Differential Rotation and Dynamo Action in Solar-like Stars

J. Varela and S. Brun

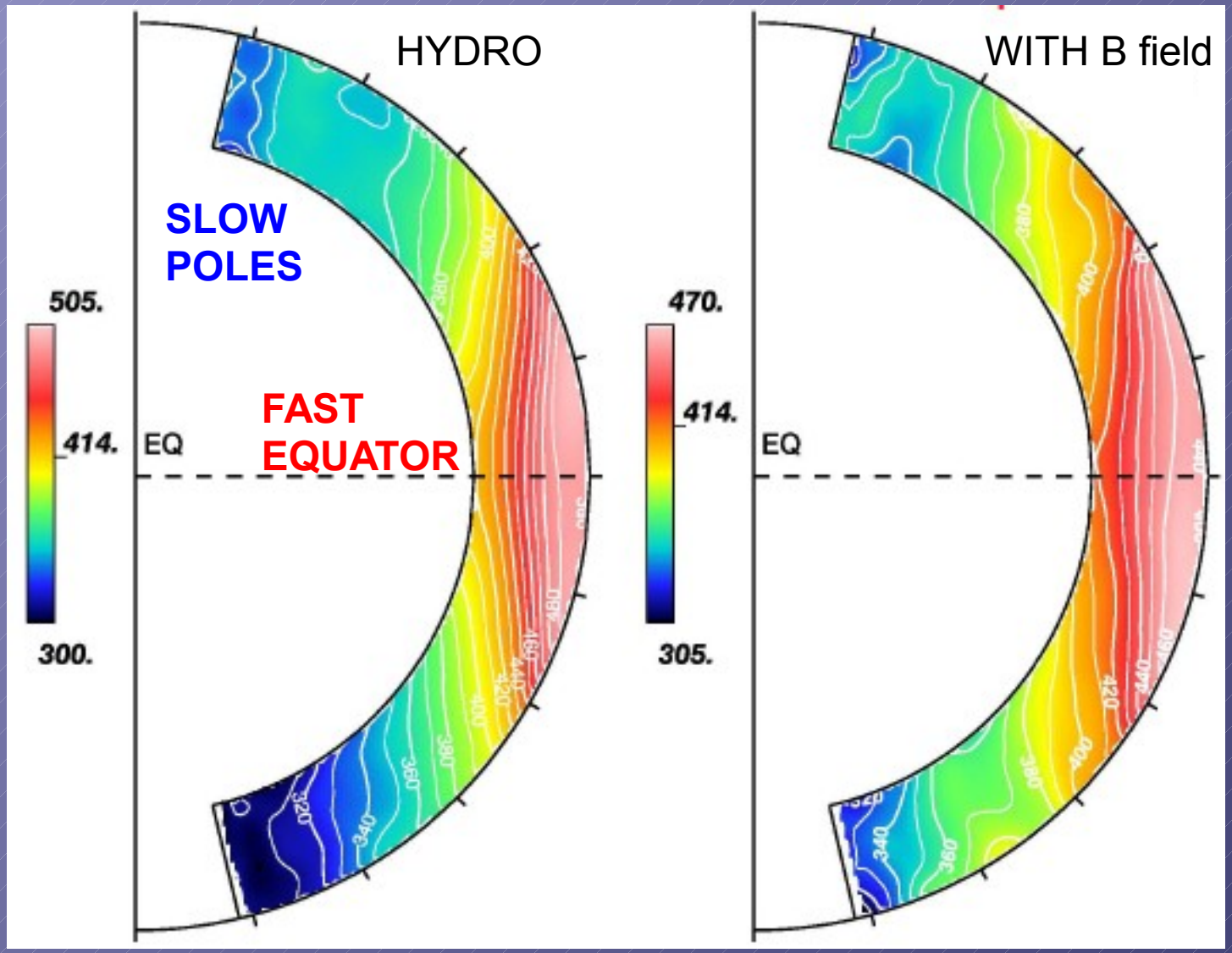
Laboratoire Dynamique des Etoiles et de leur Environnement

DE LA RECHERCHE À L'INDUSTRIE

université PARIS-SACLAY

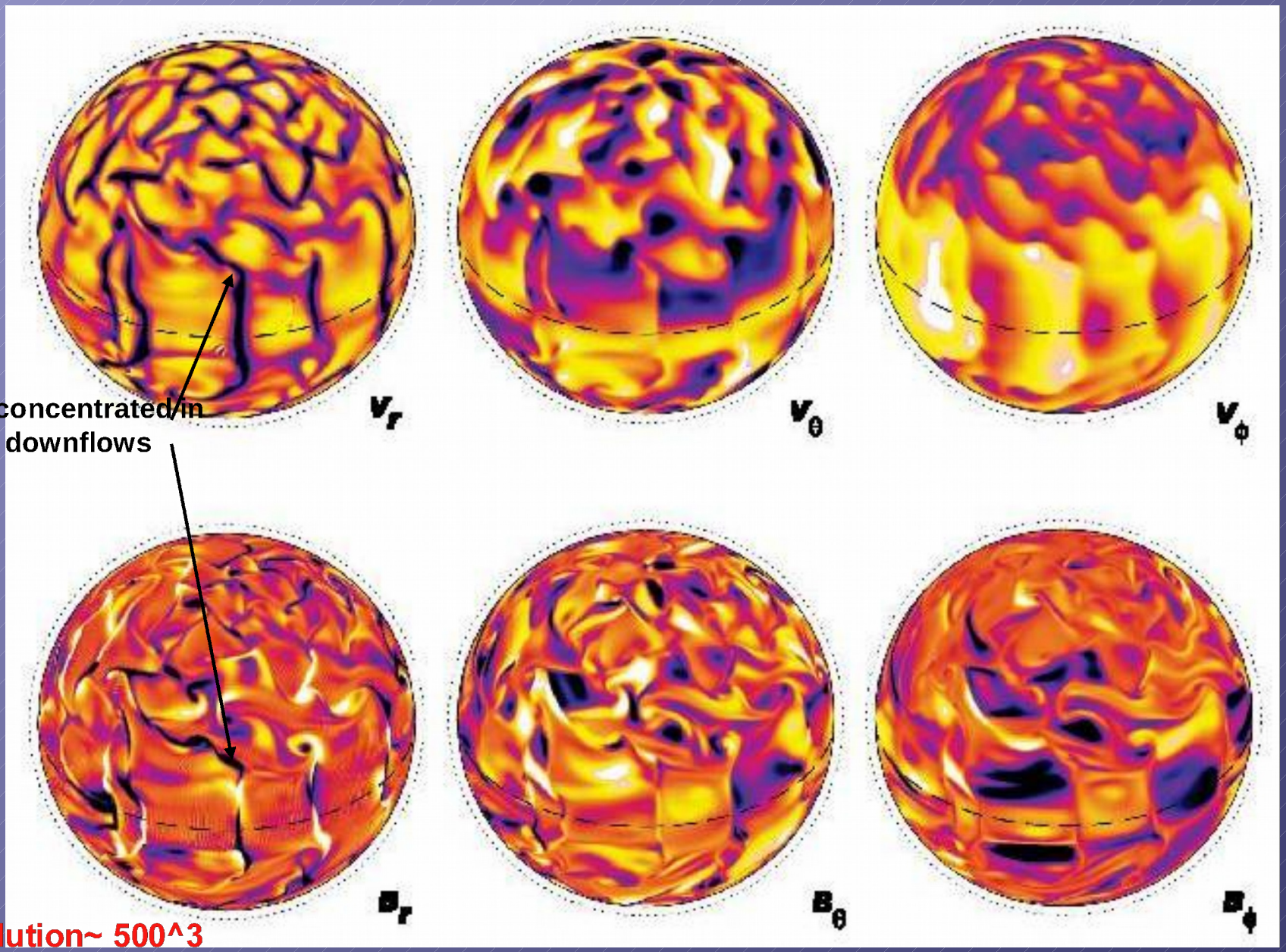
INDEX

Introduction: differential rotation ($\Delta\Omega$)



- The star rotation leads to the stretching of the poloidal magnetic field and the generation of the toroidal magnetic field (Ω effect).
- Strong feedback between the Lorentz force and the star differential rotation.

Introduction: Magnetic convection (Vr)



Br concentrated in the downflows

Resolution~ 500^3

Re=VrmsD/n~150,P=0.25, Pm=4 MAGNETIC CASE M3 (Brun, Miesch, Toomre 2004, ApJ, 614)

- Driver of the poloidal B field (α effect) and the toroidal B field too in α^2 dynamos

Solar-like stars (late F, G and early K type)

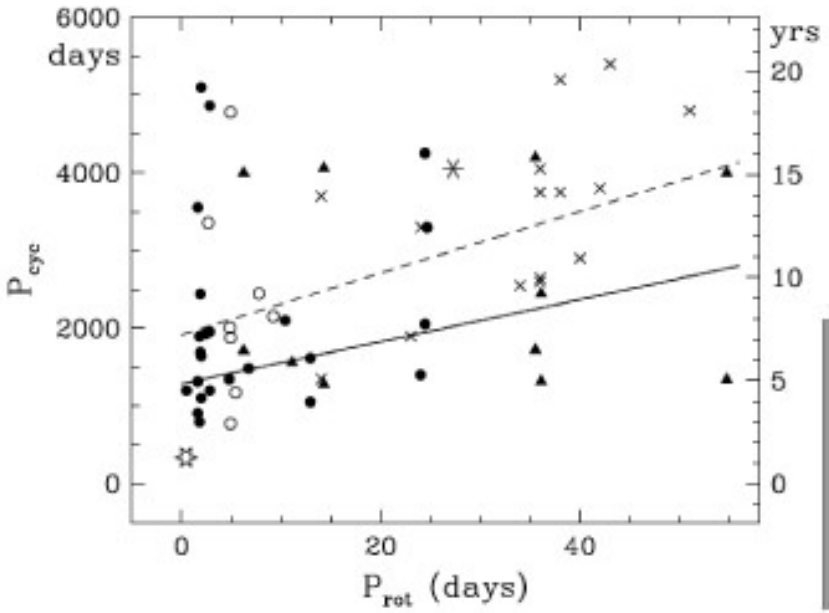


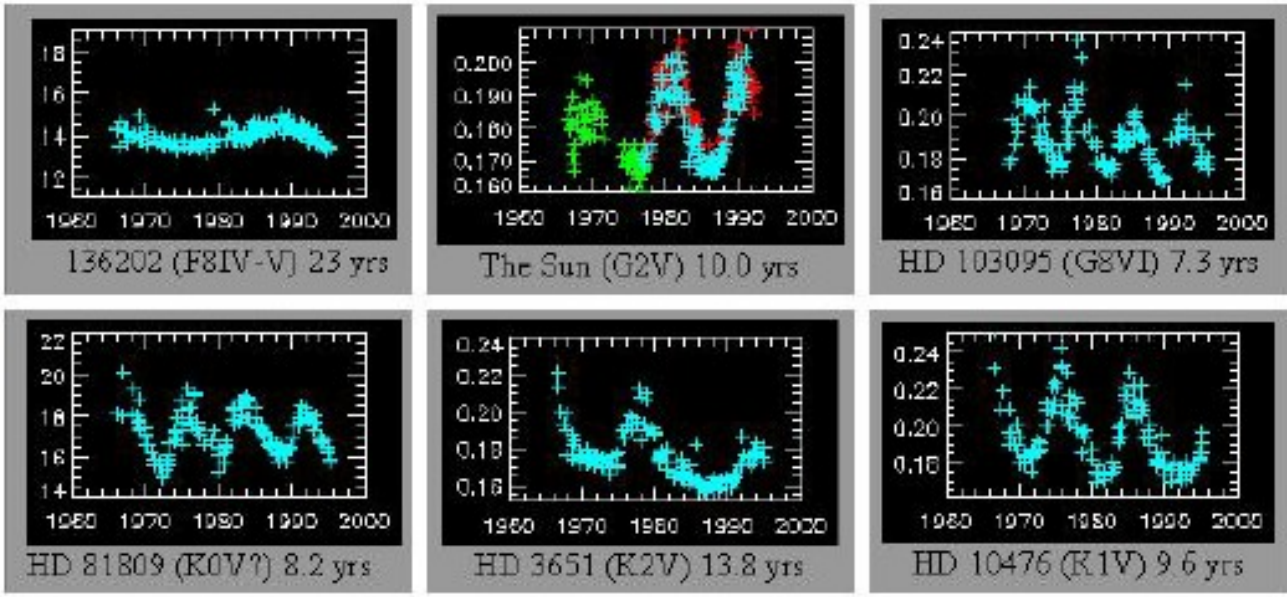
Fig. 6. The rotational period-cycle period diagram, with symbols as Fig. 5. The dashed line is the fit to all results including the ones from t literature, and the solid line is the relation for the shortest cycle lengt determined by us.

Olah et al. 2009

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

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

$$R_o \approx \frac{U}{L\Omega}$$



- Ro is the ratio of the inertial to Coriolis forces.

Ro << 1 → Coriolis dominate
Ro >> 1 → Inertial and centrifugal forces dominate

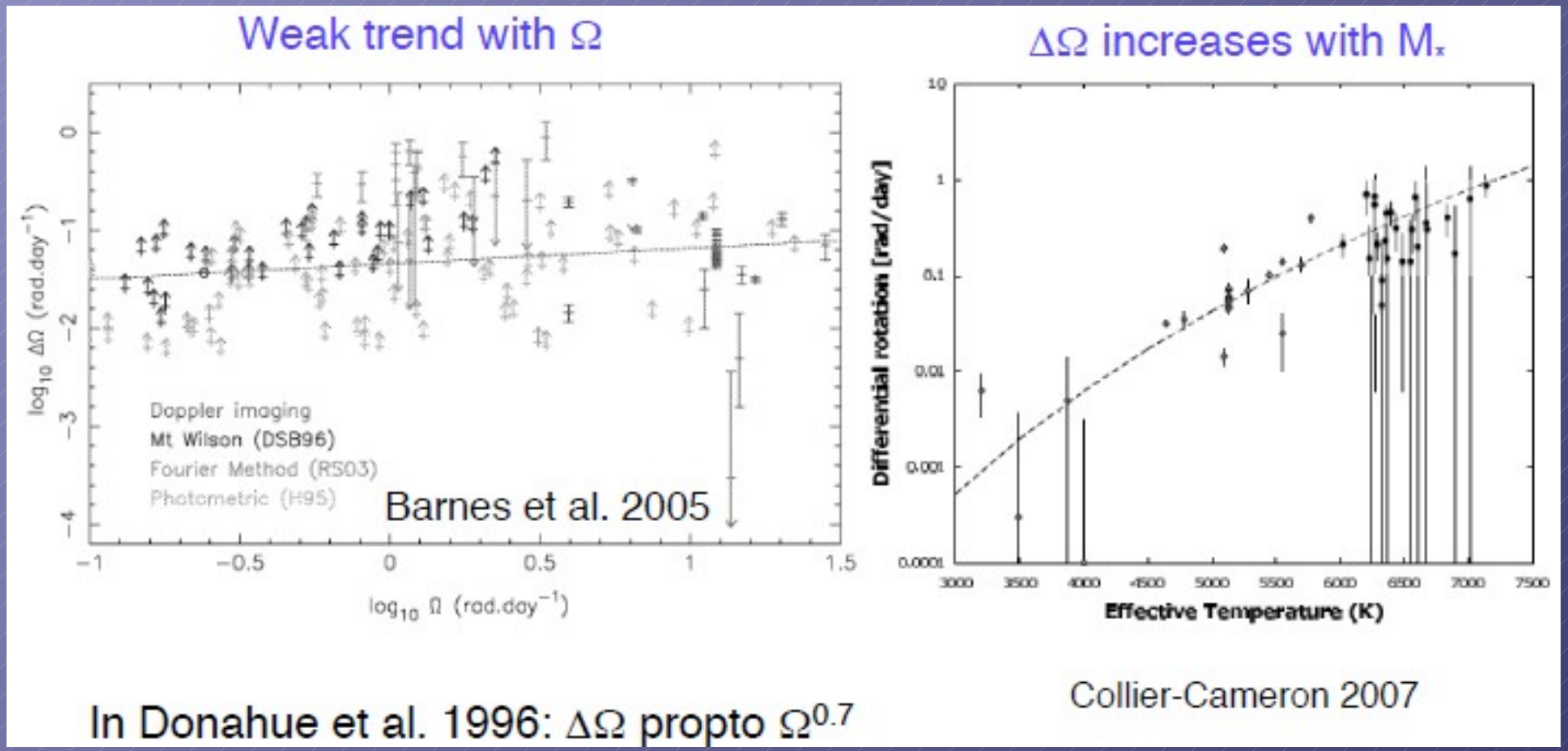
Call H & K lines , $\langle R'_{HK}\rangle$

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

=> Much more coming in Asteroseismology Era

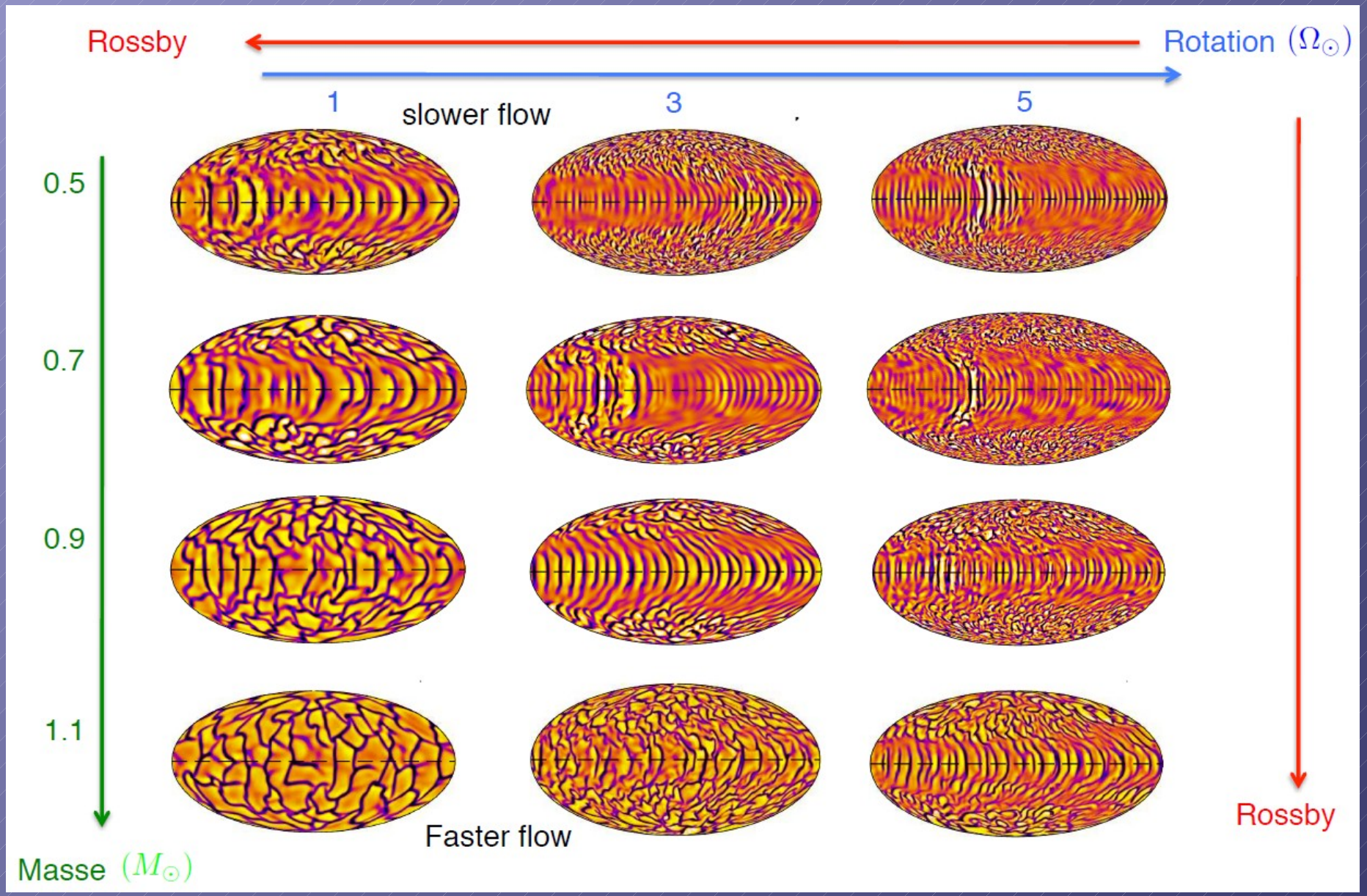
see also Noyes et al. 1984, Wilson 1978, Baliunas et al. 1995

Trends between the $\Delta\Omega$ and the star rotation and the Mass



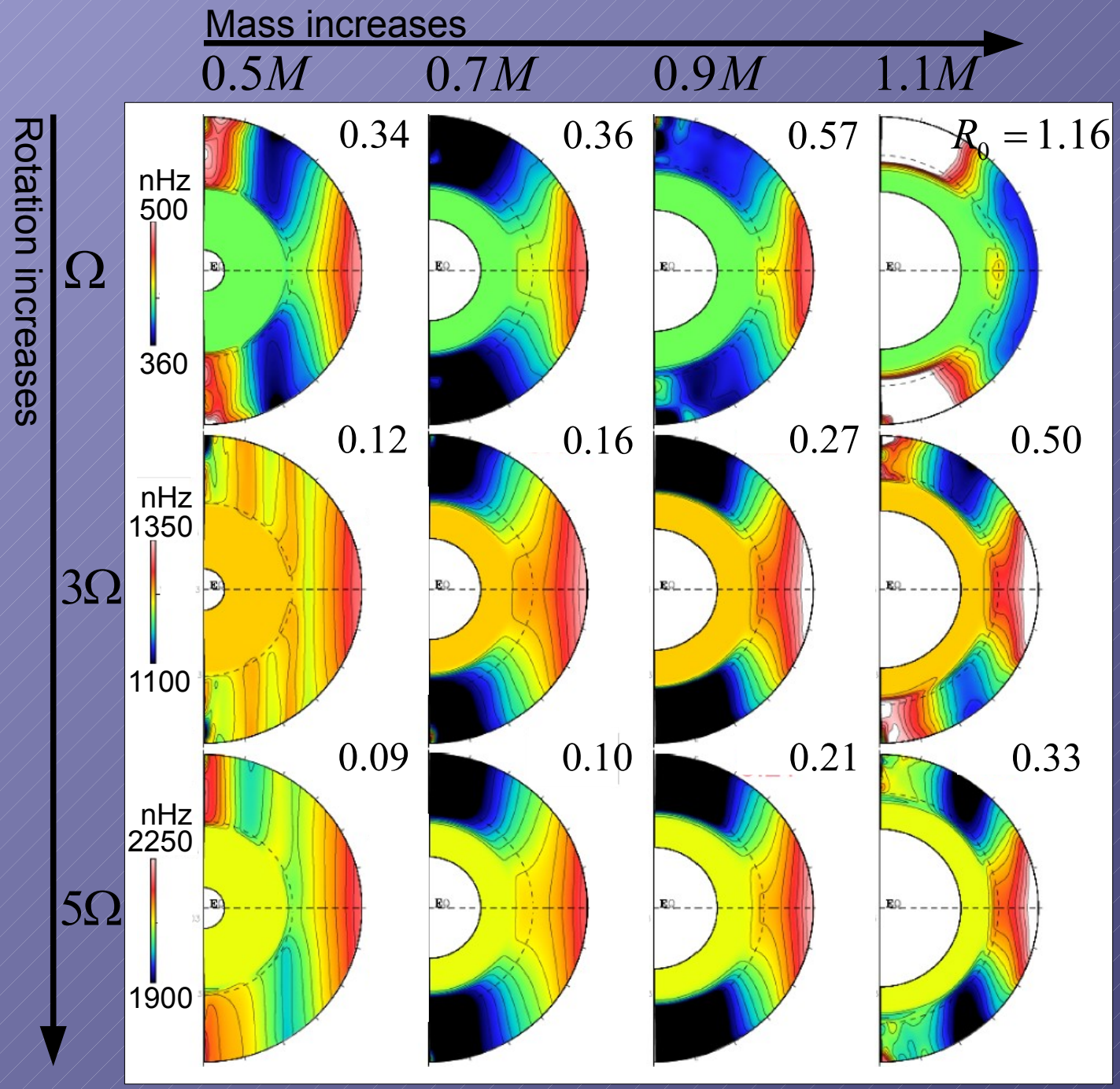
- Confirmation of the observational scaling

Introduction: Effect of rotation in the convection



- The size of the convective cells increases with the Rossby number: $R_0 = \dfrac{\omega}{2\Omega}$
- Impact in the convective dynamo of the starts.

Introduction: Differential rotation in G&K stars



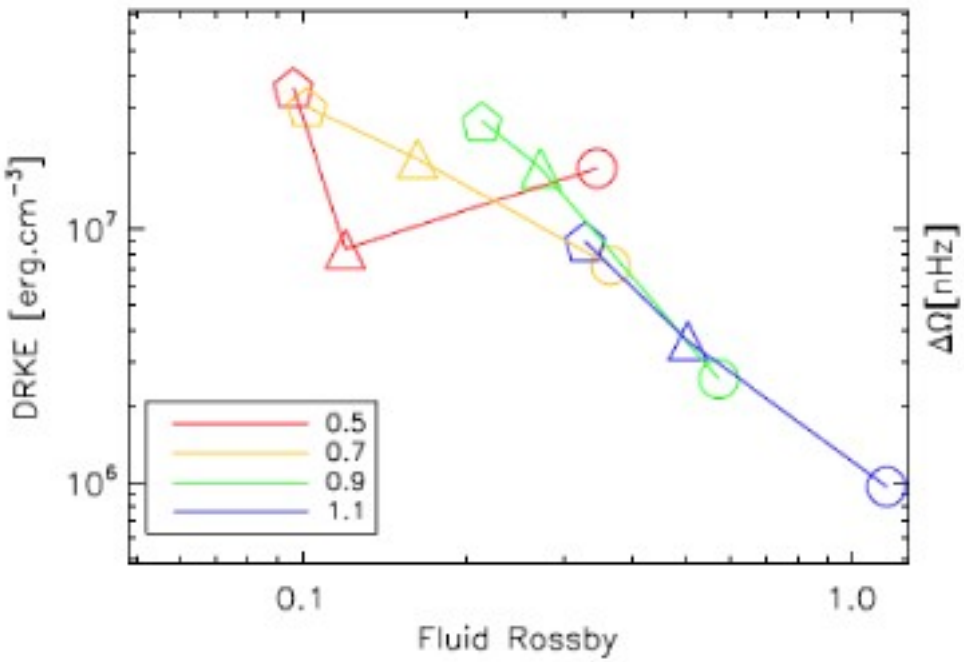
- Very different ΔΩ for the rage of Ω and M (Ro)

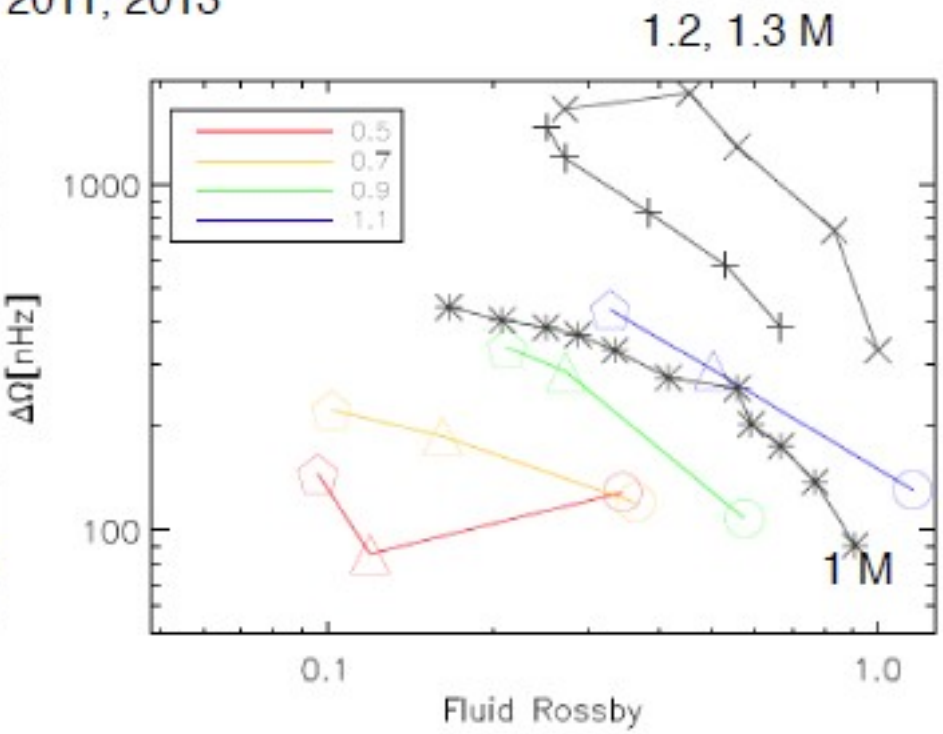
- Antisolar if the Rossby number is large.

- Latitudinal band (Jupiter like) for low mass cases.

Scaling law for ΔΩ

Matt et al. 2011, 2013





Brown et al. 2008
Augustson et al. 2012

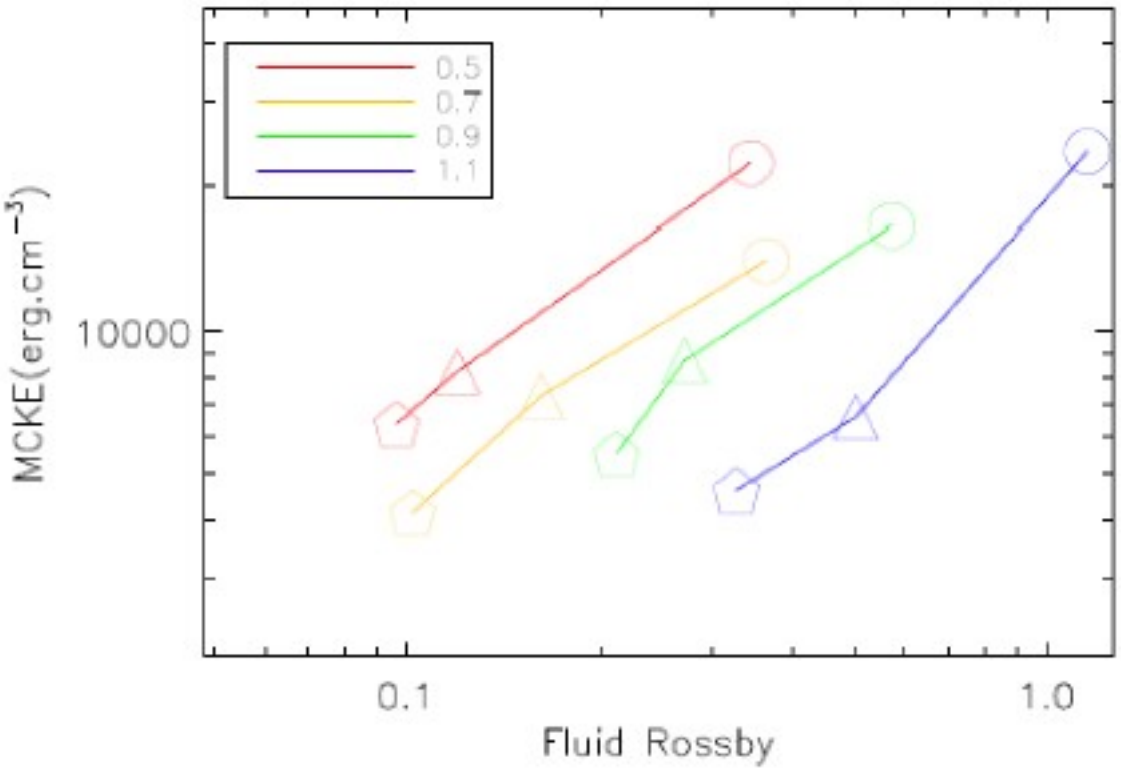
$$\Delta\Omega = 156.0 \text{ nHz} \left(\frac{M}{M_\odot}\right)^{1.0} \left(\frac{\Omega_0}{\Omega_\odot}\right)^{0.47}$$

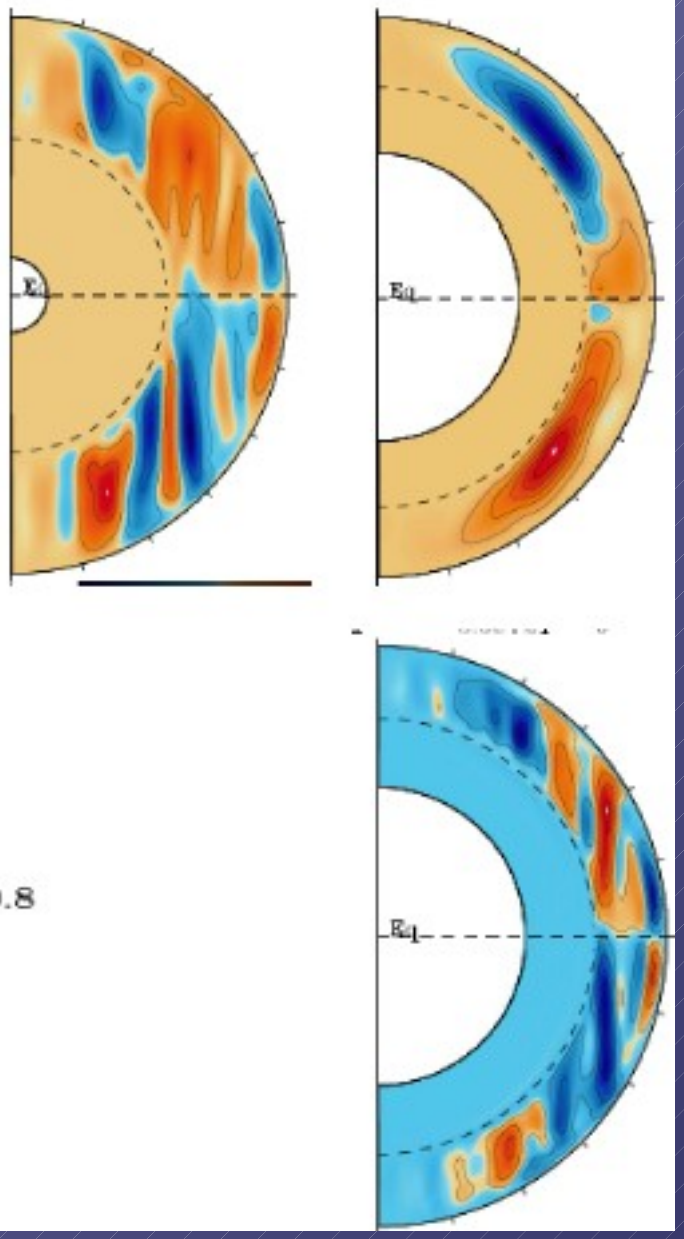
$$= 150.3 \text{ nHz} \left(\frac{M}{M_\odot}\right)^{1.85} R_{of}^{-0.52}$$

Smaller ΔΩ with smaller Mass

Estimation of the meridional flow

Matt, Brun et al. 2011, 2013

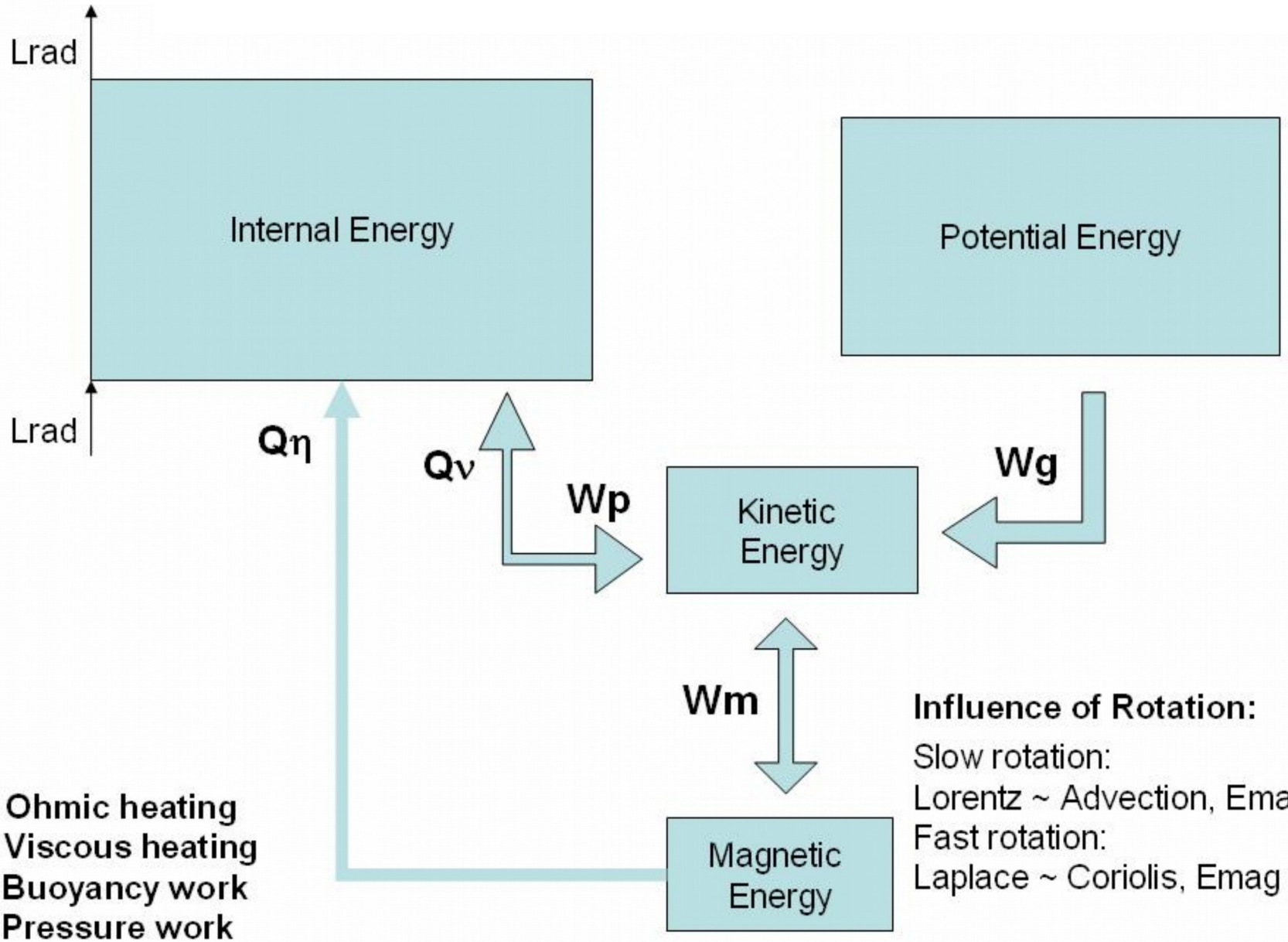




$$\mathrm{MCKE} = 1.8 \times 10^4\ \mathrm{erg.cm^{-3}} \left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{-0.14} \left(\frac{\Omega_0}{\Omega_\odot}\right)^{-0.8}$$

$$= 2.1 \times 10^4\ \mathrm{erg.cm^{-3}} \left(\frac{\mathrm{M}}{\mathrm{M}_\odot}\right)^{-1.8} \mathrm{R}_{\mathrm{of}}^{1.0}$$

Introduction: Energy balance in the convection zone



Influence of Rotation:

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

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

(Brandenburg et al. 1996, Brun et al. 2004)

Dynamo regimes and scaling

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 =>

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

Turbulent (equipartition) scaling: Lorentz ~ advection =>

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

Magnetostrophic (strong) scaling: Lorentz ~ Coriolis =>

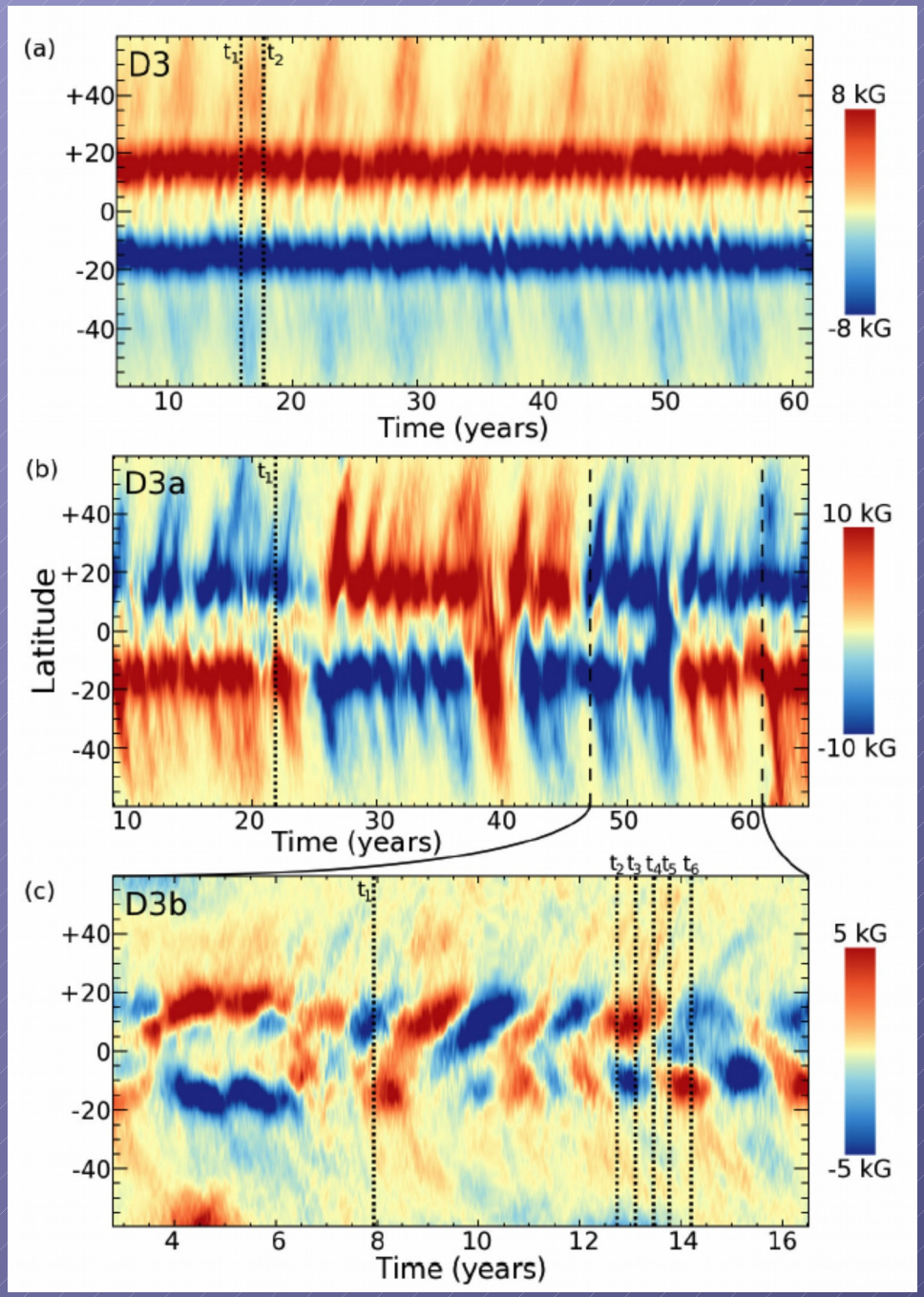
$B^2_{strong} \sim \rho\Omega\eta$ (ME > KE)

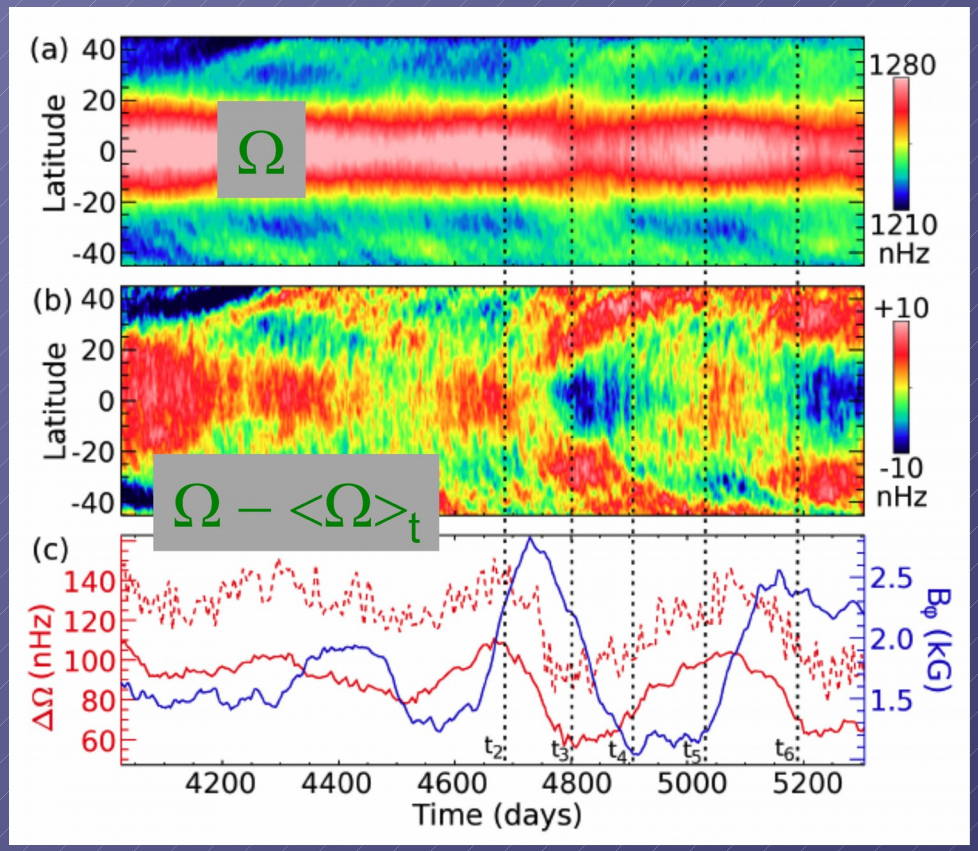
With ρ density, ν kinematic viscosity, η magnetic diffusivity, Ω rotation rate, v, L characteristic velocity & length scales, $P_m = \nu/\eta$ the magnetic Prandtl nb

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

Introduction: magnetic cycles versus convection

Turbulence degree

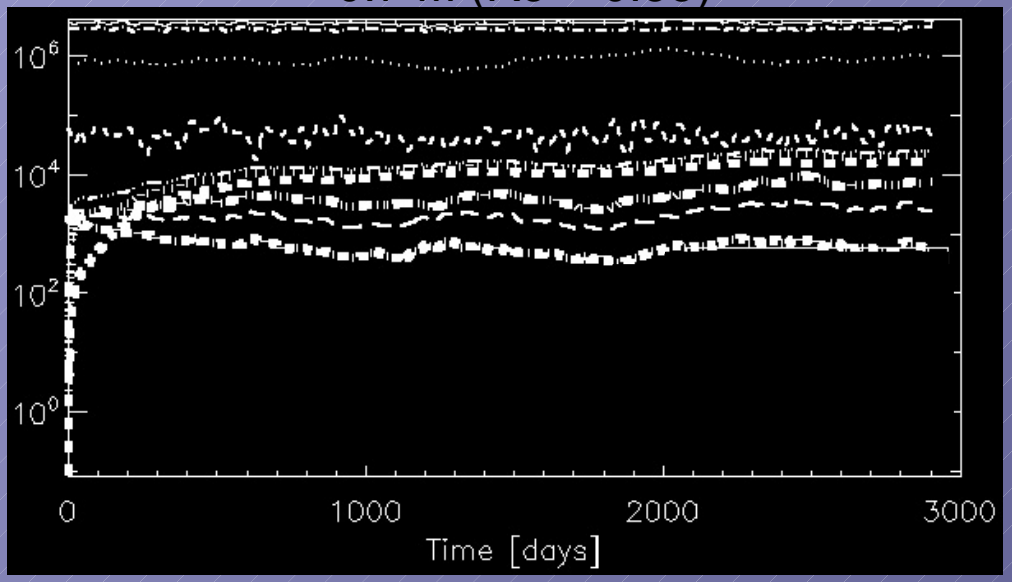




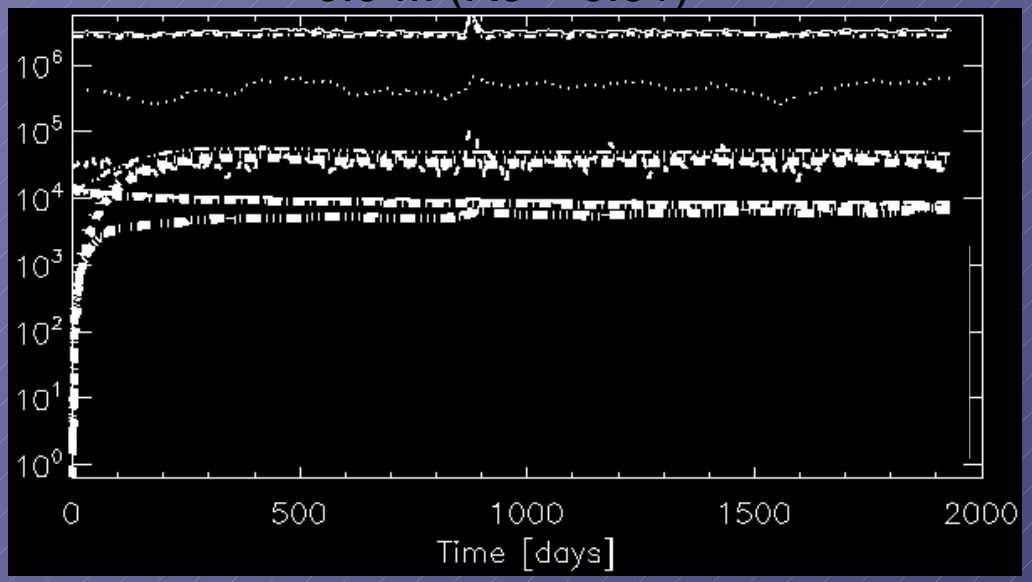
Brown et al. 2011, Nelson et al. 2012

Antisolar rotation, mass trend in G&K stars

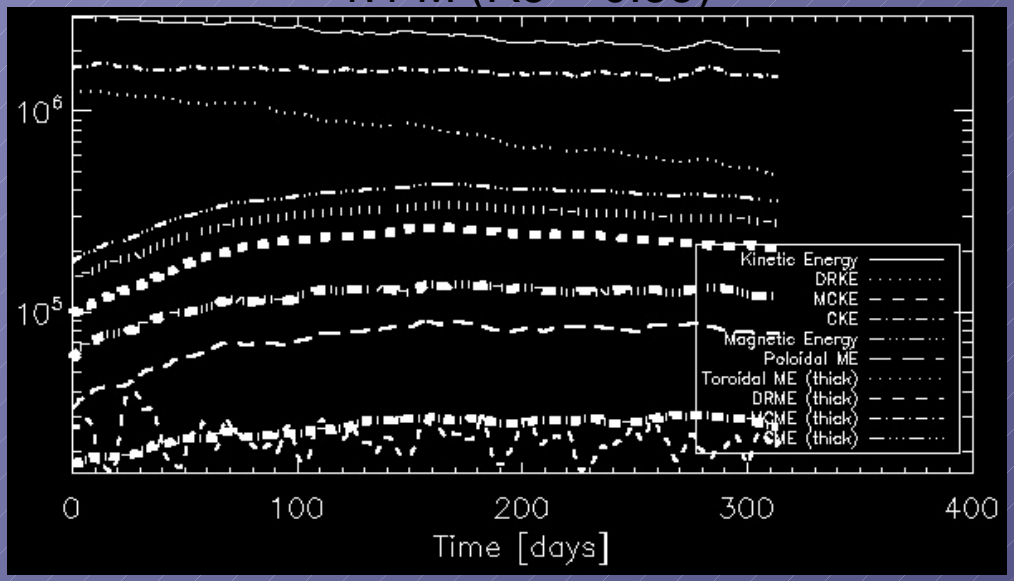
0.7 M (Ro = 0.33)



0.9 M (Ro = 0.31)



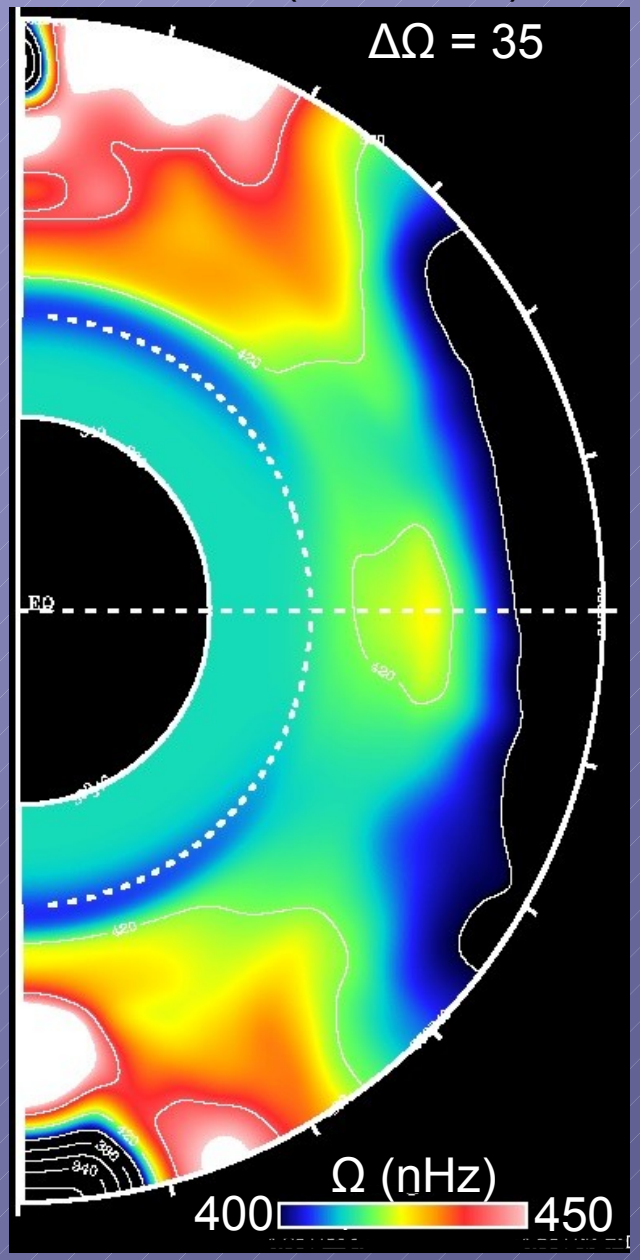
1.1 M (Ro = 0.35)



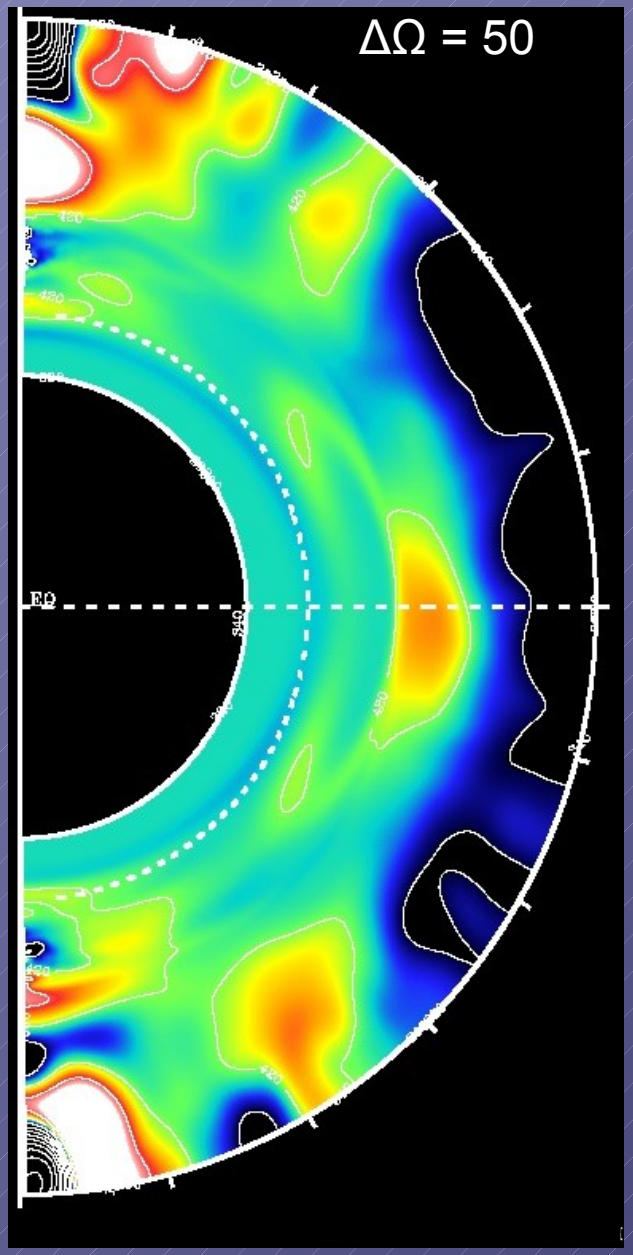
- Dynamo α^2. CKE > DRCE.
- Laminar scaling. KE > ME.
- Higher mass → DRKE drops.
- ME steady evolution for 0.9 M, oscillating for 0.7 M, drops for 1.1 M.

Antisolar rotation, mass trend in G&K stars

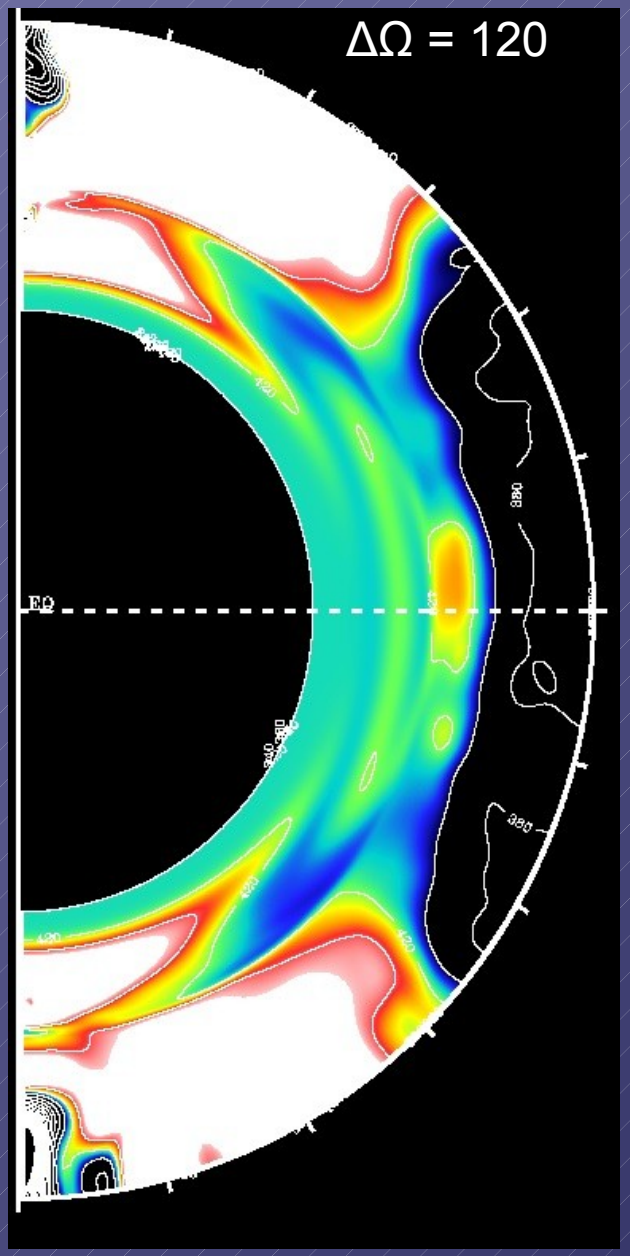
0.7 M (Ro = 0.33)



0.9 Mass (Ro = 0.31)



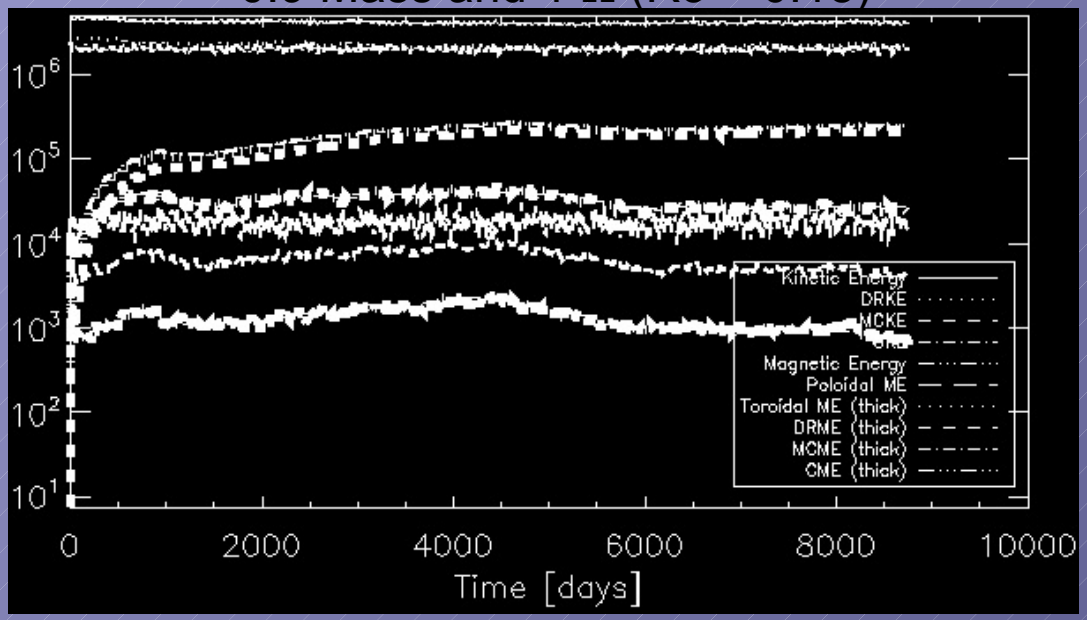
1.1 Mass (Ro = 0.35)



- ΔΩ is larger if the mass increases.

Rotation trend in G&K stars

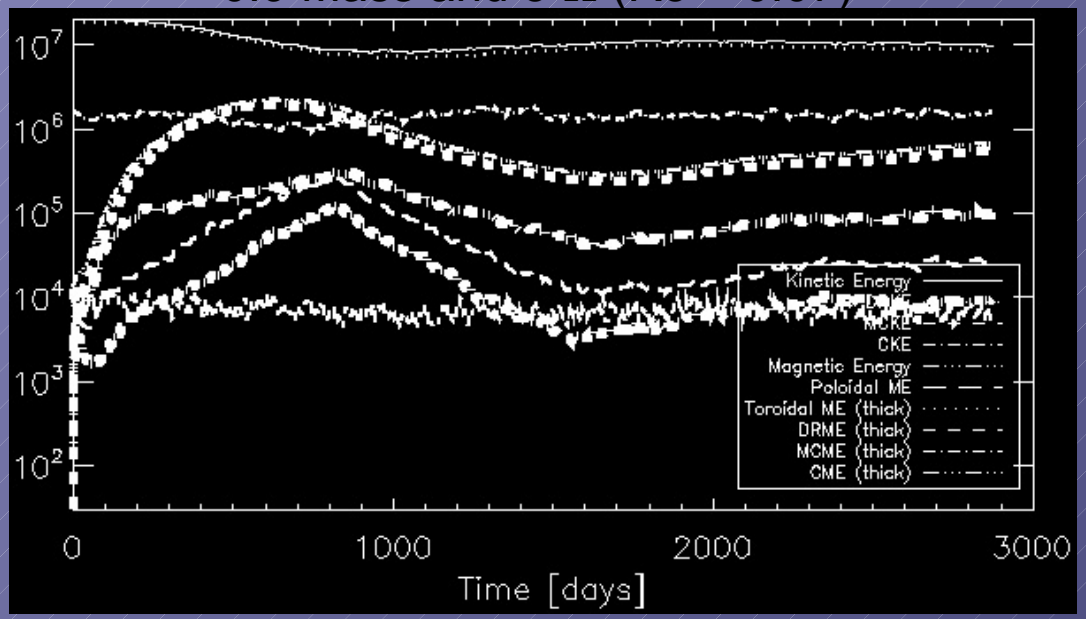
0.9 Mass and 1 Ω (Ro = 0.18)



- The 1 Ω shows a weak ME oscillations. CKE ≈ DRKE.

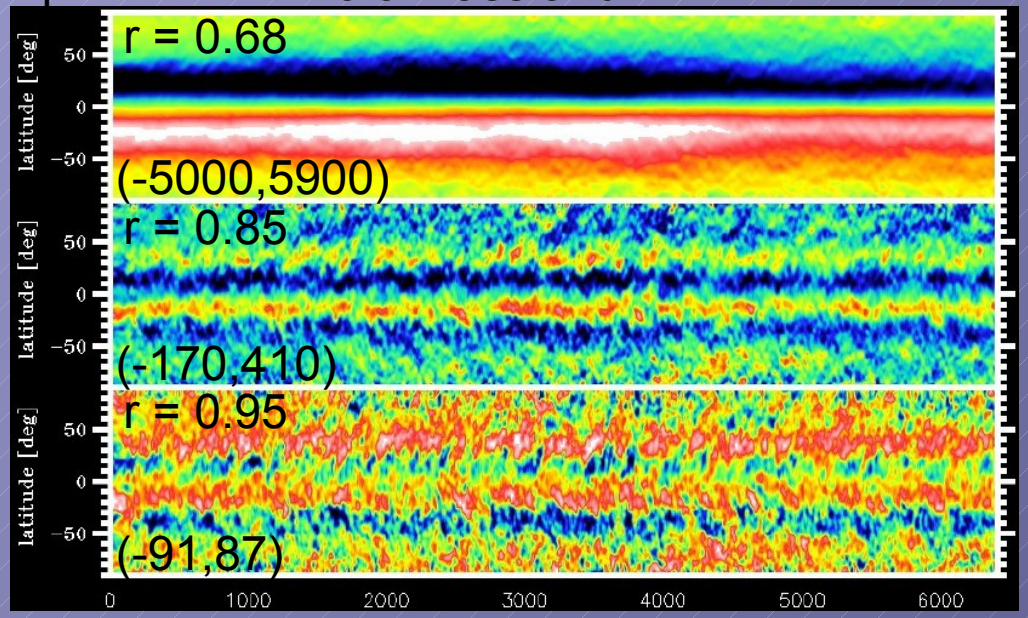
- The 3 Ω shows a strong ME oscillations. CKE < DRKE.

0.9 Mass and 3 Ω (Ro = 0.07)

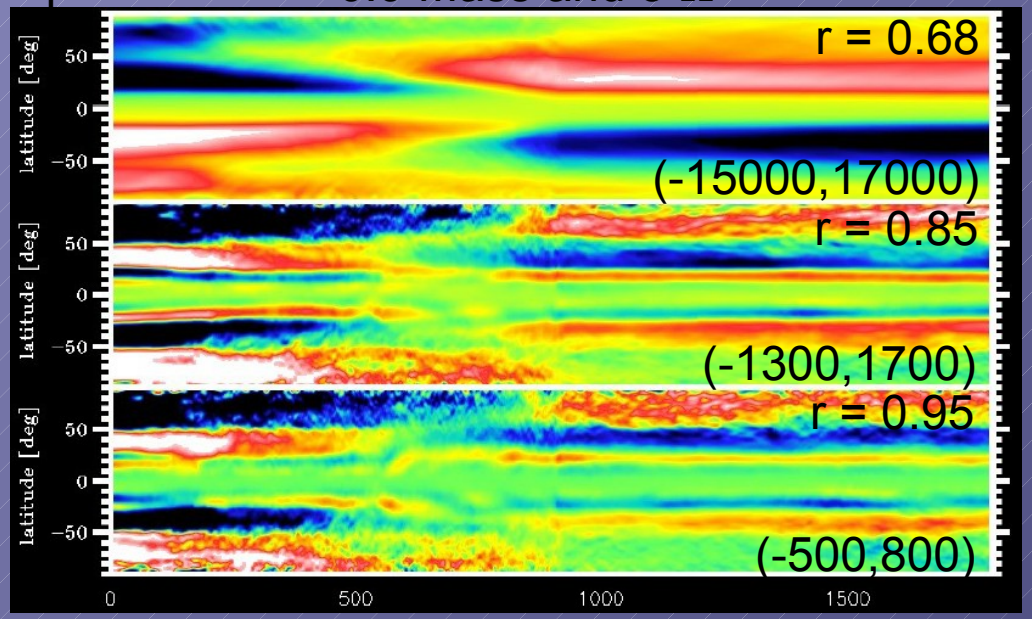


Effect of the rotation in G&K stars

Bphi 0.9 Mass and 1 Ω



Bphi 0.9 Mass and 3 Ω

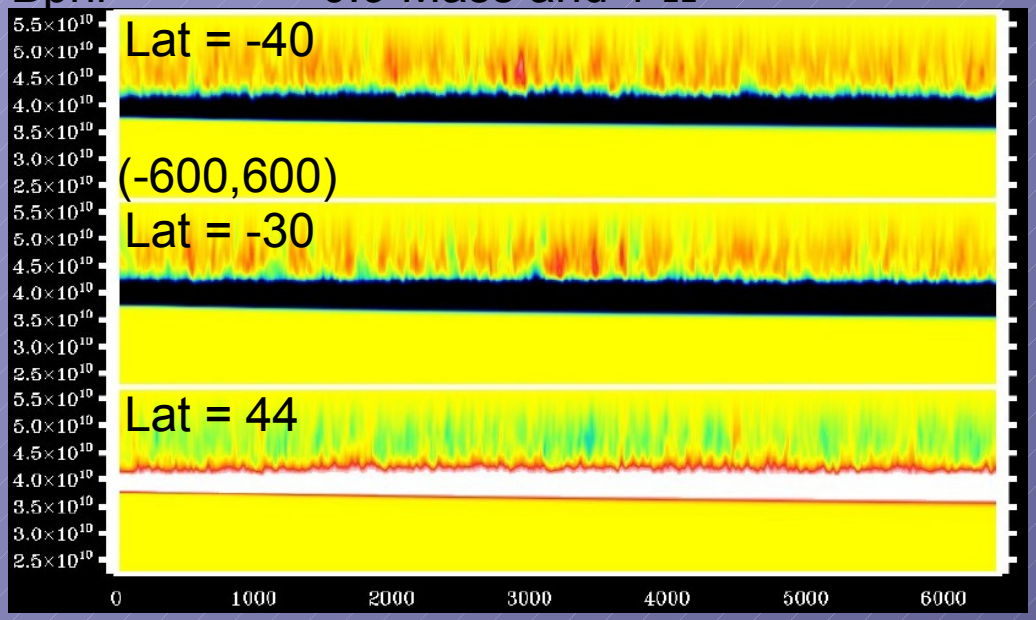


- No polar inversion in the 1 Ω simulation. Stable magnetic wreaths. Small Bphi oscillations.

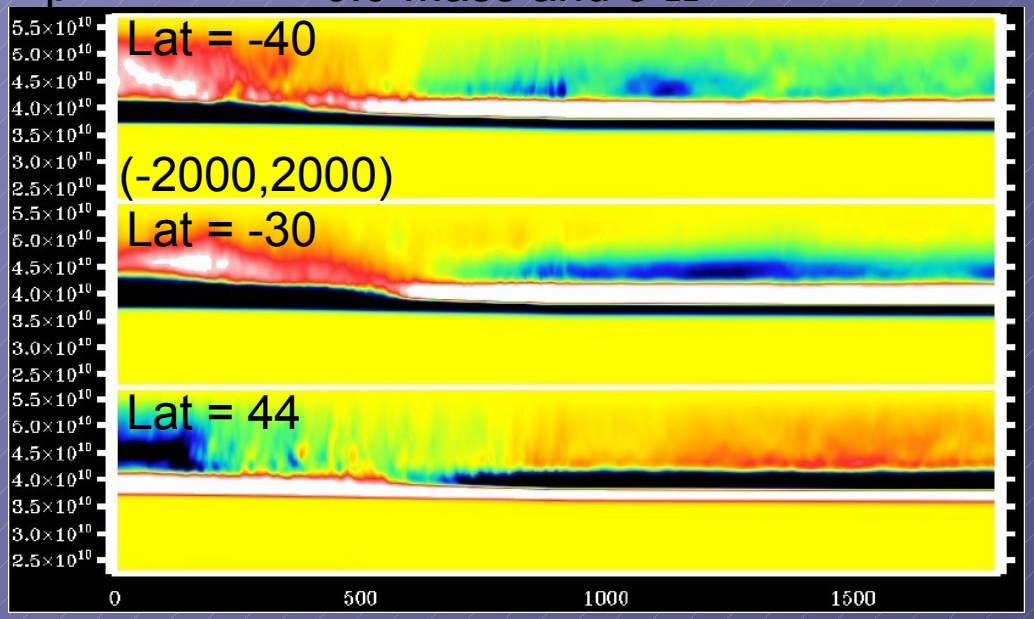
- Polar inversion in the 3 Ω simulation.

Effect of the rotation in G&K stars

Bphi 0.9 Mass and 1 Ω



Bphi 0.9 Mass and 3 Ω



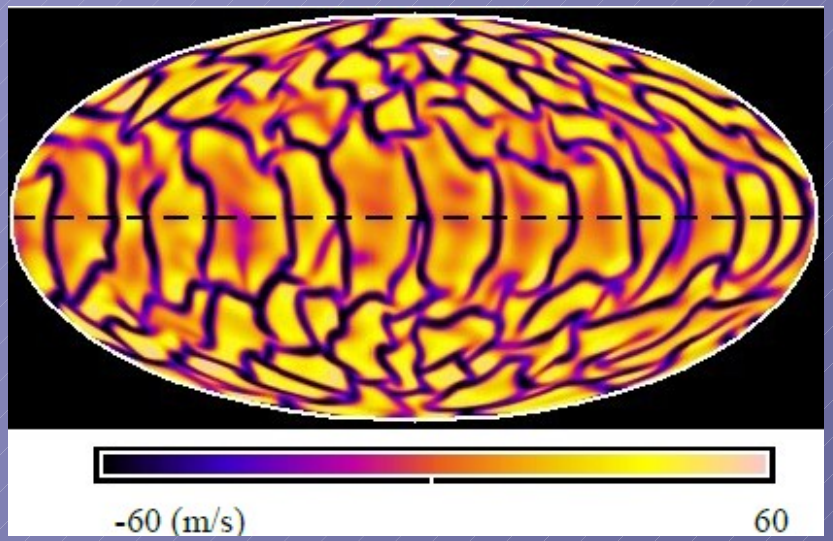
- Local weak variations for 1 Ω. Dipolar component dominates.

- During the polarity inversion in the 3 Ω simulation, the quadrupolar term dominates.

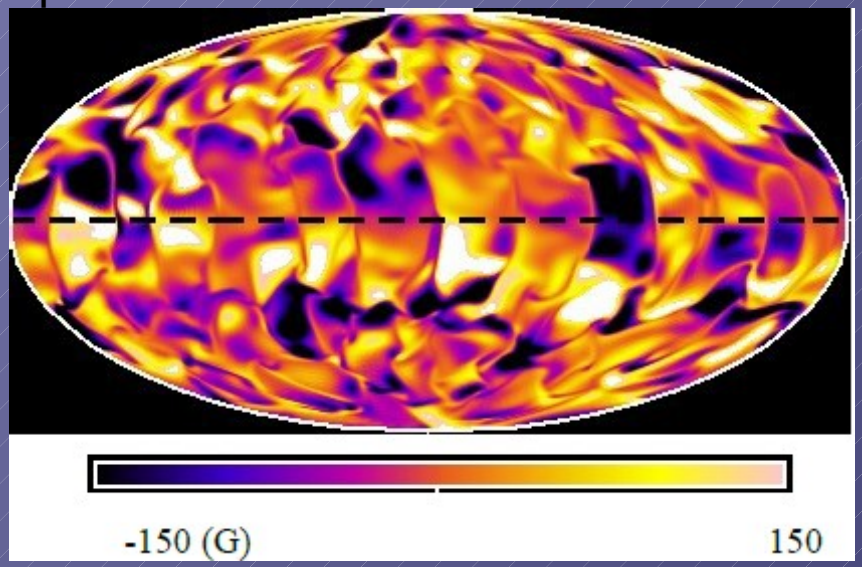
Effect of the rotation in G&K stars

0.9 Mass and 1 Ω

Vr

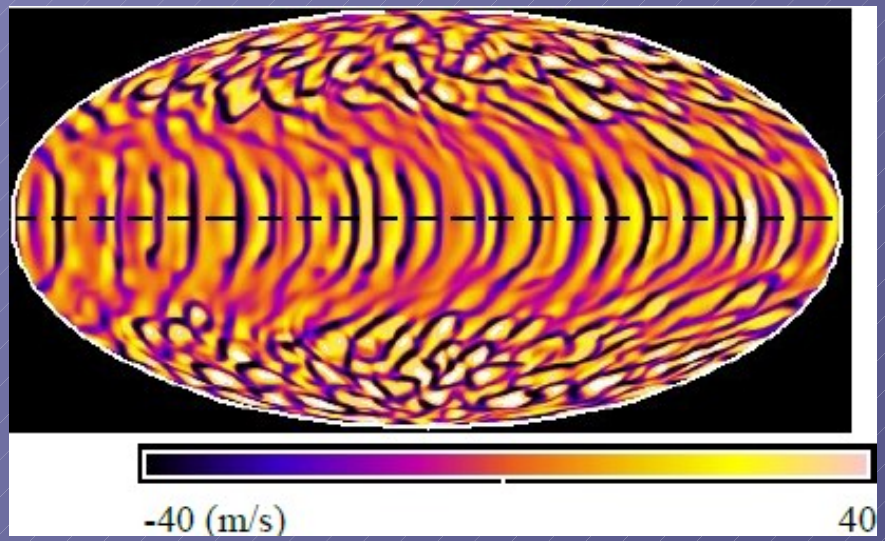


Bphi

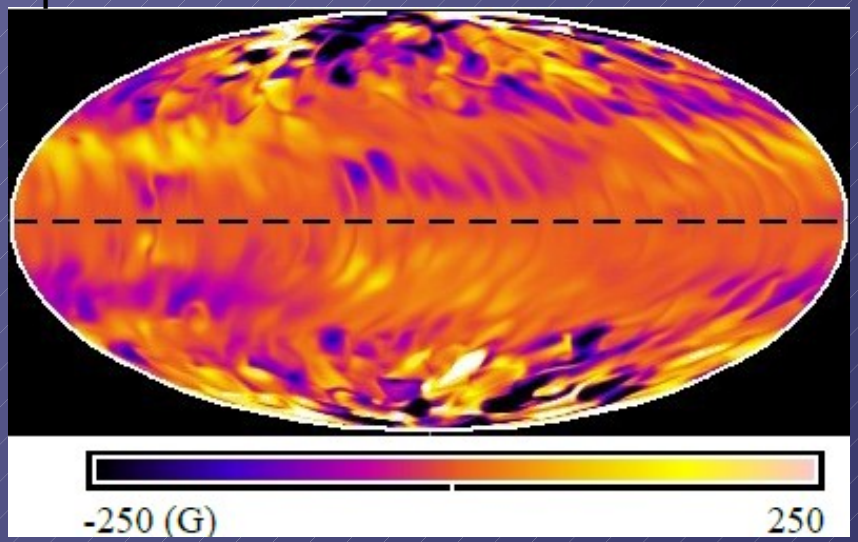


0.9 Mass and 3 Ω

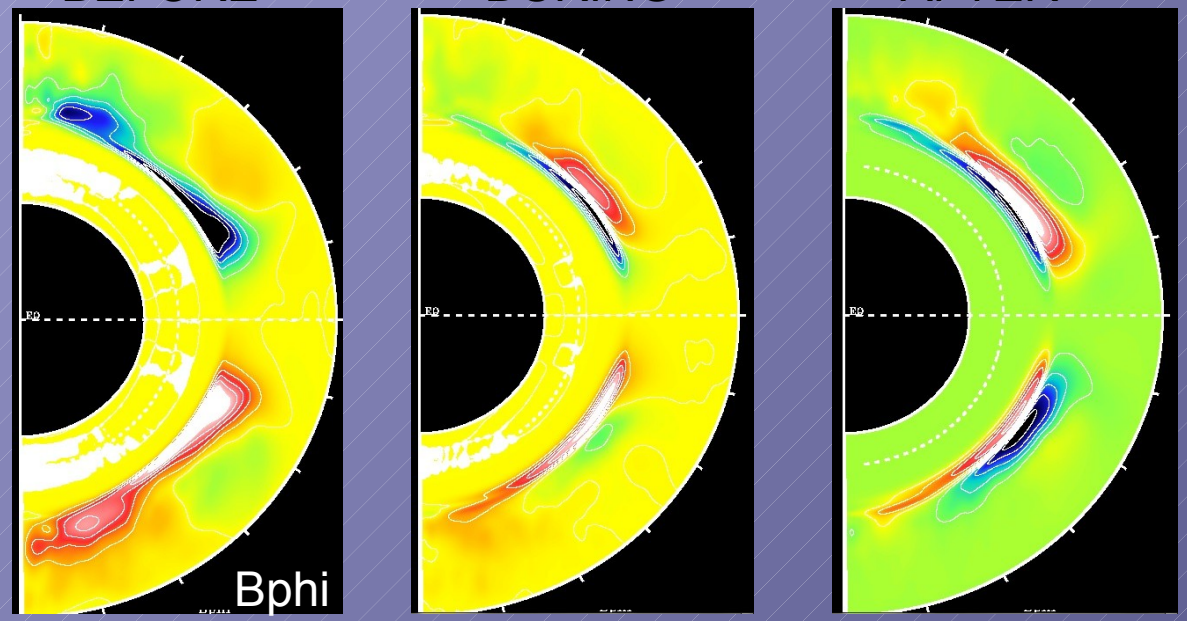
Vr



Bphi



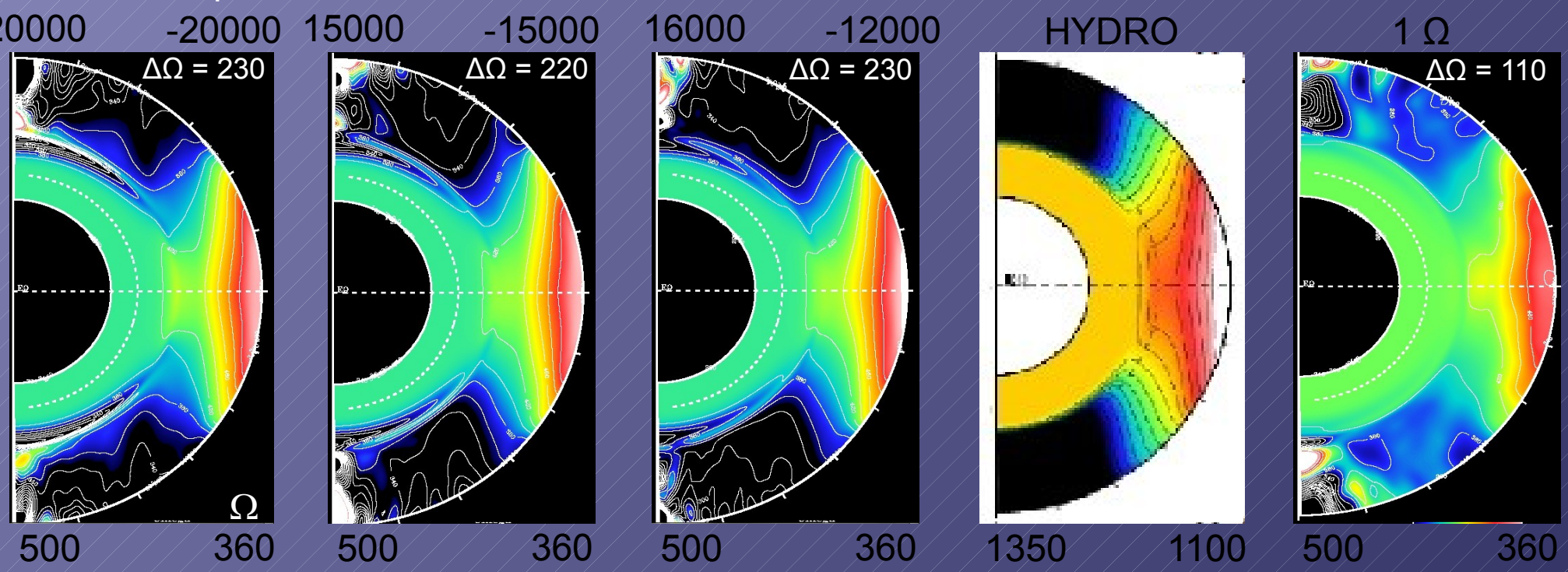
Effect of the rotation in G&K stars



- $\Delta\Omega$ changes during the cycle in the 3 Ω case. Minimum of the ME correlated with a maximum of the DRKE.

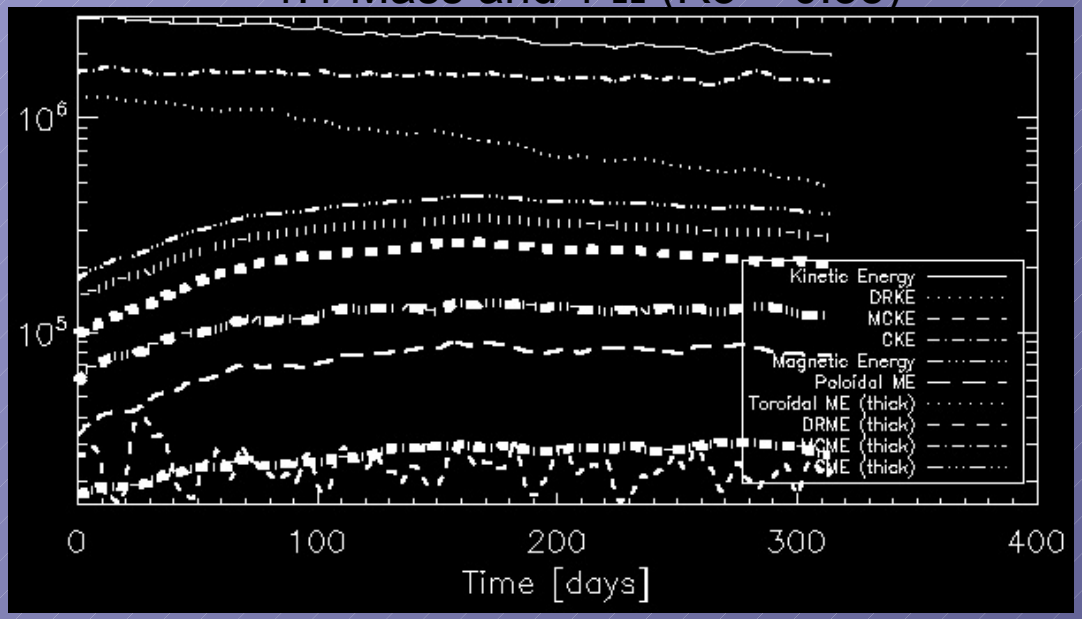
- $\Delta\Omega$ larger in the hydro case. $\Delta\Omega$ quenching by Lorenz force.

- $\Delta\Omega$ smaller in the 1 Ω case.



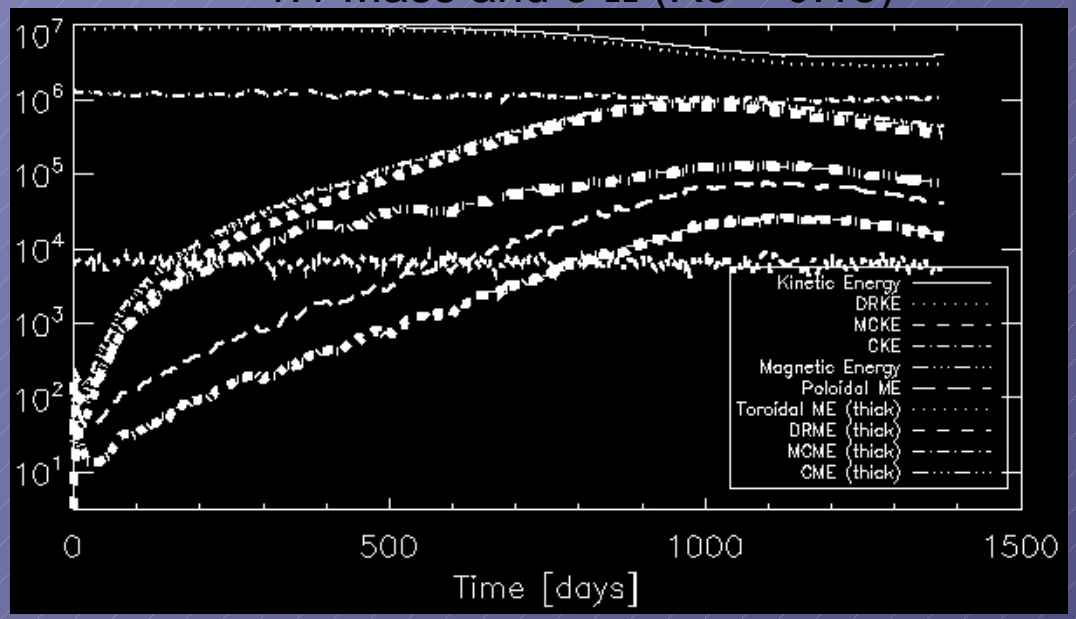
Rotation trend in G&K stars

1.1 Mass and 1 Ω (Ro = 0.35)

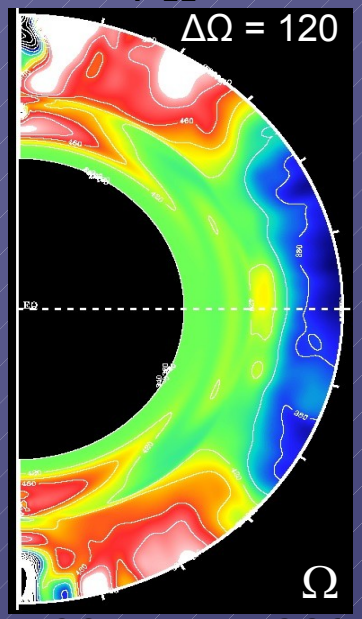


- For the 3 Ω simulation the DRKE > CKE, the opposite than in the 1 Ω case. ΔΩ is larger.
- Drop the Ro (increasing Ω) drives a cyclic dynamo as in the 0.9 M (3 Ω) case?
- DRKE in the 3 Ω stop dropping after the local maximum of the ME. Beginning of a magnetic cycle ?.

1.1 Mass and 3 Ω (Ro = 0.13)

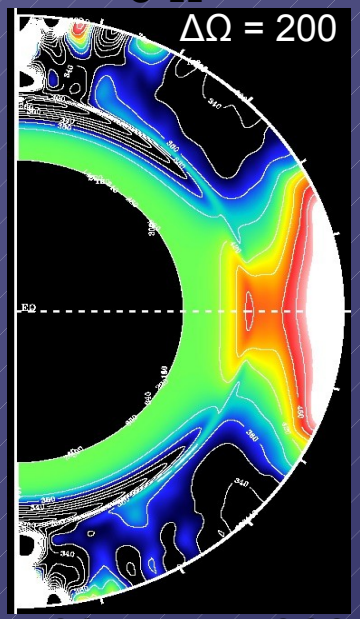


1 Ω



500 360

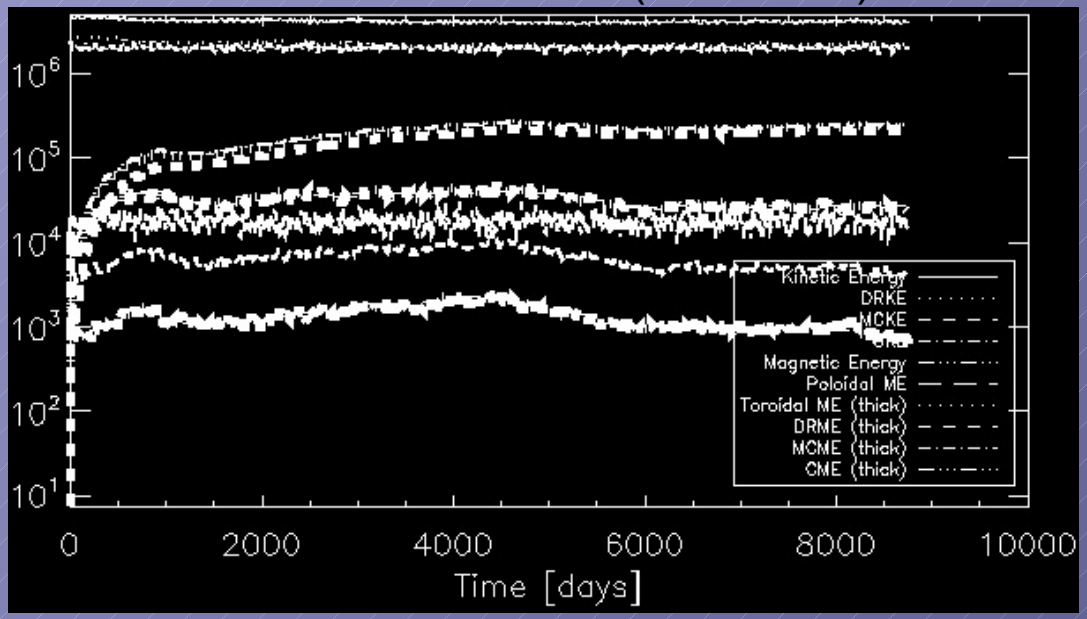
3 Ω



500 360

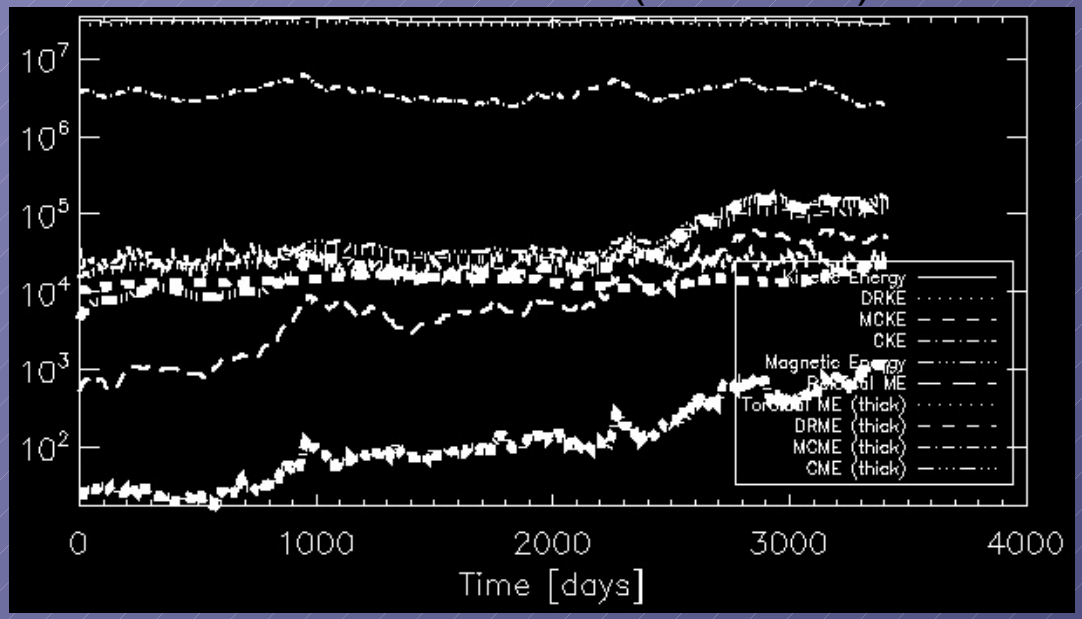
Mass trend in G&K stars

0.9 Mass and 1 Ω (Ro = 0.18)

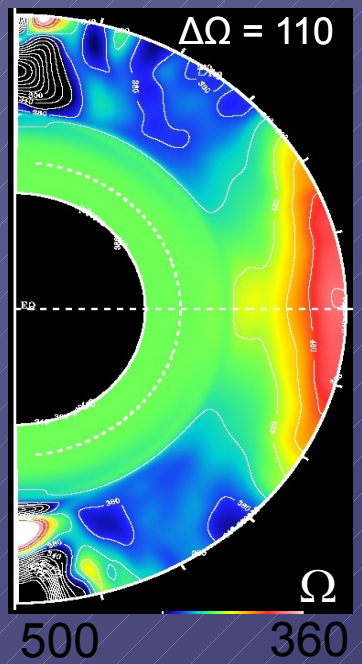


- The KE in the 0.5 M case is larger than in the 0.9 M simulation.
- The DRKE > CKE in the 0.5 M case. Larger ΔΩ.
- To drop the Ro leads to larger ME oscillations (almost one order of magnitude in the 0.5 M case).

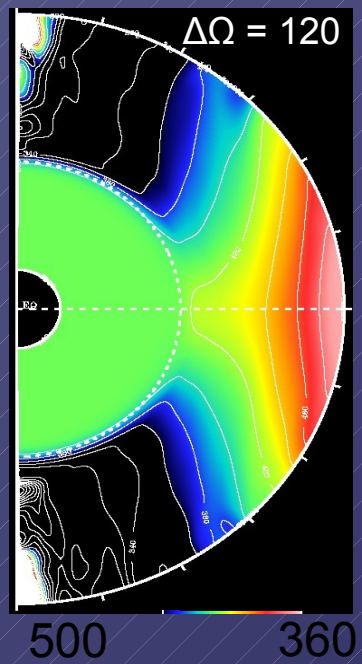
0.5 Mass and 1 Ω (Ro = 0.09)



0.9 M



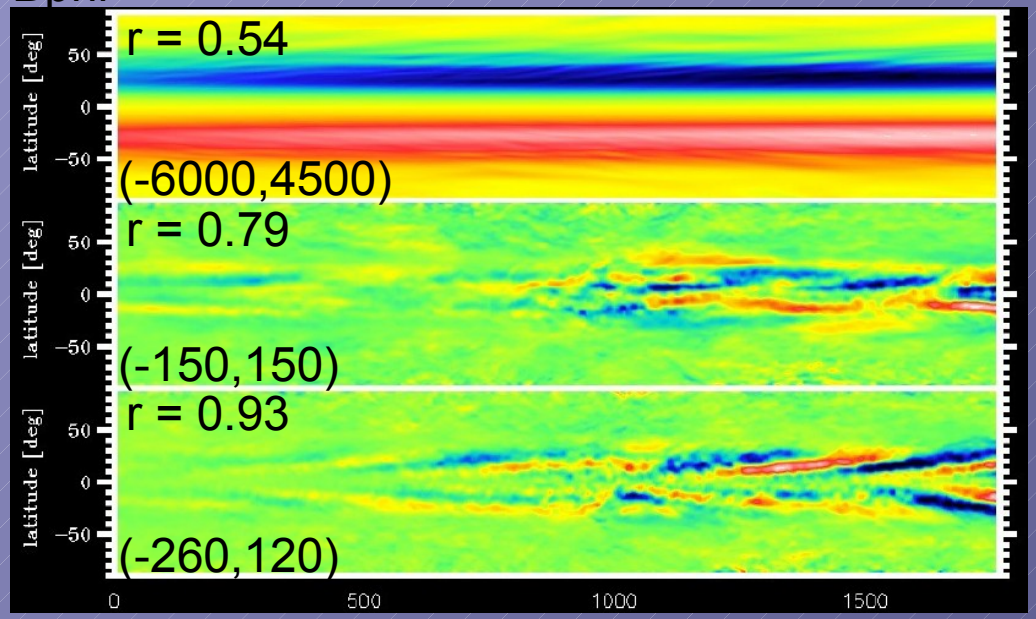
0.5 M



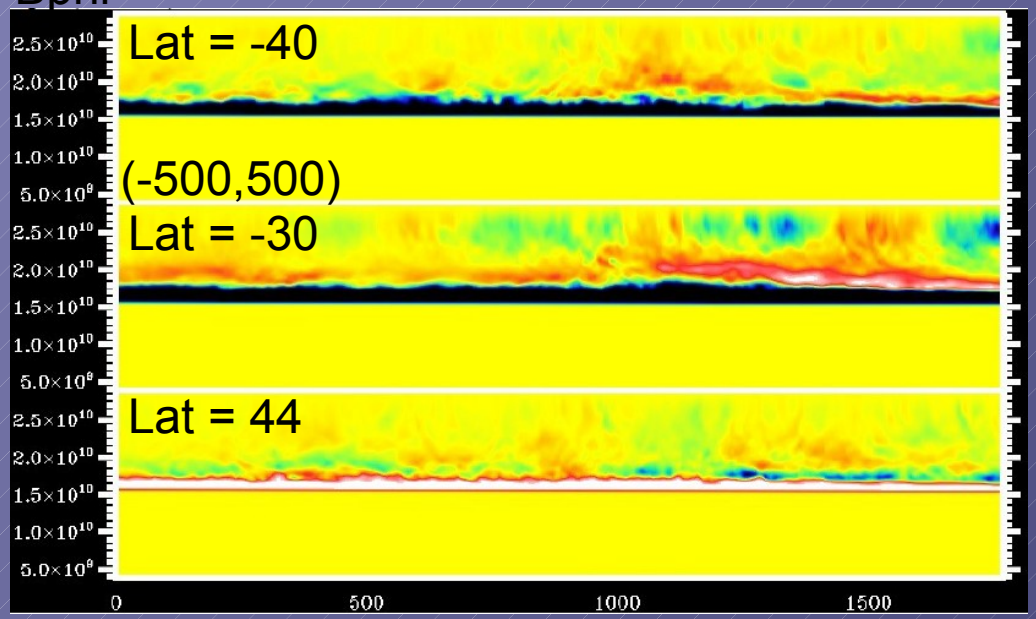
Mass trend in G&K stars

0.5 Mass and 1 Ω

Bphi



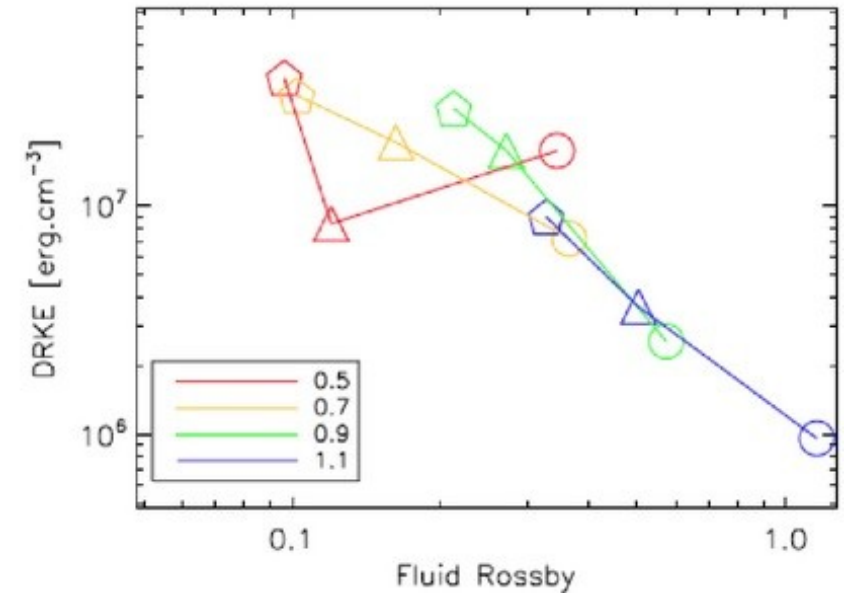
Bphi

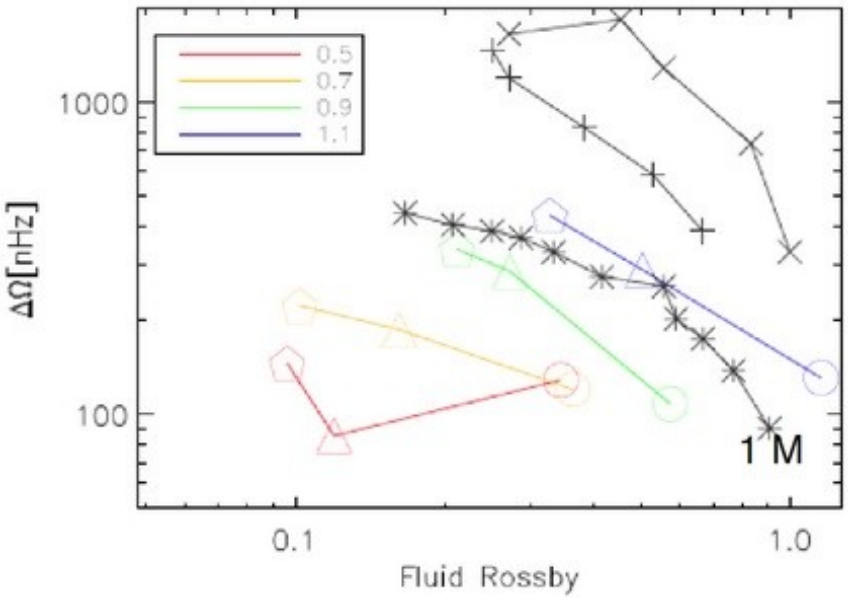


- Stable magnetic wreaths in the base of the convection zone but inversion at r = 0.79 and 0.93.

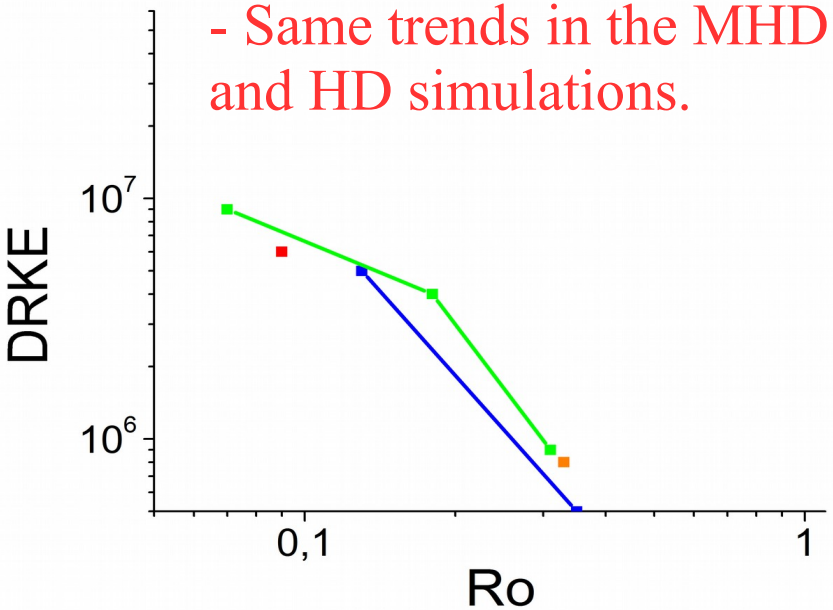
- The Bphi polarity and the magnetic field topology change further from the base of the base convection zone.

Conclusions and future research

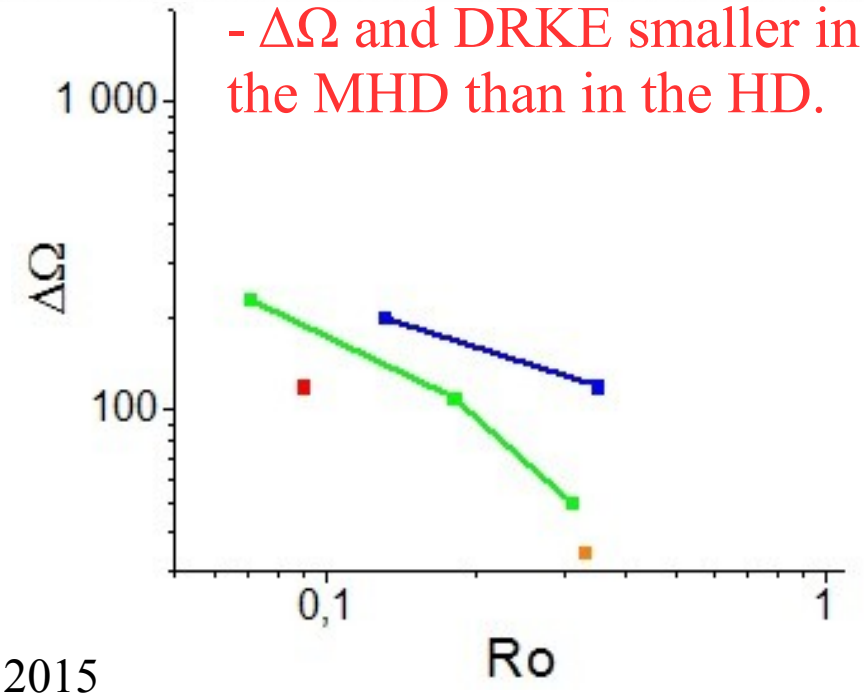




- Same trends in the MHD and HD simulations.



- ΔΩ and DRKE smaller in the MHD than in the HD.



Dynamo frontiers conference: Varela & Brun 2015

Conclusions and future research

- All simulation are in the laminar scaling.

- The anti-solar model (CKE > DRCE), α^2 dynamo. Stable magnetic wreaths. Higher mass, drop of the DRKE and increase of the $\Delta\Omega$.

- The anti-solar cases don´t show cyclic activity but the ME and KE is only steady in the mode with 0.9 M.

- The model with 0.9 M and 1 Ω shows a weak cyclic activity (CKE $\approx$ DRKE) while the 3 Ω model show a strong cyclic activity (CKE < DRKE). Similar conclusions for the 1.1M models with 1 – 3 Ω.

- The model with 0.5 M and 1 Ω shows a stronger ME oscillations than the model with 0.9 M and 1 Ω (larger Ro).

- Increase the rotation rate leads to an enhancement of the DRKE and $\Delta\Omega$, non-steady evolution of the ME and cyclic activity (polar inversion). α-Ω dynamo.

- Increase star mass, leads to a drop of the DRKE (relative to each simulation) and an enhancement of the $\Delta\Omega$. Dynamo dominated by convective motions (α^2), steady evolution ME.