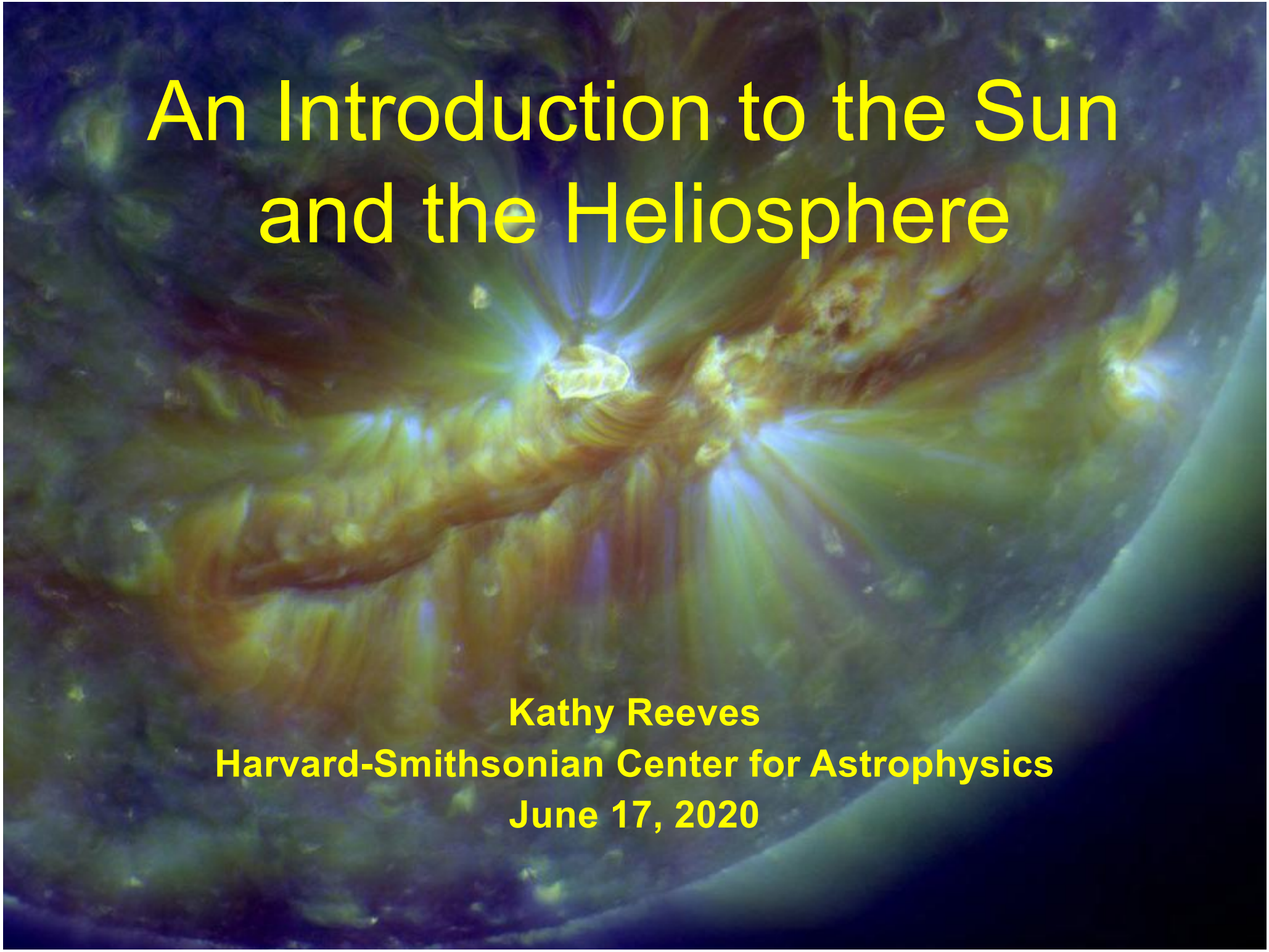


An Introduction to the Sun and the Heliosphere

Kathy Reeves
Harvard-Smithsonian Center for Astrophysics
June 17, 2020

About me

- From Colorado originally
- Undergrad degree in physics from Reed College (Portland, OR)
- Master's in Physics with a concentration in Optics from Northeastern University (Boston, MA)
- Started at Northeastern as a biophysicist, hated it
- Worked at CfA for three years as a research assistant in the Solar and Stellar X-ray Group
- PhD in physics from University of New Hampshire (Durham, NH)
- CfA again!

The Sun is made of plasma

- Plasma is ionized gas, and is electrically conductive
- Lightning, neon signs are other examples of plasma

The Sun as a star

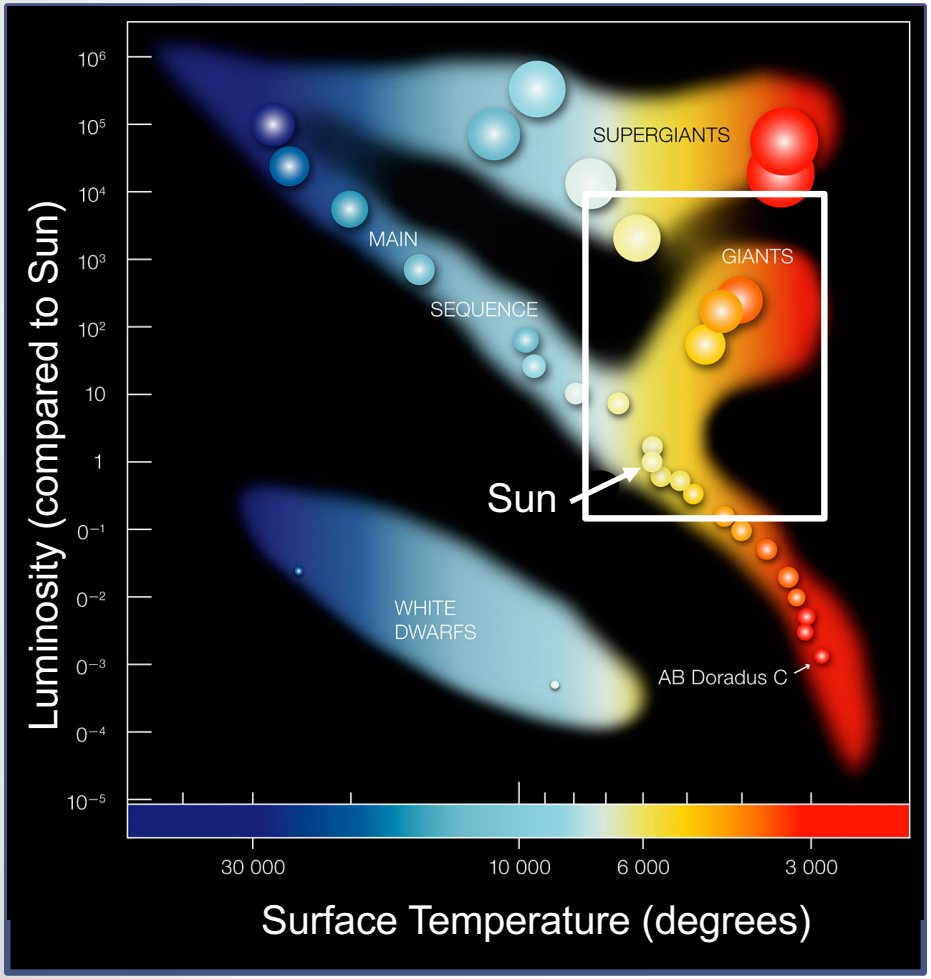
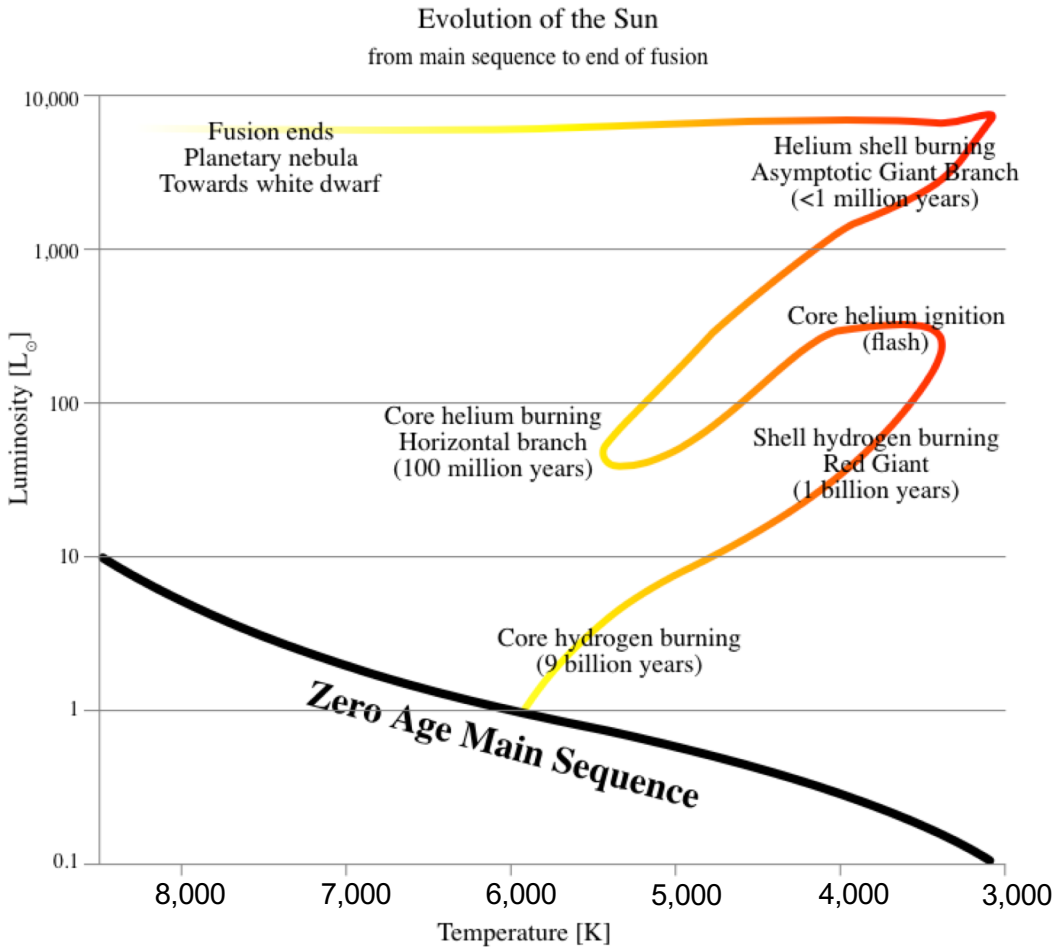
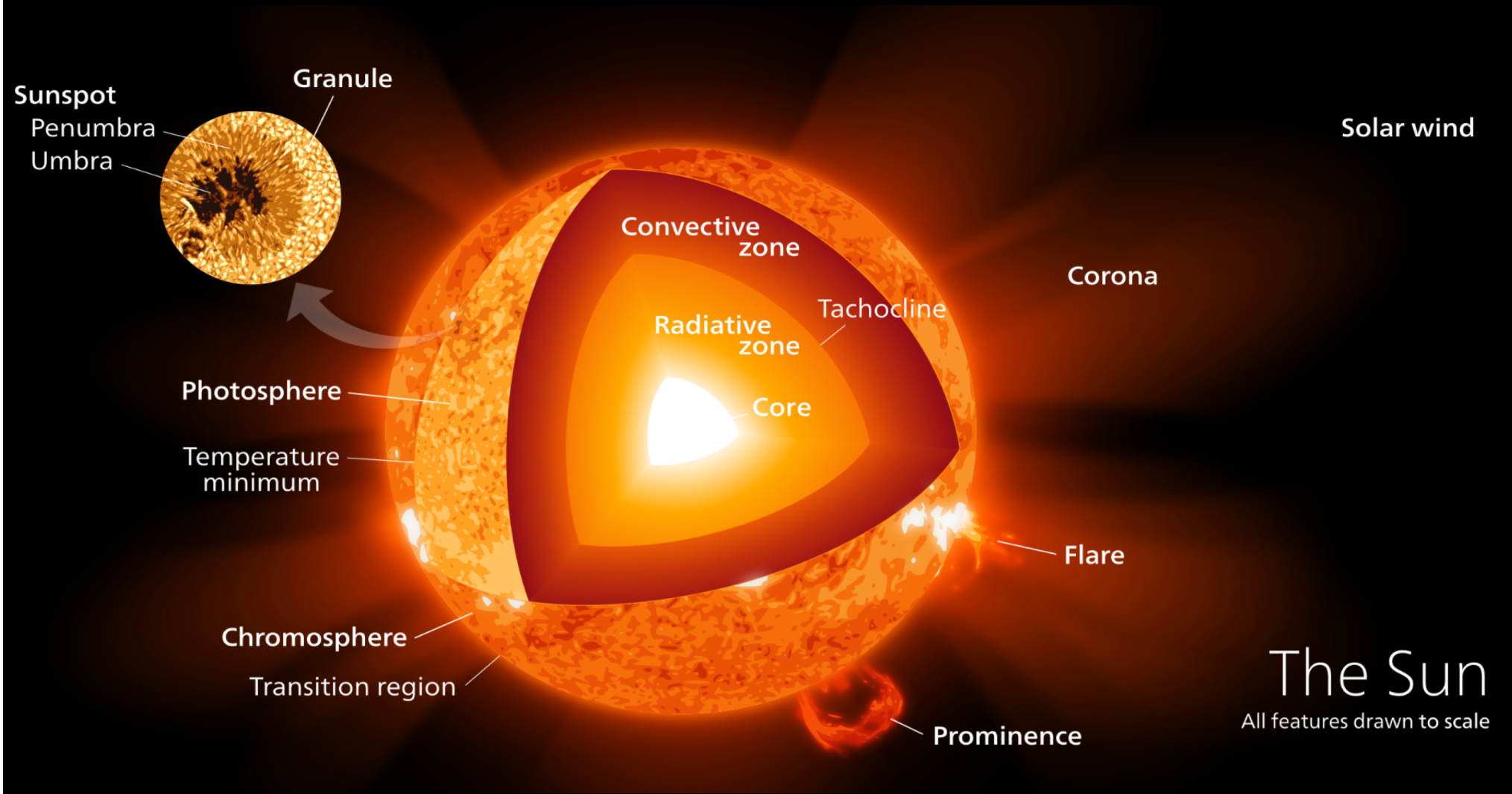


Image courtesy of the European Southern Observatory

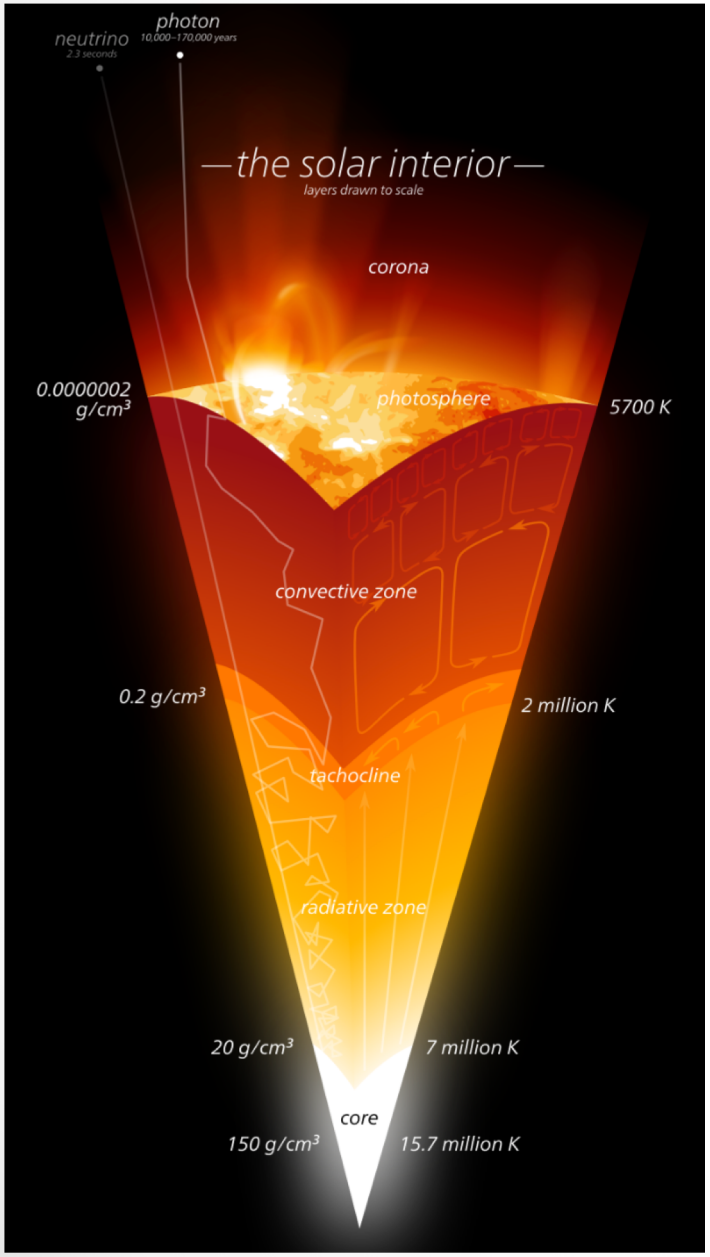


By Szczureq - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=34794215

Solar Anatomy



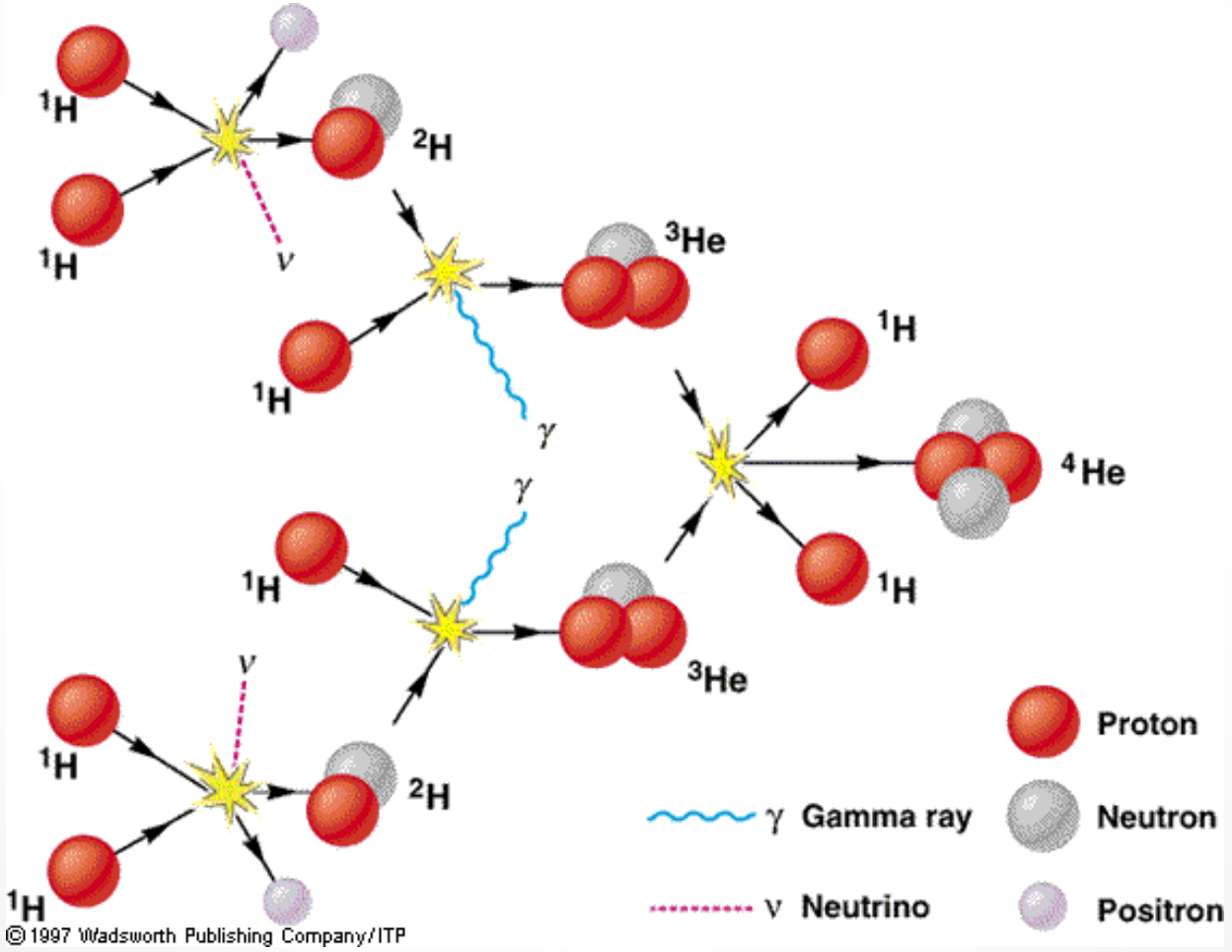
The solar interior



- **Core:**
  - Inner ~25% by radius
  - Region of nuclear fusion
  - T~15 MK
- **Radiative Zone:**
  - 0.25-0.7 $R_\odot$
  - Radiative energy transport
  - T=7MK→2MK
- **Convection Zone:**
  - 0.7-0.1.0 $R_\odot$
  - Convective energy transport
  - T=5700K
- **Atmosphere:**
  - T ≈1-5MK (20MK in flares)

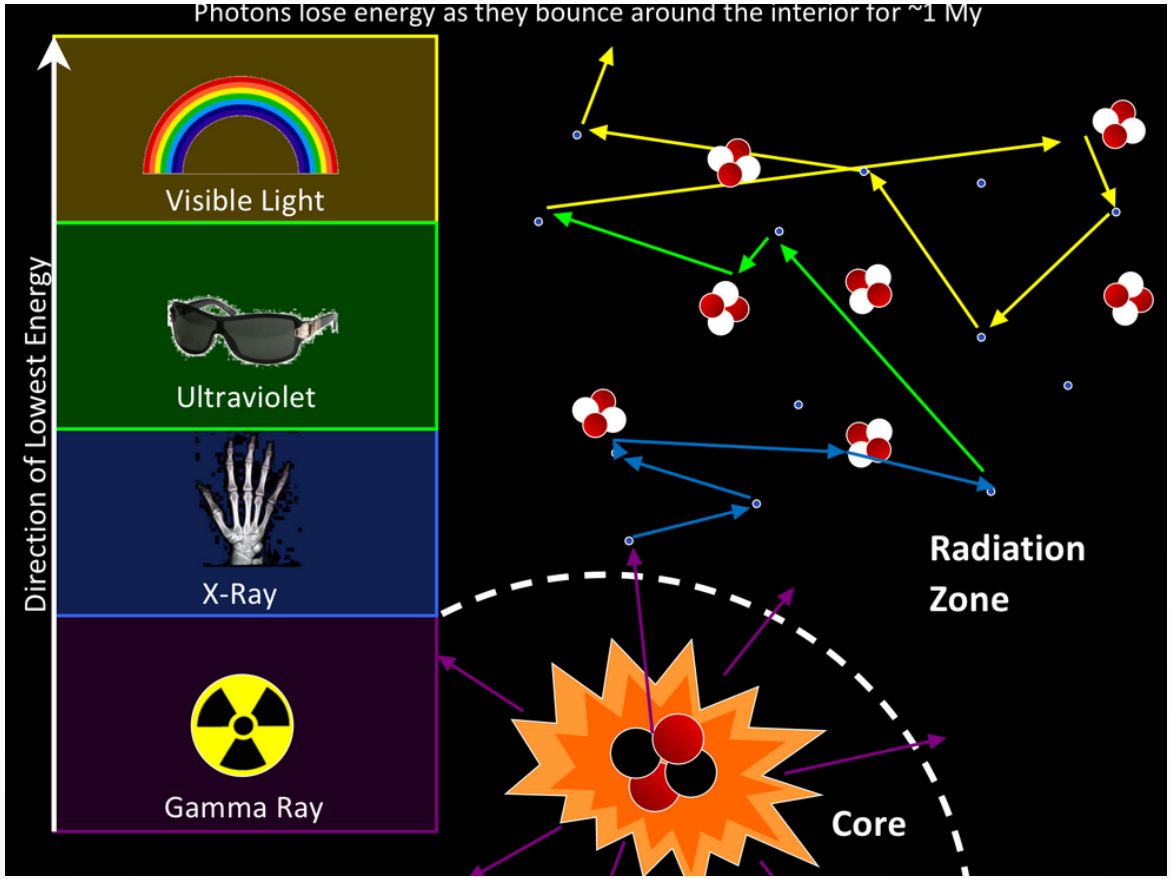
Core: Nuclear Fusion

- Proton-proton chain in the core



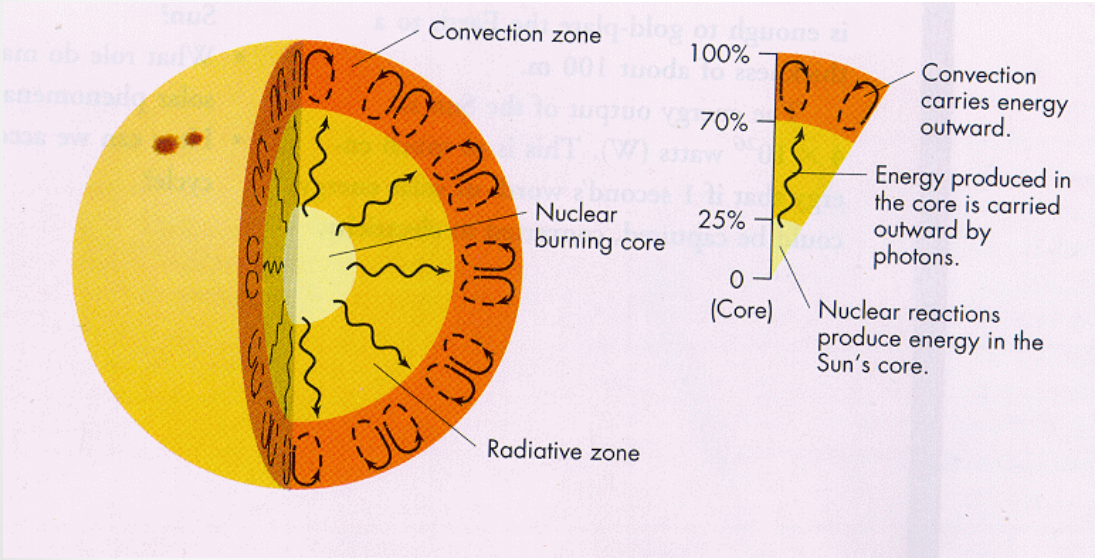
Radiation Zone

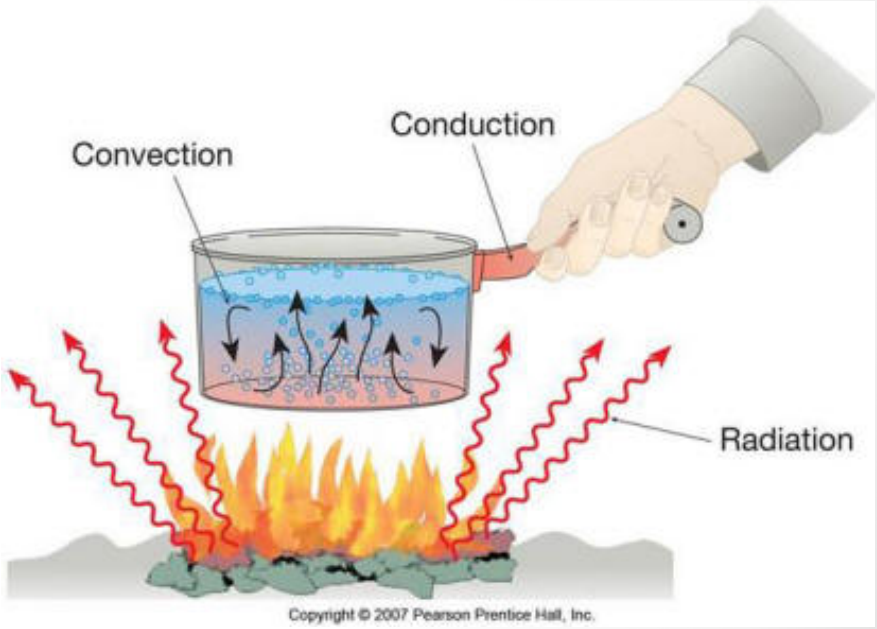
- Radiative transfer – random walk of photons



Convection Zone

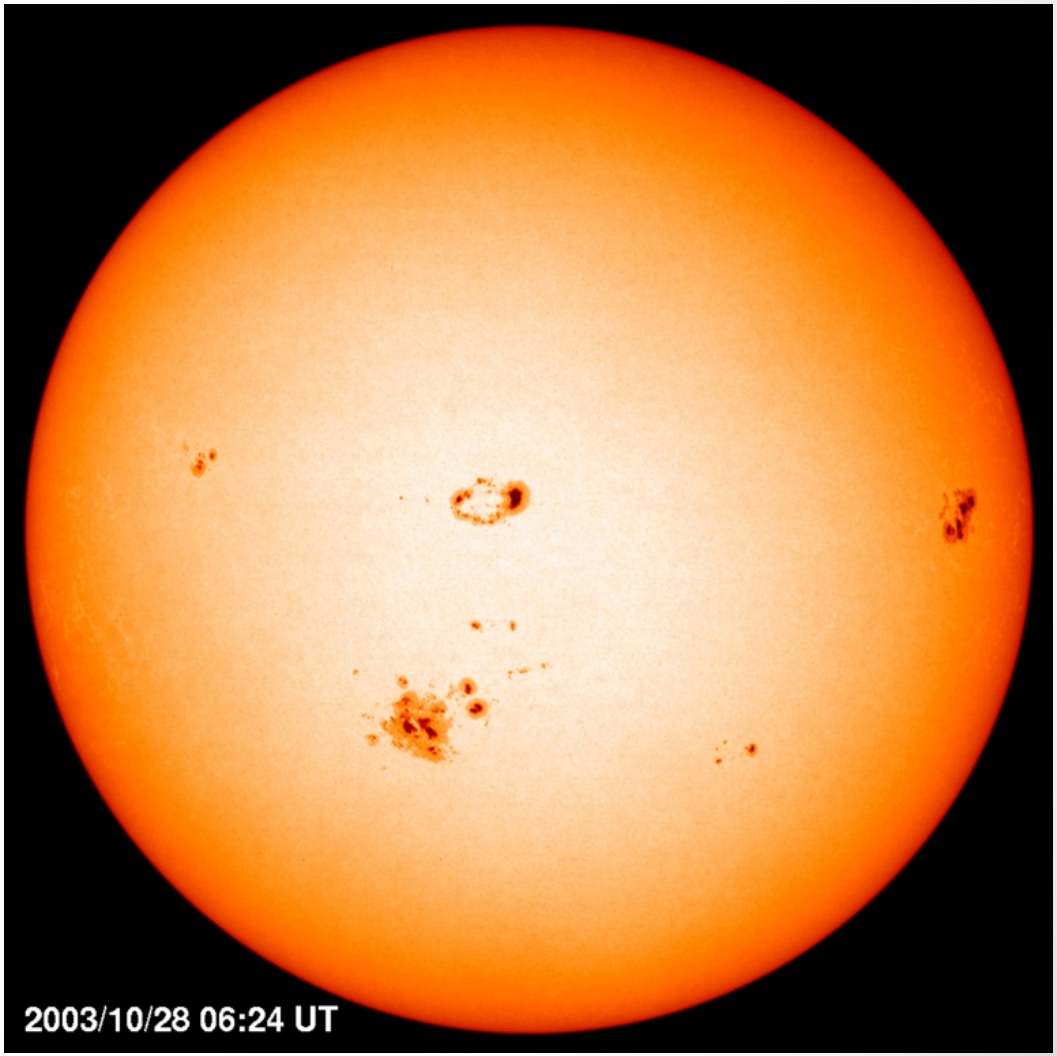
- Convection occurs when the temperature drops and opacity increases



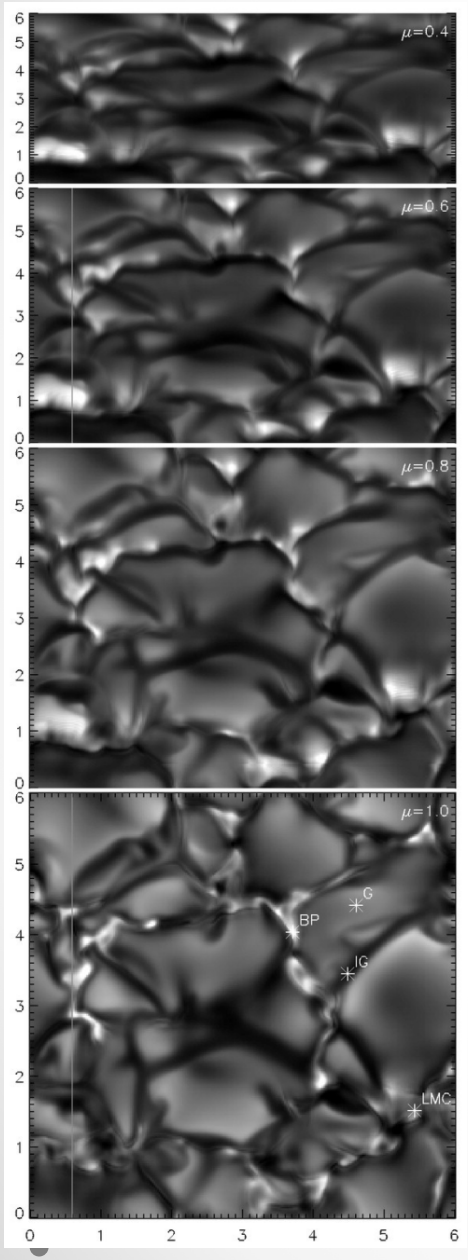


The photosphere

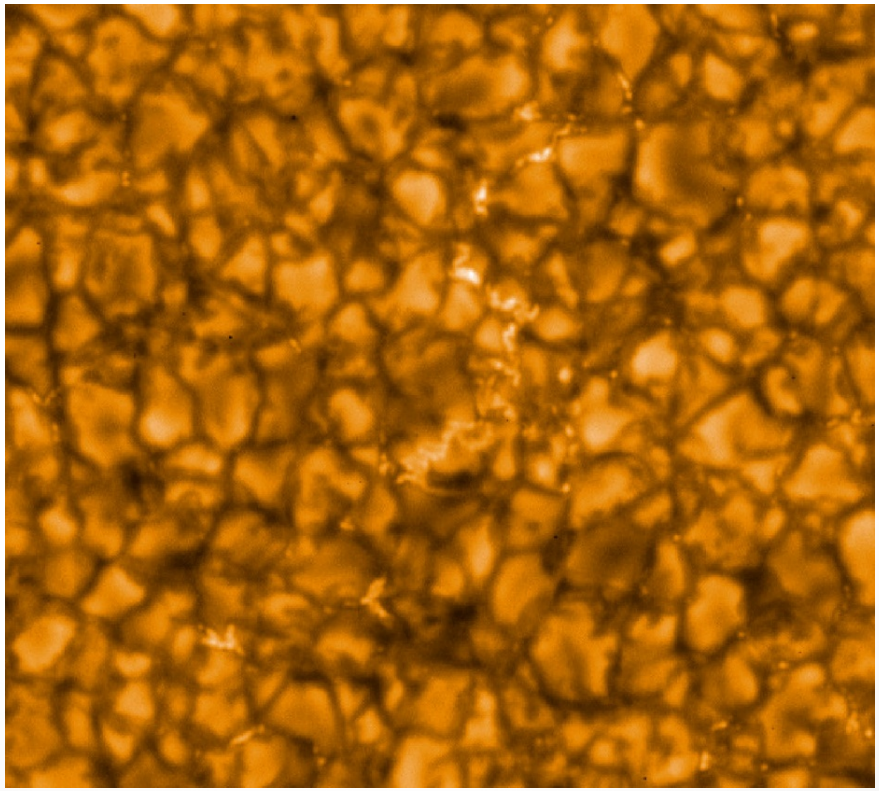
- The photosphere is the visible surface of the Sun.
- Temperature is between 4500 and 6000K with an effective temperature of 5750K.
- Photosphere is a high β plasma (gas pressure >> magnetic pressure).
- Magnetic fields are “frozen” to the plasma and move with it.



Granulation

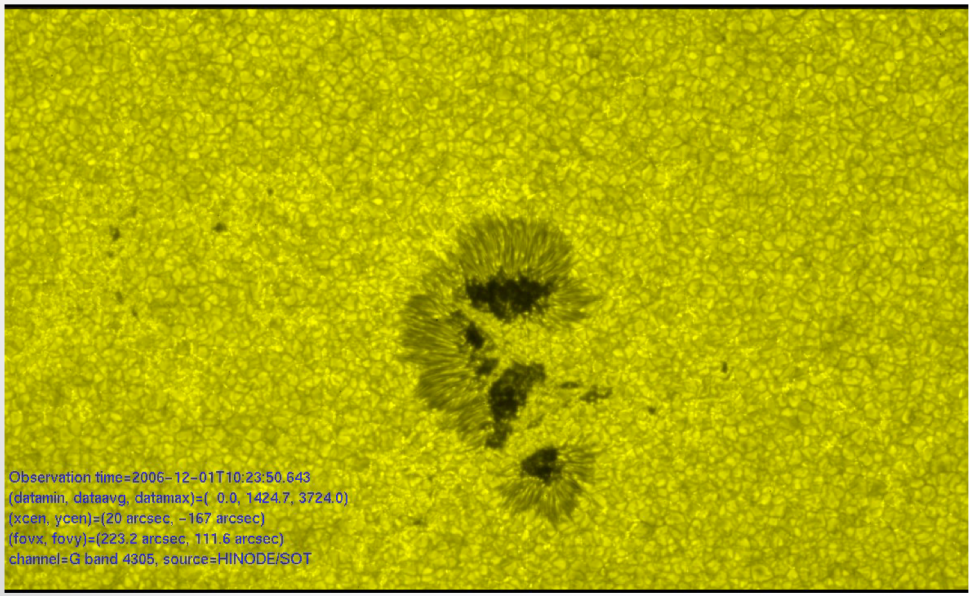


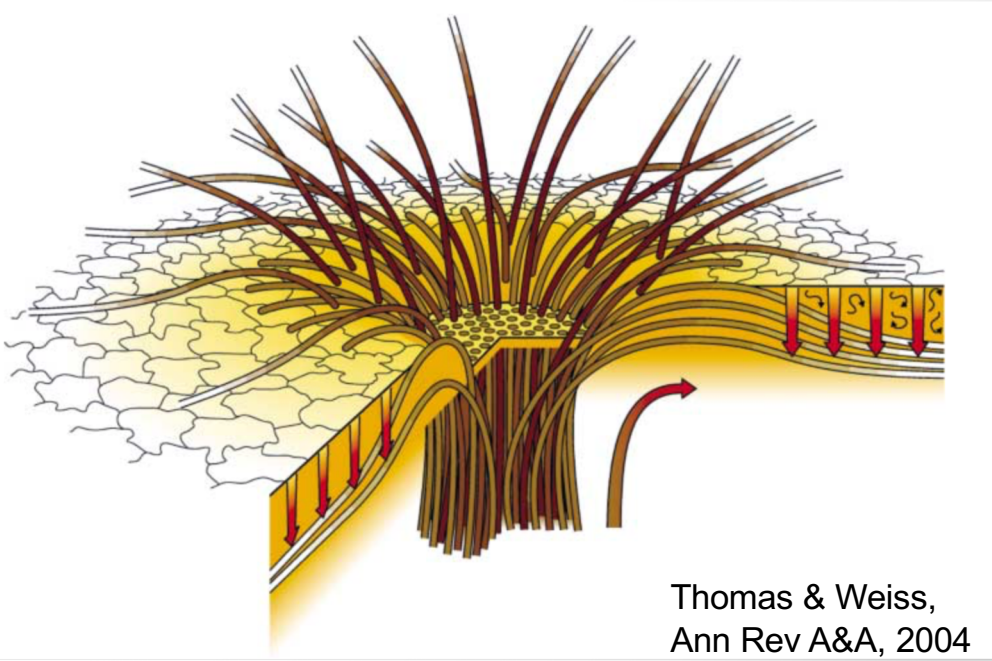
- The tops of convective cells
- Broad hot cells, and dark colder intergranular lanes
- Horizontal motions with v = 2-3km/s



Sunspots

- Arise from magnetic buoyancy in the convection zone
- Dark umbra with vertical magnetic field (B)
- Lighter penumbra with mostly horizontal B
- Cooler than the surrounding photosphere (4000-4500K)
- Convection is suppressed due to strong B (~3000G)

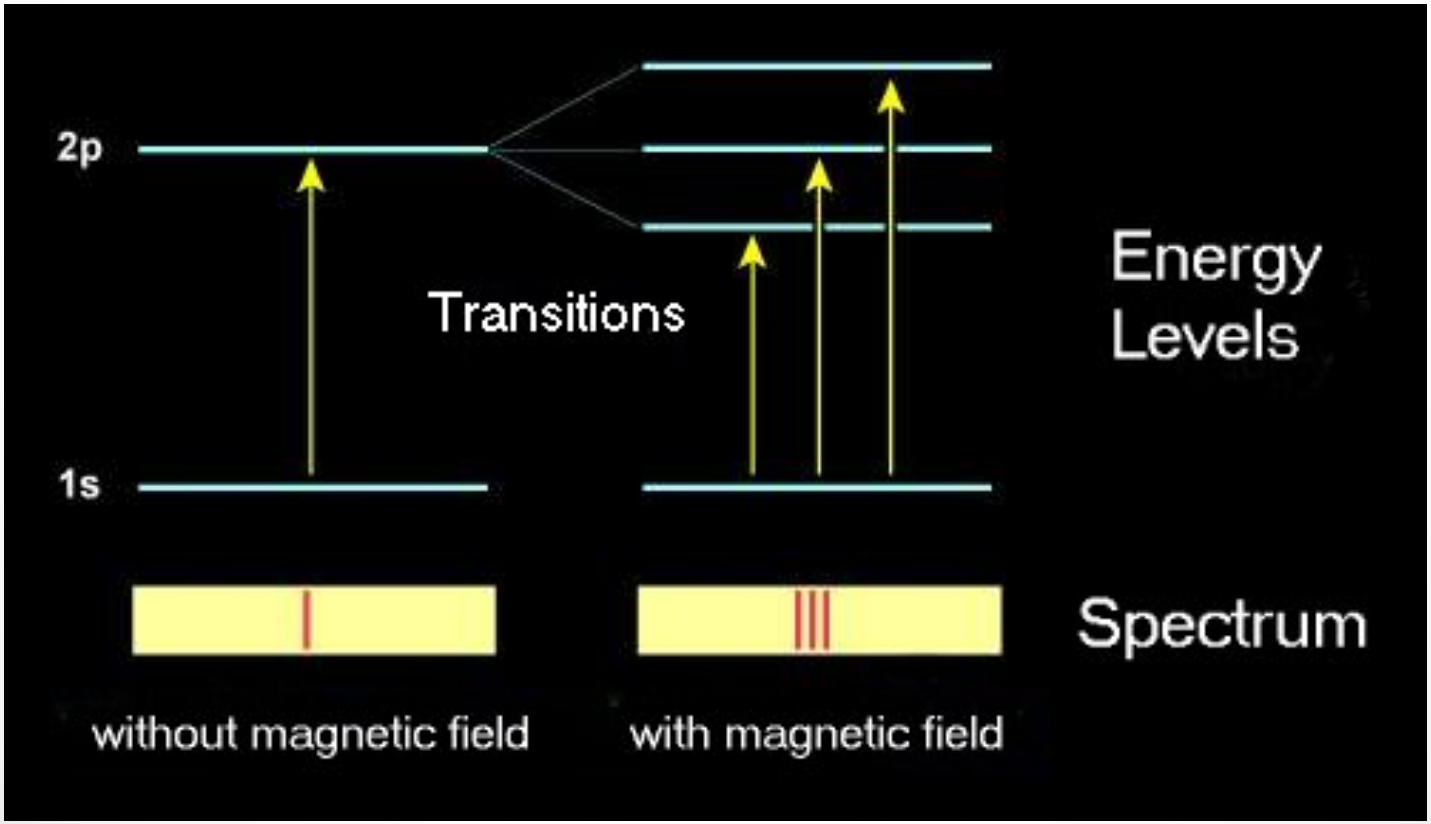




Thomas & Weiss,
Ann Rev A&A, 2004

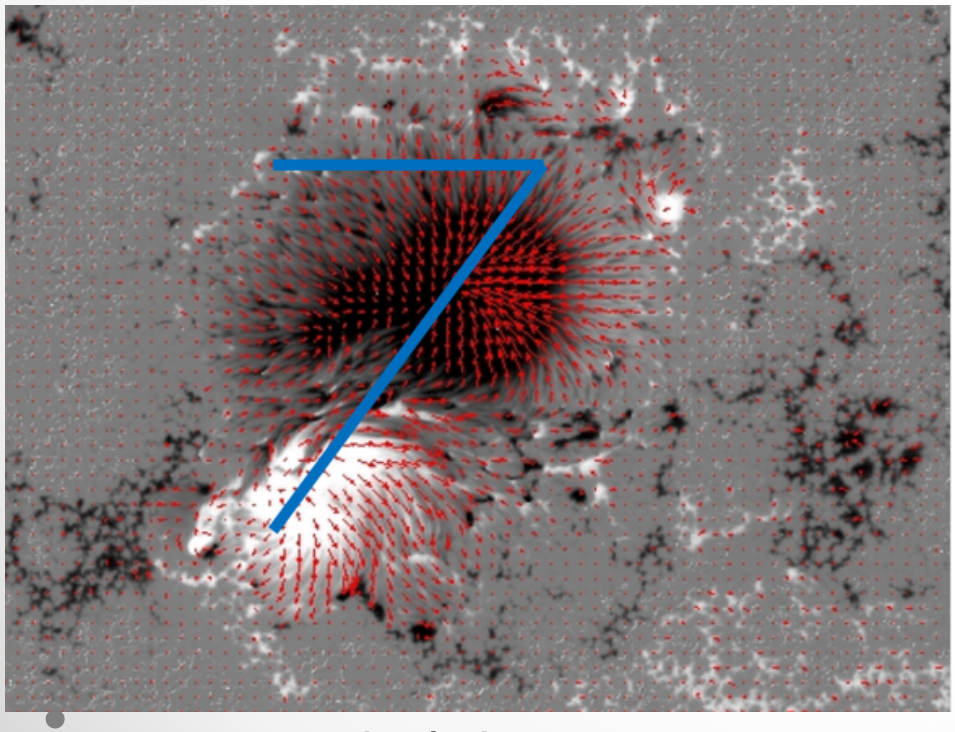
The Zeeman Effect

- Magnetic fields split energy levels, produce multiple spectral lines - discovered in 1897.
- George Ellery Hale discovers magnetic fields in sunspots using Zeeman effect (1908)

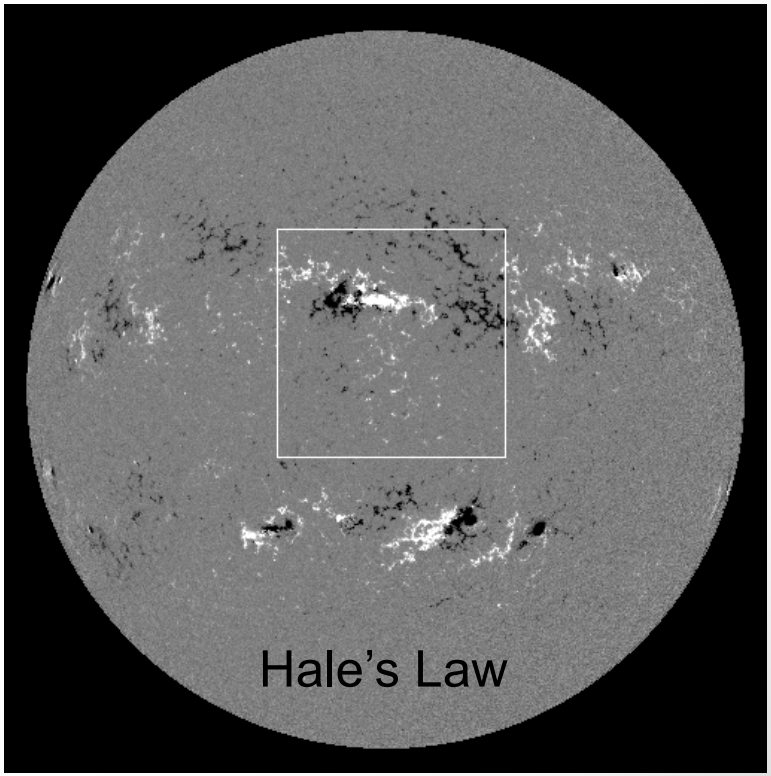


Magnetic field in sunspots

- Sunspots have systematic tilt, which increases with latitude (Joy's law).
- The leading/trailing sunspot polarity orientation is opposite in the two hemispheres (Hale's law).



Joy's Law



Historical observations

- Galileo observed sunspots in the 1600s
- Heinrich Schwabe observed sunspots for 17 years (1826-1843), and proposed a 10-year sunspot cycle

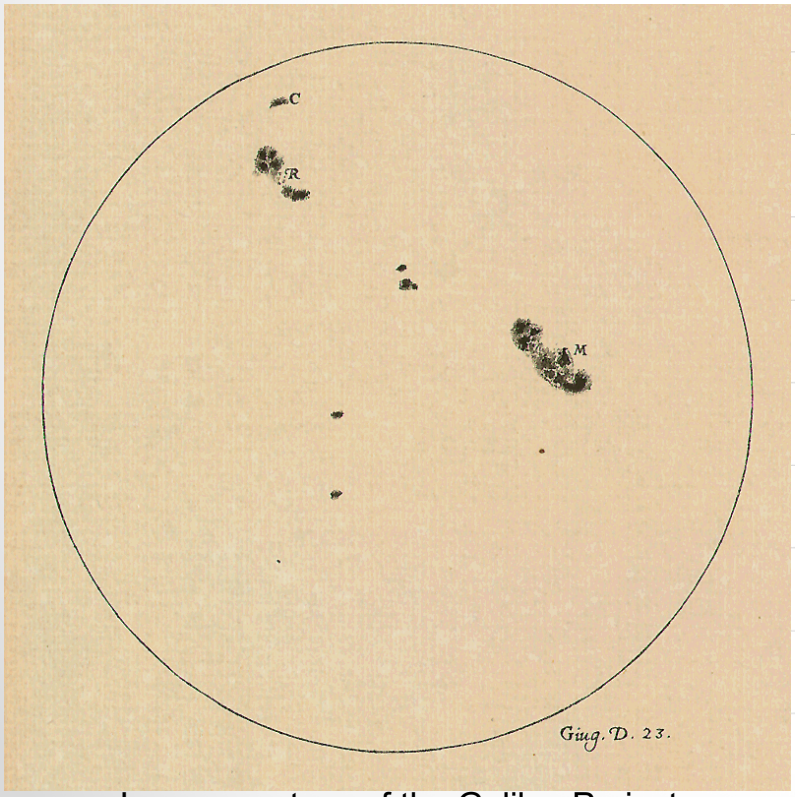
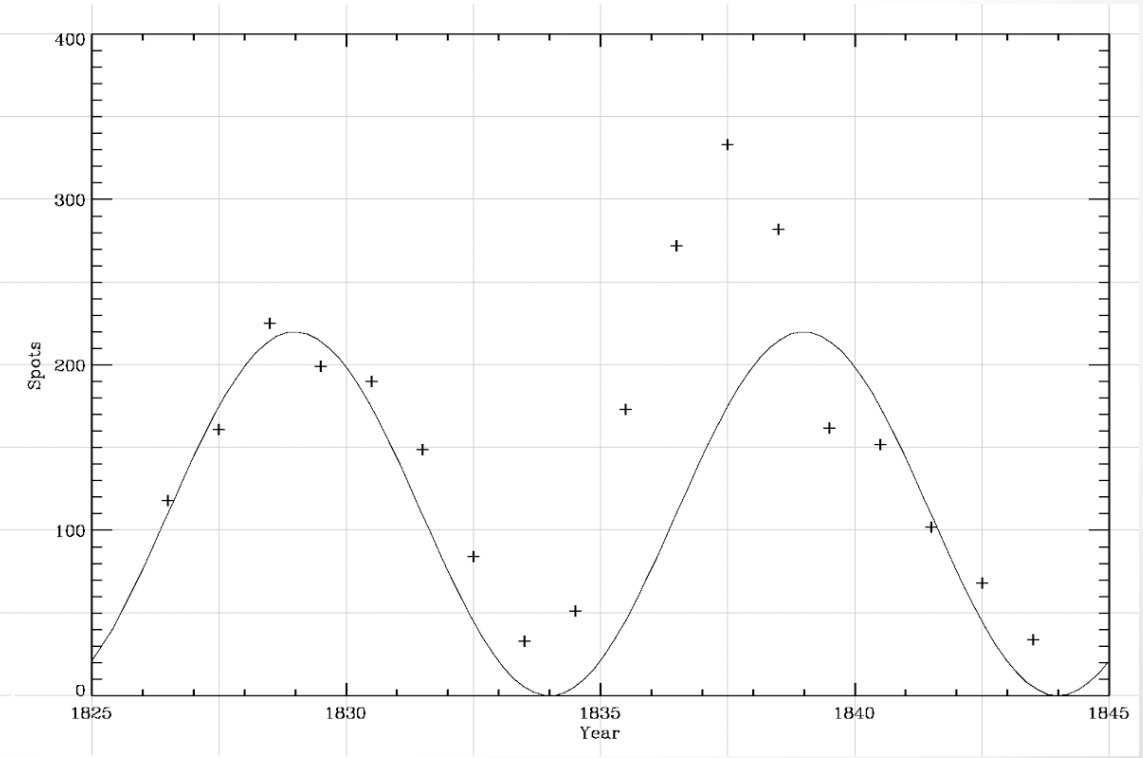
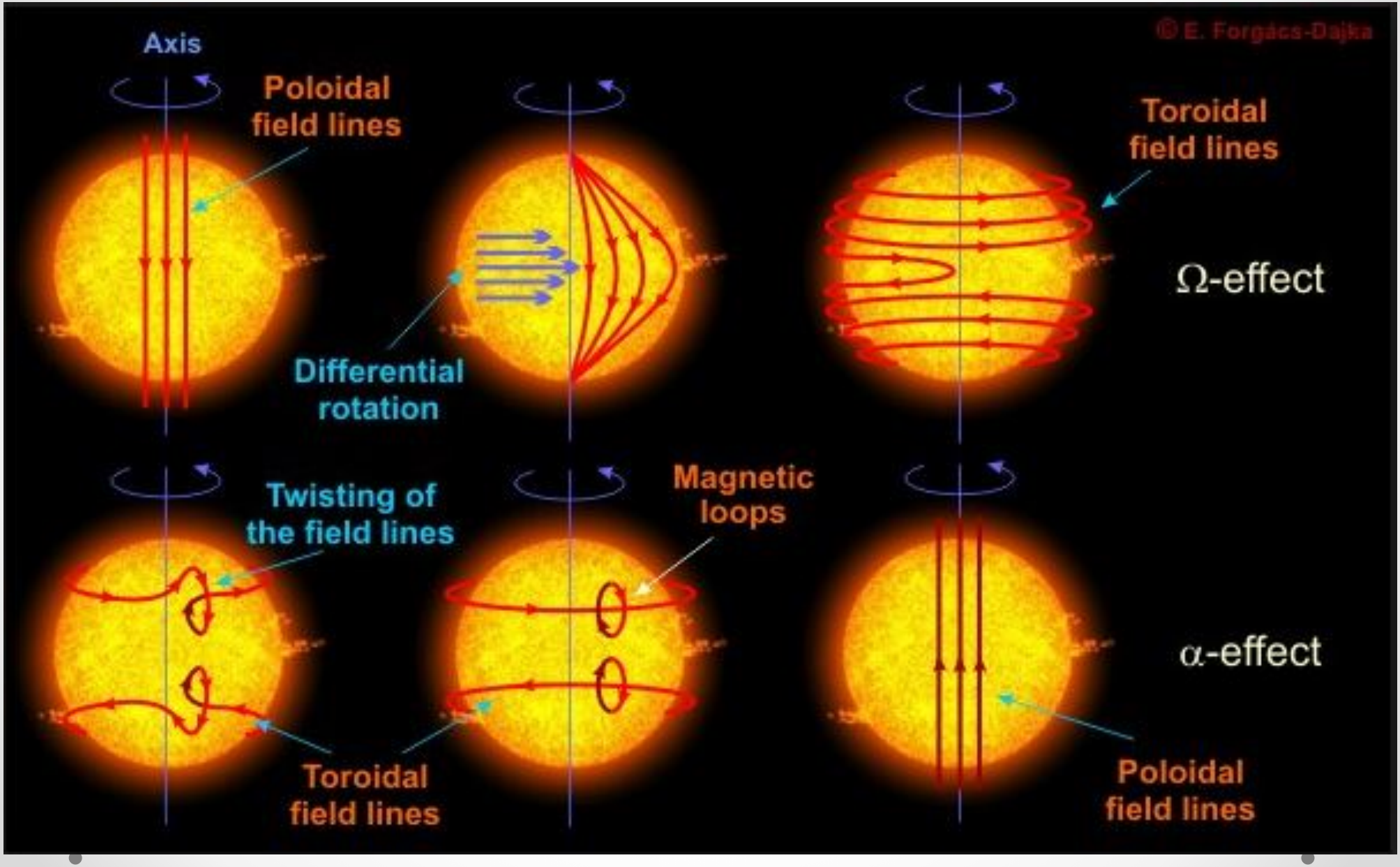


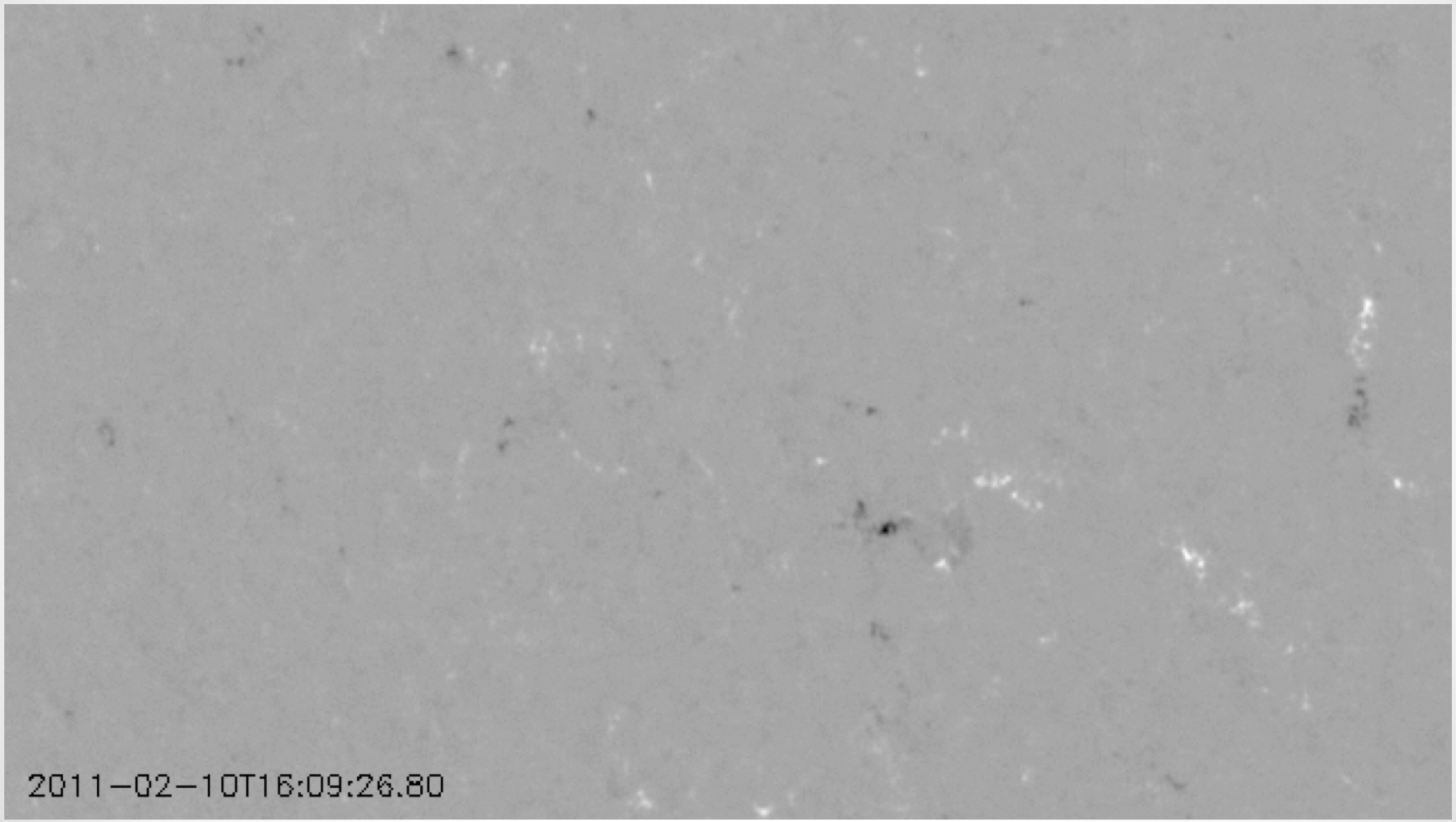
Image courtesy of the Galileo Project



Solar cycle origins



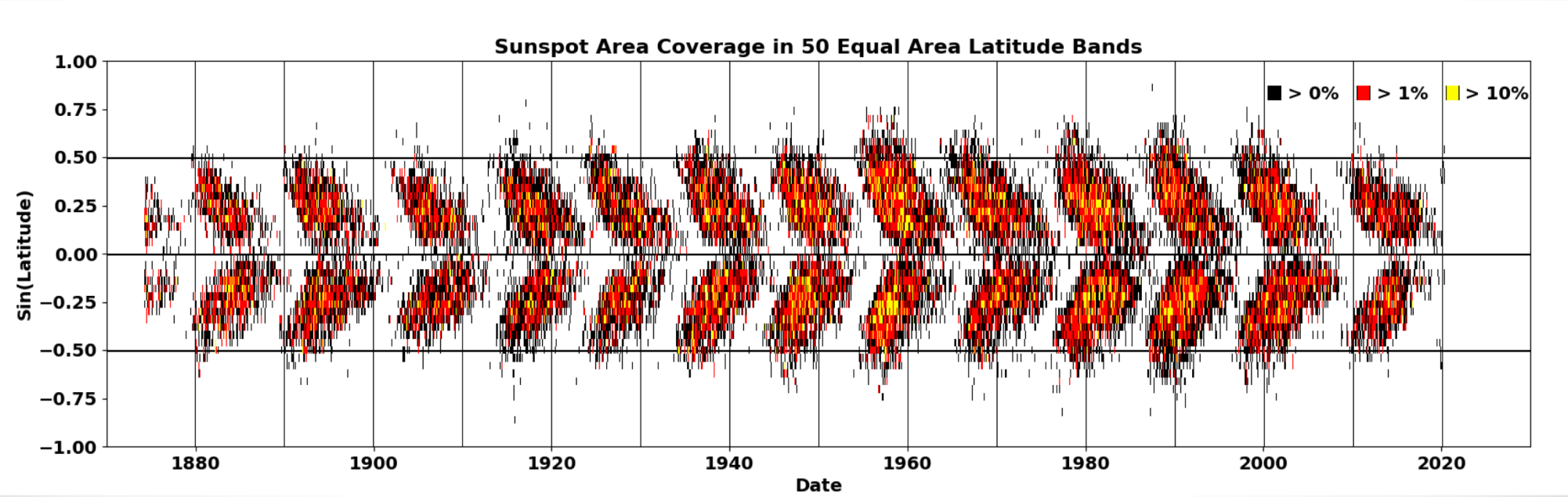
Formation of sunspots



NASA SDO/HMI

A more systematic look

Active regions appear at around 30° latitude, then migrate toward equator. Old and new cycles can overlap.

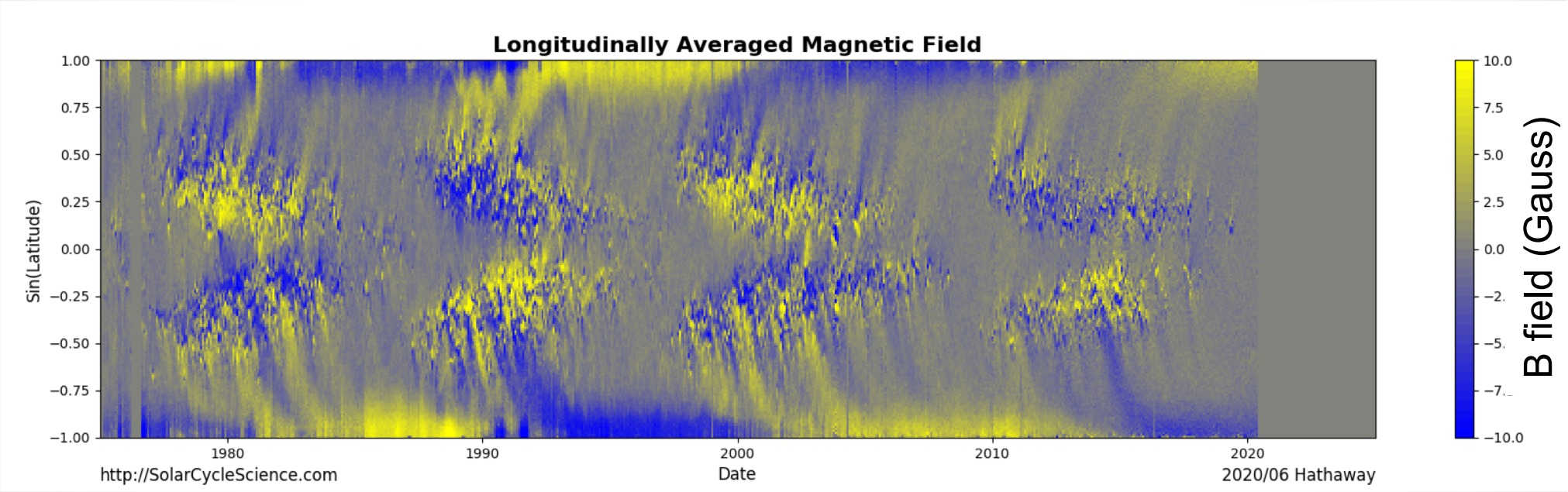


Butterfly Diagram

Images from http://solarcyclescience.com/solarcycle.html

A more systematic look

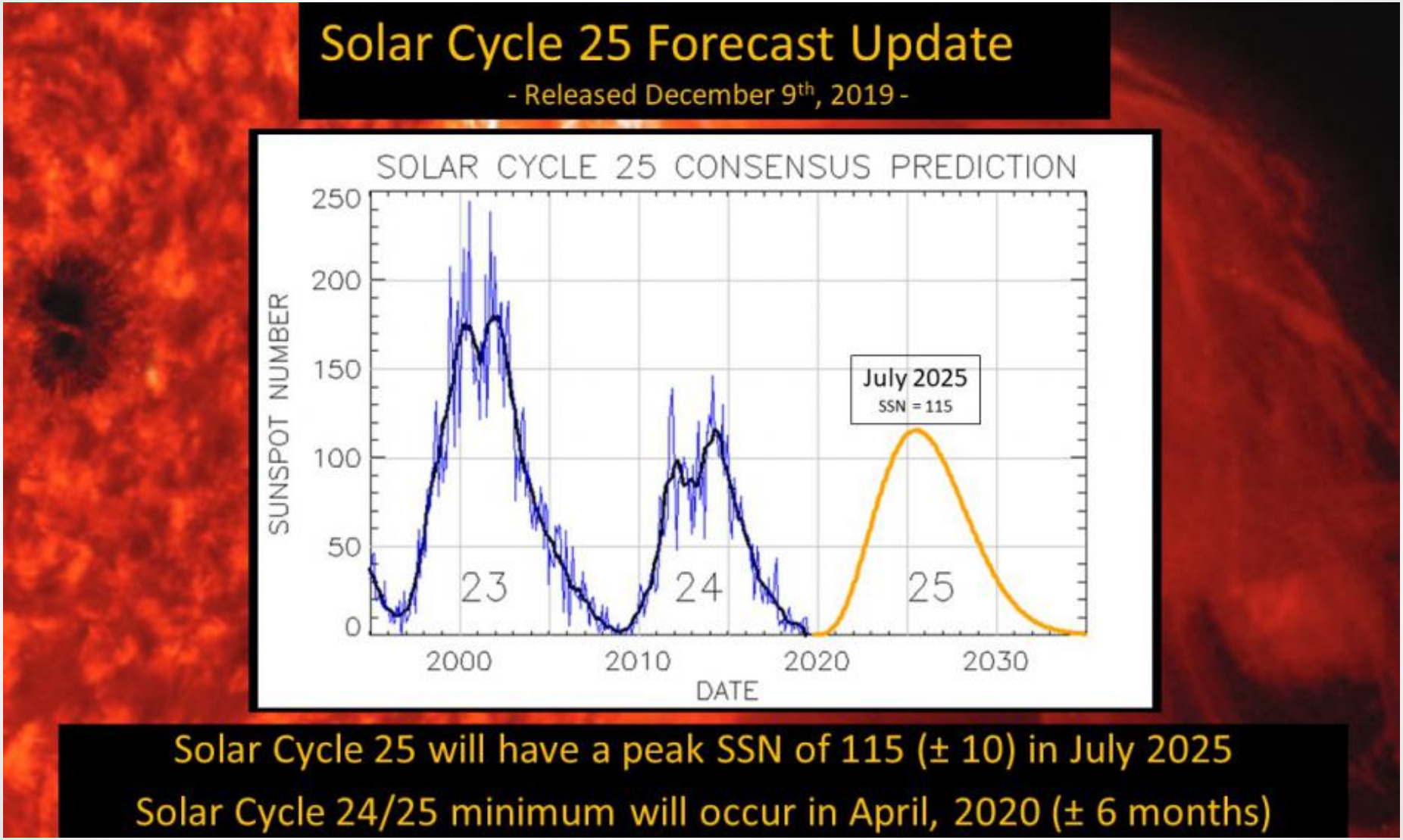
Active regions appear at around 30^{o} latitude, then migrate toward equator. Old and new cycles can overlap.



Magnetic Field

Images from http://solarcyclescience.com/solarcycle.html

Solar cycle 25 forecast

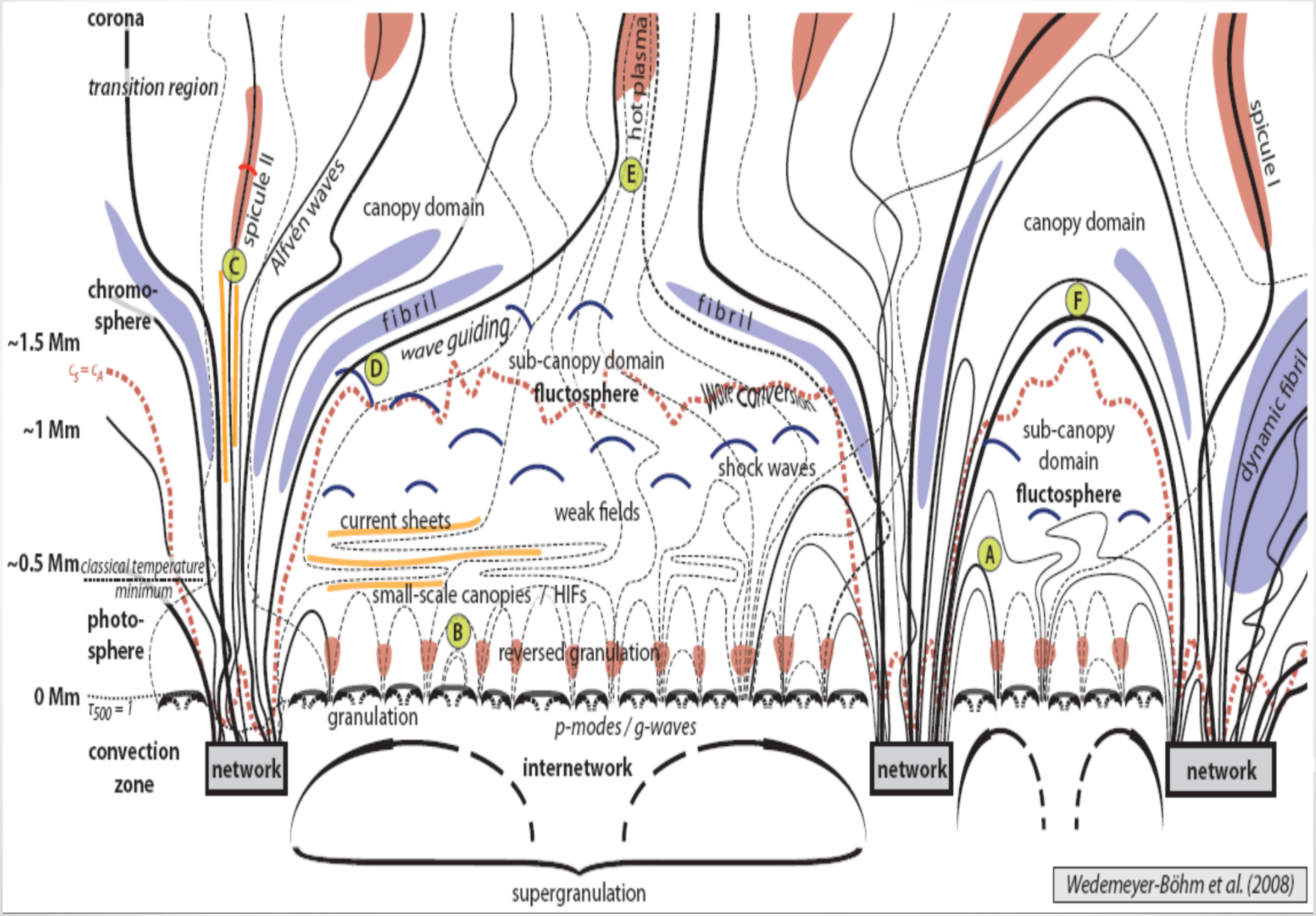


https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update

Chromosphere

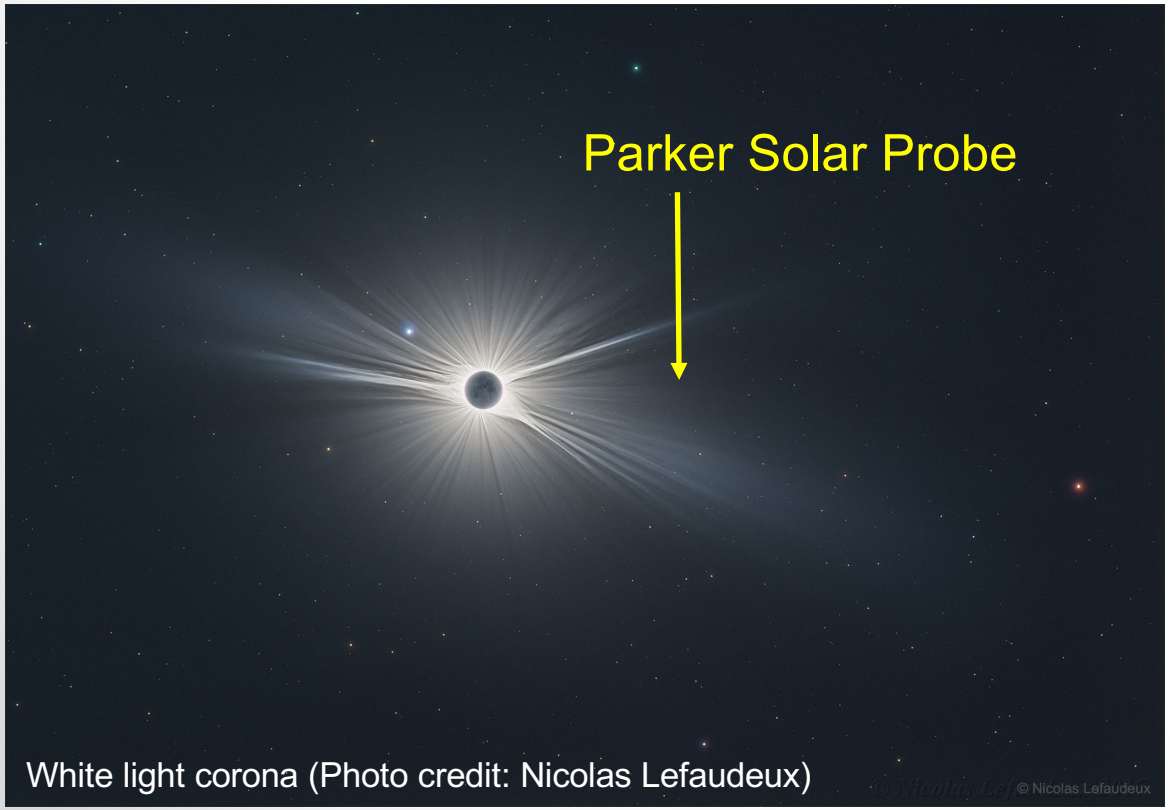
- Name comes from strong red color produced by Hα emission (“chromo”=“color”)
- Temperature increases, density decreases
- Plasma transitions from high β (fluid-dominated) to low β (magnetically dominated)

Chromosphere

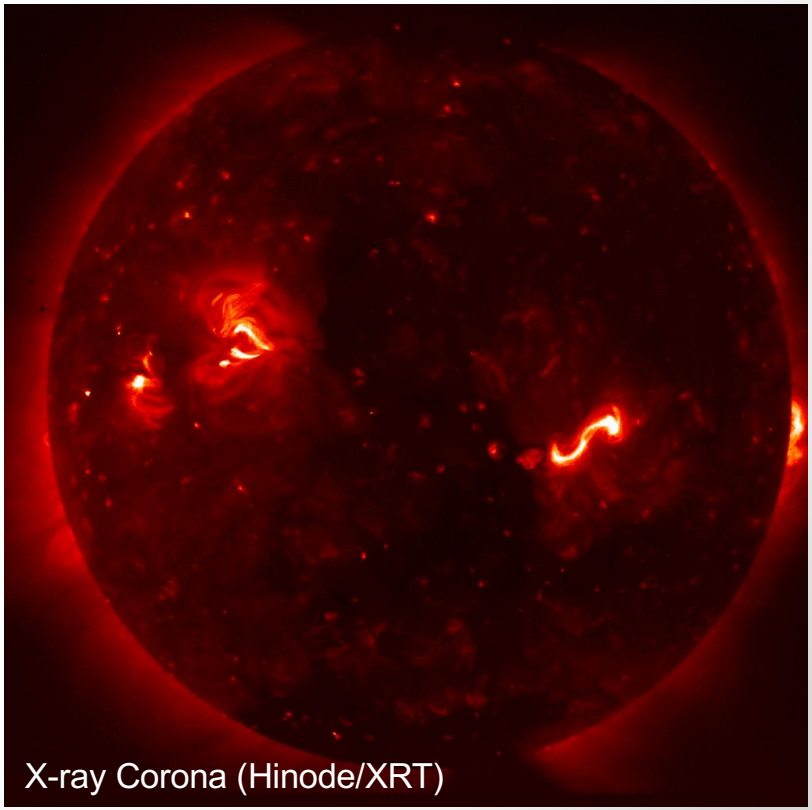


Corona

- Extends into interplanetary space
- Studied in white light from eclipses and coronagraphs
- Visible from space in X-rays (Hinode/XRT) and extreme UV (SDO/AIA)

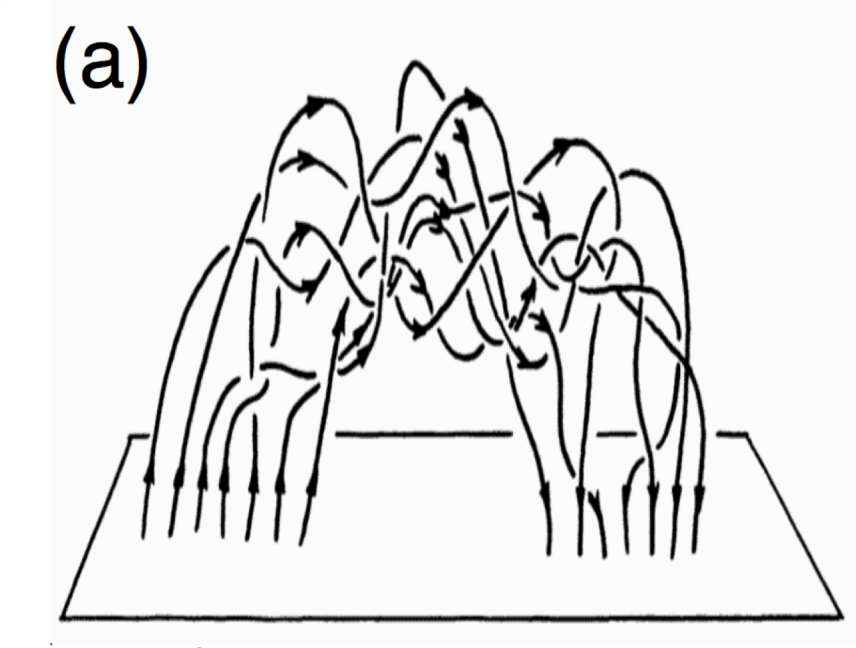


White light corona (Photo credit: Nicolas Lefaudeux)

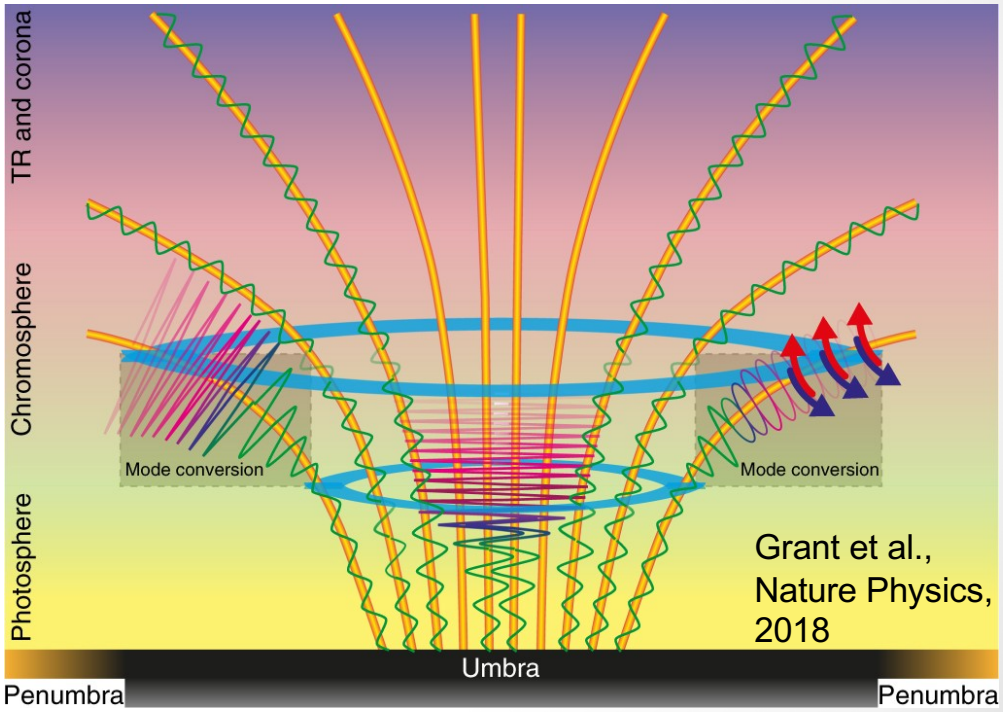

X-ray Corona (Hinode/XRT)

Coronal heating problem

- The corona is 1-2 MK. The photosphere is ~6000K.



Parker, E. Solar Physics, 1989

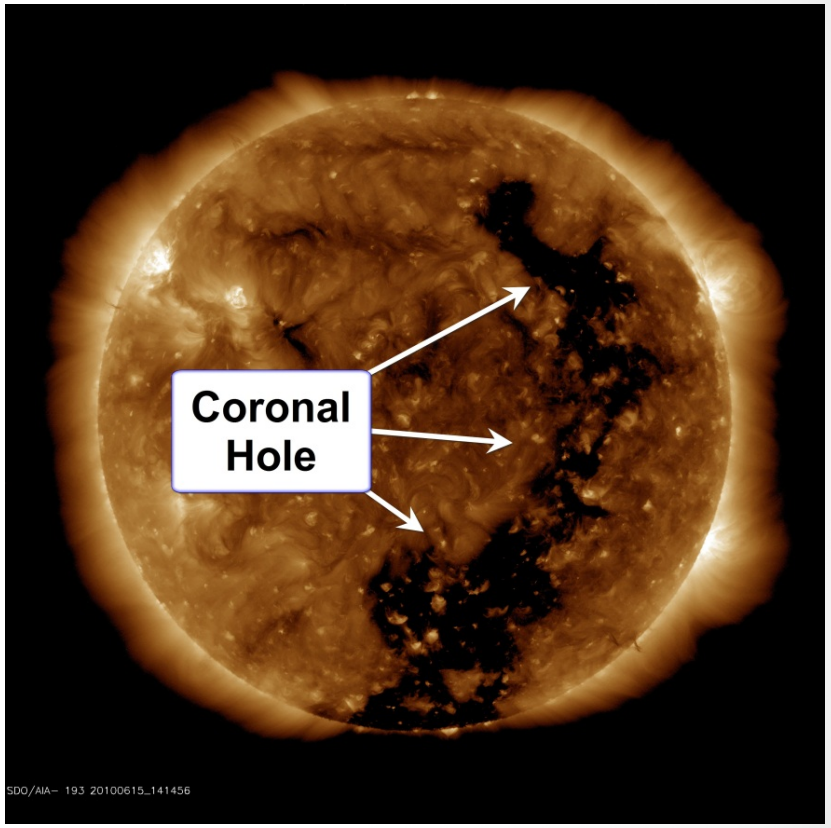


Nanoflares: Many small, tangled field lines reconnect, releasing energy

Waves: Upward moving waves generated in the photosphere deposit energy in the upper atmosphere.

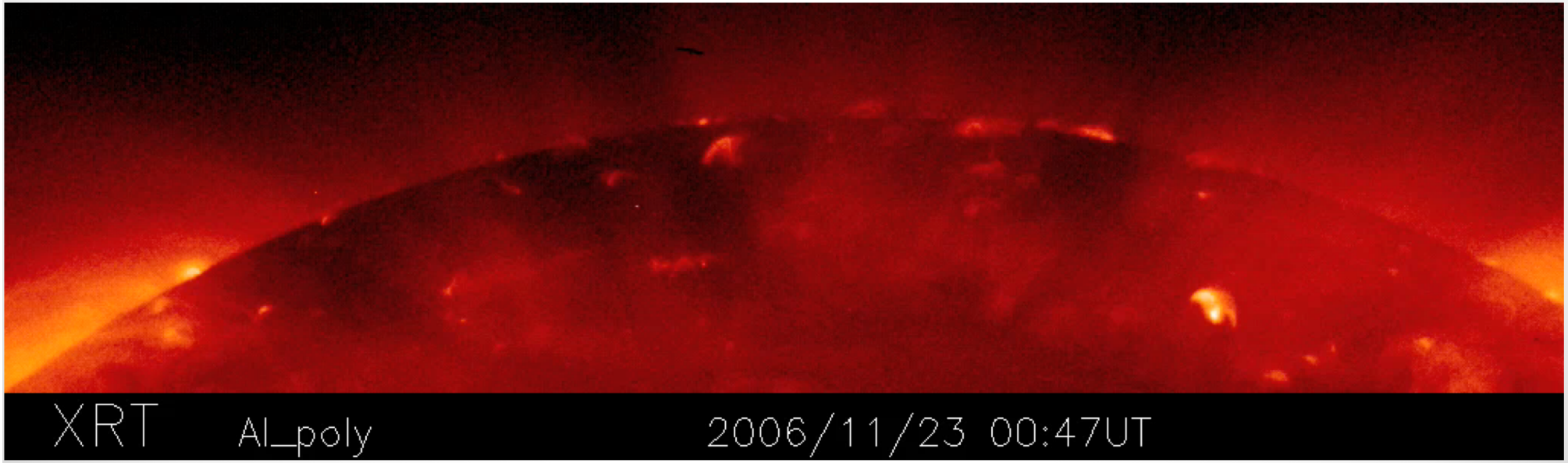
Coronal holes

- Dark regions in X-rays and EUV
- Low temperature and density
- Regions with open magnetic field
- Sources of the fast solar wind
- Commonly found at the poles during solar minimum, closer to the equator during active times



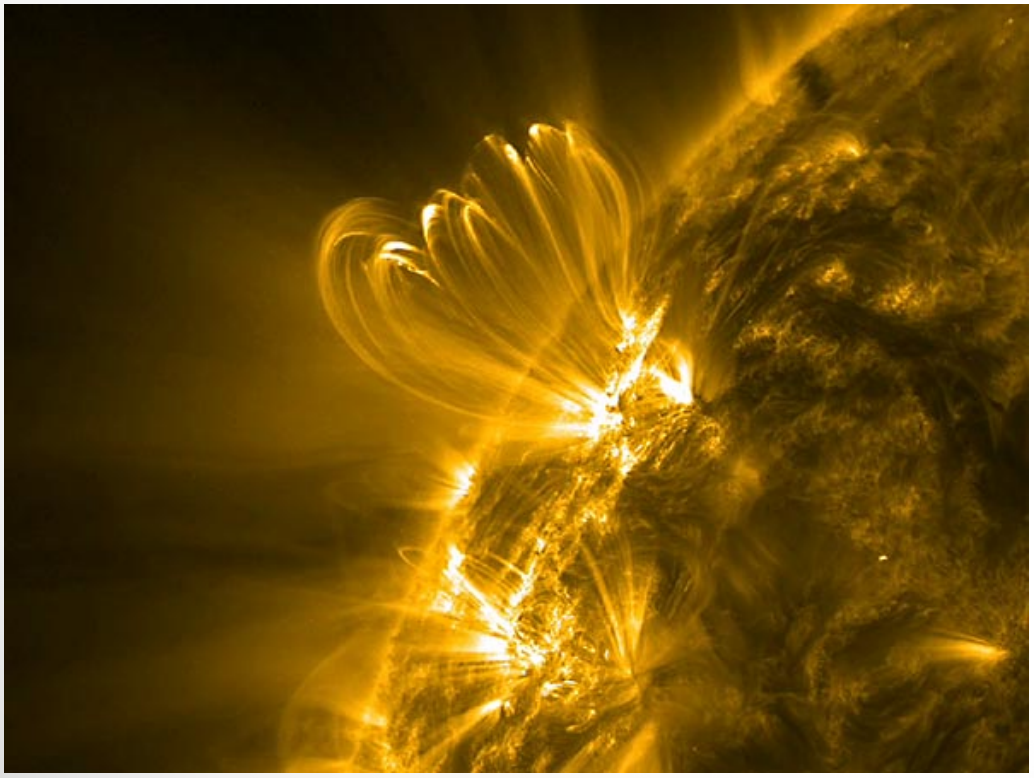
Bright points, coronal jets

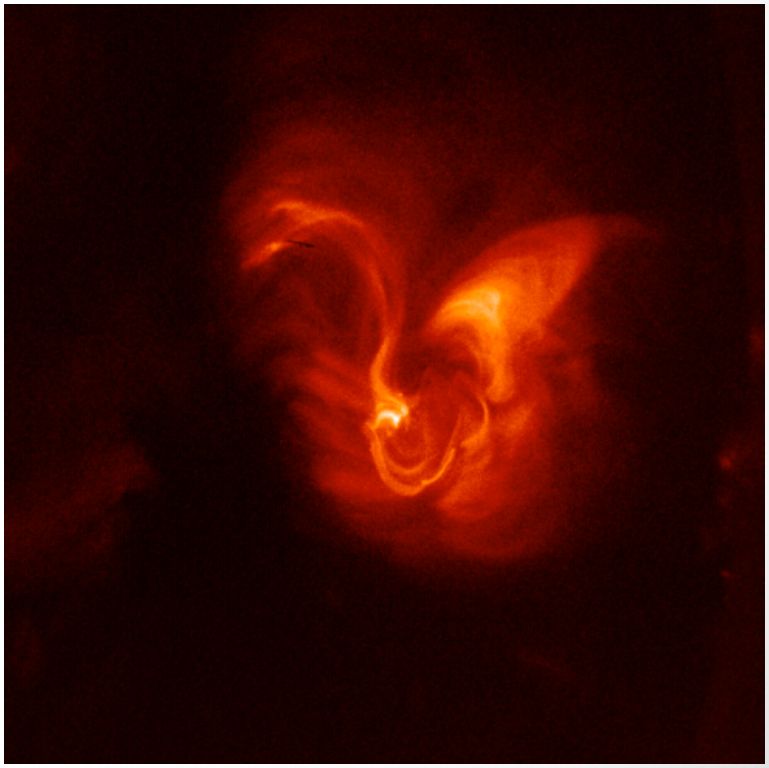
- Jets occur in small bipoles of magnetic flux
- Simple example of magnetic reconnection
- Velocities of 200-1000 km/s, lifetimes of 10s of minutes
- Ubiquitous in polar coronal holes



Active regions

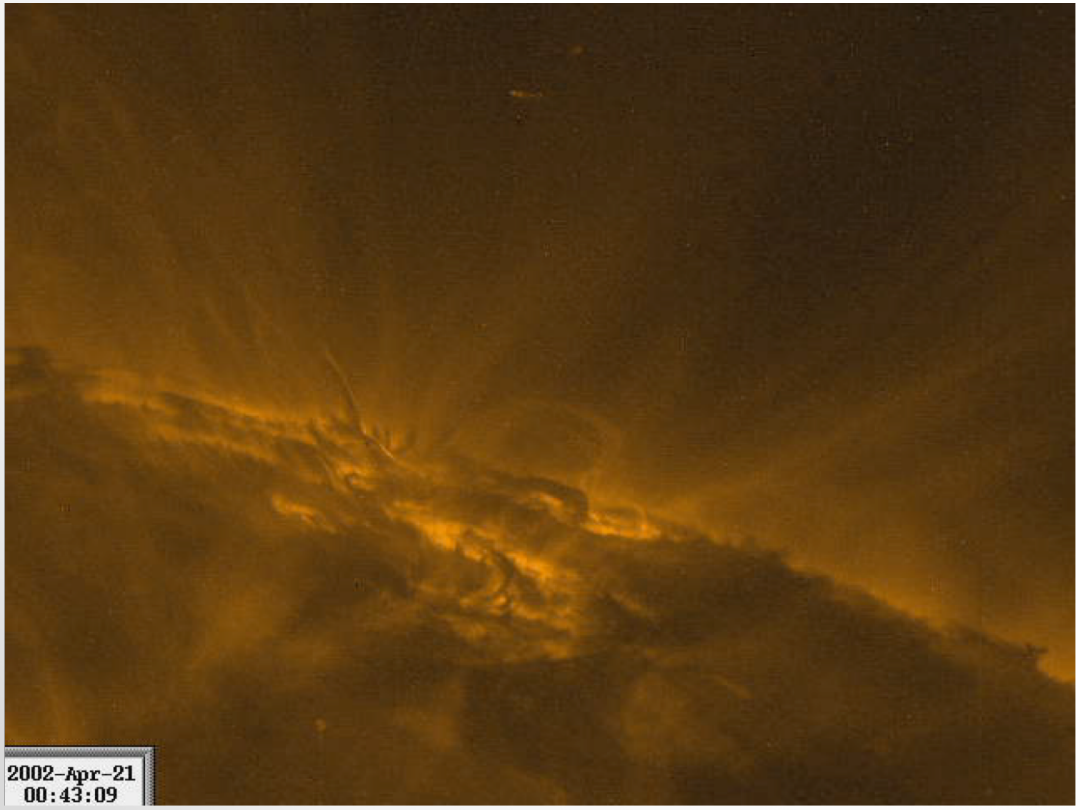
- Bright regions in the corona, higher density, temperature
- Associated with sunspots in the photosphere
- Composed of loops - plasma following along field lines

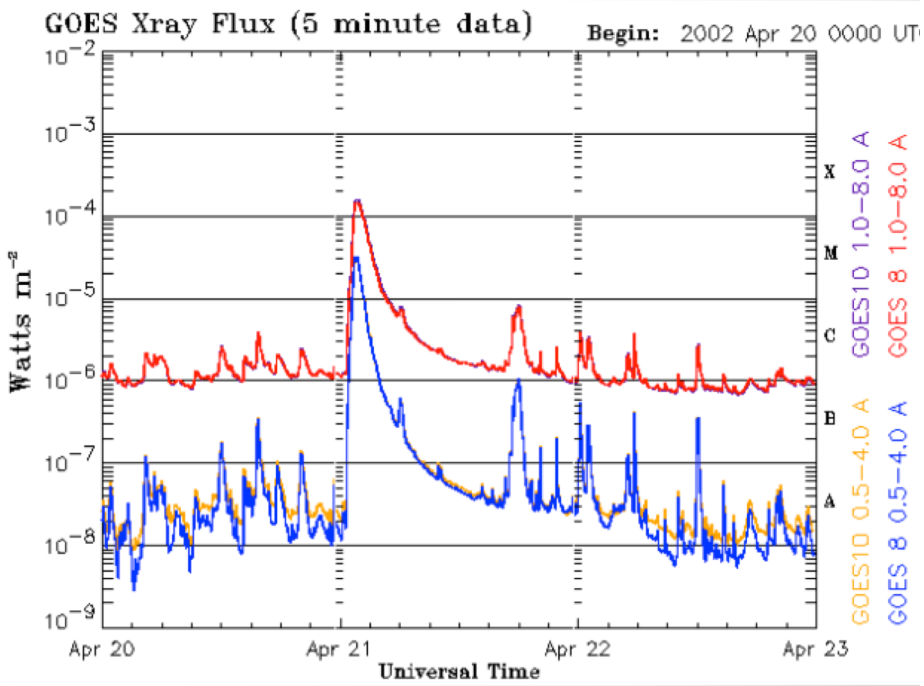




Solar flares

- Caused by a sudden reconfiguration of the magnetic field (“magnetic reconnection”)
- Converts magnetic energy to radiation, kinetic energy, energetic particles
- Intense X-rays, but most energy is radiated in the visible

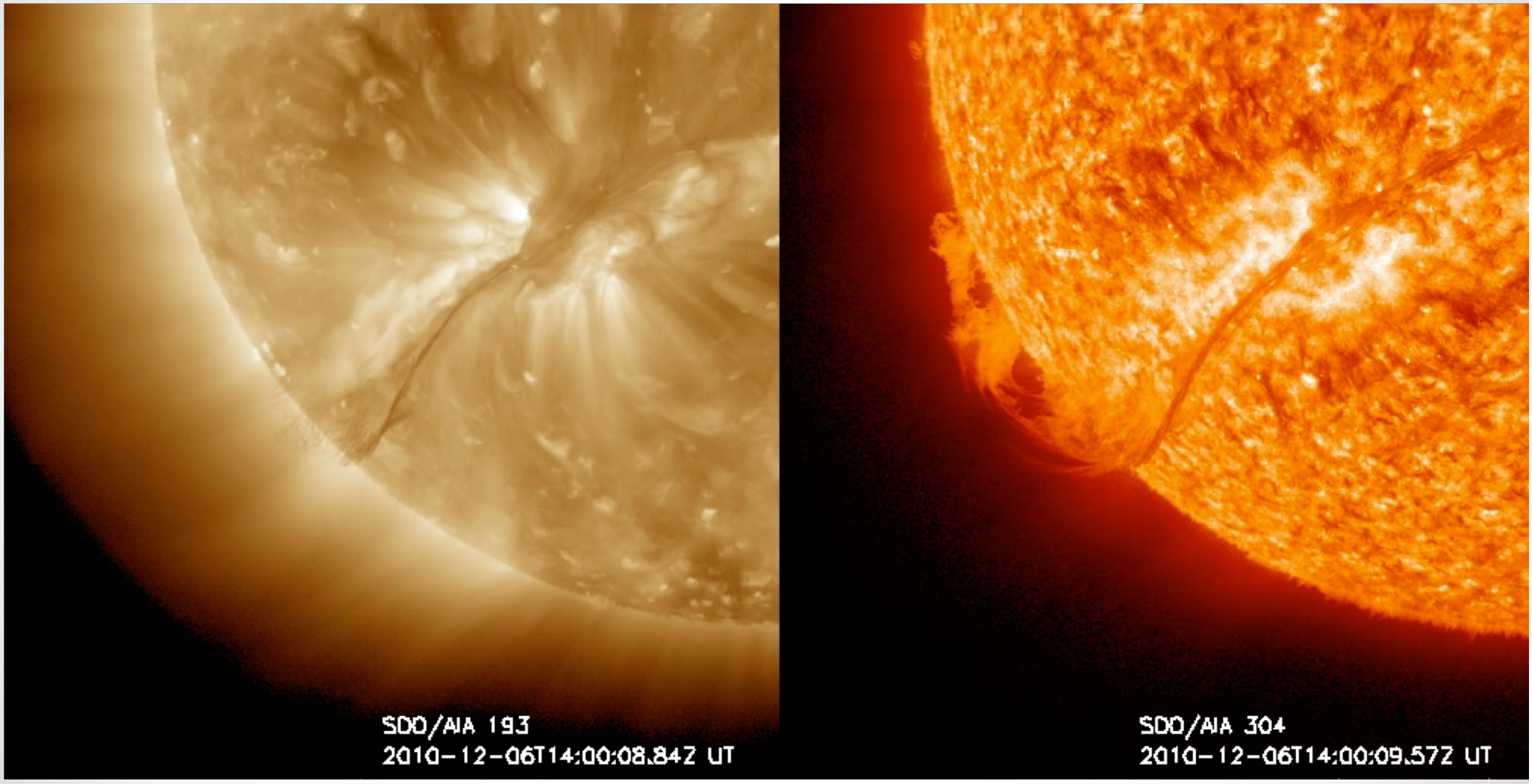




Filaments, prominences

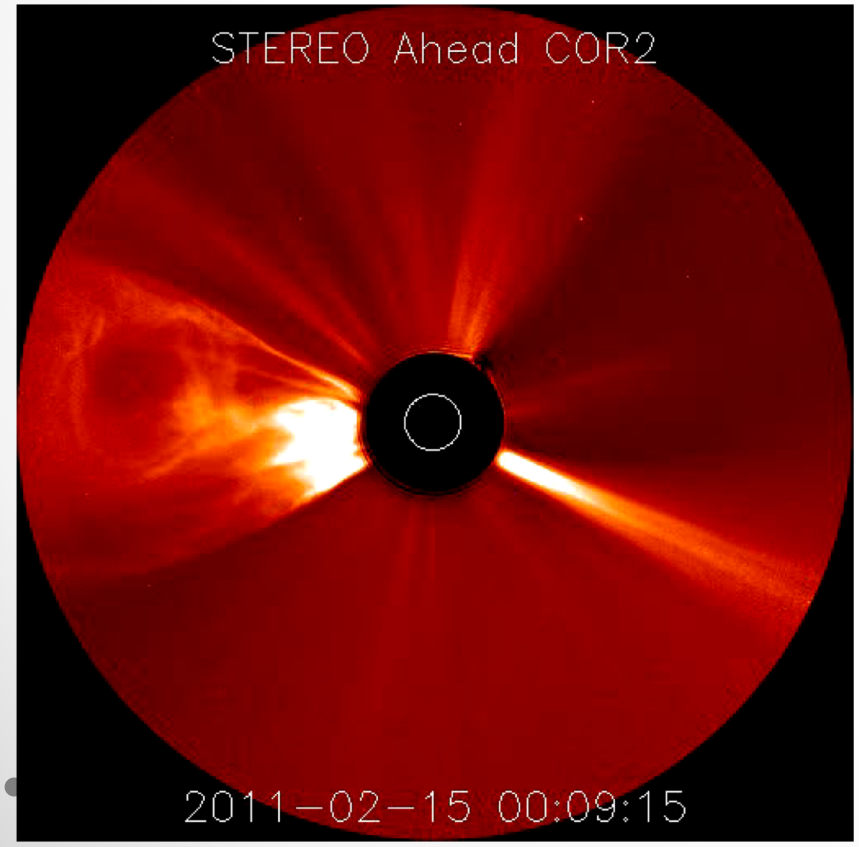
- Cold (chromospheric) gas suspended by magnetic fields in the corona
- Can reach up to 150,000km height
- Stable for many days
- Filament ejections are associated with CMEs

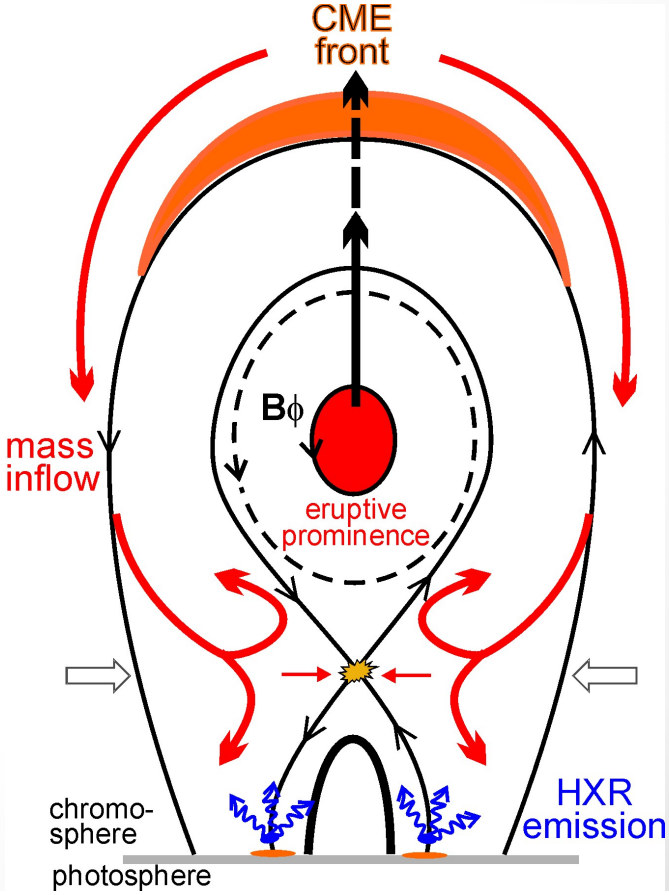
Prominence eruptions



Coronal Mass Ejections

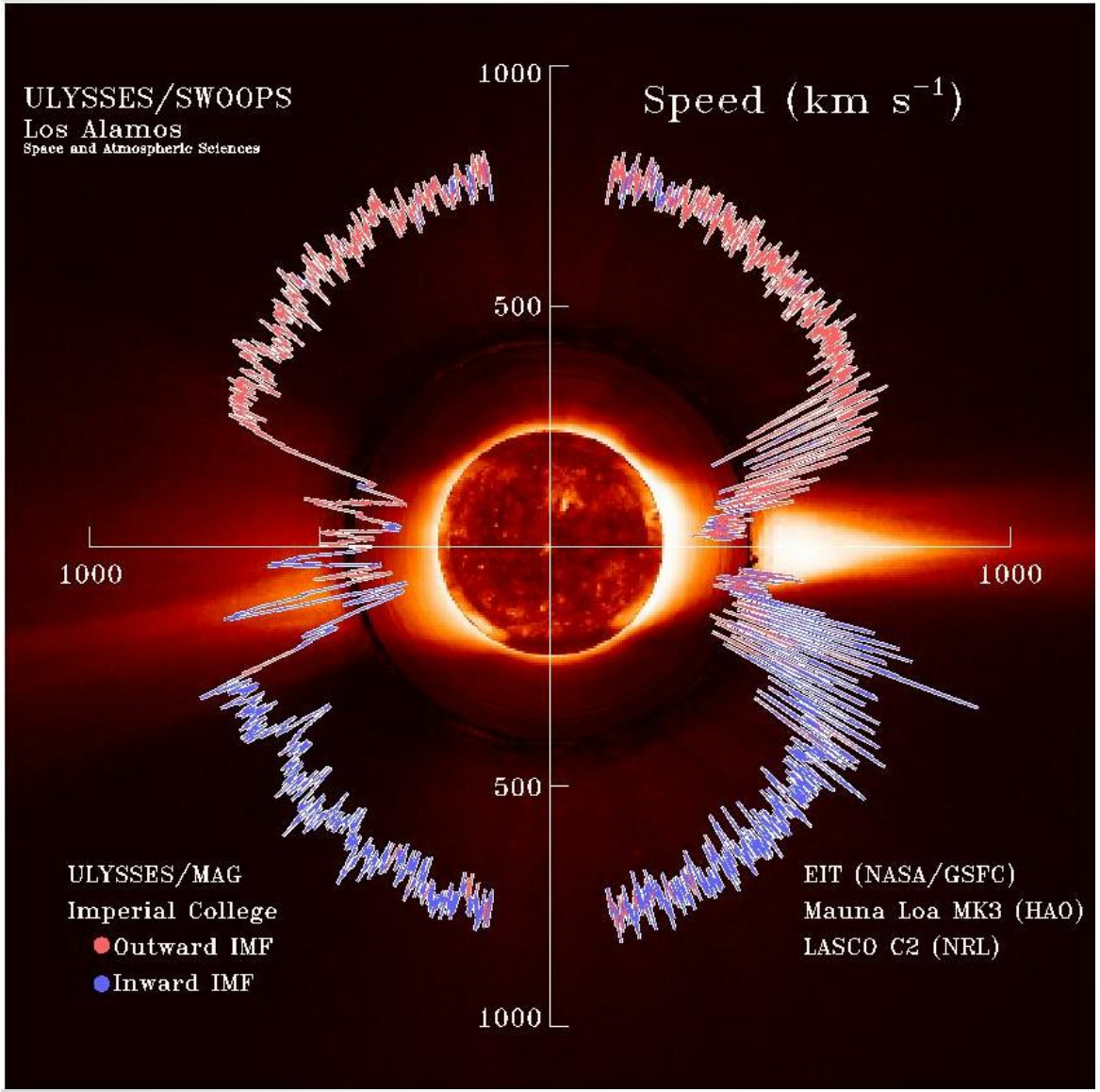
- Loss of force balance causes eruption, reconnection drives it
- Ejection of material into interplanetary space
- Often associated with flares, prominence eruptions





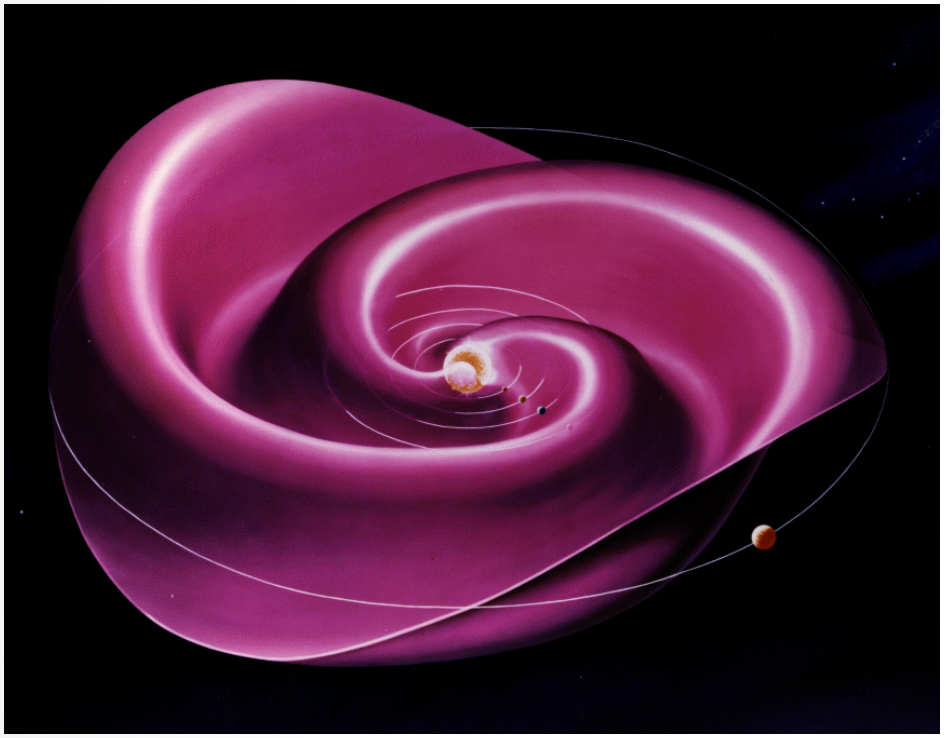
Temmer et al., ApJ, 2010

Solar wind



- Originates from the pressure difference between the corona and interplanetary space
- Fast wind comes from coronal holes
- Source of the slow wind is less clear

Heliospheric current sheet

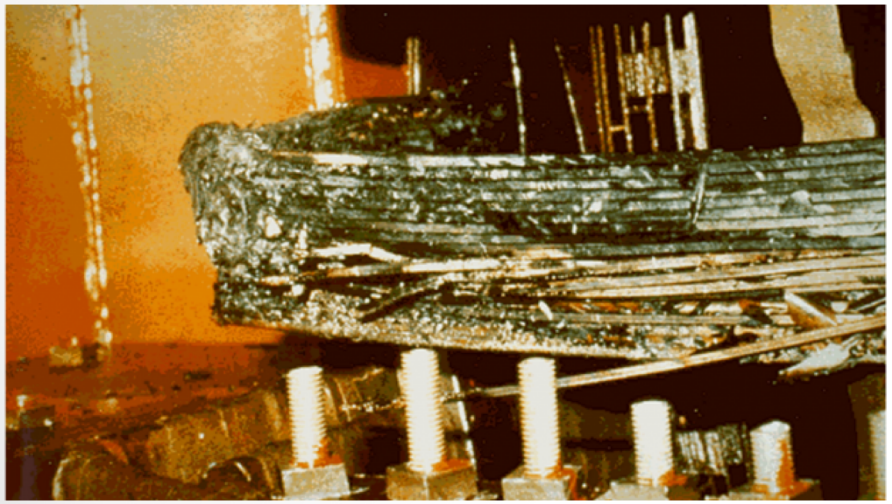


Wilcox et al. Science, 1980

- Boundary between north and south magnetic field
- Also called the “Parker Spiral”
- Like a rotating sprinkler, rotation of the Sun and outward solar wind combine to form the spiral
- Magnetic field is frozen in to the solar wind

Space Weather

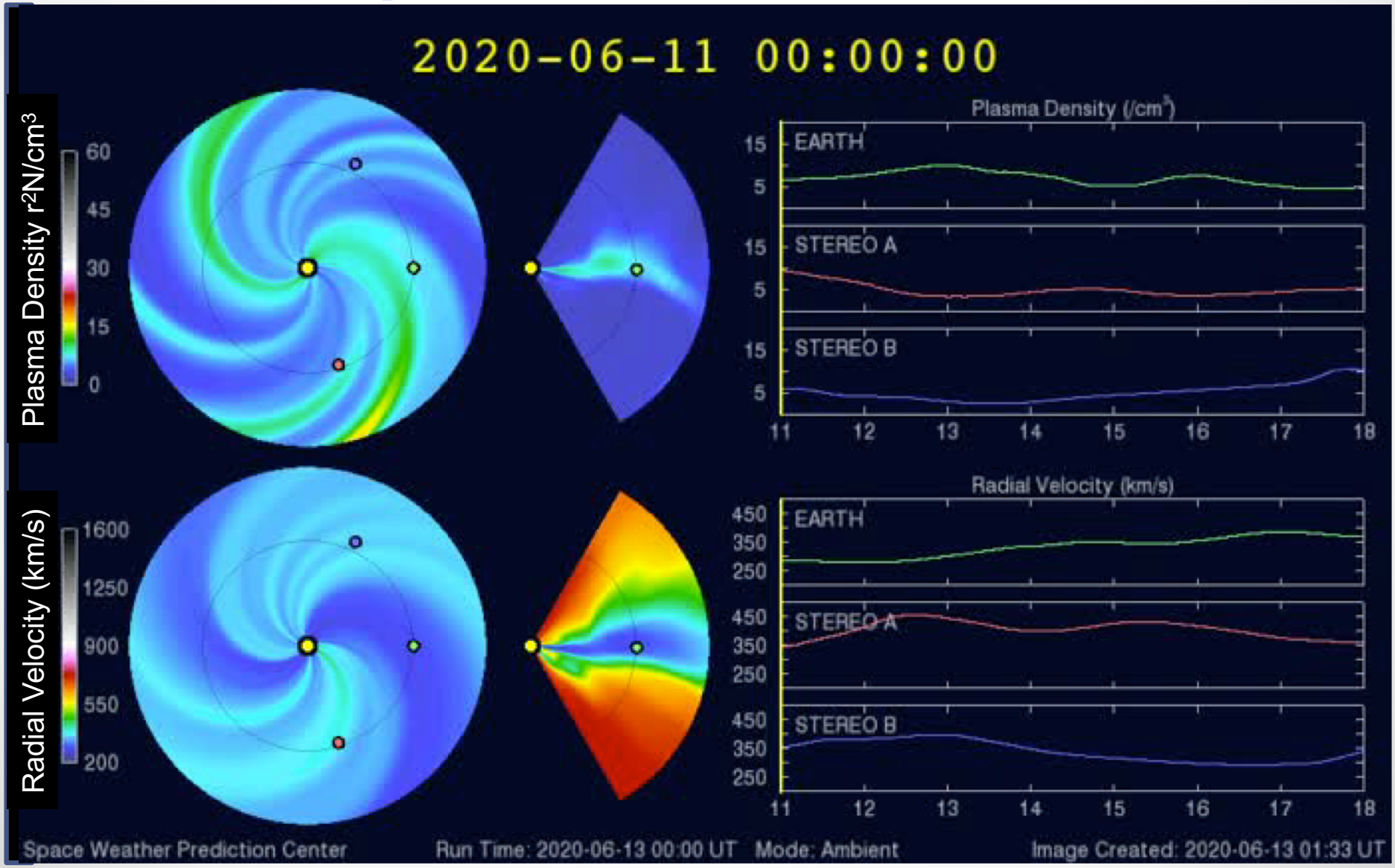
- CMEs, solar wind are a source of energetic particles
- Particles can damage satellites, endanger astronauts, cause aurorae
- Shaking of Earth's magnetic field can cause power outages



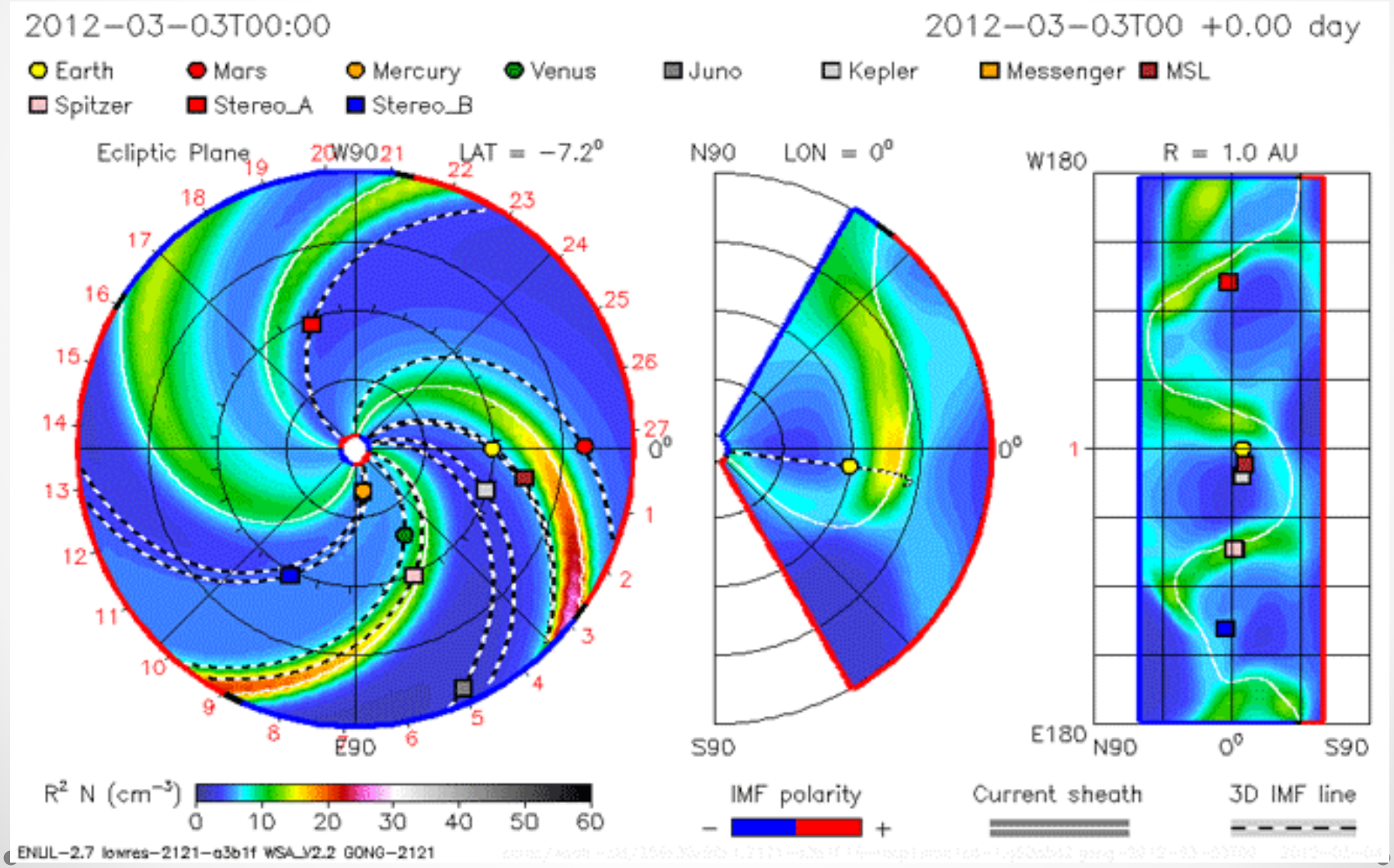
Transformer damage due to a solar storm (JA Marusek: "Solar Storm Threat Analysis", 2007)

Aurora over Bozeman, MT (photo credit David McKenzie)

Space weather



Space weather



Instrumentation Observing the Sun-Earth System