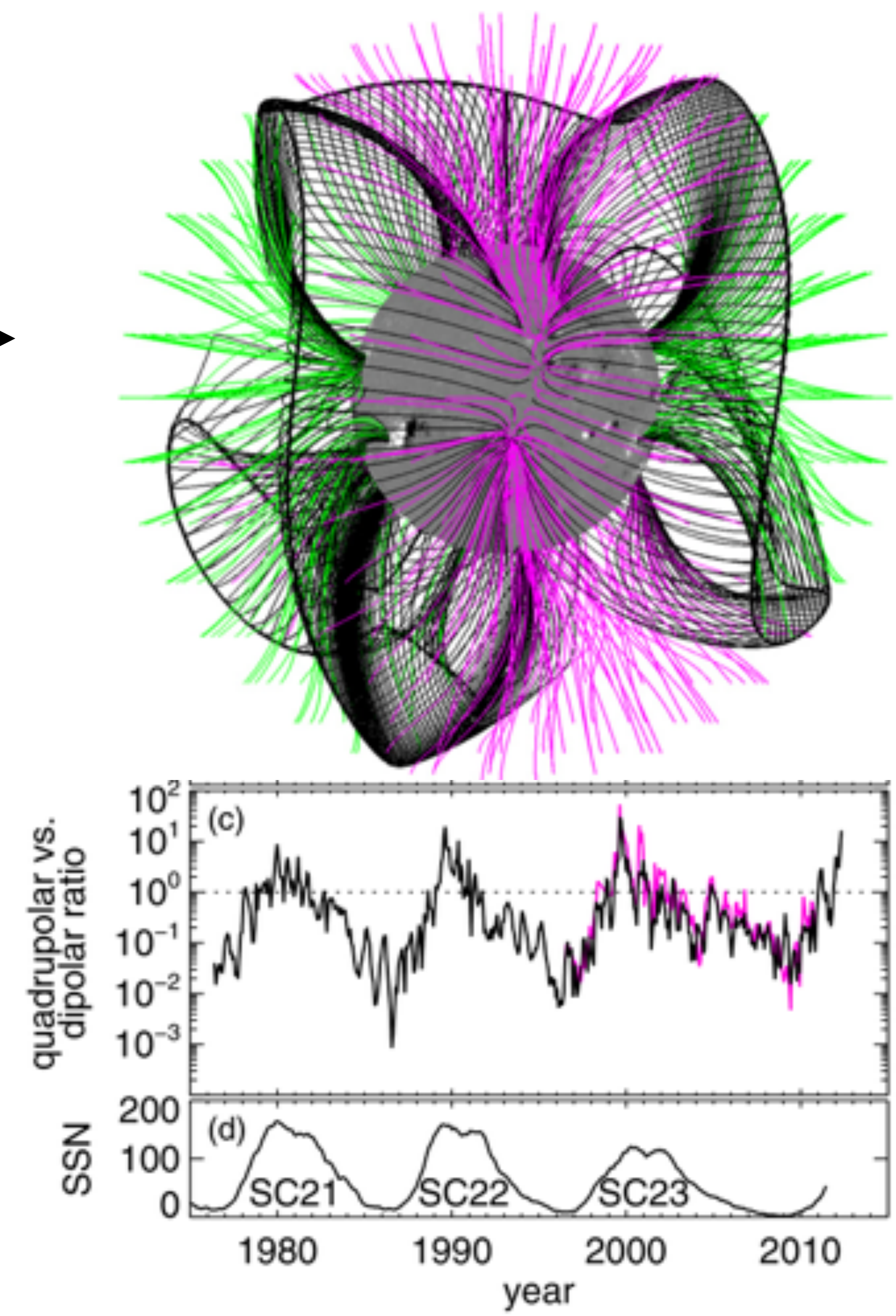
Skumanich's law:

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

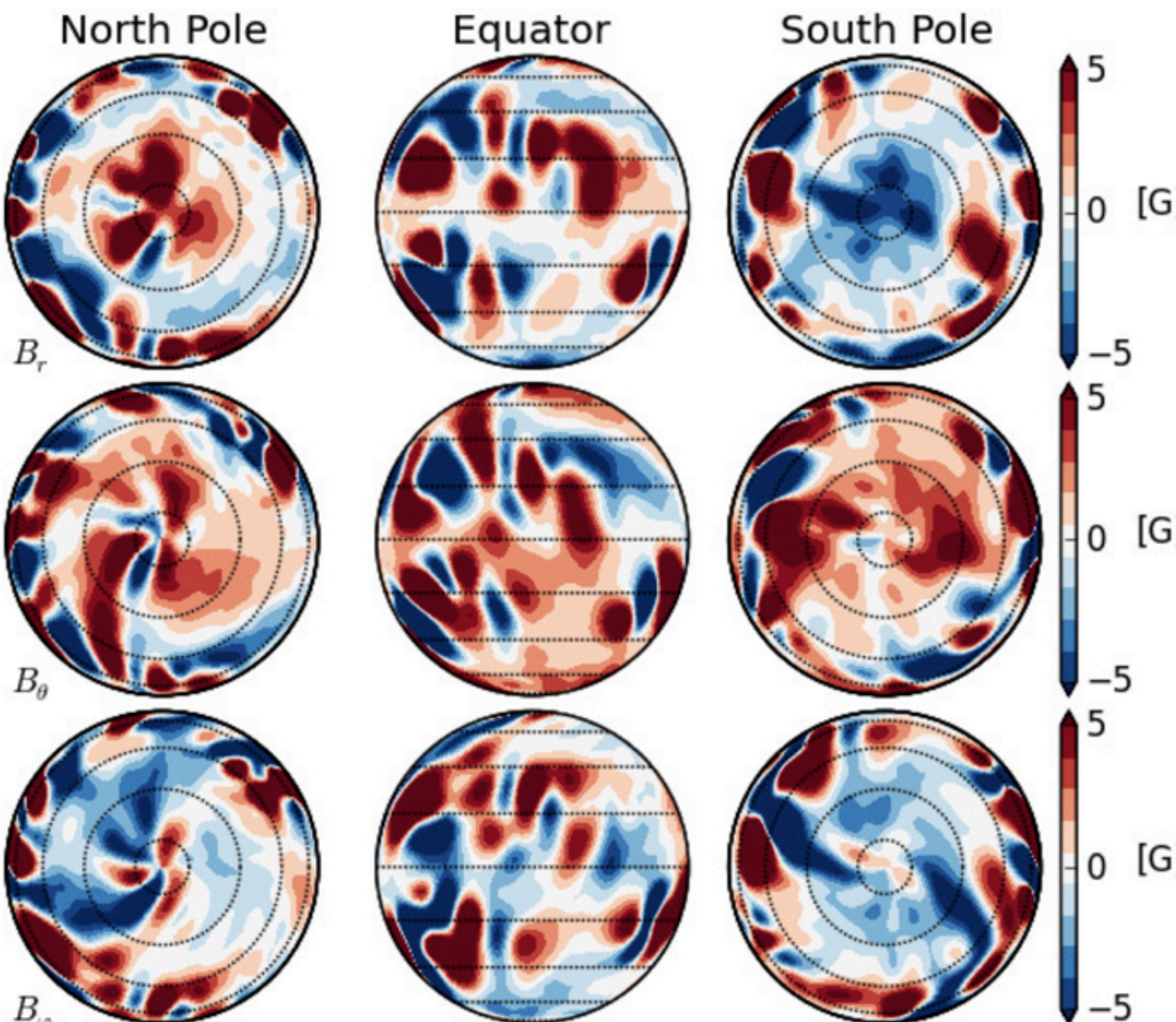
dynamo

wind

Magnetic Activity
[De Rosa, Brun, Hoeksema 2012]



SOLAR CYCLE


North Pole
Equator
South Pole
5
0
[G]
−5
5
0
[G]
−5
5
0
[G]
−5
B_r
B_θ
B_φ

STELLAR WIND BRAKING

[Bouvier et al 1997]

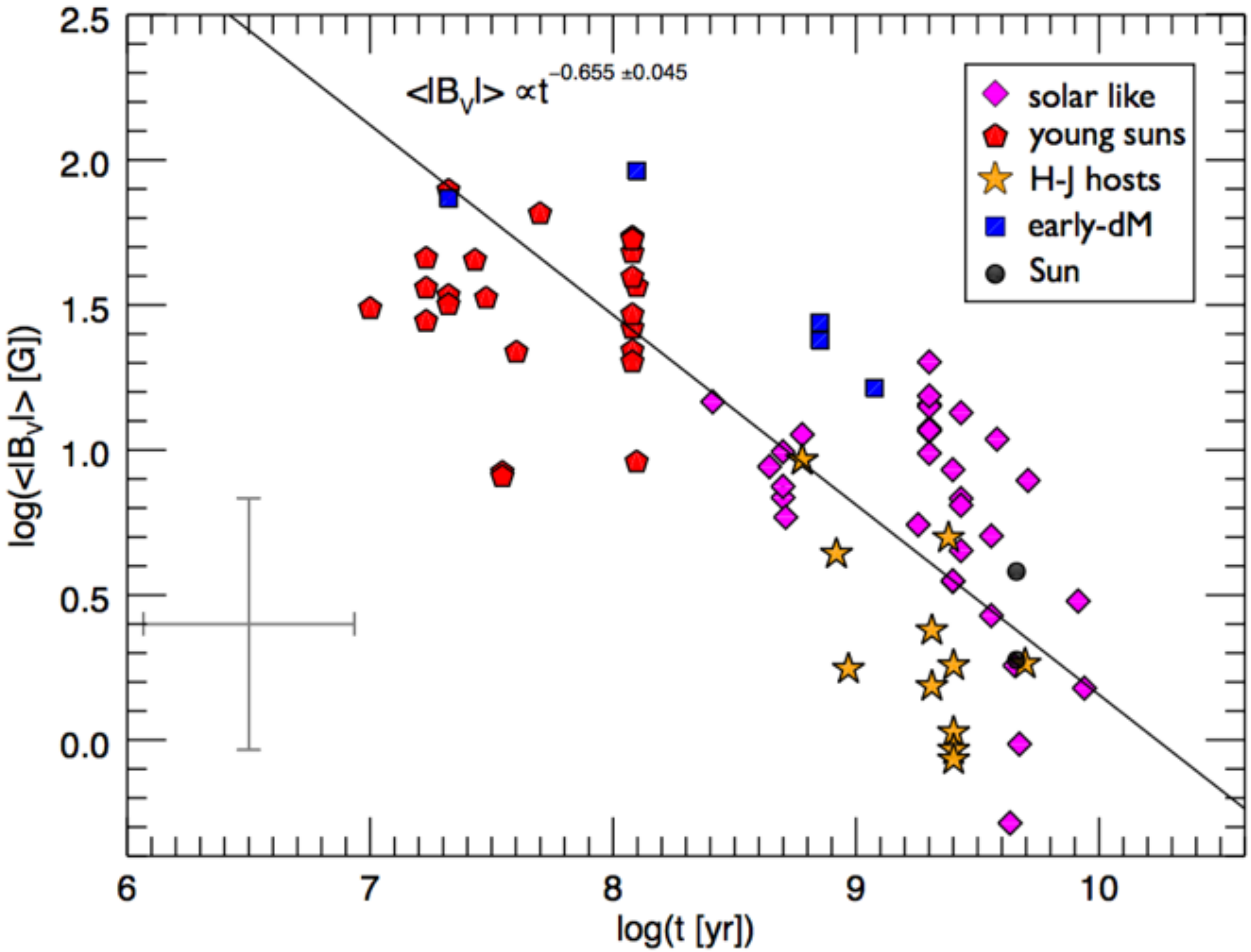
$$\frac{d\Omega}{dt} = \begin{cases} -f_P B_W \Omega^3 & \text{when} \quad \Omega \leq \omega_{\rm sat} \\ -f_P B_W \omega_{\rm sat}^2 \Omega & \text{when} \quad \Omega > \omega_{\rm sat} \end{cases}$$

$$B_W = 2.7 \times 10^{47} \frac{1}{C} \sqrt{\left(\frac{R}{R_\odot} \frac{M_\odot}{m}\right)} \qquad \text{(cgs units)}$$

Empirical, old braking law

what is hidden: $B^2 \propto \Omega^2 \propto R_o^{-2}$

MAGNETOCHRONOLOGY



Skumanich's law:

$$B \propto \Omega \propto t^{-1/2}$$

[Vidotto 2014]

THE ALFVÉN RADIUS AS A LEVER ARM

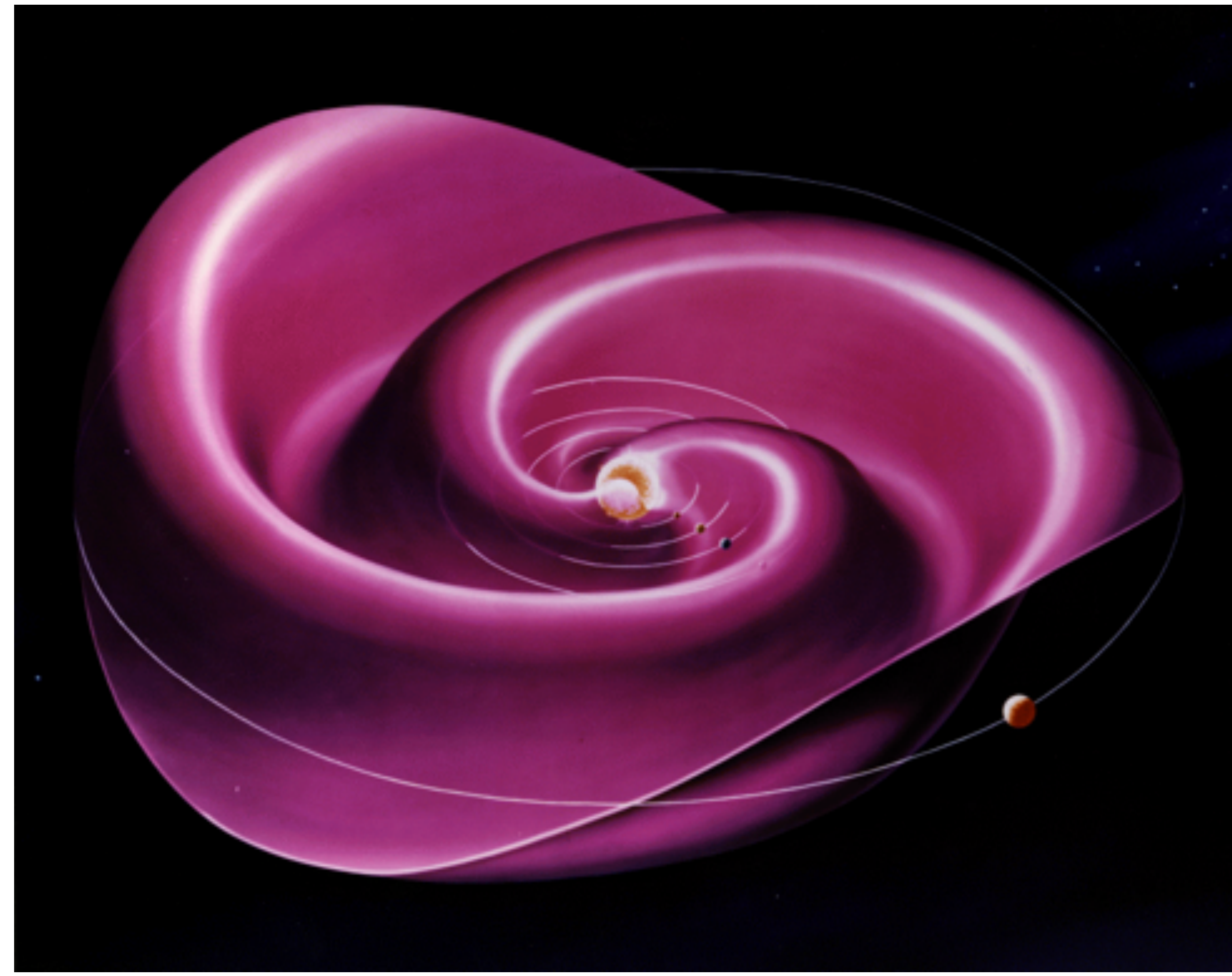
[Schatzmann 1962]

[Weber & Davis 1968]

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

$$v_A = \frac{B}{\sqrt{4\pi\rho}}$$

Angular momentum transport by the wind = braking !



Parker spiral and heliospheric current sheet

2.5D SIMULATIONS : A PARAMETRIC STUDY

- 7 rotation rates:

$P_{rot} \in [0.3, 1000](\text{days})$

- 2 orders of magnitude for the magnetic fields strength.

- fixed temperature around 1MK

x Dipole / Quadrupole / Octupole **=** *~60 Ideal MHD simulations with the PLUTO code*

[Mignone 2007]

Main output : $\langle R_A \rangle = \sqrt{\frac{\dot{J}}{\dot{M}\Omega_*}}$

PLUTO

A modular code for computational astrophysics

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

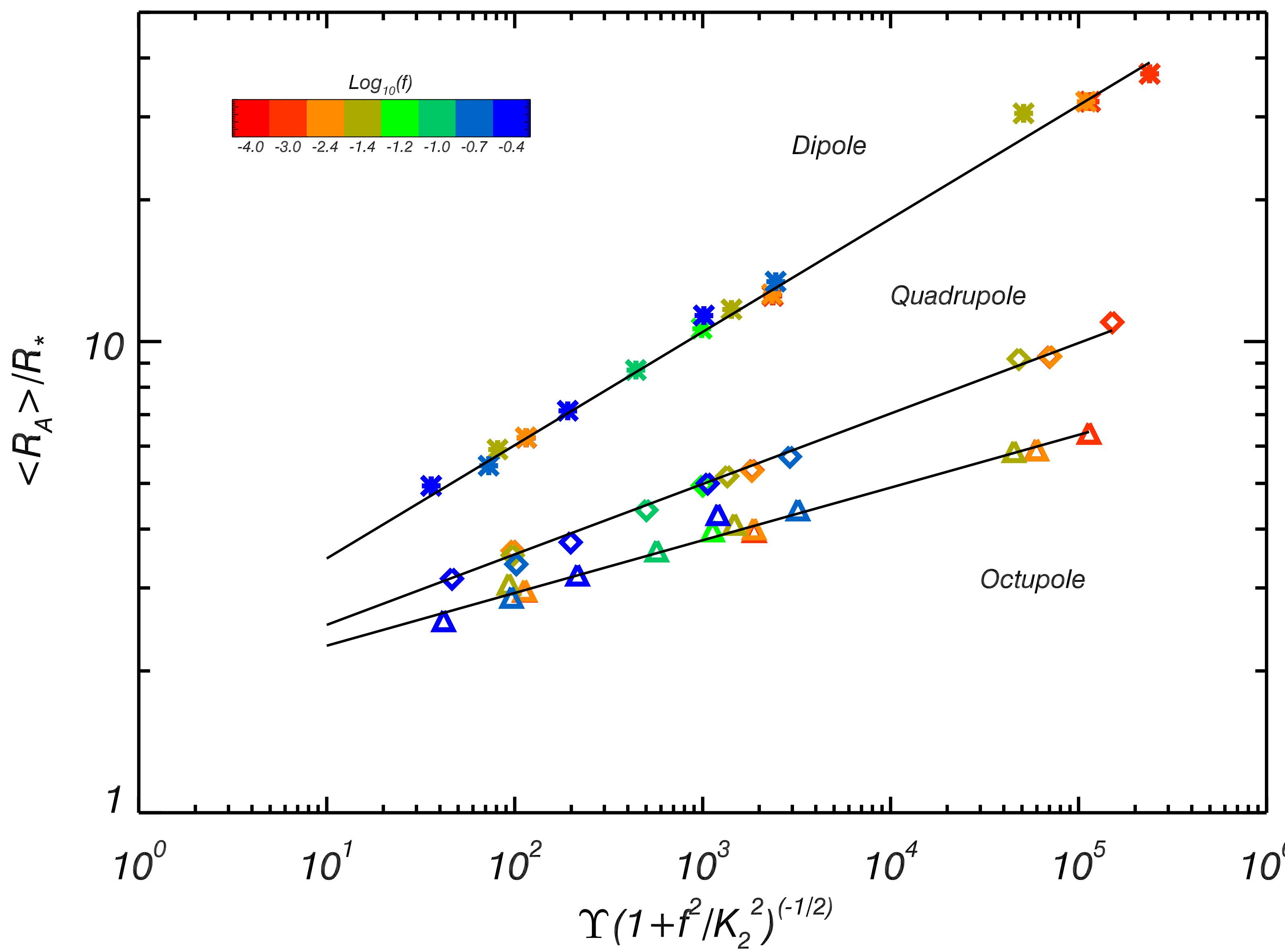
2.5D SIMULATIONS: SCALING LAW

$$\langle r_A \rangle = K_3 \left(\frac{\Upsilon}{(1 + f^2/K_4^2)^{1/2}} \right)^m$$

[Réville et al 2015a]

Magnetization parameter:

$$\Upsilon = \frac{B_*^2 R_*^2}{\dot{M} v_{esc}}$$



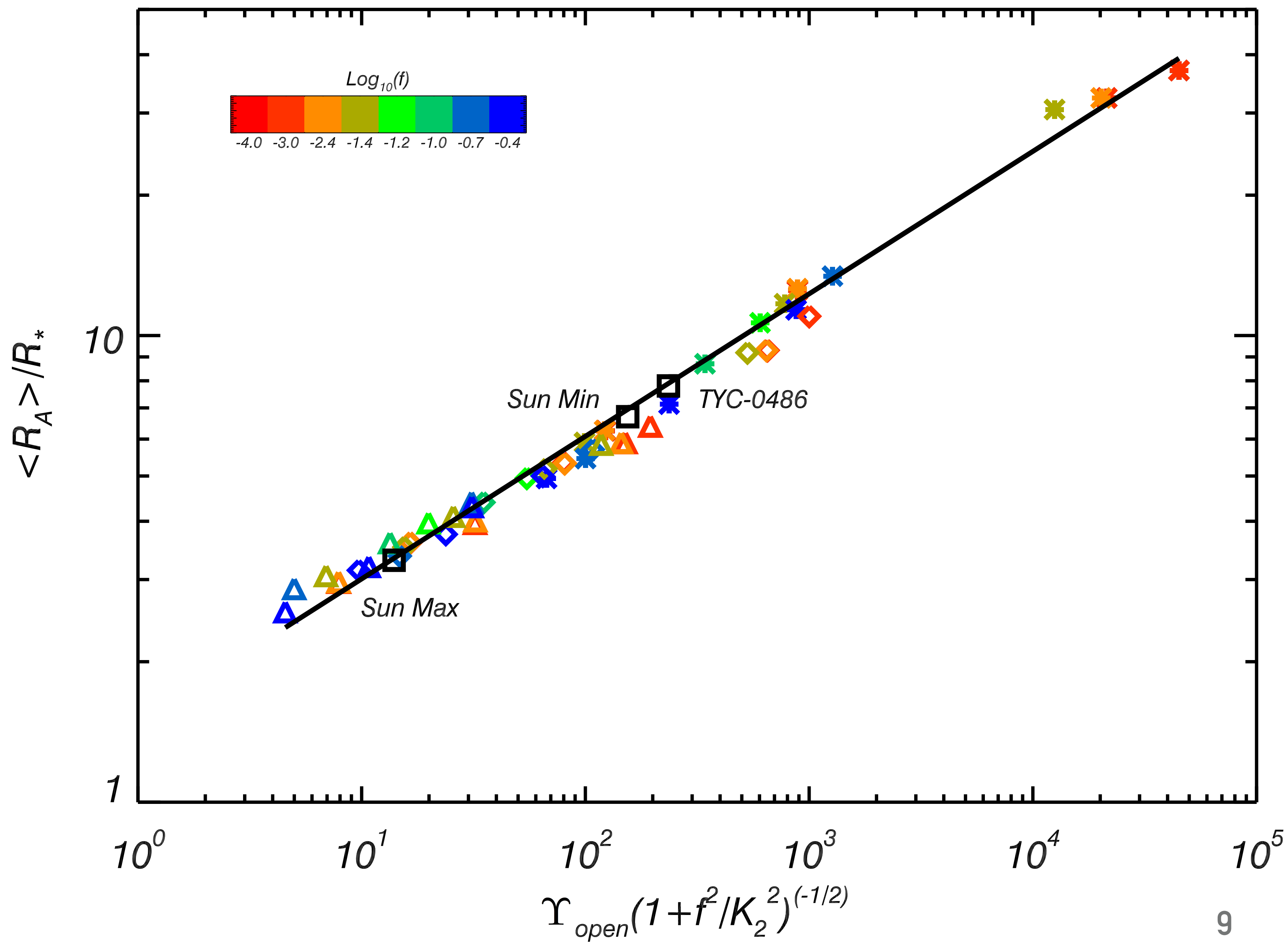
2.5D SIMULATIONS: SCALING LAW

$$\langle r_A \rangle = K_3 \left(\frac{\Upsilon_{open}}{(1 + f^2/K_4^2)^{1/2}} \right)^m$$

[Réville et al 2015a]

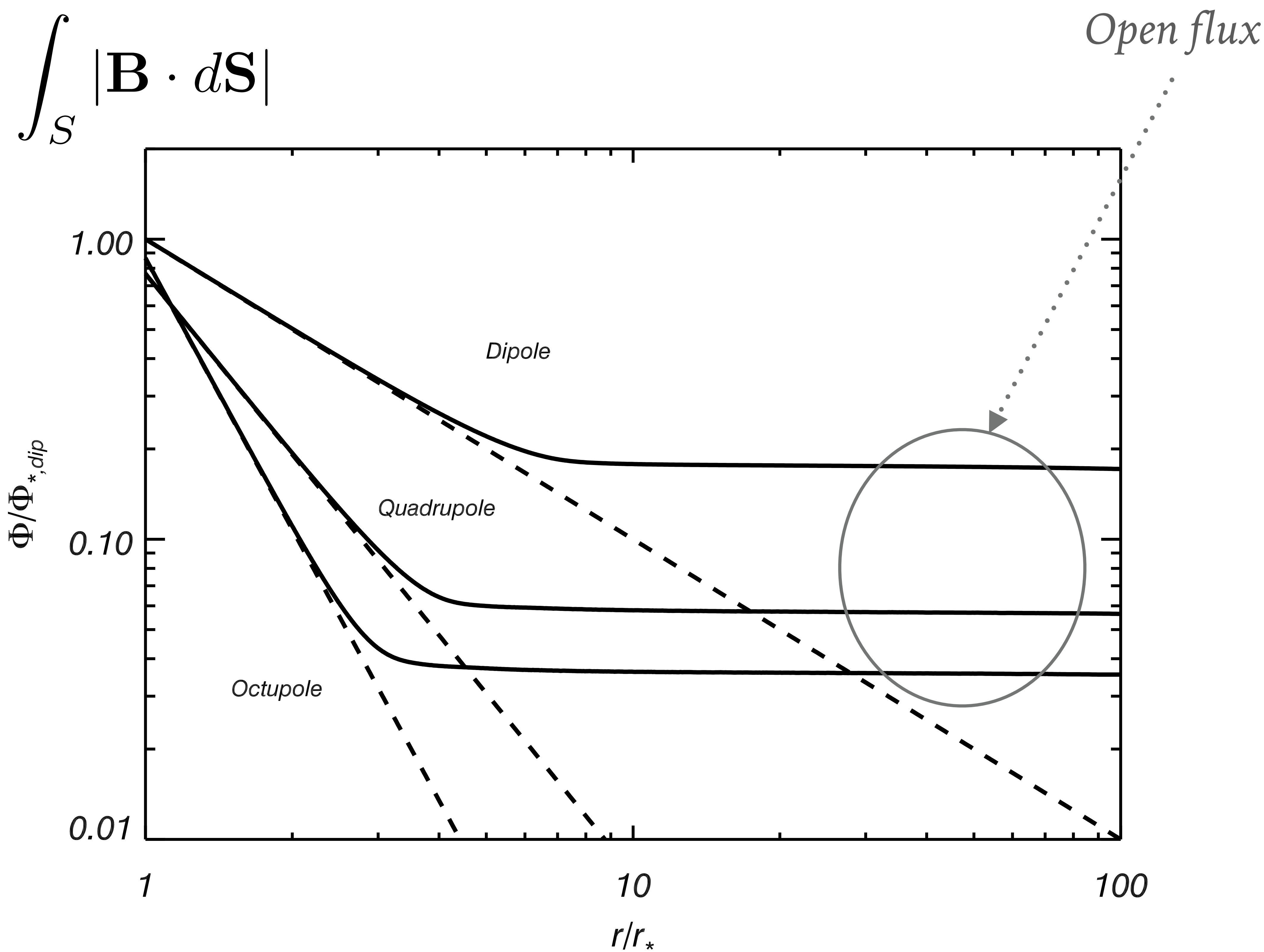
Magnetization parameter:

$$\Upsilon_{open} = \frac{\phi_{open}^2}{R_*^2 \dot{M} v_{esc}}$$



OPEN MAGNETIC FLUX

$$\Phi = \int_S |\mathbf{B} \cdot d\mathbf{S}|$$



WHAT HAS CHANGED ?

$$\frac{dJ}{dt} = \frac{dM}{dt}^{1-2m} \Omega_* R_*^{2-4m} K B_*^{4m} v_{esc}^{-2m}$$

[Kawaler 1988]
$m = 0.5$

[Matt & Pudritz 2008]
$m = 0.22$

[Matt et al 2012]
magneto-centrifugal effect

[Réville et al 2015a]
$m = 0.3$ *w/ open flux*

$$\frac{dJ}{dt} = \frac{dM}{dt}^{1-2m} \Omega_* R_*^{2-4m} K_3 \Phi_{open}^{4m} (1 + f^2/K_4^2)^{-m} v_{esc}^{-2m}$$

Dependence on the mass-loss rate, inclusion of the magneto-centrifugal acceleration !

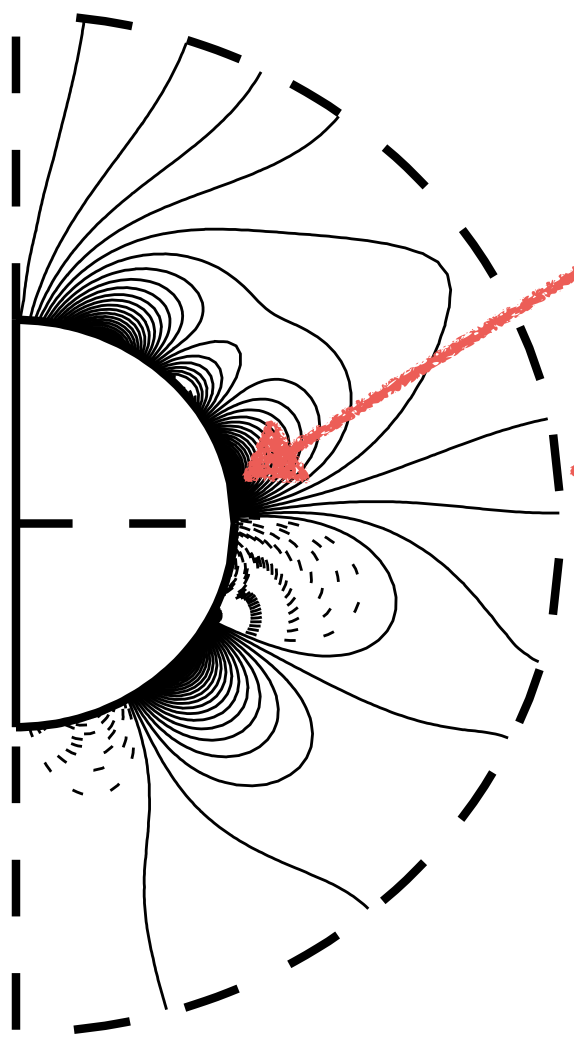
SEMI-ANALYTICAL MODEL : POTENTIAL EXTRAPOLATION

$\nabla \times \mathbf{B} = 0$ $-\nabla\Phi = \mathbf{B}$ *Current free 1<r< Rss*

The potential is solution of Laplace's equation: $\Delta\Phi = 0$

$$\left.\frac{\partial\Phi}{\partial r}\right|_{r=1} = -B_r(1, \theta', \phi),$$

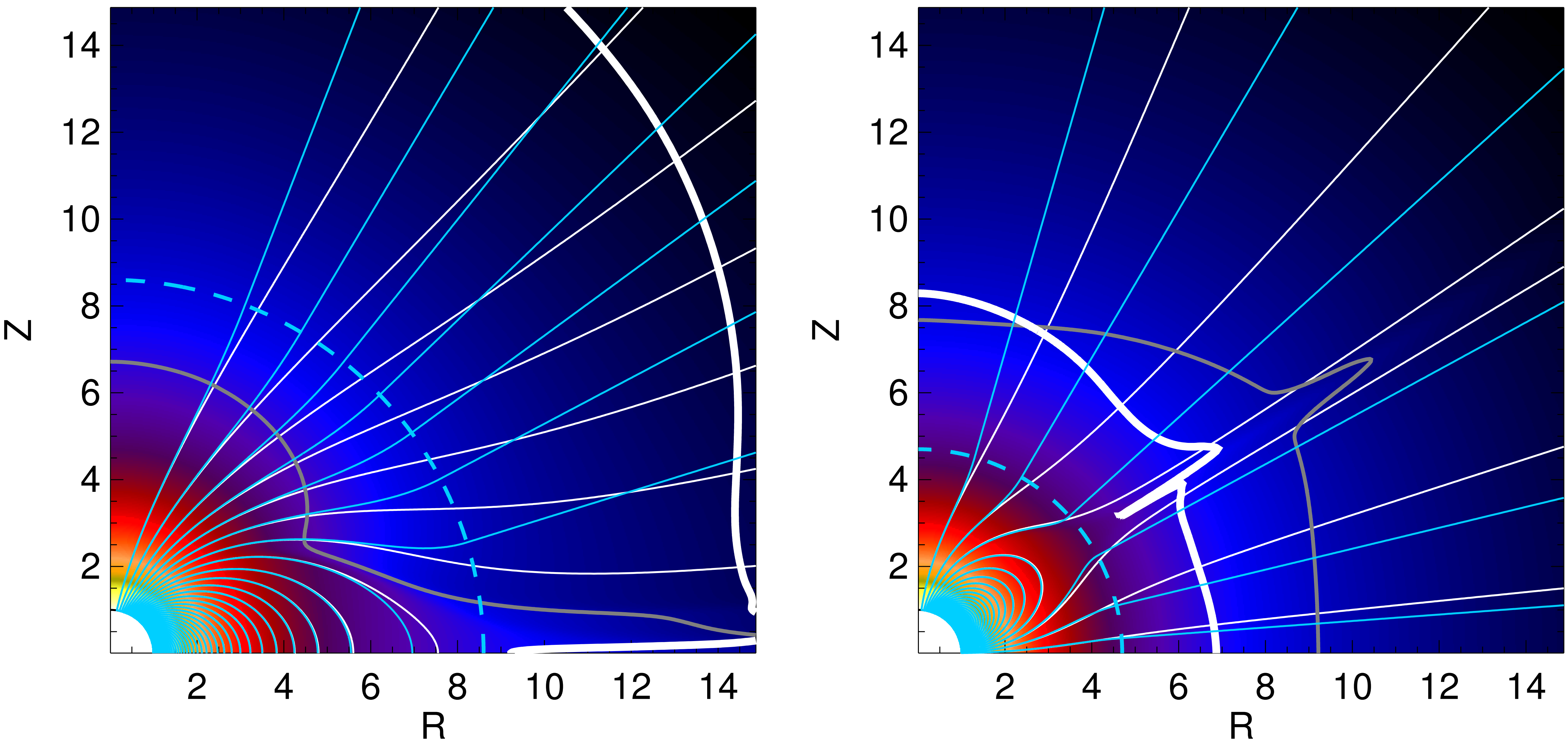
$$\Phi = 0 \quad \text{at} \quad r = R_{ss}$$



The field is potential between the stellar surface and a source surface, radial beyond.

Rss = 2.5 R usually*

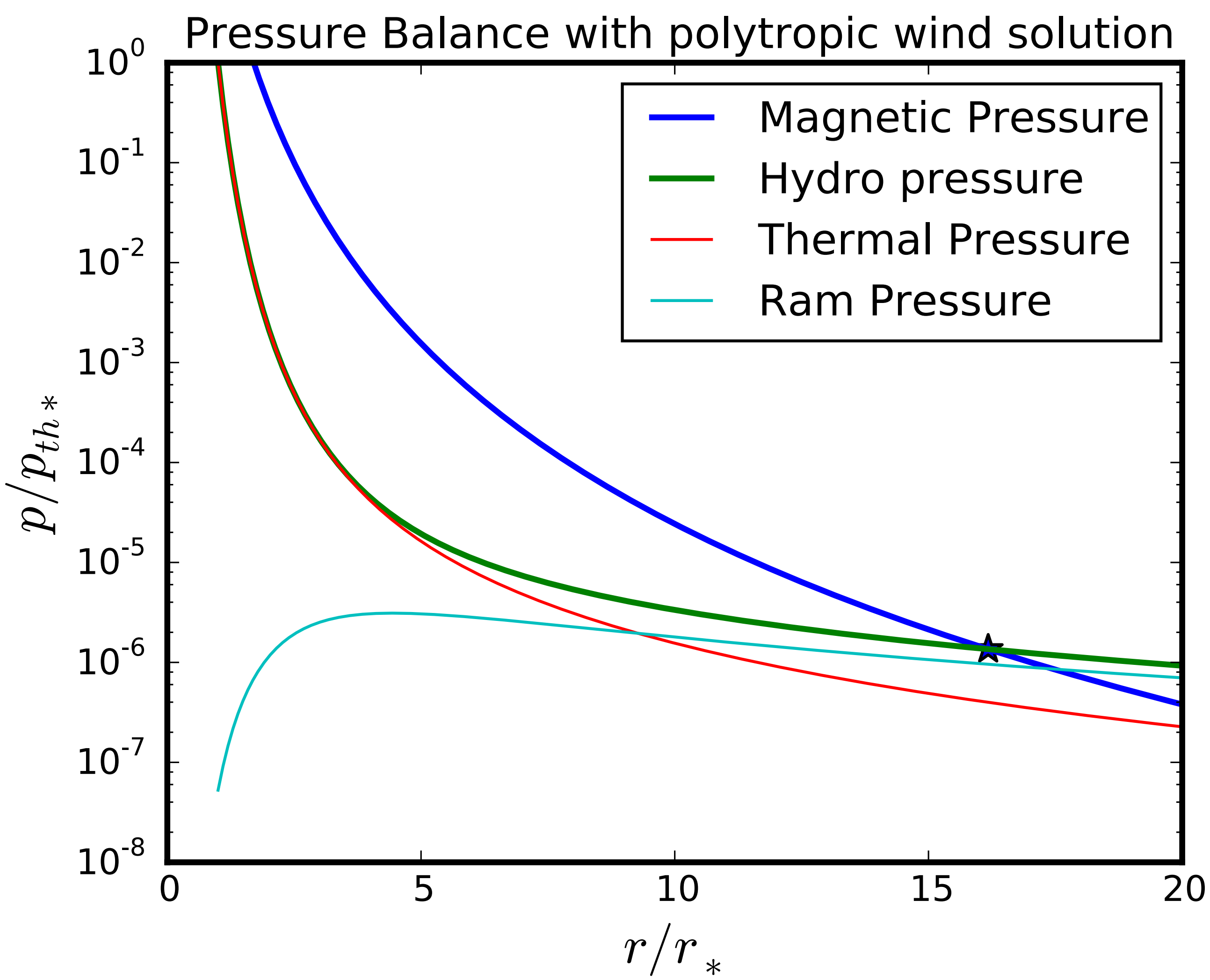
SEMI-ANALYTICAL MODEL : POTENTIAL EXTRAPOLATION

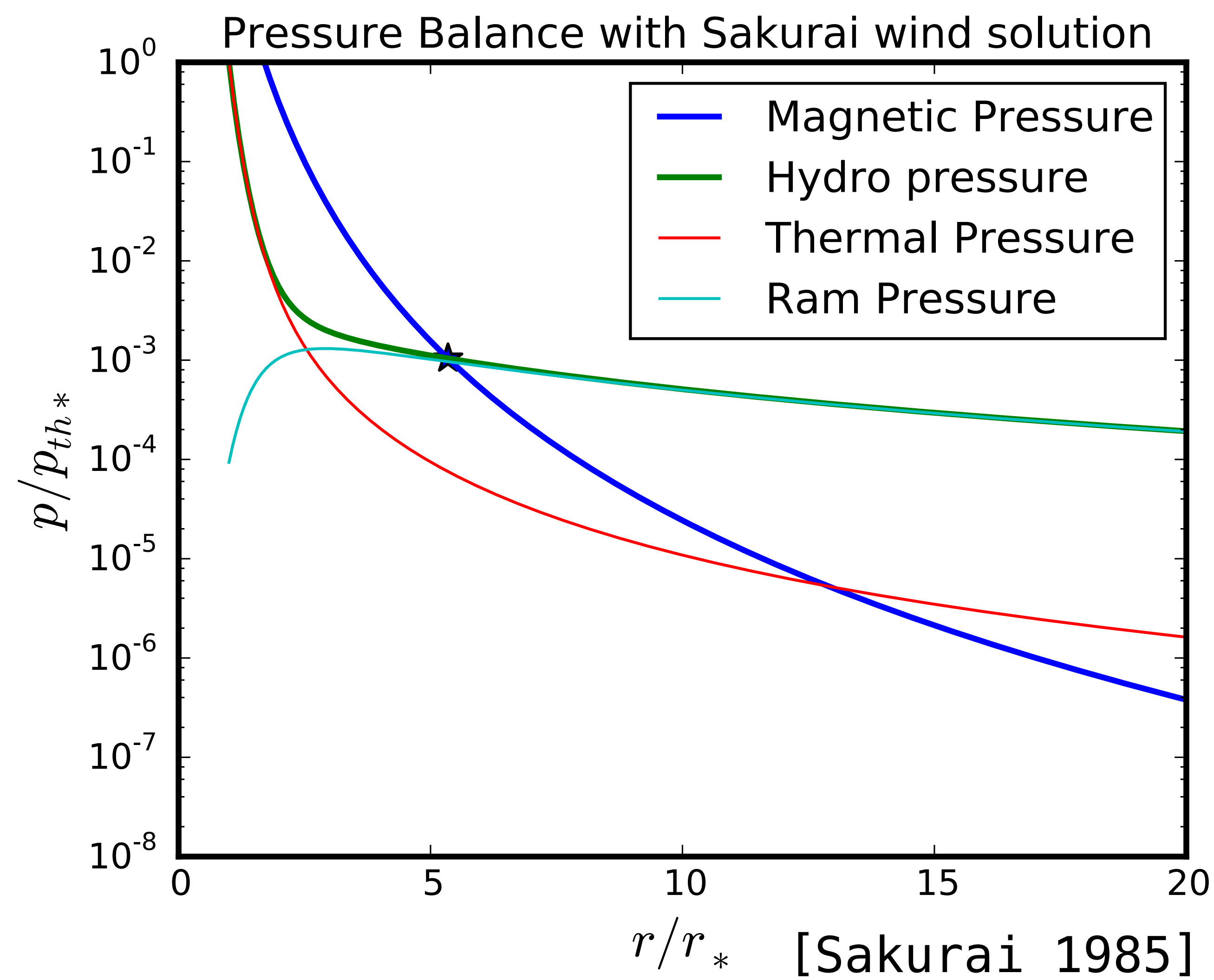


[Réville et al 2015b]

SEMI-ANALYTICAL MODEL : PRESSURE BALANCE FOR RSS

$$P_{th} + P_{ram} = P_{mag} \quad / \quad p + \rho v^2 = \frac{B^2}{2\mu_0}$$





[Sakurai 1985]

[Réville et al 2015b]

The Sakurai wind solution is obtained through a 6D Newton-Raphson Method

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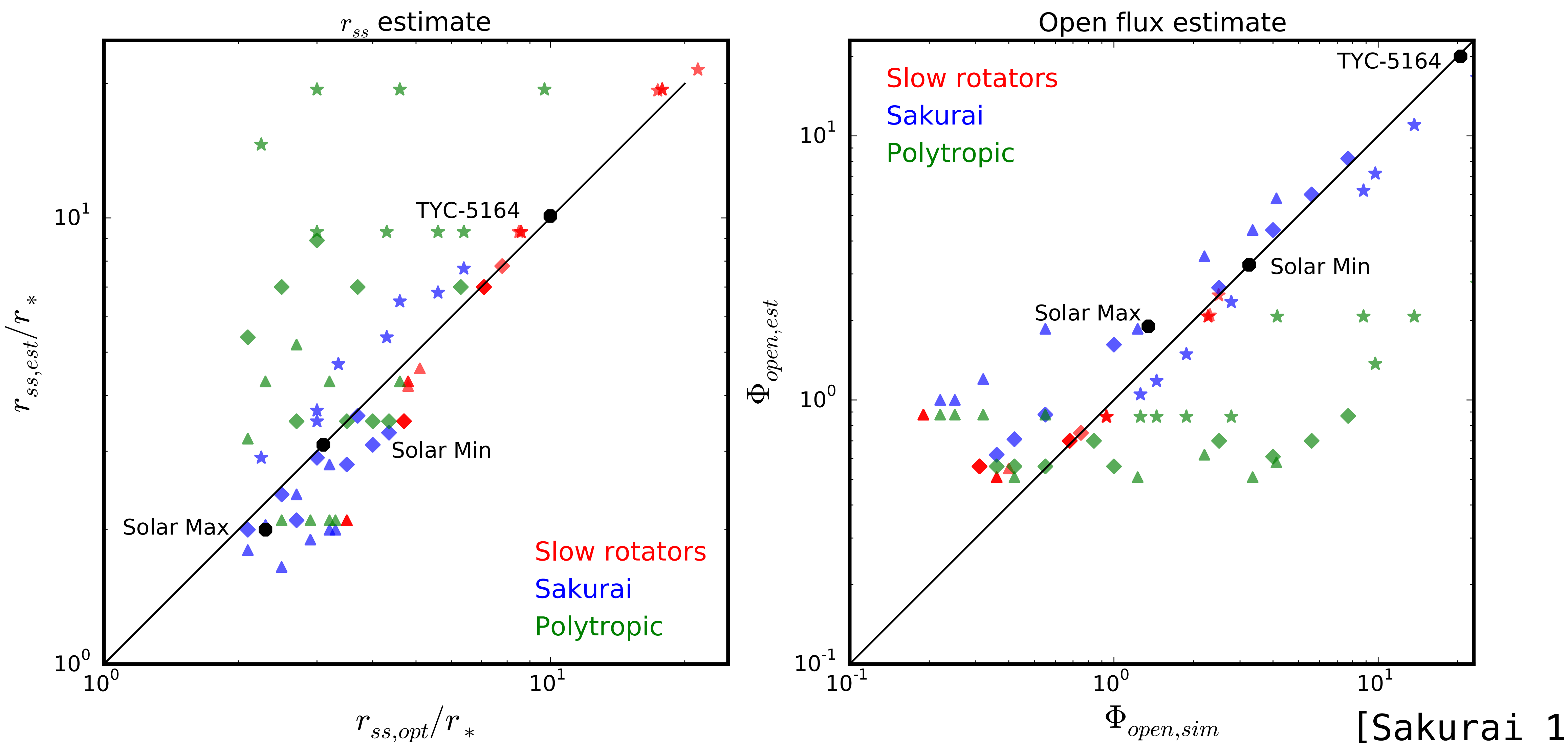


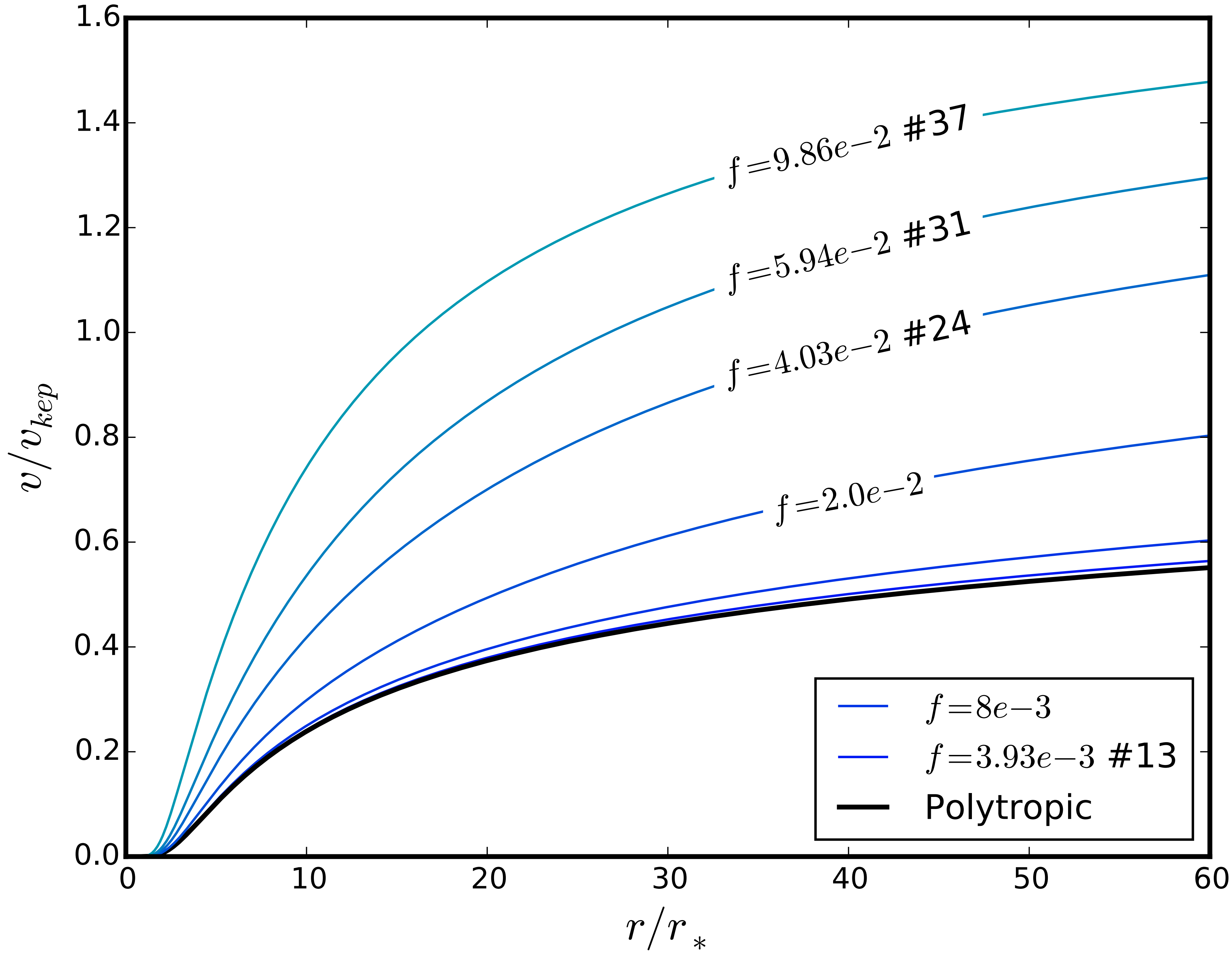
[Sakurai 1985]

[Réville et al 2015b]

The Sakurai wind solution is obtained through a 6D Newton-Raphson Method

WEBER & DAVIS / SAKURAI WIND

Magneto-centrifugal acceleration



[Réville et al 2015b]

A PYTHON CLASS: STAR AML

```
class starAML(object):
    """ Python class for the computation of angular momentum loss as described in R\'eville et al. 2015b"""

    def __init__(self,Gamma,Mass,Radius,Period,Teff,mapfile,Tc=1.5e6,Nc=1e8,Tlawexp=0.1,Nlawexp=0.6,ngrid=100):
        self.Gamma=Gamma        # Adiabatic index
        self.Mass=Mass          # Mass in solar mass
        self.Radius=Radius      # Radius in solar radii
        self.Period=Period      # Period in days
        self.Teff=Teff          # Effective temperature in Kelvin
        self.mapfile=mapfile    # Name of the ZDI map file
        self.Tc=Tc              # Coronal temperature in Kelvin
        self.Nc=Nc              # Coronal base density in Kelvin
        self.Tlawexp=Tlawexp    # Exponent of the temperature vs. omega power law
        self.Nlawexp=Nlawexp    # Exponent of the density vs. omega power law
        self.theta, self.phi = np.mgrid[1e-5:np.pi-1e-5:(ngrid+1)*1j, 0:2*np.pi:(2*ngrid+1)*1j] # (Theta,Phi) Grid
        Grid=np.ones((np.shape(self.theta)[0],np.shape(self.theta)[1]))
        self.gridArea=zdi.cmpMagFlux(self.theta,self.phi,Grid,1.0)
        # Constants Dictionnary
        self.Constants={'G':6.67e-8,'Msun':1.9891e33,'Rsun':6.96342e10,'Psun':28,'Teff_sun':5778}
```

Computes the optimal source surface radius, and the estimated open flux and angular momentum loss for 3D realistic geometries.

Computes the Sakurai solution.

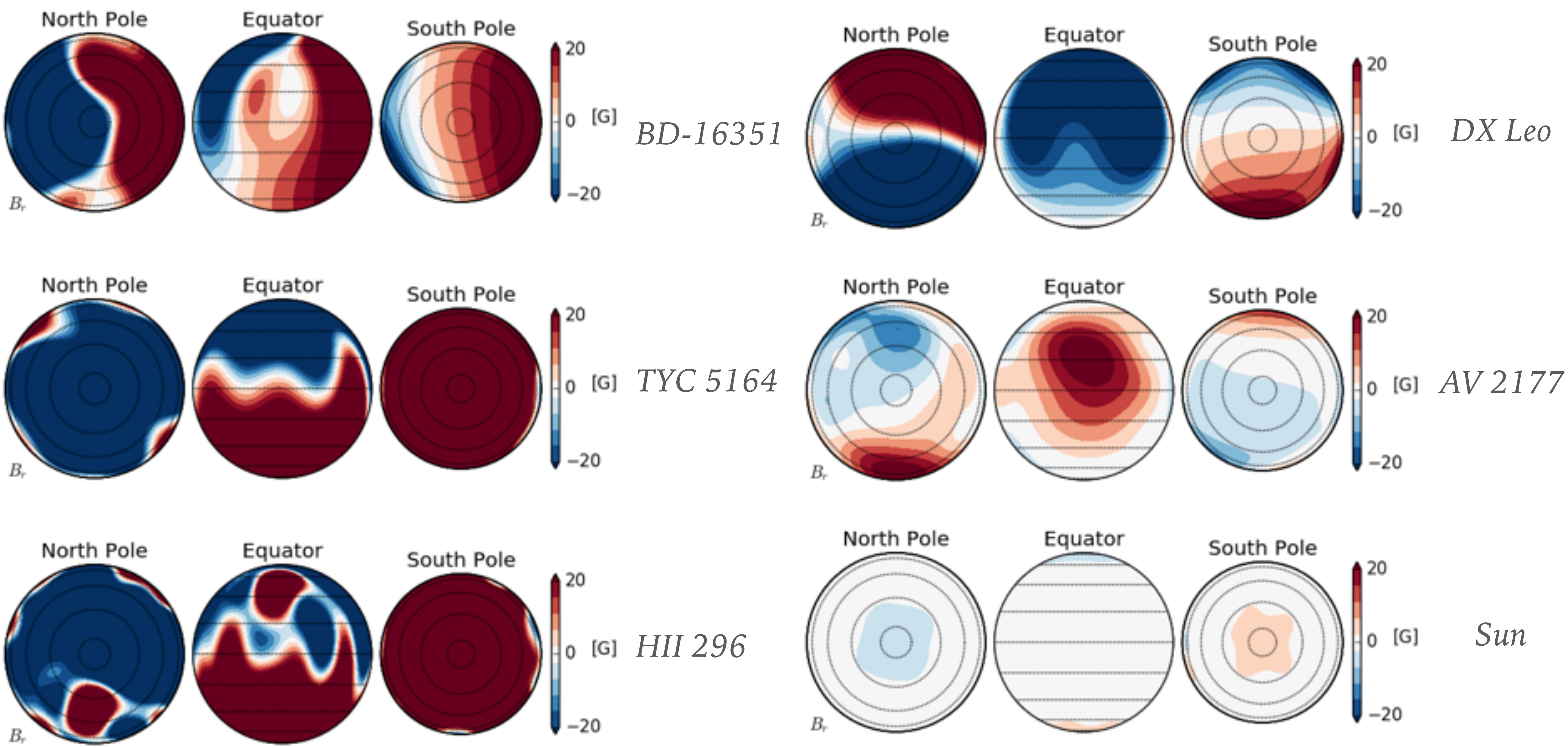
GNU GPL, ask me for the piece of code.

ZEEMAN-DOPPLER IMAGING

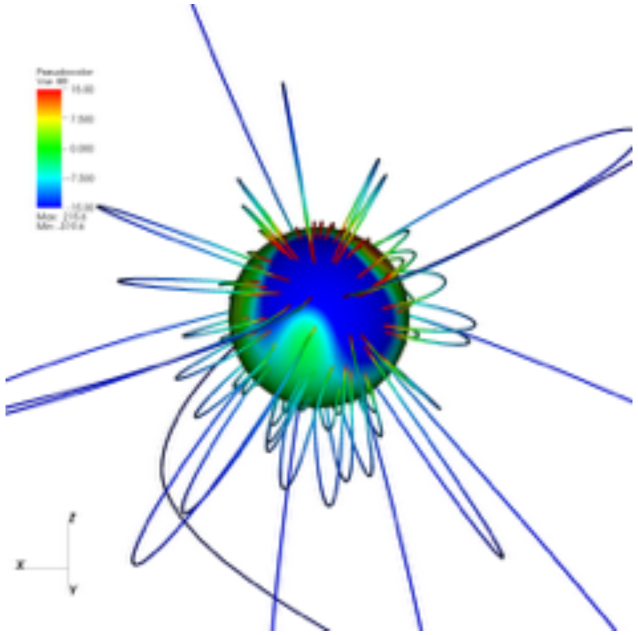
Spectropolarimeters:

Narval 375nm à 1050nm @TBL
& Espadons (370nm à 1000 nm) @CFHT

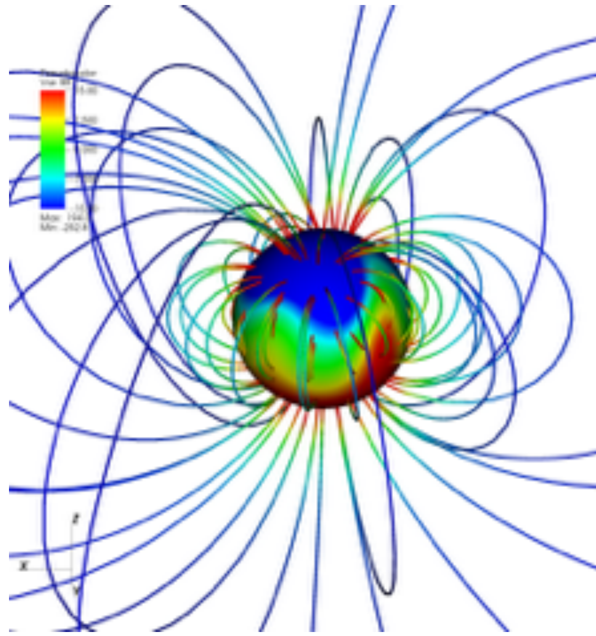
Zeeman Doppler Imaging consist in extracting Stokes parameters as a function of phase, on several wave-lengths to increase signal over noise ratio.
Works well on fast rotators.



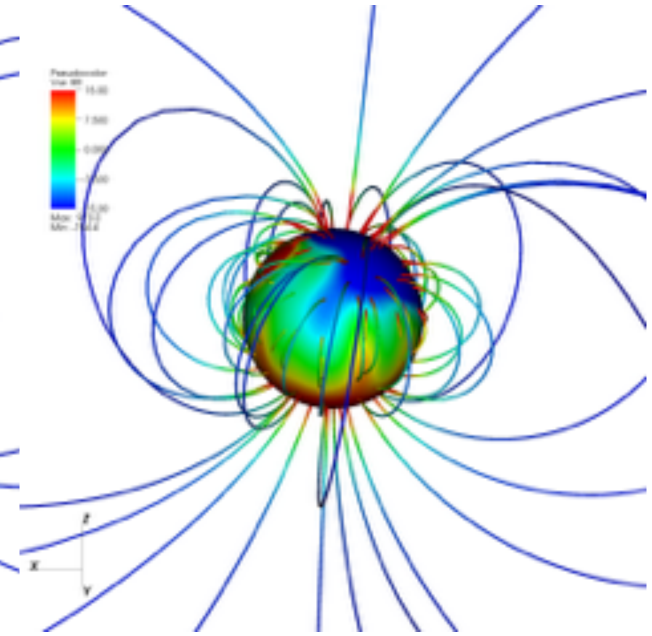
3D SIMULATIONS : EVOLUTION OF AML WITH AGE



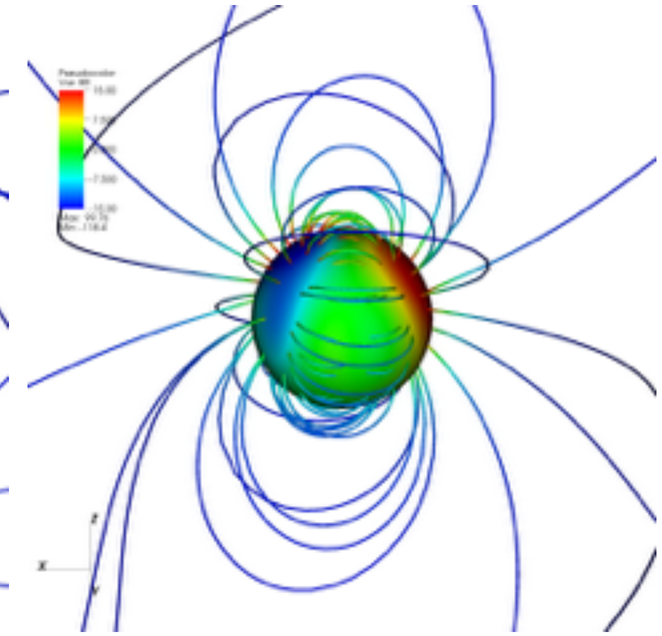
BD-16351



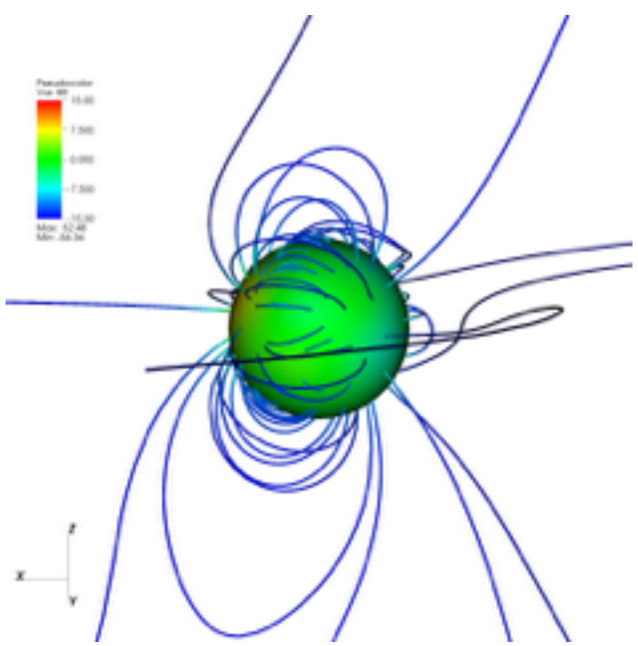
TYC 5164



HII 296



DX Leo



AV 2177

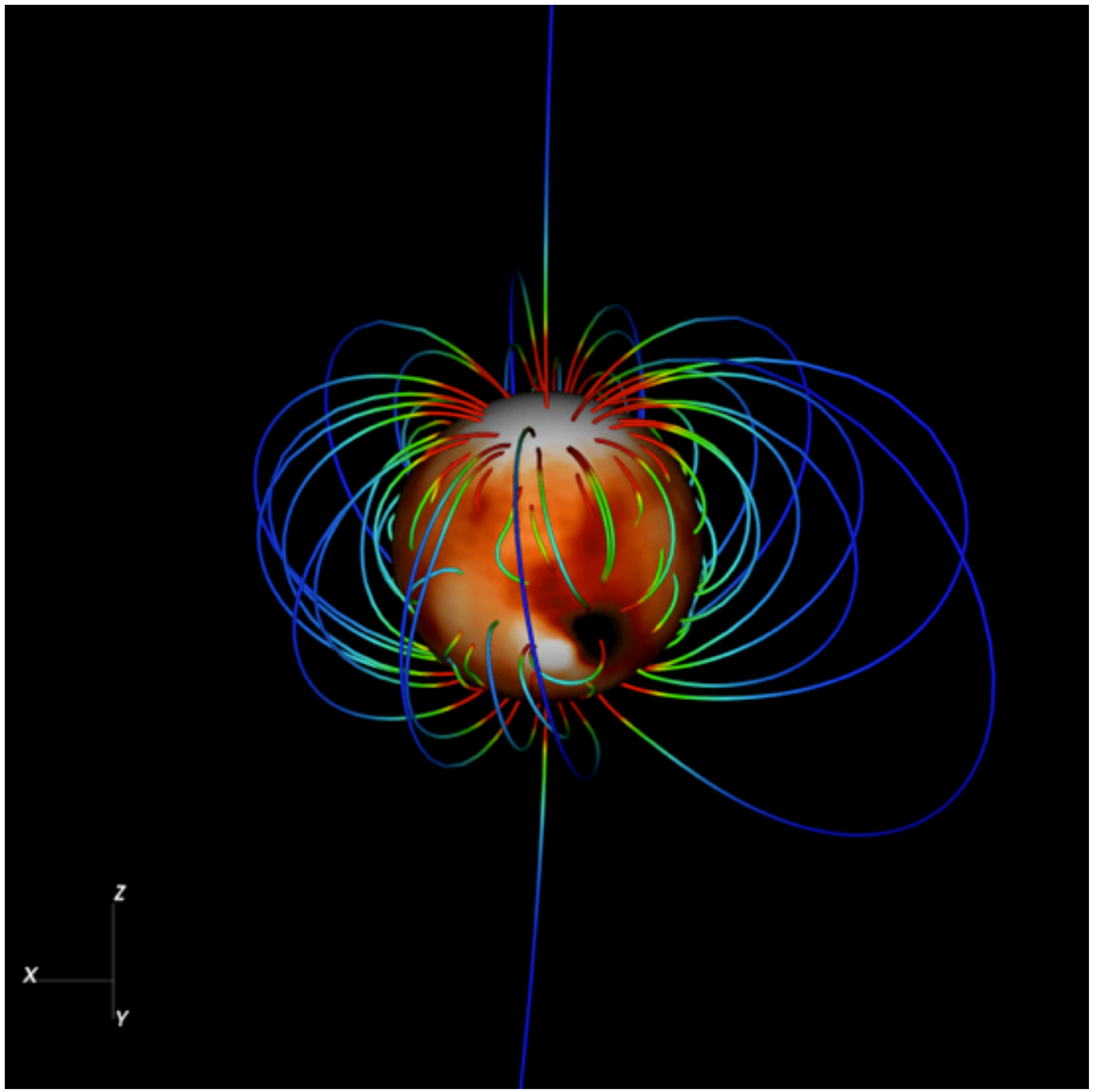
Name	Age (Myr)	Period (days)	Mass ($M_\odot$)	Radius ($R_\odot$)	T_{eff} (K)	$\langle B_r \rangle$ (G)
BD 16351	27	3.3	0.9	0.9	5243	33
TYC 5164-567-1	120	4.7	0.85	0.85	5130	48.8
HII 296	125	2.6	0.9	0.9	5322	52
DX Leo	257	5.4	0.9	0.9	5354	21.3
AV 2177	584	8.4	0.9	0.9	5316	5.4
Solar Min	4570	28	1.0	1.0	5778	1.1
Solar Max	4570	28	1.0	1.0	5778	2.6

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

[Réville et al 2016 in prep]

3D SIMULATIONS : EVOLUTION OF AML WITH AGE

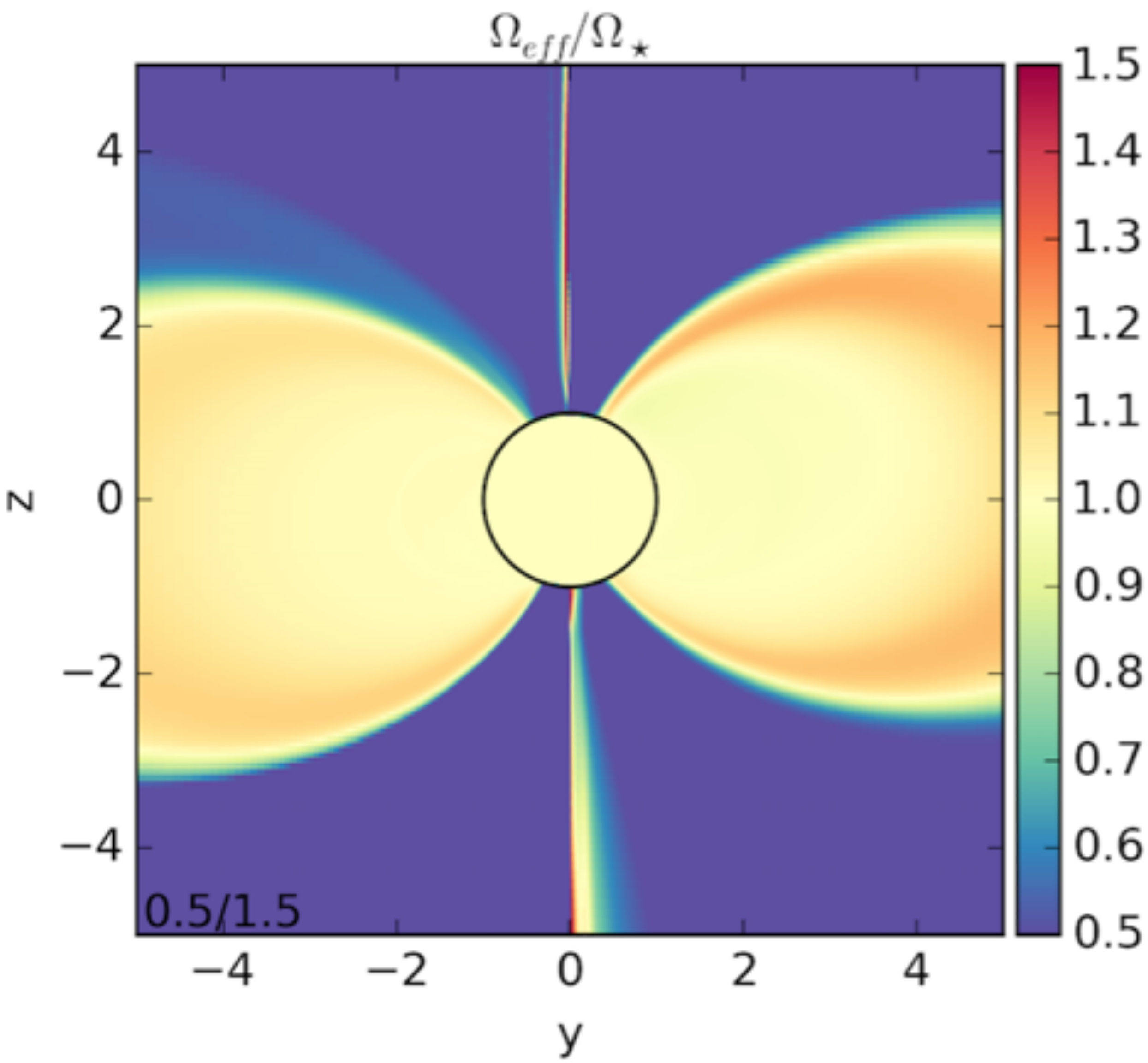
The Sun in 1996 Minimum of cycle 22



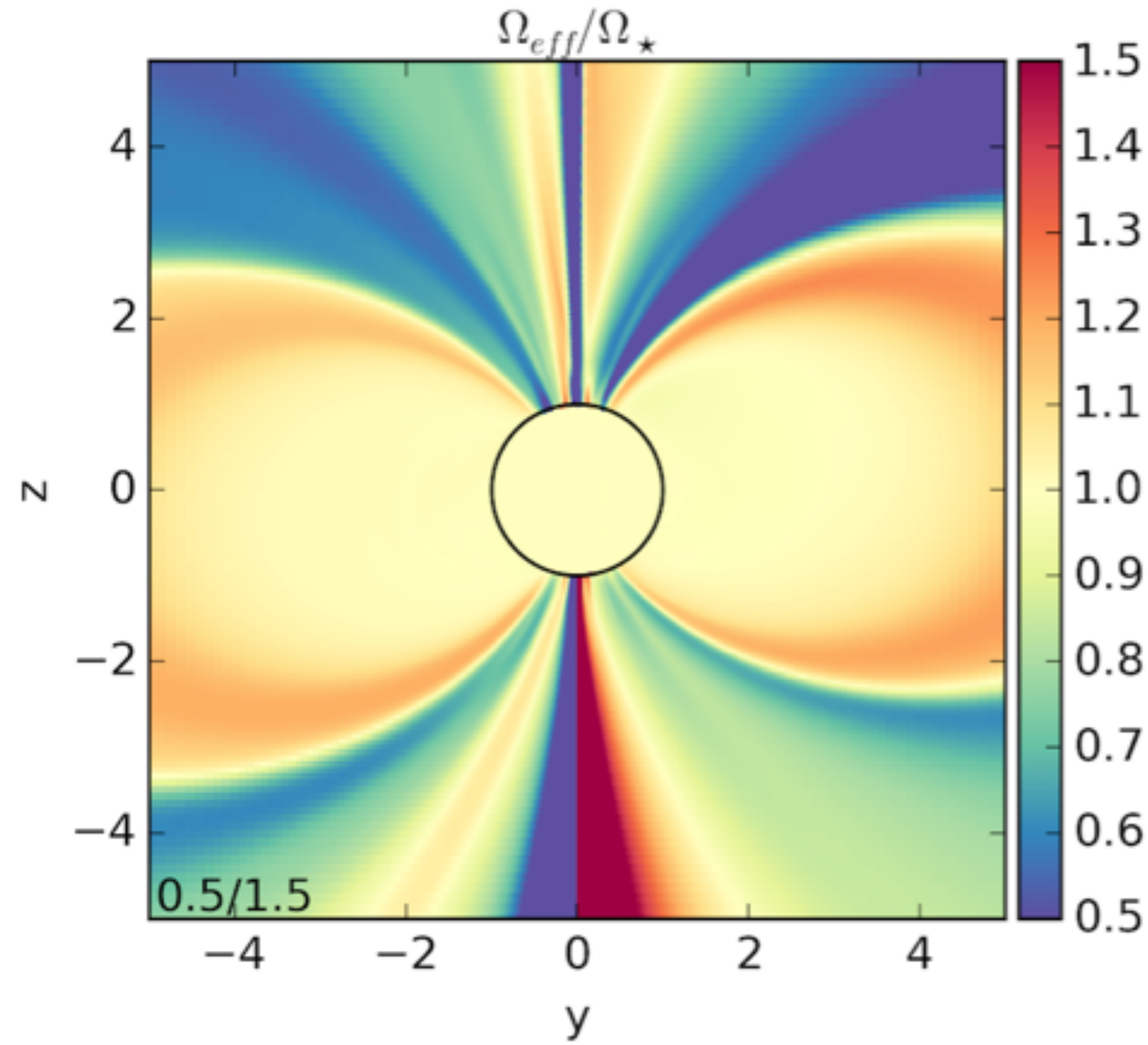
3D SIMULATIONS : BOUNDARY CONDITIONS

Omega effective with:

Bad Boundary Conditions



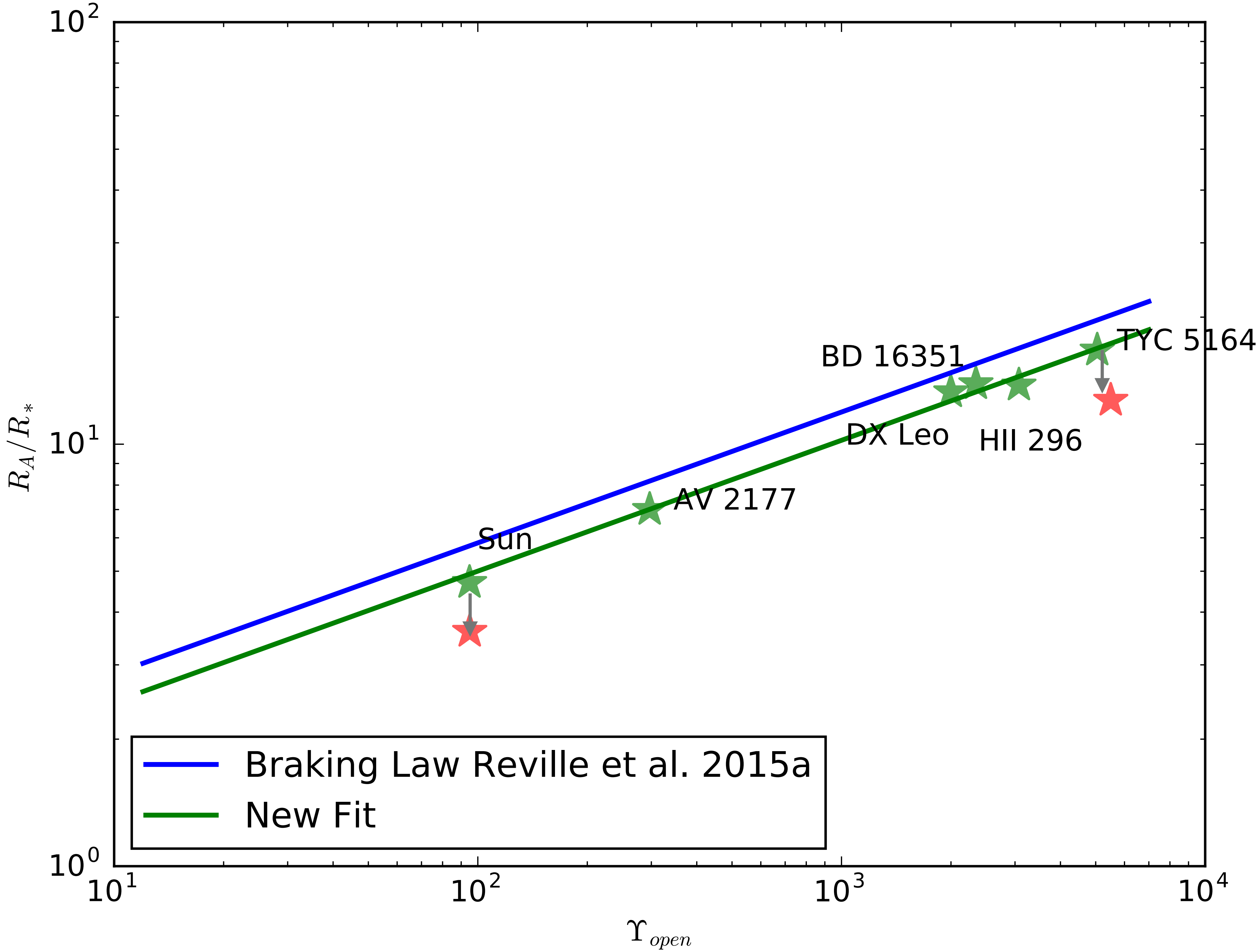
Improved Boundary Conditions



The star is a perfect conductor :

$$\nabla \times \mathbf{B} = \nabla \times (\mathbf{B_{pot}} + \delta B_\varphi) = -\frac{\partial \delta B_\varphi}{\partial z}\mathbf{e_r} - \frac{1}{r}\frac{\partial (r\delta B_\varphi)}{\partial r}\mathbf{e_z} \approx 0$$

3D SIMULATIONS : BOUNDARY CONDITIONS



CONCLUSIONS

- New braking formulation that includes complex magnetic fields geometry
- Works for 3D, and a wide range of temperature, magnetic field strength and rotation rates
- Can be used, combined with semi-analytical wind and coronal models, to avoid MHD simulations
- Good agreement of the 3D - ZDI simulations with the braking law (reajustement of a constant due to temperature increase).

Thanks for your attention !