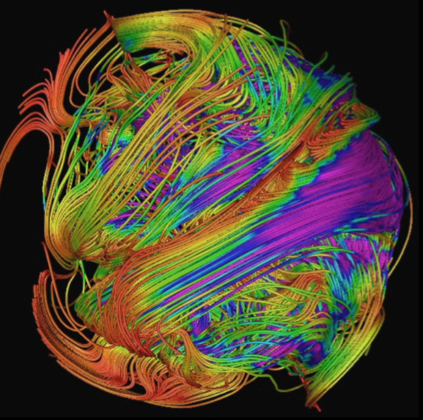
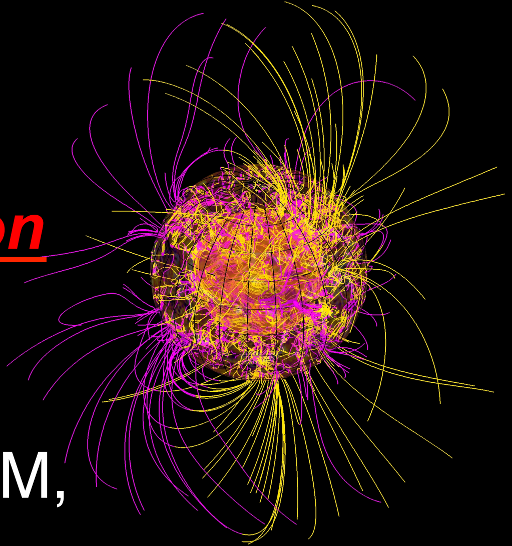
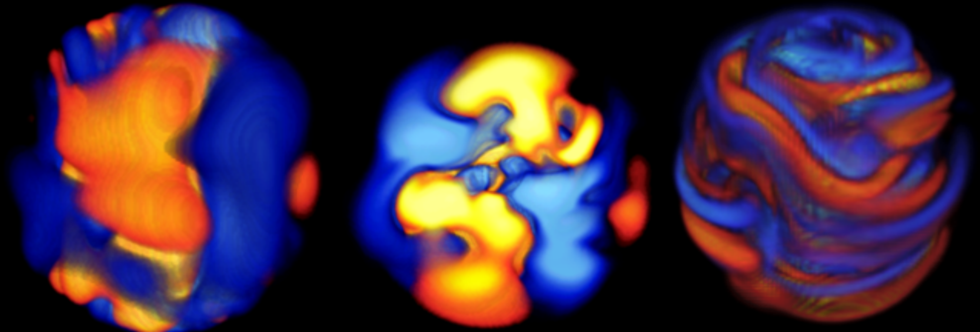


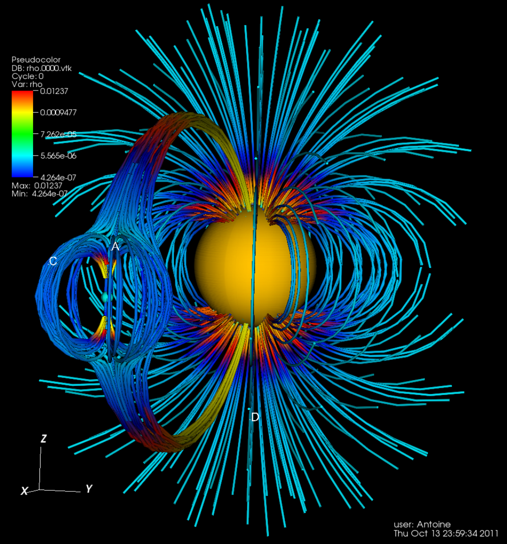
Stellar Dynamos and Magnetic Star-Planet Interaction



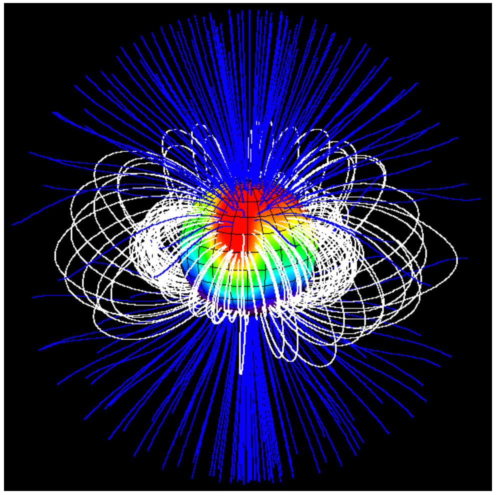
Allan Sacha Brun
Service d’Astrophysique/UMR AIM,
CEA-Saclay
with J. Toomre, J.P. Zahn, M. Browning, N. Featherstone, K. Augustson, B. Brown, A. Strugarek, S. Matt, L. Jouve, L.Alvan, V. Reville & the STARS2 Team

- Dynamo action in core and envelope convection
- Magnetic interactions with planets

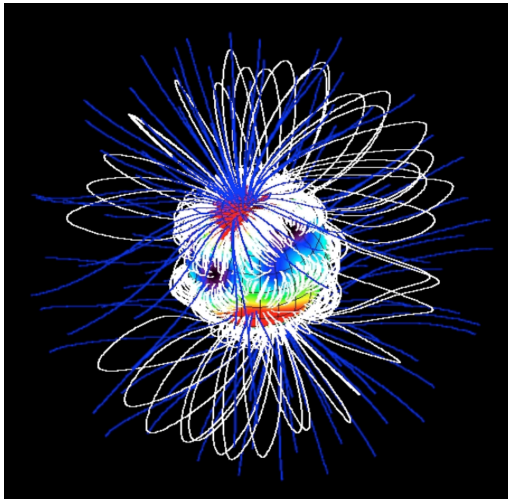




Stellar magnetism



ultra-cool star V374 Pegasi (Donati et al.)



Young star V2129 Oph (Donati et al.)

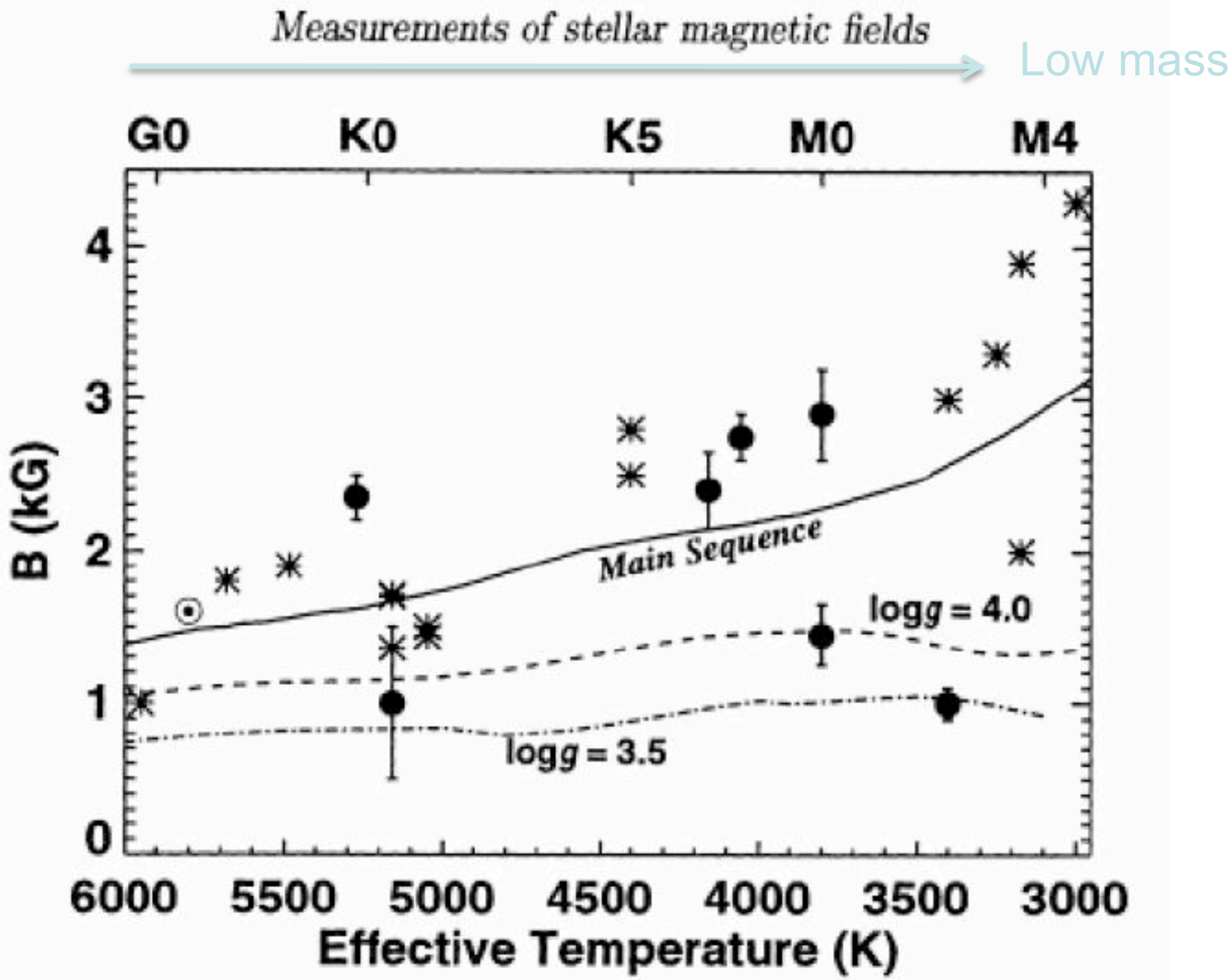


Figure 5. Predicted surface “equipartition” magnetic fields for cool stars. Also shown are measurements of main sequence stars (asterisks) and TTS (solid circles). The sun is shown by an encircled dot.

From Johns-Krull & Valenti

Solar Analogs

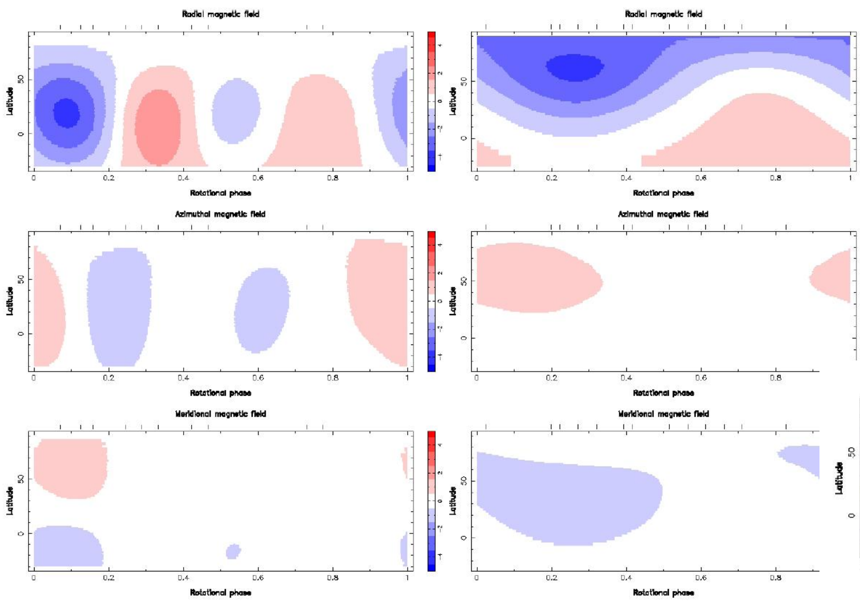


Figure 4. Magnetic maps of HD 146233 and HD 76151 (left and right panel, respectively). Each chart illustrates the onto one axis of the spherical coordinate frame. The magnetic field strength is expressed in Gauss. Vertical ticks above the the observed rotational phases. Note that color scales are not the same for every star.

Fast young Suns/stars

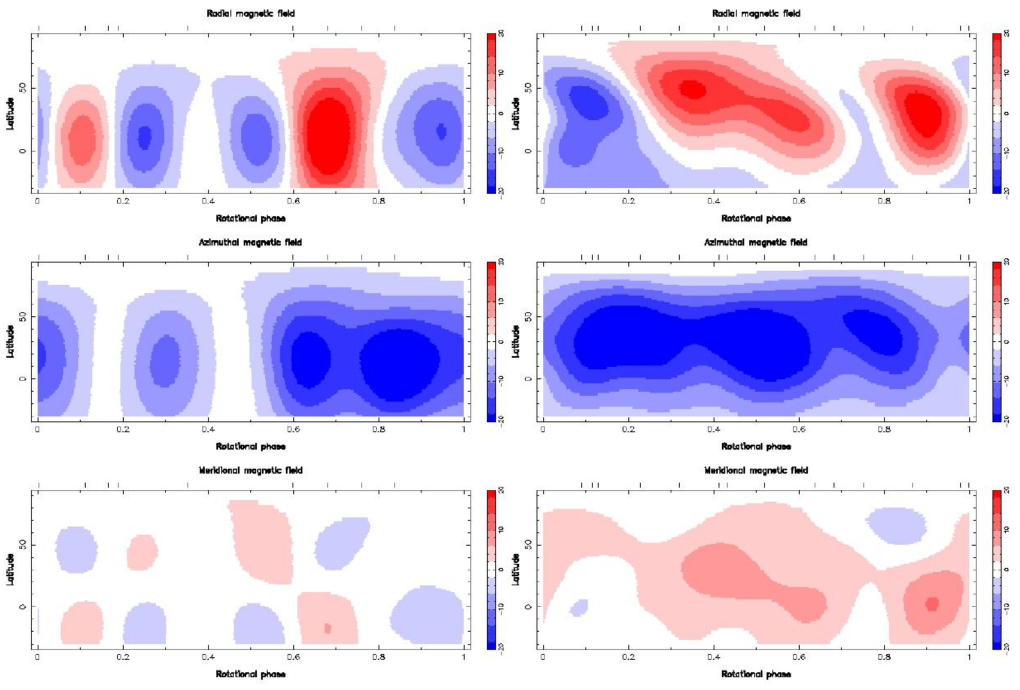


Figure 5. Same as Fig. 4, for HD 73350 (left panel) and HD 190771 (right panel).

Faster the solar analogs rotate more toroidal field contribution they possess.

Petit et al. 2008, MNRAS

ESPADON/NARVAL

Taille= IBI

Couleurs: poloidal
vs toroidal

Formes: axi
vs non-axi (étoiles)

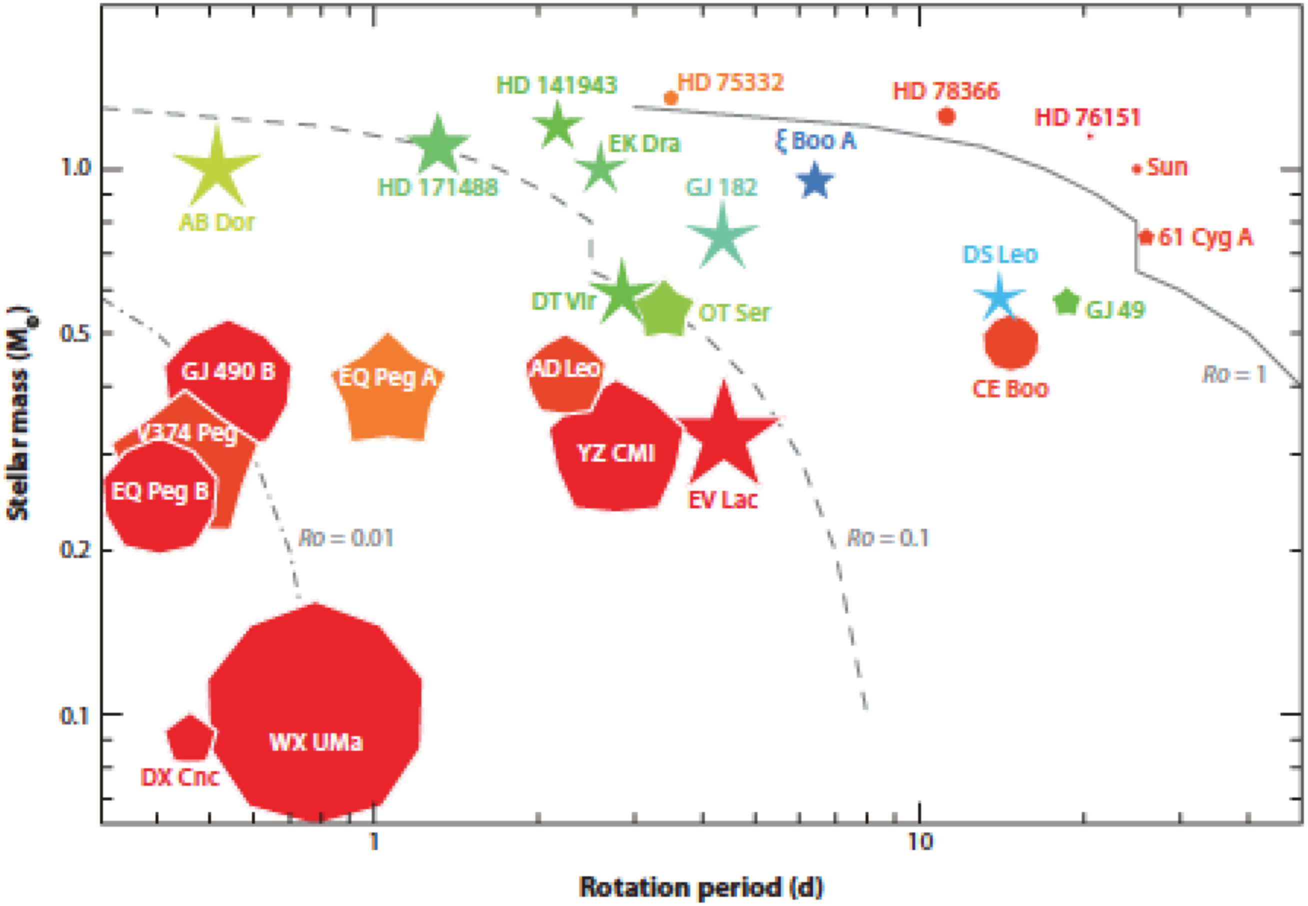
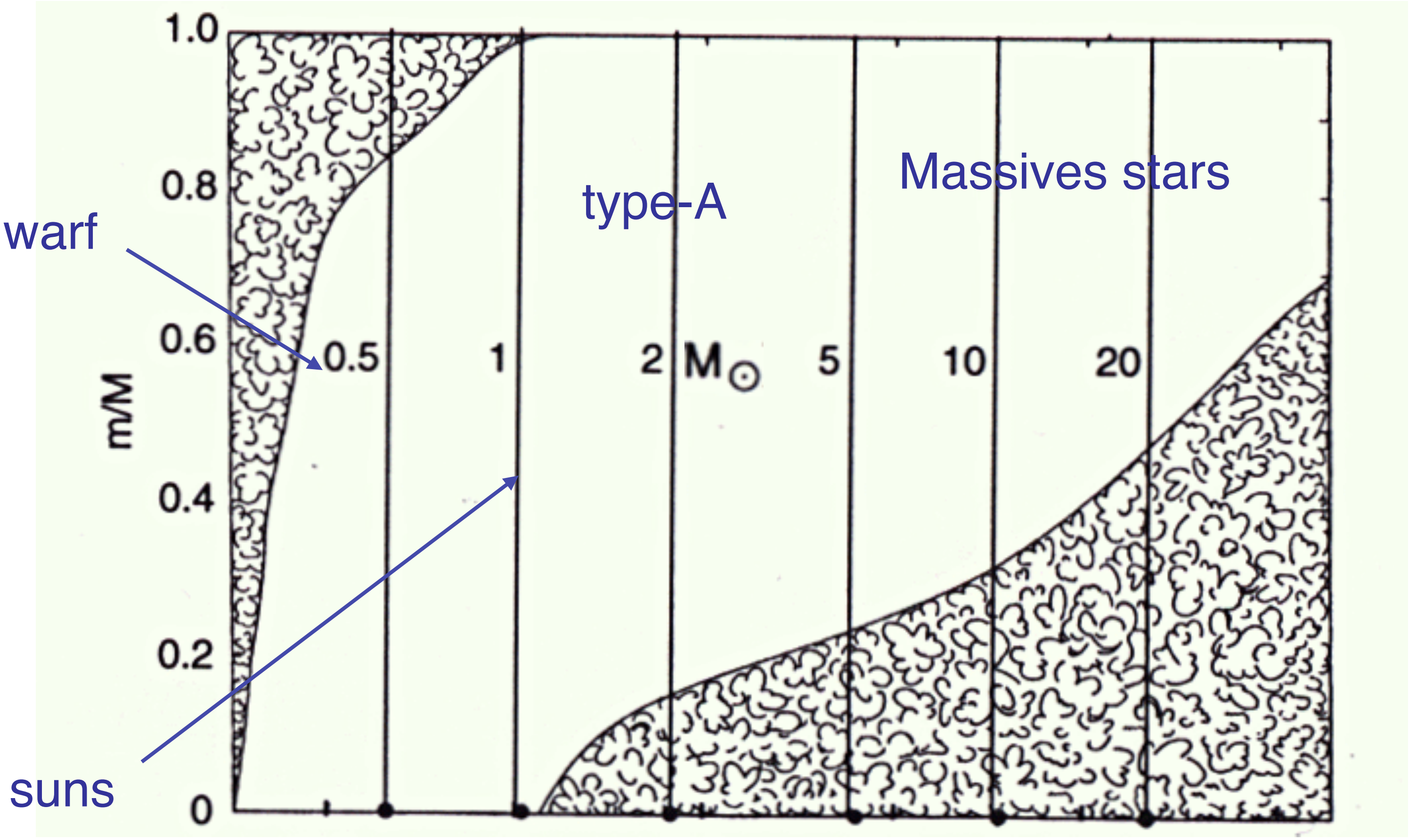


FIGURE 1.13 – Propriétés globales du champ magnétique observé dans les étoiles de faible masse, en fonction de la masse de l'étoile et de sa période de rotation. La taille du symbôle indique la densité d'énergie magnétique e, sa couleur indique la configuration du champ magnétique (bleue et rouge étant purement toroidale et purement poloidale respectivement), et la forme illustre le degré d'asymétrie du champ poloidal (un décagone et une étoile représentant un champ purement axisymétrique et purement non axisymétrique respectivement). Les lignes plein, tiret et mixte représentent un nombre de Rossby stellaire constant égal à 1, 0.1 et 0.01 (utilisant les temps de retournement convectif de Kiraga and Stepien (2007)). Crédits : Donati and Landstreet (2009).

Convection in Stellar Interior

Transition between envelope and core convection: M ~1.3 Msol



type-A

Massives stars

dwarf

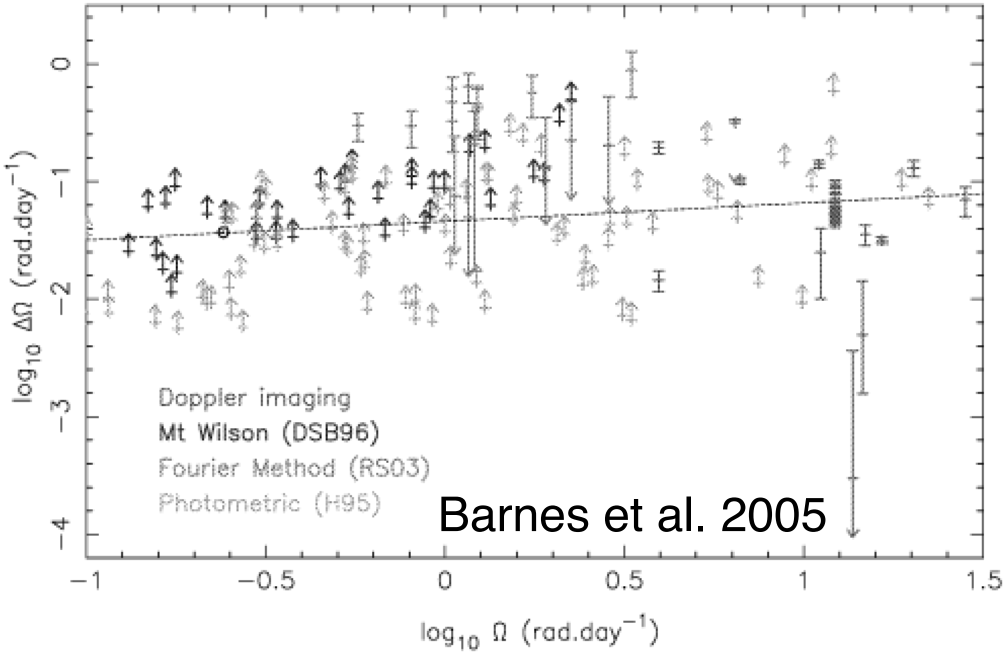
suns

Chaines pp

Cycles CNO

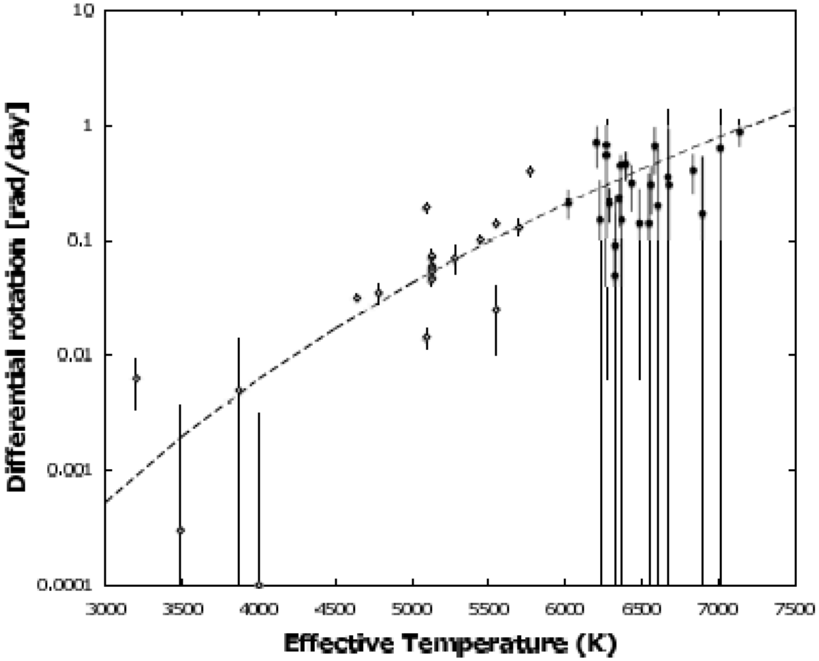
Trends in Differential Rotation with Ω & Mass (Teff)

Weak trend with Ω



Barnes et al. 2005

ΔΩ increases with M_*



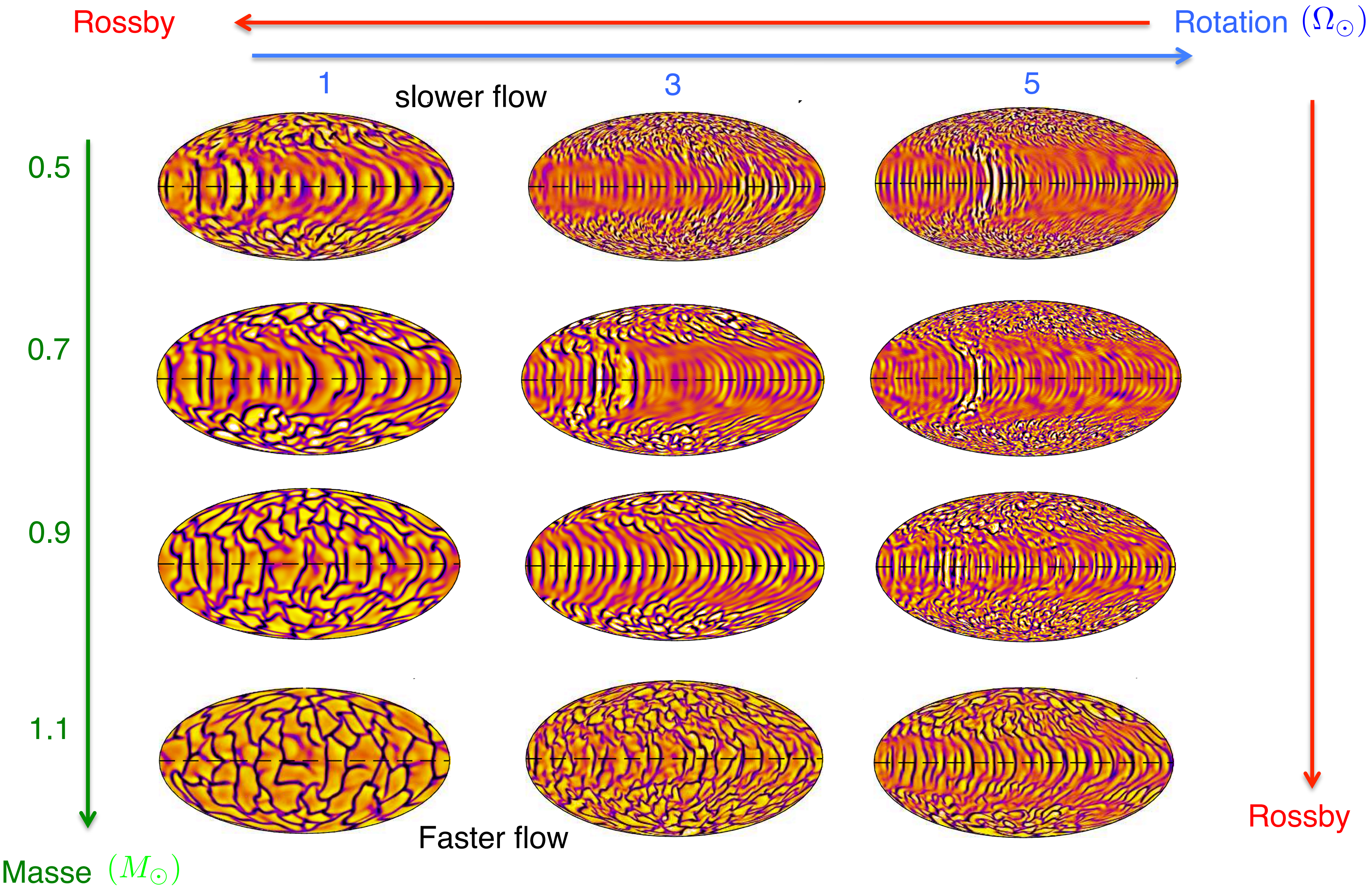
Collier-Cameron 2007

In Donahue et al. 1996: ΔΩ propto $\Omega^{0.7}$

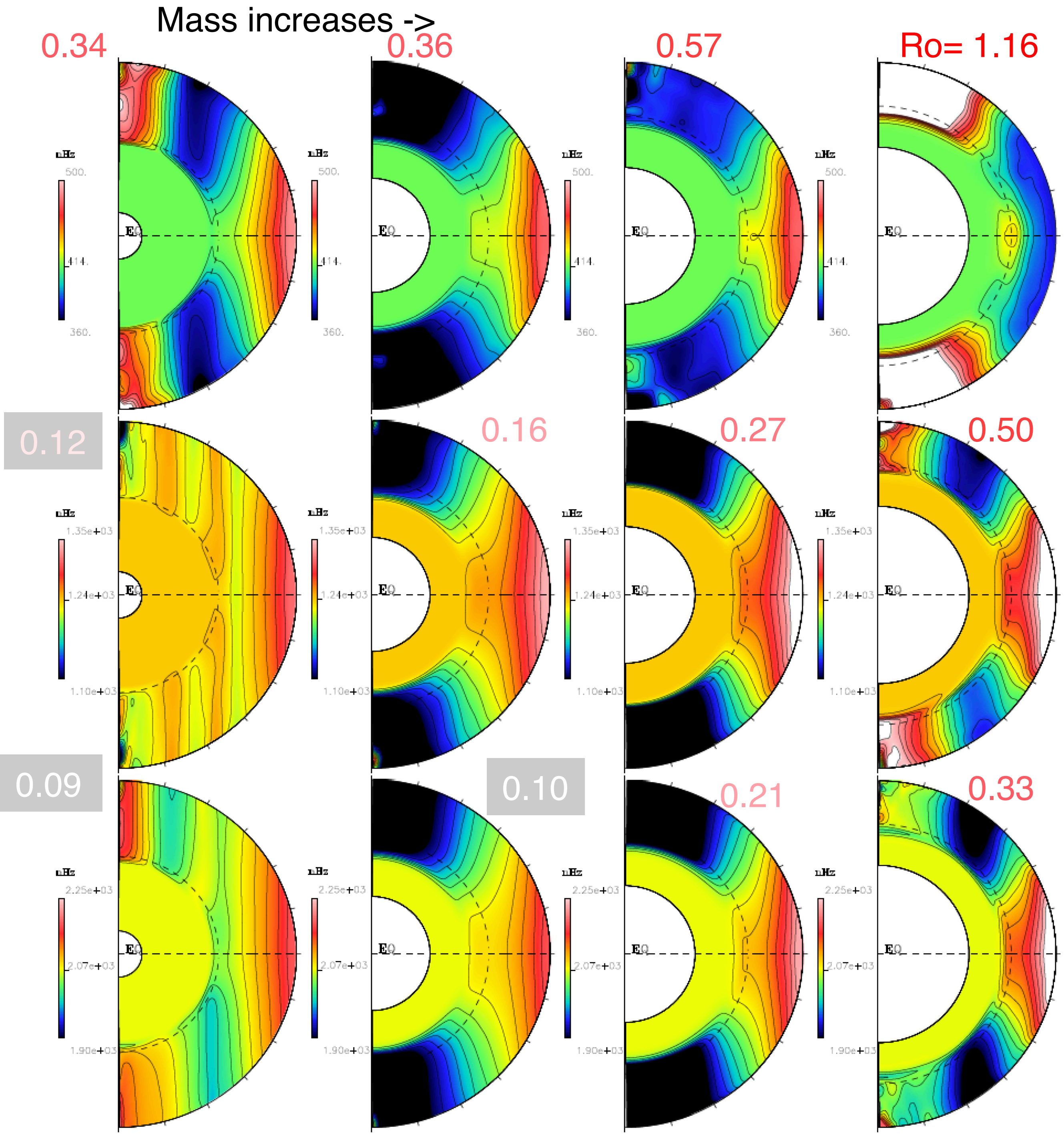
Confirming these observational scaling is key

Effect of Rotation on Convection

Matt, DoCao, Brun et al. 2011, 2013



Differential Rotation In G & K stars



Matt et al. 2011, 2013

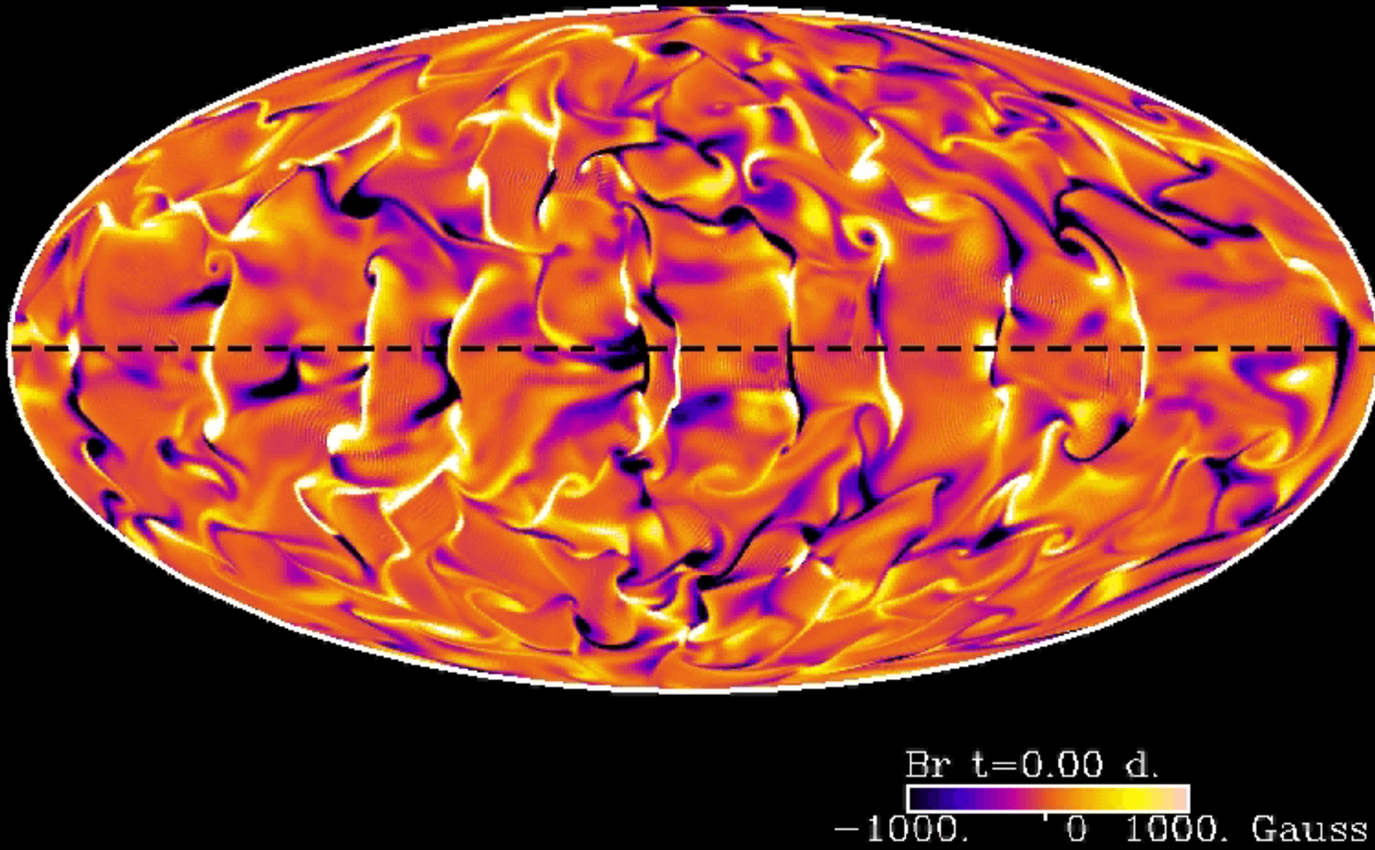
Ω

Rotation Increases

Rossby nb $Ro=\omega/2\Omega_*$

5 Ω

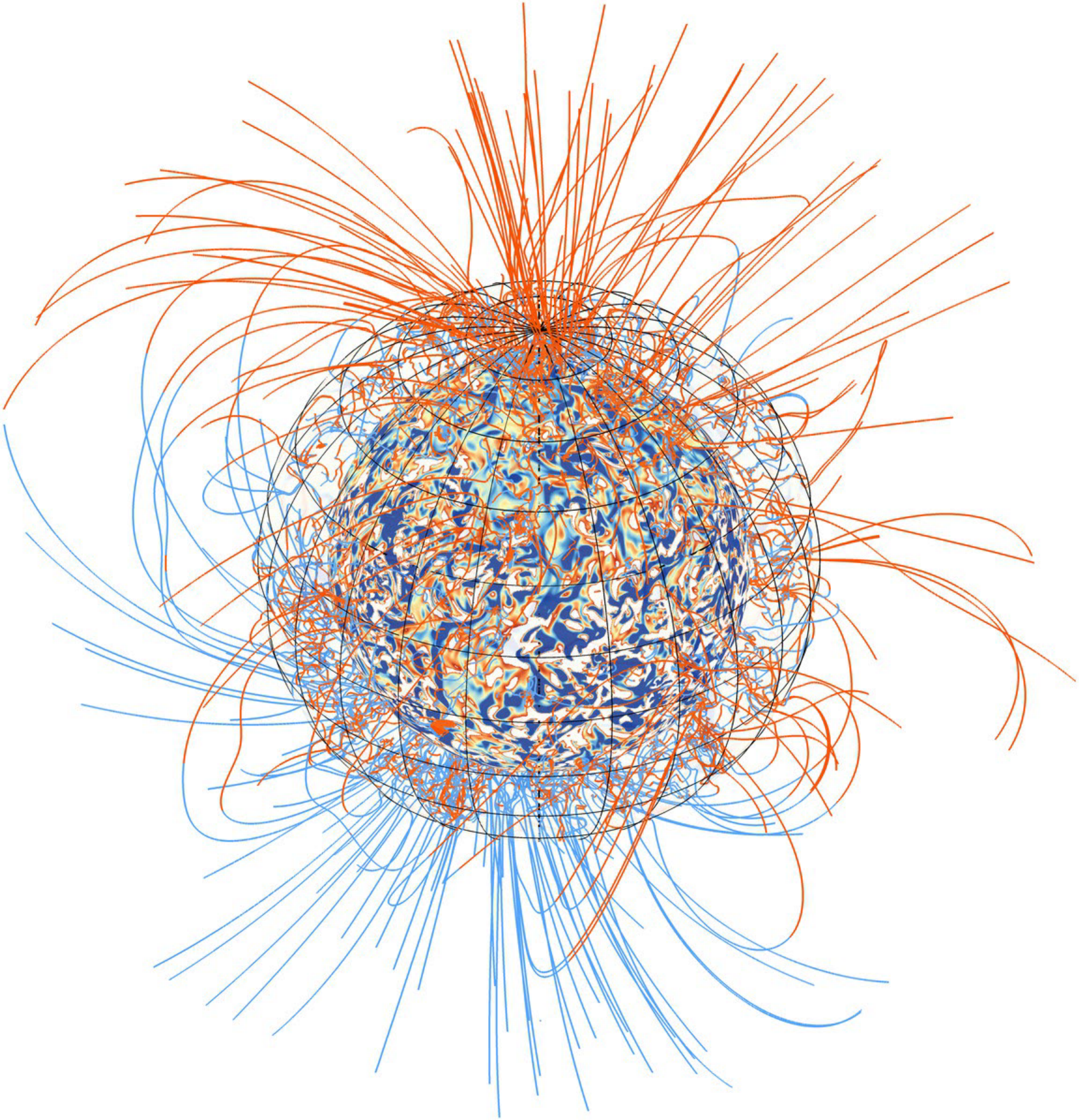
3-D Convective Solar Dynamo



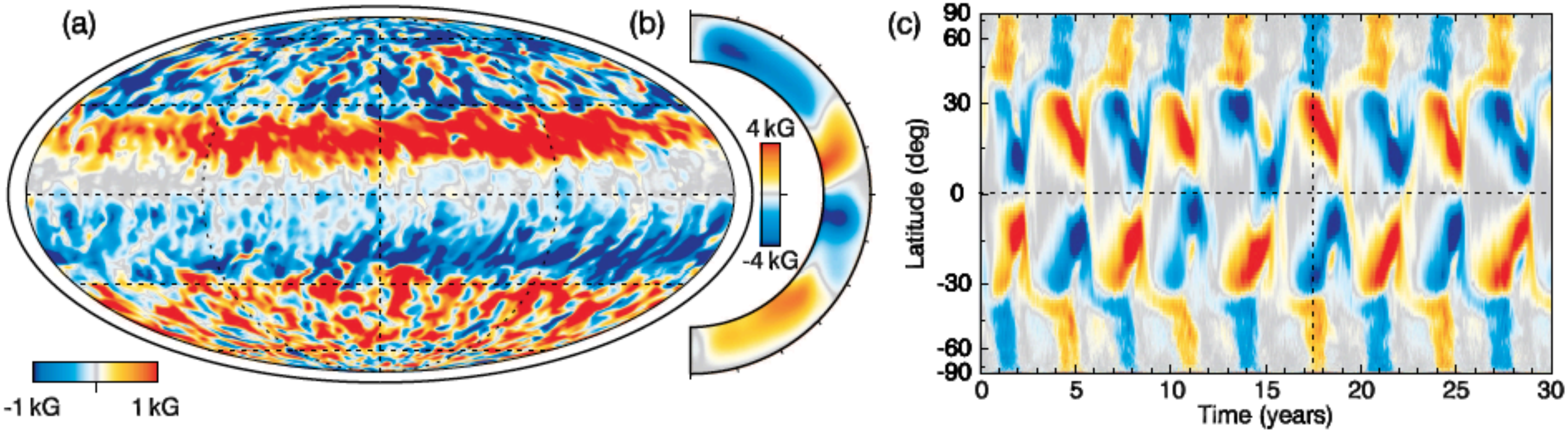
Brun et al. 2004

see also Browning et al. 2006, Brown et al. 2011, Racine et al. 2010

Magnetic field in a solar-like star dynamo

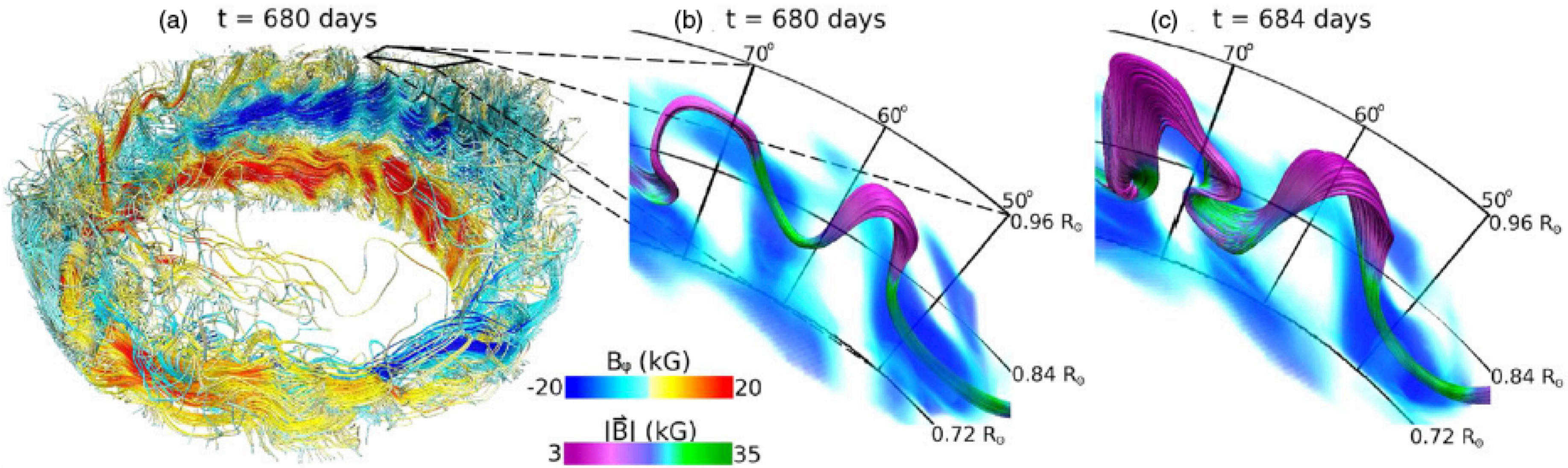


Getting cycle and equatorward branch in 3-D dynamo



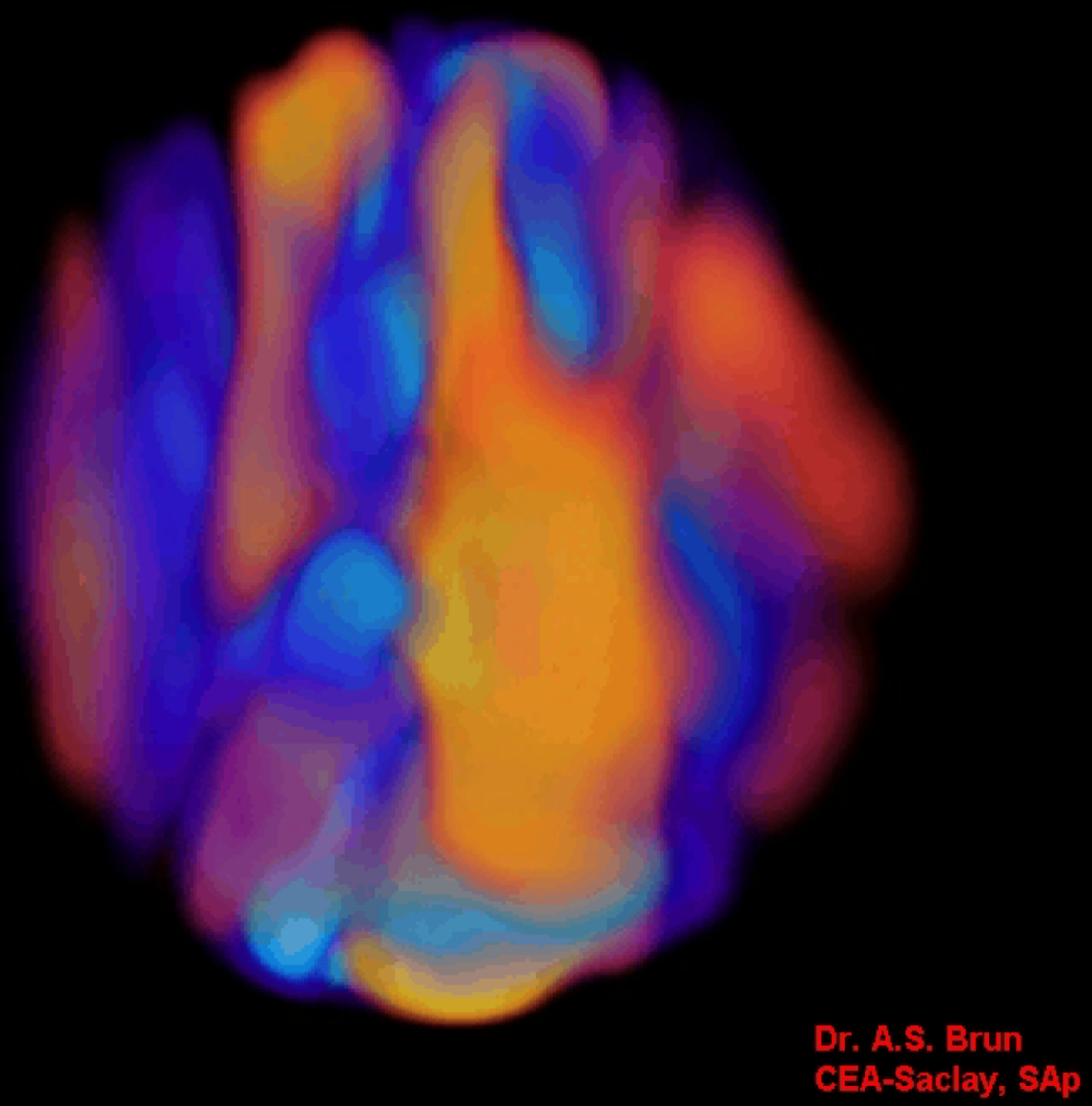
Augustson, Brun et al. 2013, ApJL, submitted

Wreaths can generate Buoyant Loops



Nelson et al. 2011, 2013a, 2013b

Towards getting first "spot-dynamos"…



Dr. A.S. Brun
CEA-Saclay, SAp

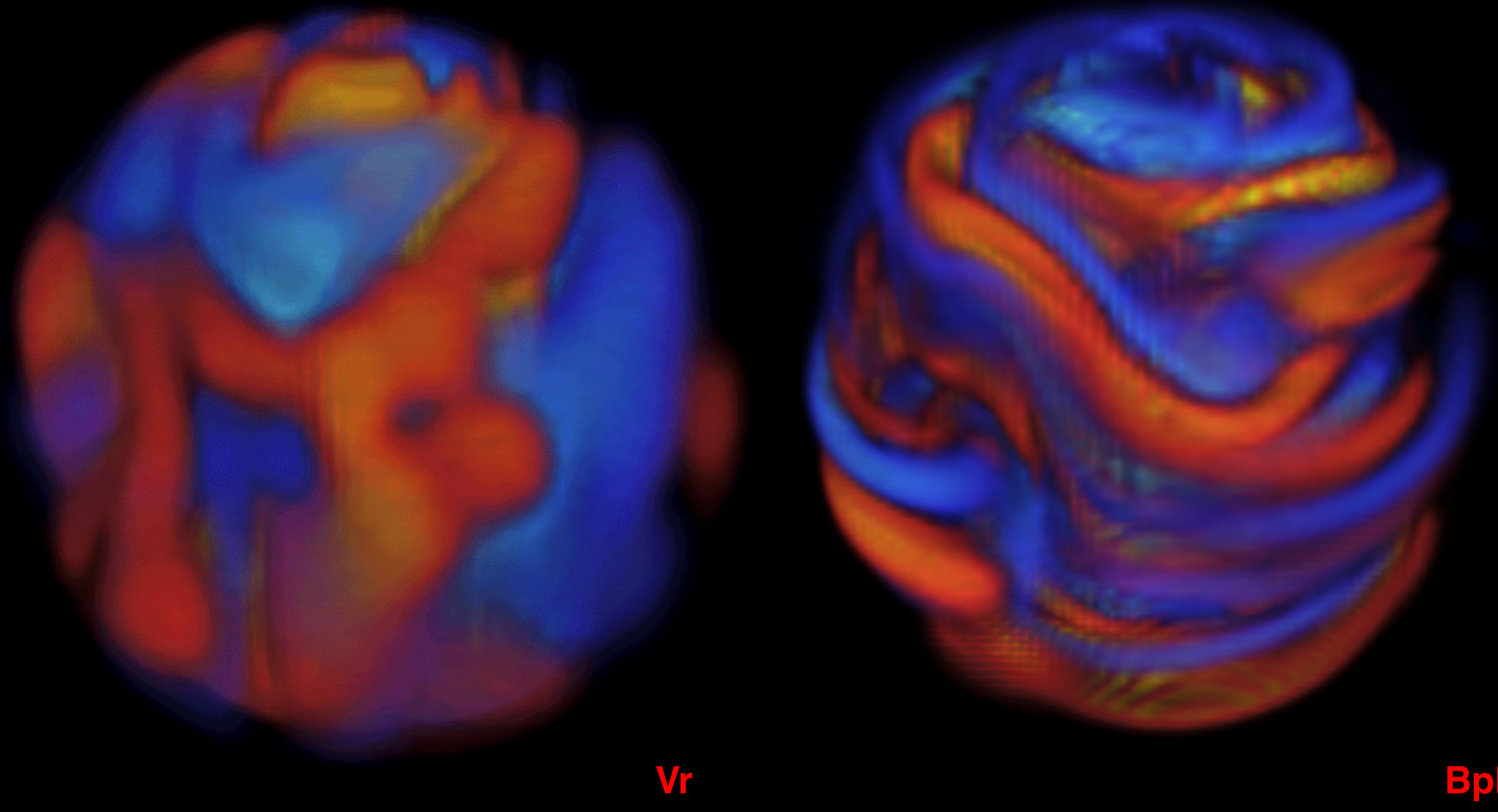
Rendu 3D
de la
Vitesse radiale

Re~140, P=0.25

(Browning,
Brun &
Toomre 2004,
ApJ, 601, 512)

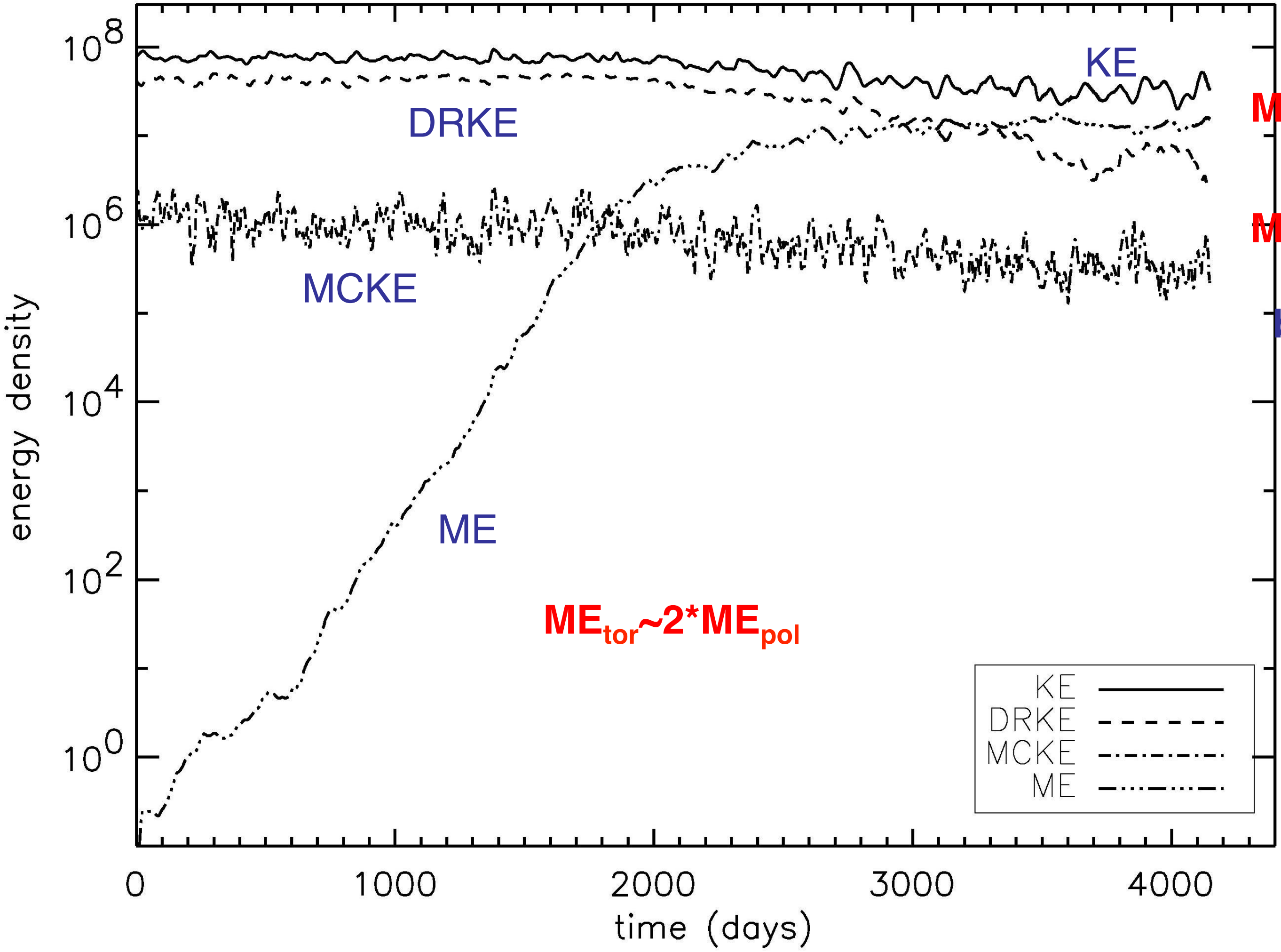
Core Dynamo

(Brun, Browning, Toomre 2005, ApJ 629, 461)



The convective core motions amplify the magnetic field B by many order of magnitude.

Dynamo Effect –Magnetic Energy



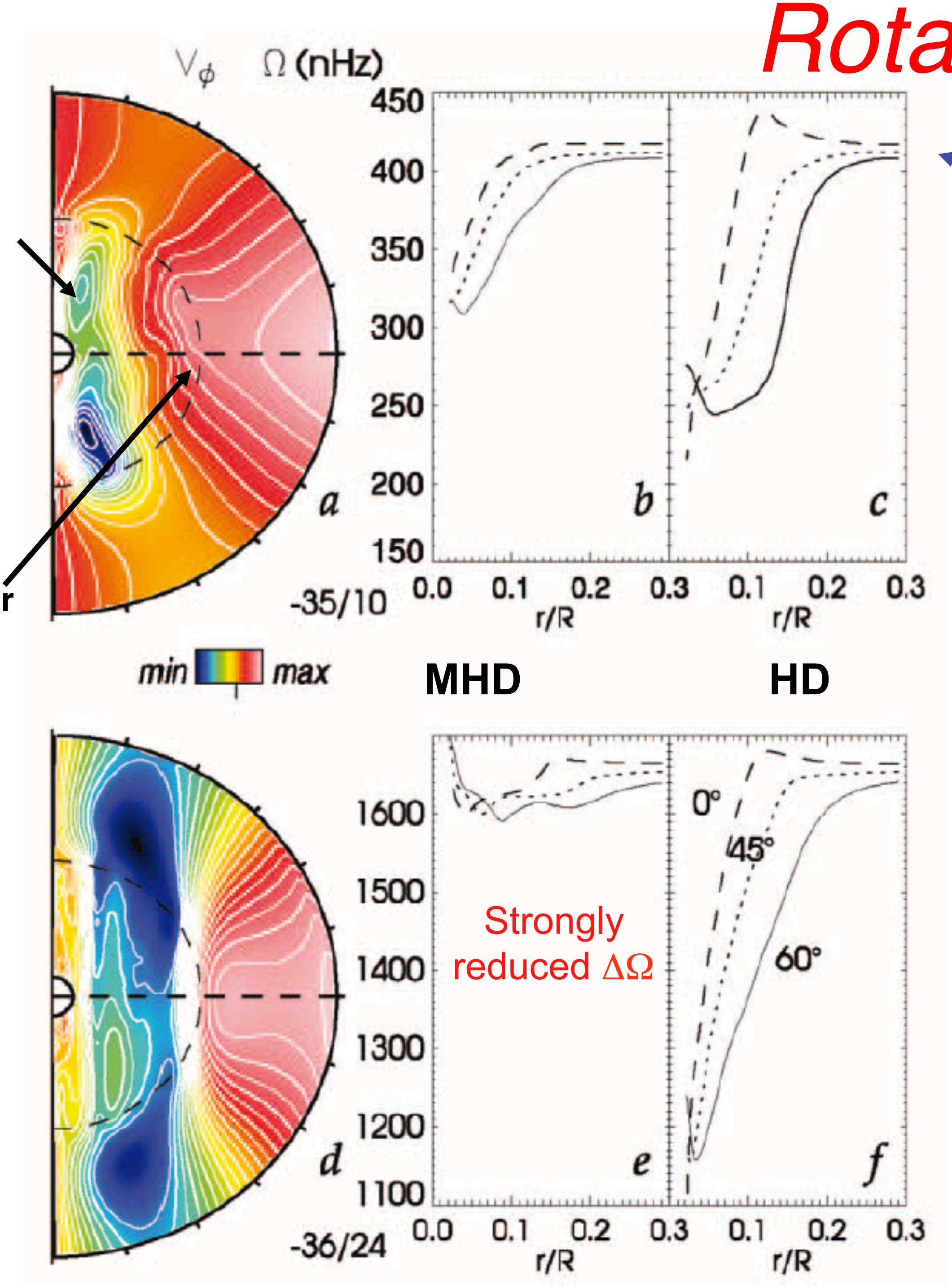
ME~40%KE

ME>DRKE &
MCKE
but < CKE

ME_{tor}~2*ME_{pol}

The Lorentz force jxB feeds back nonlinearly on the motions and seems to slow them down

Rotation Profile



Slow Poles

Slightly Faster Equator

$\Omega=\Omega_{sol}$

$\Omega=4\Omega_{sol}$

MHD

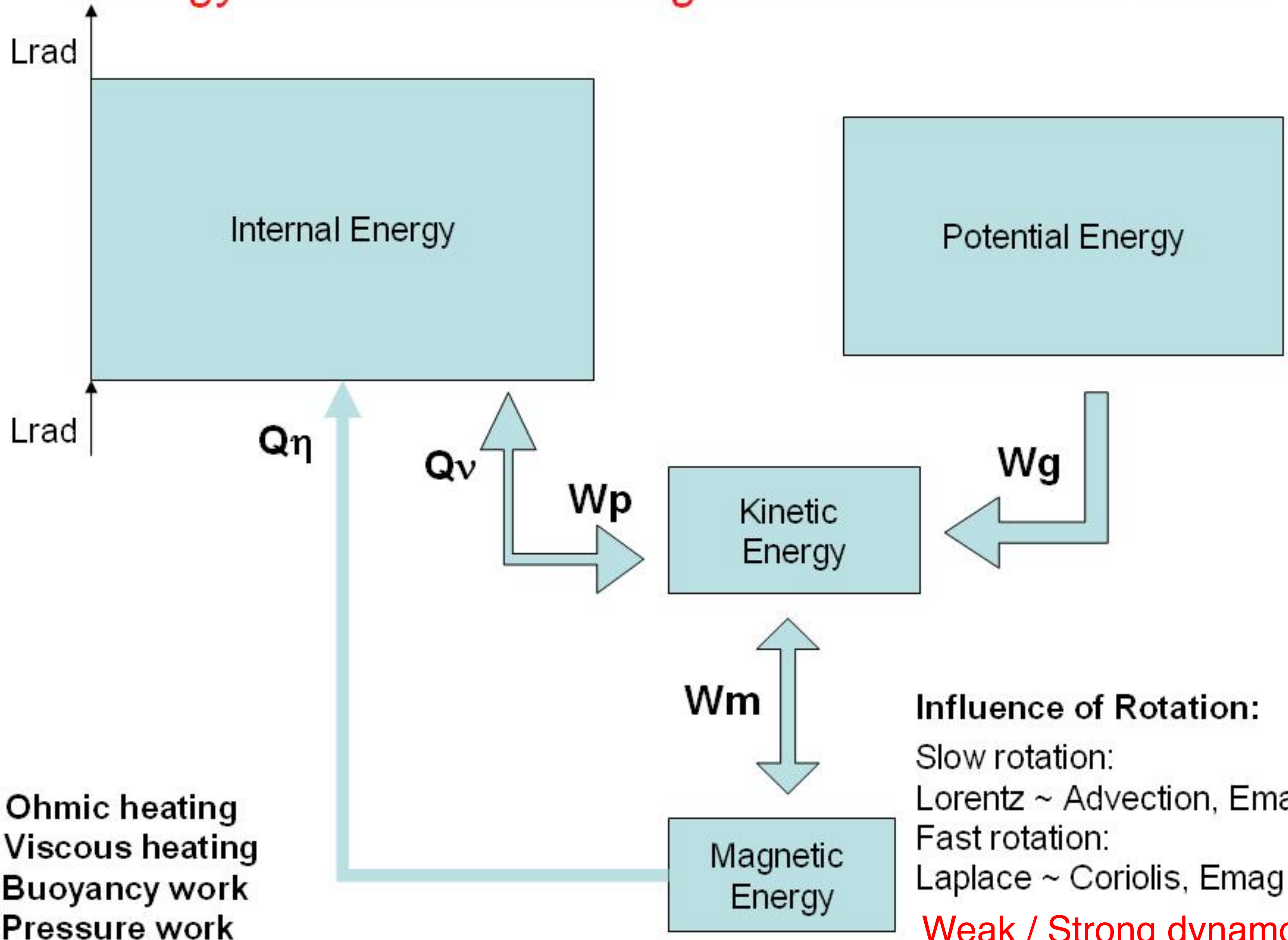
HD

Strongly reduced $\Delta\Omega$

Almost rigid rotation of radiative envelope

The transport of angular momentum by the Reynolds stresses remain at the origin of the equatorial acceleration, helped by the meridional circulation. The Maxwell stresses seek to speed up the poles.

Energy Reservoirs in a Magnetized Convection Zone



Lrad

Internal Energy

Potential Energy

Lrad

Qη

Qν

Wp

Kinetic Energy

Wg

Wm

Magnetic Energy

Qη: Ohmic heating
Qν: Viscous heating
Wg:Buoyancy work
Wp:Pressure work
Wm: Lorentz force work

Influence of Rotation:

Slow rotation:
Lorentz ~ Advection, Emag ~ Eke
Fast rotation:
Laplace ~ Coriolis, Emag > Eke

Weak / Strong dynamo regime

(Brandenburg et al. 1996, Brun et al. 2004) Simitev & Busse 2009

Various Dynamo Regimes and Scalings

Equilibrium field : $B_{eq} \sim \mathrm{sqrt}(8\pi P_{gaz}) \sim \mathrm{sqrt}(\rho_*)$

If magnetic Reynolds number Rm ~1 , $v = \eta/L$, then

Laminar (weak) scaling: Lorentz ~ diffusion =>

$$B^2_{weak} \sim \rho\nu\eta/L^2$$

Turbulent (equipartition) scaling: Lorentz ~ advection =>

$$B^2_{turb} \sim \rho v^2 \sim \rho\eta^2/L^2 \Leftrightarrow |B_{weak}| \sim |B_{turb}|\, P_m^{1/2}$$

Magnetostrophic (strong) scaling: Lorentz ~ Coriolis =>

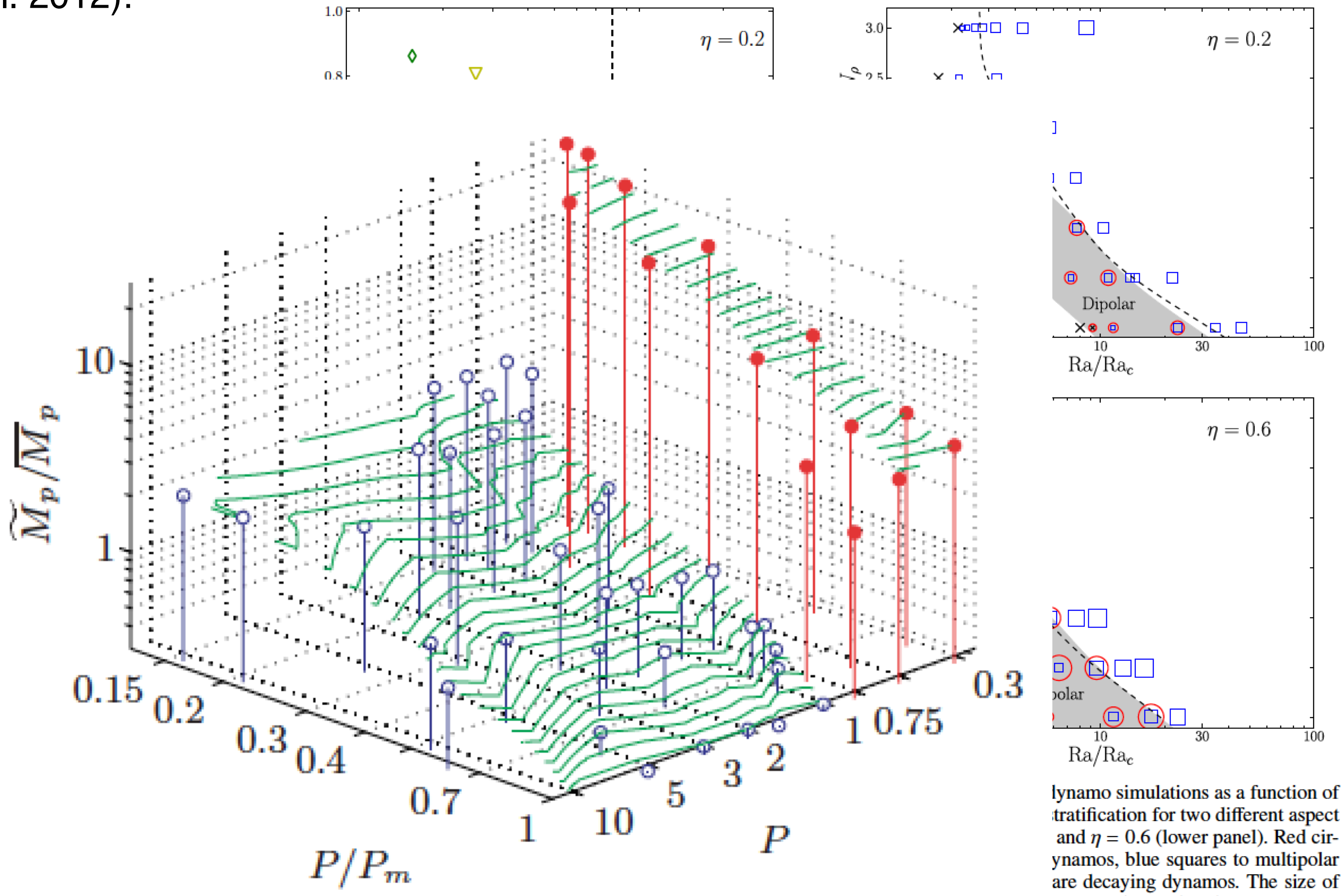
$$B^2_{strong} \sim \rho\Omega\eta$$

With ρ density, ν kinematic viscosity, η magnetic diffusivity, Ω rotation rate, v, L characteristic velocity & length scales, $P_m = \nu/\eta$ the magnetic Prandtl nb

Fauve et al. 2010, Christensen 2010, Brun et al. 2013

Dipole vs multipolar strength

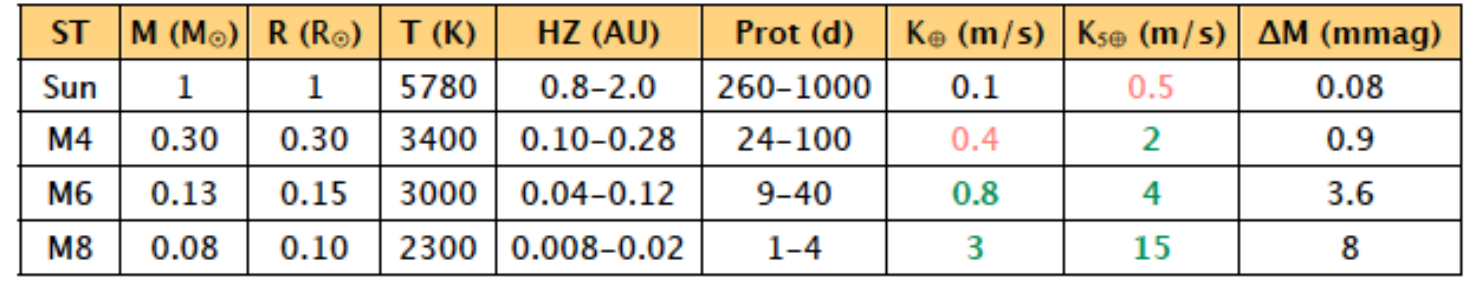
Recent studies have advocated the existence of bi-stability (weak vs strong dynamo branches) following the initial work in Boussinesq of Simitev & Busse (2009) on the geo-dynamo.
They have been found for aspect ratio and or stratification (Morin et al. 2011, Gastine et al. 2013, Schrinner et al. 2012):



Elsasser number (Eq. 13). Vertical lines are tentative transitions between dipolar and multipolar dynamos.

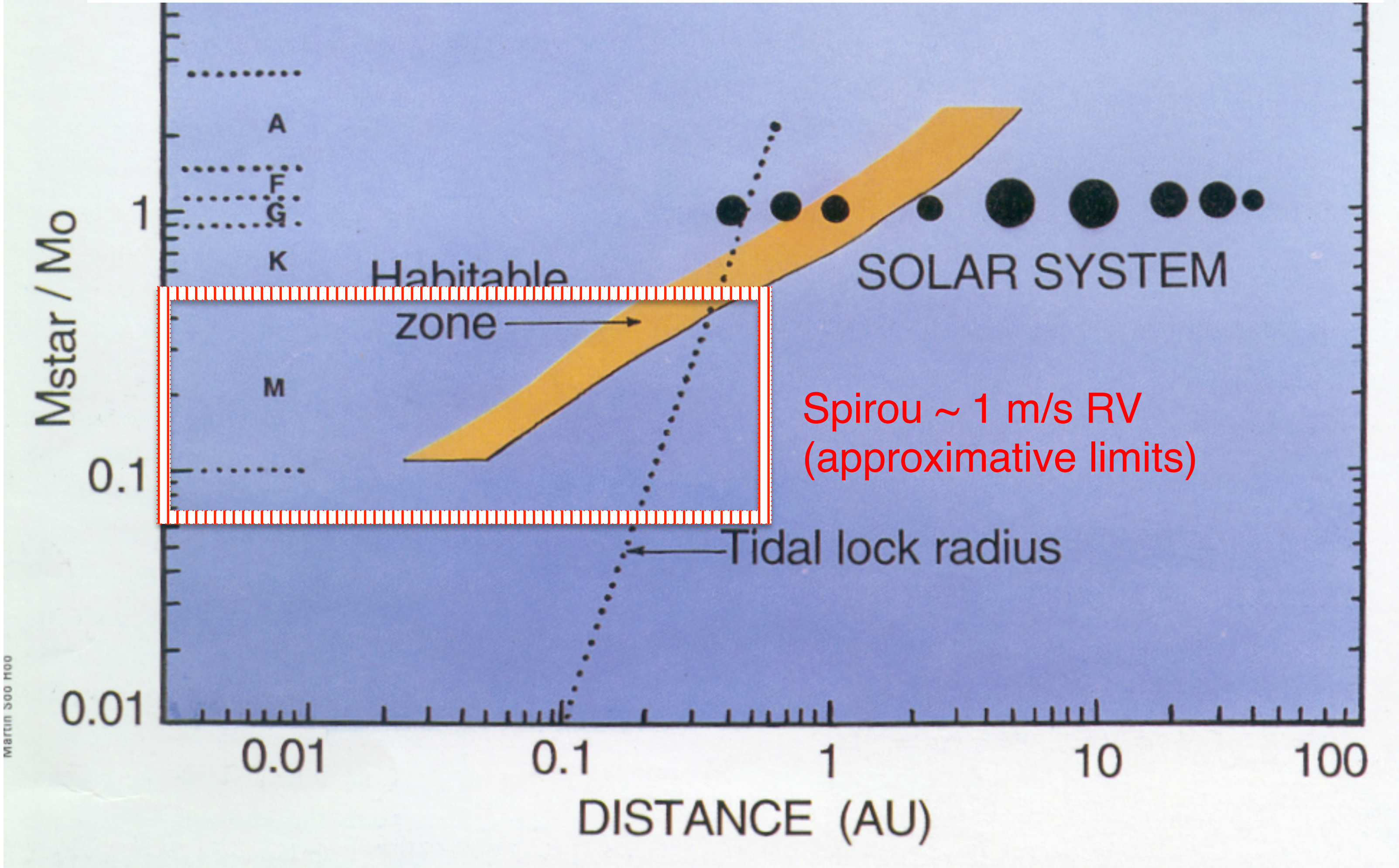
lynamo simulations as a function of tratification for two different aspect and $\eta = 0.6$ (lower panel). Red cir- ynamos, blue squares to multipolar are decaying dynamos. The size of alue of the modified Elsasser number (Eq. 13). The grey-shaded area highlights the dipolar region, while the dashed lines correspond to the critical $\mathrm{Ro}_{\ell c}$ values that mark the limit between dipolar and multipolar dynamos (see the

Star-Planet Interaction



ST	M ($M_\odot$)	R ($R_\odot$)	T (K)	HZ (AU)	Prot (d)	$K_\oplus$ (m/s)	$K_{5\oplus}$ (m/s)	ΔM (mmag)
Sun	1	1	5780	0.8–2.0	260–1000	0.1	0.5	0.08
M4	0.30	0.30	3400	0.10–0.28	24–100	0.4	2	0.9
M6	0.13	0.15	3000	0.04–0.12	9–40	0.8	4	3.6
M8	0.08	0.10	2300	0.008–0.02	1–4	3	15	8

Min 57 R
17 R

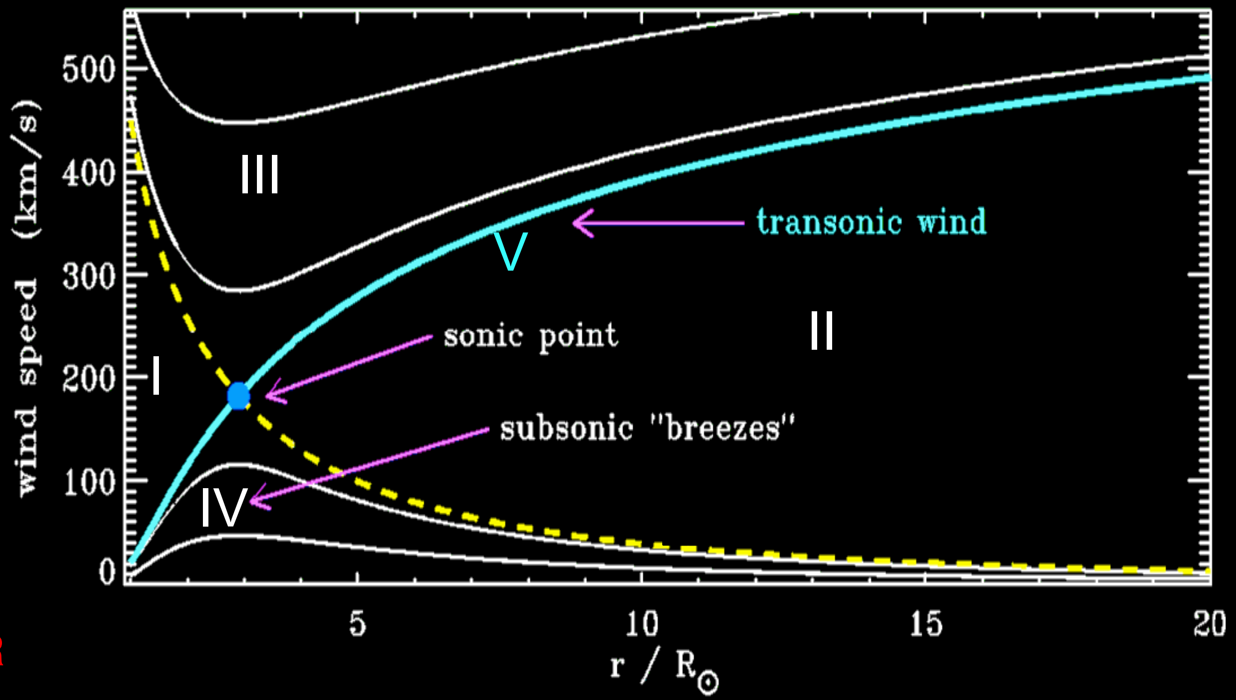


Spirou ~ 1 m/s RV
(approximative limits)

Stellar Wind & Star-Planet Interaction

- Hydrostatic isothermal corona at T=1 Mk yields pressure ratio $p_\infty/p_\star \sim 10^{-4}$
- but interstellar value yields $p_\infty/p_\star \sim 10^{-14}$!
- Parker [1958] propose to consider a dynamic atmosphere

solution V is the solar wind solution



Solutions I & II unphysical

Solutions III (fast wind) et IV (breeze) do not match obs.

Note: Alfven radius ~ 10-20 R

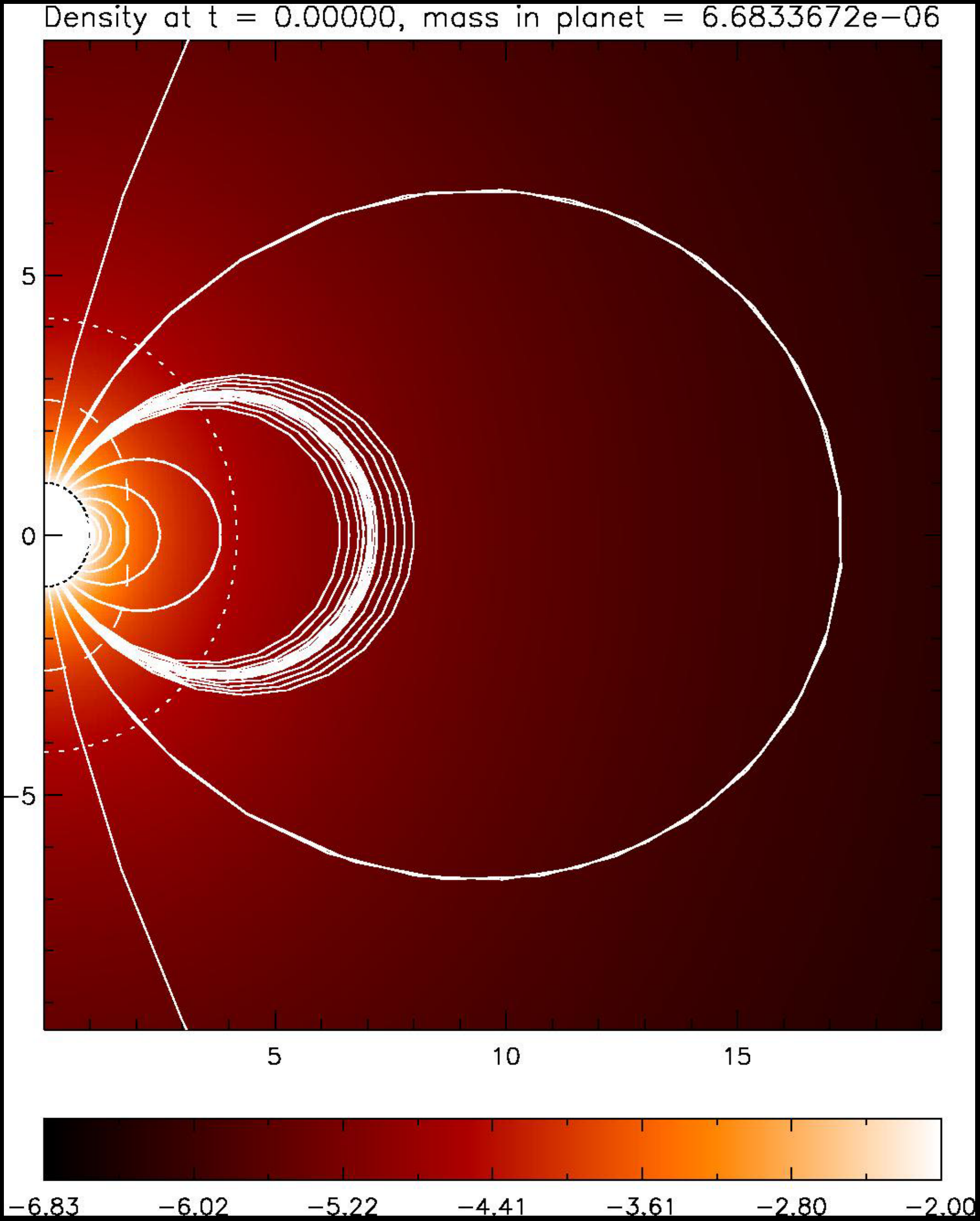
Stellar Wind

Simple Parker-like wind

$$c_s^\star/v_{esc} = 0.27$$

$$v_\varphi^\star/v_{esc} = 0.08$$

$$v_a/v_{esc} = 0.32$$



Pinto et al. 2011
Strugarek et al. 2013

Intrinsic Magnetoshpere

- « bow shock » at planet/ wind interface

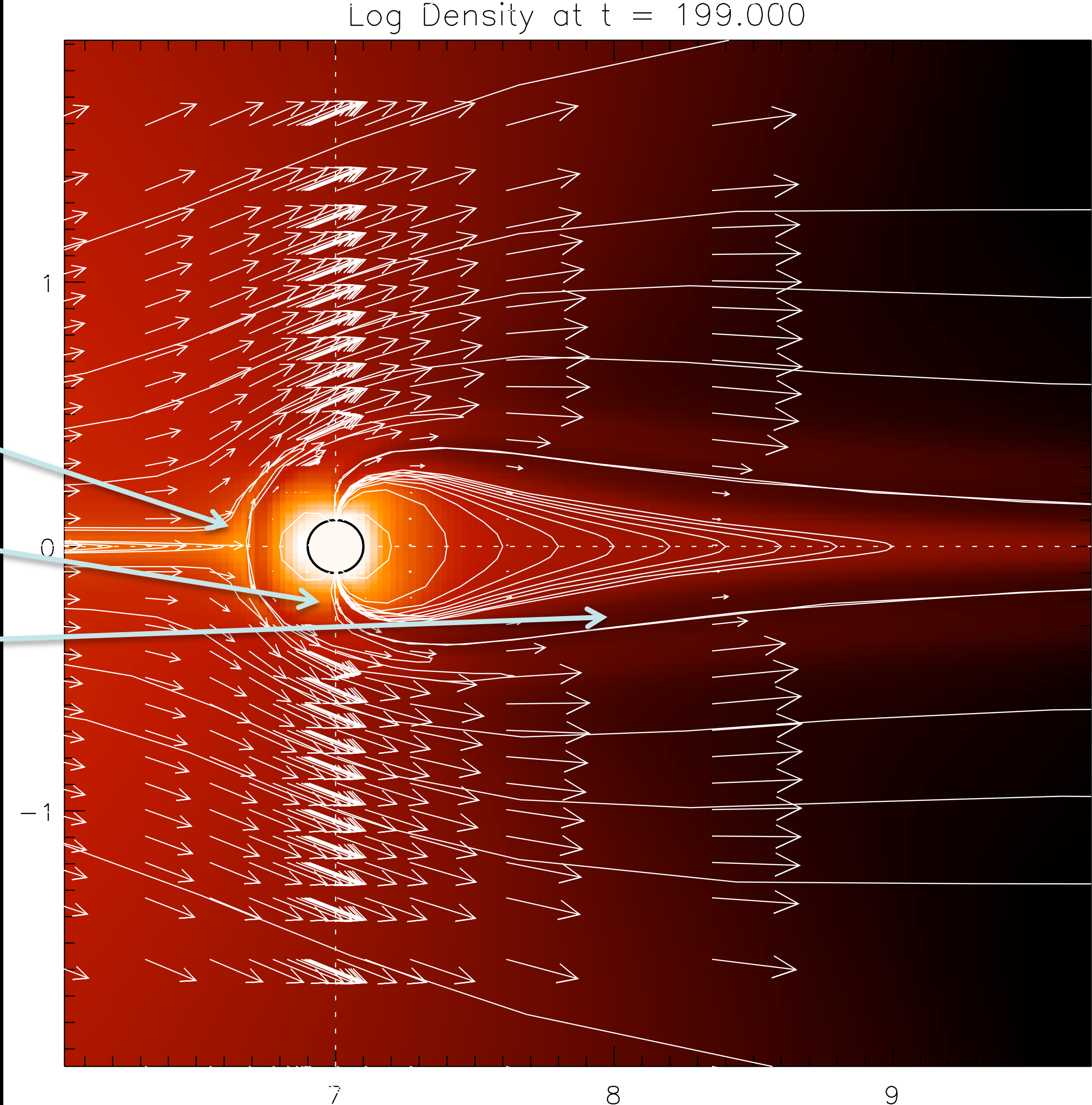
- We see:

- a magnetopause

- lobes

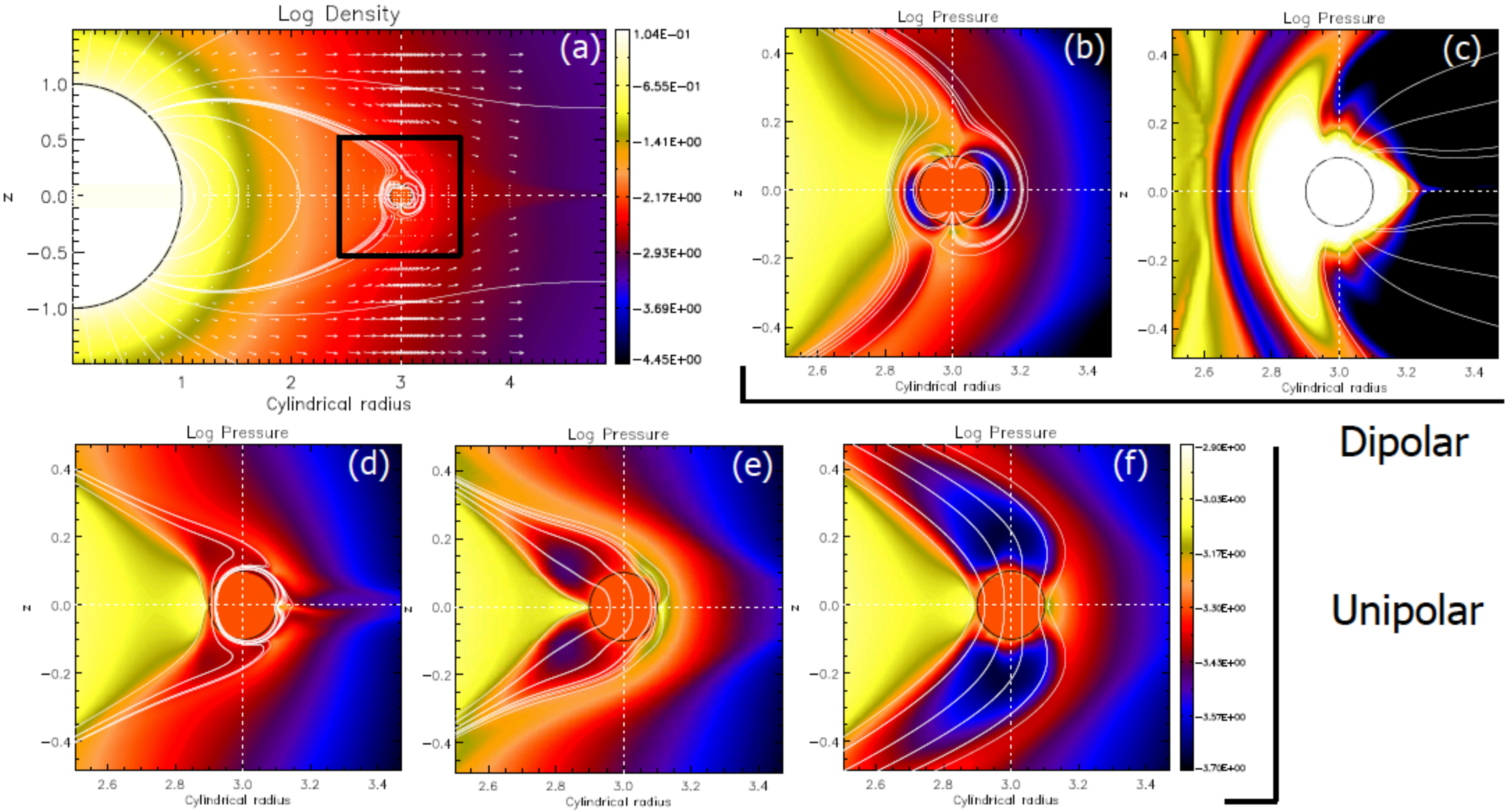
- and magnetotail

- If the planet is far enough little influence on host star



Stellar wind impact: intrinsic vs induced magnetosphere

Nearby planet: influence host star



Dipolar

Unipolar

Strugarek, Brun et al. 2013

SPIROU vs Stellar Magnetism & SPI

- In nIR for low mass stars thousands of spectral lines to get magnetic fields via Zeeman effect using LSD technique (lines “collapse”)

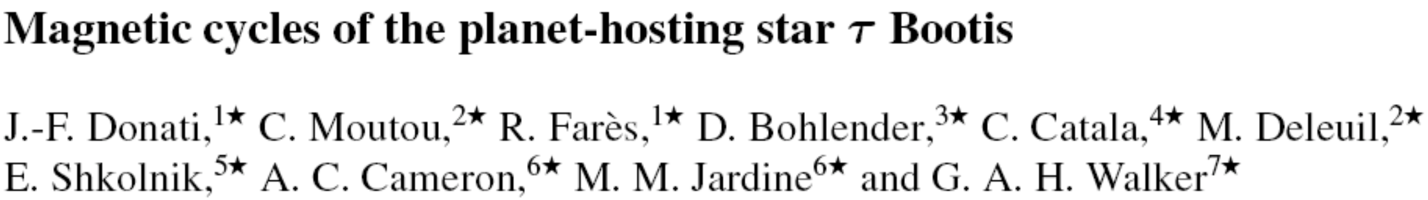
- Probe the influence of the internal structure of M-dwarfs on dynamo: Fully convective vs envelope, what type of dynamo

- Get magnetic field topology (symmetries) and strength, assess how they vary with stellar parameters for both M-dwarfs and young Suns (TTauri)

- Probe differential rotation of stars for fastly rotating one

- Probe star-planet interactions, winds on magnetosphere, can be complementary to radio obs

- Check influence of nearby planet on rotation and dynamo cycle (ex Tau-boo)



Magnetic cycles of the planet-hosting star τ Bootis

J.-F. Donati,[1★] C. Moutou,[2★] R. Farès,[1★] D. Bohlender,[3★] C. Catala,[4★] M. Deleuil,[2★]
E. Shkolnik,[5★] A. C. Cameron,[6★] M. M. Jardine[6★] and G. A. H. Walker[7★]

Conclusions

Convective velocities Vr roughly scales with cubic root of L/(rho*R^2) (star's luminosity)

⇒ Prograde vs retrograde state changes at different Ω_0 as spectral type is changed (since Ro=V/2Ω_0d and V changes with spectral type)

⇒ Cylindrical vs conical vs shellular differential profiles depends on Reynolds stresses & thermal (baroclinic) effects/tachocline

⇒ Magnetic field B reduces or can even supress diff rot Ω

⇒ Multipolar or Dipolar magnetic bi-stability exist but Multipolar fields seem to dominate at high stratification

⇒ Self consitent buoyant loops generation possible, may yield first « Spot-Dynamo »