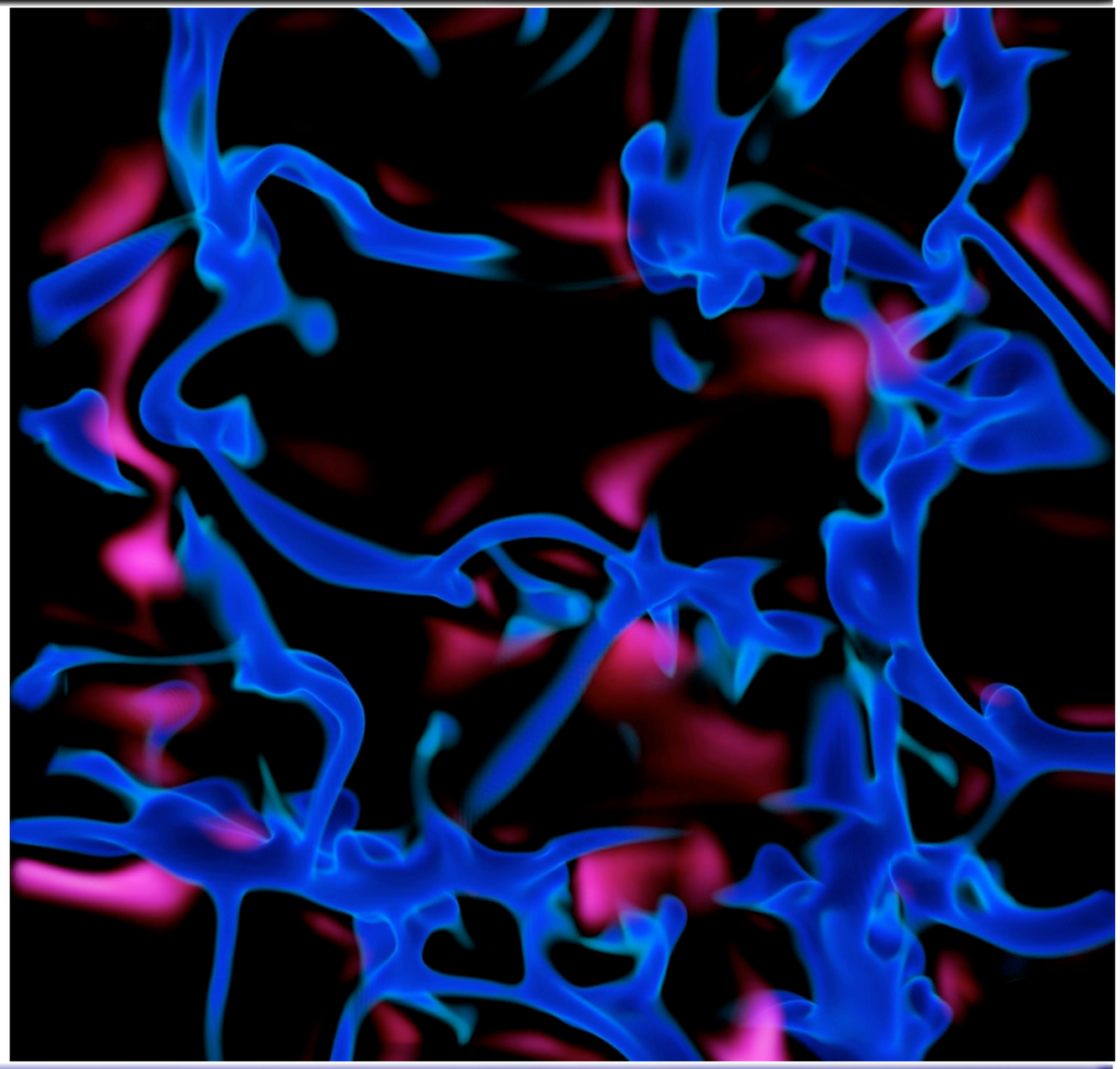
Exploring the Sun and its effects on the
Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

Turbulent Convection and Dynamo Processes in the Solar Interior



Mark Miesch
HAO/NCAR

Symposium on Turbulence and Dynamos at Petaspeed
NCAR, Boulder, CO
Oct 15-19, 2007

High Altitude Observatory (HAO) – National Center for Atmospheric Research (NCAR)

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Colleagues

Juri Toomre (Univ. of Colorado, Boulder)

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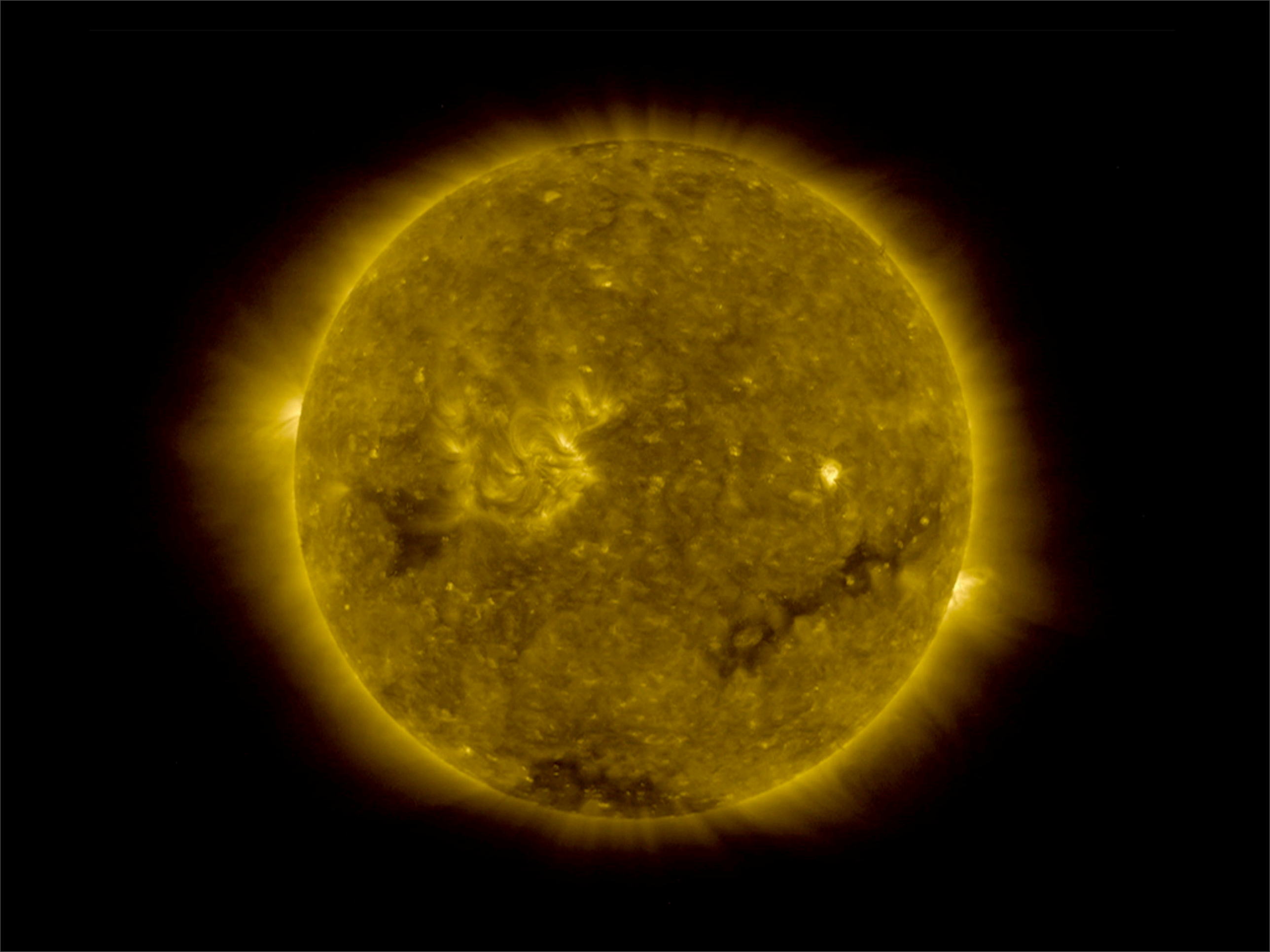
Matt Browning (Univ. of Chicago)

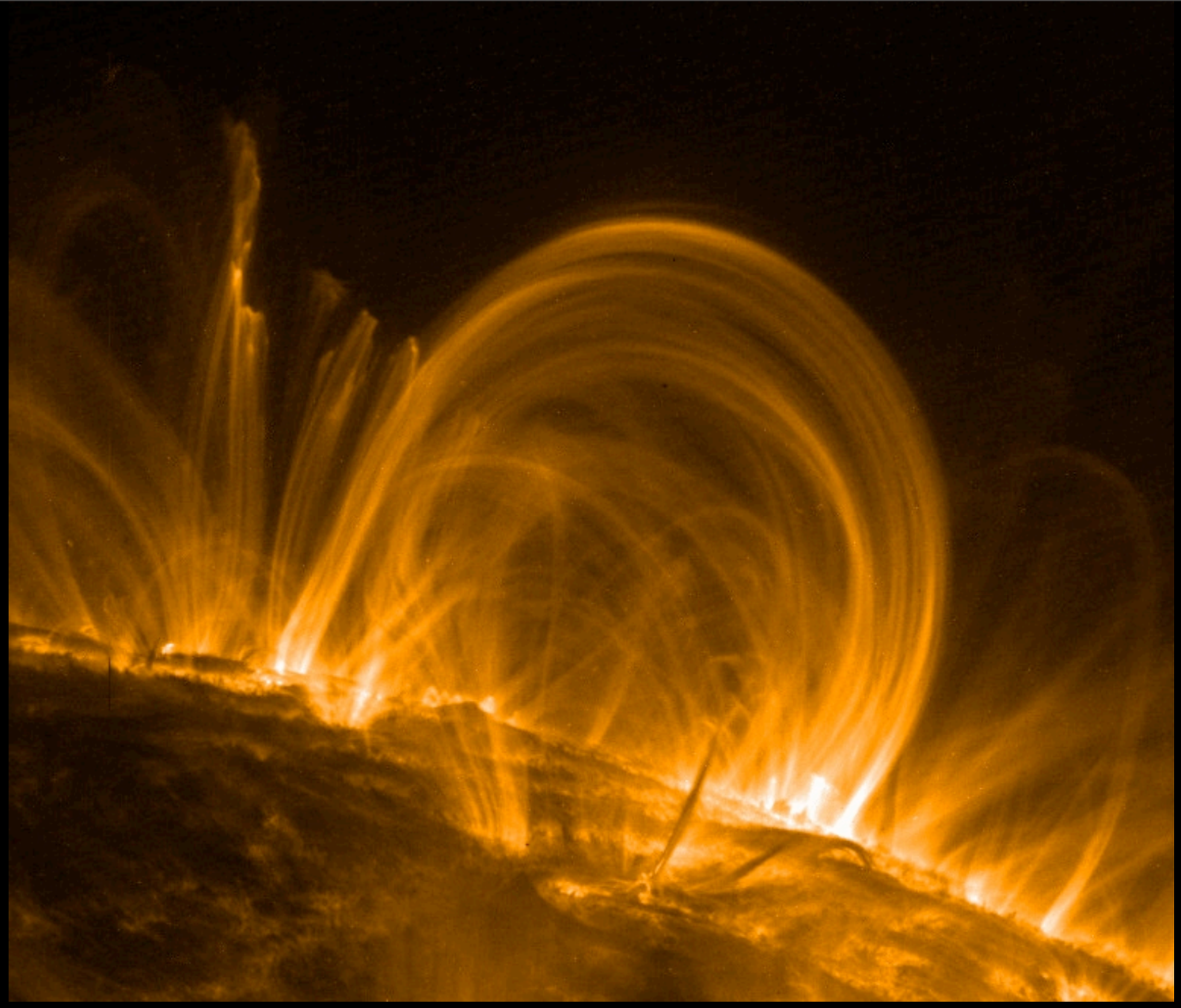
Ben Brown, Nicholas Featherstone, Kyle Auguston, Nicholas Nelson
(Univ. of Colorado, Boulder)

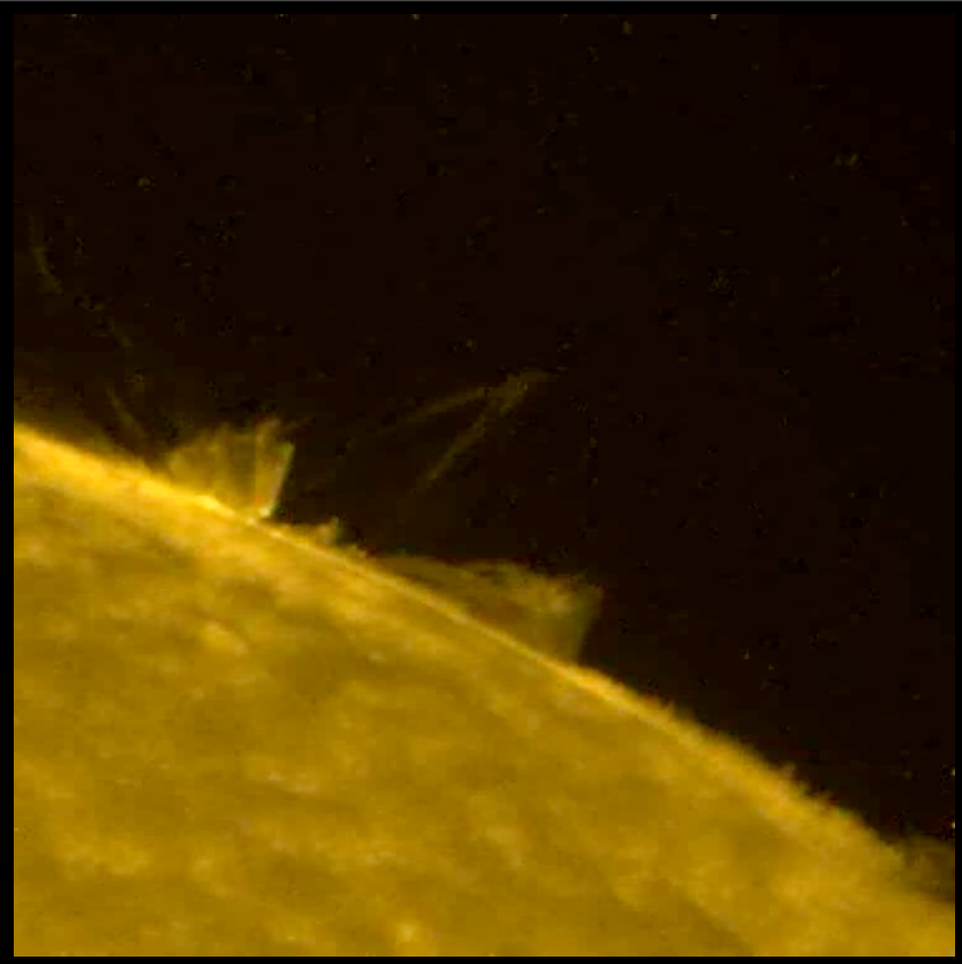
Marc DeRosa (Lockheed Martin)

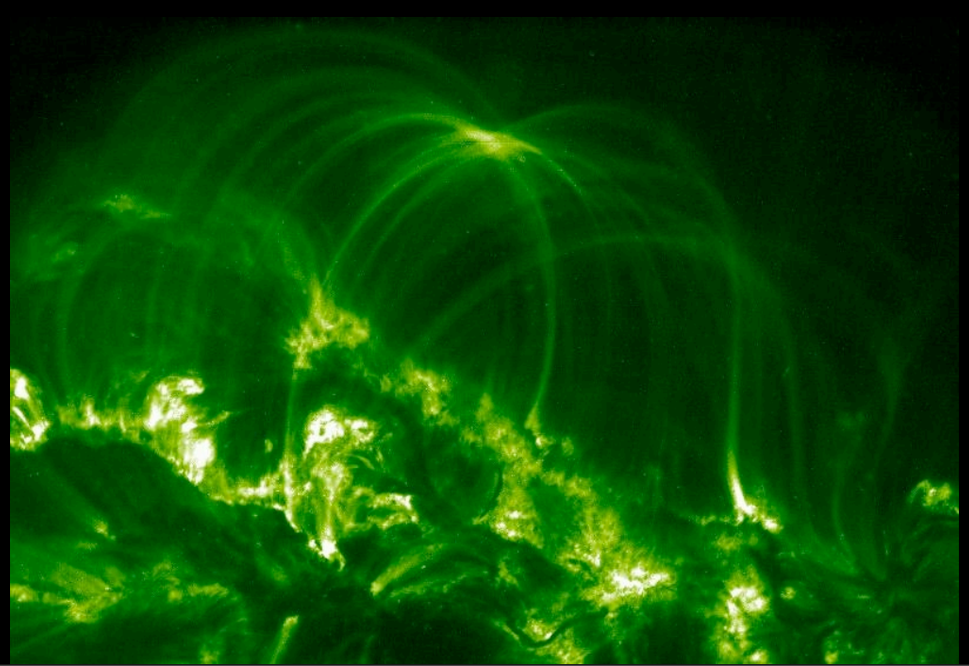
Outline

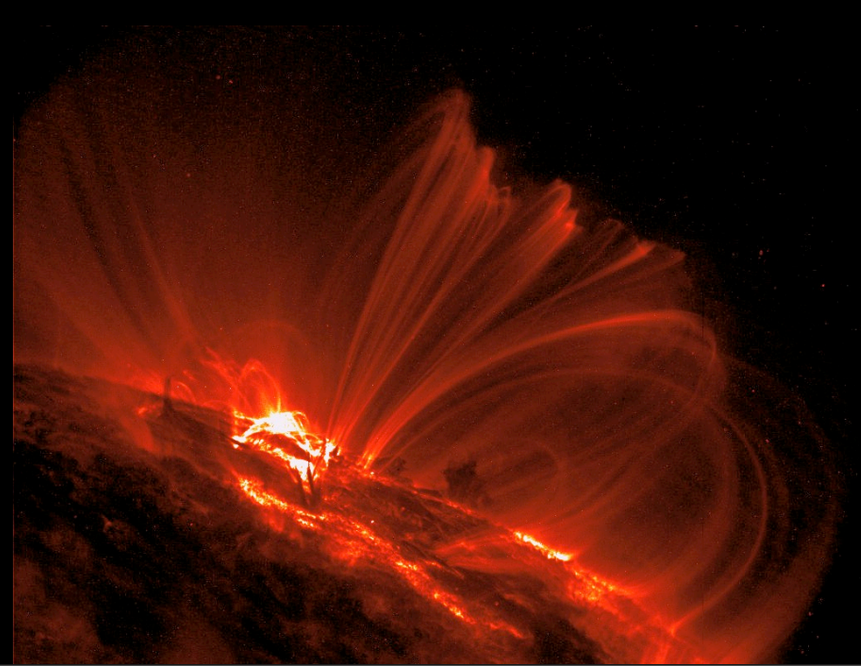
- The Dynamic Sun
- Probing the Solar Interior
- Computational Challenges and Tools
  - ★ The *ASH* code
- Simulations of Solar Convection
- The Solar Dynamo
- Other Stars
- Summary and Outlook

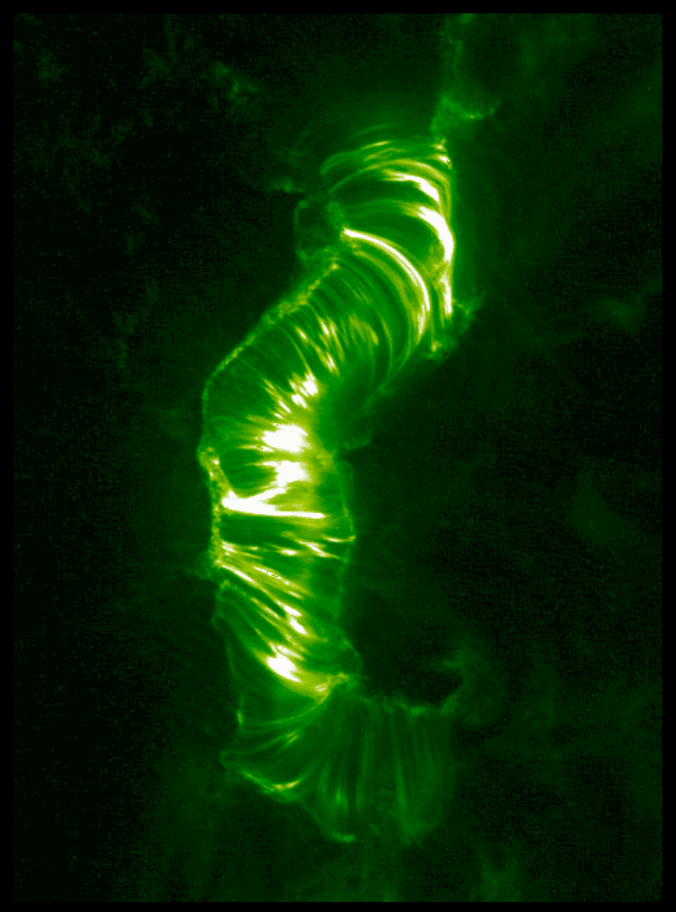


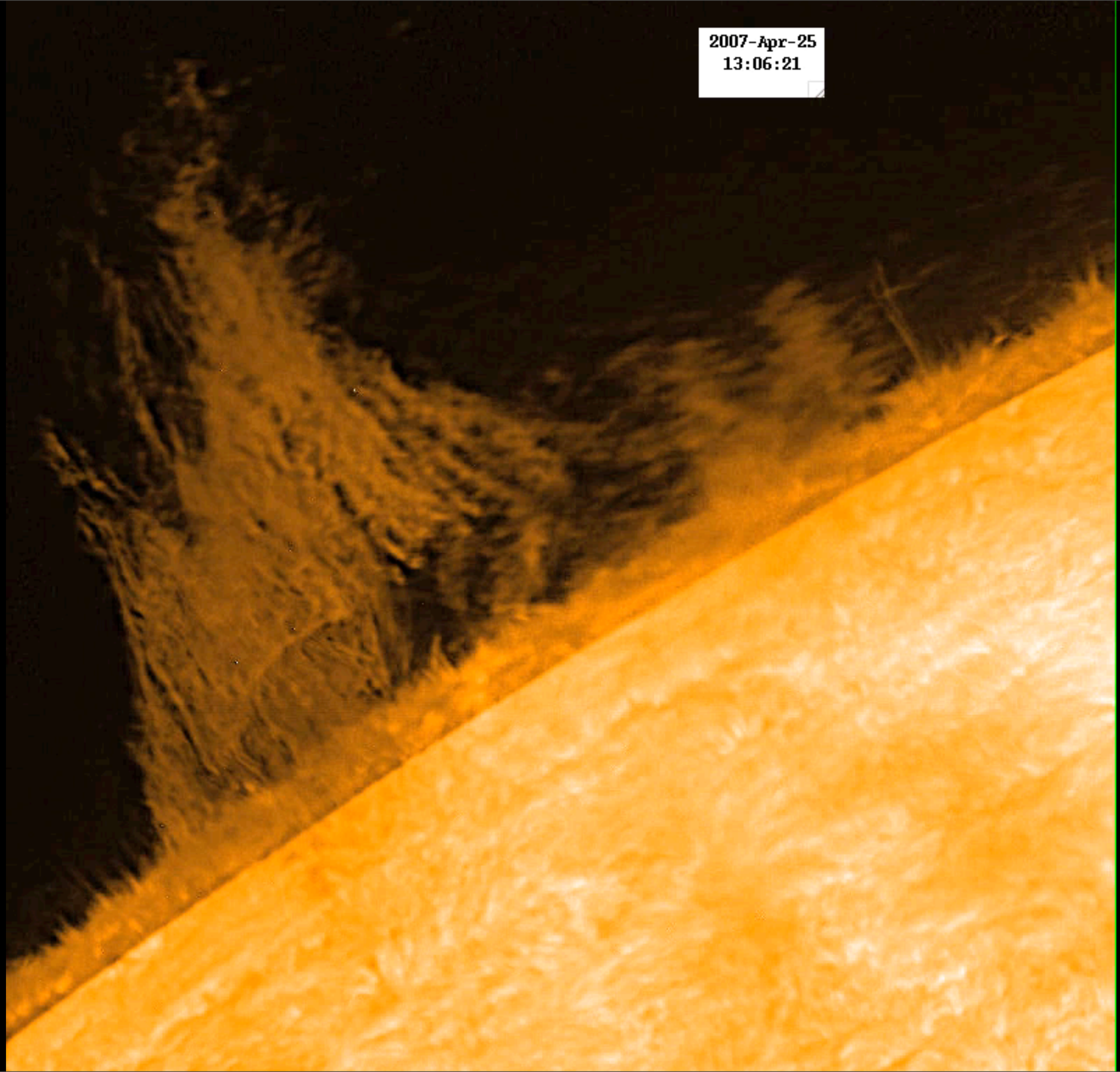








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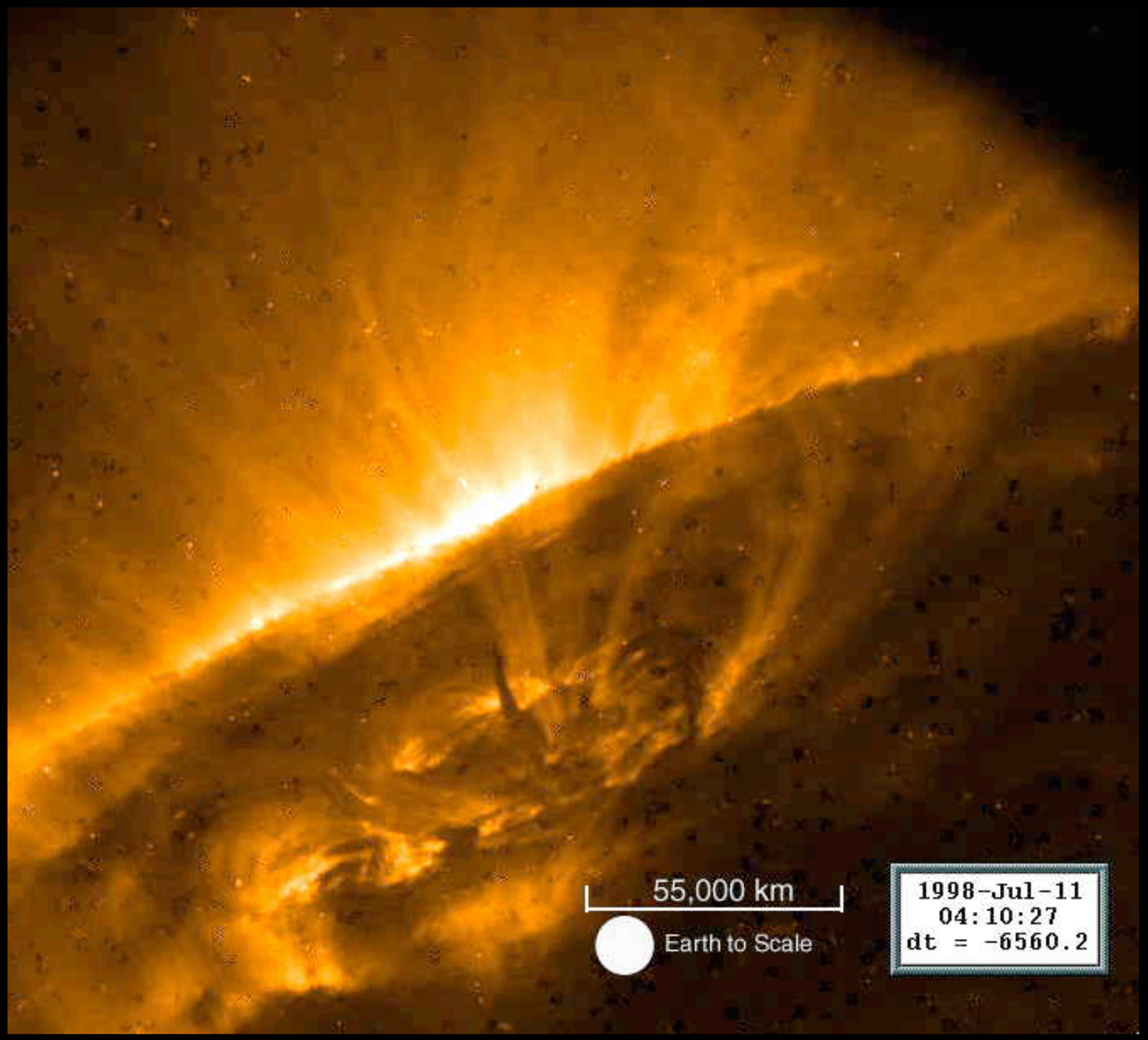
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Earth to Scale
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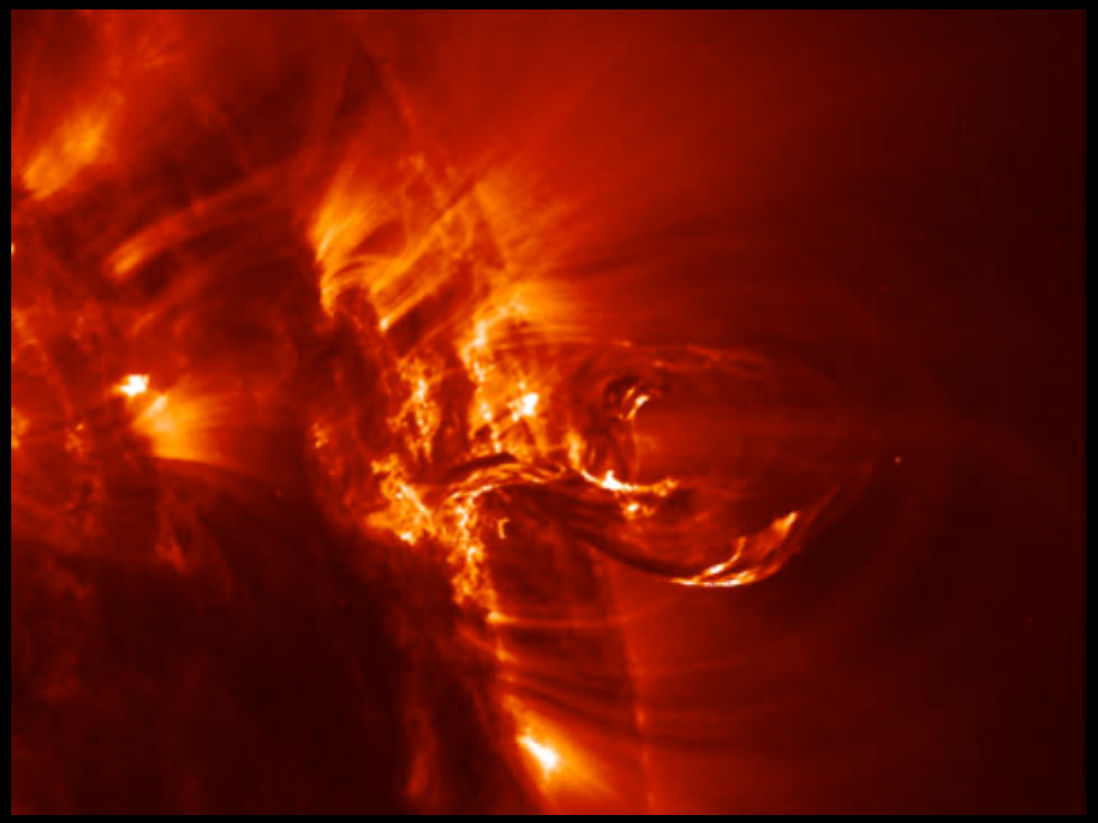
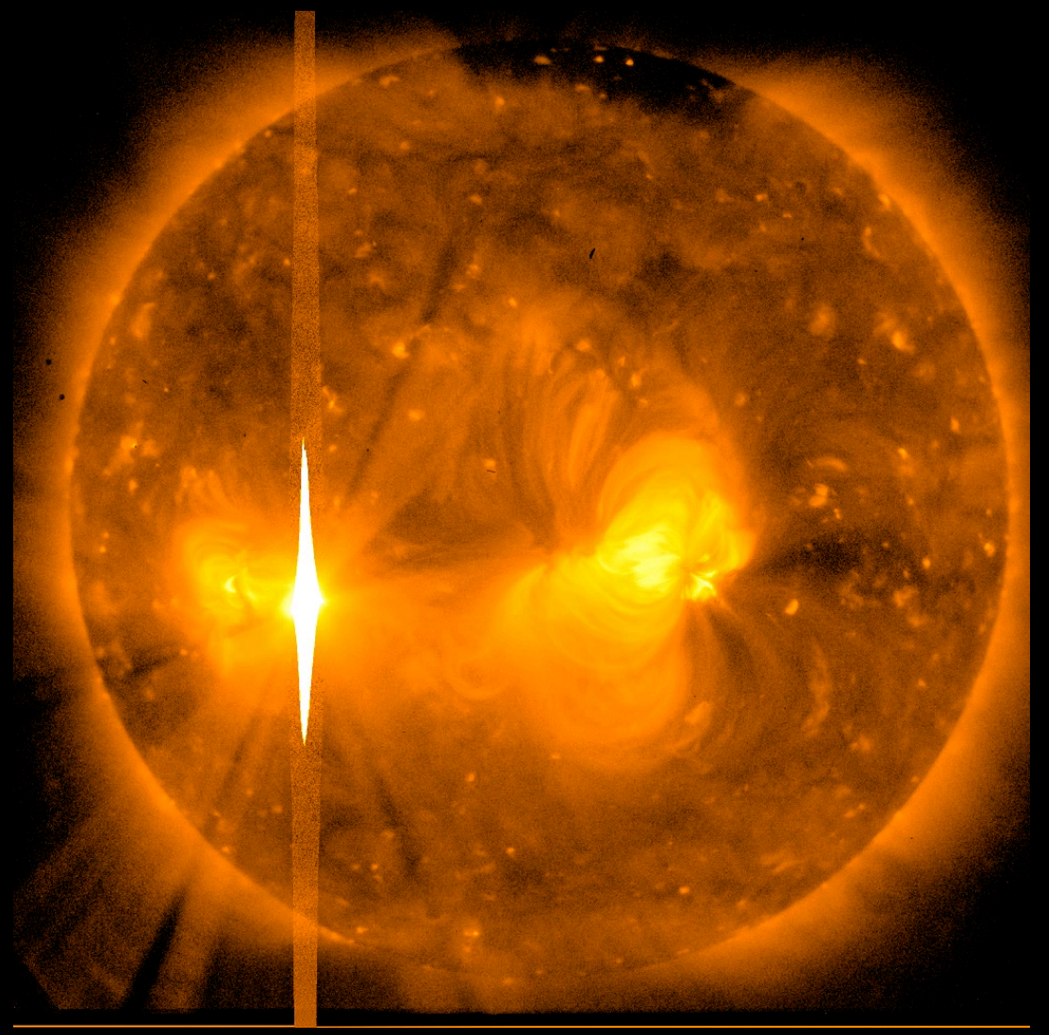
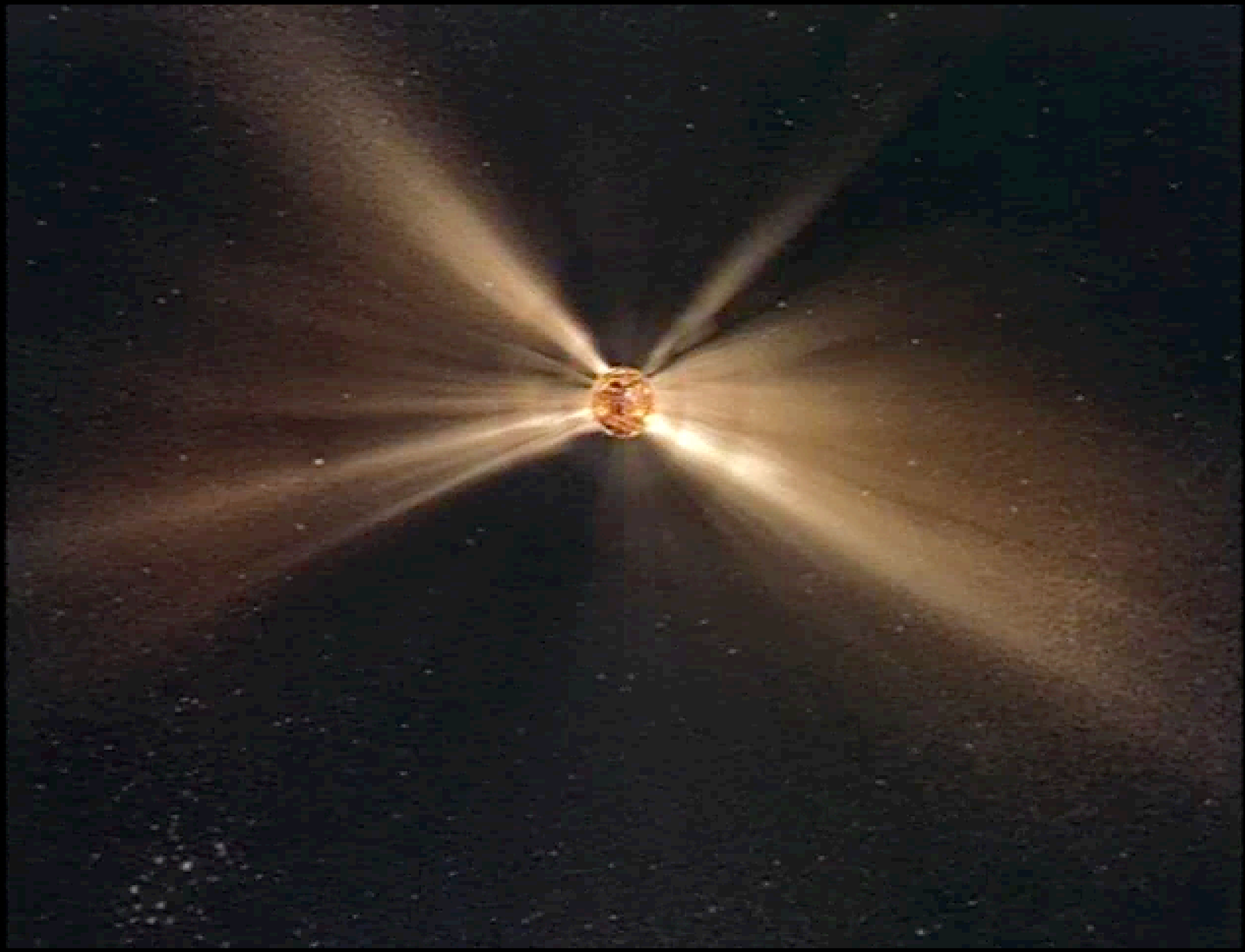
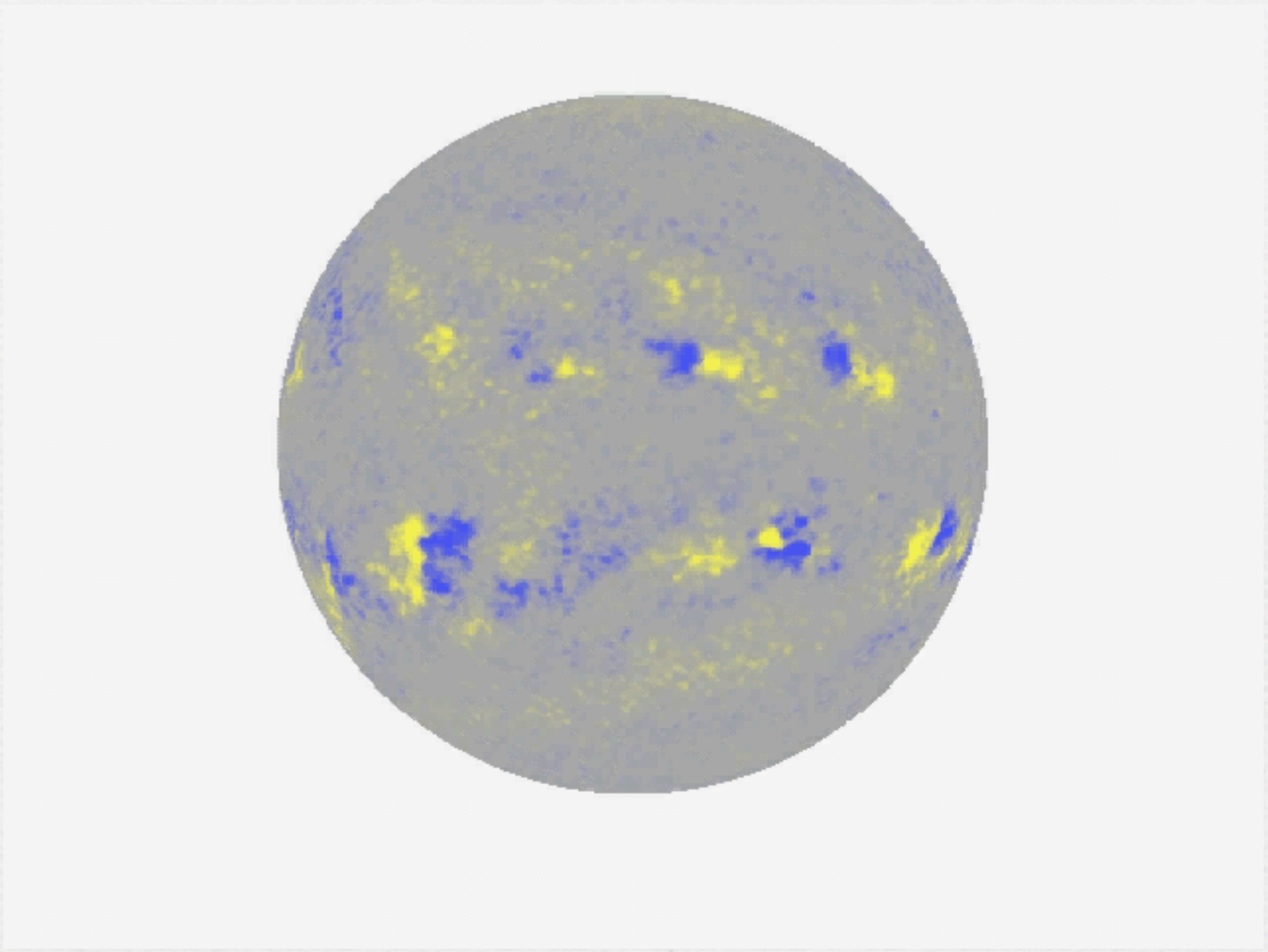


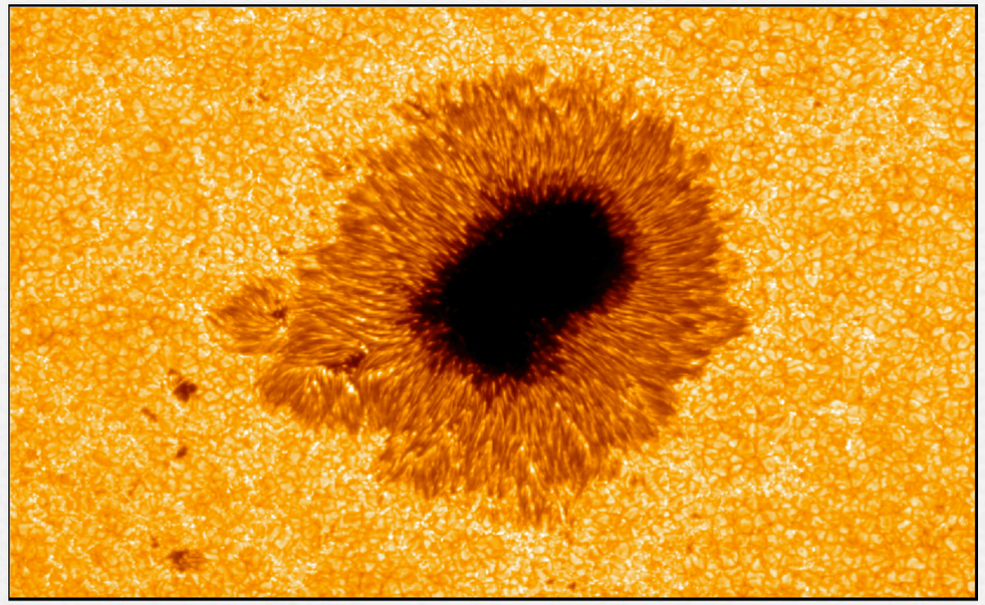


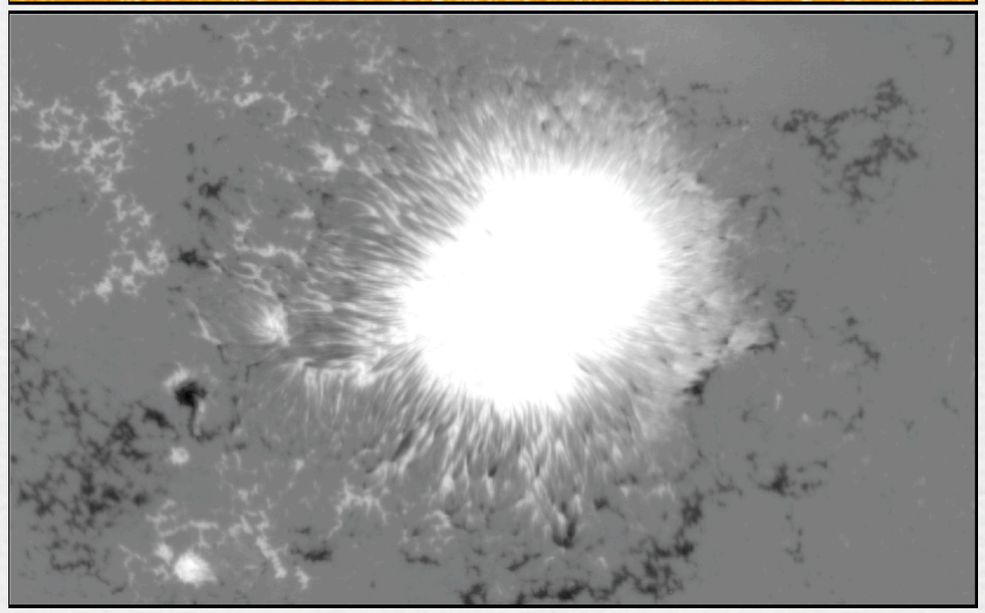


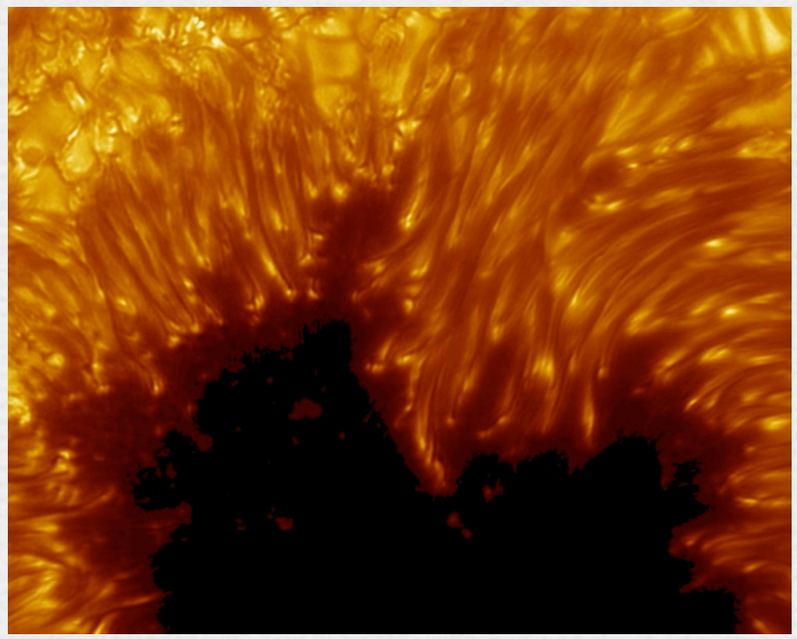
Sunspots reflect cyclic magnetic activity



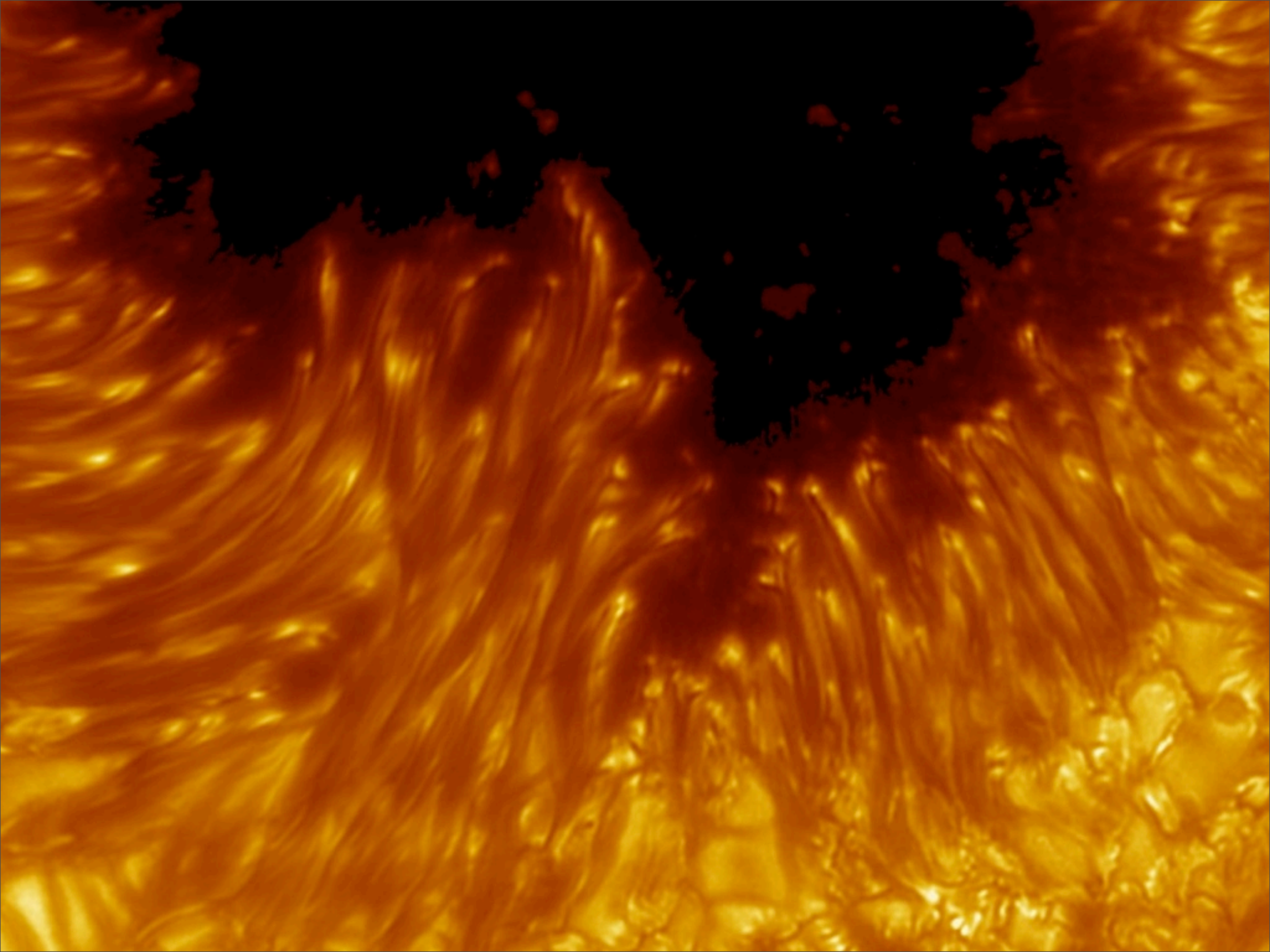
D. Hathaway (NASA MSFC)



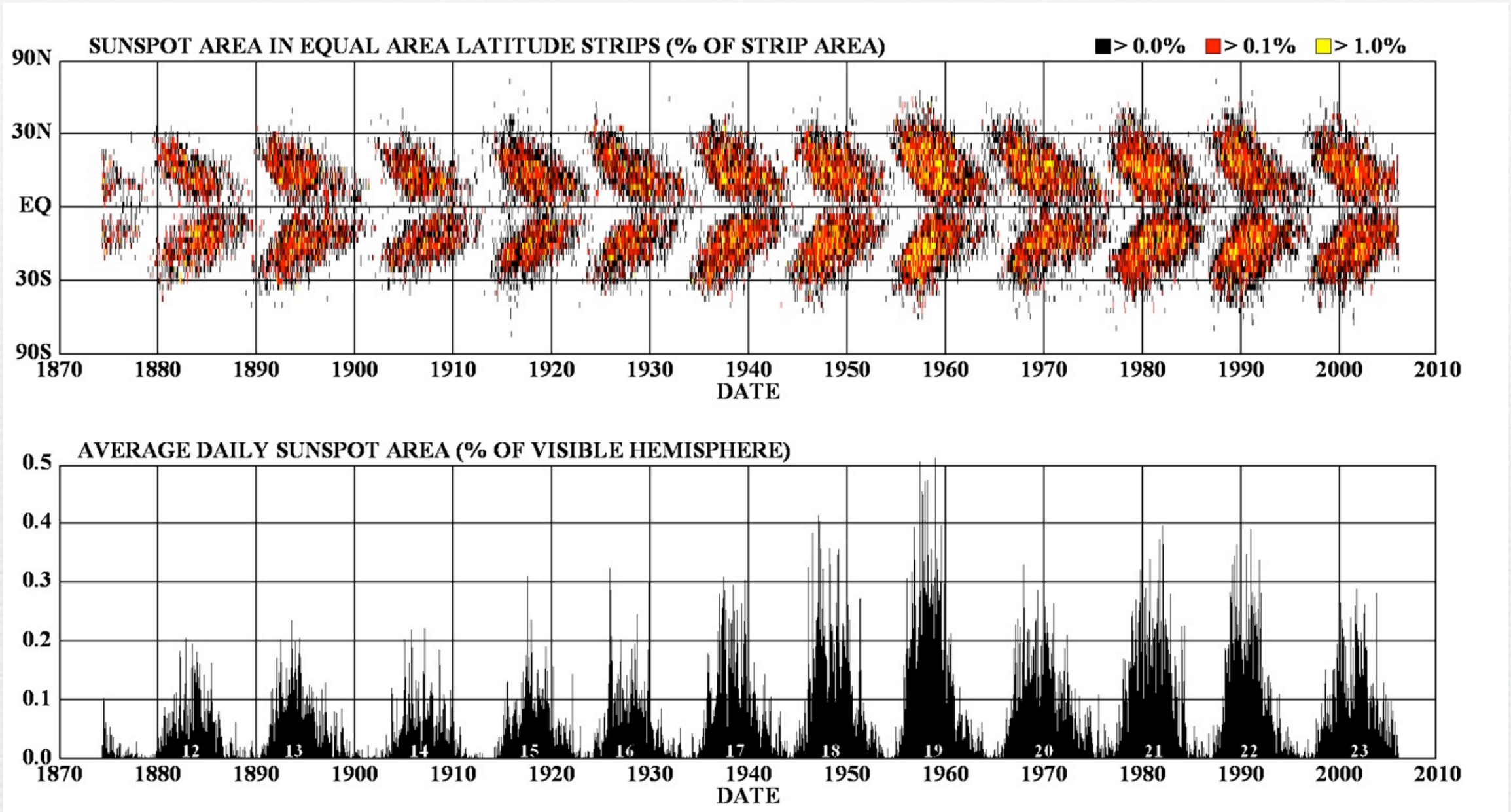




22-year activity cycle

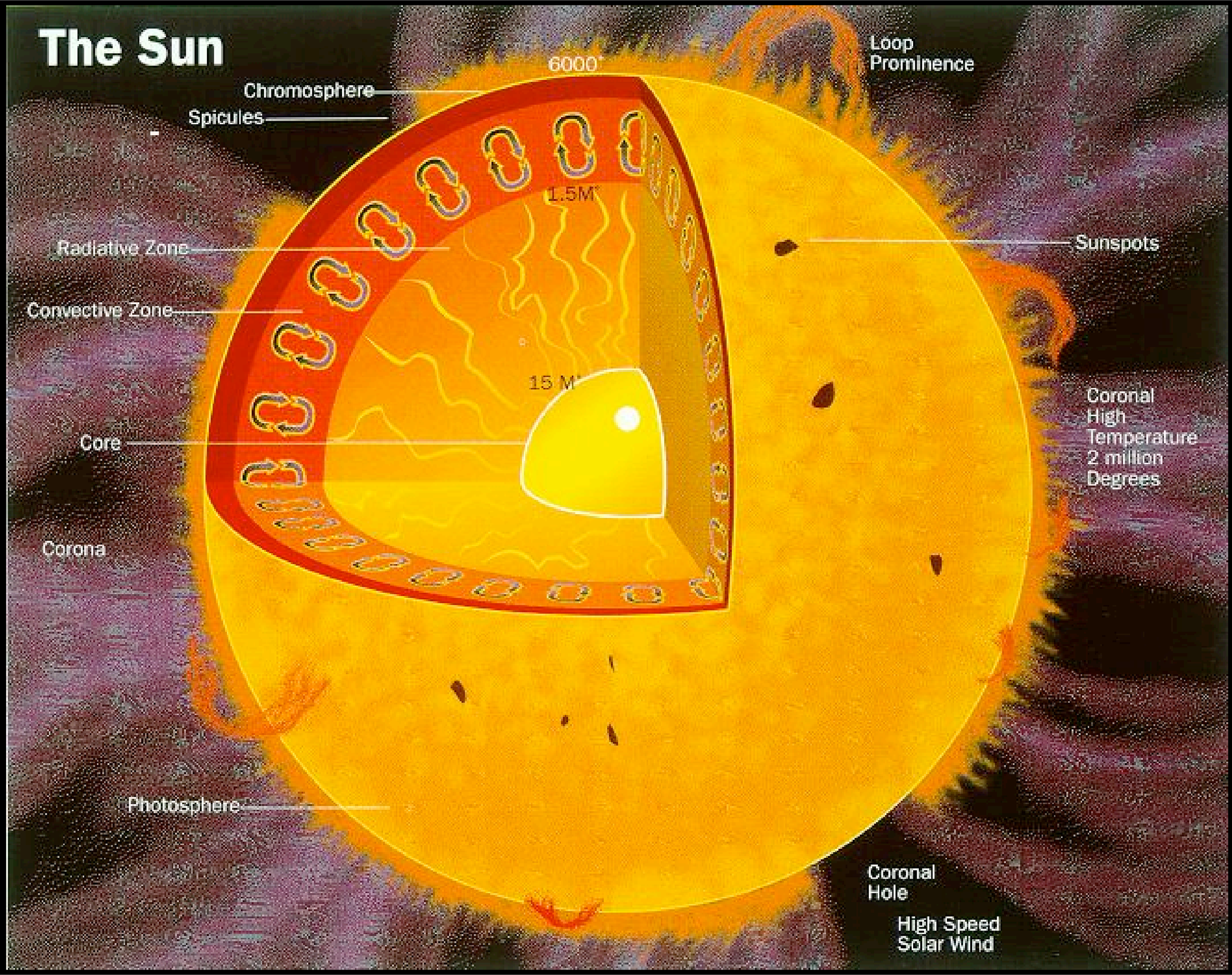


The Solar Butterfly Diagram



D. Hathaway (NASA MSFC)

Order amid Chaos
How does it arise?


The Sun
6000°
Chromosphere
Spicules
Loop
Prominence
1.5M°
Radiative Zone
Sunspots
Convective Zone
15 M°
Core
Coronal
High
Temperature
2 million
Degrees
Corona
Photosphere
Coronal
Hole
High Speed
Solar Wind

The Sun

6000°

Chromosphere

Spicules

Loop Prominence

Radiative Zone

Sunspots

Convective Zone

Core

Corona

Photosphere

Coronal Hole

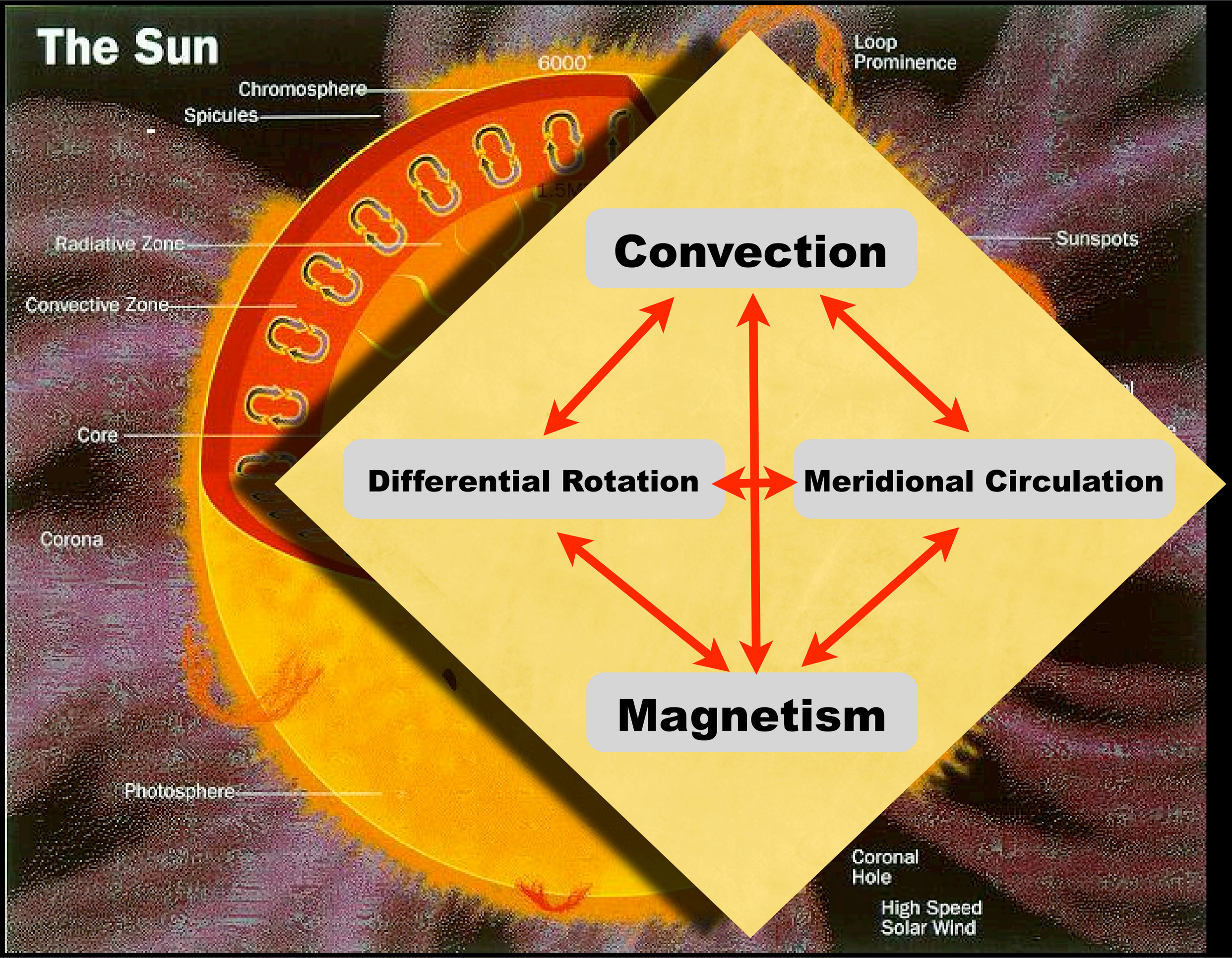
High Speed Solar Wind

Convection

Differential Rotation

Meridional Circulation

Magnetism


The Sun
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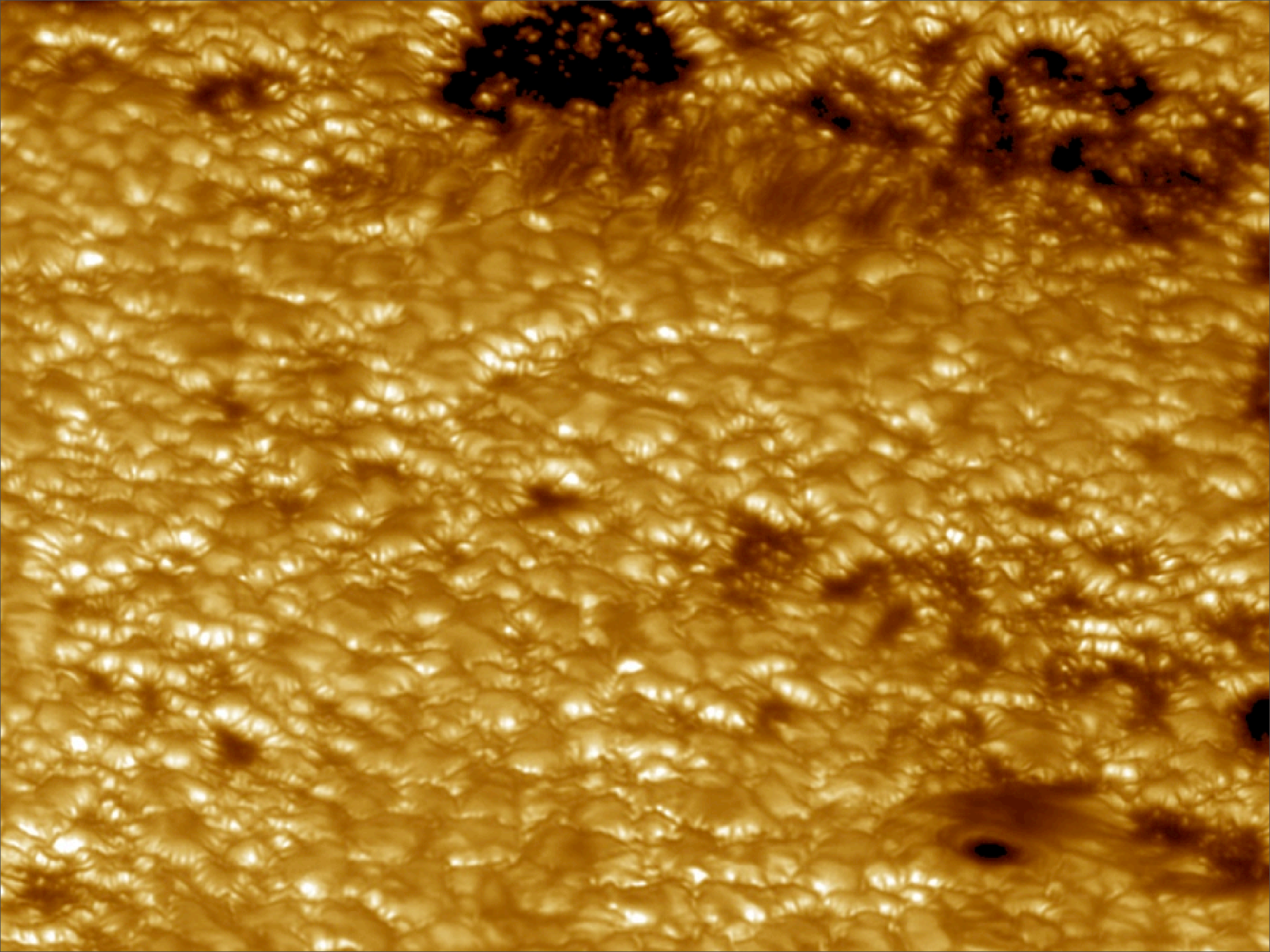
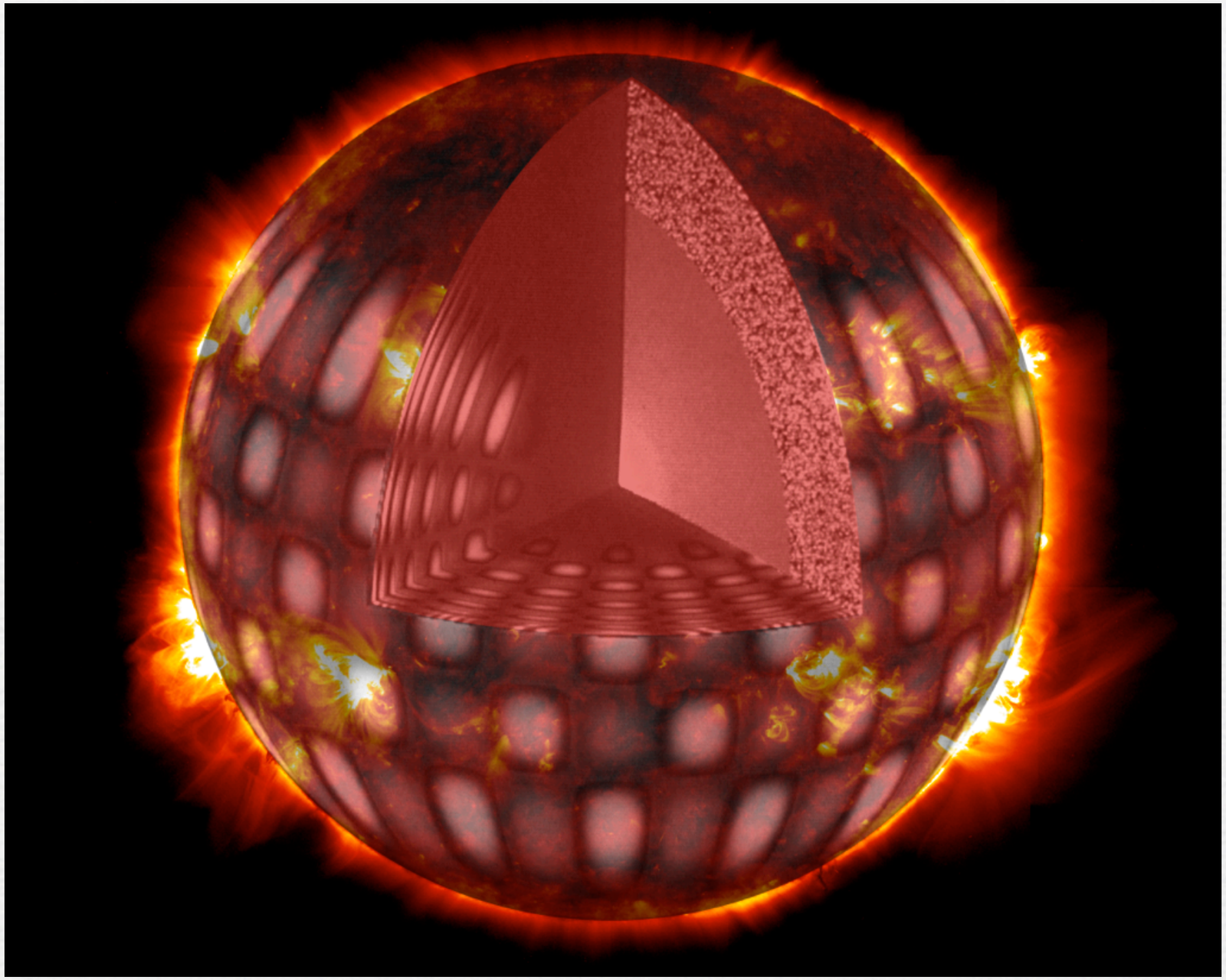
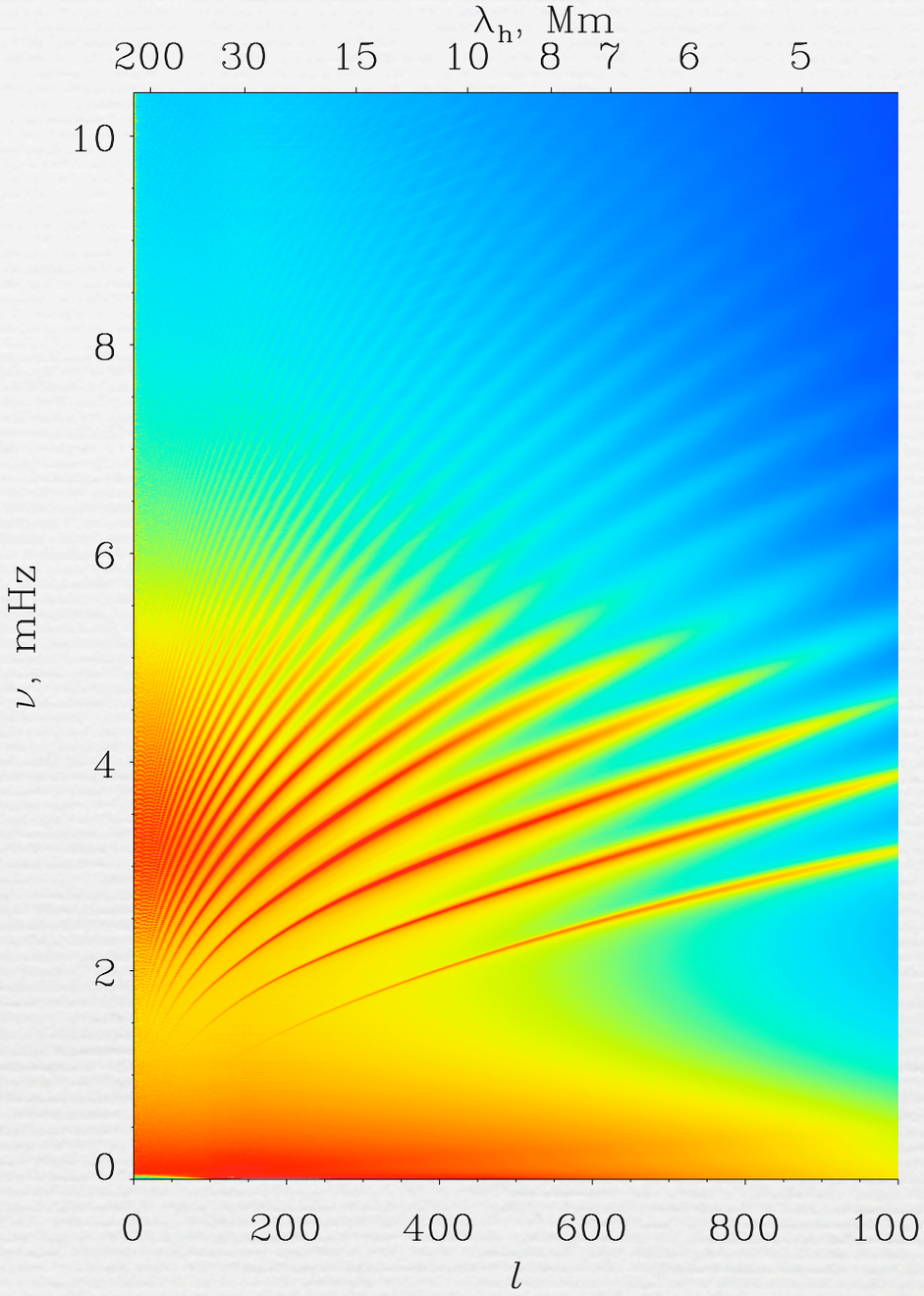
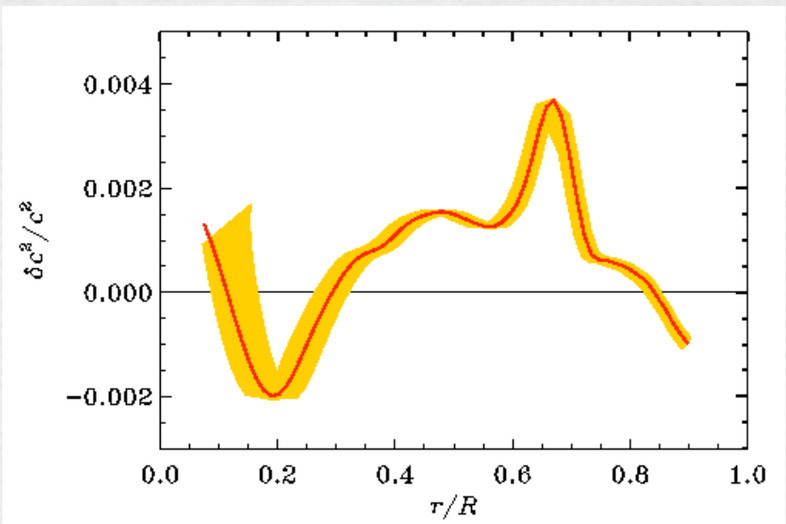


Helioseismology



T. Metcalfe (HAO/NCAR)

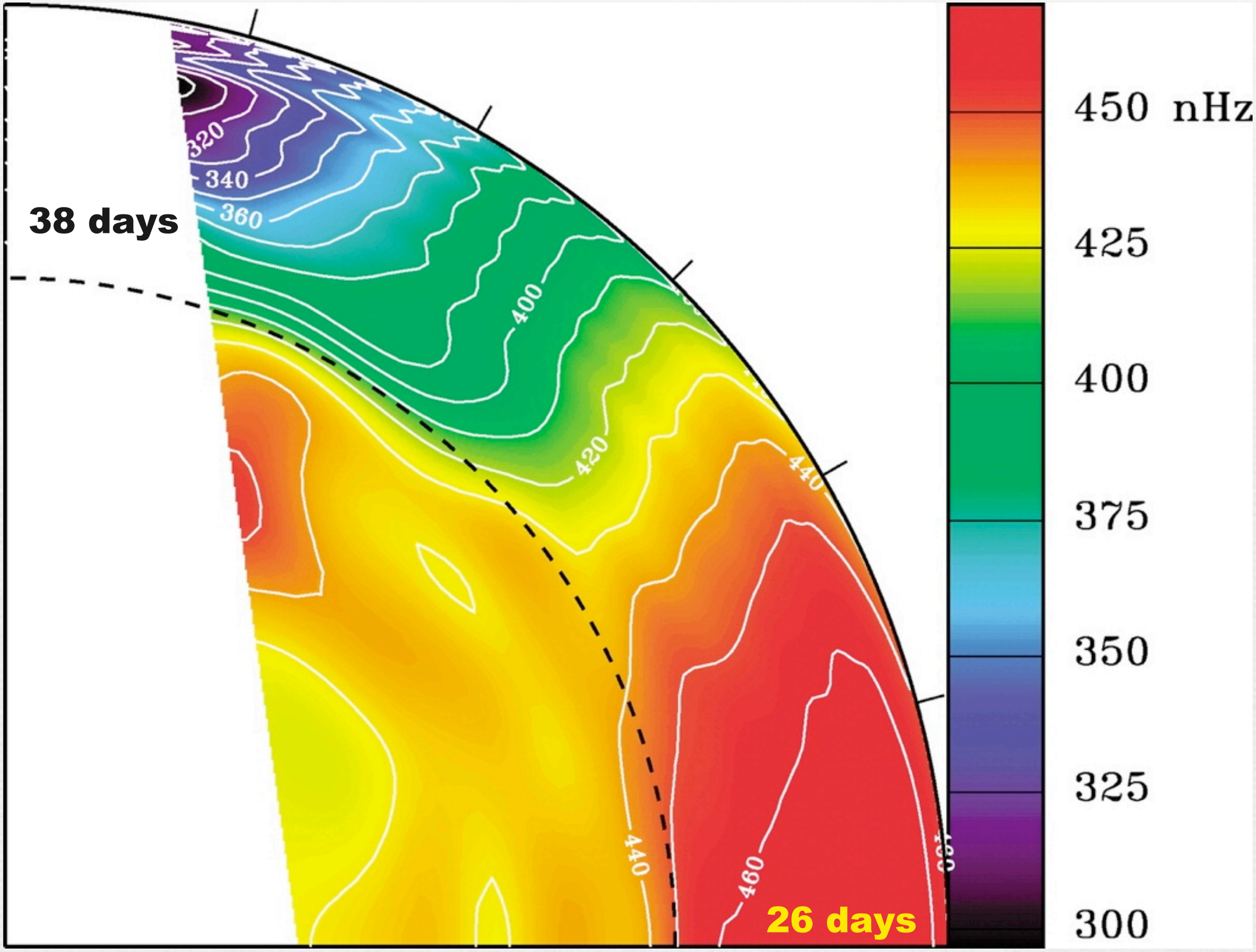




The Sun rings like a bell!

The Solar Internal Rotation

Thompson et al (2003)



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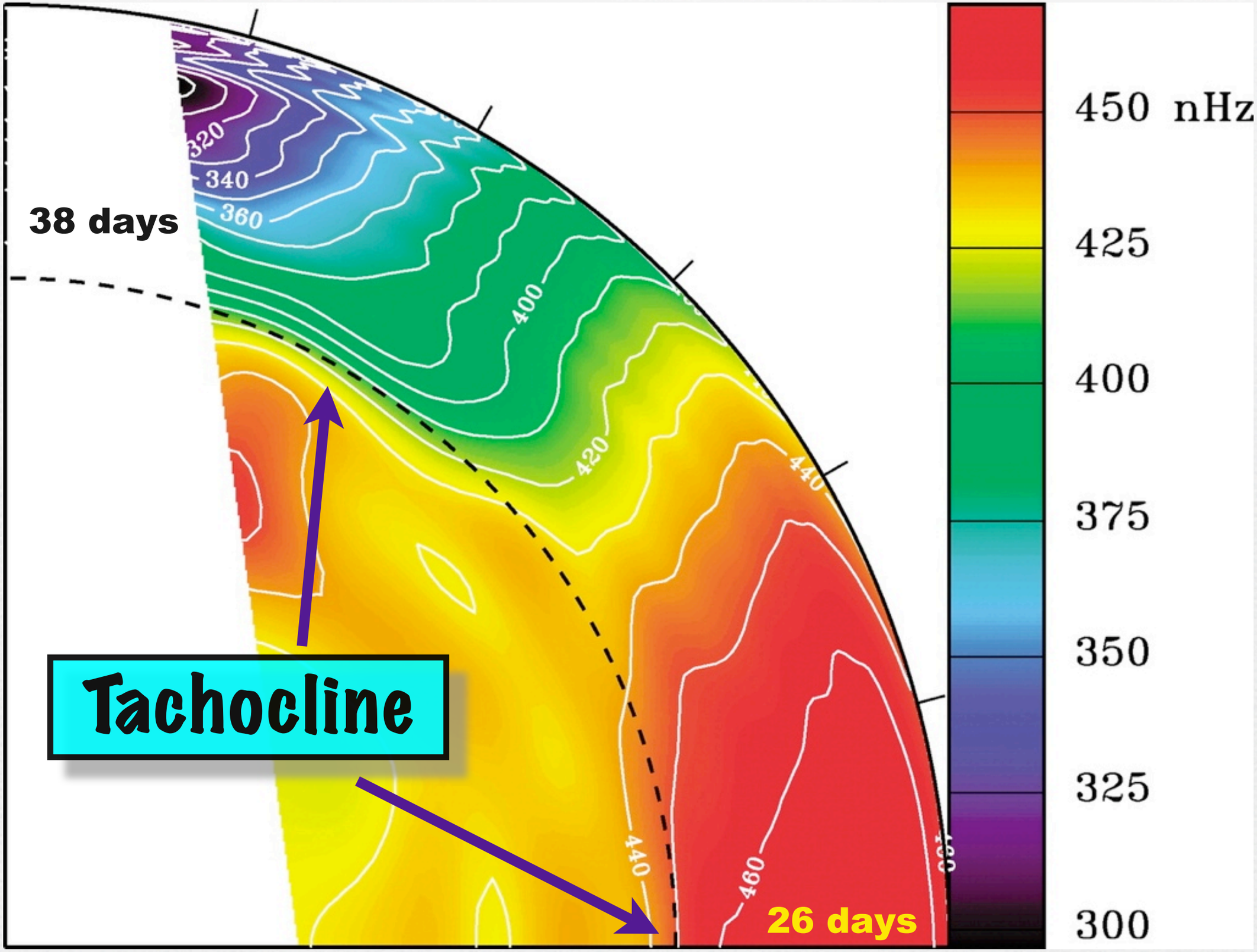
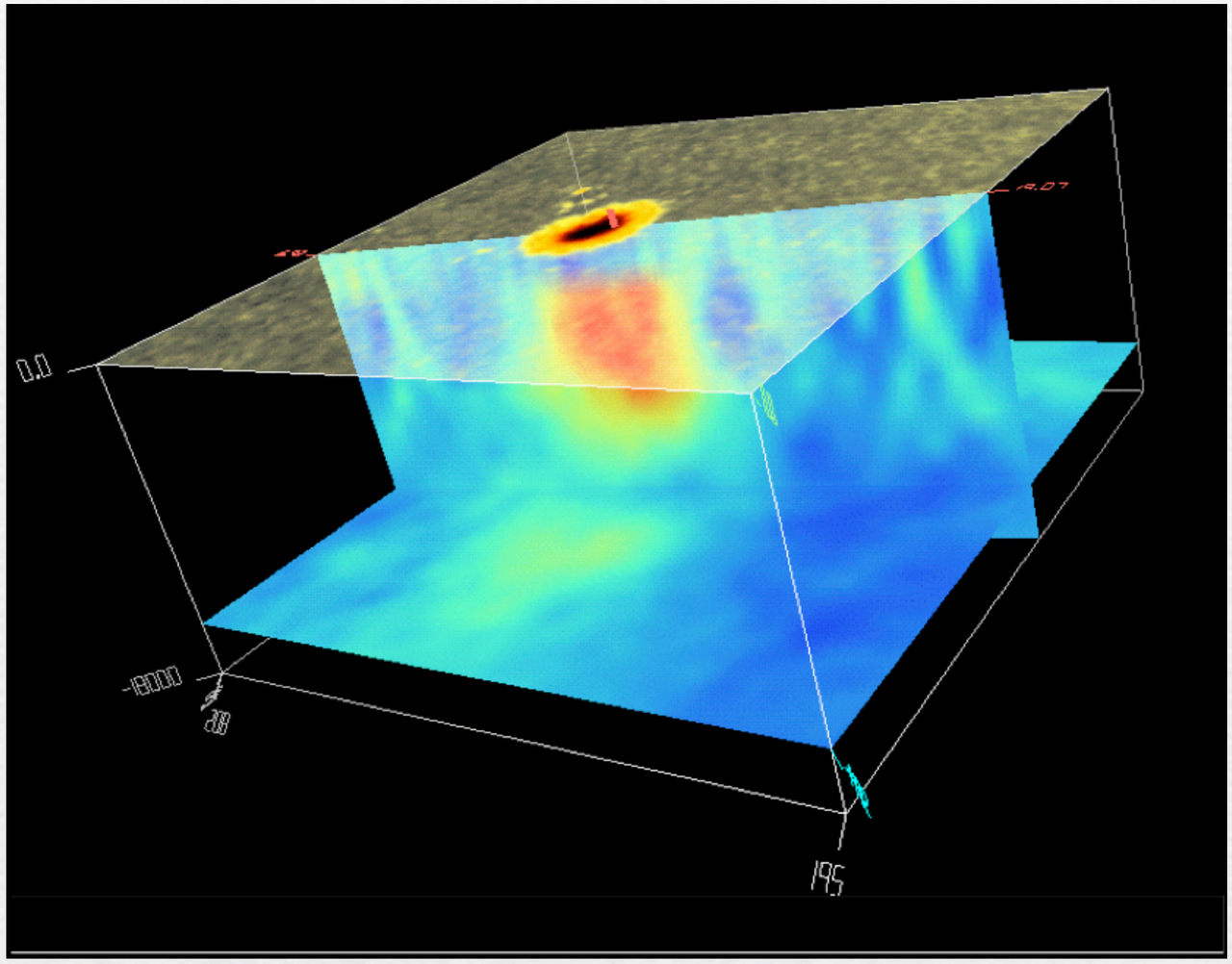
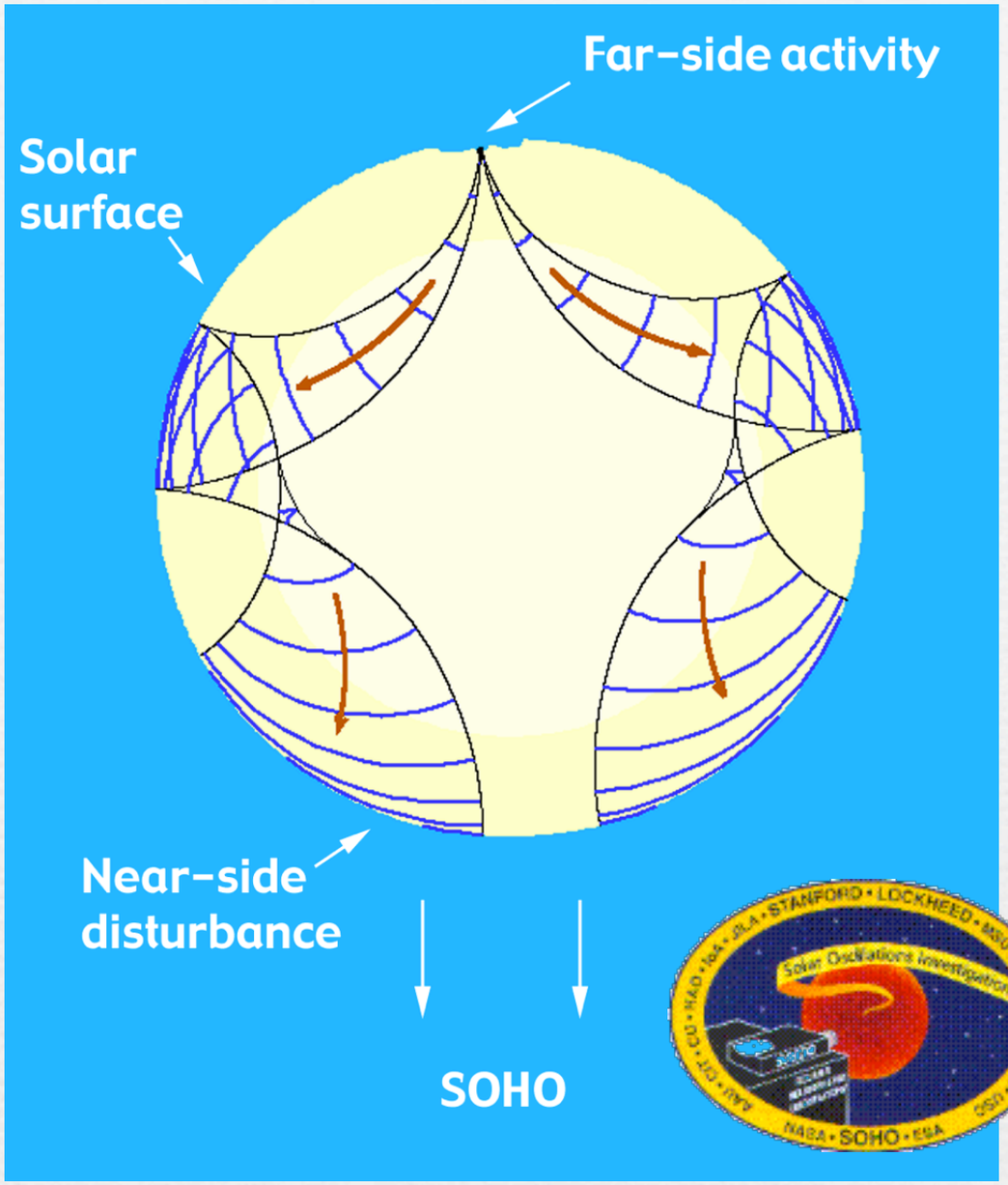


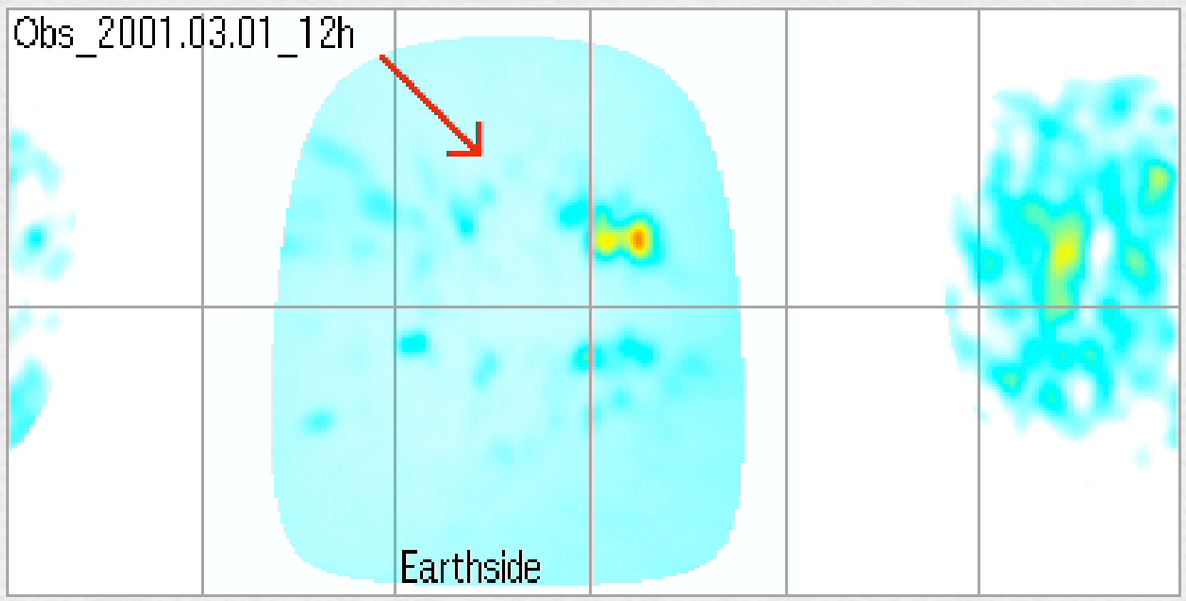
Local Helioseismology



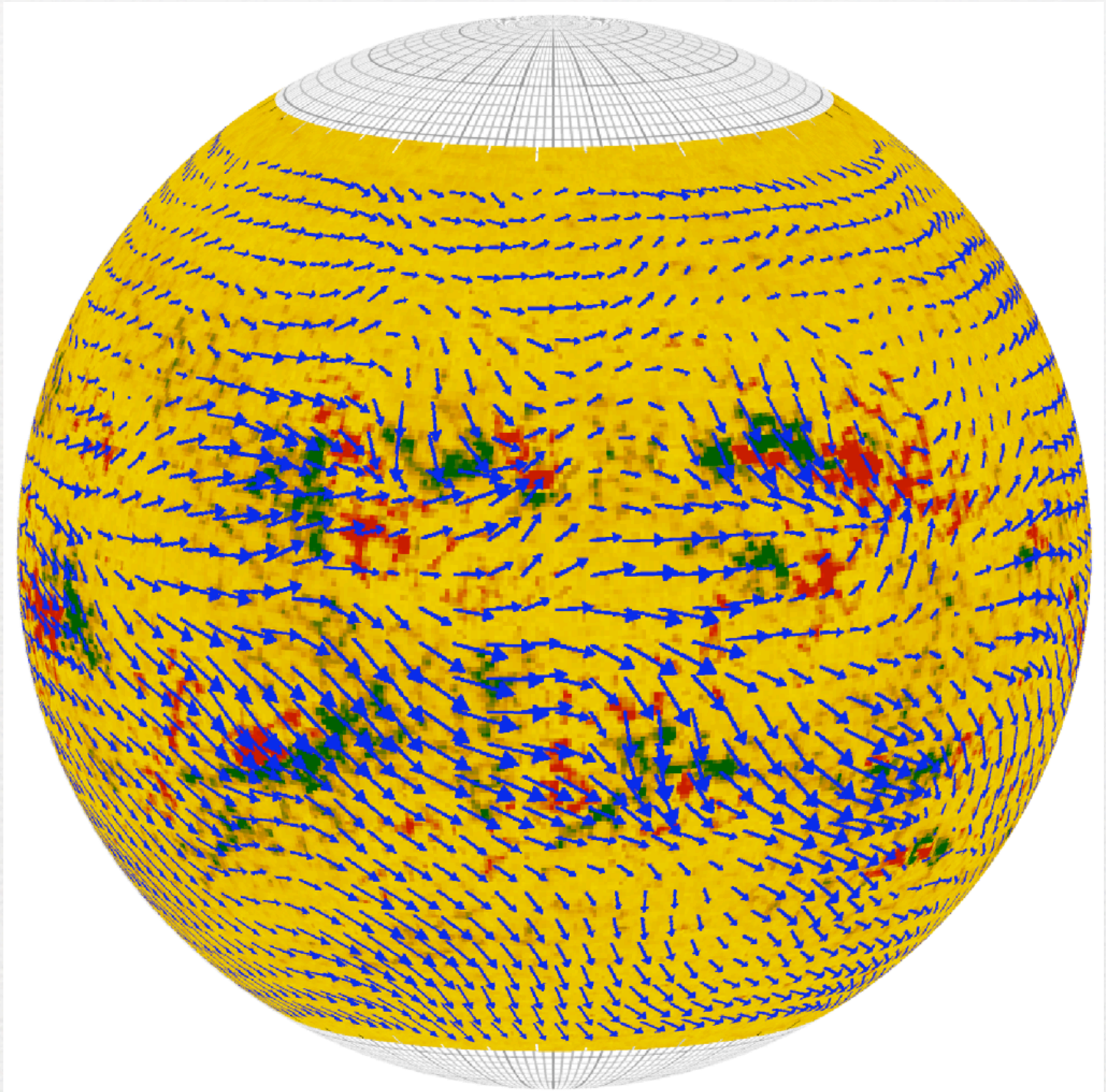


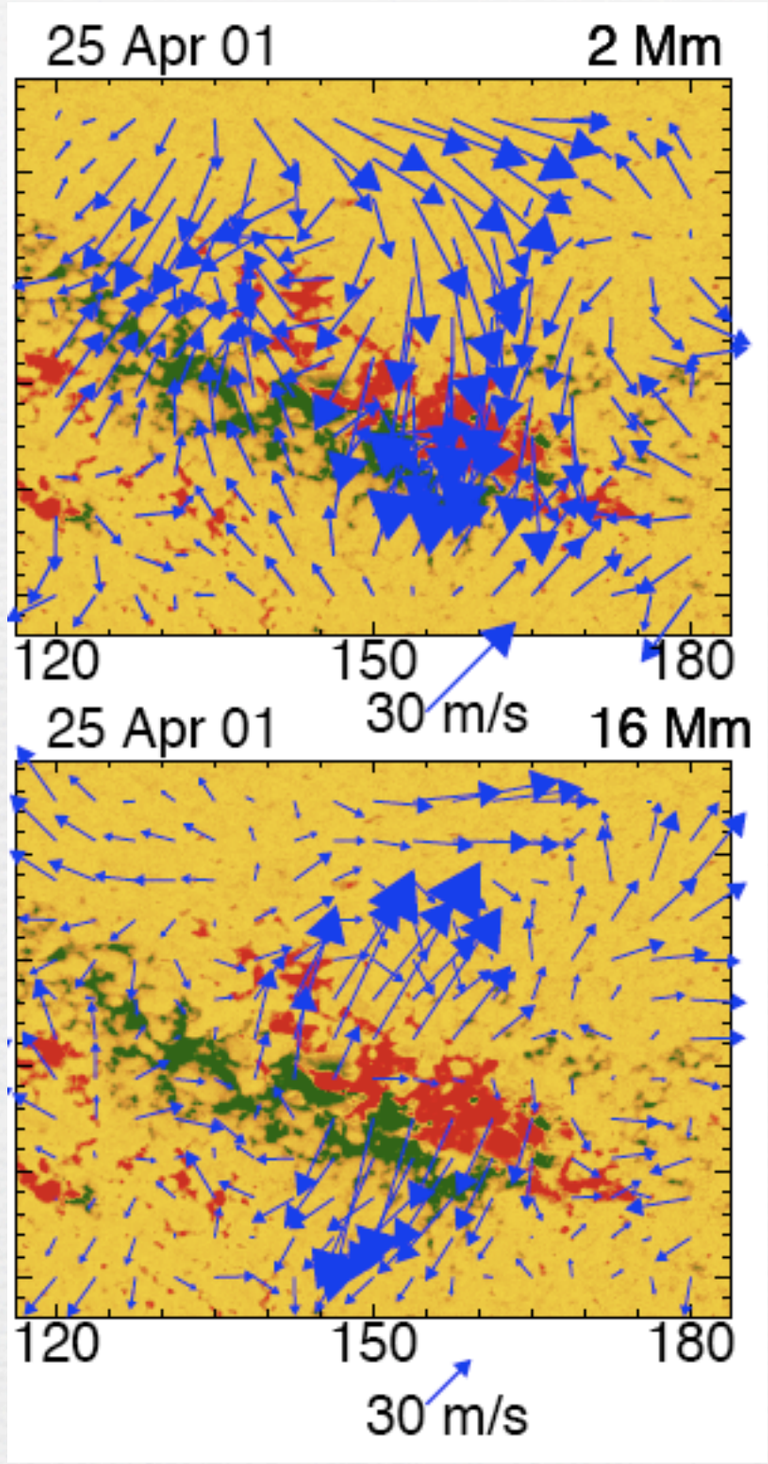
Peering beneath sunspots

Far-side imaging

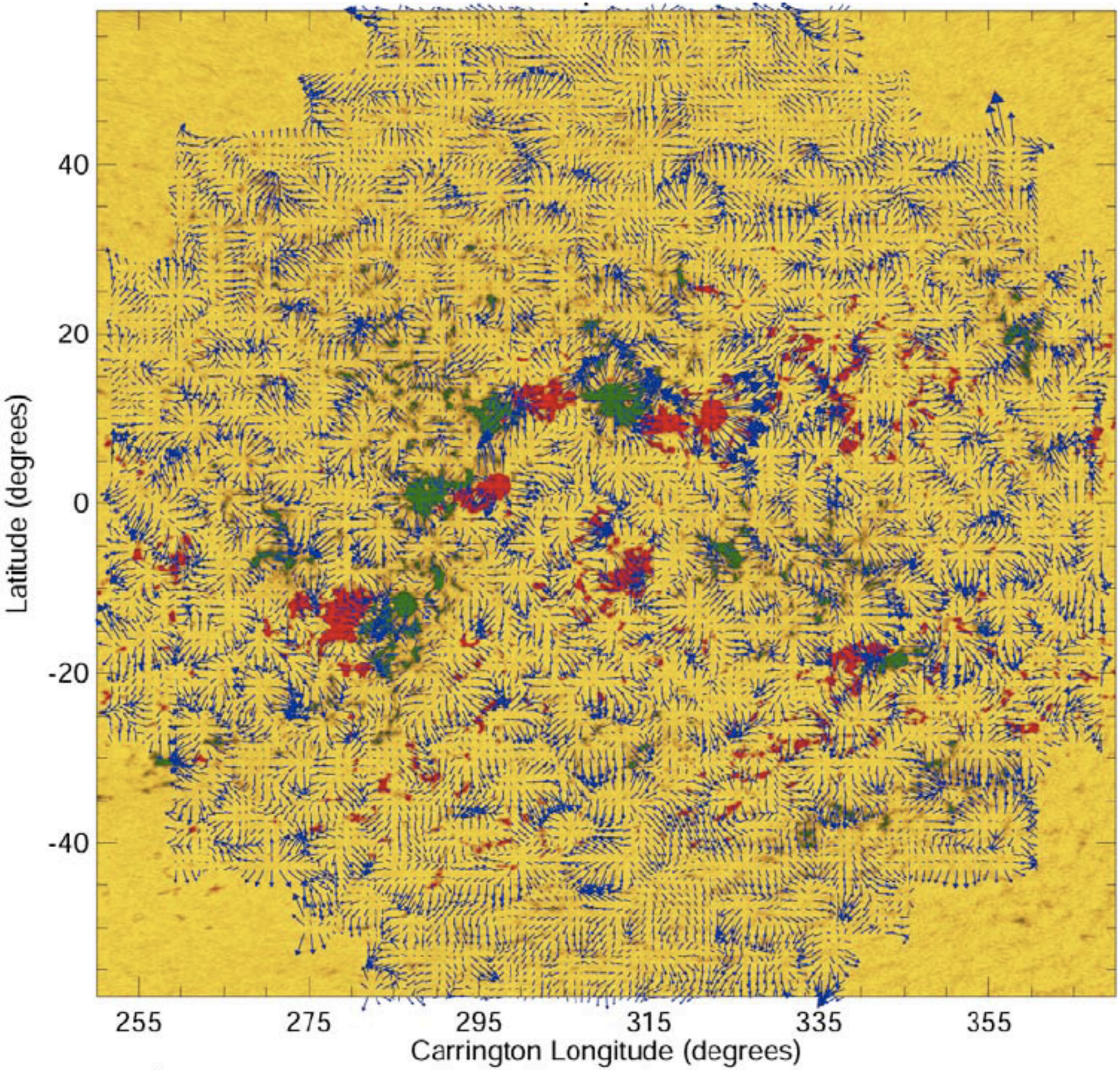


Solar Subsurface Weather (SSW)



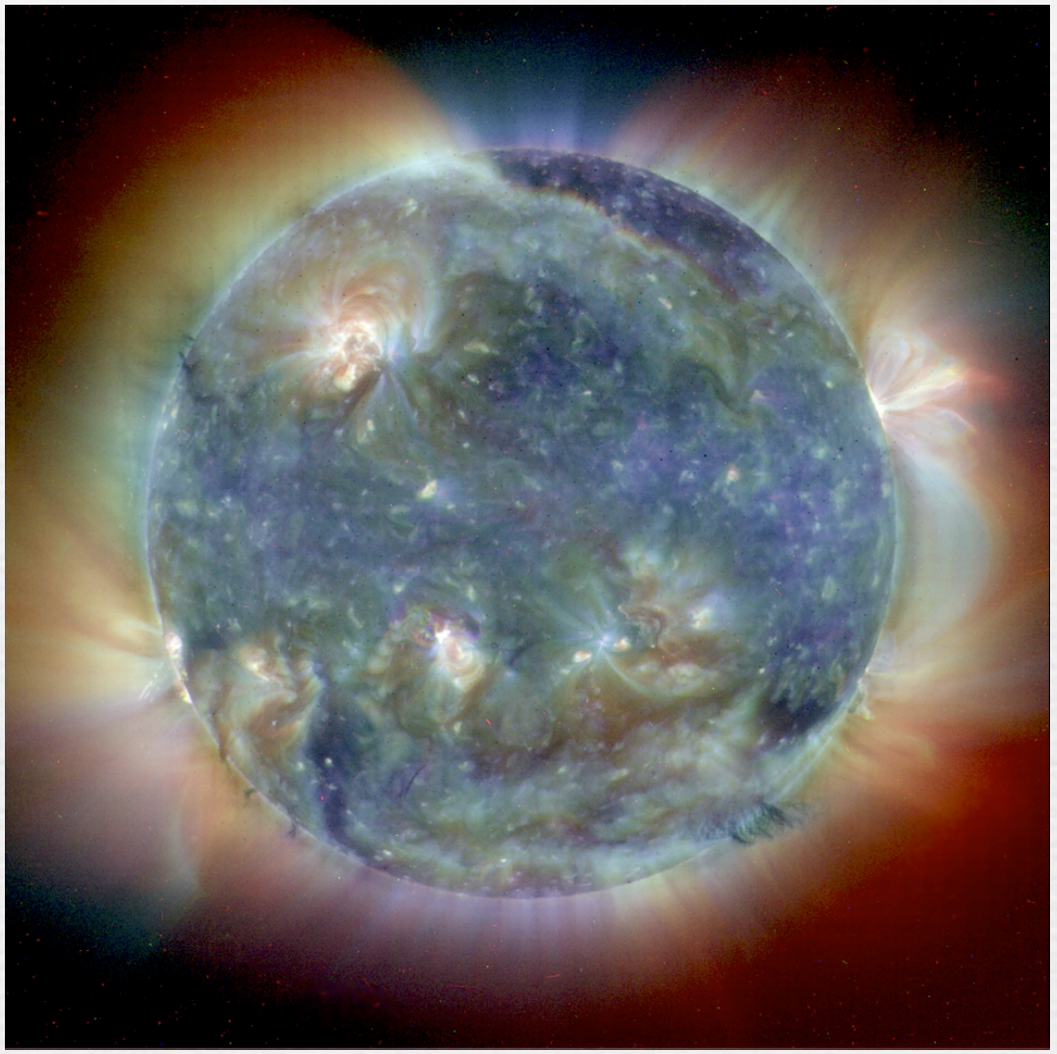


D. Haber, B. Hindman & J. Toomre
(Univ. of Colorado)


40
20
0
-20
-40
Latitude (degrees)
255
275
295
315
335
355
Carrington Longitude (degrees)

The Challenge

Now How do we go about modeling this mess??

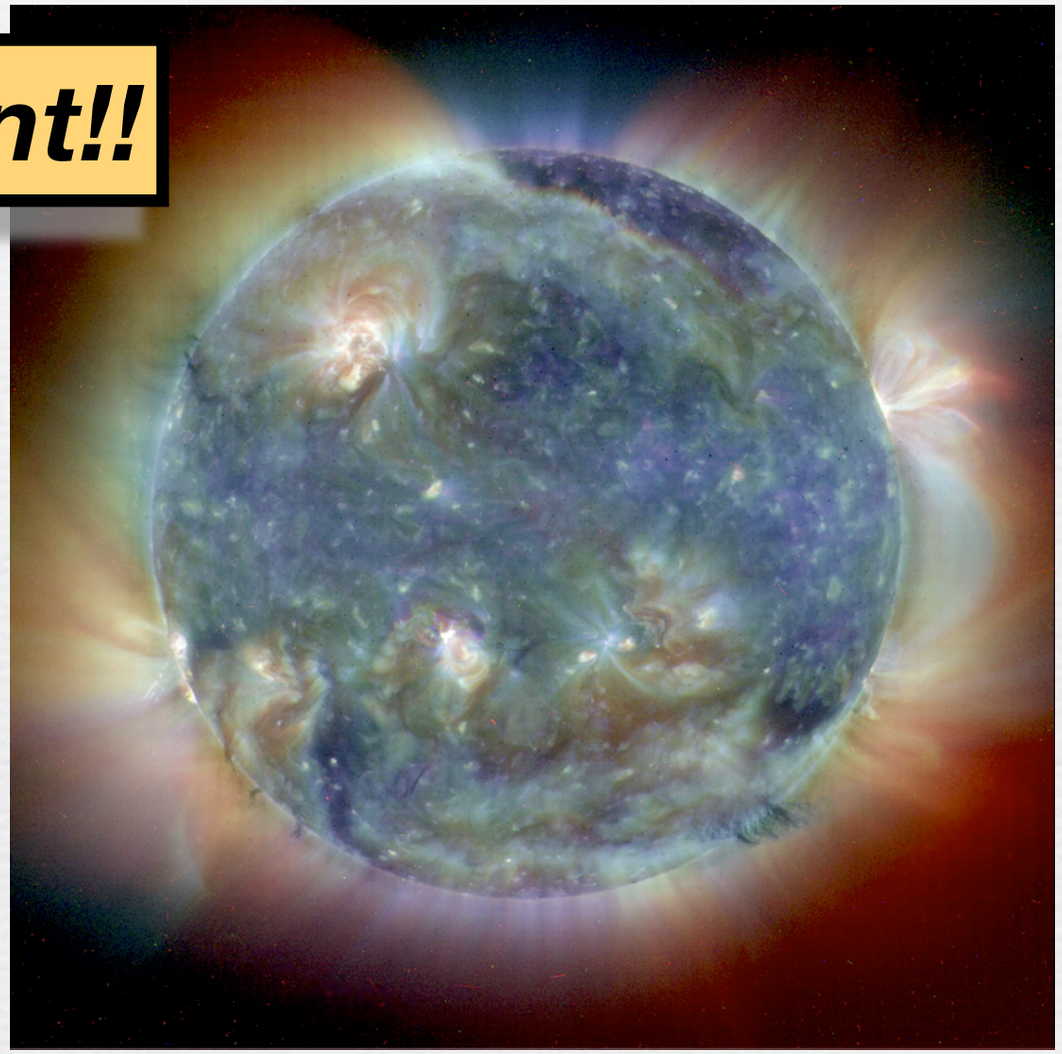


- **Length Scales**
  - Solar radius: 700 Mm
  - Tachocline width: 20 Mm
  - viscous dissipation scale: 1 cm
- **Time Scales**
  - period of sound waves: 5 min
  - period of gravity waves: 1.5 hours
  - rotation period: 1 month
  - activity cycle: 22 years
- **Other nastiness**
  - spherical geometry
  - stratification, rotation, magnetism, shear
  - boundary layers
    - top: granulation, ionization, compressibility, radiative transfer
    - bottom: tachocline, convective penetration, instabilities, waves

The Challenge

Now How do we go about modeling this mess??

Turbulent!!



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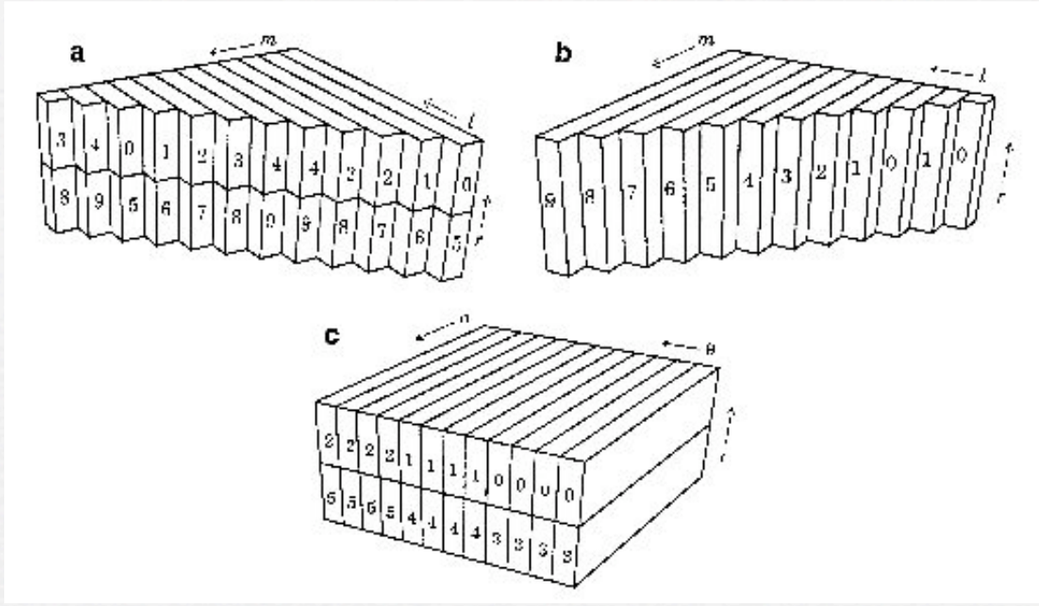
The ASH Code



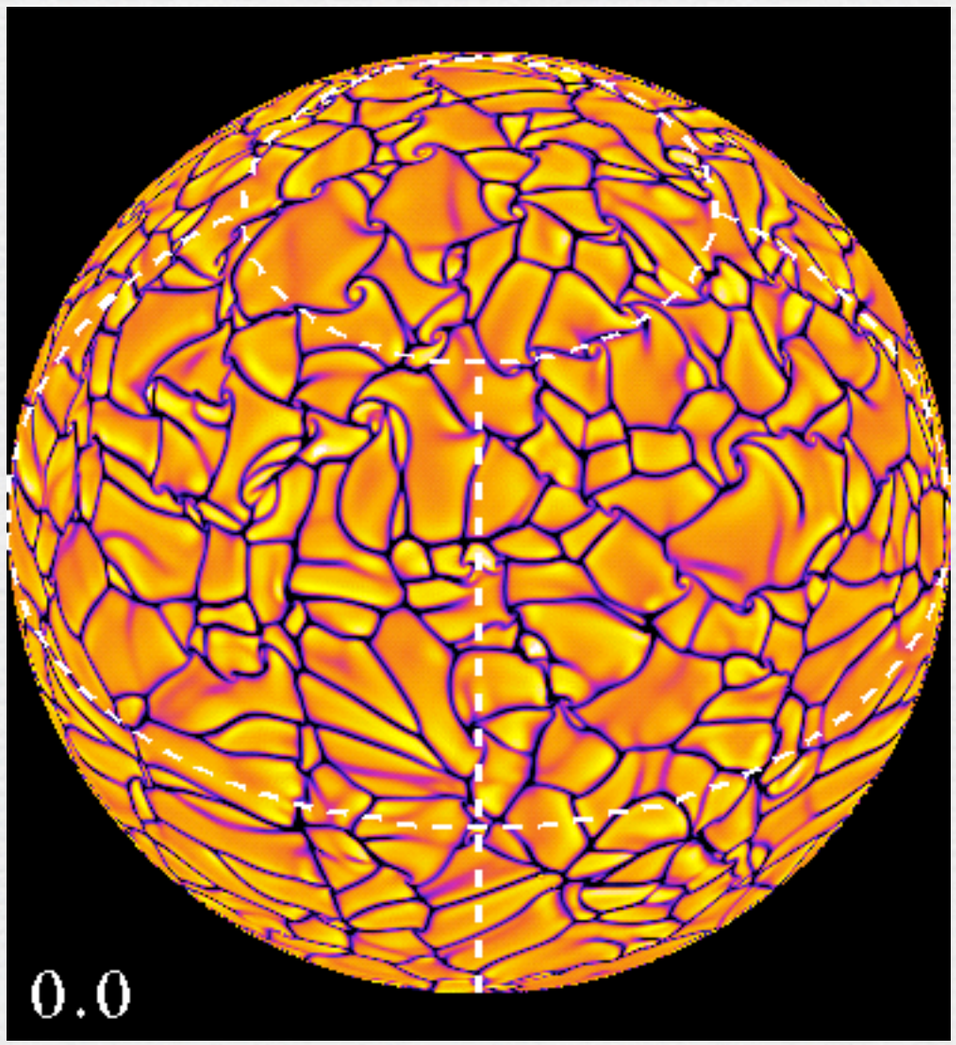
- **LES/SGS Strategy**
  - Eddy viscosity, diffusivities
  - shave off granulation layer

- **Anelastic approximation**
  - perturbations about a hydrostatic reference state
  - filters out acoustic waves
  - density stratification
  - streamfunction formulation

ASH

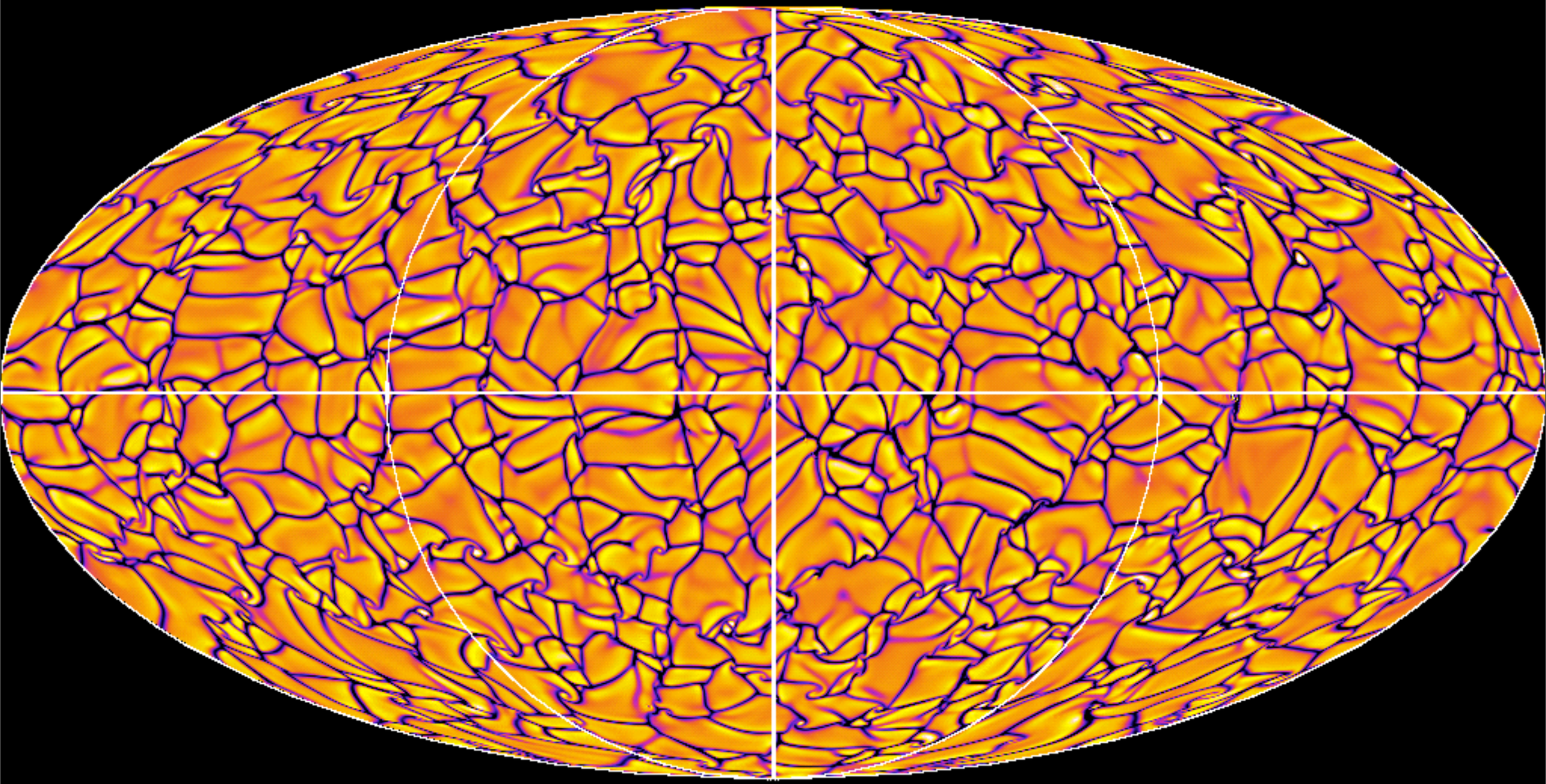
- **Pseudospectral**
  - Spherical Harmonic
  - Stacked Chebyshev
  - Crank-Nicholson/Adams-Bashforth

- **Parallel**
  - FORTRAN 90 / MPI
  - serial transforms, transposes
  - optimal data decomposition



radial velocity, r = 0.98R

Giant Cells



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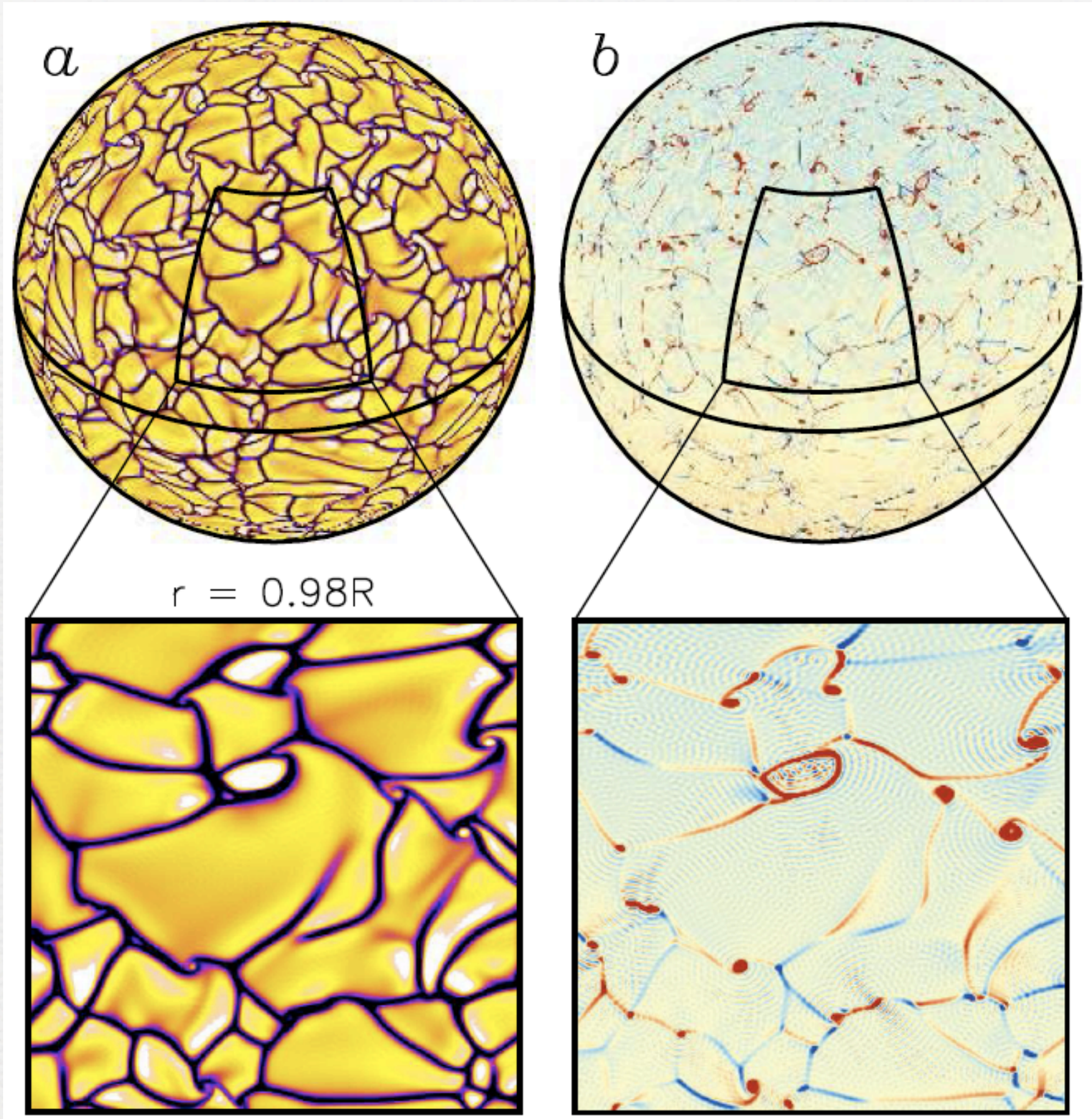
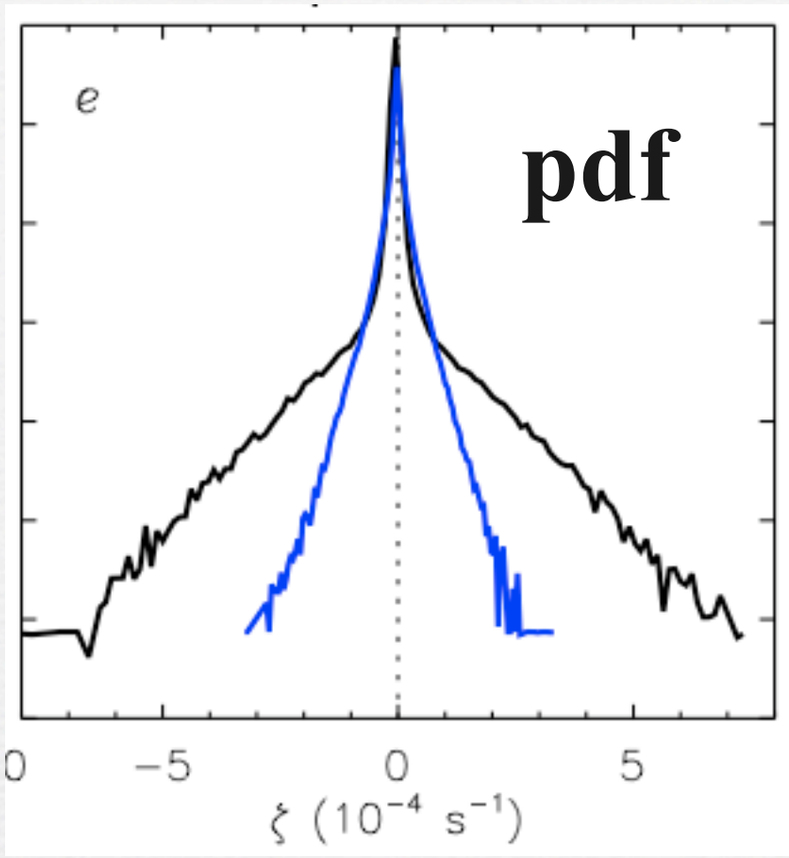
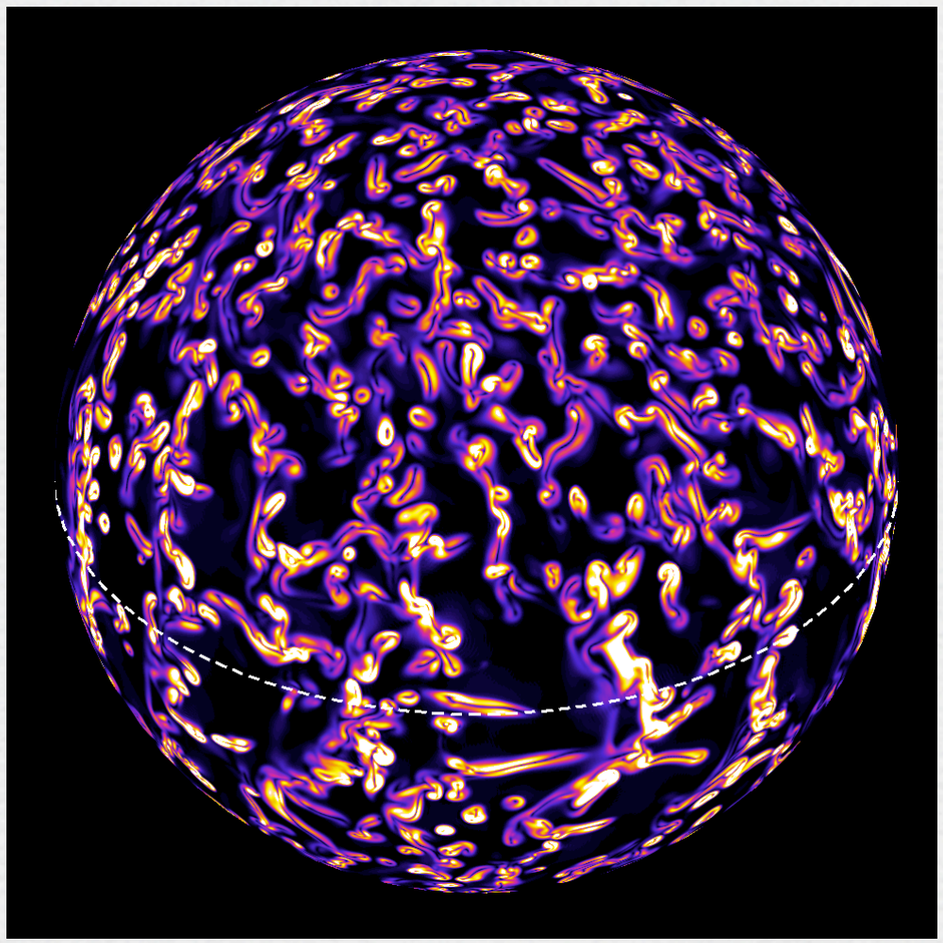
Miesch, Brun, DeRosa & Toomre (2007)

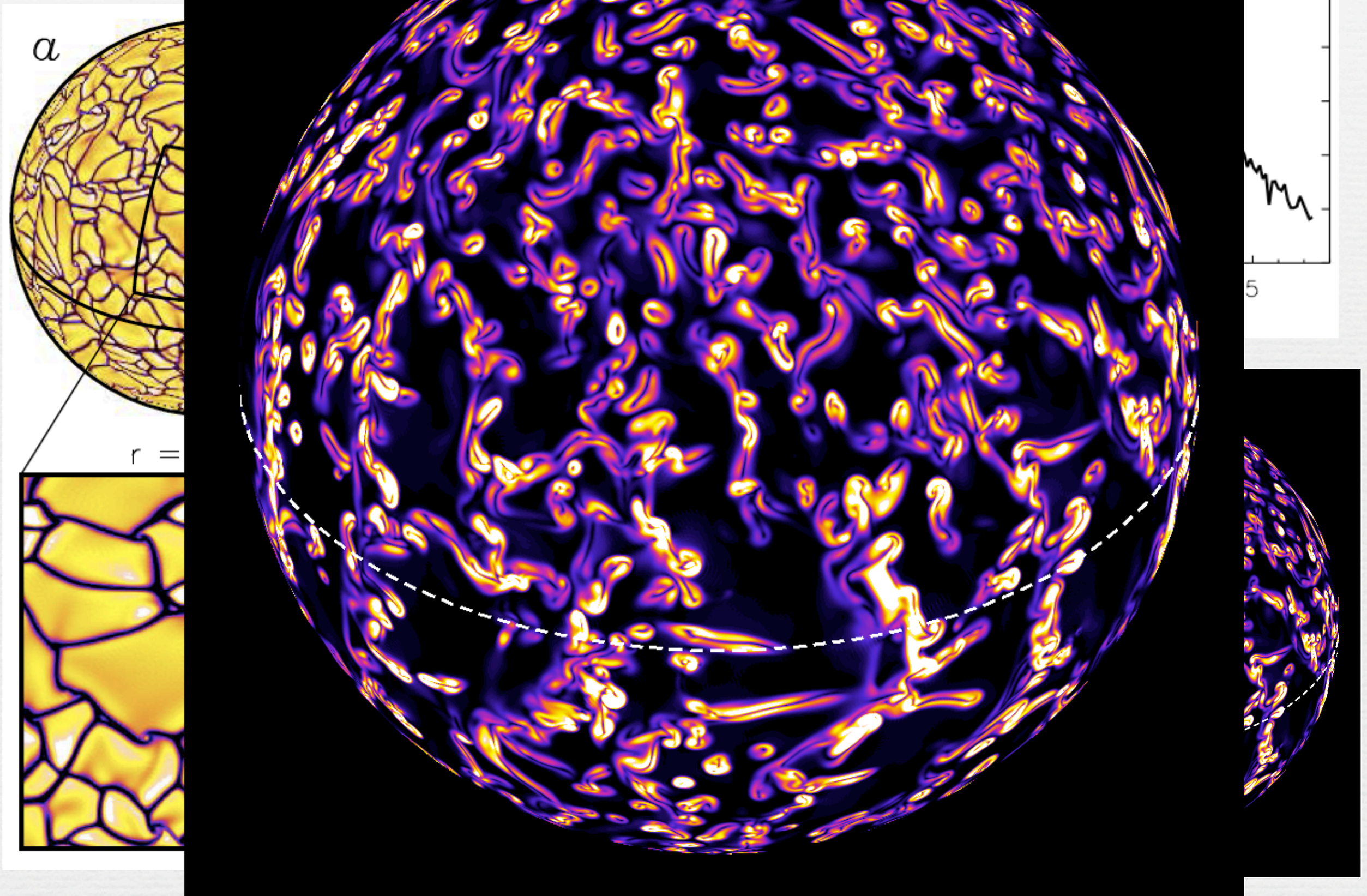
ASH

Solar Cyclones

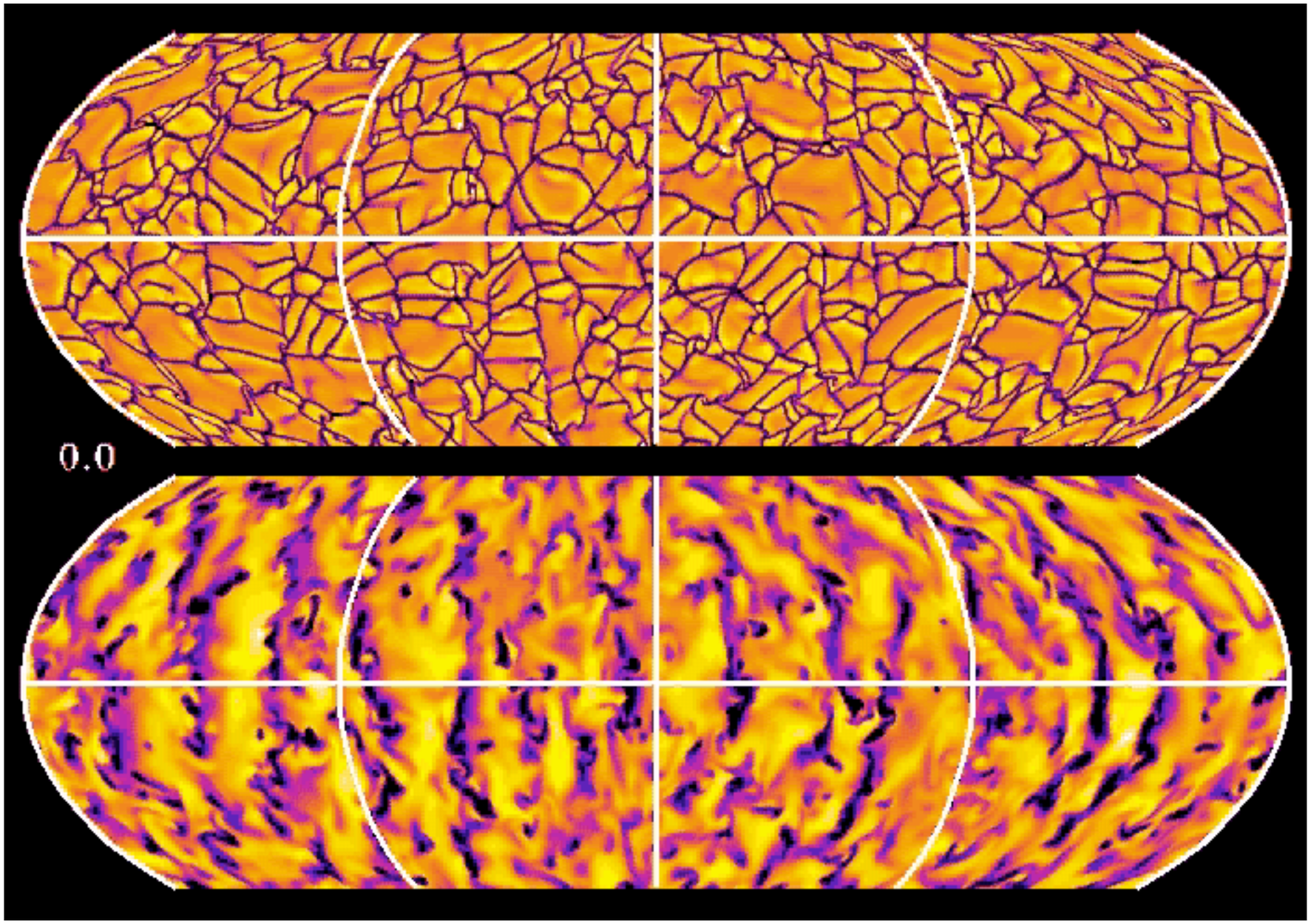


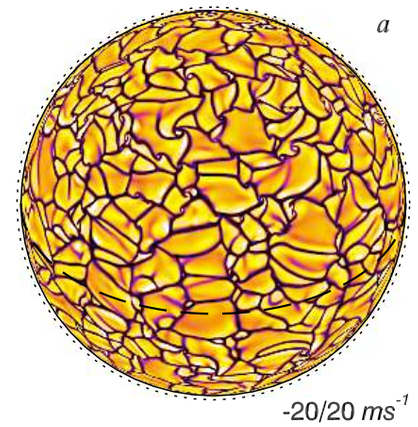


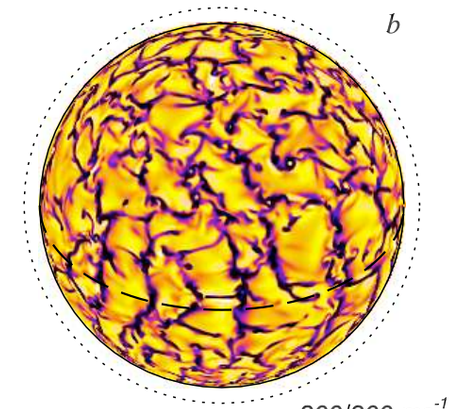


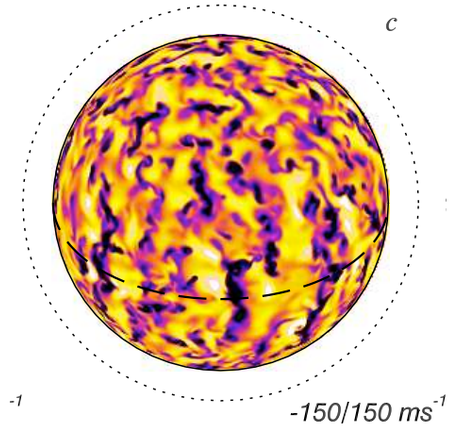

α
r =
lf
5

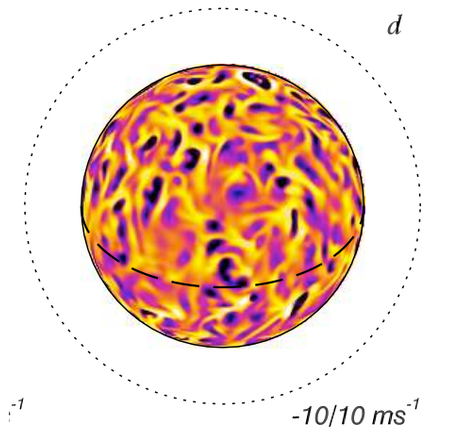
North-South Downflow Lanes

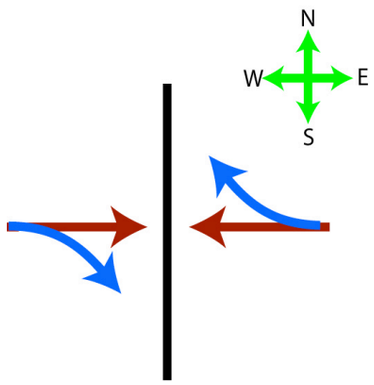






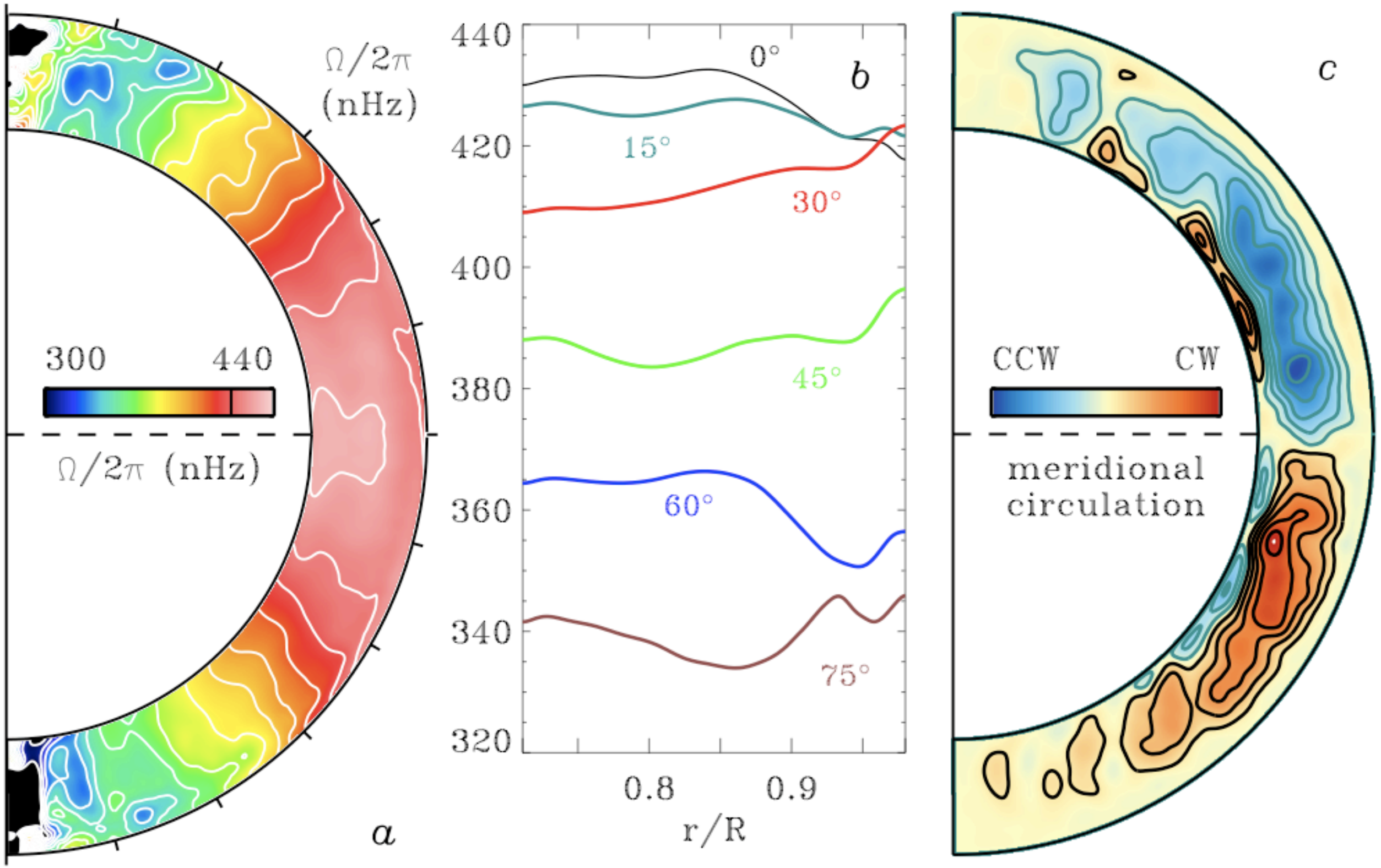






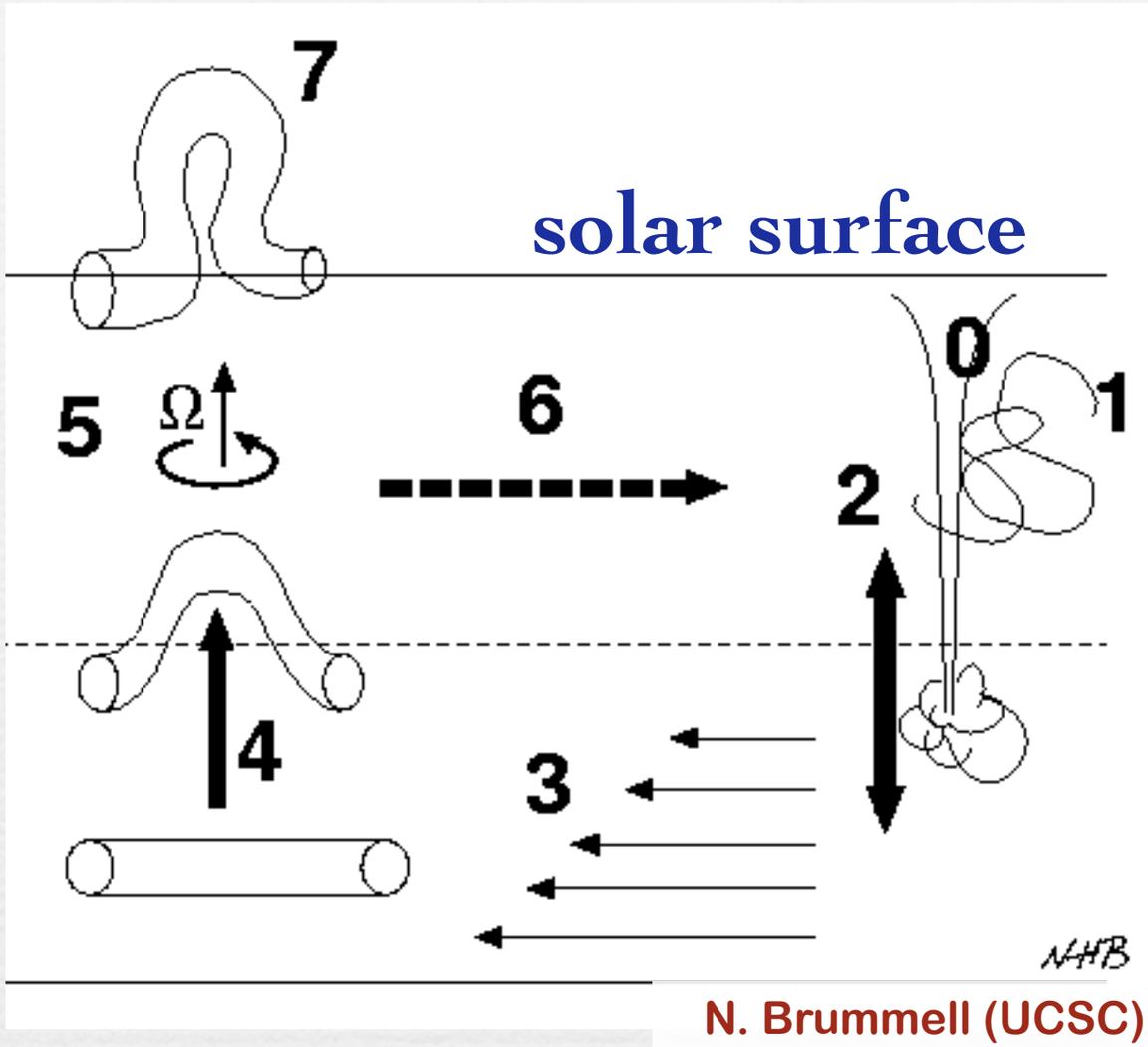
Equatorward Angular momentum transport

Differential Rotation, Meridional Circulation

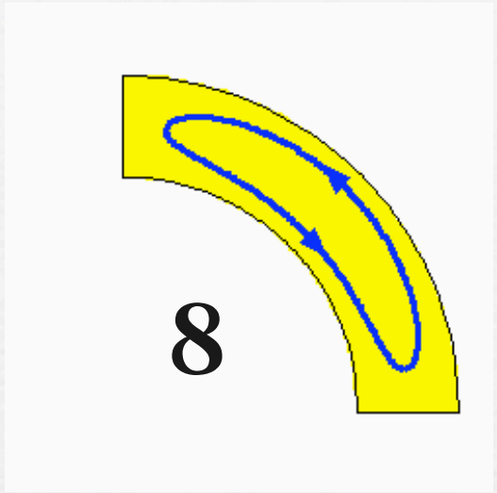


The Solar Dynamo

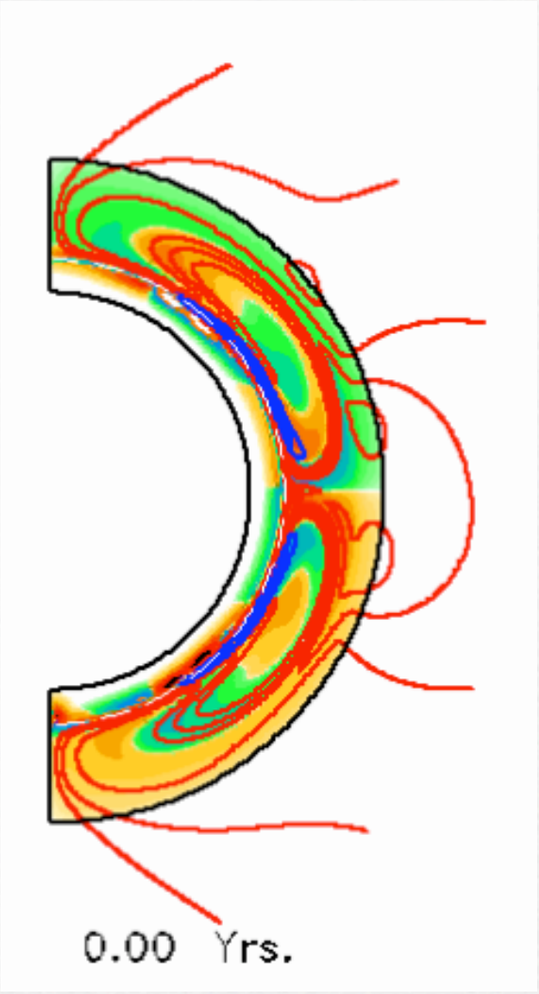
tachocline convection

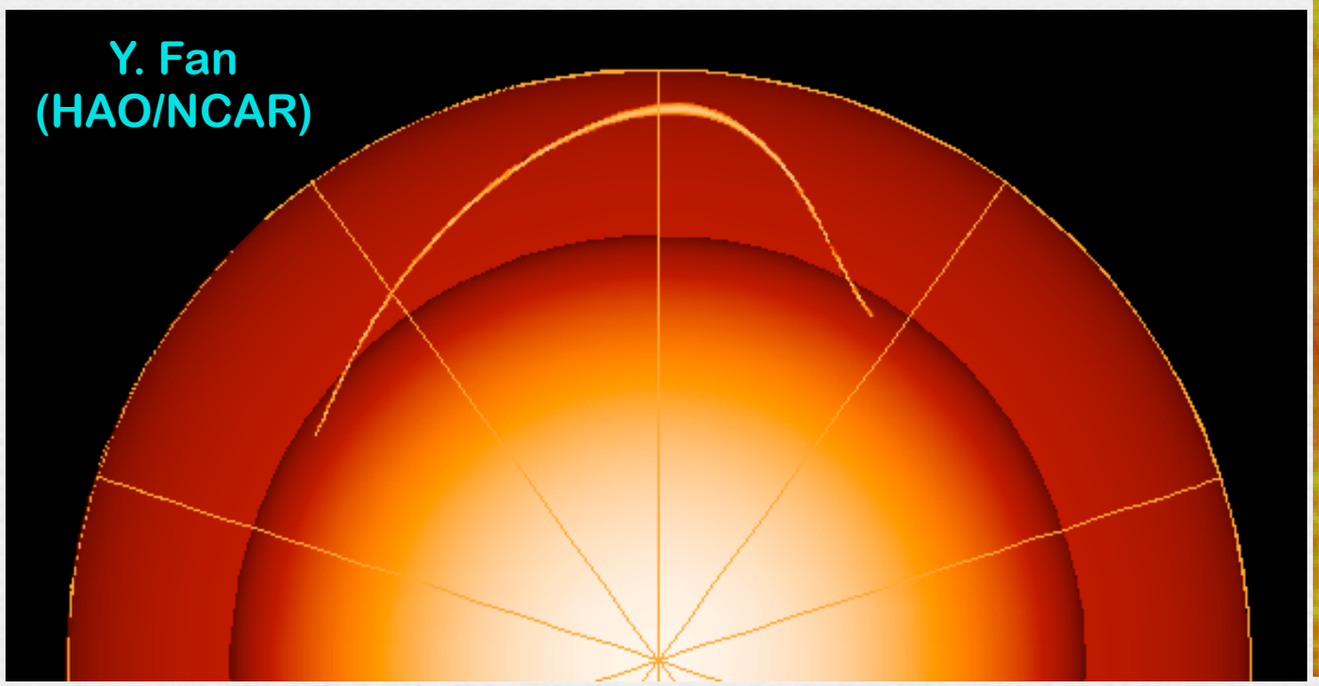


N. Brummell (UCSC)



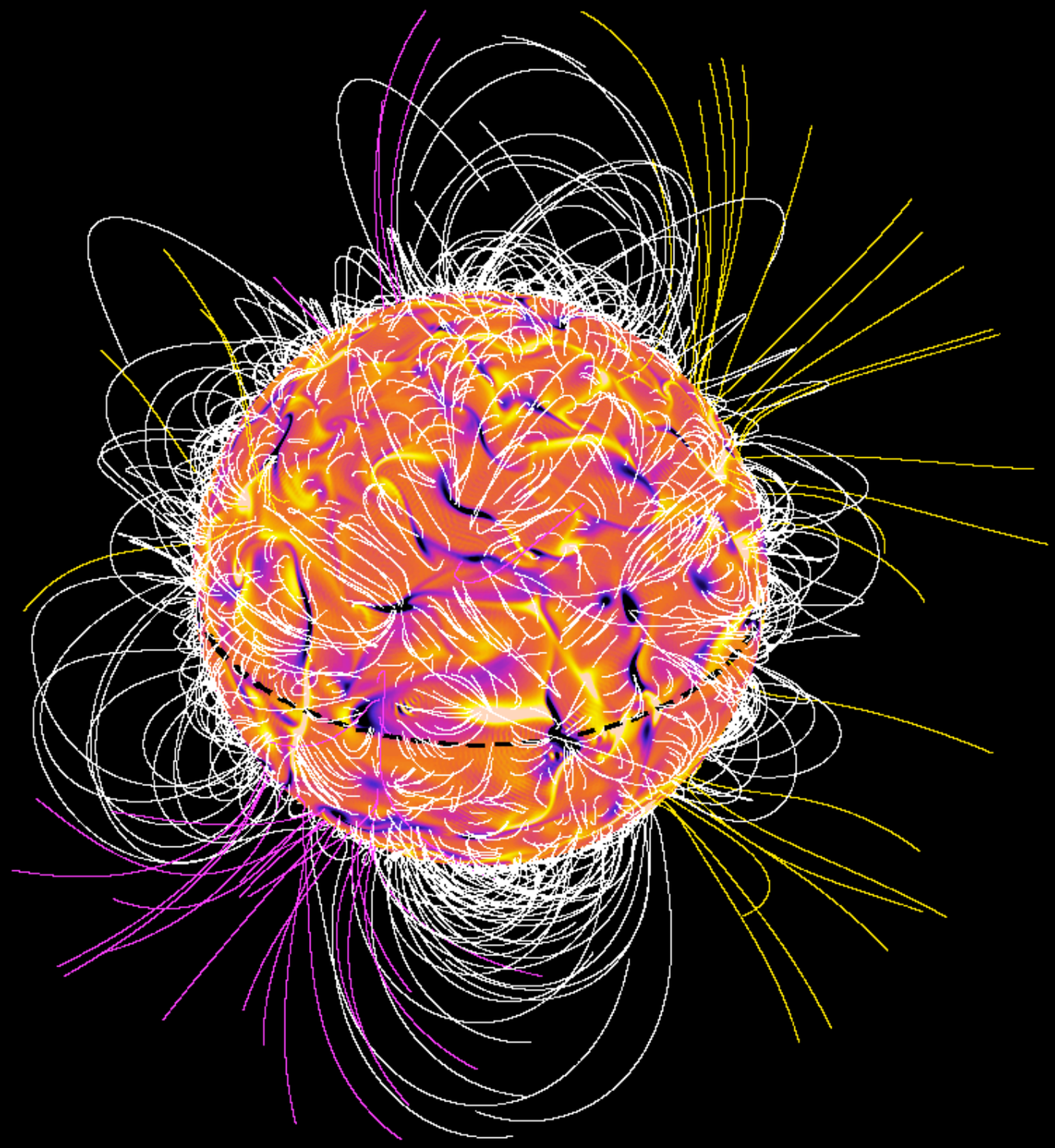
M. Dikpati & P. Gilman
(HAO/NCAR)

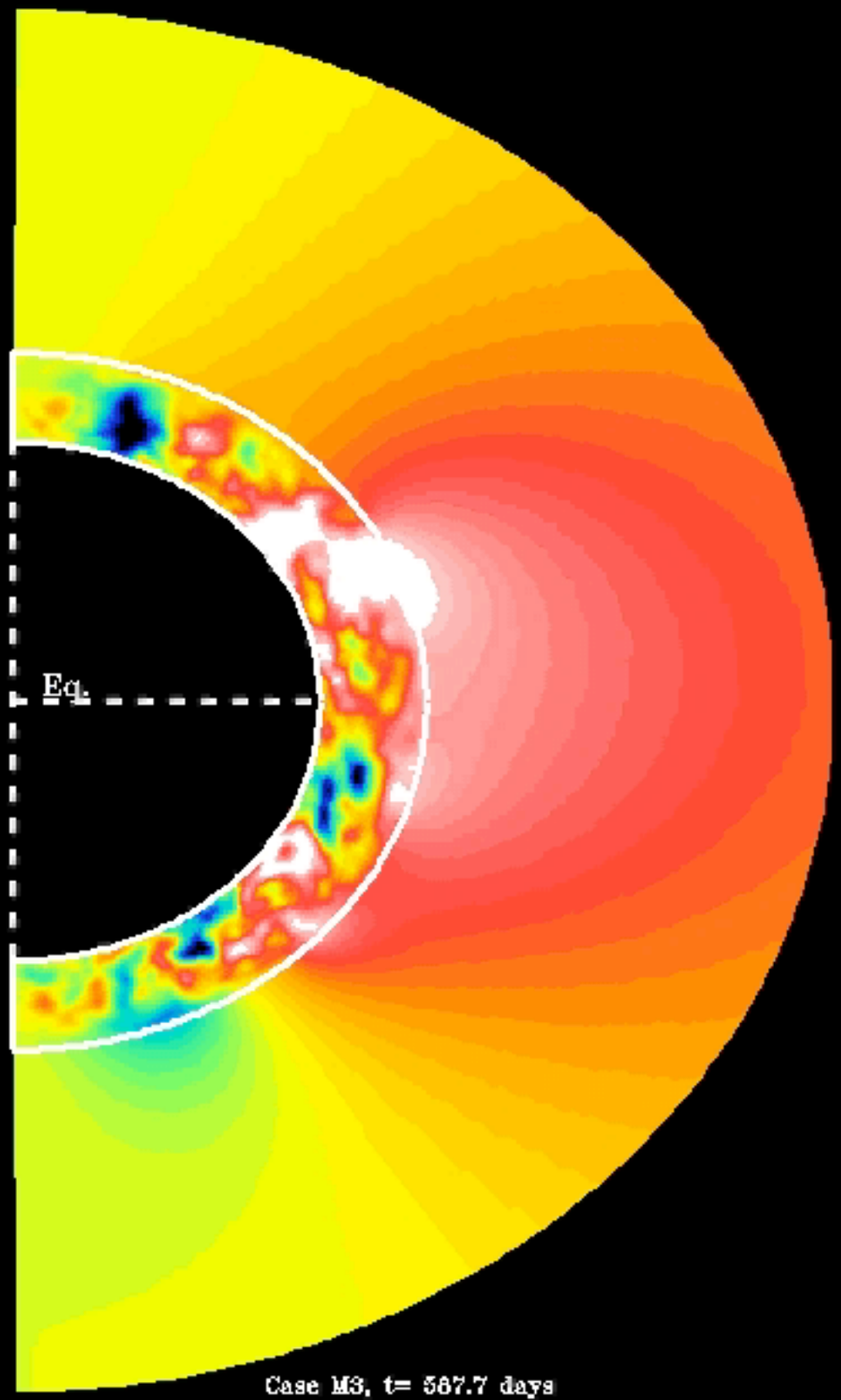




SOHO/ESA/NASA

Dynamo Processes



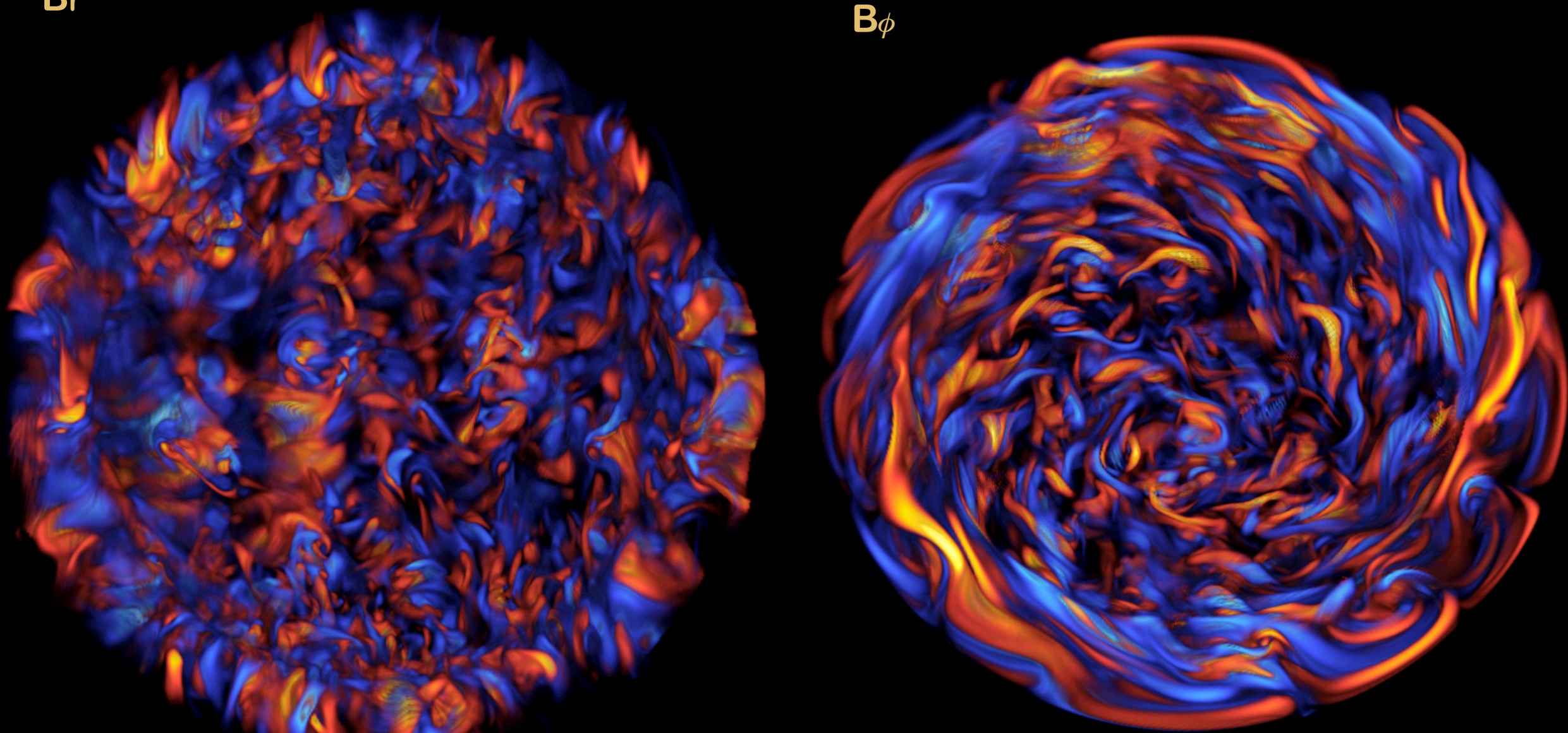


Brun, Miesch & Toomre (2004)

Intricate, intertwined field lines and ribbons

B_r

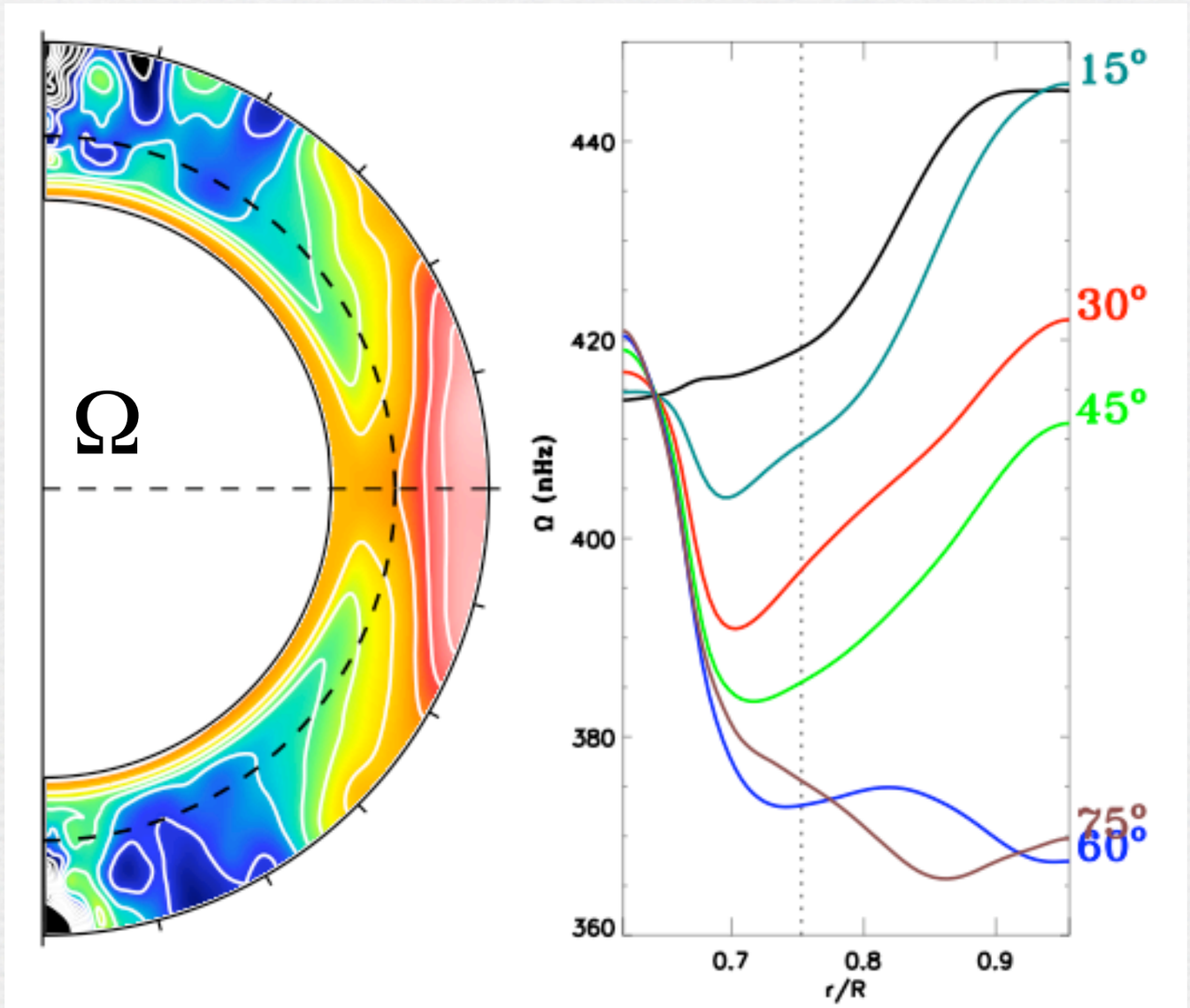
B_ϕ



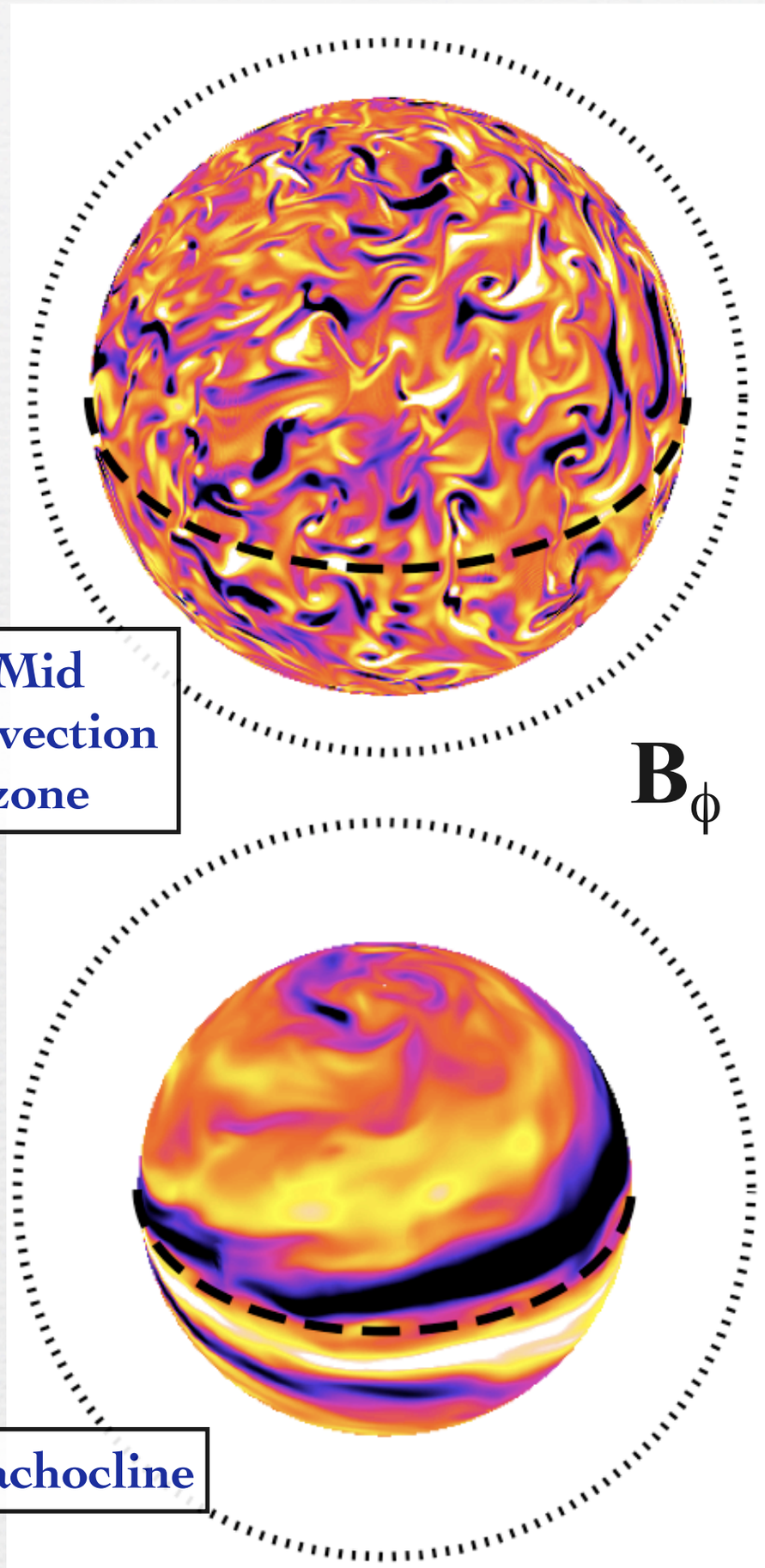
Brun, Miesch & Toomre (2004)

Tachocline

Pumping, amplification, organization of toroidal magnetic fields

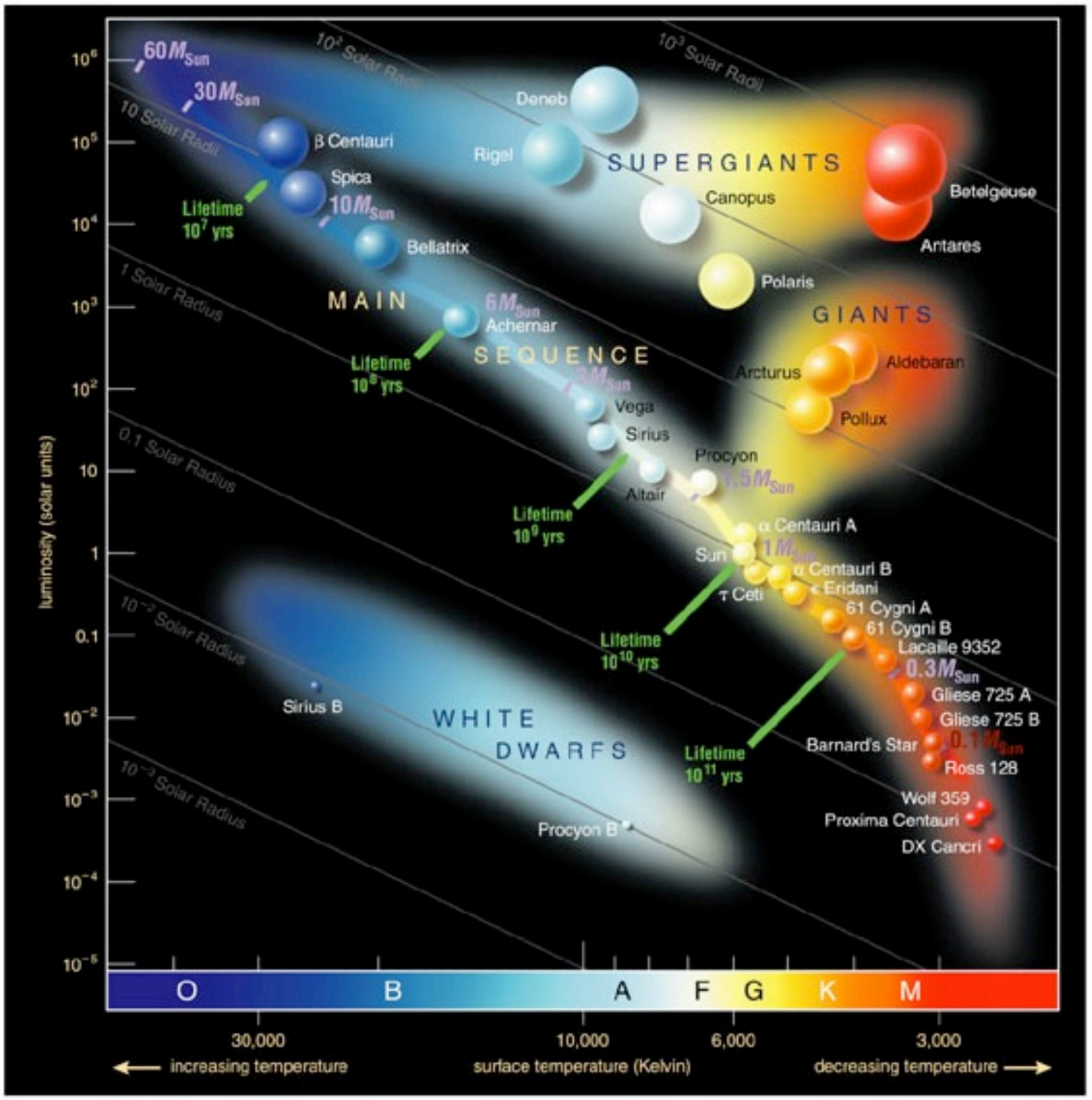


Browning, Miesch, Brun & Toomre (2006)

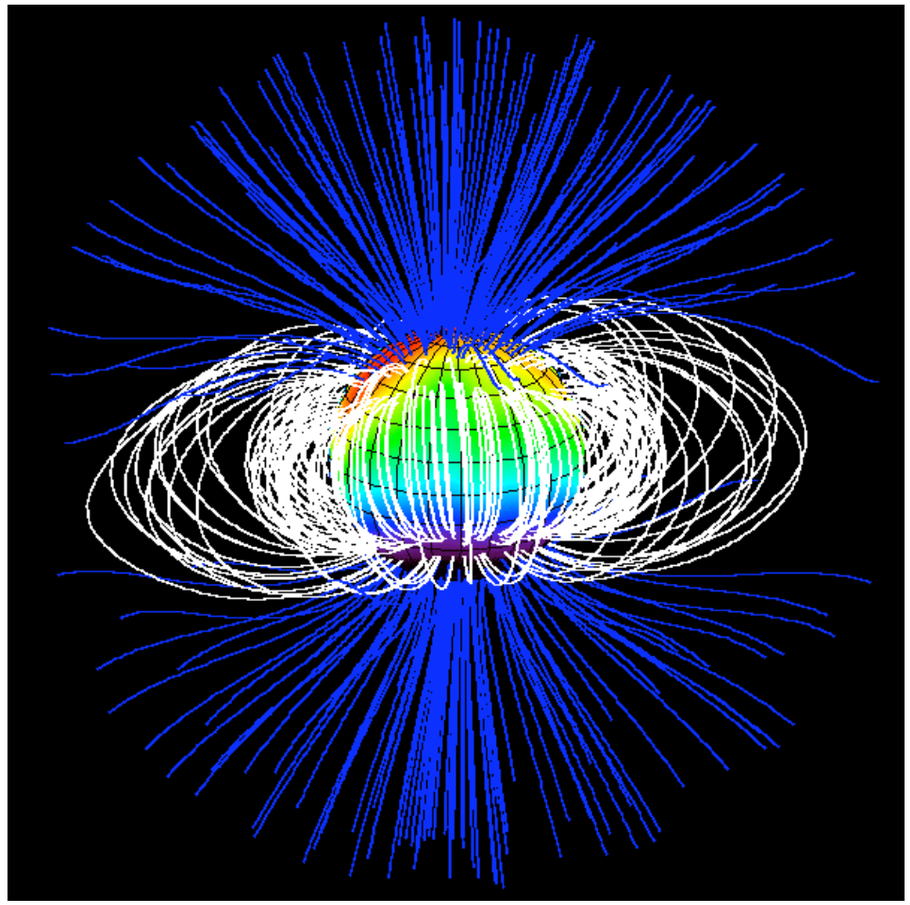


So Many Stars

...and so little time



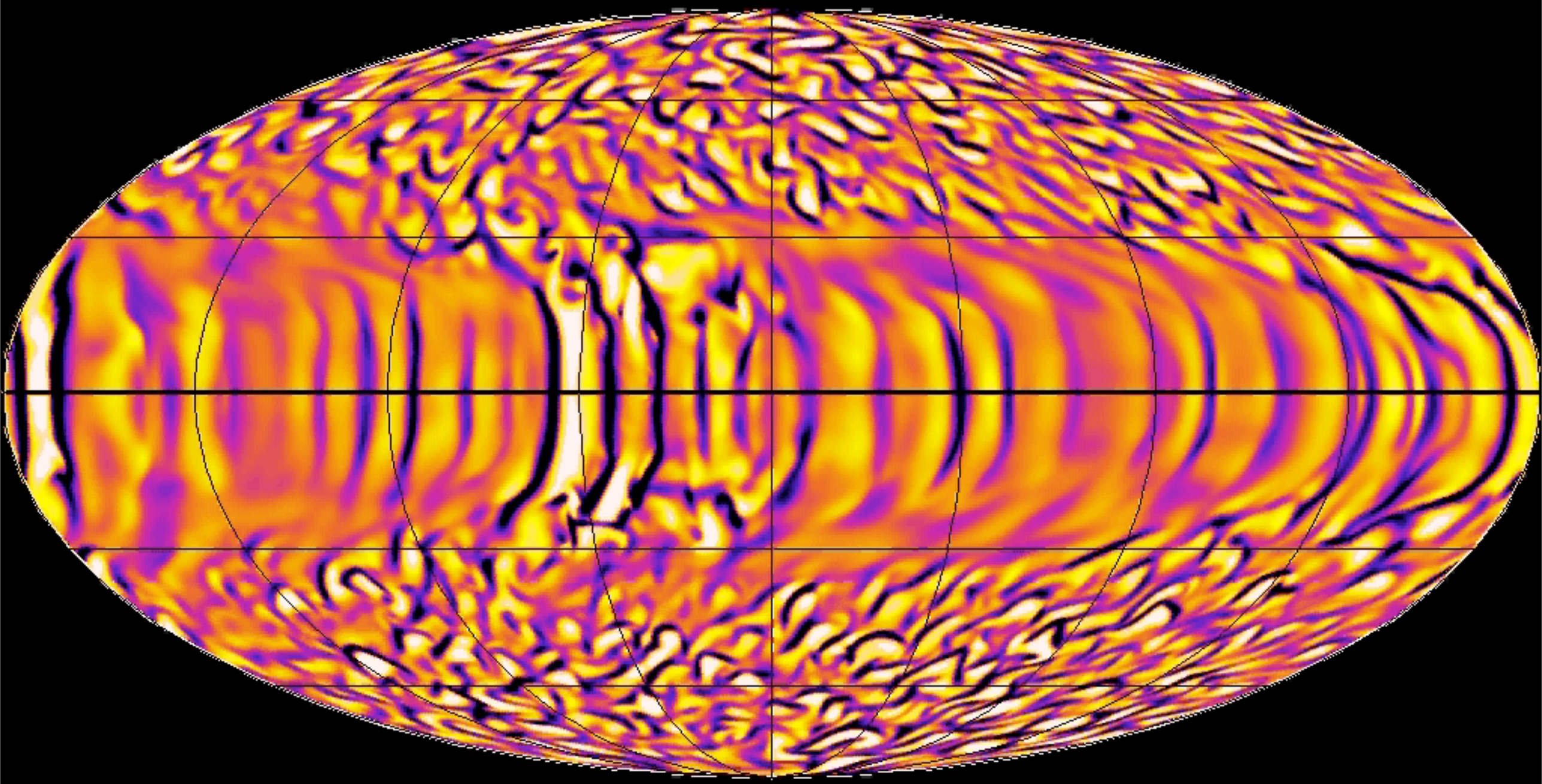
Magnetism inferred in an M dwarf



Donati et al (2006)

Convective Cores	Convective Envelopes	Fully Convective

Top convection zone



-70 m/s 70 m/s

Vr at 5.0 Ω_0

0 days

Brown et al 2007

Mid convection zone

-10 kG 10 kG

$B\phi$ at 5.0 Ω_0

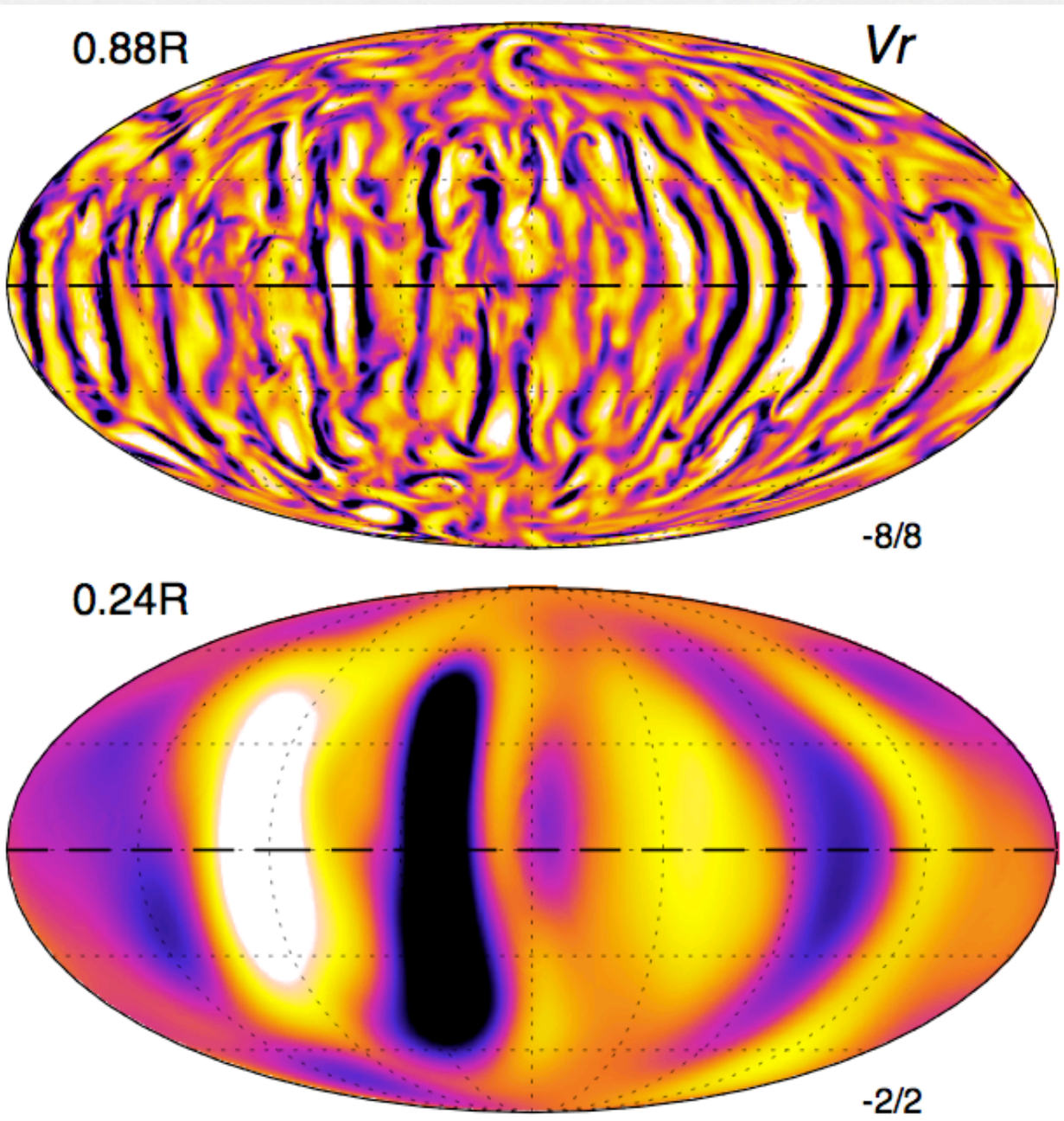
0 days

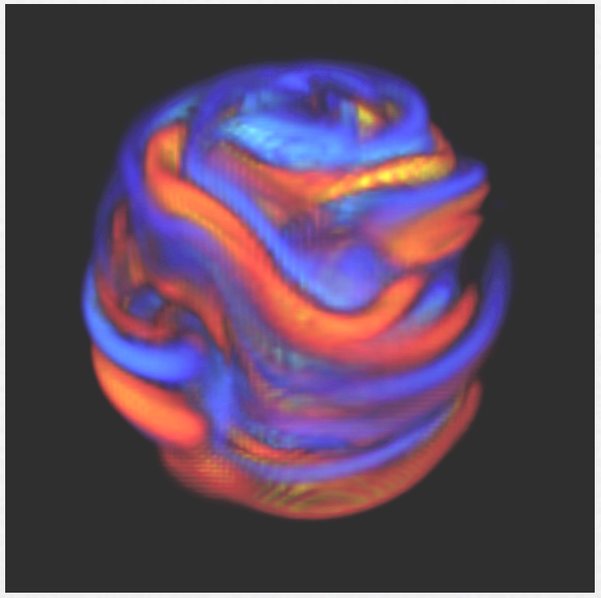
B. Brown
(Univ of Colorado)

http://www.vapor.ucar.edu

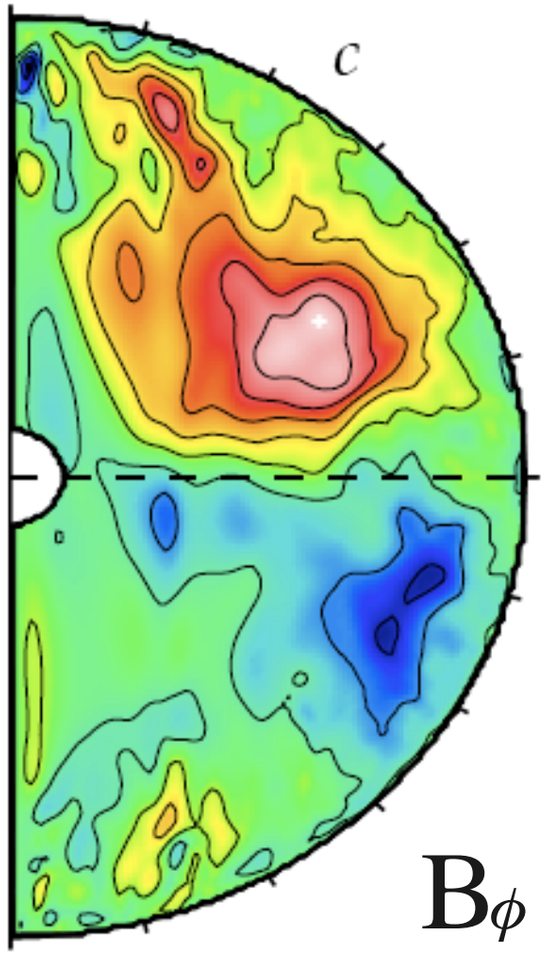
M Stars

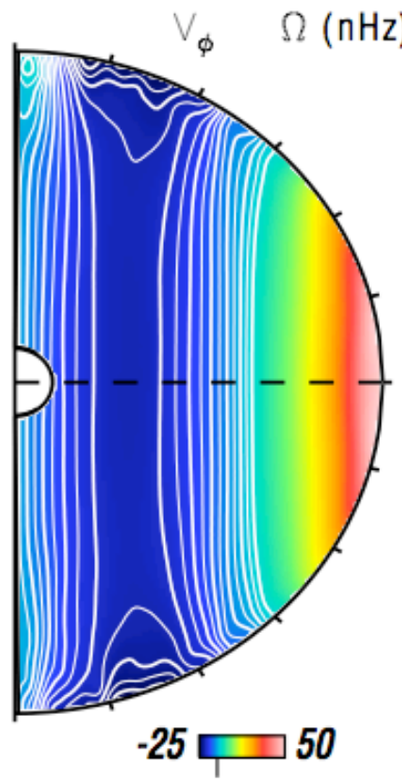
Small (0.3 M_{sun}), Cool (3000K)
Fully Convective

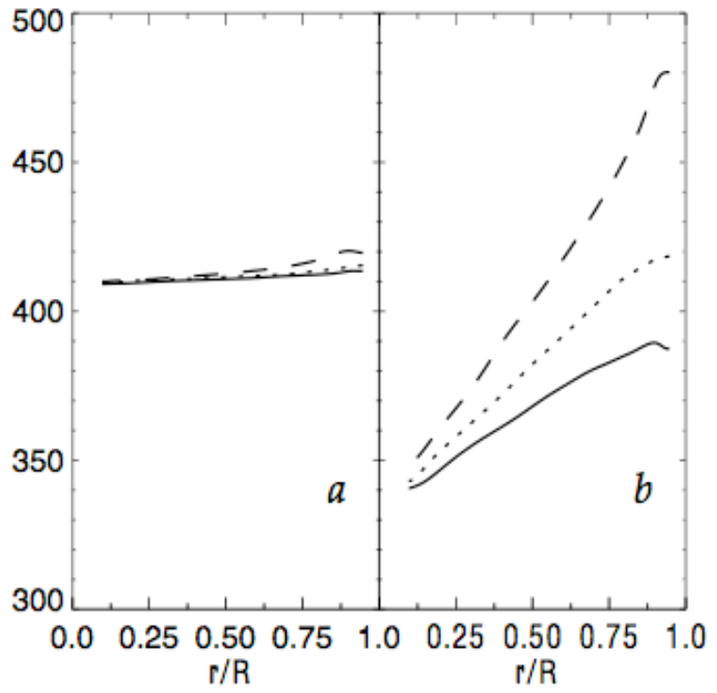




Browning (2007)

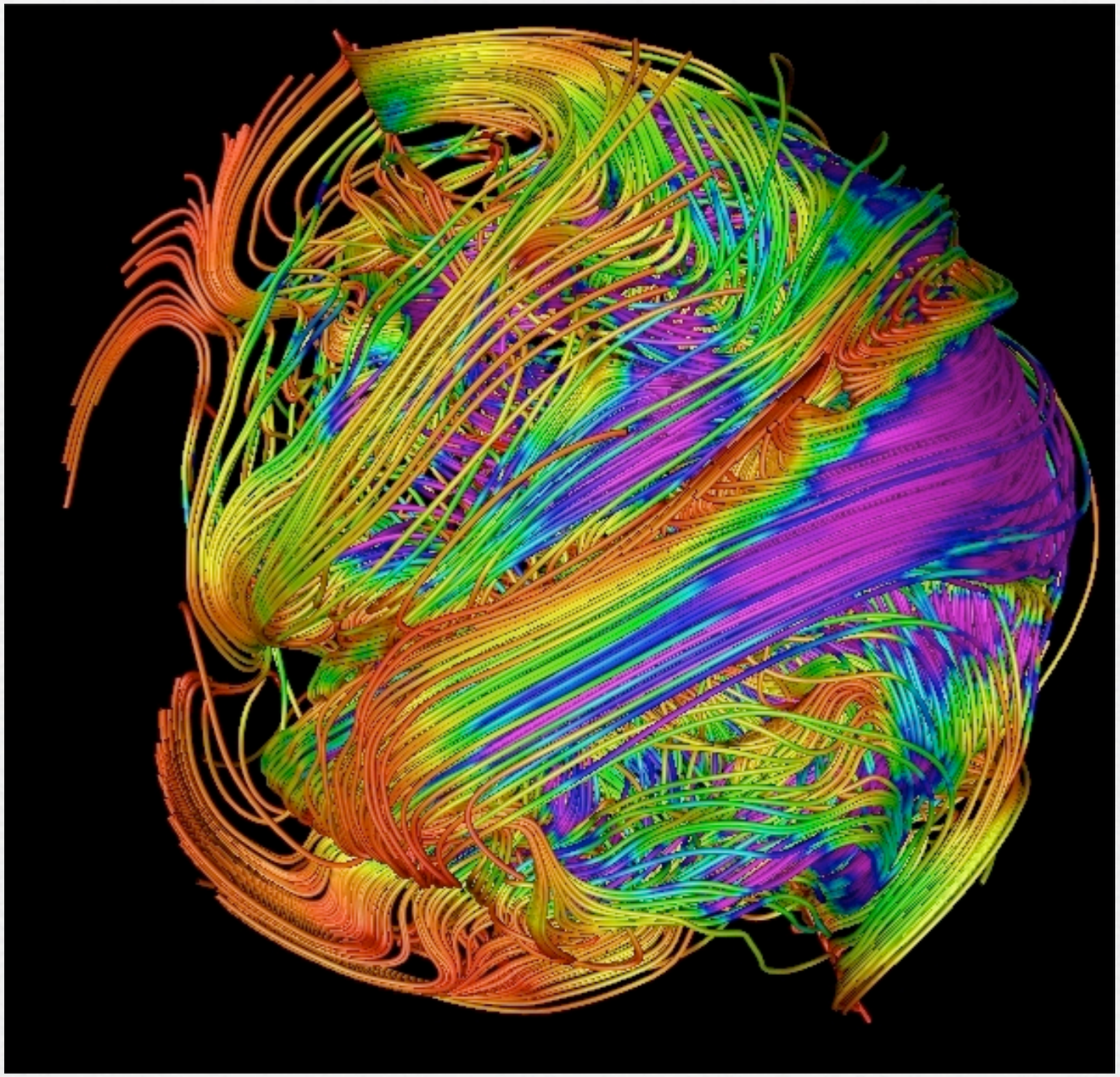




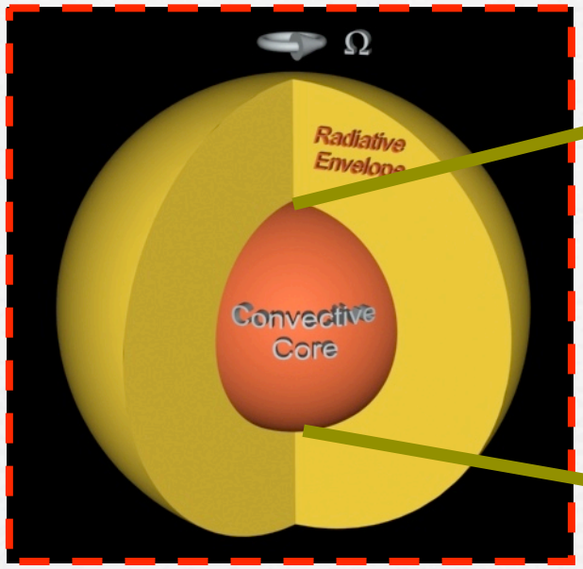


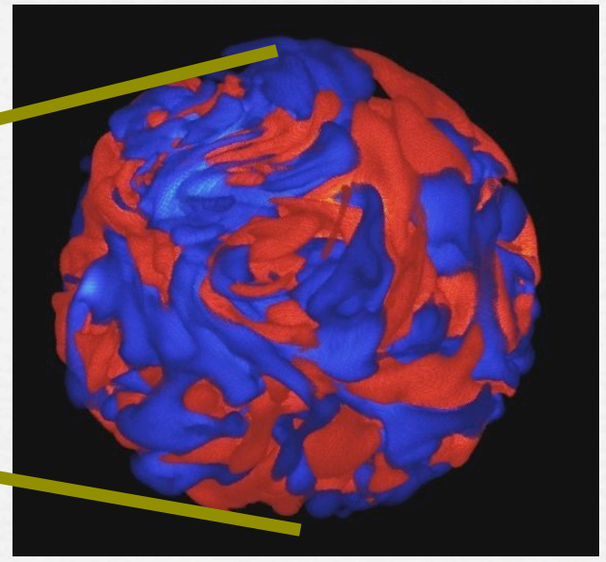
A Stars

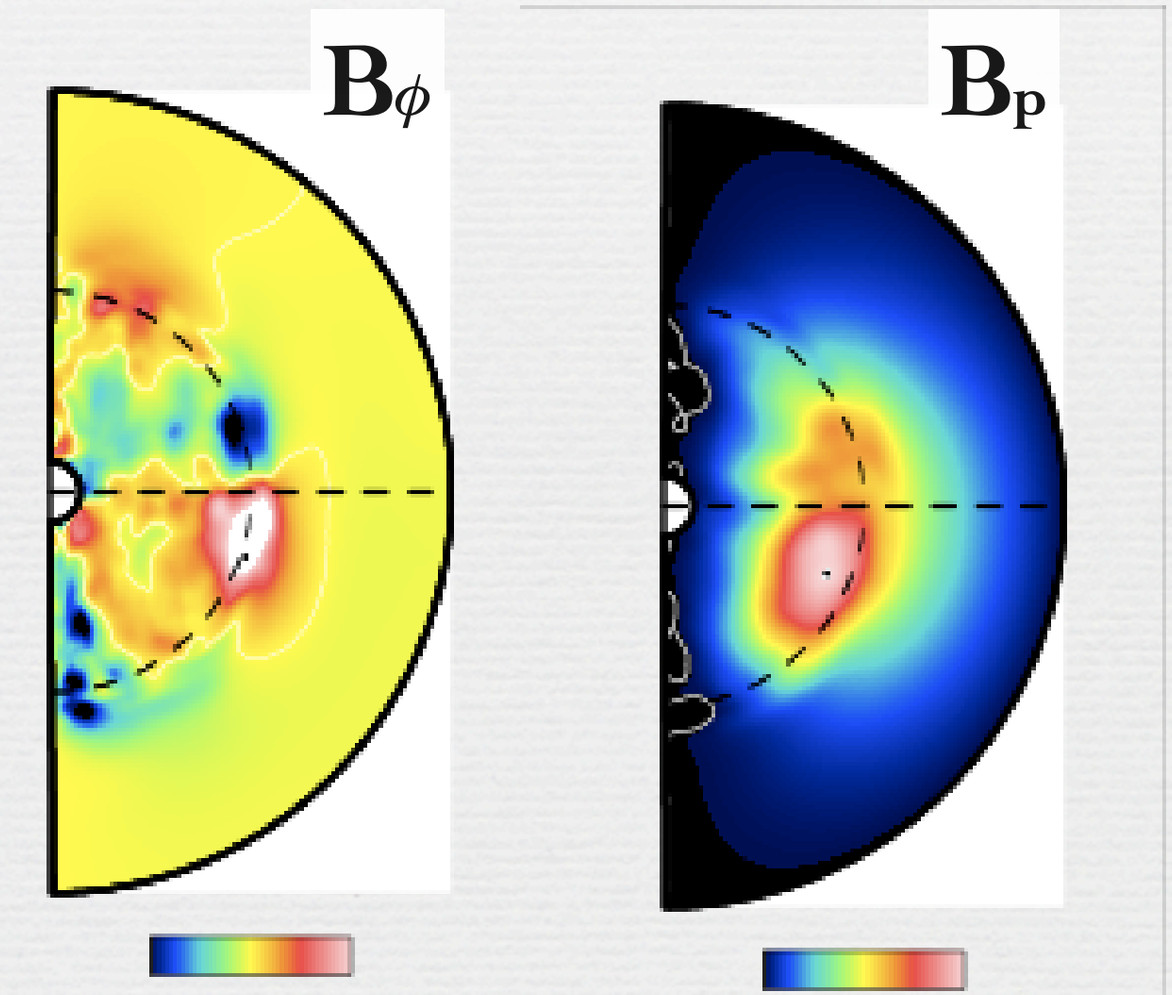
Big (2 M_{sun}), Hot (8000K)
Convective Core



N. Featherstone (Univ. of Colorado)

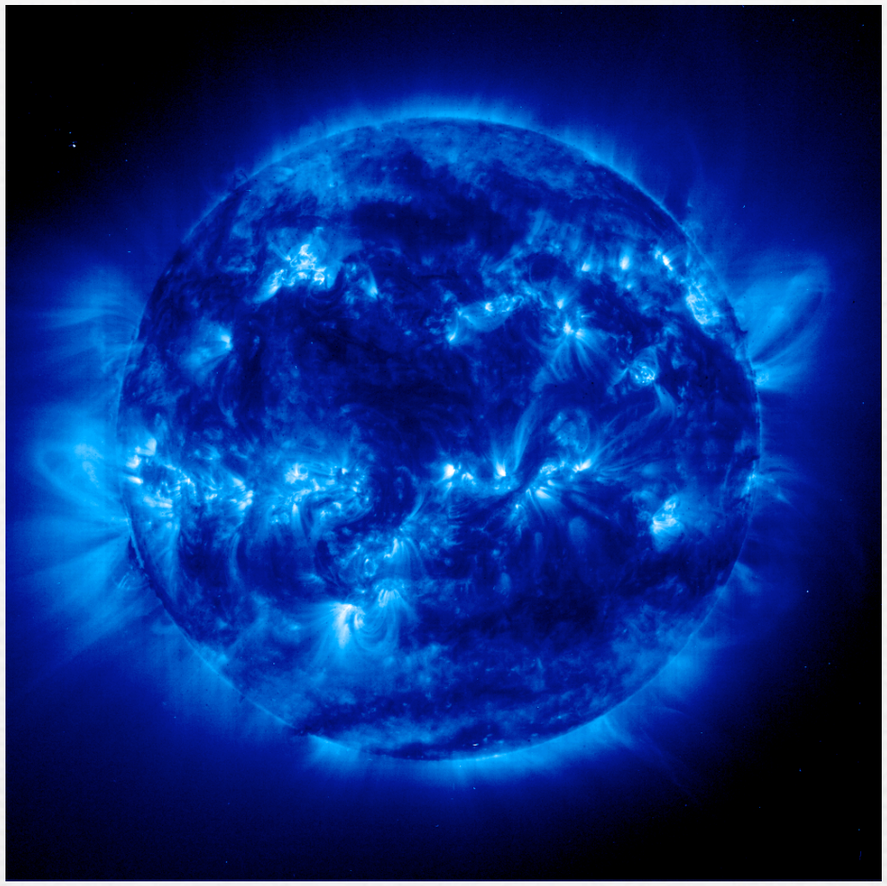




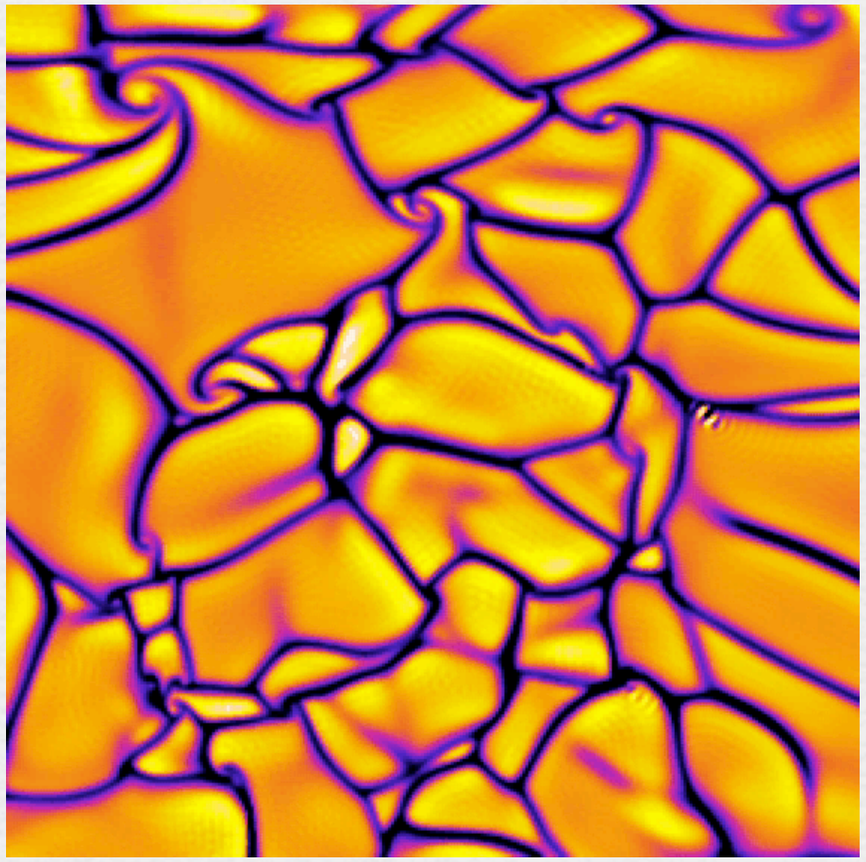


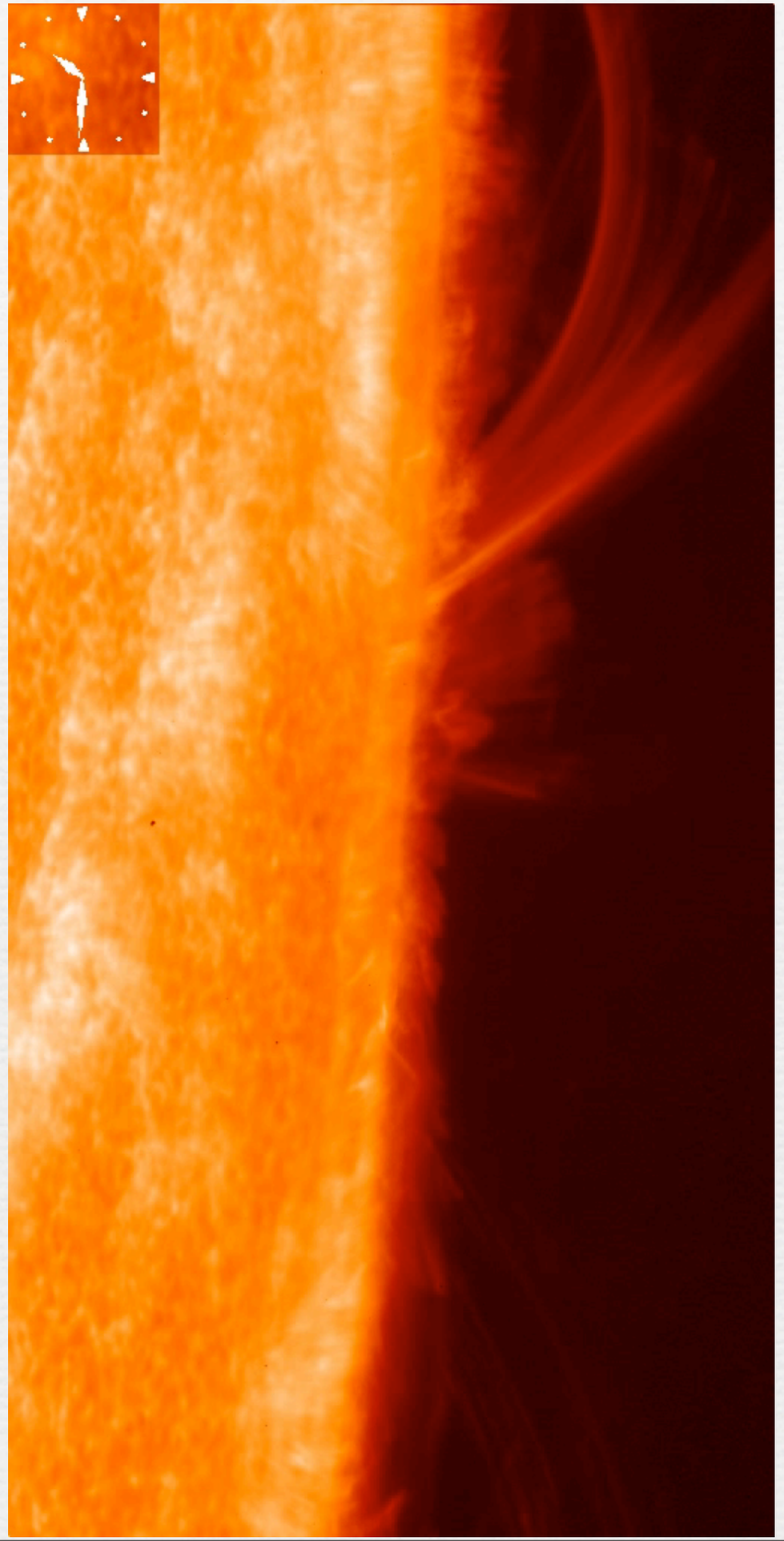
Featherstone, Brun, Browning & Toomre (2007)

Summary and Outlook



- **A Vibrant Sun**
  - Magnetism!
  - SOHO, TRACE, SST, Hinode, Stereo, SDO
  - Helioseismogy: Peering inside a star
- **Convection and Dynamo Processes**
  - Solar Cyclones, NS lanes
  - Differential rotation, meridional circulation
  - Sustained magnetic field generation
  - Pumping of fields into a *tachocline*
  - Amplification, organization by rotational shear
- **A Universe of Stars**
  - Astroseismology: CoRot, Kepler
- **Big computers may be used to tackle big problems!**





Next Generation ASH

- **Scalably Parallel**
  - High Resolution
  - Long time integrations
  - Finite elements?
- **Non-uniform grid**
  - Spherical geometry
  - Photosphere
  - Overshoot region & Tachocline
  - Time splitting?
- **Subsonic**
  - Poisson equation
  - Multigrid?
- **MHD**
  - Div(B) = 0