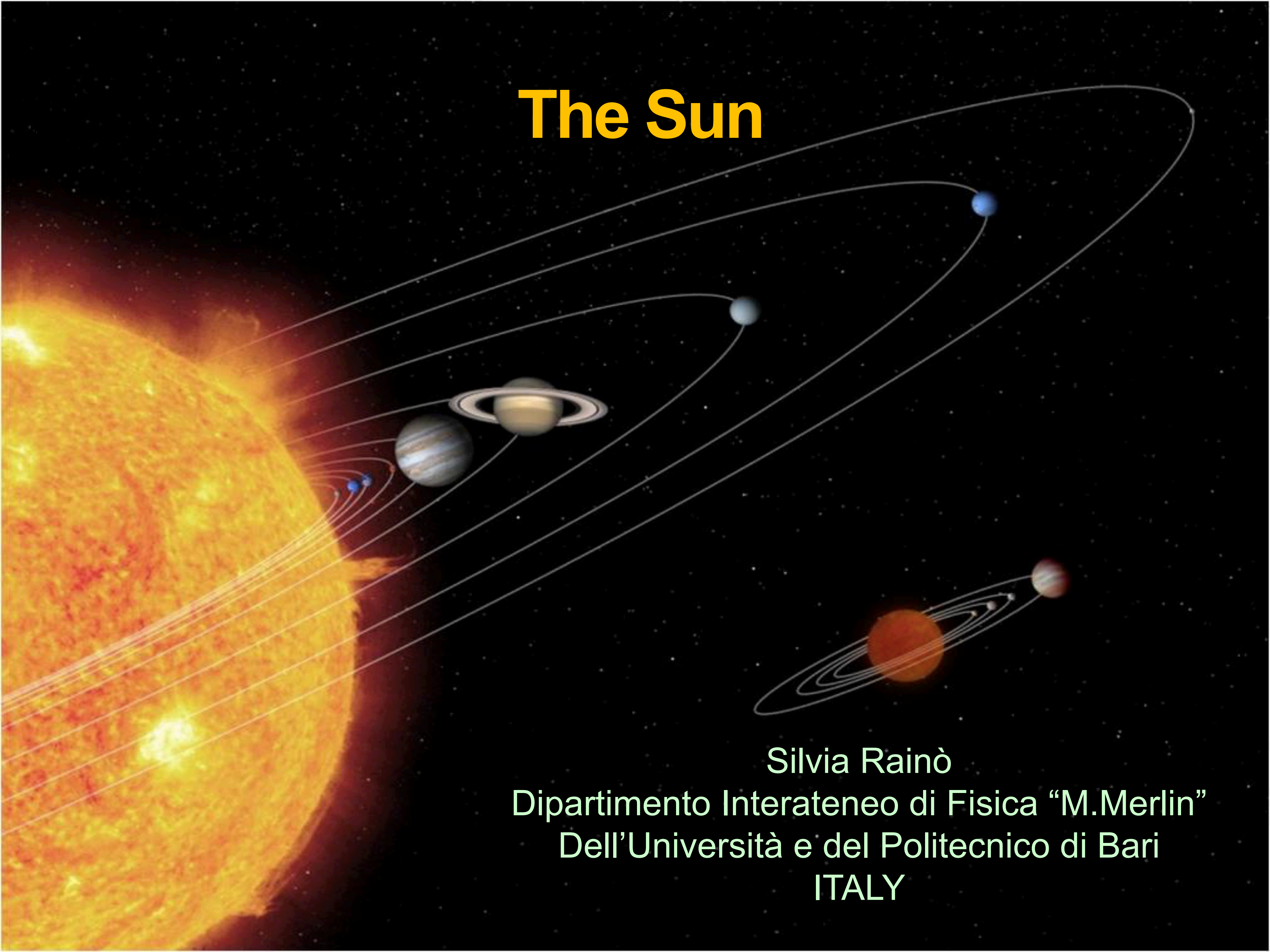
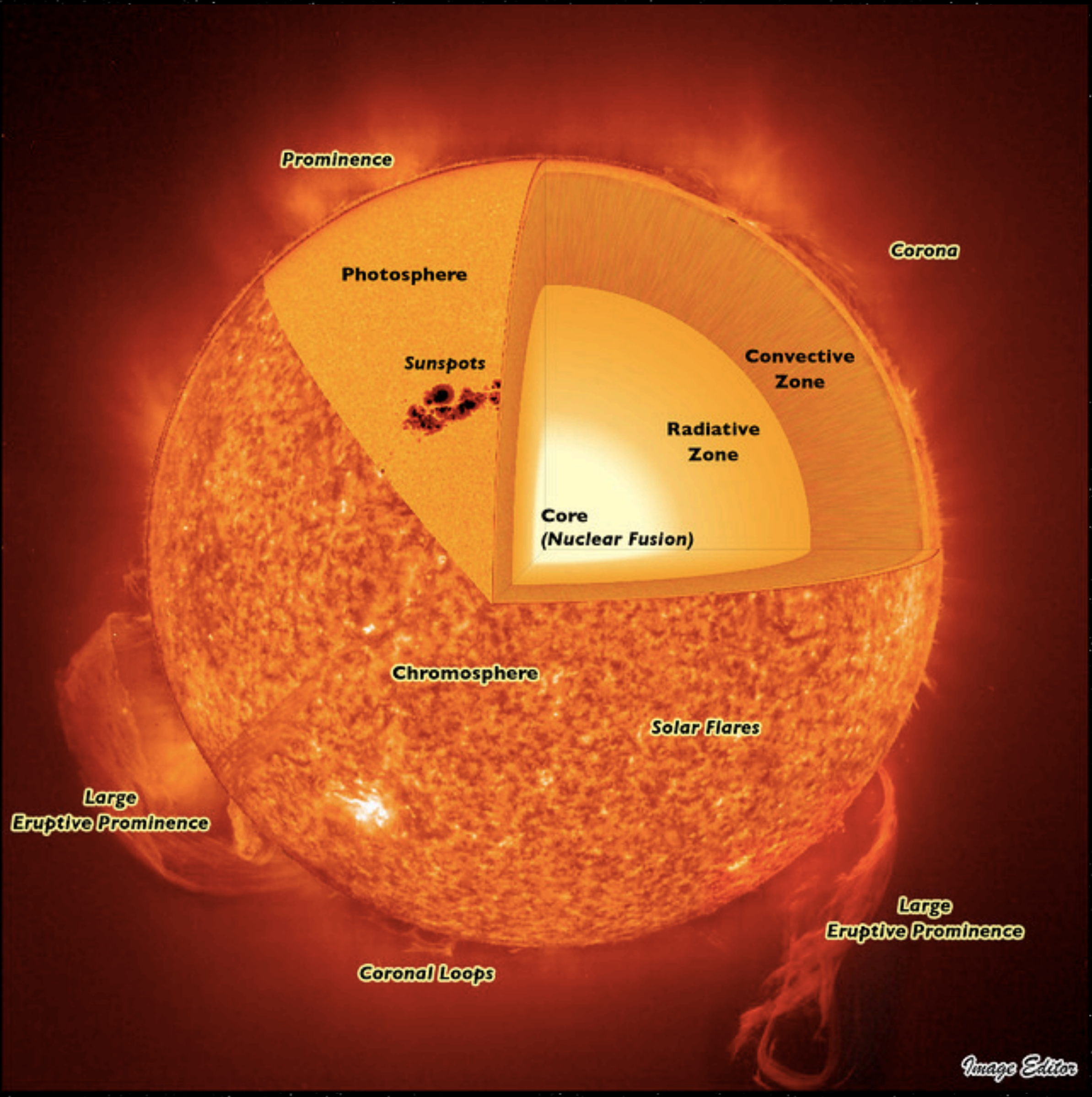
The Sun



Silvia Rainò
Dipartimento Interateneo di Fisica “M.Merlin”
Dell’Università e del Politecnico di Bari
ITALY

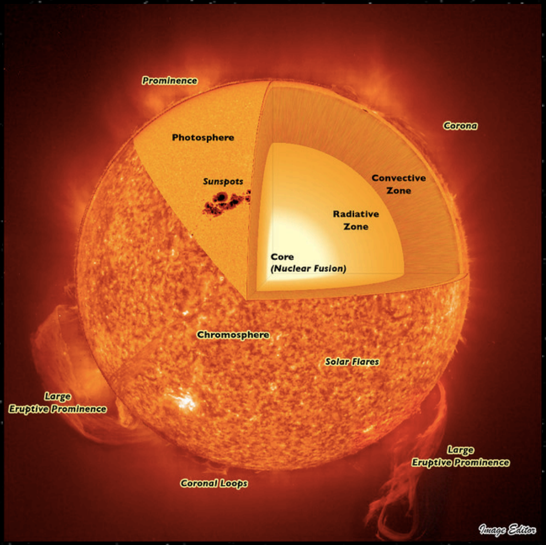
The Sun and its internal structure



Star type: yellow dwarf
Radius: 695000km

Rotation Period:
27d (equator)
>30d (at the poles)
Temperature:
on the surface 5777K
in the corona: 5×10^6K
in the nucleus: 2×10^7K
Distance Sun-Earth:
150×10^6km (1UA)

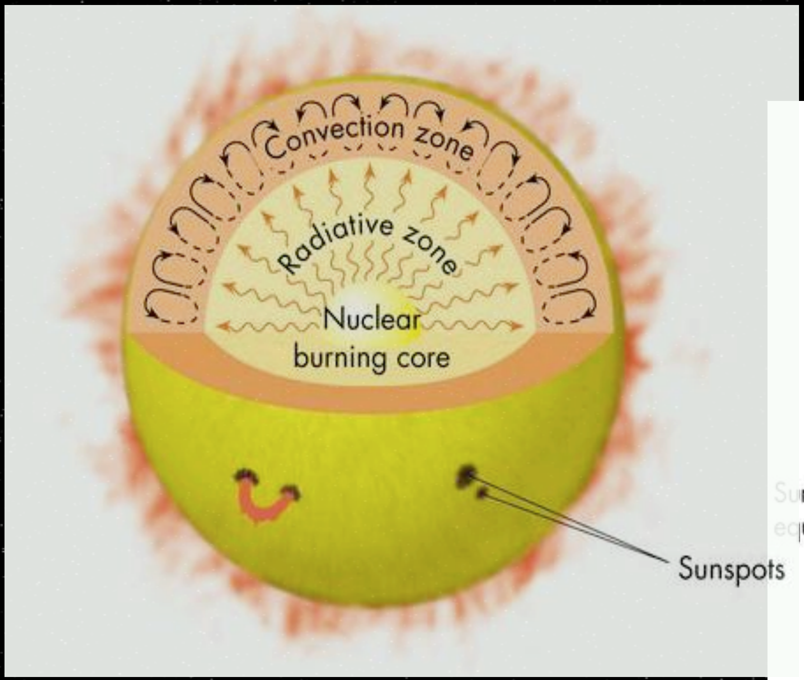
The Sun and its internal structure

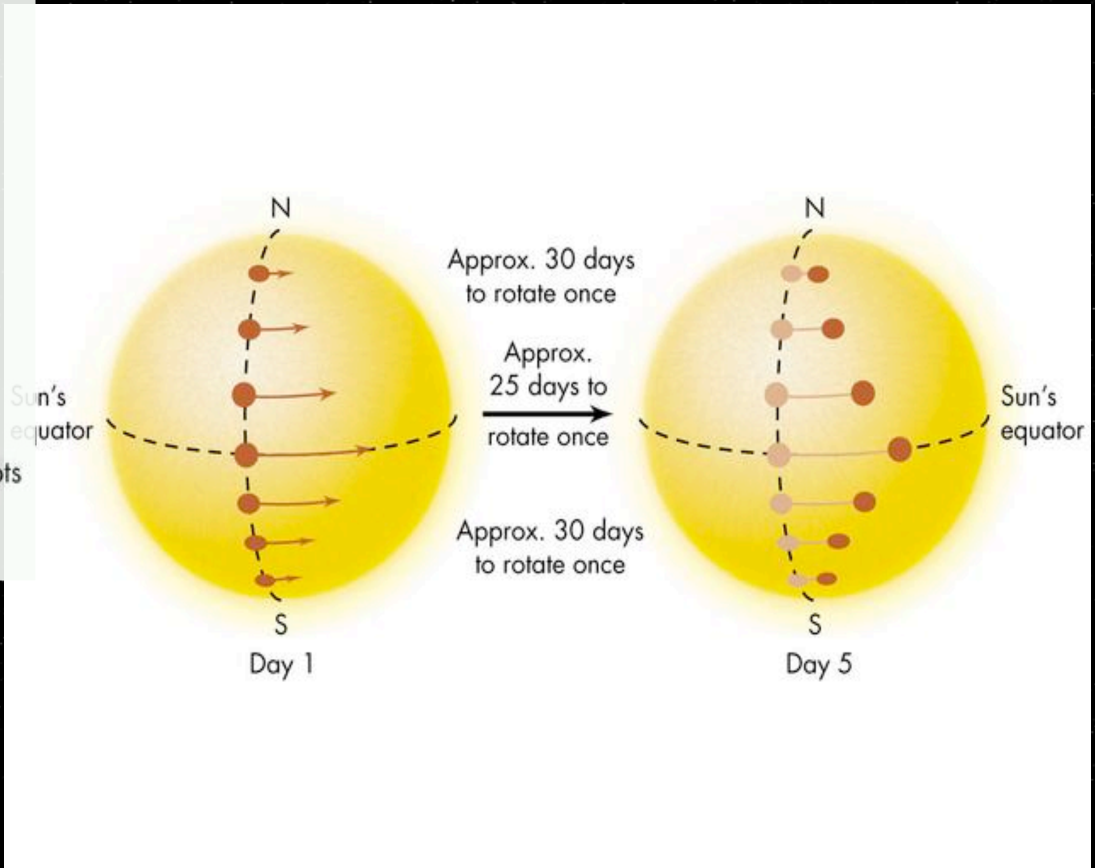


The Sun can be split into 2 regions

- The interior is a sphere with radius $R=7*10^8$m divided into:
  - Core
  - Radiative zone
  - Convection zone
- The atmosphere lies on the top and has the following layers:
  - The photosphere about 300 km thick. Most of the Sun visible light that we see originates from this region
  - The chromosphere is about 2000 km thick. We only see this layer and outer layers during an eclipse
  - The corona extends outwards for more than a solar radius

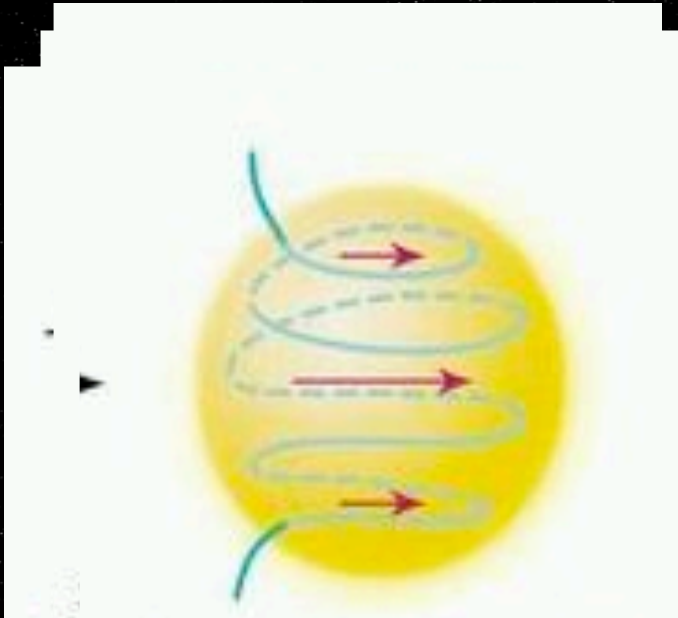
Other view of the Sun structure





Solar magnetic field

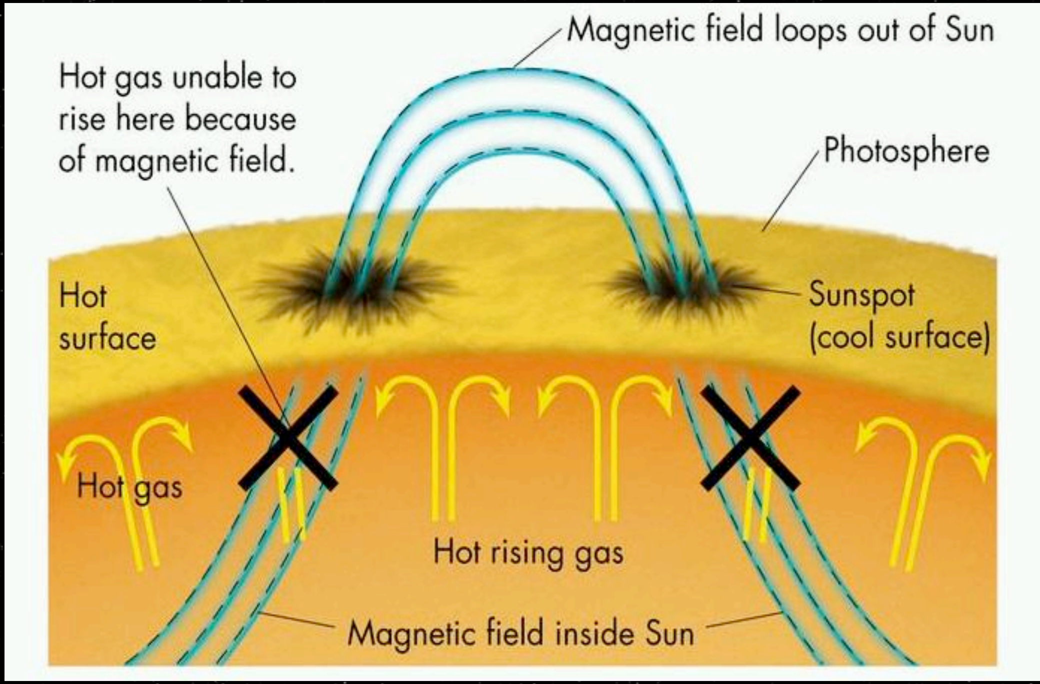
- The Solar magnetic field evolves over an 11-year cycle, at the end of which the polarity is inverted
- The Sun is not a rigid solid, it is in rotation (period 25.38 days at the equator), it has a differential rotation with latitude and this causes the distortion of the magnetic field lines
- Tipically, the magnetic fields originate (as in the Earth) due to stretching of the matter between the moving parts of the Sun at different speeds (dynamo)
- The Sun is also a **conductive fluid** so the magnetic field lines of the "dynamo" are dragged into the motion of the various parts, are amplified in the motion and then evolve during the cycle sometimes emerging on the surface (sunspots)



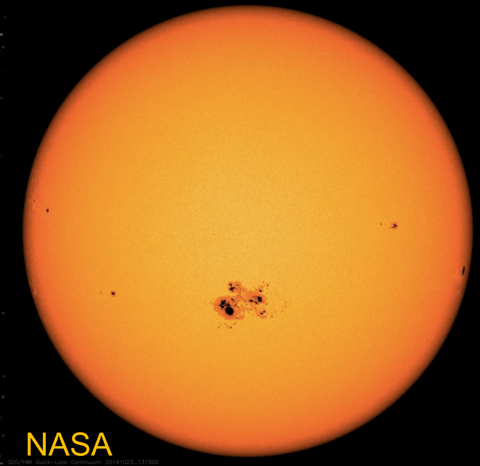
Winding continues–only a single field line is shown for clarity

Sunspots

The magnetic field lines interfere with the convective movement of the plasma which is relatively cold with respect to the surroundings

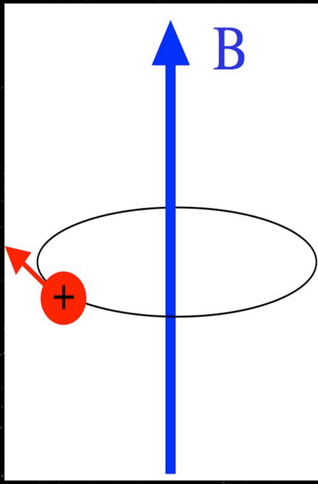


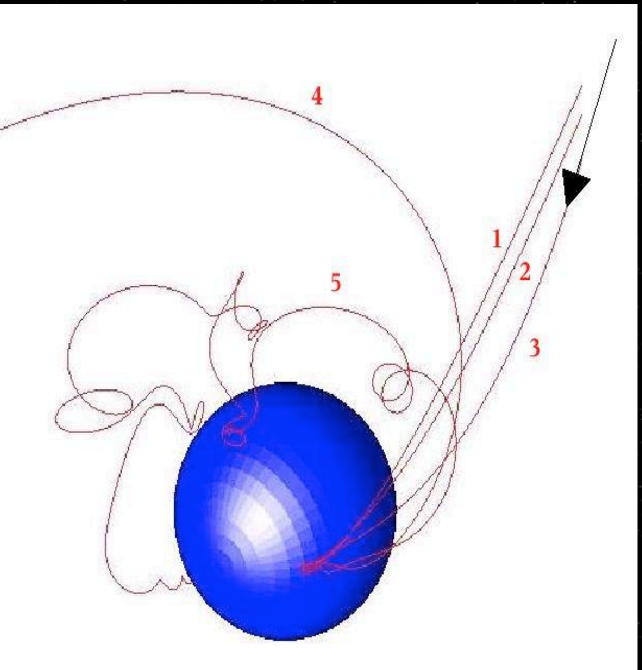
The number of sunspots is an indication of solar activity



Cosmic rays and magnetic fields

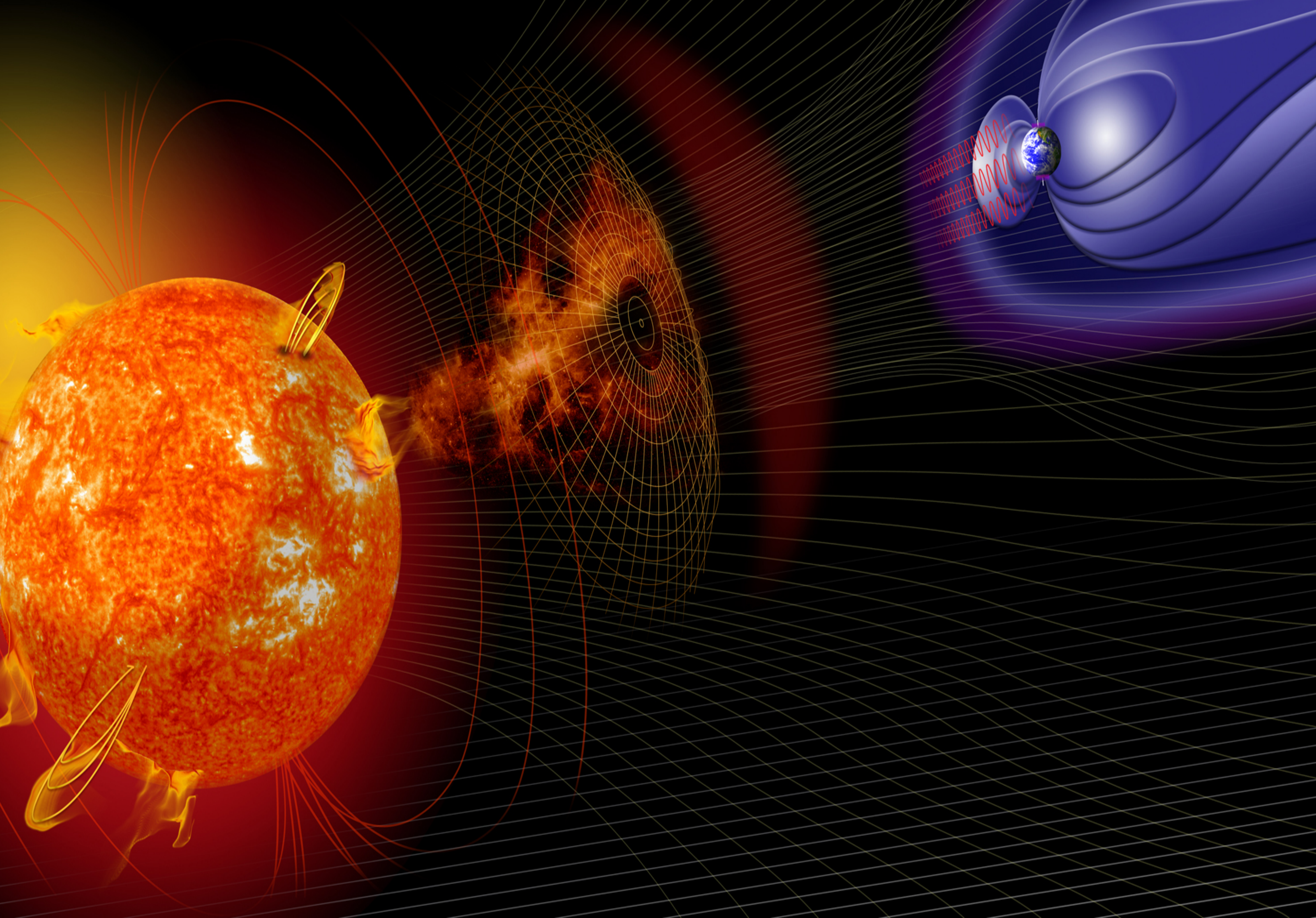
- The charges are affected by magnetic fields and if they are low energy they are diverted
- Therefore any change in the Earth's magnetic field (caused by solar activity) produces a change in the flow of cosmic rays.
- From Earth, solar activity is also followed by cosmic ray and neutron monitor detectors (vedi http://www.nmdb.eu)



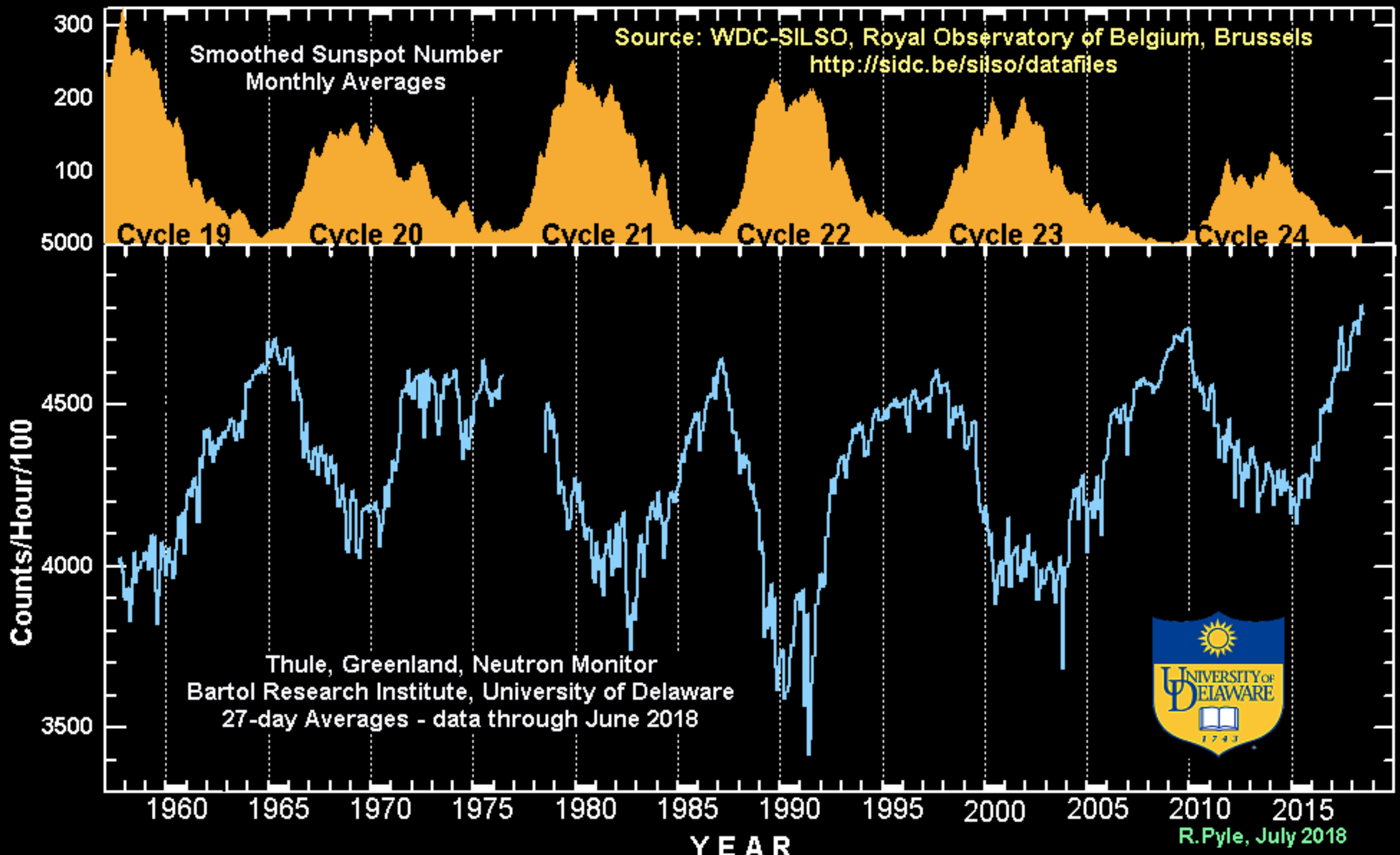


At intermediate energies the path followed are more complex

Solar activity modifies the Earth magnetic field



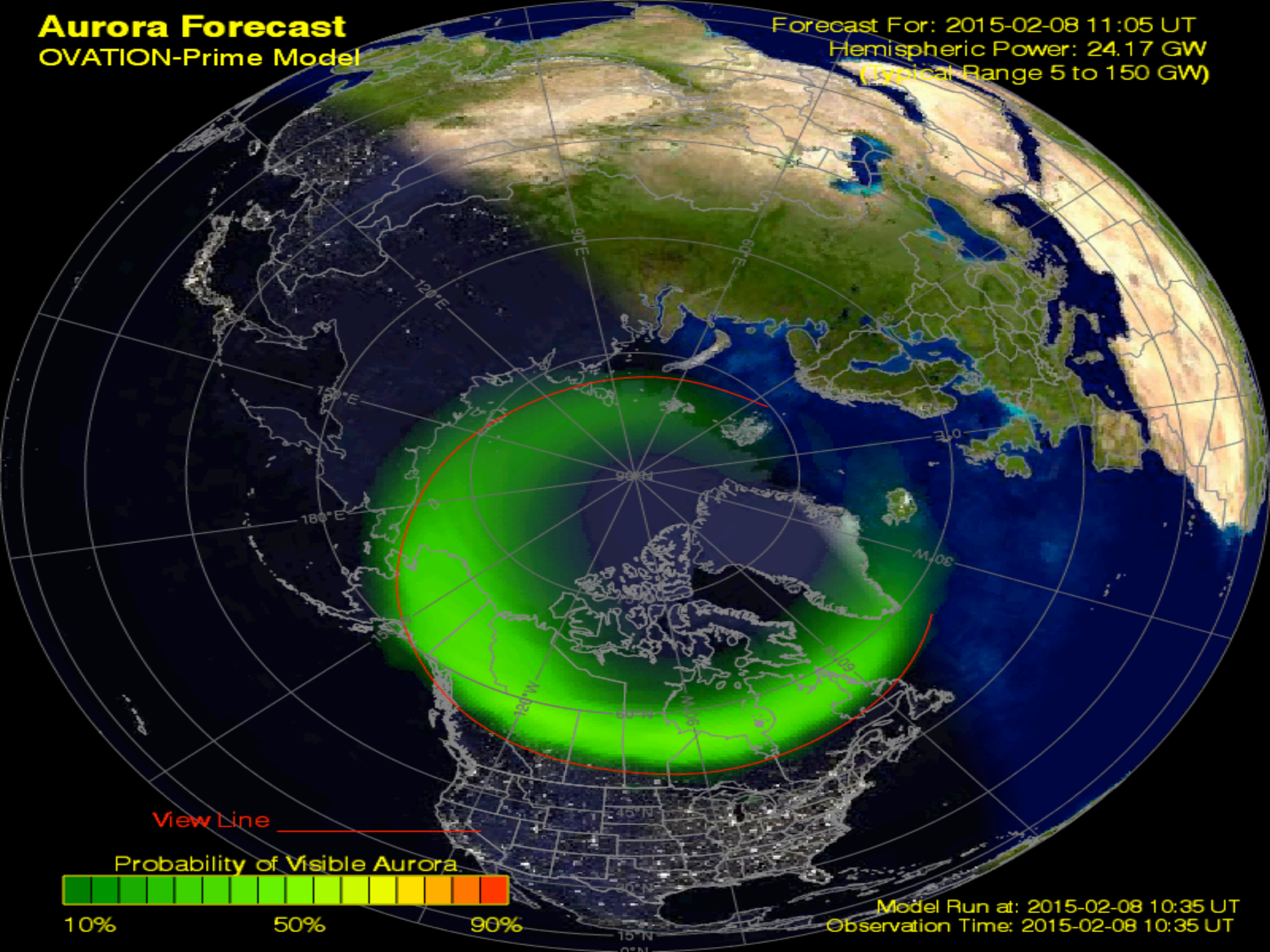
Anti-correlation with solar activity



Solar magnetic activity

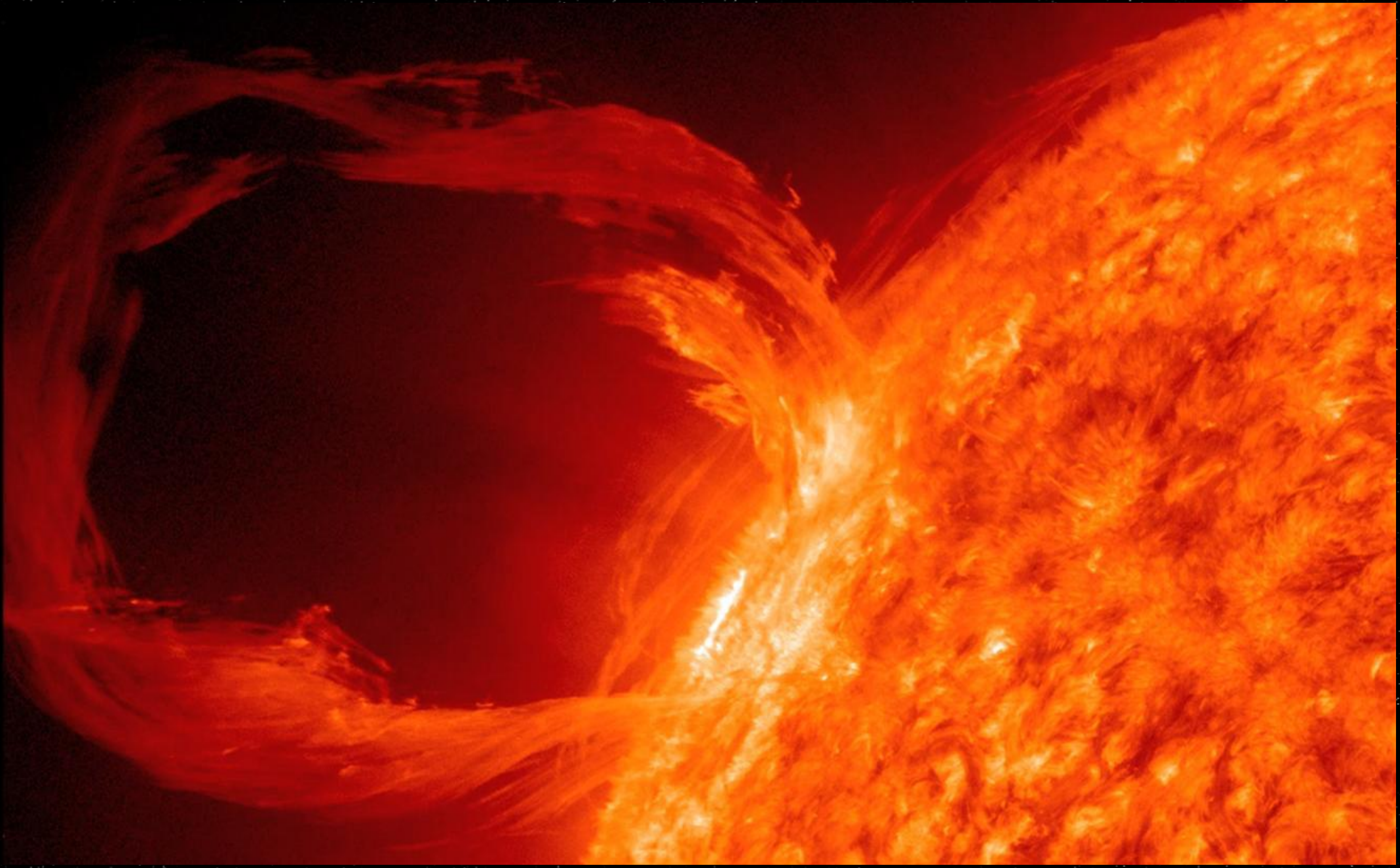
▪ The solar magnetic field (on the surface) is thousands of times more intense than the Earth magnetic field. There are several situations that lead to the variation of the magnetic field:

- Solar flares, eruptions of plasma (hot gas) in the chromosphere
- Solar wind: flares and solar activity contribute to heating the chromosphere and the corona that partly escapes from the Sun towards interplanetary space, constituting a constant flow of charged particles (electrons and protons) from the Sun to the outside.
- CME (Coronal Mass Ejection) in this case an arc of mass of gas is expelled from the Sun towards space, if it arrives on Earth it contributes to auroras or solar storms



Aurora Forecast
OVATION-Prime Model
Forecast For: 2015-02-08 11:05 UT
Hemispheric Power: 24.17 GW
(Typical Range 5 to 150 GW)
View Line
Probability of Visible Aurora
10%
50%
90%
Model Run at: 2015-02-08 10:35 UT
Observation Time: 2015-02-08 10:35 UT

CME – Coronal Mass Ejections

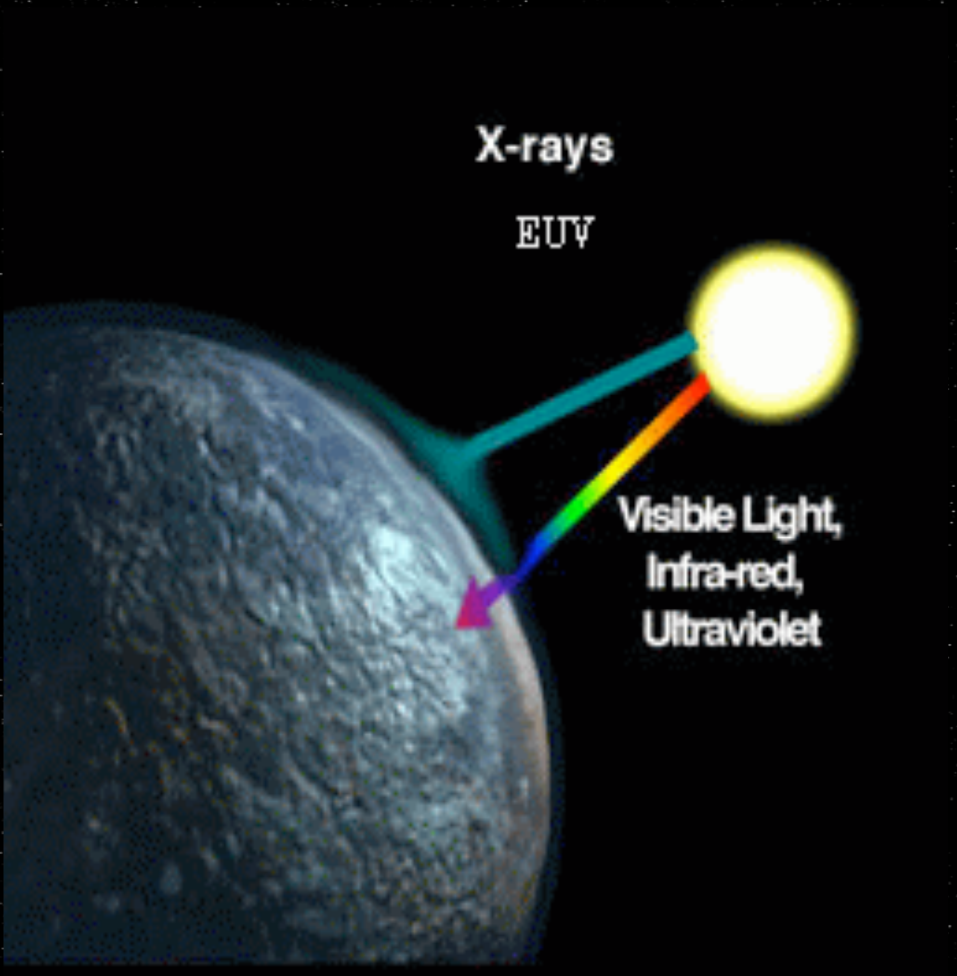


Space Weather

- Forecast of solar activity,
- Monitoring and auroral boreal forecasts,
- Warnings in case of CME that can propagate towards the Earth,
- Monitoring of magnetic fields and
- Any information useful to understand solar activity :

http://www.swpc.noaa.gov/

How we observe the Sun

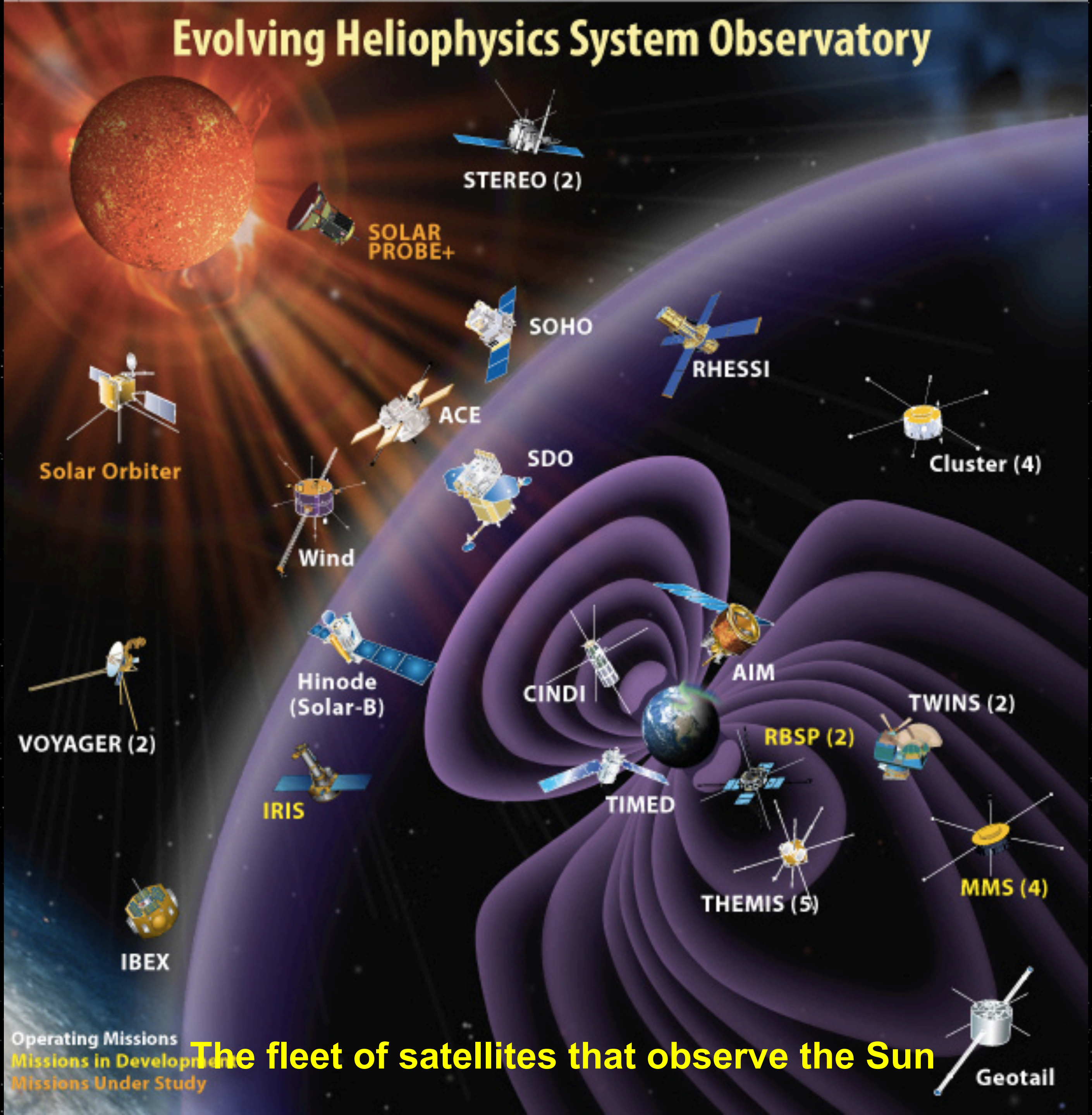


From the Earth:
Visible, infrared, UV, radio+CRs

From Satellites:
X and gamma-rays, microwaves+CRs

Solar Monitoring

- X-rays and gamma-ray observations
- Observations in visible light
- Acoustic wave propagation measurements in the Sun (via Doppler effect, helioseismology)
- Radio and Microwaves observations (also on Earth)
- Measurements of cosmic ray fluxes
- Measurements of interplanetary magnetic fields



The fleet of satellites that observe the Sun

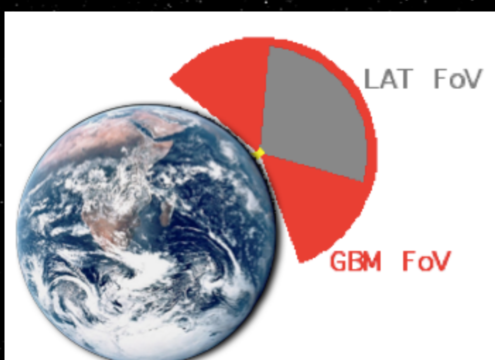
PFISR
RISR
Sondrestrom
MLSO
NSO/
DKIST
BBSO
WSO
OVSA
NSO SP/KP
Millstone Hill
NRAO
SuperDARN
Super DUAL AURORAL RADAR NETWORK
MSO
SFO
Arecibo
Jicamarca

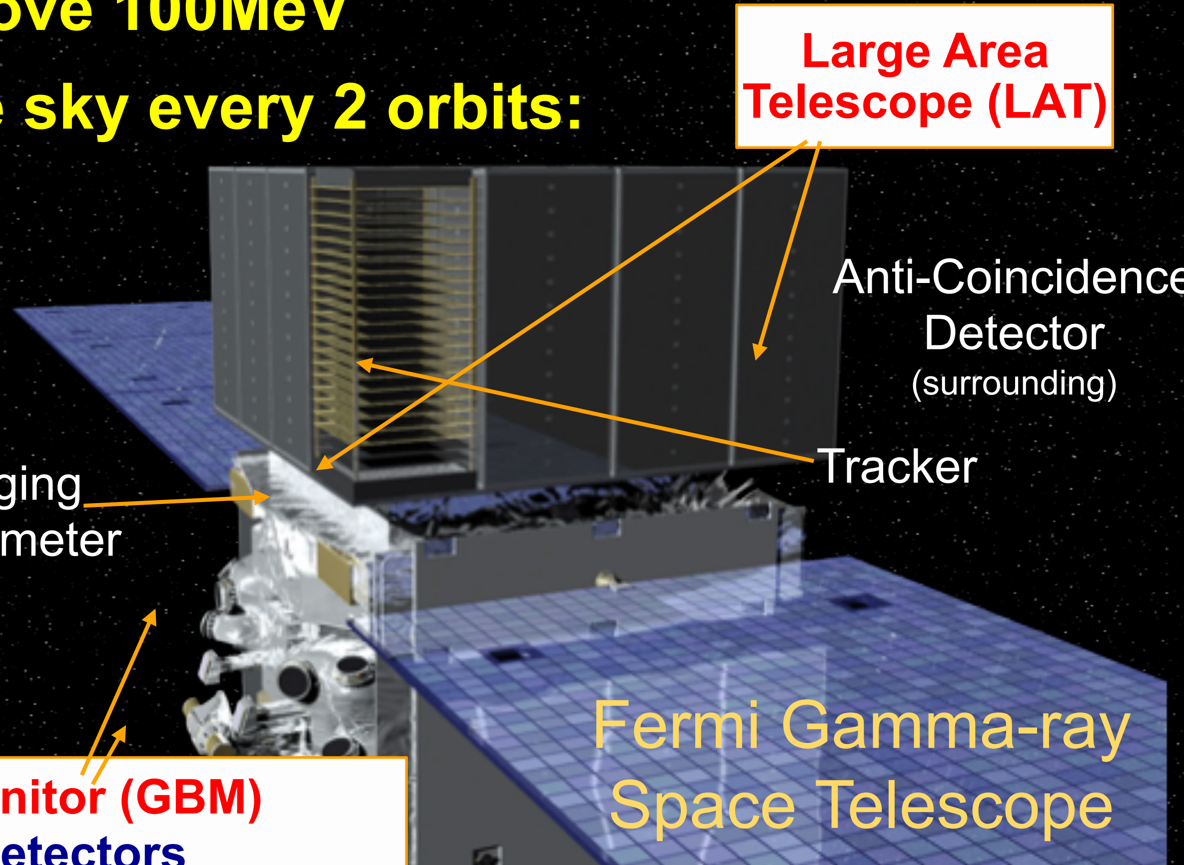
High energy observations

- The gamma-ray observations were rather limited before the launch of the Fermi satellite (2008).
- Only 9 flares observed as gamma-rays before launch, associated with significant intensity flares observed in the 1990s

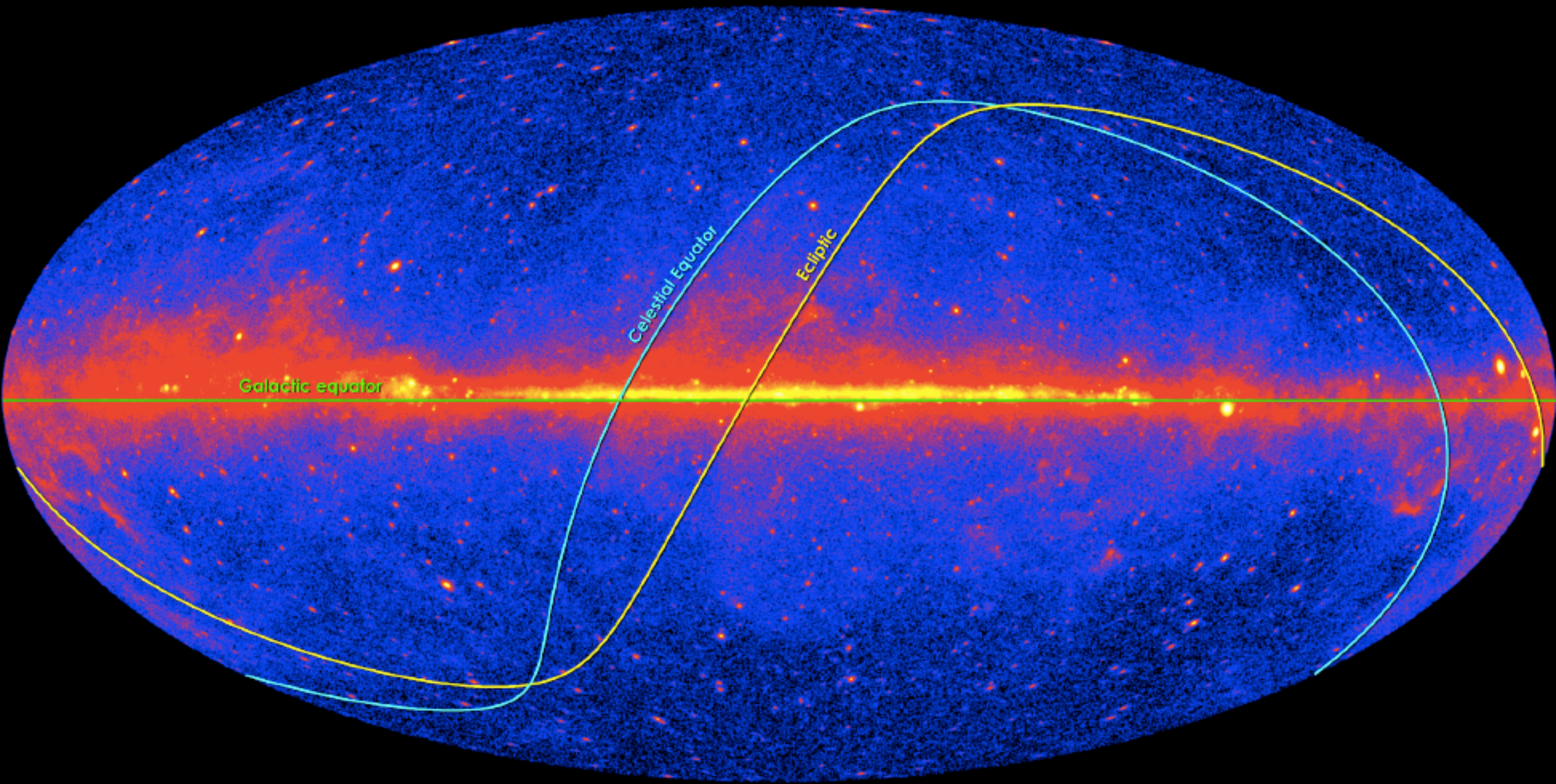
Fermi-LAT as a Solar Observatory

- Launched in 2008
- Wide Field of View
- High sensitivity above 100MeV
- Observes the entire sky every 2 orbits:
  - Sun in the FoV about 30min every 3 hours





Gamma-ray Burst Monitor (GBM)
12 NaI and BGO Detectors
8keV-40MeV
Whole unocculted sky



Celestial Equator
Ecliptic
Galactic equator

High energy emission from the Sun

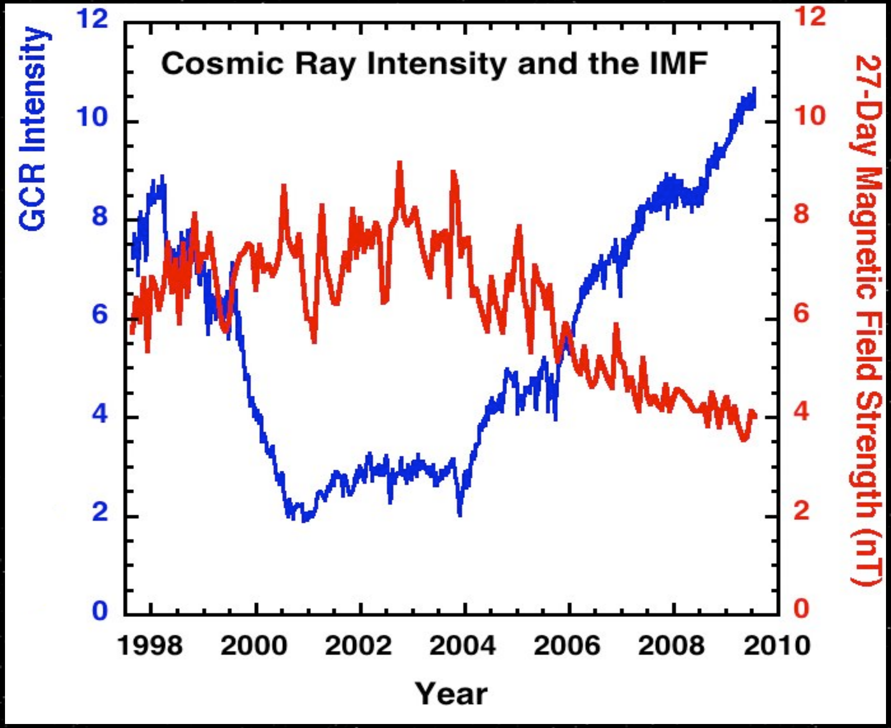
- Quiet gamma-ray emission from the Sun has two components (Fermi-LAT observations in the first 18 months ApJ 734 (2011) 116):
  - Extended emission: Inverse Compton (IC) due to the CR electron scattering off solar photons in the heliosphere
  - Pointlike emission: CR nuclei interactions with the solar atmosphere
- Gamma-ray emission studies are a sensible probe for CR fluxes in the solar system and for electrons in the inner heliosphere
- IC solar emission is extended and is a background for many studies; a detailed knowledge of this emission is needed

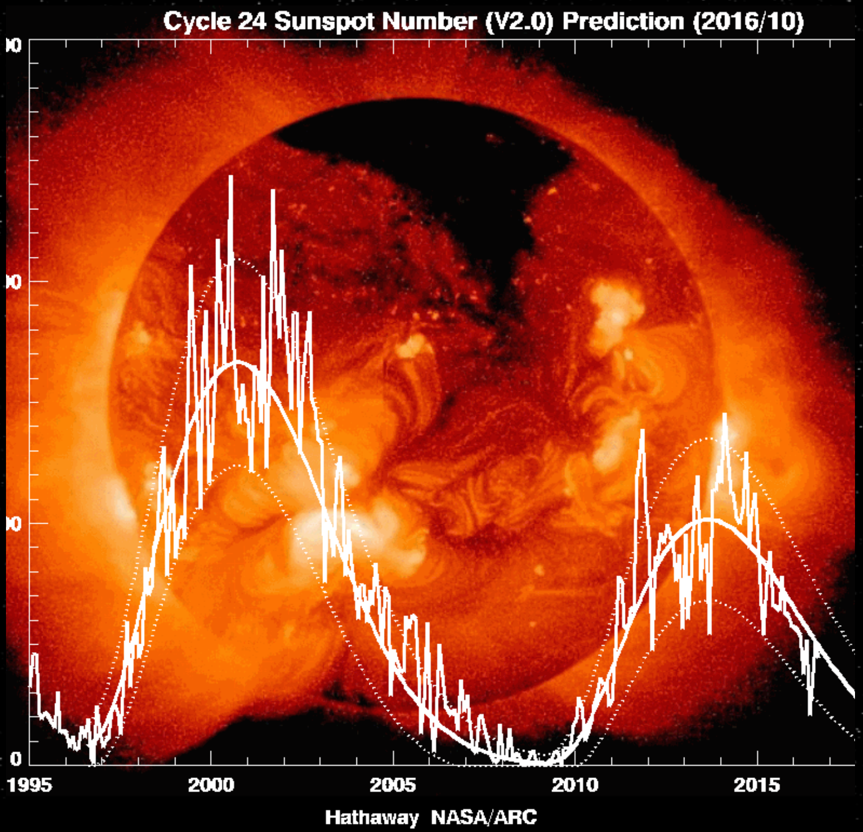
Solar activity and Cosmic rays

Gamma-ray flux measurements depend on the solar cycle, and so on CRs flux intensities

Max solar activity -> min cosmic-ray flux

Min solar activity -> max cosmic-ray flux

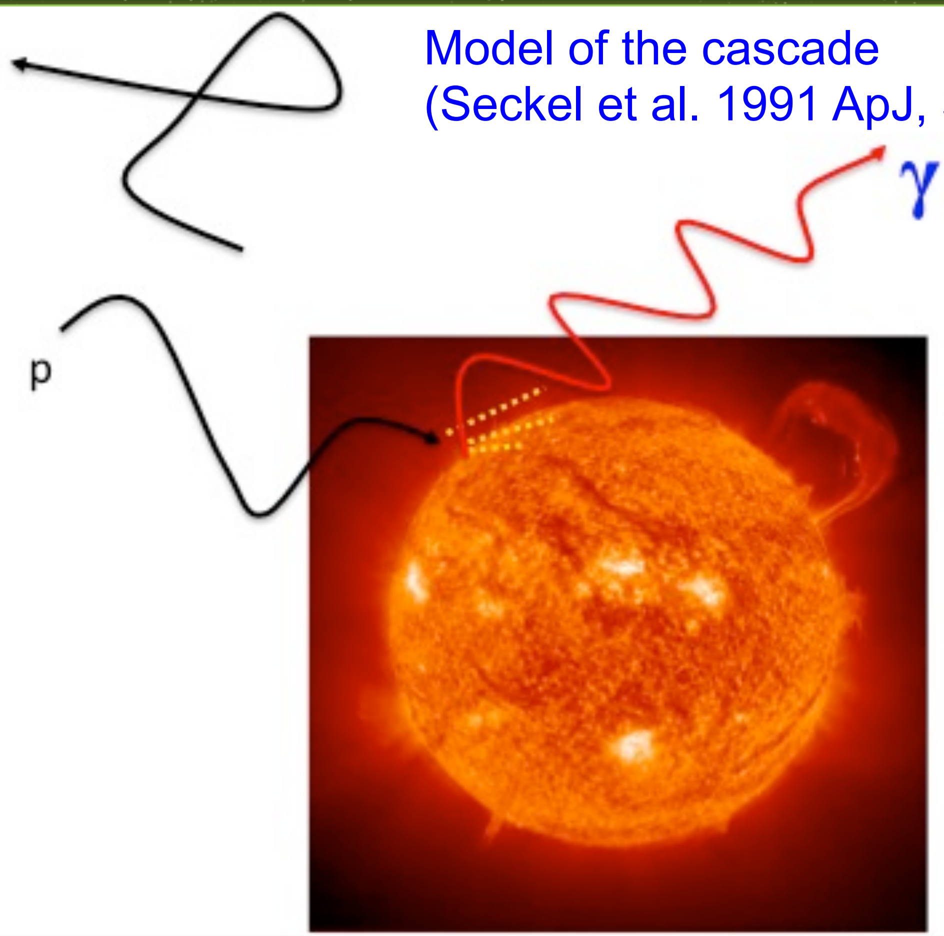




1) Emission from the disk

Hadronic interactions of cosmic rays with the solar atmosphere

Model of the cascade
(Seckel et al. 1991 ApJ, 382, 652)



Thompson et al. 1997
JGR, 102, 1473 ->
upper limit with EGRET

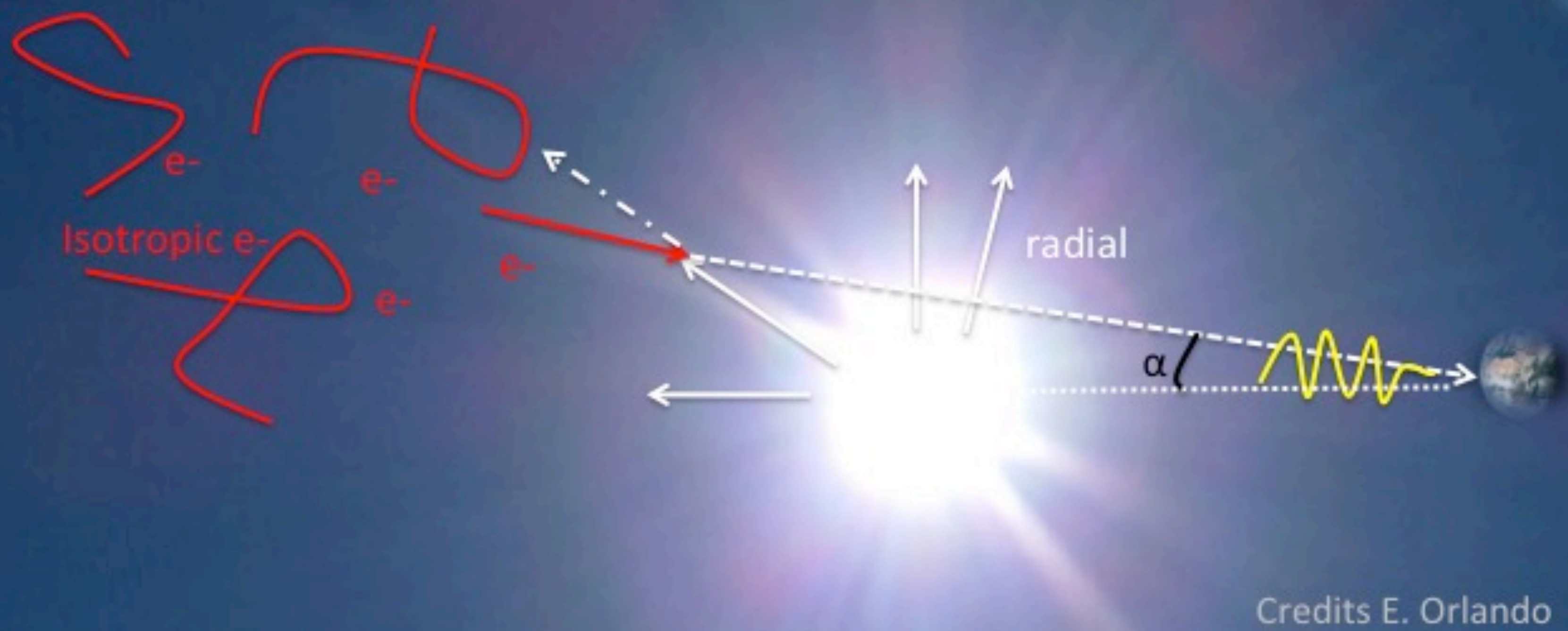
Credits: E.Orlando

2) Extended Inverse Compton (IC) emission

GeV electrons (CR) + eV photon (solar photons)→ gamma rays

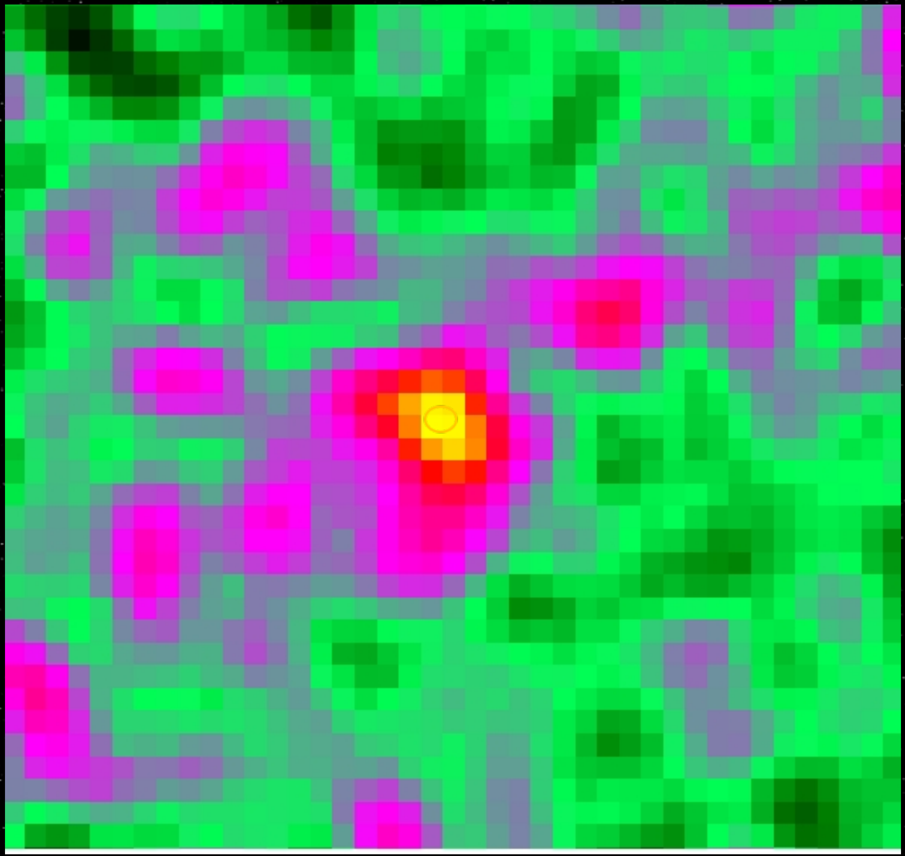
First theory:

Orlando & Strong, 2006 arXiv:astro-ph/0607563; 2007 Ap&SS, 309, 59; and Moskalenko, Porter & Digel, 2006 ApJ 652, L65 independently



First Detection of the Quiet Sun in Gamma Rays

Orlando & Strong (2008) A&A 480, 847



EGRET

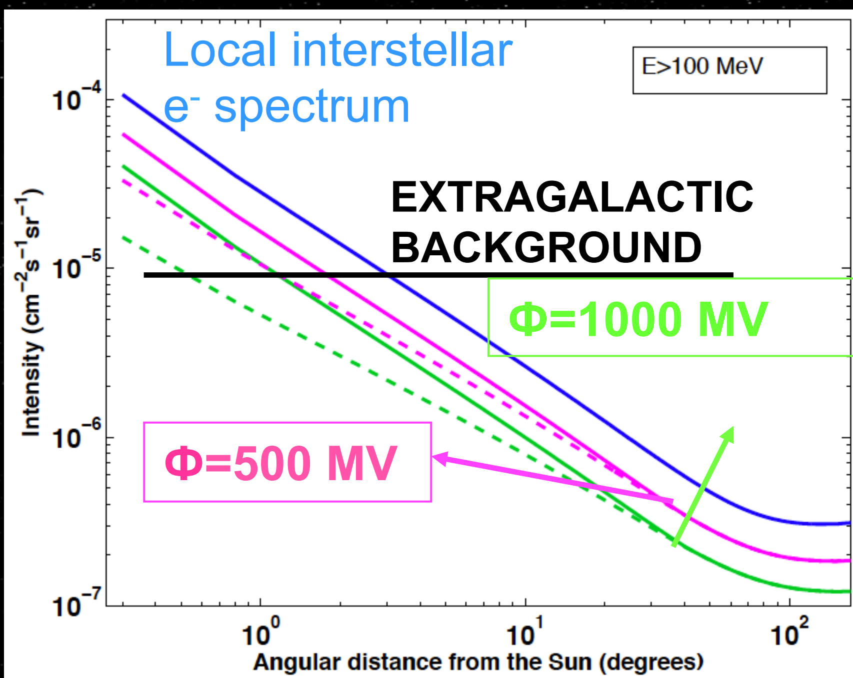
Analysis in Sun-centered system:
Disk and extended IC components were detected and separated.
IC emission found in agreement with models.

Credits: E.Orlando

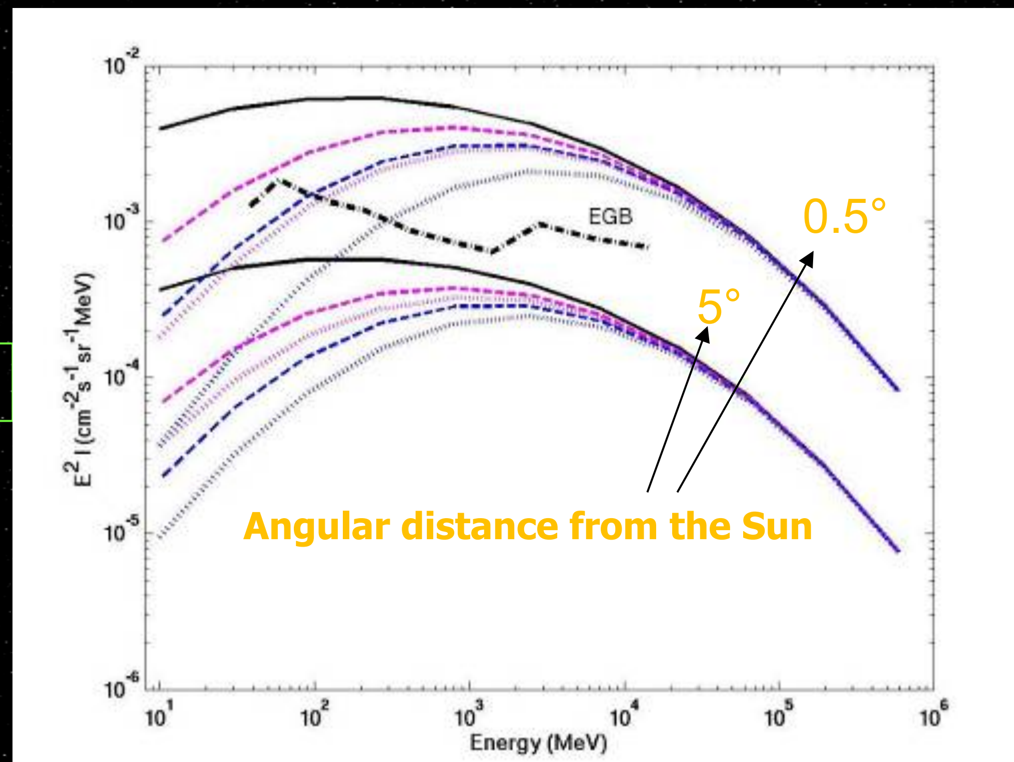
Examples of IC Models

From Orlando & Strong (2008) A&A 480, 847

Gamma intensity vs angular distance from the Sun

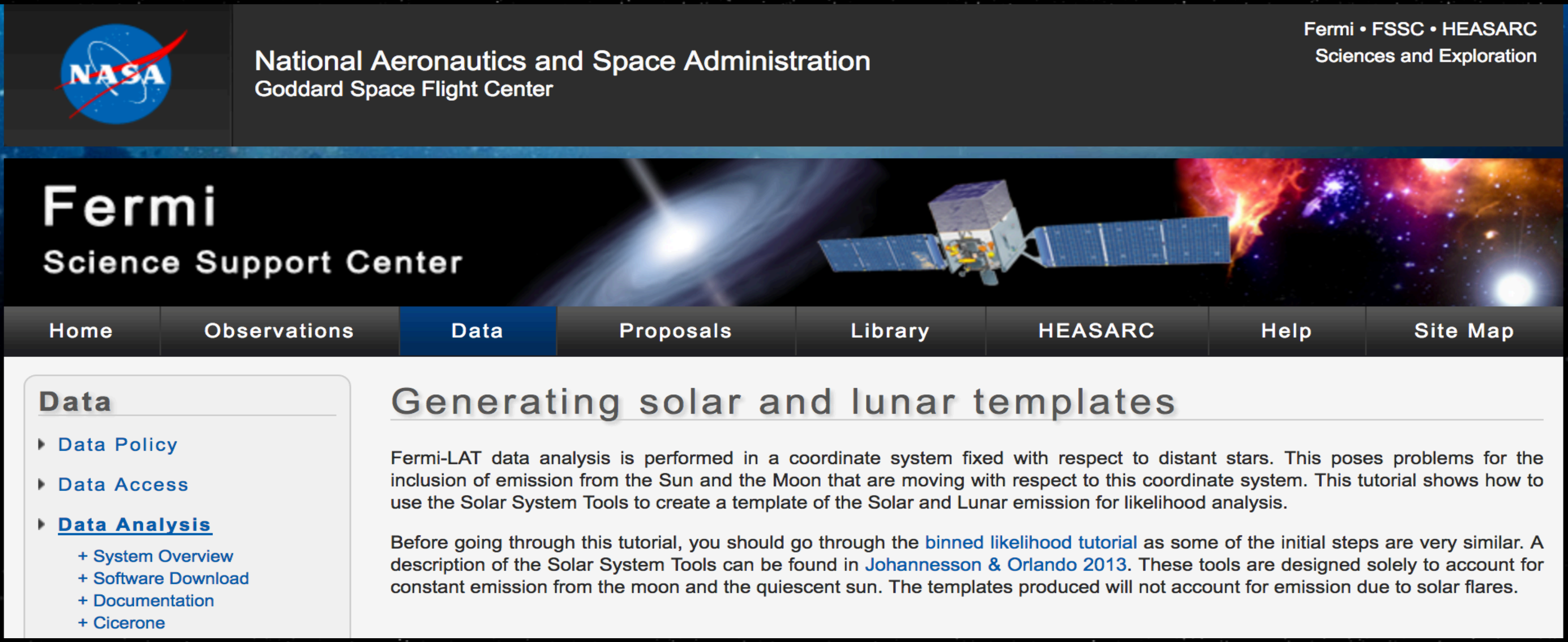


Gamma-ray spectrum for different solar modulation conditions



Credits: E.Orlando

Accounting for the Sun in Fermi LAT analyses



1) Dedicated Fermi Science Tools
(Johannesson & Orlando (2013) arXiv:1307.0197)

2) The Fermi Science Tools need input of IC models
(Orlando & Strong (2013) NuPhBS, 239, 266)

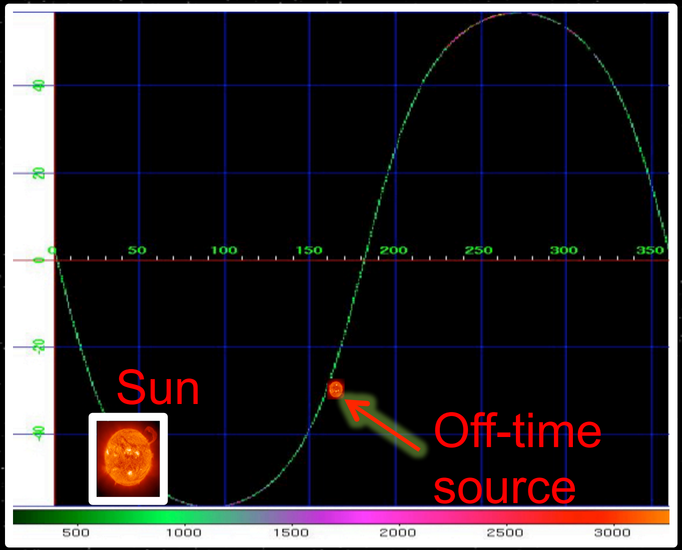
Credits: E.Orlando

Fermi-LAT data analysis

- Energy range: 30 MeV – 300 GeV
- ROI: 20 deg
- Zenith angle: <100°
- Sun centered data analysis
- Further selections:
  - Galactic plane cut: |b| >30°
  - Moon-Sun angular separation > 20°
  - Cut on bright sources with F(>100MeV) > 5 10^{-7} ph/cm^2s within 20deg from the SUN
  - Solar flares and all flaring sources excluded

Background estimation

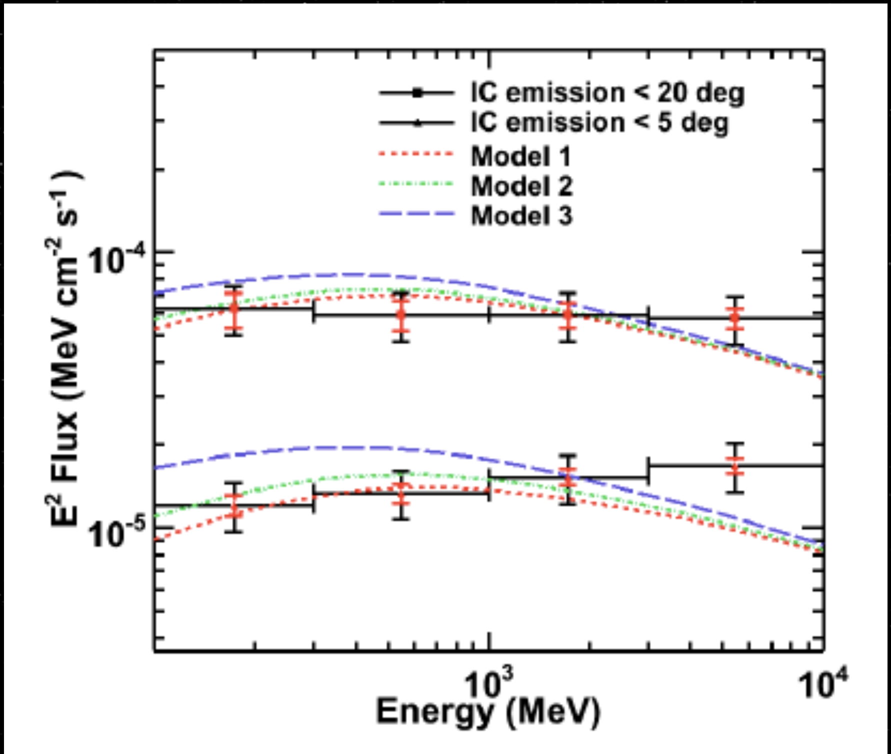
- Off-source ("fake" source) follows the path of the real source but at different times at 90° (120°,180°) distance (passes through the same areas in the sky but at different times)



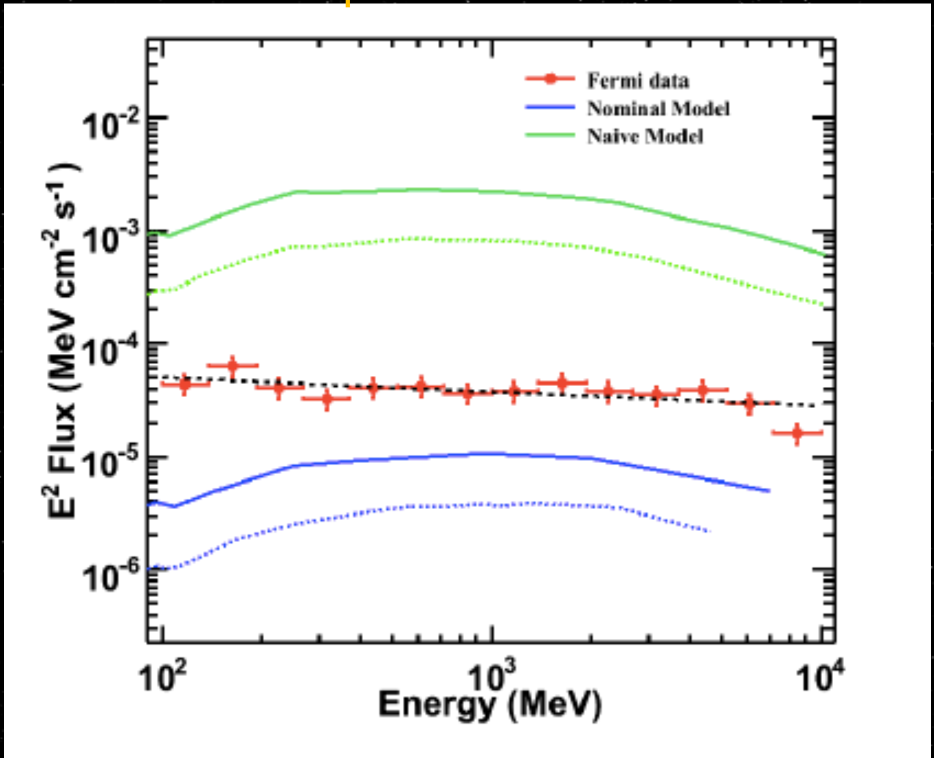
- Same data selection cuts applied to the sun data sample
- Modeling spectrum using a:
  - A generic file spectrum
  - A generic radial dependence starting from a dummy flat distribution
- Adjusting the energy spectrum and spatial distribution to minimize residuals, few iterations to convergence
- Output of likelihood analysis is the background model for the sun region

The Quiet Sun seen by Fermi-LAT

IC component

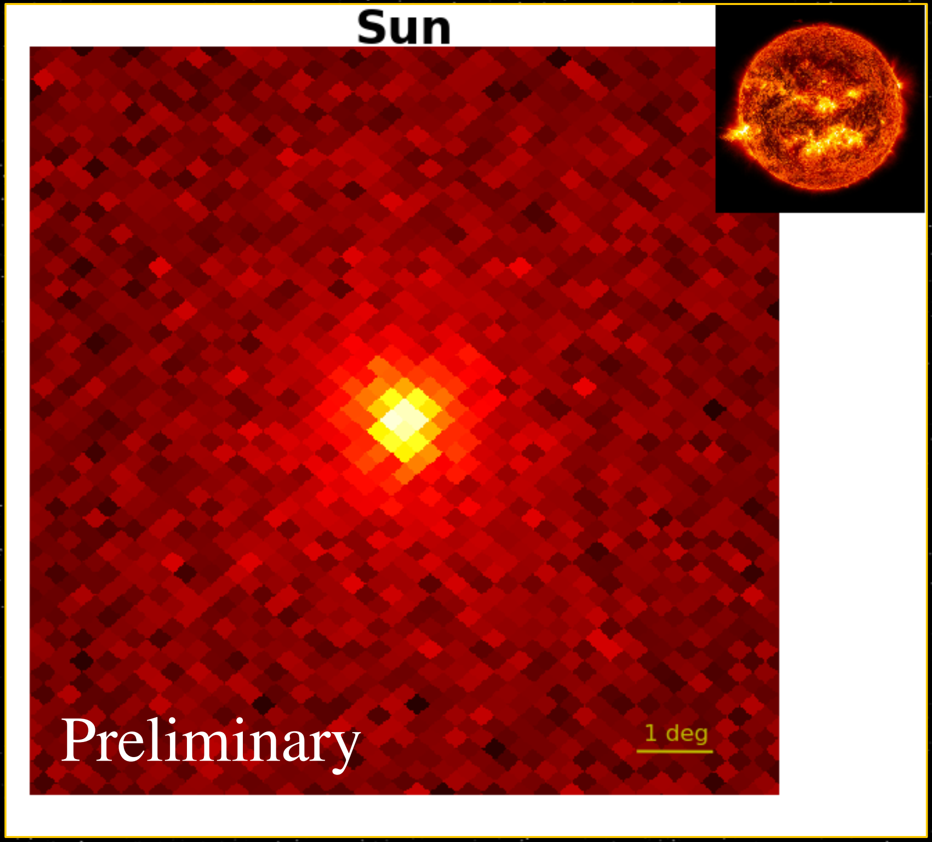


Disk component



A. A. Abdo *et al.* 2011 *ApJ* **734** 116

Significance map

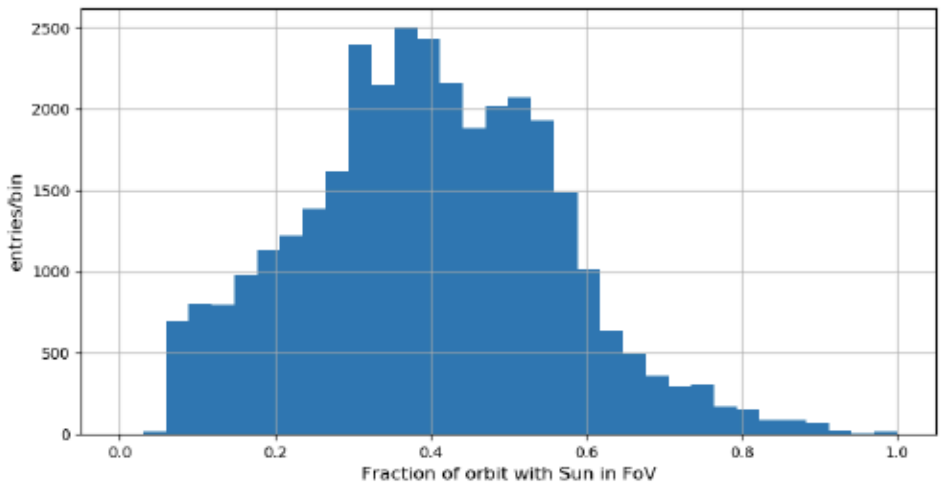


Significance map of the Sun as a function of RA and DEC in +/-5 degrees from the instantaneous position of the Sun

Coordinates are offsets from the Sun position in ecliptic coordinates.

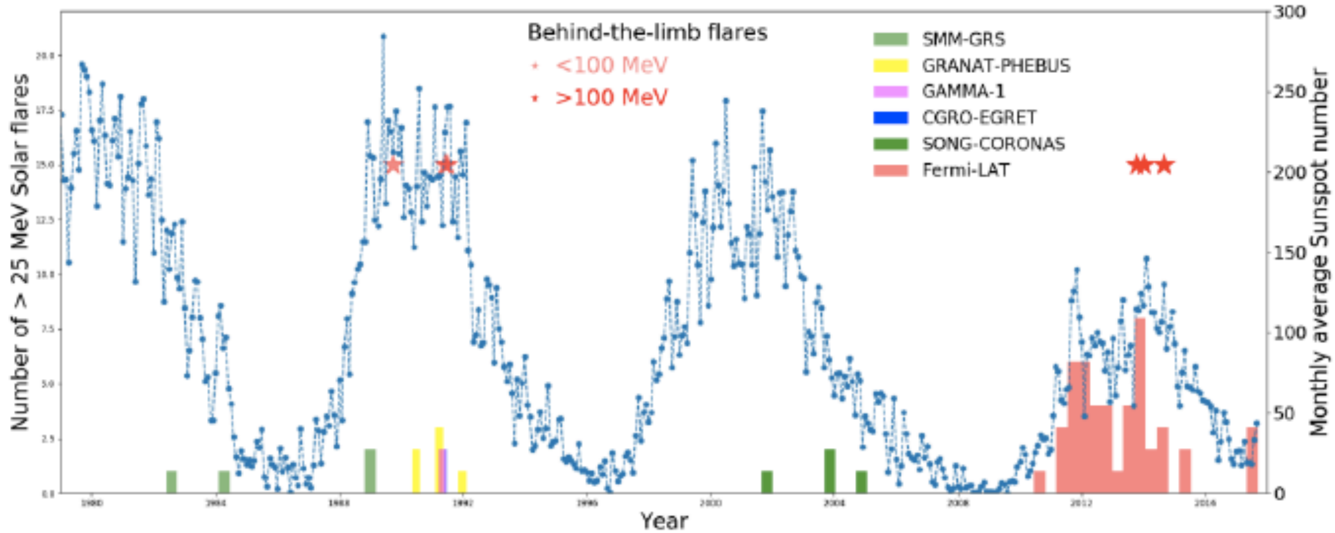
Energy range: 30 MeV - 100MeV

The Fermi-LAT Solar Coverage



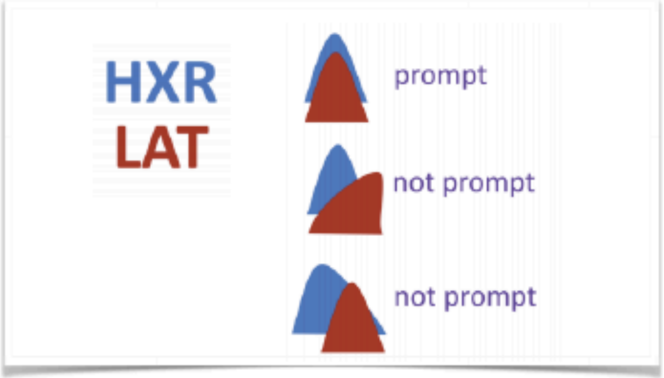
- Fermi-LAT is by no means a Solar observatory!
  - On average the Sun is in the field of view (FoV) only 40% of the orbit
  - *Fermi*-LAT has a 90 minute orbital period

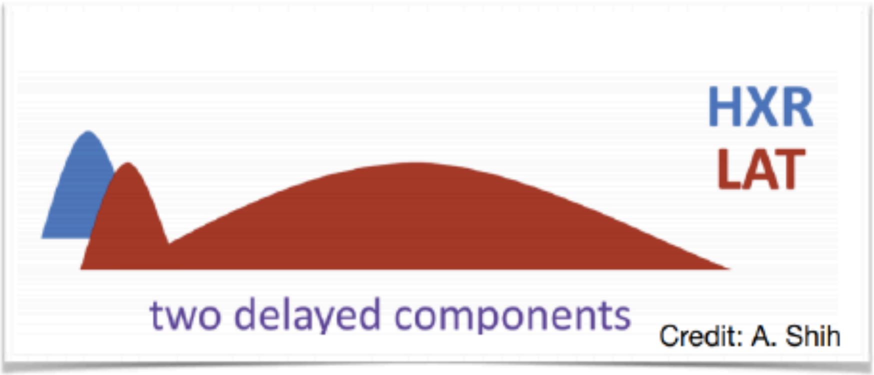
Nonetheless the number of > 30 MeV γ-ray flares has drastically increased after the launch of *Fermi*



Credits: M.Pesce-Rollins

Categories of Fermi-LAT Solar Flares





Fermi-LAT Solar Flare (FSF) Catalog contains 45 flares

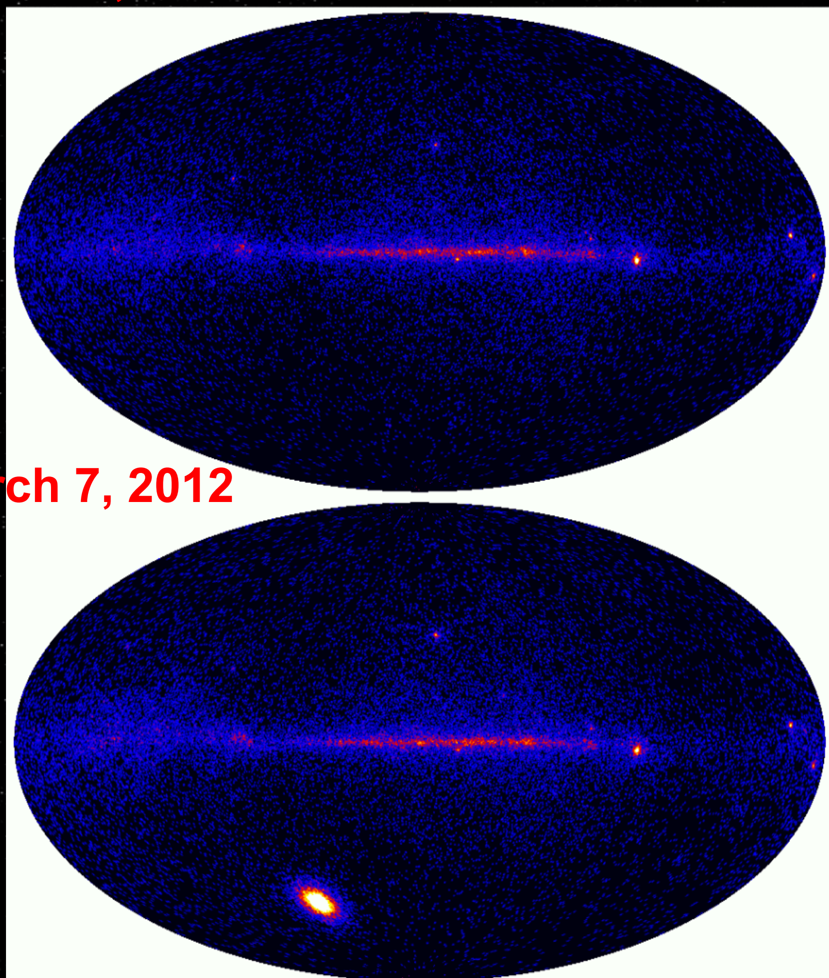
- 18 with a prompt component synchronized with HXR
- 37 with some delayed component beyond HXR
  - 21 exhibit delayed emission lasting longer than 2 hours
  - 16 exhibit delayed emission lasting less than 2 hours
  - 4 exhibit only delayed emission–no prompt emission detected
- 8 with only a prompt component
- 3 behind the limb

Credits: M.Pesce-Rollins

SOL2012-03-07 flare : the big one!

March 6, 2012

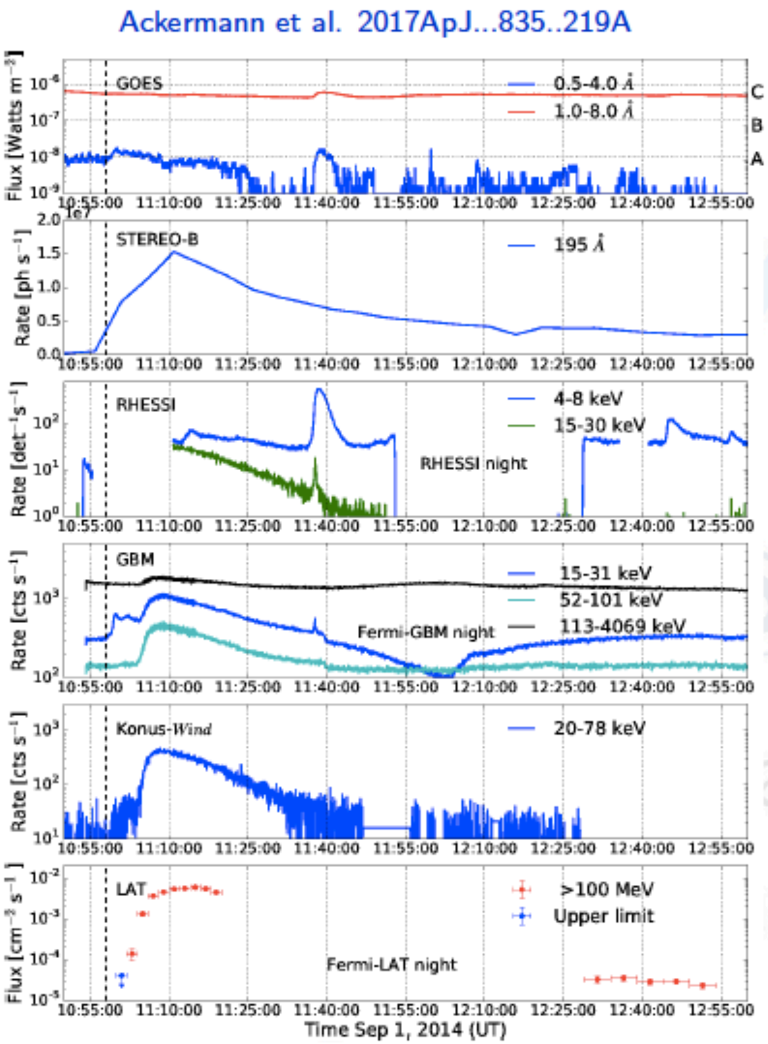
March 7, 2012

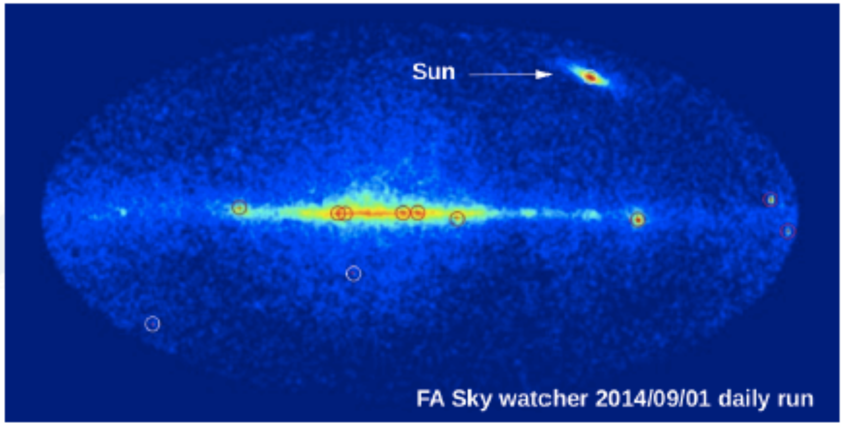


March 15, 2012 Astronomy picture of the day
http://apod.nasa.goc/apod/ap120315.html

- The most powerful flare ever observed
- The most durable: emission lasted for more than 20 hours
- The most energetic solar photon ever observed in a flare (4.5 GeV)

Exceptional behind the limb solar flare

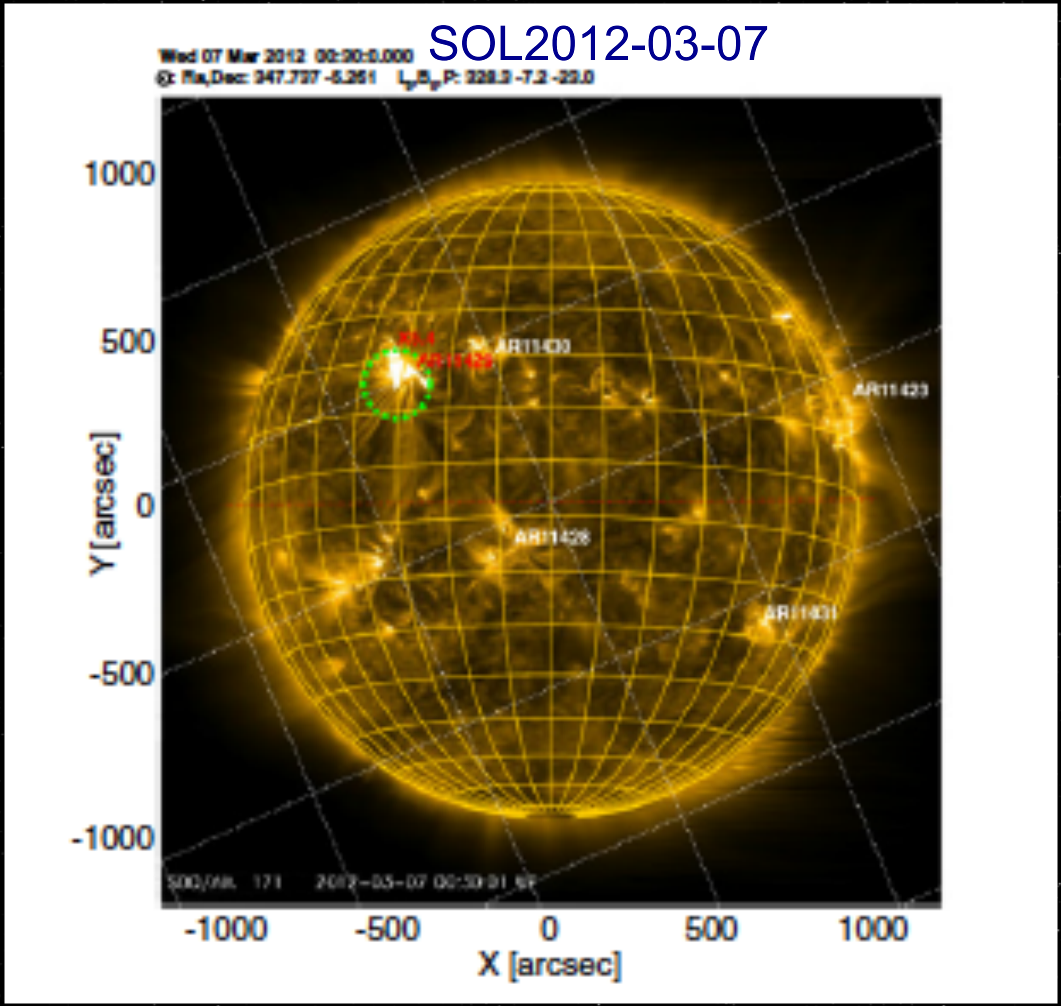




- The September 1st 2014 flare was unleashed from an active region near 40° behind the visible limb
- 15 photons withe E>1 GeV detected during the first 15 minutes (including 3.5 GeV photon)
- Press release at 2017 APS meeting in Washighton D.C
- Other BTL flares detected: SOL20131011 and SOL20140106

Credits: M.Pesce-Rollins

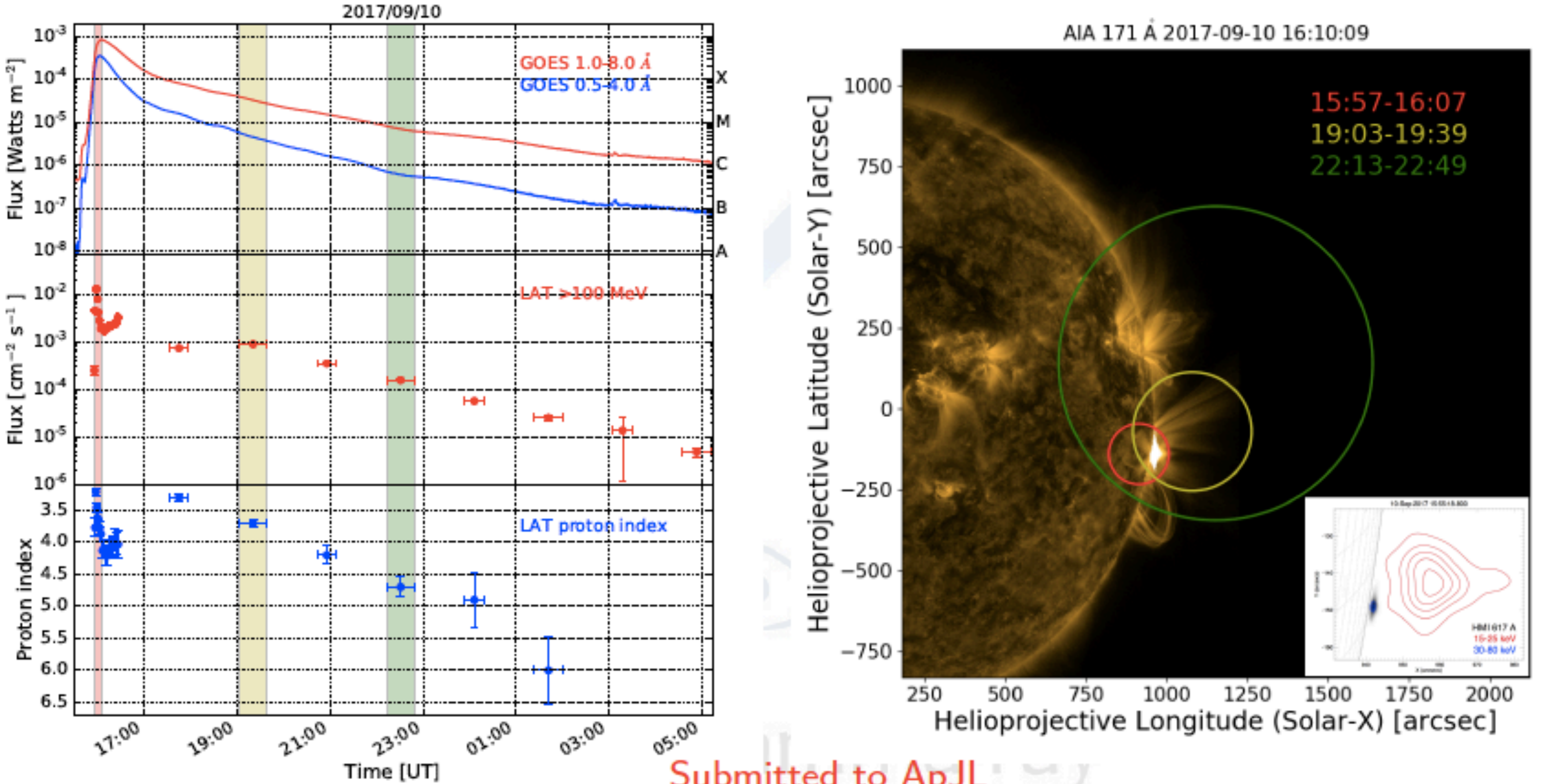
Localization of the high energy gamma-rays



Ajello et al., 2014 ApJ…789..20

- Localization studies provide insight to the source of the accelerated particles
- The position of the emission centroid is measured by a likelihood analysis
- For the brightest flares the >100 MeV emission centroid is found to be consistent with the location of the active region on the solar disk
  (picture integrated in time)

September 10th, 2017 solar flare



Submitted to ApJL

- First long duration GeV flare detected in association with a GLE
- CME initial speed (LASCO) 3620 km s^{-1}
- Emission detected for more than 12 hours, localized to the AR

Credits: M.Pesce-Rollins

Summary

- The Sun causes the variability of cosmic ray flux at low energy (<10GeV) both for particles it emits and for the variability of the magnetic field
- We have not yet fully understood the mechanism of particle acceleration and the details of the Sun's magnetic field
- The high energy emission from the Sun accounts for two distinct components: disk hadronic component and Inverse Compton component
- Several solar flares have been detected at high energy and are included in the Fermi LAT Solar Flare Catalog in preparation
- **Bibliography and references:**

  - http://www.spaceweather.com/
  - http://solarscience.msfc.nasa.gov/
  - http://www.solarmonitor.org/index.php (Sun in real time with various detectors)
  - https://www.swpc.moaa.gov/communities/space-weather-enthusiasts

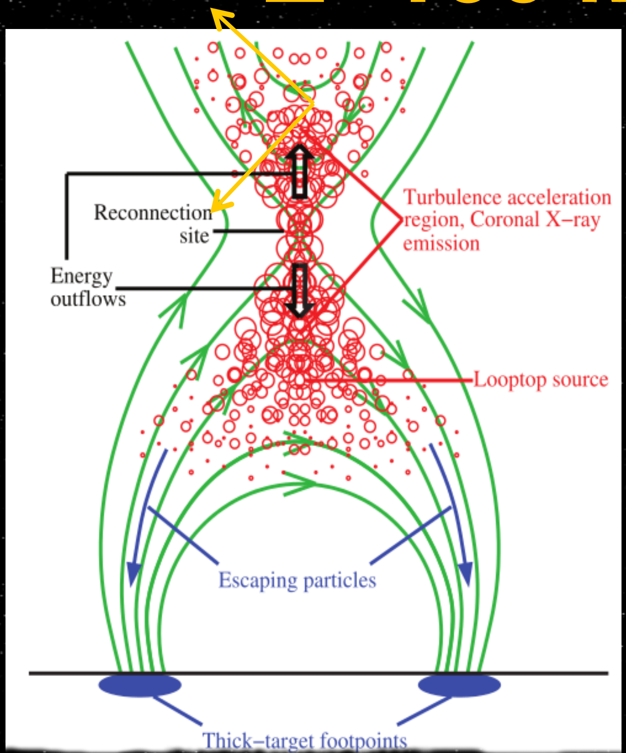
- Neutron Monitors:

  - http://www.nmdb.eu/nest/search.php
  - http://cr0.izmiran.rssi.ru/apty/main.html

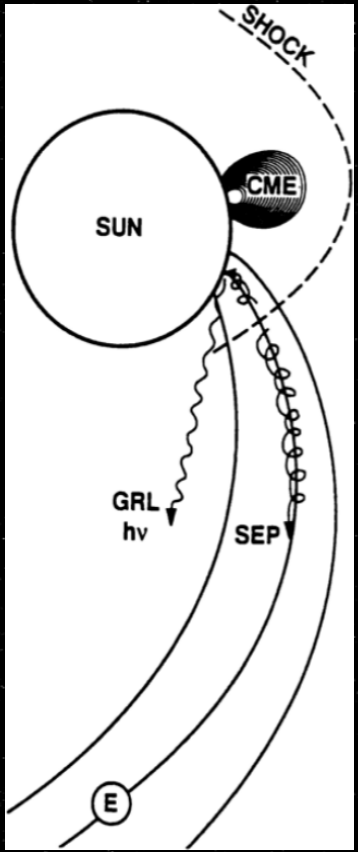
Thank you!

Back-up

How to explain the long duration γ-ray E>100 MeV mechanism?

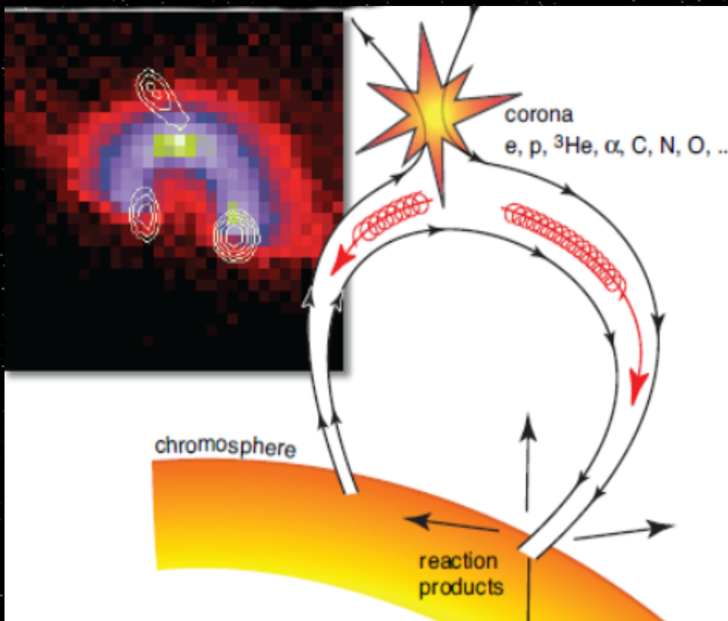


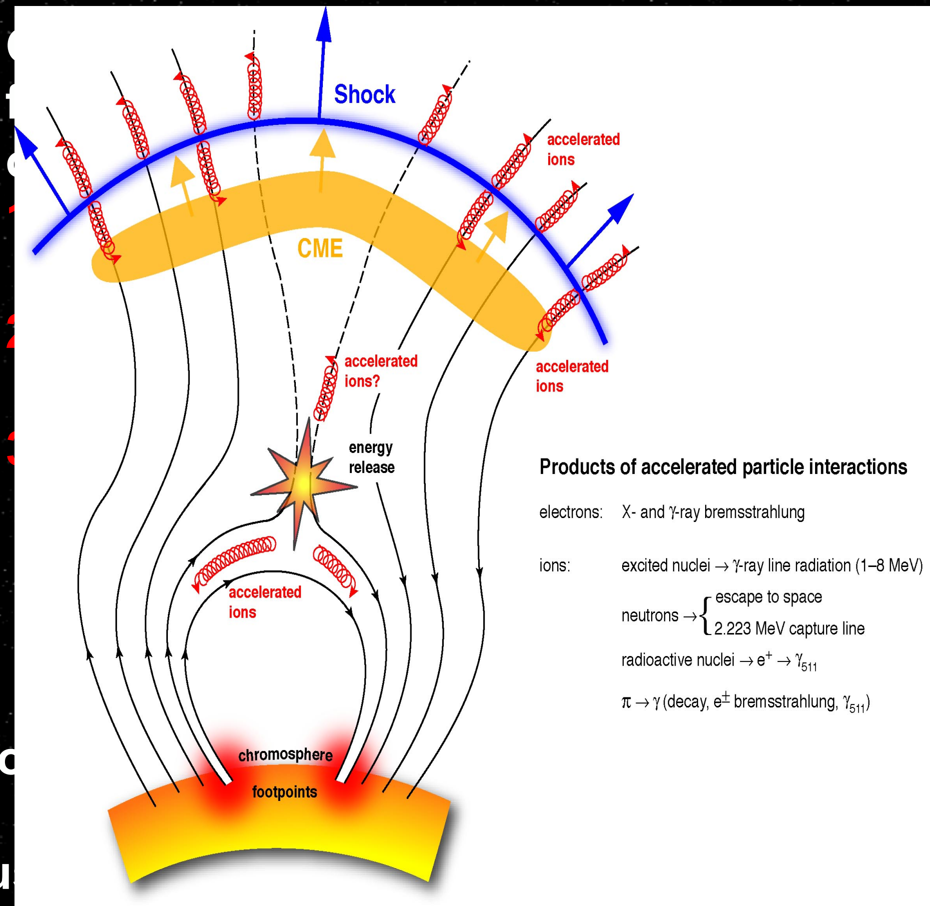
- Continuous acceleration at flare reconnection region via **Stochastic acceleration** (Petrosian&Liu 2004)
- Accelerated particle spectra become softer as turbulence weakens
- **Can explain the spectral evolution seen for SOL2012-03-07**



- **CME-driven shock** (Murphy et al 1987) can accelerate particles
- γ emission cannot occur at CME site (density is too low)
- Particles must travel back to the Sun
- **Cannot explain long lasting emission**

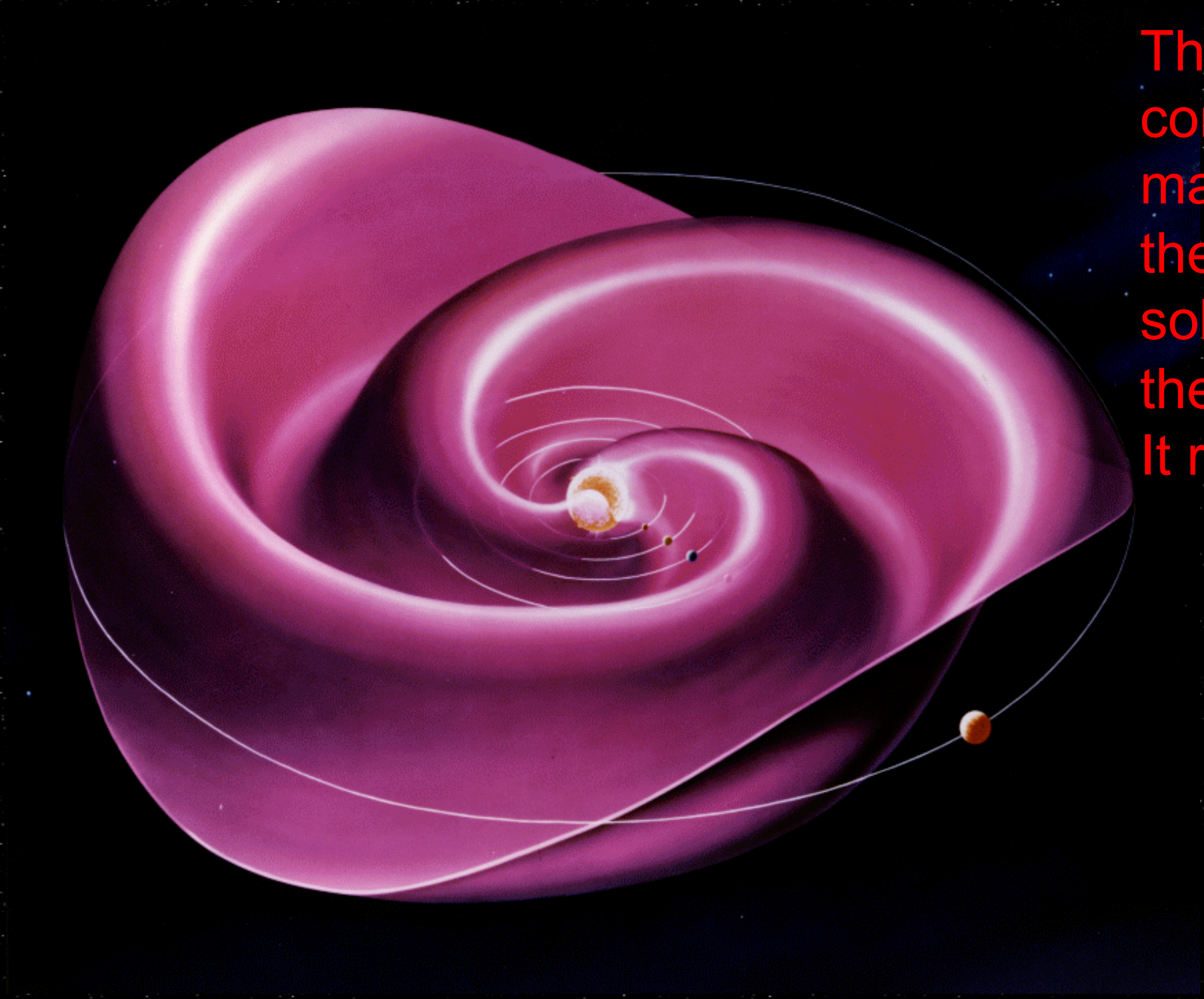
Gamma ray solar flares





- ✧ The acceleration mechanism is tho magnetic field lines
- ✧ The study of gamma-rays allows u the time evolution
- ✧ We want to understand how a structure that evolves chaotically is maintained for so long

Interplanetary magnetic field



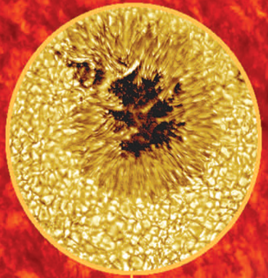
The IMF or HMF is the component of the solar magnetic field carried by the solar wind out from the solar corona and that fills the solar system.
It rotates like the Sun

Space Weather

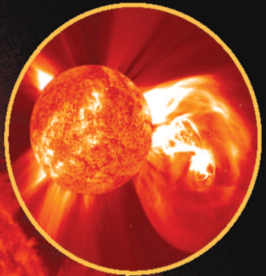
Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-based and ground-based technological systems, as well as endanger life or health. Just like weather on Earth, space weather has its seasons, with solar activity rising and falling over an approximate 11 year cycle.

Sunspots

Sunspots are comparatively cool areas at up to 7,700° F and show the location of strong magnetic fields protruding through what we would see as the Sun's surface. Large, complex sunspot groups are generally the source of significant space weather.



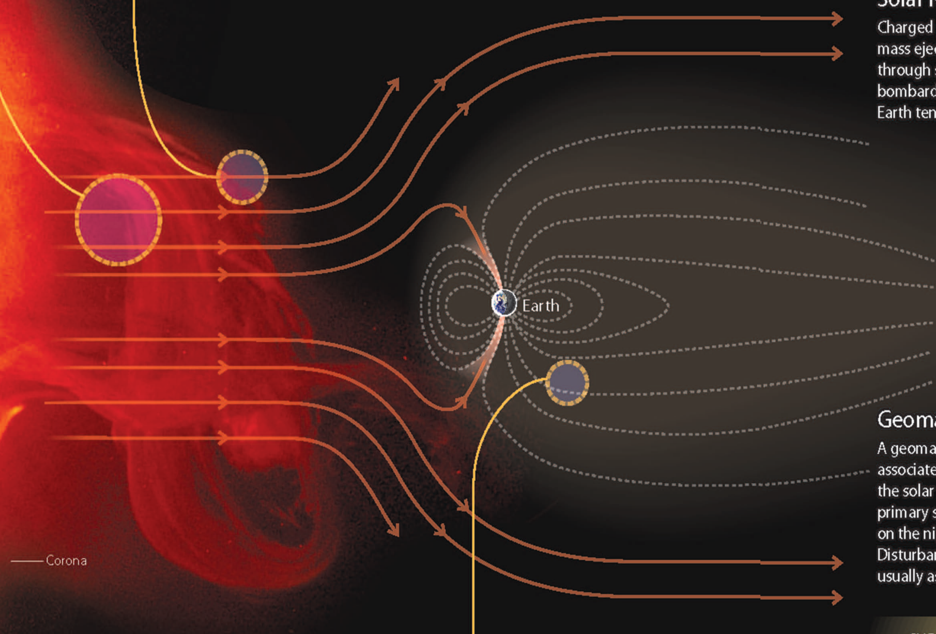
Coronal Mass Ejections (CMEs)



Large portions of the corona, or outer atmosphere of the Sun, can be explosively blown into space, sending billions of tons of plasma, or superheated gas, Earth's direction. These CMEs have their own magnetic field and can slam into and interact with Earth's magnetic field, resulting in geomagnetic storms. The fastest of these CMEs can reach Earth in under a day, with the slowest taking 4 or 5 days to reach Earth.

Solar Wind

The solar wind is a constant outflow of electrons and protons from the Sun, always present and buffeting Earth's magnetic field. The background solar wind flows at approximately one million miles per hour!

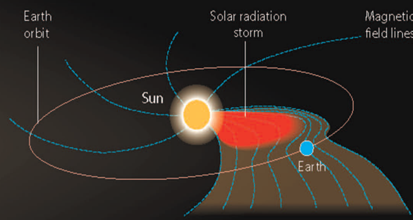


Sun's Magnetic Field

Strong and ever-changing magnetic fields drive the life of the Sun and underlie sunspots. These strong magnetic fields are the energy source for space weather and their twisting, shearing, and reconnection lead to solar flares.

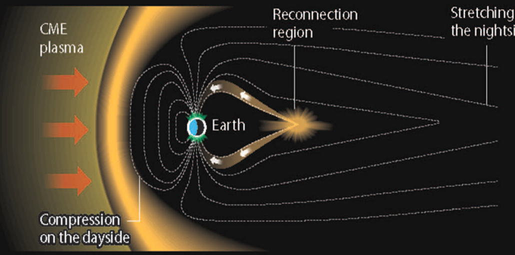
Solar Radiation Storms

Charged particles, including electrons and protons, can be accelerated by coronal mass ejections and solar flares. These particles bounce and gyrate their way through space, roughly following the magnetic field lines and ultimately bombarding Earth from every direction. The fastest of these particles can affect Earth tens of minutes after a solar flare.

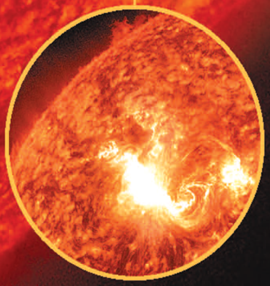


Geomagnetic Storms

A geomagnetic storm is a temporary disturbance of Earth's magnetic field typically associated with enhancements in the solar wind. These storms are created when the solar wind and its magnetic field interacts with Earth's magnetic field. The primary source of geomagnetic storms is CMEs which stretch the magnetosphere on the nightside causing it to release energy through magnetic reconnection. Disturbances in the ionosphere (a region of Earth's upper atomosphere) are usually associated with geomagnetic storms.



Solar Flares



Reconnection of the magnetic fields on the surface of the Sun drive the biggest explosions in our solar system. These solar flares release immense amounts of energy and result in electromagnetic emissions spanning the spectrum from gamma rays to radio waves. Traveling at the speed of light, these emissions make the 93 million mile trip to Earth in just 8 minutes.

Earth's Magnetic Field

Earth's magnetic field, largely like that of a bar magnet, gives the Earth some protection from the effects of the Sun. Earth's magnetic field is constantly compressed on the day side and stretched on the night side by the ever-present solar wind. During geomagnetic storms, the disturbances to Earth's magnetic field can become extreme. In addition to some buffering by the atmosphere, this field also offers some shielding from the charged particles of a radiation storm.

NOAA Space Weather Prediction Center – www.spaceweather.gov

Source images: NASA, NOAA.