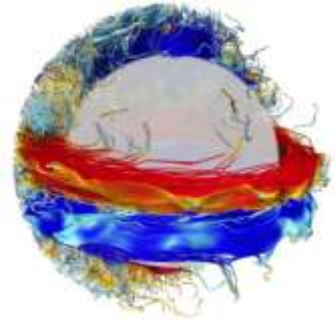
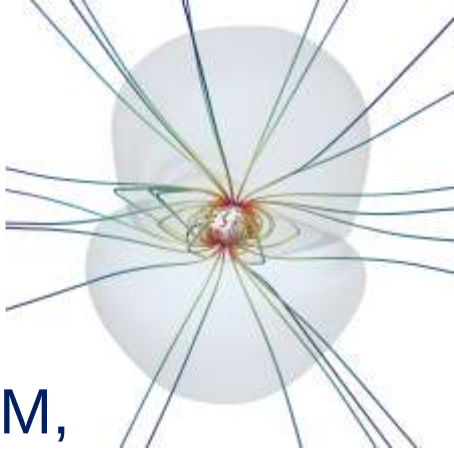


The Evolving Solar-Stellar Dynamo

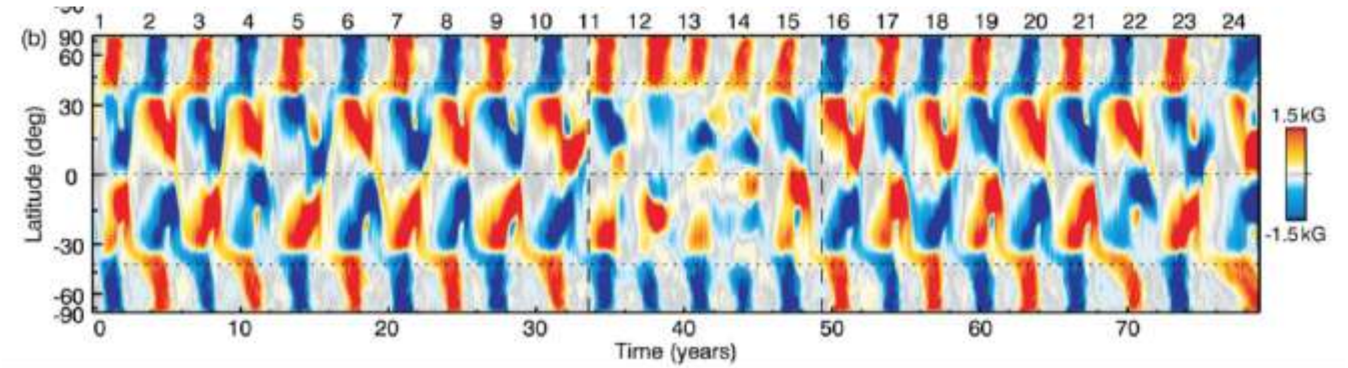


Allan Sacha Brun

Département d'Astrophysique/UMR AIM,
CEA Paris-Saclay

with L. Jouve, A. Strugarek, K. Augustson, V. Réville and the Whole Sun Team

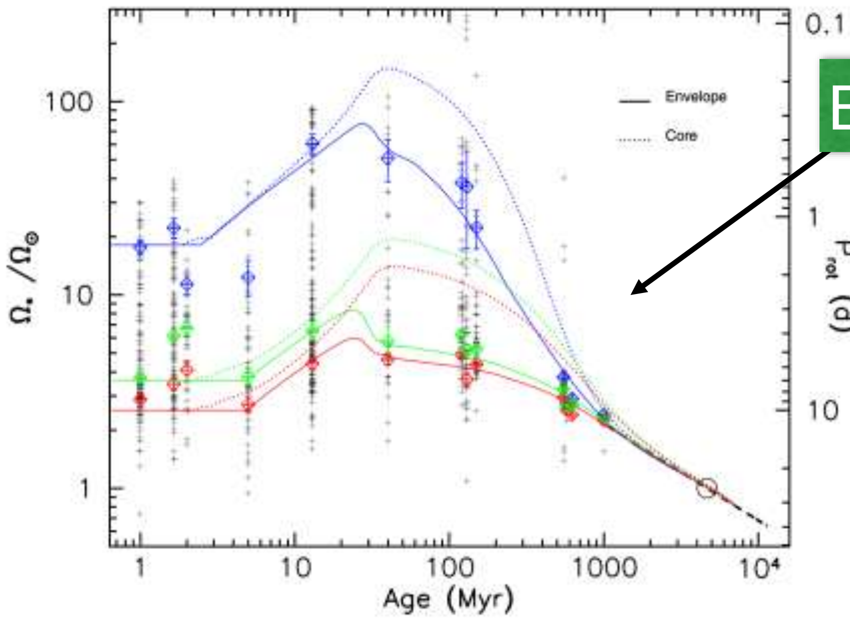
- Observational evidence of solar and stellar magnetism
- 2D & 3-D simulations of the Nonlinear stellar dynamos and wind



Wind, Stellar magnetism and gyrochronology

Stellar Spin down Models

(Gallet & Bouvier 2013)



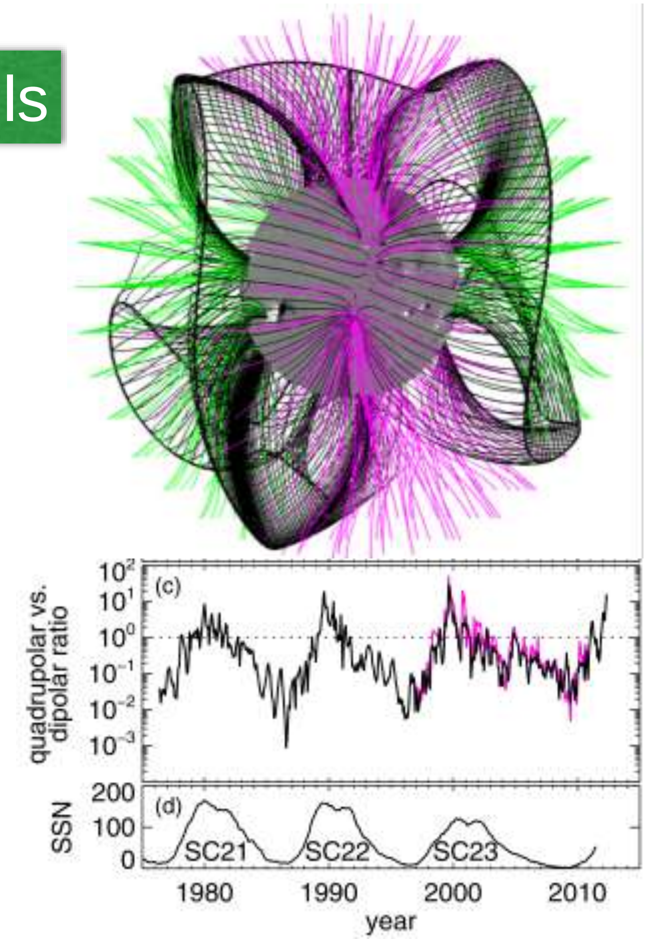
Braking models

dynamo

wind

Magnetic Activity

(De Rosa et al. 2012)



Skumanich's law: $\Omega_* \propto t^{-1/2}$

Gyrochronology: Barnes 2003, Magnetochronology: Vidotto et al. 2014

Most of what I will speak about can be found in this
2017 Living Review in Solar Physics

Springer Link

Living Reviews in Solar Physics

December 2017, 14:4 | Cite as

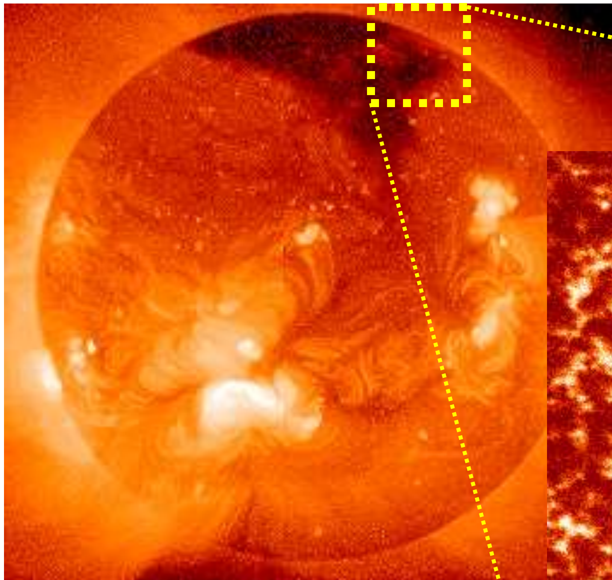
Magnetism, dynamo action and the solar-stellar connection

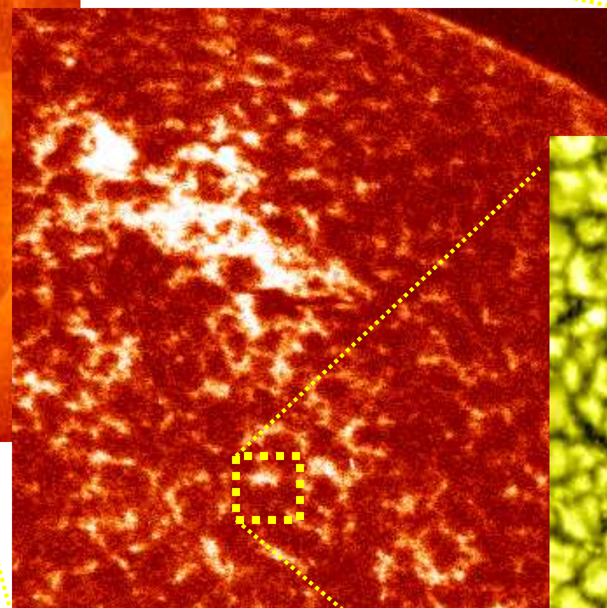
Authors | Authors and affiliations

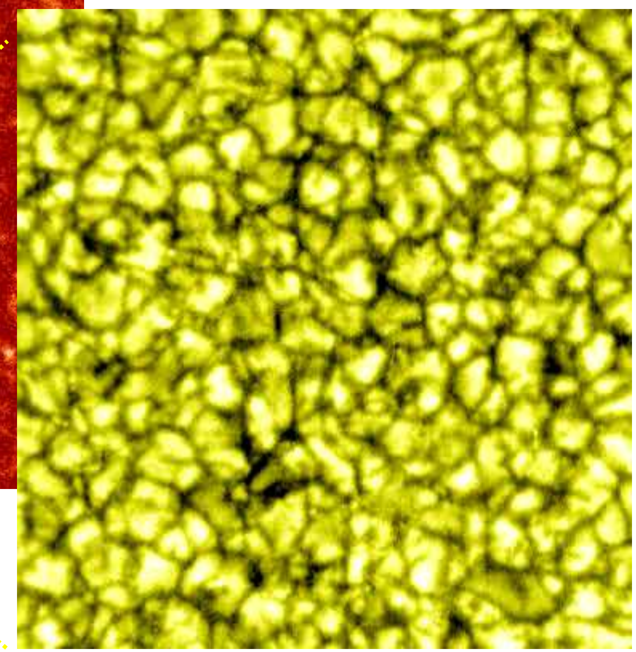
Allan Sacha Brun, Matthew K. Browning

LIVING REVIEWS
in solar physics

Solar Convection Scales







Order in chaos!

Really big stuff:
Flares,
Coronal holes,
CMEs

Giant cells?:
200+ Mm
10-20 days

Supergranulation:
30-50 Mm
20 hours

Mesogranulation?:
7-10 Mm
2 hours

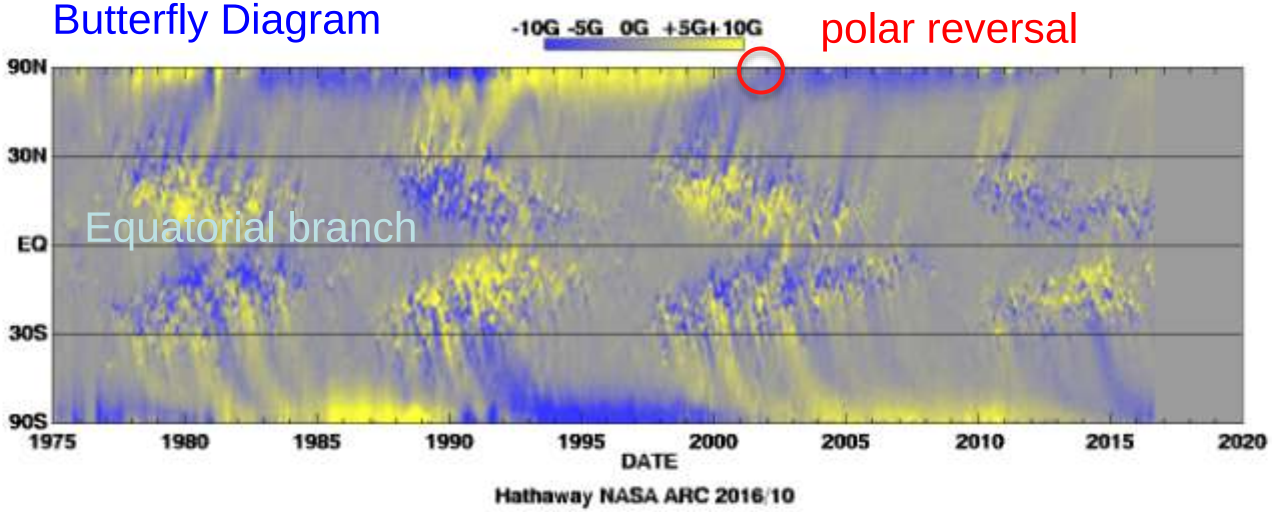
Granulation:
1-2 Mm
5 mins

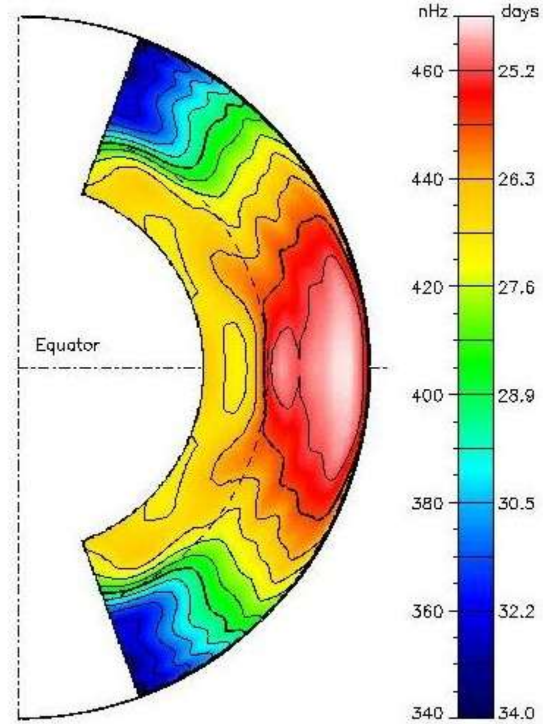
Smaller stuff:
Intergranular lanes,
magnetic bright
points, diffusion

Solar Cvcle and Flows

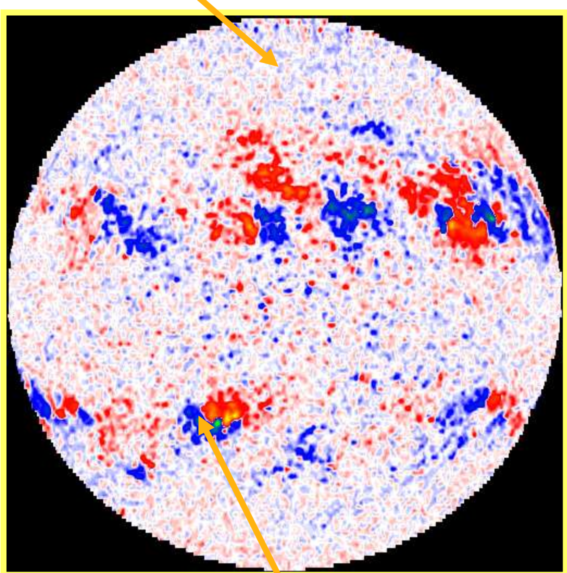
Butterfly Diagram

polar reversal



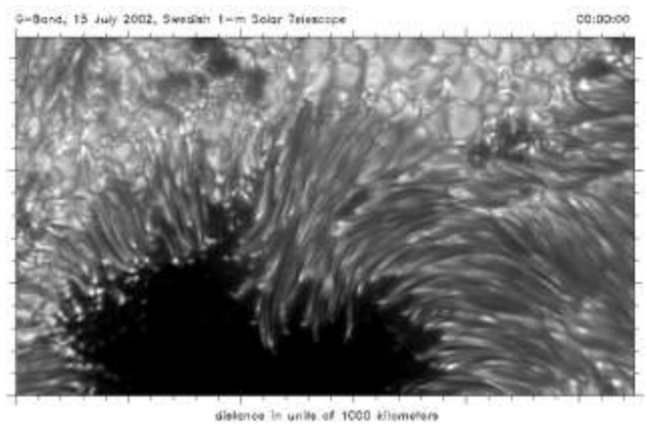


Quiet



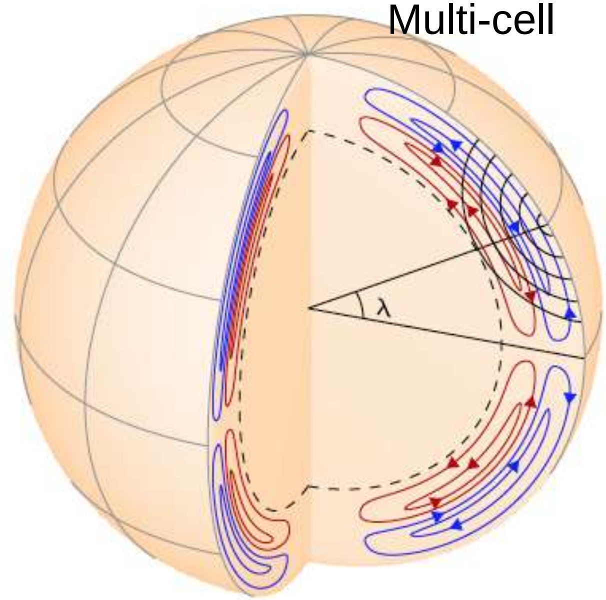
Active

Small vs Large Scale Dynamos



Zhao et al. 2013

Multi-cell

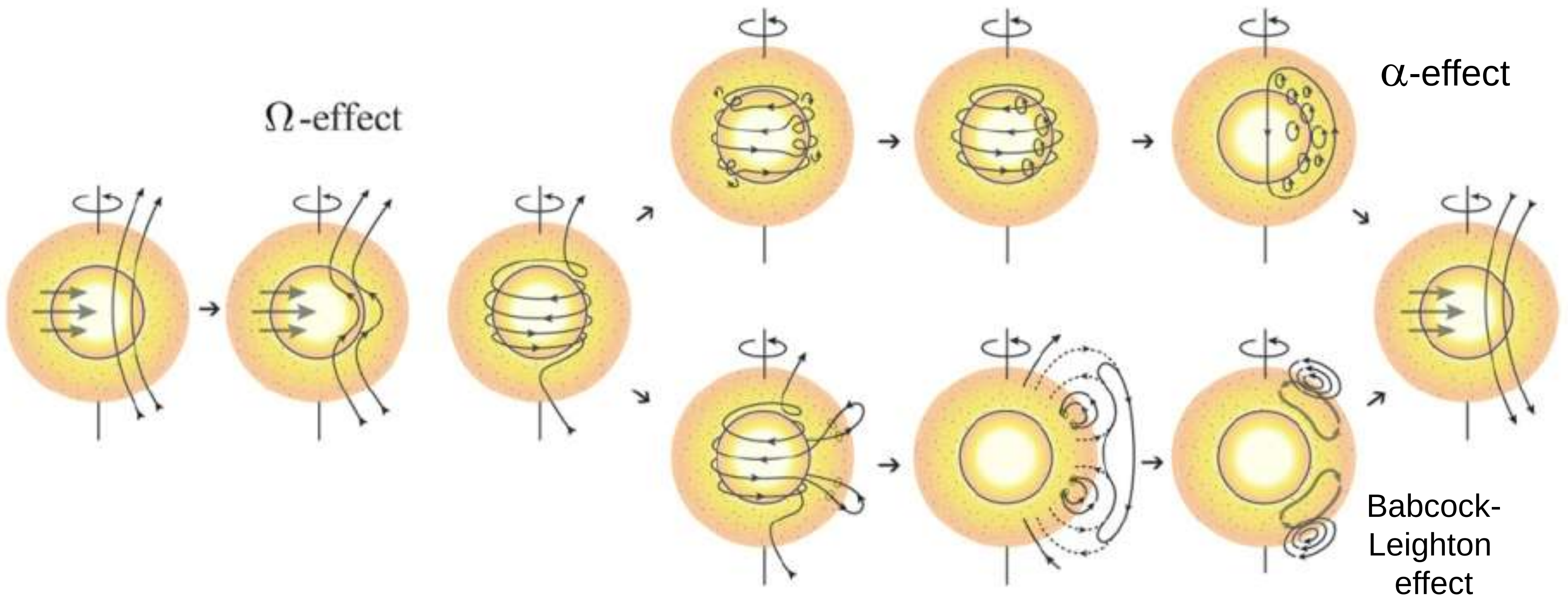


The Dynamo Effect what is it exactly?

The main source of magnetic filed in the Universe is the due to dynamo action:

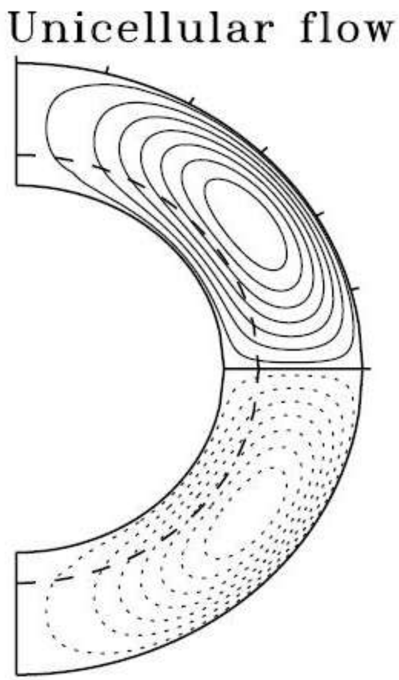
<u>A definition</u>: this is the property that a conducting fluid possesses to generate a magnetic field B via its motions (self-induction) and to sustain it against Ohmic dissipation

This is intrinsically a tri dimensional effect, there is for exemple an anti-dynamo Theorem (Cowling's theorem) forbidding purely axisymmetric dynamos

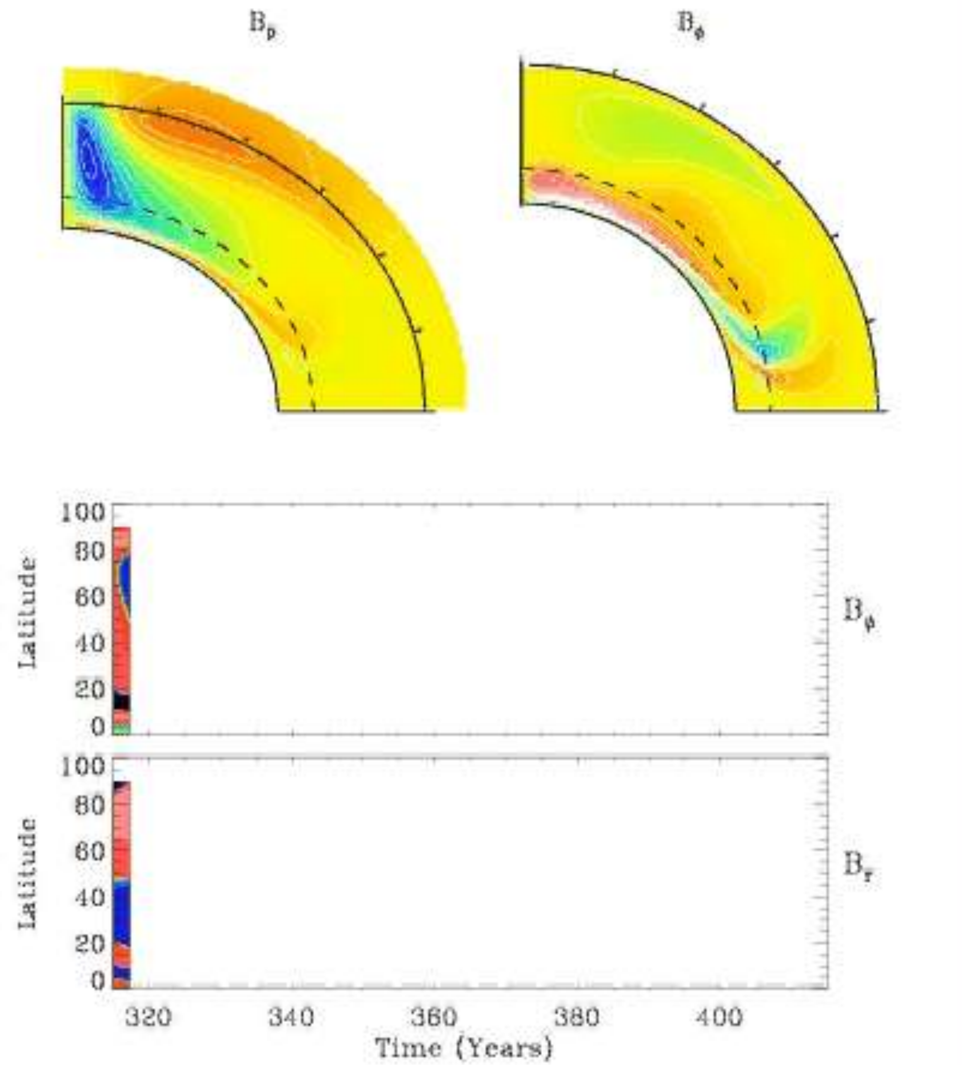


2-D Mean Field Dynamo: Standard Babcock-Leighton

1 cell per hemisphere, symmetric flow



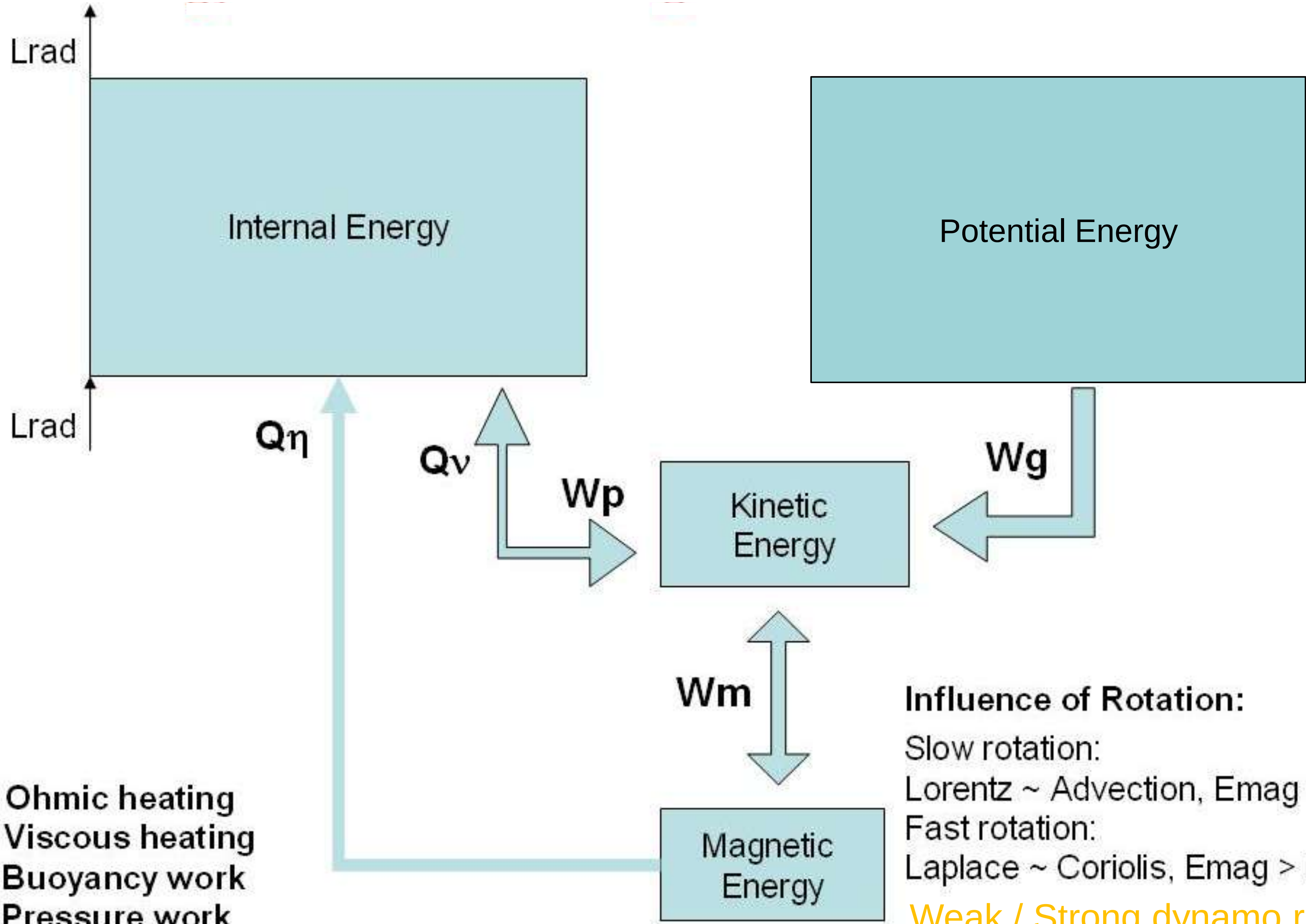
$$\psi(r,\theta) = -\frac{2(r-r_b)^2}{\pi(1-r_b)} \sin\left(\frac{\pi(r-r_b)}{1-r_b}\right) \cos\theta \sin\theta.$$



Jouve & Brun, 2007 A&A, 474, 239
See also Dikpati et al. series of papers

Check International Benchmark: Jouve et al. 2008, A&A
Or review by Charbonneau 2010 (LRSP)

Energy Reservoirs in a Magnetized Convection Zone



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

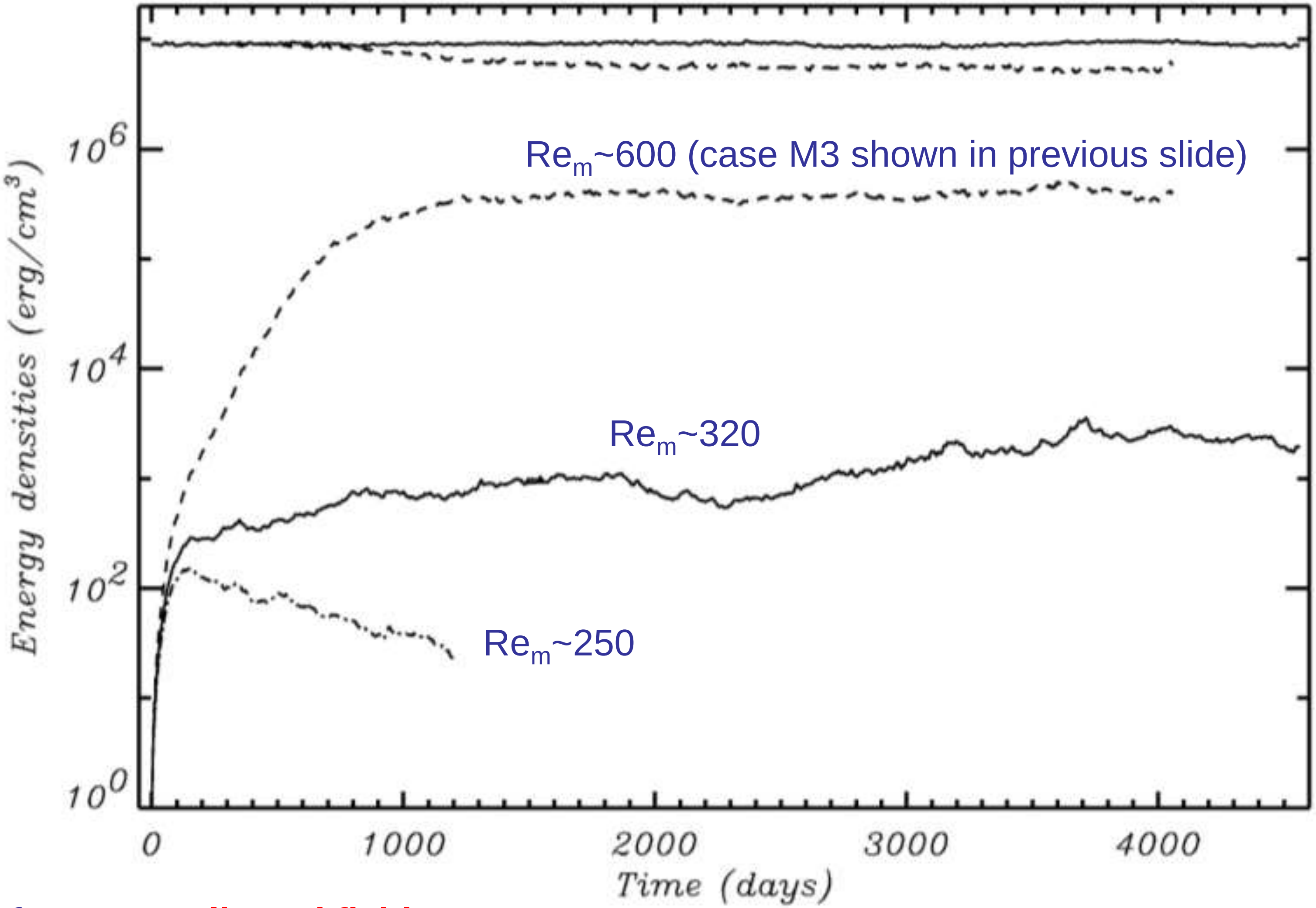
Influence of Rotation:

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

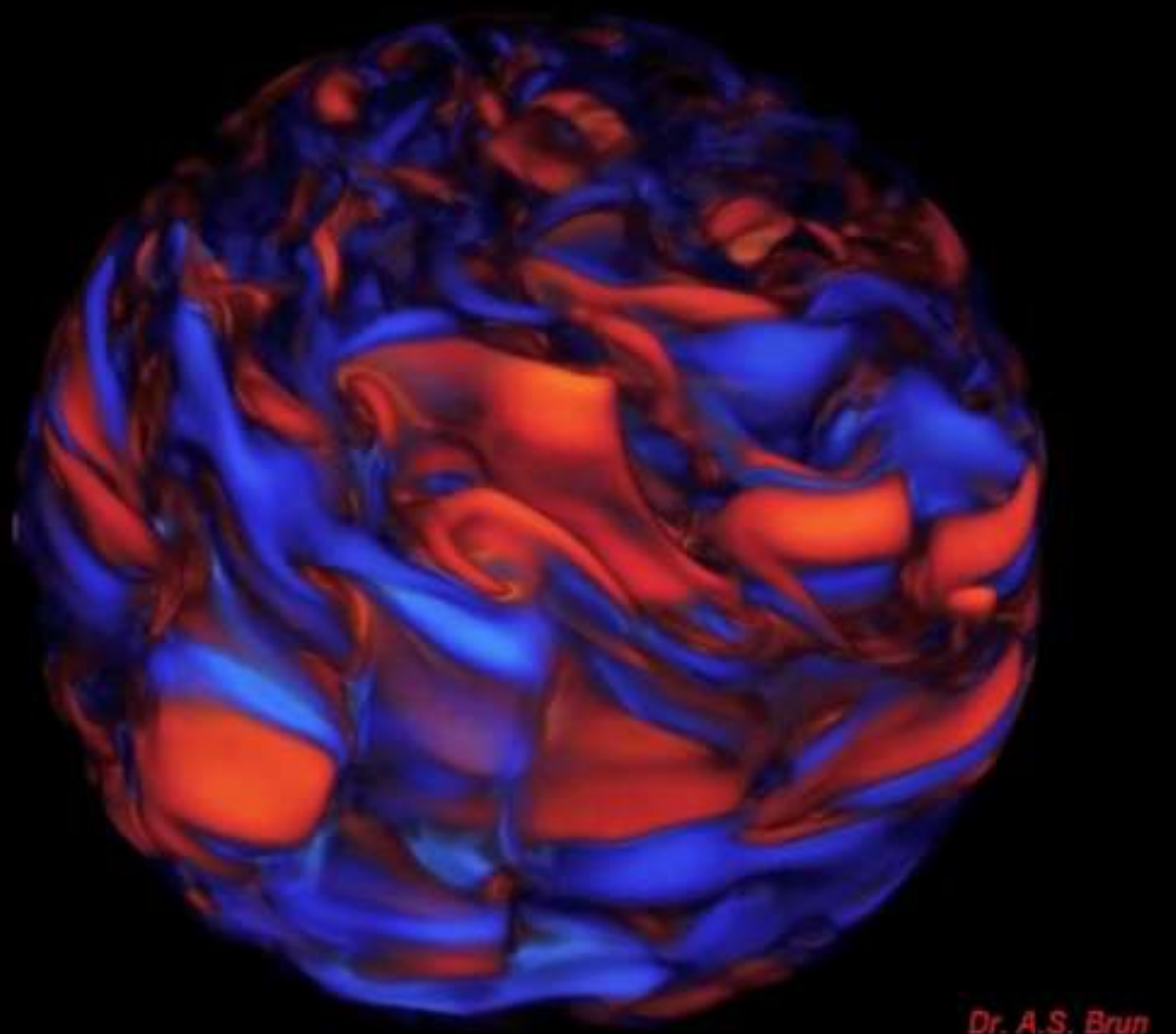
Dynamo Action –Magnetic Energy



Starting from a small seed field B the magnetic energy reach a level of ~8% of KE while keeping a solar like differential rotation

Dynamo Threshold around $Re_m = V_{rms}D/\eta \sim 300$

Dynamo Simulation in a Convective Rotating Shell



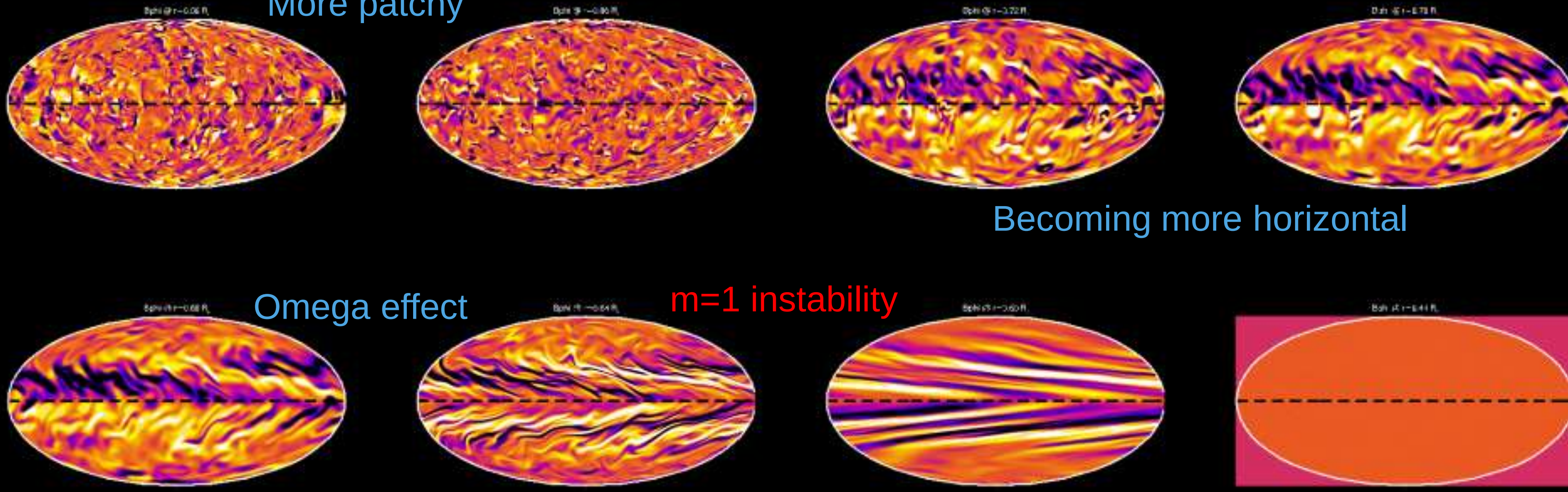
Brun et al. 2004, case M3

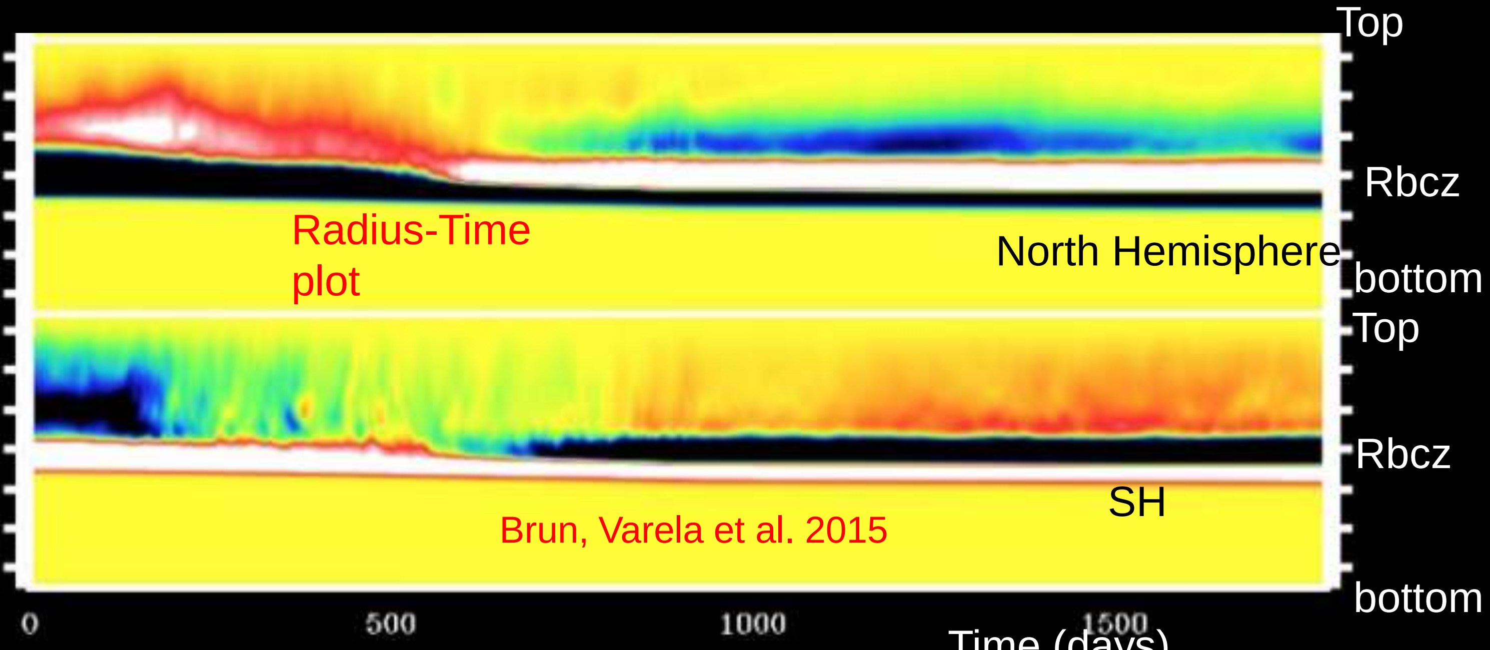
Magnetic flux emergence is linked to
Intense magnetic toroidal ribbons:

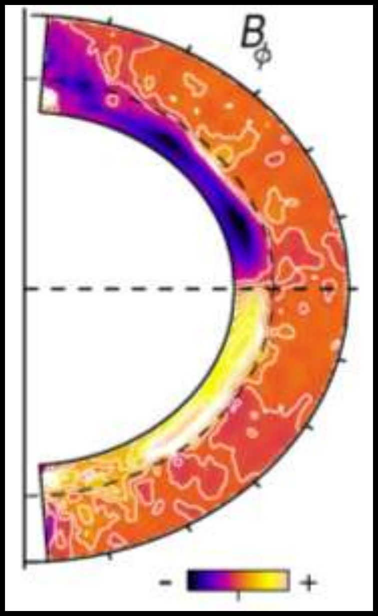
So Where do you form such
magnetic ribbons/flux tubes?

Wherever there is strong shear so in the tachocline but
also in convective envelope
(most likely near its base due to magnetic pumping)

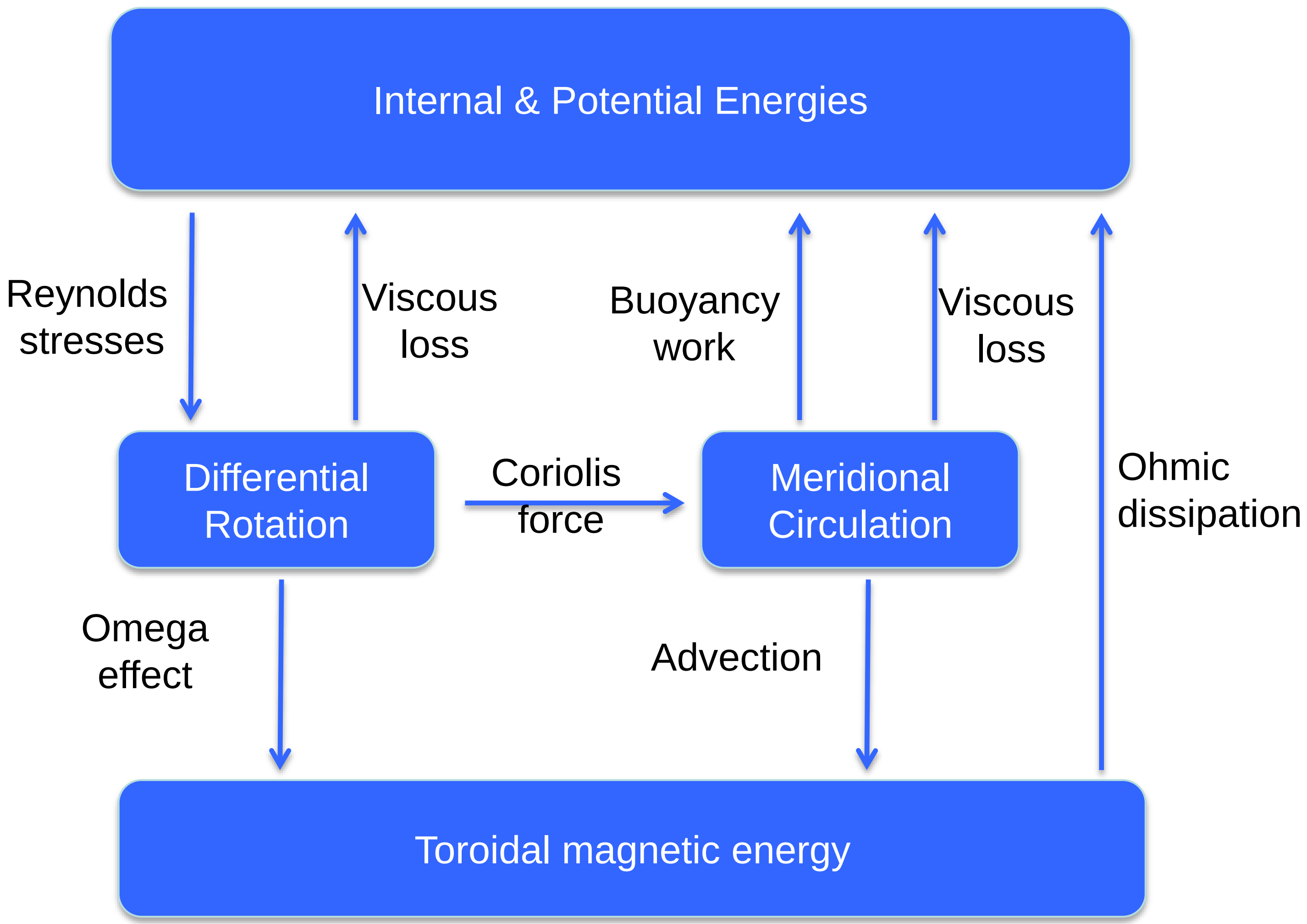
Localisation of Toroidal Field (Bphi)







MHD Energy Transfer Flow Map (toroidal field)



Starr & Gilman 1966, Brun et al. 2004, Rempel 2006, Brun et al. 2015, 2019

Various Dynamo Regimes and Scalings

Equilibrium field : $B_{eq} \sim \text{sqrt}(8\pi P_{gas}) \sim \text{sqrt}(\rho_*)$ (ρ* decreases with M*)

Assuming magnetic Reynolds number Rm=1 => $v=\eta/L$; better assessment would use $v=v_{conv} \sim (L_*/(\text{rho } R_*^2))^{1/3}$

Laminar (weak) scaling: Lorentz ~ diffusion =>

$$B^2_{weak} \sim \rho\nu\eta/L^2 \Rightarrow ME < KE$$

Turbulent (equipartition) scaling: Lorentz ~ advection =>

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

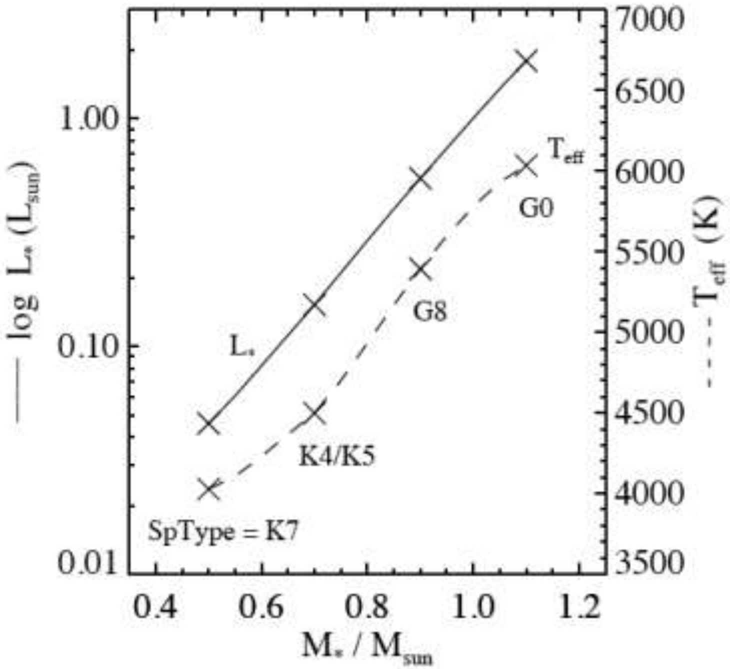
Magnetostrophic (strong) scaling: Lorentz ~ Coriolis =>

$$B^2_{strong} \sim \rho\Omega\eta \Rightarrow ME > KE\ !$$

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

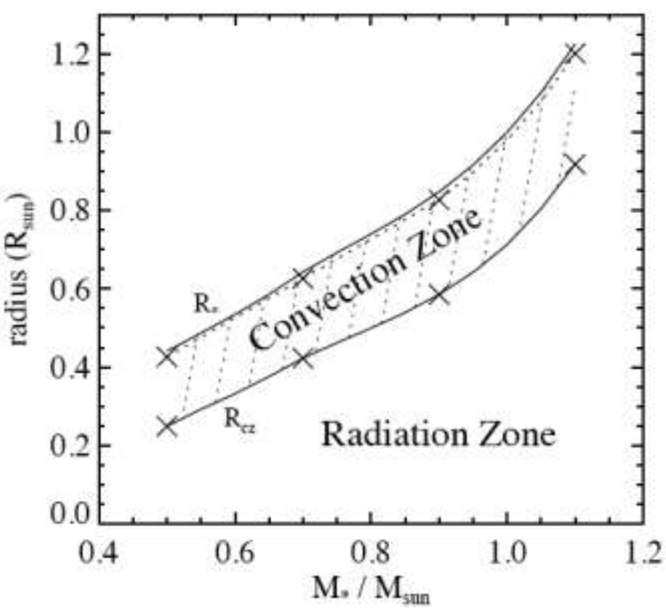
Fauve et al. 2010, Brun et al. 2015 (Space Science Rev), Christensen 2010, Augustson et al. 2019

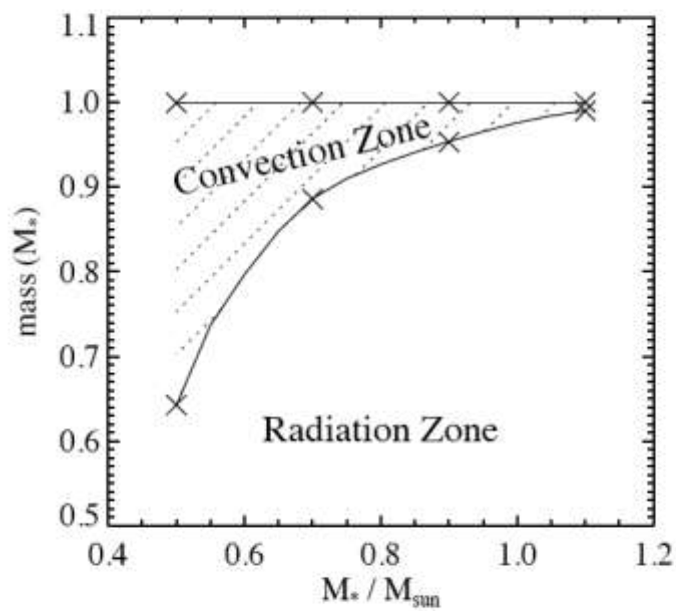
Our G & K star Models



	Mass ($M_\odot$)	Radius ($R_\odot$)	L_* ($L_\odot$)	$T_{\rm eff}$ (K)	SpT
M05x	0.5	0.44	0.046	4030	K7
M07x	0.7	0.64	0.15	4500	K4/K5
M09x	0.9	0.85	0.55	5390	G8
M11x	1.1	1.23	1.79	6030	G0

	$M_{\rm cz}$ ($M_\odot$, M_*)	$R_{\rm cz}$ ($R_\odot$, R_*)	$T(R_{\rm cz})$ (K)	$\rho(R_{\rm cz})$ ($\rm g\,cm^{-3}$)
M05x	0.18, 0.36	0.25, 0.56	4.3×10^6	14
M07x	0.079, 0.11	0.42, 0.66	3.0×10^6	2.1
M09x	0.042, 0.046	0.59, 0.69	2.6×10^6	0.51
M11x	0.011, 0.0100	0.92, 0.75	1.6×10^6	0.048

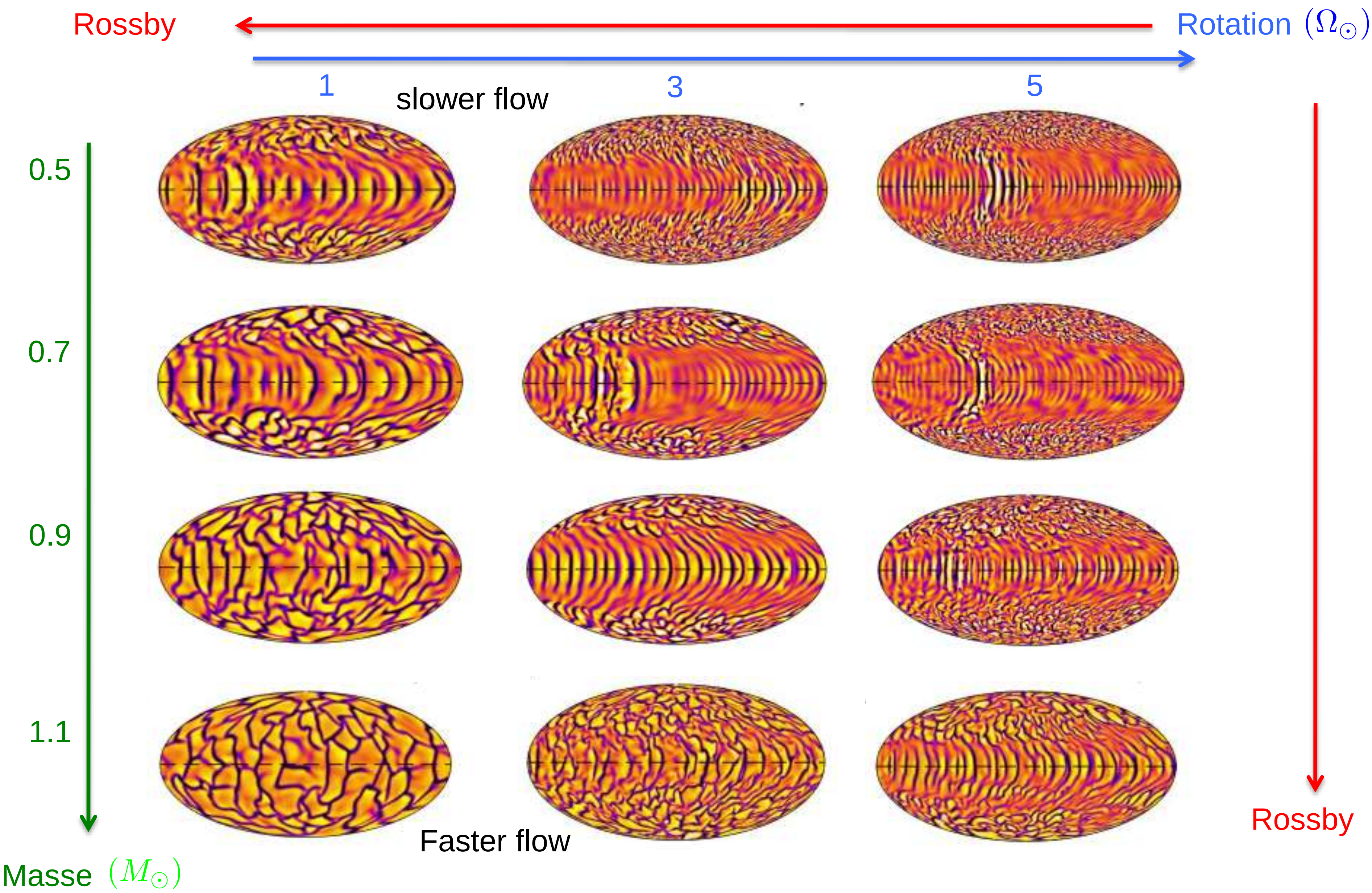




($\rho*$ decreases with M*)

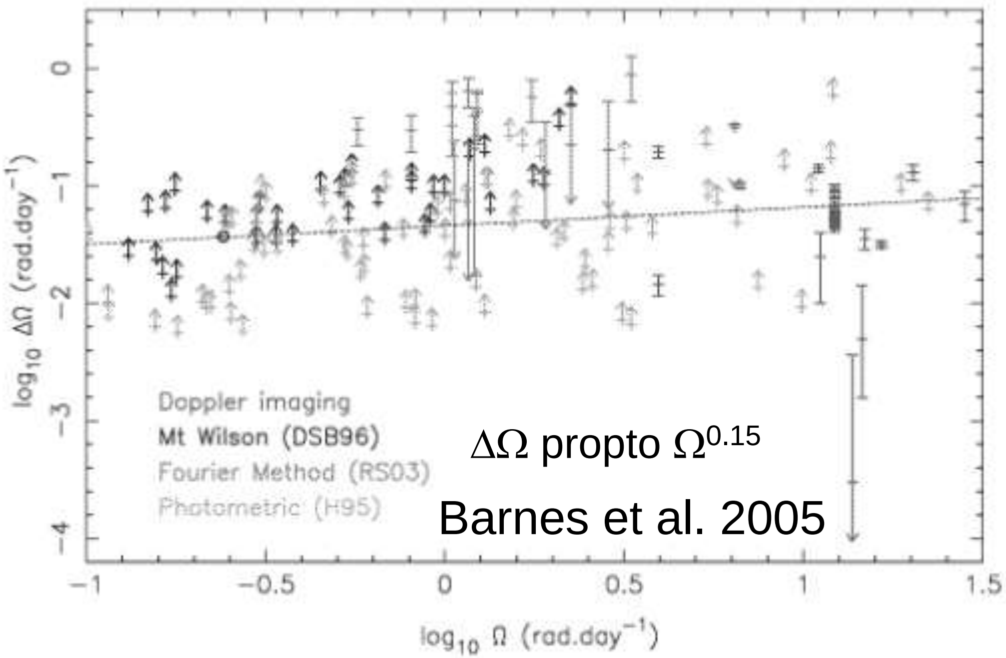
Effect of Rotation on Convection

Matt, Brun et al. 2011
Brun et al. 2015, 2017



Trends in Differential Rotation with Ω & Mass (Teff)

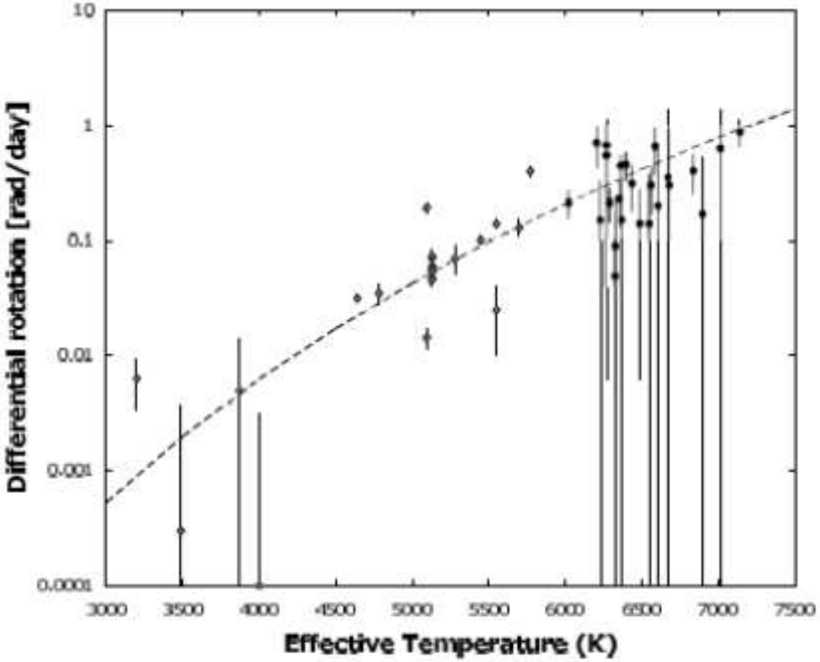
Weak trend with Ω



$\Delta\Omega$ propto $\Omega^{0.15}$

Barnes et al. 2005

$\Delta\Omega$ increases with M_*



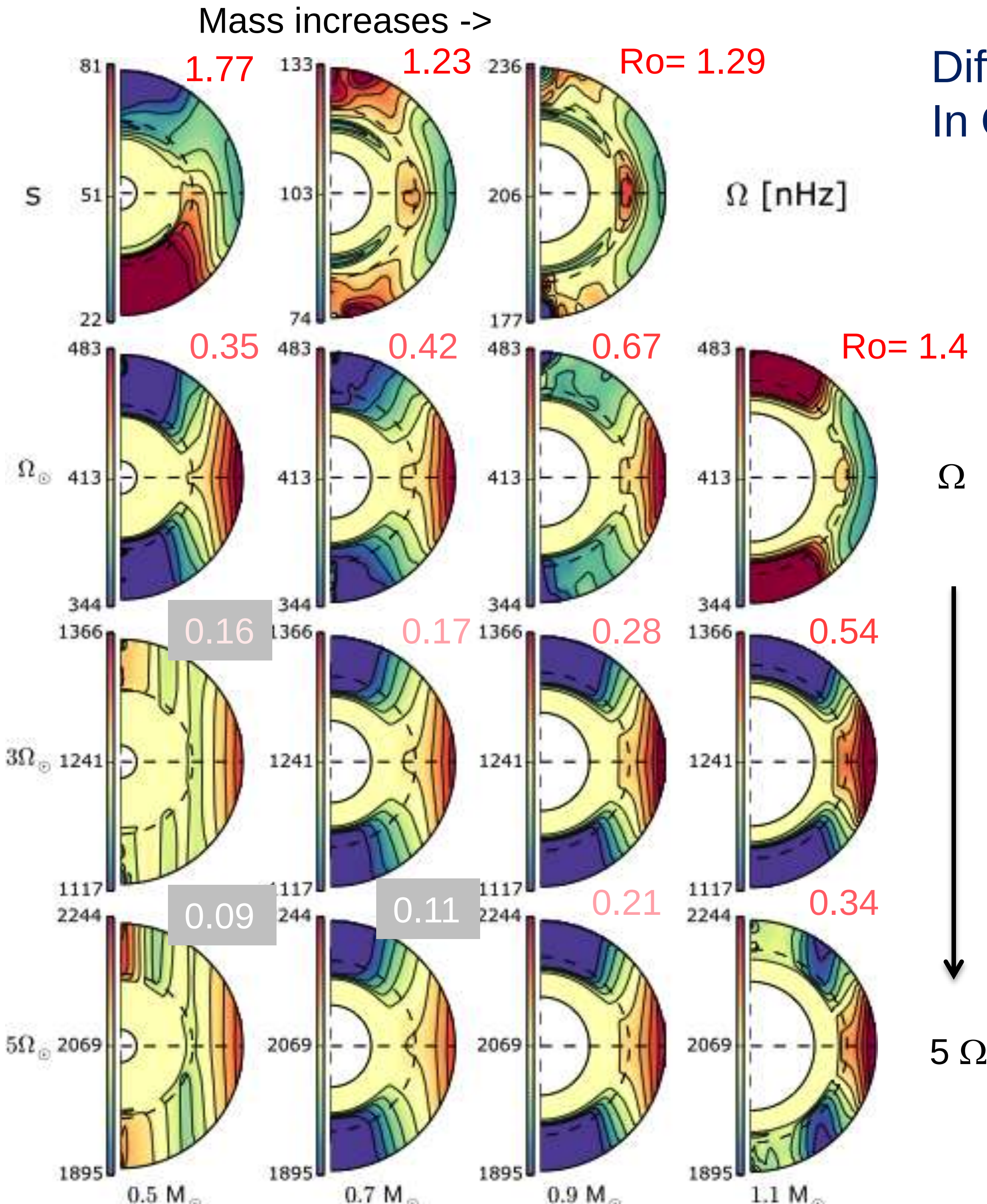
Collier-Cameron 2007

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

So currently exponent n in $\Delta\Omega$ propto Ω^{n} ranges [0.15, 0.7]

Confirming these observational scaling is key

Differential Rotation In G & K stars



Matt et al. 2011
Brun et al. 2015, 2017

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

Rotation Increases

Back of the Envelope Rossby number

$$v = c_1 \left(\frac{L_*}{\rho_{bcz} R_*^2} \right)^{1/3}$$

MLT Convective velocity

$L_* \sim M_*^{4}$, $R_* \sim M_*^{0.9}$, rho $\sim M_*^{n}$ => $v \sim M_*^{(2.2-n)/3}$

From CESAM 1-D GK star models:

$L_* \sim M_*^{4.6}$, $R_* \sim M_*^{1.3}$, rho $\sim M_*^{-6.9}$ => $v \sim M_*^{3}$

$$\text{Rossby number } R_{of} = v/2\Omega_* R_* = c_1 M_*^{1.7}/\Omega_*$$

THE ASTROPHYSICAL JOURNAL, 836:192 (28pp), 2017 February 20

https://doi.org/10.3847/1538-4357/aa5c40

CrossMark

On Differential Rotation and Overshooting in Solar-like Stars

Allan Sacha Brun[1], Antoine Strugarek[1,2], Jacobo Varela[1], Sean P. Matt[1,3], Kyle C. Augustson[1], Constance Emeriau[1], Olivier Long DoCao[1], Benjamin Brown[4], and Juri Toomre[5]

[1] AIM, CEA/CNRS/University of Paris 7, CEA-Saclay, F-91191 Gif-sur-Yvette, France

[2] Astronomy Dept., University of Montreal, Montreal, Canada

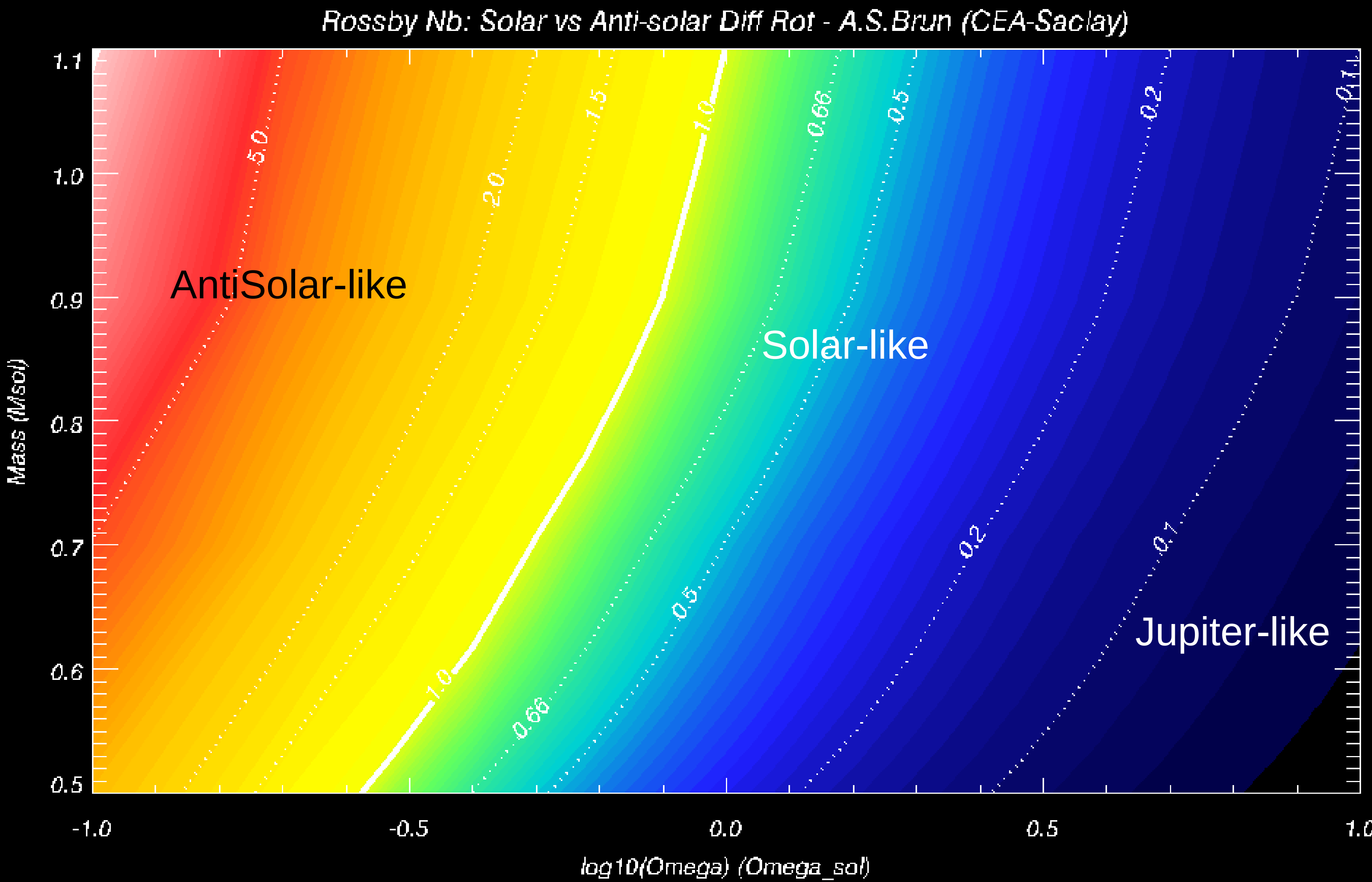
[3] Physics and Astronomy, University of Exeter, Stocker Road, Exeter EXA4 4QL, UK

[4] Laboratory for Atmospheric and Space Physics and Department of Astrophysical & Planetary Sciences, University of Colorado, Boulder, Colorado 80309, USA

[5] JILA, University of Colorado, Boulder, CO 80309, USA

Received 2016 September 16; revised 2017 January 23; accepted 2017 January 23; published 2017 February 21

Rossby Number vs Stellar Mass and Rotation



Brun et al. 2015, 2017

Solar Type Stars (late F, G and early K-type)

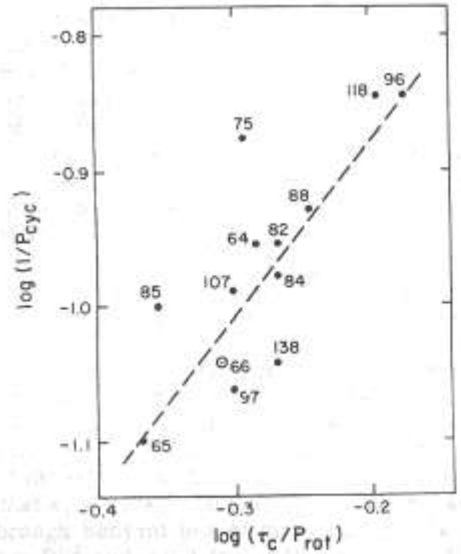
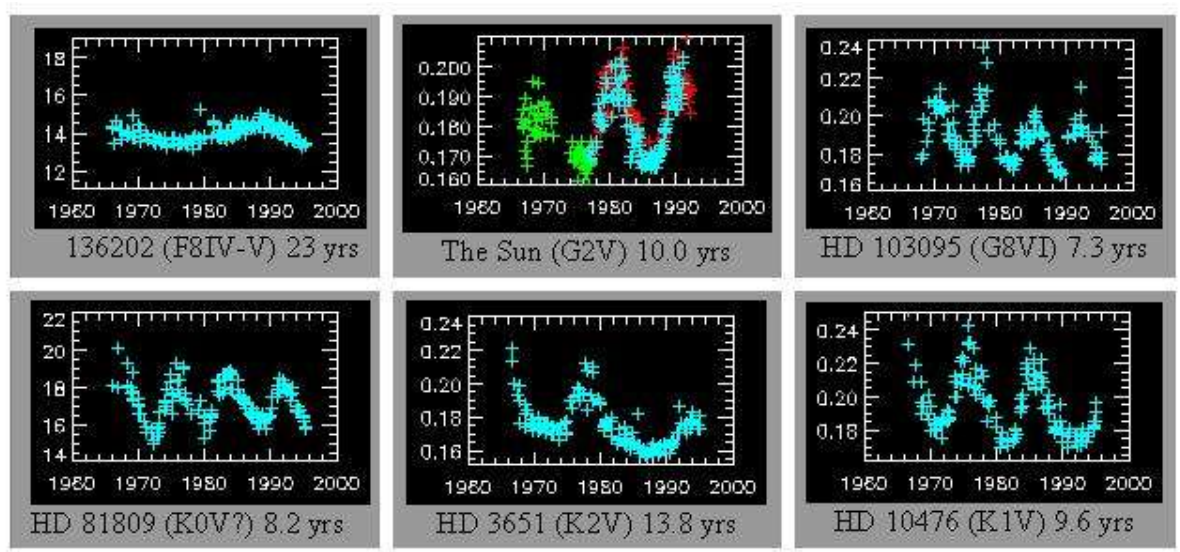


FIG. 2.—Log ($1/P_{cyc}$) vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.

Noyes et al. 1984



CaII H & K lines , $\langle R'_{HK} \rangle$

In stars activity depends on rotation & convective overturning time via Rossby nb $Ro=P_{rot}/\tau$

$\langle R'_{HK} \rangle = Ro^{-1}$, $P_{cyc}=P_{rot}^{1.25+/-0.5}$

Wilson 1978
Baliunas et al. 1995

<u>Over 111 stars in HK project (F2-M2):</u>
31 flat or linear signal
29 irregular variables
51 + Sun possess magnetic cycle

=> Much more coming in Asteroseismology Era

Quid of Star-Planet Interaction and cyclic activity?

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★]

Solar Analogs

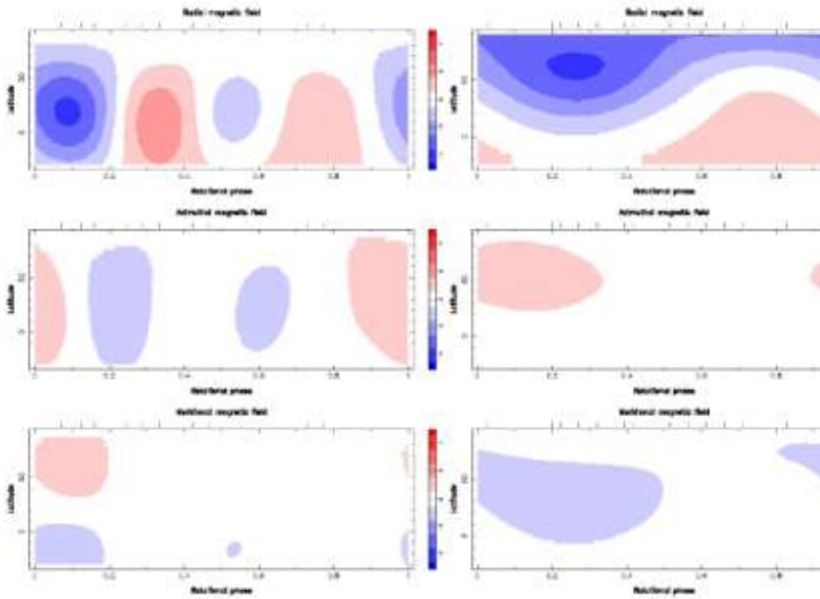


Figure 4. Magnetic maps of HD 146233 and HD 76151 (left and right panel, respectively). Each chart illustrates the onto one axis of the spherical coordinate frame. The magnetic field strength is expressed in Gauss. Vertical ticks above the the observed rotational phases. Note that color scales are not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

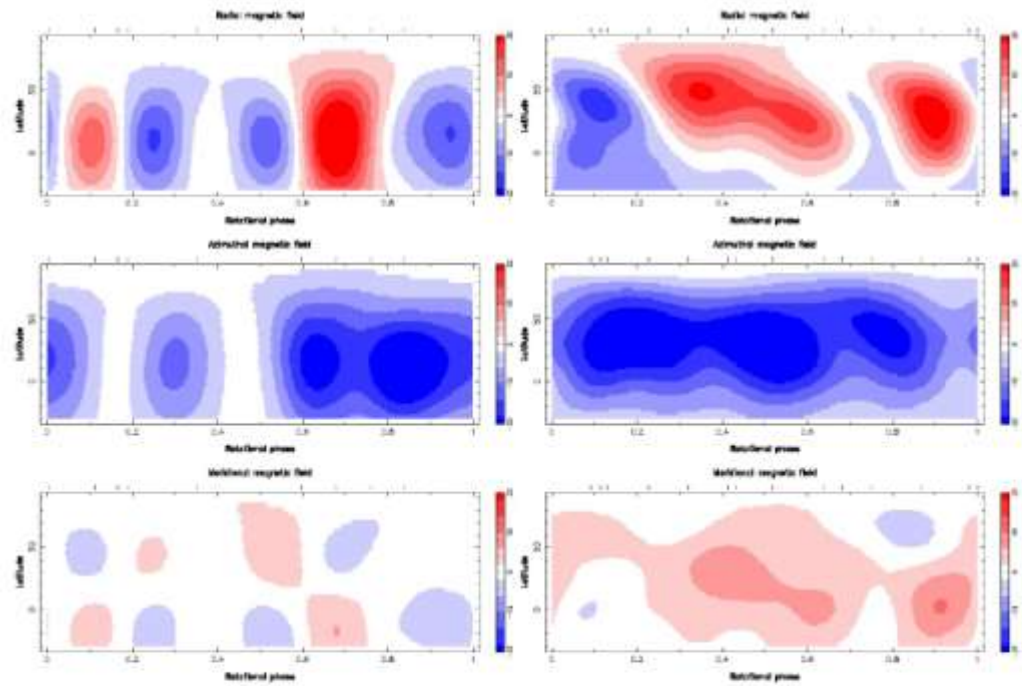


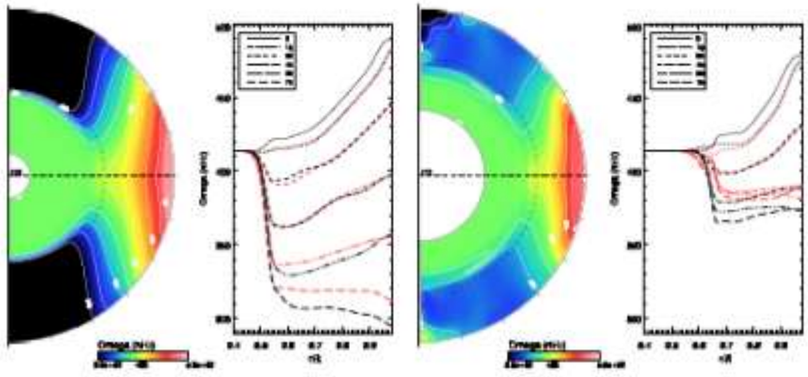
Figure 5. Same as Fig. 4, for HD 73350 (left panel) and HD 190771 (right panel).

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

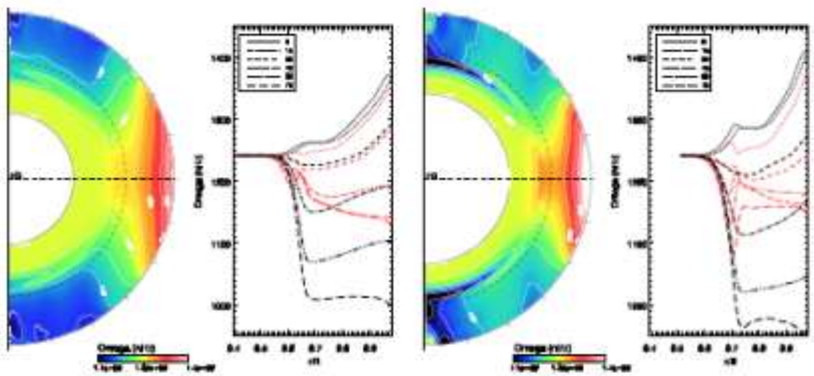
Petit et al. 2008, MNRAS

ESPADON/NARVAL

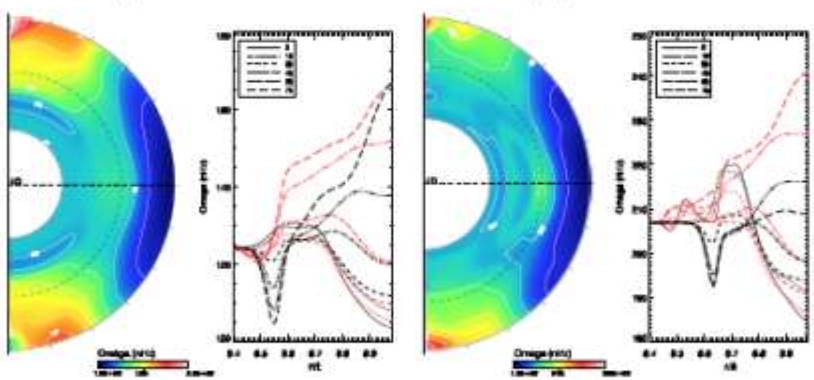
Lorentz force feedback on Differential Rotation



(a) $M05_{d1}$ (b) $M09_{d1}$



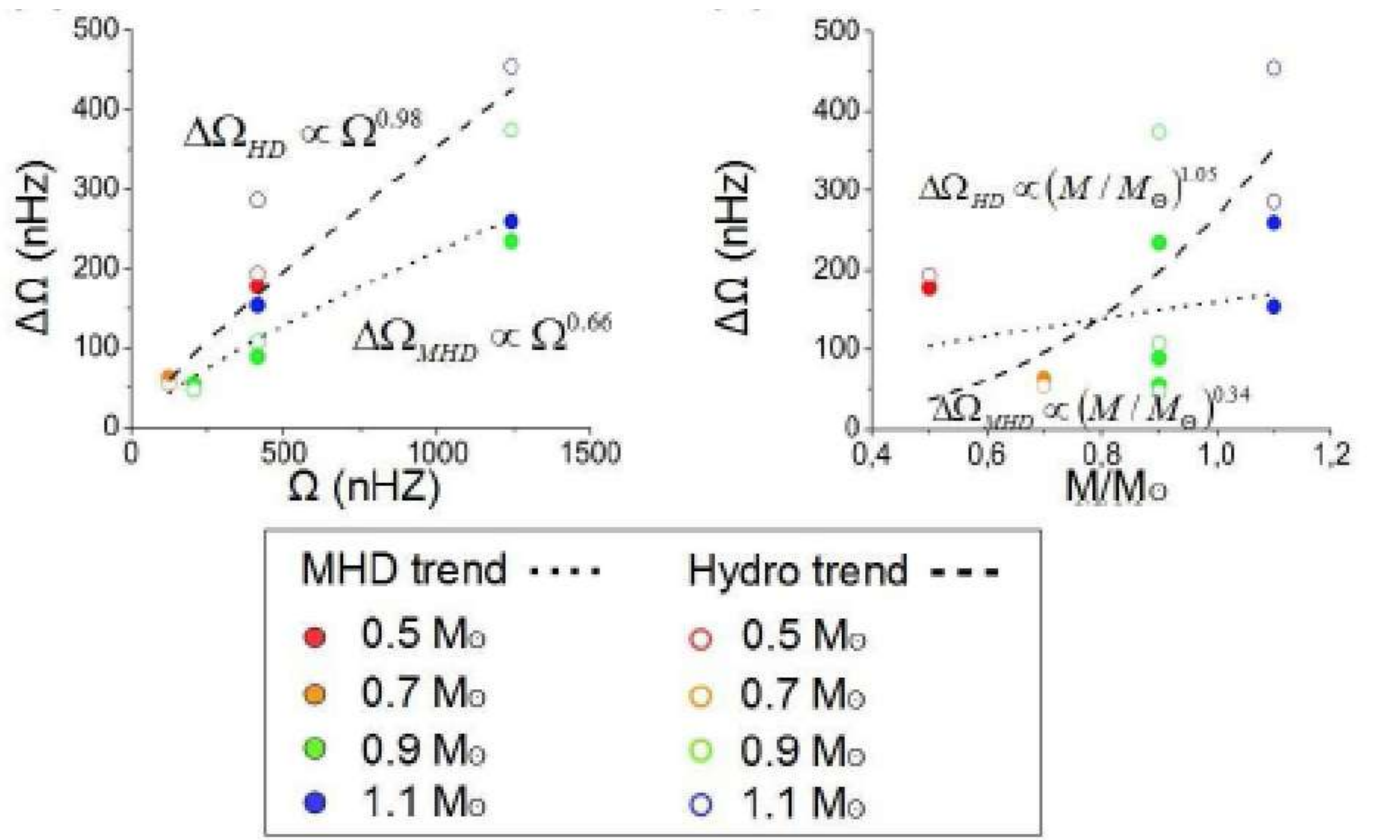
(c) $M09_{d3}$ (d) $M11_{d3}$



(e) $M07_s$ 22 (f) $M09_s$

Varela, Strugarek, Brun 2016, AdSpR
see also Karak et al. 2015, Guerrero et al. 2016

Lorentz force feedback on Differential Rotation

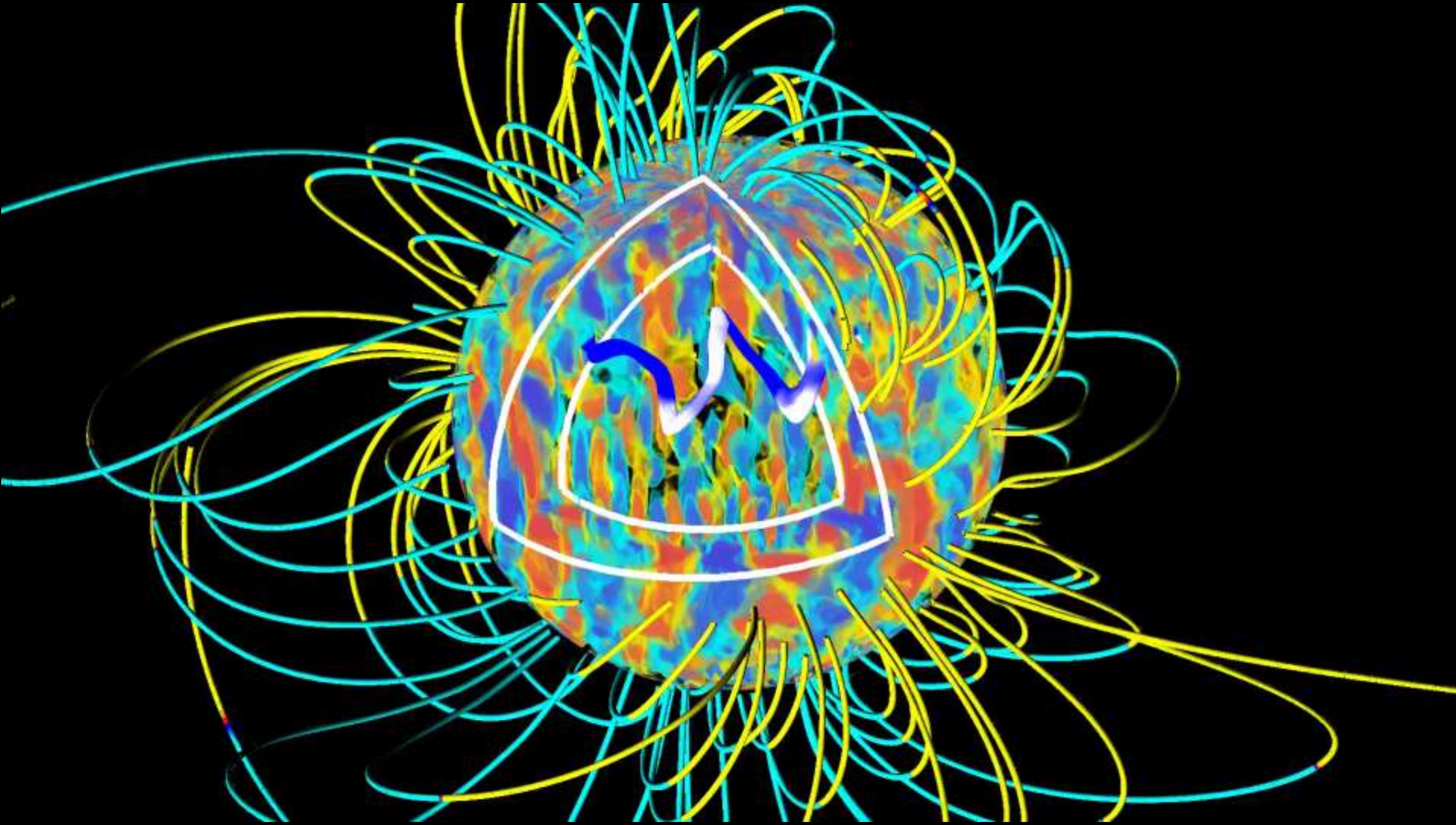


Overall trend in better agreement with observations

No clear change of ME content with anti-solar Ω

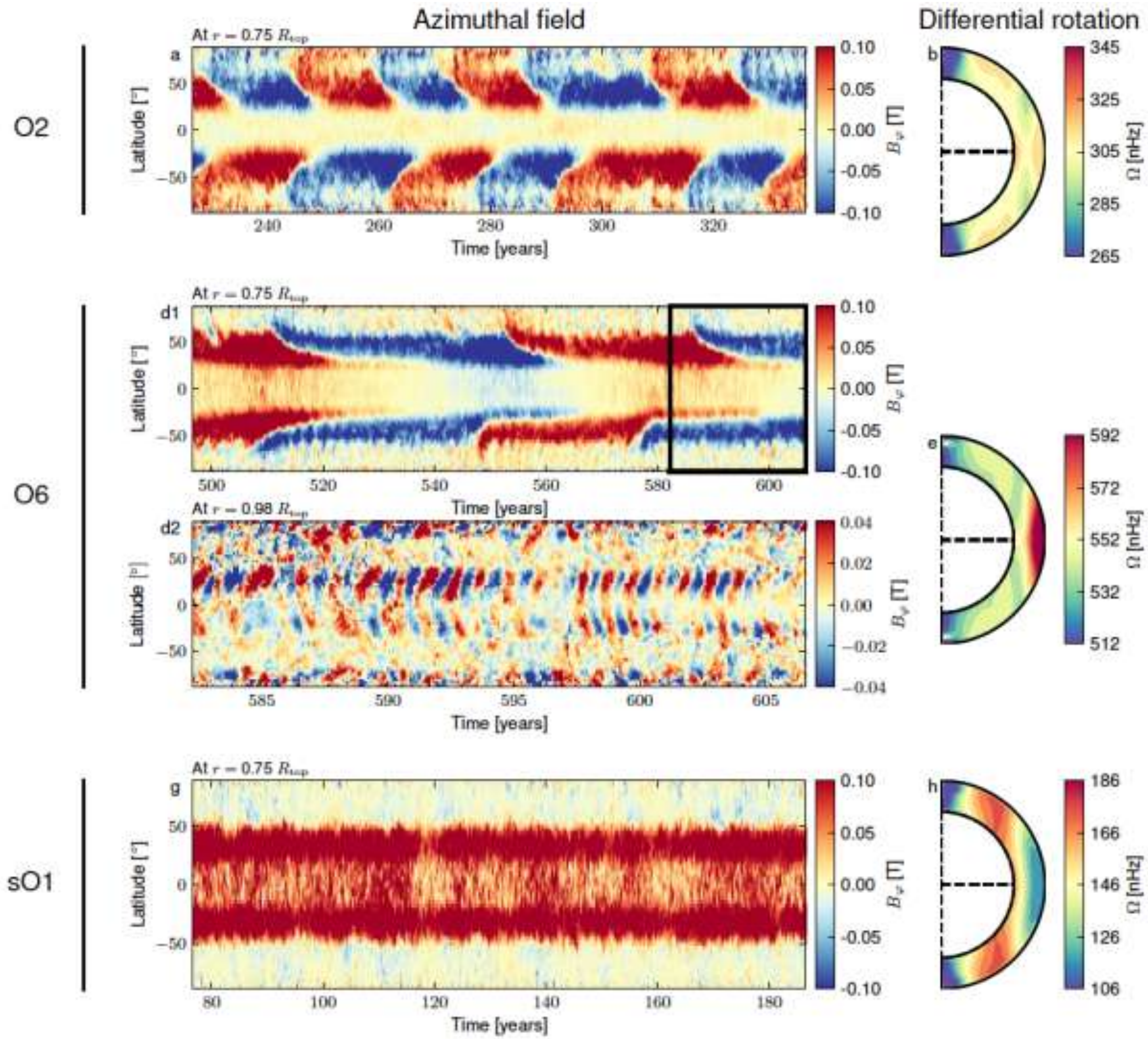
Varela, Strugarek, Brun 2016, AdSpR
see also Karak et al. 2015, Guerrero et al. 2016

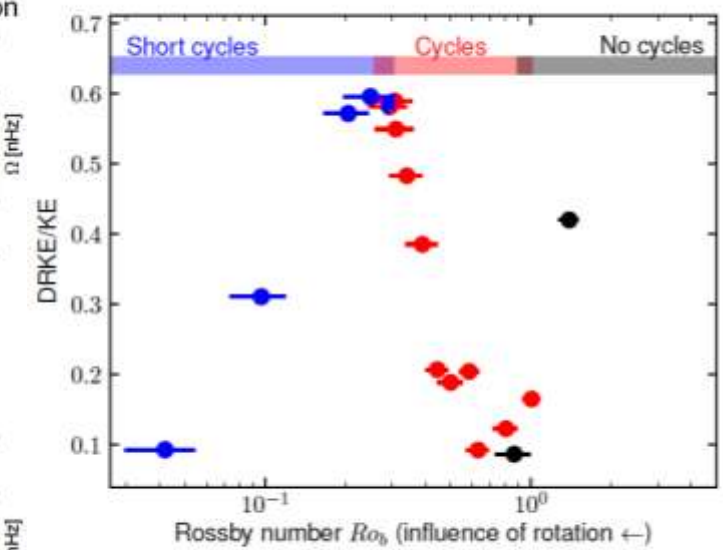
An exemple of cyclic dynamo action

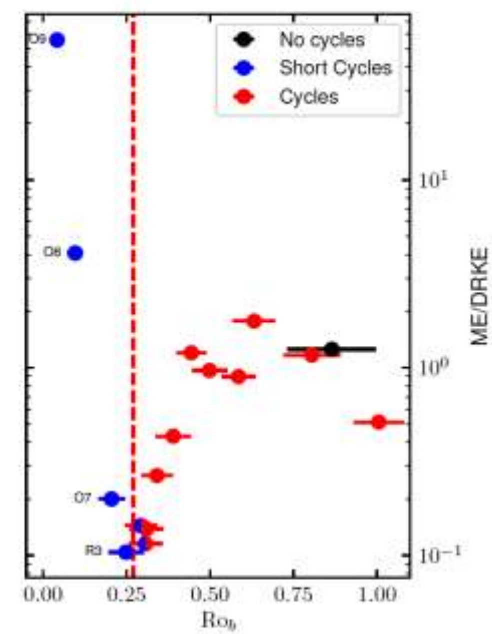


Strugarek et al. 2017

Cycle type (short vs long) vs Rossby nb for different cases



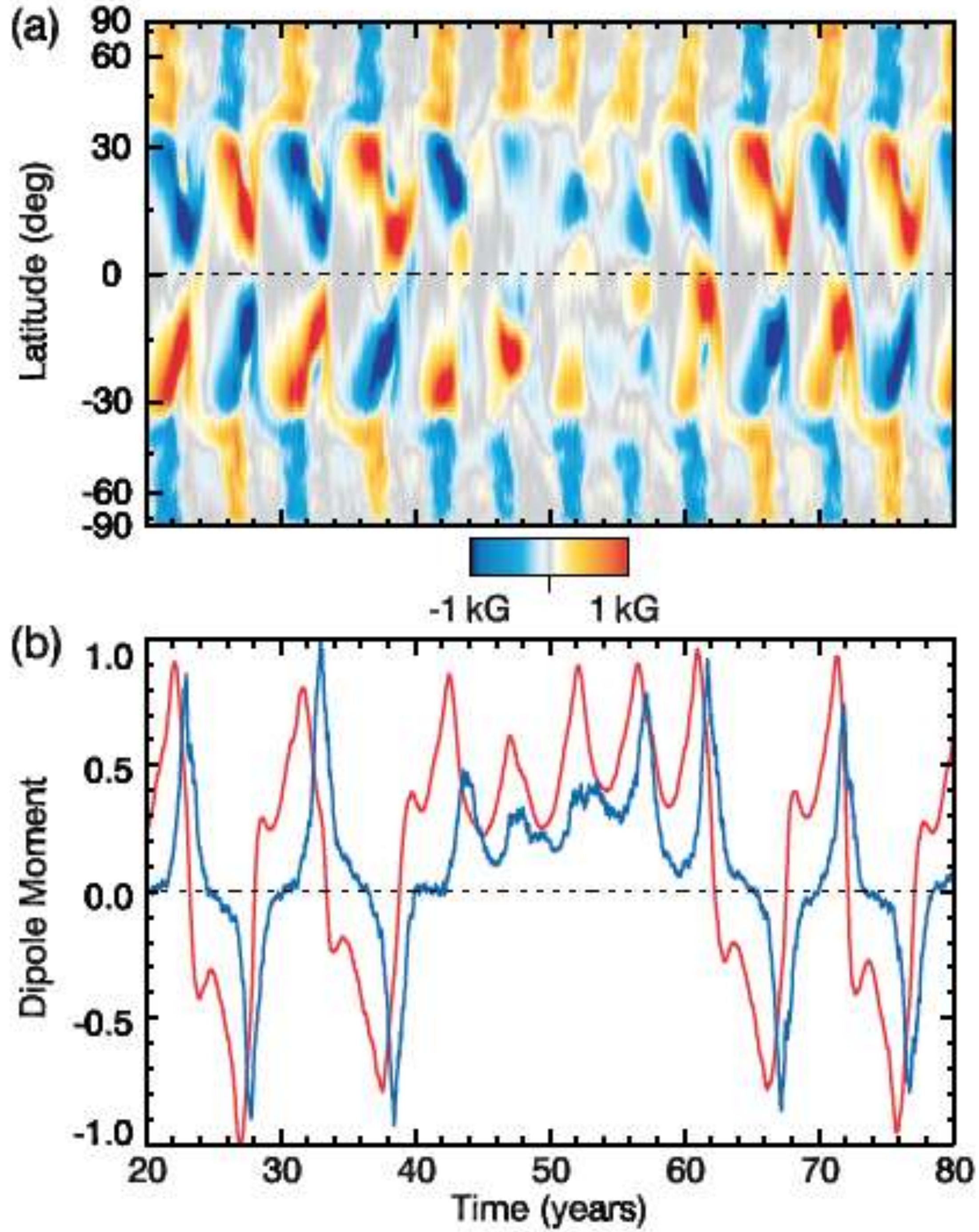




Strugarek, Brun et al. 2018

KE = total kinetic energy in convection zone,
DRKE = KE in differential rotation, ME = total magnetic energy)

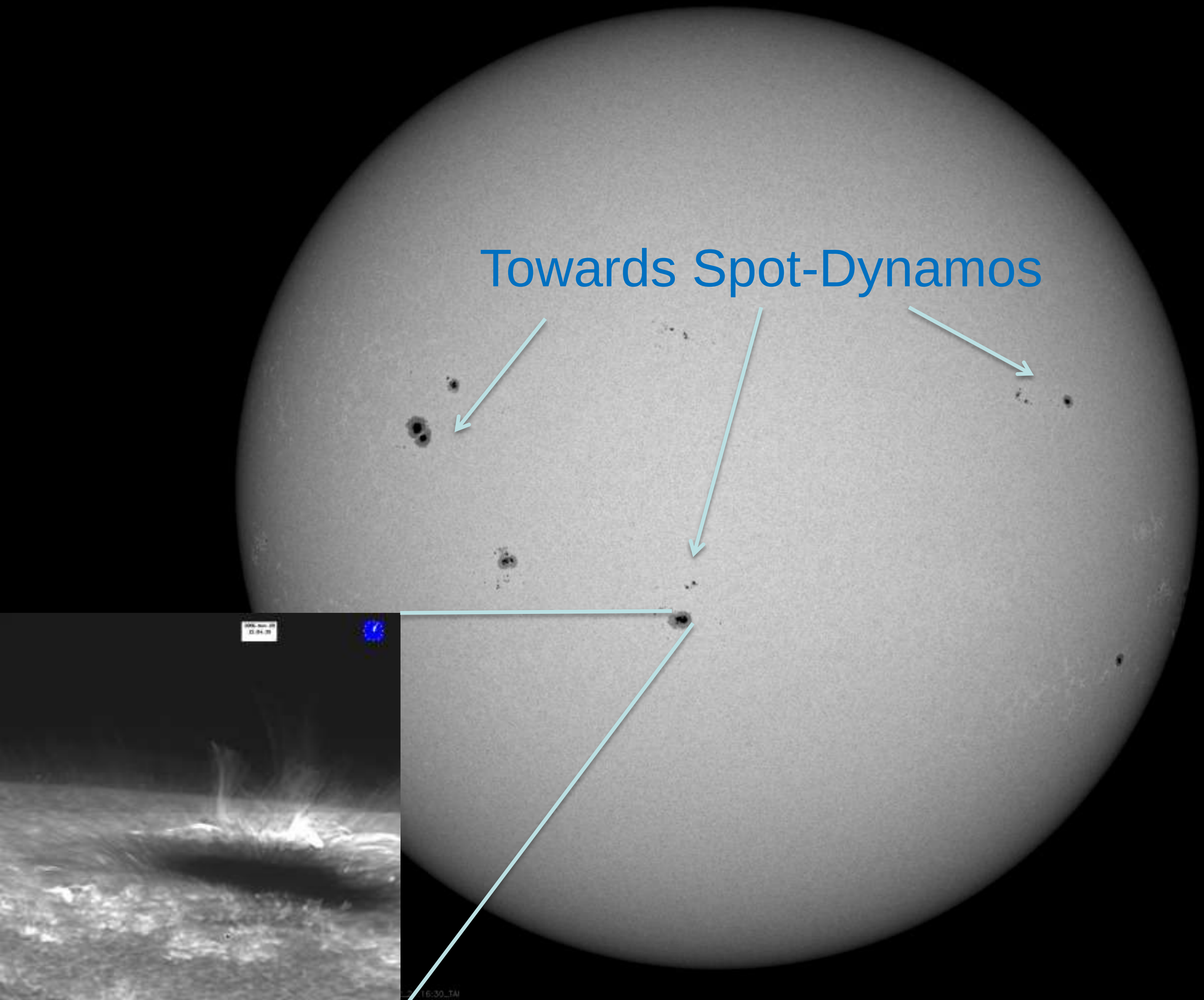
Latest solar-like case:
Getting Maunder like minimun



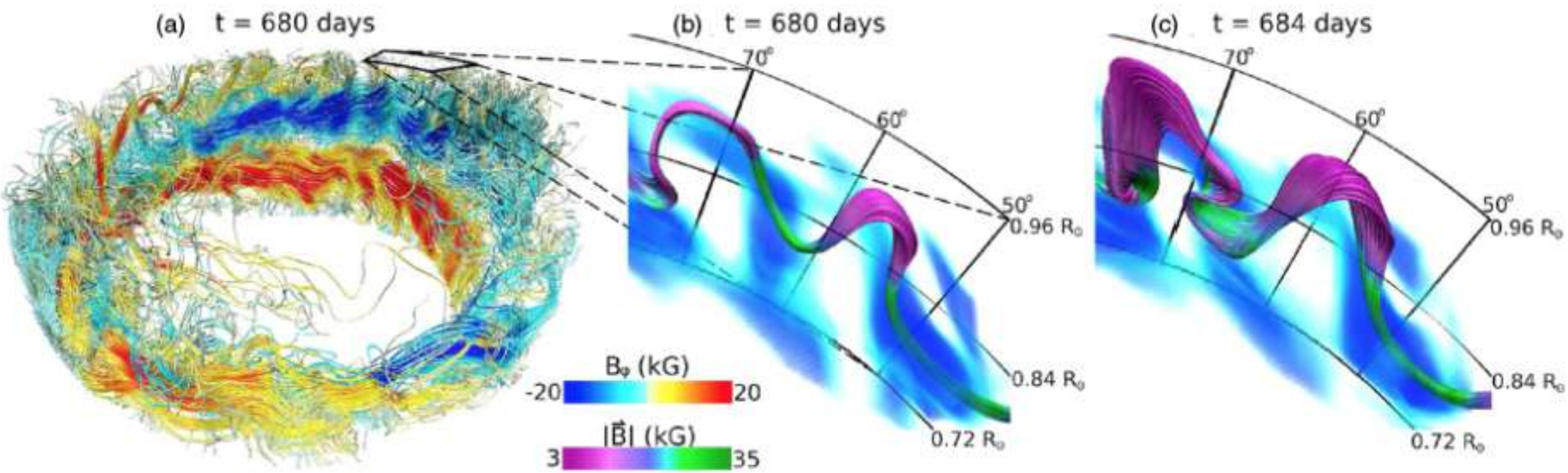
Quadrupole dominates over Dipole during reversal and Grand minimum phase

Augustson, Brun et al. 2015, ApJ

Towards Spot-Dynamos



Going Beyond the introduction of flux tube:
Self-consistent buoyant Loops generations



Nelson et al. 2011, 2013a, 2014, see alson Fan & Fang 2014

Magnetic Wreath and Intermittency yielding flux emergence

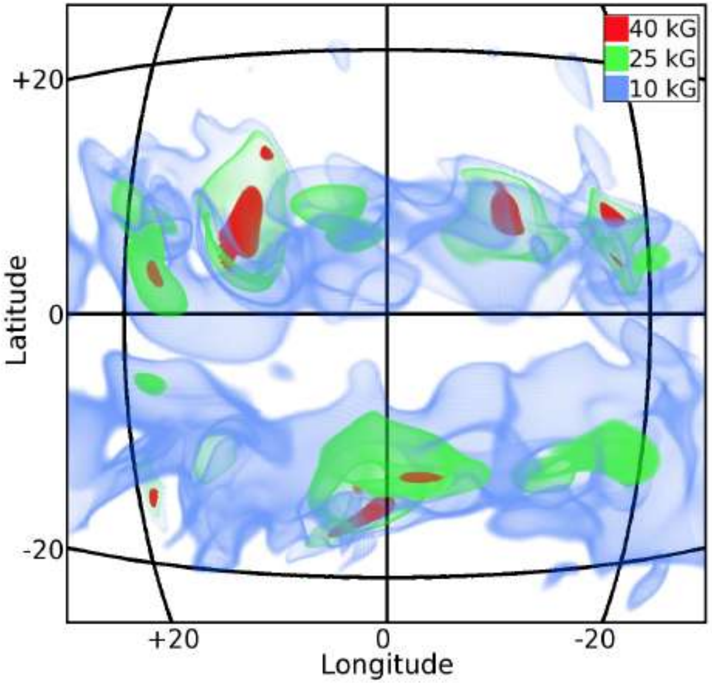


Figure 17. Three-dimensional volume renderings of isosurfaces of magnetic field amplitude in case S3. Blue surfaces have amplitudes of 10 kG, green surfaces represent 25 kG, and red surfaces indicate 40 kG fields. Grid lines indicate latitude and longitude at 0.72 $R_\odot$ as they would appear from the vantage point of the viewer. Small portions of the cores of these wreaths have been amplified to field strengths in excess of 40 kG while the majority of the wreaths exhibit fields of about 10 kG or roughly in equipartition with the mean kinetic energy density (see Figure 2).

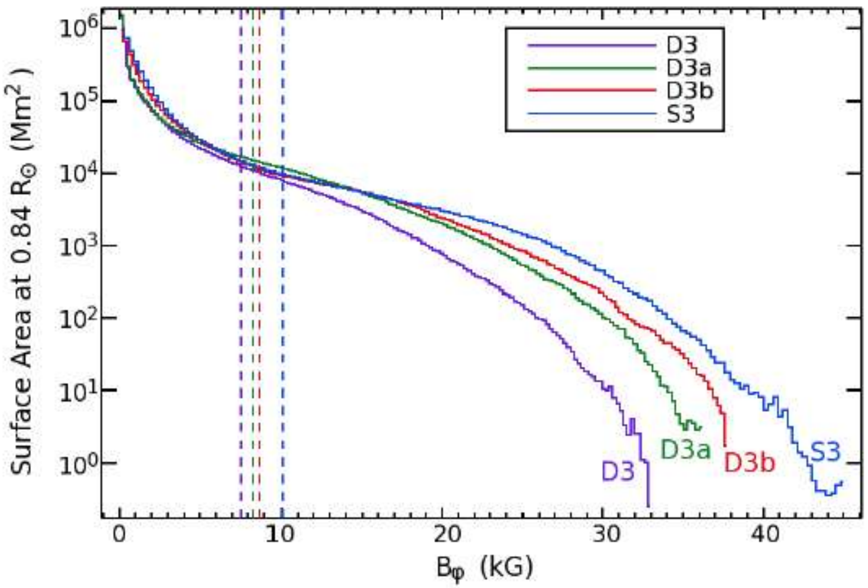


Figure 2. Probability distribution functions for unsigned B_ϕ at mid-convection zone for cases D3 (purple), D3a (green), D3b (red), and S3 (blue) showing the surface area covered by fields of a given magnitude. Distributions are averaged over about 300 days when fields are strong and as steady as possible. Dashed vertical lines show the field-strength at which equipartition is achieved with the maximum fluctuating kinetic energy (FKE) at mid-convection zone for each case. Case D3b shows a deficit of field in the 10 kG range, but an excess of surface area covered by extremely strong fields above 25 kG range, as well as higher peak field strengths. Case S3 shows significantly greater regions of fields in excess of 20 kG than all other cases.

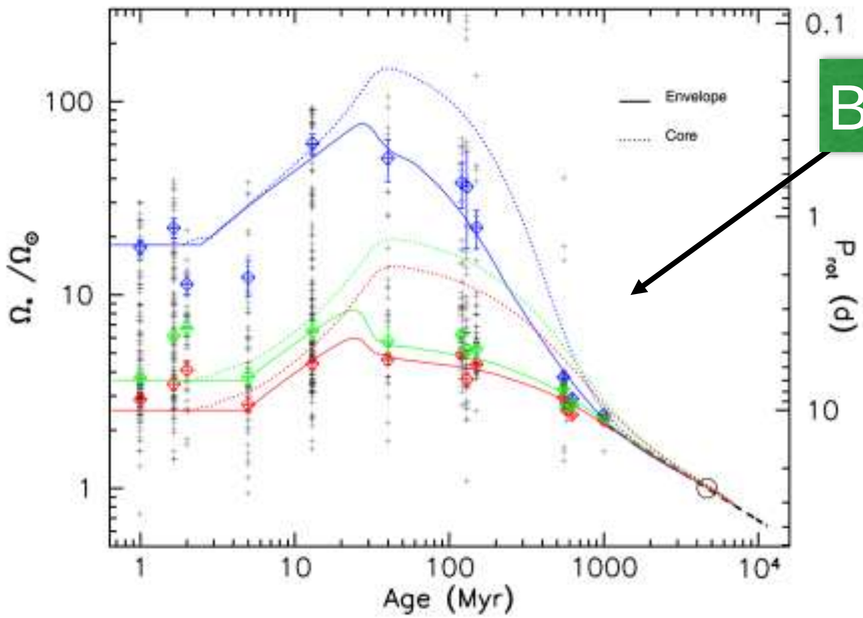
Nelson et al. 2013, ApJ

Stellar Wind and Complex Magnetic Geometries

Wind, Stellar magnetism and gyrochronology

Stellar Spin down Models

(Gallet & Bouvier 2013)



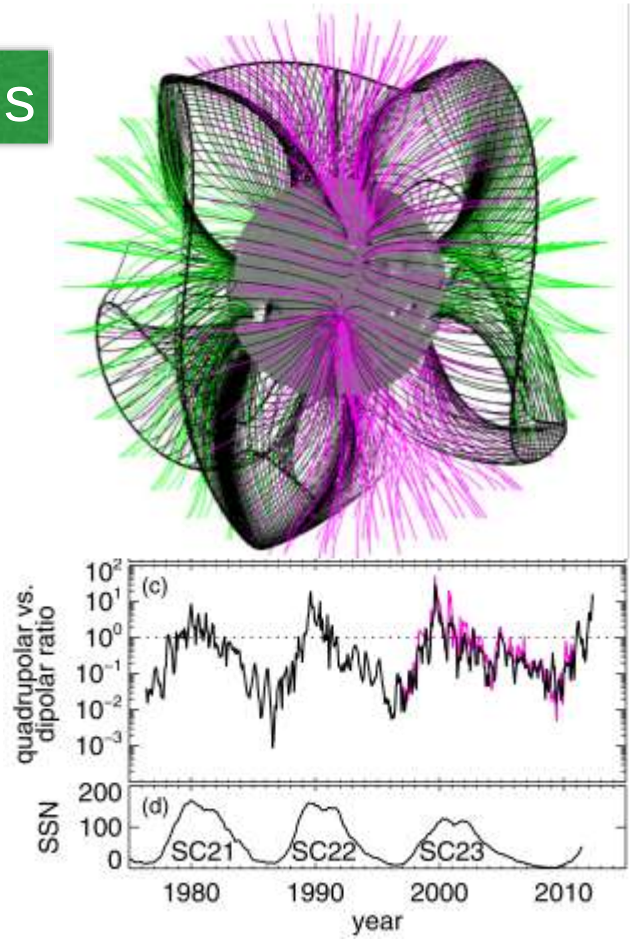
Braking models

dynamo

wind

Magnetic Activity

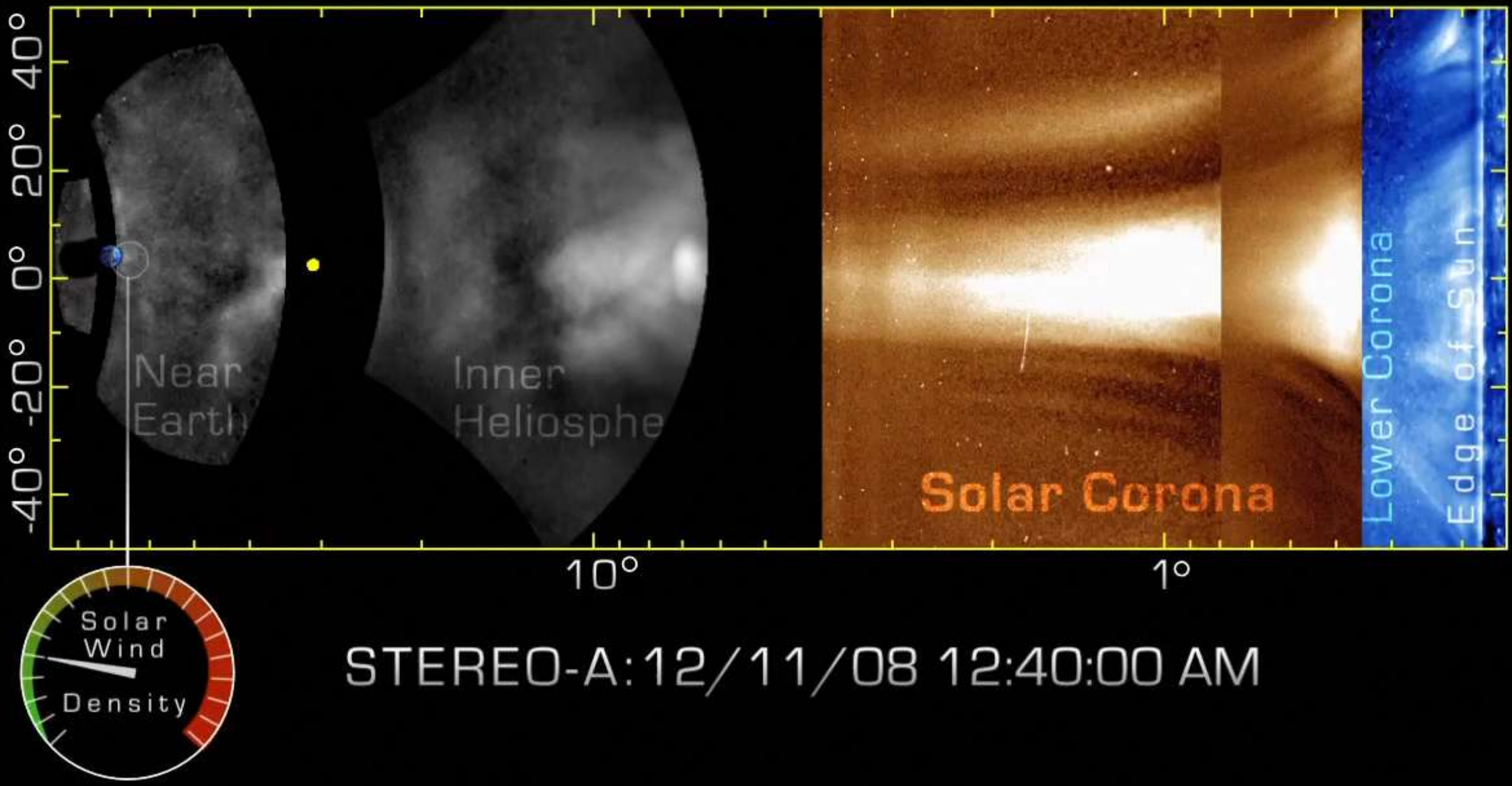
(De Rosa et al. 2012)



Skumanich's law: $\Omega_* \propto t^{-1/2}$

Gyrochronology: Barnes 2003, Magnetochronology: Vidotto et al. 2014

Solar Wind and the Earth



Courtesy: Craig de Forest (SwRI)

Parker's Solar Wind Model

Simple hydrostatic model (u=0) for an isothermal corona at T= 1 Million K leads to a pressure ratio between the solar surface (~100 mb) and the pressure at « infinity » of 4 orders of magnitude, i.e p_inf / p_surf ~10^{-4} , whereas it should be at least 10^{-14} ! Since p_inf = p_ism (the pressure of the interstellar medium).

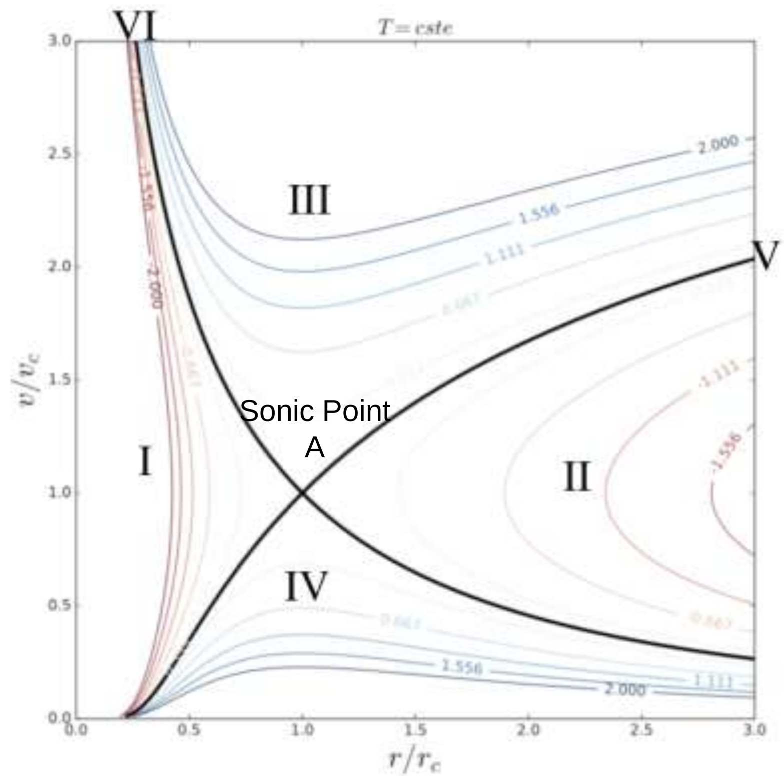
In 1955 E. Parker proposed that the Sun possesses a wind (solar wind of particles, mostly protons, electrons, alpha's), i.e a dynamical atmosphere with u=/=0 .

5 solutions are found mathematically (cf. figures), only 3 are meaningful, type III, IV & V

$$1/2\,u^2 - c_s^2 \ln u = 2c_s^2 \ln r + GM/r + C$$

Type V is the solar wind solution: A slow wind accelerating to supersonic speed. It leads to a very small p_inf compatible with p_ism

A is the sonic point, u=c_s



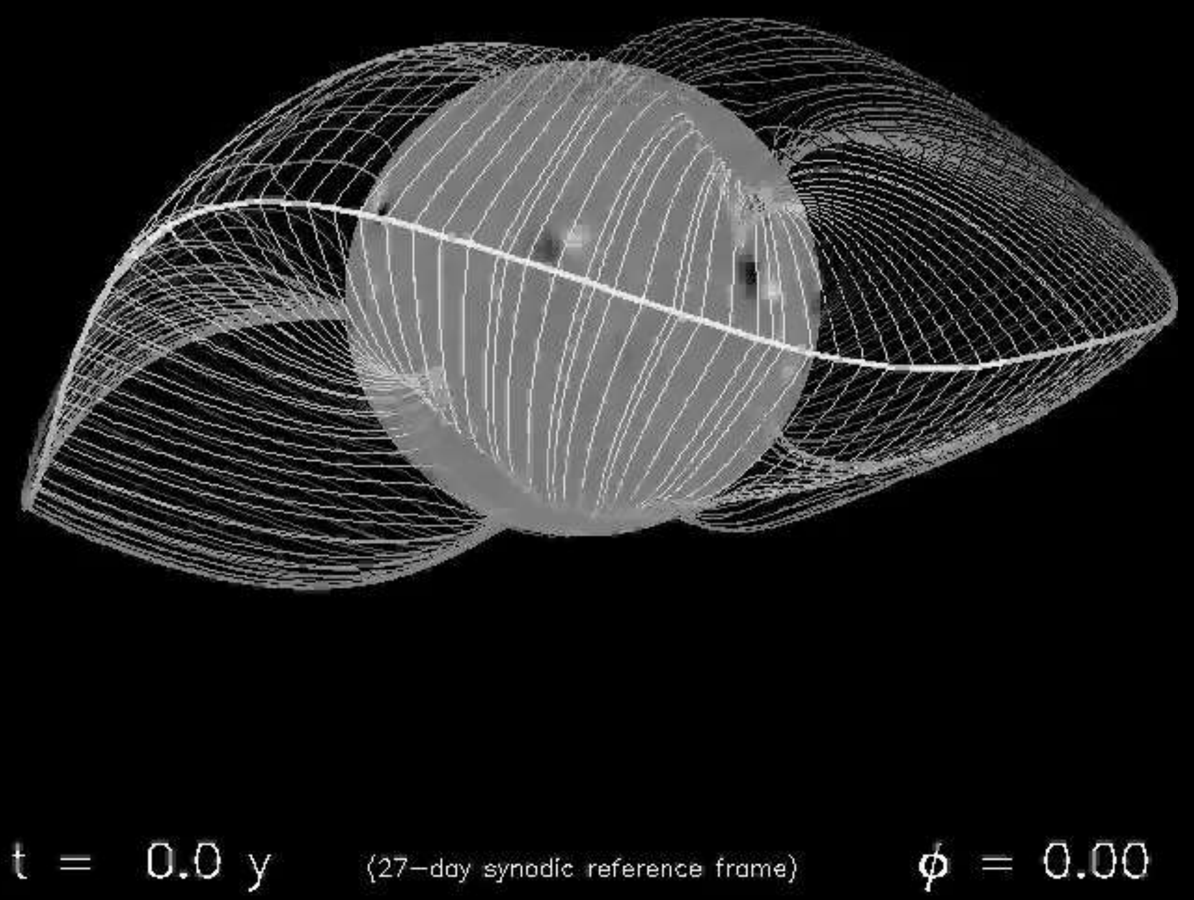
No fast wind is Observed near the Surface so III can be discarded.

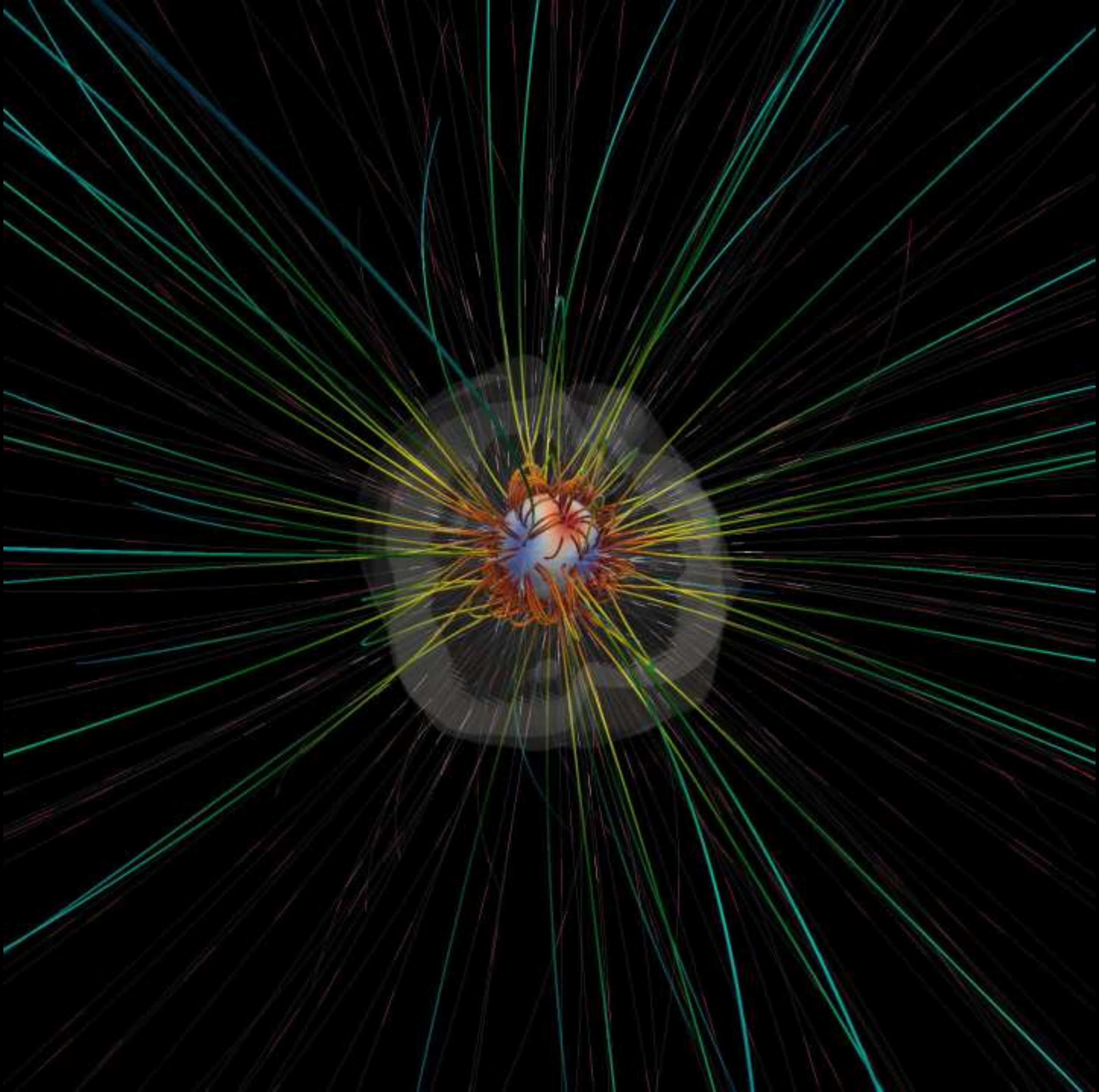
IV remains subsonic (the solar breeze) but p_inf still too large Compared to p_ism

Velli 1994 also showed that it is an unstable solution

The sun: a complex temporal evolution as well…

credit M. De Rosa





MHD Wind Simulations

Why are they necessary ?

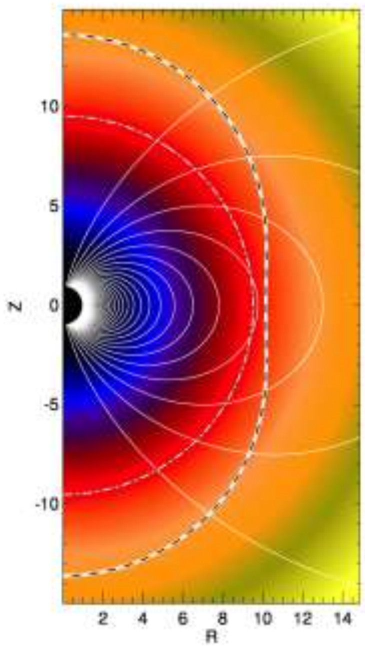
- Magnetic fields > split monopole
- Rotation
- 3D, non-axisymmetry

Parametric study of the torque as a function of:

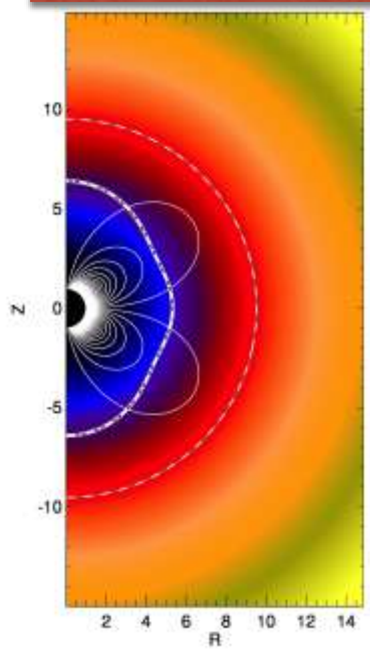
Rotation
Magnetic field strength
Magnetic field topology

Coronal temperature and gamma held fixed.

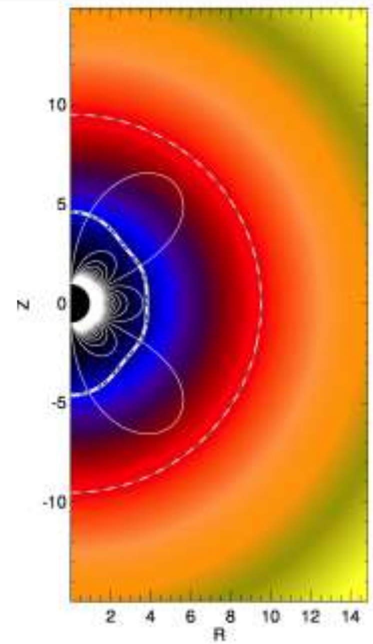
Decreasing Alfvén surface !



Dipole



Quadrupole



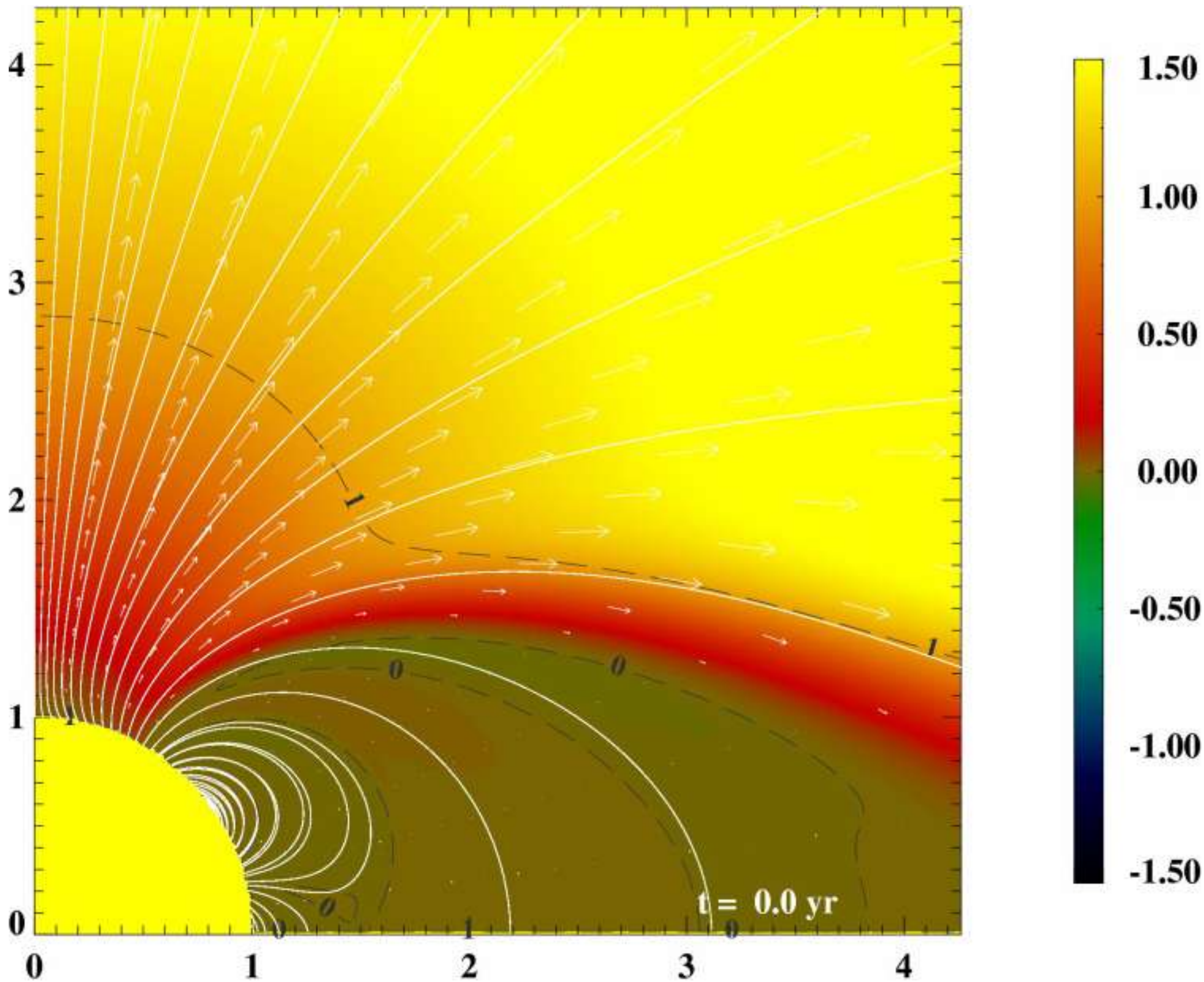
Octupole

60 cases with compressible MHD code PLUTO

(Réville, Brun et al. 2015, ApJ)

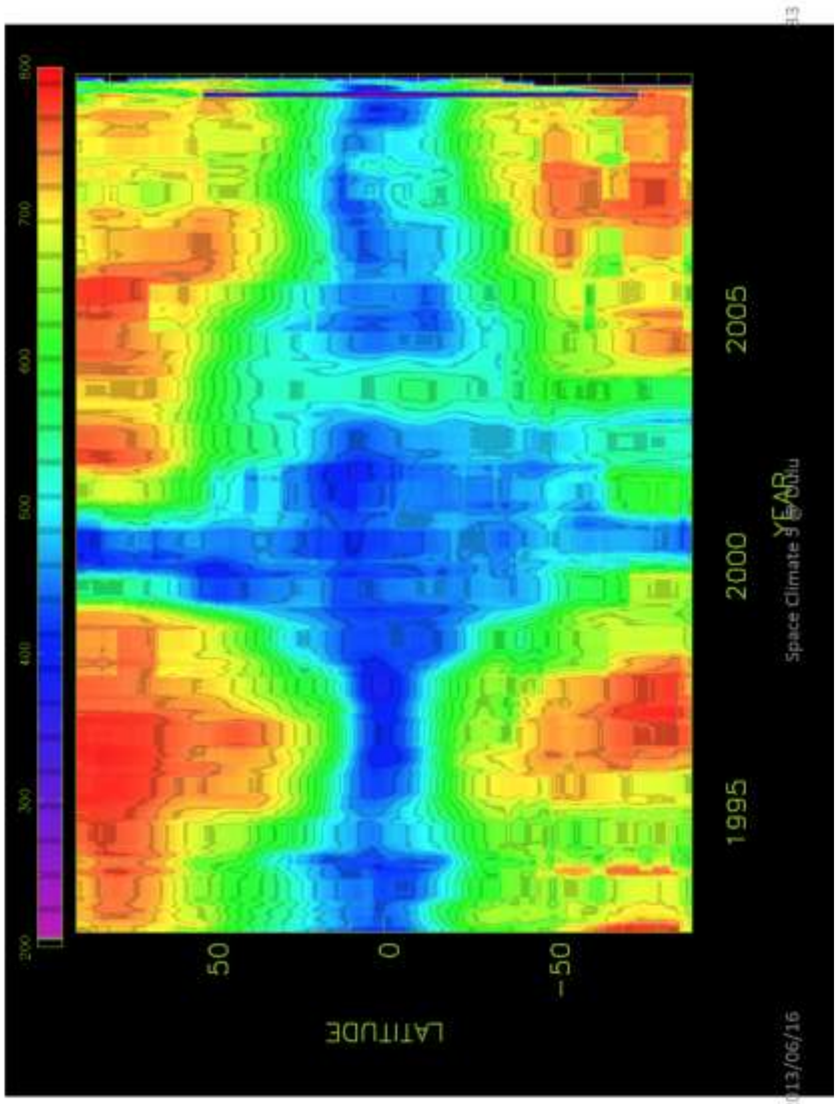
Coupling Solar Dynamo to Solar Wind

Pinto, Brun et al. 2011, ApJ



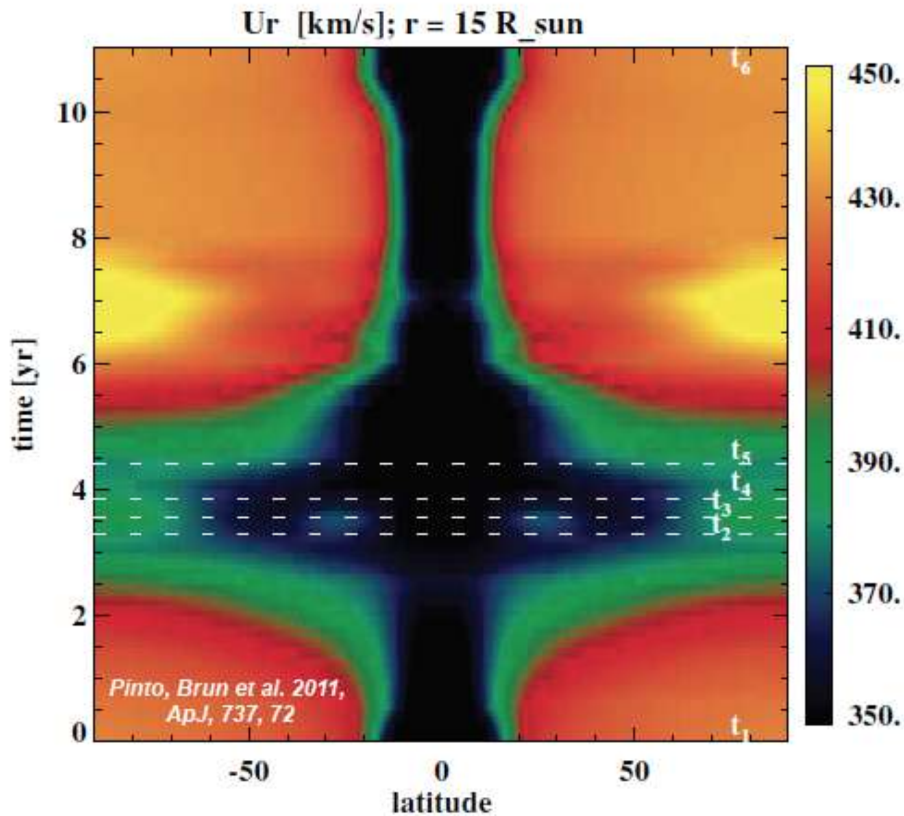
11-yr Cycle Variations of Solar Wind

Solar Wind Speed



Observations (IPS@ 327 MHz)

Tokumaru et al. 2010, Sokol et al. 2015

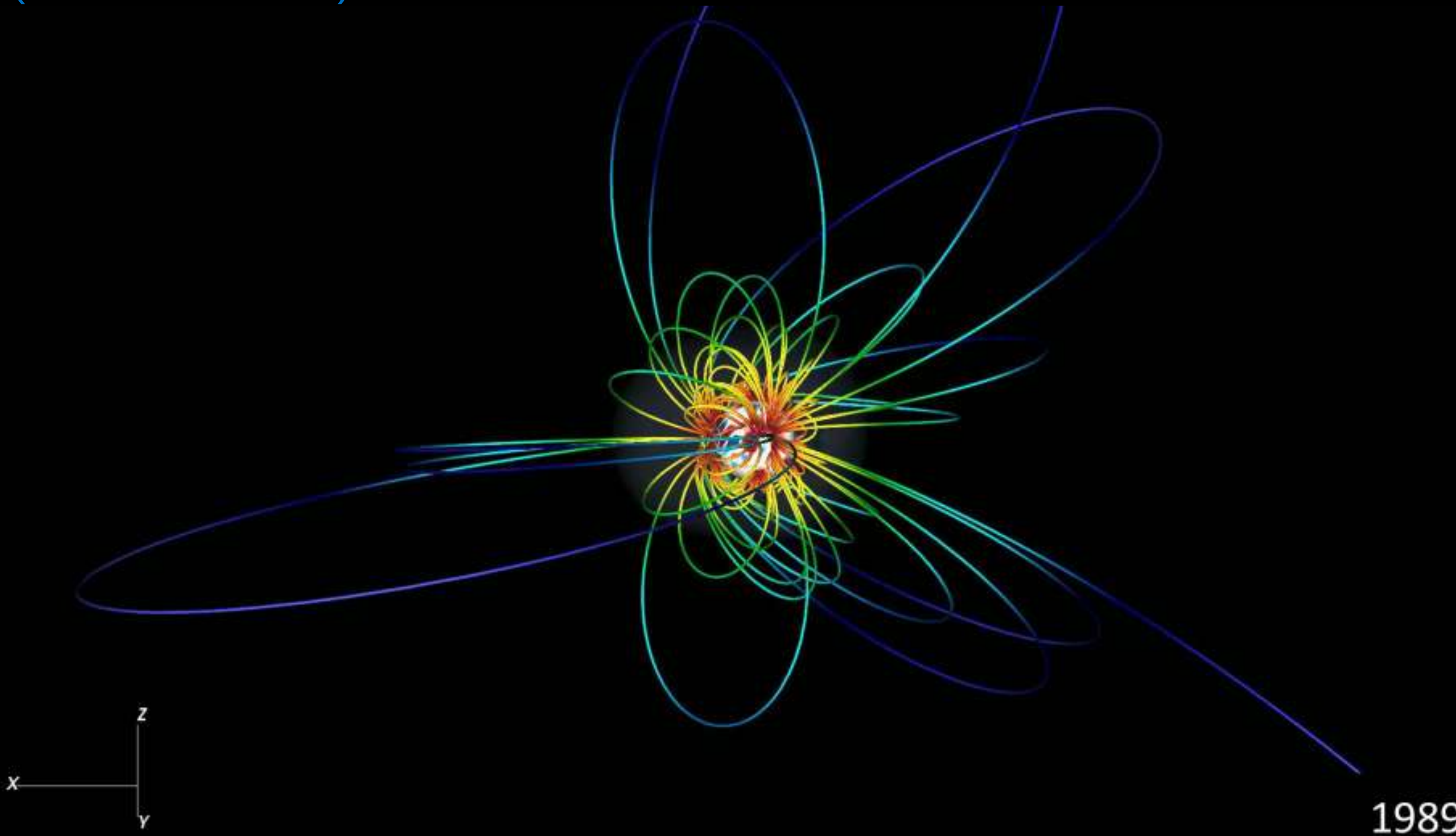


Dynamo-wind model

Pinto, Brun et al. 2011

Going 3-D: Solar case from 1989 to 2000

(Wilcox Obs data)



Reville & Brun 2017, ApJ

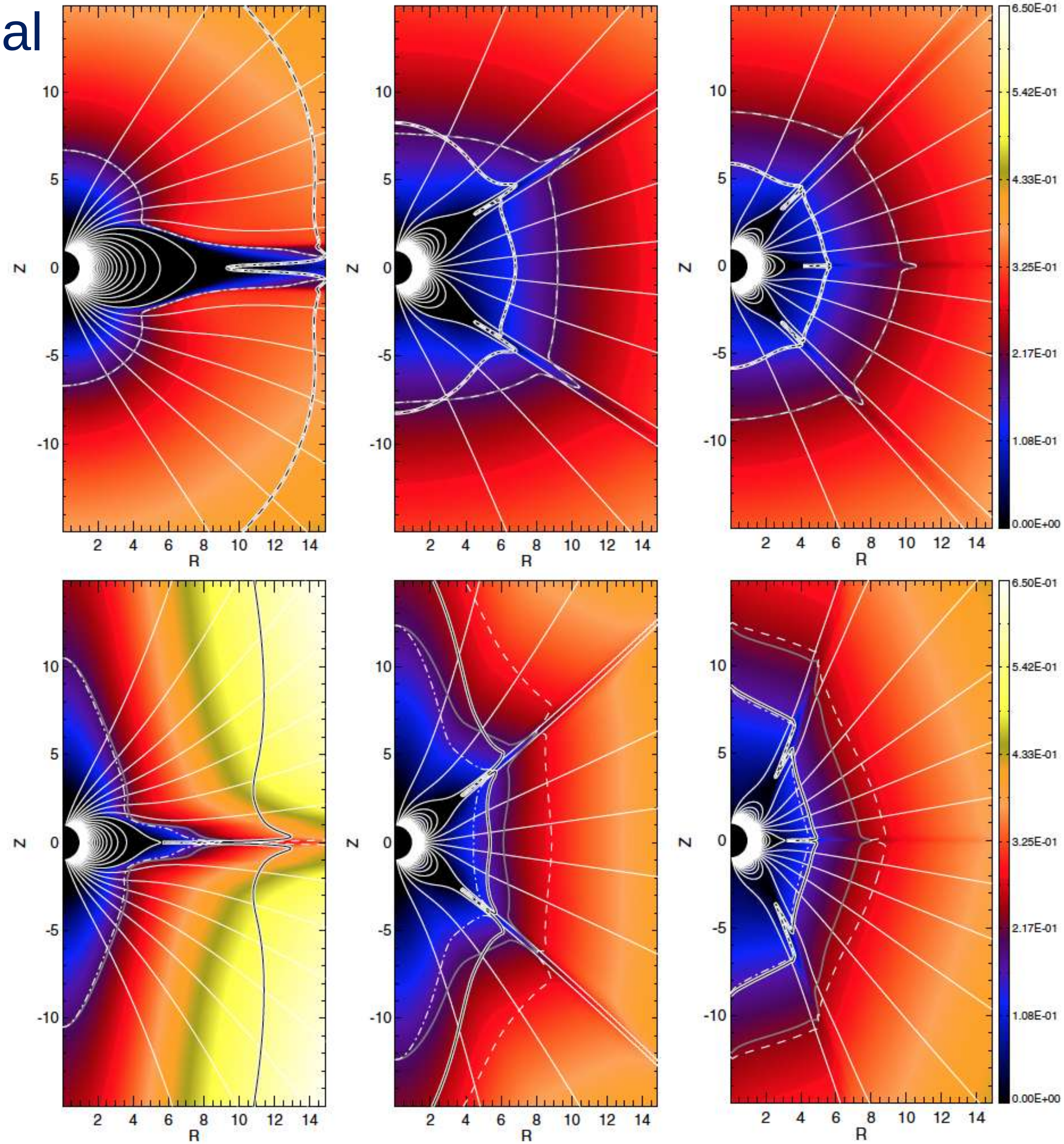
Magneto-Centrifugal Effect

Sakurai 1985

Slow rotation

Fast rotation

Reville et al. 2015a



Angular Momentum Loss from Wind Simulations

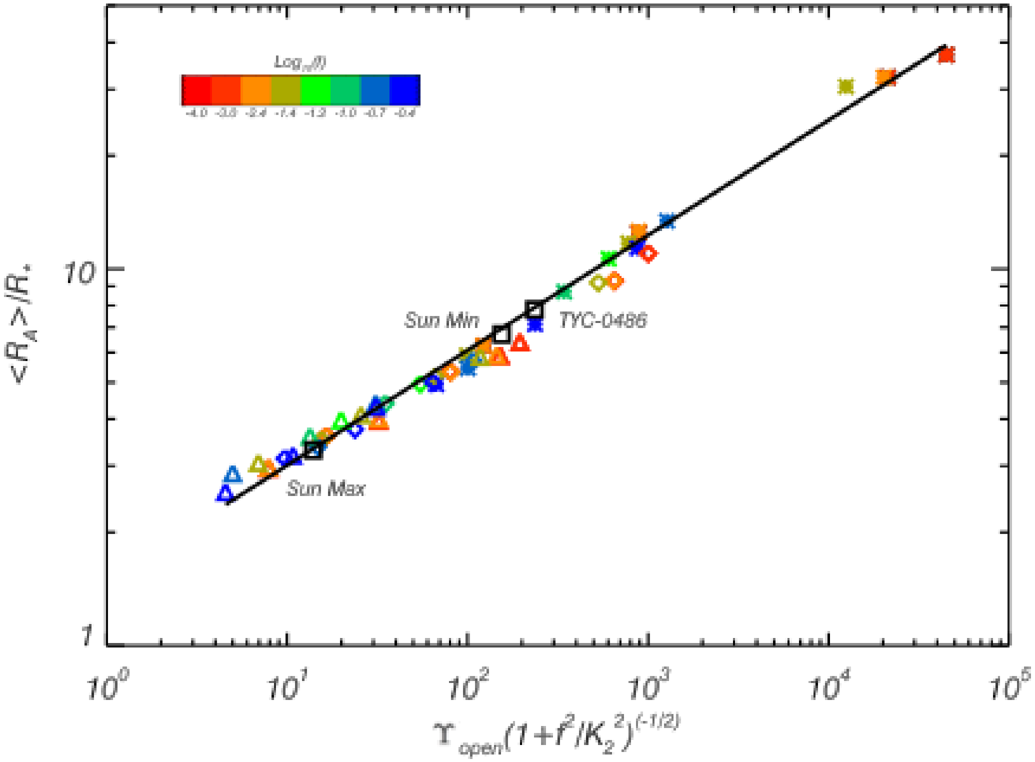
The most general law as of today:

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

open flux

$$\Phi_{open} = \int_S |\vec{B} \cdot d\vec{S}|$$

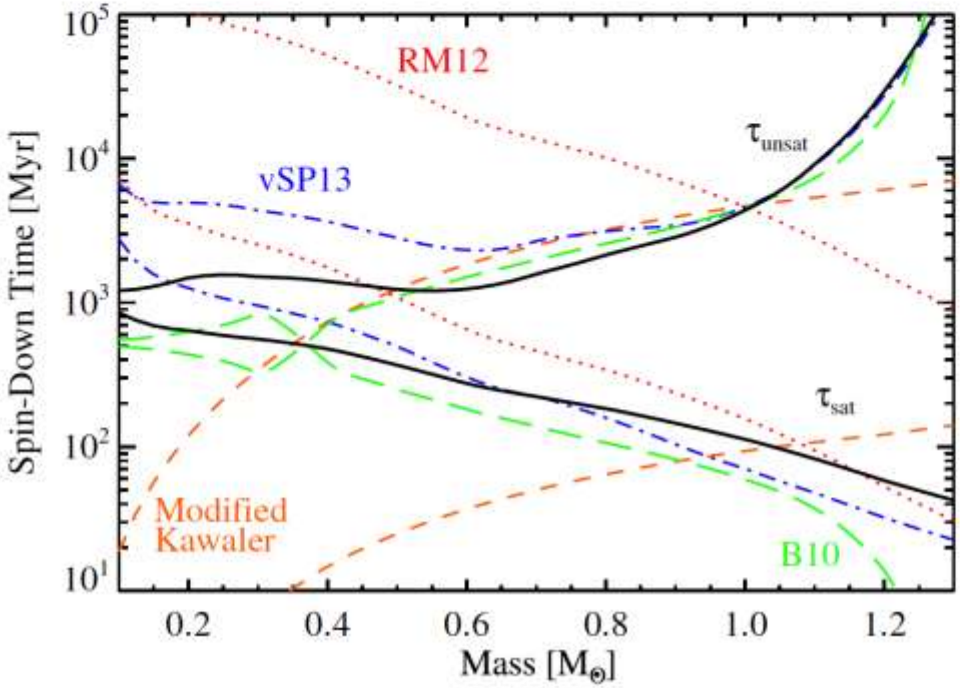
$$\frac{dJ}{dt} = \frac{dM}{dt}^{1-2m} \Omega_* R_*^{2-4m} K_1^2 \Phi_{open}^{4m} (1 + f^2 / K_2^2)^{-m} v_{esc}^{-2m}$$

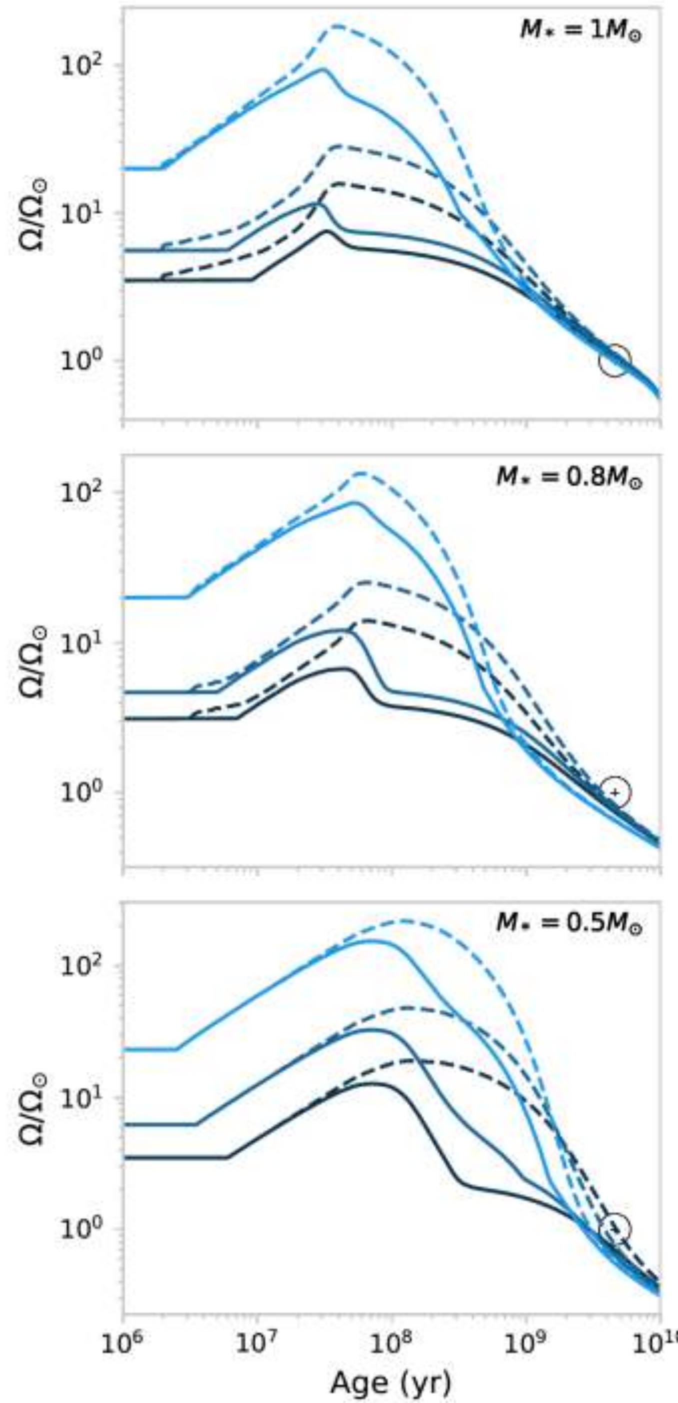


m=0.31
K1=0.64
K3=0.06

Réville et al. 2015a, ApJ 798:116

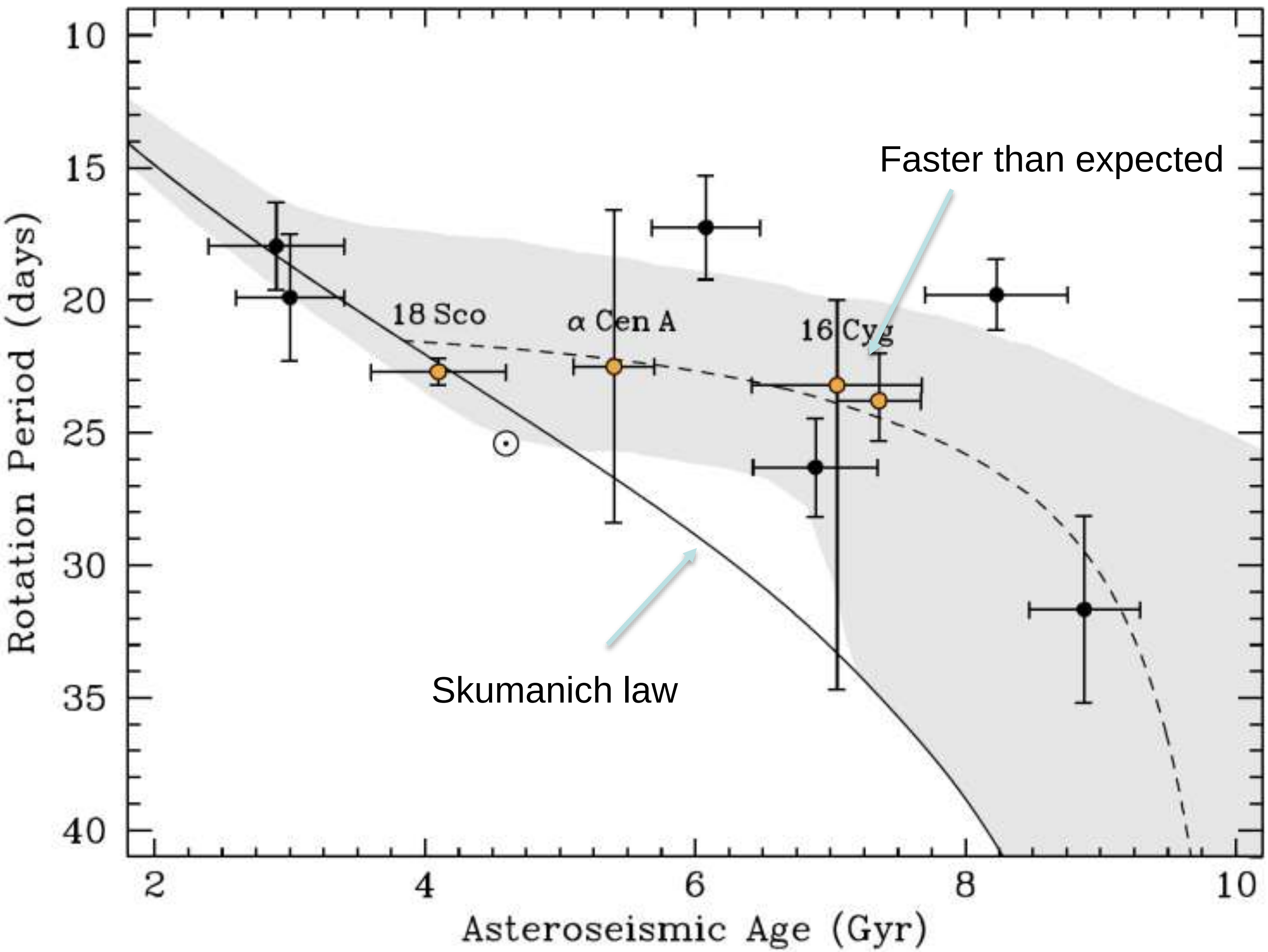
Stellar wind brake down vs Mass





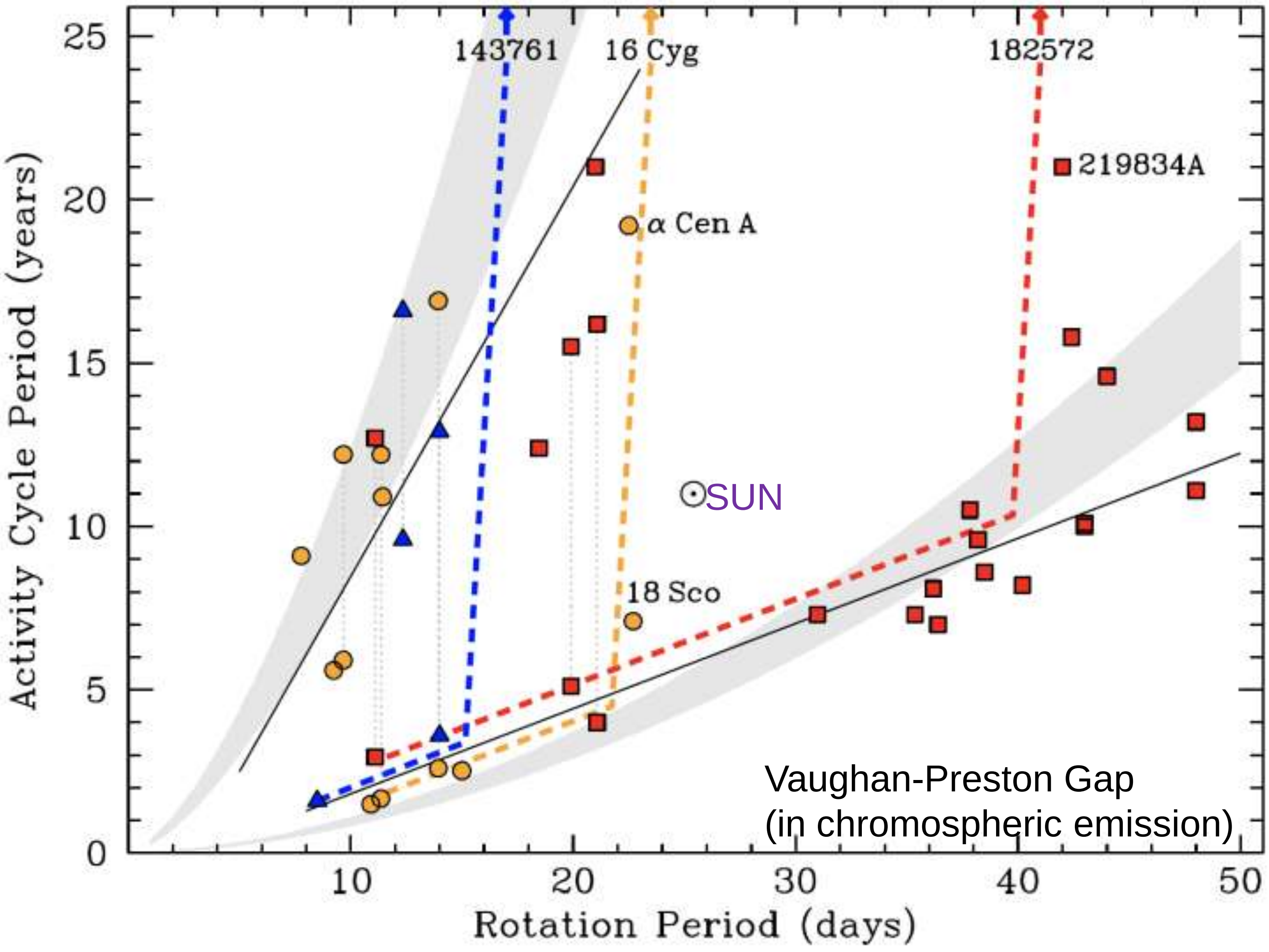
Matt, Brun et al. 2015, ApJ
Benbakoura, Brun et al. 2019

Possible Departure from Gyrochronology for old stars:
What is the source of desagreement with Asteroseismic age?



Van Saders et al. 2016

Is the Sun in a transitional rotation/dynamo State?

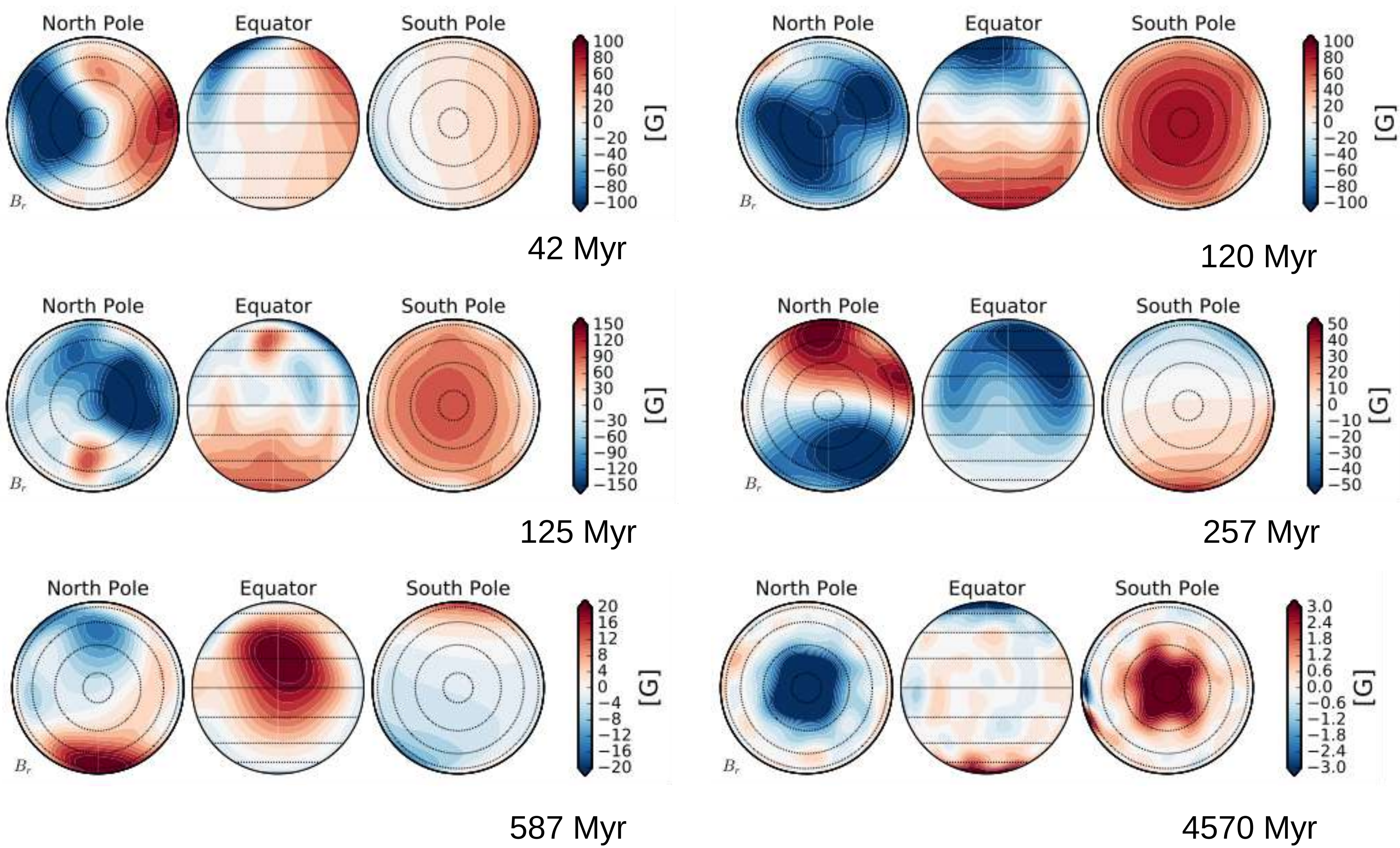


Metcalfe et al. 2016, 2017

But not so clear from Models that topology is the final solution
(see next slides)

Complex magnetic topologies

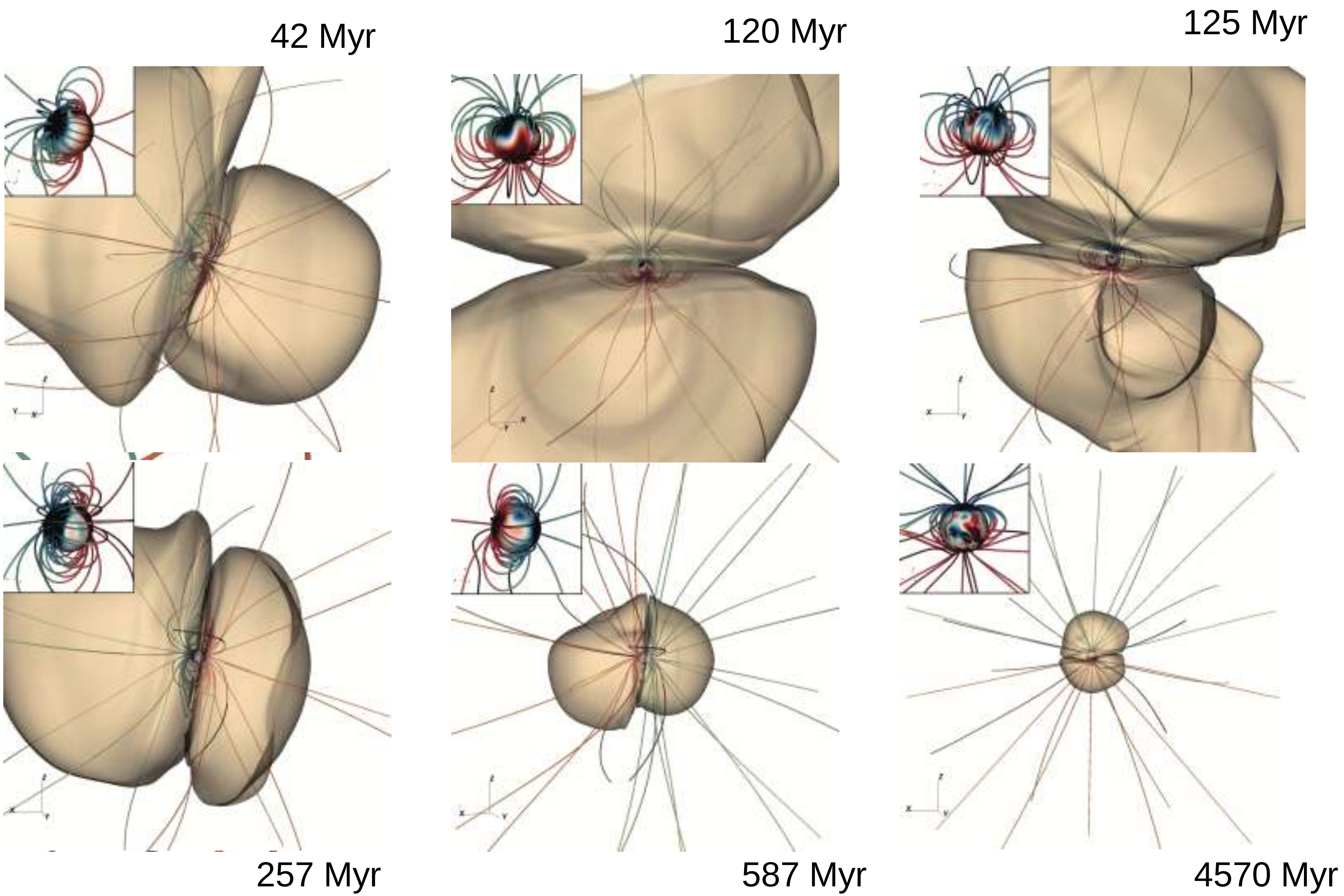
Field strength decreases with age !



[Réville+ 2016]

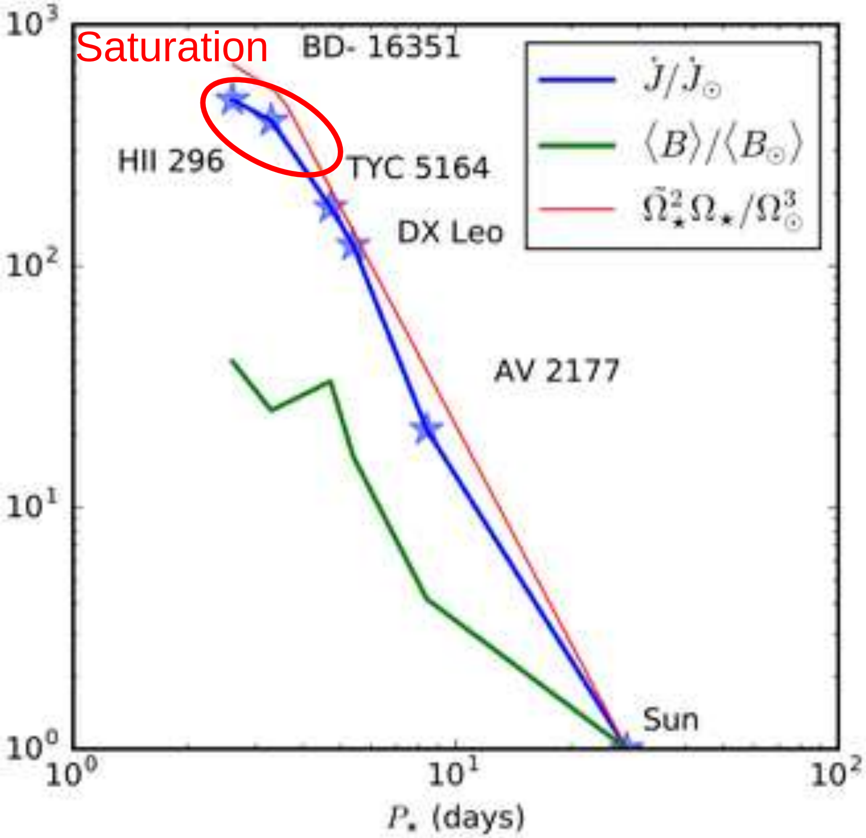
Complex magnetic topologies

Alfvén Surface => Lever arm



[Réville+ 2016]

Saturation of angular momentum loss



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

Two correlated competing mechanisms

Large-scale B ↗

Coronal heating ↗

Magnetic confinement

Alfvén radius ↗

Mass loss ↙

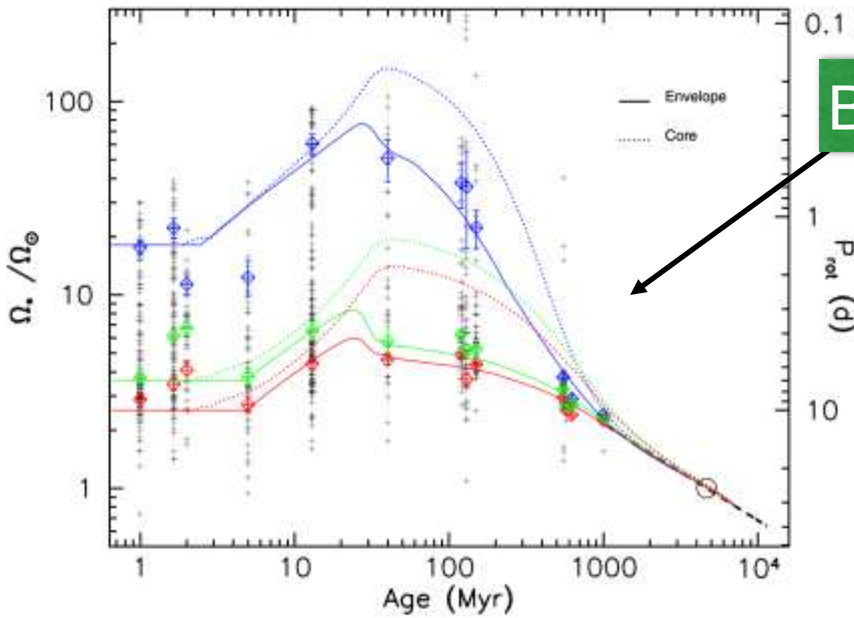
Angular momentum loss (dJ/dt) ↗

[Réville+ 2016]

Wind, Stellar magnetism and gyrochronology

Stellar Spin down Models

(Gallet & Bouvier 2013)



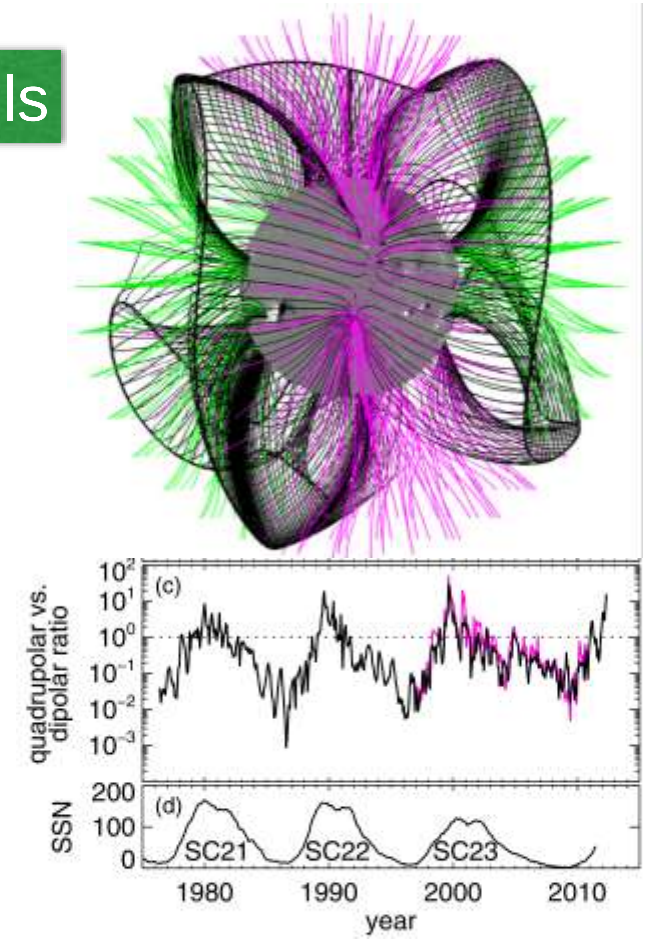
Braking models

dynamo

wind

Magnetic Activity

(De Rosa et al. 2012)



Skumanich's law: $\Omega_* \propto t^{-1/2}$

Gyrochronology: Barnes 2003, Magnetochronology: Vidotto et al. 2014

Conclusions

Convective velocities Vr roughly scales with cubic root of $L_*/(R_*^2 \rho_{meanCZ})$ (star's luminosity devided by mean density in CZ)

$\Rightarrow$ Prograde vs retrograde state changes at different Ω_0 as spectral type is changed (since $Ro=V/2\Omega_0 L$ and V changes with spectral type)

$\Rightarrow$ Magnetic field B reduces or can even supress diff rot Ω

$\Rightarrow$ at high rotation rate we get magnetic wreaths that generate omega-loops as we lower diffusivity, cyclic dynamos easier to get

$\Rightarrow$ There are more and more evidence that Nonlinear dynamos show a different cycle – rotation period relationship

$\Rightarrow$ Stellar wind are sensitive to magnetic field topology and braking efficiency as well but Heating mechanism likely key

$\Rightarrow$ there is an open flux pb as 3-D simulation and secular models seems to disagree on torque level