Implicit Large Eddy (ILES) Global Simulations of Solar Convection and Dynamo Action

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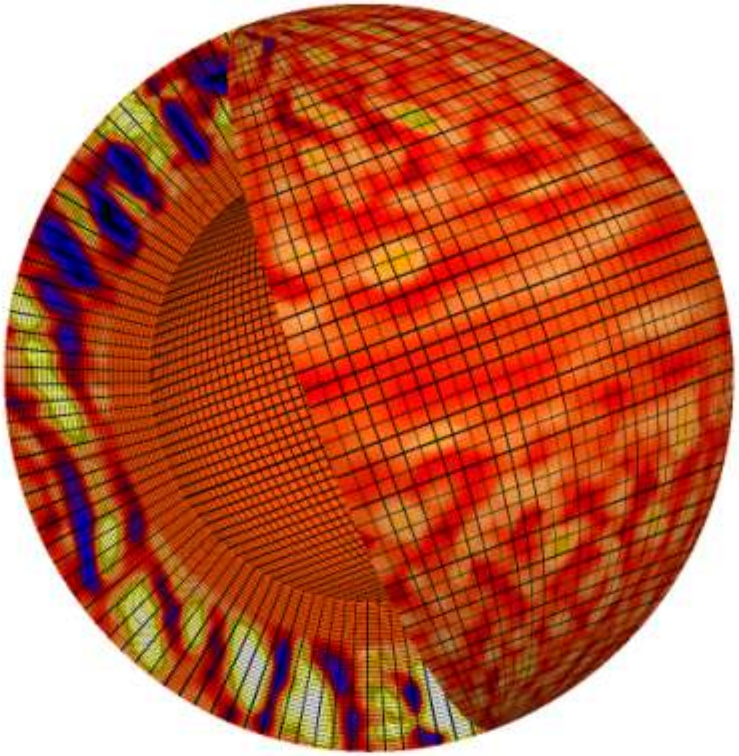
THE MODEL → EULAG-MHD



Solve the ideal MHD equations in the anelastic approximation in a rotating stratified shell of electrically conducting plasma, from 0.61 to 0.96 $R_\odot$, with the solar luminosity forced between bottom and top.

$$\frac{D\boldsymbol{u}}{Dt} = -\nabla\pi' - \mathbf{g}\frac{\Theta'}{\Theta_o} + 2\boldsymbol{u}\times\boldsymbol{\Omega} + \frac{1}{\mu\rho_o}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B},$$

$$\frac{D\Theta'}{Dt} = -\boldsymbol{u}\cdot\nabla\Theta_e + \mathcal{H} - \alpha\Theta',$$

$$\frac{D\boldsymbol{B}}{Dt} = (\boldsymbol{B}\cdot\nabla)\boldsymbol{u} - \boldsymbol{B}(\nabla\cdot\boldsymbol{u}).$$

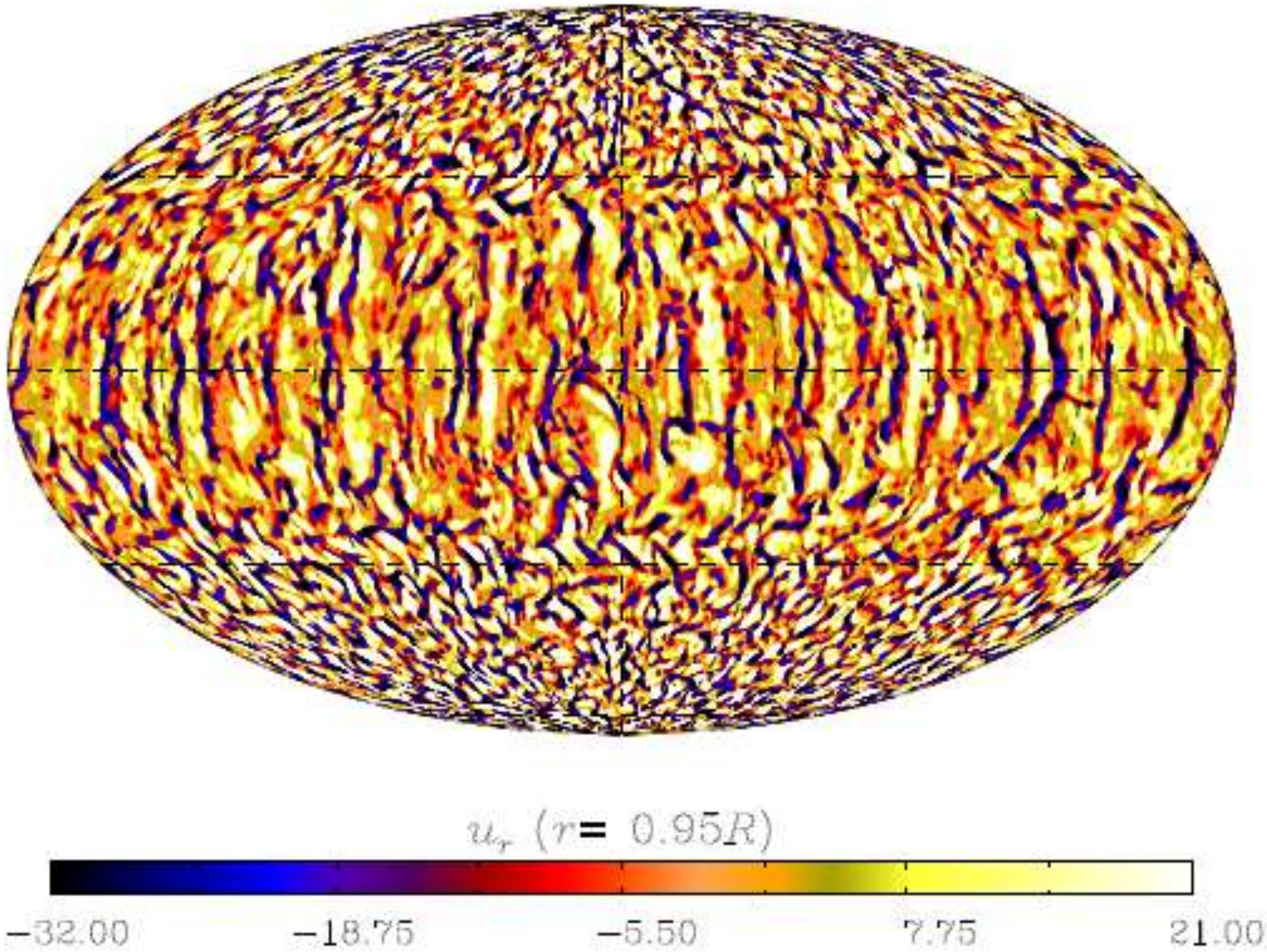
$$\nabla\cdot(\rho_o\boldsymbol{u}) = 0,$$

$$\nabla\cdot\boldsymbol{B} = 0.$$

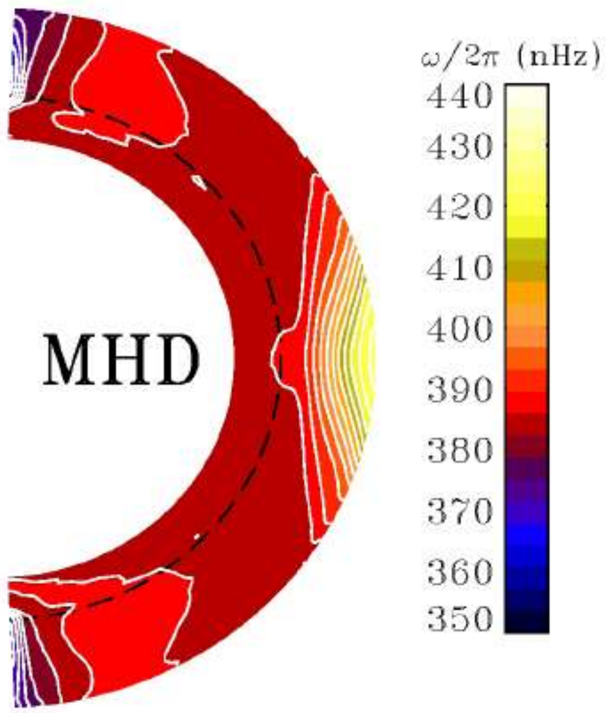
- ✓ The background stratification is convectively unstable between $r/R_\odot = 0.71$ and $r/R_\odot = 0.96$, and stable below.
- ✓ Initial conditions: unmagnetized hydrostatic, random flow and field perturbations introduced at t=0.
- ✓ Typical resolution used: 128 in ϕ x 64 in θ x 47 in r
- ✓ Parallelized to 128 cores (scalable up to ~ 10000 cores and possibly more…)

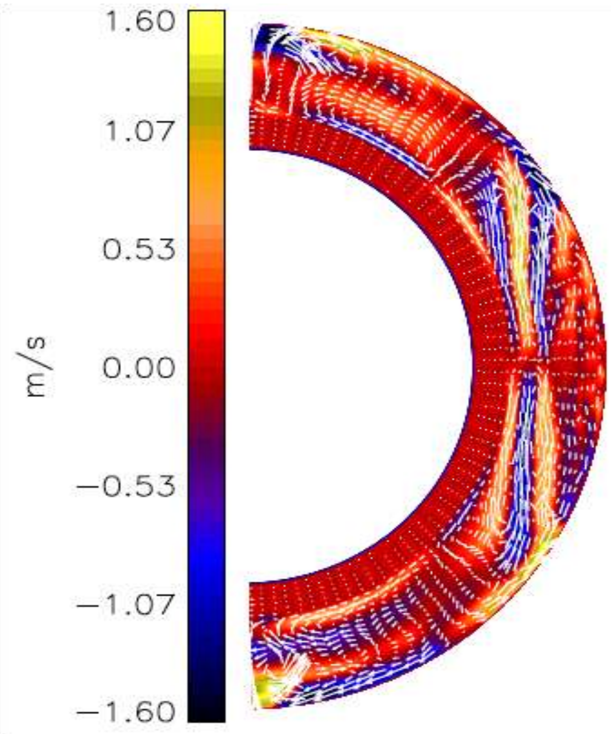
*Ghizaru et al 2010, ApJL, **715**, L133*
Smolarkiewicz, P K , Charbonneau, P, 2013 J. Comput. Phys. 236, 608-623

SMALL SCALE FLOWS



LARGE SCALE FLOWS



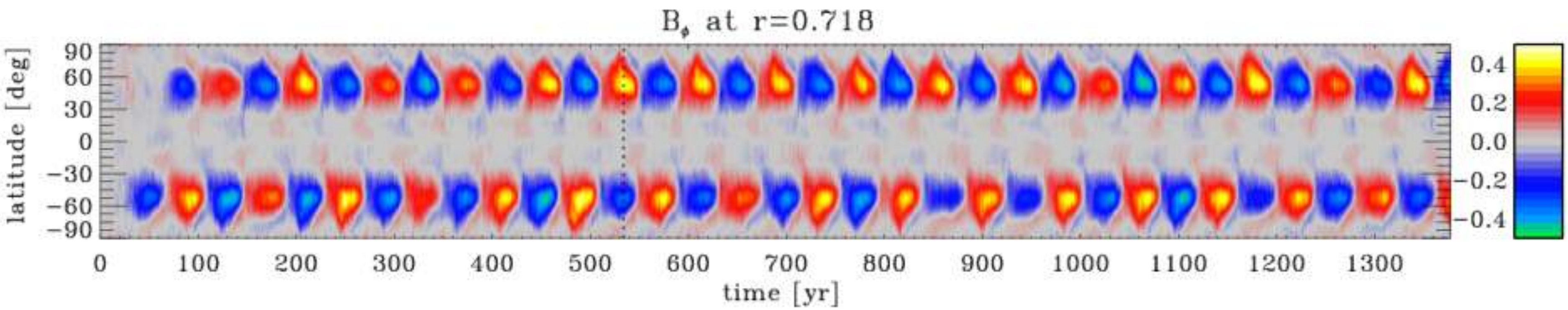


✓ Reasonably solar-like internal differential rotation (ratio pole to equator 3 times slower than the Sun)

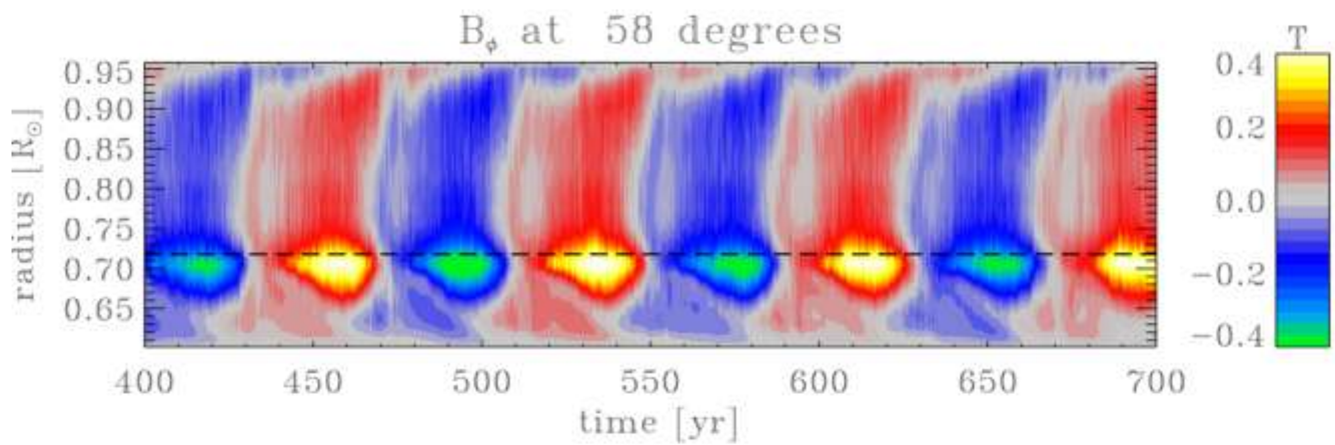
✓ Tachocline-like shear layer below convection zone

✓ Complex meridional circulation pattern (return flow at the BCZ and poleward directed in the top layers, in the mid to high latitudes interval)

LARGE SCALE FIELDS *(SIMULATION M37A)*

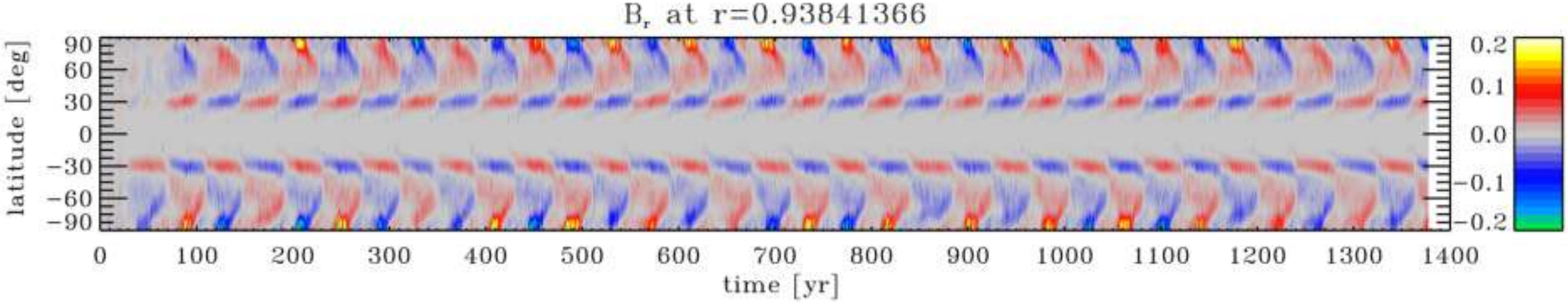


✓ Kilo Gauss-strength, large-scale magnetic fields, antisymmetric about equator and undergoing regular polarity reversals every ~ 40 years. The toroidal component is concentrated at mid-latitudes, rather than low latitudes.



✓ Toroidal component strongly concentrated immediately beneath core-envelope interface.

LARGE SCALE FIELDS *(SIMULATION M37A)*



✓ Well-defined dipole moment, with rotation axis but in phase with internal toroidal component

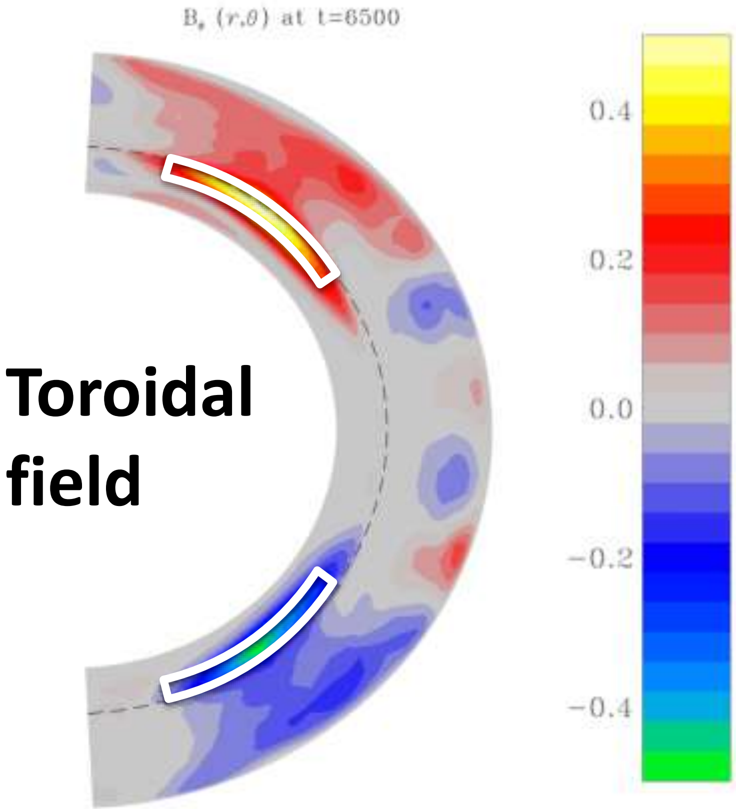
Other interesting features in these simulations

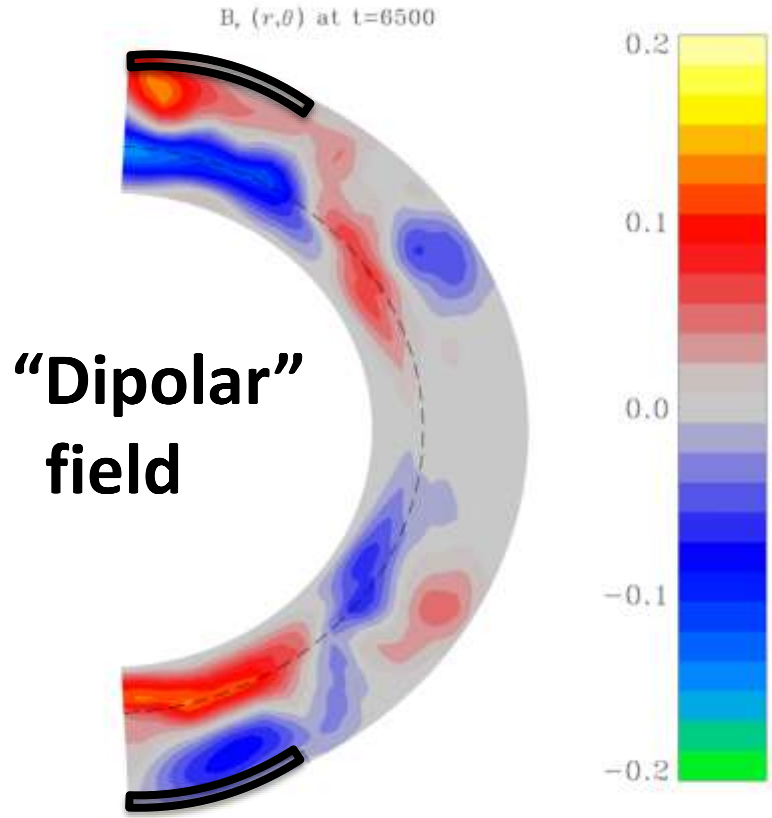
✓ Evidence for the presence of a $\alpha^2\Omega$ dynamo working
Racine, E. et al 2011, ApJ, 735, 46
Simard, C. et al 2013, ApJ, 768, 16

✓ Magnetic related cyclic modulation of large-scale meridional flow in convection zone
Passos, D. et al 2012, Sol. Phys., 279, pp.1-22

✓ Solar-like cyclic torsional oscillations (correct amplitude and phasing).
Beaudoin, P. et al 2013, Sol. Phys., 282, pp.335-360

BUILDING PROXIES OF SOLAR ACTIVITY

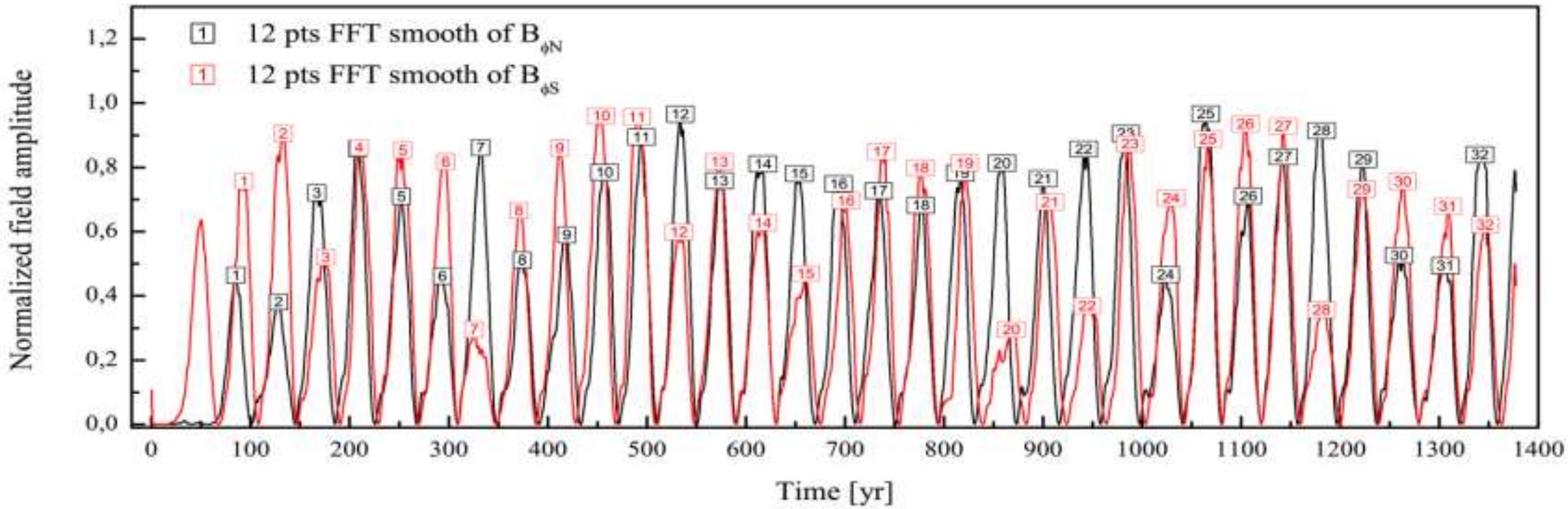


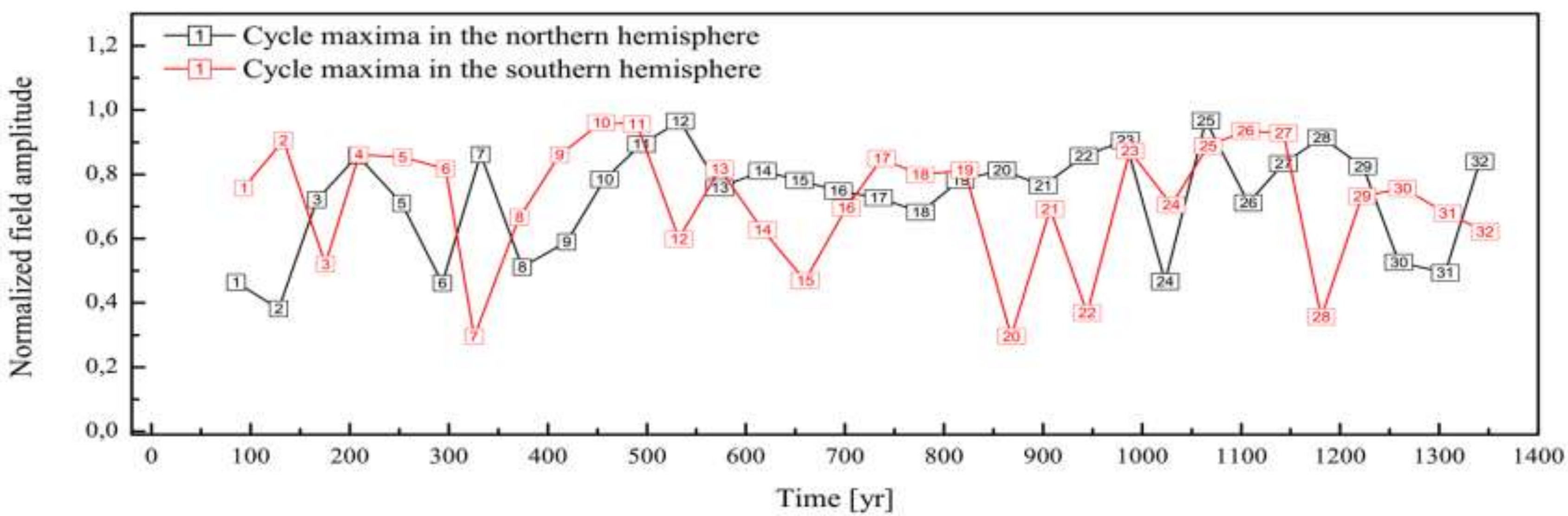


Procedure: *integrate over highlighted areas (independently in both hemispheres), square and normalize amplitude*

PROXIES OF SOLAR ACTIVITY (1)

Toroidal field proxy





STATISTICAL PROPERTIES

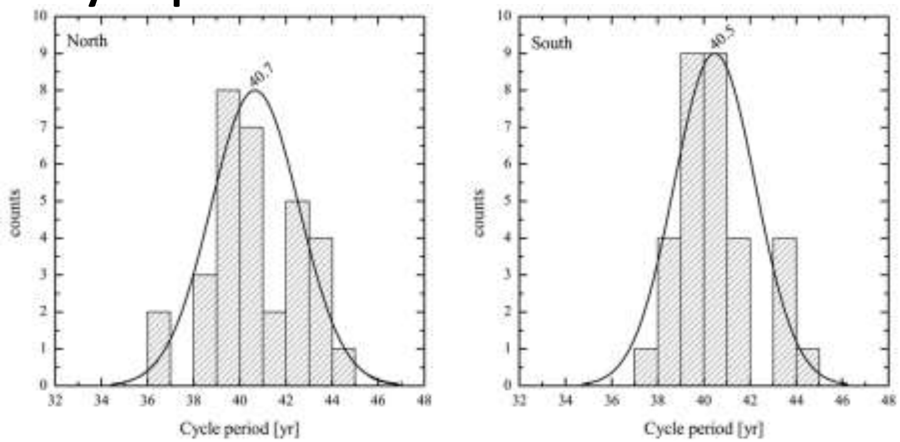
Correlation between maxima in both hemispheres

m37a $\rightarrow$ $r = -0.21$

Sun $\rightarrow$ $r = 0.83$

Li et al 2009, ApJ 691, 75

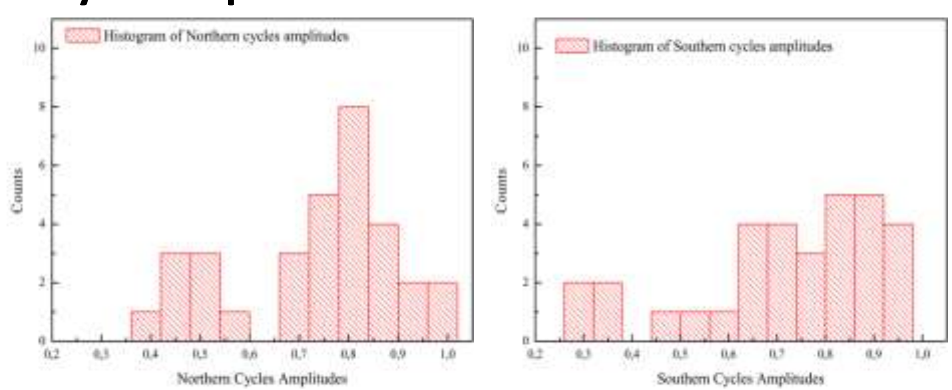
Cycle period



Histogram of cycle period for the north and south

Peak at ~ 40 yr

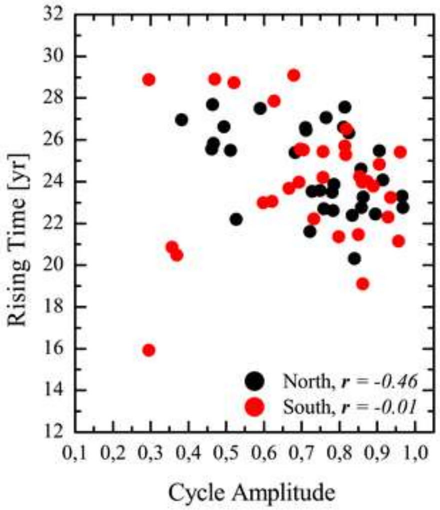
Cycle amplitude

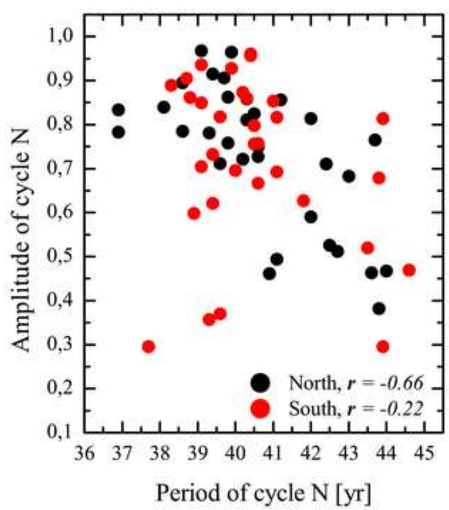


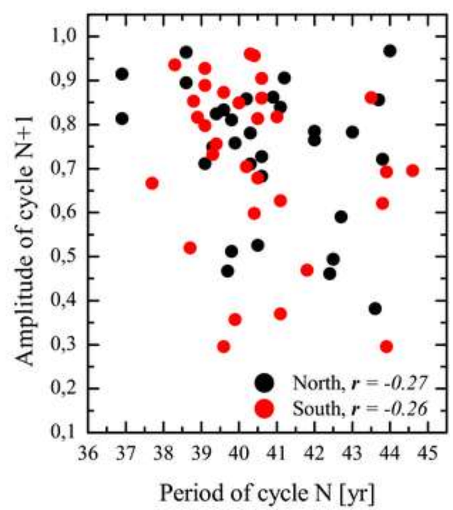
Histogram of cycle amplitude for the north and south

Bimodal distribution?

"WALDMEIER" RULES





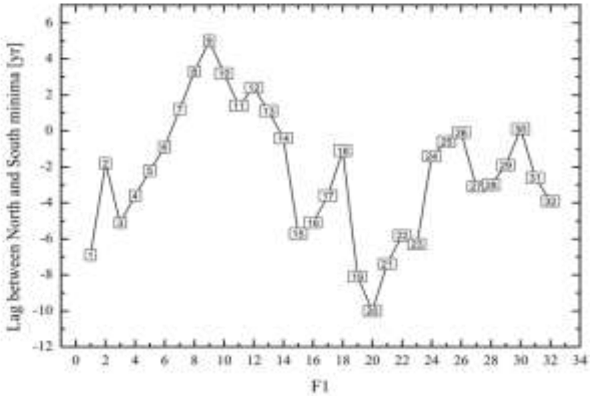


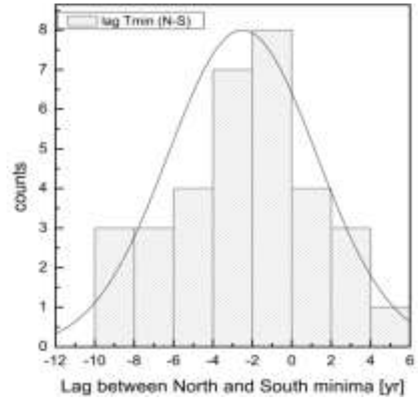
Sun $\rightarrow$ *r = -0.7 (SSN)*
r = -0.34 (SSGN)

Sun $\rightarrow$ *r = -0.3*

Sun $\rightarrow$ *r = -0.68*

Lag analysis between minima in both hemispheres

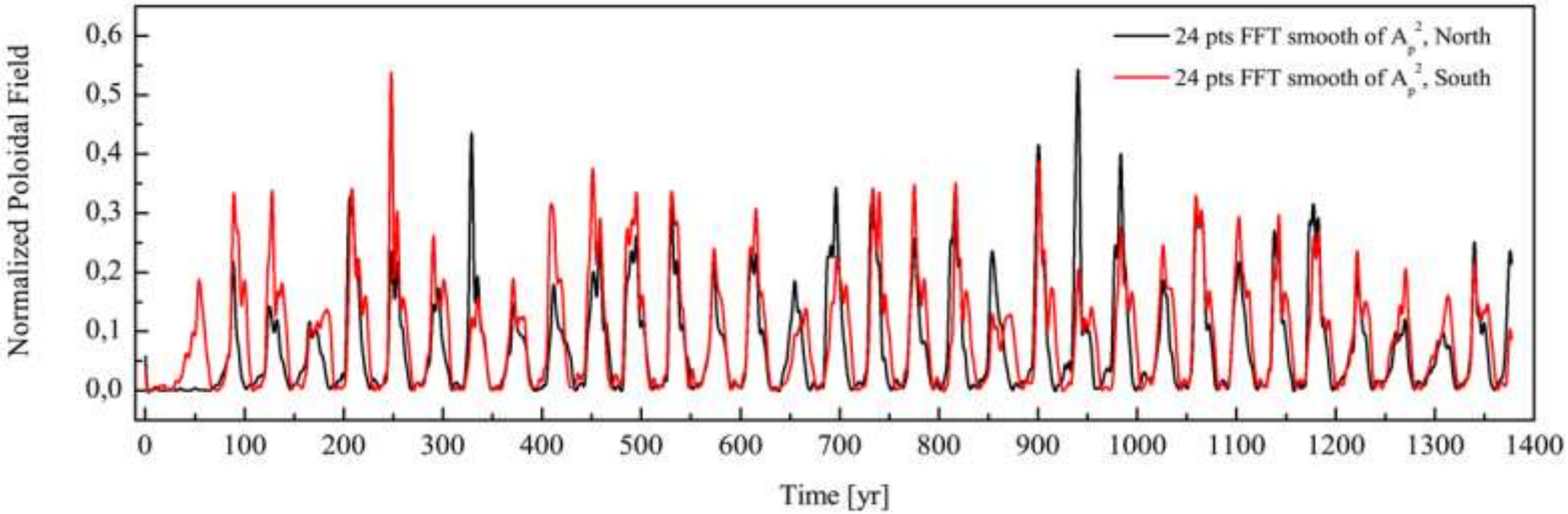


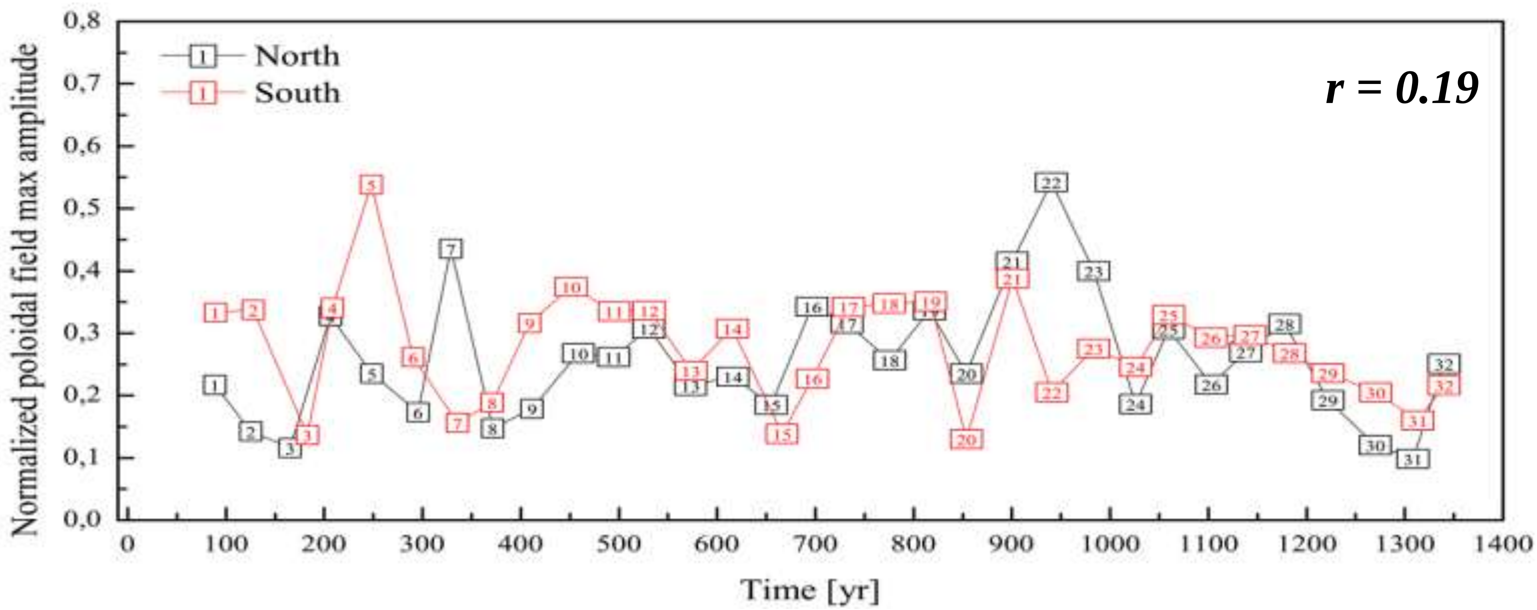


Histogram peaks at -2,6 yr. Tendency for minima to occur first on the northern hemisphere

PROXIES OF SOLAR ACTIVITY (2)

Dipolar field proxy



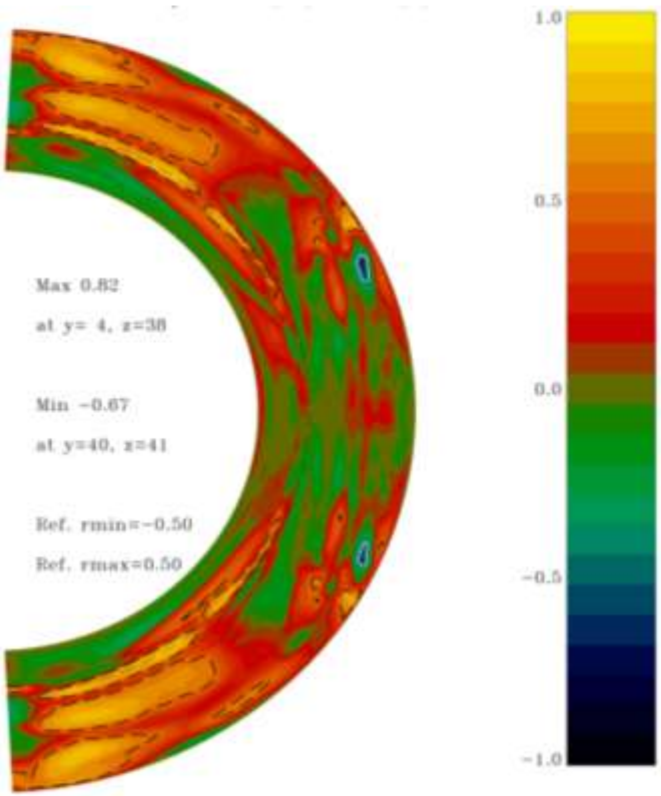


RELATIONSHIPS BETWEEN PROXIES (EXAMPLES...)

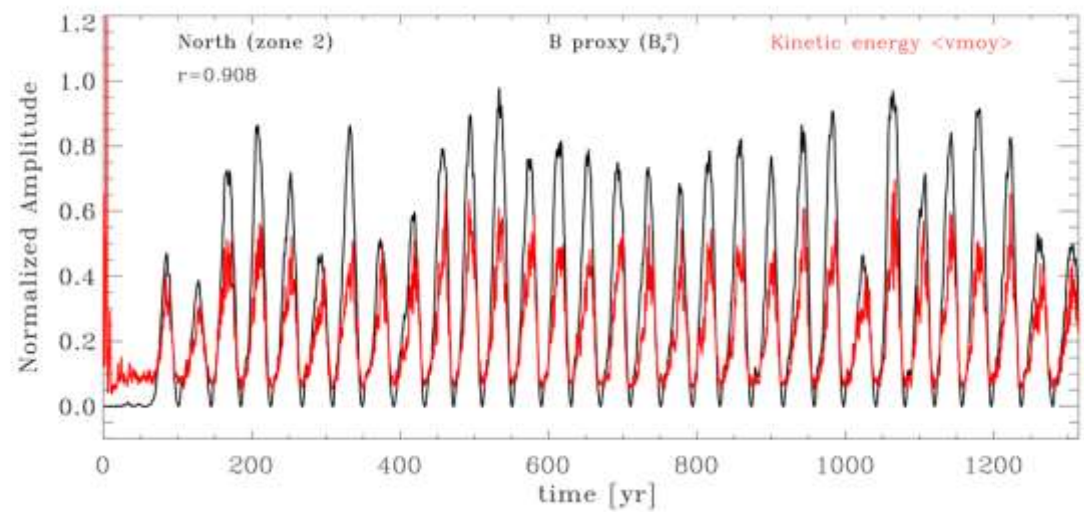
orrelations	Cycle N Amp. North	Cycle N Amp. South	Cycle N+1 Amp. North	Cycle N+1 Amp. South
Cycle N Amp. North	*1*	*-0.214*	*0.097*	*0.05*
Cycle N Period North	*-0.662*	*-0.079*	*-0.273*	*0.222*
Rising time N North	*-0.462*	*0.017*	*-0.19*	*0.044*
Dipole N Amp. North	*0.637*	*-0.23*	*0.021*	*-0.02*
Cycle N-1 Amp. South	*0.024*	*-0.035*	*0.435*	*-0.049*
Cycle N Period South	*-0.107*	*-0.228*	*0.147*	*-0.262*
Rising time N South	*-0.372*	*-0.011*	*0.168*	*-0.154*
Dipole N Amp. South	*0.061*	*0.634*	*-0.075*	*-0.024*

Note: complete table 24 x 24

HUNTING FOR OTHER RELATIONSHIPS…



Example: Correlation map between the toroidal field amplitude and U_θ



Comparison between the kinetic energy of the U_θ component compared to the proxy for the toroidal field

✓ **We can play the same game between all large scale field and flow components**

PRELIMINARY RESULTS SUMMARY

- ✓ Possibility to generate long stable solution with many cycles

- ✓ Hemispheric magnetic activity decoupling in terms of cycle amplitude. Does this implies independent dynamo saturation mechanisms for the two hemispheres?

- ✓ The Waldmeier rules are moderately reproduced in these cycles

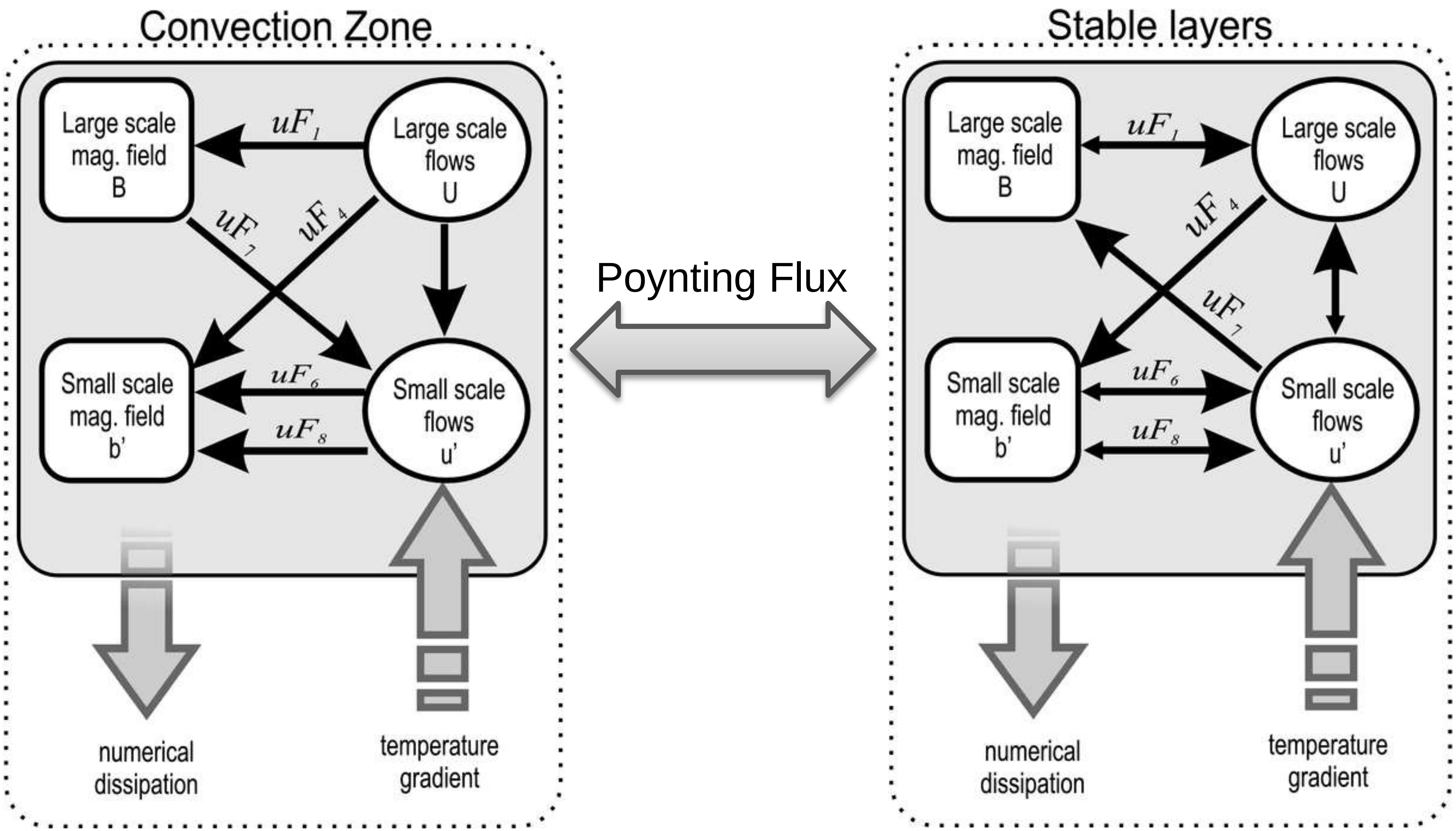
- ✓ Cyclic modulation of large scale flows, specially in the θ direction

- ✓ So far no precursor for the cycle amplitude have been found.

- ✓ Analysis keep in other fronts…

ONGOING ANALYSIS TO THE SIMULATIONS AND OTHER PRELIMINARY RESULTS (1)

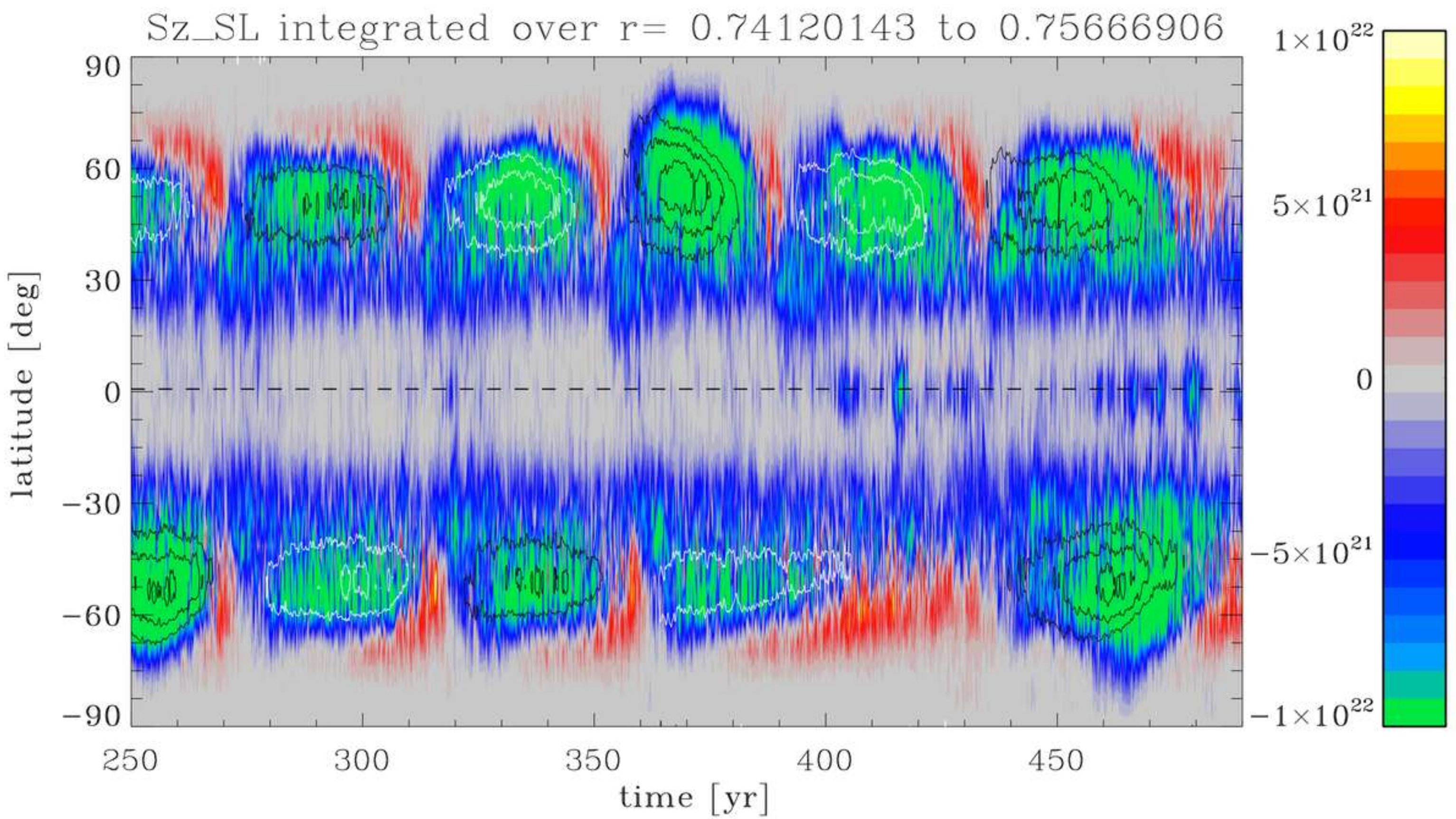
Exchanges between energy reservoirs…



Passos, Beaudoin, Cossette, Charbonneau

ONGOING ANALYSIS TO THE SIMULATIONS AND OTHER PRELIMINARY RESULTS (1)

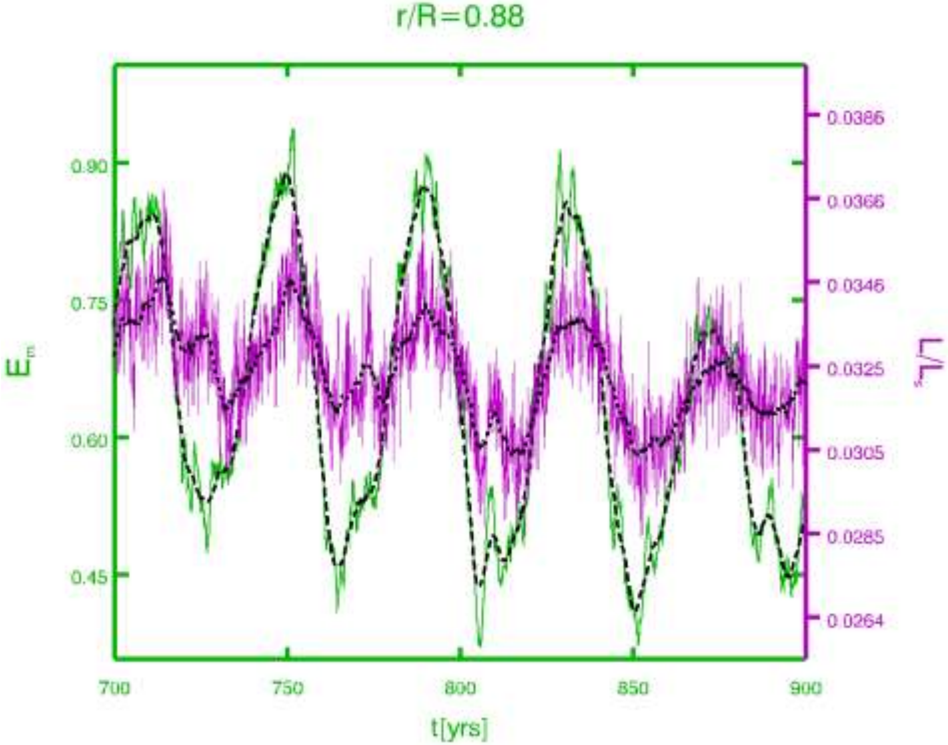
Radial component of the Poynting flux

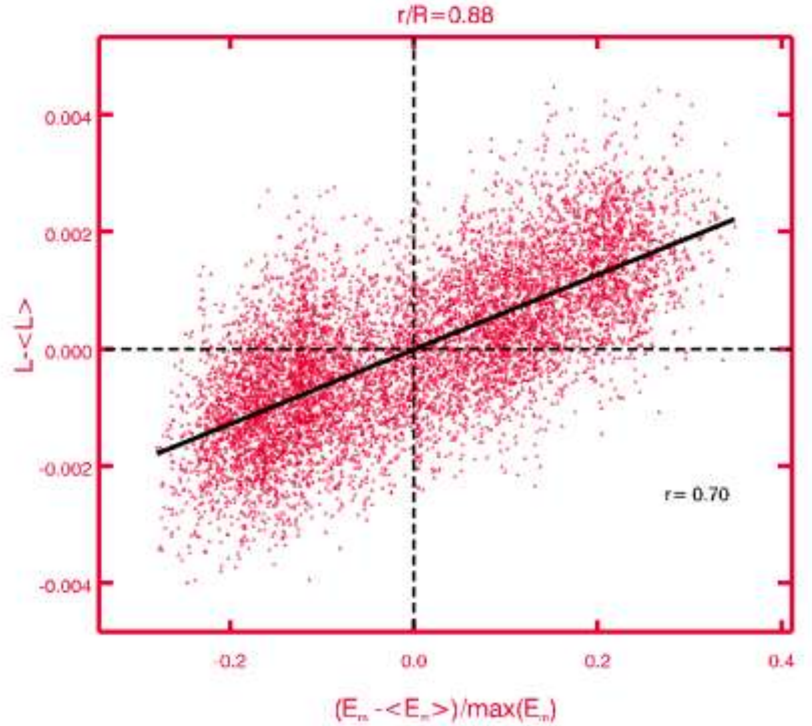


Passos, Beaudoin, Cossette, Charbonneau

ONGOING ANALYSIS TO THE SIMULATIONS AND OTHER PRELIMINARY RESULTS (2)

Convective energy cyclic modulation…

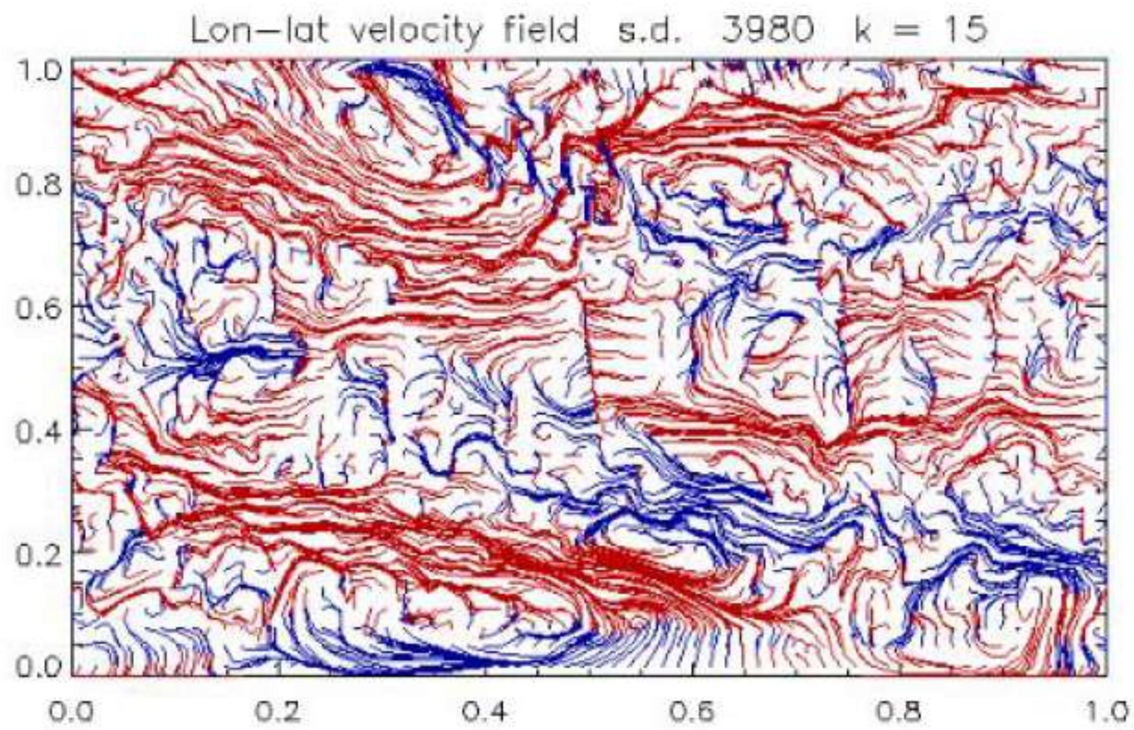




Cossette, Beaudoin, Charbonneau, …

ONGOING ANALYSIS TO THE SIMULATIONS AND OTHER PRELIMINARY RESULTS (3)

Tachocline MHD instabilities and the dynamo saturation



Ghizaru, Charbonneau, Smolarkiewicz

Stay tuned!

http://www.astro.umontreal.ca/~paulchar/grps

Energy evolution in the simulation