Perspectives on the Rotating Solar Convection Zone

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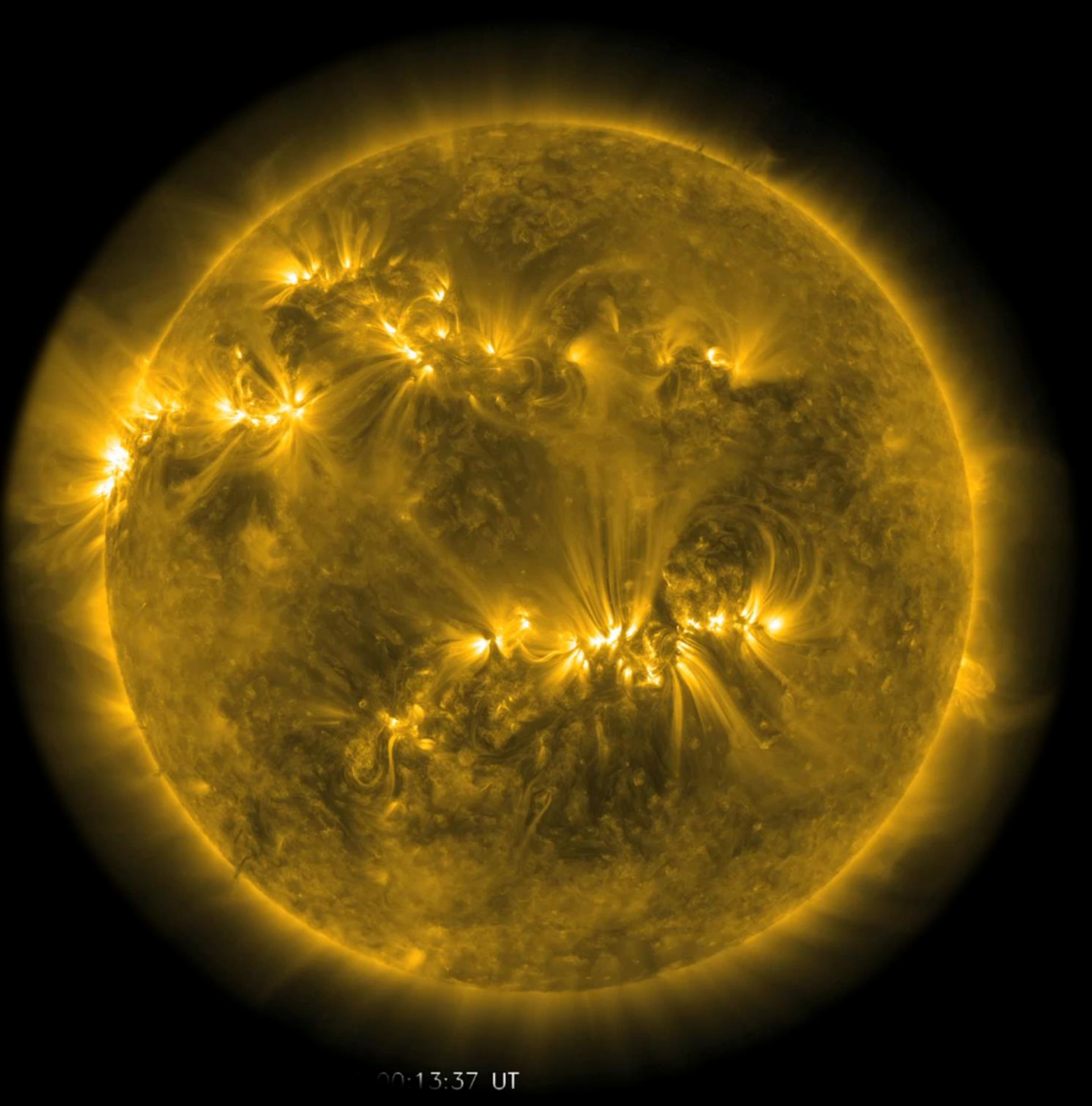
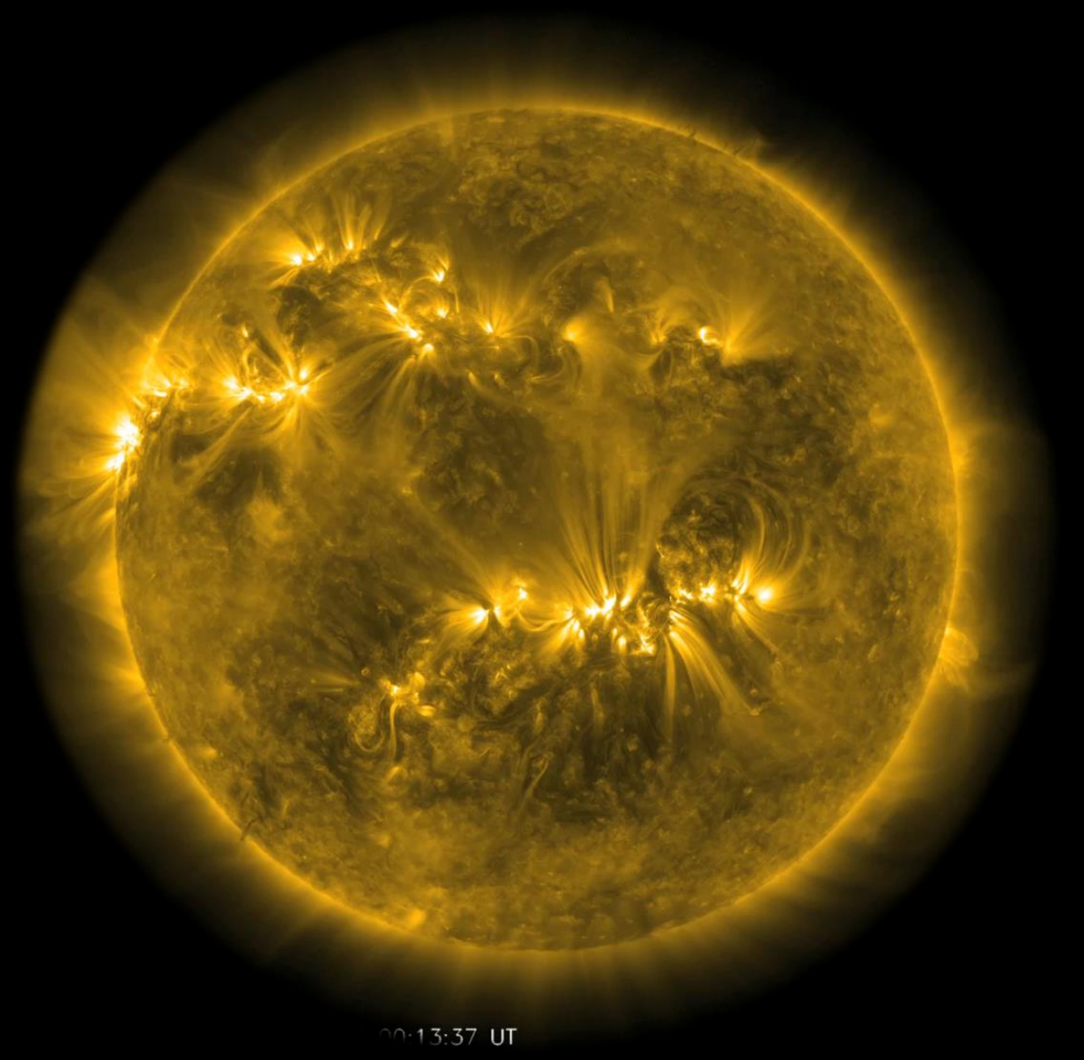
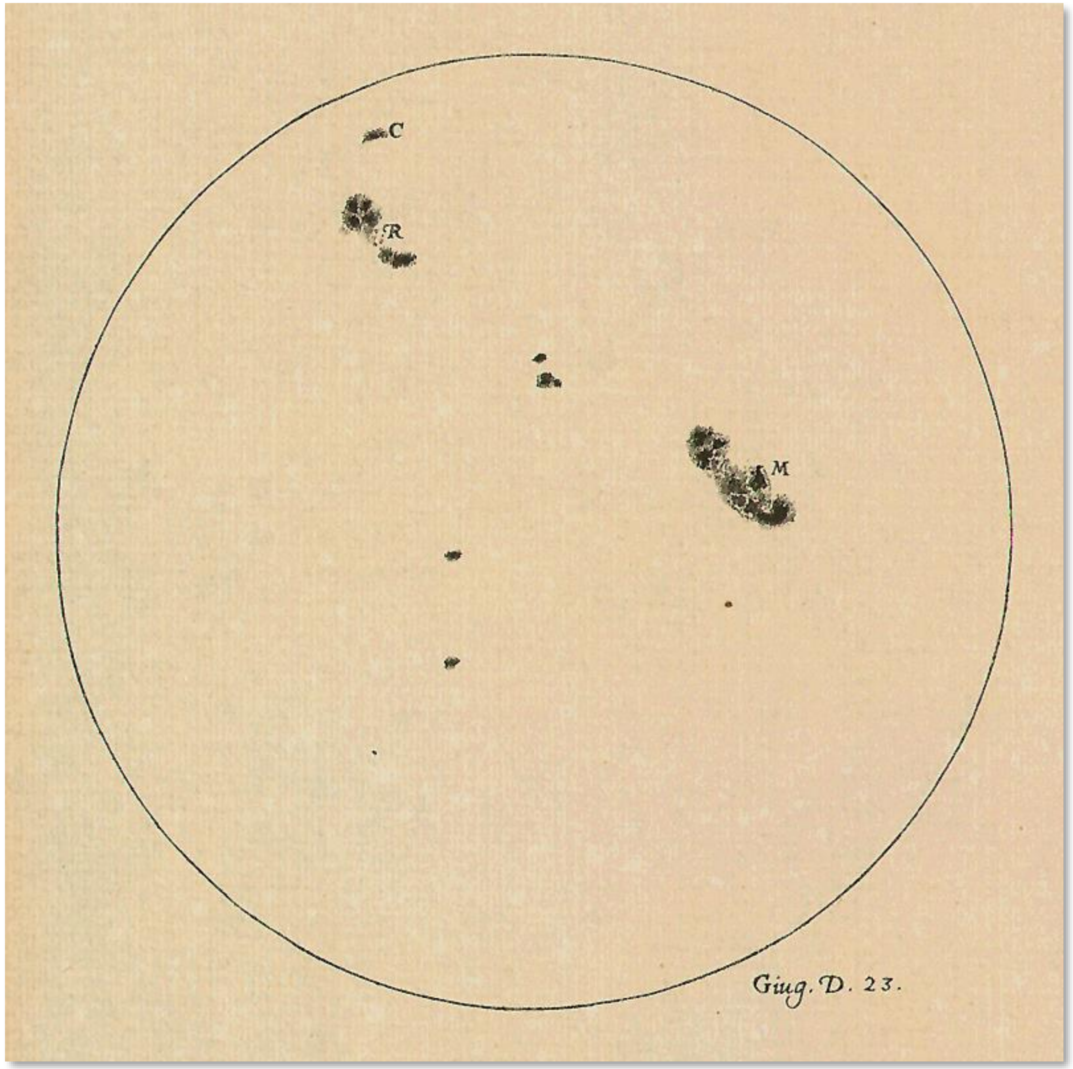


Outline

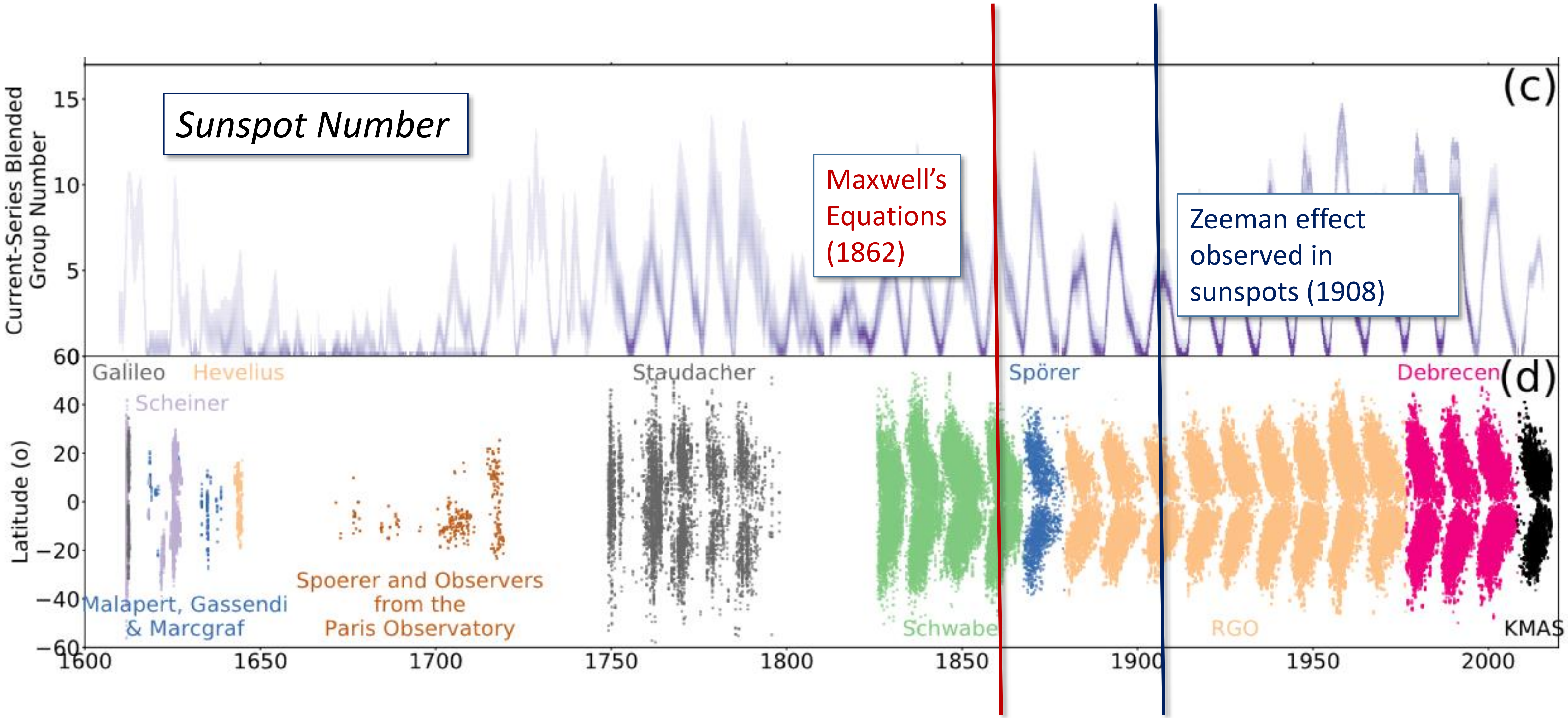
- Some background on the solar magnetism
- Fluid motions in the Sun
- The "Convective Conundrum"
  - An application of rotating convection
- Future directions in solar convection research





Detailed sunspot records from 1600s onward
(Galileo Galilei, 1612)

Naked-eye observations from China since 23 BCE

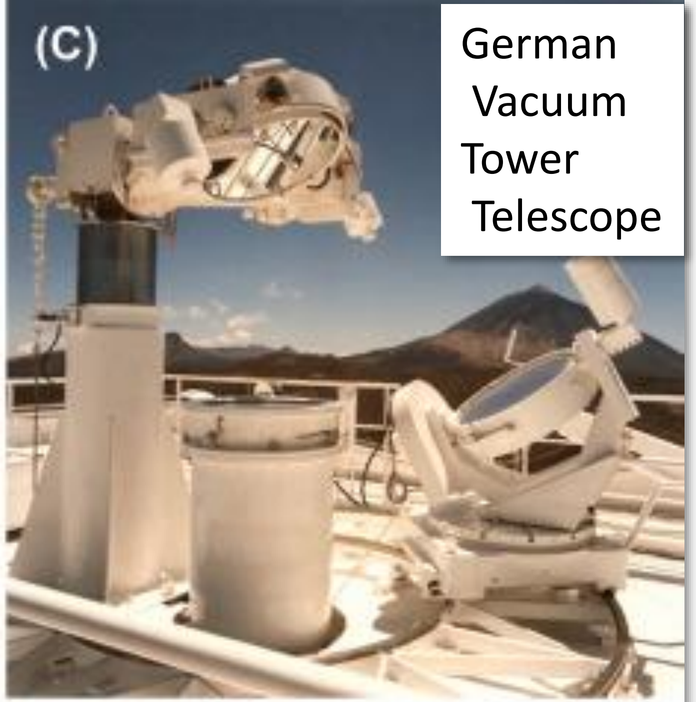


Munoz-Jamarillo & Vaquero 2019

,


Swedish
Solar
Telescope


GREGORY


(C)
German
Vacuum
Tower
Telescope

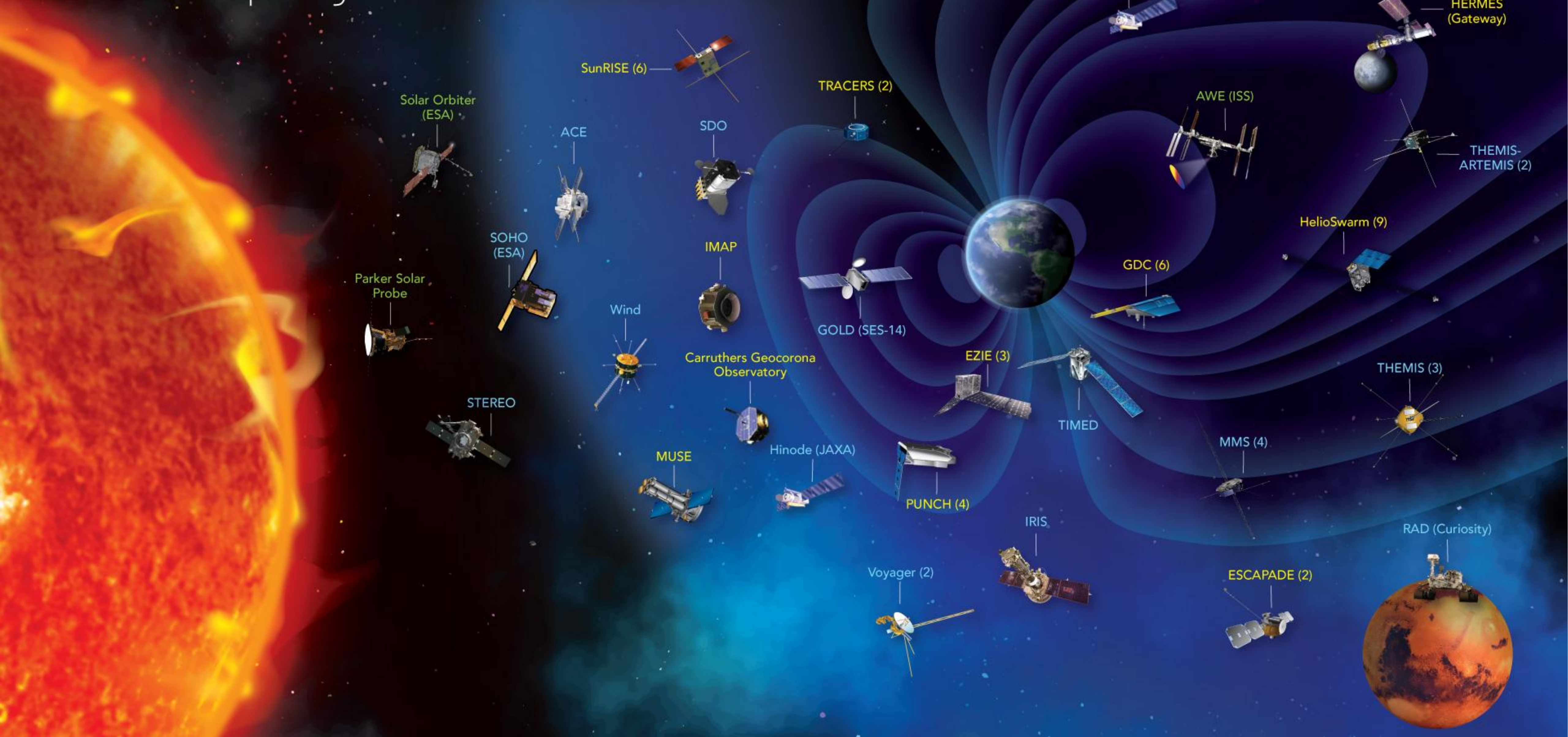

THEMIS


Fuxian Lake

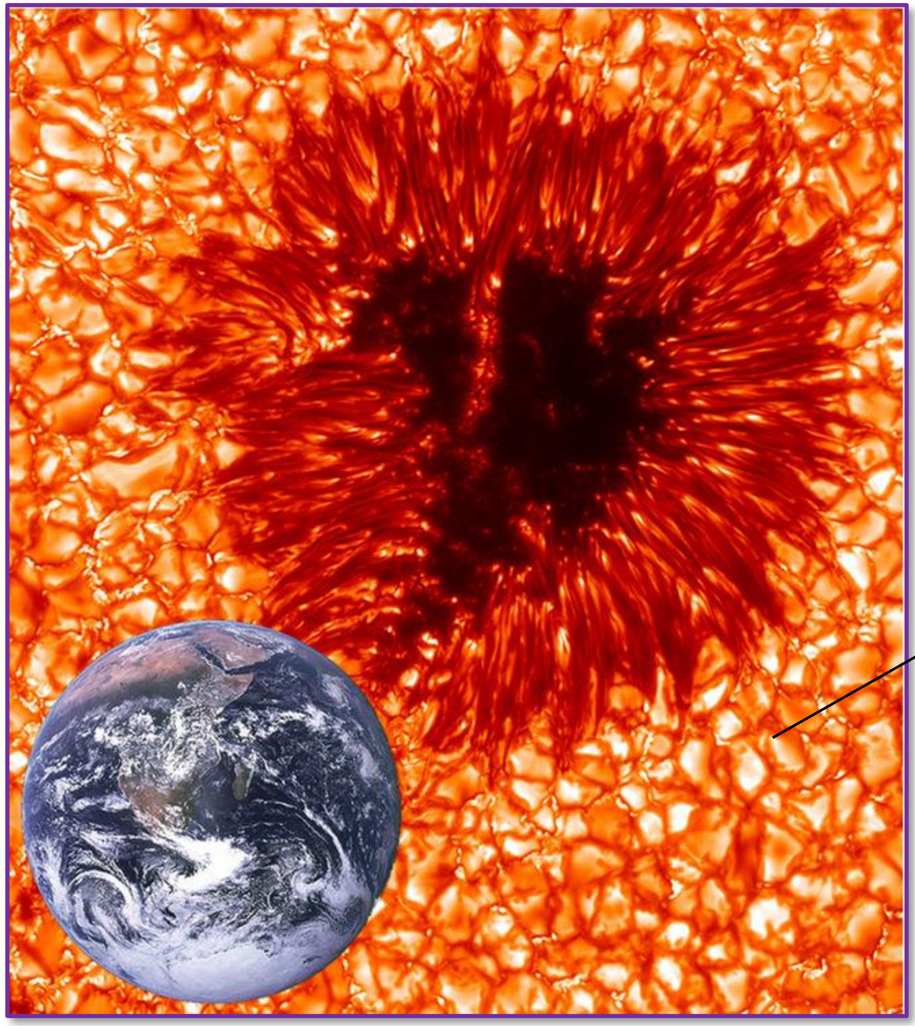

Big Bear


Dutch Open
Telescope

Heliophysics Missions

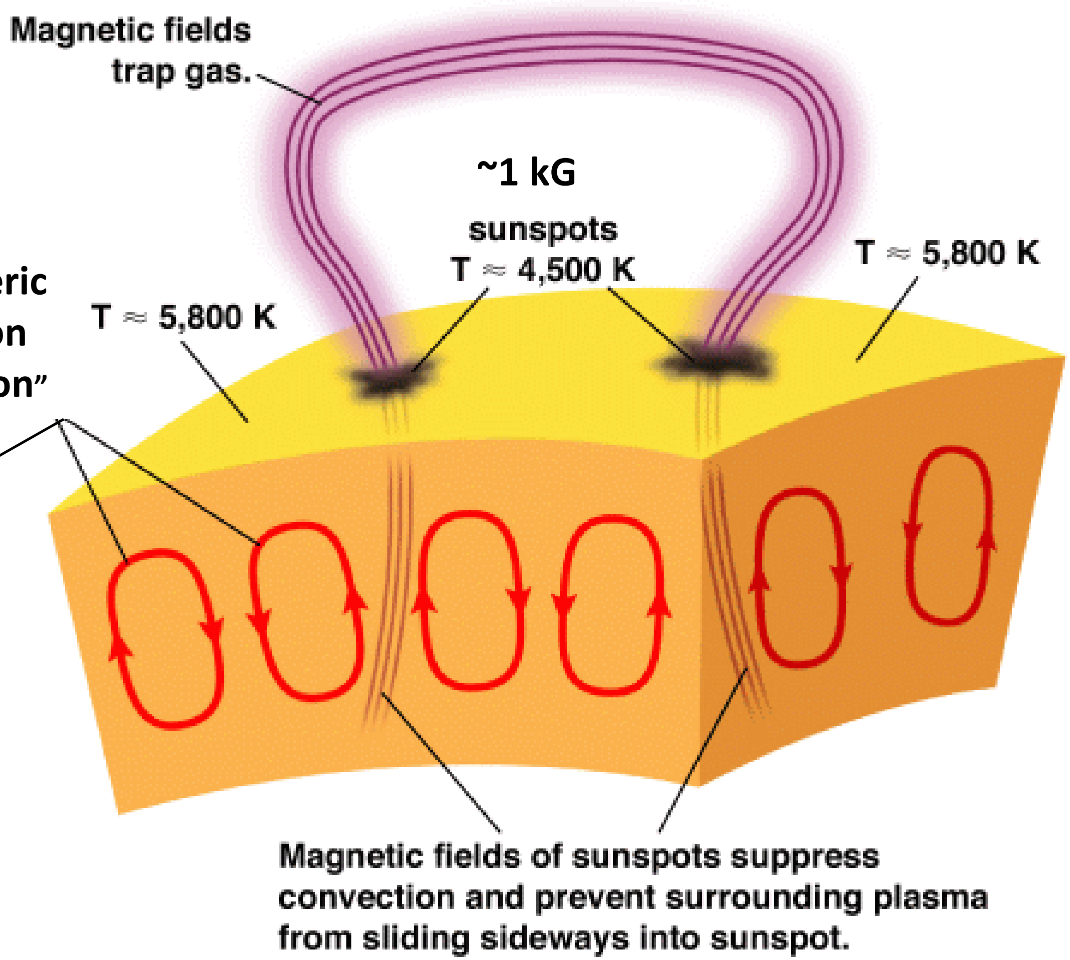


Sunspots: A Closer Look

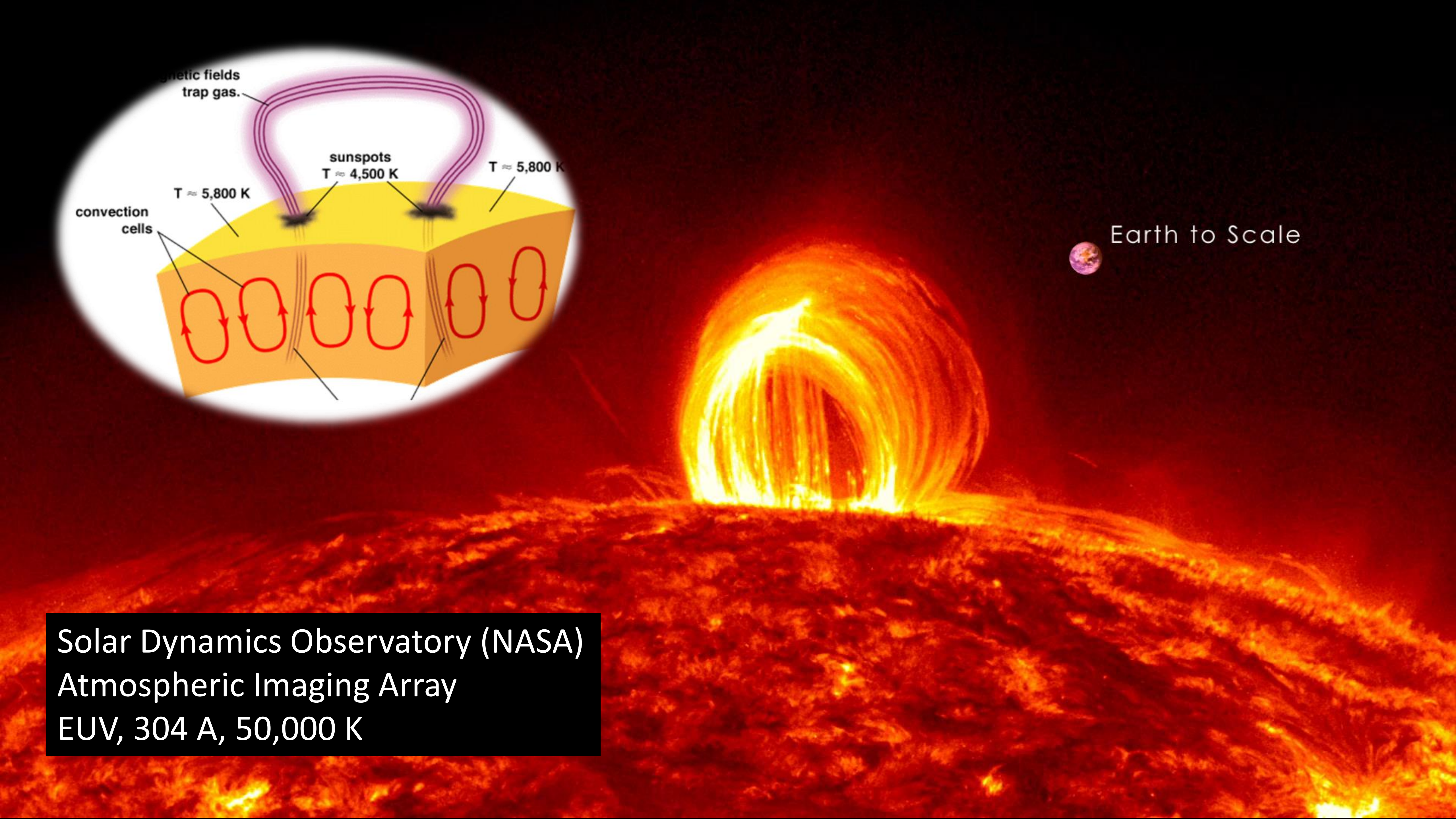


Swedish Solar Telescope (visible; 430 nm)

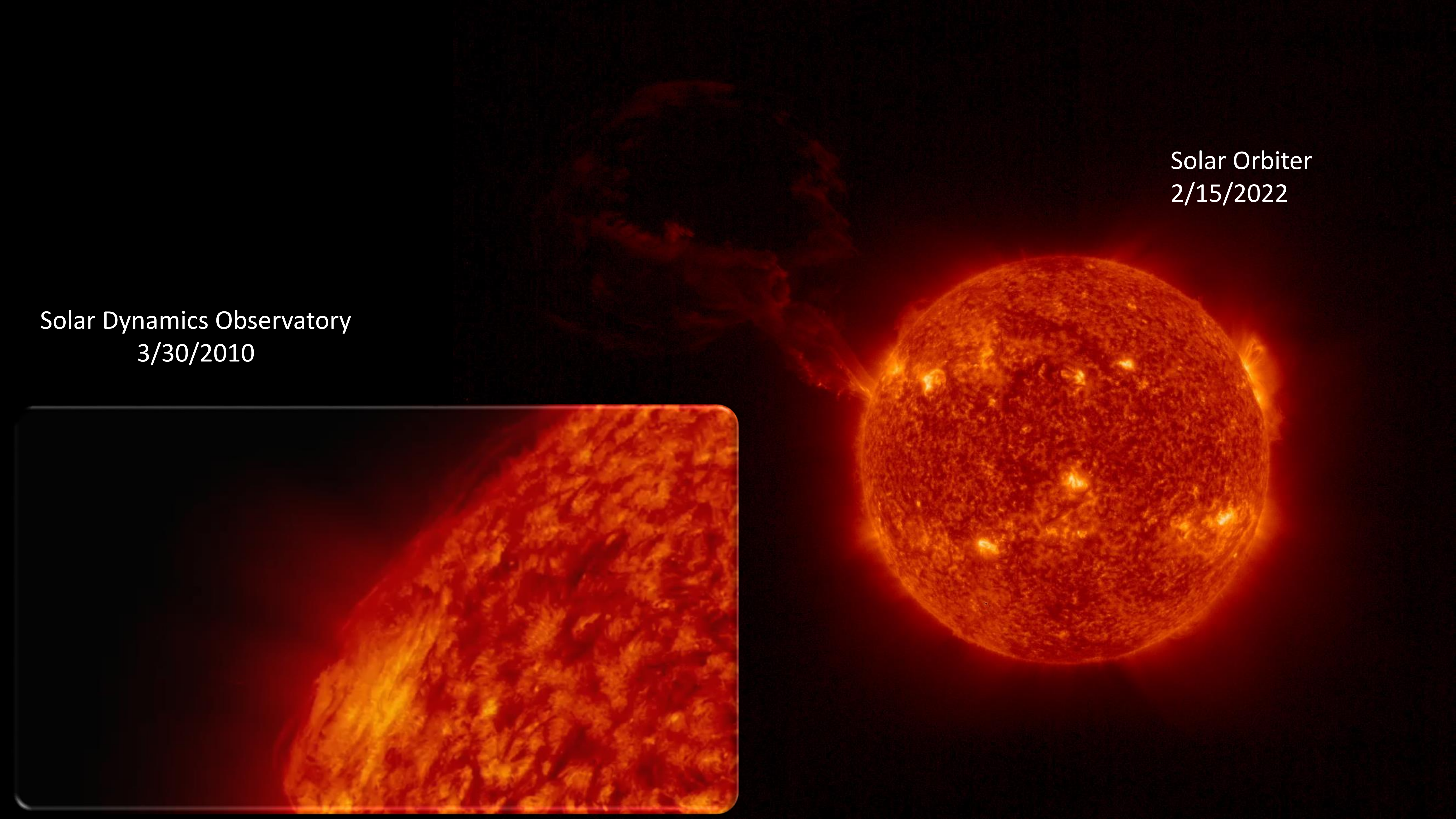
photospheric convection "granulation"



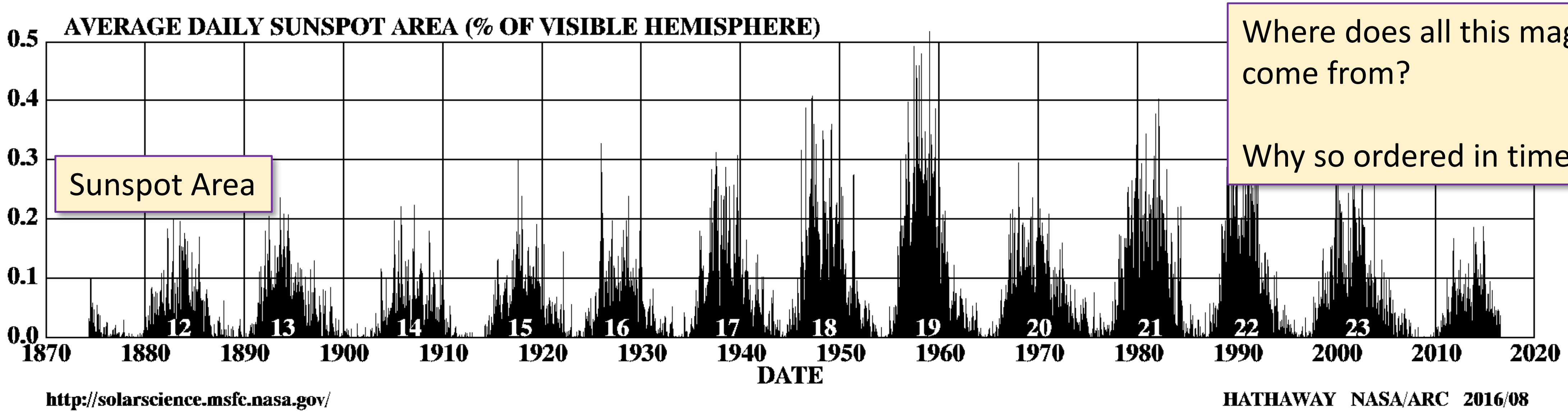
Cosmic Perspective, 3rd Ed.



Solar Dynamics Observatory (NASA)
Atmospheric Imaging Array
EUV, 304 A, 50,000 K

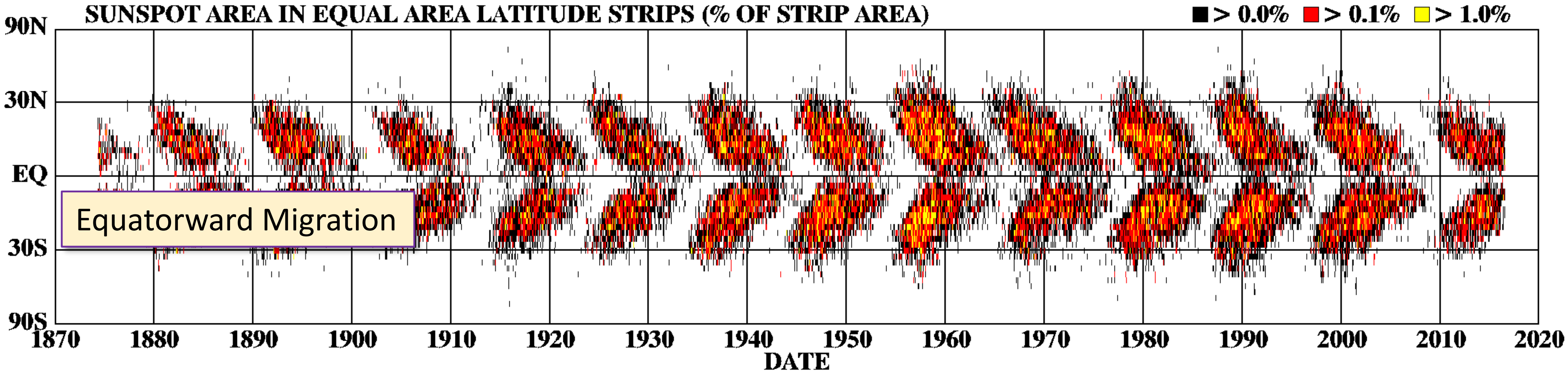

Solar Orbiter
2/15/2022
Solar Dynamics Observatory
3/30/2010

The Sun's Magnetic Cycle



Where does all this magnetism come from?

Why so ordered in time/space?



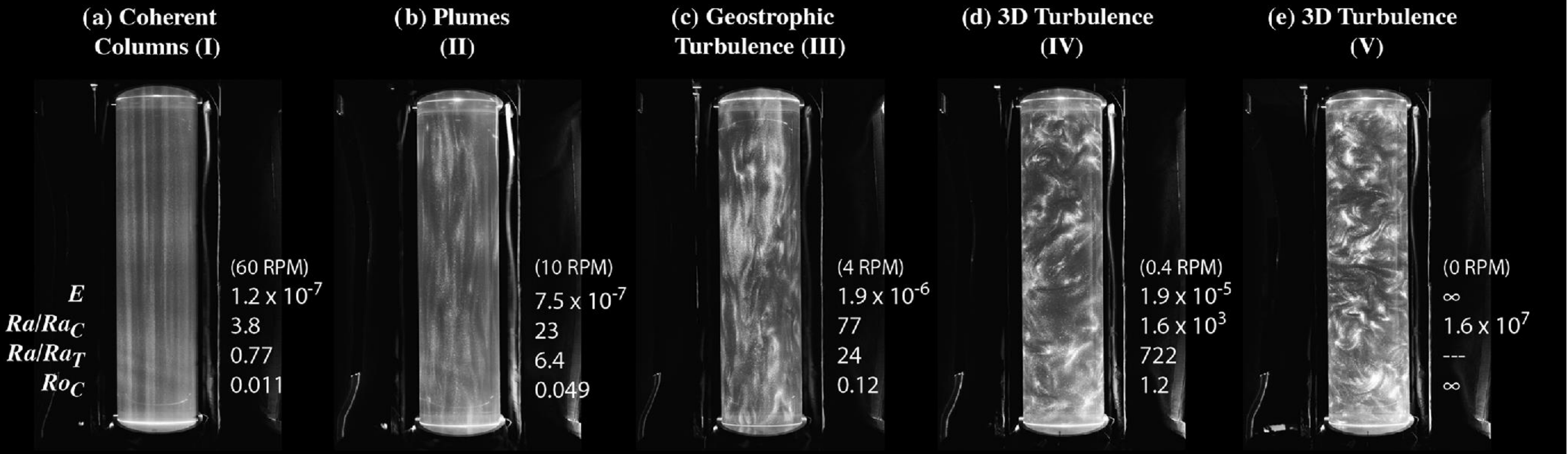
The Speed of Sun?

$$\text{Rossby Number (Ro)} = \frac{\text{Rotational Timescale}}{\text{Convective Timescale}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (U \times \boldsymbol{B}) - \nabla \times (\eta \boldsymbol{\nabla} \times \boldsymbol{B})$$

- Generation of **B** hinges on structure and amplitude of **U**
- The Sun rotates
- Ro expresses the significance of the Coriolis force
- Its value can influence the dynamo

Rotating Convection: Experimental Results

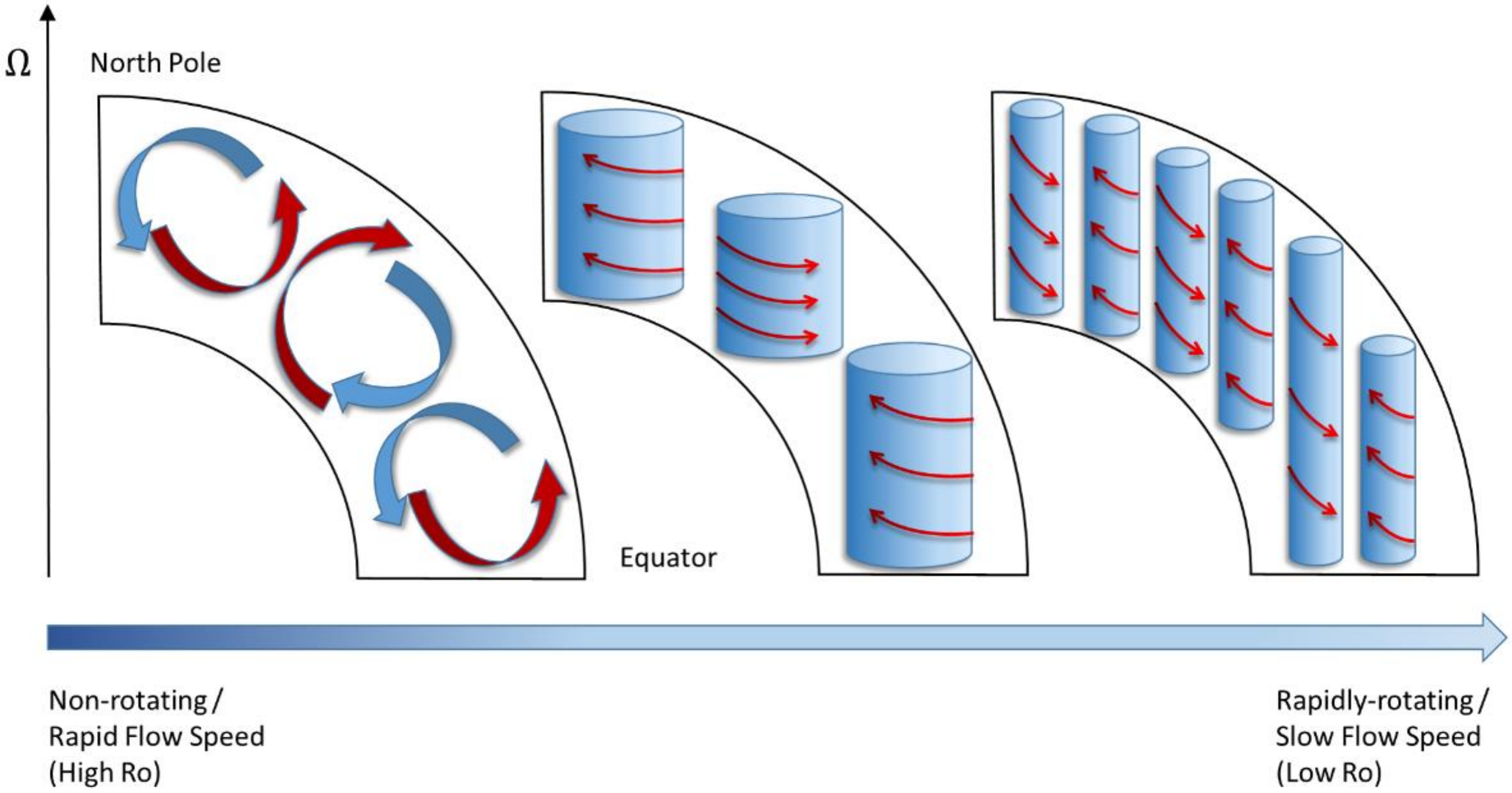


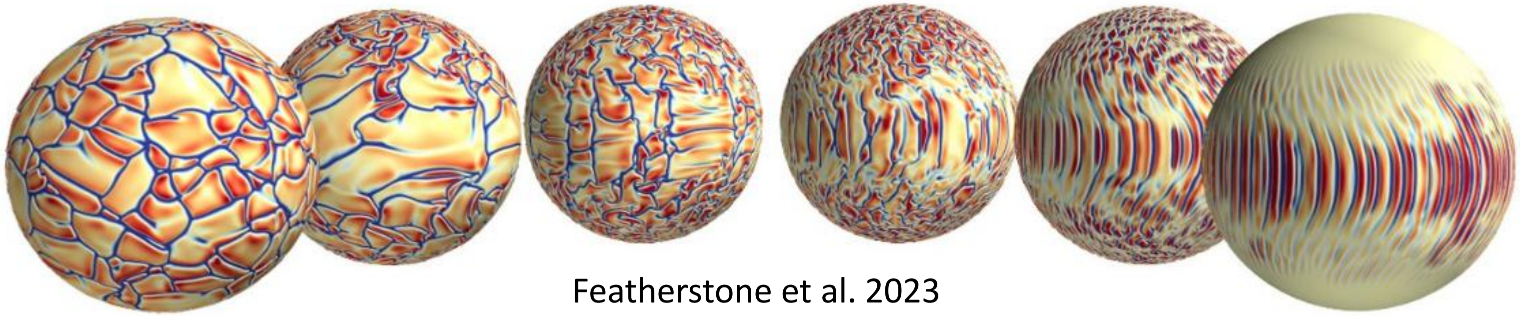
Cheng et al., 2015, GJI, 201,1   NoMag Experiment, SpinLab UCLA

rapid rotation /
columnar cells

no rotation /
Isotropic turbulence

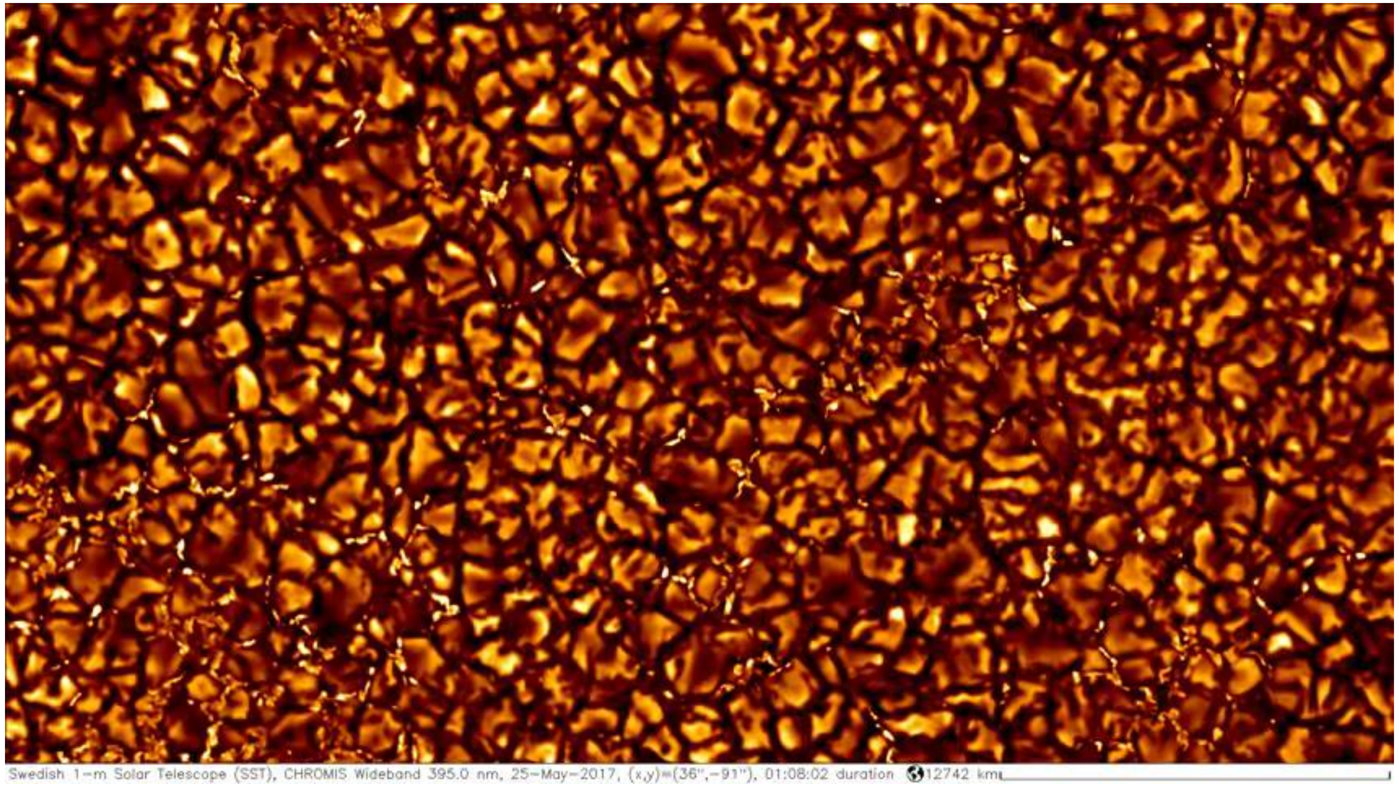
What is Characteristic Flow Speed in the Deep Sun?



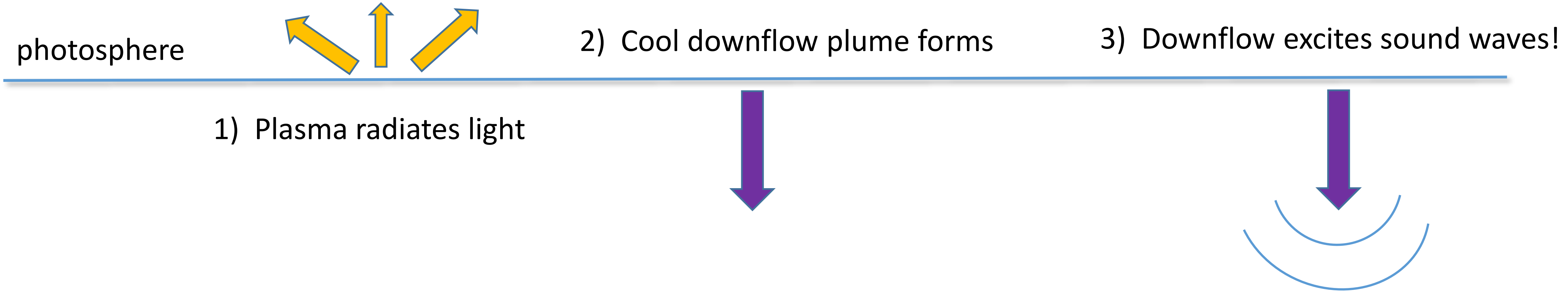


Featherstone et al. 2023

The Sound of Granulation

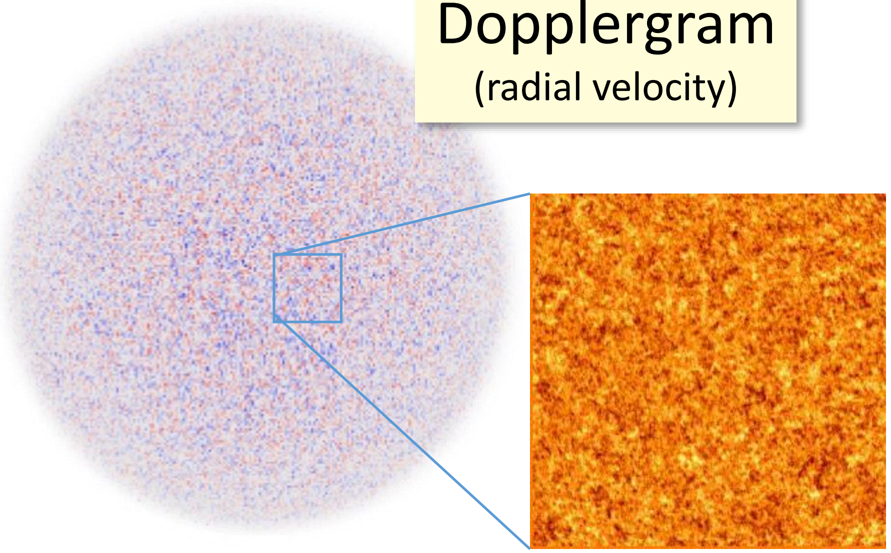


Solar Granulation Movie
Swedish Solar Telescope
Wavelength: 395 nm (blue visible)
Movie Duration: 1 hour
Length Scale: 1,000 km
Convective timescale: minutes

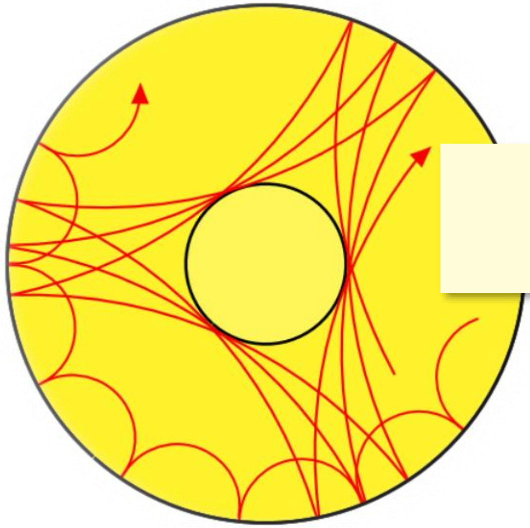


What Lies Beneath?
Solar Helioseismology

Dopplergram
(radial velocity)



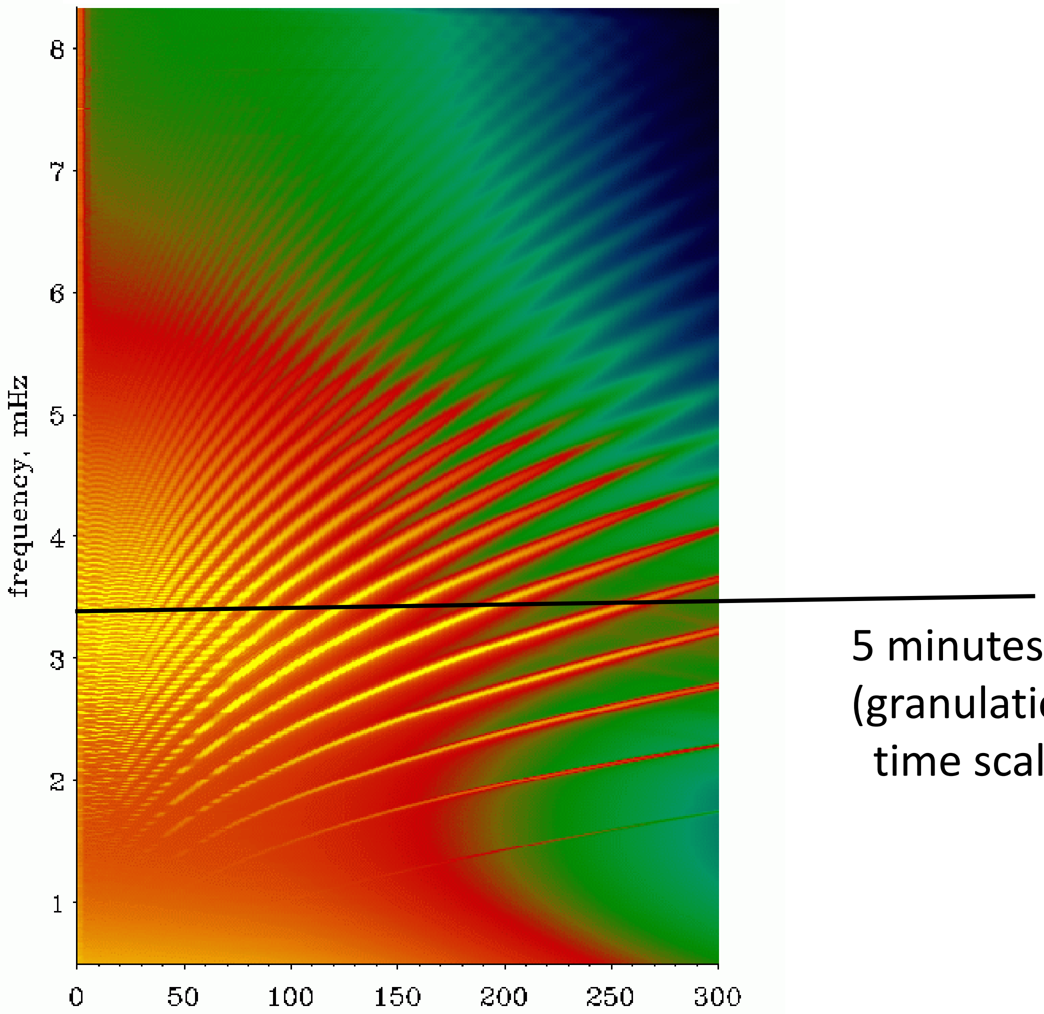
SOHO/MDI
(NASA/ESA)



Resonant
Acoustic Modes

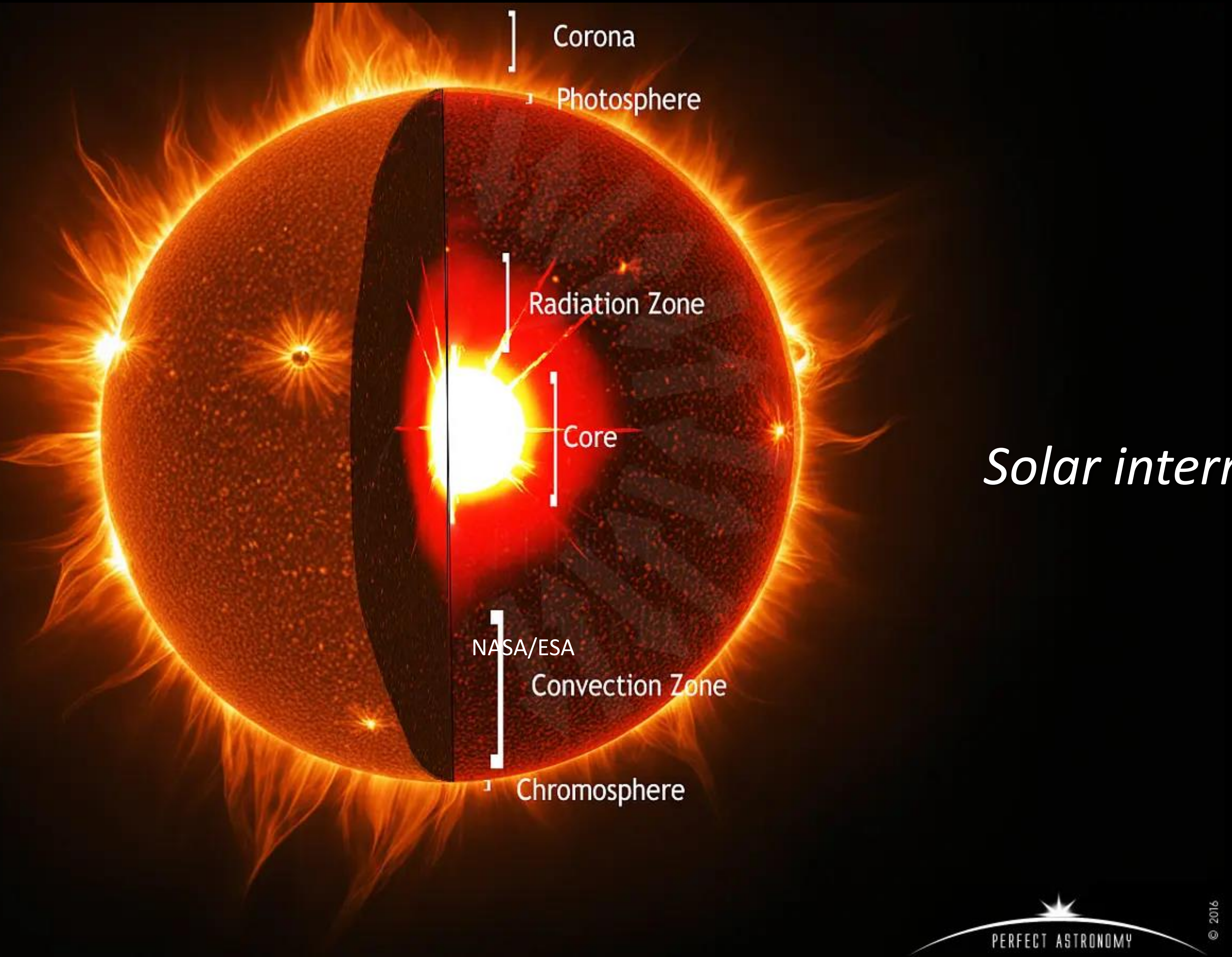
MDI Medium-ℓ Power Spectrum

Frequency (mHz)

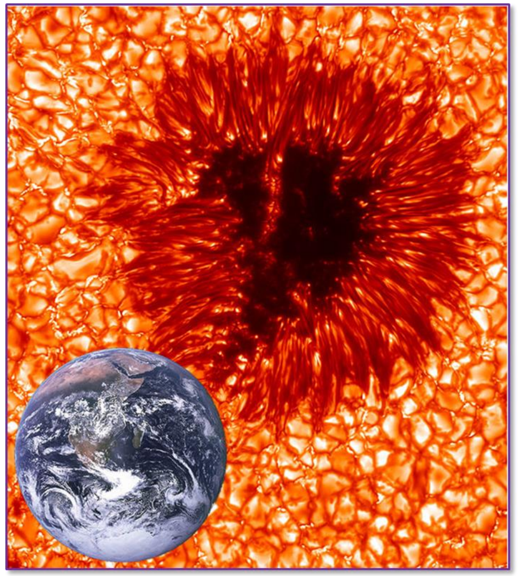


5 minutes
(granulation
time scale)

Spherical Harmonic Degree ℓ

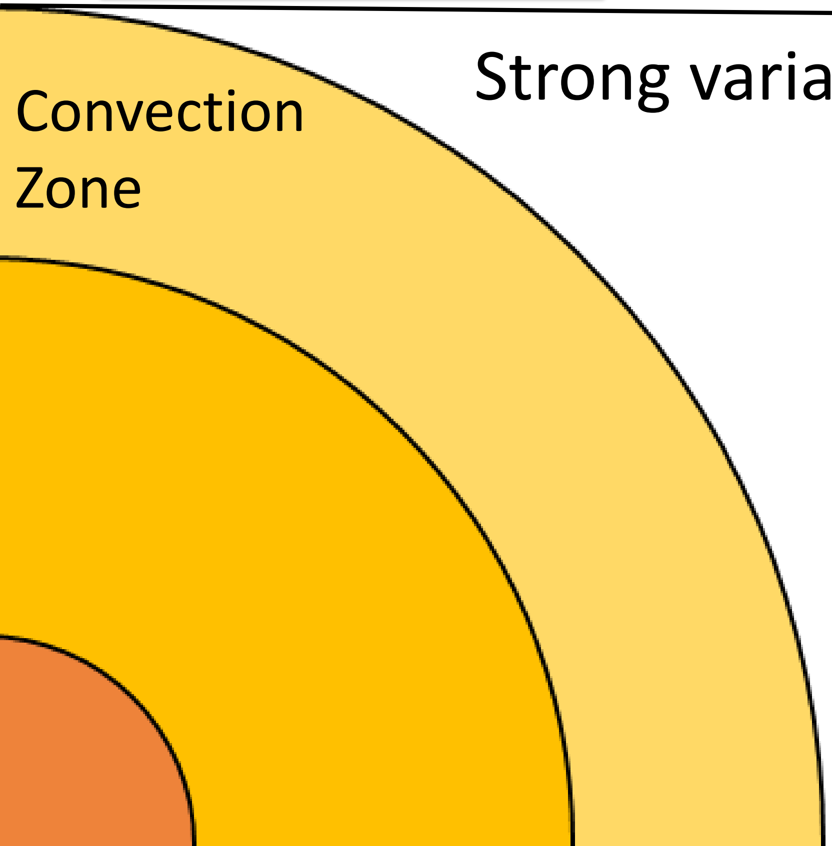


Solar internal structure



Note:

Photospheric motions that we observe occur in a region thinner than the width of this line (about 1,000 km in depth)

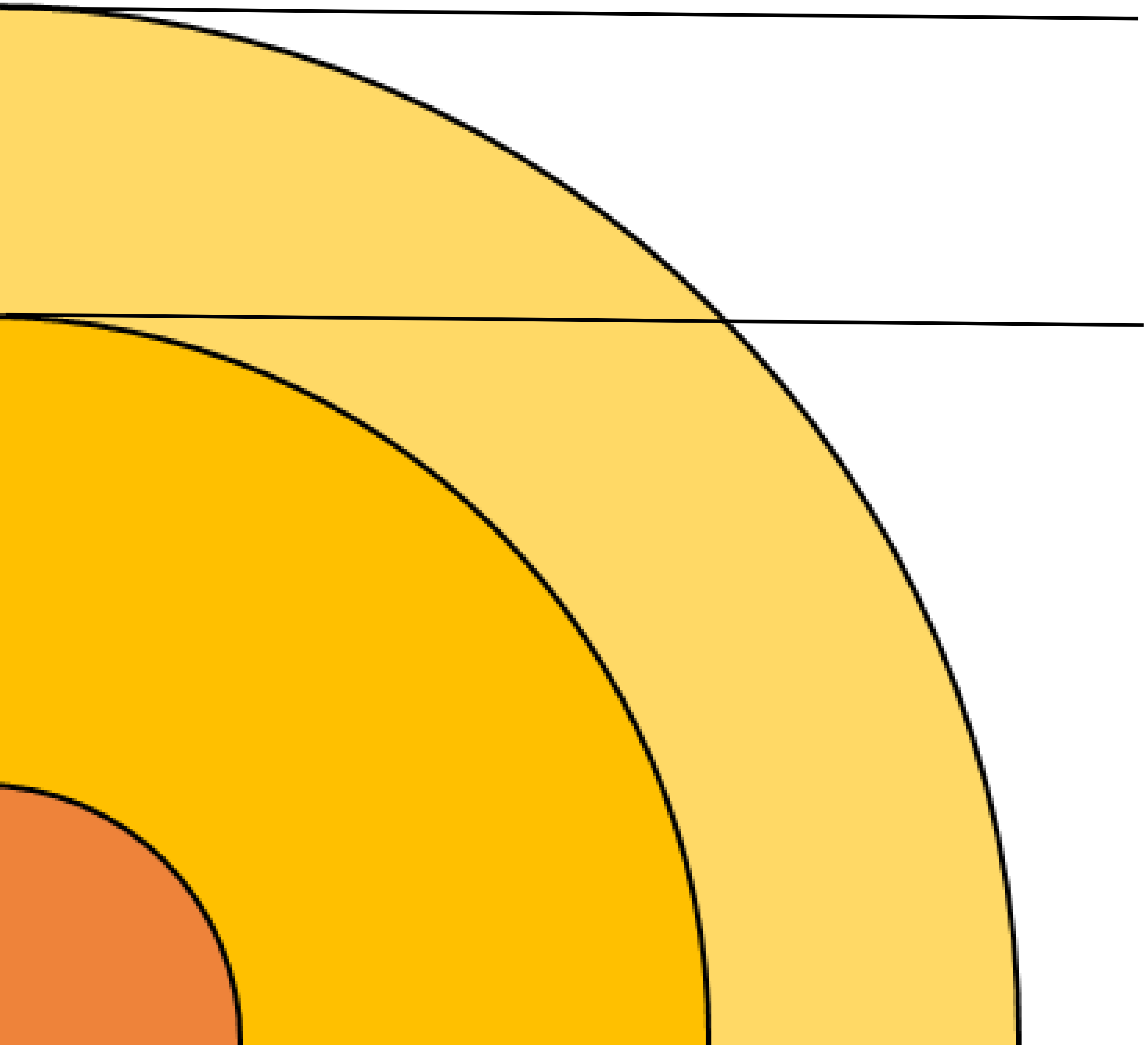


Strong variation with depth

Temperature: 5,800K
Density: 2×10^{-7} g cm^{-3}
Radius: 1 R_{sun}

Temperature: 14,400K
Density: 2×10^{-6} g cm^{-3}
Radius: 0.9985 R_{sun}

Convection Zone Bulk



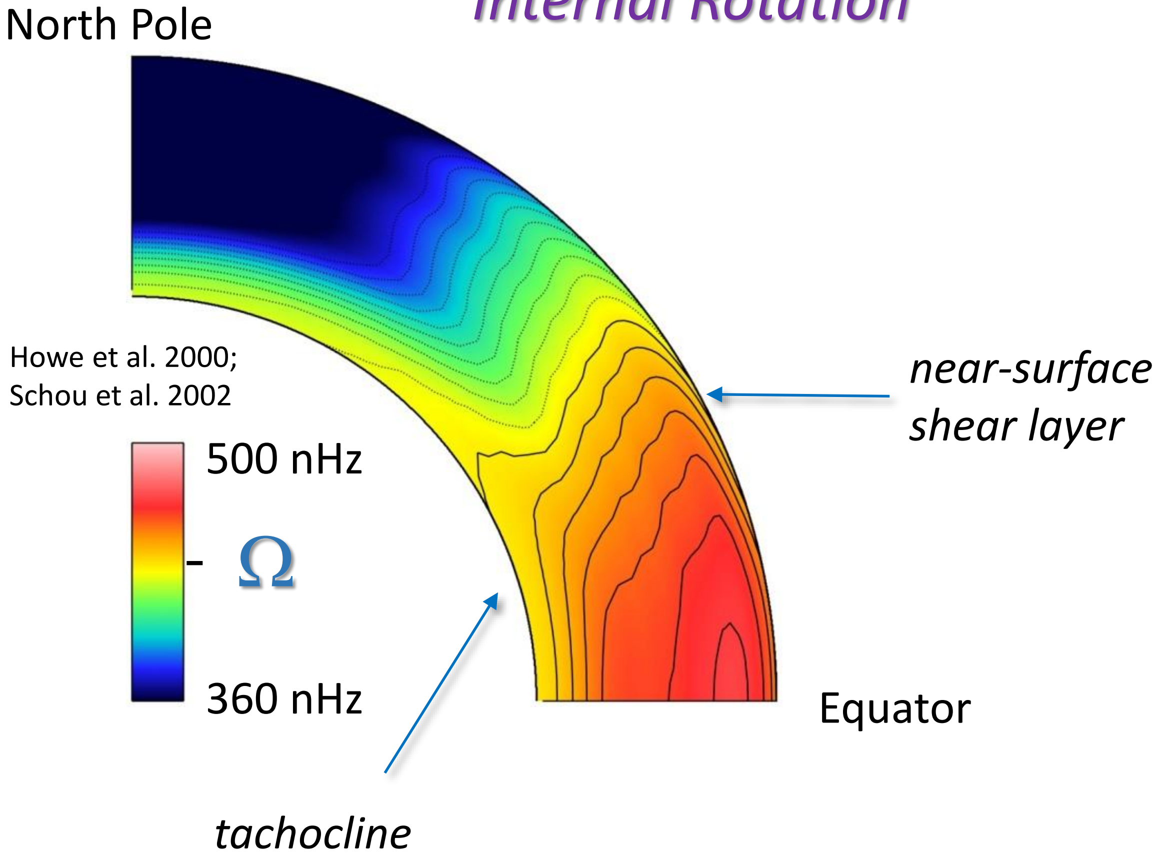
Temperature: 14,400K
Density: 2×10^{-6} g cm^{-3}

Temperature: 2.3 million K
Density: 0.2 g cm^{-3}

- 11 density scaleheights
- 17 pressure scaleheights
- Reynolds Number $\approx 10^{12} - 10^{14}$
- Rayleigh Number $\approx 10^{22} - 10^{24}$
- Magnetic Prandtl Number ≈ 0.01
- Prandtl Number $\approx 10^{-7}$
- Ekman Number $\approx 10^{-15}$

Solar Mean Flows

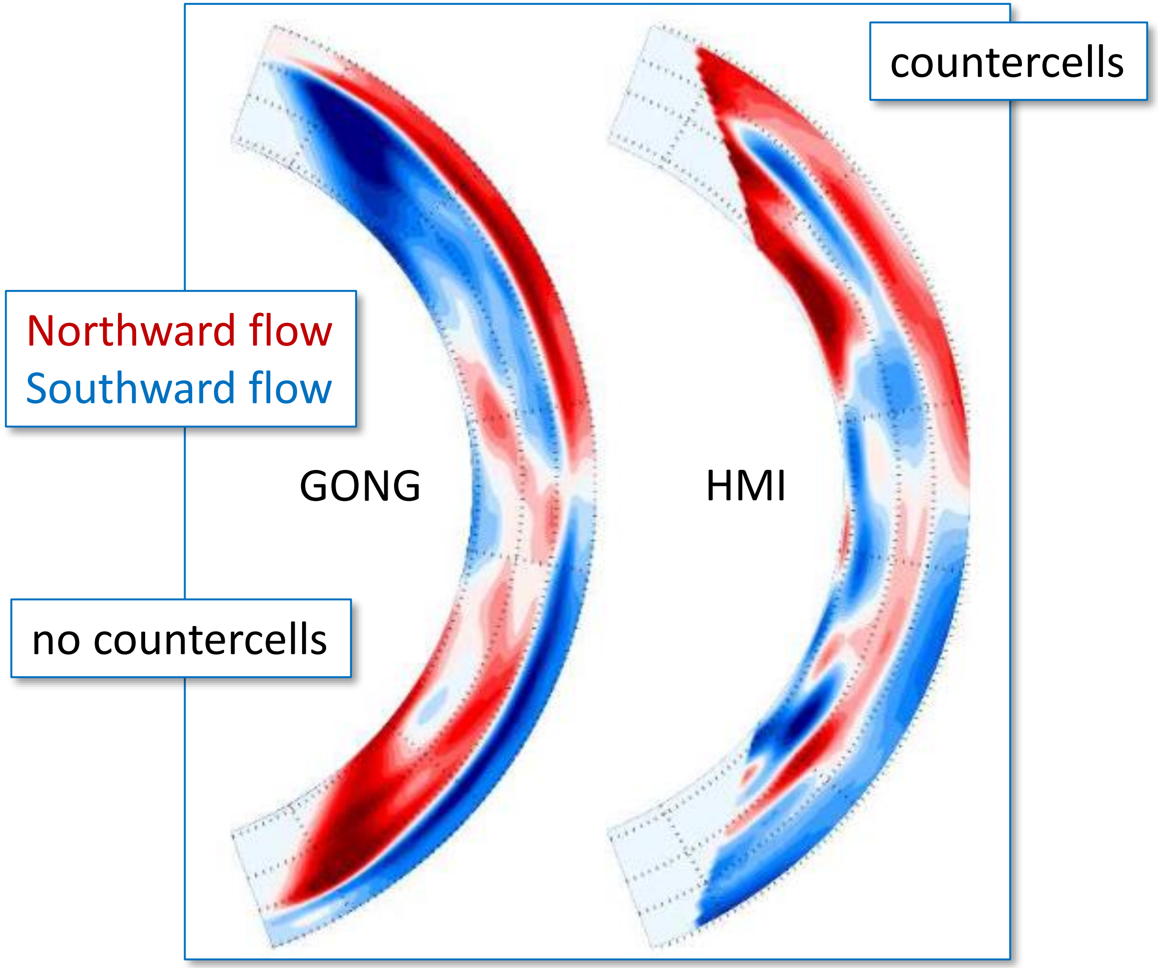
Internal Rotation



Howe et al. 2000;
Schou et al. 2002

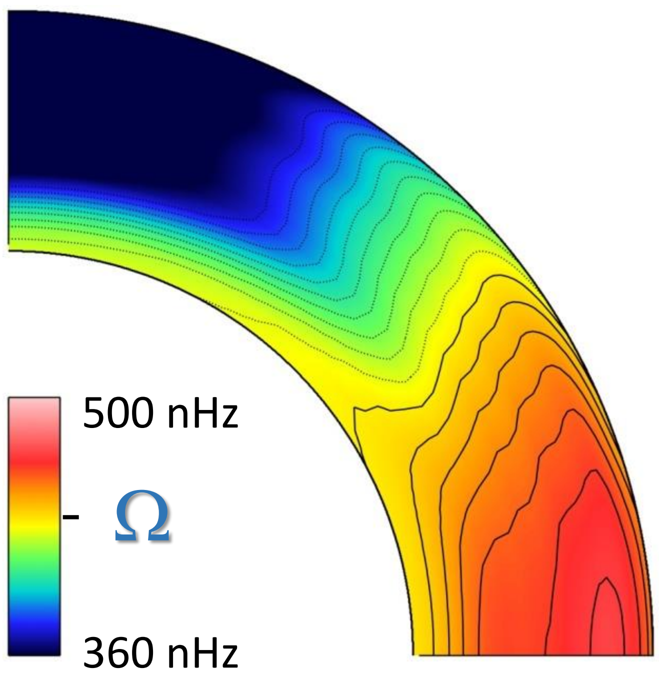
- differential rotation in radius and latitude
- solid-body radiative zone (why?)
- Near-surface shear layer (why?)

Meridional Circulation (?)



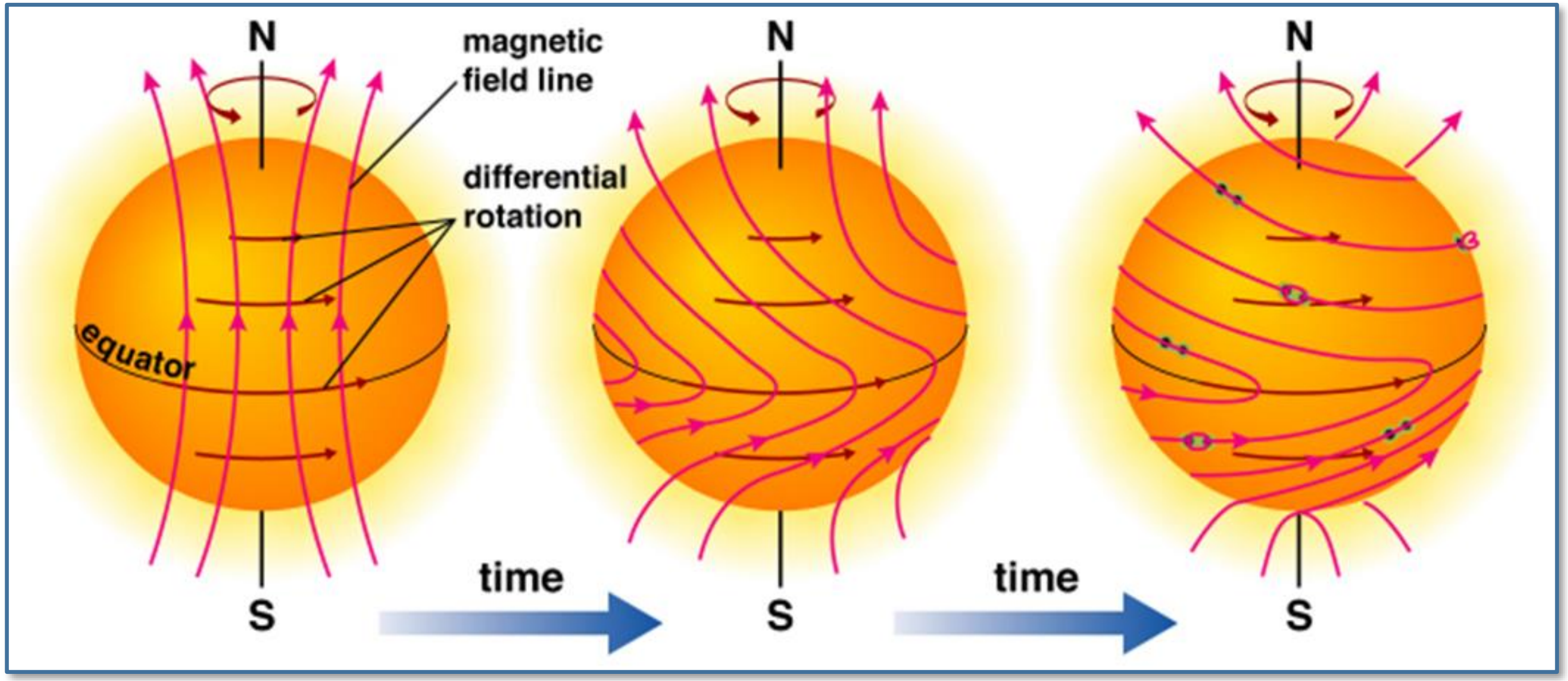
Jackiewicz et al., 2015

Differential Rotation & The Dynamo



Howe et al. 2000; Schou et al. 2002

“Omega effect”



Bennett, et al. 2003

- 24-day period equator
- 30-day period poles

An Interface Dynamo?

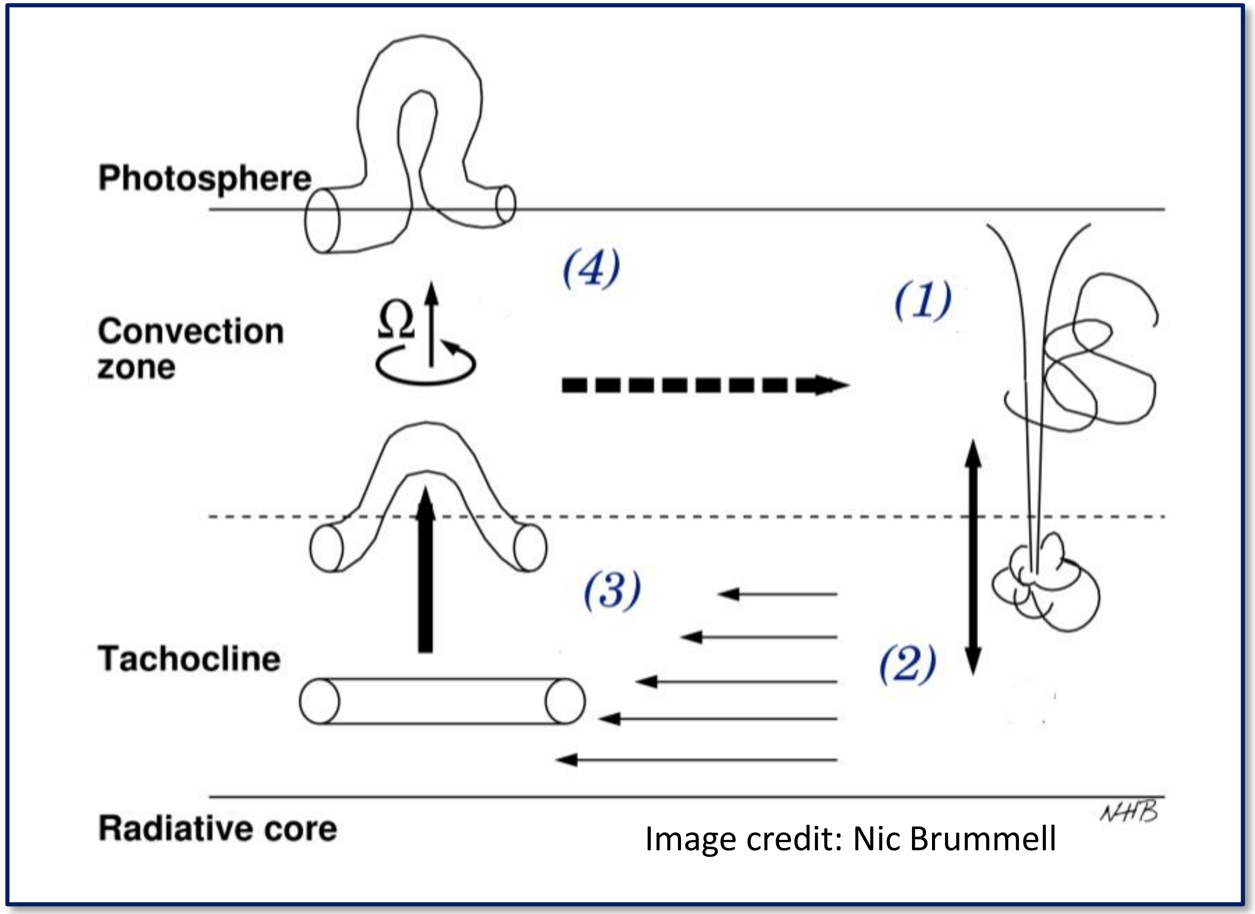
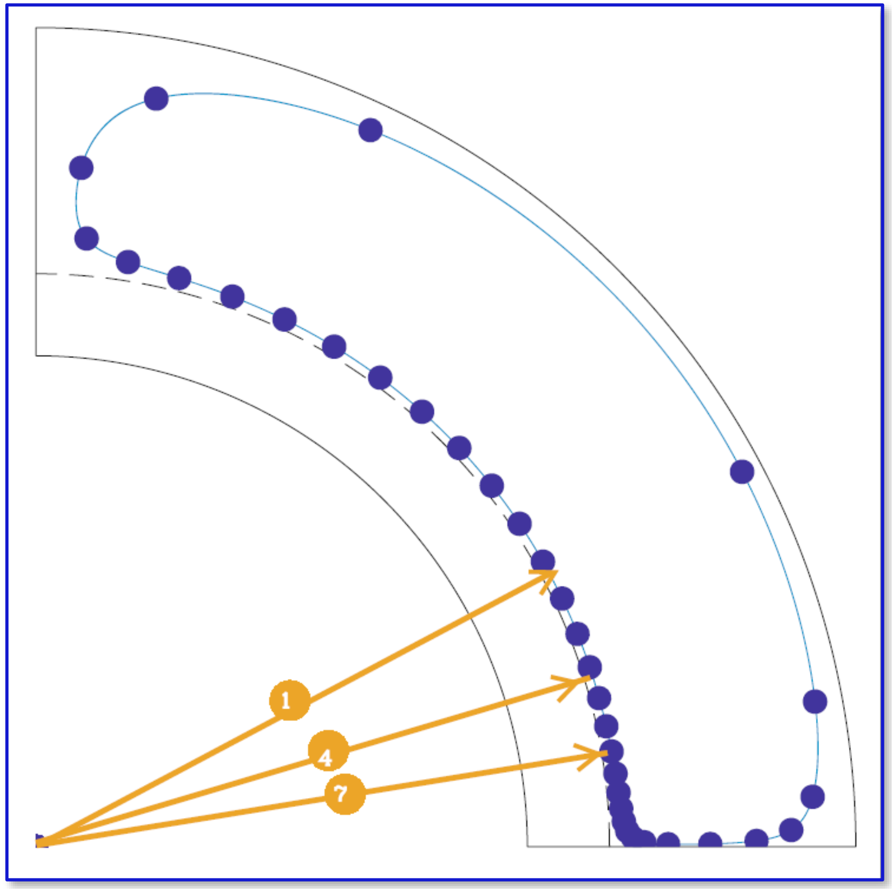


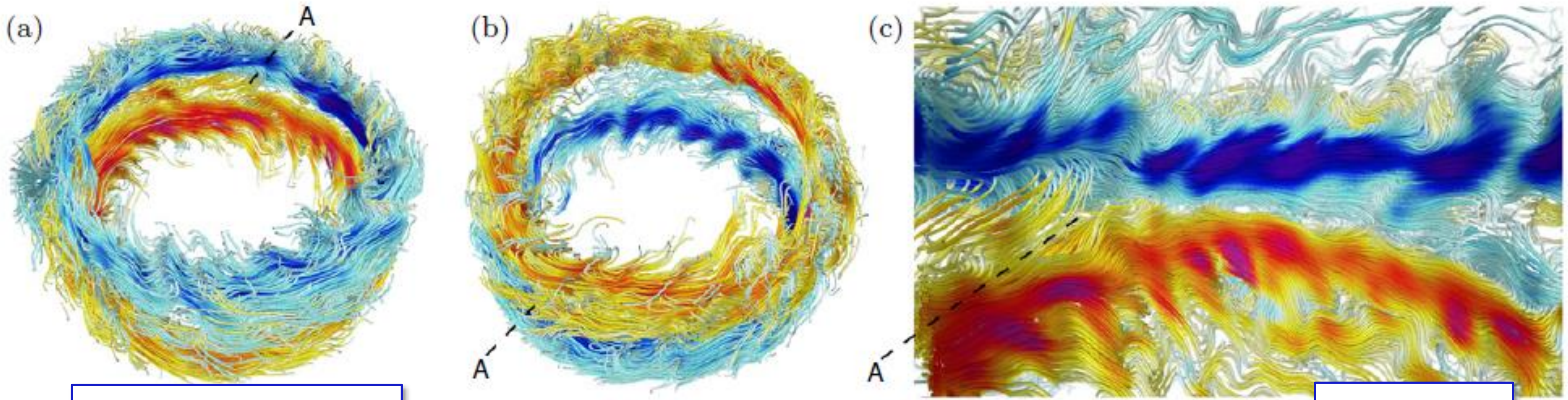
Image credit: Nic Brummell



Dikpati & Gilman 2009

- Is the source of the dynamo in the tachocline?
- Dos meridional flow influence cycle timing?

Or Something Else Altogether?

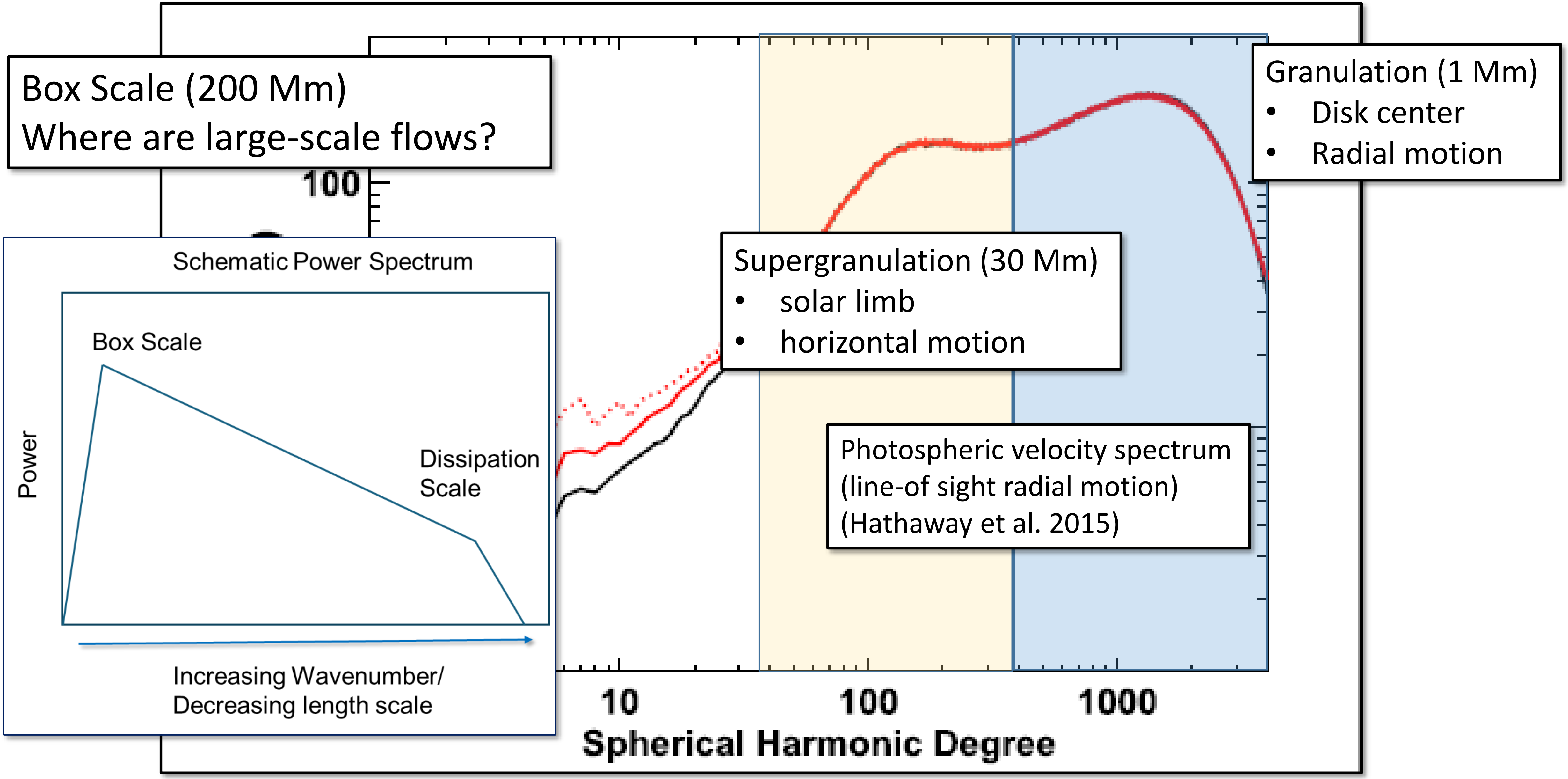


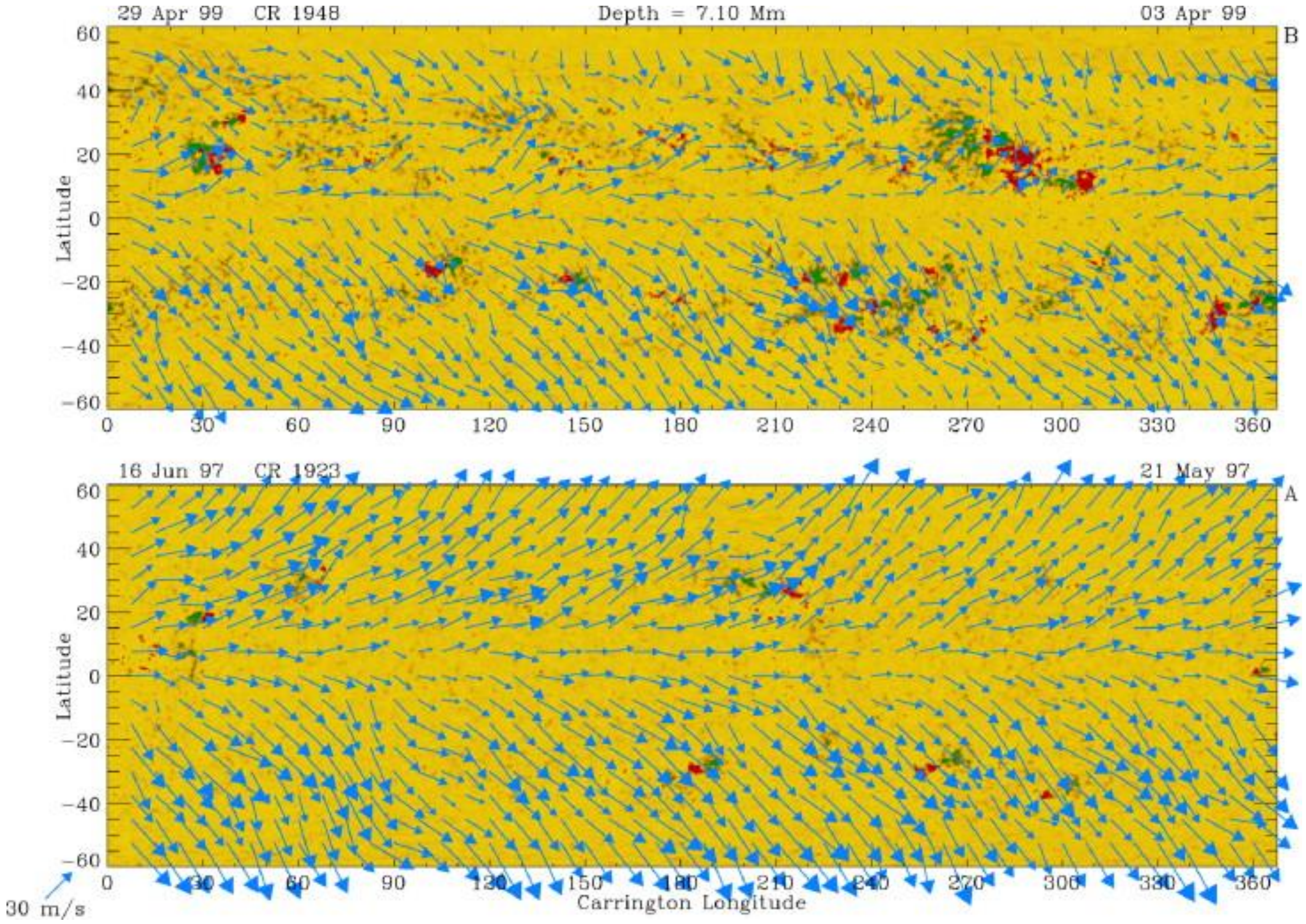
Brown et al. 2010

Ro ≈ 0.03

- Possible alternative to interface dynamo?
- Coherent, cycling structure without tachocline
- Tends to arise in low-Ro regimes
- Where is the Sun?

What do we see on the Sun? Surface Convective Spectrum

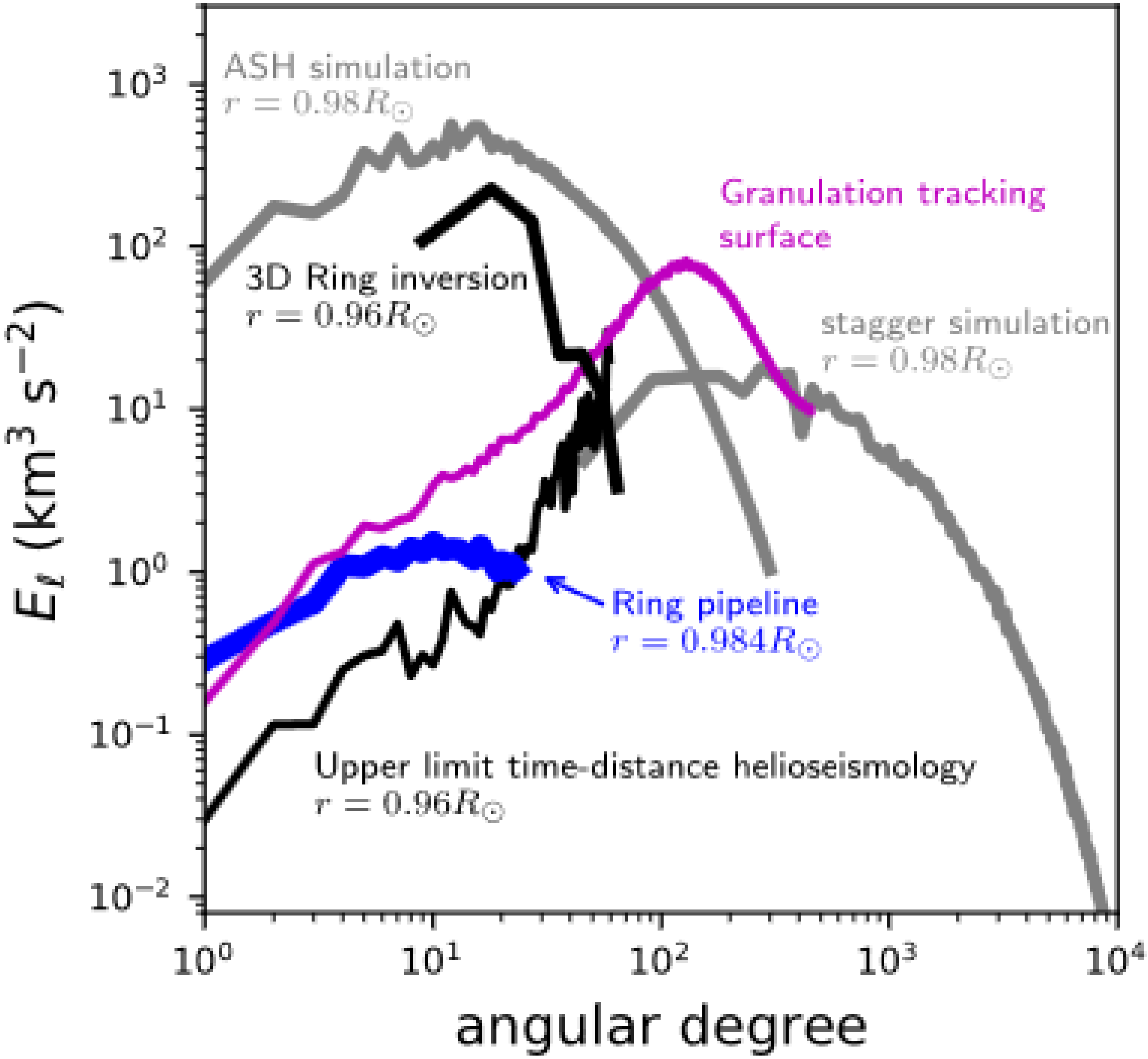




"Solar Subsurface Weather"

- Not very cellular
- Rather weak

Haber et al., 2002, ApJ, 570, 855
(ring diagram analysis)



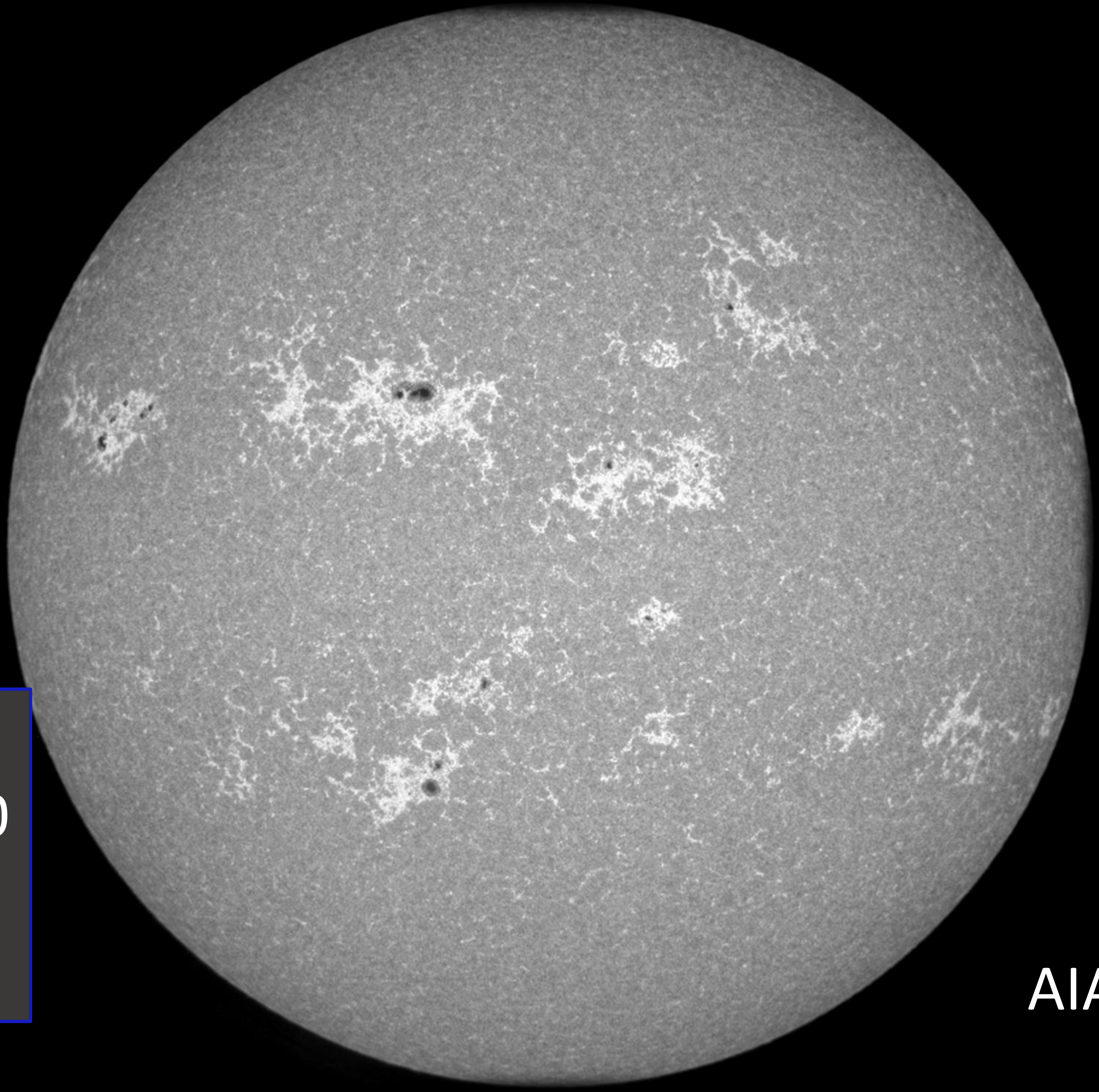
Peering Deeper

- disagreement among observations
  - the convective conundrum
- robust ack of large-scale power
- Is this puzzling or not?

Birch et al., 2024, Phys. Fluids, 36, 117136

Supergranulation

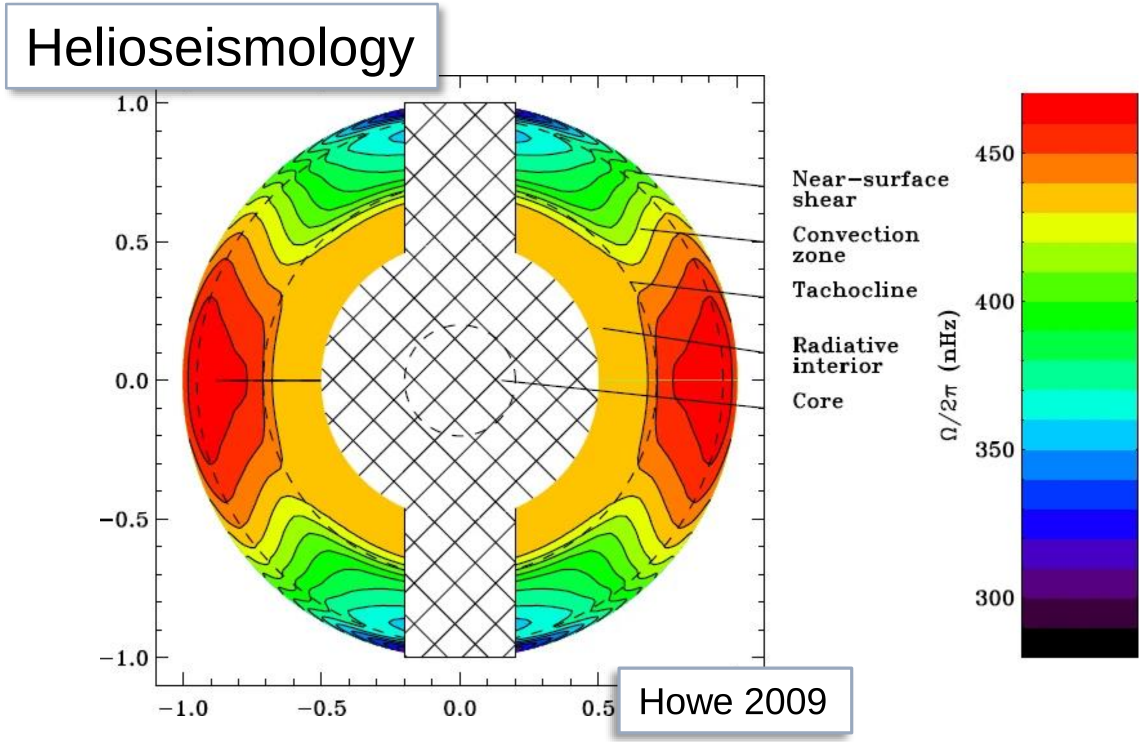
… the largest spatial scale of
convection that we seem to see

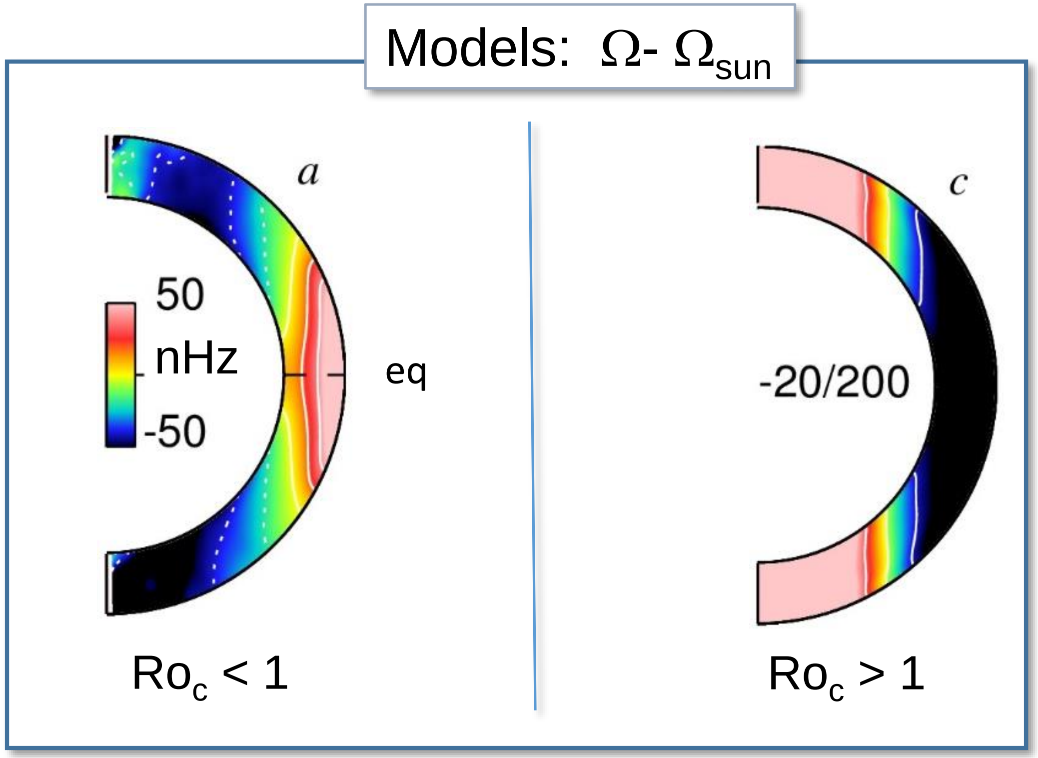


L $\approx$ 30 Mm
Harmonic Degree 100
U $\approx$ 400 m s^{-1}
Ro $\approx$ 3

AIA 1700

Rossby Number and Differential Rotation



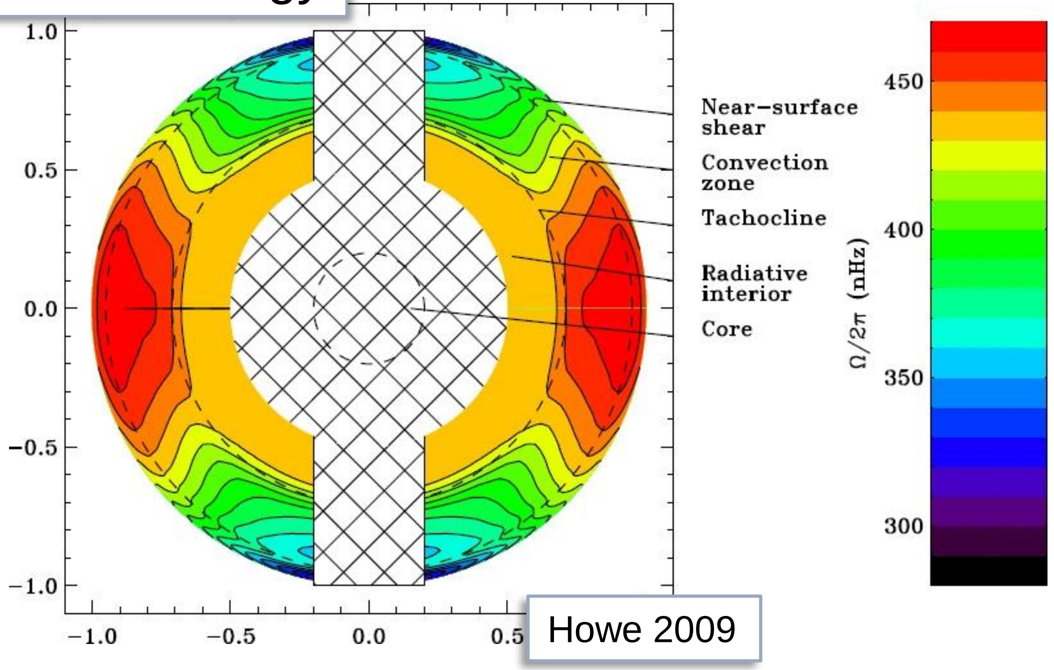


- Solar differential rotation clearly evinces low-Ro behavior
- Implications for convective flow speed?

- Ro$_c$ = 1 *robustly* divides two regimes of differential rotation.
- Corresponds to roughly 150– 200 m/s flows

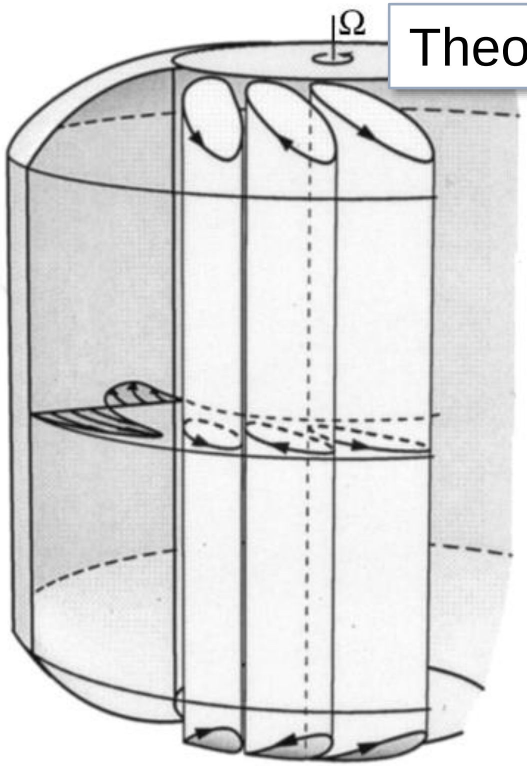
Rossby Number and Differential Rotation

Helioseismology



Howe 2009

Theory



- Solar differential rotation clearly evinces low-Ro behavior
- Implications for convective flow speed?

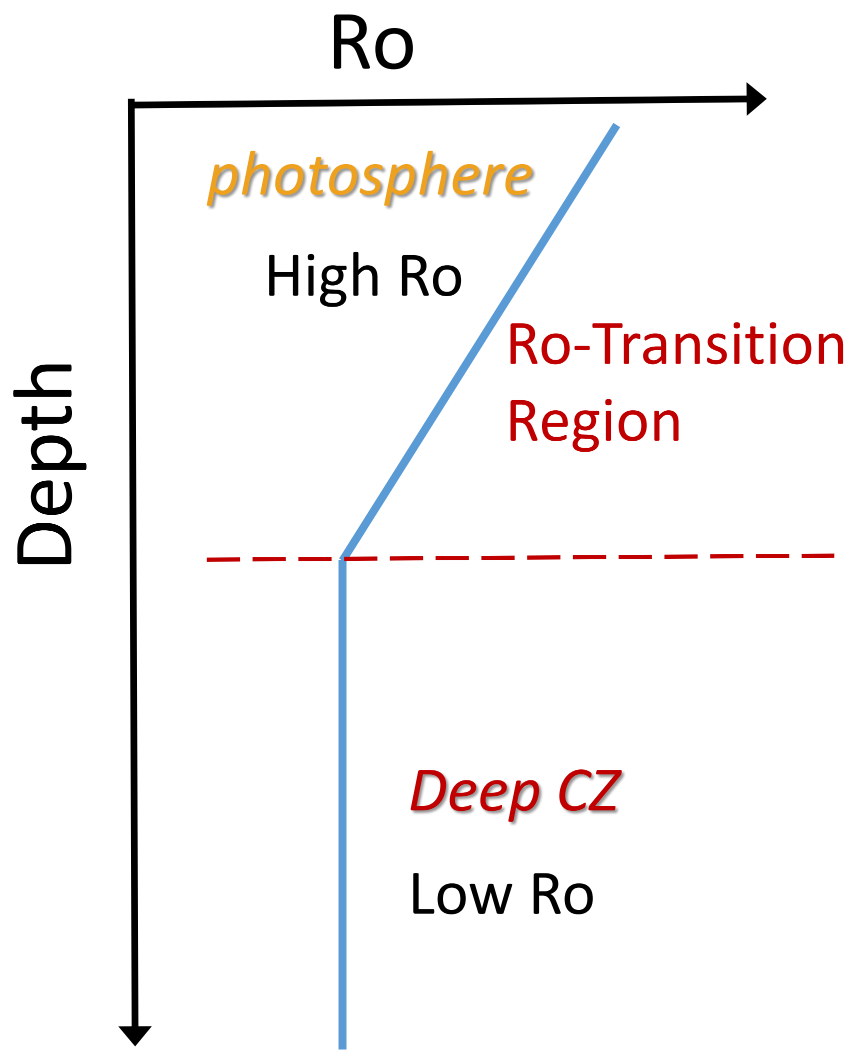
Busse, F.H., 2002,
Physics of Fluids **14**, 1301

What might we expect at the solar surface?

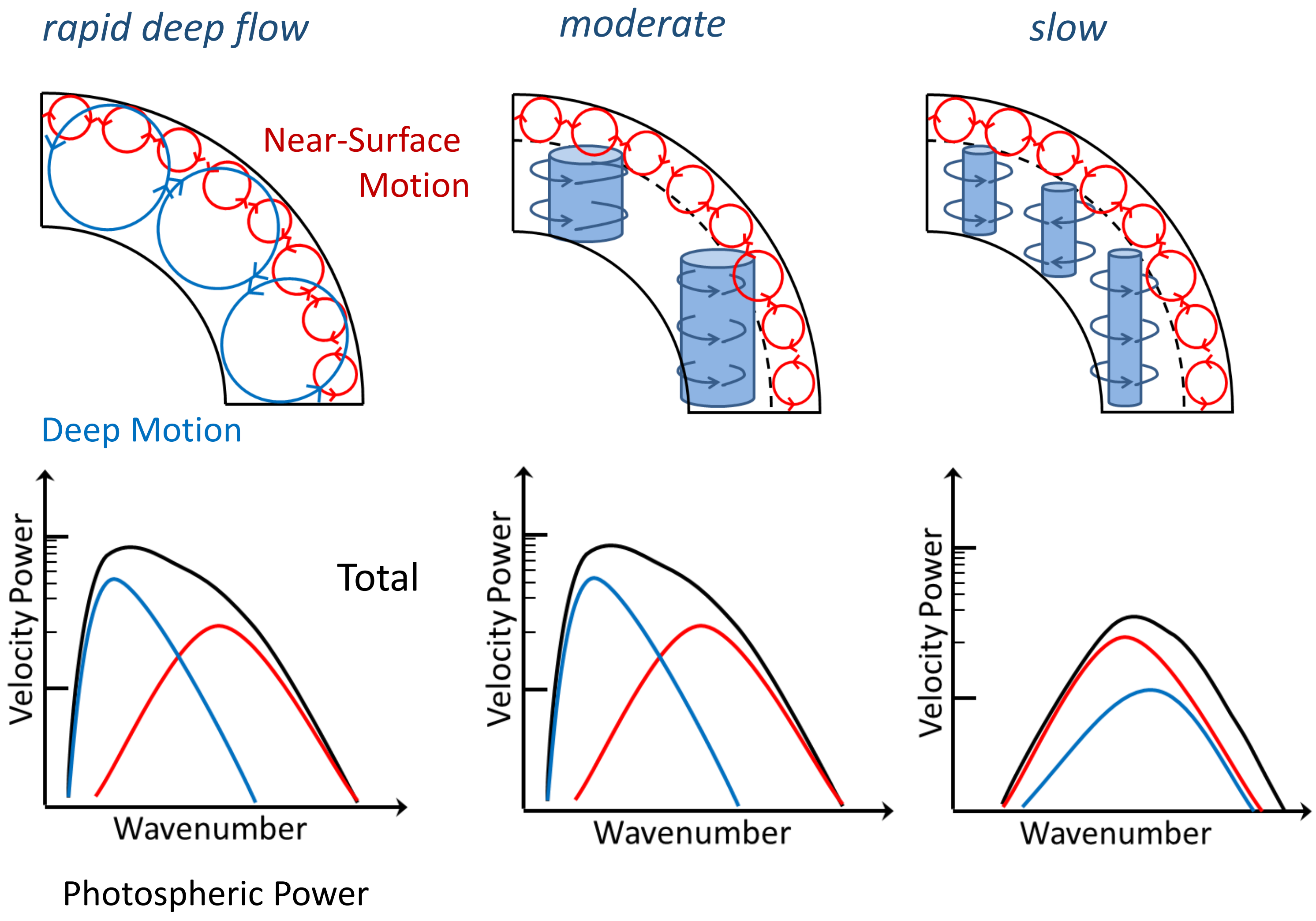
Recall two things…

1. Near the surface we see *high-Ro* motions
   - Granulation
   - Supergranulation
   - Both too fast for Coriolis force to matter

2. At depth we infer low-Ro motion:
   - Differential rotation consistent with slow, not rapid, convection



Convective Structure: Some Possibilities



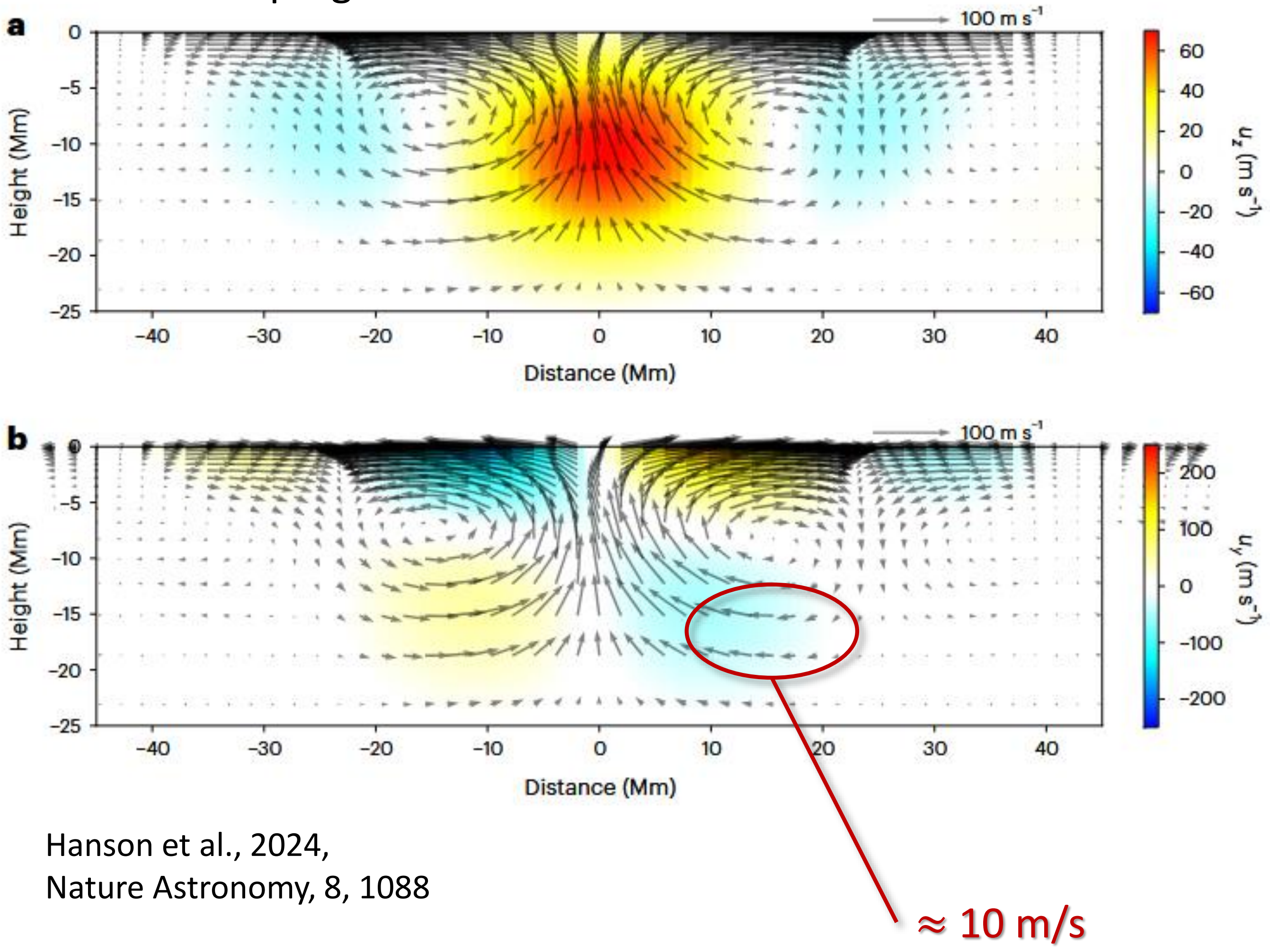
Question:
How slow must deep motions be to achieve the something like the right-hand panel?

Answer:
Numerical simulations indicate that this occurs around Ro = 0.01, or v = 10 m/s.

Featherstone & Hindman, 2016
Camisassa & Featherstone, 2022
Kapyla et al., 2024

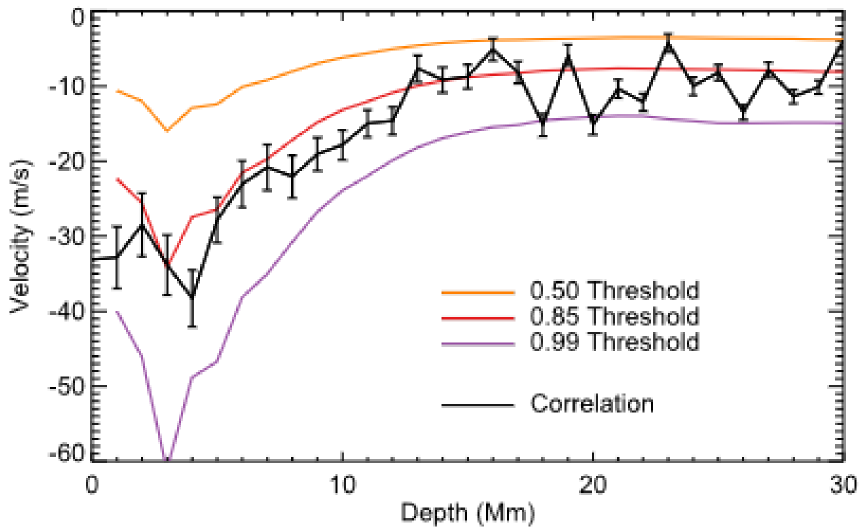
What if we just … look at supergranules?

Supergranular flows from time-distance…



Hanson et al., 2024,
Nature Astronomy, 8, 1088

…and from ring-diagram analysis



Greer et al., 2016, ApJ, 824, 128

- Independent measurements suggest 10 m/s is a relevant flow speed
- Corresponds to roughly 30 Mm.

Estimation Based on Photospheric Intensity Variations

$$\mathrm{Ro_c} \equiv \frac{\text{coriolis timescale}}{\text{freefall time}} = \frac{1}{2\Omega}\sqrt{\frac{g}{2L}\frac{T'}{T}}$$

$T_0 \approx 10^6\mathrm{K}$

$g \approx 368\, m\, s^{-2}$

$\mathrm{Depth} \approx 2 \times 10^8\mathrm{m}$

What should temperature perturbation be?

Equator-to-pole emissivity variation:

Rast et al., 2008, ApJ, 673, 1209
Kuhn et al., 1998, Nat. Lett., 392, 155

$$T' \approx 1\mathrm{K}$$

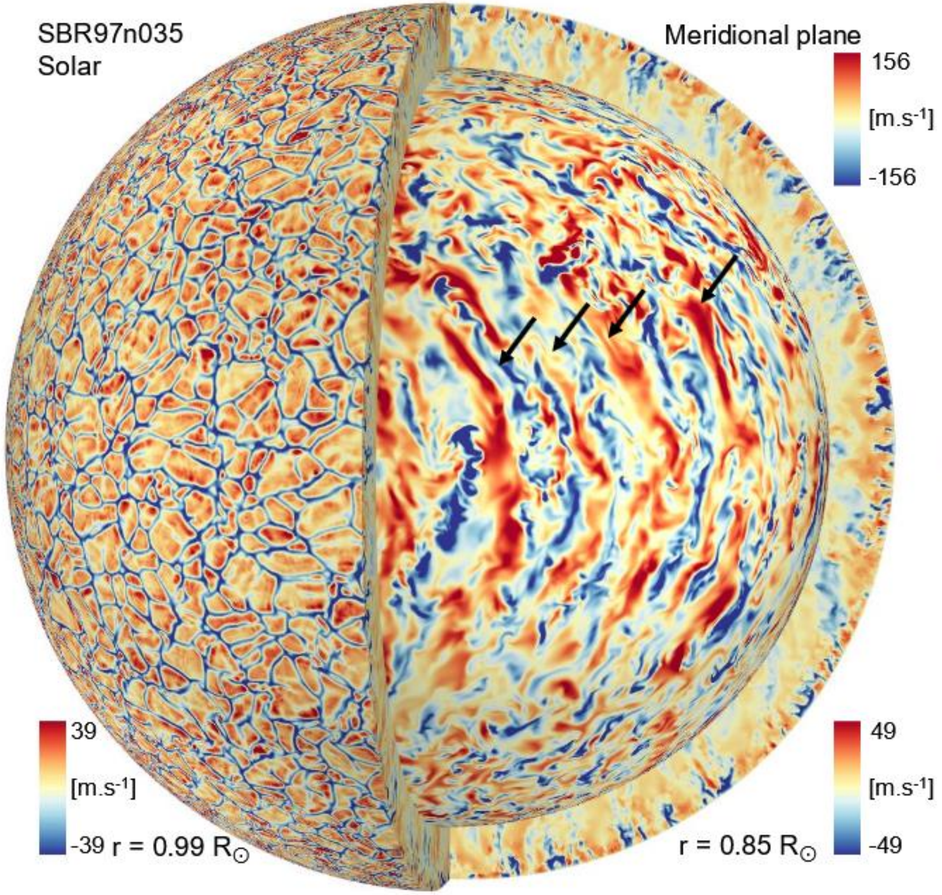
Supergranular intensity variation:

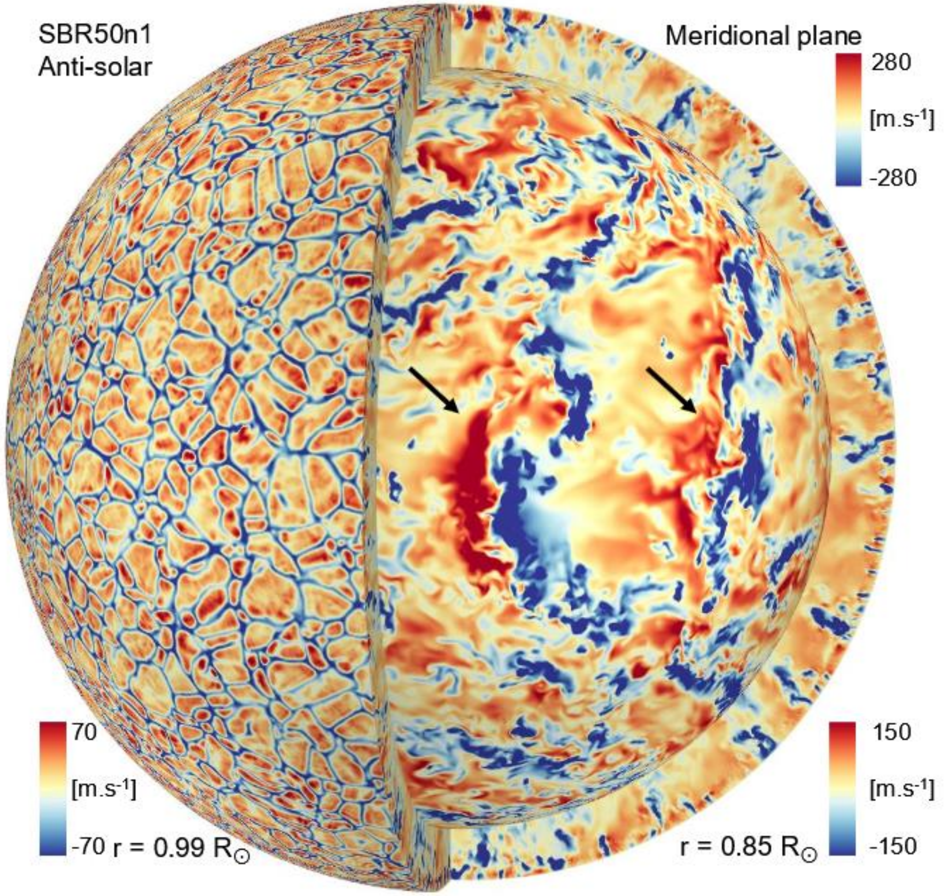
Goldbaum et al., 2009, ApJ, 707, 67
Langfellner et al., 2016, A&A, 596, 66

$\mathrm{Ro_c} = 0.178$

$\mathrm{v} \approx 27\, m/s$
(from models)

Some Numerical/Theoretical Support?



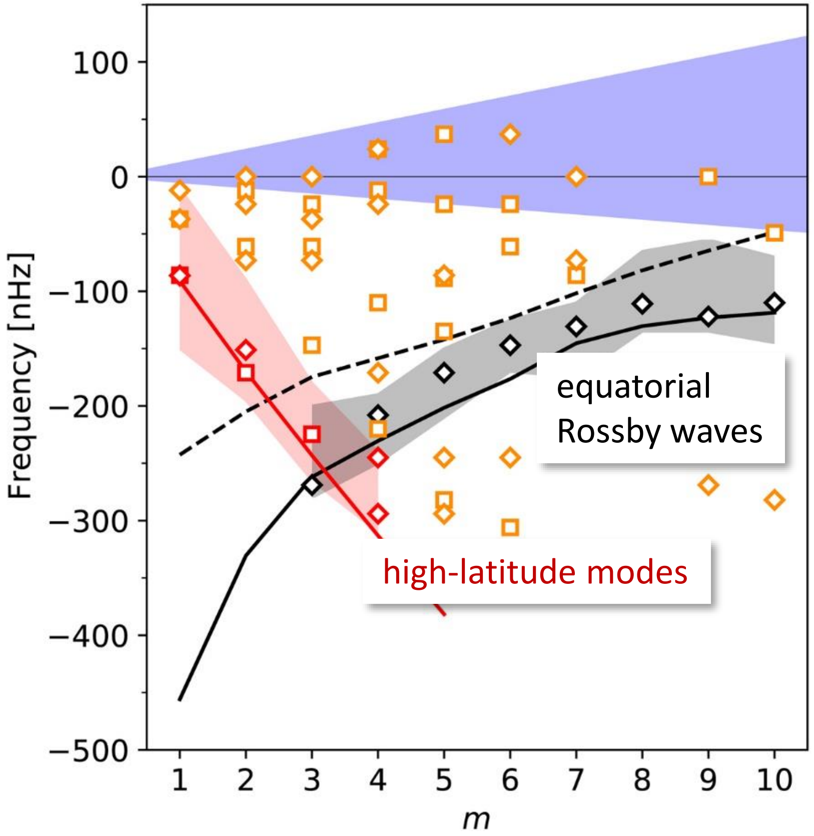


Noraz, Brun & Strugarek 2025

See also Vasil et al. 2020 PNAS, vol. 118 no. 31 e2022518118

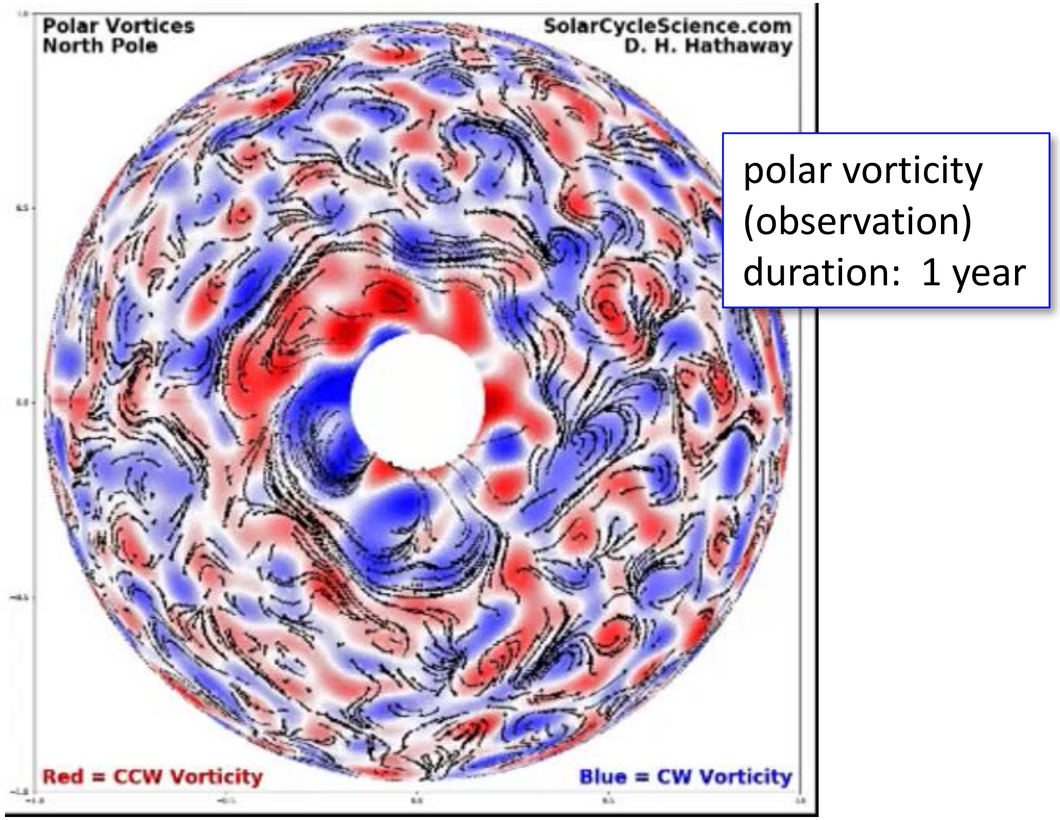
The Solar Poles: A New Frontier?

- Polar vortices and inertial modes
  - What are they telling us?



Gizon et al. 2021

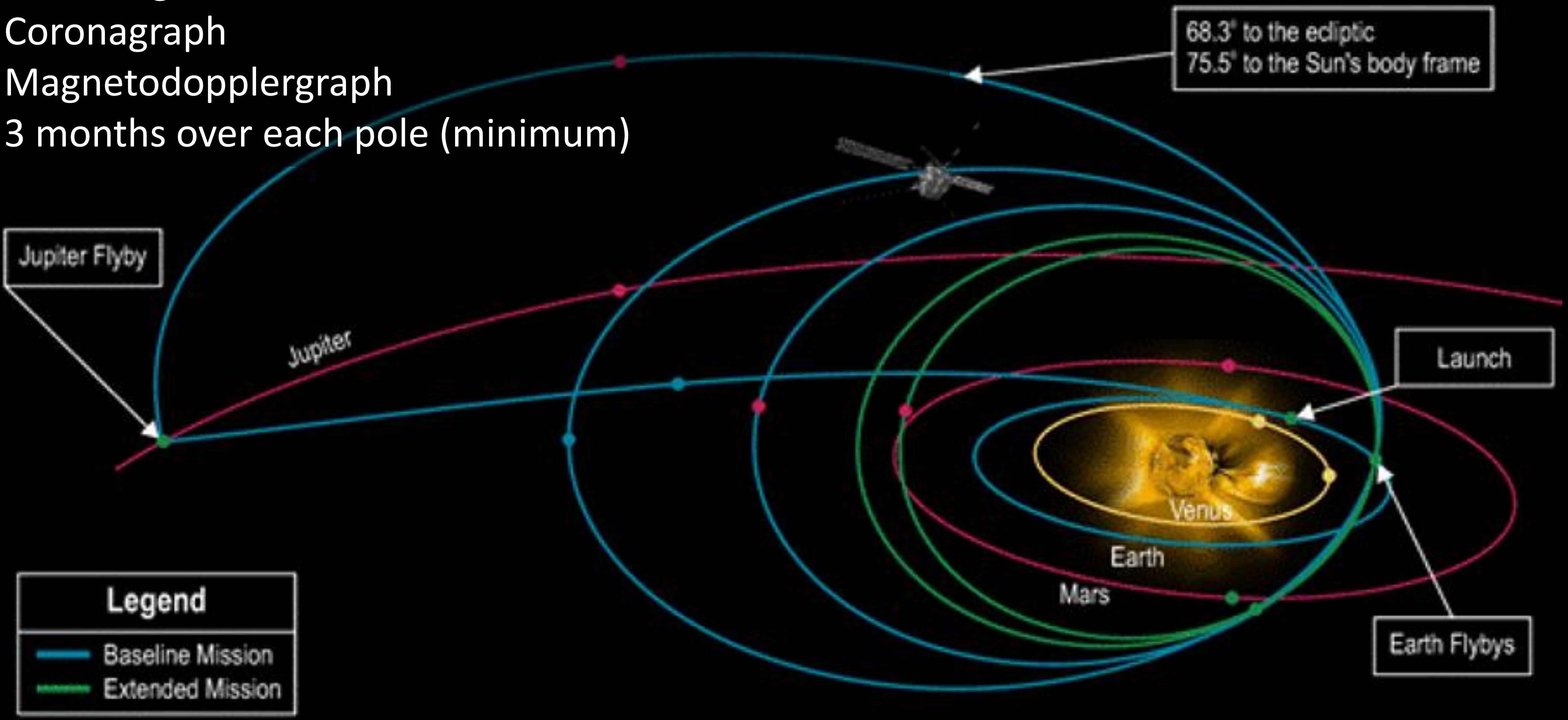
- What is the high latitude structure of
  - Near-surface shear layer?
  - Meridional circulation



Hathaway & Upton 2021
(also Basu and Bogart 2015)

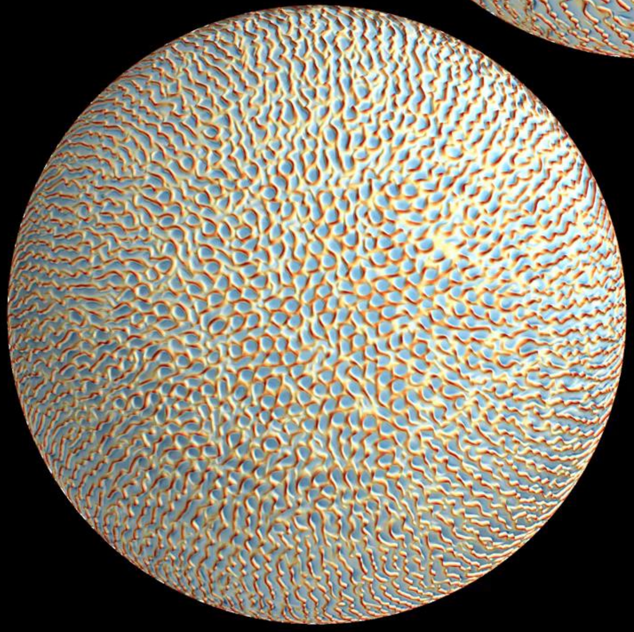
Decadal Survey in Heliophysics: Solar Polar Orbiter

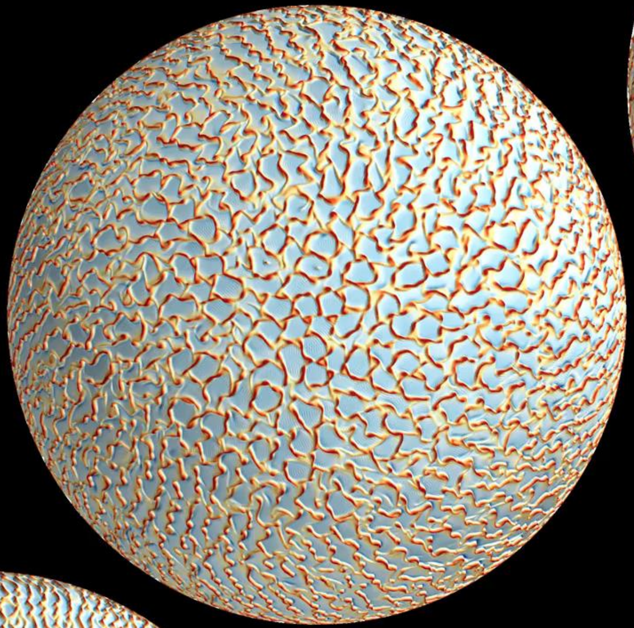
- EUV Imager
- Coronagraph
- Magnetodopplergraph
- 3 months over each pole (minimum)

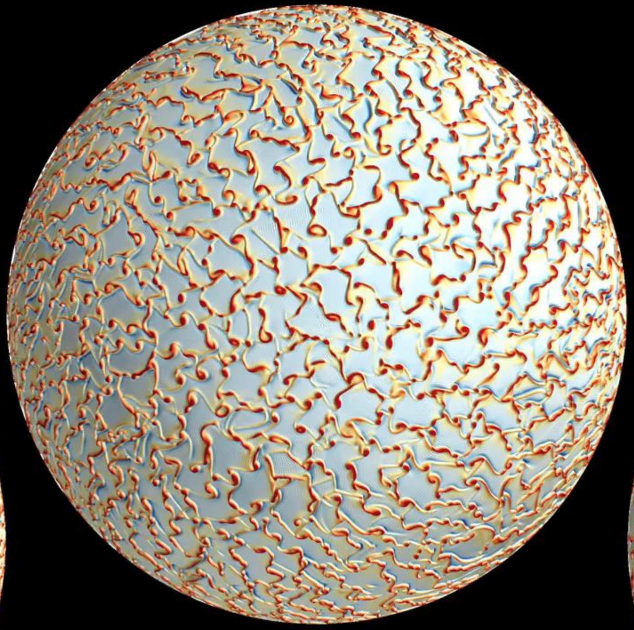


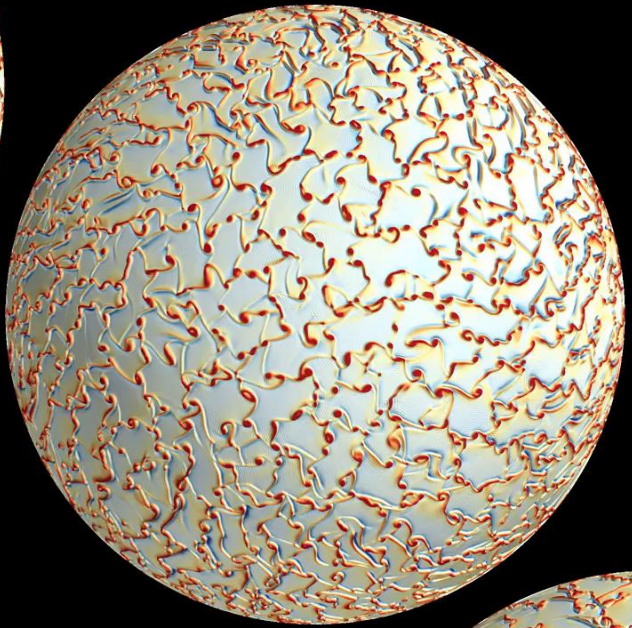
Polar Flows:
What might we expect?

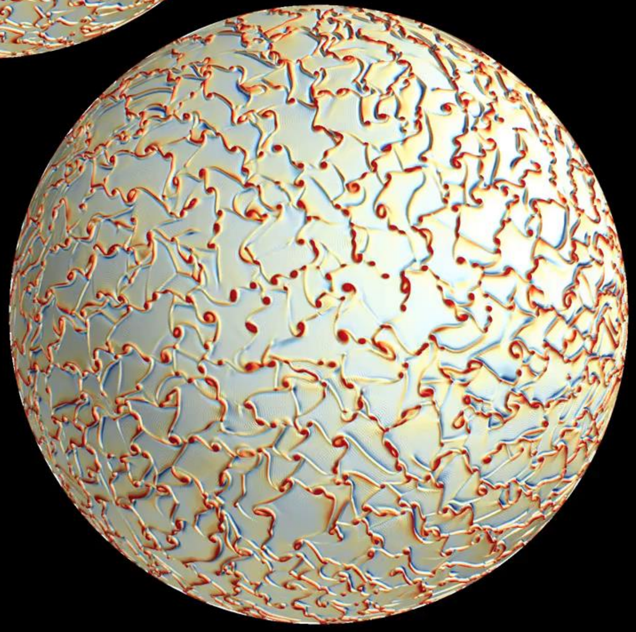
axial vorticity











Simulations of solar convection
(Rayleigh code, 5 Nrho)

Ro_c varies by 8x (left to right)

Credit: Boulder Convection/Etc. Team