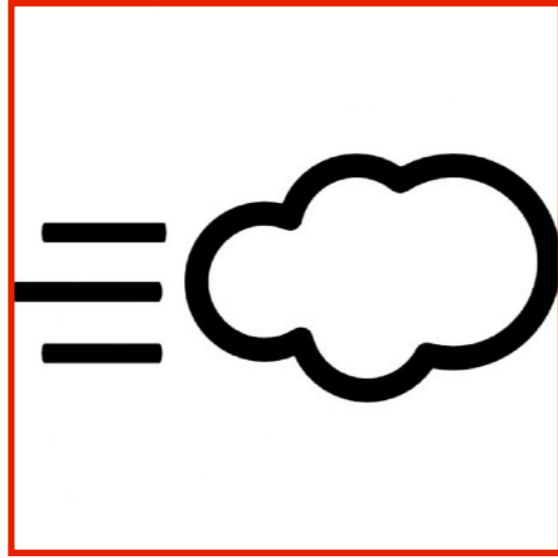
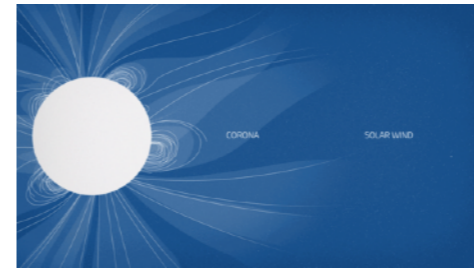
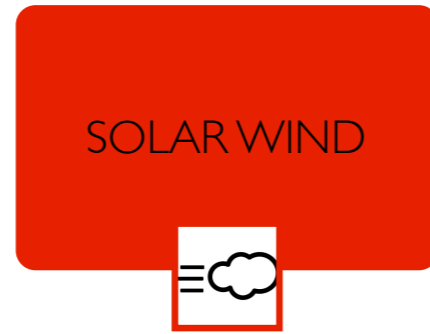


Magnetic reconnection at the sun leads to an energy release into the form of
green: thermal radiation – random motion of particles in matter (>absolute zero)
Red and blue: kinetic energy – moving plasma: CME or particles



SOLAR WIND





Continuous radial outflow of gas.

Consists of charged particles that can carry magnetic structures.

Shapes the IMF.



Radial outflow: linked to open magnetic field lines
Example of a Magnetic structure: a CME

The solar wind plasma is glued to the IMF – or the IMF is glued to the plasma.

The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fills the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you have solar weather. Outside the heliosphere, you have the rest of the galaxy. Earth is in the heliosphere.

INTERPLANETARY MAGNETIC FIELD + PLASMA

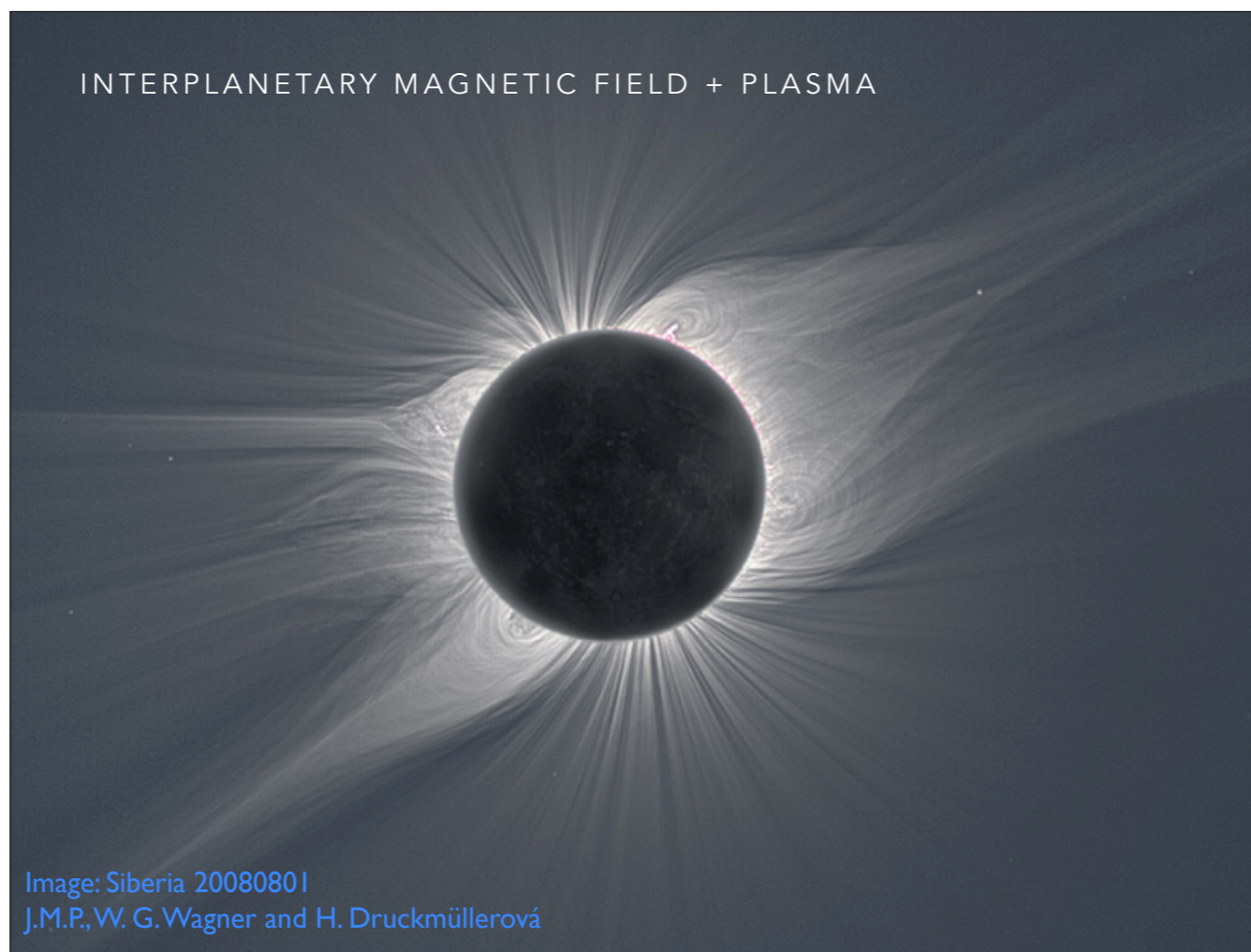


Image: Siberia 20080801
J.M.P., W. G. Wagner and H. Druckmüllerová

The IMF

- Shows the dipolar structure of the sun
- Is shaped by the solar wind → open magnetic field lines
- If no solar wind → closed magnetic field lines

The IMF

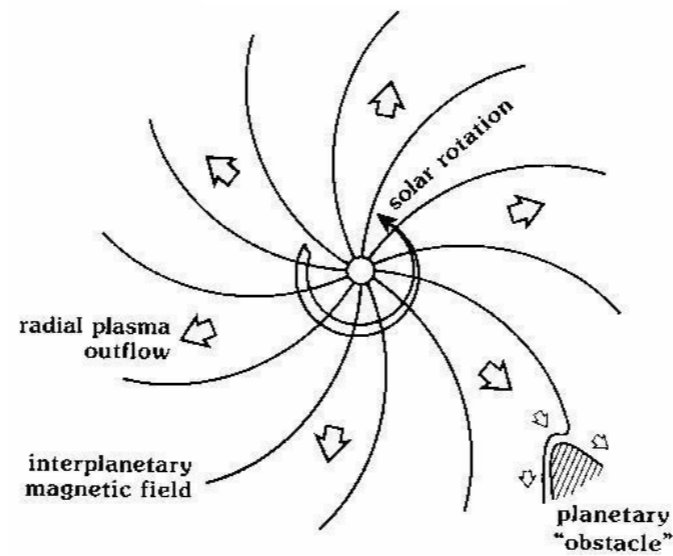
- important for the energy transport in the form of plasma.
- The form indicates how the plasma streams through space. The IMF guides the plasma.

Magnetic signature visible here is at a large length scales. It changes over a period of 11 years.

Large spatial and time scale: Solar dipole – visible during a solar eclipse, more pronounced at solar minimum, orientation and geometry vary during the solar cycle.

PARKER SPIRAL

The magnetic field stays connected to the Sun. As the Sun rotates, the magnetic field gets bended. Nevertheless, the plasma goes radial.

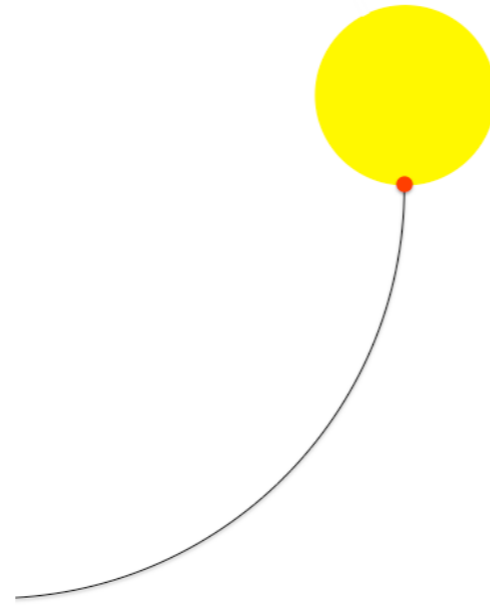


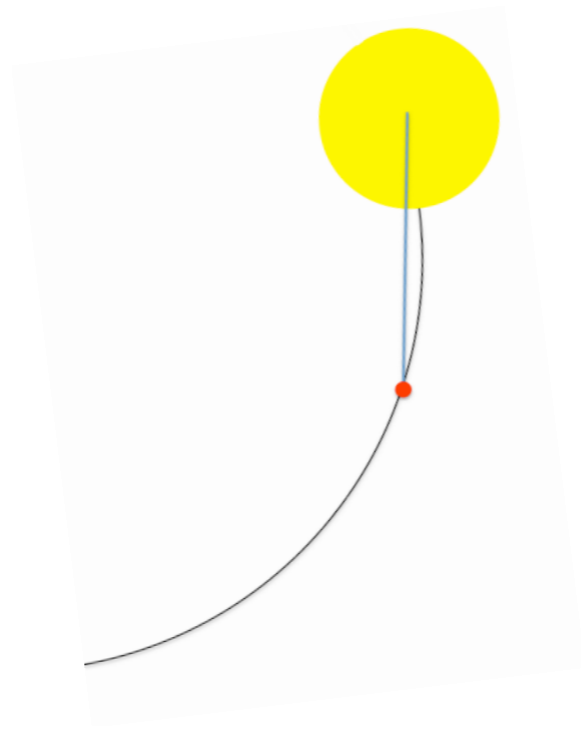
This is a view of the IMF in the solar equatorial plane.

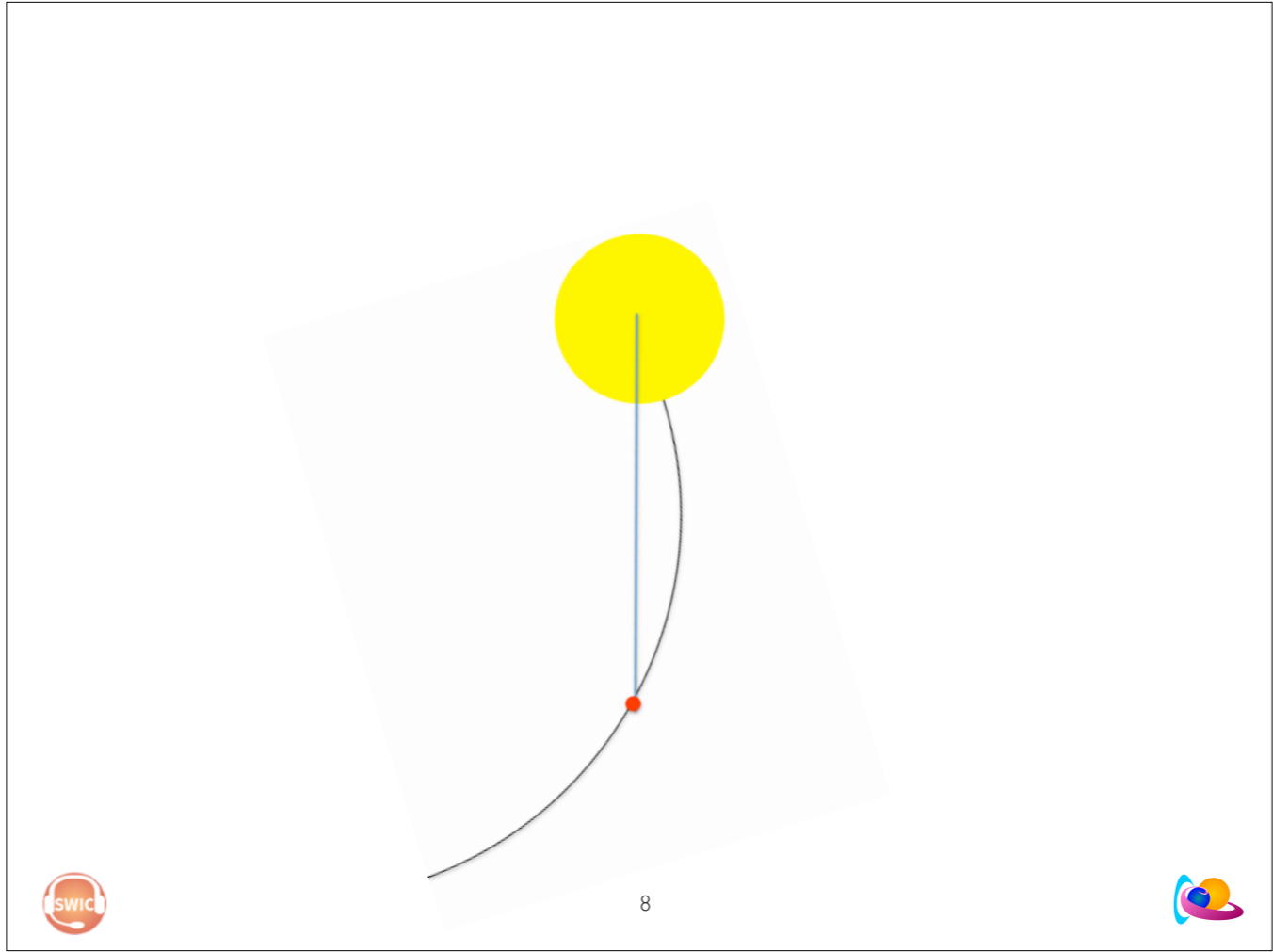
The frozen-flux theorem: IMF and plasma are glued.

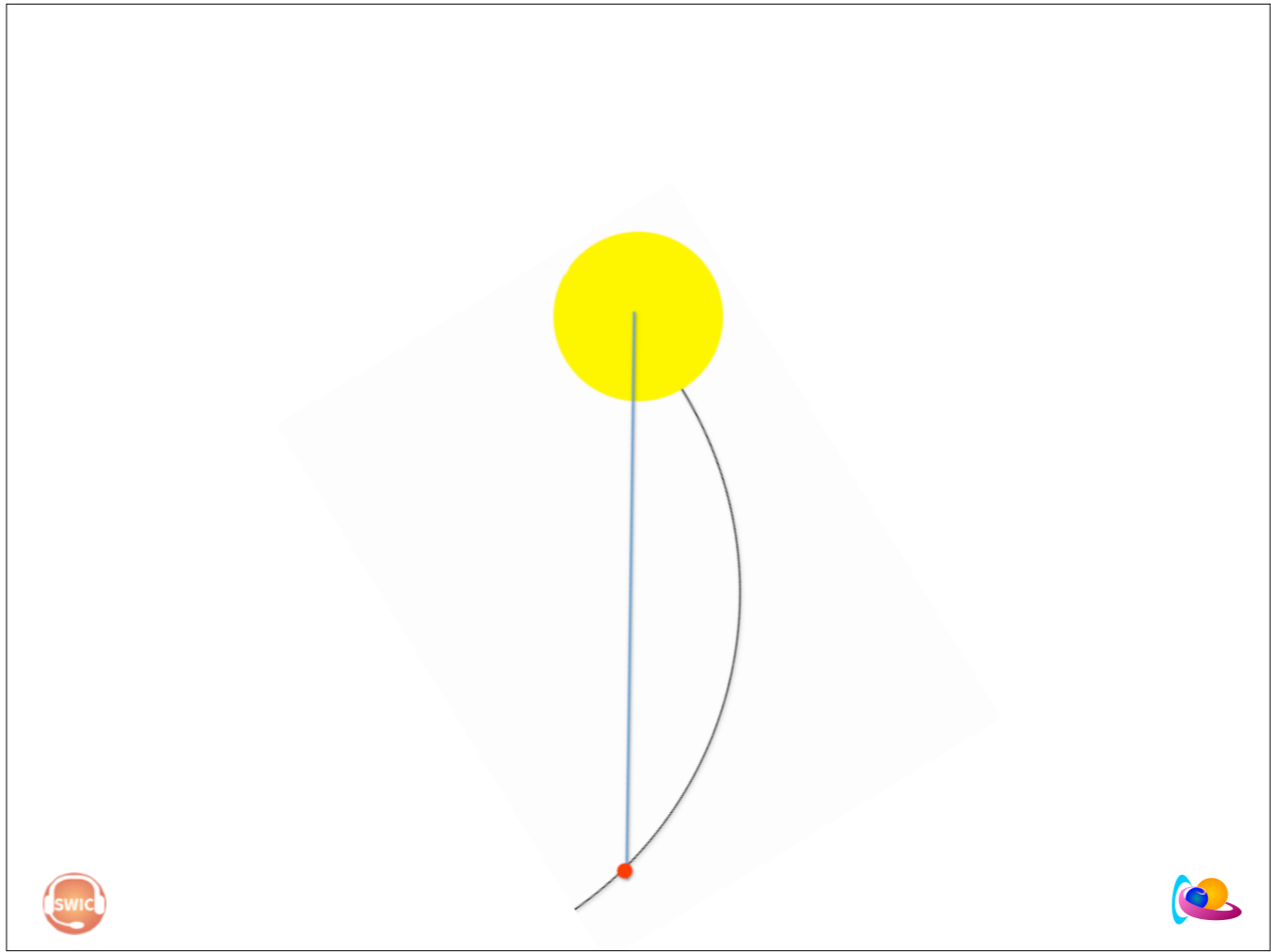
The foot points of the magnetic field lines are attached to the sun. At the same time, the plasma of the solar wind on the further distance is glued to that same magnetic field line. When the sun rotates, the IMF is forced to bend.

SOLAR WIND IS RADIAL & IMF BENDS?









SOLAR WIND VARIATIONS

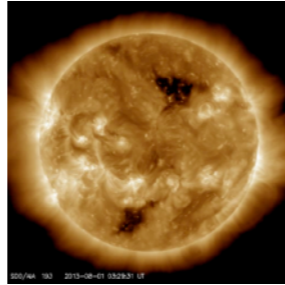


Non-eruptive
No B reconnection

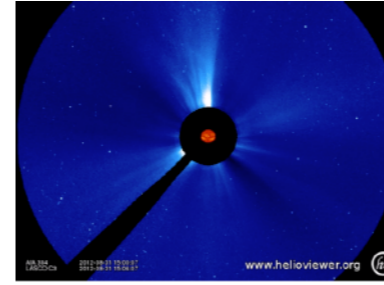


Eruptive
B reconnection

Coronal Hole



Coronal Mass Ejection

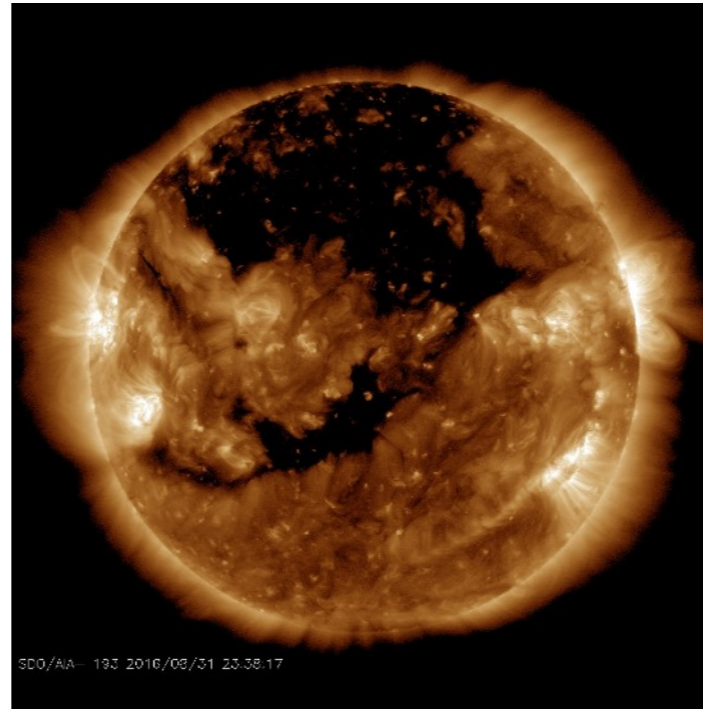
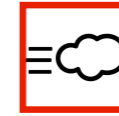


The variations in the solar wind introduce space weather events.

CME – suddenly, a mass is ejected into space. A CME is an eruptive event.
—> magnetic reconnection is involved

A CH is not eruptive. A CH is present, it doesn't pop up suddenly. A CH can of course slowly appear or disappear, become bigger, become smaller but not on time scale of a few minutes. It is also not the case that a CH ejects material and a little bit later, not any more. The solar wind continuously emanate from a CH.
—> no magnetic reconnection is involved

CORONAL HOLE



11



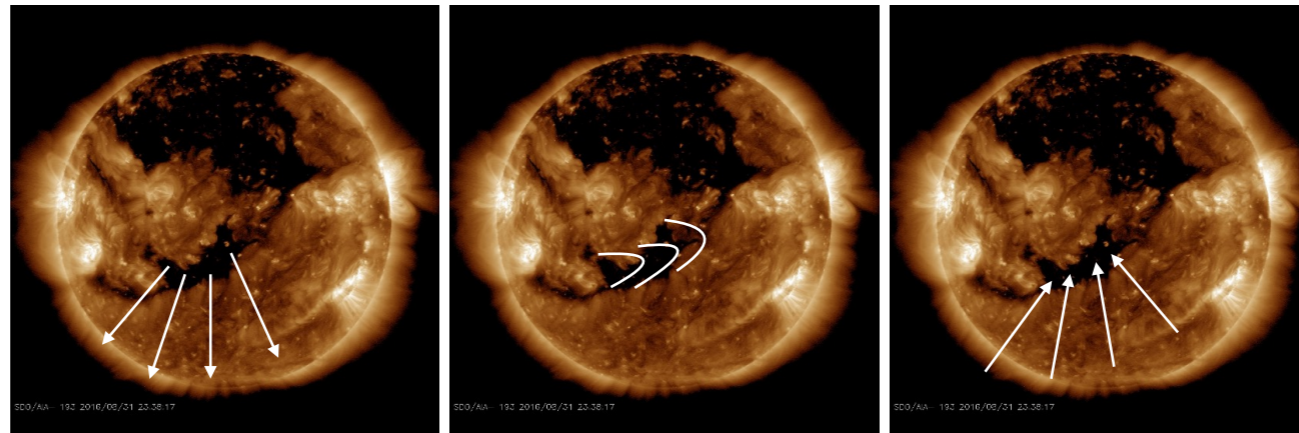
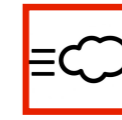
open field structure, source of fast solar wind
non eruptive
radial – plasma leaving when it is at the central meridian, reaches Earth

What is important determining when and how strong the impact of a CH will be:

- The heliographic latitude of earth
- The latitude of the CH on the solar disk: the part of a CH with a low latitude is important. Polar coronal holes have only an impact when they extent to lower latitudes.
- It is the material that leave at the central meridian that will reach earth. You have to guess how fast the solar wind is. Calculate the time the material needs to cross the distance 1AU and you have an estimate of the arrival time of the CH wind near Earth.

at the central meridian

B OF CORONAL HOLE



open field structure, source of fast solar wind
non eruptive
radial – plasma leaving when it is at the central meridian, reaches Earth

What is important determining when and how strong the impact of a CH will be:

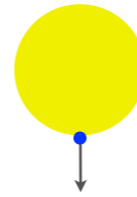
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at the central meridian

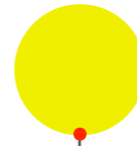
WHAT HAPPENS WHEN FAST CATCHES SLOW?

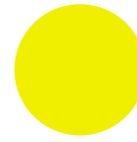


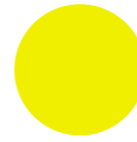
Top View

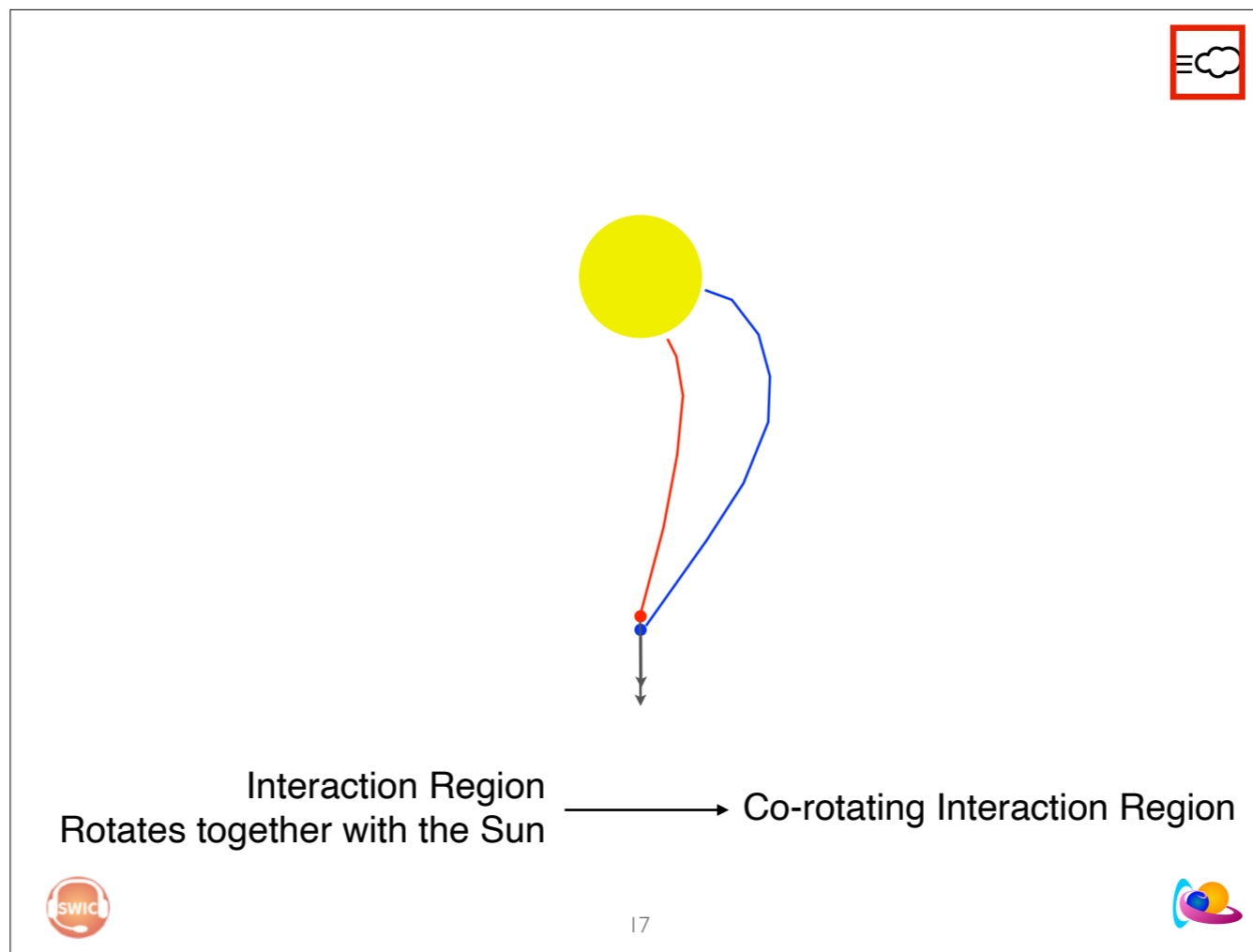


What happens when fast catches slow solar wind material?









Continuous process – the source of the fast particles, i.e. stays present.

When fast solar-wind streams, emanating from coronal holes, interact with slow streams, they can produce Co-rotating Interaction Regions in interplanetary space. The magnetic fields of the slow streams in the solar wind are more curved due to the lower speeds, and the fields of the fast streams are more radial because of their higher speeds. Intense magnetic fields can be produced at the interface (IF) between the fast and slow streams in the solar wind. The Co-rotating Interaction Regions are bounded by a forward shock (FS) and a reverse shock (RS).

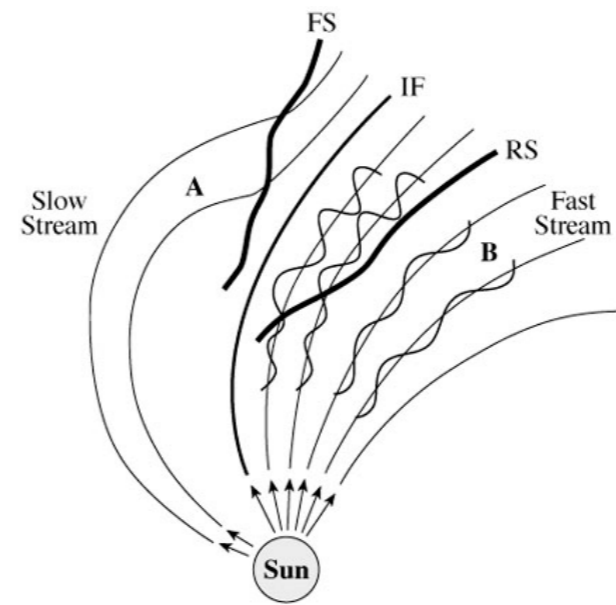
One reason why two shocks are eventually formed at a CIR is due to symmetry about the pressure enhancement caused by compression and entraining of the slow wind ahead of the fast stream (Figure 10.9 [Gosling, 1996]): shocks are driven away from the pressure increase in both directions, resulting in a so-called "Forward-Reverse shock pair" in which the forward shock propagates away from the Sun while the reverse shock propagates towards the Sun but is carried out with the solar wind flow.

<http://www.boulder.swri.edu/~deforest/Movies.html>

Coronal Hole

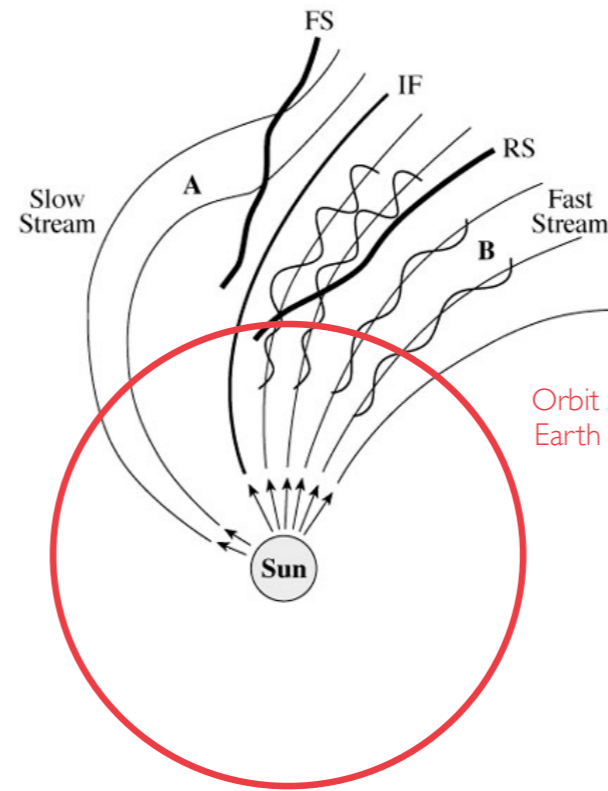
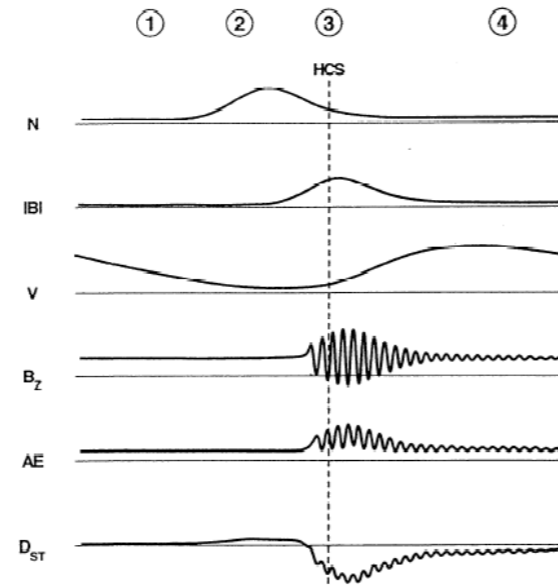


- Co-rotating structure
- Radial!
- No extra mass-flux



Coronal hole is not the source of more plasma, but of faster plasma.

Coronal Hole

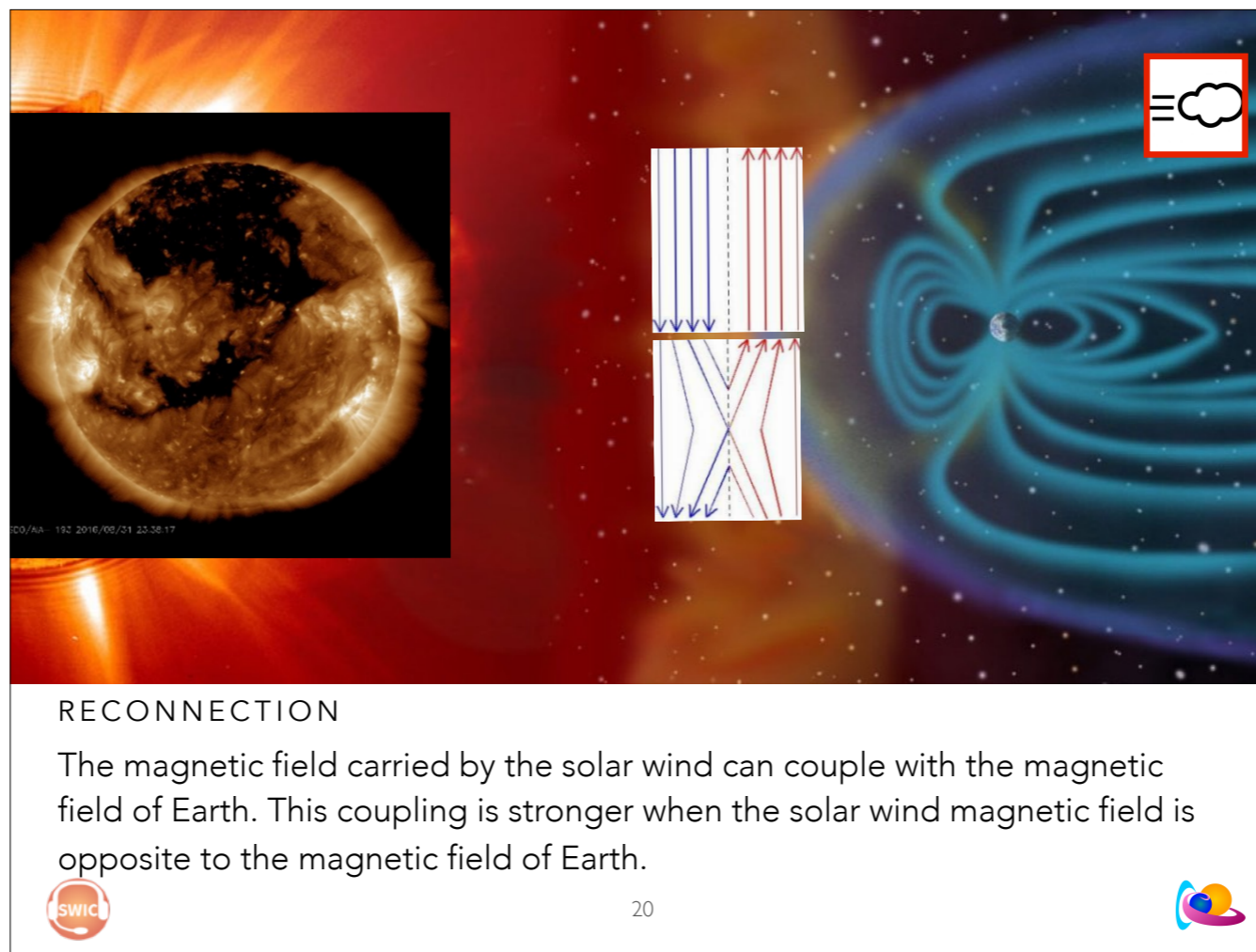


At a point in space: the total flux of mass is the same

—> v high, density low

—> v low, density high

When your plasma is more dense, the closer the magnetic field lines.



RECONNECTION

The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.



20



This is the earth's magnetosphere. The sun is somewhere far away in the right top corner.

The earth is a giant dipole – similar as the sun. Except, the solar magnetic dipole field reverses every 11 year. The Earth's magnetic poles don't. They are already for ages like this.

The part of the earth's dipole facing the sun/solar wind is pushed more together, while the part behind the earth is stretched and forms a tail. In front of the magnetic structure, you have a shock.

This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiates are slower compared to the speed of the boat. The boat is super-water wave.

When a plane is super-sonic, there is also a shock in front of it. The pressure waves that the moving plane creates move much slower than the plane.

In the case of a speed boat, the boat moves through the water.

In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

A magnetic field is imbedded in the solar wind. This magnetic field can interact with the magnetic field of the earth at the boundaries of the earth magnetosphere. This interaction is called reconnection. It happens when 2 magnetic regions are confronted with each other.

The blue magnetic field lines are imbedded in the solar wind.

The red magnetic field lines represent the earth magnetosphere.

The blue and the red magnetic region have to face each other. Opposite magnetic field lines can reconnect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.

Therefore, it is very important to know how strong the

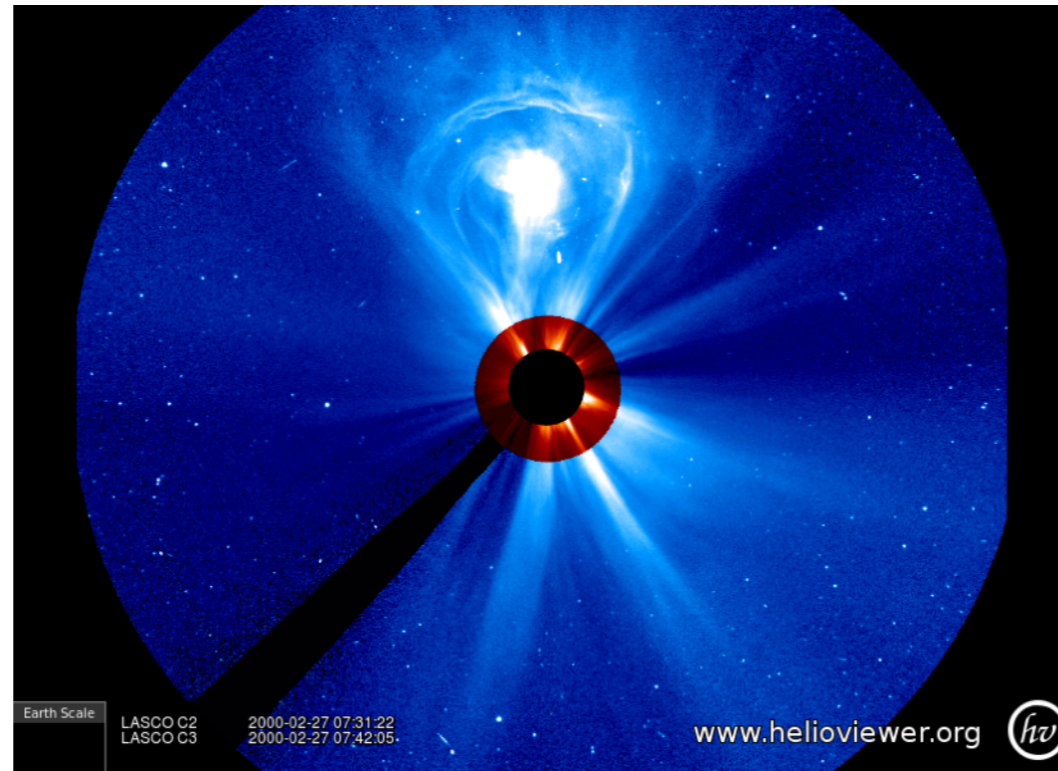
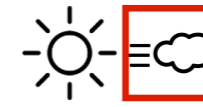
0.3 T – solar sunspot

5mT – strength of a typical refrigerator magnet

31.869 μT (3.1×10^{-5} T) – strength of Earth's magnetic field at 0° latitude (North/South), 0° longitude (west/east)

1 to 5 nT – IMF at L1

CORONAL MASS EJECTION



Earth Scale

LASCO C2
LASCO C3

2000-02-27 07:31:22
2000-02-27 07:42:05

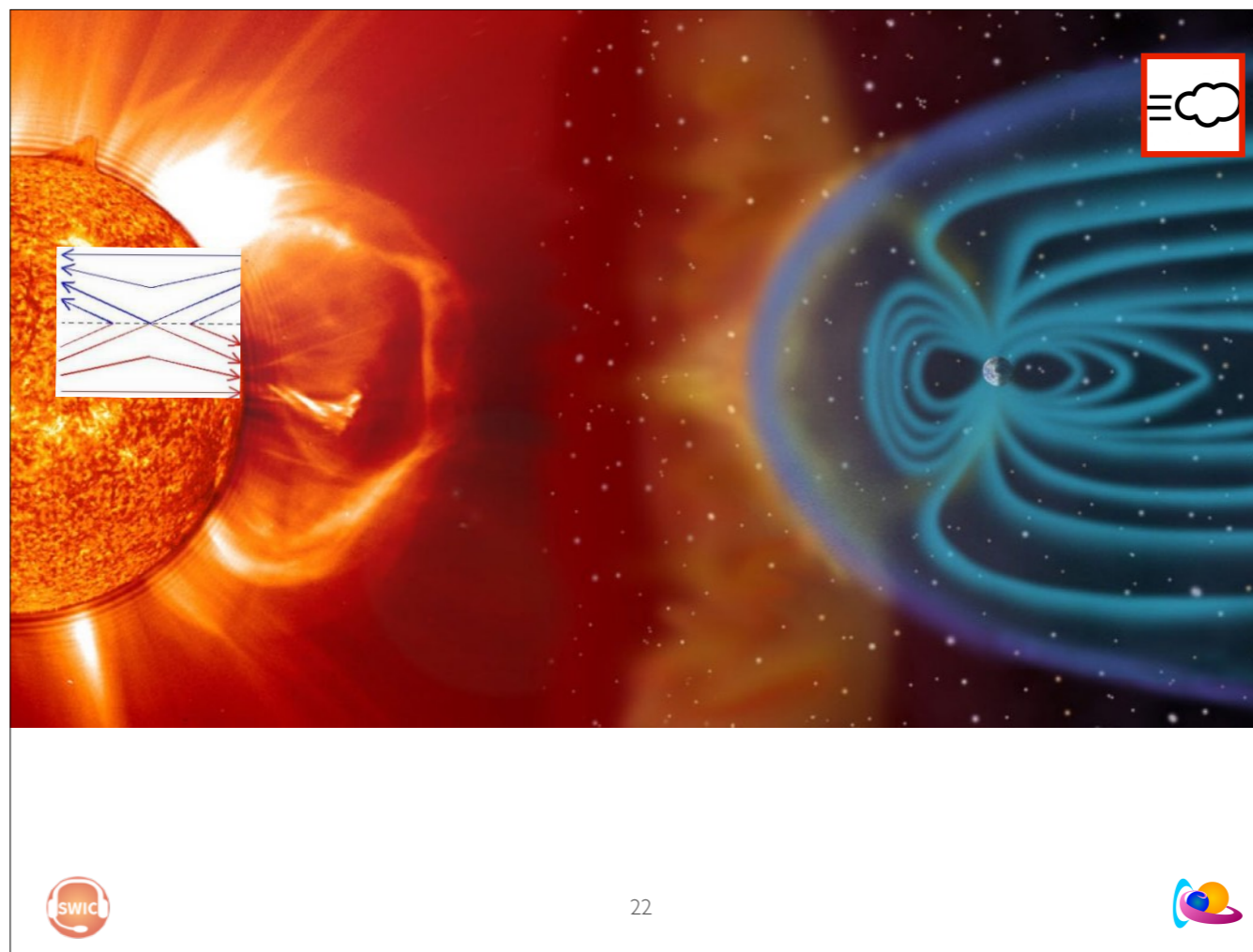
www.helioviewer.org



Transient: only lasting for a short time

Low density, but enormous and therefore massive.

CME is large: compare its size with the size of the sun.



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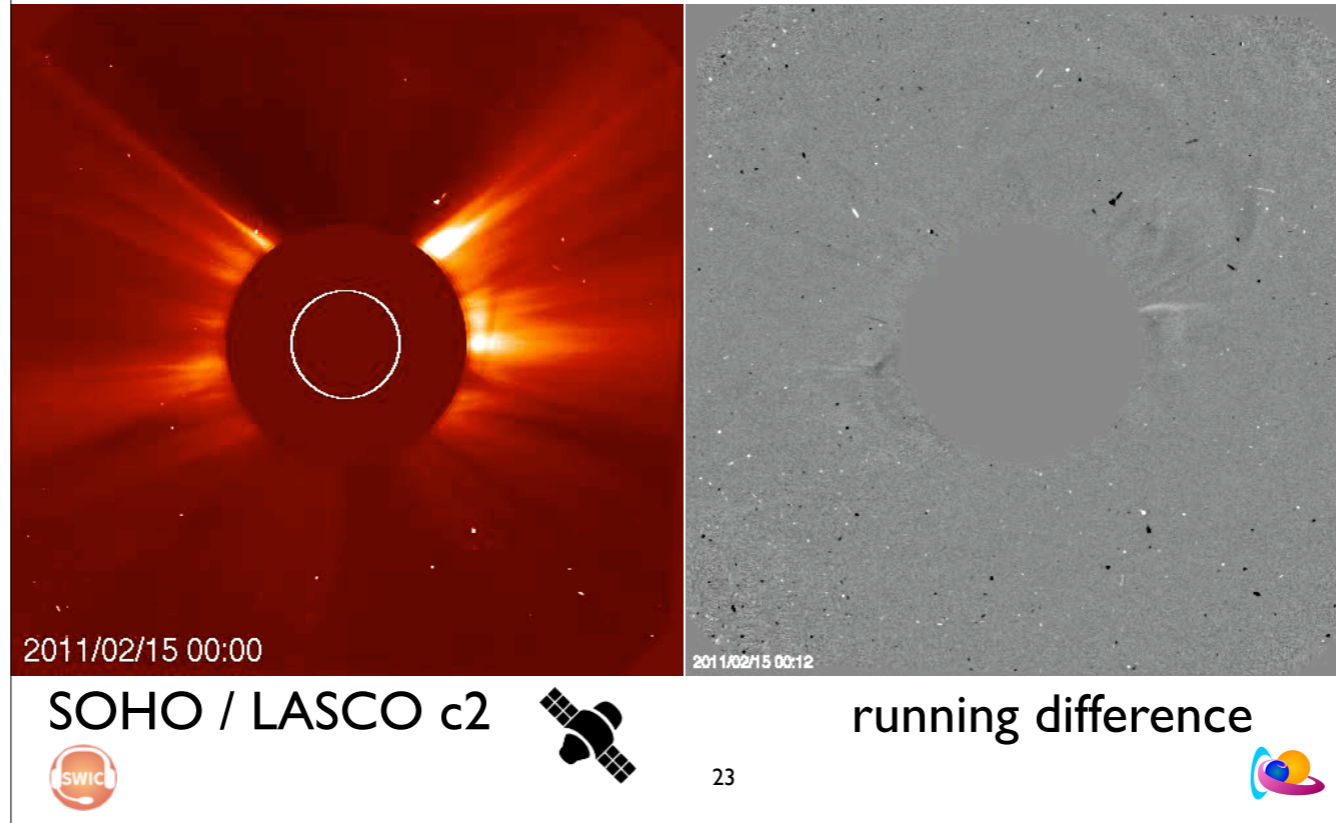
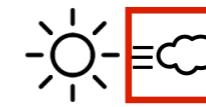
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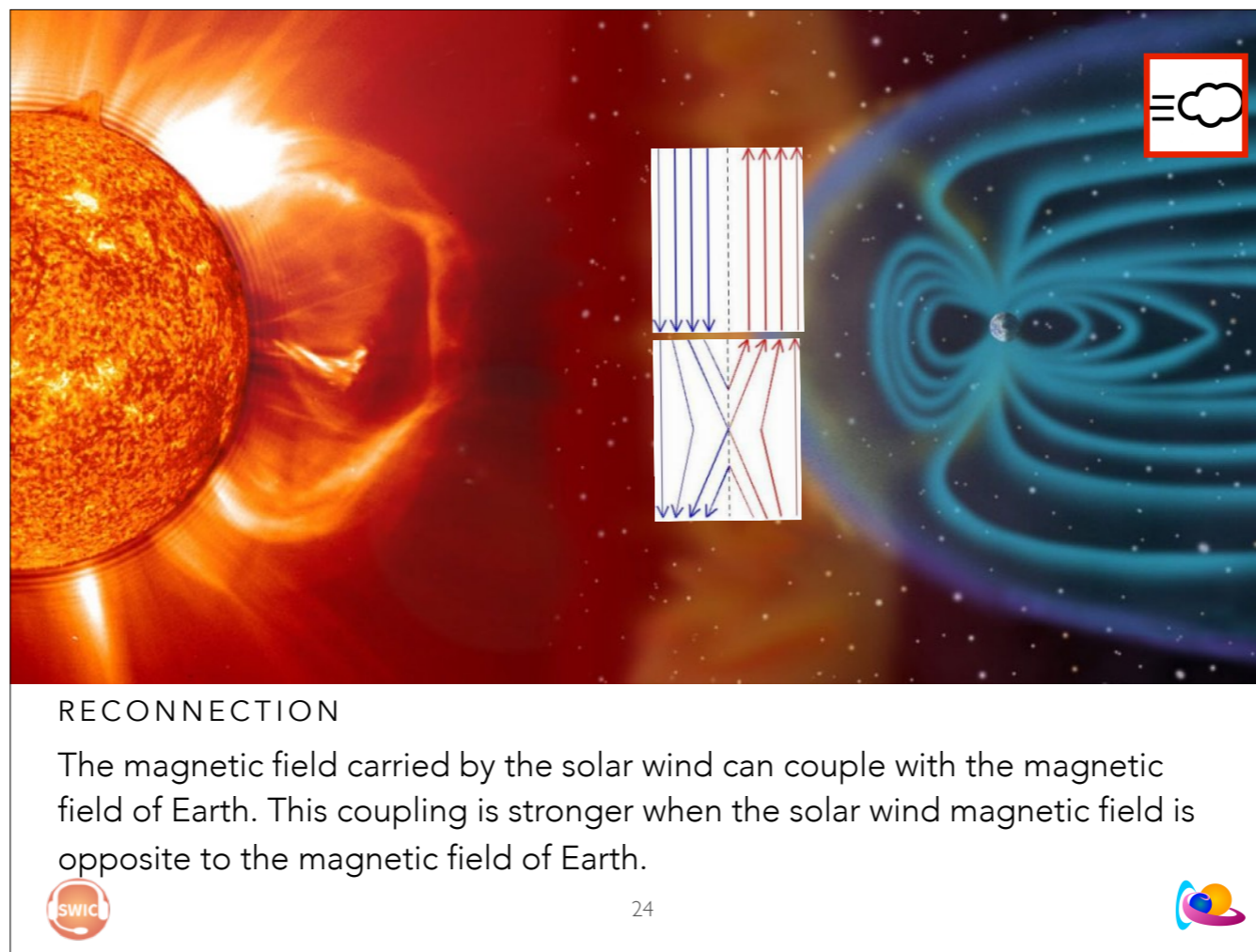
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1 to 5 nT – IMF at L1



CMEs cause the most extreme geomagnetic storms. Therefore, there is great interest in understanding the properties of CMEs, especially when they have a halo signature around the solar disk that indicates the CME is aimed at Earth. Furthermore, if the CME results in a magnetic cloud with a strong and out of ecliptic magnetic field, forecasts are likely for strong to extreme storms.



RECONNECTION

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24



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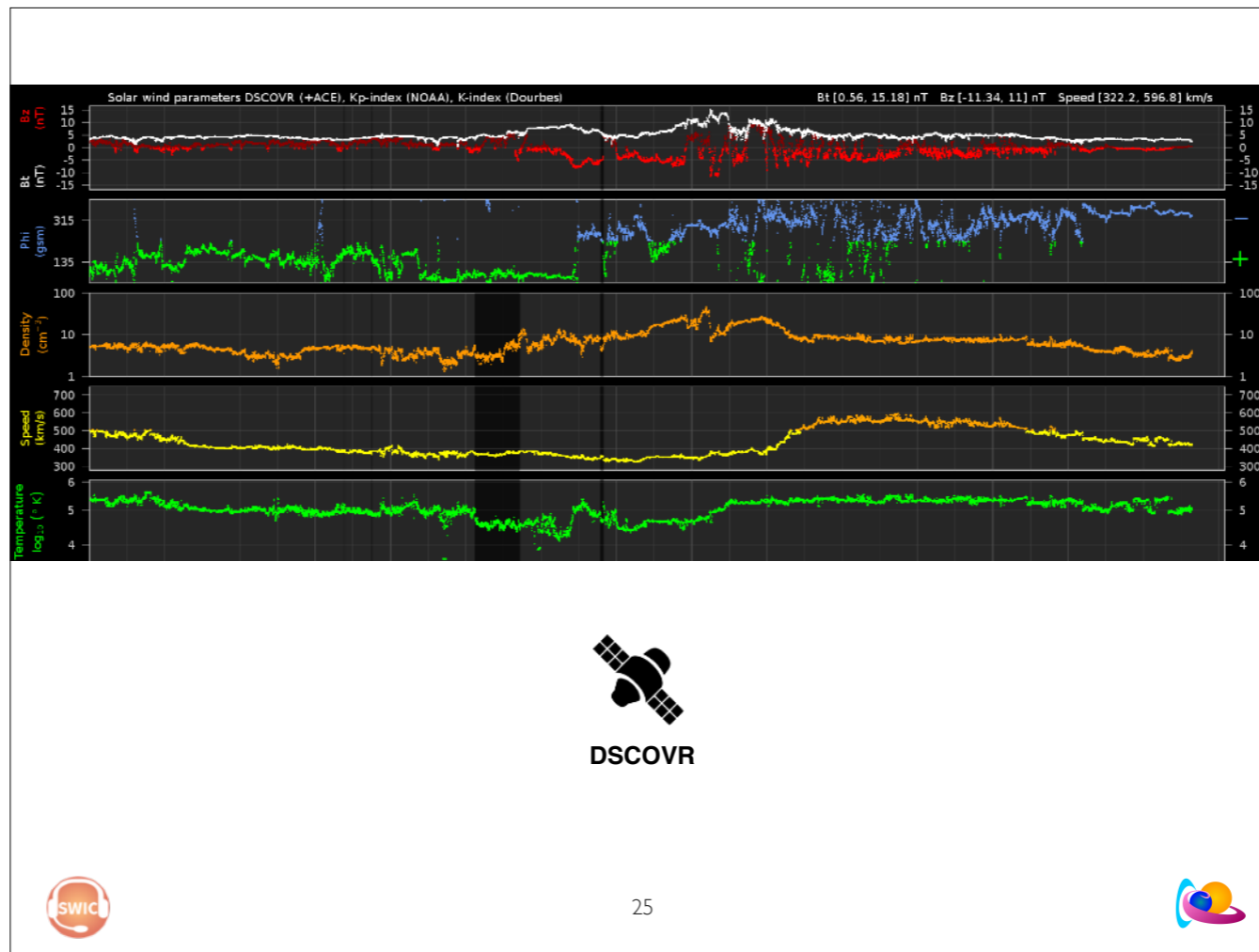
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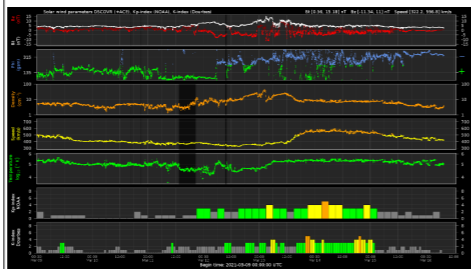
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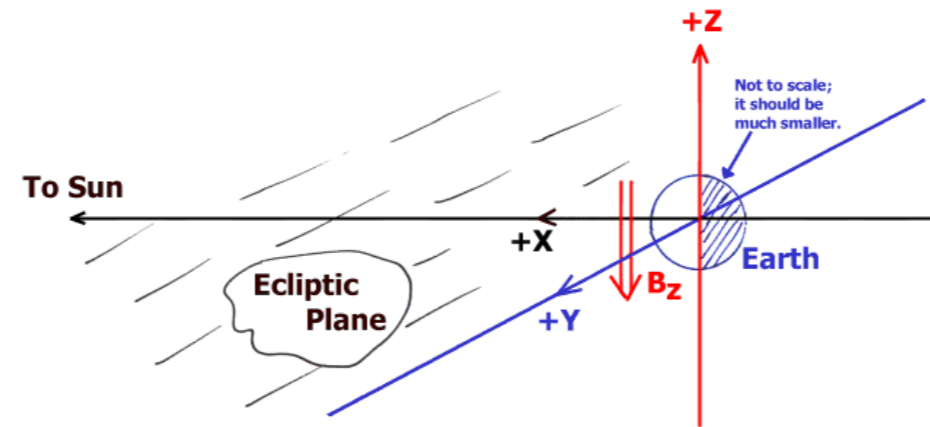
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Introduction to the exercise



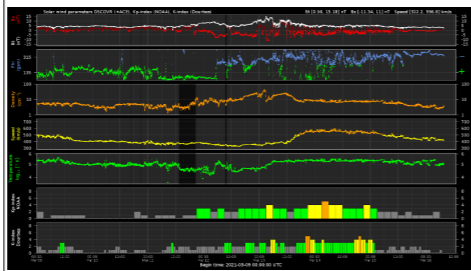
COORDINATE SYSTEM



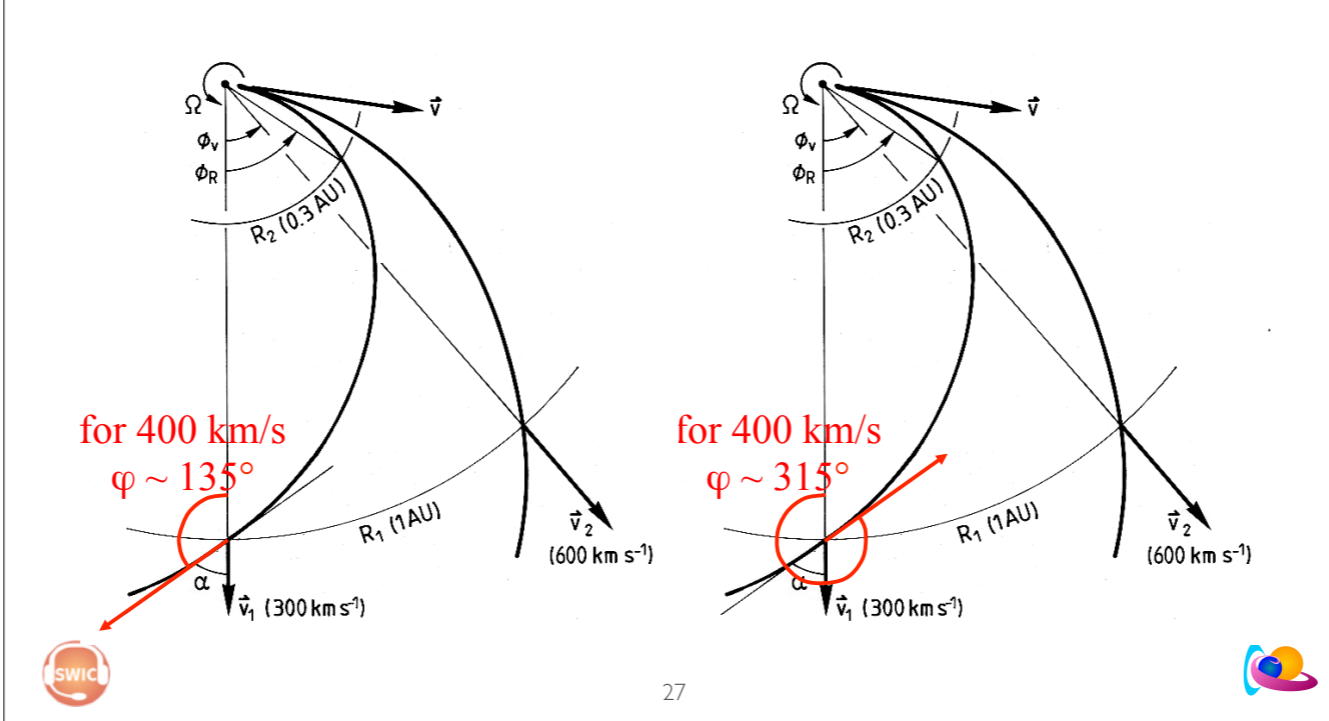
+Z is perpendicular to the Ecliptic Plane.



GSM: Geocentric Solar Magnetospheric System. This has its X-axis pointing from the Earth toward the Sun and its Y-axis is chosen to be in the ecliptic plane pointing towards dusk (thus opposing planetary motion). Its Z-axis is parallel to the ecliptic pole. Relative to an inertial system this system has a yearly rotation.



IMF POLARITY



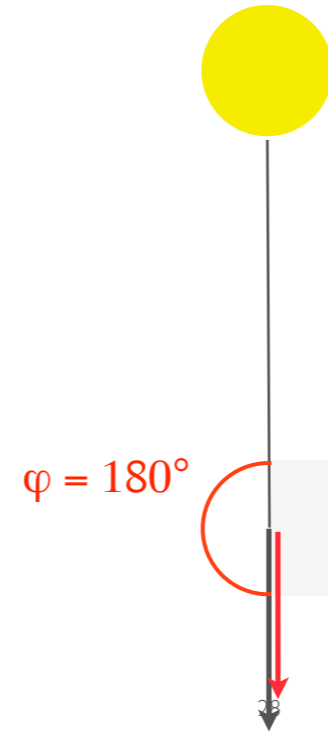
This is the IMF in the XY plane of the GSM coordinate system – not in the solar equatorial plane.

Phi is a value between

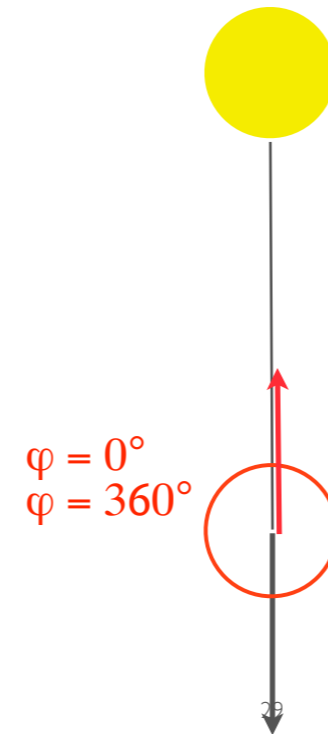
90° and 180°

270° and 360°

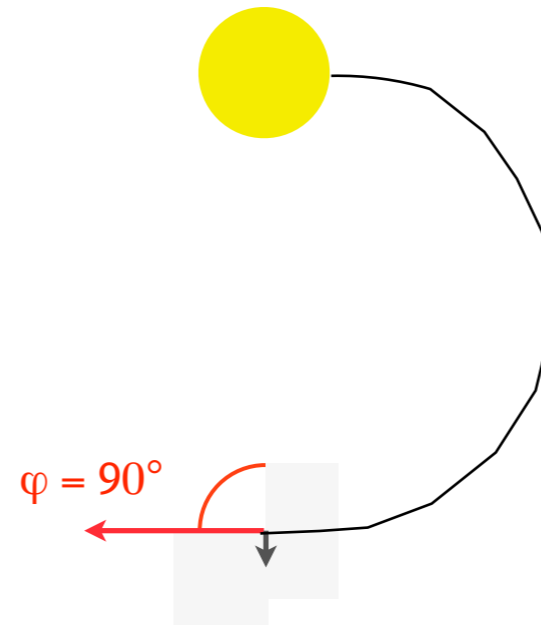
EXTREME FAST

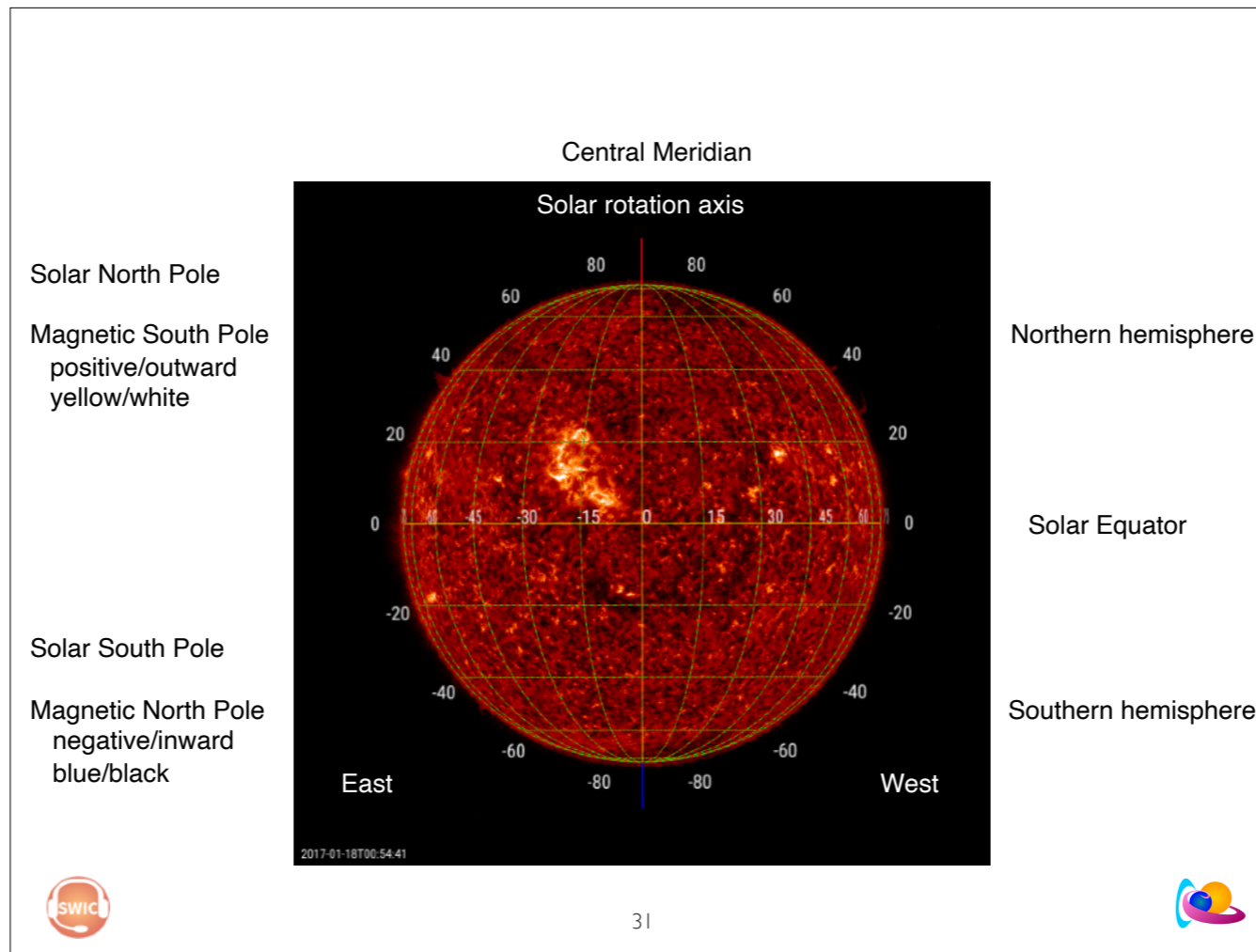


EXTREME FAST



EXTREME SLOW





Before going into more detail of flares (e.m. waves), CME's and CH's (solar plasma that moves through space) and SEPs (Solar Energetic Particles)/plasma storms (electrically charged particles that move along magnetic field lines through space), we have to be able to 'navigate' on the sun.

Two important circles/lines are: the central meridian and the solar equator.
You determine positions on the solar surface

Solar equatorial plane is not the ecliptic (plane in which the Earth orbits). The earth has a certain heliographic latitude. In summer and winter, the earth looks more on the poles. While in spring and autumn, earth is located in the solar equatorial plane.

magnetic reversal – at solar maximum: magnetic north pole becomes the magnetic south pole and reversed.
A magnetic cycle of 22 years.



Beacon COR2 CME speed calculator

<https://wwwbis.sidc.be/cactus/>



