Origin of long-term variations in solar and stellar dynamos

- from the point-of-view of global-scale magnetoconvection models

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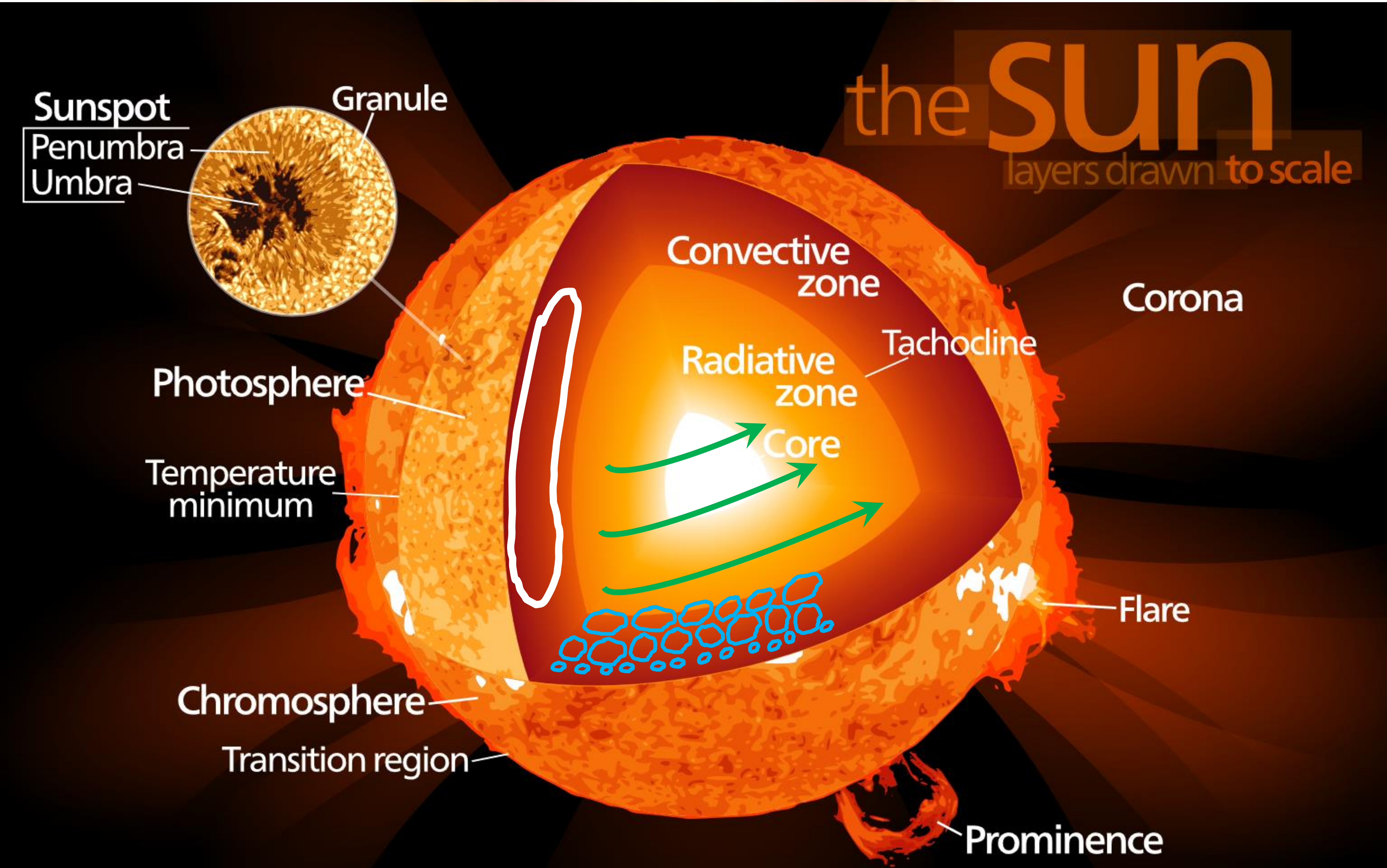
Astroinformatics and SOLSTAR groups, especially **Mariangela Viviani (2), Jörn Warnecke (2), Matthias Rheinhardt (1), Ameya Prabhu (2), and Frederick Gent (1)**

Dynamo – the driver of space weather and climate



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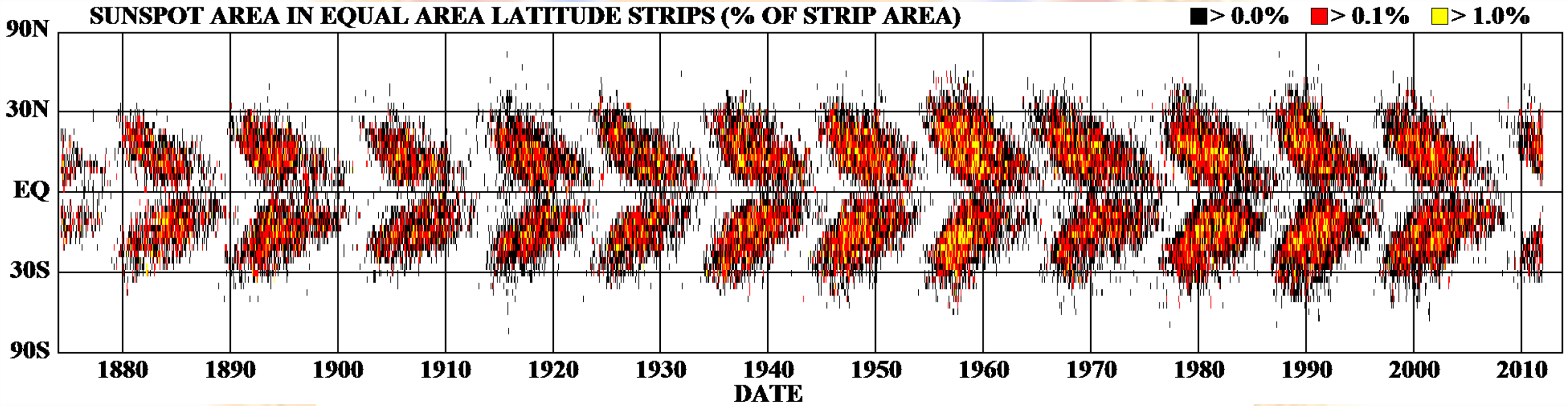
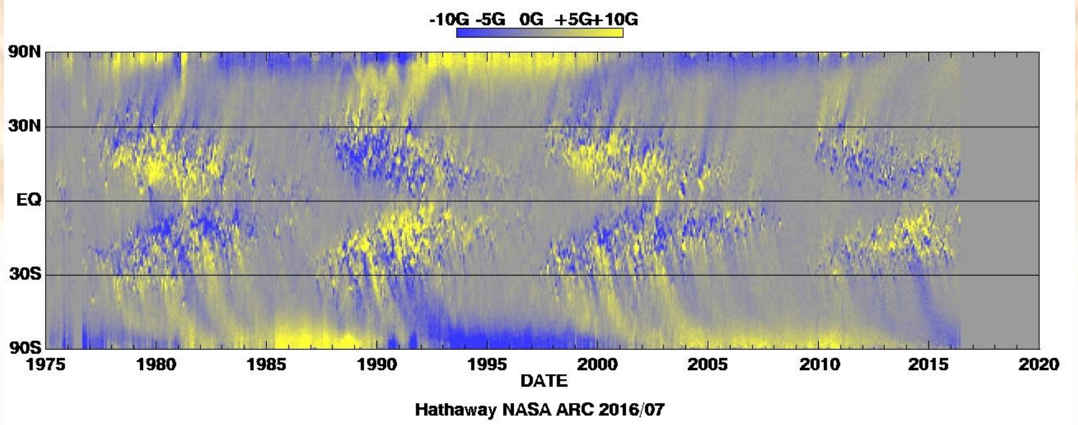
Outline

- Many cycles
- Irregular variations
- Big dynamo picture
- What can we reproduce and explain?
- Best studied with global magnetoconvection models
- What we do not understand
- What next?

Basic cycle

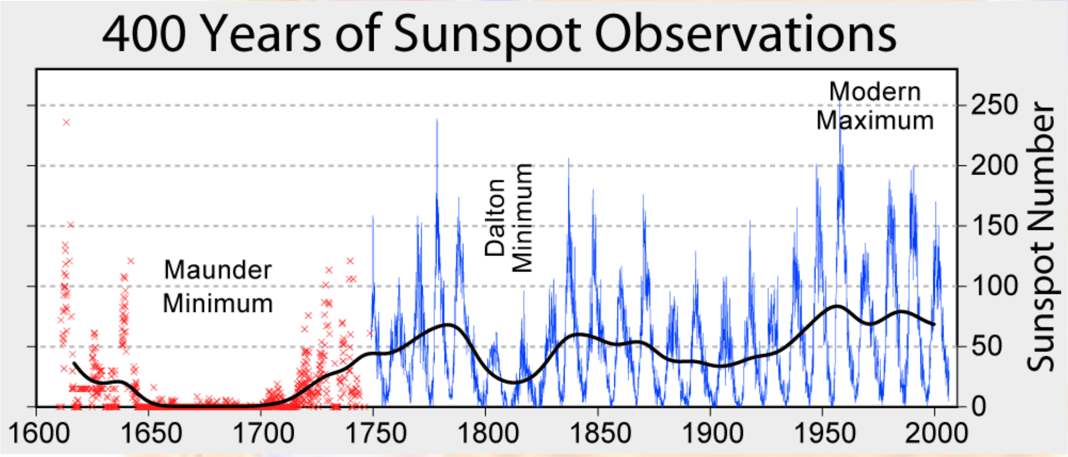
- the ”basic" 22-year magnetic cycle



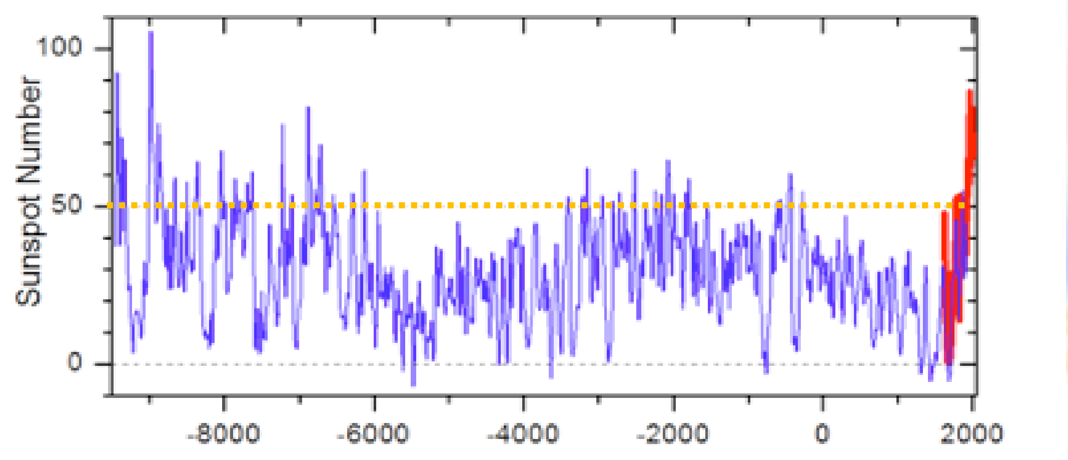


Long cycle(s)

- Long cycles, e.g. the Gleissberg cycle (70-100 yr), the deVries cycle (~200 yr), the Halstatt cycle (~2300yr), …



Hoyt & Schatten, 1998, Sol. Phys., 181, 491



Solanki et al. 2015, *TOSCA Handbook on Space Climate, Chapter 2.5*: Sunspot number (10-year averages) reconstructed from **^{14}C data** since 9500 BC (blue curve).

Short cycle(s)

- Evidence for cyclic variability on a ~ 2 year timescale in number of activity indicators; QBOs (0.6-4 yrs)

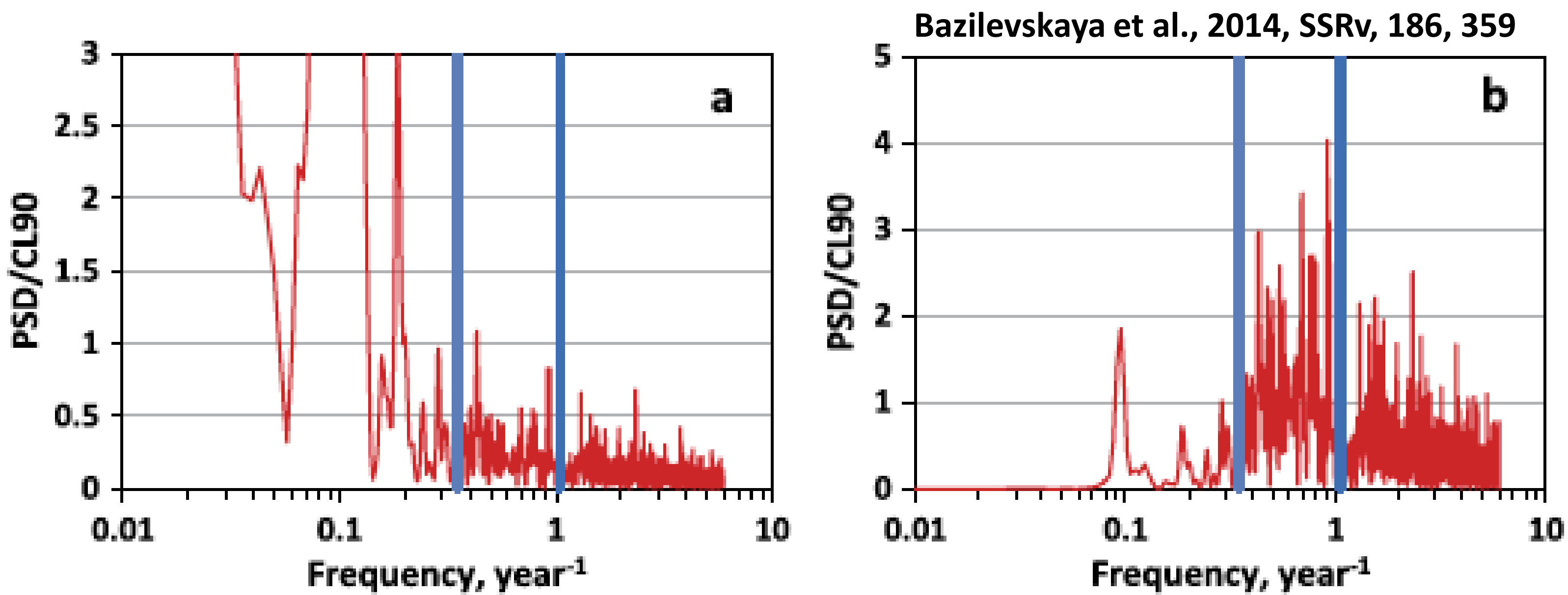
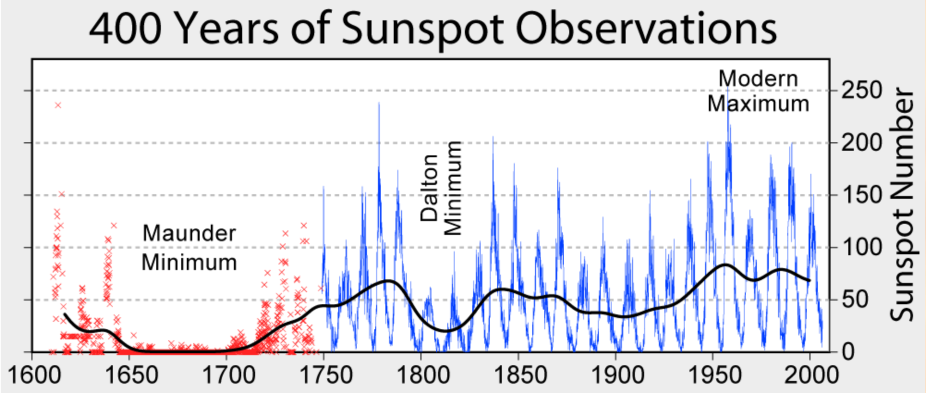
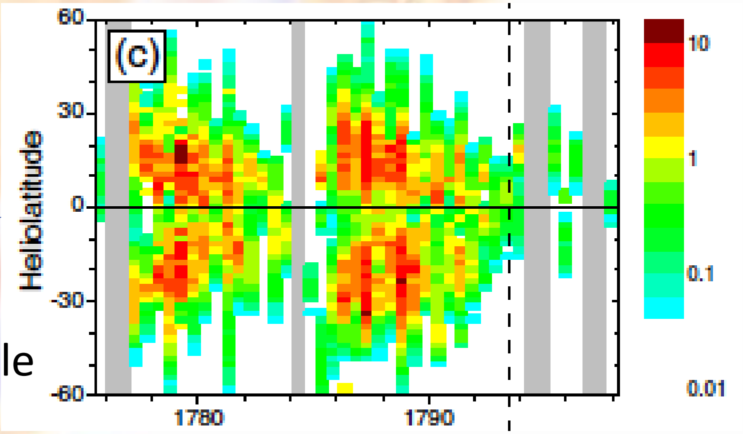


Fig. 2 (**a**): Power spectrum density of the monthly meanings of the sunspot area for the whole solar disk from 1875 to 2012. (**b**): The same as (**a**) but with an ~11 yr variation withdrawn by subtraction of 25-month running averages from the monthly values of sunspot area. PSD is given in the units of 90 % confidence level for the highest peak, meaning that values greater than unity imply that there is less than a 10 % chance of such power in noise. *Vertical bars* denote approximately the frequency range of QBOs indicated by this data, however, we note that many authors consider periodicities outside these limits (see Table 1)

Solar cycle irregularities

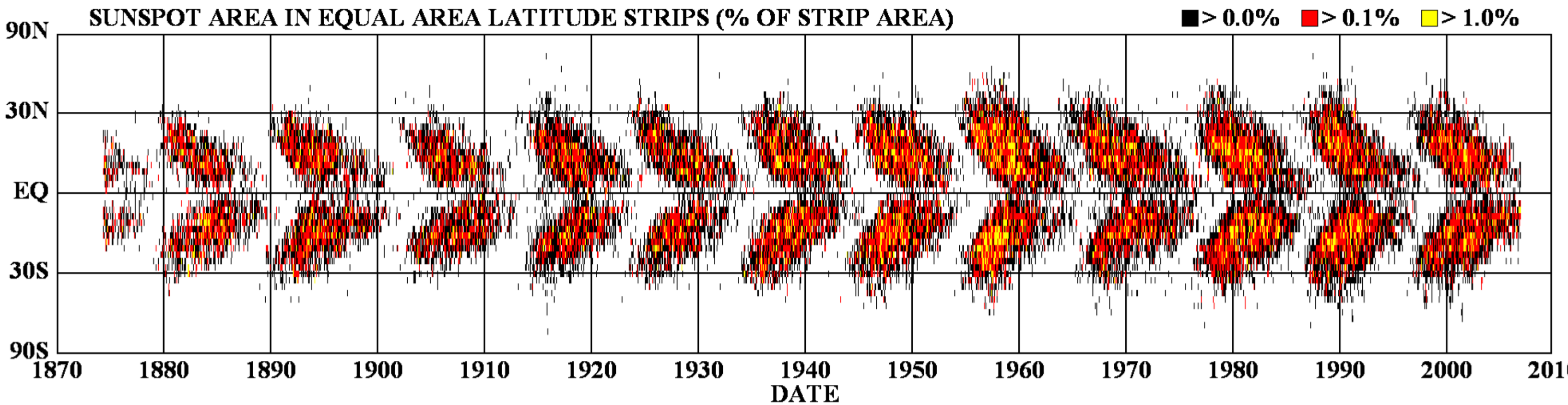
- QBOs are often reported to be intermittent (“forrest of spikes” in spectral analysis)
- The basic cycle: amplitude-cycle length variations + short-term irregularities such as “missing cycles” + grand minima (and maxima) + strong NS asymmetrities

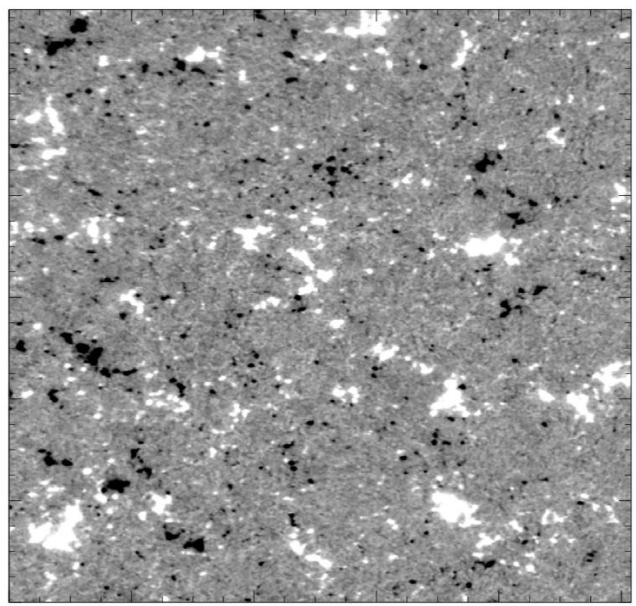




“Missing cycle”
turned out to be a weak and short asymmetric cycle
Usoskin et al. 2009, ApJL, 700, L154

Big dynamo picture

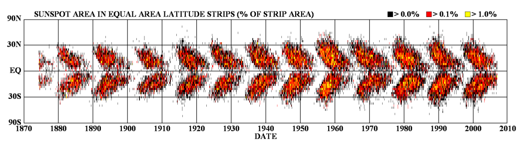




Quiet Sun LOS mgf
HINODE/SOT/NFI 2007

Big dynamo picture

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \boldsymbol{\nabla} \times (\overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \overbrace{\overline{\boldsymbol{u}' \times \boldsymbol{b}'}}^{\mathcal{E}}) - \boldsymbol{\nabla} \times \eta \boldsymbol{\nabla} \times \overline{\boldsymbol{B}}$$



Large-scale dynamo (LSD)

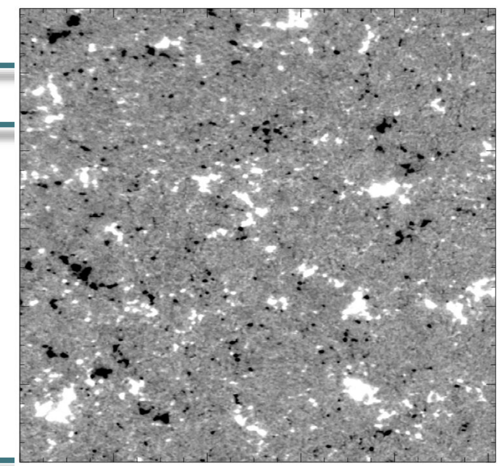
Low-order (mean-field) models

Turbulent or "$\alpha\Omega$" dynamos

Babcock-Leighton dynamos

Global magnetoconvection models

Small-scale dynamo (SSD)



$$\frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{u} \times \boldsymbol{B} - \mu_0 \eta \boldsymbol{J},$$

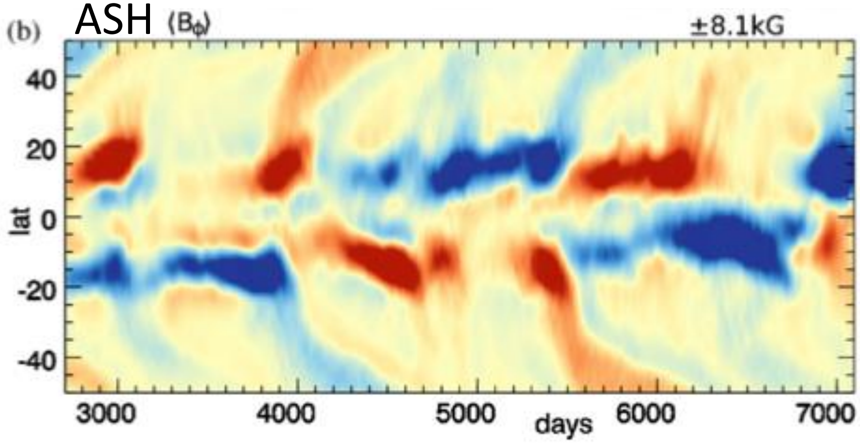
$$\frac{D \ln \rho}{Dt} = -\boldsymbol{\nabla} \cdot \boldsymbol{u},$$

$$\frac{D\boldsymbol{u}}{Dt} = \boldsymbol{g} - 2\boldsymbol{\Omega}_0 \times \boldsymbol{u} + \frac{1}{\rho}(\boldsymbol{J} \times \boldsymbol{B} - \boldsymbol{\nabla} p + \boldsymbol{\nabla} \cdot 2\nu\rho \mathbf{S}),$$

$$T\frac{Ds}{Dt} = \frac{1}{\rho}\left[-\boldsymbol{\nabla} \cdot (\boldsymbol{F}^{\mathrm{rad}} + \boldsymbol{F}^{\mathrm{SGS}}) + \mu_0 \eta \boldsymbol{J}^2\right] + 2\nu \mathbf{S}^2,$$

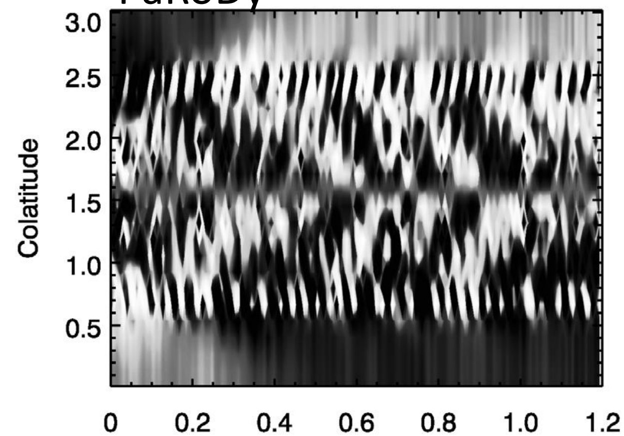
10+ years of cycles!

ASH

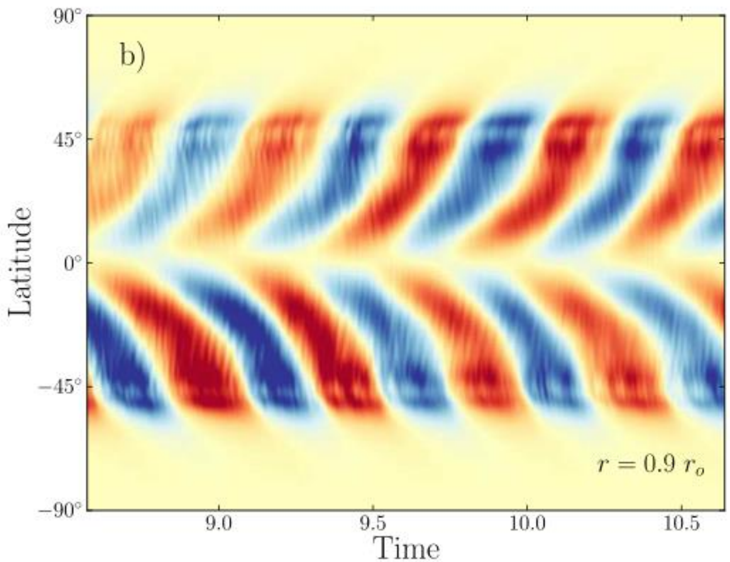


Brown et al. (2011), *Astrophys. J*, 731, 69

PaRoDy

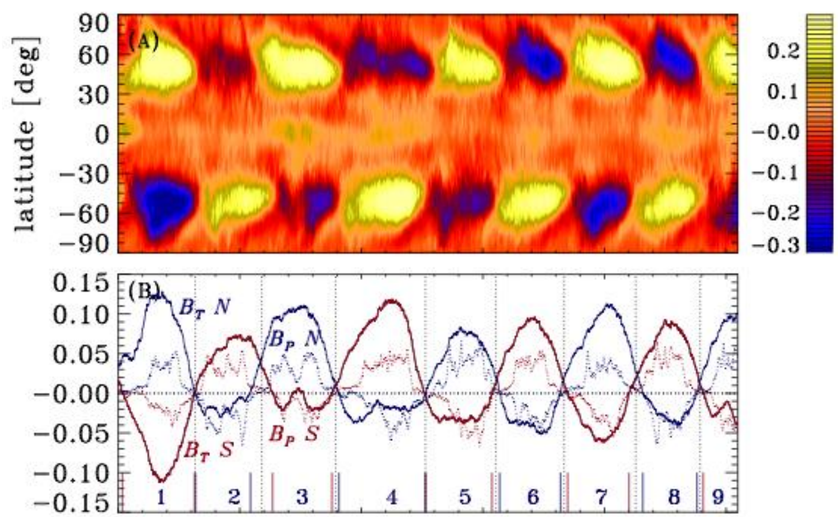


Schrinner et al. (2011), *Astron. Astrophys*, 530, A140



Gastine et al. (2012), *Astron. Astrophys*, 546, 19

MagIC

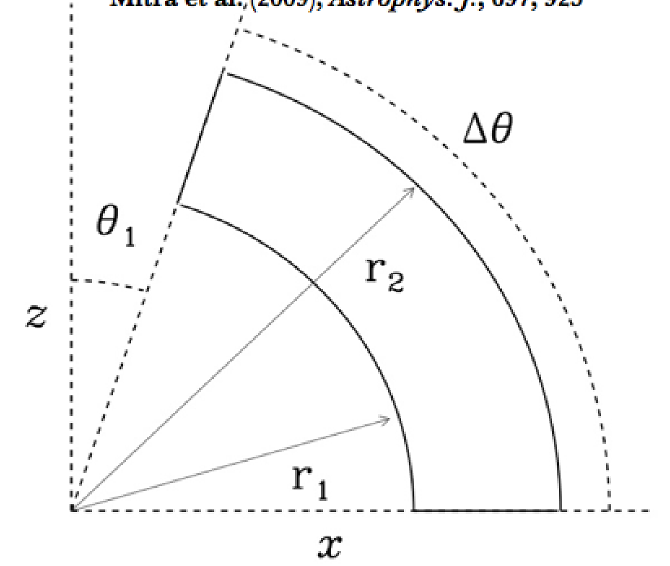


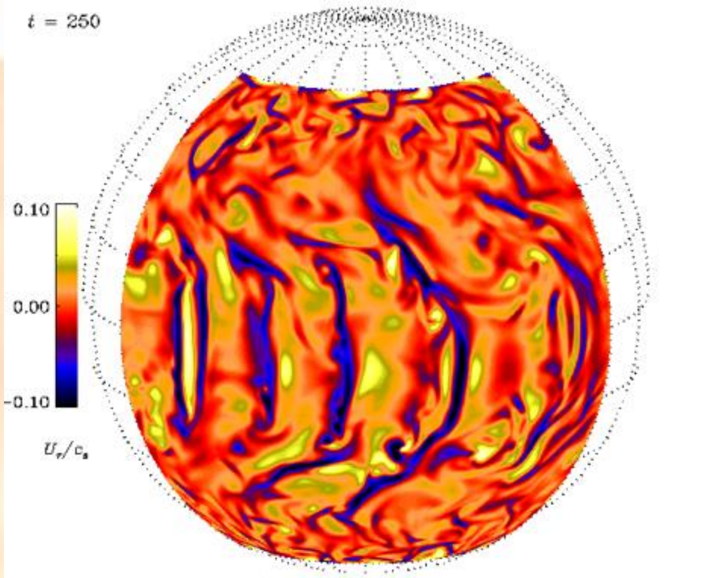
Ghizaru et al. (2010), *Astrophys. J Lett*, 715, 133

EULAG

PENCIL CODE wedges

Mitra et al. (2009), *Astrophys. J.*, 697, 923





Käpylä et al. (2010b), *Astron. Nachr.*, 331, 73

$0.7R < r < R$ $\theta_1 < \theta < \theta_2$ $0 < \phi < \Delta\phi$ $k_{\mathrm{f}} = 2\pi/\Delta R$

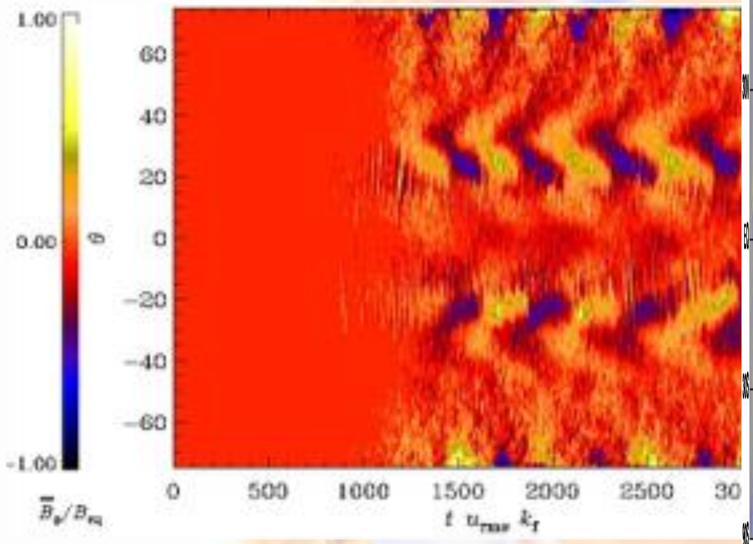
Fast, capable of semi-global models

Test-field suite

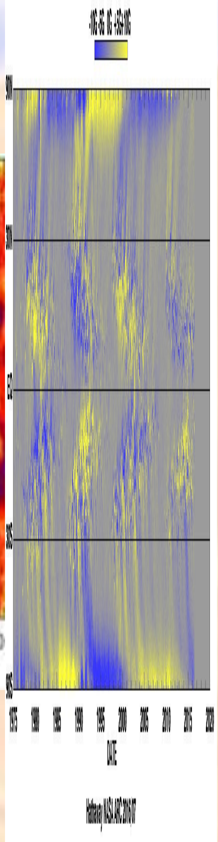
MF mode

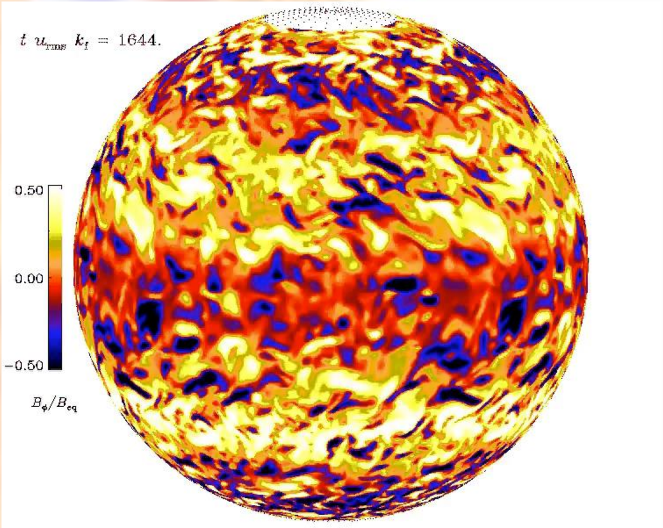
Code coupling

PENCIL CODE wedges



Käpylä, Mantere & Brandenburg (2012), ApJL, 755, 22





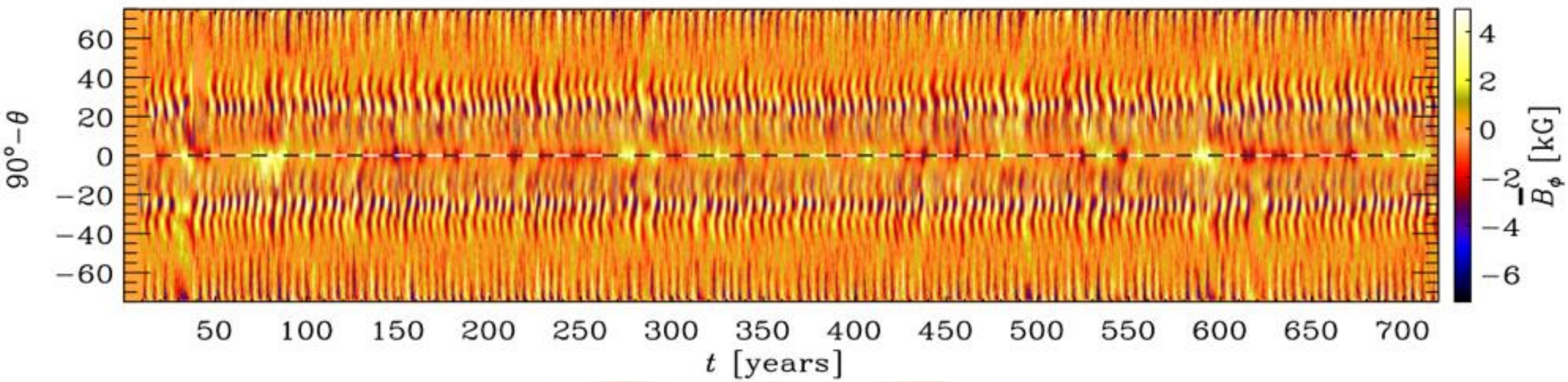
Evolution of azimuthal magnetic field near the surface over time.

Challenge: to run such a model long enough to detect multiple dynamo modes and irregular variations

The Millennium PENCIL CODE run

- A run integrated over 1000 years in physical units
- Developing a ‘basic’ cycle of roughly 5 years (the data contains 200 magnetic cycles); despite of the too short cycle length, very similar properties to the solar cycle.
- Enough statistics to explore Gleissberg-DeVries type cycles, and everything shorter than that. Special data analysis tools required.

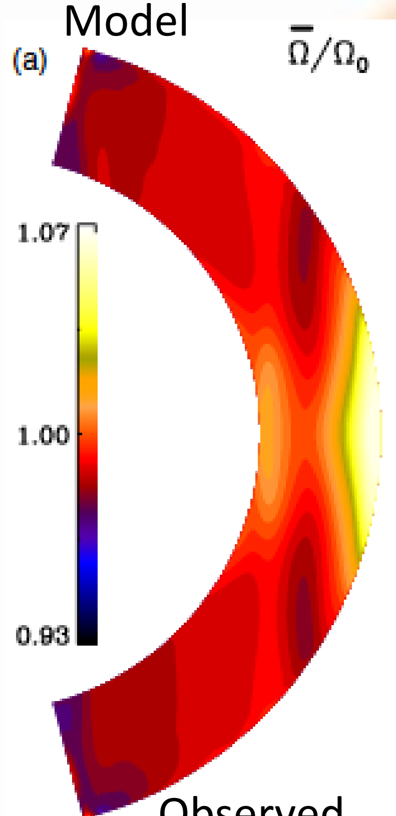
Käpylä et al. (2016), Astron. Astrophys., 589, 56, (data openly available upon request)



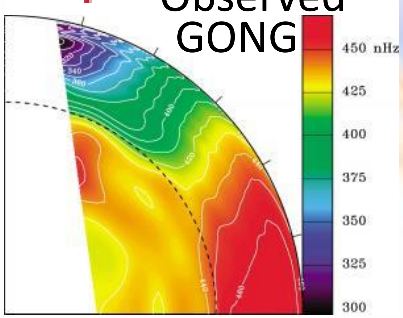
Mean azimuthal field near the surface for the first ¾ of the run

The Millennium PENCIL CODE run

Model

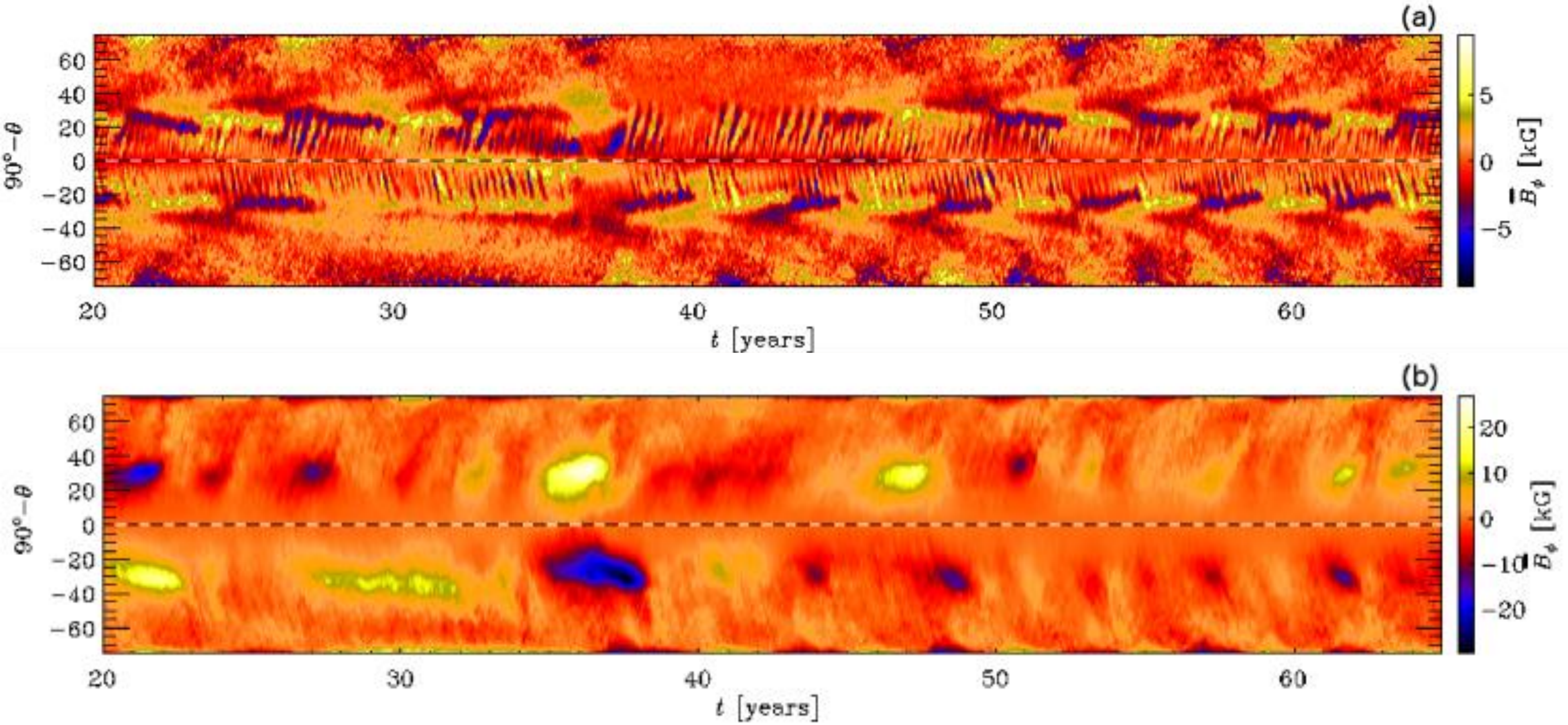


Observed
GONG



- Run started with uniform rotation
- Faster equator – slower pole differential rotation generated due to anisotropic turbulence (mainly the Reynolds stresses)
- The rotation law is NOT EXACTLY solar-like
  - Contains NO tachocline; no prominent NSSL
  - Too cylindrical isocontours of angular velocity
  - Multi-cellular meridional flow structure
  - The influence of the meridional flow is very weak on the flow; structure largely unimportant

The Millennium PENCIL CODE run

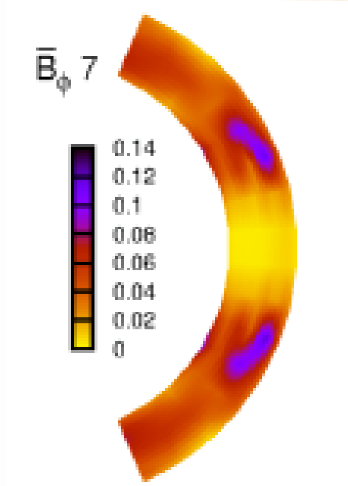


- Basic mode (equiv. of the 11-year cycle), long period-mode (Gleissberg cycle), high-frequency mode
- **Episodes of reduced surface magnetic activity akin to grand minima** (2 such episodes over the whole timeseries; missing and disrupted cycles 4 times)

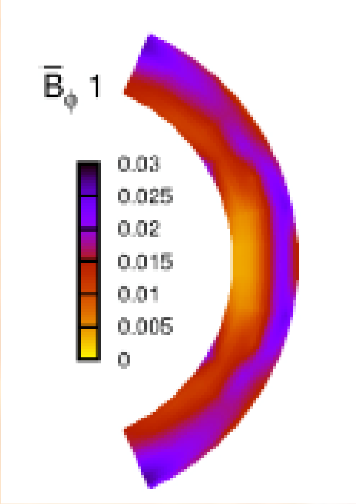
The Millennium PENCIL CODE run

- Special data analysis techniques required; Ensemble Empirical Mode Decomposition and D^2 phase dispersion statistics

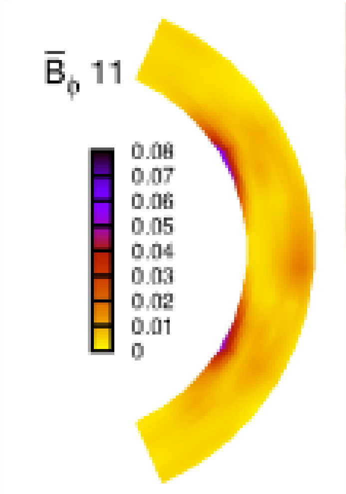
Olspert et al., 2016, SABID workshop, IEEE Big Data conference 2016, arXiV: 1612.01791



Basic mode of 5 years, medium coherence time, N/S asymmetric



Short mode of 0.1 years, shortest coherence time

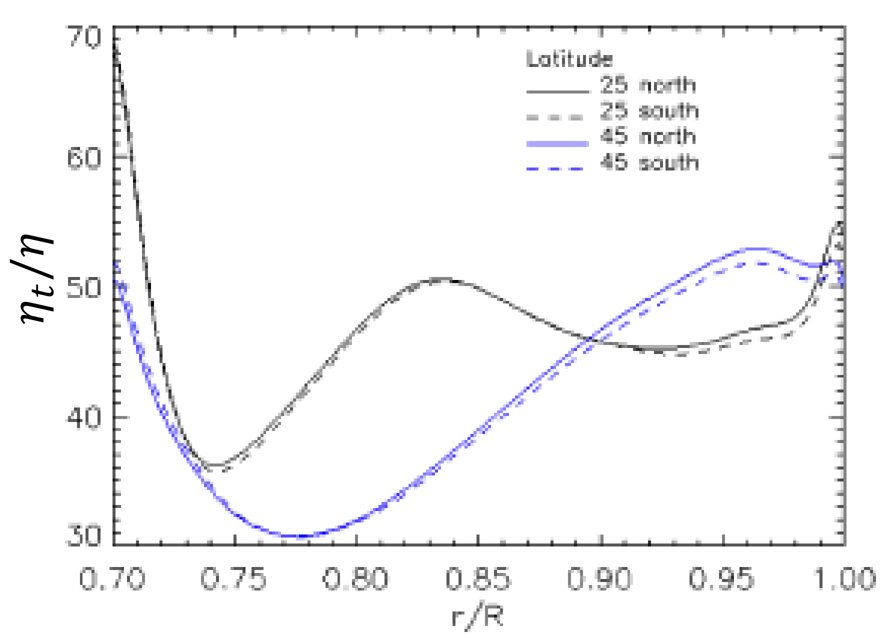


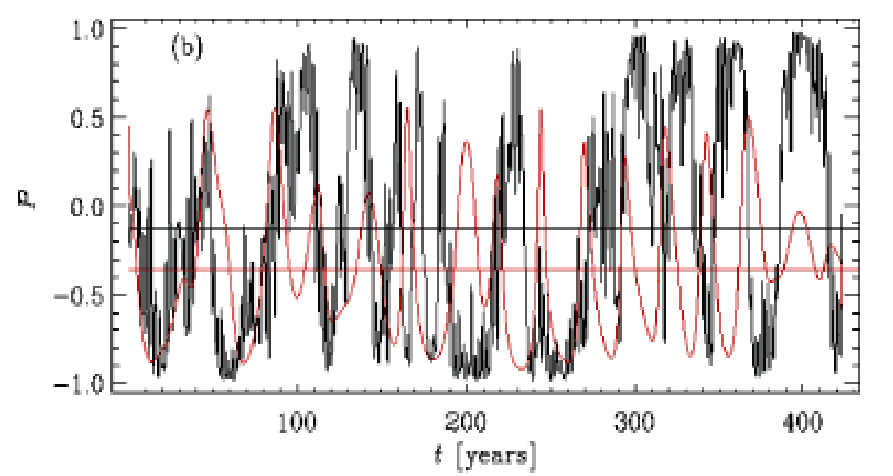
Long mode of 100 years, longest coherence time, N/S asymmetric

Multiple cycles, distinct locations, coherence times and symmetry properties

Absolute values not trustworthy; ratios ~1:100:1000

What are these different modes?





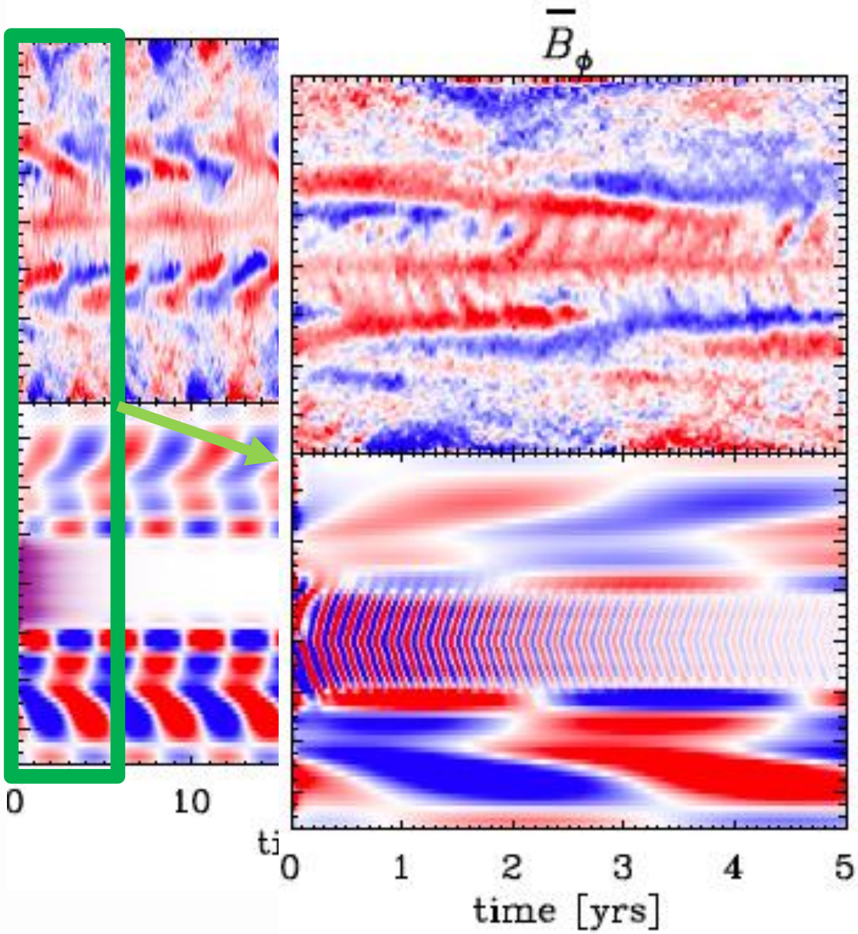
- One and the same? The variation of turbulent magnetic diffusion as function of depth is not sufficient to explain such a variation in the periods ($P \propto \tau_{diff} \propto \eta_t^{-1} \propto 1/(u_{rms}\,\ell)$)

- The modes exhibit vastly different symmetry properties

$$P = \frac{E_{\text{even}} - E_{\text{odd}}}{E_{\text{even}} + E_{\text{odd}}},$$

What are these different modes?

Warnecke+18, A&A, 609, A51; Warnecke+21, ApJL, 919, L13

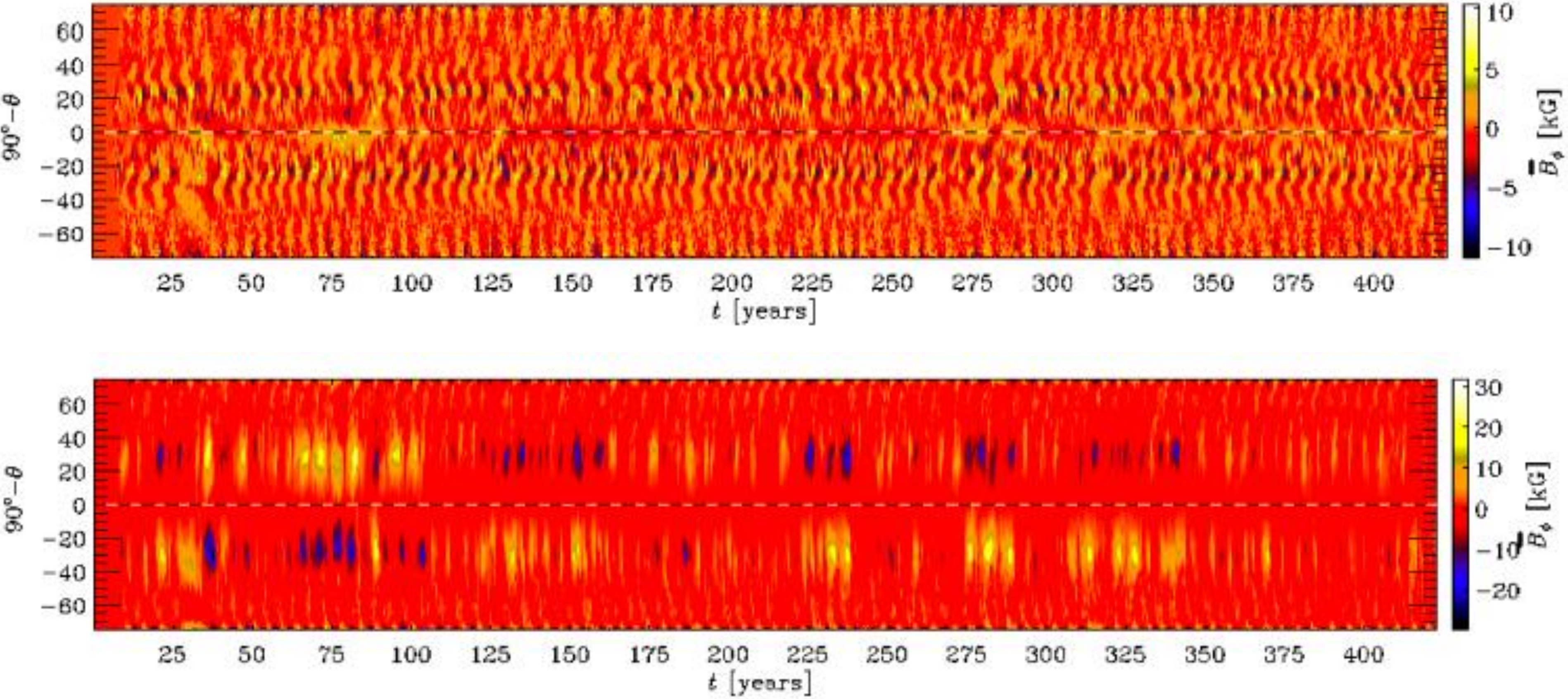


- Analysis with the test-field method (Next talk by Jörn Warnecke & refs below)
- The 5-year cycle is a dynamo mode driven by a $\alpha^2\Omega$ dynamo mechanism
- The short cycle is a distinct dynamo mode, the first one to be excited in the kinematic excitation state, driven by a α^2 dynamo mechanism
- No clear explanation for the long mode found from this analysis

Simard, C., Charbonneau, P., & Bouchat, A. 2013, ApJ, 768, 16
Simard, C., Charbonneau, P., & Dubé, C. 2016, Adv. Spa. Res., 58, 1522

What drives irregular behavior?

Käpylä+16; Gent+17,AN, 338, 885



TFM analysis explains vanishing surface activity by enhanced radial turbulent pumping; no clear reason for disruptions found by TFM. The only explanatory factor is the parity-locking of the top and bottom modes.

Conclusions & Future

- Global models of the solar cycle are becoming useful in understanding the operation of the solar dynamo
  - **We can reproduce qualitatively the appearance and properties of multiple cycles in solar-like stars, and with quantitative data analysis tools, such as the TFM, we understand the basic excitation mechanisms.**
- Rotation profiles are not realistic enough
- Small-scale dynamo not properly included, effects largely unknown, but indications of its importance already exist
- Role of tachocline not instrumental for solar-like solutions, but role of shear layers is not fully established
- Irregular episodes triggered through the non-linear interplay of the dynamo modes; hard to quantify.

Thanks!

Astroinformatics group, Aalto university

http://research.cs.aalto.fi/astroinformatics/

Frederick Gent, Johannes Pekkilä, Matthias Rheinhardt

SOLSTAR group, MPS

http://www.mps.mpg.de/solar-stellar-magnetic-activity

Jörn Warnecke