Ground-Based Experiments

EST: The European Solar Telescope

The European Solar Telescope (EST) is a next generation large-aperture solar telescope. This **4-metre telescope** will be **optimized for** studies of the **magnetic coupling** between the deep photosphere and upper chromosphere. This will require diagnostics of the thermal, dynamic and magnetic **properties of the plasma over many scale heights**, by using **multiple wavelength** imaging, spectroscopy and **spectropolarimetry**. To achieve these goals, the EST will specialize in **high spatial and temporal resolution** using various instruments simultaneously that can efficiently produce 2D spectral information. EST will be located in Canary Islands, one of the first-class locations for astronomical observations.

Dario Del Moro
Dipartimento di Fisica
Università di Roma “Tor Vergata”

european solar telescope

The scientific challenges

What can the Sun teach us about fundamental astrophysical processes?

Observations of the Sun reveal intricate patterns of magnetic fields and the complex dynamics of a stellar atmosphere at the physically relevant spatial scales.

What drives solar variability on all scales?

The Sun varies on a wide range of spatial and temporal scales, displaying important energetic phenomena over the whole range. We do not fully understand and cannot accurately predict basic aspects of solar variability.

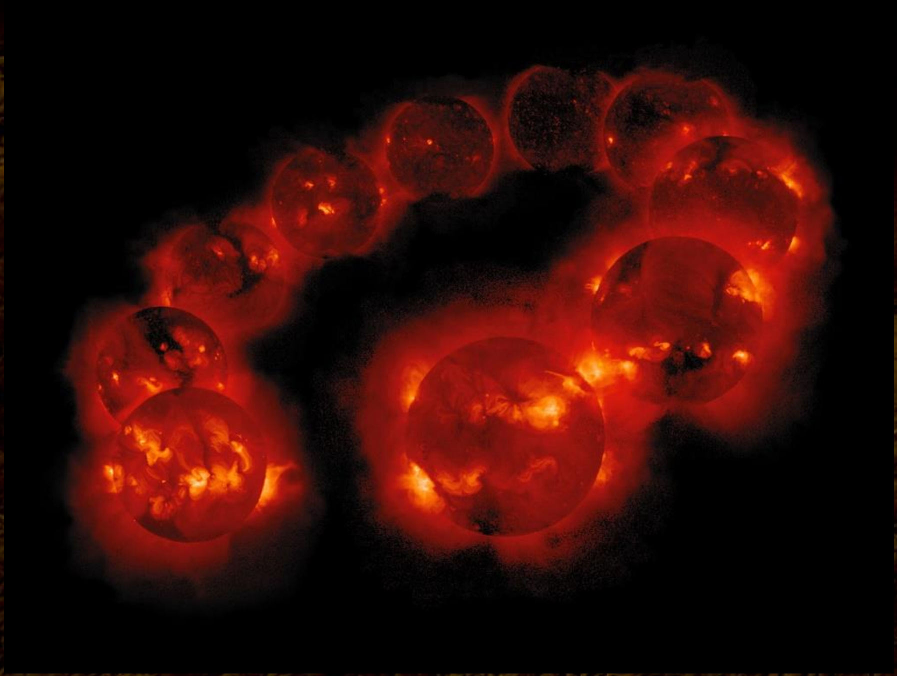
What is the impact of solar activity on life on Earth?

Solar magnetic activity variations induce terrestrial changes, which can affect millions of humans on short and long time scales. We need to predict disturbances of the space environment, which are induced by the Sun and to understand the links between the solar output and the Earth’s climate

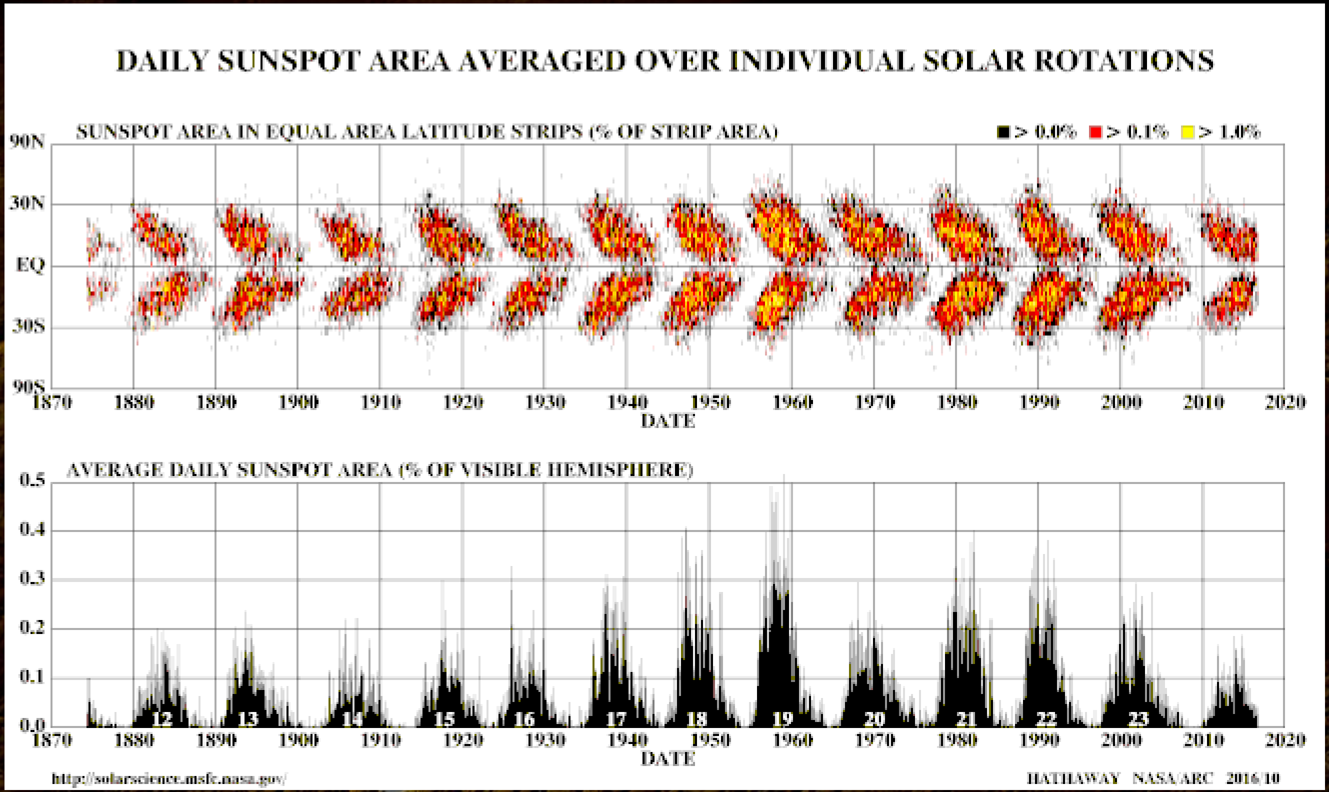
Common Ground?

Title: Evolution of Magnetism on the Sun.ogv
Author: D.H. Hathaway/NASA
Date: 3 December 2010

https://en.wikipedia.org/wiki/Solar_cycle

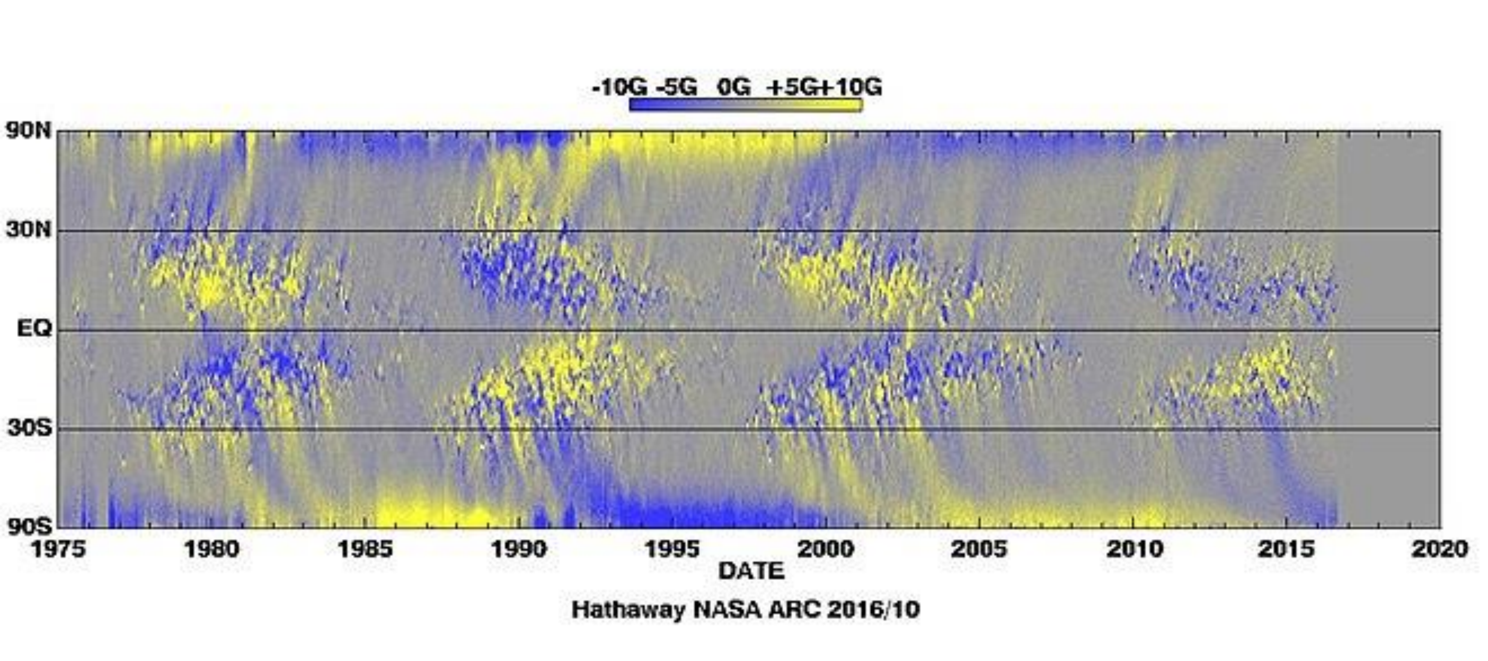


Common Ground?

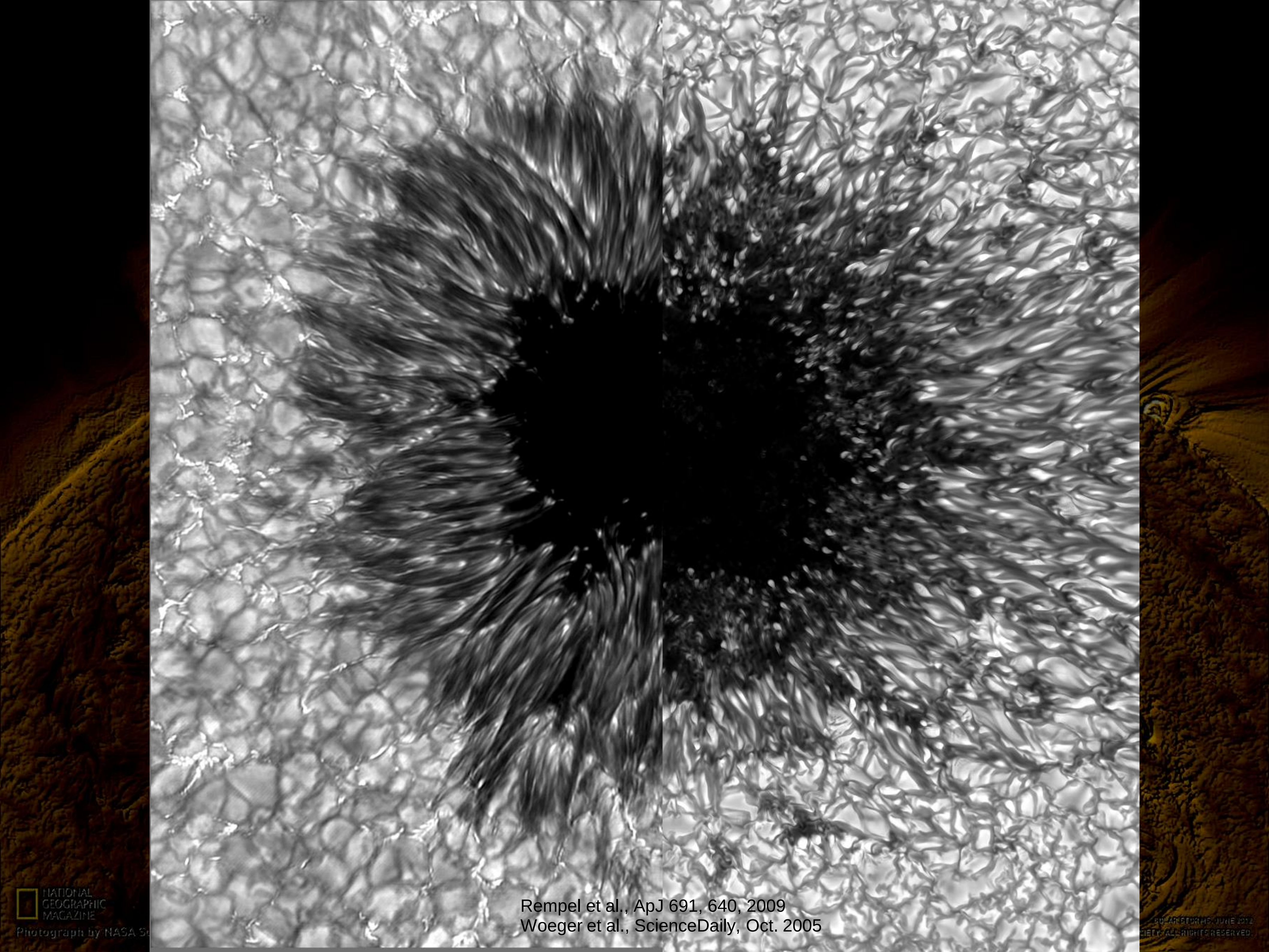


As each cycle begins, sunspots appear at mid-latitudes, and then move closer and closer to the equator until a solar minimum is reached. This pattern is best visualized in the form of the so-called butterfly diagram. Images of the Sun are divided into latitudinal strips, and the monthly-averaged fractional surface of sunspots is calculated. This is plotted vertically as a color-coded bar, and the process is repeated month after month to produce this time-series diagram.

Common Ground?



Time vs. solar latitude diagram of the radial component of the solar magnetic field, averaged over successive solar rotation. The "butterfly" signature of sunspots is clearly visible at low latitudes.



Rempel et al., ApJ 691, 640, 2009
Woeger et al., ScienceDaily, Oct. 2005

The MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \ ,$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p + \mathbf{g} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau} \ ,$$

$$\frac{\mathrm{D}e}{\mathrm{D}t} + (\gamma - 1)e\nabla \cdot \mathbf{u} = \frac{1}{\rho}\Big[\nabla \cdot \Big((\chi + \chi_r)\nabla T\Big) + \phi_\nu + \phi_B\Big] \ ,$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) \ .$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{B} \cdot \nabla \mathbf{B} + \nu \nabla^2 \mathbf{u}$$

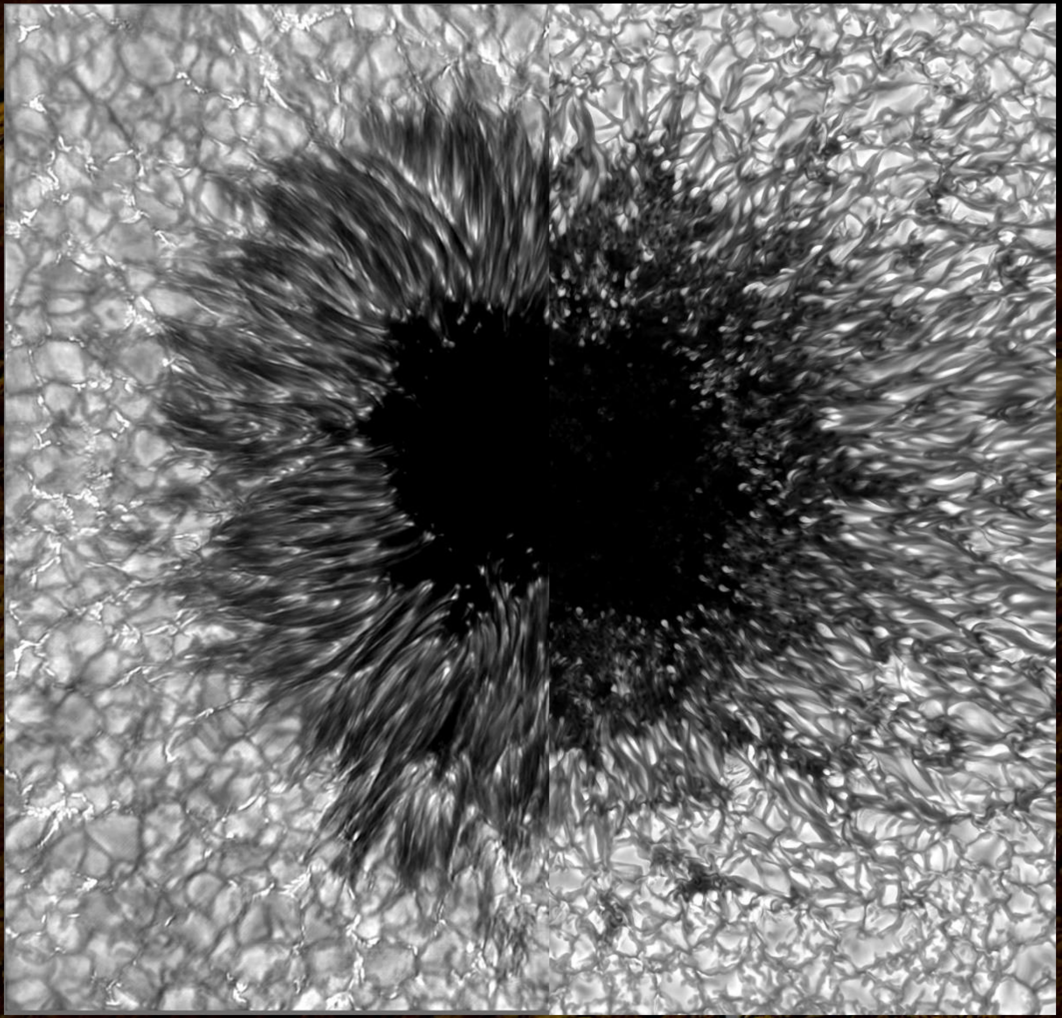
$$\frac{\partial \mathbf{B}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{B} = \mathbf{B} \cdot \nabla \mathbf{u} + \eta \nabla^2 \mathbf{B}$$

$$\nabla \cdot \mathbf{u} = 0$$

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

Prof. Manfred Schussler, 2008:

"In 100 years we will have the computing power to perform MHD simulations from the large scales (1400 Mm) down to the dissipation scale (10 cm)."



In the meanwhile…we need **simplified models** that can mimic the complexity of the solar dynamics

The flux-transport dynamo

Toroidal field
- Just below the CZ
- Created by shear

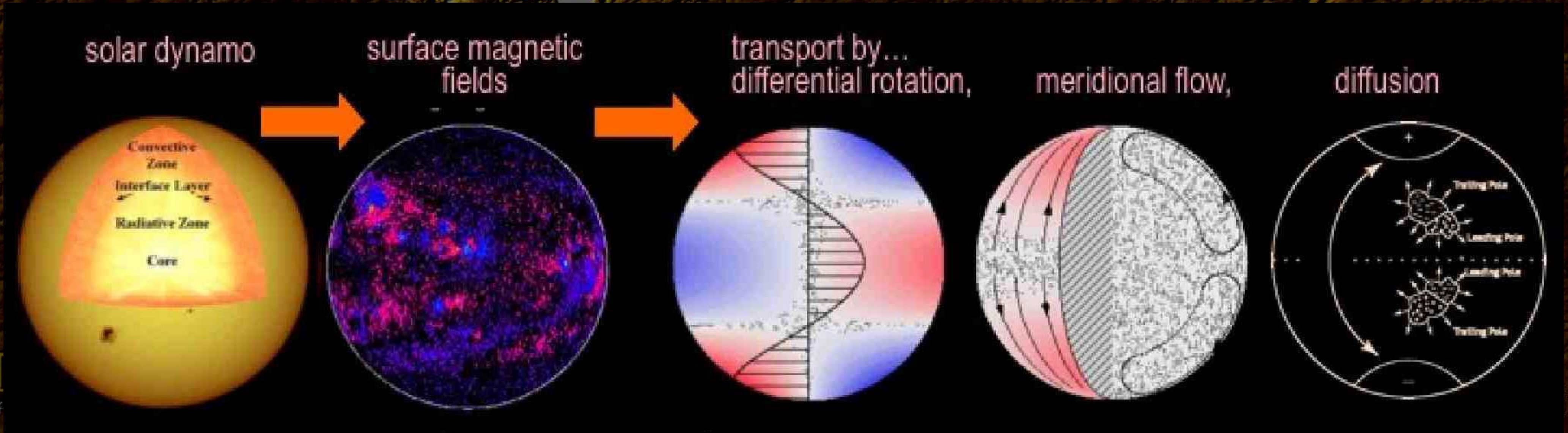
Buoyancy of flux tubes
- Tilted AR emergence
- Active latitudes

Decay by shredding
- Diffuse field

Meridional flow
- Poleward migration for a new poloidal field

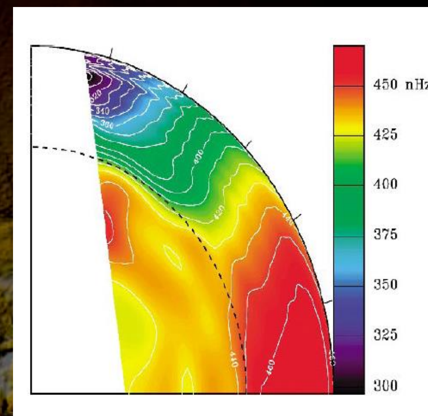
+ Right time scales
+ Right starting latitudes
+ Right tilt angle between emerging polarities
+ Variation of the meridional flow affects the cycle
- Decay of AR still a problem
- JUST a kinematic model

Rudiger & Hollerbach, *The Magnetic Universe*, Wiley-VCH, 2004



A kinematic dynamo model

MAIN INGREDIENTS:
<u>Differential rotation</u>
Diffusion
<u>Meridional flow</u>



- Surface B flux values strongly dependent on rotation rate and profile

- Period determined by the characteristics of the return flow

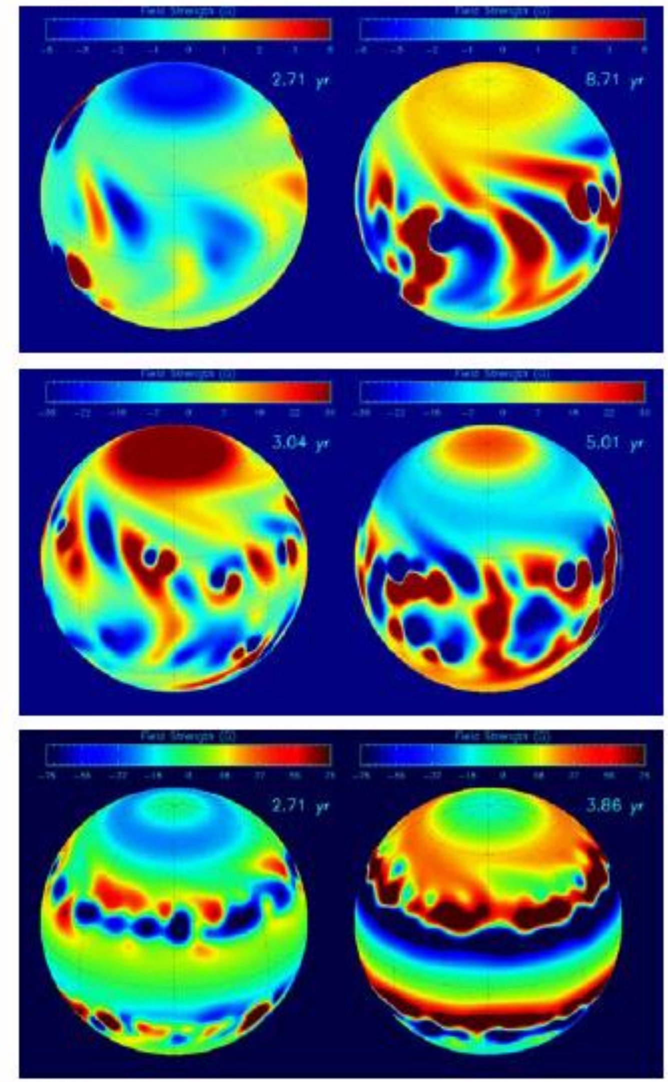
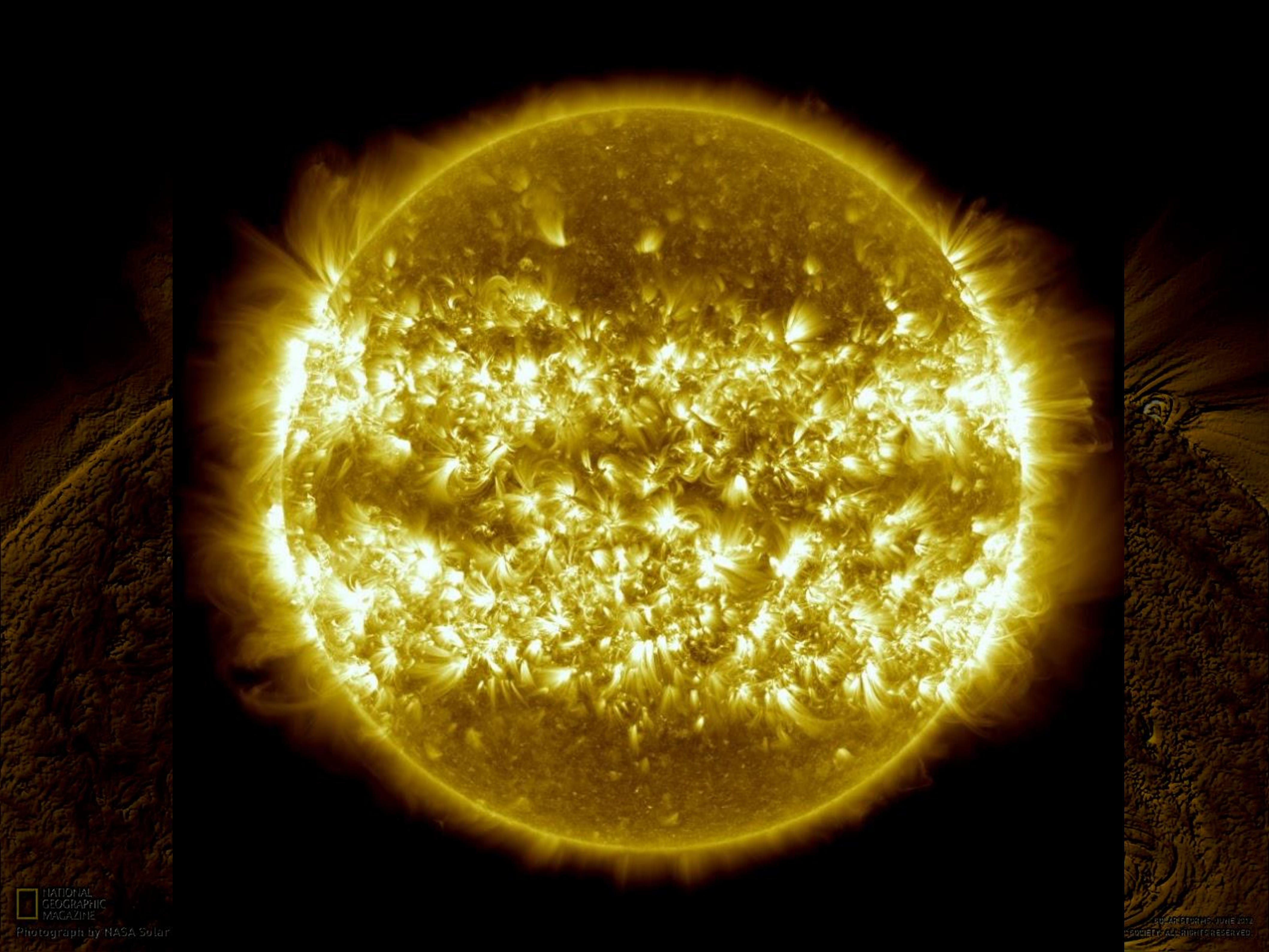
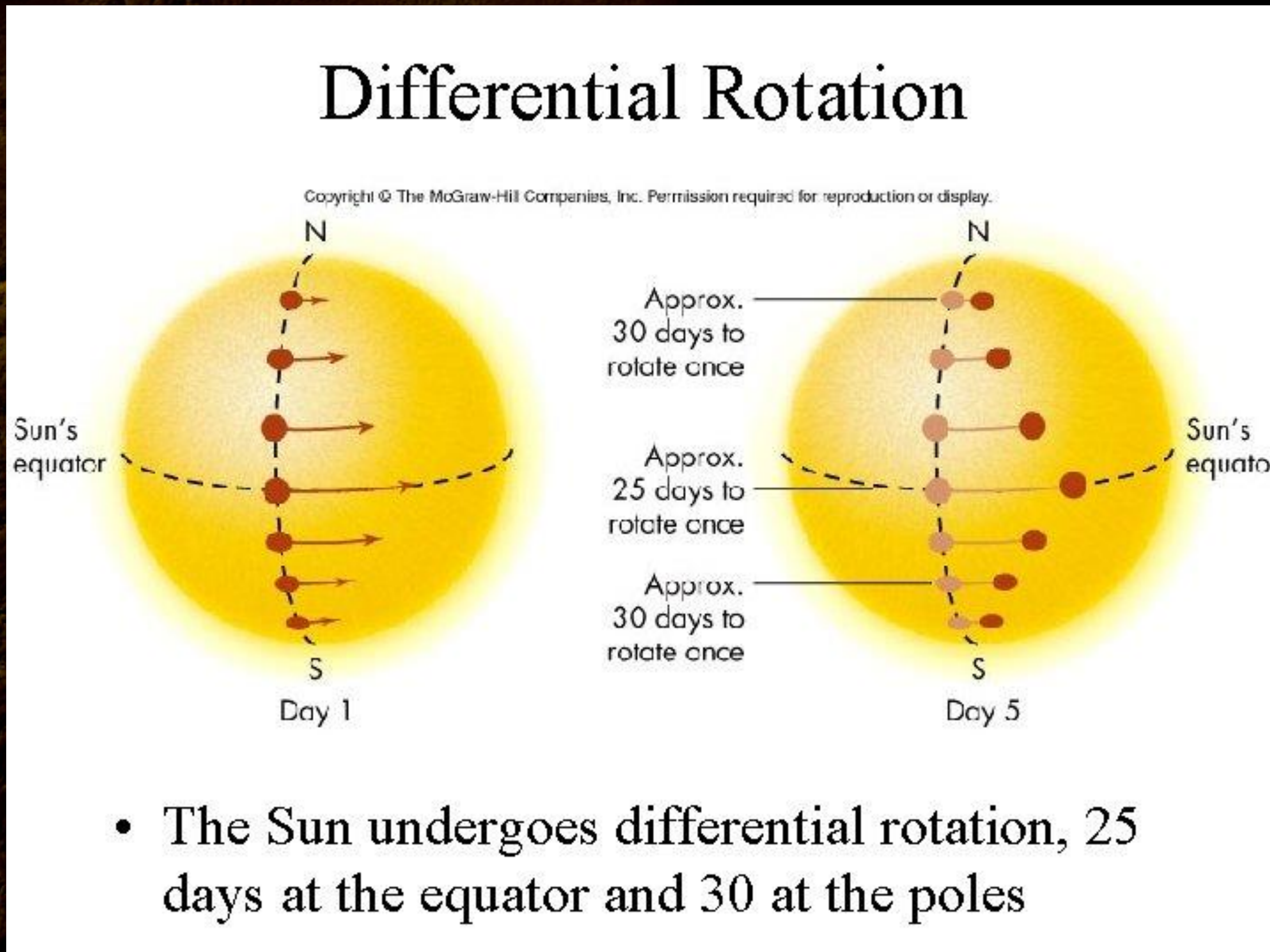


Fig. A.1. The surface distributions of magnetic flux for the Sun-like star with P_{rot} = 27 d (*top panels*), P_{rot} = 9 d (*middle panels*), and P_{rot} = 2 d (*bottom panels*), near the activity minimum (*left panels*) and the maximum phases (*right panels*). The colour scale for the magnetic field strength saturates at ±5, 30, and 75 G for top, middle, and bottom panels, respectively. The corresponding time-latitude diagrams for the azimuthally averaged magnetic field strength are shown in Figs. 5c, 7c, and 9c.

Isik et al., A&A 528, A135, 2011
Bonanno, Geophys. Astrophys. Fluid Dyn., 107, 2013


NATIONAL
GEOGRAPHIC
MAGAZINE
Photograph by NASA Solar
SOLAR STORMS, JUNE 2012
SOCIETY. ALL RIGHTS RESERVED.

What is the Solar Differential Rotation?



Howe, R. Solar Interior Rotation and its Variation.
Living Rev. Sol. Phys. 6, 1 (2009). https://doi.org/10.12942/lrsp-2009-1

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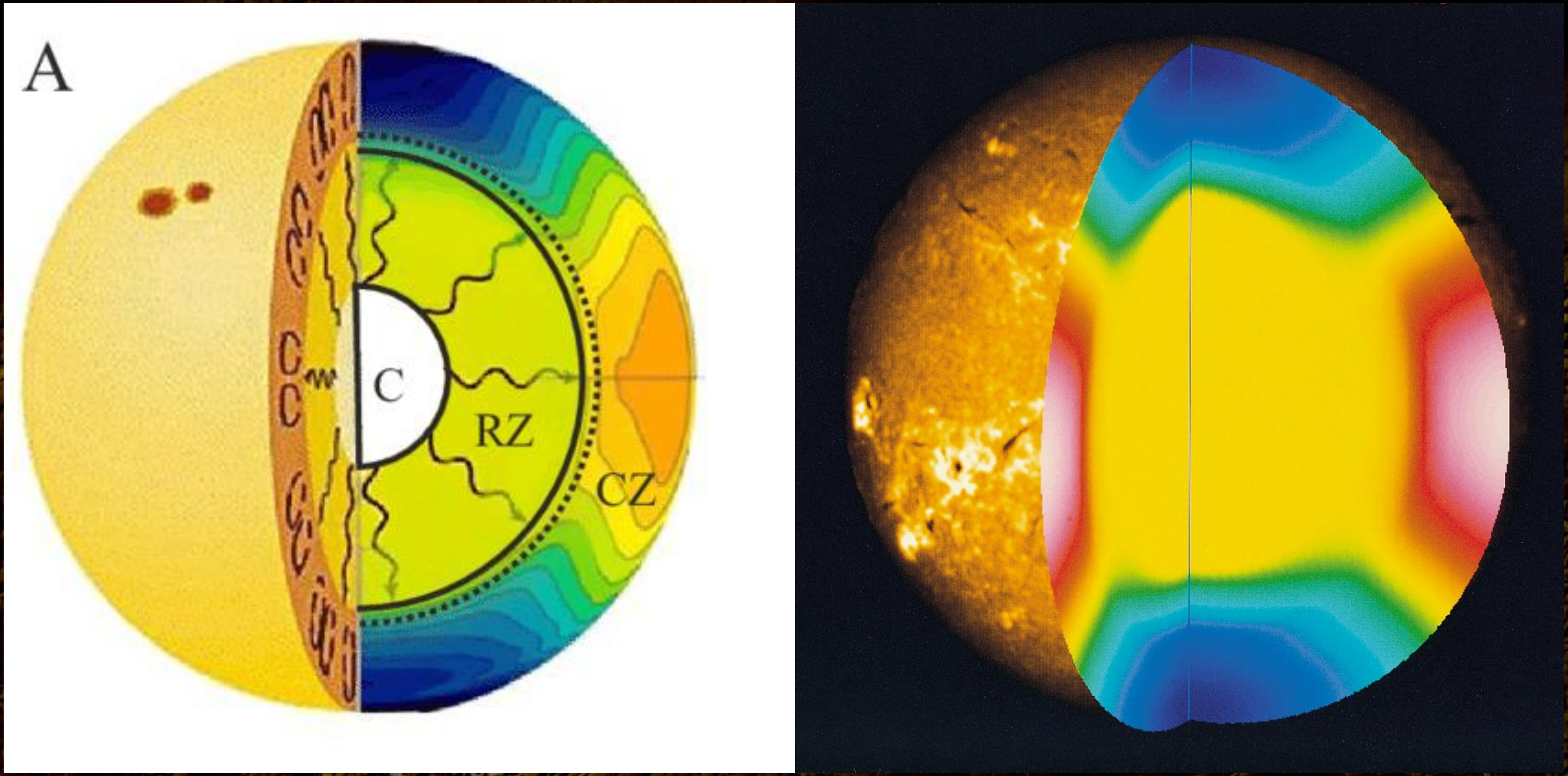
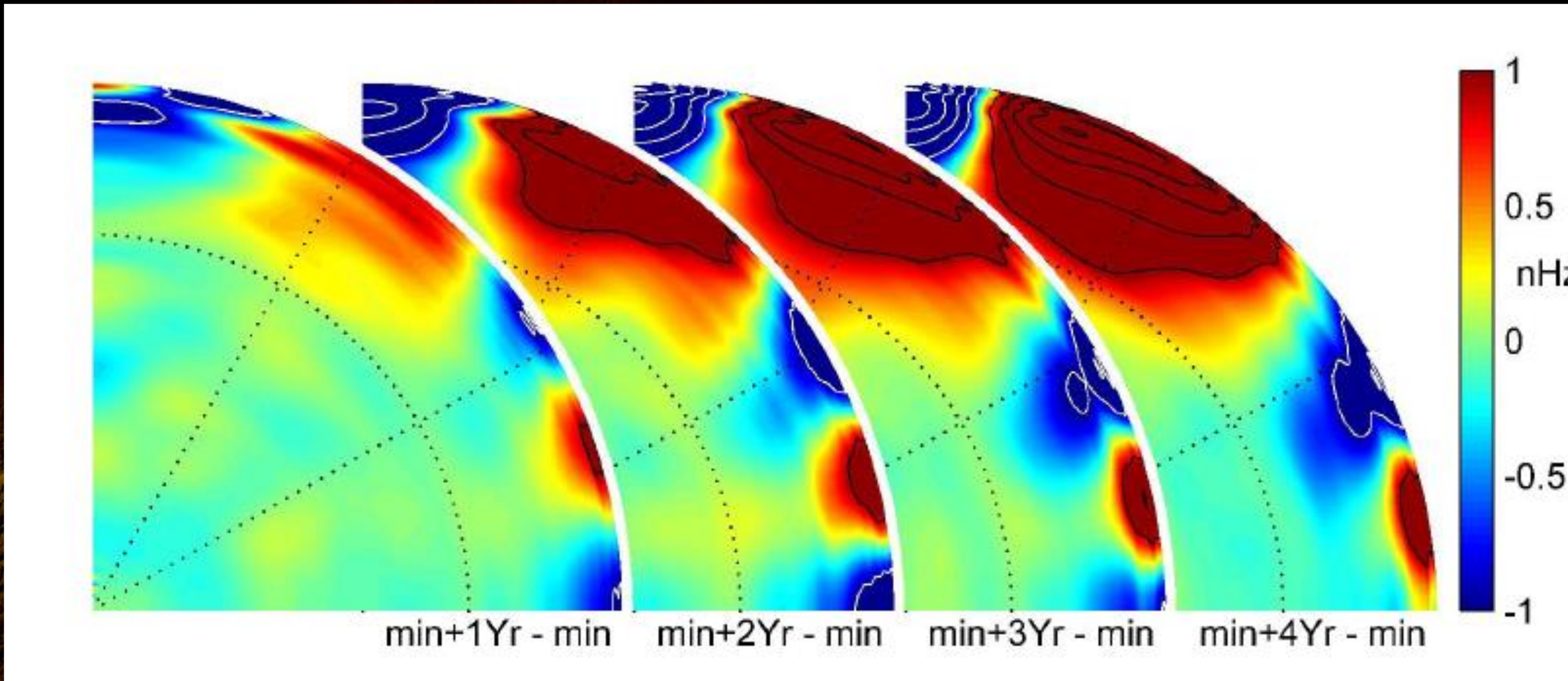
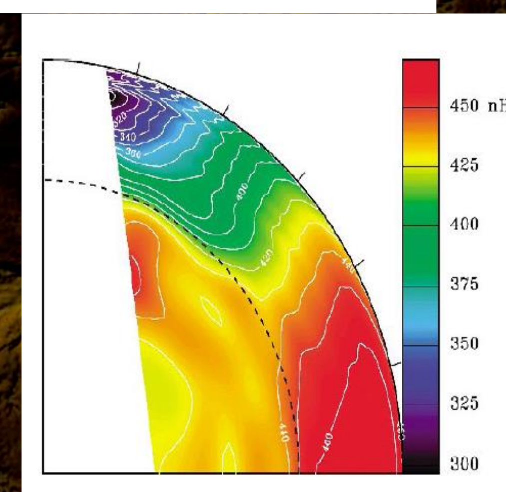


HOW does Solar Differential Rotation vary?





NATIONAL GEOGRAPHIC MAGAZINE
Photograph by NASA Solar Dynamics Observatory

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Buoyancy of flux tubes
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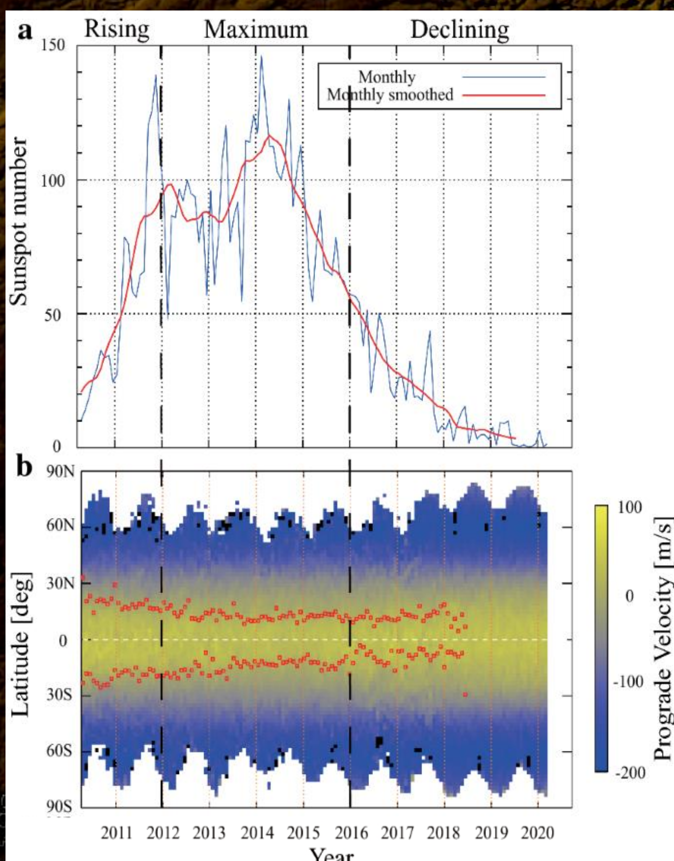
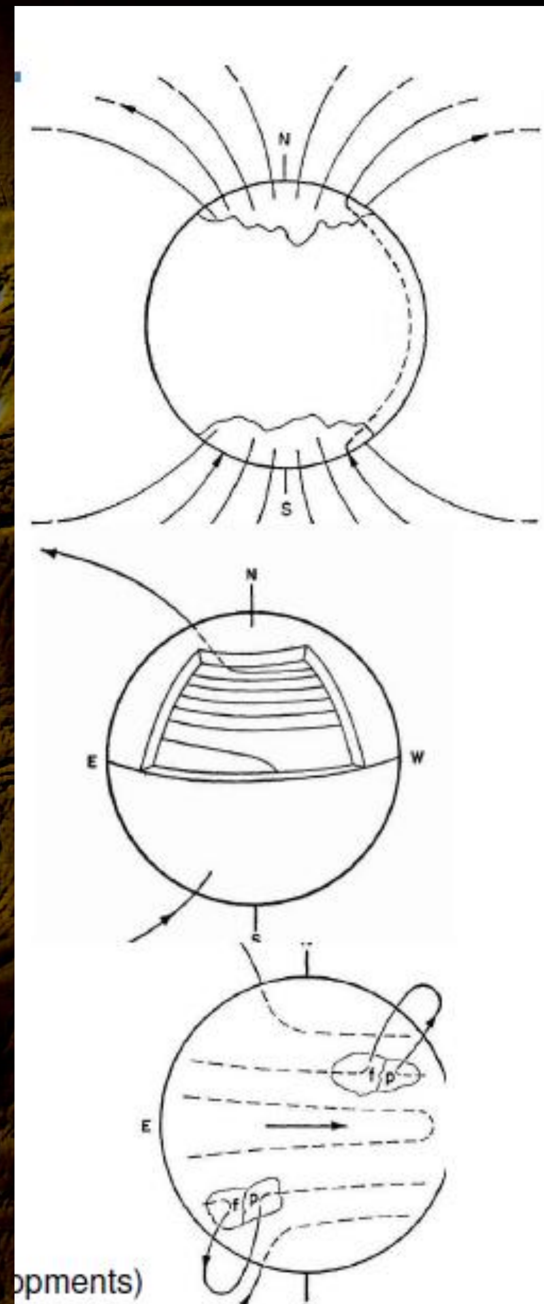
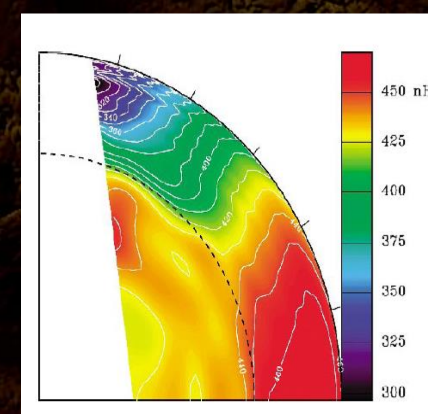
- Active latitudes







- Surface B flux values strongly dependent on rotation rate and profile

A kinematic dynamo model

MAIN INGREDIENTS:
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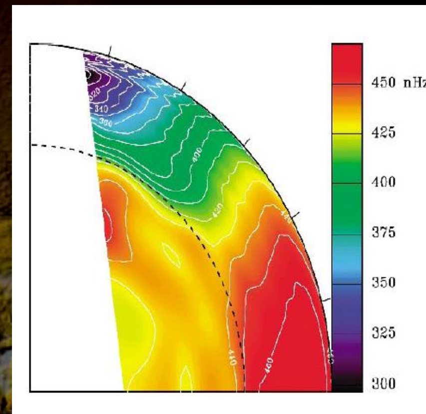
Meridional flow



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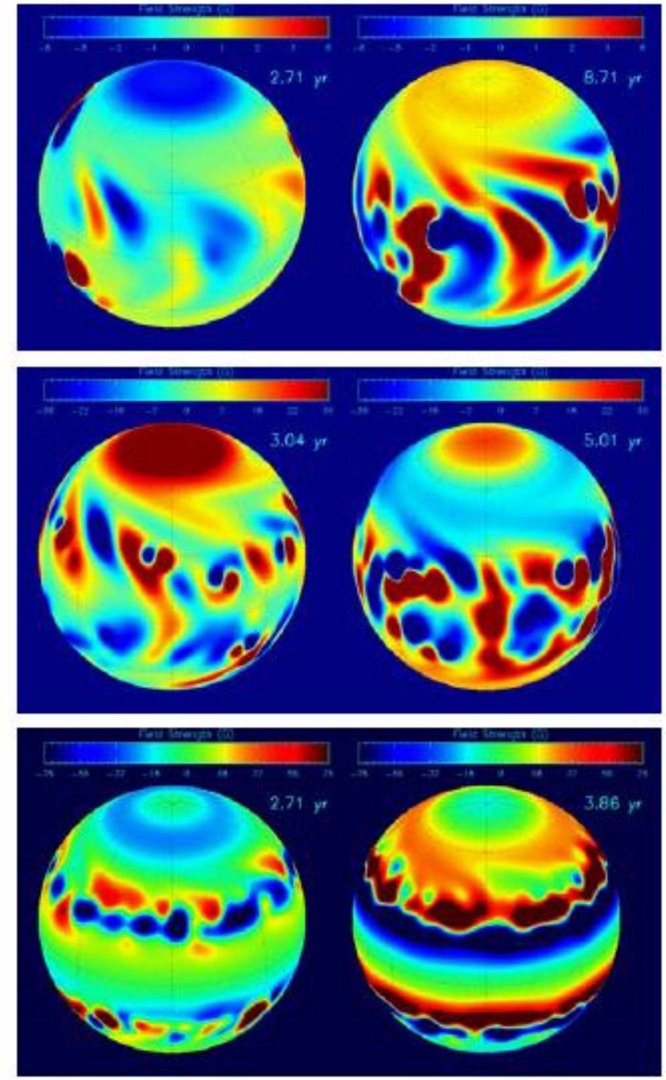

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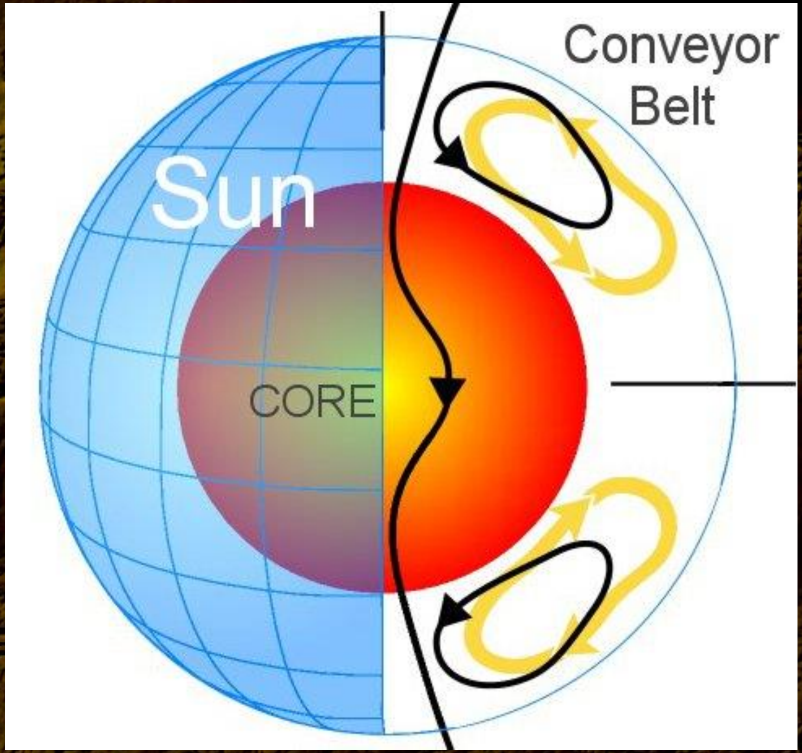
Isik et al., A&A 528, A135, 2011
Bonanno, Geophys. Astrophys. Fluid Dyn., 107, 2013

What is the Return Flow?

A global flow pattern within the Sun that transports hot plasma near the surface from the solar equator to the poles and back to the equator in the deeper layers of the convection zone.
The flow at the surface is rather slow, with typical speeds of 10-15 m/s.



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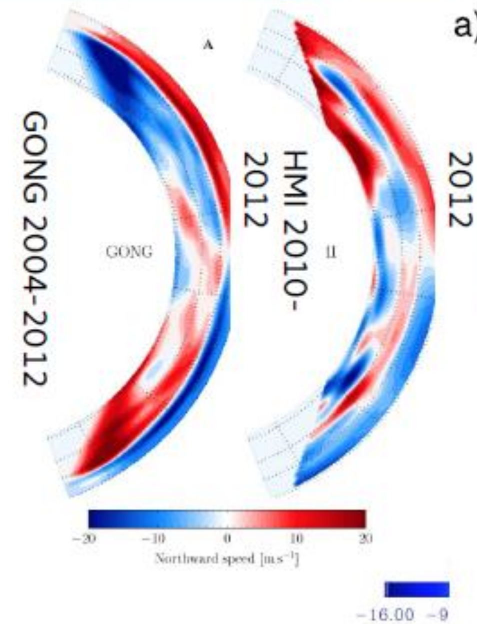
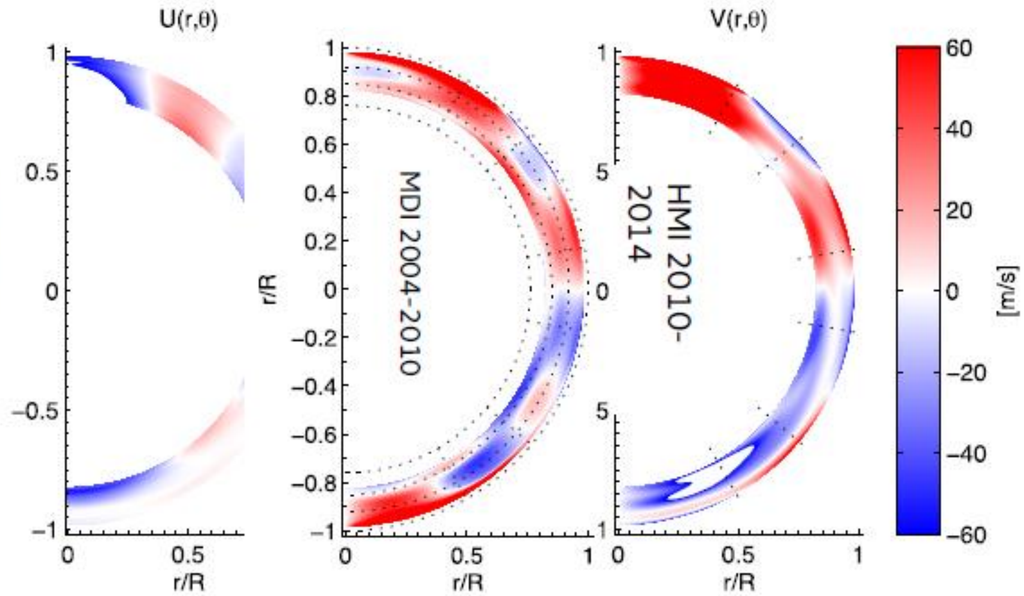
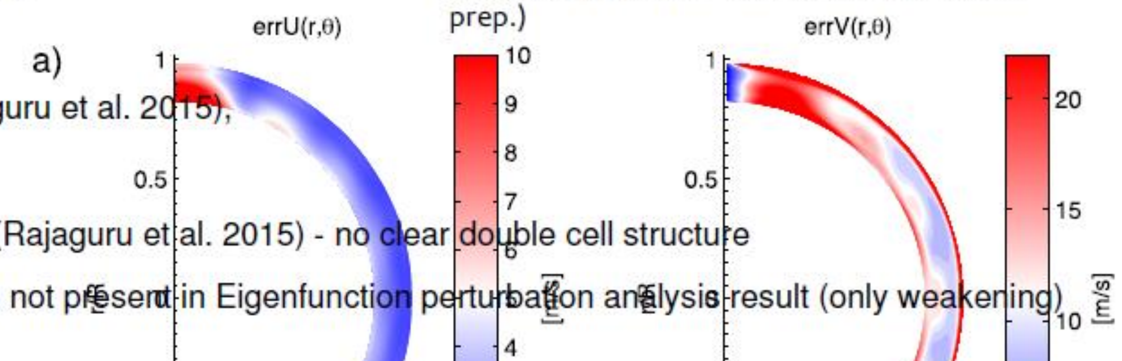


(Jackiewicz et al. 2015; Zhao et al. 2
2015)



(Schad et al. 2013; Schad & Roth 2016 in prep.)



Various Results:

- **Single cell** (Jackiewicz et al 2015., Rajaguru et al. 2015),
  Double-cell flow (Zhao et al. 2013)
  Multiple "cells" (Schad et al. 2013);
  incorporating mass conservation to TDA (Rajaguru et al. 2015) - no clear double cell structure
- Flow reversal at 0.93 R by Time-Distance not present in Eigenfunction perturbation analysis result (only weakening)

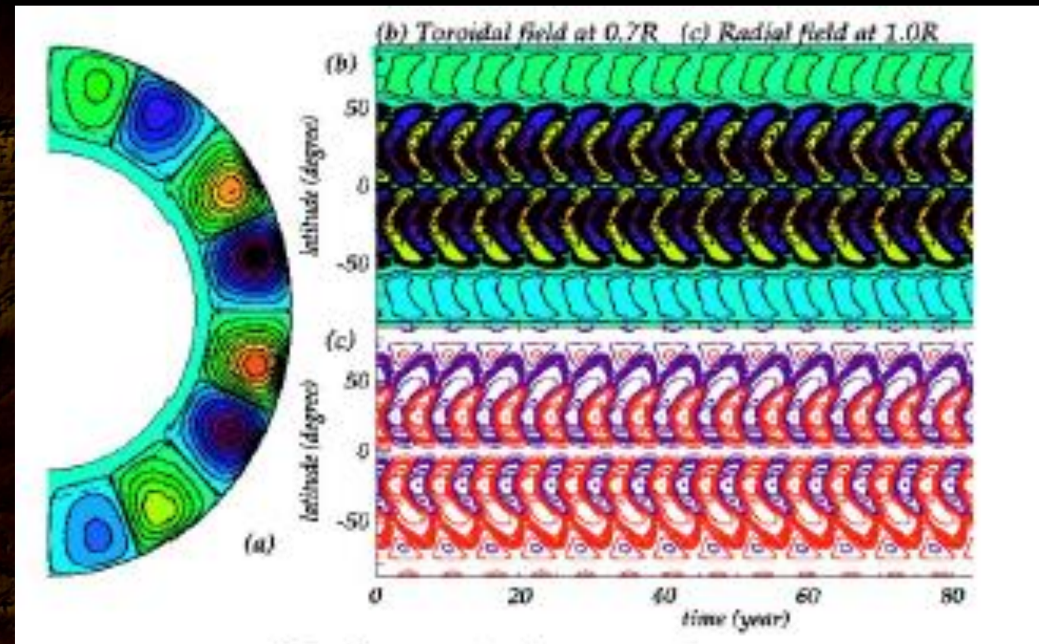
What is the Return Flow?

We can not ‘properly see it’→ SIMULATE!

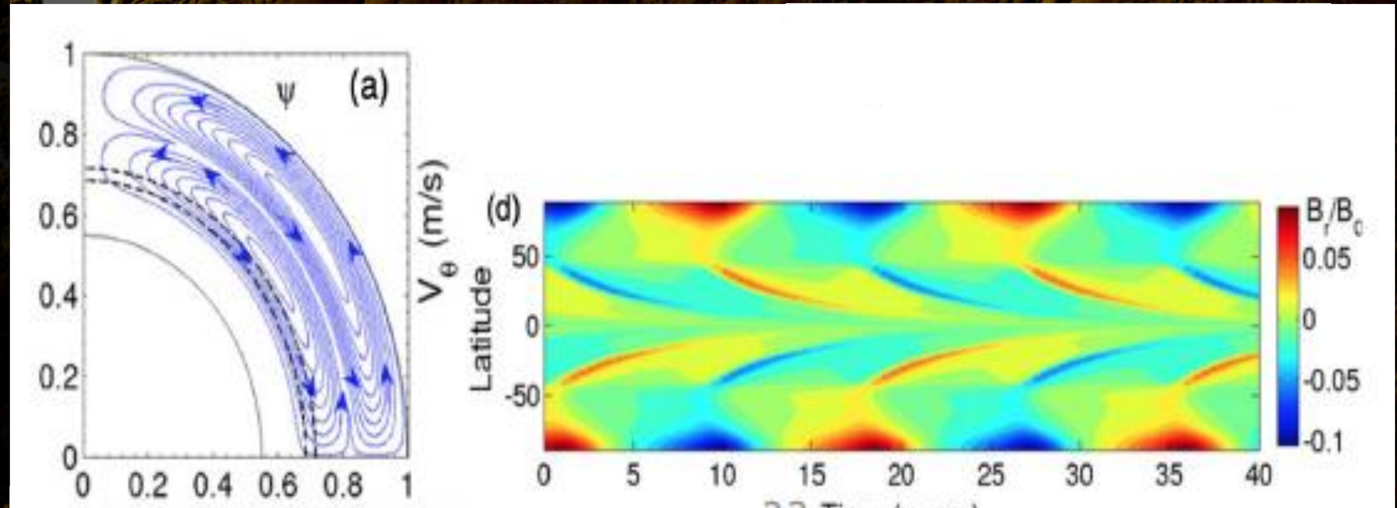
A combination of three forcing terms:

1) the Coriolis force acting on the differential rotation;
2) a latitudinal pressure/temperature gradient;
3) a Reynolds stress due to correlations between radial and latitudinal motions in the convective flows.

Simulations of compressible convection in rotating spherical shells give highly structured and variable meridional flows. Miesch et al. (2000)



(Belucz et al., 2015)



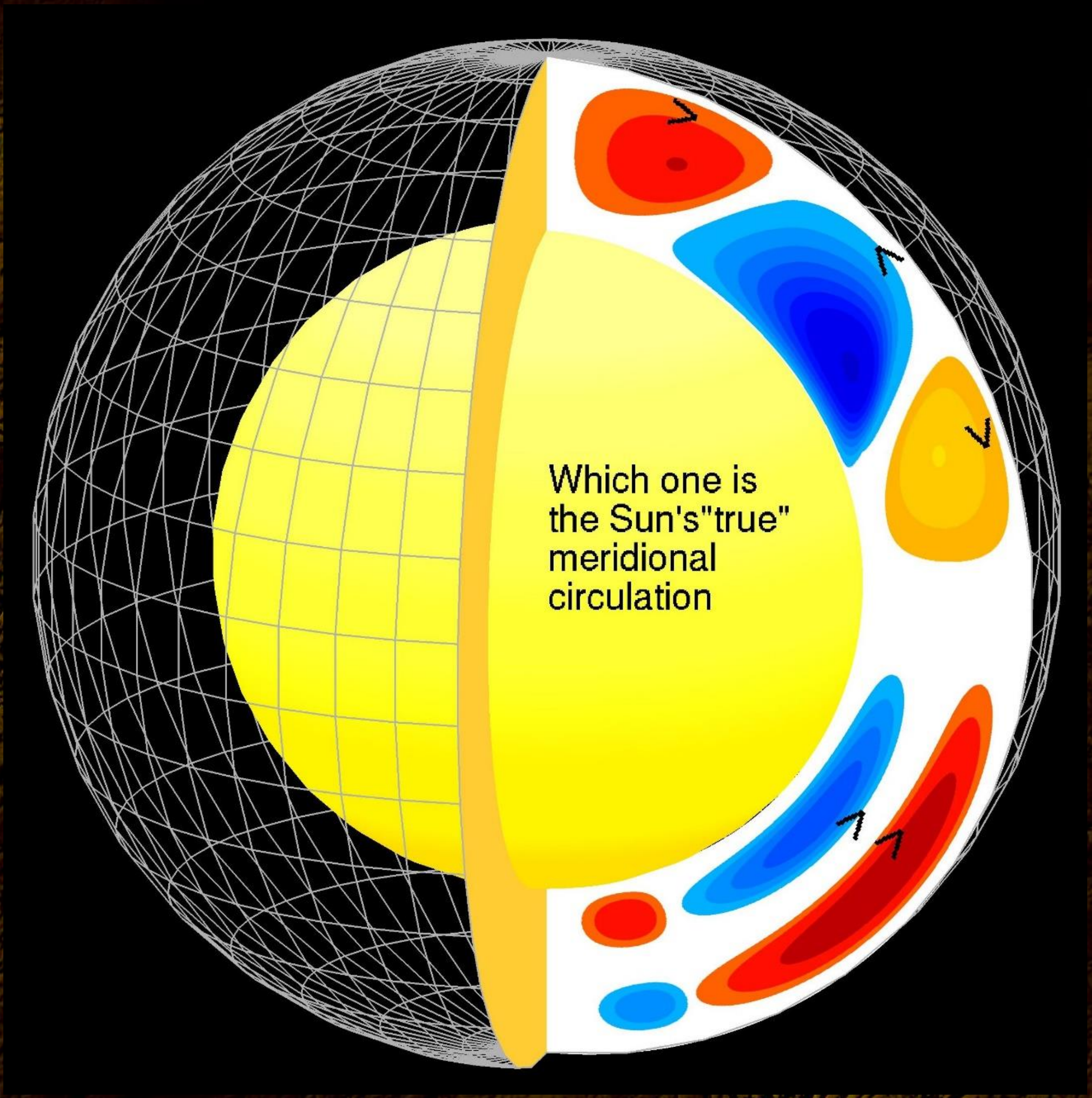
(Hazra et al. 2014)

HOW is the Return Flow?

We can not ‘properly see it’→ SIMULATE!

The meridional flow speed controls both the dynamo period and its strength.

We then choose that MF that reproduce the observation!



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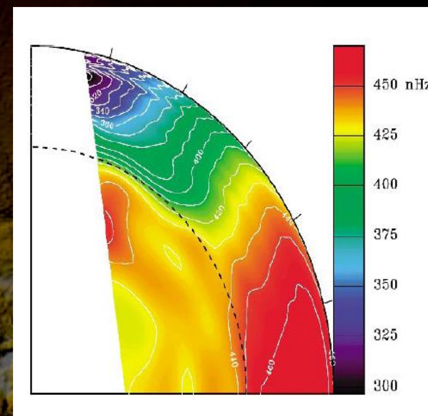

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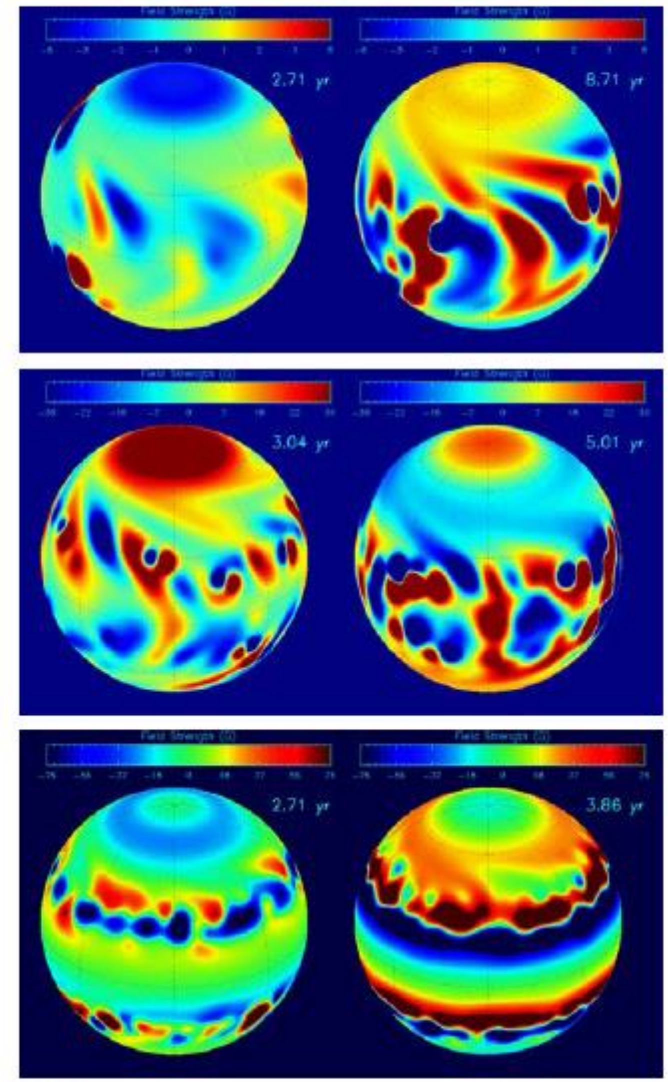

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Another kinematic dynamo model

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- Surface B diffusion strongly dependent on turbulent convection properties

Case SUN: prescriptions matching measurements of solar flux emergence and evolution.
Case DISP: same emergence as Case SUN, but dispersal 10 times less efficient.
Case LIN: dependence of magnetic feature mobility on flux removed
Case LIN+DISP: combination of LIN and DISP.

Convection and Diffusion on the Photosphere

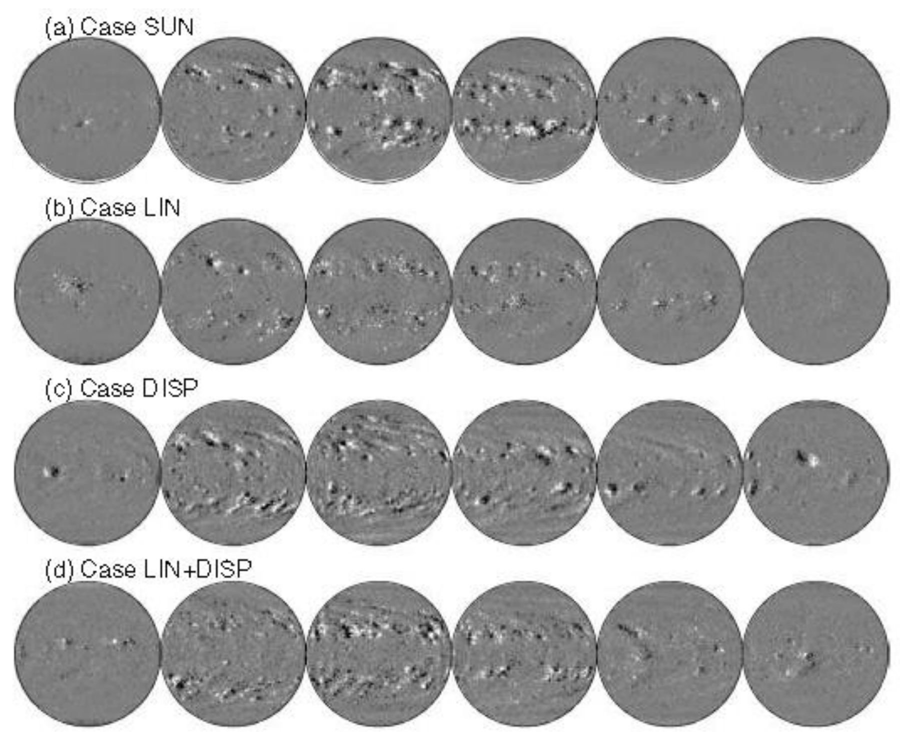


Figure 3. Equatorial views of Cases SUN, LIN, DISP, and LIN+DISP throughout half of a polarity (or a full sunspot) cycle, all scaled to $\pm 4 \times 10^5$ Mx cm^{-2}. The first and last images in each row correspond to successive minima in the sunspot cycle.

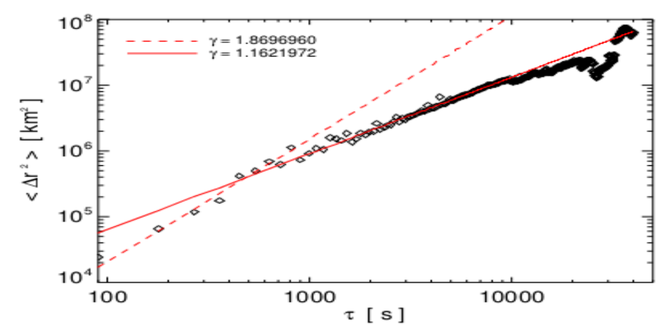
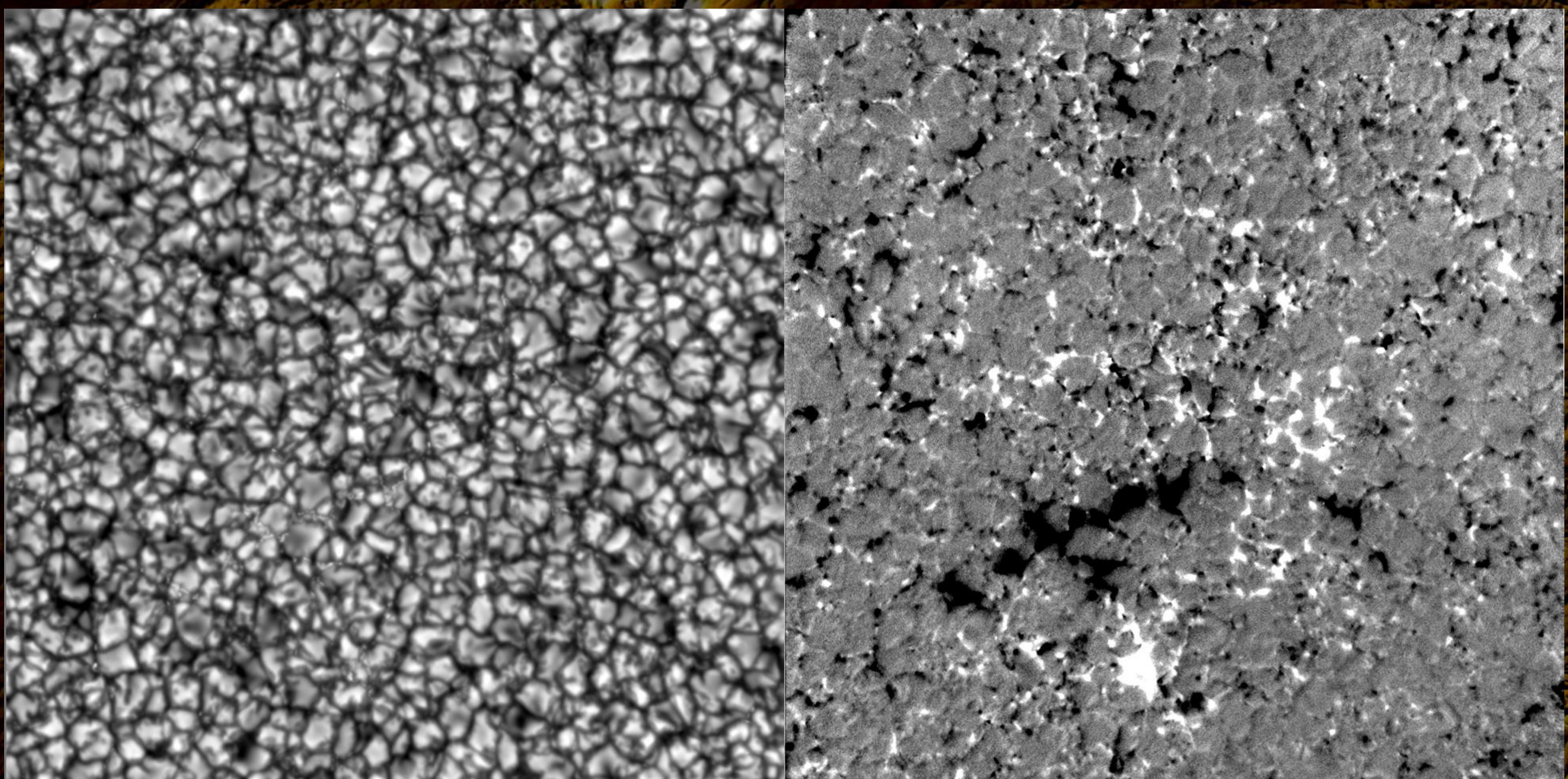


Fig. 6. Displacement spectrum for all the 20145 magnetic elements tracked in the FOV. The dashed line fits the data point up to ~ 1000 s; the continuos line fits the data points up to ~ 9000 s.

De Rosa, Proc. IAU, S233, 2, 25, 2006
Giannatasio et al., ApJL, 2013

What is the Magnetic Diffusion?

This movie shows the evolution of quiet Sun fields over the course of three hours. As can be seen, they continually move in response to the varying surface convective flow field, change shape, and interact with nearby magnetic fields.

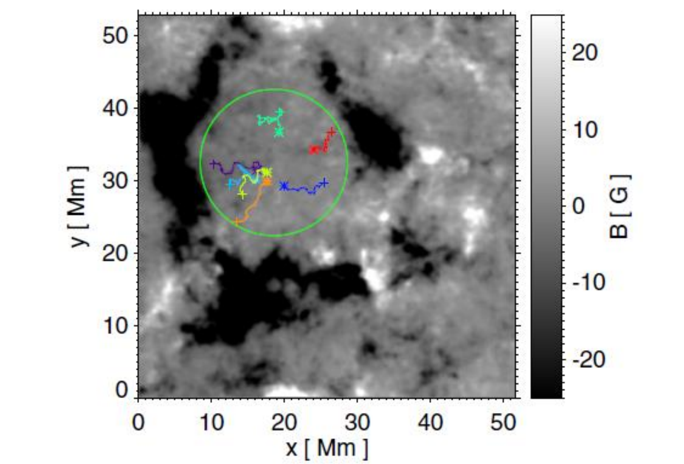


HOW is the Magnetic Diffusion?

Magnetic element tracking to study the **transport and diffusion** of the magnetic field on the solar photosphere.

From the analysis of the **displacement spectrum** a regime of **super-diffusivity** dominates the solar surface.

Turbulent magneto-convection!



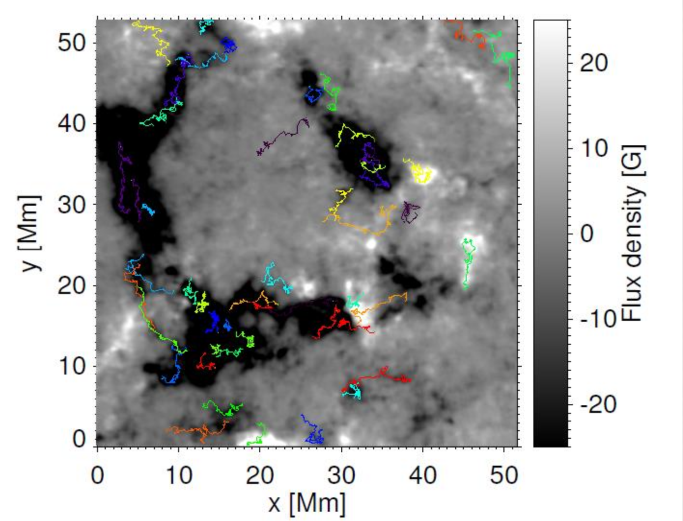


Fig. 2. Mean magnetogram saturated at ±25Mx cm^{-2}. The coloured tracks represent the trajectories of the 50 longest living magnetic elements. Their lifetime spans the range from ∼ 4 to ∼ 11 hours.

Giannattasio et al. A&A 569 A121, 2014.

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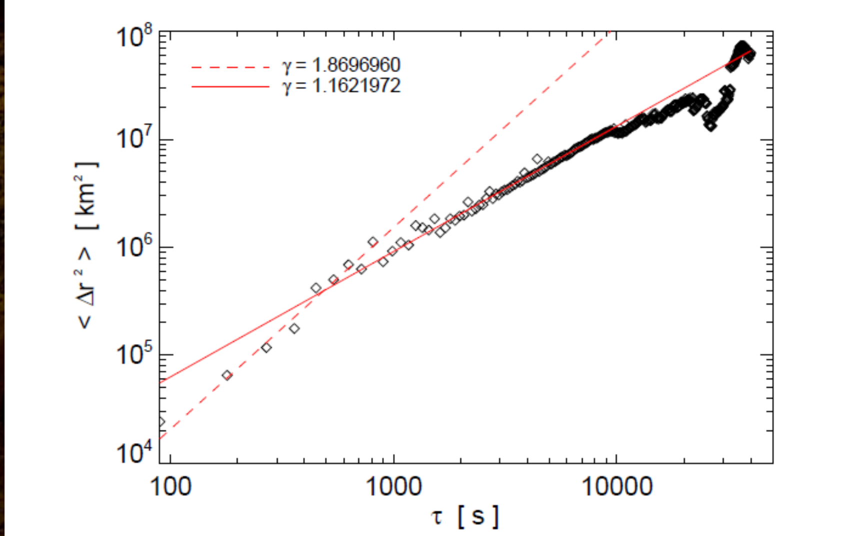

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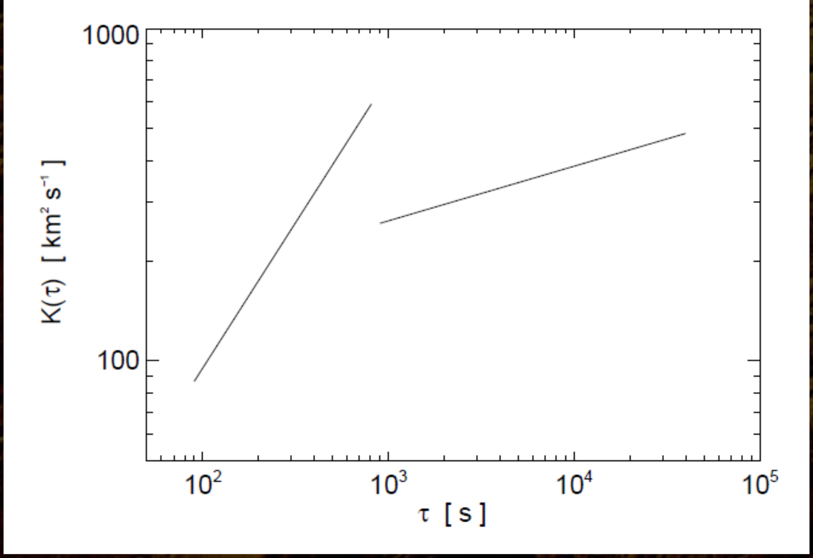

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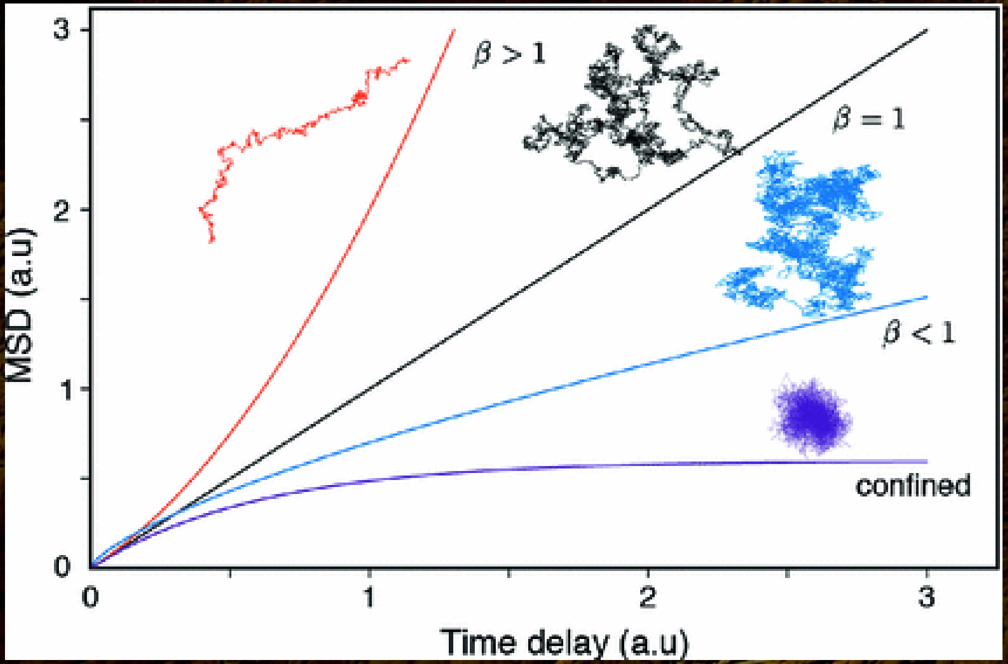
Turbulence?

Turbulent magneto-convection!



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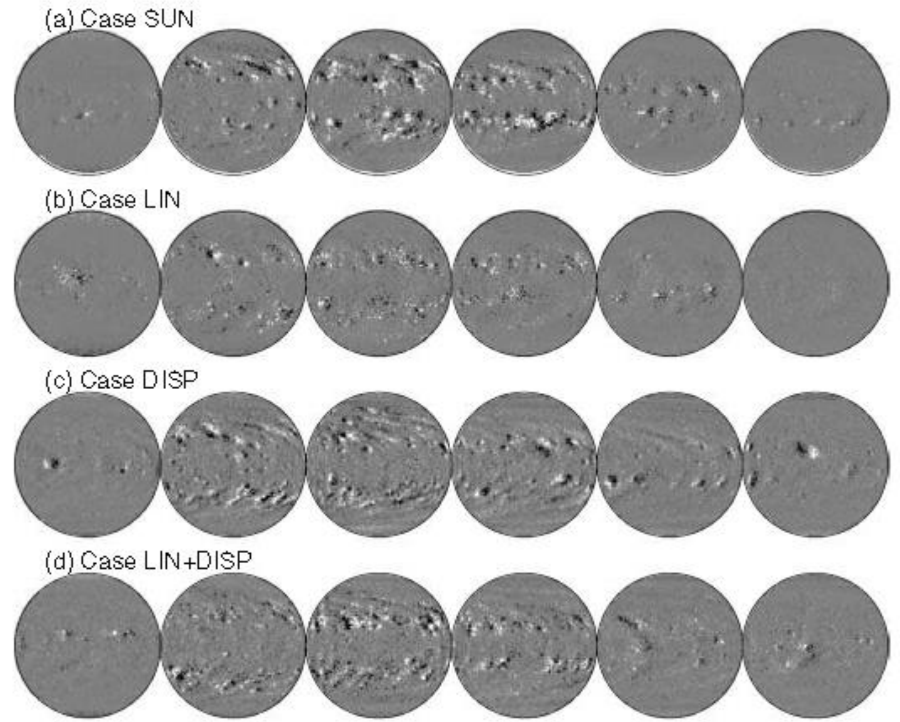

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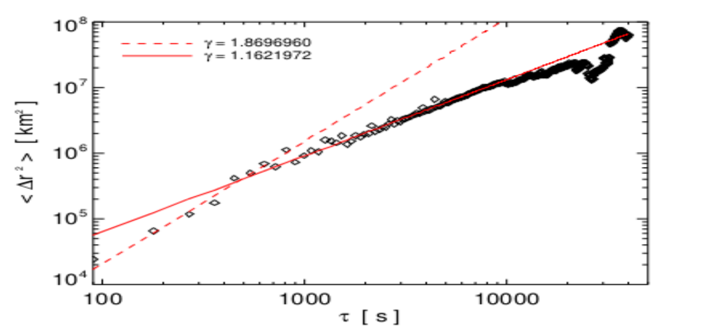

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Giannatasio et al., ApJL, 2013

A quick look at the poles...

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Diffusion
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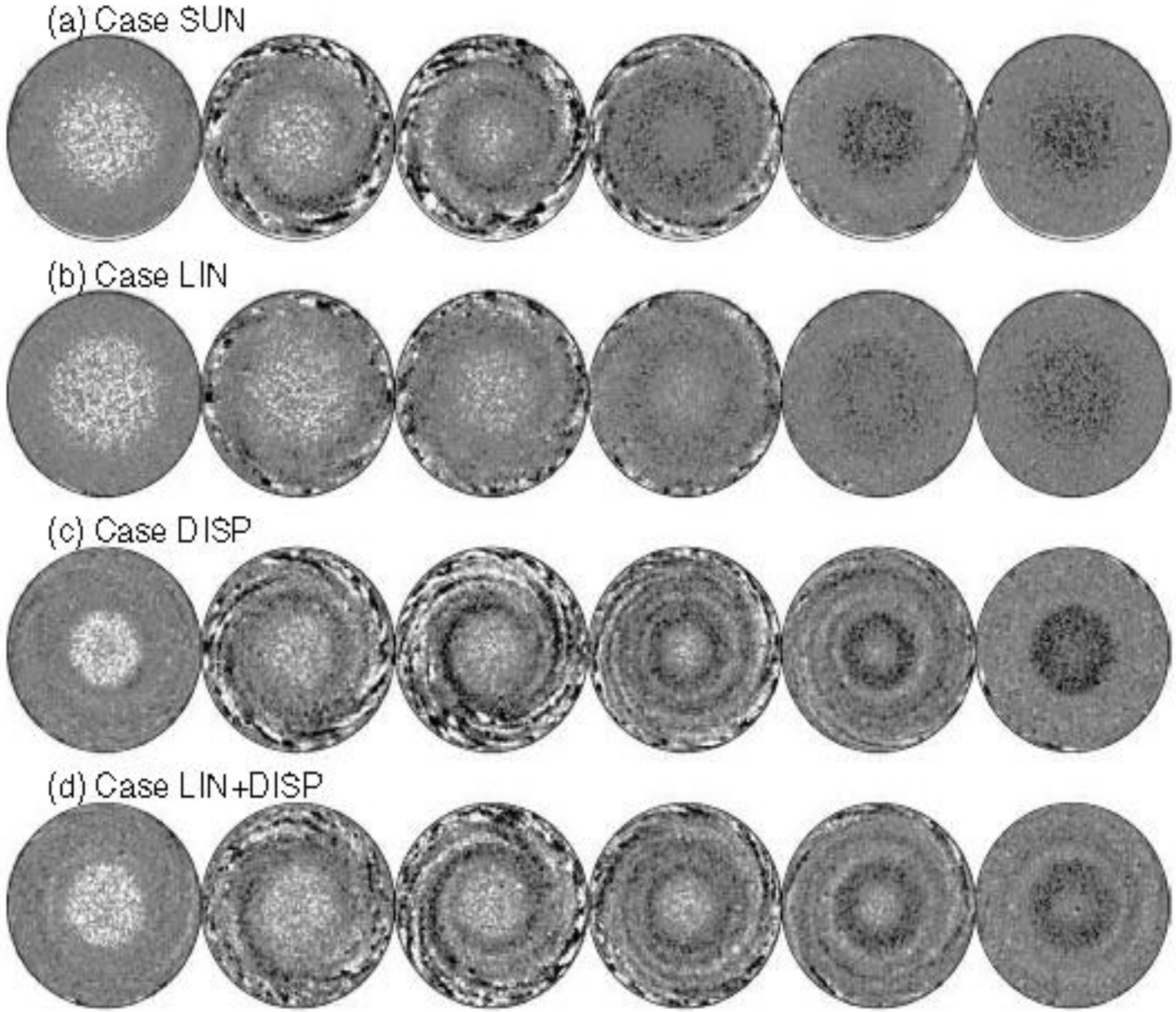


Figure 4. Polar views of Cases SUN, LIN, DISP, and LIN+DISP throughout half of a polarity (or a full sunspot) cycle, all scaled to $\pm 10^5$ Mx cm^{-2}. The first and last images in each row correspond to successive minima in the sunspot cycle.

The verges of magnetic activity

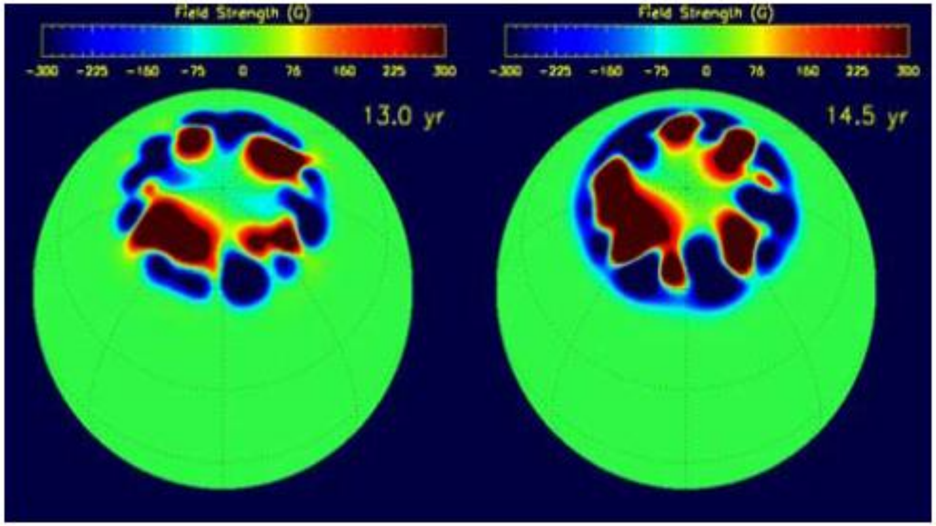


Fig. 13. Field strength distribution at an activity minimum (*left panel*), and at a maximum (*right panel*), for the K1 subgiant star. The inclination of the rotation axis with respect to the line of sight is 30°. The colour table shows the field strength with a saturation level at ±300 G.

Isik et al., A&A 528, A135, 2011

Super-flares on Kepler stars (and their star-spots)

Observed amplitudes of the optical brightness modulation imply that a large fraction of the stellar photosphere is covered by starspots.

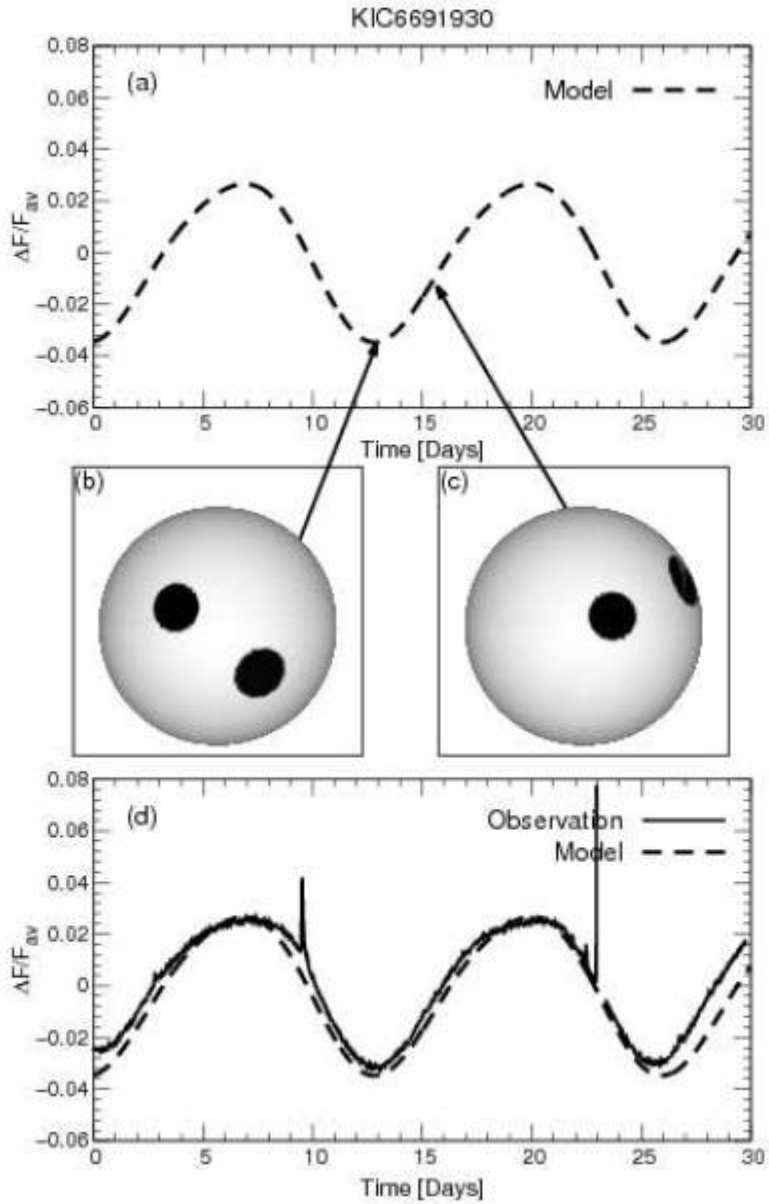


Fig. 4.— (a) : Model light curve for KIC6691930. The model parameters are given in Table 3. (b) & (c): Model pictures of the visible area of the photosphere with two starspots. (d): Observed light (solid line; the same as in Figure 1 (b)) and the model one (dashed line) for KIC6691930.

Maheara et al., Nature, 485, 478, 2012
Notsu et al., ArXiv:1304.7361v1, 2013

Using the Sun (Real or Simulated) to study the impact of stellar activity on exoplanet detectability

Stellar activity produces signals that can be observed in photometric light curves and radial velocities.

They are due to:

1. Magnetic activity.
Due to spots and plages.
Varies on day-month time-scales and on year-decade time-scales.

2. Oscillations and pulsations.
They usually have an impact on minute-hour time-scales

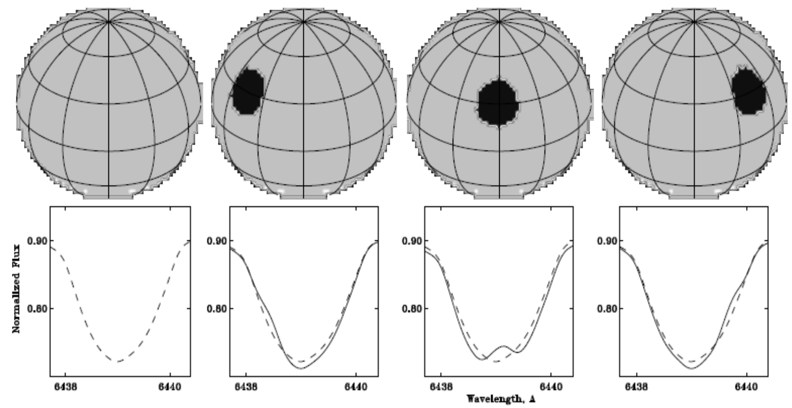


Figure 2: Spectral line profiles for a model fast rotating star with no spots (dashed line) and with a spot moving across the disk as the star rotates (solid line). See also animation at http://www.astro.phys.ethz.ch/staff/berdyugina/private/StellarActivity/StellarAct.html

Use the models as templates to investigate the impact of magnetic activity and turbulent convection diffusion on our ability to detect planetary signals

→ IMPROVE the models!!

Berdyugina, Living Rev. Solar Phys. 2, 8, 2005
Lagrange et al., A&A, 512, A38, 2010
Lanza et al., A&A, 520, A53, 2010

What we need to improve the kinematic models?

Among others:

Establish observationally the physical processes affecting the surface distribution of magnetic flux: emergence, submergence, aggregation, cancellation, fragmentation…

Quantify the relative contributions of small-scale turbulent dynamo and active region decay to the magnetic flux budget of the “quiet sun” photosphere

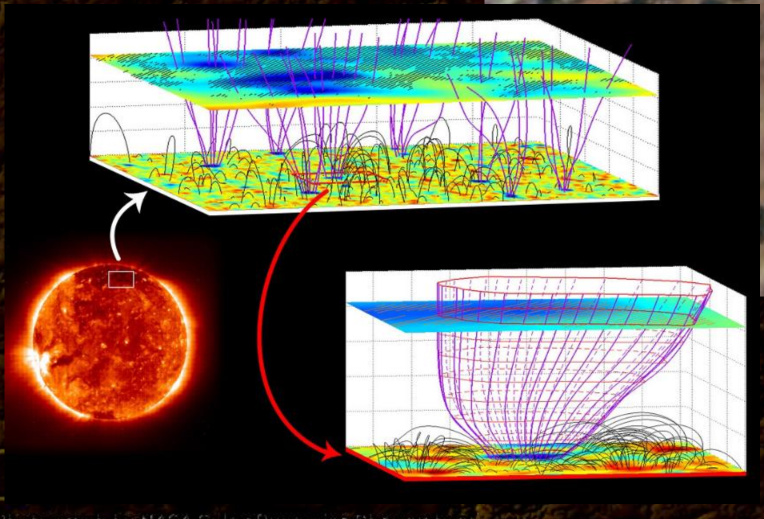
Determine whether/how polar cap magnetic field feeds back into the solar interior

How to?

High Resolution (spatial/spectral/temporal) + High accuracy Polarimetry

→ Photon starved!

EST



Photograph by NASA Solar Dynamics Observatory

SOLAR STORMS, JUNE 2012

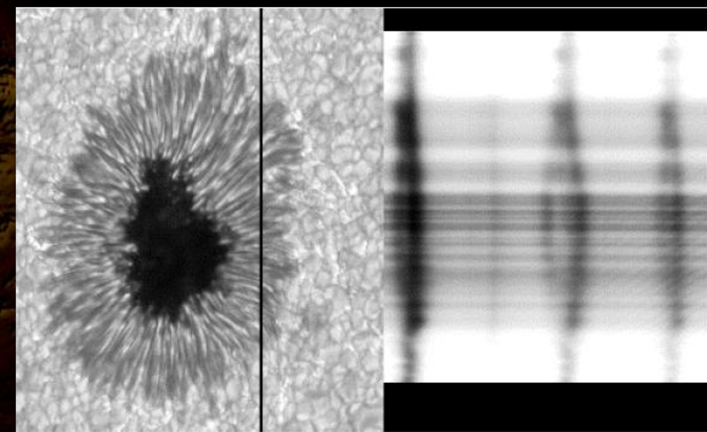
High spectral/spatial/temporal resolution measures of the magnetic field

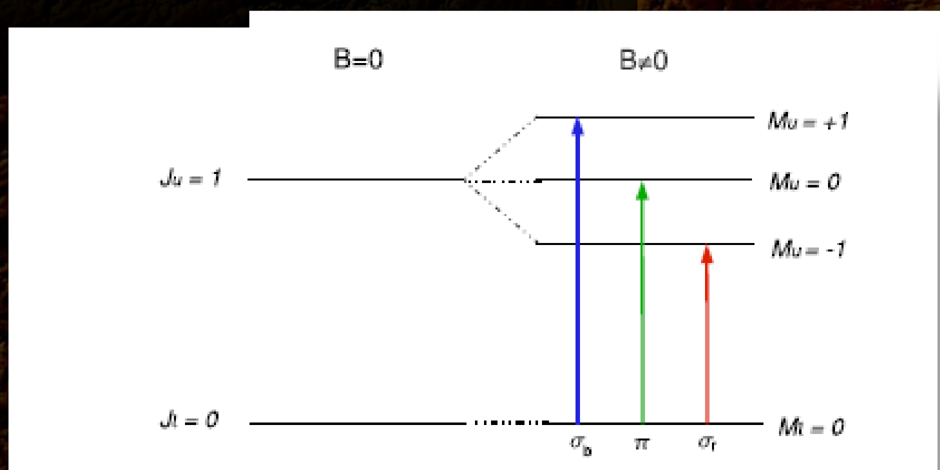
Photon starved → 4m

High spatial resolution → Aperture, MCAO
High spectral/temporal resolution → NBI
Measures of **B** → Spectropolarimetry

What is Spectropolarimetry?

Within an intense magnetic field some elements' spectral lines are split in more components and polarized





A spectral line from a gas discharge lamp is split into 3 components at

$$\nu_0 - \nu_L \, , \nu_0 \, , \nu_0 + \nu_L$$

ν_0 unperturbed emission frequency

$$\nu_L = \frac{e_0 B}{4\pi mc} = 1.3996 \times 10^6 B s^{-1}$$

Larmor Frequency

Normal Zeeman Effect

How is Spectropolarimetry performed?

Why spectra + polarimetry?
1) Magnetic fields not strong enough
2) Zeeman Splitting provides an approximation and gives no information about the geometry of the field

Polarization of the spectrum:

- Parallel to magnetic field
  The central component disappears
  The other components are circularly polarized

- Perpendicular to magnetic field
  All the components are linearly polarized, the central parallel to magnetic field (π), the others perpendicular (σ)

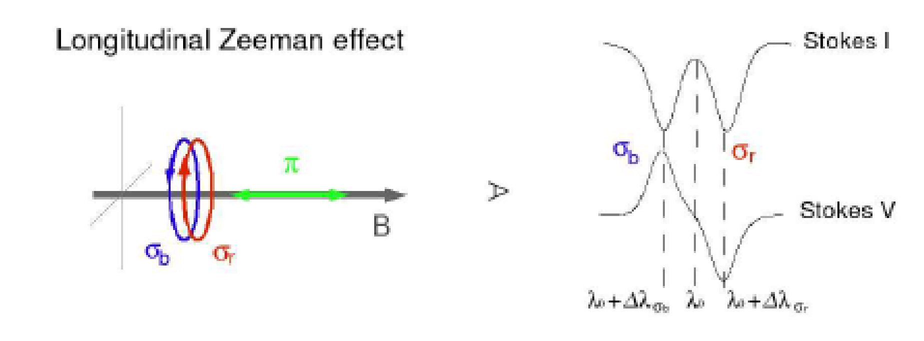


Figure 2.2: Schema of the *longitudinal* Zeeman effect.

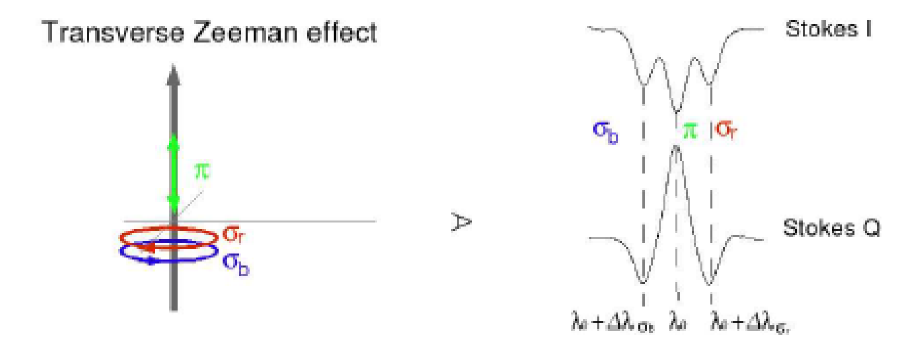


Figure 2.3: Schema of *transverse* Zeeman effect.

How is Spectropolarimetry performed?

Why spectra + polarimetry?
1) Magnetic fields not strong enough
2) Zeeman Splitting provides an approximation and gives no information about the geometry of the field

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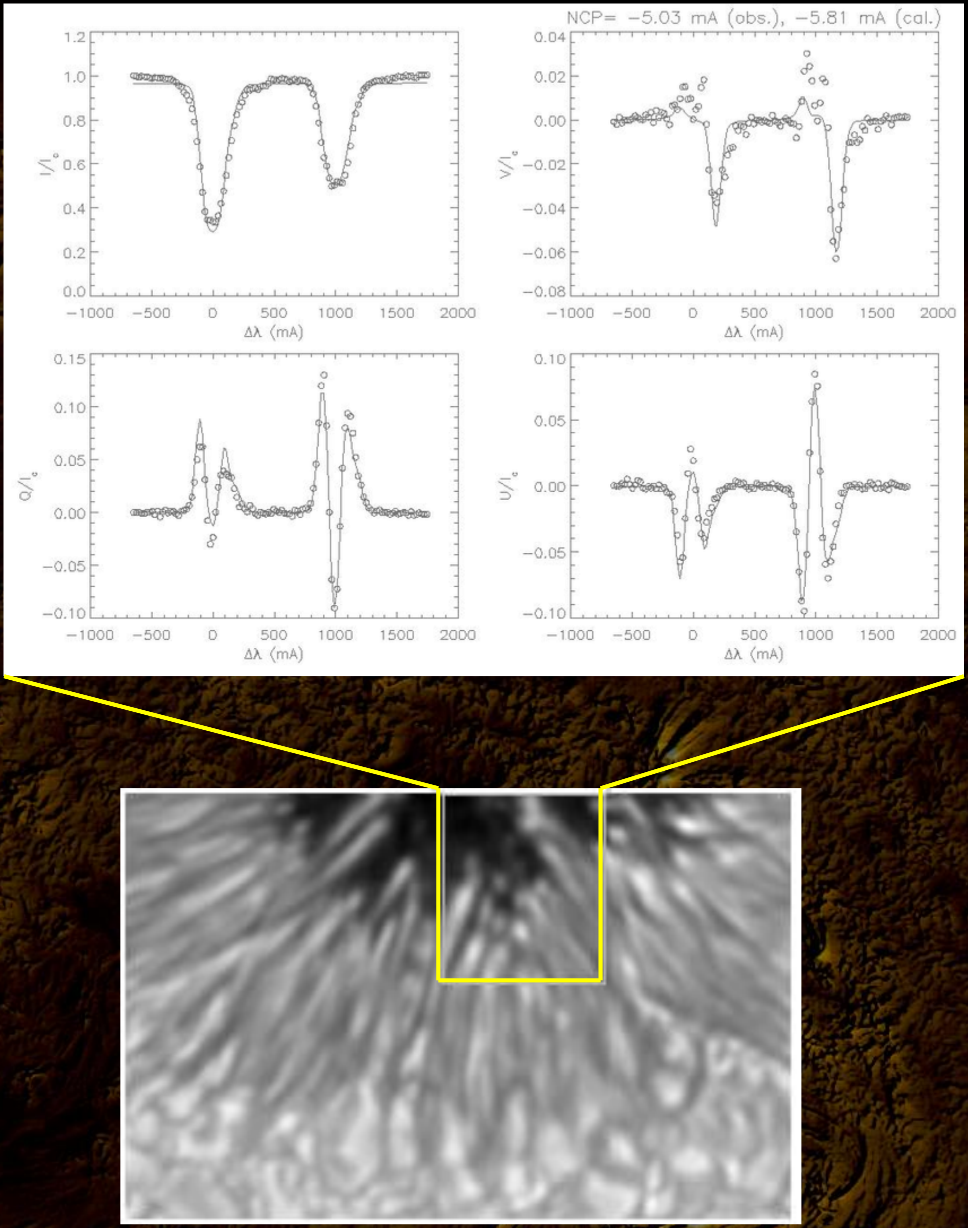


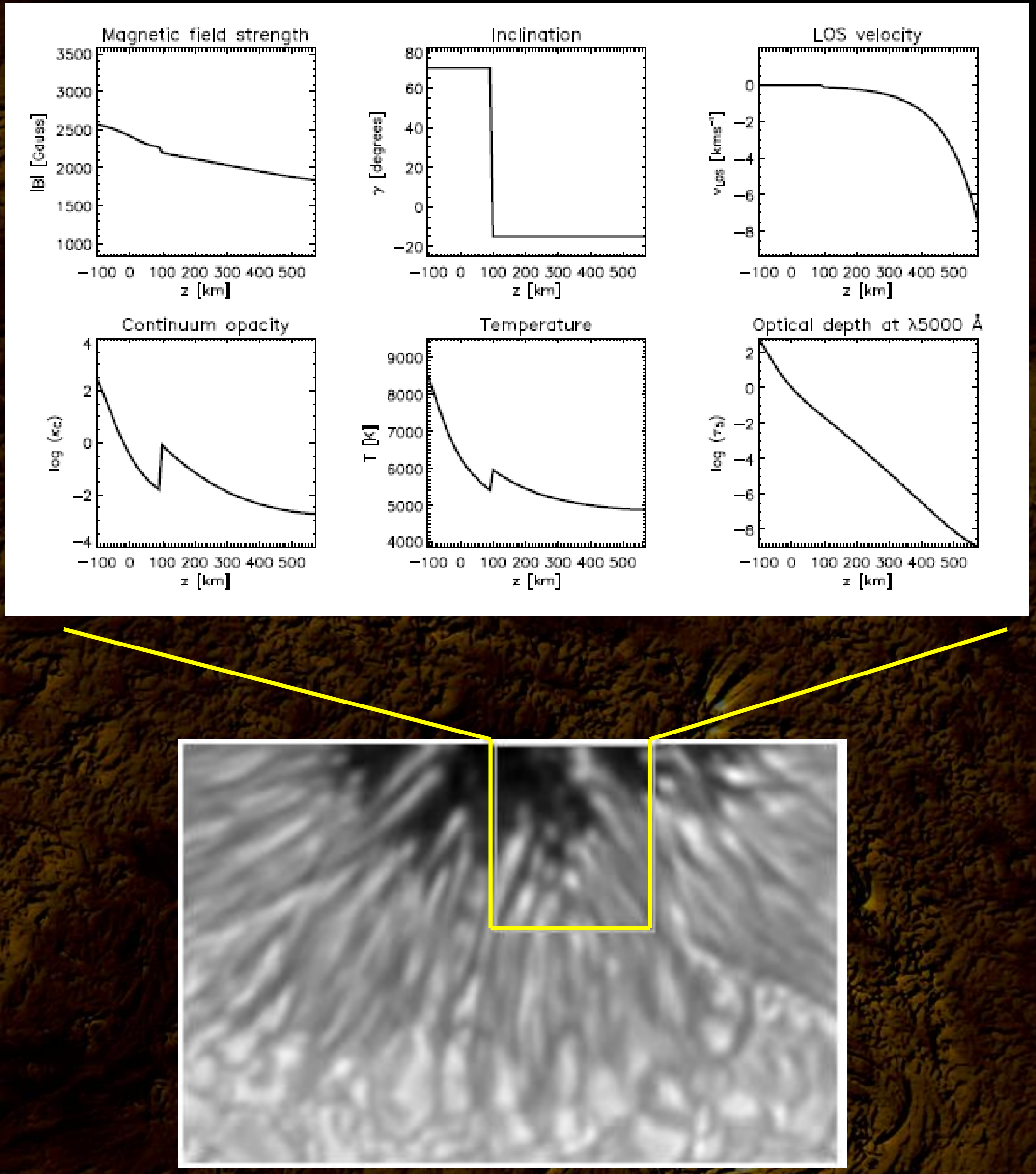
How is Spectropolarimetry performed?

Polarimetric inversion:

the observed Stokes profiles carry much information about the magnetism and dynamics of the structures where they are formed.

To extract this information a synthesis of profiles simulating the observed ones is required

→ Iterative fitting to get the structure of that pixel of solar atmosphere



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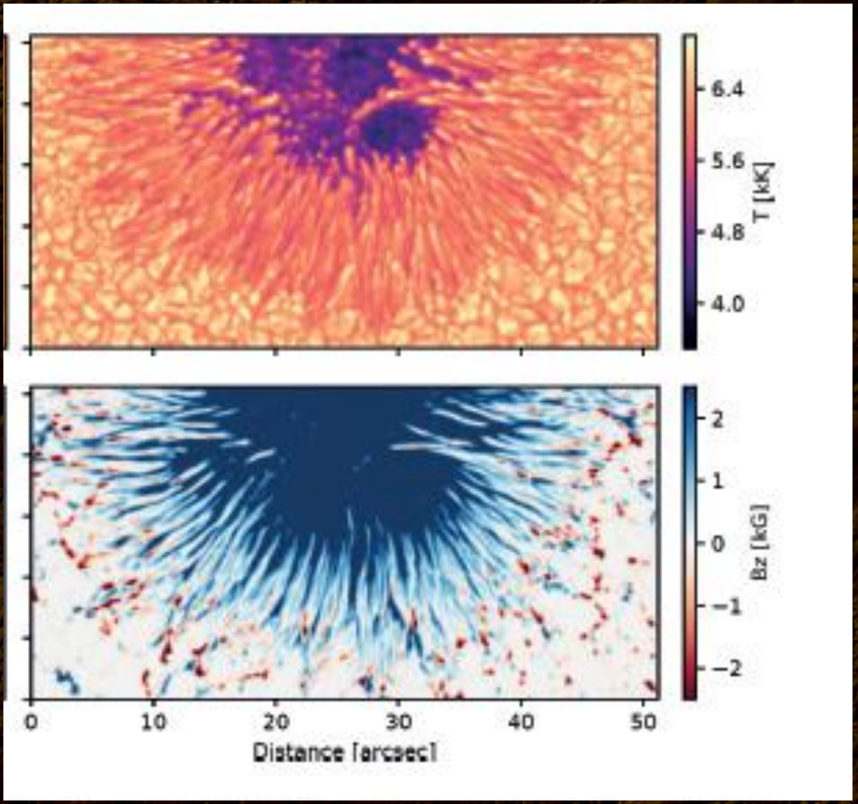
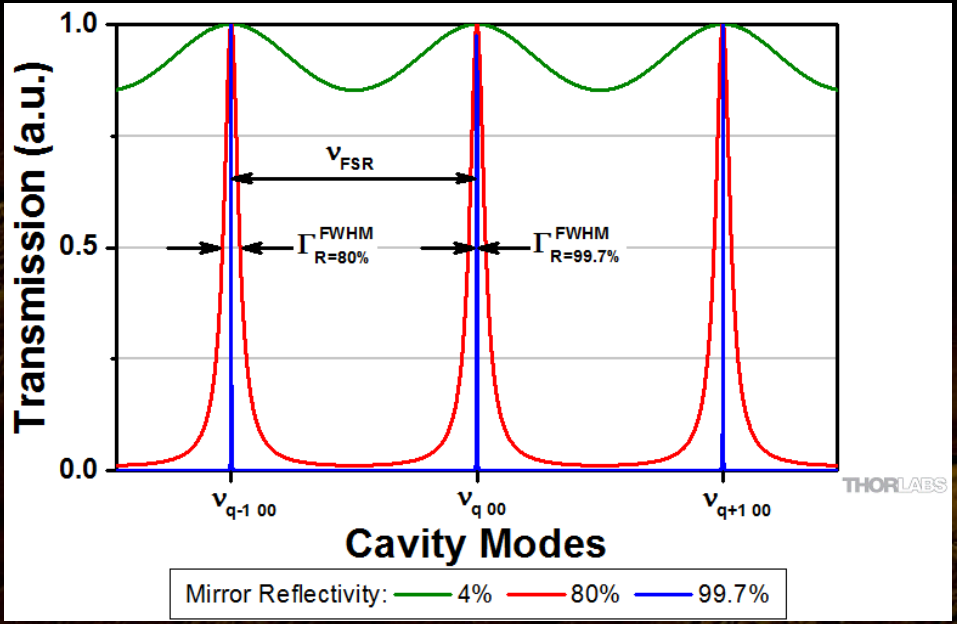


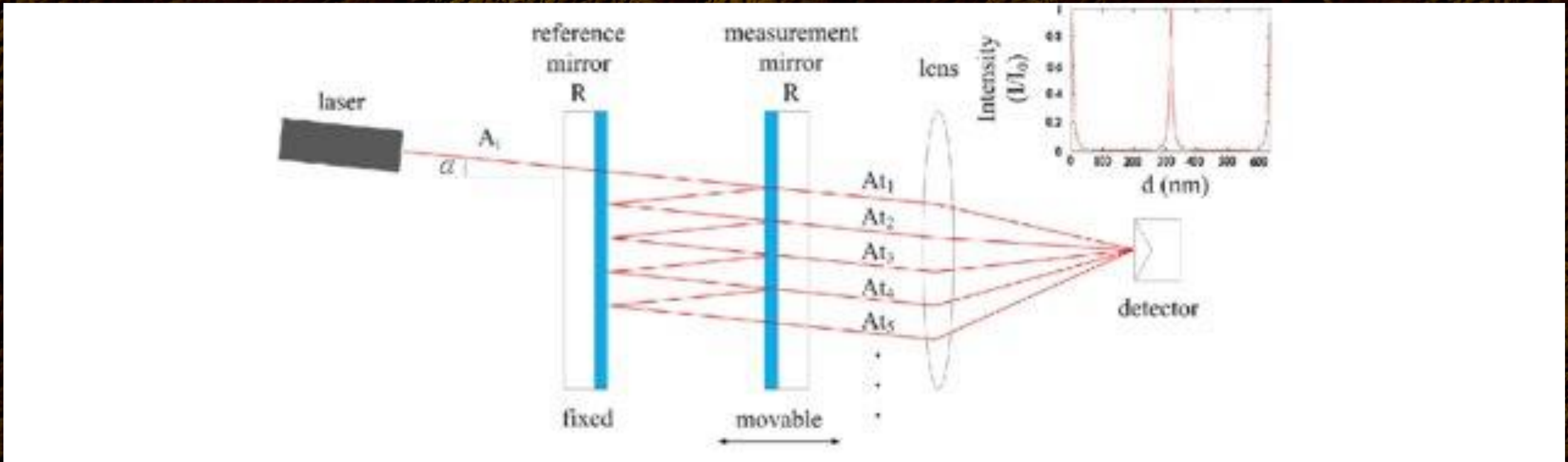
What is a Narrow Band Interferometer?

NBI is based on a resonant optical cavity:
Only wavelentghts that:

$$m\lambda = 2\, n_i\, d\, cos\theta$$

are transmitted.



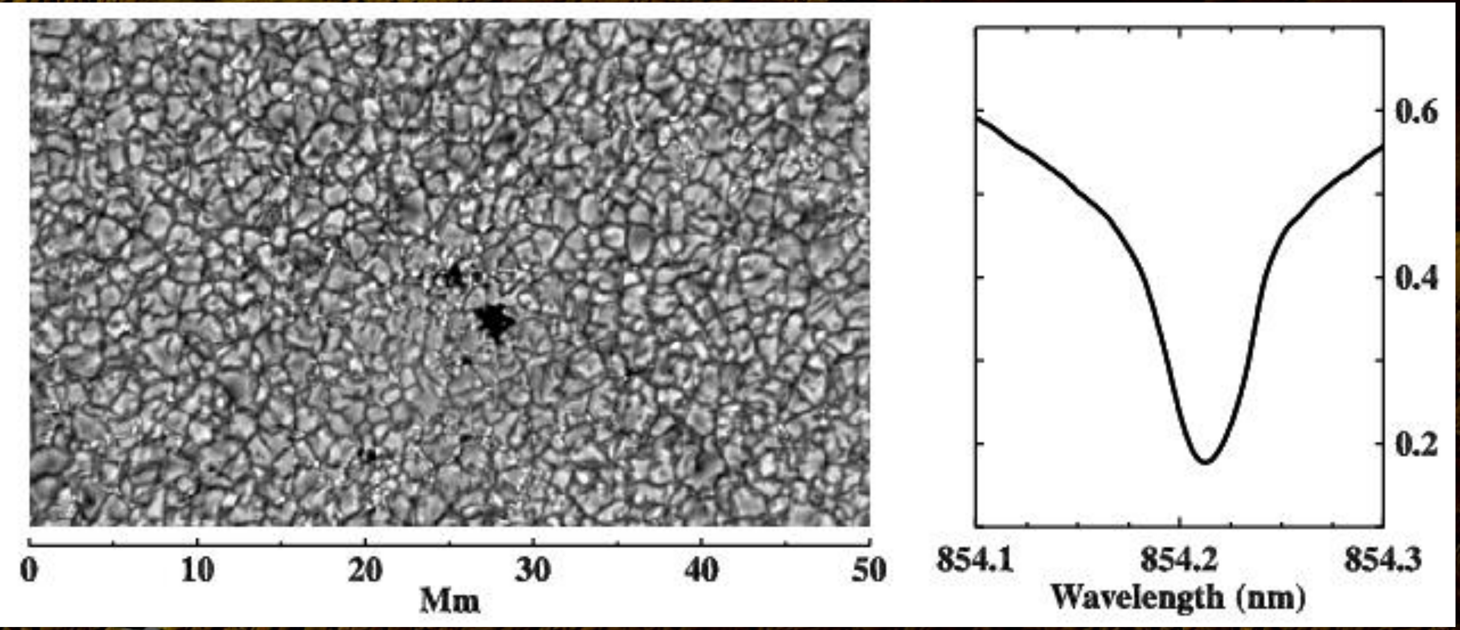


How is Narrow Band Interferometer?

Acquiring monochromatic images in different points of the "profile" of spectral lines at once over a large FoV

Scan the line

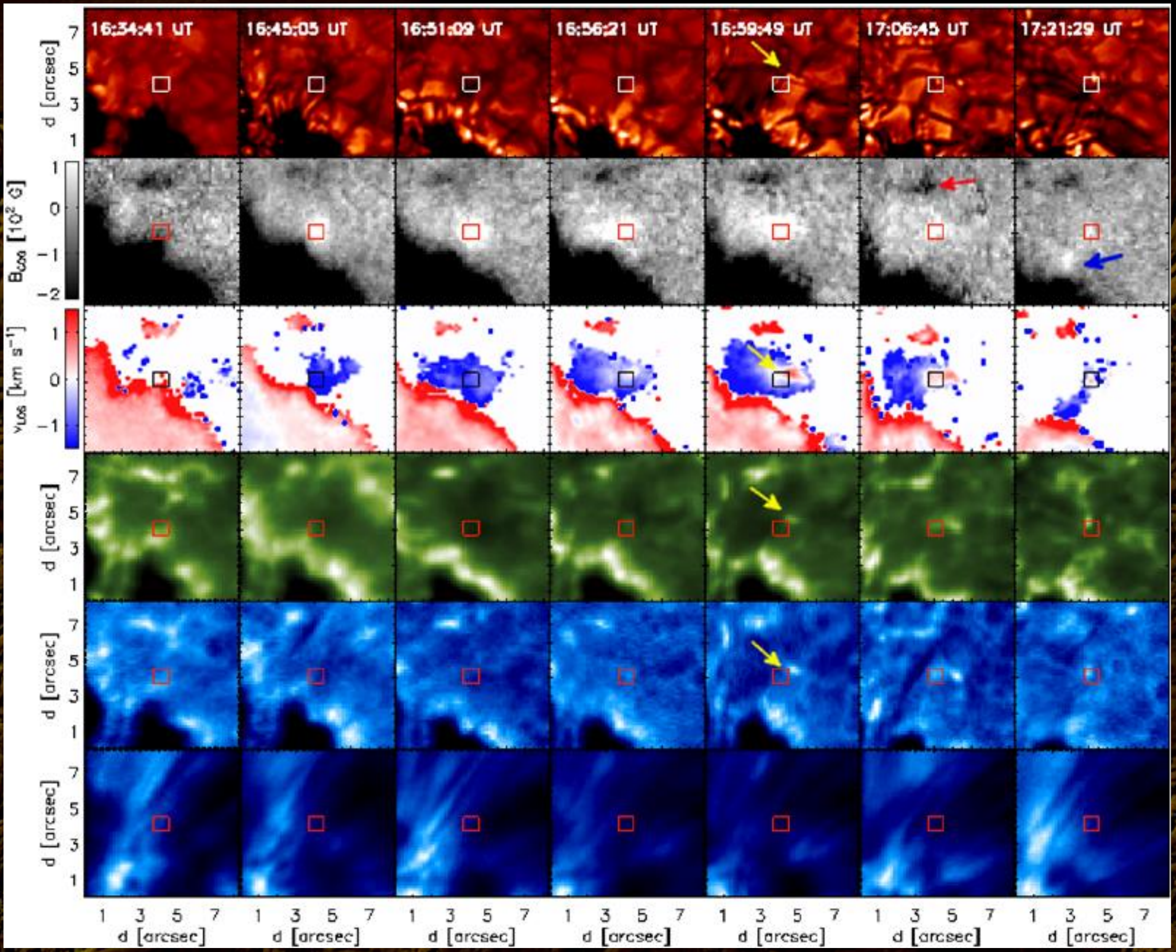
Repeat



How is Narrow Band Interferometer?

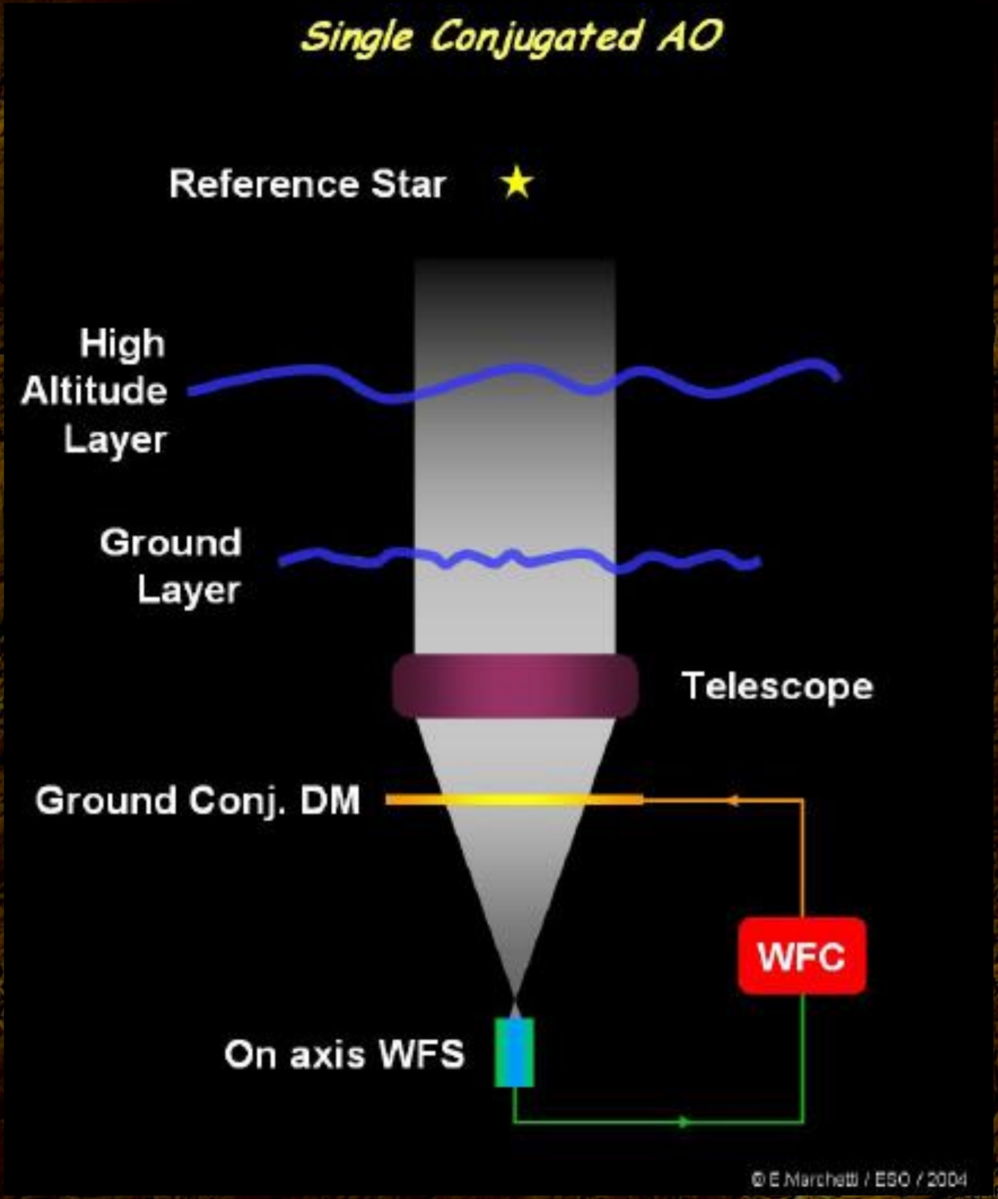
Also multi-line!

High ‘enough’ temporal resolution
Or close to that



What is Multi-Conjugate Adaptive Optics?

High spatial resolution
→ Aperture, MCAO



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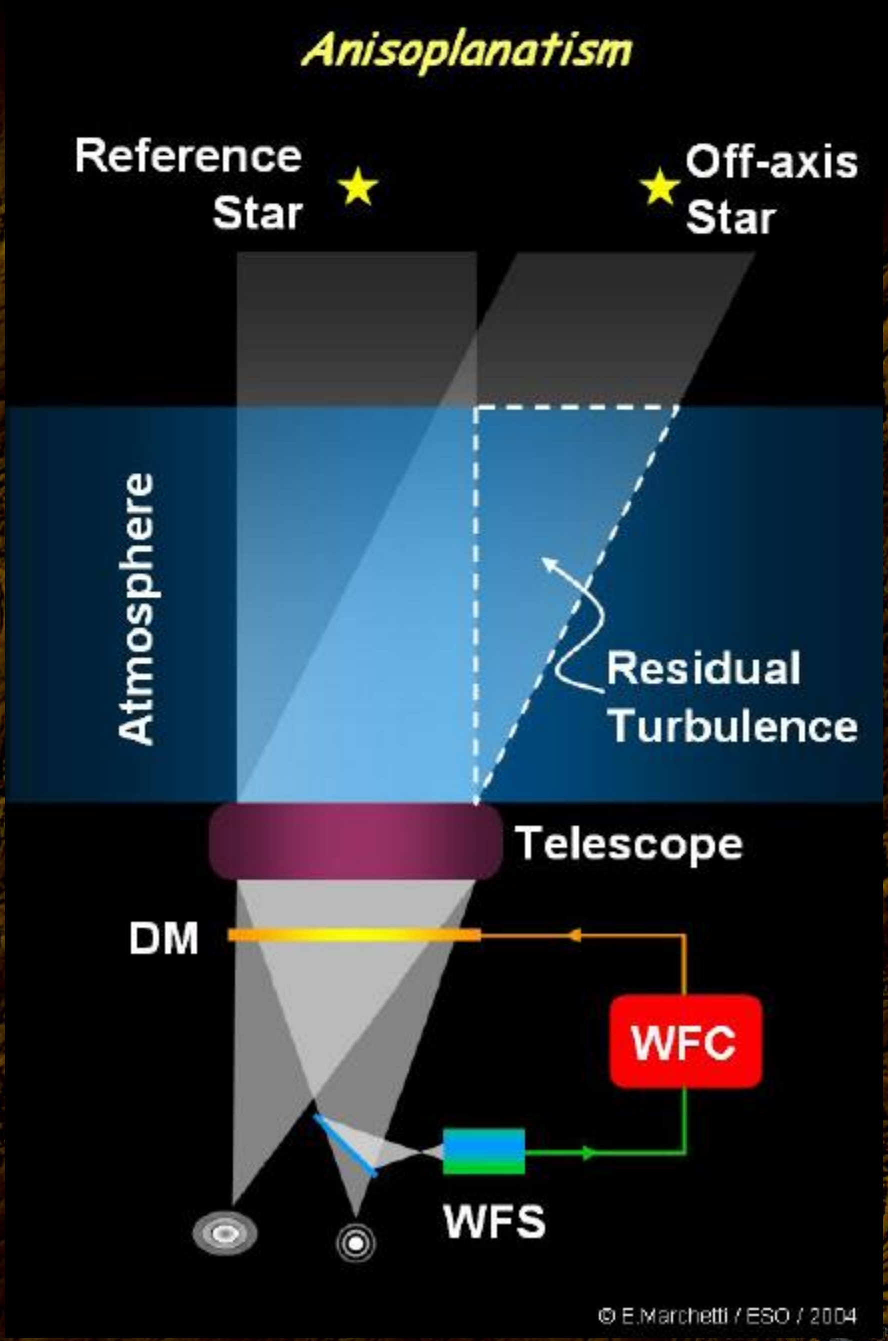

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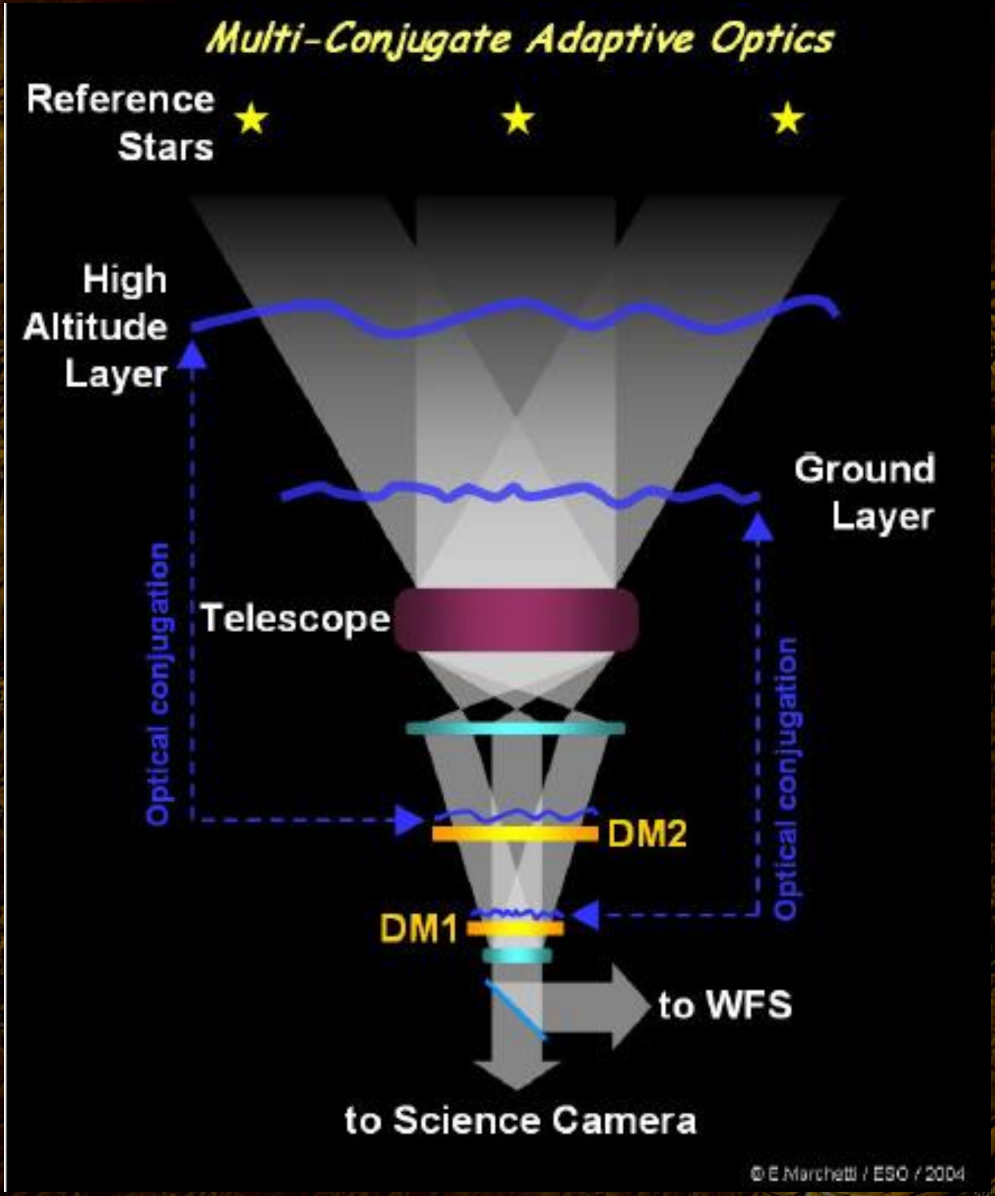
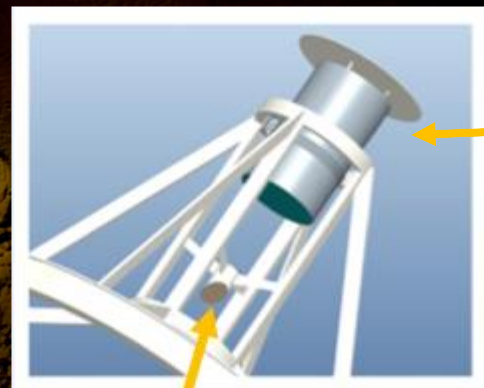
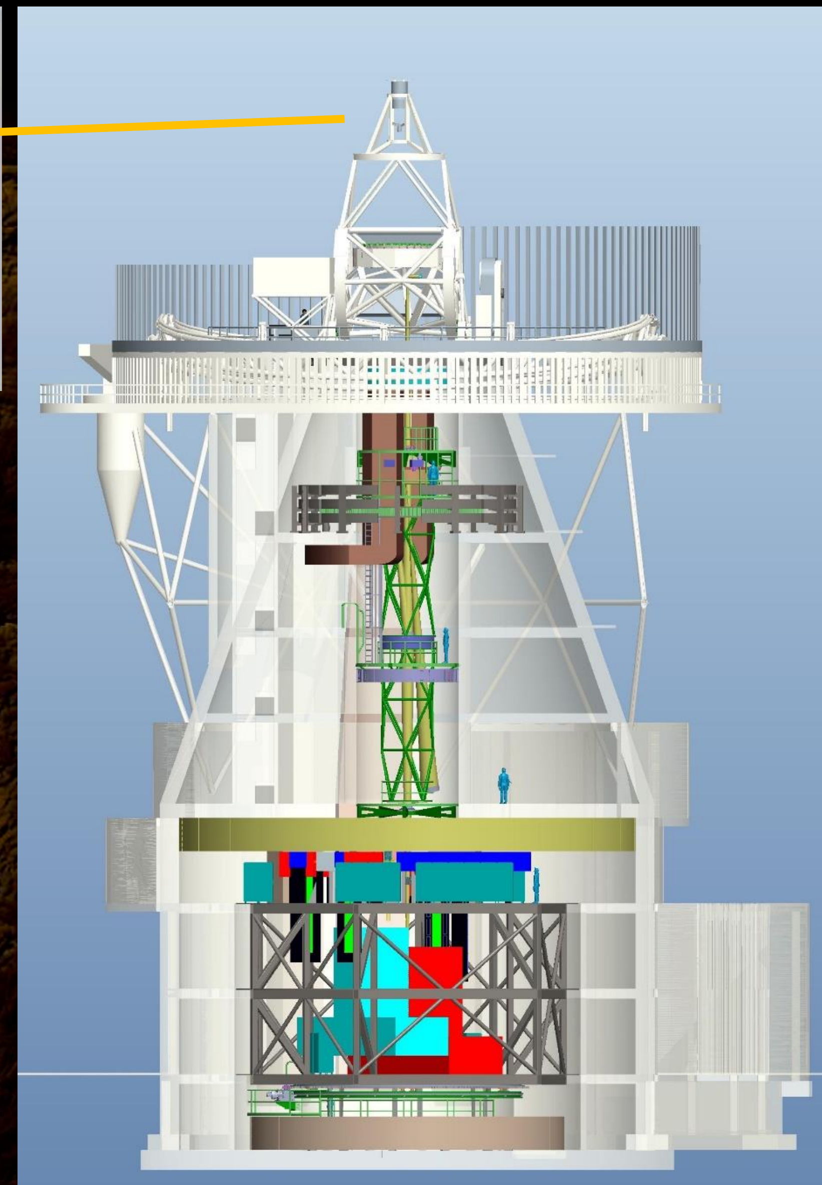


Any other problem with a 4m Solar Telecope?

Photon starved → 4m

Heat rejecter





So, what’s nEST?

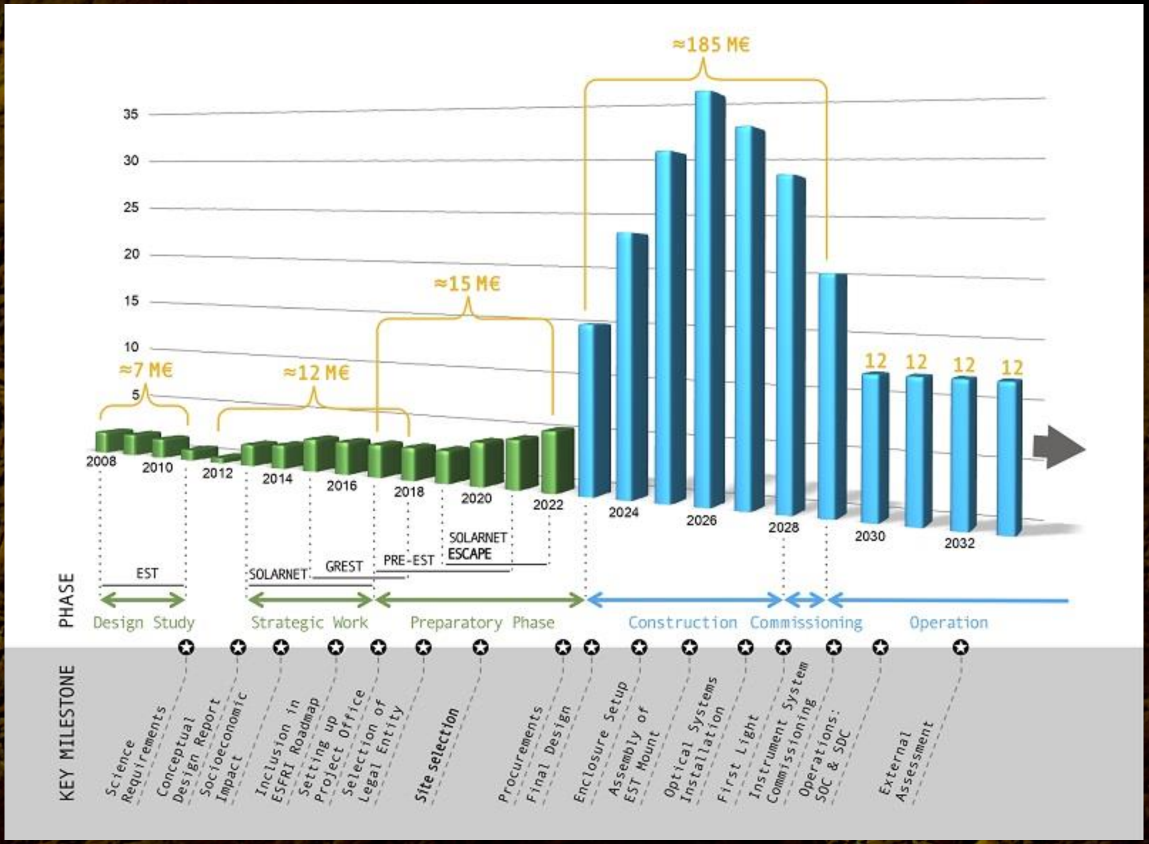
The European Solar Telescope (EST) will be the **largest solar telescope ever built in Europe,** pursuing unique observations of the magnetic processes taking place on the Sun.

EST will have a **4.2-m primary mirror and the latest technology available**, giving astronomers the most powerful tool ever conceived for observing the Sun.

EST will be deployed in the **Canary Islands, a first-class location** thanks to the sky quality and excellent conditions for astronomical observations.

The **European Association for Solar Telescopes (EAST)** is the entity promoting the project and intends to develop, construct and operate EST. It is currently formed by 26 research institutions from 18 European countries.

EST was included on the **ESFRI Roadmap** in 2016 and is therefore considered a strategic research infrastructure for Europe.



Want to know more?

P.Charbonneau, 2020 Dynamo models of the solar cycle, Living Reviews in Solar Physics volume 17, Article number: 4 (2020)

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D. H. Hathaway (2015) The Solar Cycle Living Reviews in Solar Physics volume 12, Article number: 4 (2015)

R. Howe 2009 Solar Interior Rotation and its Variation Living Reviews in Solar Physics volume 6, Article number: 1 (2009)

EST Website (https://est-east.eu/est-project)