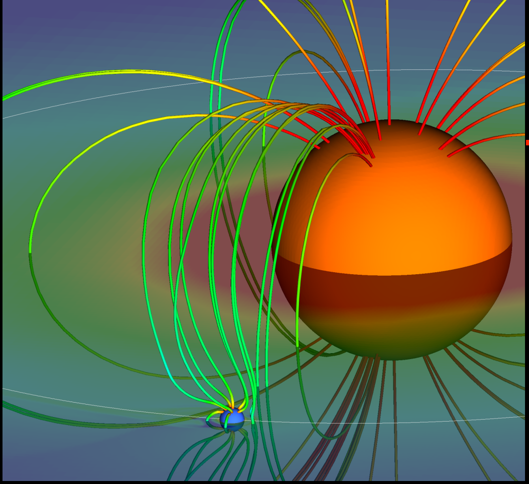
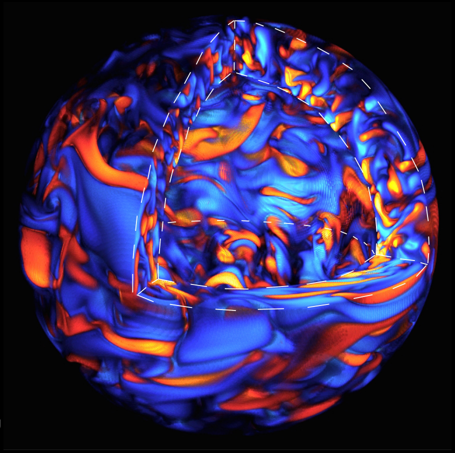
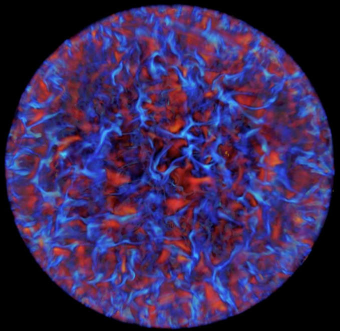


Stellar Dynamo and Wind

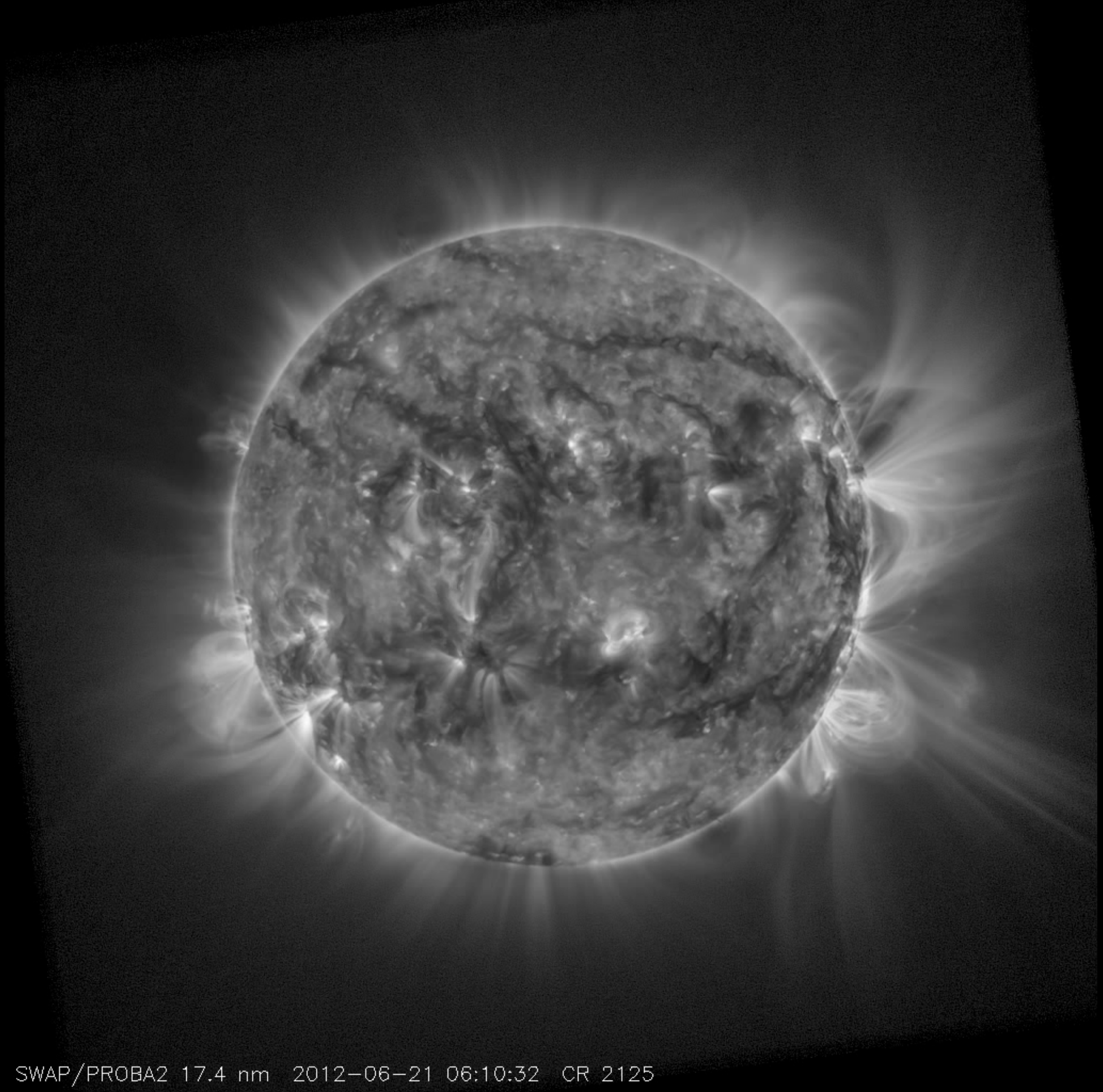


Allan Sacha Brun
Service d' Astrophysique/UMR AIM,
CEA-Saclay
with A. Strugarek, K. Augustson, J. Toomre, V. Reville and the STARS2 Team

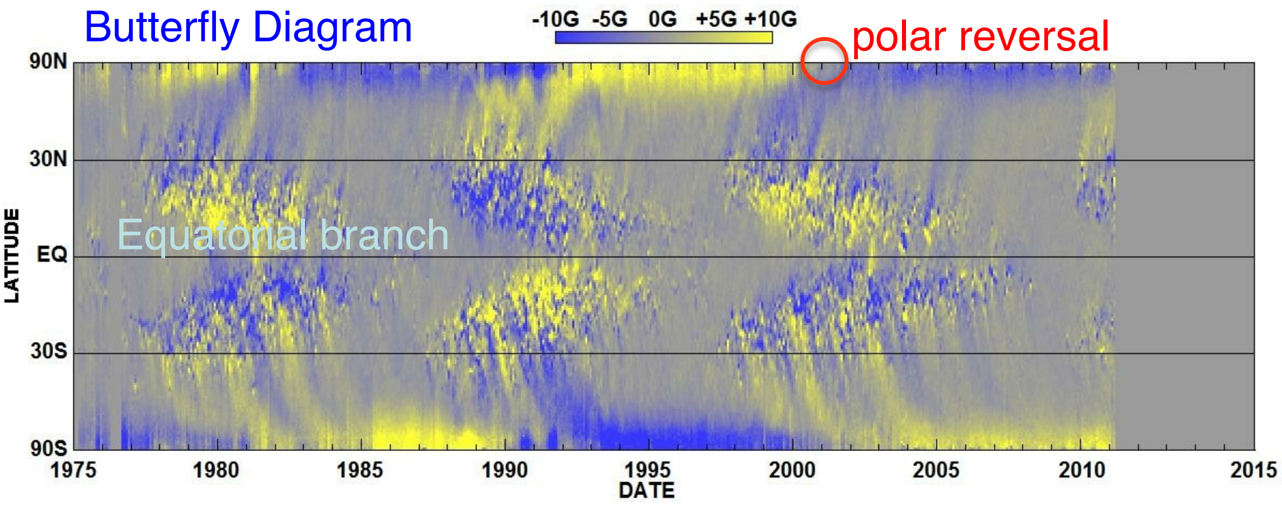
- Observational evidence of stellar dynamics and SPI
- 3-D simulations of solar-like stars, Wind and SPI



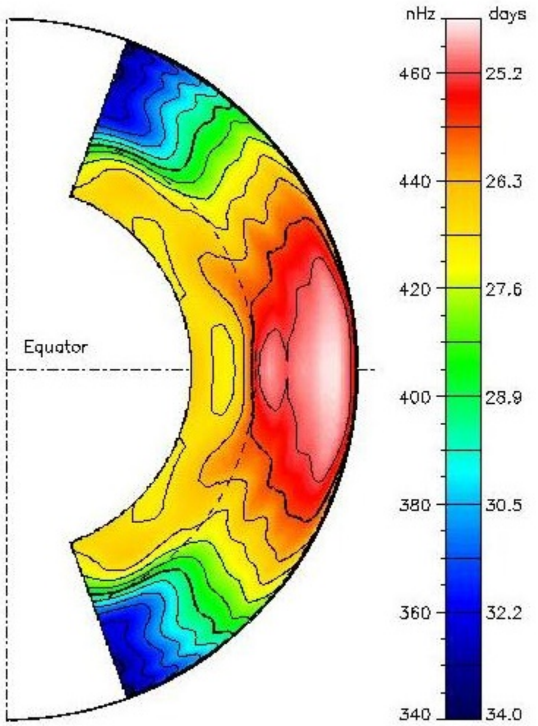
Soleil en UV
(ESA/Proba2)

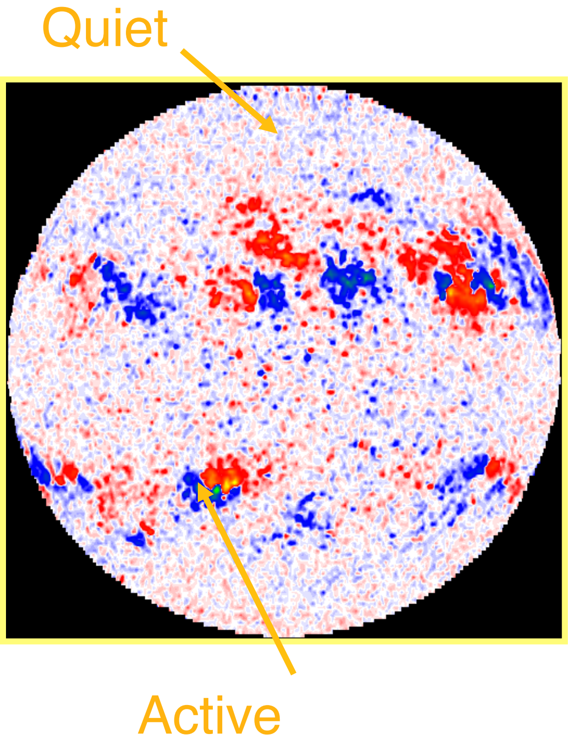


Solar Cycle and Flows

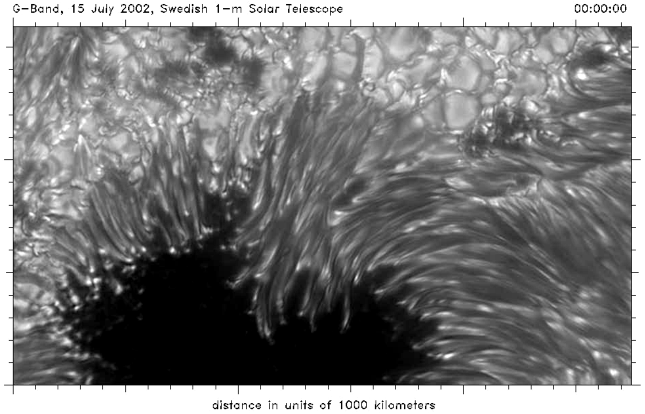


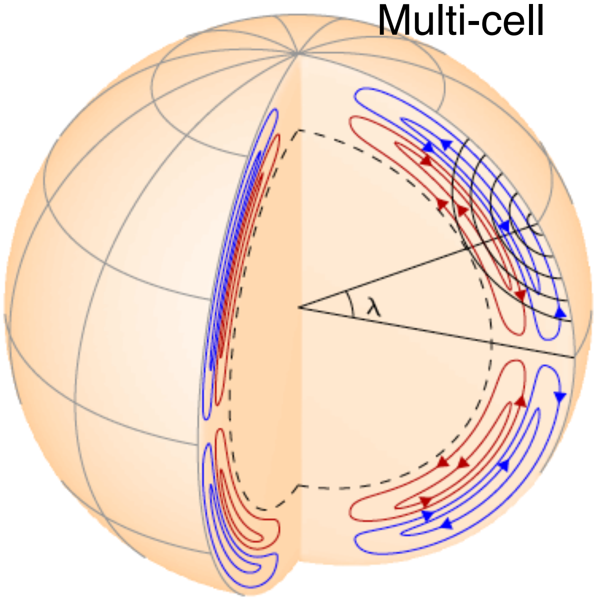
Hathaway/NASA/MSFC 2011/04





Small vs Large
Scale Dynamos





Zhao et al. 2013

Going 3-D: nonlinear convection dynamo MHD simulations

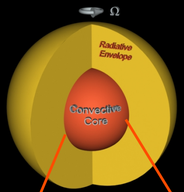
Simulations 3-D Hautes Performances de la MHD Stellaire

par Allan Sacha BRUN

(CEA/DRF/IRFU/Sap/LDEE & AIM)

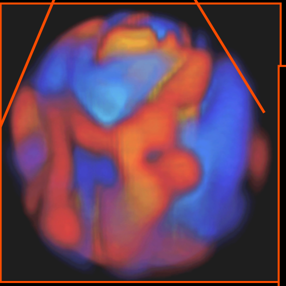
Projet STARS^2
www.stars2.eu

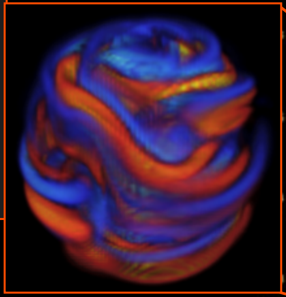
Asterosismologies/Magnetisme
SoHO/Corot/Espadon/XMM



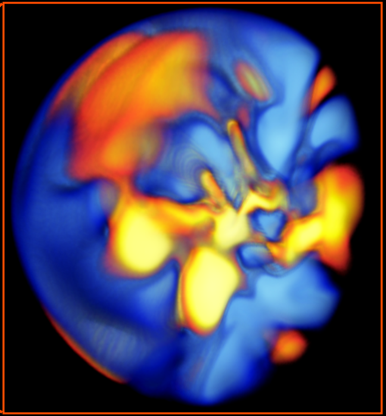
Etoiles massives

(Alvan et al. 2014, 2015,Augustson et al. 2012,2013, 2015, 2016, Brun et al. 2002, 2004, 2005, 2006, 2007, 2011, 2015, Nelson et al 2011, 2013)
Ballot et al. 2007, Browning et al. 2004, Jouve & Brun 2009, 2013, Zahn, Brun & Mathis 2007, Brown et al. 2008,10, 11,

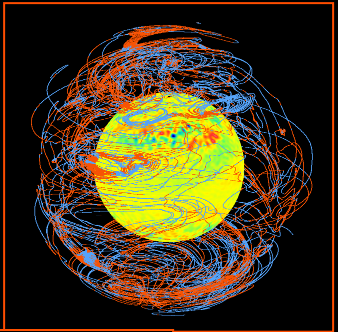


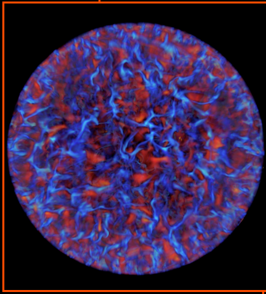


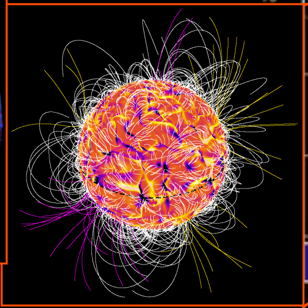
Evoluées(RGB)

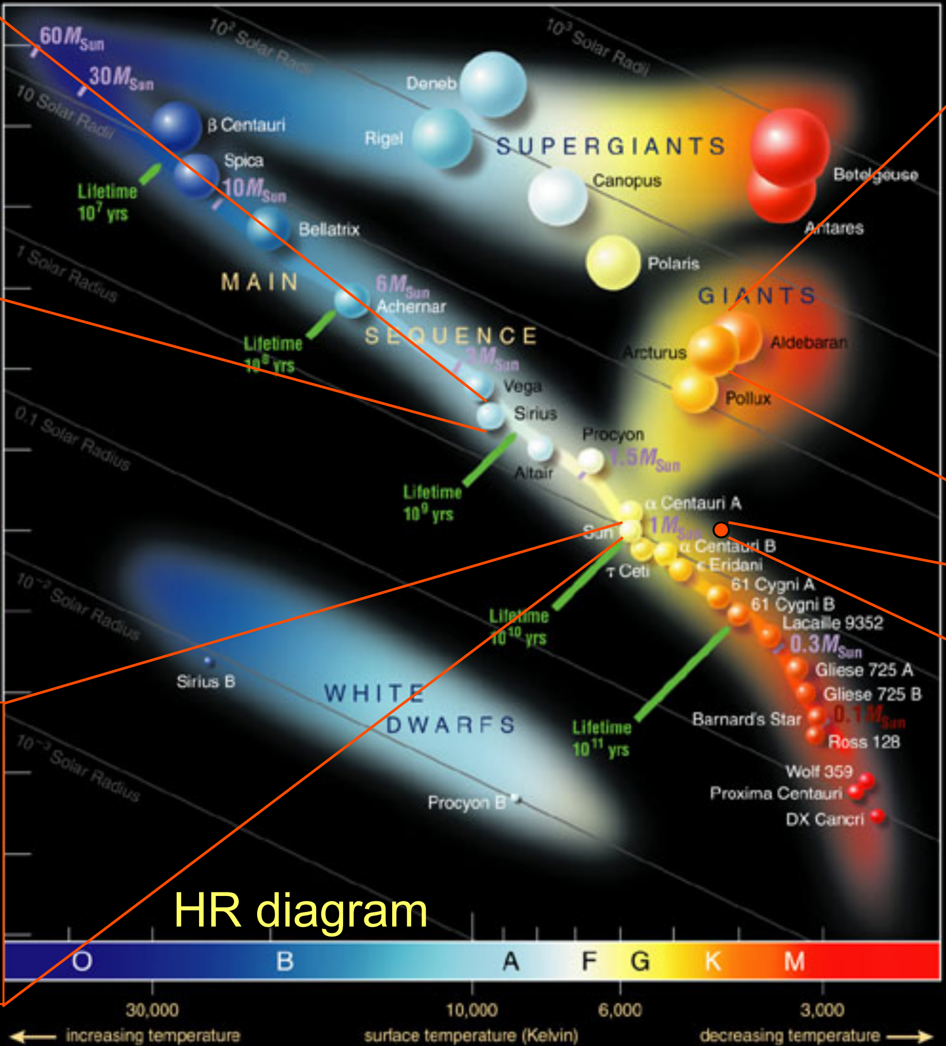


Soleil



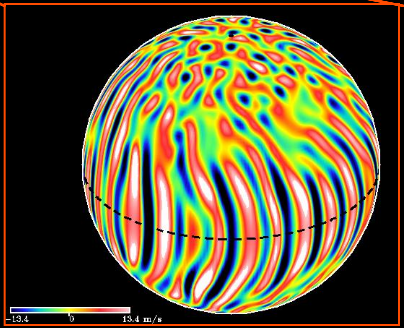


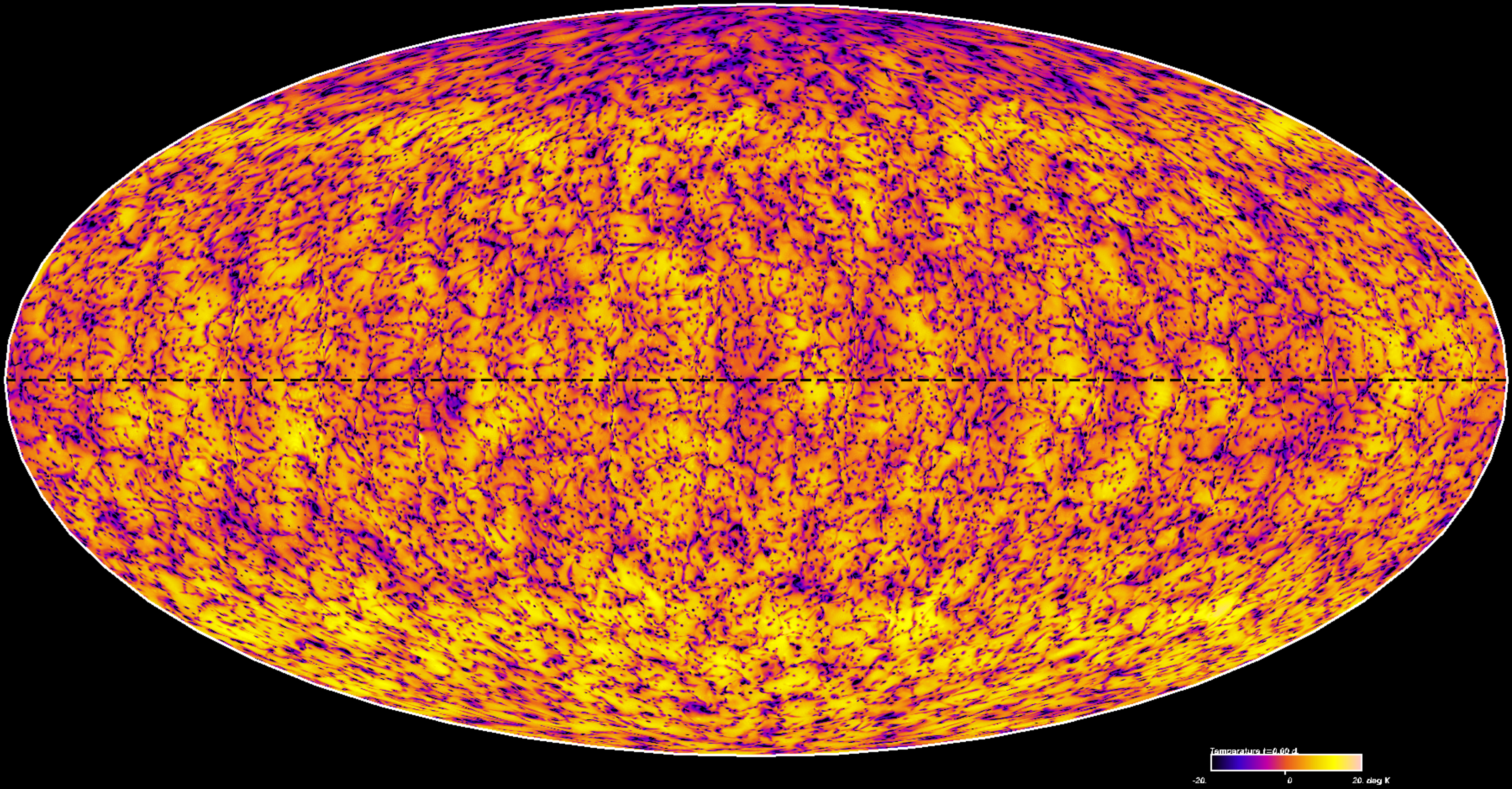




HR diagram

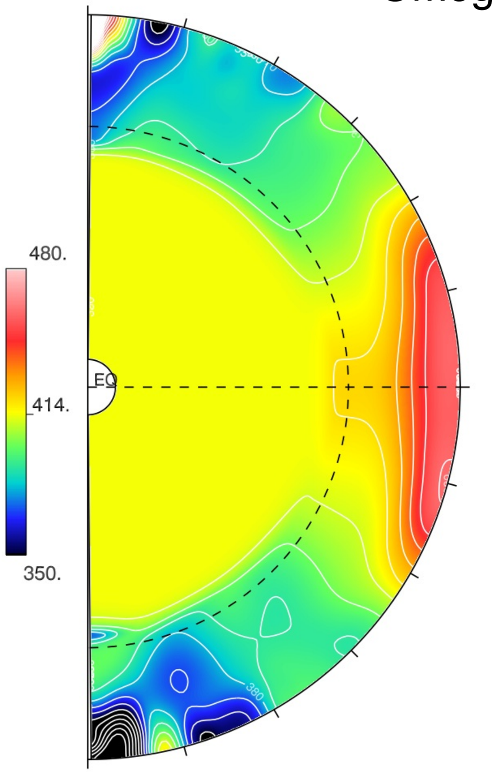
Soleils jeunes

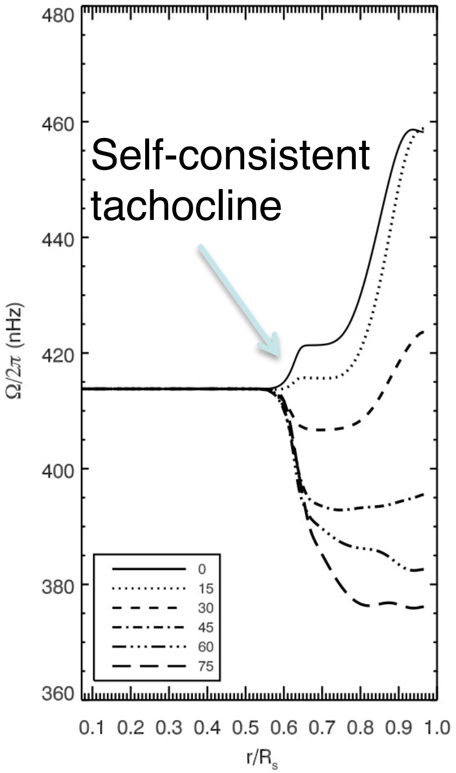



Temperature t=0.00 d
-20.
0
20. deg K

Omega Profile & Thermal Perturbations

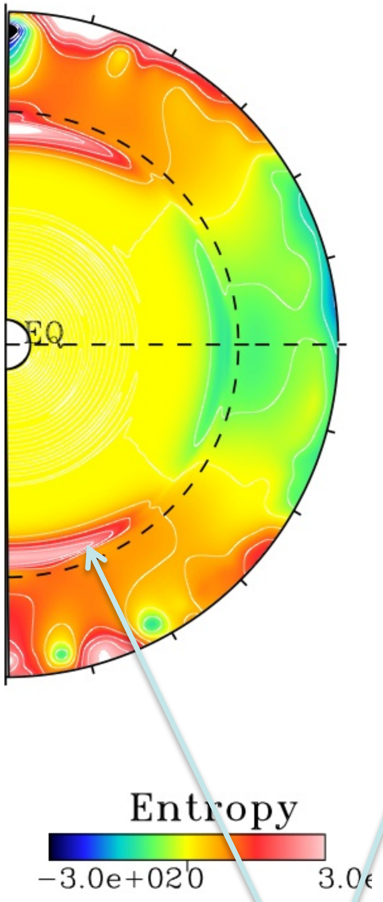
Omega

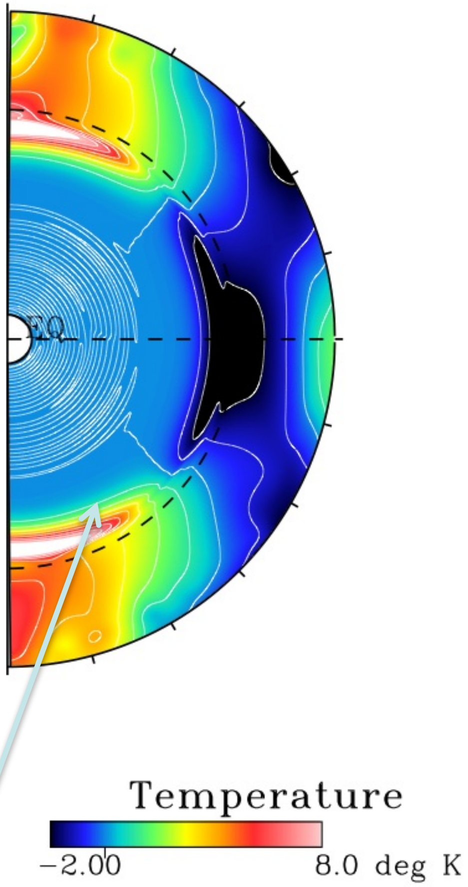




Self-consistent tachocline

Warm poles, cool equator

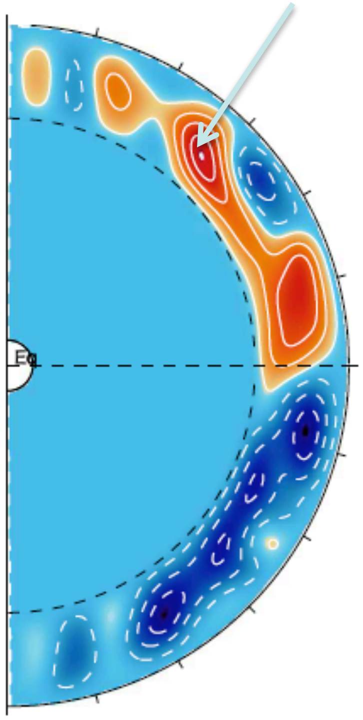


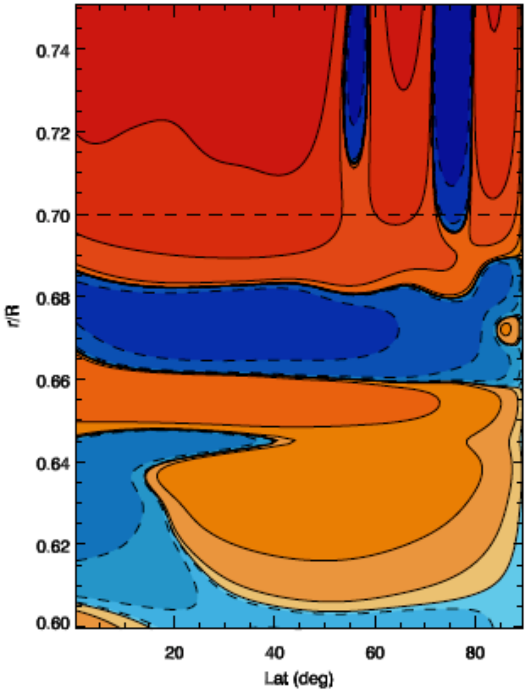


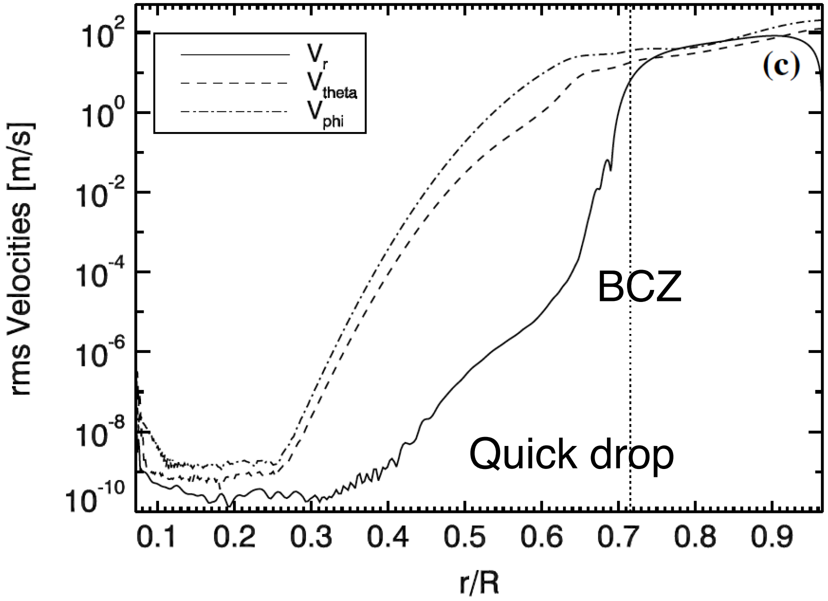
LARGER fluctuations at bcz

Meridional Circulation

Almost unicellular flow







BCZ

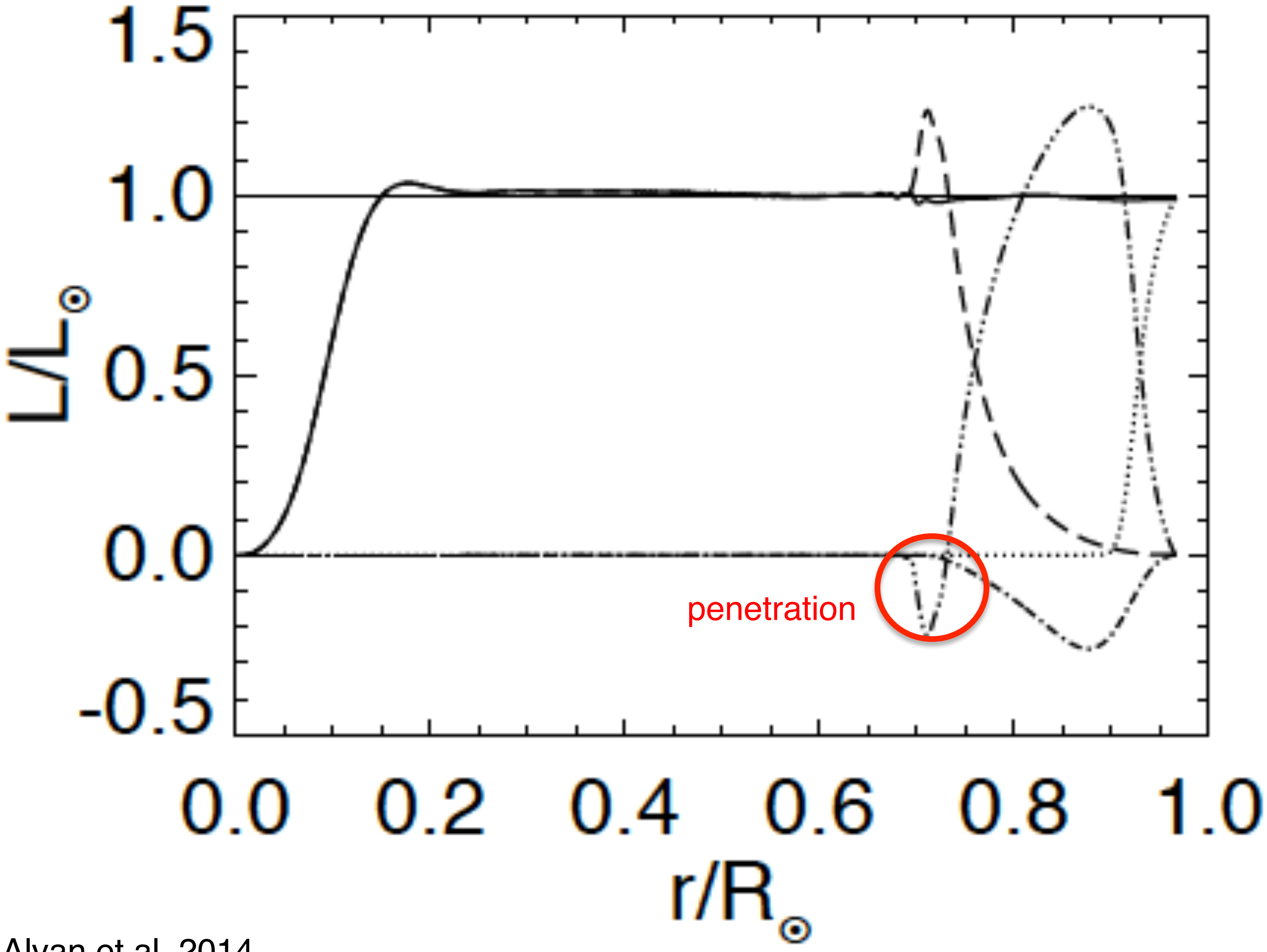
Quick drop

Penetrationof MC flow
< 0.02 Rsol

Drop by
3 orders of
magnitude
over 0.04 R

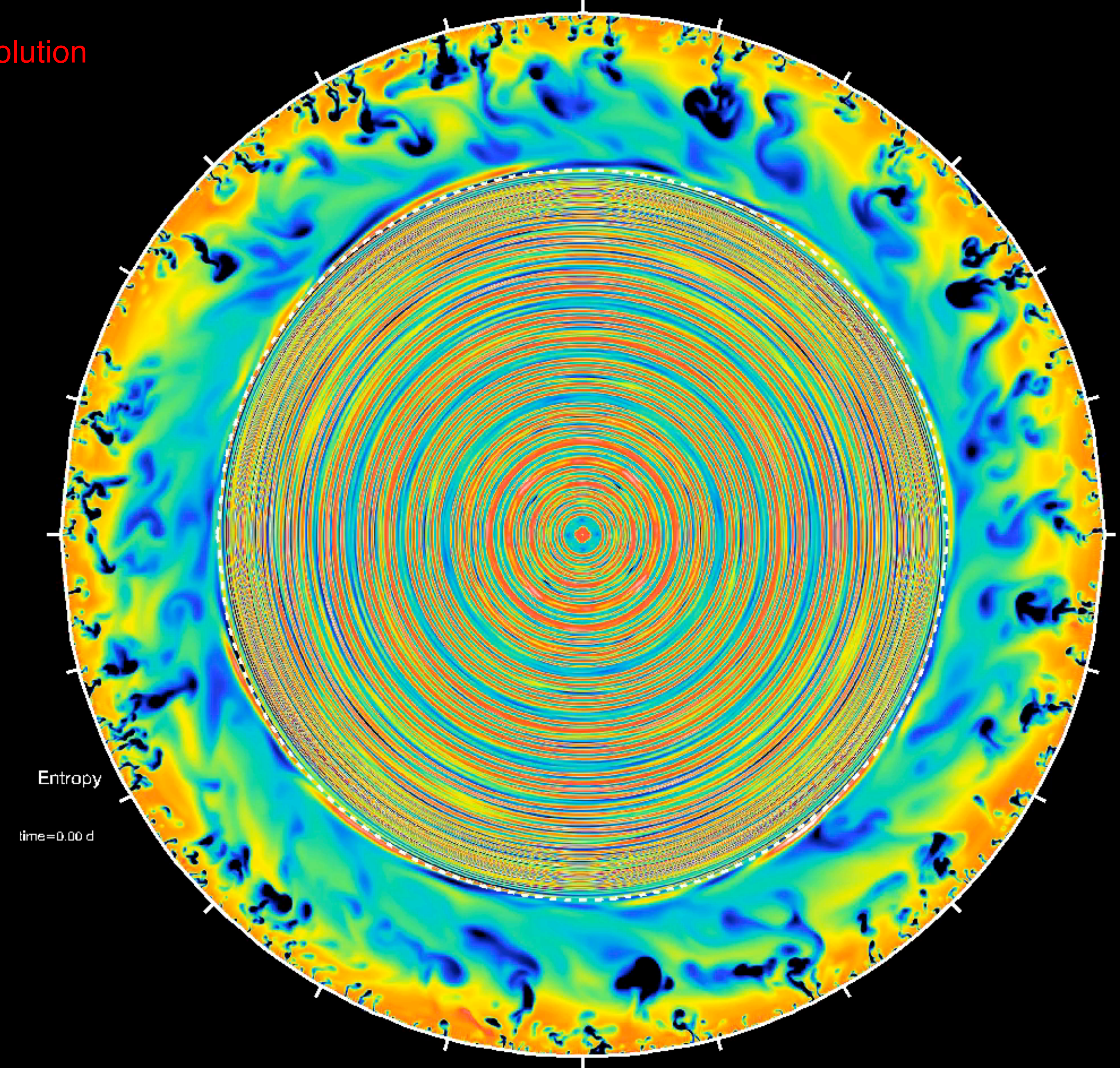
Brun, Miesch, Toomre, 2011, ApJ , 742

Going to r=0

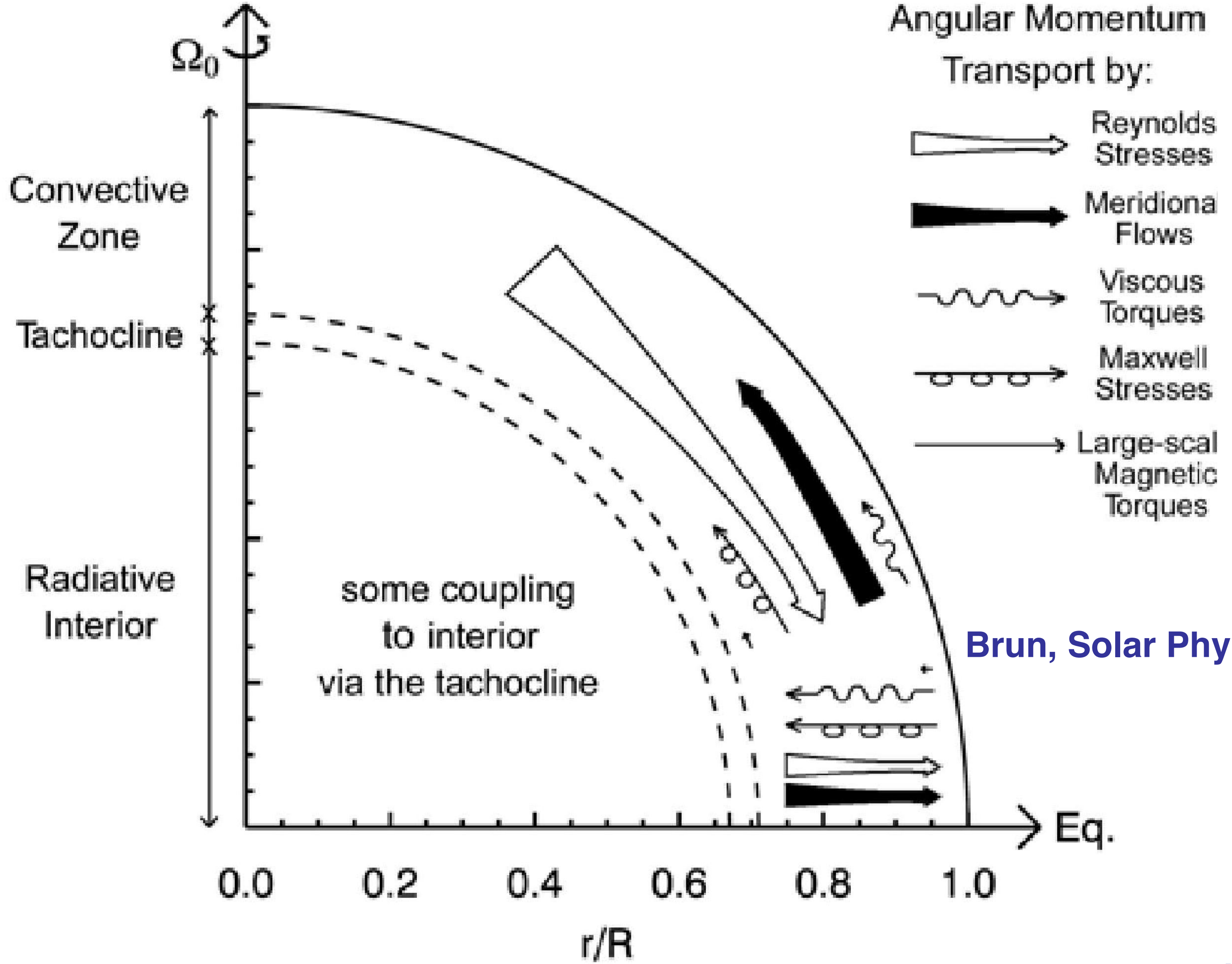


Alvan et al. 2014

Higher Resolution



Angular Momentum Balance in Presence of B

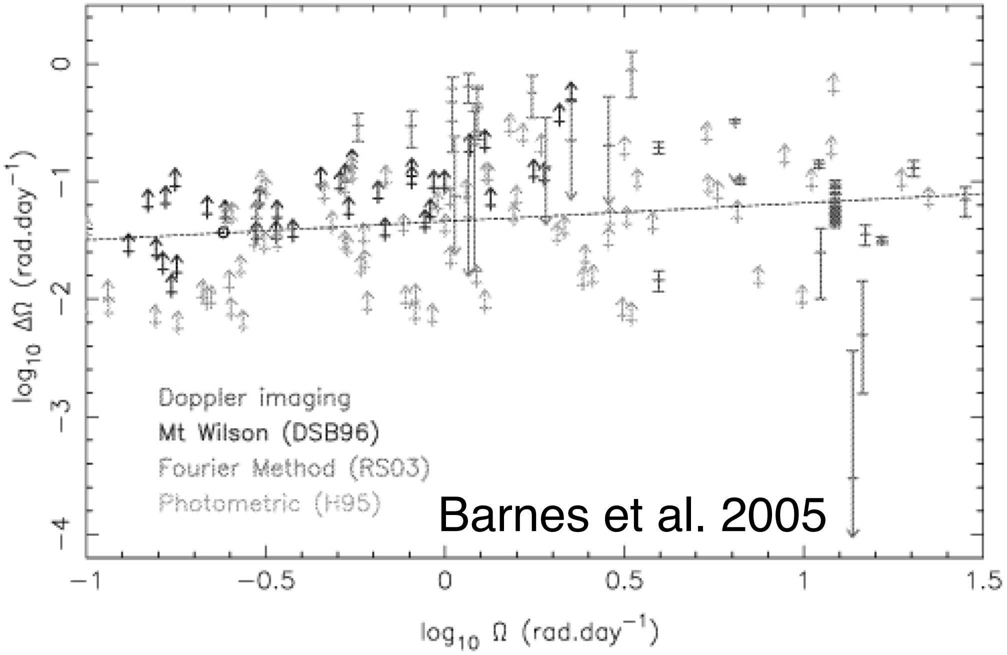


Brun, Solar Physics, 2004

The transport of angular momentum by the Reynolds stresses remains at the origin of the equatorial acceleration. The Maxwell stresses seeks to speed up the poles.

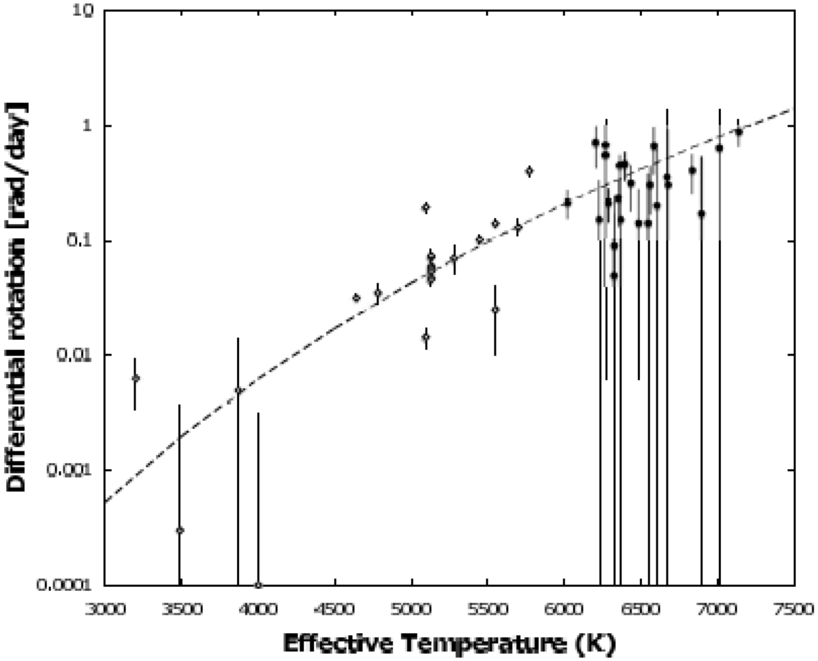
Trends in Differential Rotation with Ω & Mass (Teff)

Weak trend with Ω



Barnes et al. 2005

ΔΩ increases with M_*



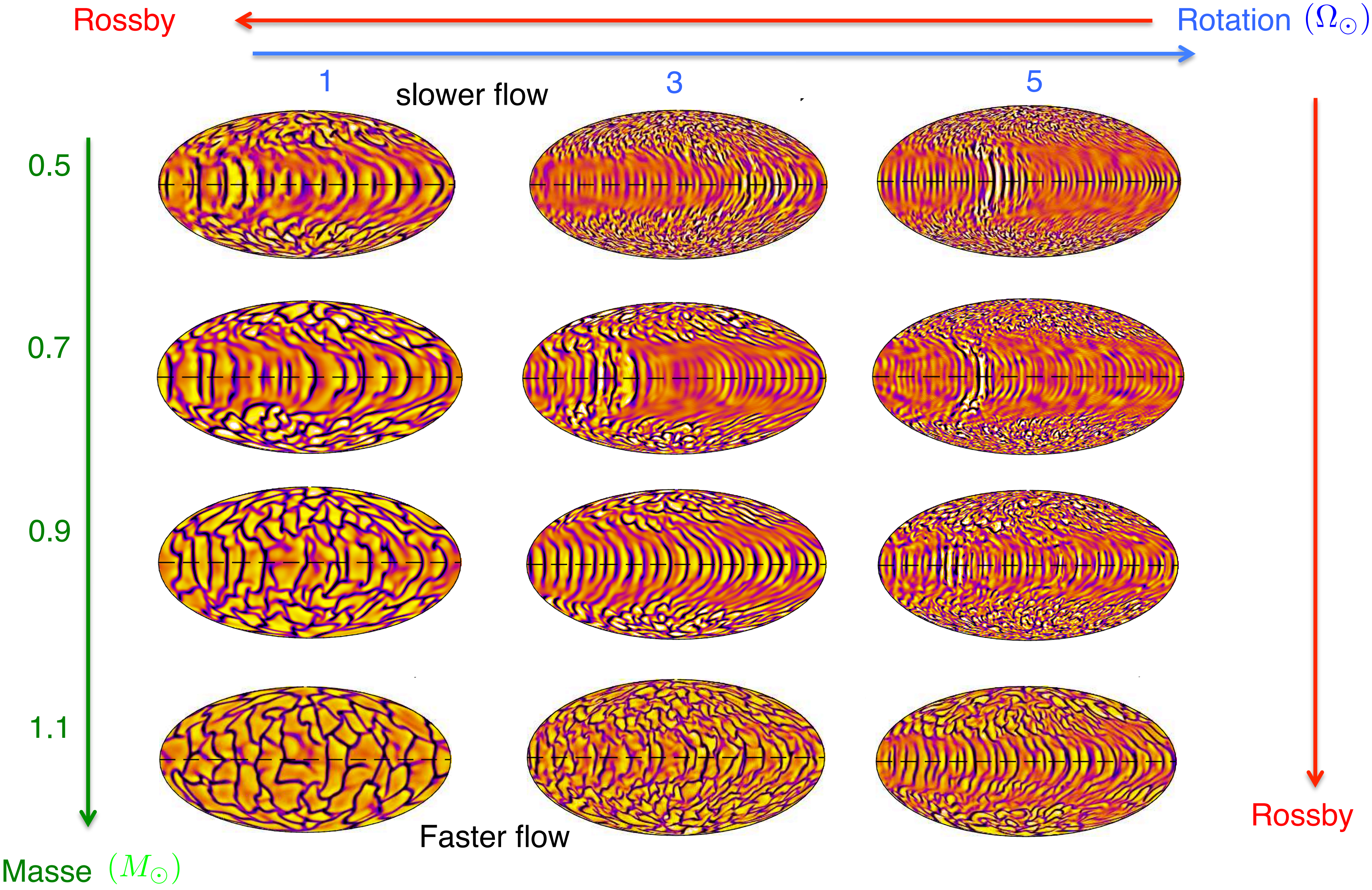
Collier-Cameron 2007

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

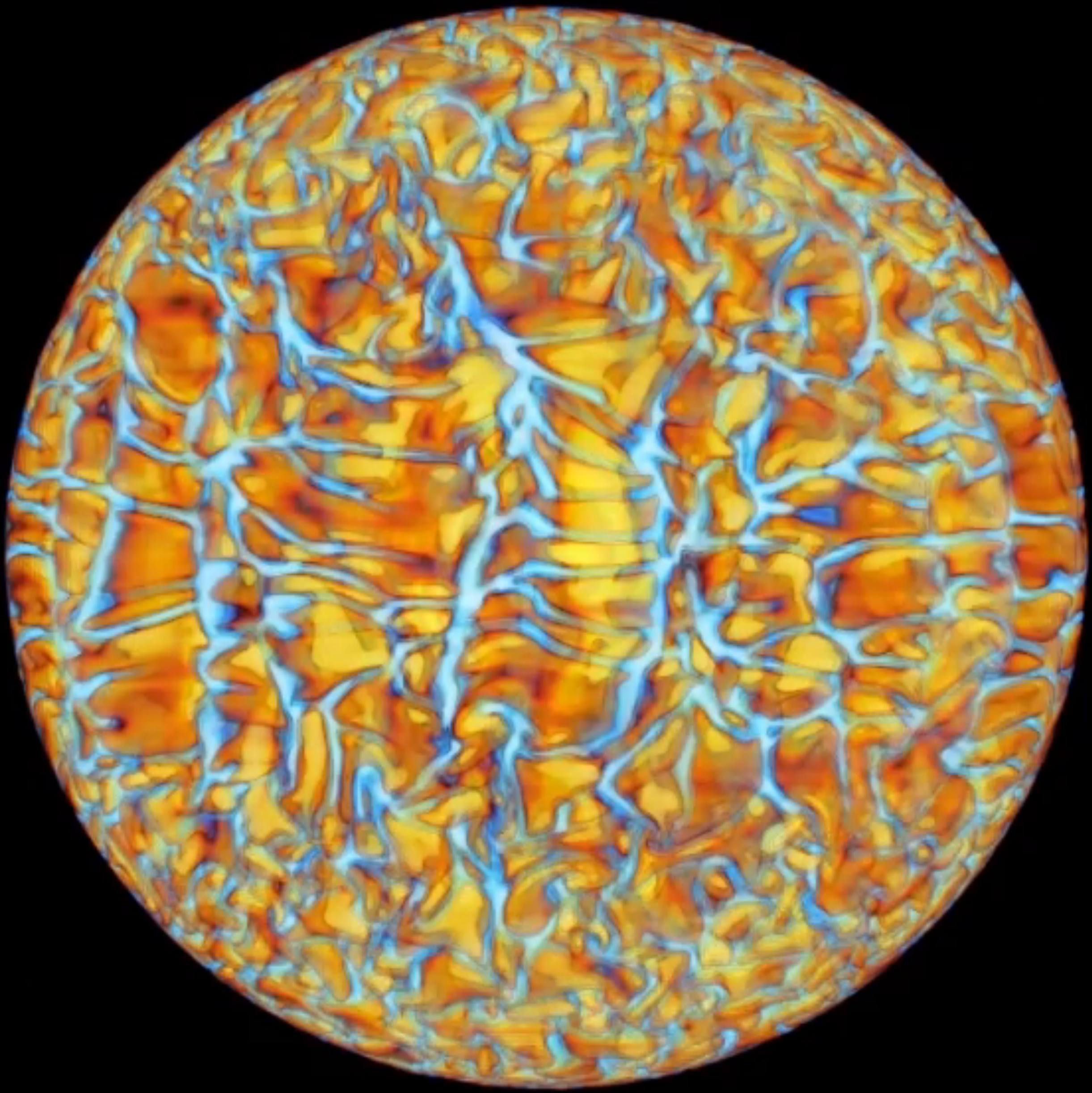
Confirming these observational scaling is key

Effect of Rotation on Convection

Matt, DoCao, Brun et al. 2011, 2013



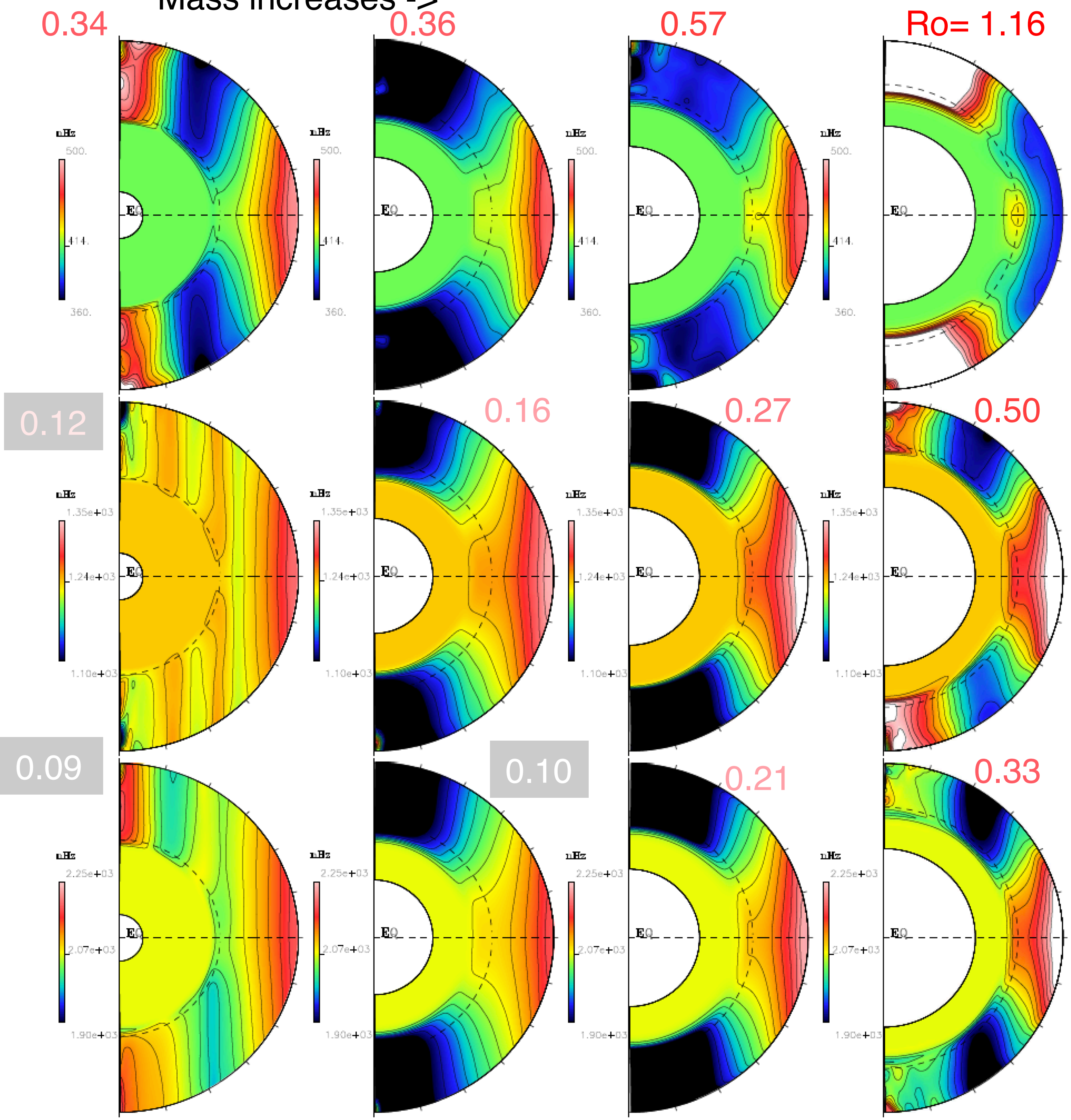
Turbulent Convection in Stars



Bessolaz & Brun 2011

Differential Rotation In G & K stars

Mass increases ->



Ω

Matt et al. 2011
Brun et al. 2014

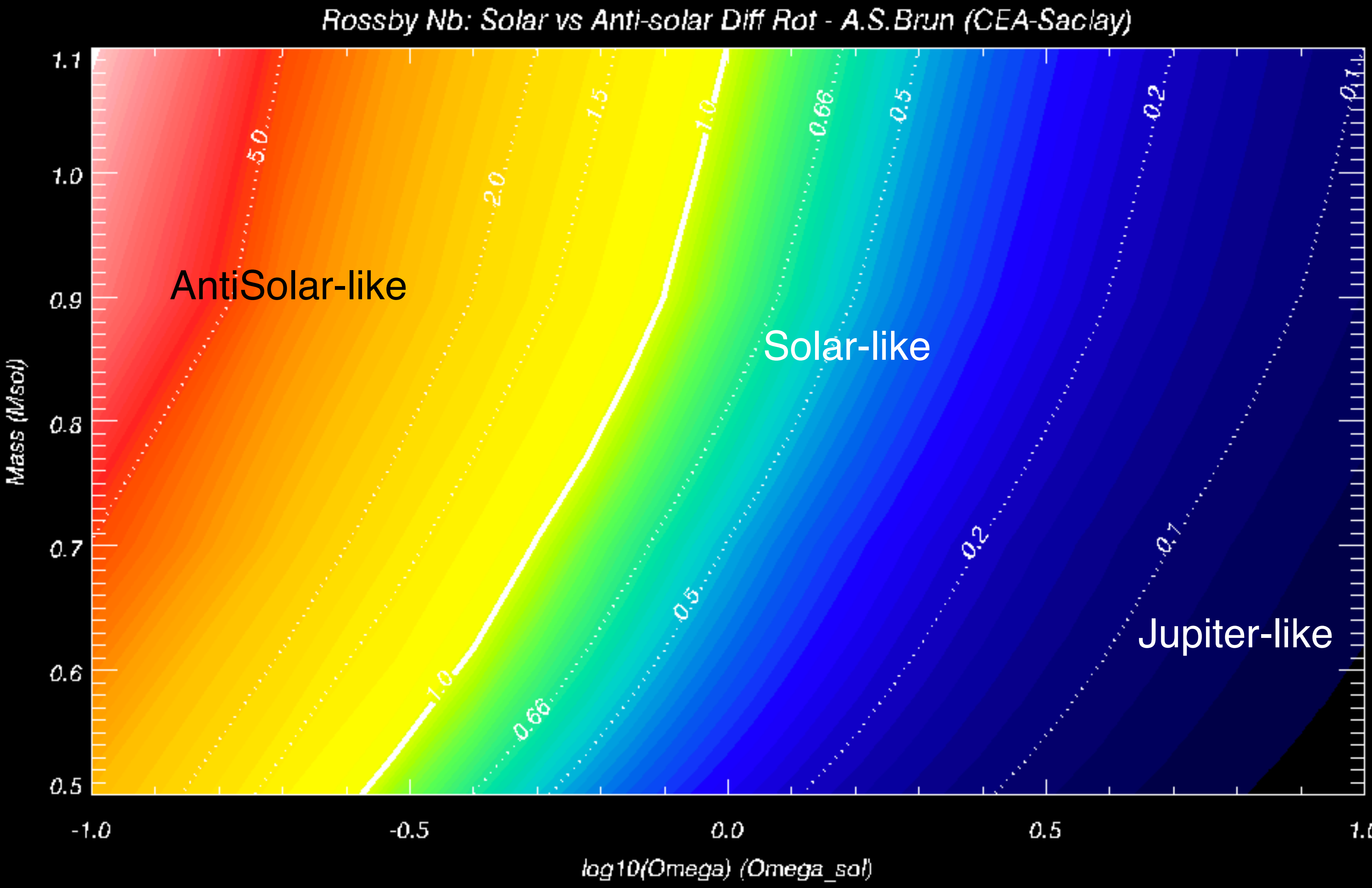
Rotation
Increases

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

5 Ω

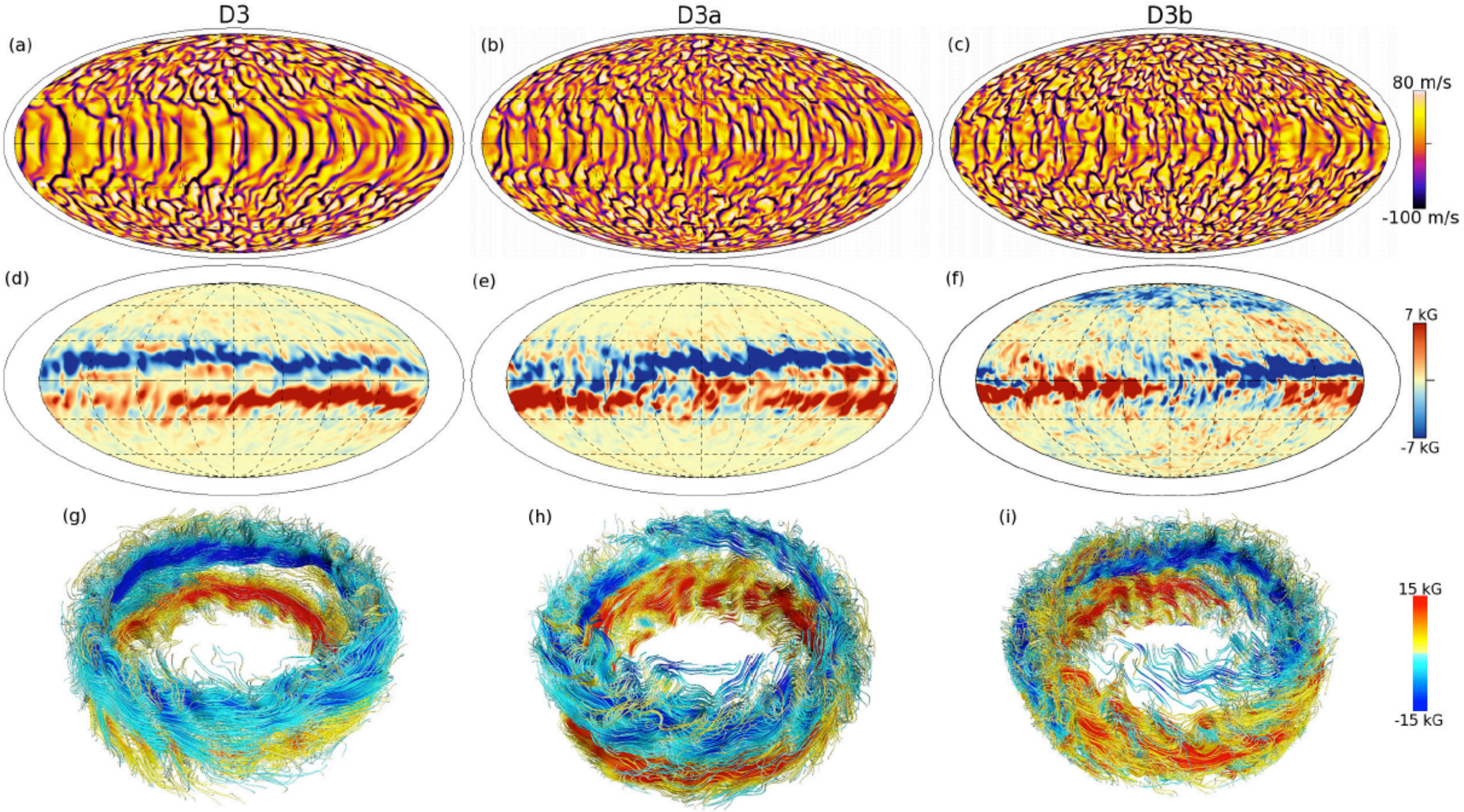
See also: Gastine et al. 2014
Kapyla et al. 2013

Rossby Number vs Stellar Mass and Rotation



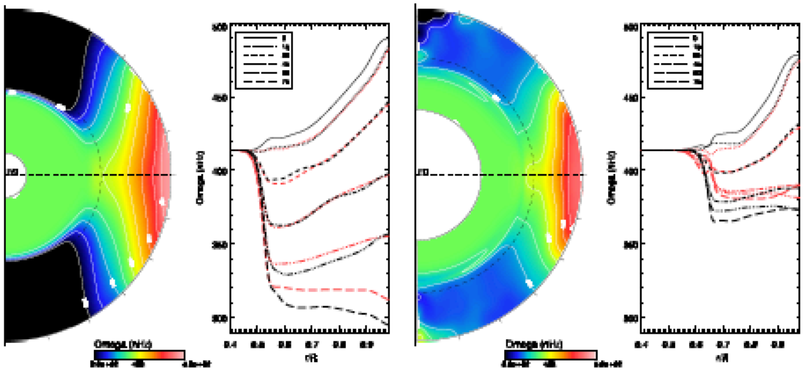
Brun et al. 2014, 2015

Magnetic Wreaths vs Turbulence

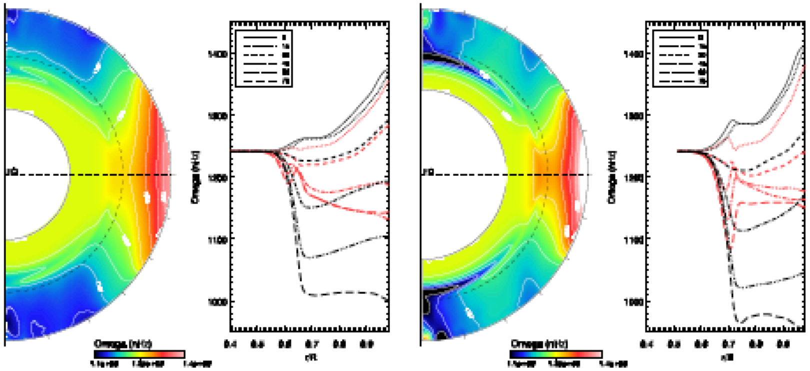


Nelson et al. 2013a

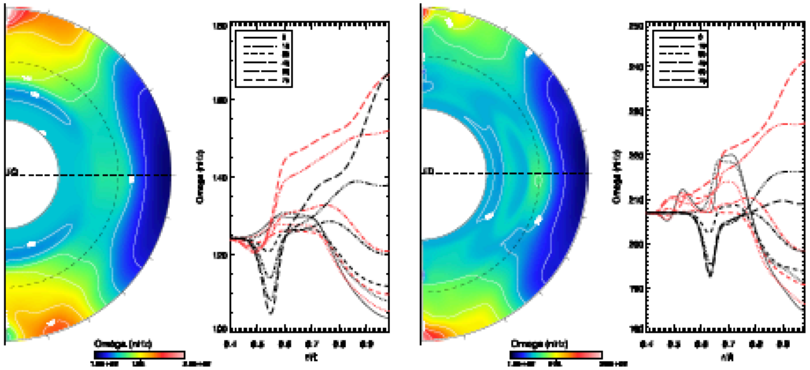
Lorentz force feedback on Differential Rotation



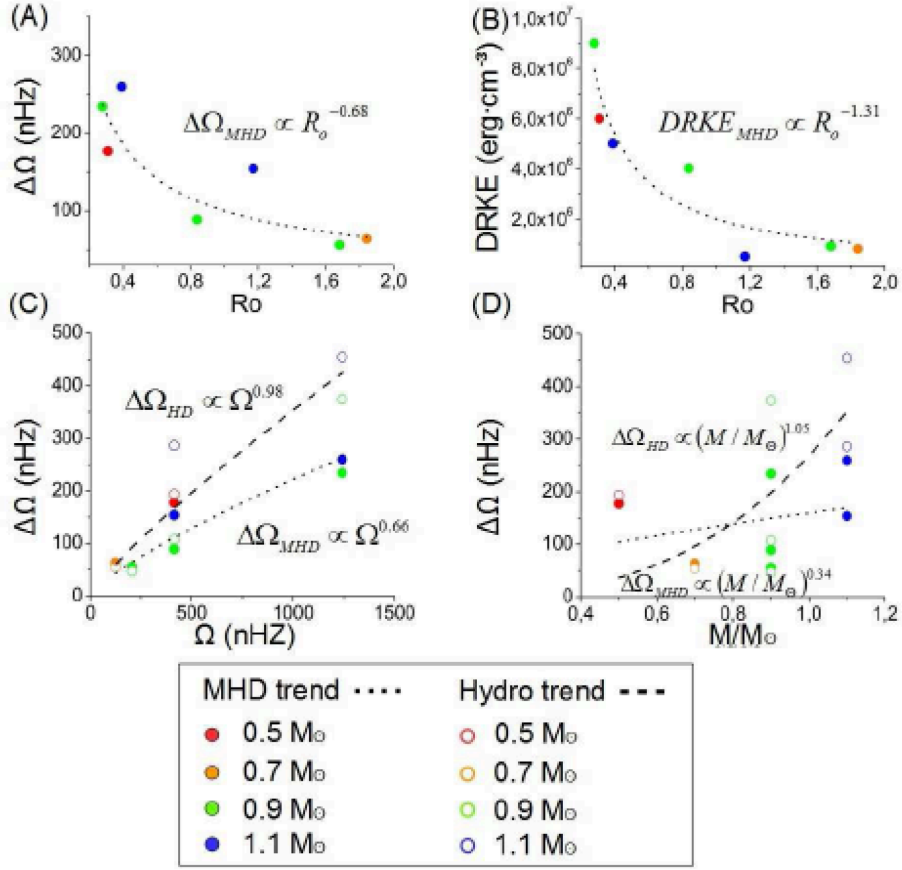
(a) $M05_{d1}$ (b) $M09_{d1}$



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

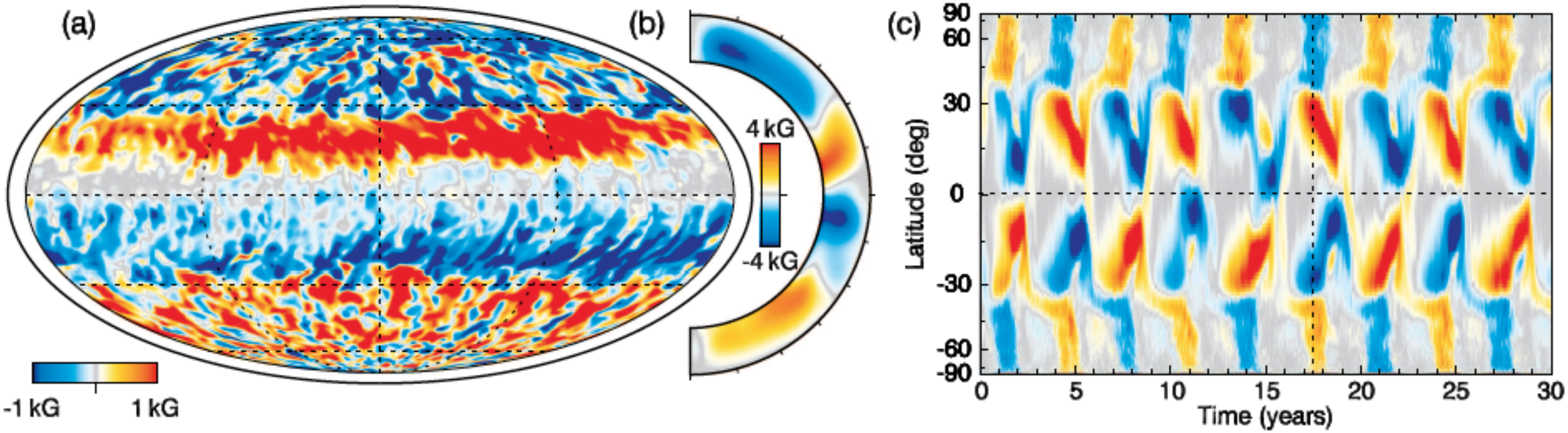


(e) $M07_s$ 22 (f) $M09_s$



Overall trend in better agreement with observations

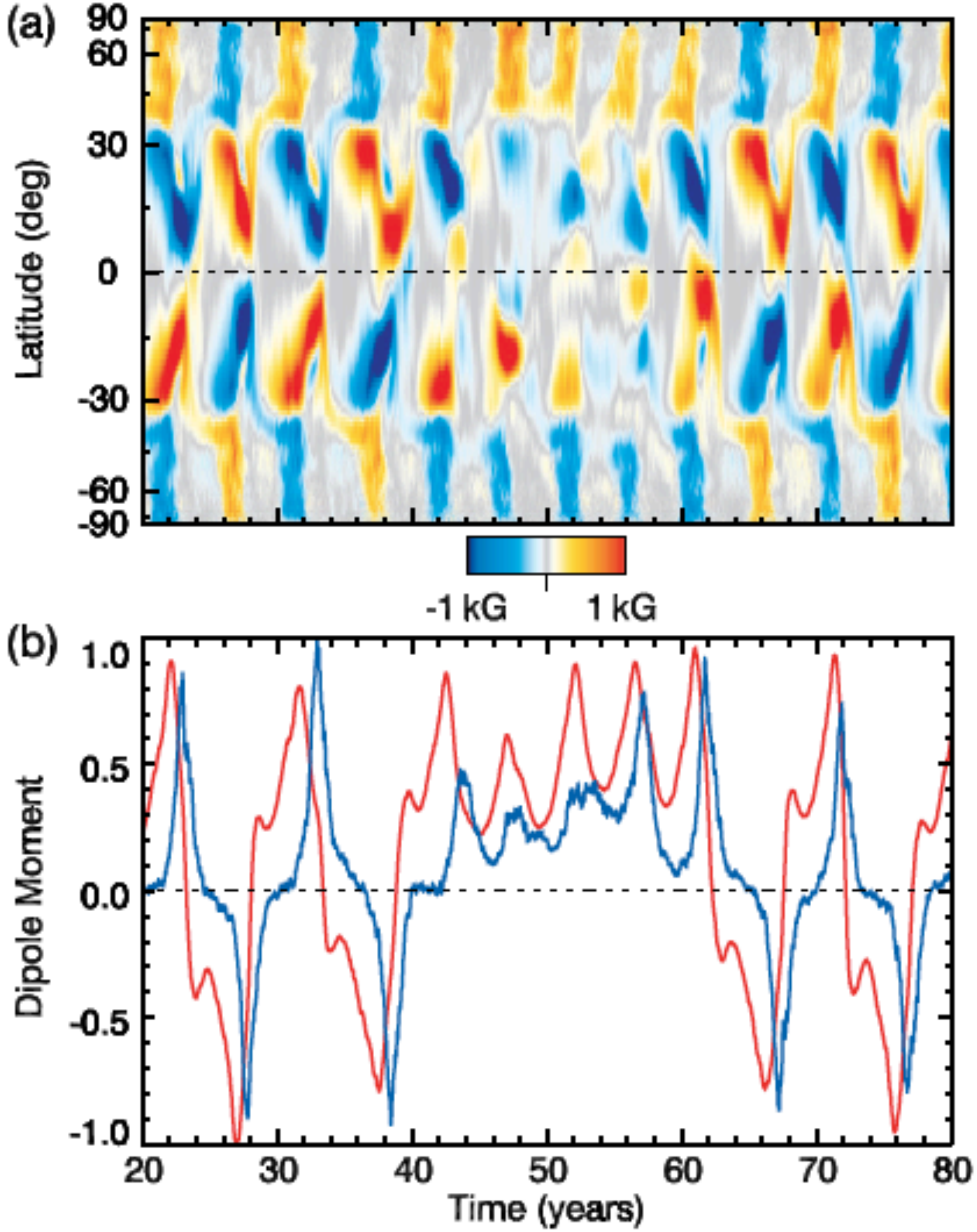
Latest solar-like case D3: getting cycle and equatorward branch



Reducing nu even further nu by using SLD scheme makes the simulation develop a more regular cyclic behavior

Augustson, Brun et al. 2015, ApJ

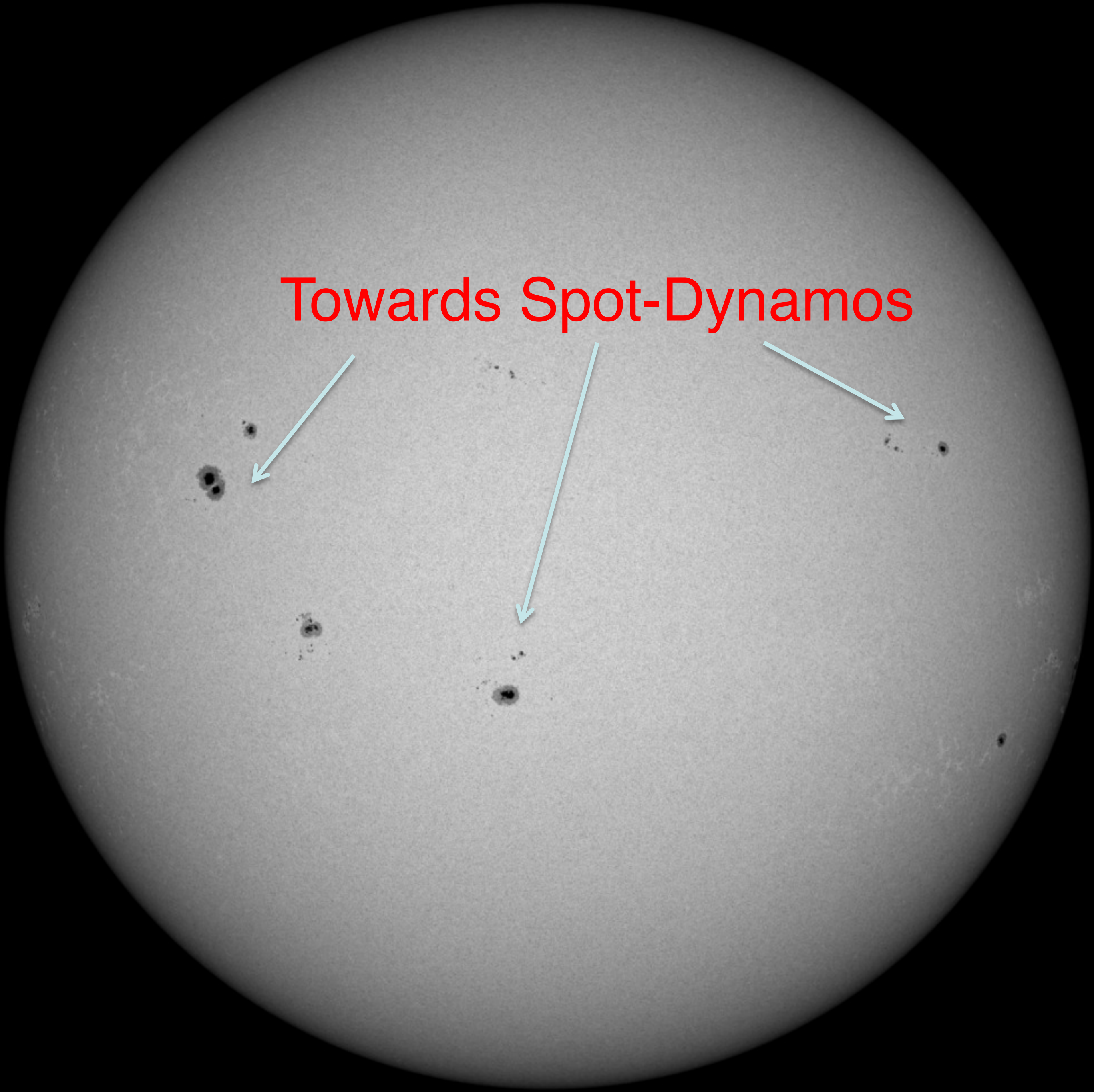
Latest solar-like case DS3:
Getting Maunder like minimun



Quadrupole dominates over Dipole during reversal and Grand minimum phase

Augustson, Brun et al. 2015, ApJ

Towards Spot-Dynamos

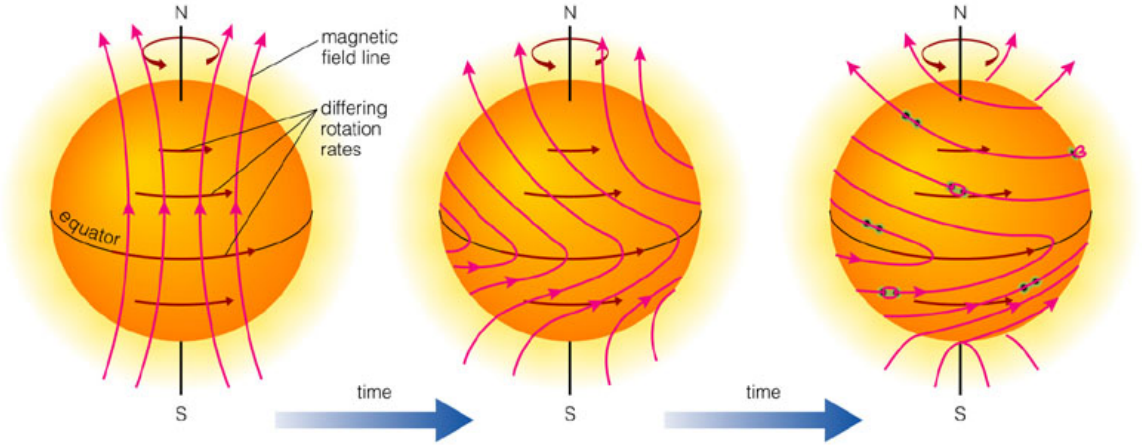


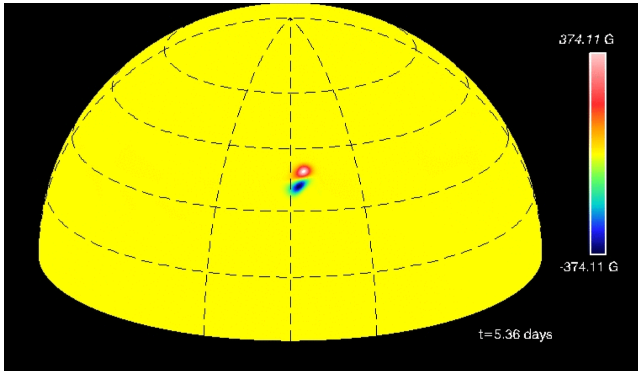
SDO/HMI Quick-Look Continuum: 2013.12.12_21:16:30_TAI

Transport et génération du champ toroidal Btor

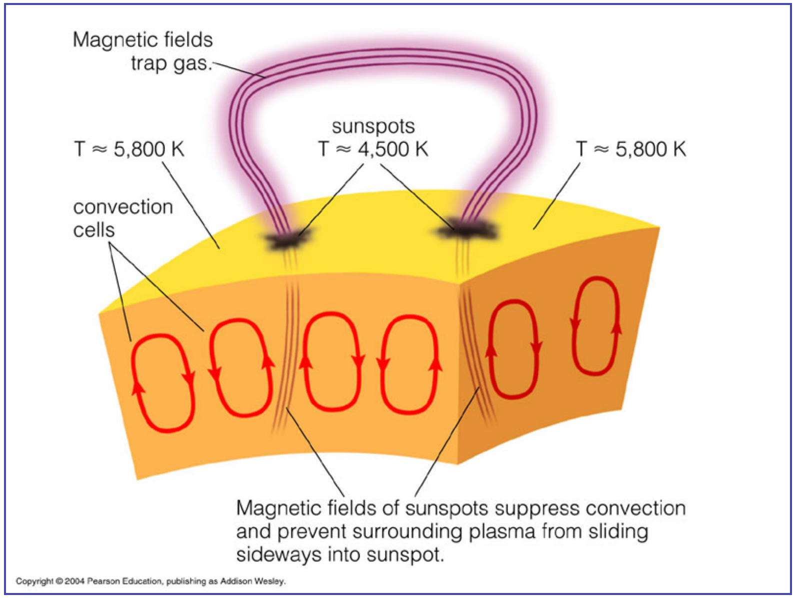
Jouve & Brun 2009, 2013

Effet Omega (Ω): enroulement des lignes de champ





Simulations CEA projet STARS2



Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.

Magnetic Wreath and Intermittency yielding flux emergence

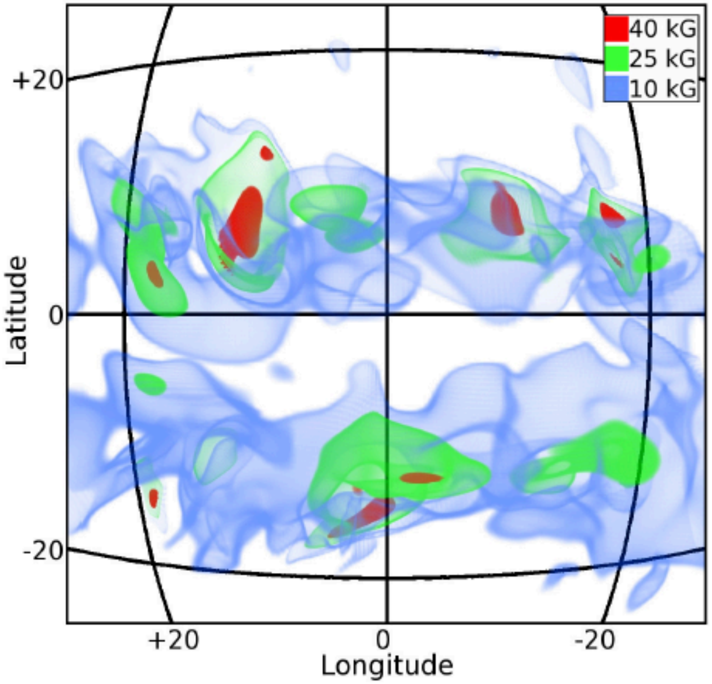


Figure 17. Three-dimensional volume renderings of isosurfaces of magnetic field amplitude in case S3. Blue surfaces have amplitudes of 10 kG, green surfaces represent 25 kG, and red surfaces indicate 40 kG fields. Grid lines indicate latitude and longitude at 0.72 $R_\odot$ as they would appear from 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).

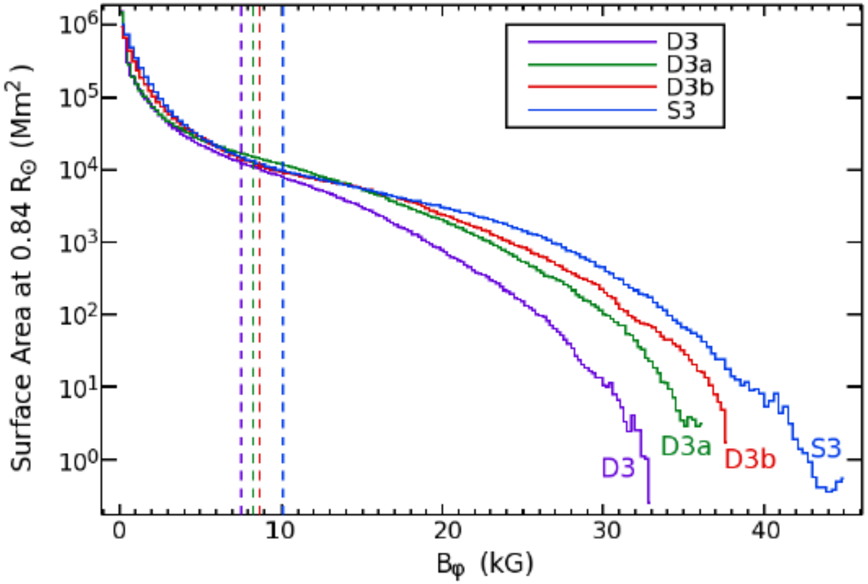
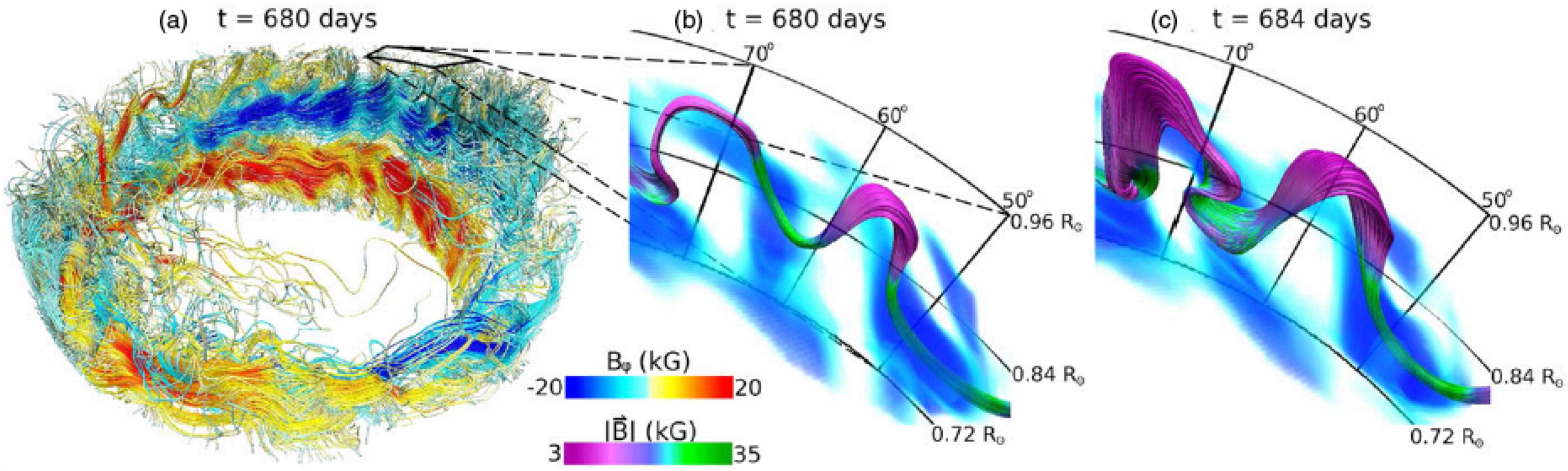


Figure 2. Probability distribution functions for unsigned B_ϕ at mid-convection zone for cases D3 (purple), D3a (green), D3b (red), and S3 (blue) showing the surface area covered by fields of a given magnitude. Distributions are averaged over about 300 days when fields are strong and as steady as possible. 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

Wreaths can generate Buoyant Loops



Nelson et al. 2011, 2013a, 2013b

Towards getting first “spot-dynamos”…

Conclusions

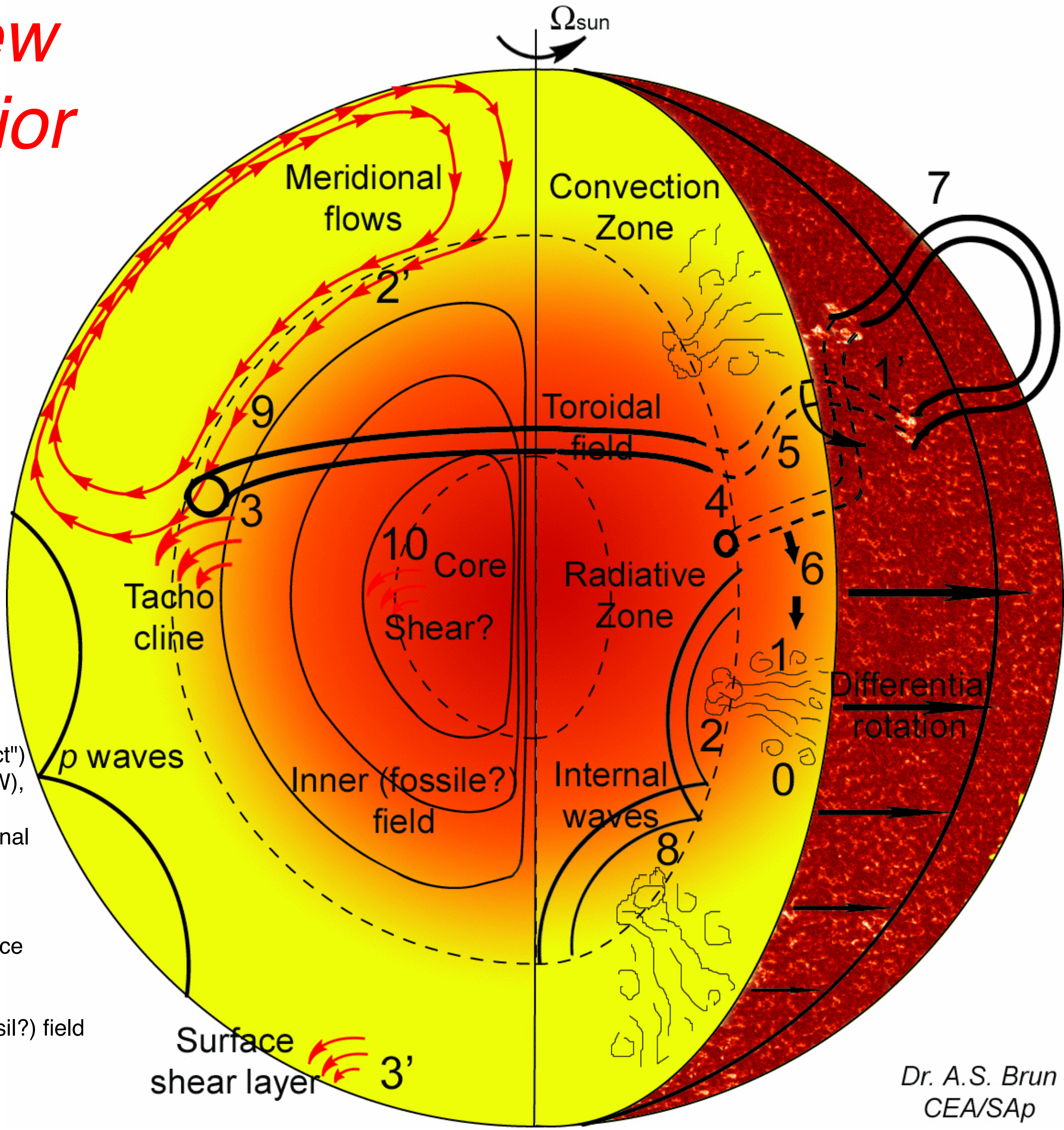
Convective velocities Vr roughly scales with cubic root of $L_*/(R_*^2\rho_{meanCZ})$ (star's luminosity devided by mean density in CZ)

$\Rightarrow$ 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

A Theoretical View of the Sun’s Interior Dynamics



Dr. A.S. Brun
CEA/SAp

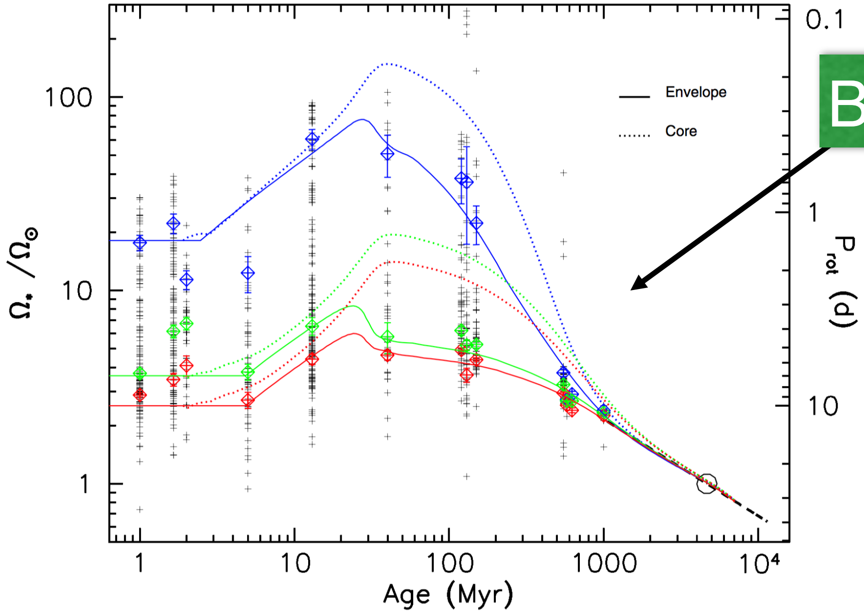
Figure Caption:
0: Turbulent convection (plumes)
1: Generation/self-induction of B field ("alpha-effect")
or 1': Tilt of active region, source of poloidal field
2: Turbulent pumping of B field in tachocline
or 2': Transport of B field by meridional flows in CZ into the tachocline
3: Field ordering in toroidal structures by large scale (radial and latitudinal) shear in tachocline ("omega-effect")
3': Surface shear layer, Solar sub surface weather (SSW), surface dynamics of sun spot?
4: Toroidal field becomes unstable to m=1 or 2 longitudinal instability (Parker's)
5: Rise (lift) + rotation (tilt) of twisted toroidal structures
6: Recycling of weak field in CZ
or 7: Emergence of bipolar structures at the Sun's surface
8: Internal waves propagating in RZ and possibly extracting angular momentum
9: Interaction between dynamo induced field, inner (fossil?) field in the tachocline (with shear, turbulence, waves, etc...)
10: Instability of inner field (stable configuration?) + shearing via “omega-effect” at nuclear core edge?
Is there a dynamo loop realized in RZ?

Stellar Wind and Complex Toplogies

Wind, Stellar evolution and gyrochronology

Stellar Spin down Models

(Gallet & Bouvier 2013)



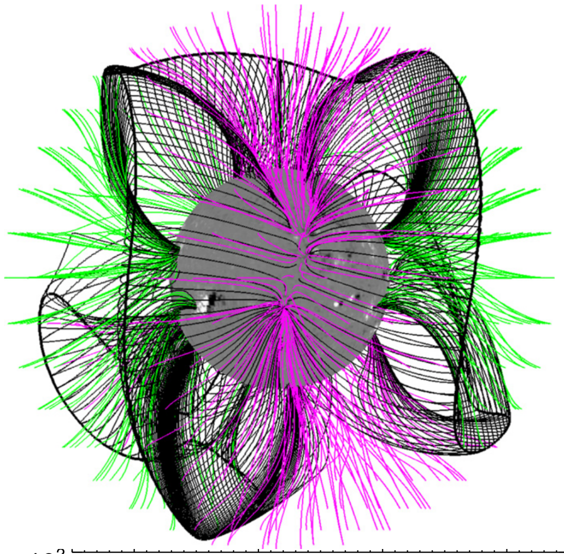
Braking models

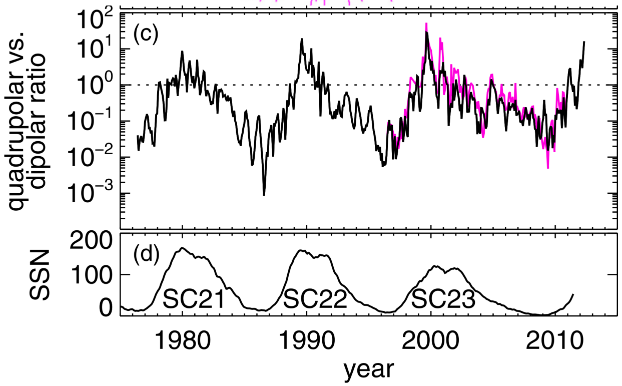
dynamo

wind

Magnetic Activity

(De Rosa et al. 2012)





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

MHD Wind Simulations

Why are they necessary ?

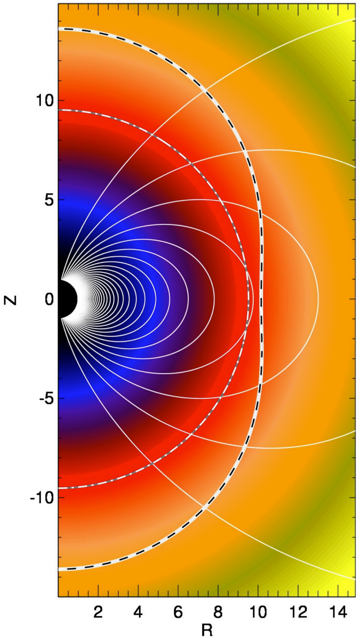
- Magnetic fields > split monopole
- Rotation
- 3D, non-axisymmetry

Parametric study of the torque as a function of:

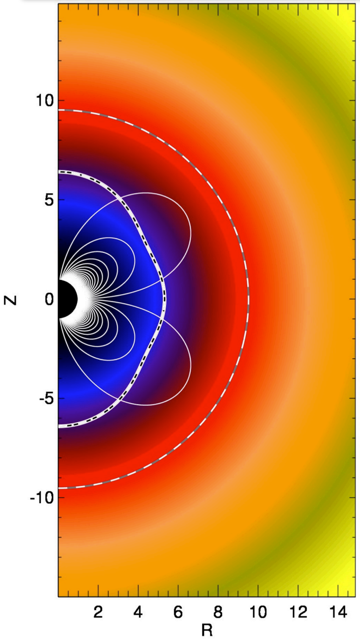
Rotation
Magnetic field strength
Magnetic field topology

Coronal temperature and gamma held fixed.

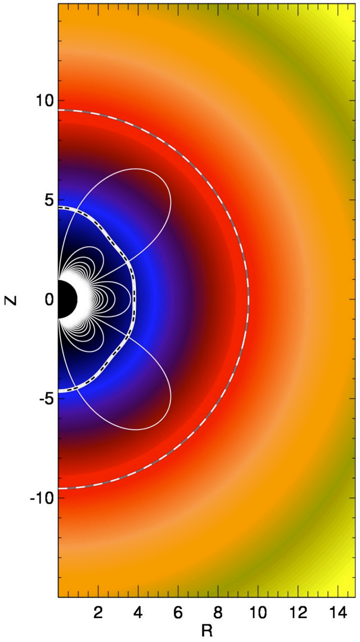
Decreasing Alfvén surface !



Dipole



Quadrupole

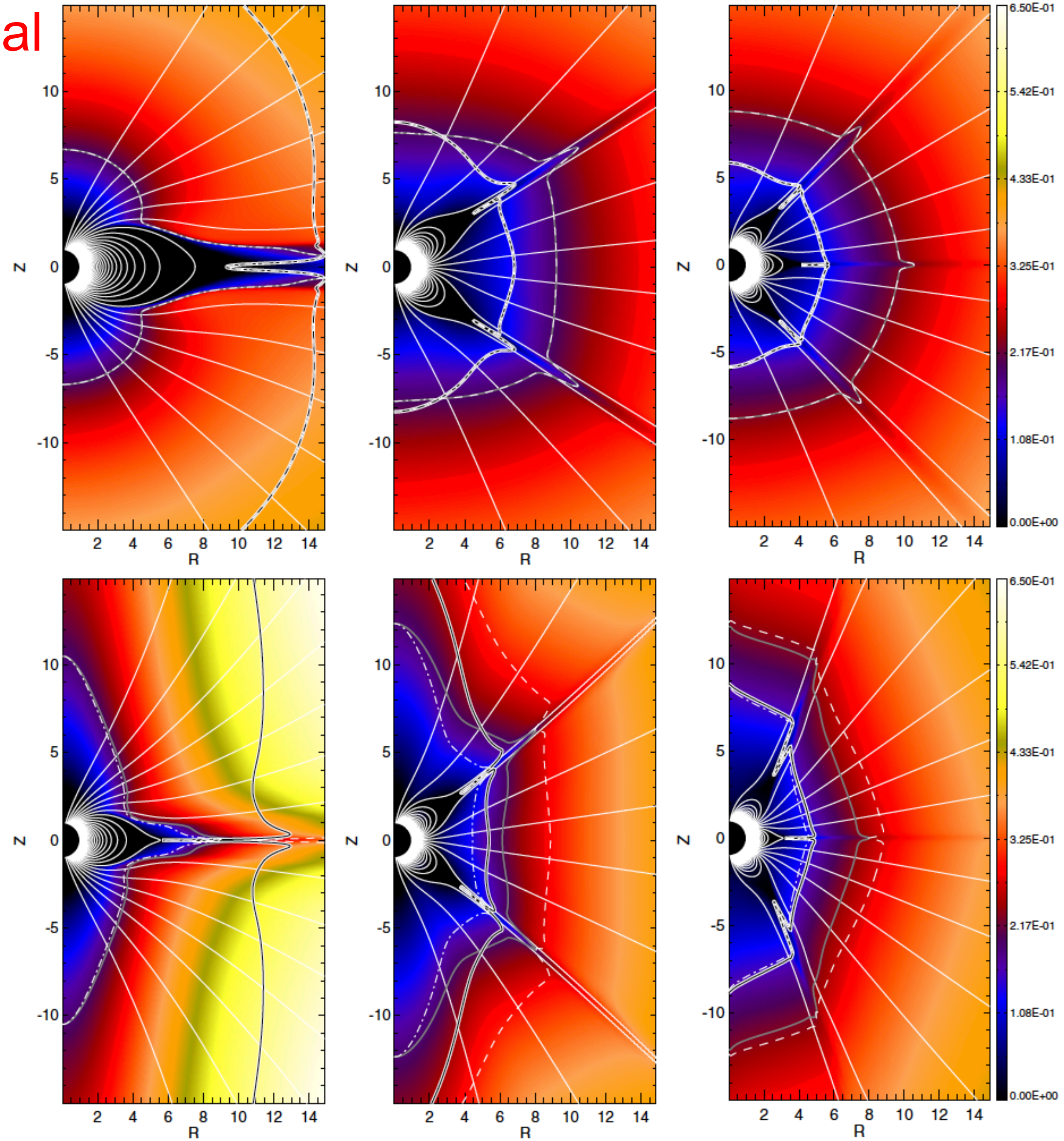


Octupole

60 cases with compressible MHD code PLUTO

(Réville et al. 2015, ApJ)

Magneto-Centrifugal Effect



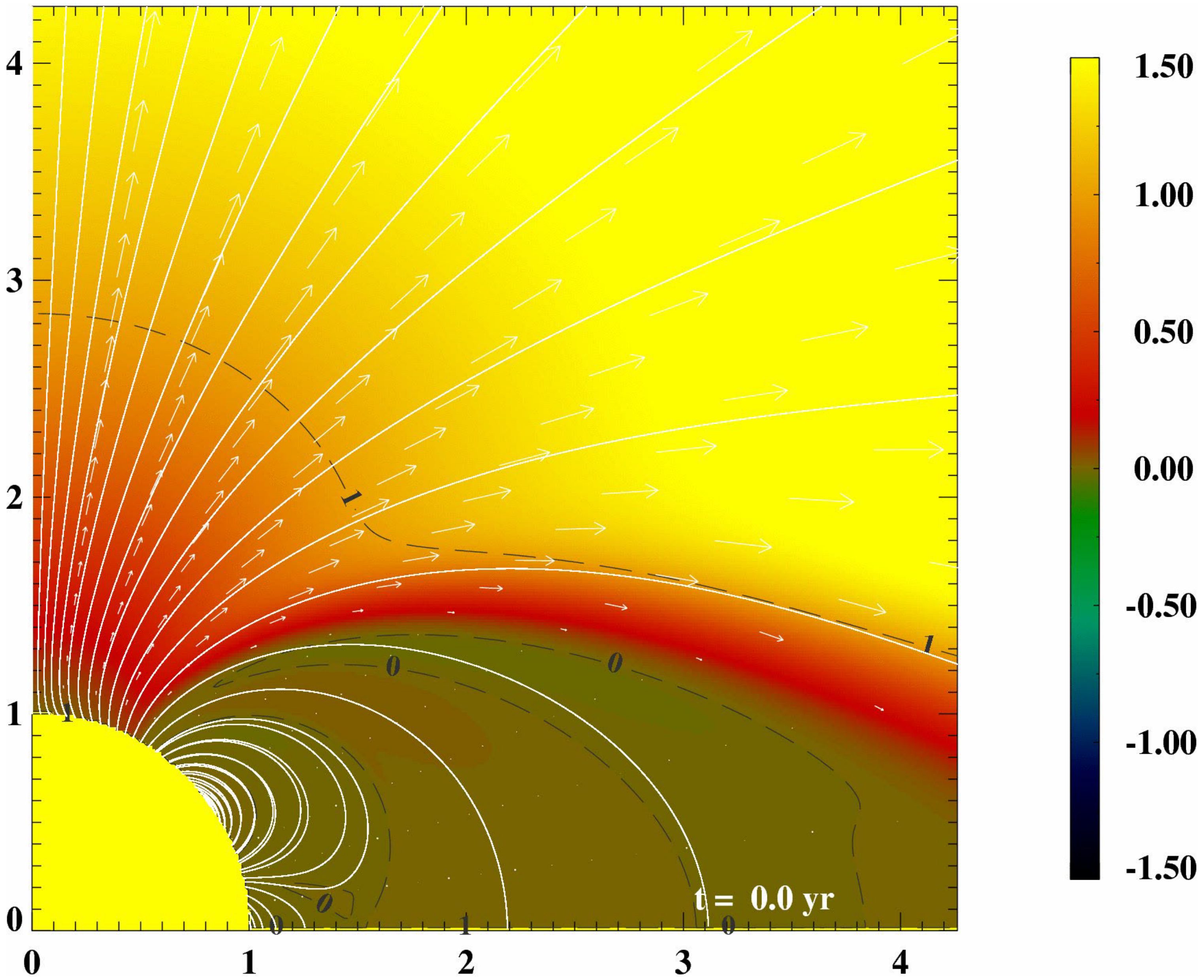
Slow rotation

Fast rotation

Reville et al. 2015a

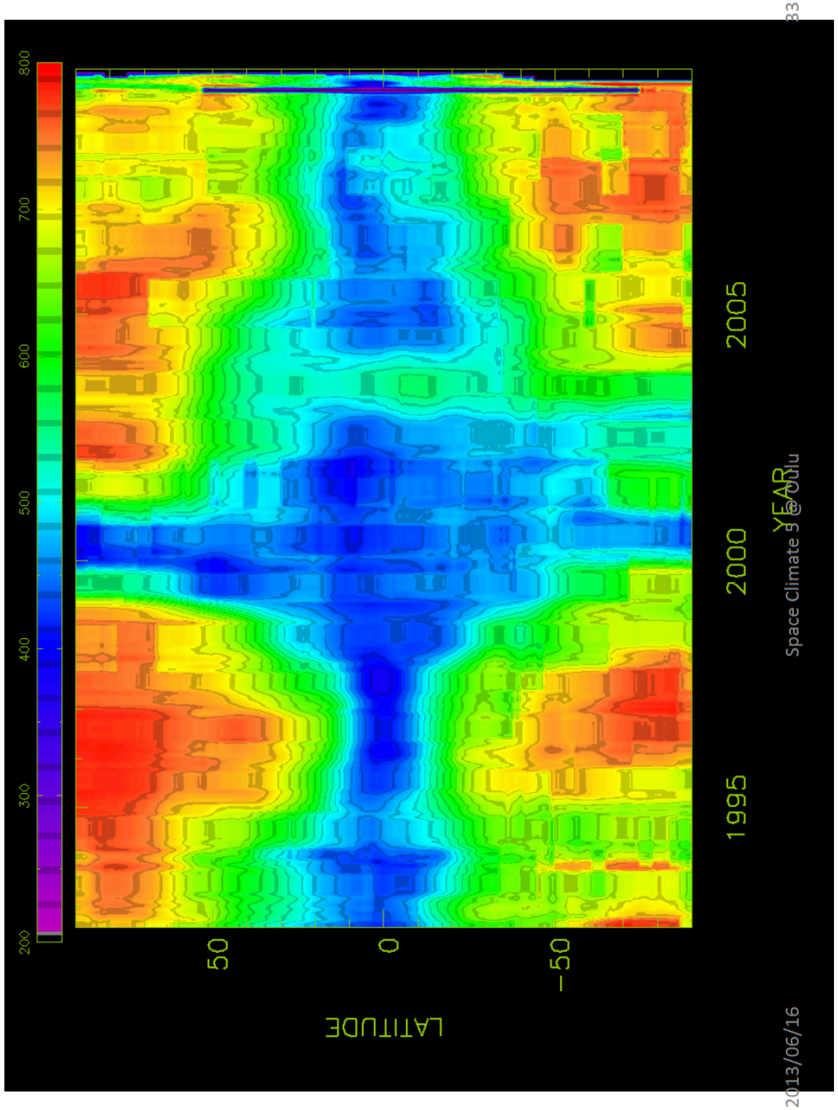
Coupling Solar Dynamo to Solar Wind

Pinto, Brun et al. 2011, ApJ



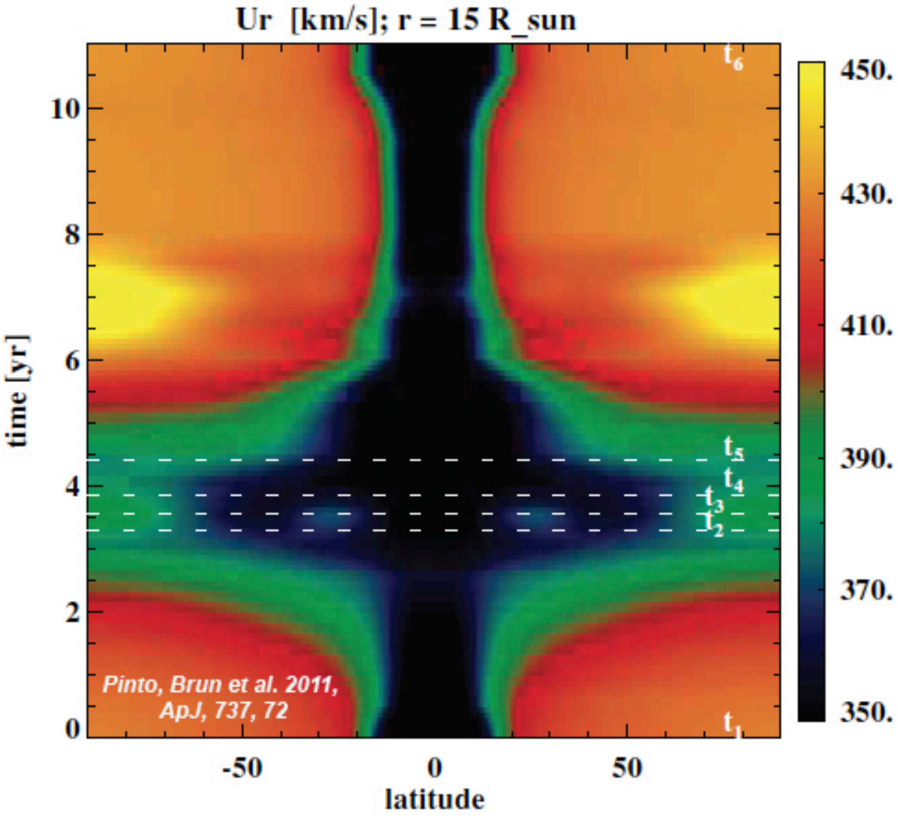
11-yr Cycle Variations of Solar Wind

Solar Wind Speed



Observations

Tokumaru et al.

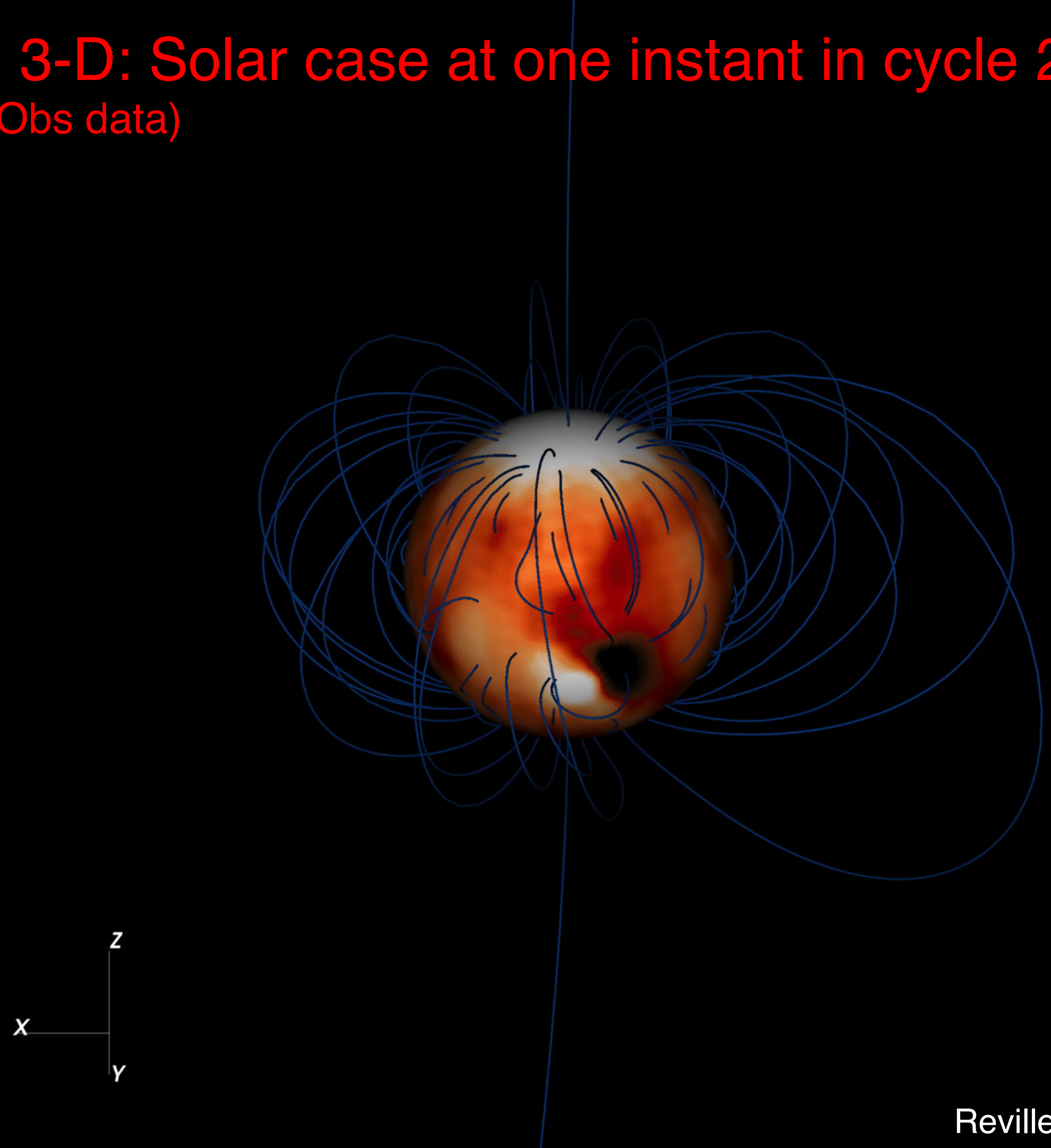


Dynamo-wind model

Pinto, Brun et al. 2011

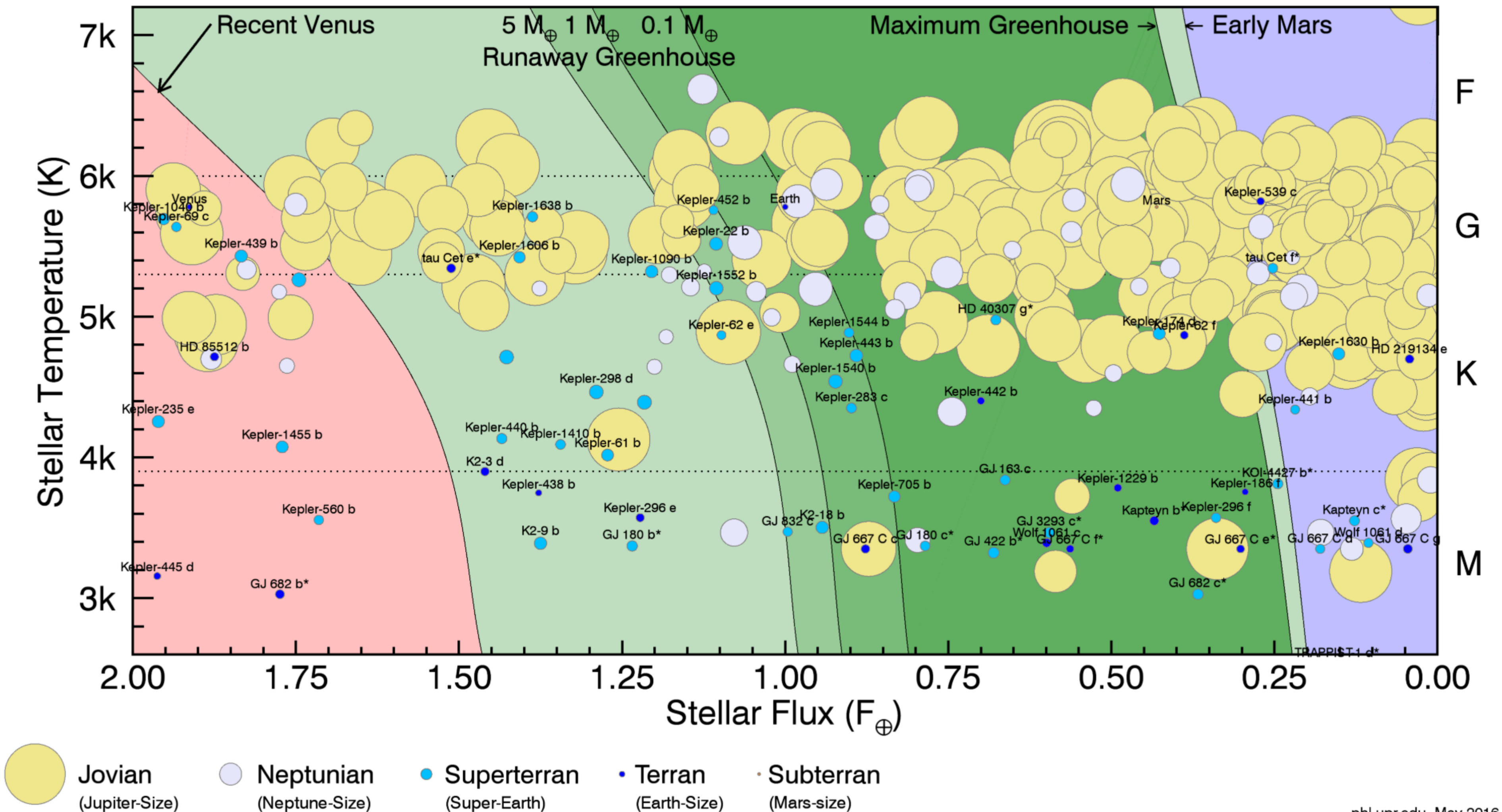
Going 3-D: Solar case at one instant in cycle 22

(Wilcox Obs data)



Reville, Brun et al. 2016

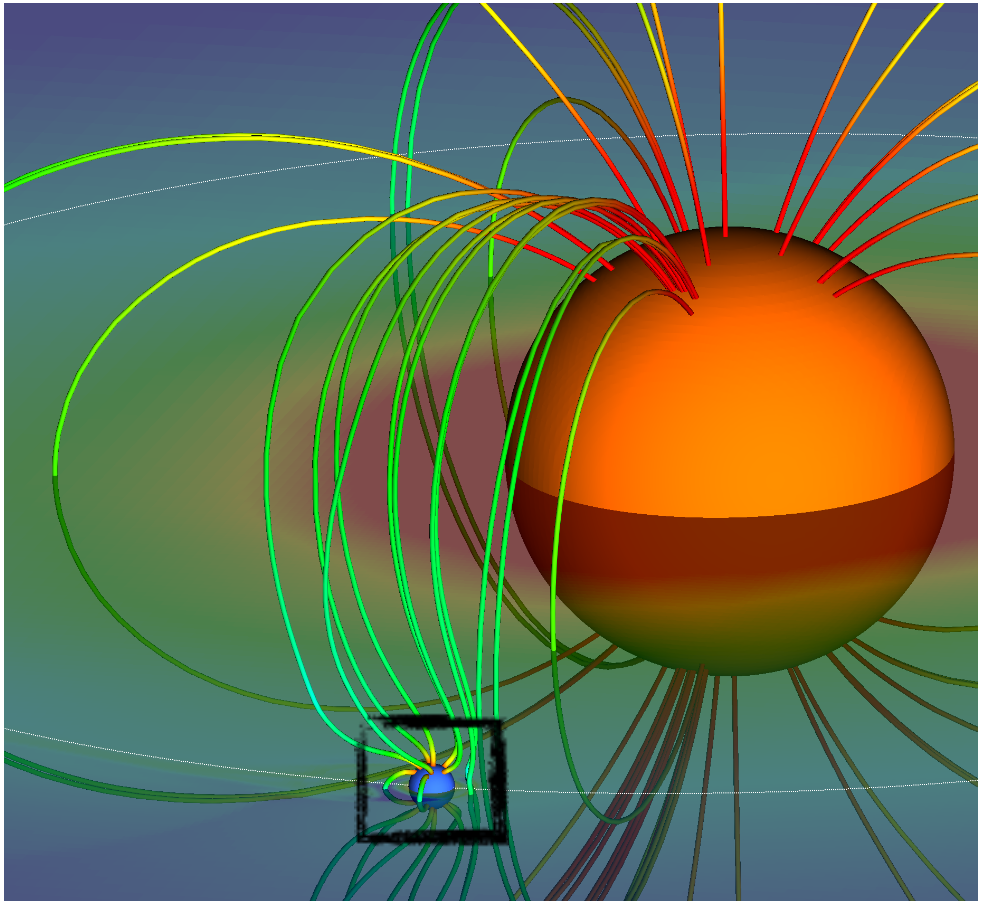
Exo - Planetary Systems

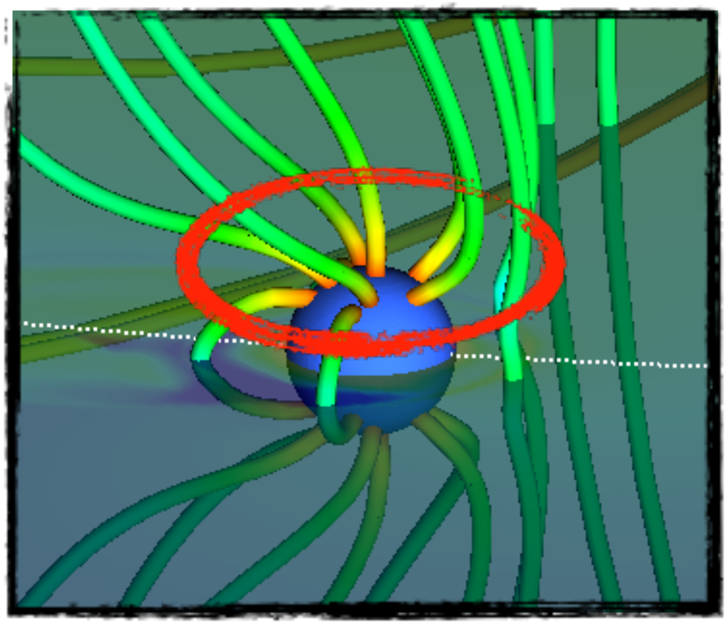


phl.upr.edu, May 2016

http://phl.upr.edu/projects/habitable-exoplanets-catalog/media/pte

Origin of the planet migration: a 3D picture



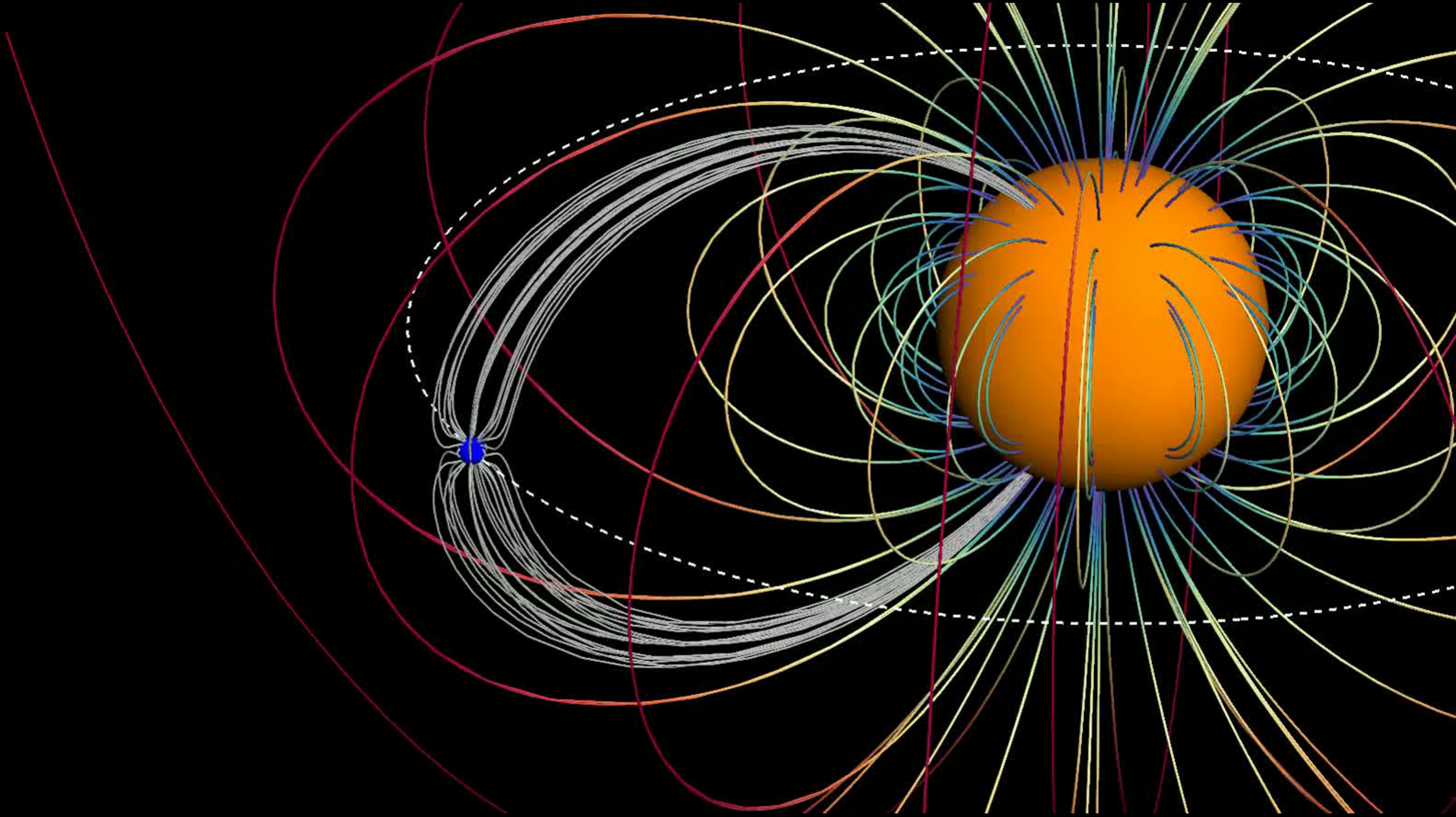


Integrate the flux of angular momentum on concentric spheres around the planet

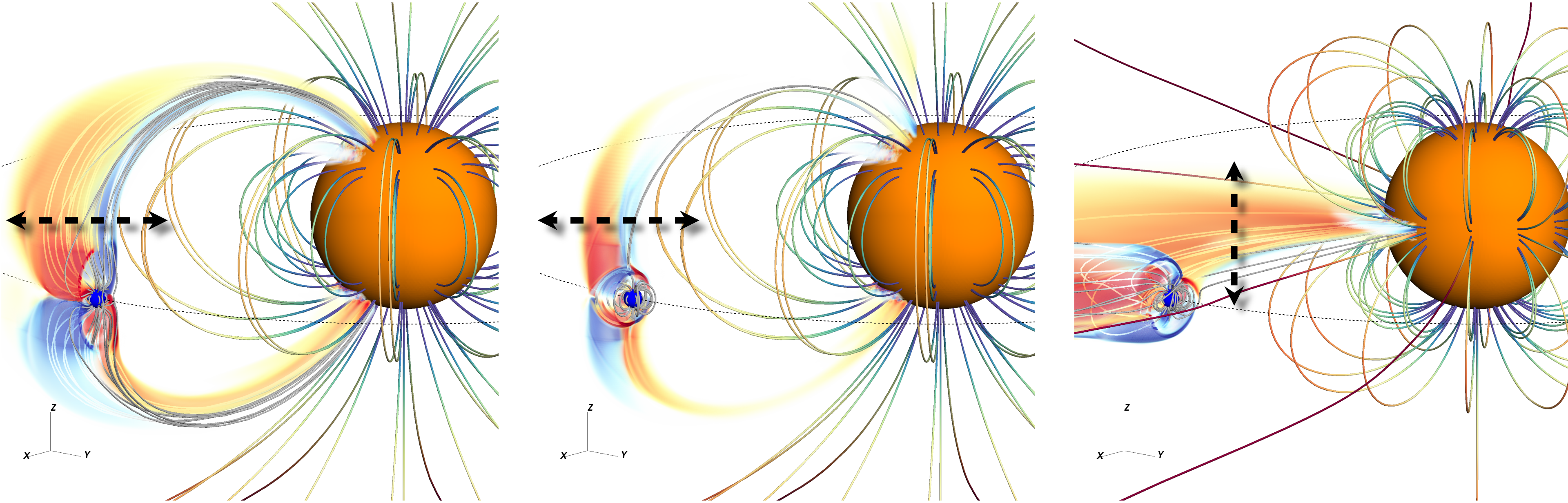
The magnetic torque originates mainly from the connection of the planet's field to the ambient magnetic field

[Strugarek+ 2015, ApJ]

Star-Planet Interaction and Alfvén wings



3D modelling of star-planet interactions



Two strong Alfvén wings

Two weak Alfvén wings

One strong Alfvén wing

Alfvén wings foot point localized at specific latitude and longitude

Alfvén wing foot point
localized at the equator over
a large longitudinal range

[Strugarek+ 2015, ApJ]

Parametrizing the migration torque

$$T_P = c_d \overbrace{r_o A_{eff} P_t}^{\text{Angular momentum convected on the \textbf{\textit{obstacle}}}}$$

Torque on planet

Drag coefficient ~ $(1+M_A^2)^{-1/2}$

Orbital radius

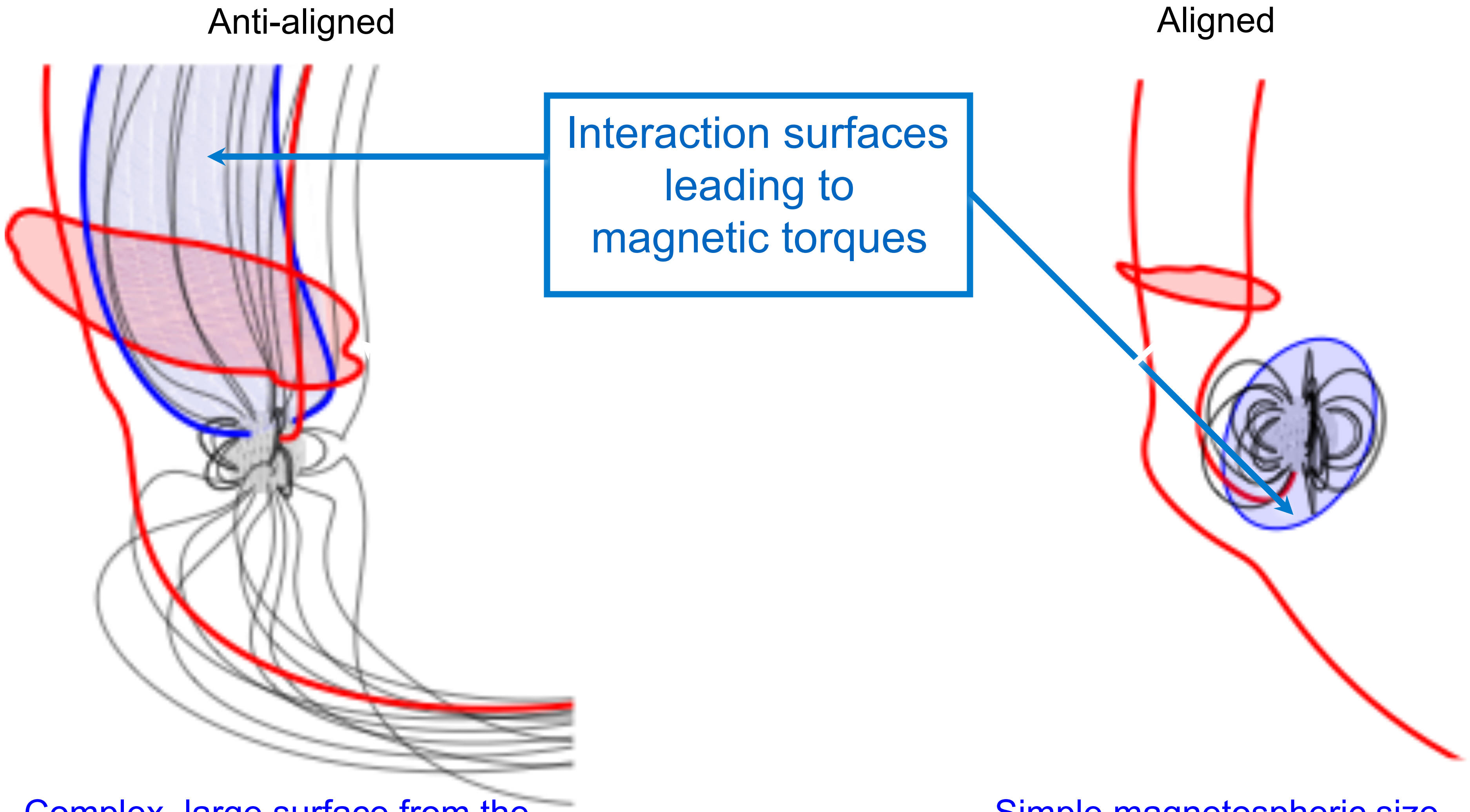
Effective area of the obstacle

Wind total pressure (ram+thermal+magnetic)

see also [Zarka 07; Lovelace+ 08; Vidotto+ 10]

[Strugarek+ 2015, ApJ]

Two configurations of the magnetic interaction



Anti-aligned

Aligned

Interaction surfaces leading to magnetic torques

Complex, large surface from the whole Alfvén wing

Simple magnetospheric size estimate from pressure balance

Conclusion

Close-in planets are expected to interact **magnetically** with their host in a large variety of ways

The knowledge of the **location** of the **stellar wind’s Alfvén surface** is **mandatory** to estimate the effect of magnetic interactions

☛ **Rotation**, **magnetic field, mass loss rate and T** of the host star

The magnetic interactions **strongly** depend on the **topology** of the **stellar** and **planetary** magnetic field

A close-in planet can *a priori* migrate **due to star-planet magnetic interactions**

[Strugarek+ 14]