RESOLVE
CENTRE OF EXCELLENCE

FINNISH METEOROLOGICAL INSTITUTE

Aalto University

Maunder minimum in silico

Maarit Käpylä[1], Petri Käpylä[1], Nigul Olspert[1], Axel Brandenburg[2,4], Bidya Karak[3], Jaan Pelt[5]

[1]Department of Computer Science, Aalto University
[2]Nordita, Stockholm, Sweden
[3] Max-Planck Institute for Solar System Research, Göttingen, Germany
[4] JILA, University of Colorado, Boulder, USA.
[5]Tartu Observatory, Toravere, Estonia

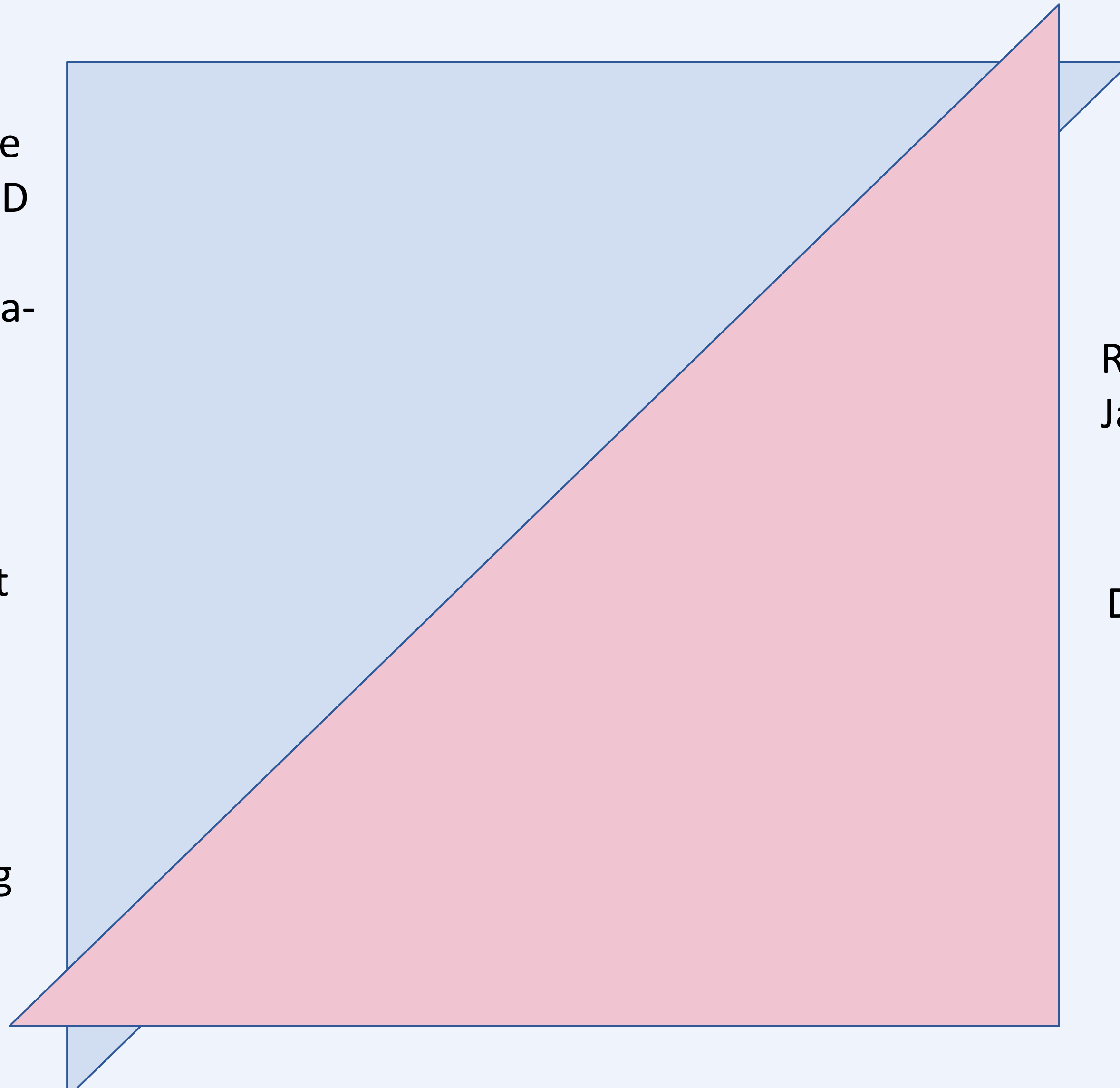
Maarit.kapyla@aalto.fi

Team overview

High-performance computing & MHD theory:

- form Peta to Exa-scale
- from CPUs to accelerators
- from simple to more intelligent tools

Resource person:
Axel Brandenburg

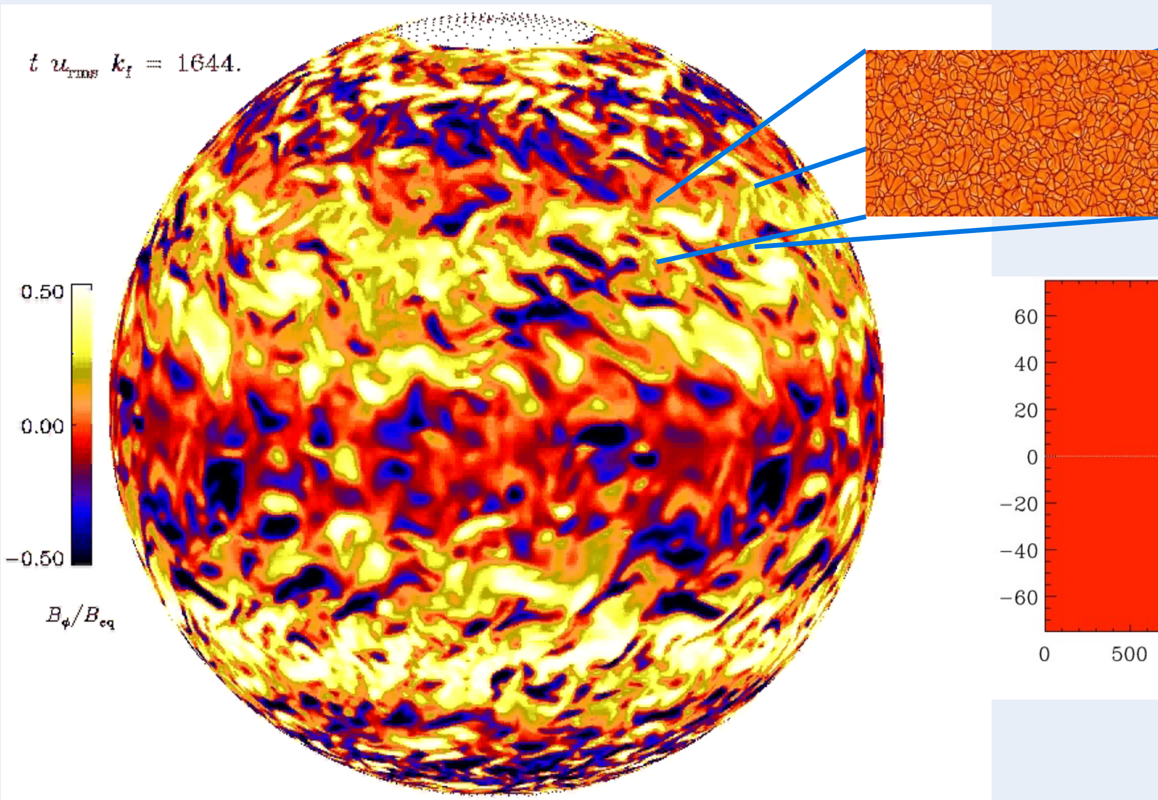


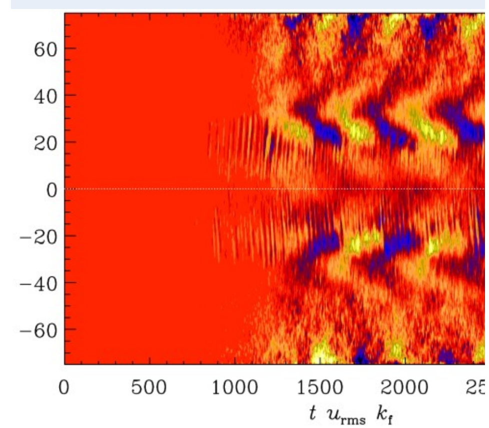
Resource person:
Jaan Pelt

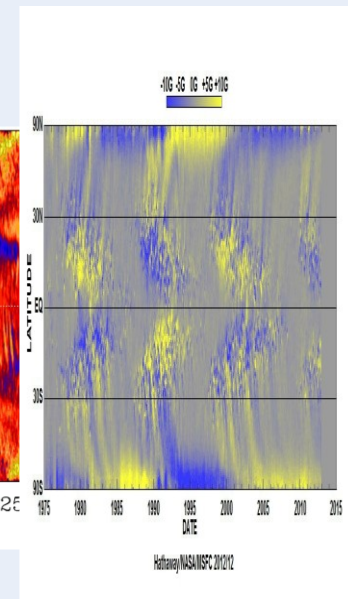
Data analysis:

- Big data
- Small data
- Sparse data
- Cyclic data

Topic of today: MHD models

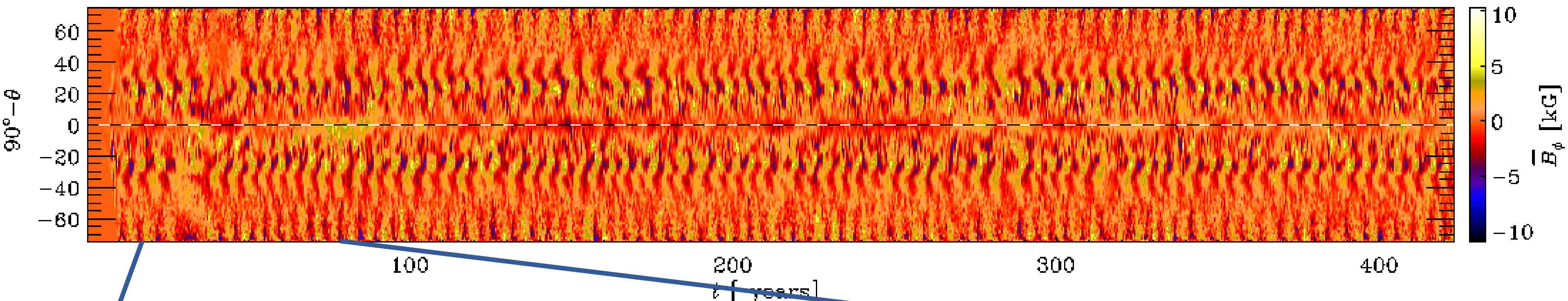


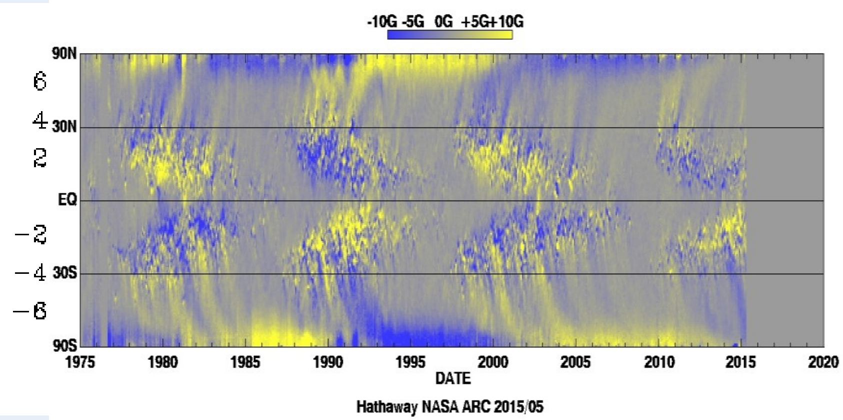


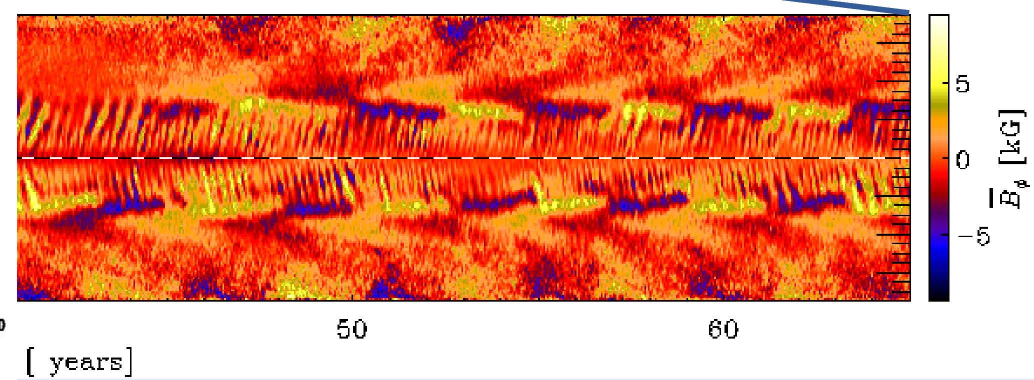


Käpylä, Mantere & Brandenburg, 2012, ApJL, 755, L22

"Millennium" simulation



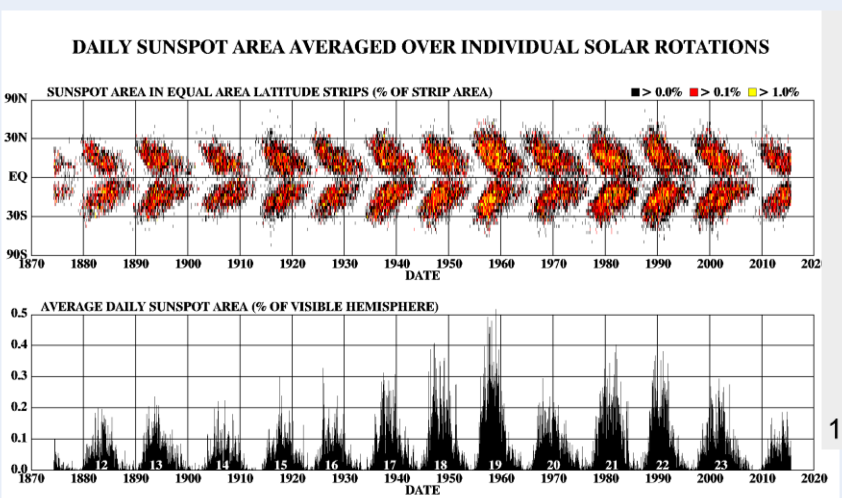


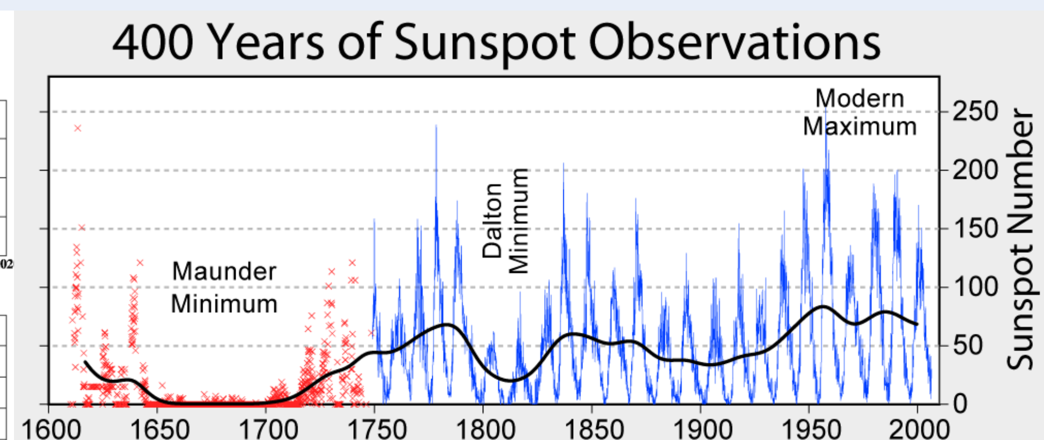


Brute force integration of the equations for an extremely long time; a model that covers 80 cycles. This is the most extensive solar-like simulation performed so far; two times larger cycle count in comparison to the EULAG-"Millennium" simulation, one of the competing modeling effots. *Käpylä et al. A&A, submitted, arXiv: 1507.05417*

“Millennium” simulation

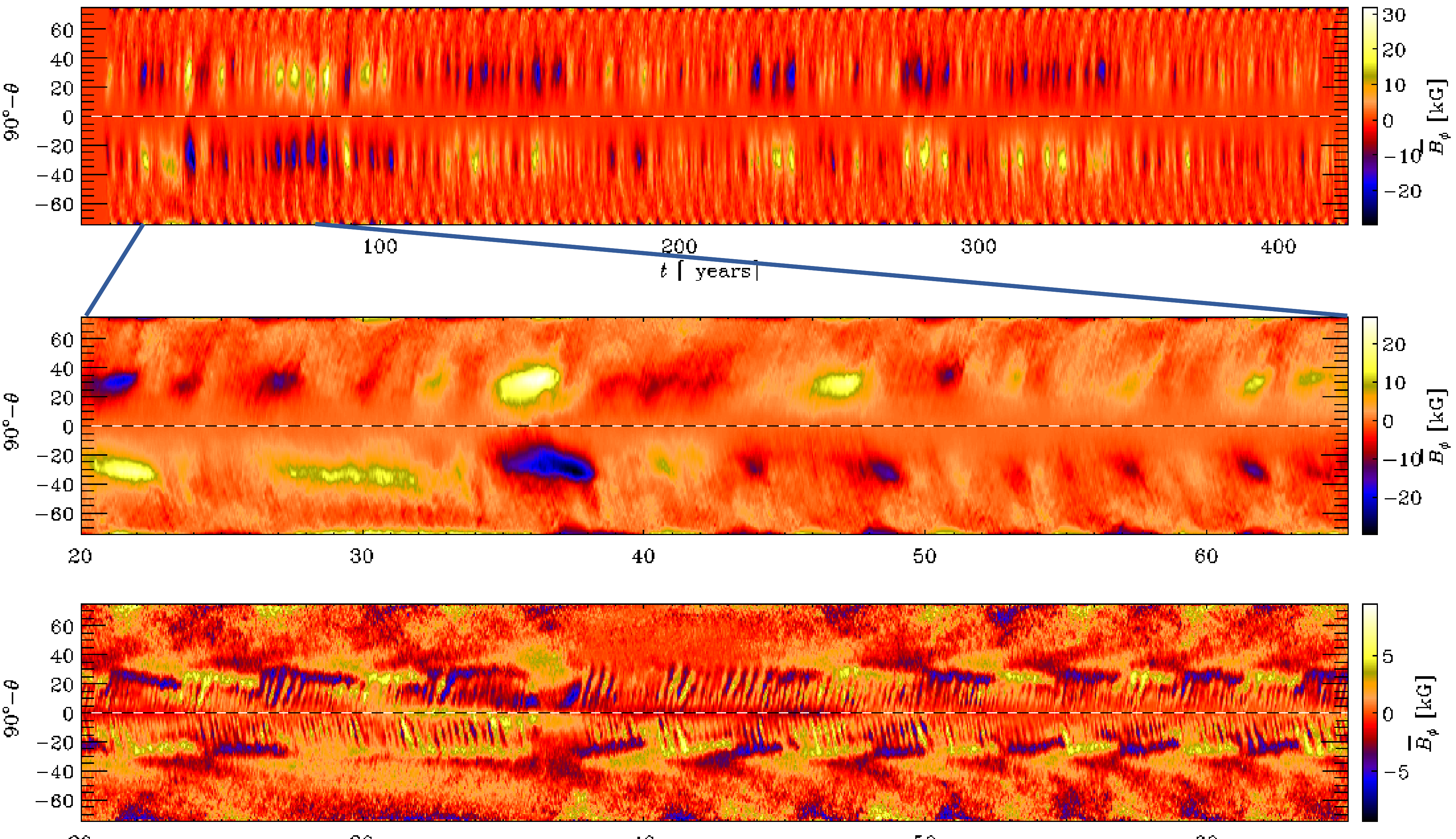
- From observations, we can only deduce the surface magnetic field and activity indicators (sunspots, flares, …).
- The further back in time we go, the less we know observationally.
- There are controversies related to the long time series, and we do not actually yet know what we have seen *(Ilya Usoskin’s talks cover this interesting topic!)*.
- In silico, we see all the depths and latitudes



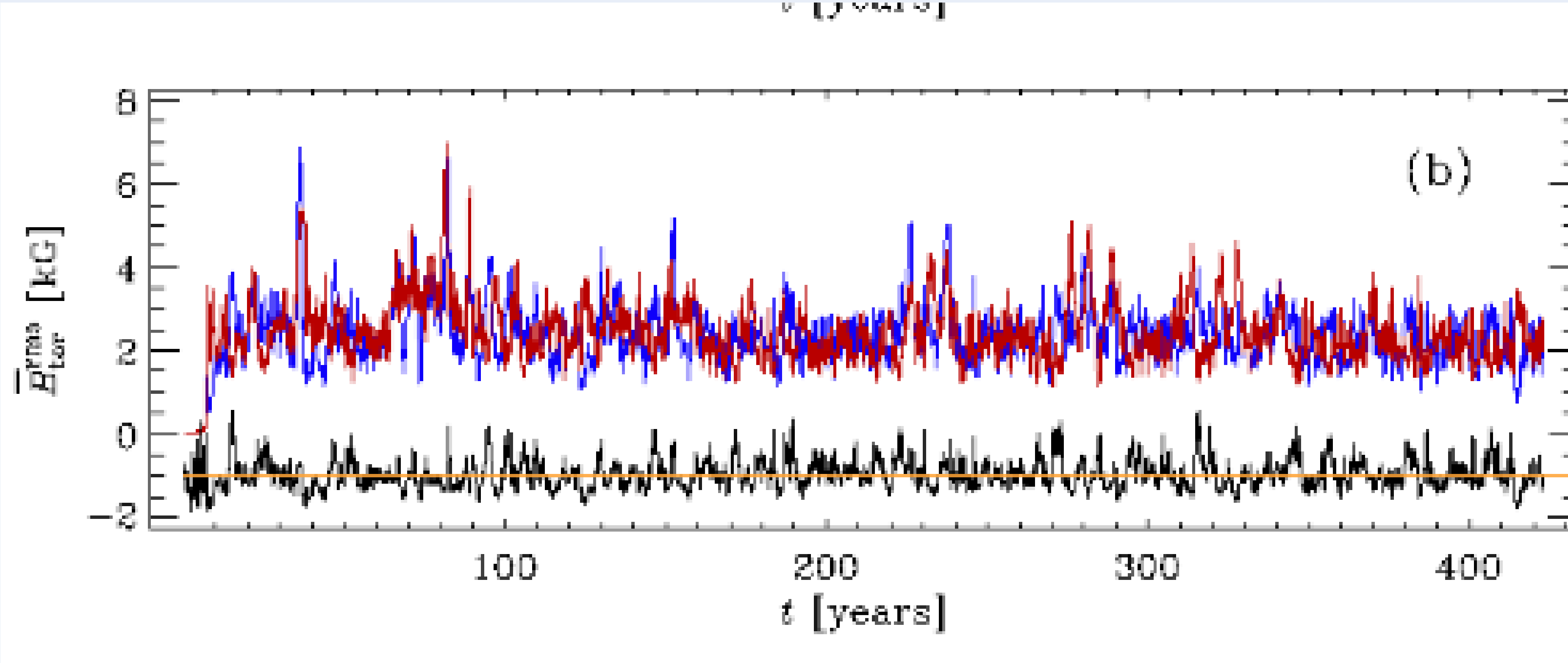


Maunder minimum in silico

What do we see deep down in silico during a grand minimum?



Maunder minimum in silico

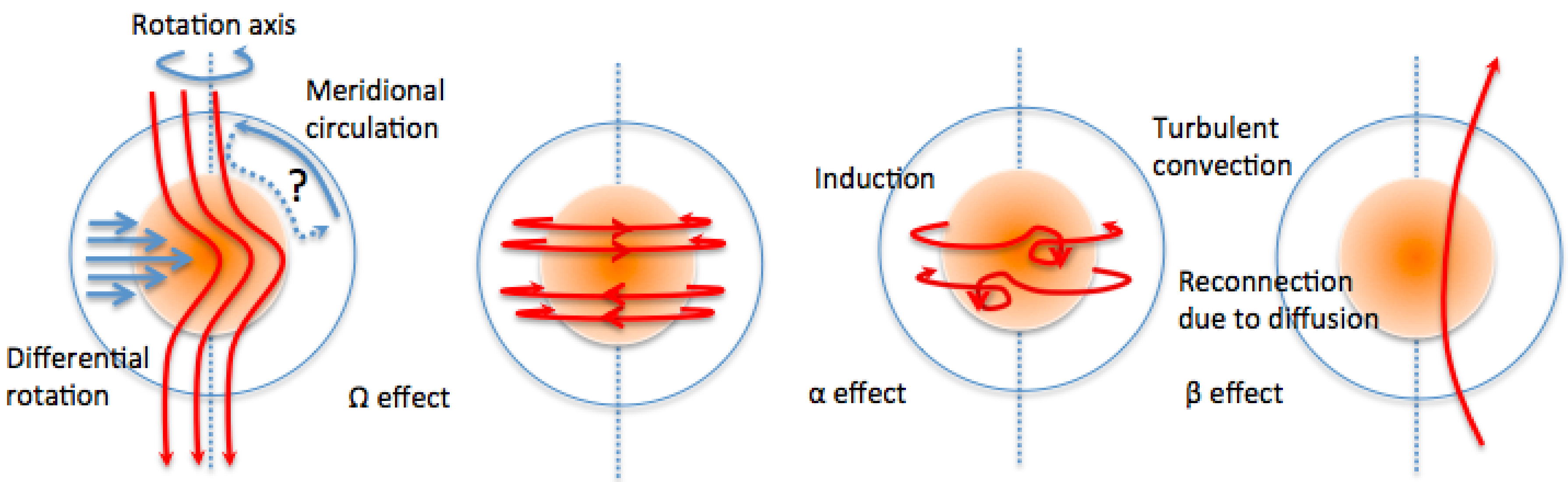


- This silico realization of a surface magnetic activity disappearance actually is a *global magnetic energy maximum*!
- But not always; the presence of large amounts of magnetic energy can also lead to *disturbed/missed cycles*.

Data analysis

- Even visually, it is evident that there *are several dynamo modes* present, at different locations of the convection zone.
- The evolution is *cyclic*, NOT periodic
  - method for detecting cycles of varying period and amplitude
- Various types of *irregularities*
  - characterization
- Finding *physical causes*, as all the ingredients are present in the model, but the model is really complex
  - methods of analysing massive datasets and retrieving the relevant information are needed

Once upon a time there was a simple dynamo…



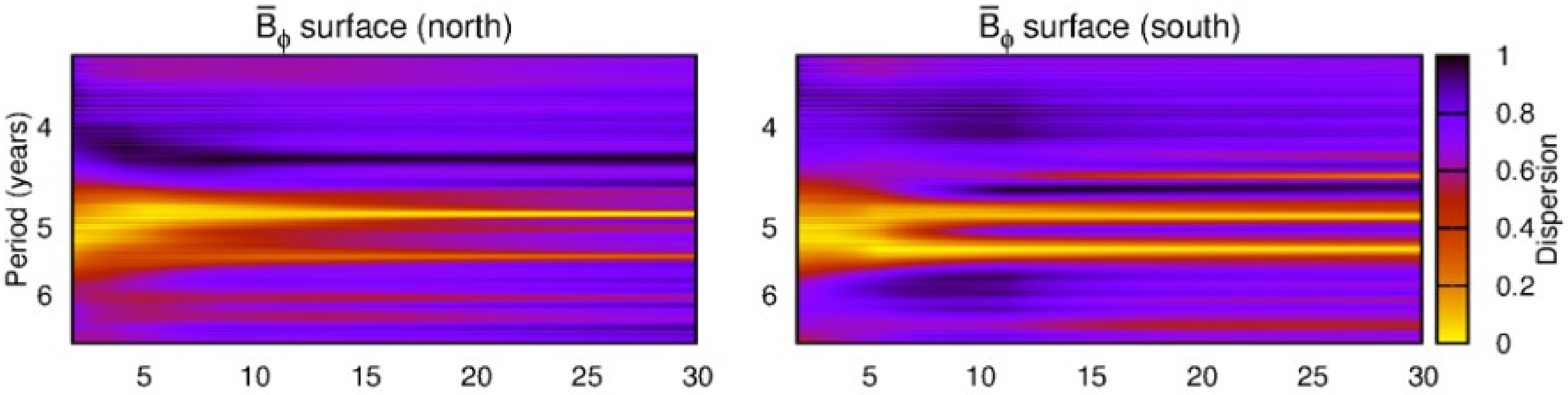
… with the basic ingredients of

- differential rotation (generator of strong toroidal fields)
- turbulent effects due to convection (source of poloidal fields, reconnection, and short memory of the dynamo due to high diffusion due to mixing)
- meridional circulation (can re-shape the magnetic field by advecting it around)

Is the cause of the irregularities in the *dynamo drivers* themselves, or is the behavior simply the result of the *highly nonlinear nature* of the system of equations?

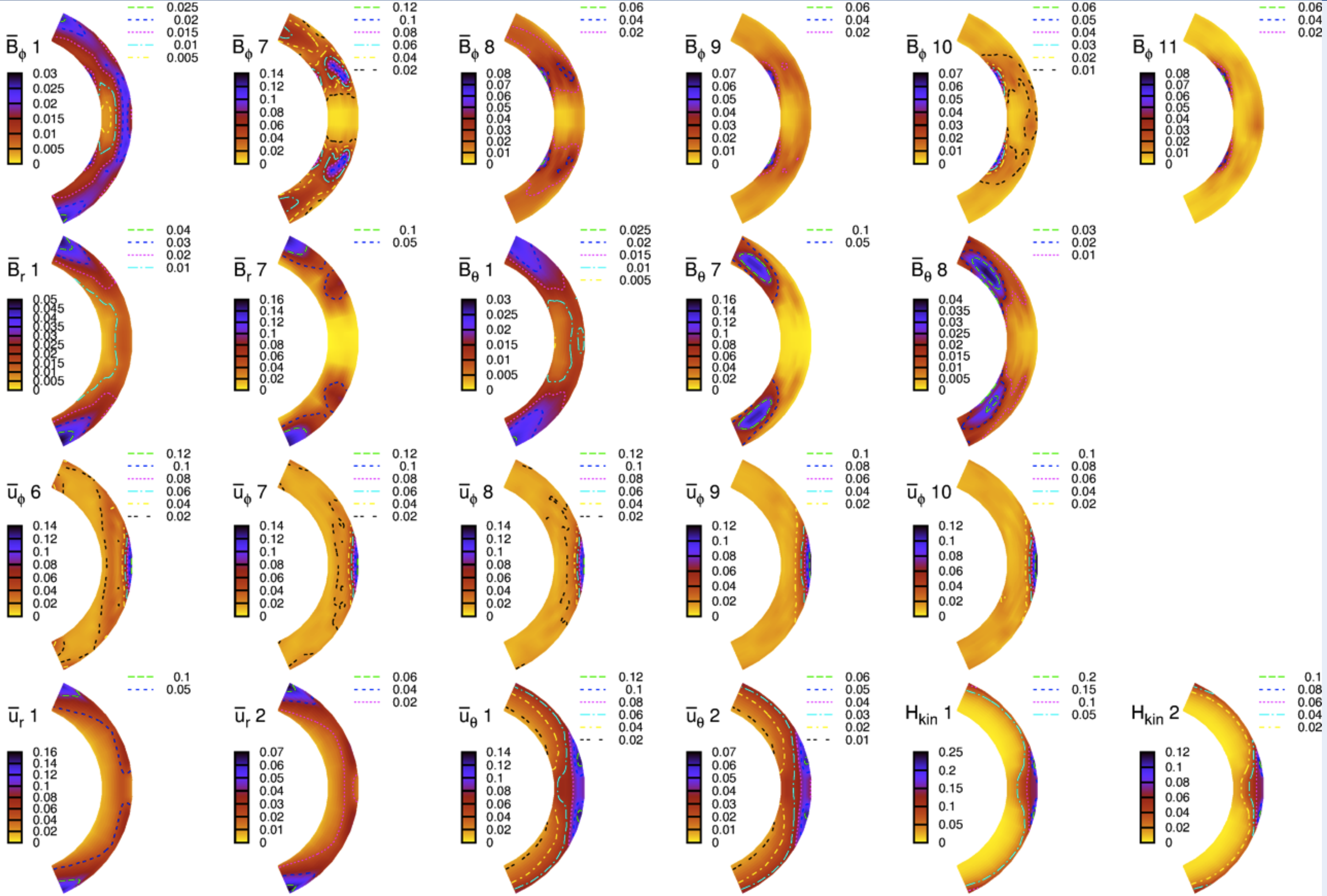
Extracting dynamo modes - D^2

- EMD and a phase dispersion statistics (D^2) used for the analysis of the cycles seen at different depths and latitudes *(see the poster by N. Olspert)*



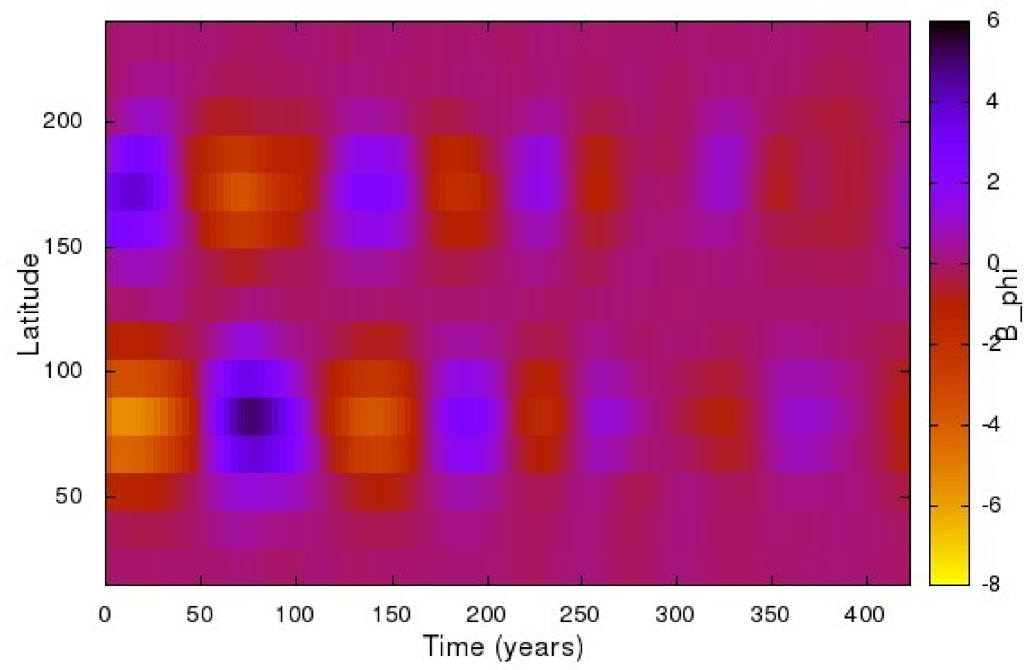
- D^2 analysis (correlating only phases over a certain coherence time, not over the full time span) reveals the *dominating "solar butterfly" –like period of roughly 5.35 years.*
- This is roughly 4 times shorter than the solar cycle, but if scaled back to solar time units, the simulation length would be roughly 2 millennia.

Extracting dynamo modes - EMD



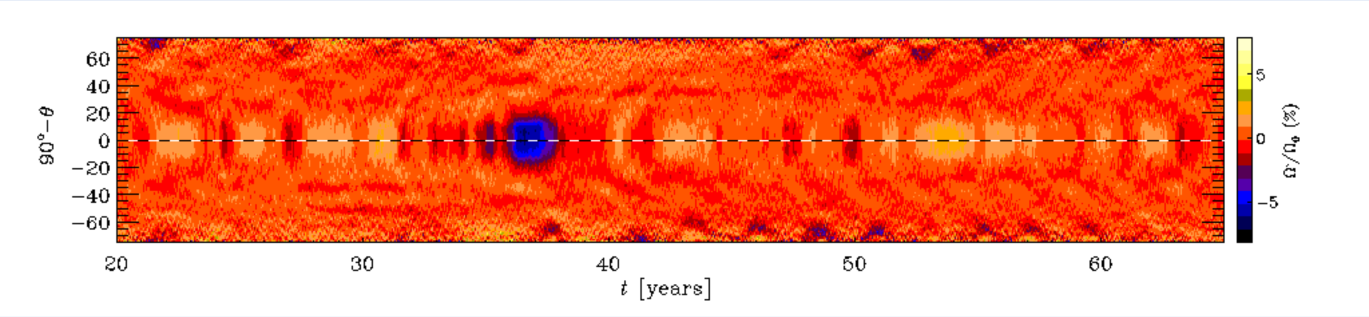
Extracting dynamo modes - EMD

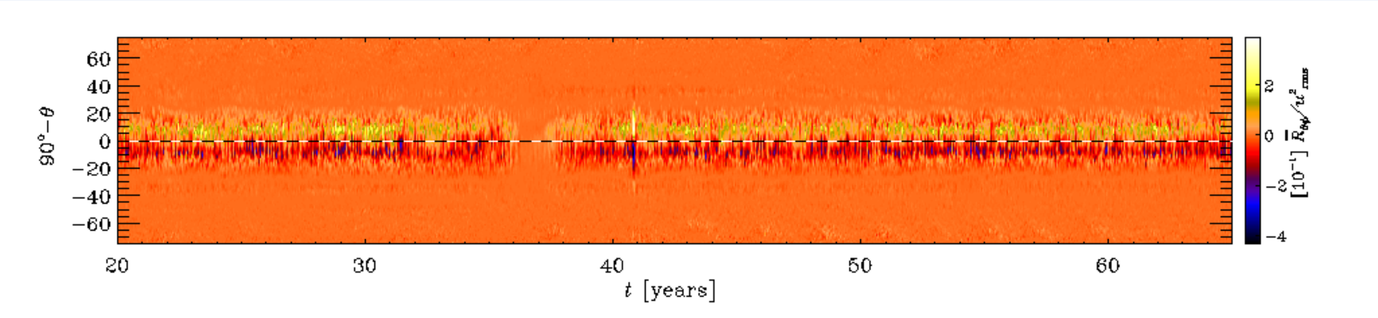
- **Three main types of dynamo modes confirmed**
  - Different spatial distribution
  - Different cycle lengths (1:10:100)-(surface, bulk, bottom)
  - Different symmetry properties: dominating cycle – nearly symmetric; long cycle: - nearly perfectly antisymmetric with respect to the equator
  - Each mode has a rather smooth behavior when separated
  - *Their interference* can cause abrupt and chaotic-looking events
  - The longest mode and especially its polarity reversals are related to the overall irregular behavior



Inspecting the dynamo drivers (simple method)

- Inspection of the turbulent effects, for the first approximation, made with computing proxies of these quantities
  - *no success*; **no significant variation during the irregular events** detected with this approach
  - the need of test methods *(the talk by Matthias Rheinhardt)*
- Differential rotation *notably affected by the magnetic field*
  - cyclic signal called as the *torsional oscillations* identified
  - the **irregularities are NOT caused by changes in the differential rotation**
  - the magnetic suppression is *mediated by turbulent effects (Reynolds stresses)*





Inspecting the dynamo drivers (simple method)

- Meridional flow
  - in relation to all other effects weak
  - multi-cellular, very much different from the generally accepted picture of simple dynamos
  - shows no systematic variation during the irregularities
  - **cannot be the cause of them**

- *Conclusions (scientific)*
  - With the caution that the test field analysis of the Millennium simulation has not yet been completed (Fred Gent performing at the moment), *the most likely cause of the irregularities is the interference of the different dynamo modes with vastly different symmetries.*

Future directions (CS perspective)

- HPC computing and data analysis are *intrinsically connected* in the future at Exascale computing
- At the moment, the huge amounts of data are *becoming a bottleneck* for performing Millennium-type simulations.
- Currently, the data analysis is de-coupled from the actual computations, but in the future as many as possible tasks should be done *on the fly*.
  - we cannot afford to store so much data, but only the relevant parts (*intelligent information retrieval*)
  - the algorithms need to be efficient not to compromise the efficiency of computations