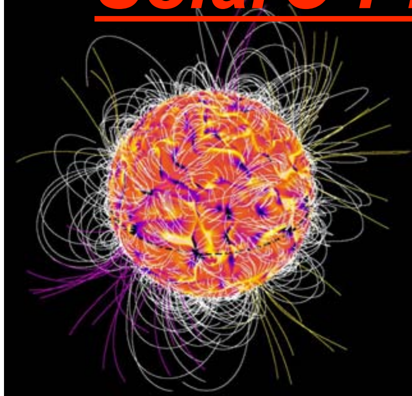
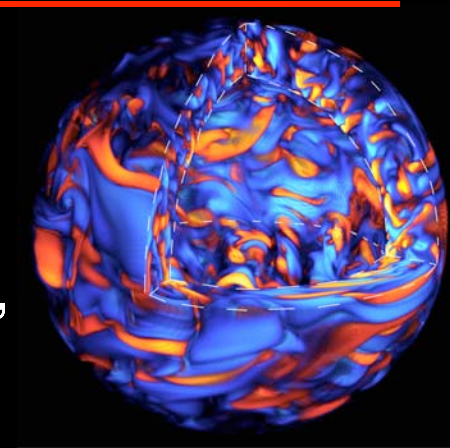
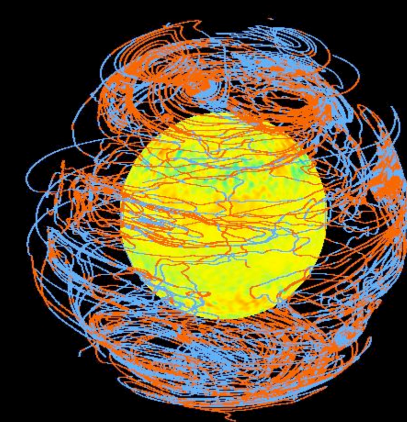
SolarC-Plan A: Unraveling The Origin of the Solar Magnetic Field





Allan Sacha Brun
Service d'Astrophysique/UMR AIM,
CEA-Saclay

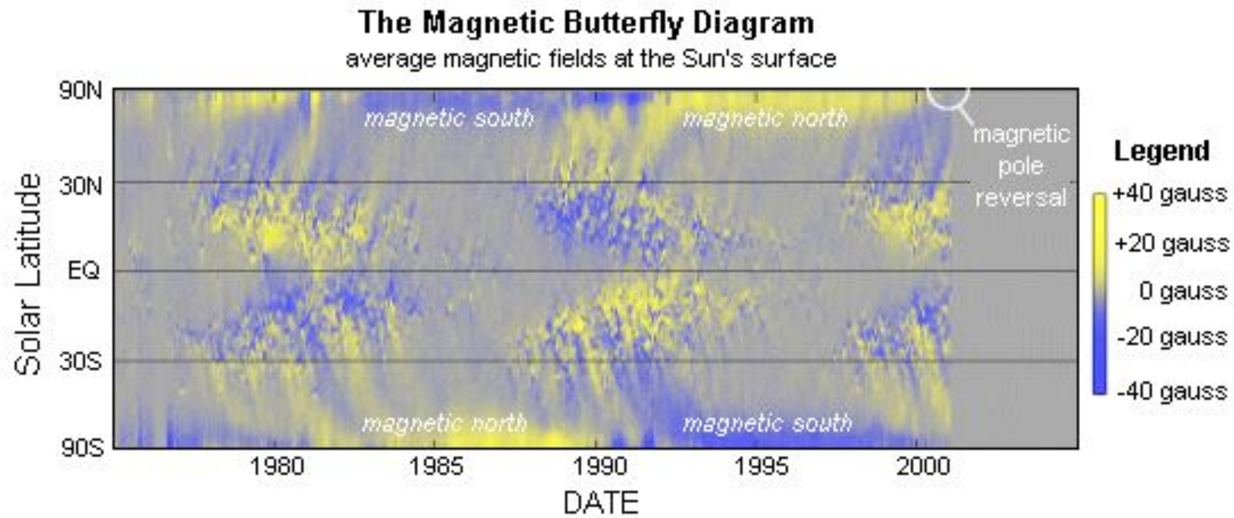
- Observational evidences of solar magnetism and current limitations
- 3D MHD simulations of the magnetic Sun: what is needed
- The Sun as a star: magnetism, rotation



Observational Contraints for the Solar Dynamo and their current limitation

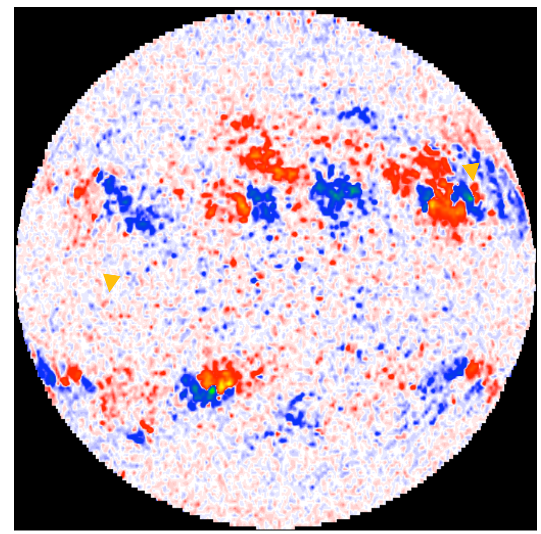
Magnetic Solar Cycle 23-24

(HAO, SST & Mt Wilson Data)



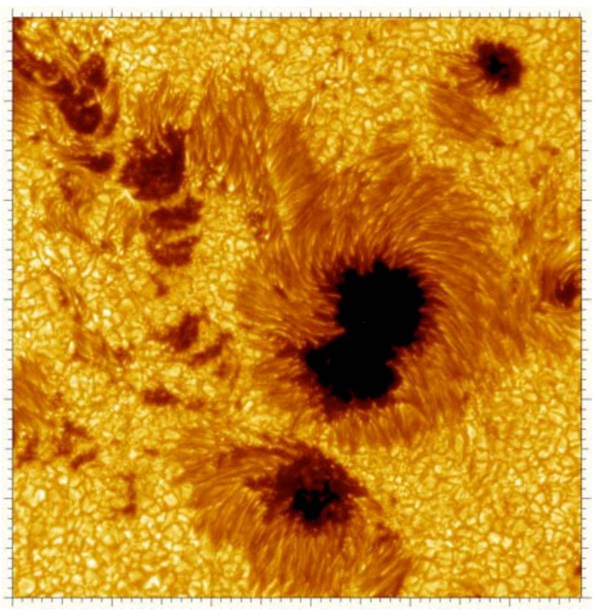
Regions

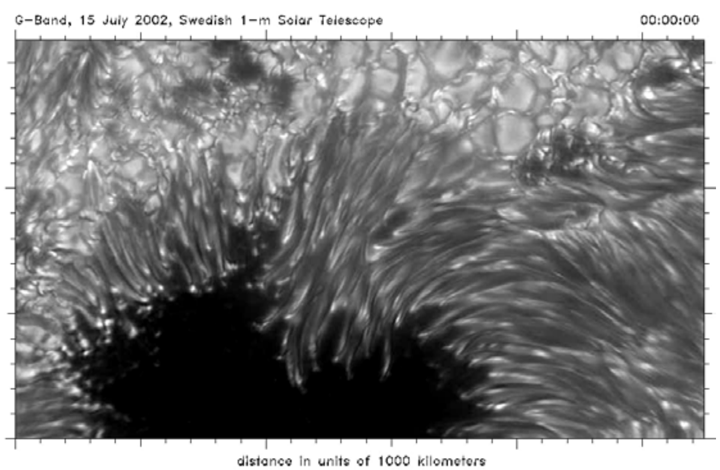
Quiet Active



5895.9Å Na I

Magnétogramme





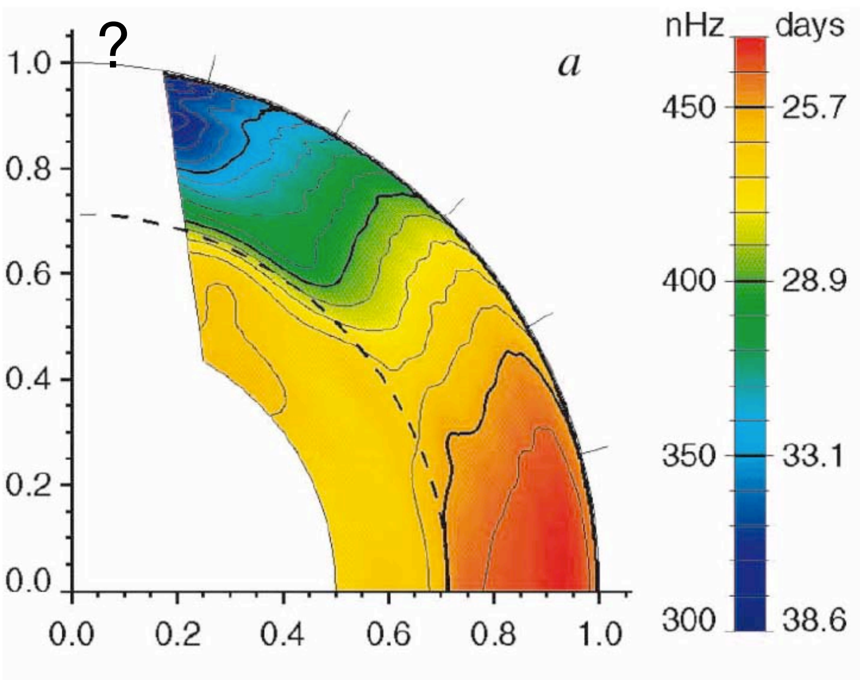
Small vs Large Scale Dynamos

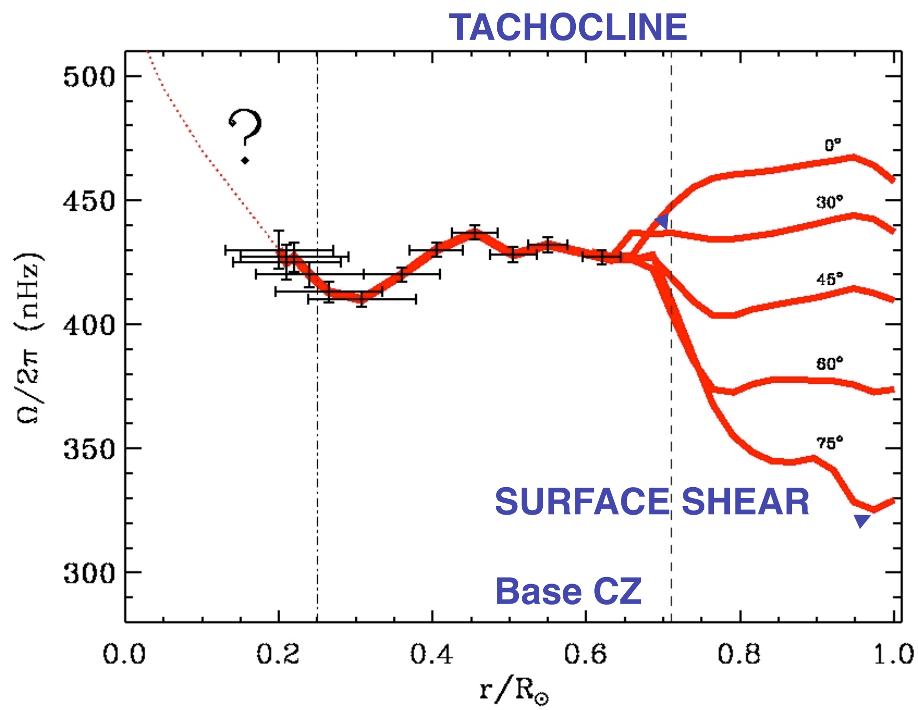
Wide range of dynamical scales!

Solar Internal Rotation

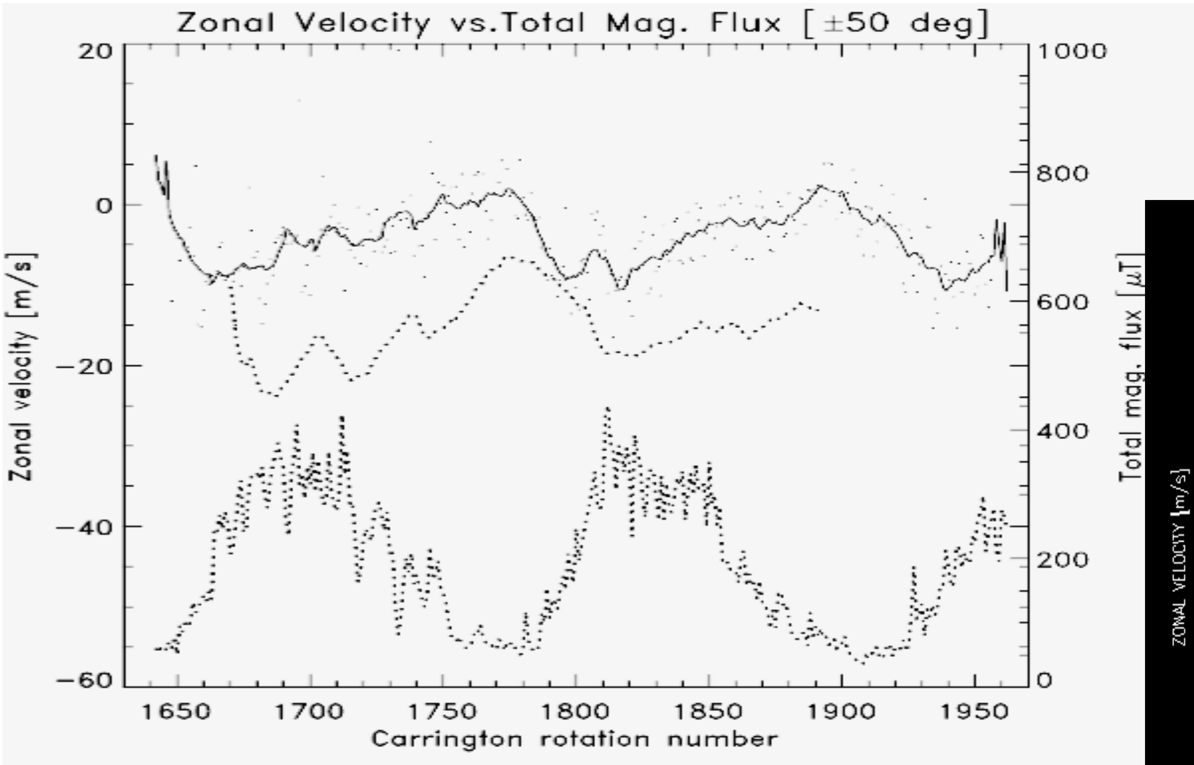
Helioseismology Results

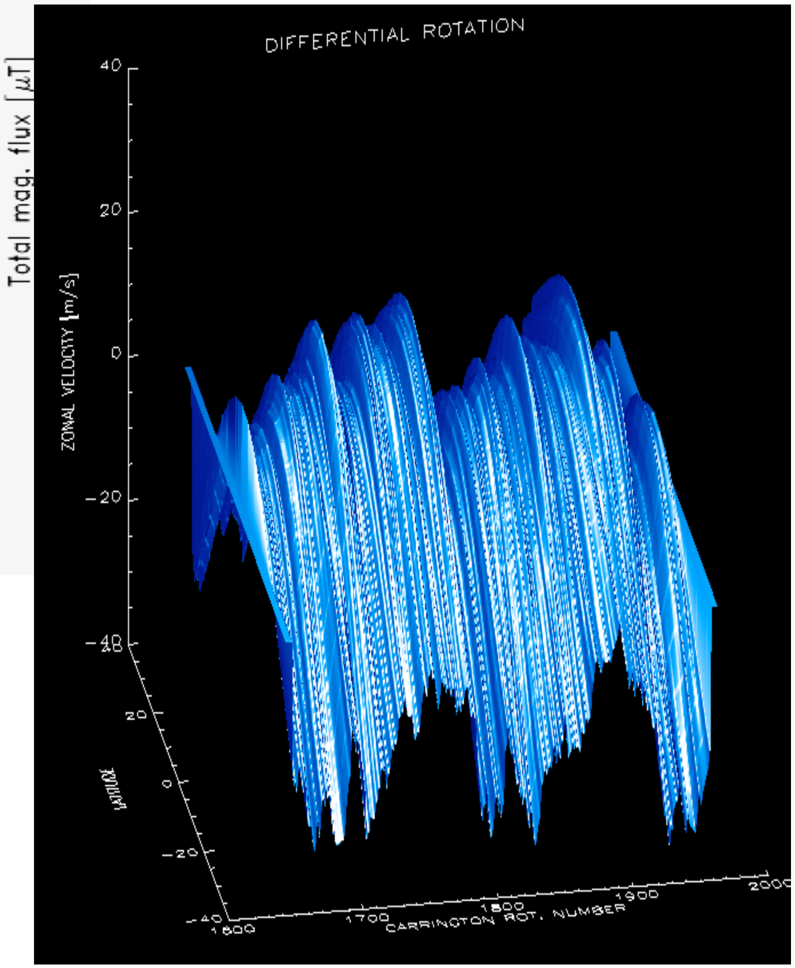
(GONG, MDI, GOLF data)





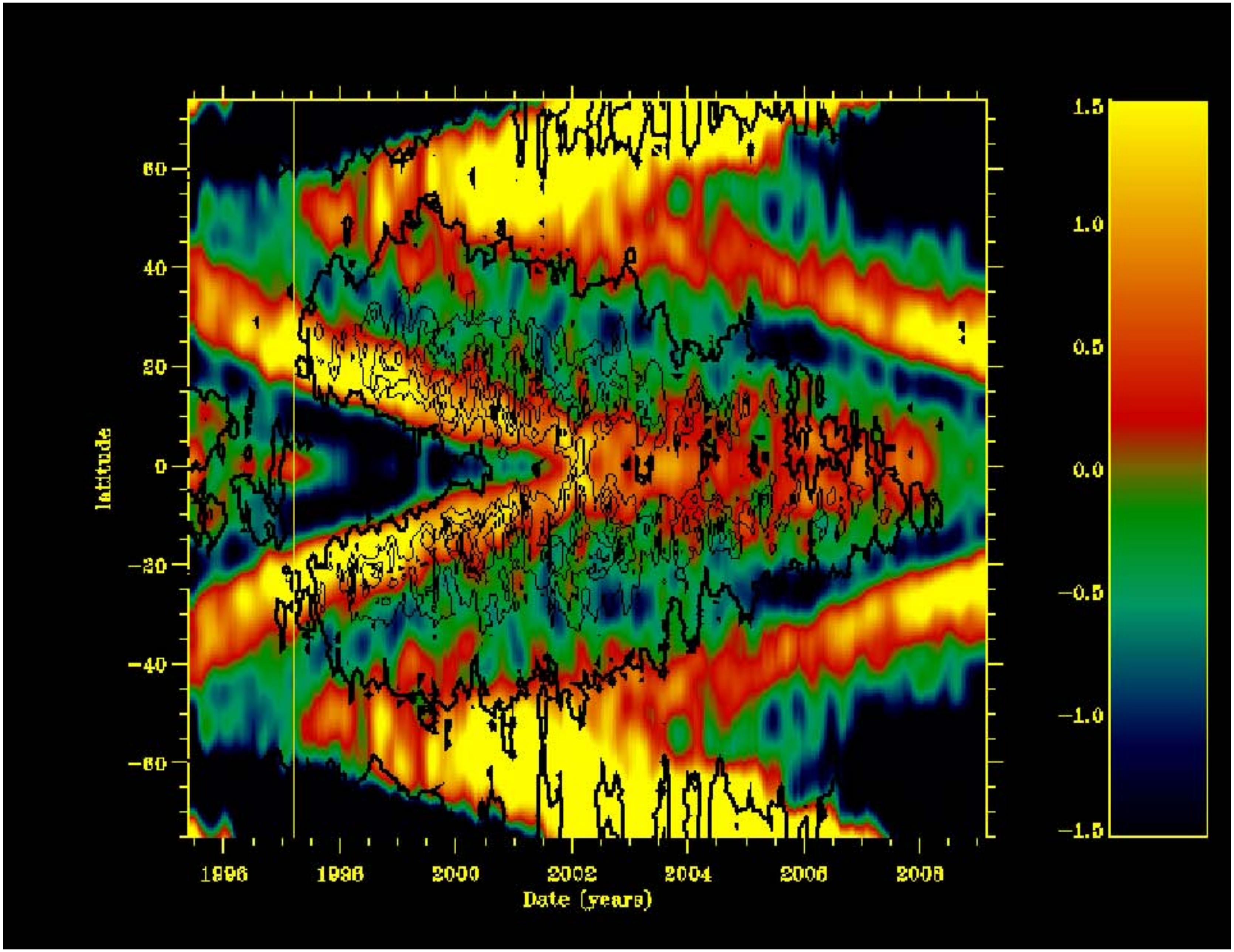
Modulation of Differential Rotation Amplitude with Cycle





Courtesy of Ambroz

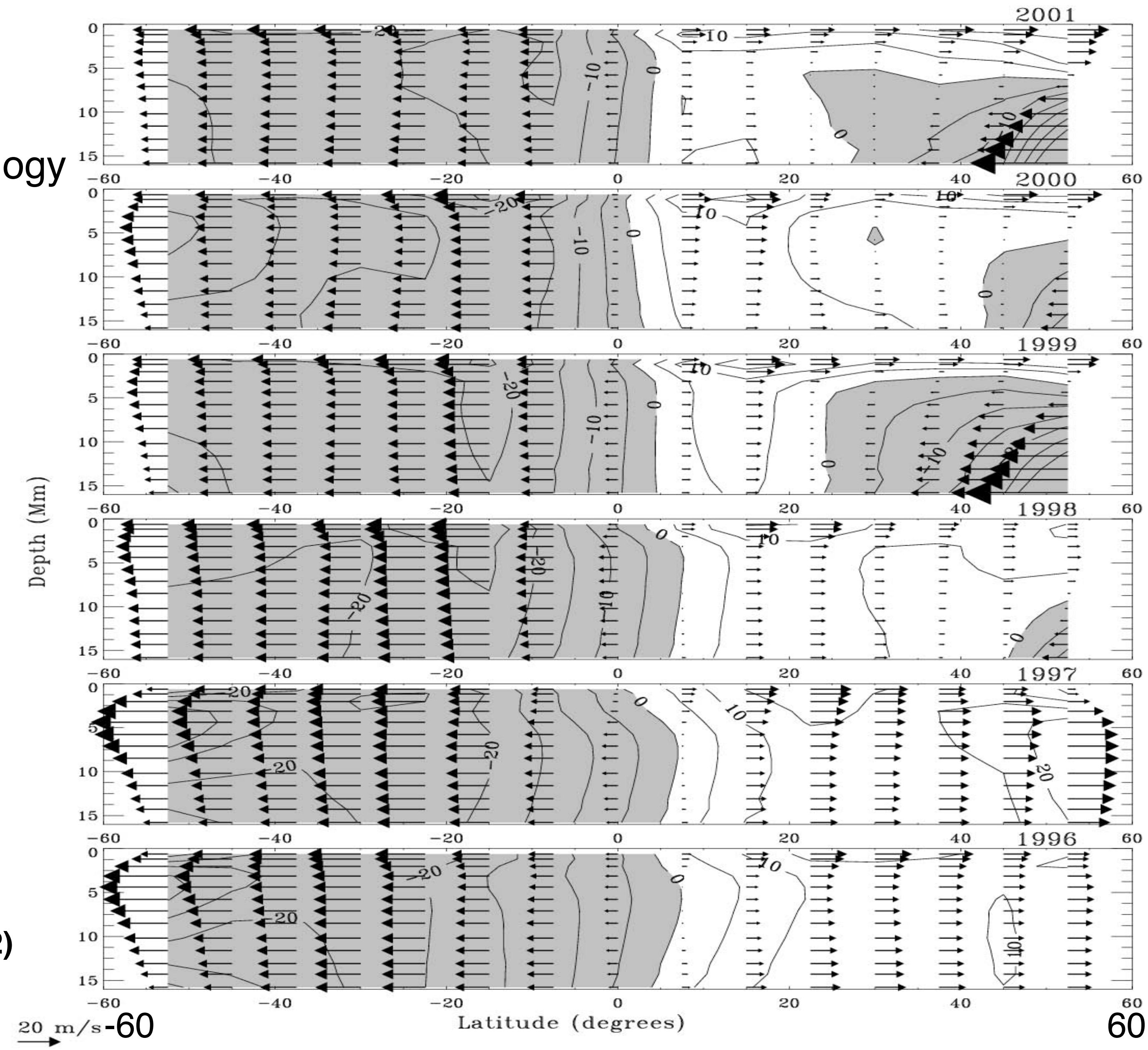
Torsional Oscillations



Meridional Circulation

More & more evidence for multi cellular MC

Local Helioseismology

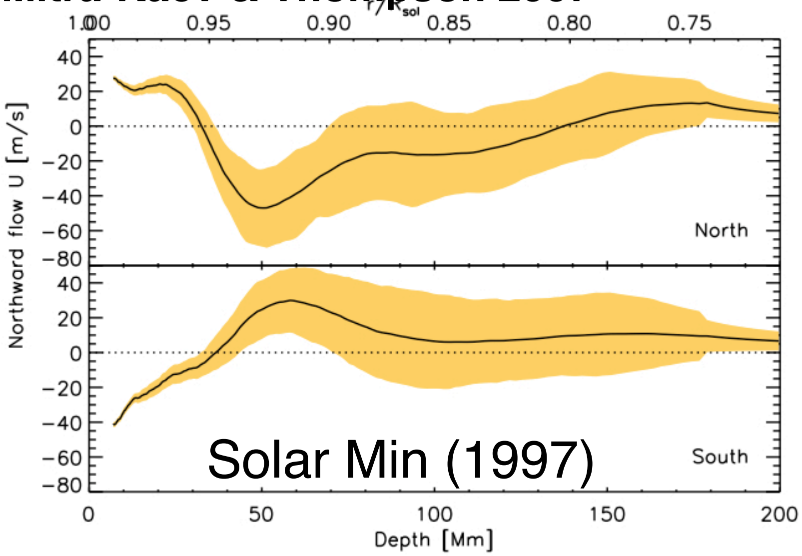


(Haber et al. 2002)

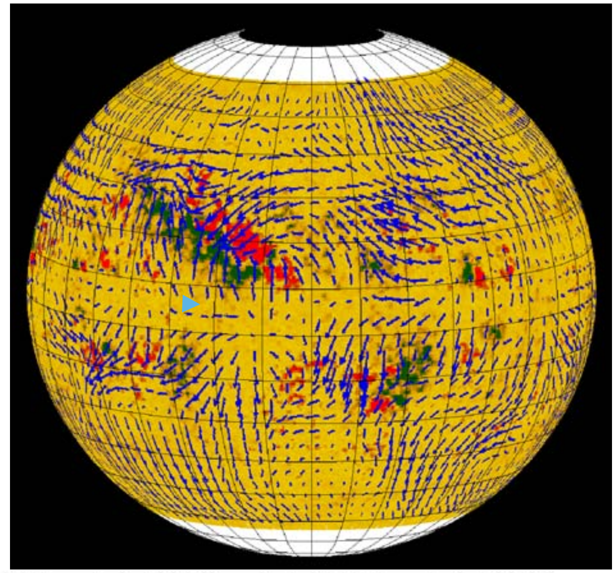
Meridional Circulation

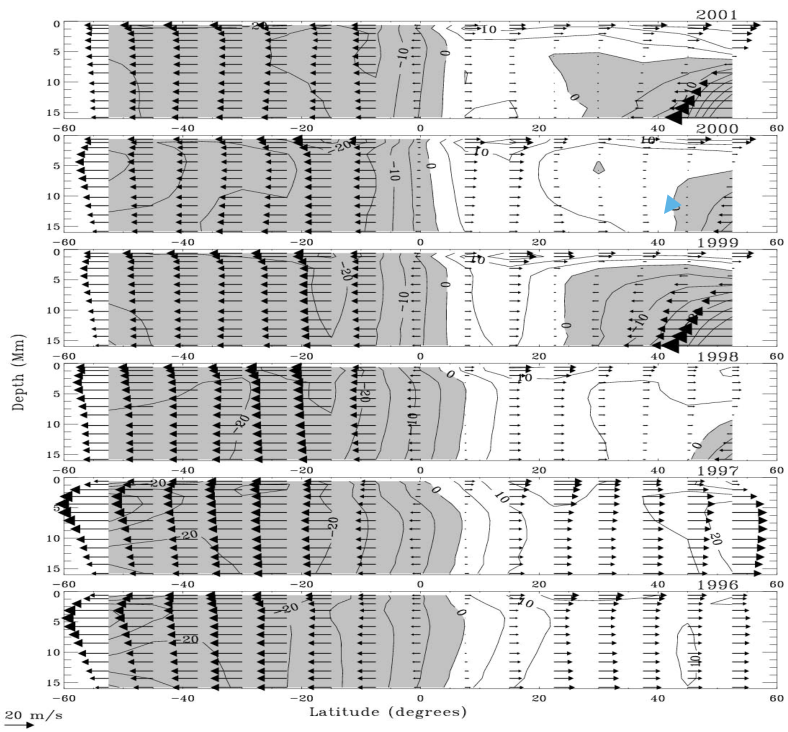
More & more evidence for multi cellular MC

Mitra-Kaev & Thompson 2007

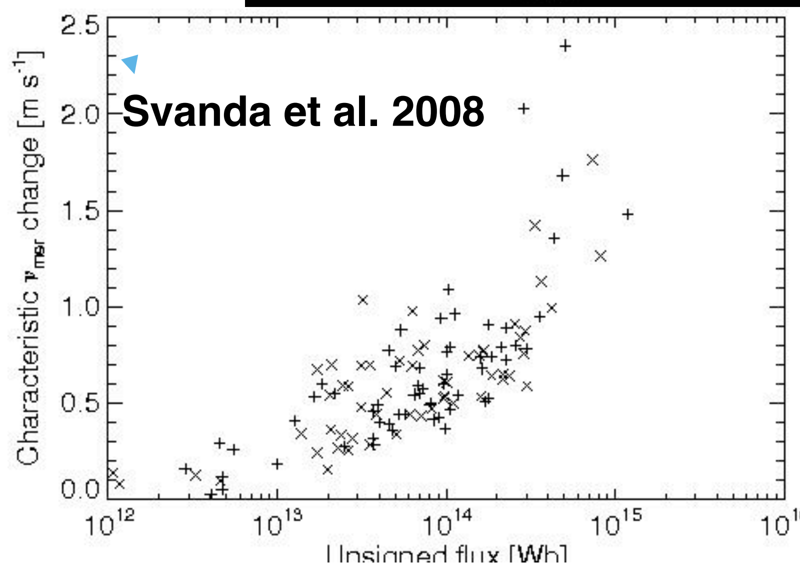


Influence of B (active region) on MC



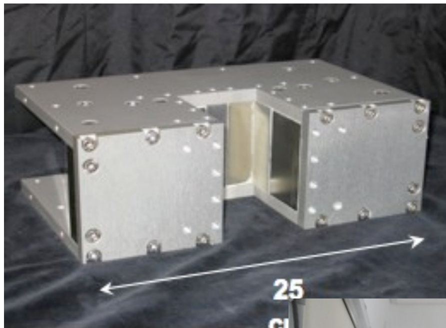


(Haber et al. 2002)



See also Hathaway et al. 1996, Gizon 2004, Zhao & Kosovichev 2004, etc…

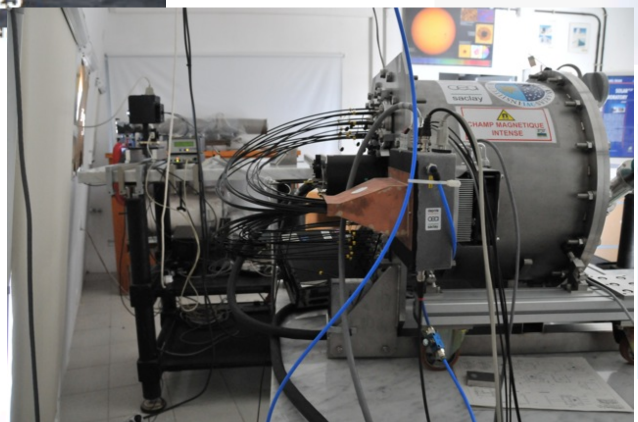
Global Helioseismology: G modes

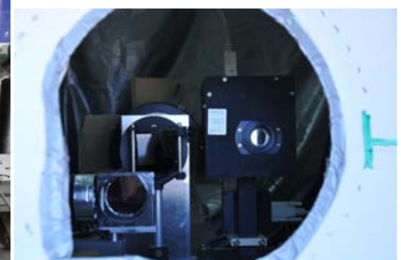


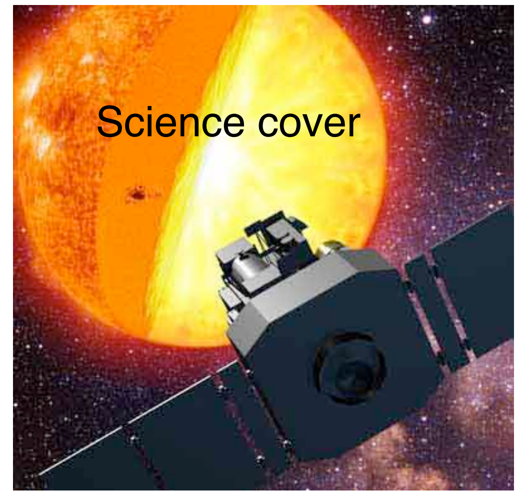
Golf-NG

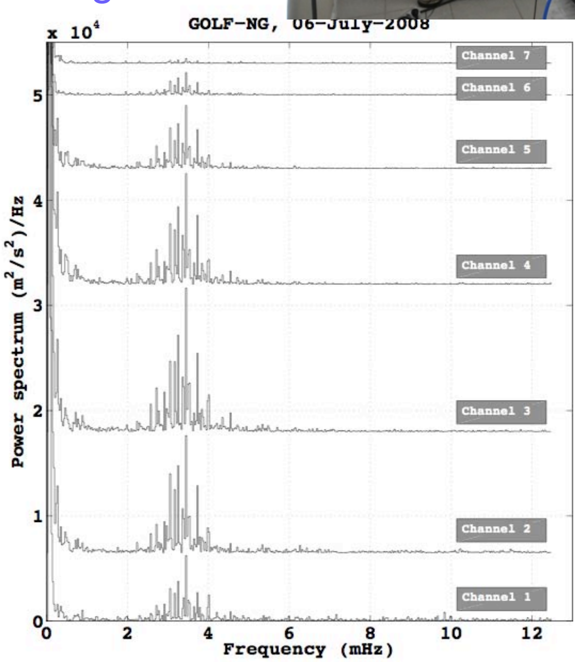
Great opportunity to detect them!
Allow a much better determination of tachocline, radiative interior and inner dynamics (fields, shear, rotation)

Only:
15 kg
15 Watt
Low Bps
So ok for margin left





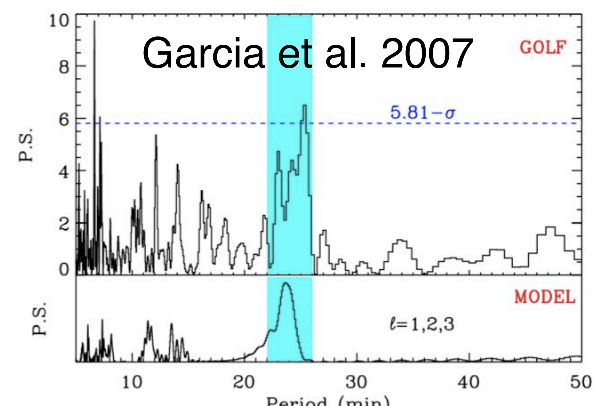




Multi-channel Observations of sodium doublet

Low noise and Granulation vs depth allows detection of G-modes

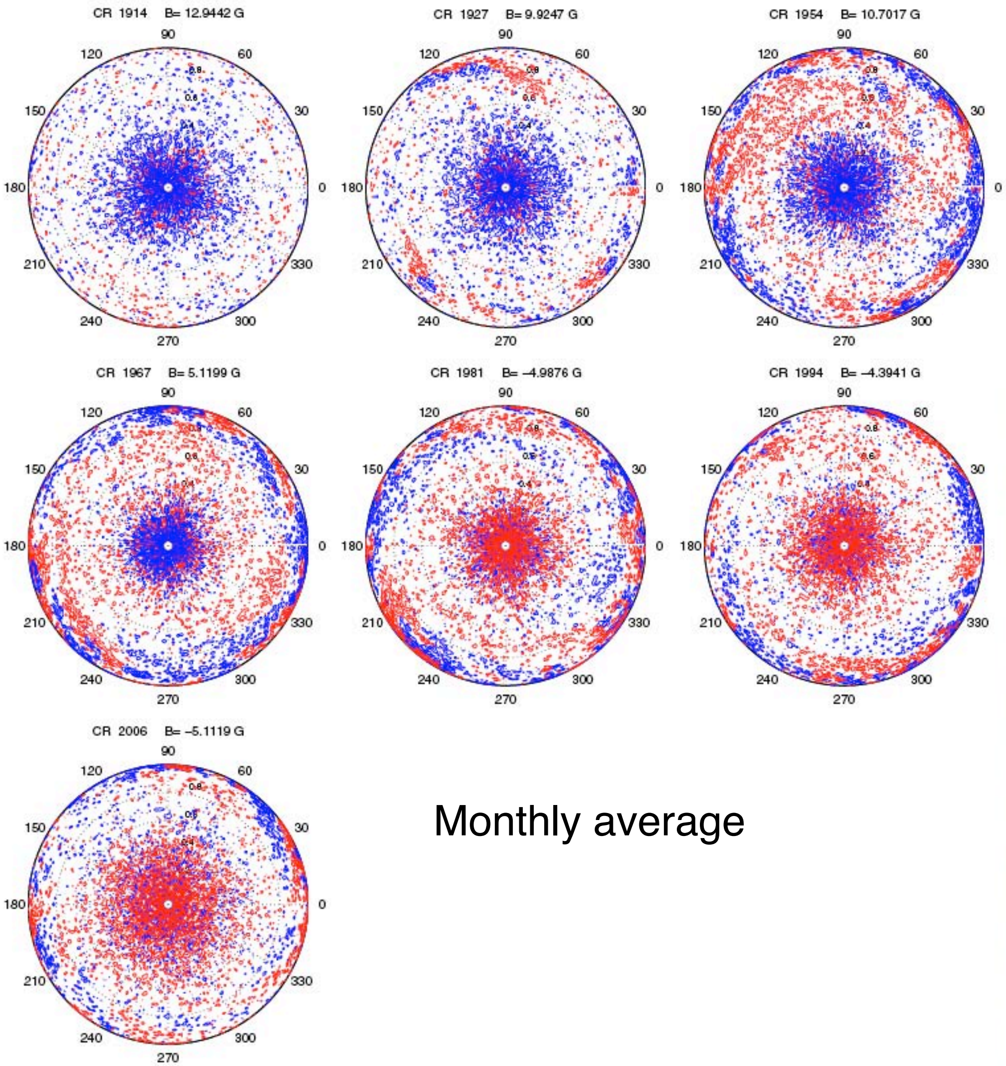
First test in Teneriffe



G-mode envelope

Polar Flux and Reversal

E. E. Benevolenskaya: Polar magnetic flux on the Sun in 1996–2003 from SOHO/MDI data

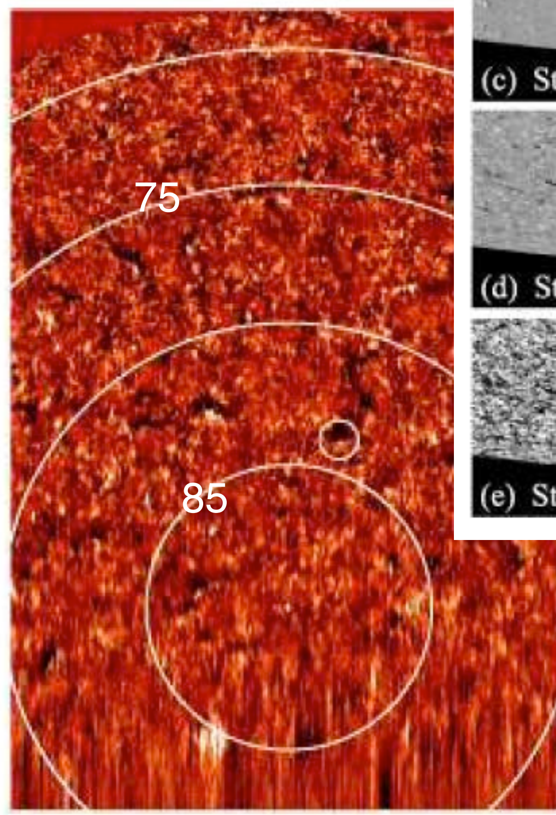


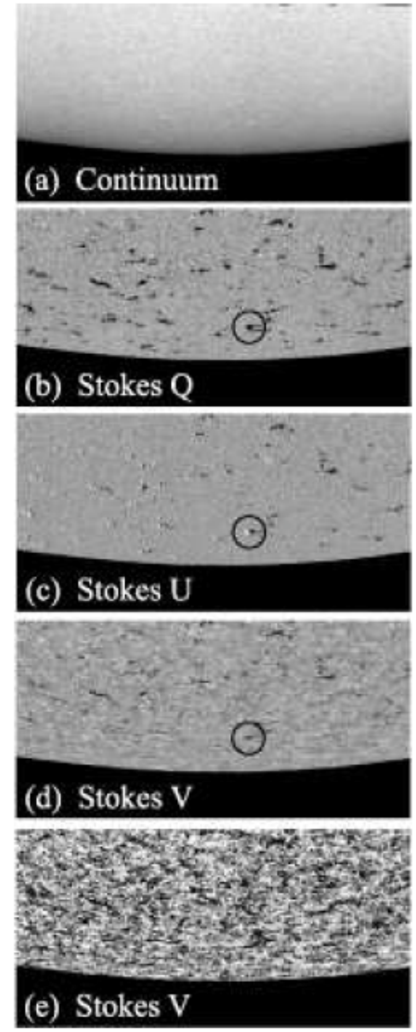
Monthly average

No high cadence continuous observations

Hinode

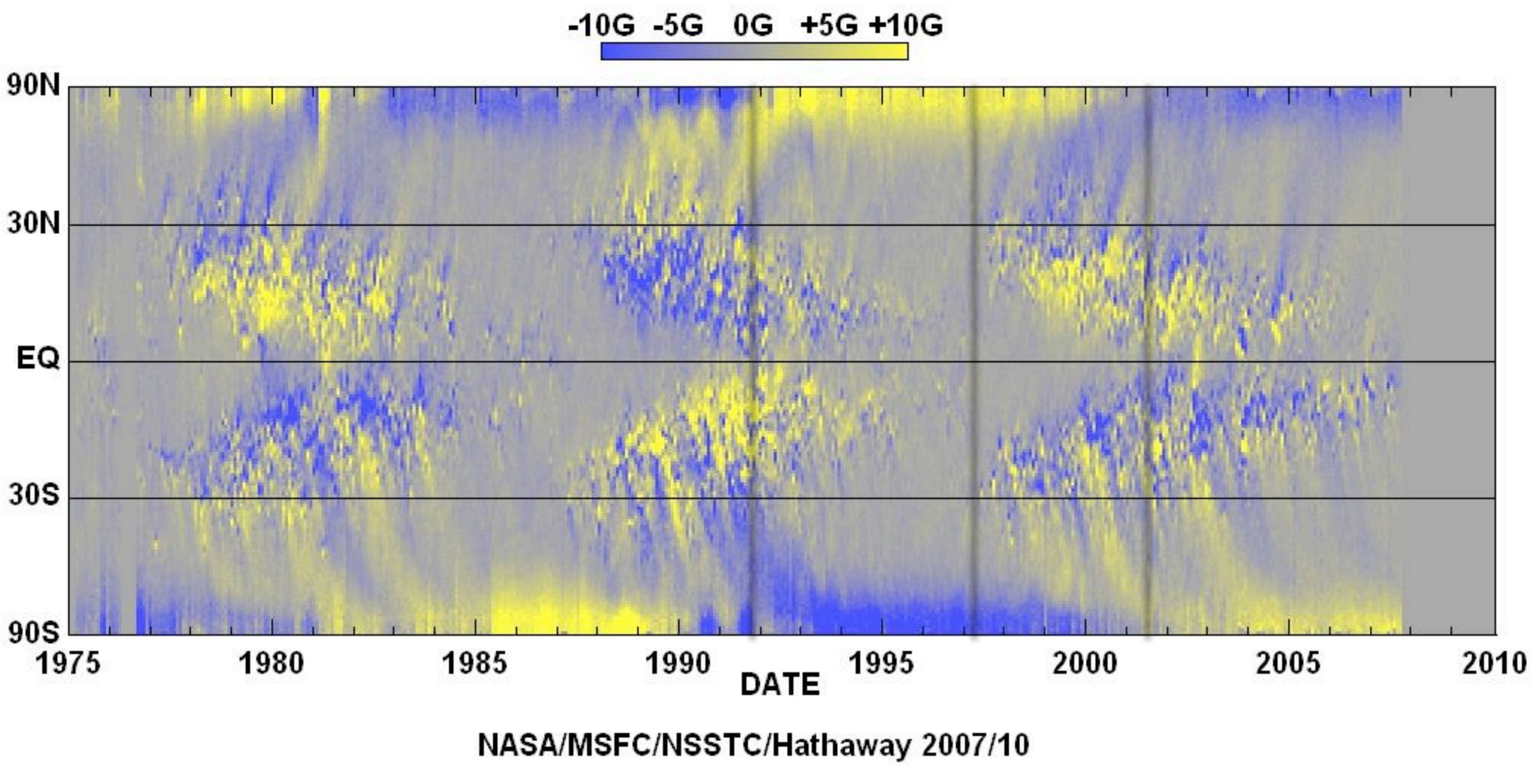
Tsuneta et al. 2008



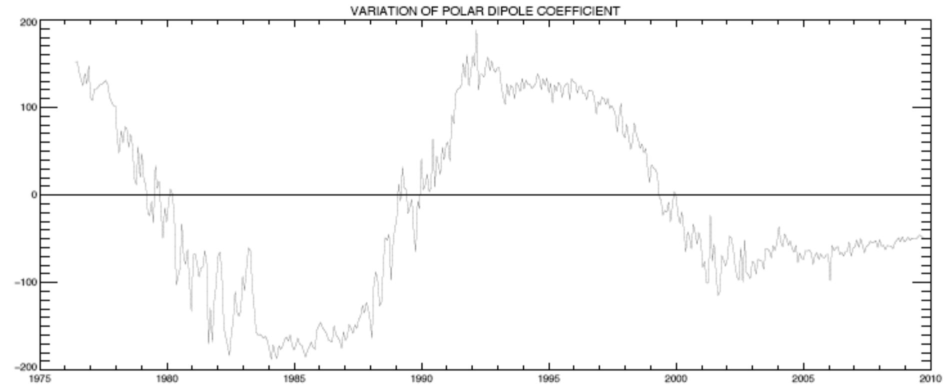


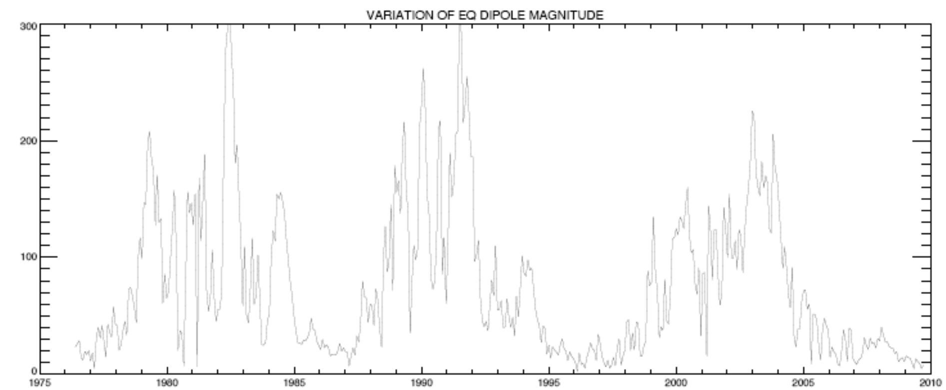
No seismology

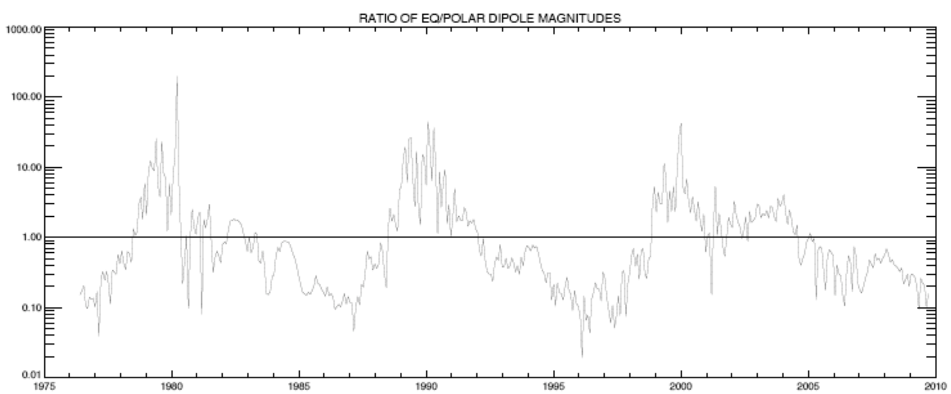
~90° Phase lag between Poloidal and Toroidal Fields



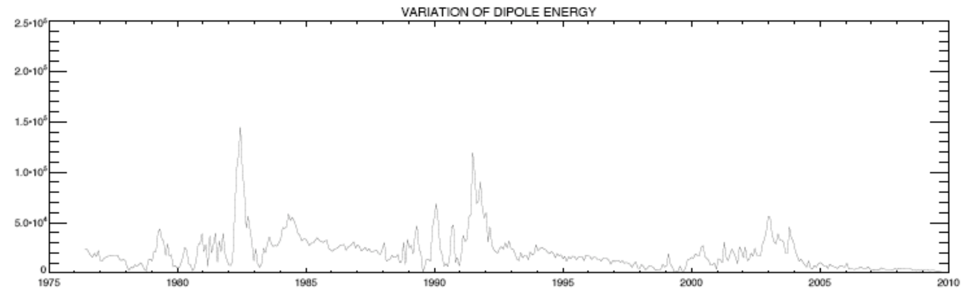
Dipole vs Quadrupole Amplitude

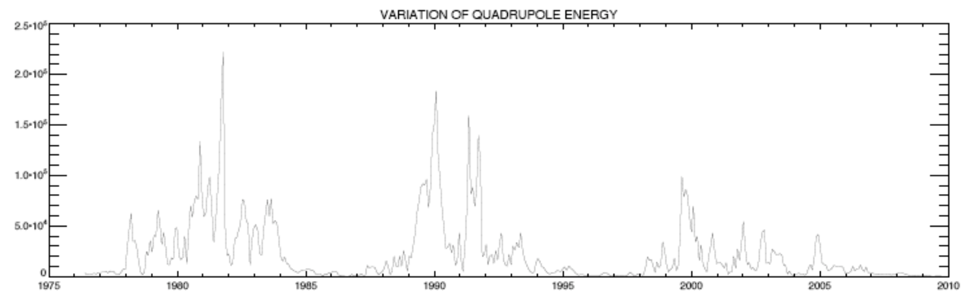


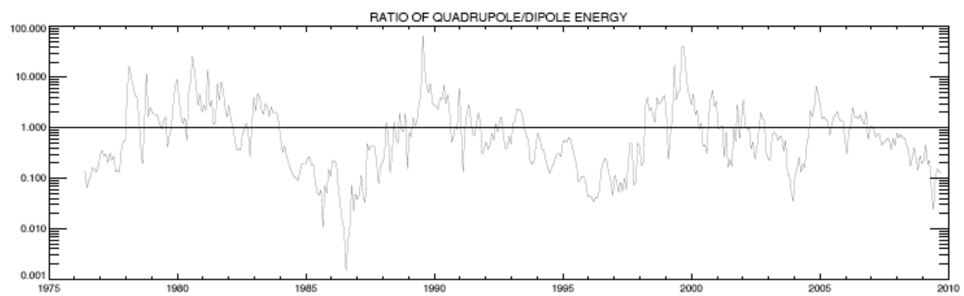




Key to determine relative amplitude with accuracy near polar reversals







Brun, Derosa, Hoeksema 2010

What Observations are Missing Today?

Surface Observations (High Temporal Cadence and Spatial Resolution):

• Constraining High latitude profile of Meridional Circulation
• Constraining High latitude profile of Differential Rotation
• Constraining Temperature latitude profile (via TSI)
• Characterizing Magnetic field in high polar region: Continuously no averages
• Quantifying exact phasing between poloidal and toroidal field and dominant mode
• Magnetic helicity budget and flux

Deep Observations (through local or global seismology)

• Constraining radial and latitudinal profile of MC
• Constraining radial and latitudinal profile of Diff Rot including Tachocline
• Constraining thermal structure
• Detecting gravity modes and sounding the energy production region
• Constraining profile of Rotation deep into the interior
• Constraining topology and amplitude of primordial field
• Link between magnetic helicity, dynamo action and solar activity (flux emergence)
• History of angular momentum => stellar physics
• Solar dynamo => stellar dynamo => magnetic field

Multi-D Models of the Solar Dynamo and Magnetism

A Theoretical View of the Sun's Interior Dynamics

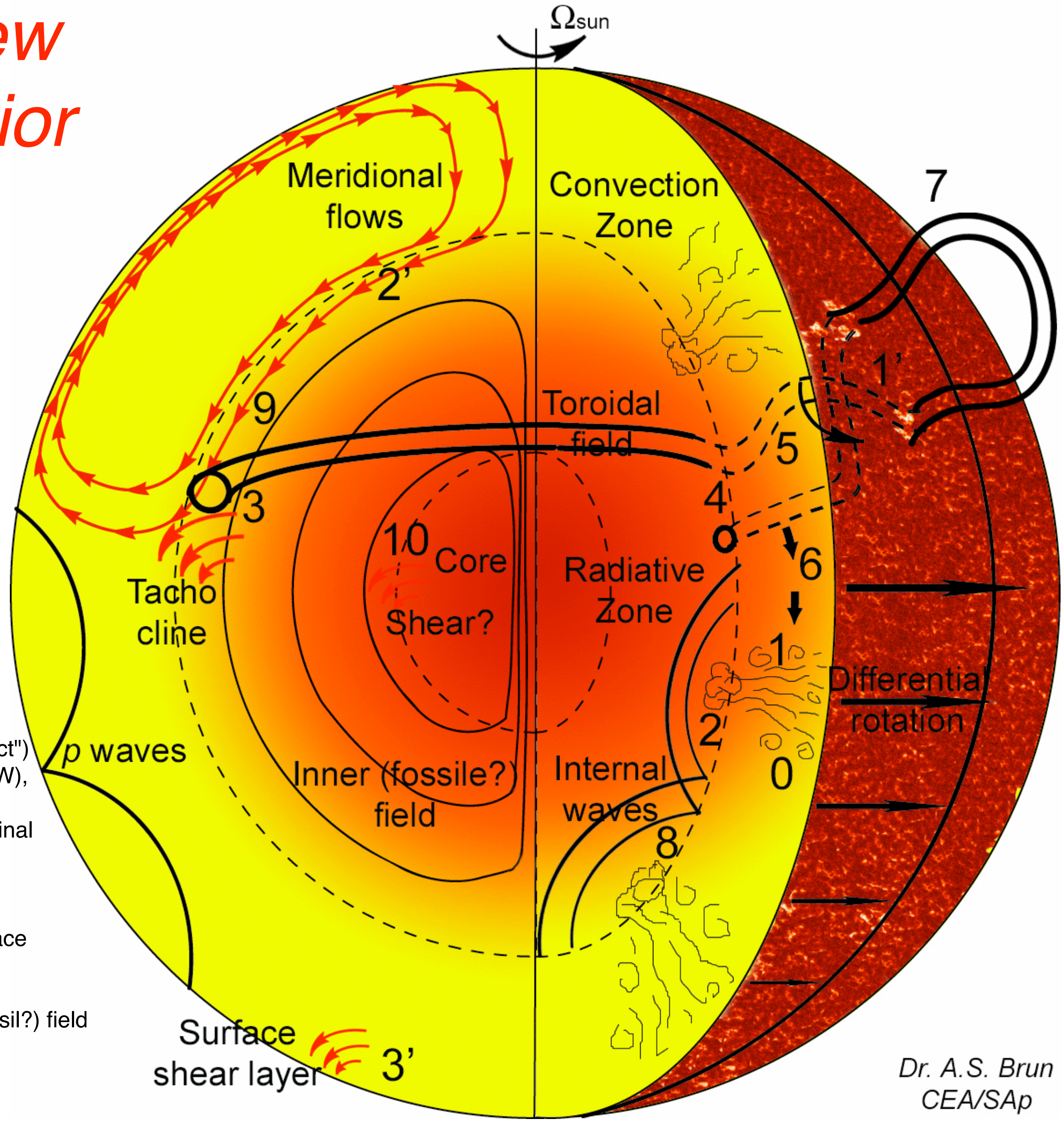


Figure Caption:
0: Turbulent convection (plumes)
1: Generation/self-induction of B field ("alpha-effect")
or 1': Tilt of active region, source of poloidal field
2: Turbulent pumping of B field in tachocline
or 2': Transport of B field by meridional flows
in CZ into the tachocline
3: Field ordering in 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?

Dr. A.S. Brun
CEA/SAp

What is needed to Constraint Solar Dynamo Theory

Interface vs distributed Dynamo : location of global dynamo

Alpha-Omega vs Babcock-Leighton : choose which models/paradigm, need to identify transport processes

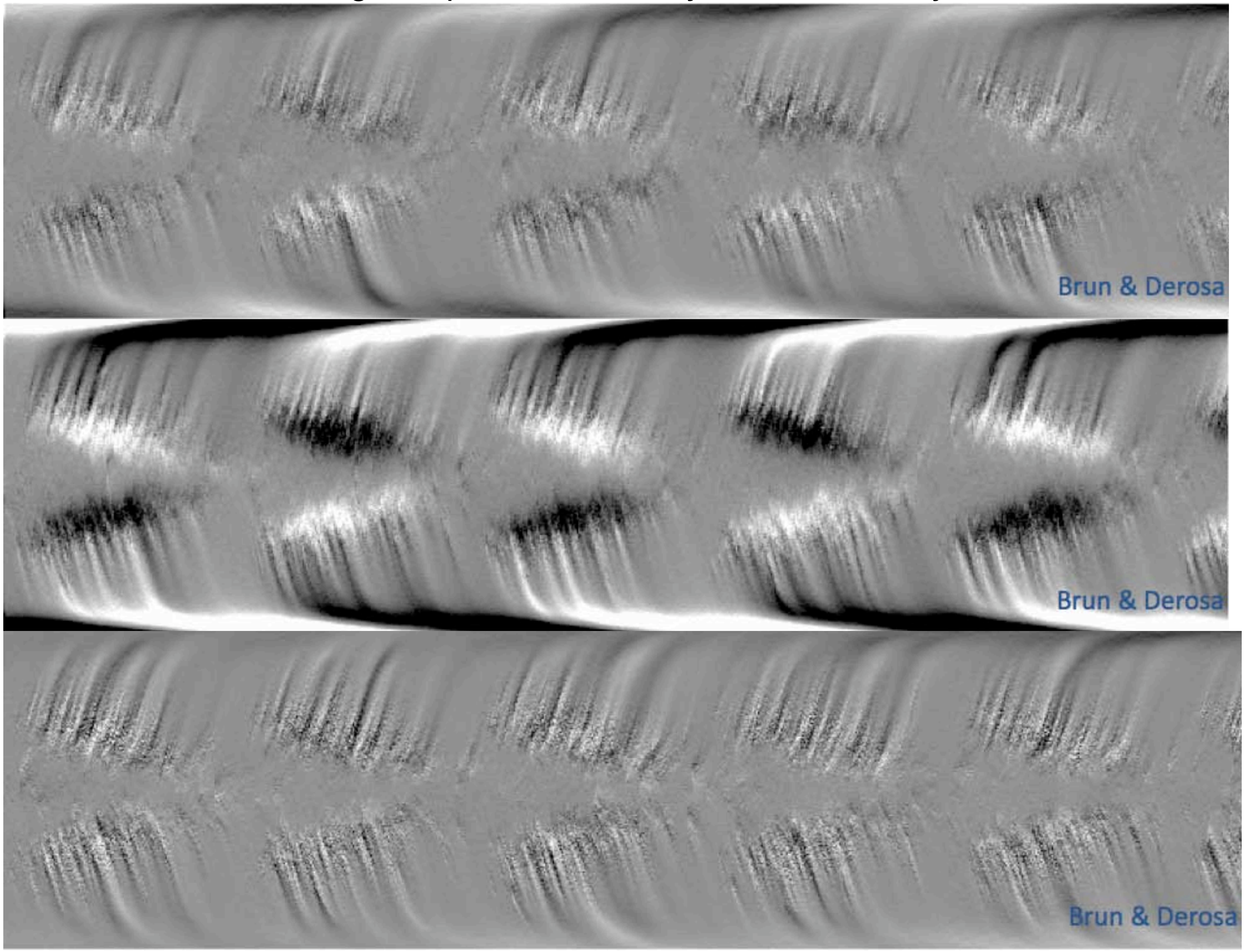
Key ingredients:

• Flow helicity and vorticity => alpha effect vs depth and latitude
• Large scale flows: topology, amplitude, variability of meridional circulation and differential rotation at all latitudes and as deep as possible
• Rotation profile: tachocline, radiative interior => angular momentum history
• Transport processes (pumping of field, diffusion, advection…)
• Large Scale magnetic field topology and amplitude in interior
• Relative amplitude poloidal/toroidal, temporal phasing, spatial location
• Flux emergence at all latitudes and scales, substructure of active regions
• Magnetic helicity budget, how dynamo generated field are build « conserving » Hmag?

Surface Flux Transport models

Strength of polar branch key to constraint dynamo!

Brun
Derosa
2010



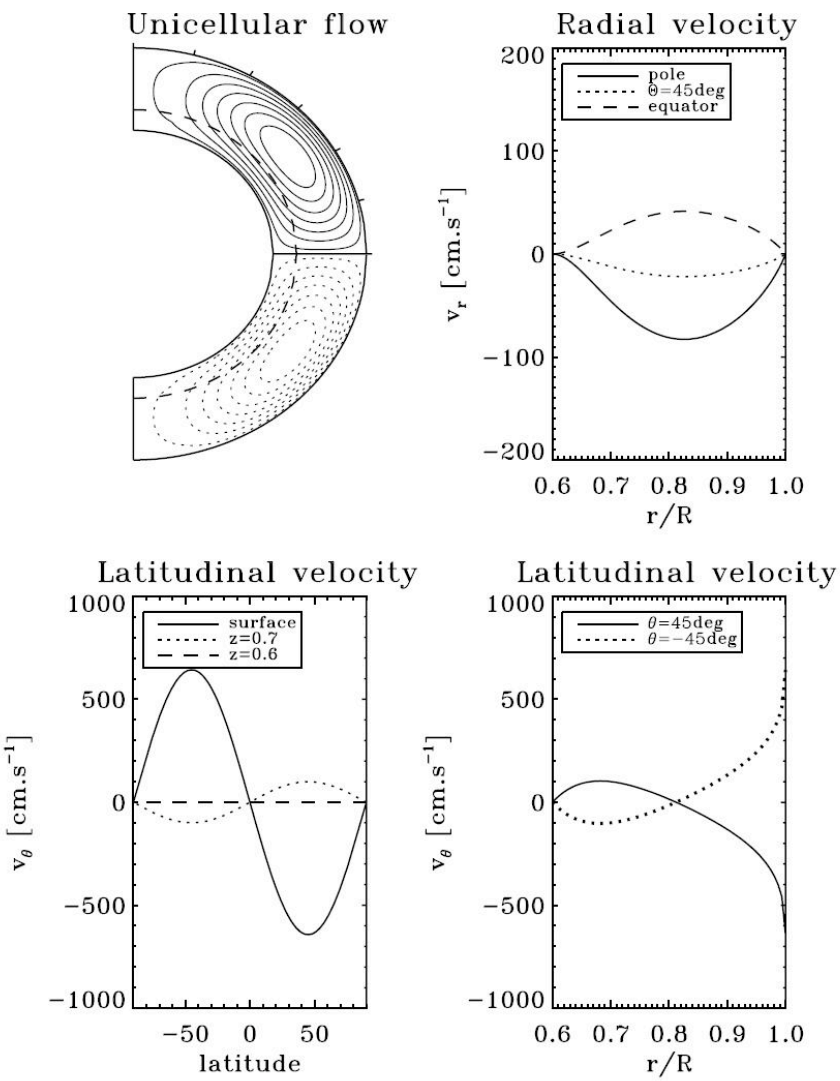
Joy's Law

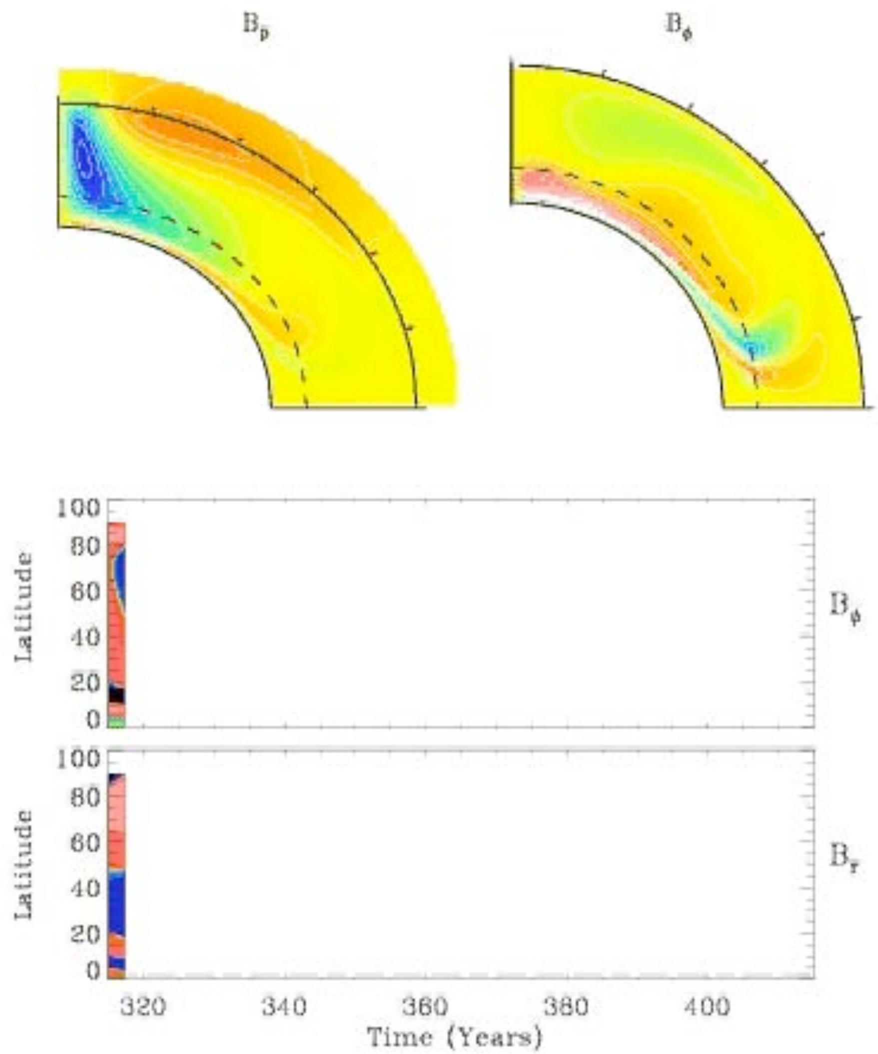
~ 20°

~ 0°

2D Mean Field models: Babcock-Leighton

Standard model: 1 cell per hemisphere





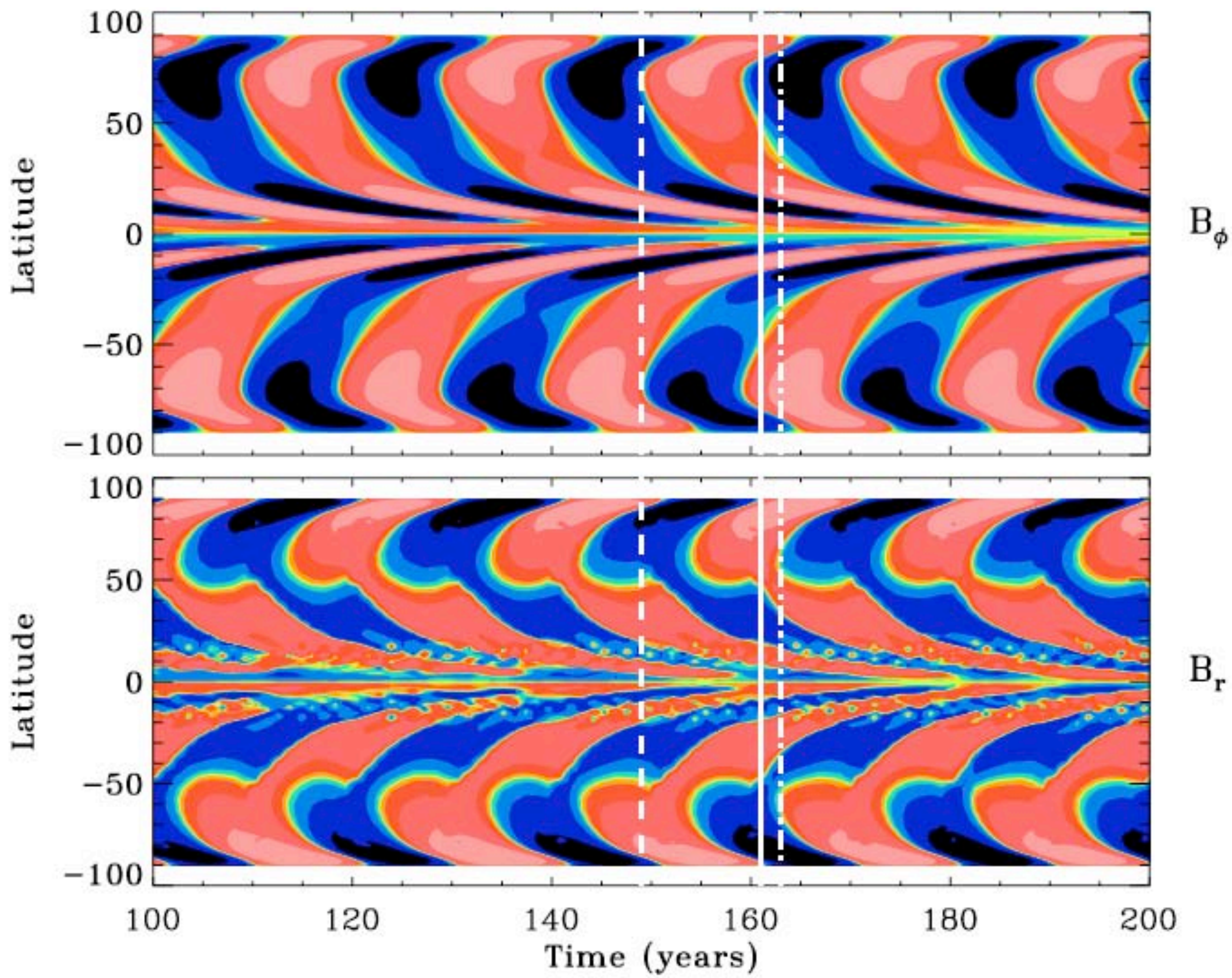
Jouve & Brun, 2007 A&A, 474, 239

Check Benchmark international: Jouve et al. 2008, A&A

2D Mean Field models: Babcock-Leighton

Standard model: 1 cell per hemisphere

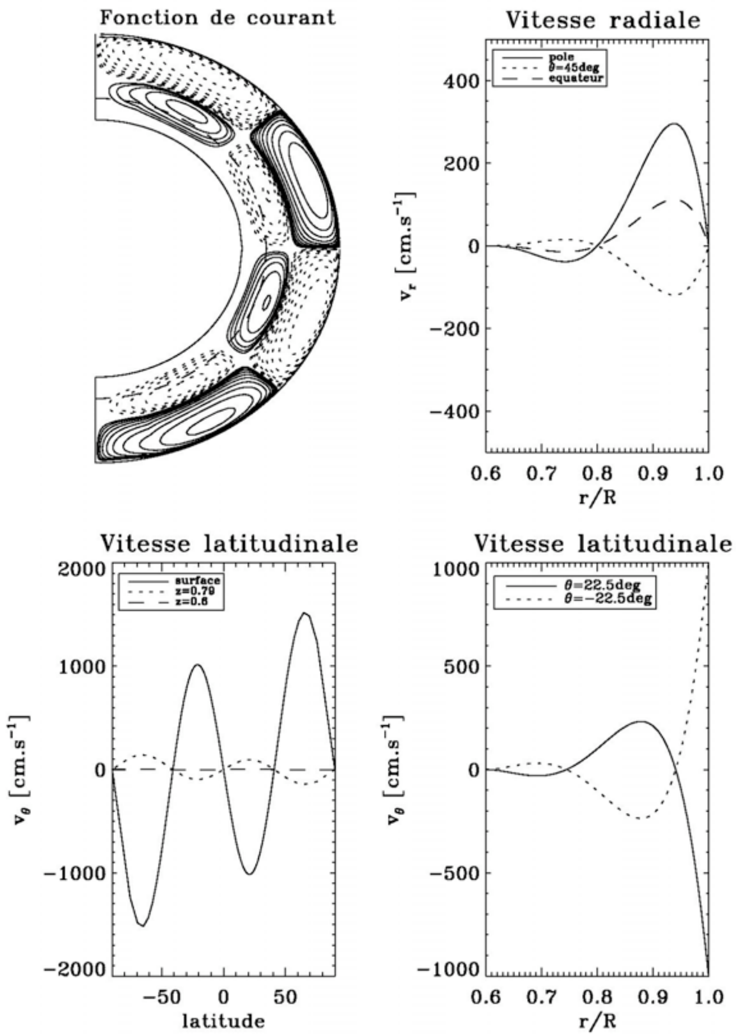
Phasing
of toro/polo

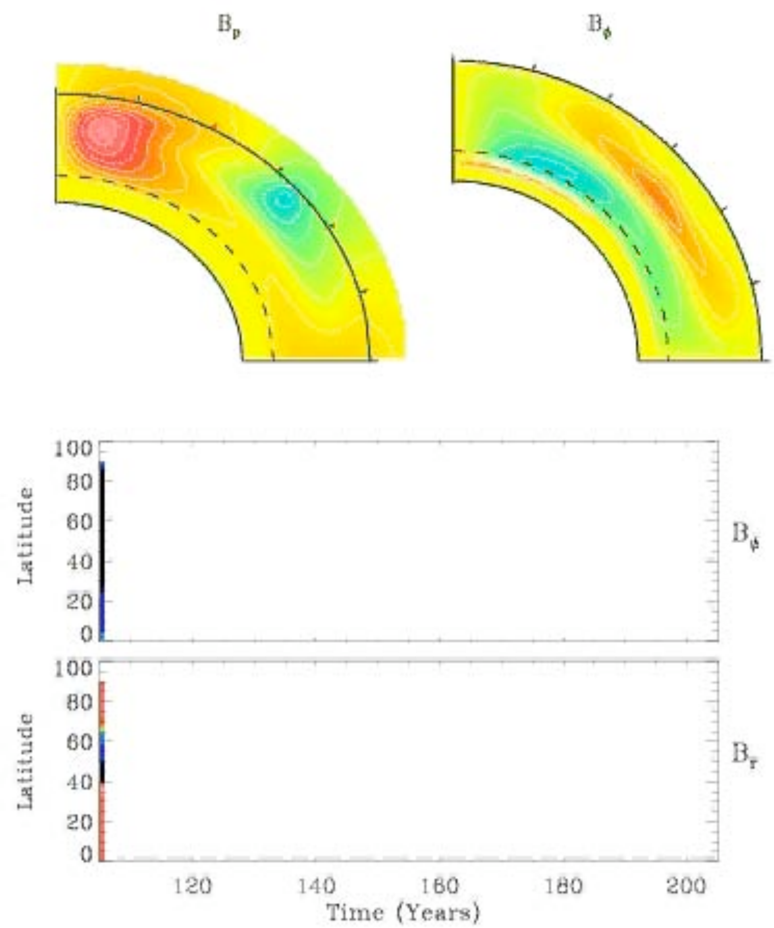


Jouve & Brun, 2007 A&A, 474, 239

2D Mean Field models: Babcock-Leighton

Influence of High Latitude and Deep Counter Cells





Slow down cycle period:
$T \sim v_0^{-0.35} \eta_t^{-0.4} s_0^{0.05}$

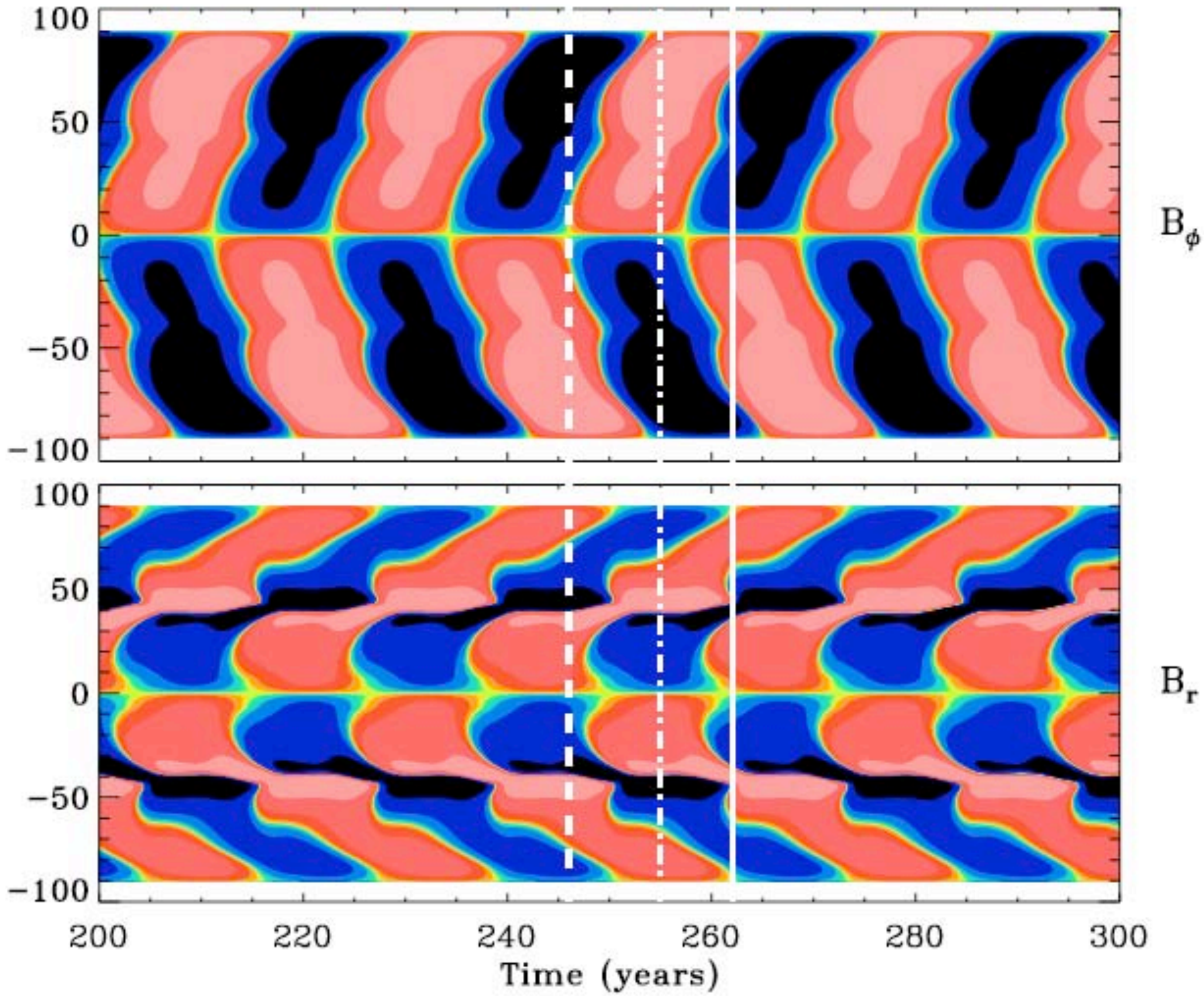
For parameter values identical to 1 cell case, find T=45 yr instead of 22, possible to get 22

Jouve & Brun, 2007 A&A, 474, 239

2D Mean Field models: Babcock-Leighton

Influence of High Latitude and Deep Counter Cells

Different
Phasing
of toro/polo

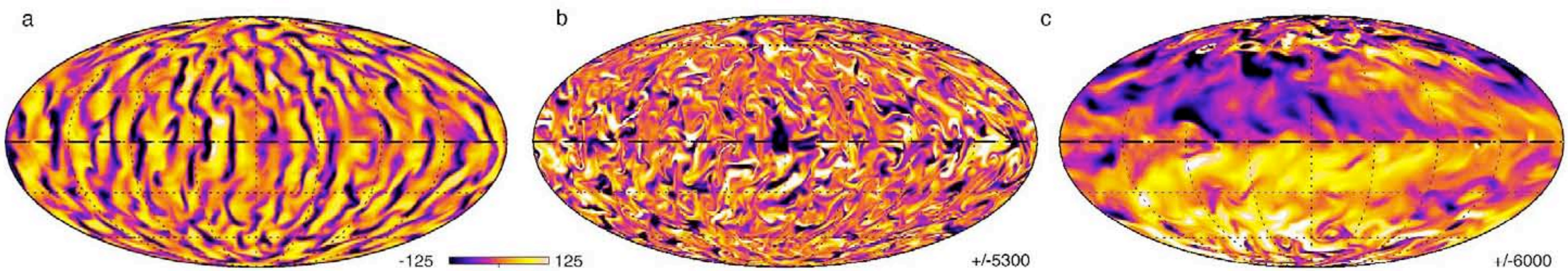


Jouve & Brun, 2007 A&A, 474, 239

Convection pattern and magnetic field structure

Mid depth CZ

In Stable zone



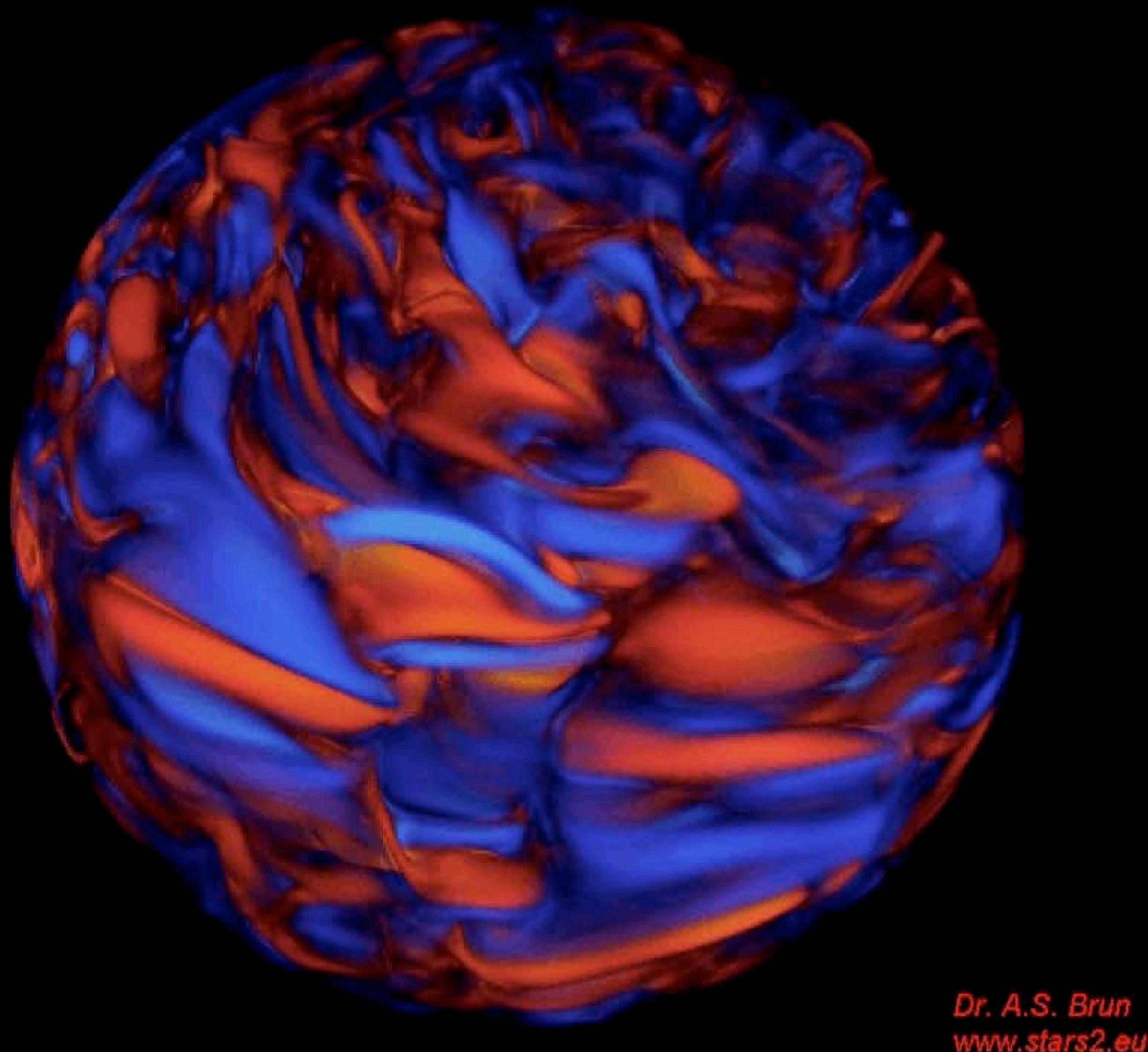
Vr

Bphi

The B field is much more organized in tachocline (possessing an antisymmetric profile)

Browning et al. 2006, ApJL

Toroidal Field in Convection



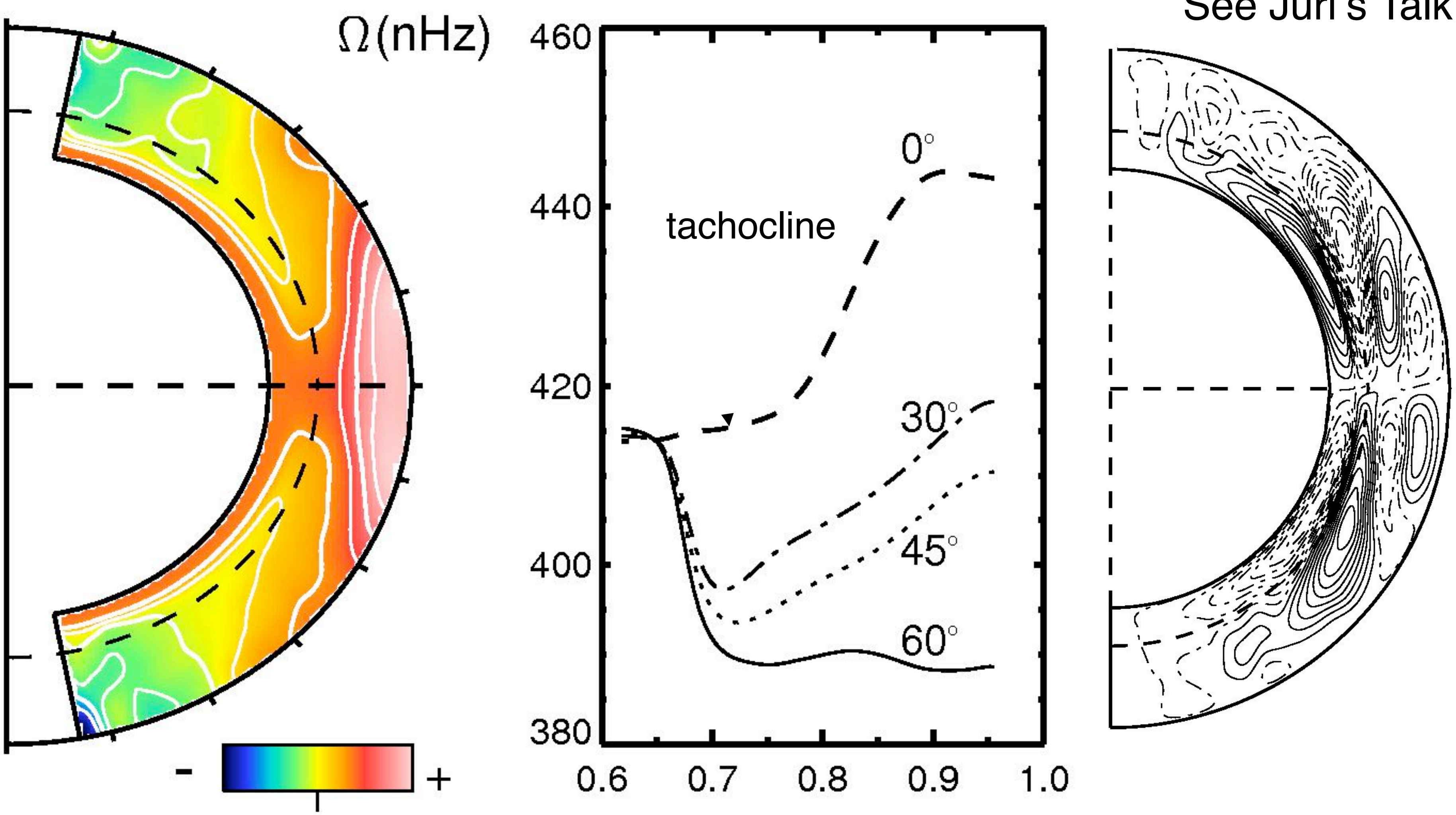
longitudinal component of B
(Pm=4)

A.S. Brun, Hinode 3rd Science Meeting, Tokyo, 12/01/09

Influence of a Tachocline?

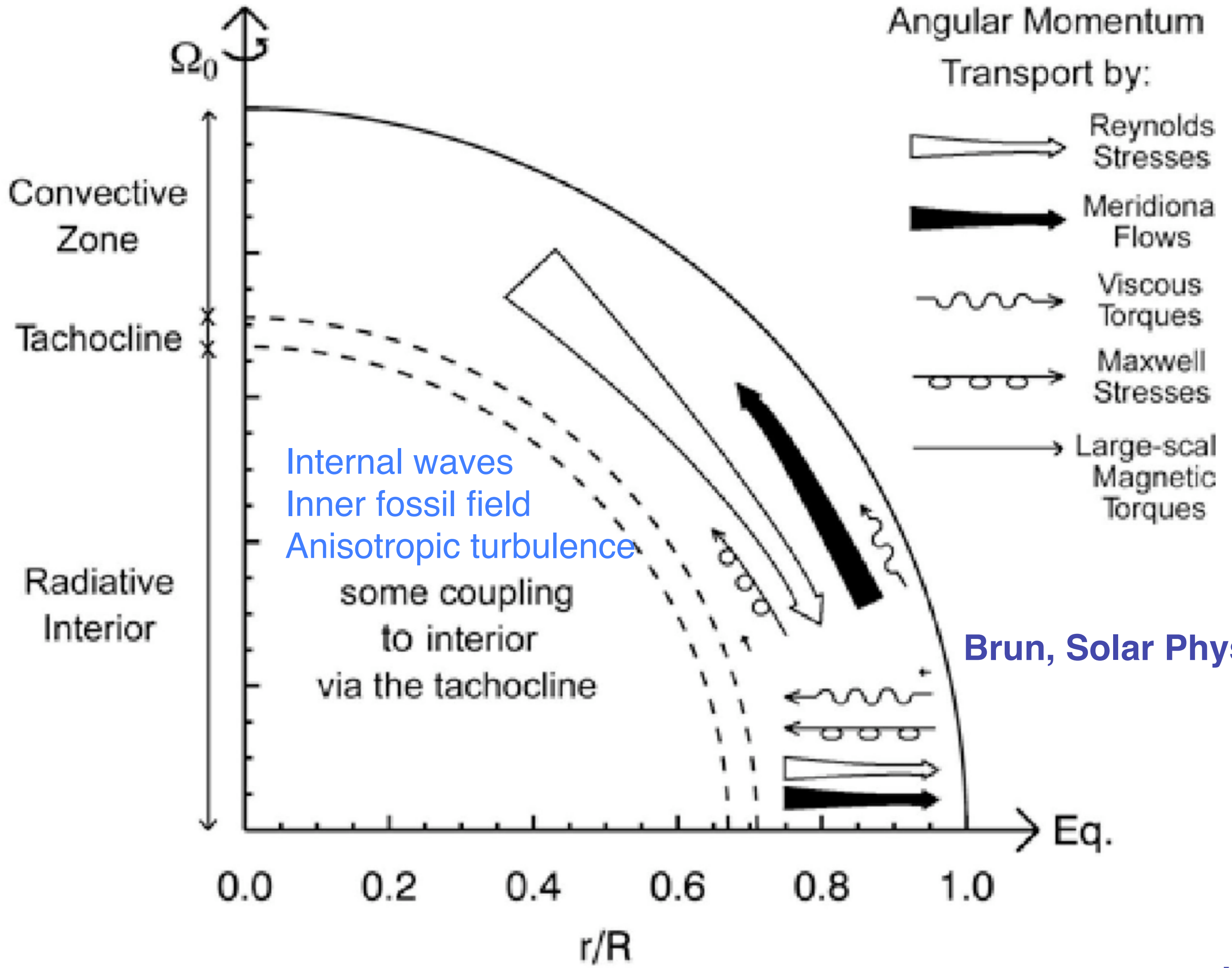
Browning et al. 2006, ApJL

See Juri's Talk



We impose a thermal wind in the stable lower zone compatible with a tachocline of shear maintained by a viscous drag.

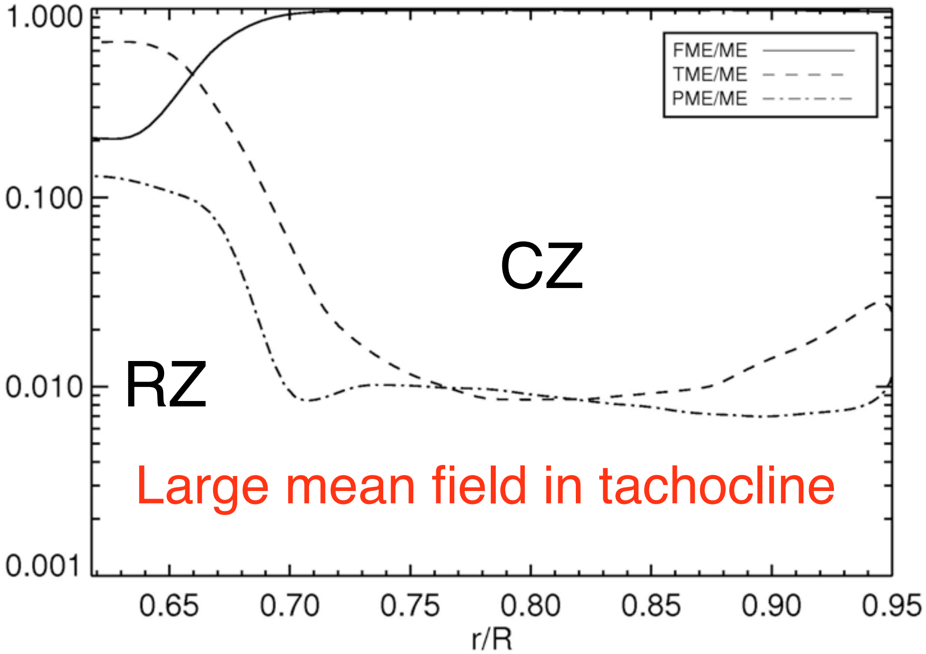
Angular Momentum Balance in Presence of B

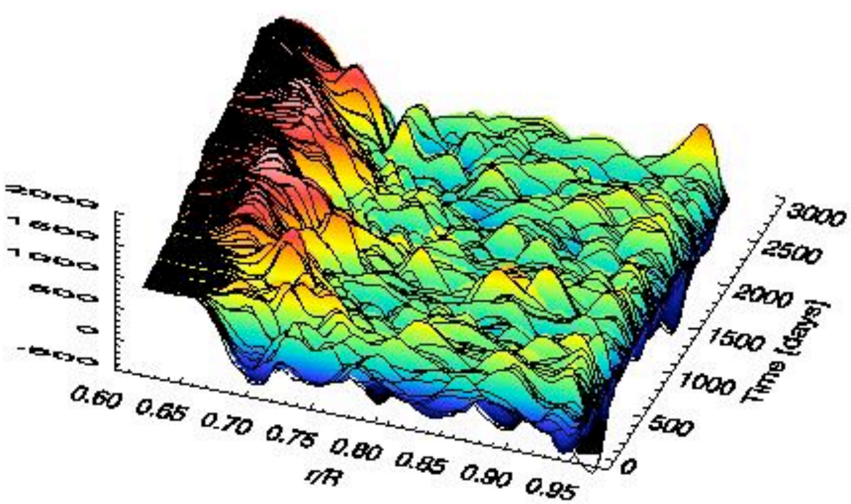


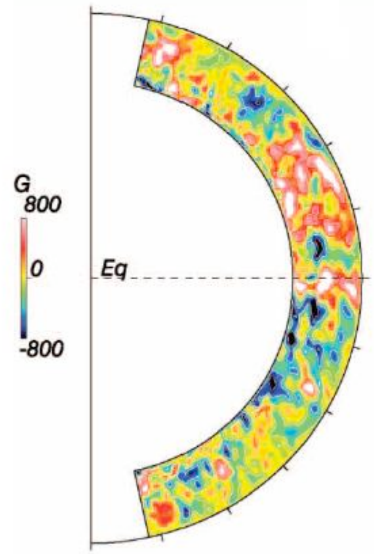
Brun, Solar Physics, 2004

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.

Getting Strong Toroidal Field



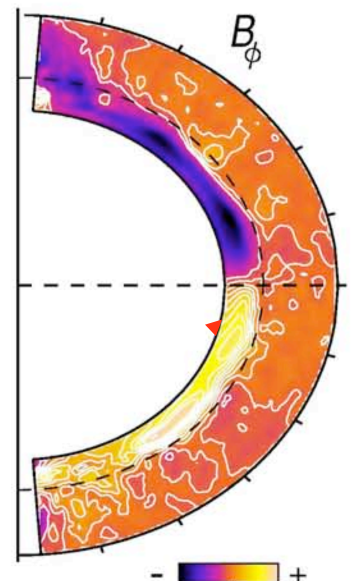


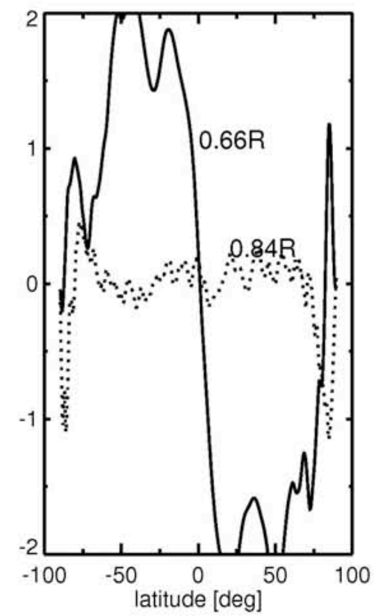


Brun et al. 2004

No tachocline:
mixed polarity
no symmetry

Browning et al. 2006



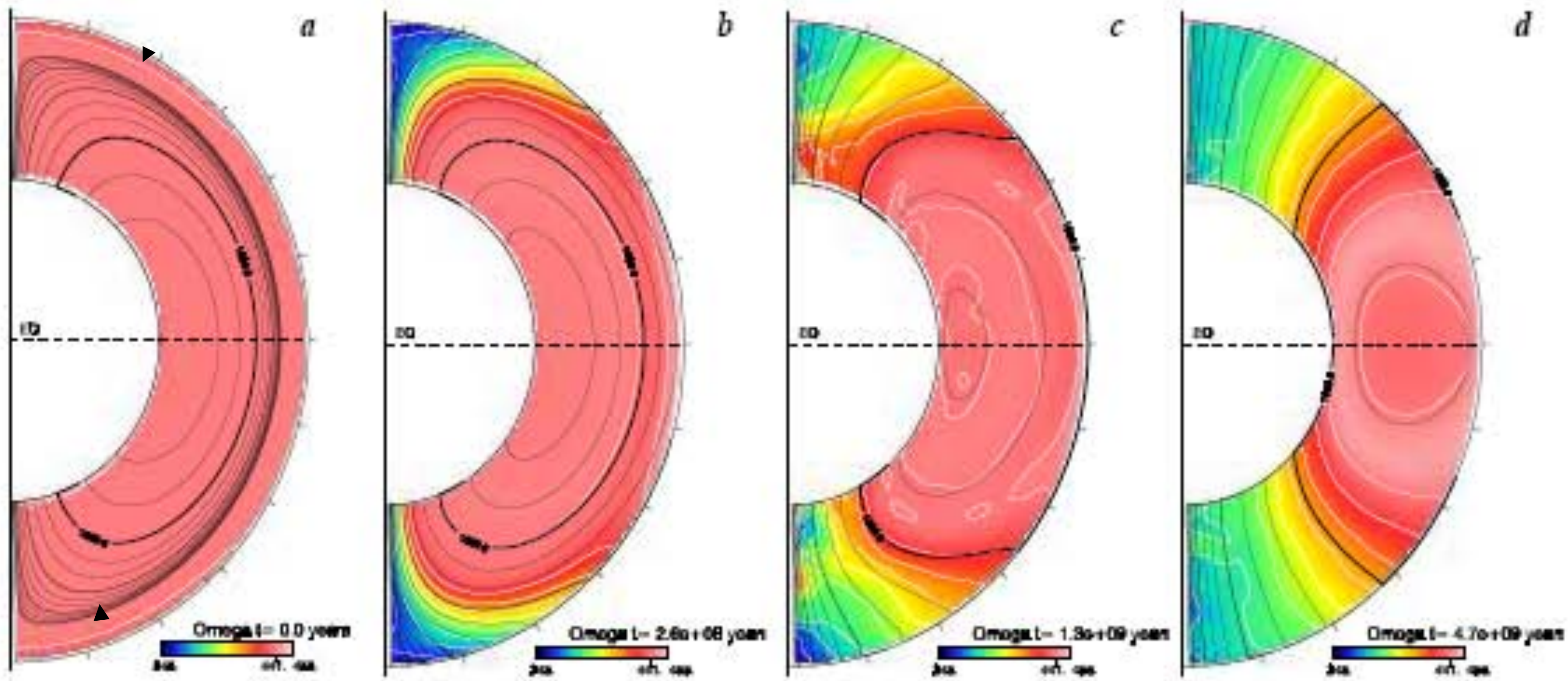


antisymmetric field

Solar Radiative Interior Dynamics

Brun & Zahn 2006, A&A, 457, 665; Zahn et al. 2007, A&A, 647, 145

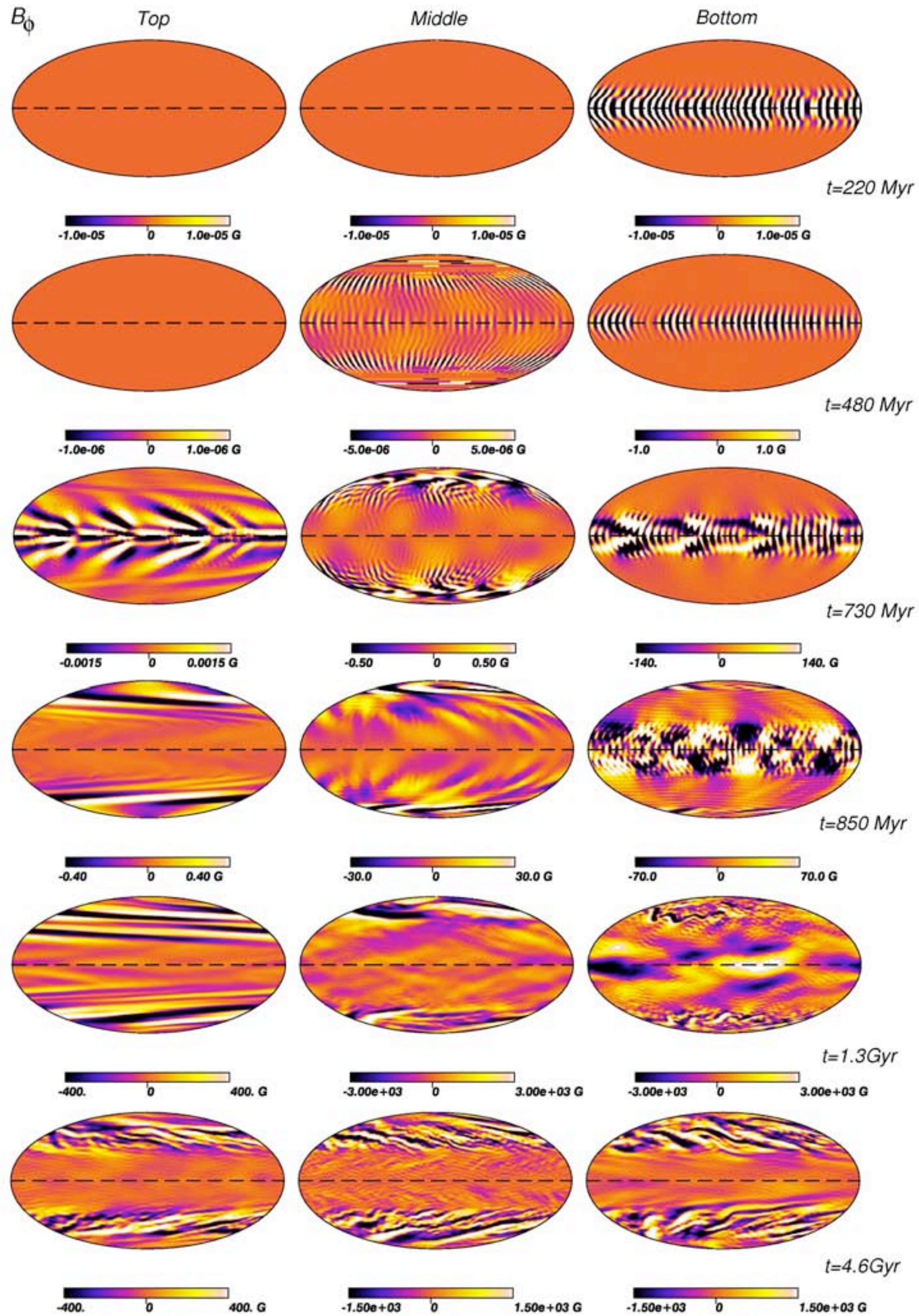
Top of radiative zone (shear imposed by convection zone on top of RZ)



Fossil magnetic field

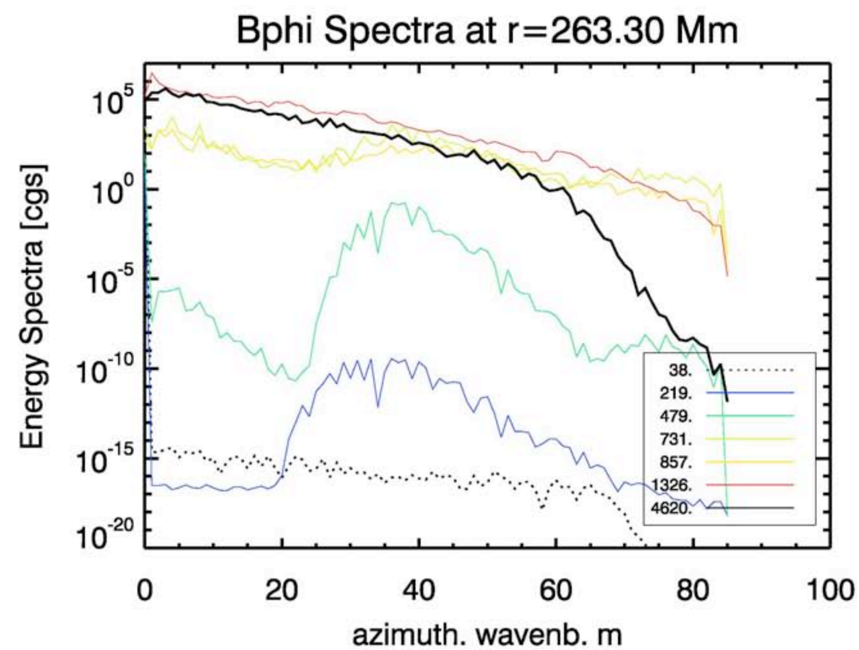
Final State: Ferraro's law of isorotation @ solar age

Interaction between a fossil field and the inward propagation of a latitudinal shear (e.g. the solar differential rotation)



Hign m

Non-Axisymmetric Instabilities of Bpol and Btor



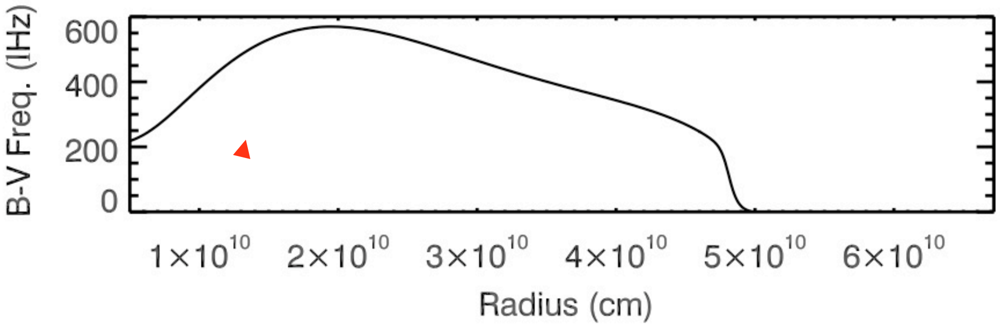
Dynamo In Radiative Interior?

(Spruit 2002, Braithwaite 2006, Zahn et al. 2007)

m=1

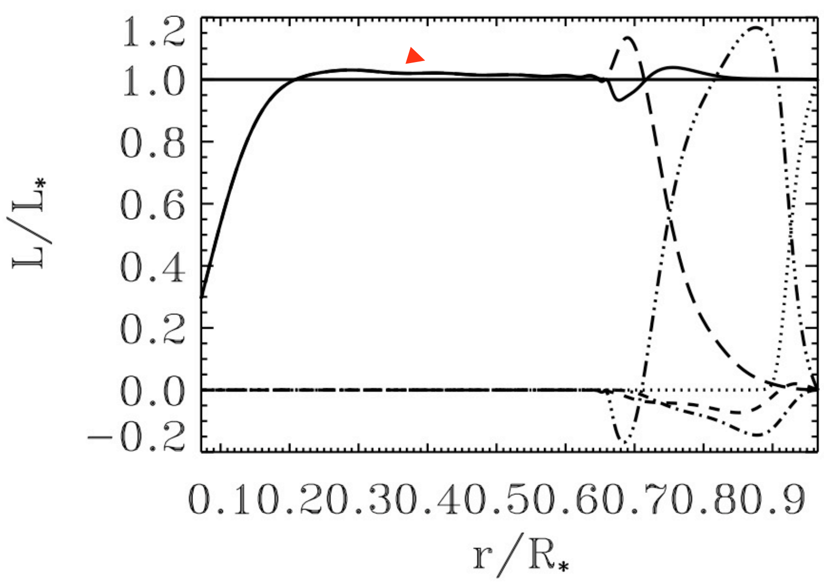
Brun & Zahn 2006, A&A

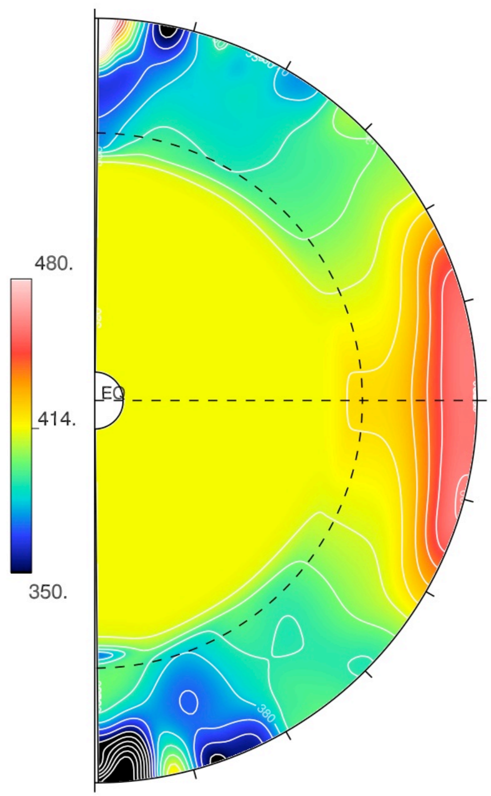
New Results on the Deep Sun

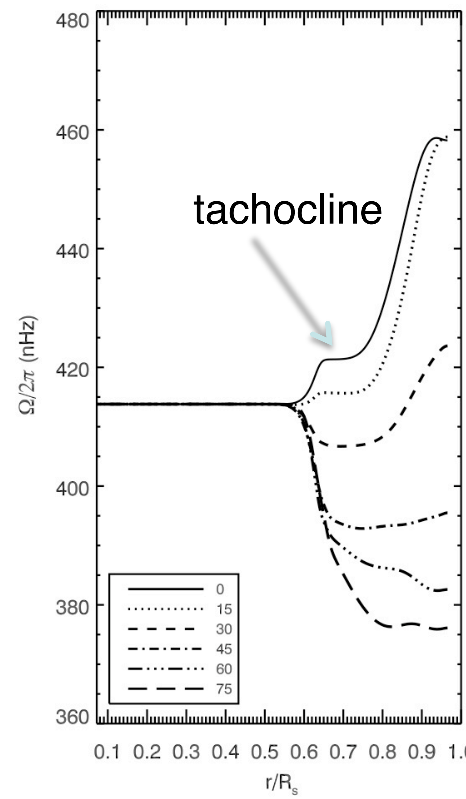


Omega

Extended RZ & realistic stratification







Taylor-Proudman Theorem & Thermal Wind

The curl of the momentum equation gives the equation for vorticity $\omega = \vec{\nabla} \times \vec{v}$ **:**

$$\frac{\partial \vec{\omega}}{\partial t} + \vec{v}.\vec{\nabla}\vec{\omega} - \vec{\omega}.\vec{\nabla}\vec{v} = \nu \vec{\nabla}^2 \vec{\omega} + \frac{1}{\rho^2} \vec{\nabla}\rho \wedge \vec{\nabla} p \qquad \text{(a)}$$

Taylor-Proudman Theorem:

In a stationary state, the φ **component of (a) can be simplified to:**

$$2\Omega \frac{\partial \hat{v}_\varphi}{\partial z} = 0$$ **=> vφ is cst along z**

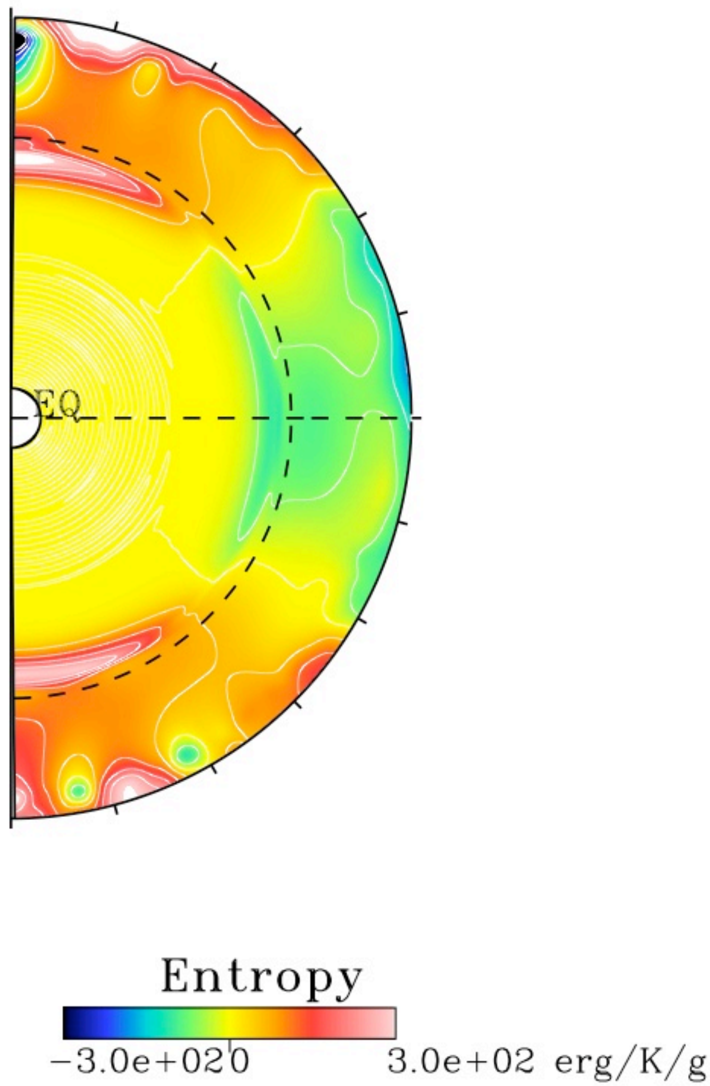
the differential rotation is cylindrical (Taylor columns) and the flows quasi 2-D.

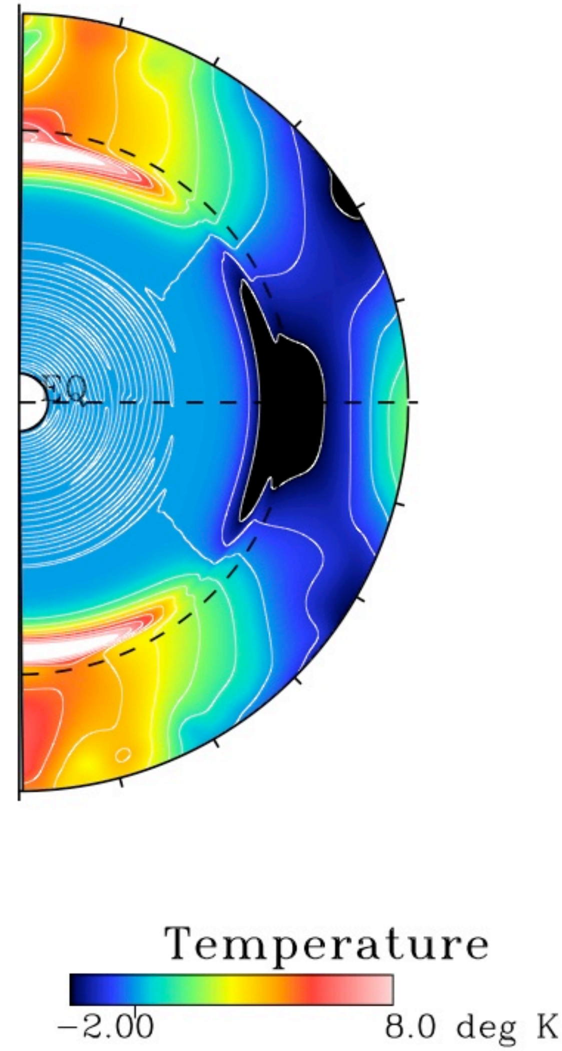
Thermal Wind:

The presence of cross gradient between p and ρ **(baroclinic effects) can break this constraint** (as well as Reynolds & viscous stresses and magnetic field) **:**

$$2\Omega \frac{\partial \hat{v}_\varphi}{\partial z} = -\frac{1}{\hat{\rho}^2} \vec{\nabla}\hat{\rho} \wedge \vec{\nabla}\hat{p}\Big|_\varphi = \frac{1}{\hat{\rho} C_p} \left[\vec{\nabla}\hat{S} \wedge -\hat{\rho}\vec{g}\right]\Big|_\varphi = \frac{g}{r C_p} \frac{\partial \hat{S}}{\partial \theta}$$

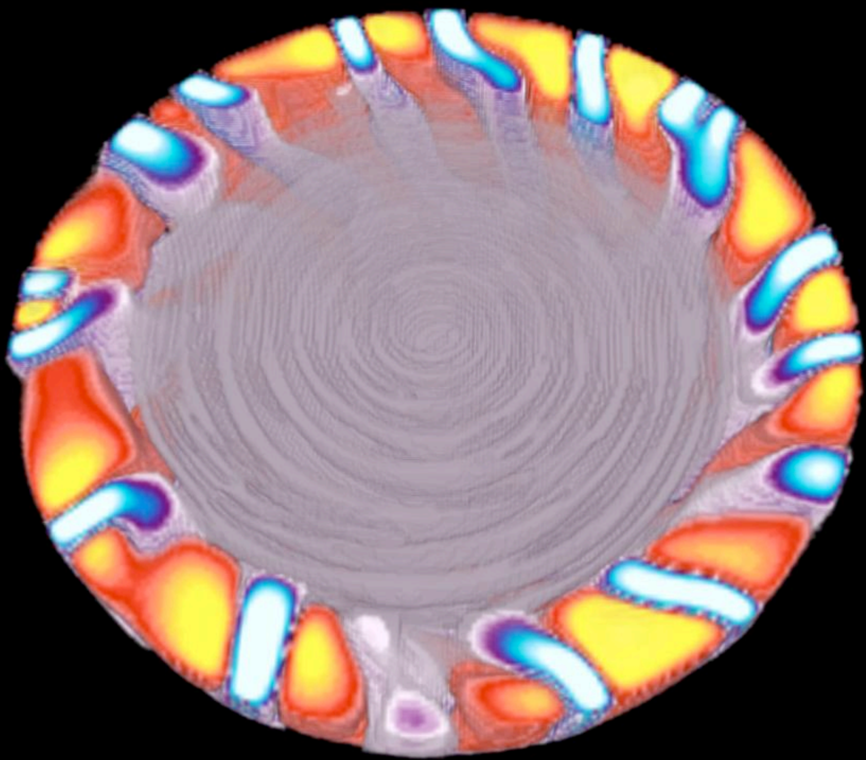
Thermal Perturbations



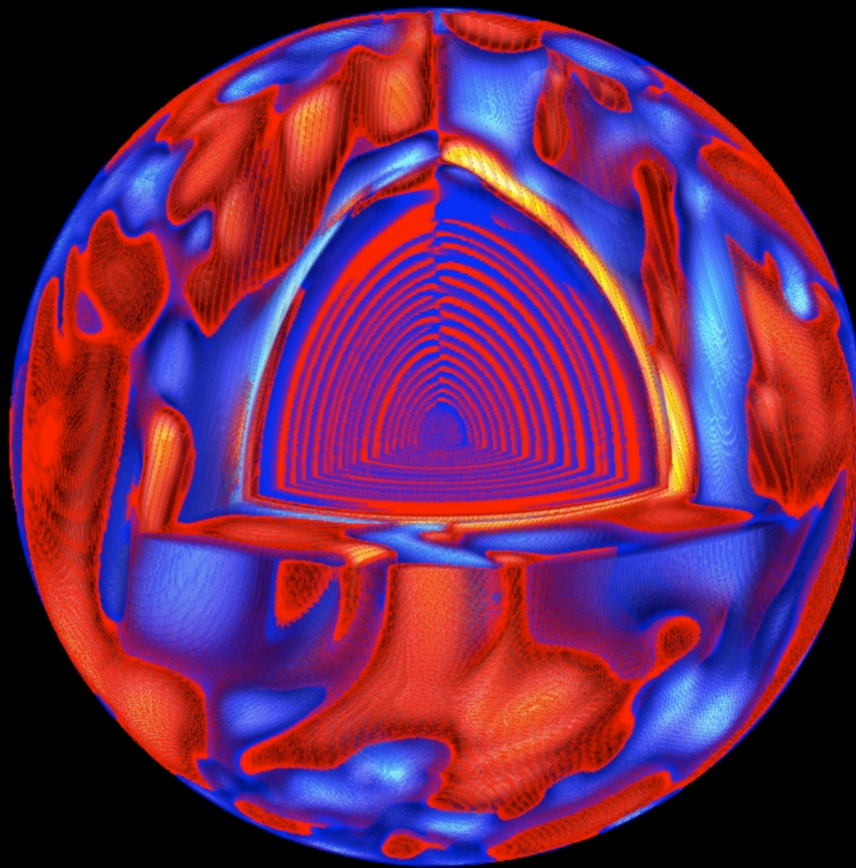


Key to determine inner dynamics and rotation profile => solar cycle

3-D Views of Internal Waves



Vr

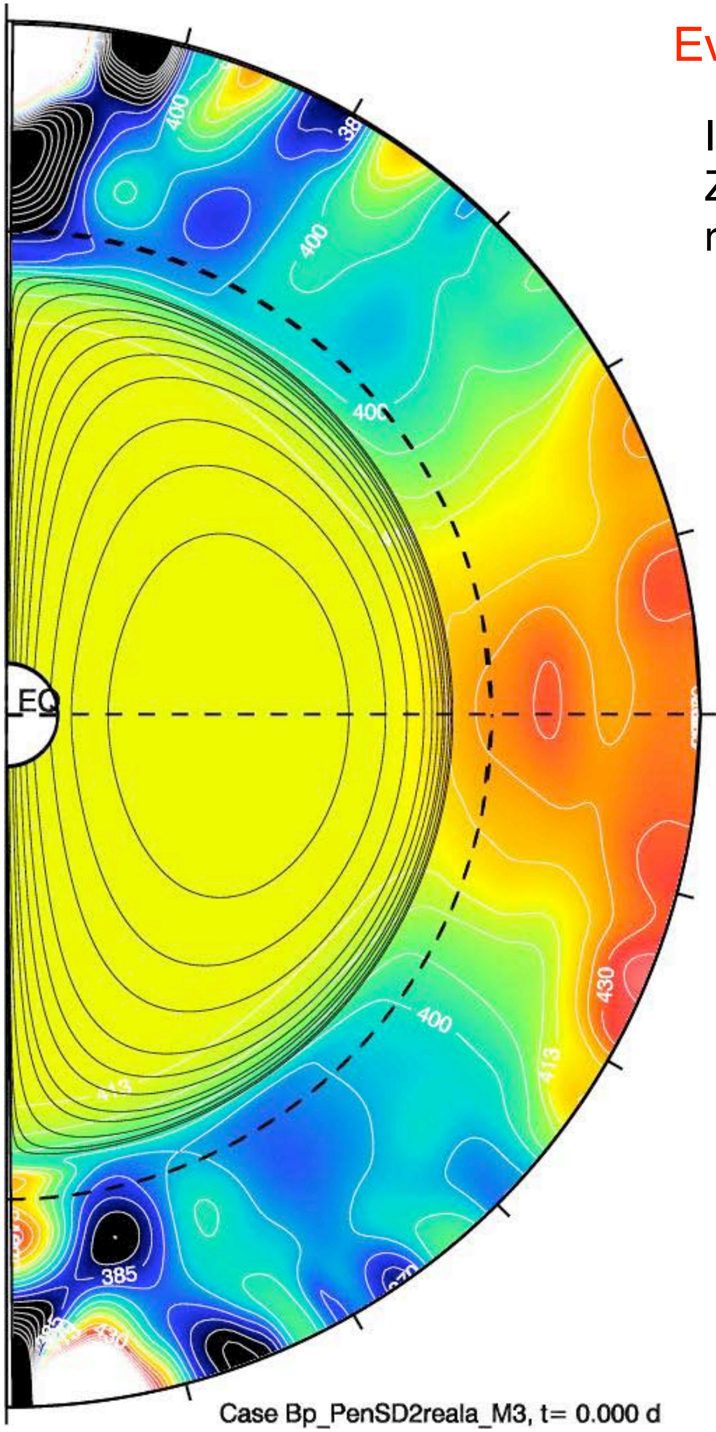


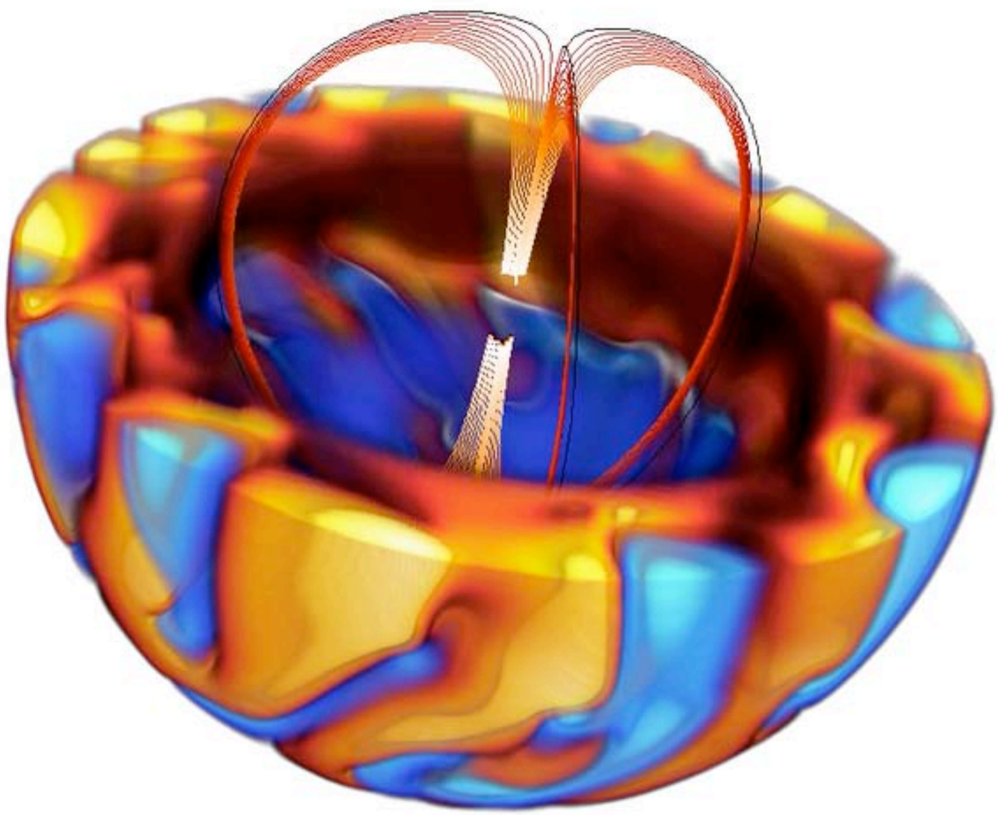
density

We see them in the models, we need to search for them: Key to contrain inner dynamics, primordial fields topology, angular momentum budget and history, deep rotation profile

Evolution of a Fossil Field in 3-D Radiative/Convective

Interaction between Radiation and Convection/Tachocline Zones fundamental to determine global solar magnetism and rotation history



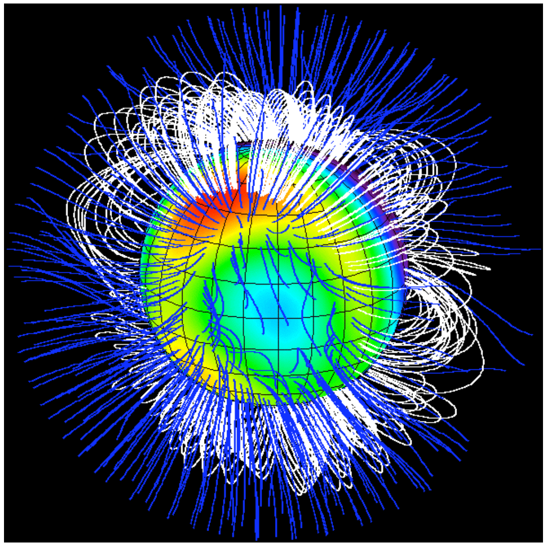


=> Ferraro's law still present (Strugarek, Brun, Zahn 2010)

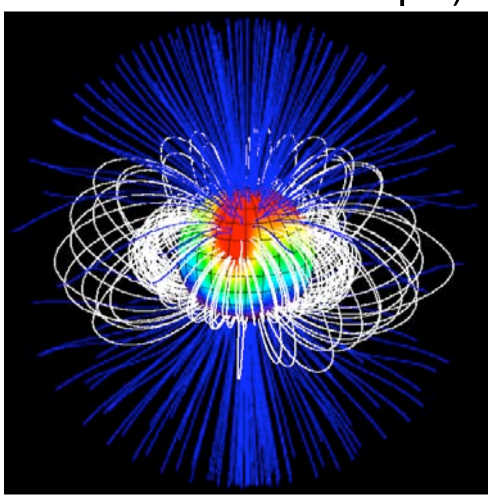
The Sun as a star:
magnetism, rotation, dynamo
=> Making the link with astrophysical questions

Stellar Magnetism: X Luminosity

(ROSAT All Sky Survey, EspaDONS)

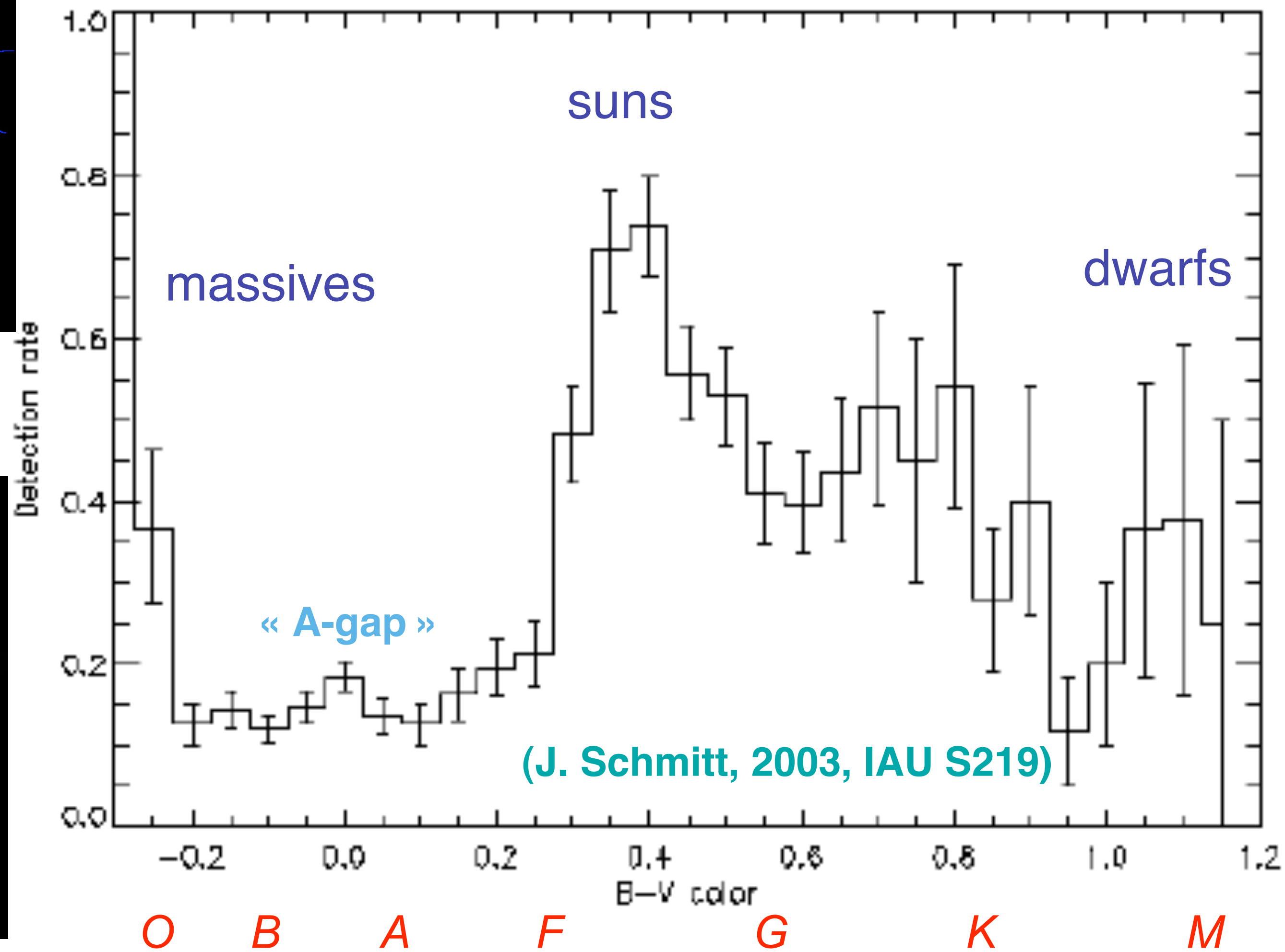


Observations Narval
(J.F. Donati,
massive star tau Scorpii)



ultra-cool star V374 Pegasi

Good correlation between activity level and surface convection



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

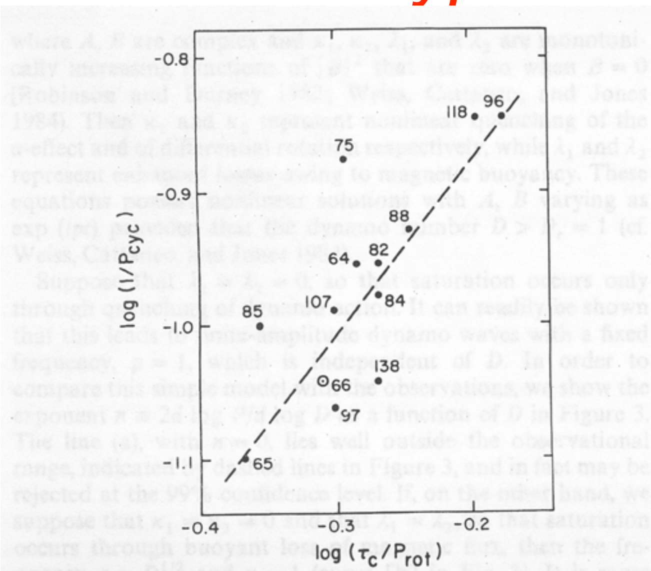


FIG. 2.—Log $(1/P_{cyc})$ vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.

Noyes et al. 1984

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

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

<u>Over 111 stars in HK project (F2-M2):</u>

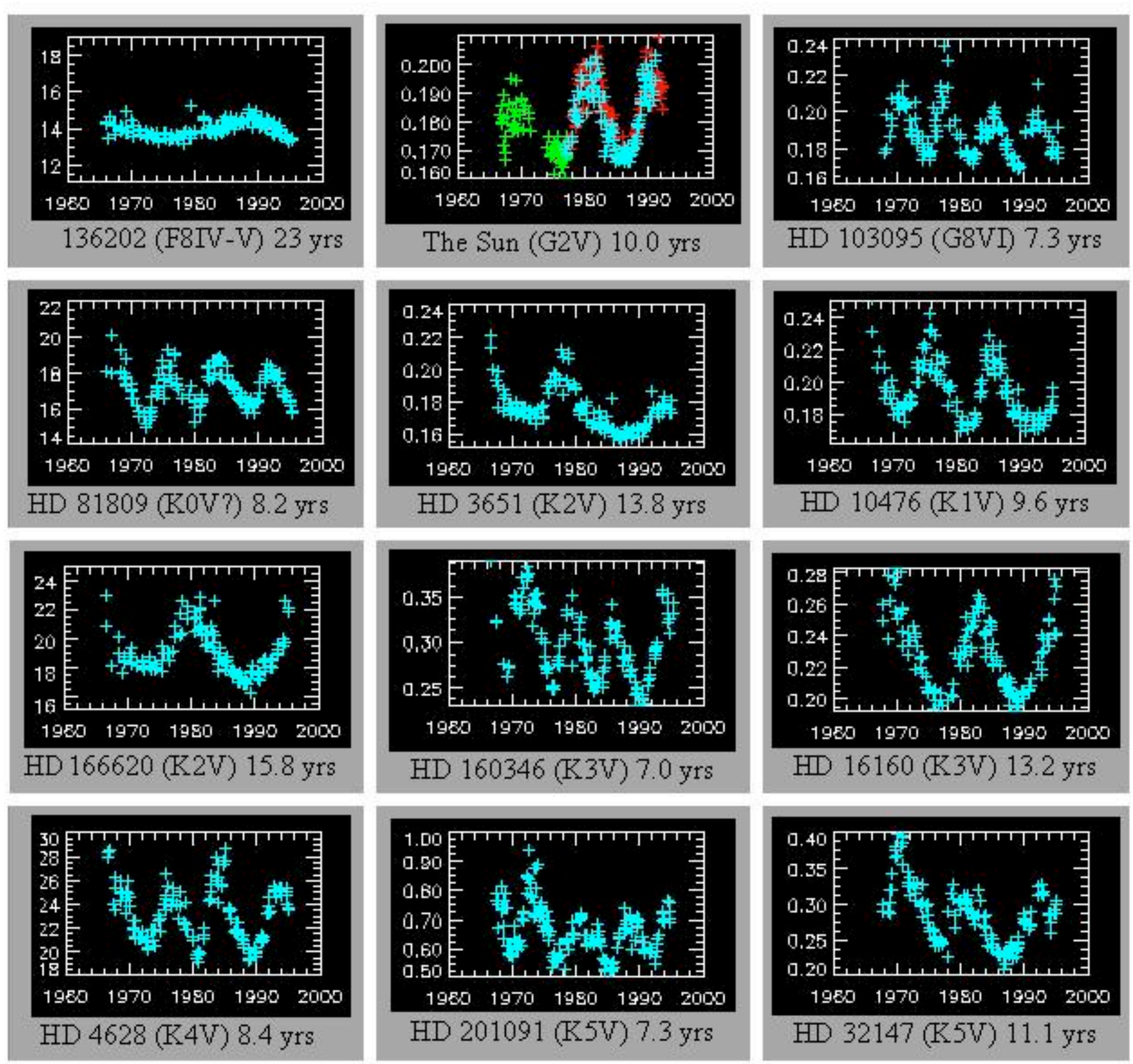
31 flat or linear signal

29 irregular variables

51 + Sun possess magnetic cycle

Wilson 1978

Baliunas et al. 1995



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

Solar Analogs

Name	T_{eff} K	log(g) [cm.s^{-2}]	[M/H] [Sun]	Mass $M_\odot$	Age Gyr	$v \sin i$ km s^{-1}	$\mathbf{P^{eq}_{rot}}$ (d)	$d\Omega$ (rad.d^{-1})	inclination (°)
Sun	5770	4.44	0.00	1.0	4.3 ± 1.7	1.7	**24**	0.05	–
HD 146233	5791 ± 50	4.41 ± 0.06	0.03 ± 0.03	0.98 ± 0.13	$4.7^{+2.7}_{-2.7}$	2.1 ± 0.5	$\mathbf{22.7 \pm 0.5}$	–	70^{+20}_{-25}
HD 76151	5790 ± 50	4.55 ± 0.06	0.07 ± 0.03	1.24 ± 0.12	$3.6^{+1.8}_{-2.3}$	1.2 ± 0.5	$\mathbf{20.5 \pm 0.3}$	–	30 ± 15
HD 73350	5802 ± 50	4.48 ± 0.06	0.04 ± 0.03	1.01 ± 0.14	$4.1^{+2.0}_{-2.7}$	4.0 ± 0.5	$\mathbf{12.3 \pm 0.1}$	0.2 ± 0.2	75^{+15}_{-20}
HD 190771	5834 ± 50	4.44 ± 0.06	0.14 ± 0.03	0.96 ± 0.13	$2.7^{+1.9}_{-2.0}$	4.3 ± 0.5	$\mathbf{8.8 \pm 0.1}$	0.12 ± 0.03	50 ± 10

Petit et al. 2008, MNRAS

Table 3. Magnetic quantities derived from the set of magnetic maps. We list the mean unsigned magnetic field ($B_{\rm mean}$), the fraction of the large-scale magnetic energy reconstructed in the poloidal field component and the fraction of the *poloidal* magnetic energy in the dipolar ($\ell = 1$), quadrupolar ($\ell = 2$) and octopolar ($\ell = 3$) components. In the last column, we also list $\log R'_{\rm HK}$ values derived from our sets of Stokes I spectra.

Name	$B_{\rm mean}$ (G)	pol. en. (% tot)	dipole (% pol)	quad. (% pol)	oct. (% pol)	$\log R'_{\rm HK}$
HD 146233	3.6 ± 1	99.3 ± 0.2	34 ± 6	56 ± 6	10 ± 10	-4.85 ± 0.02
HD 76151	5.6 ± 2	93 ± 6	79 ± 13	18 ± 8	3 ± 3	-4.69 ± 0.02
HD 73350	42 ± 7	52 ± 3	24 ± 5	29 ± 8	33 ± 5	-4.48 ± 0.02
HD 190771	51 ± 6	34 ± 1	43 ± 8	20 ± 2	23 ± 4	-4.42 ± 0.02

Theoretical models: Jouve, Brown, Brun 2010, Brown et al. 2010

ESPADON/NARVAL

How Solar-C/Plan A can help solving the Origin of Solar Magnetism (Dynamo), Structure of the Solar Interior and beyond

With Plan A High Altitude Orbit:

- By improving our knowledge of meridional circulation, differential rotation, transport processes thus constraining three key ingredients of the solar Dynamo, detection high polar branch of torsional oscillations
- By characterizing magnetic fields, polar reversals, phasing of toro/polo components, coupling between large scales flow and field
- Structure of wind, angular momentum lost
- Sounding the deep interior (tachocline and upper radiative zone) for flows, maximum field strengths and field topology, thermal structure, Dynamo in radiative core?
- g-modes detection via global seismology (Golf-NG): sound speed, density, field and rotation profiles down to the core (energy prod region)
- The Sun as a star: allow to answer key astrophysical questions: Angular momentum history, dynamo mechanism, cosmic magnetism