The Sun and the Heliosphere (at Radio Frequencies)

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Outline

- Why?
- Introduction
  - The Sun
  - The Heliosphere
  - The Sun-Earth connection
- The Radio Sun
- The Murchison Widefield Array

Astronomy: A personal reflection

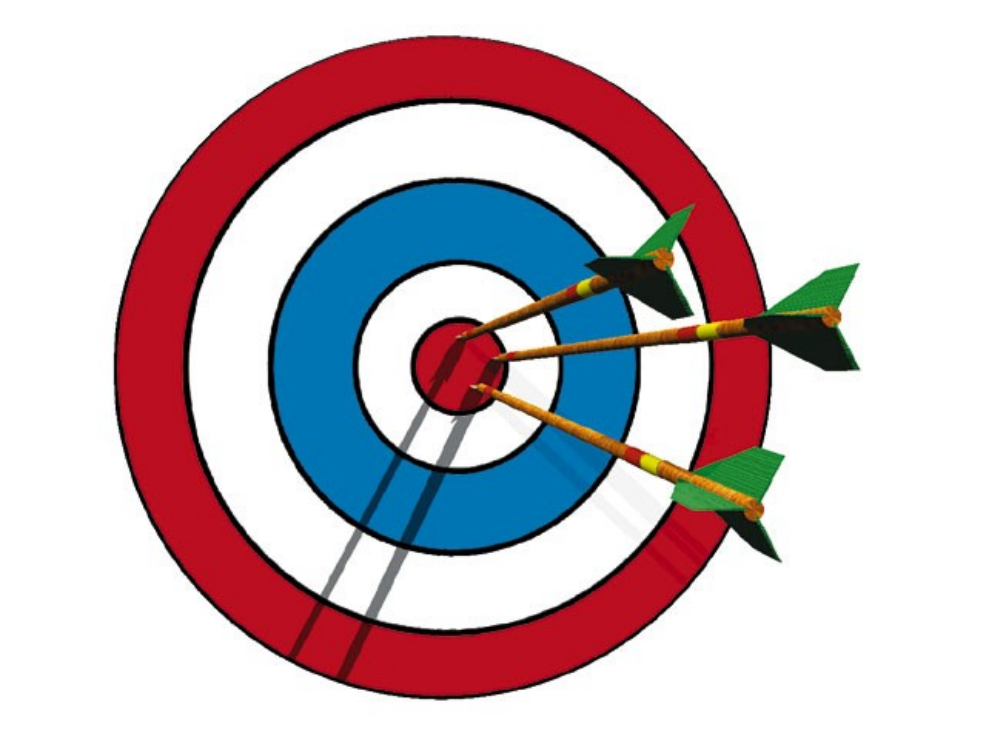
The Only Assumption - The laws of Physics are same everywhere in the Universe

Limitations of astronomers

- cannot go to the places they study
- cannot touch the things they study
- cannot do experiments
- cannot even take a look at the object from a different perspective
- can only wait for the light to come to them...

ART

The science of accurate measurements and logical deductions



Why?

- Sun is the reason why we exist
  - primary source of all energy* for the Earth, our source of life
- Understanding the Sun is the key to understanding other stars in the universe
- Heliosphere provides an opportunity to study matter (plasma) under conditions which cannot be created in our labs (yet)
- Practical reasons
  - Space Weather
  - Global Warming

* except for nuclear and geo-thermal energy

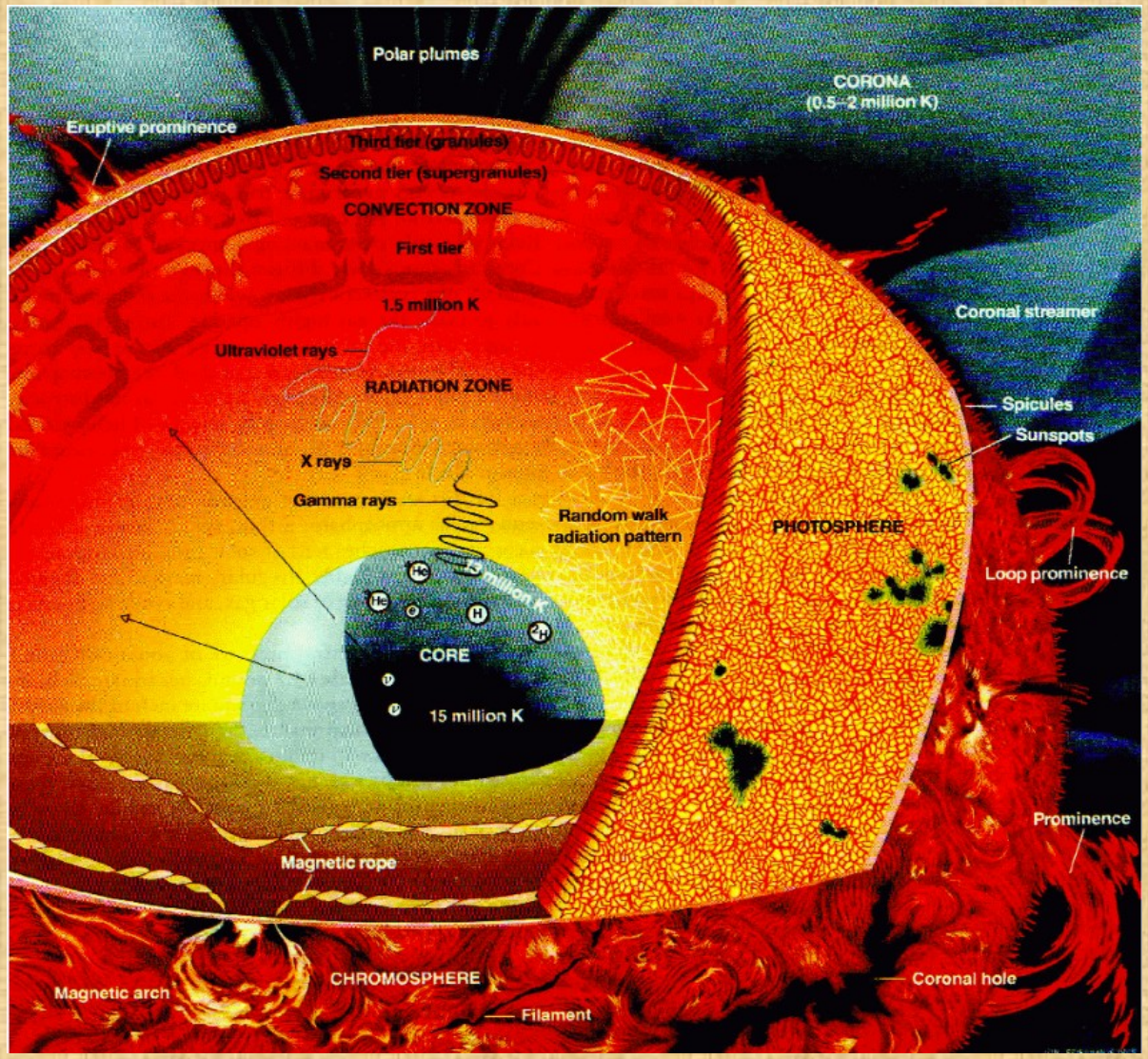
The Sun

- Radius ~7 x 10^8 m ($R_\oplus$ = 6.4 x 10^6 m)
- Mass ~2 x 10^{30} kg ($M_\oplus$ =6 x 10^{24} kg)
- Earth-Sun dist. ~1.5 x 10^{11} m (1 AU); 214 R_{Sun}

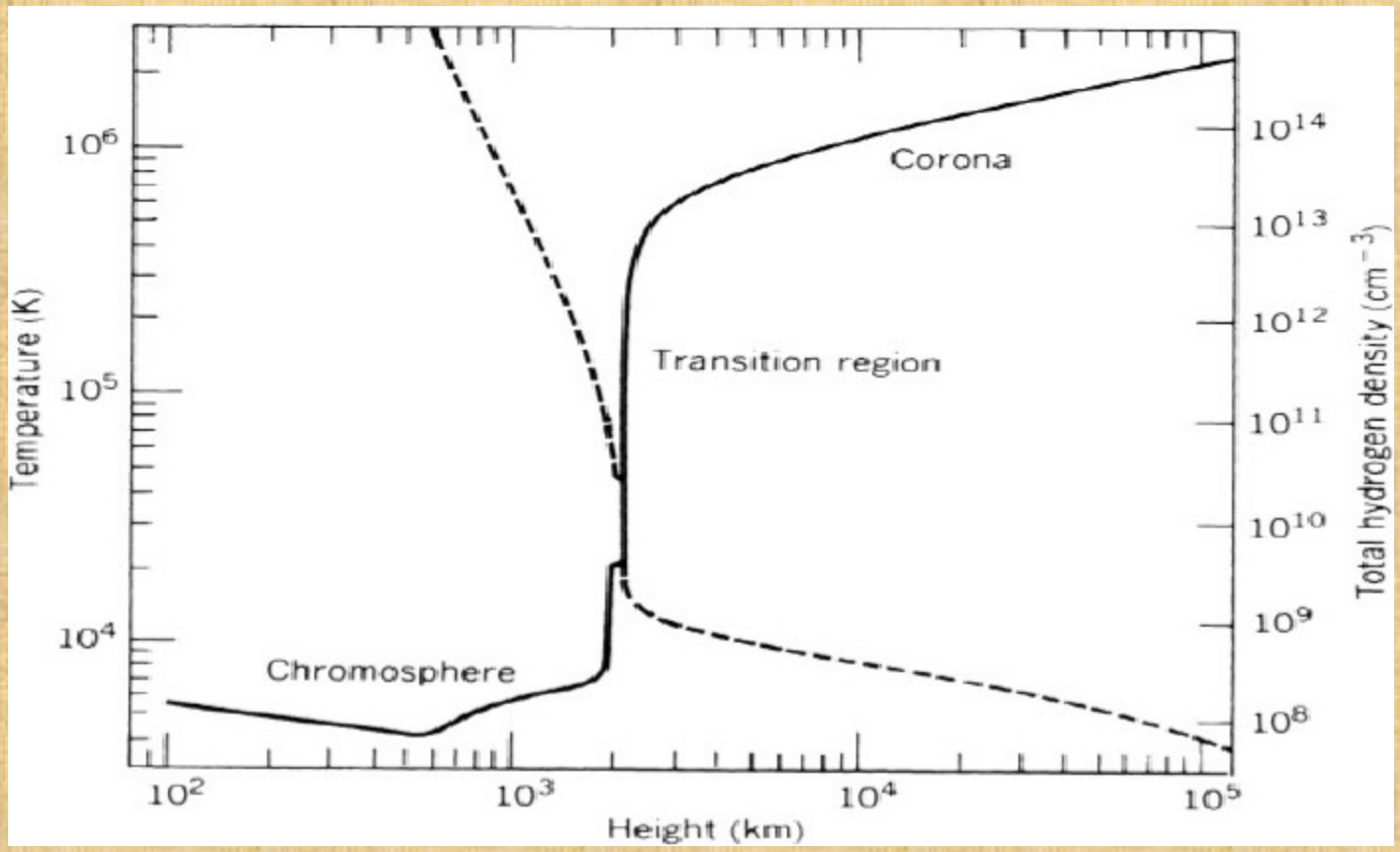
- Effective Temp ~5800 K
- Luminosity ~4 x 10^{26} W
- Solar constant ~1.36 x 10^3 W/m^2

- Age of the Sun ~5 x 10^9 yr

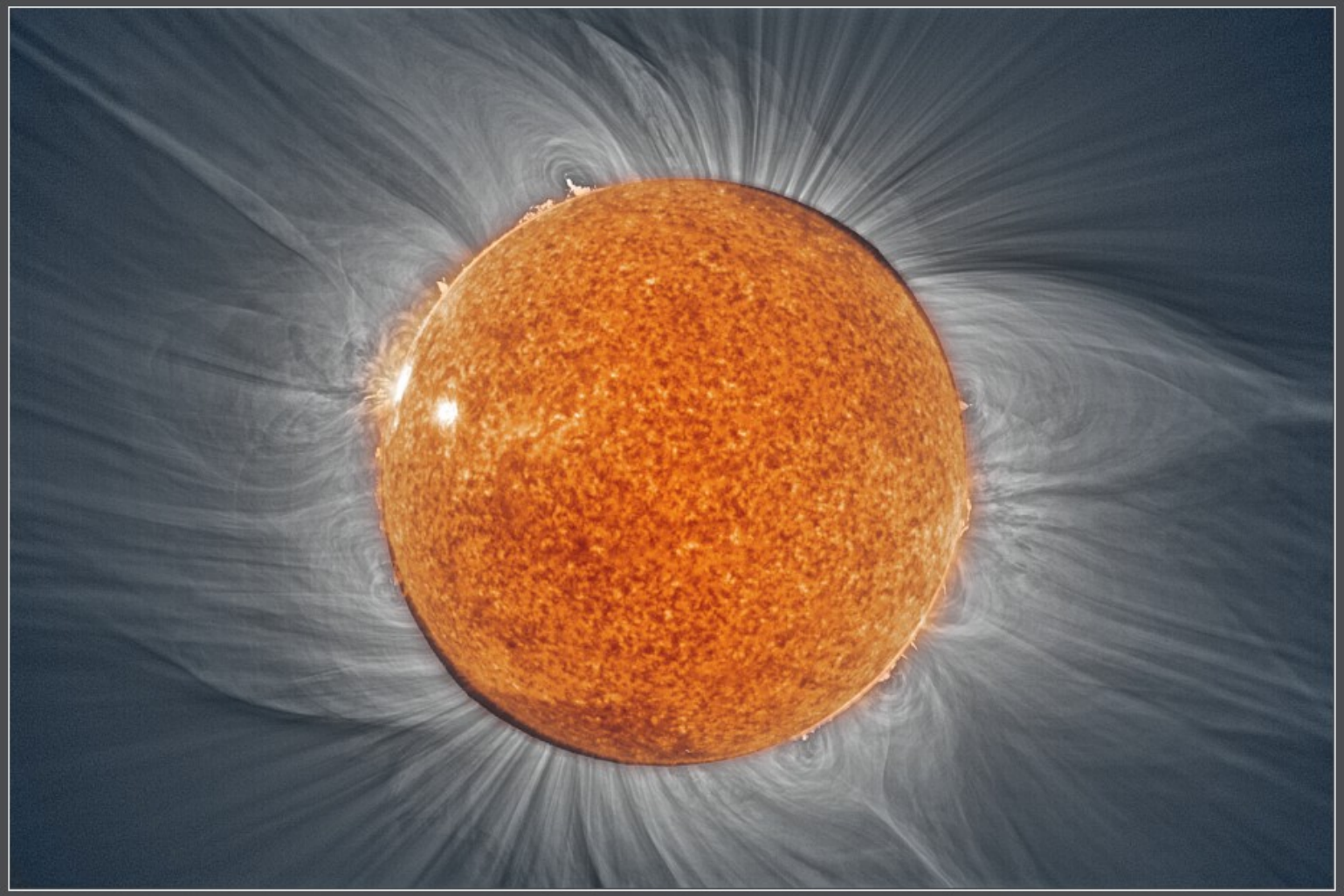
Solar structure



The Temperature Profile of the Sun

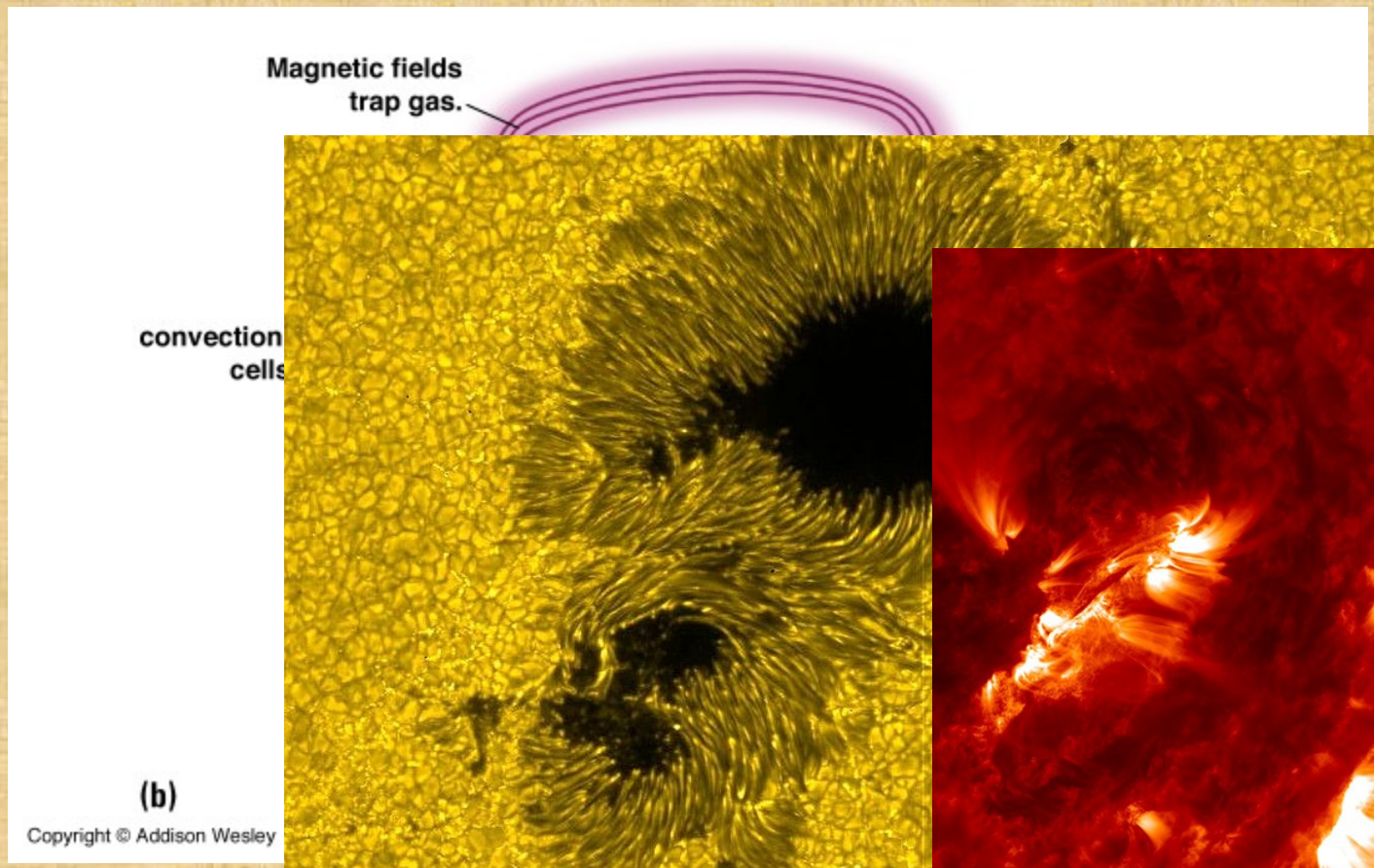


The Solar Corona

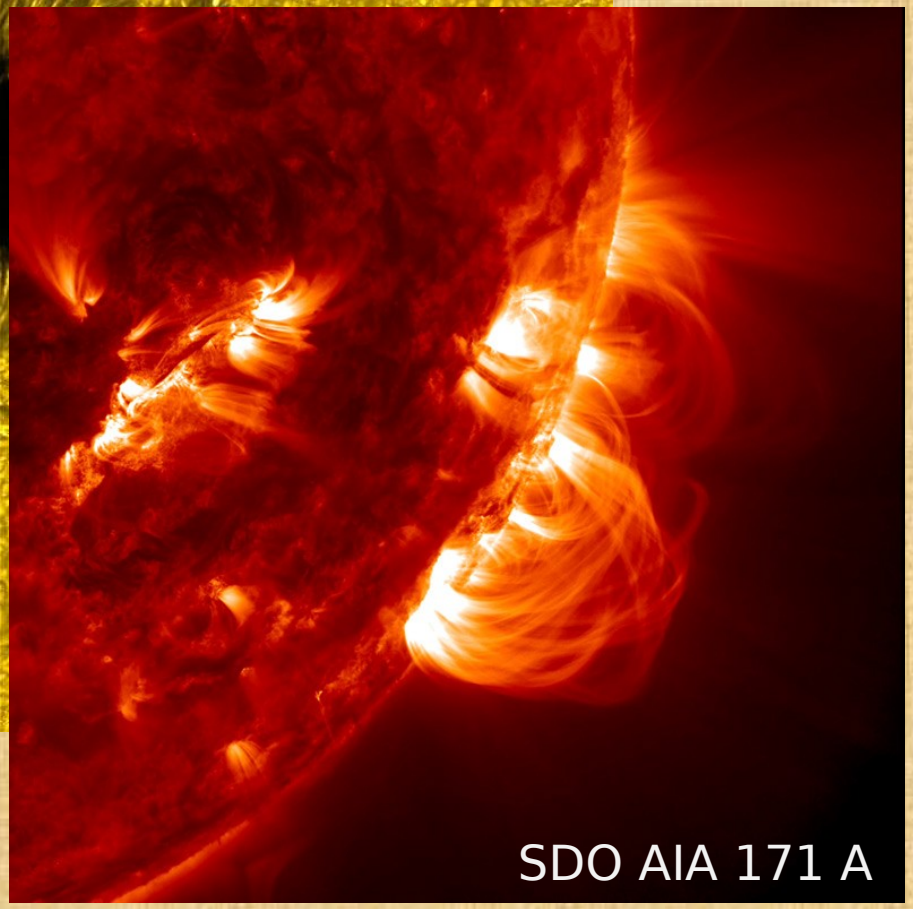


Total Solar Eclipse 2006

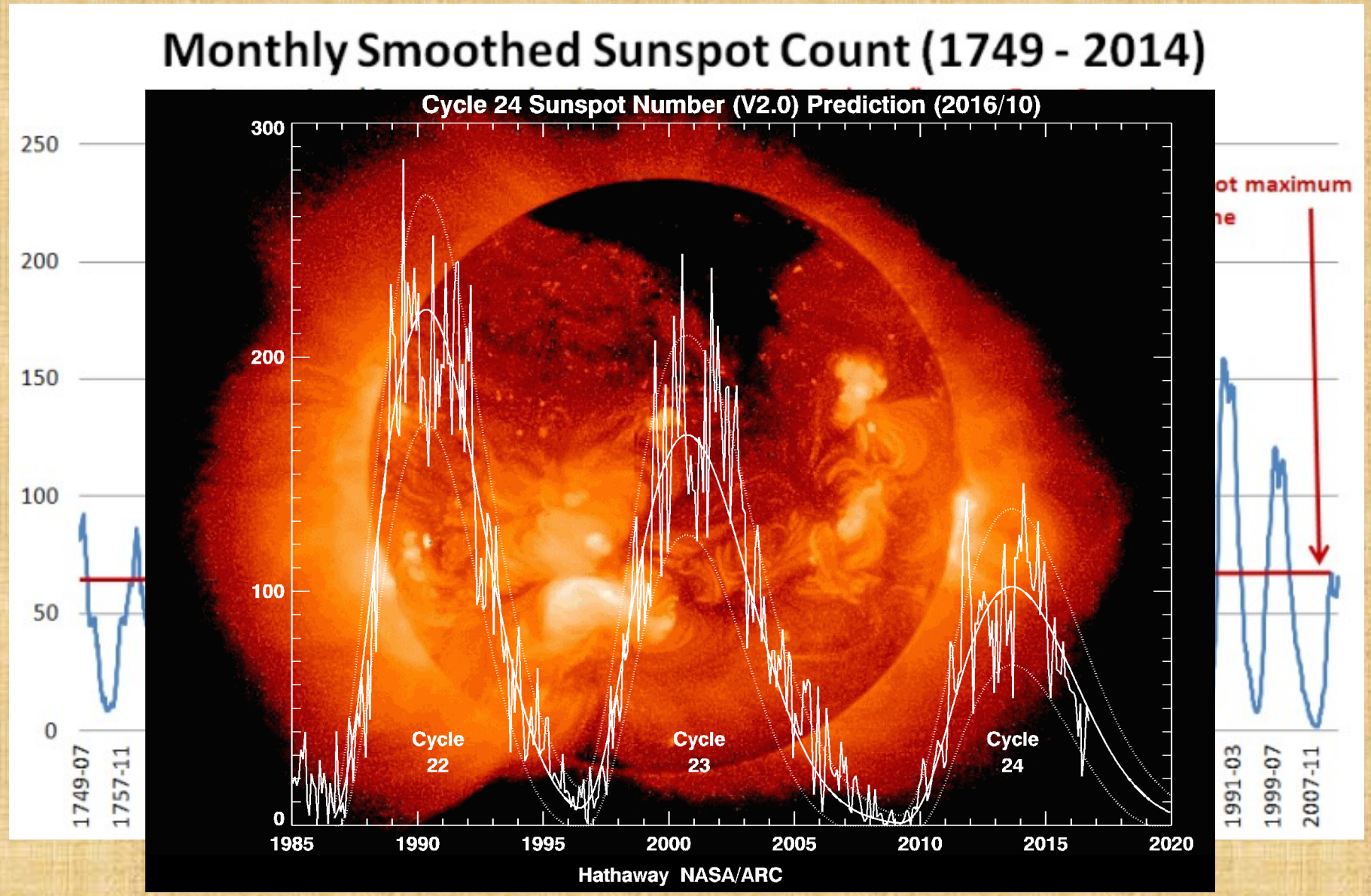
Sunspots/Active regions



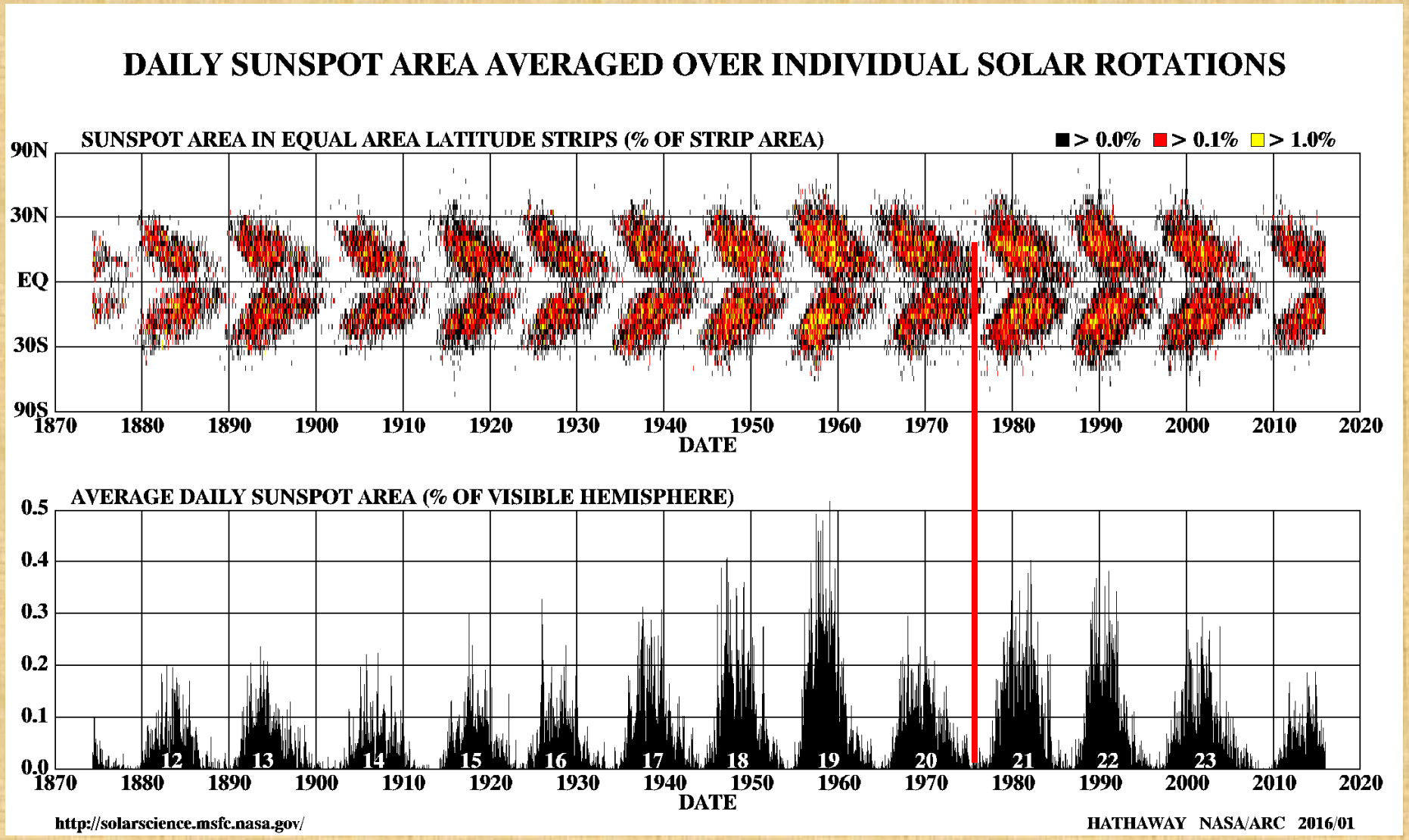
White light HINODE SOT



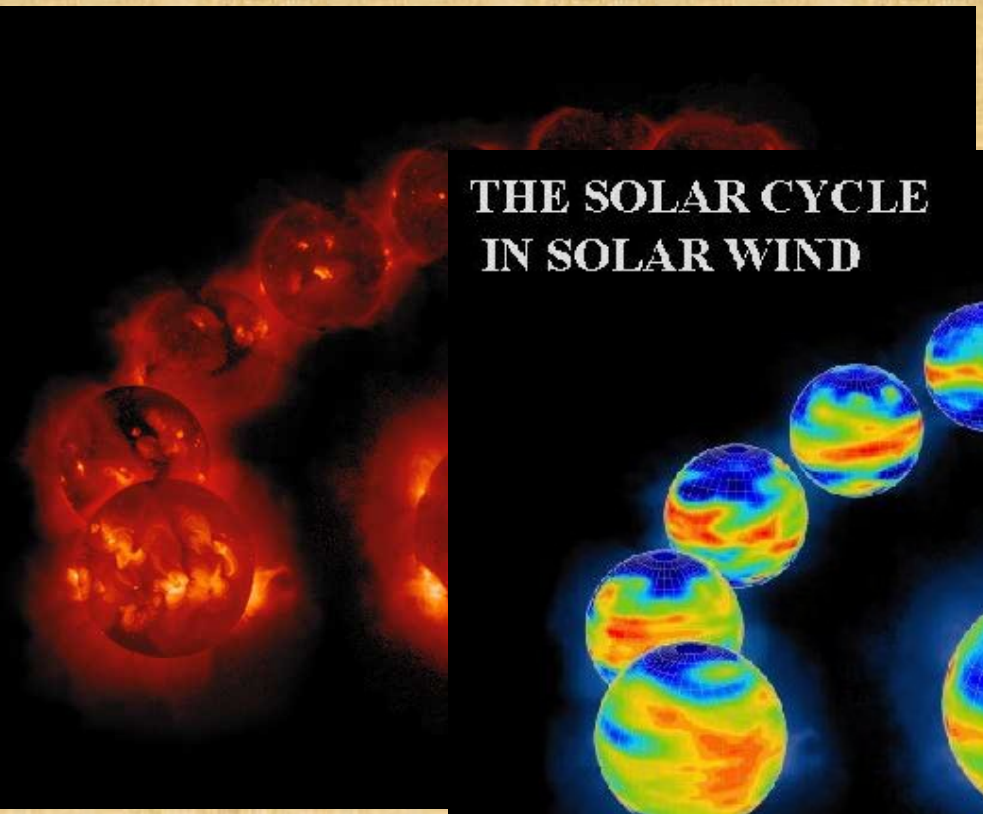
The Solar Cycle



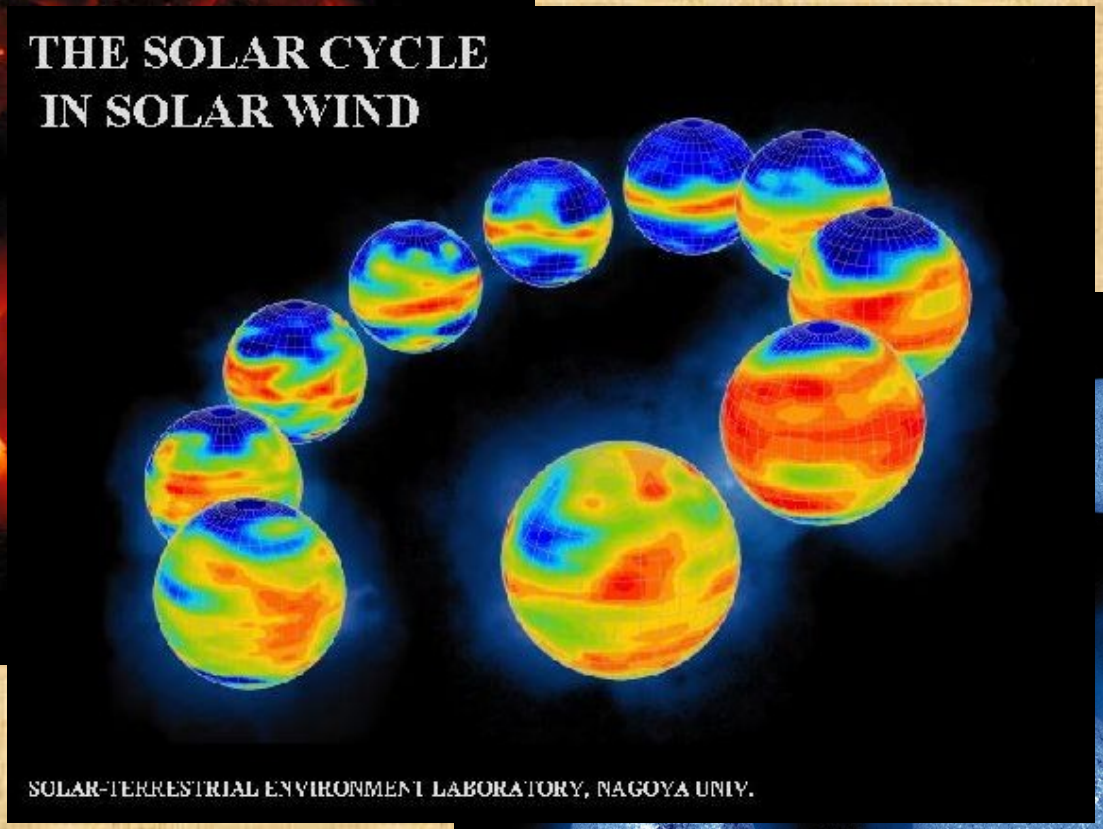
The Solar Cycle



The Solar Cycle...

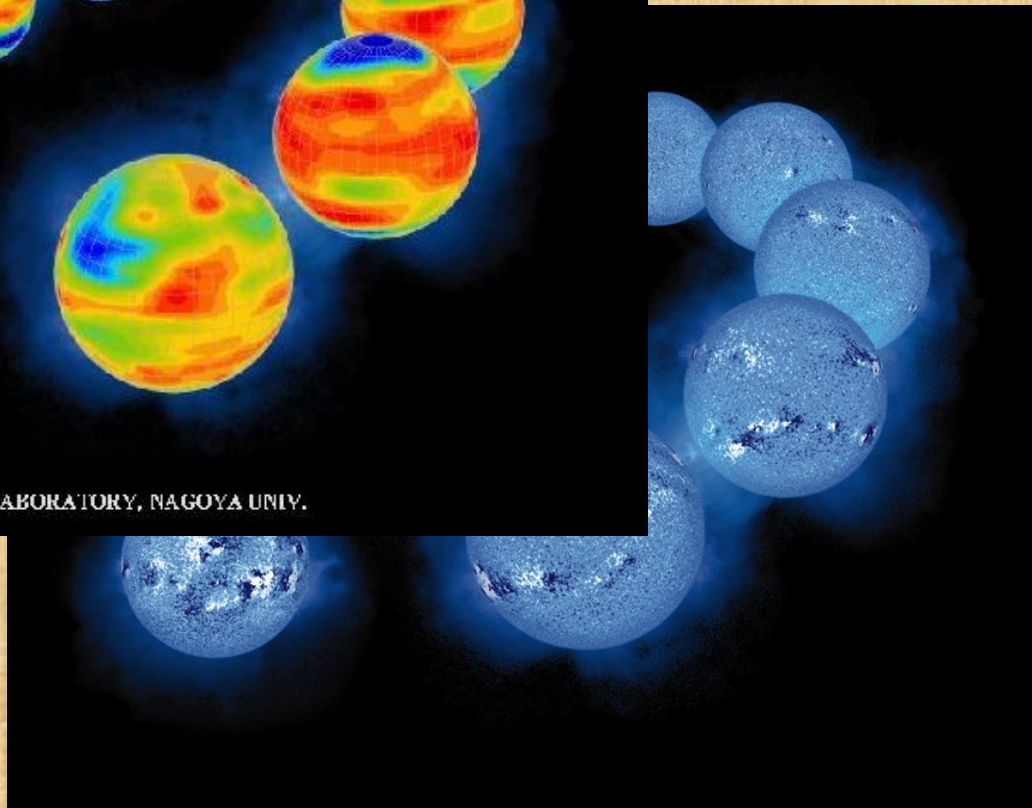


YOHKOH X-ray images

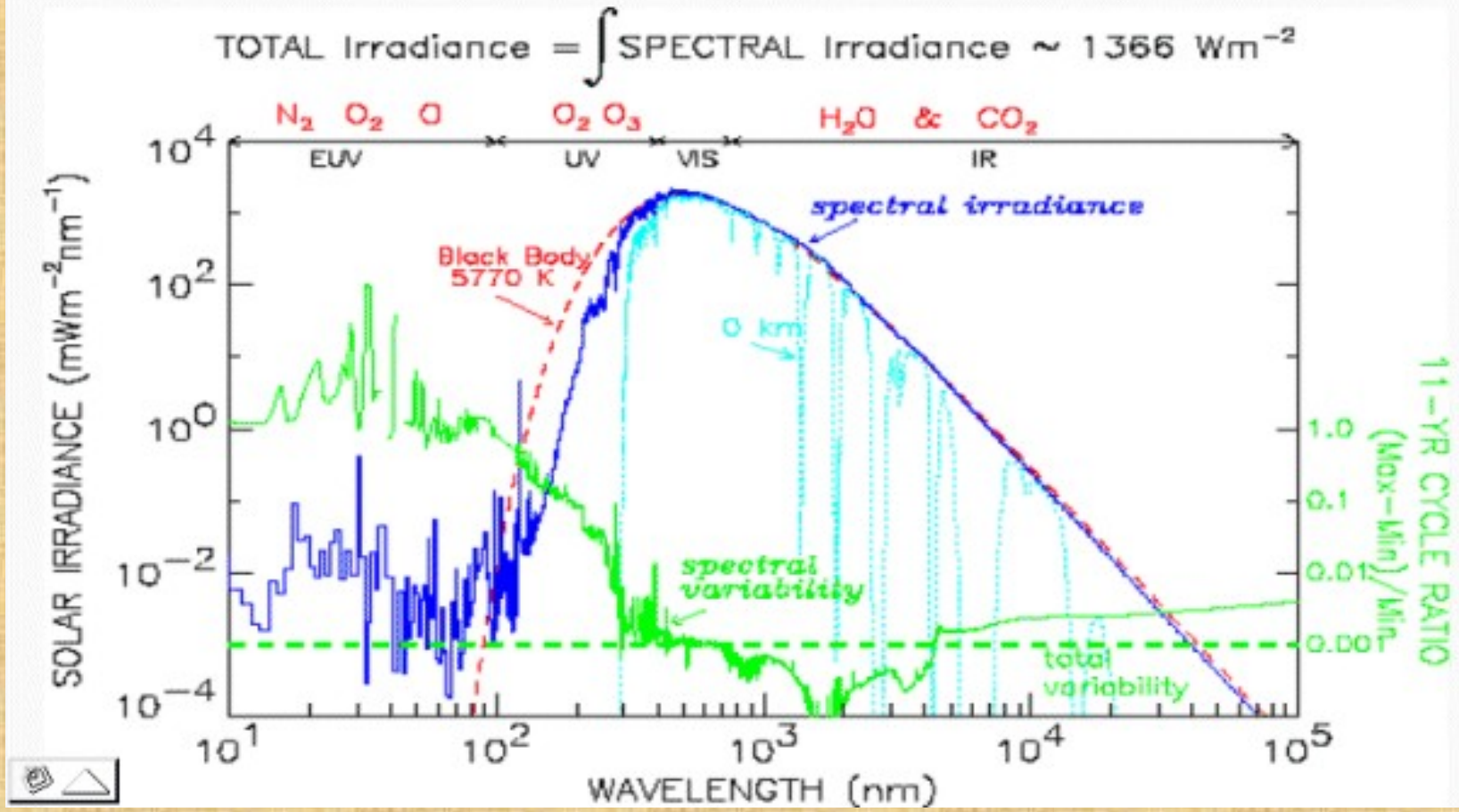


STELab Solar Wind data

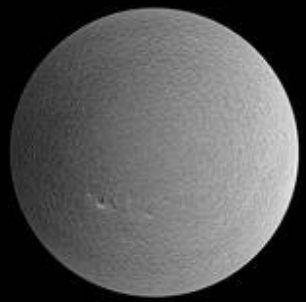
SOHO EIT



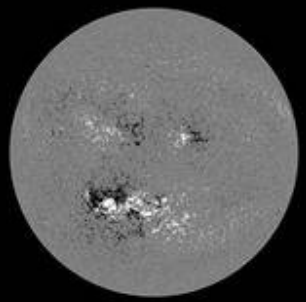
SOLAR SPECTRUM, VARIABILITY and ATMOSPHERIC ABSORPTION



Lean, J. (US NRL)

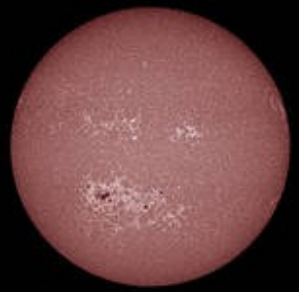


HMI Dopplergram
Surface movement
Photosphere



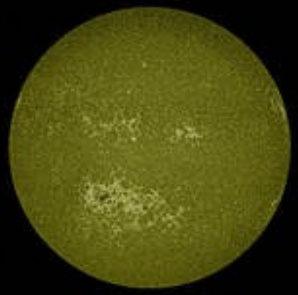
HMI Magnetogram
Magnetic field polarity
Photosphere

HMI Continuum
Matches visible light
Photosphere

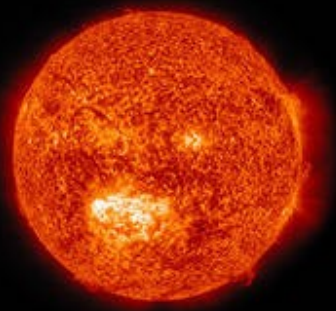


AIA 1700 Å
4500 Kelvin
Photosphere

AIA 4500 Å
6000 Kelvin
Photosphere



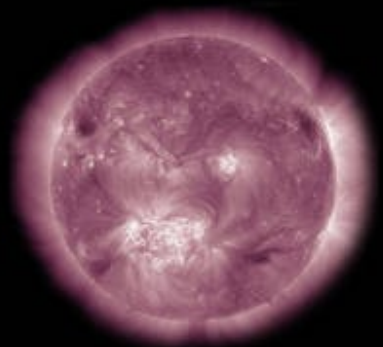
AIA 1600 Å
10,000 Kelvin
Upper photosphere/
Transition region



AIA 304 Å
50,000 Kelvin
Transition region/
Chromosphere

AIA 171 Å
600,000 Kelvin
Upper transition
Region/quiet corona

AIA 193 Å
1 million Kelvin
Corona/flare plasma



AIA 211 Å
2 million Kelvin
Active regions

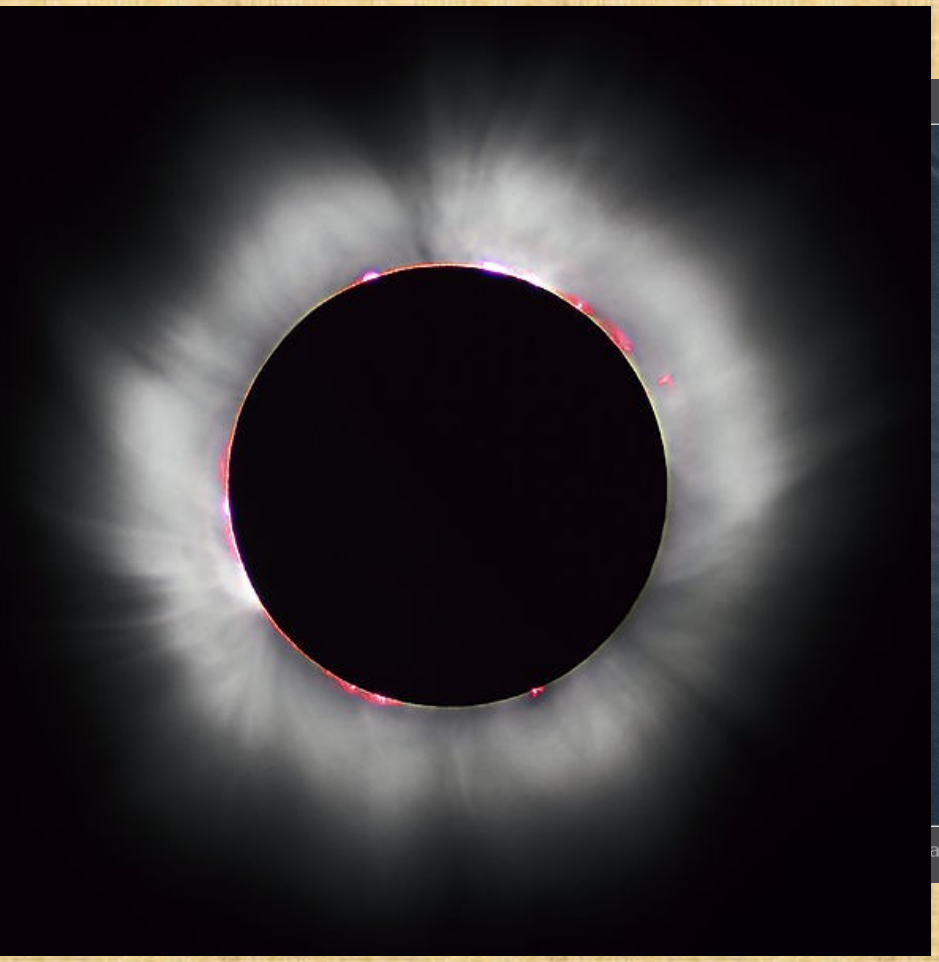
AIA 335 Å
2.5 million Kelvin
Active regions

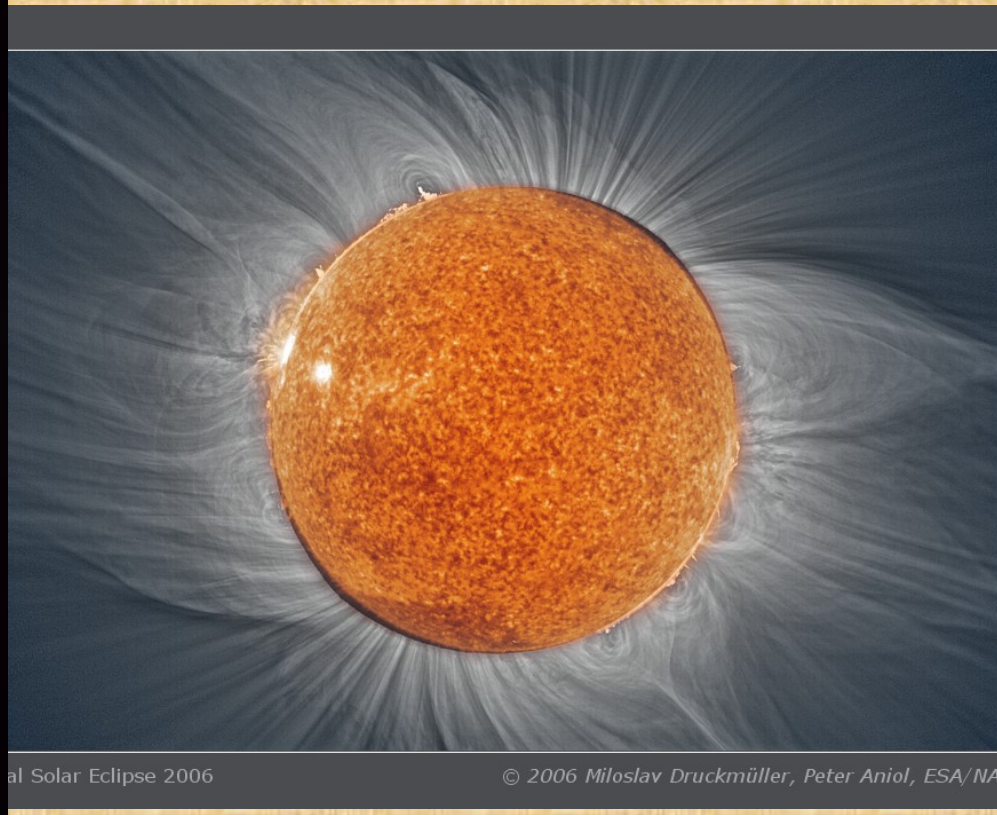
AIA 094 Å
6 million Kelvin
Flaring regions

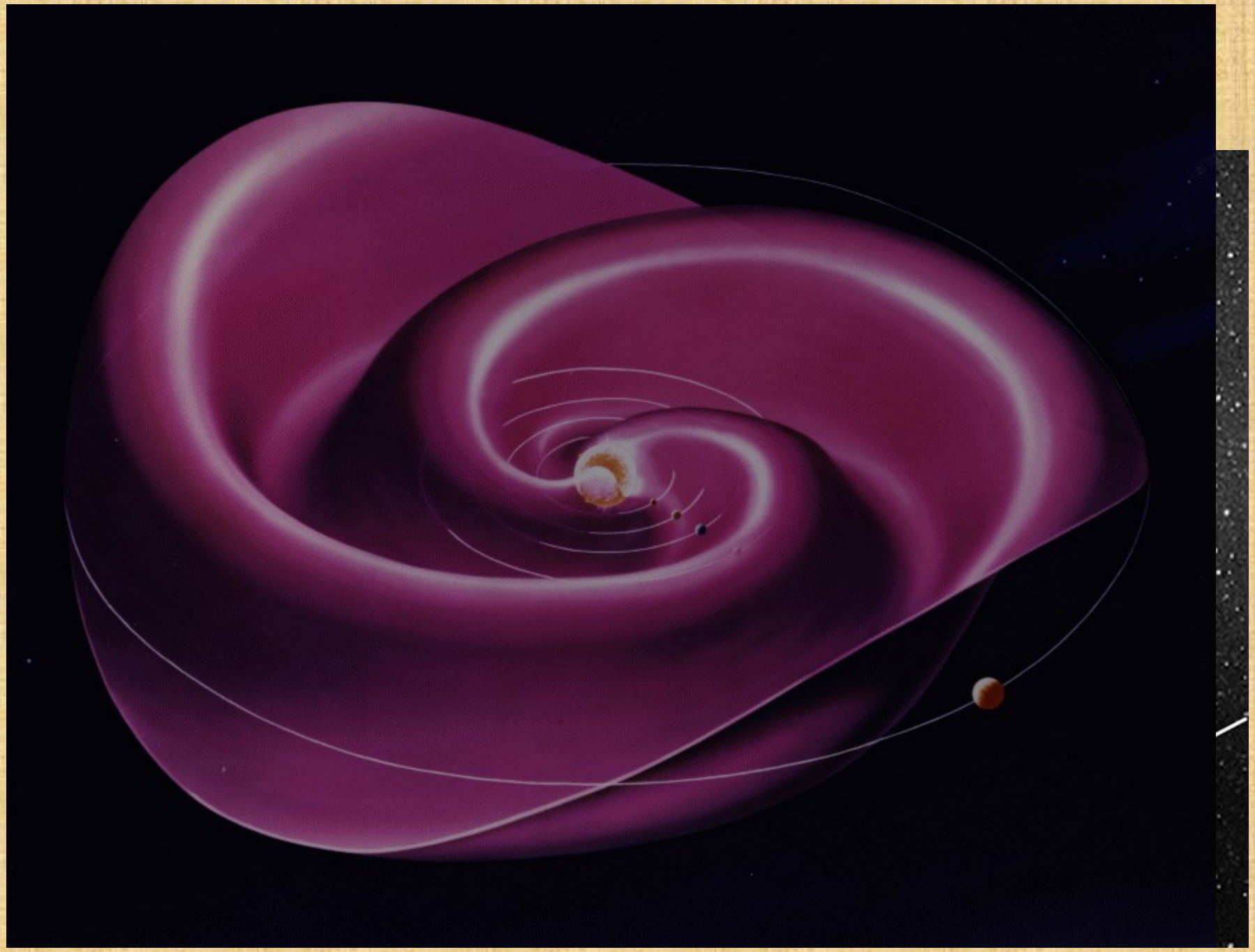
AIA 131 Å
10 million Kelvin
Flaring regions

Solar
Dynamics
Observatory

The Corona

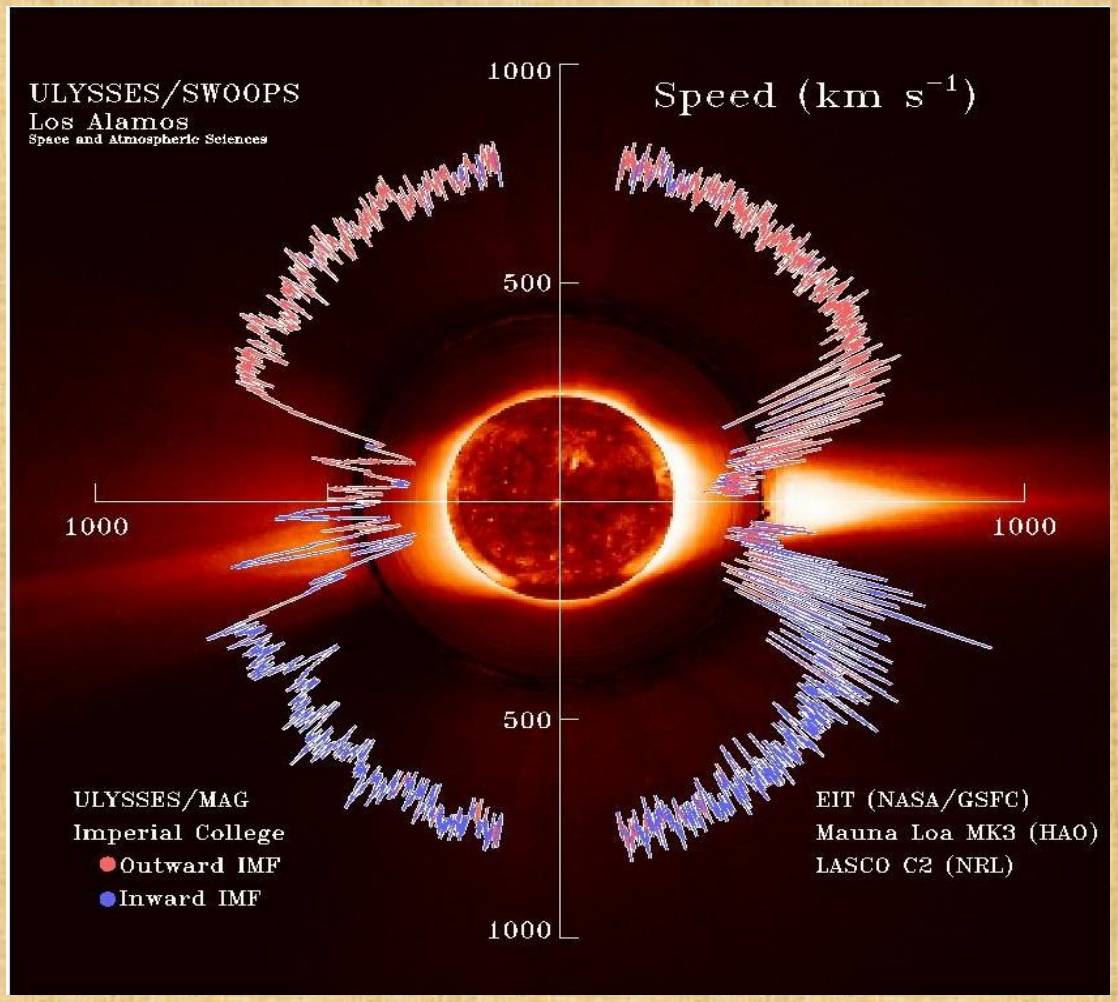



al Solar Eclipse 2006
© 2006 Miloslav Druckmüller, Peter Aniol, ESA/NA

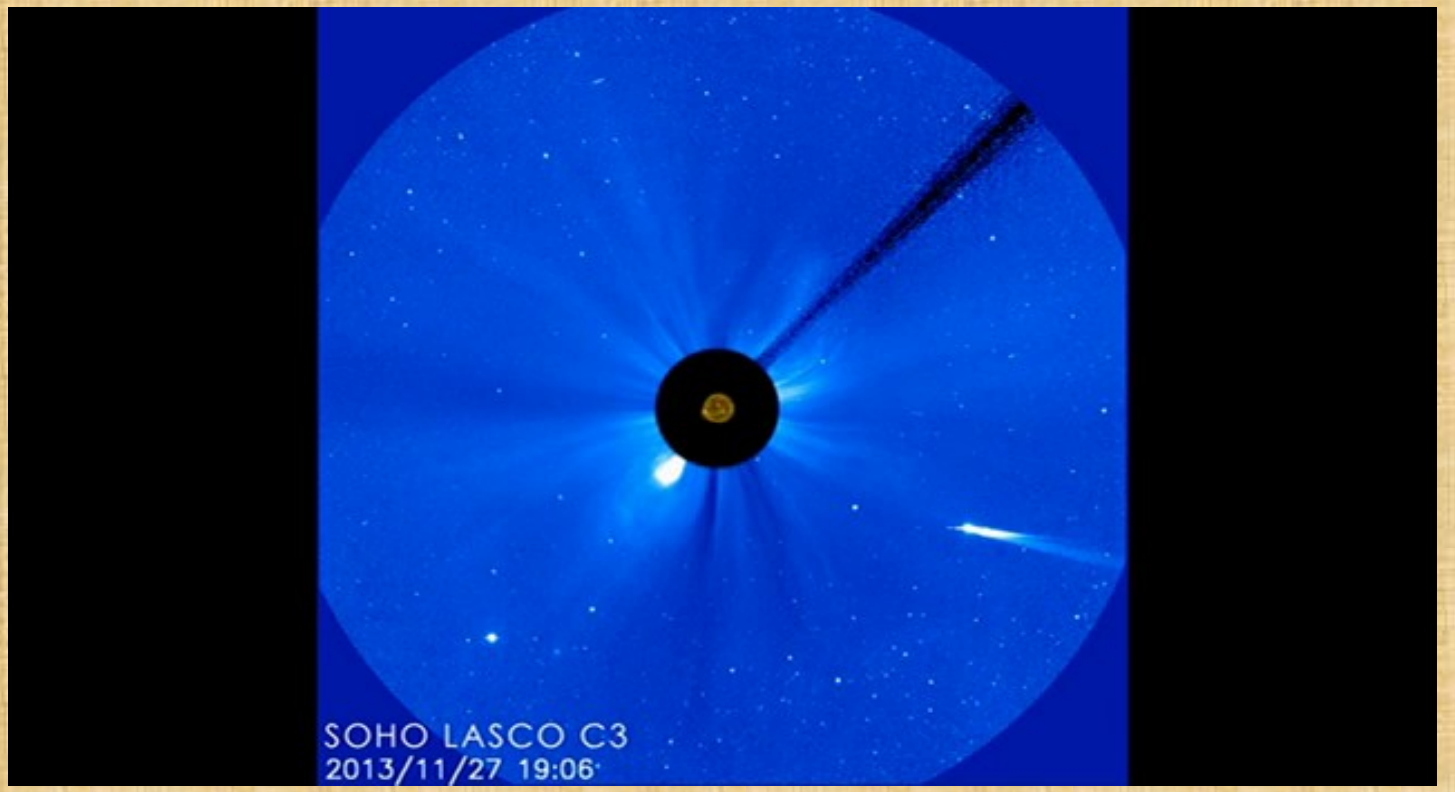


The Heliosphere

- The region dominated by this plasma of solar origin



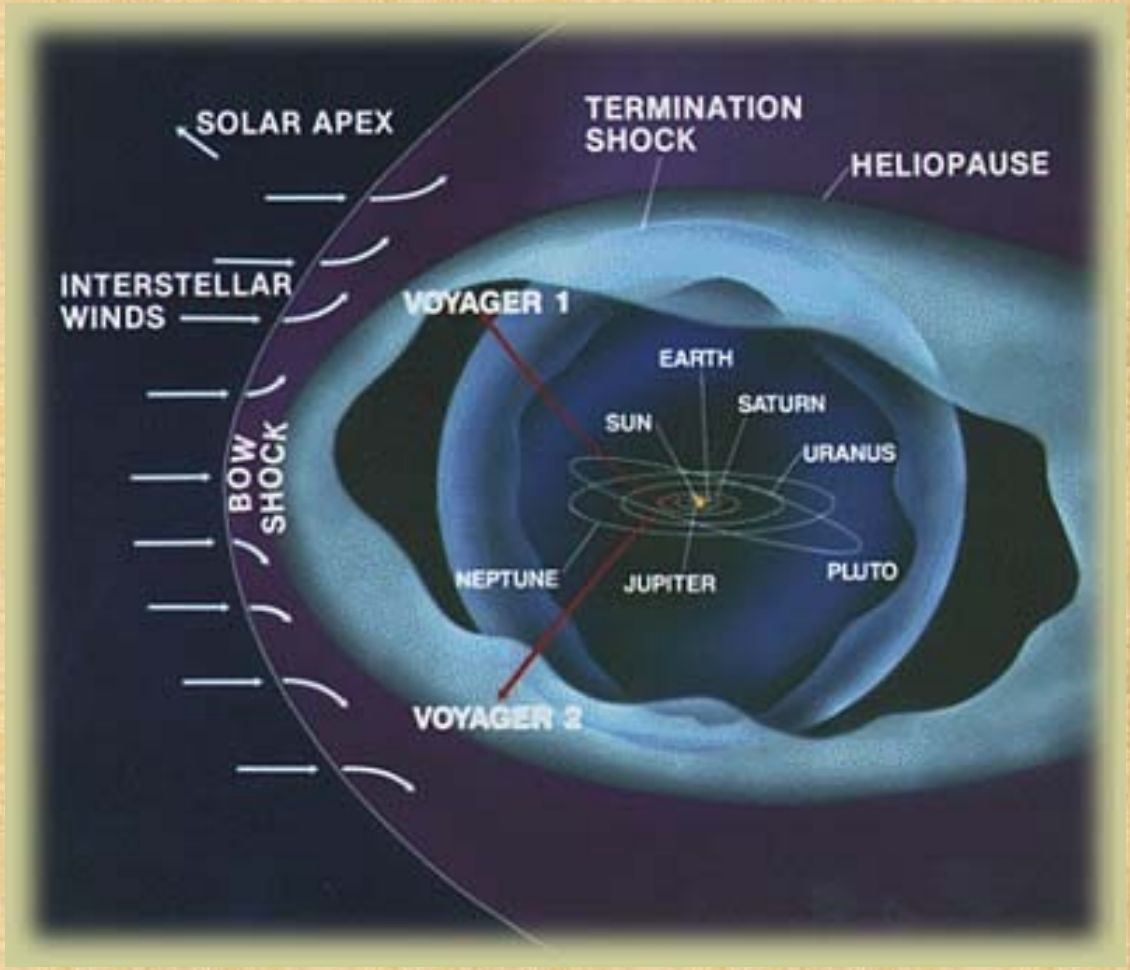
A view of the solar wind

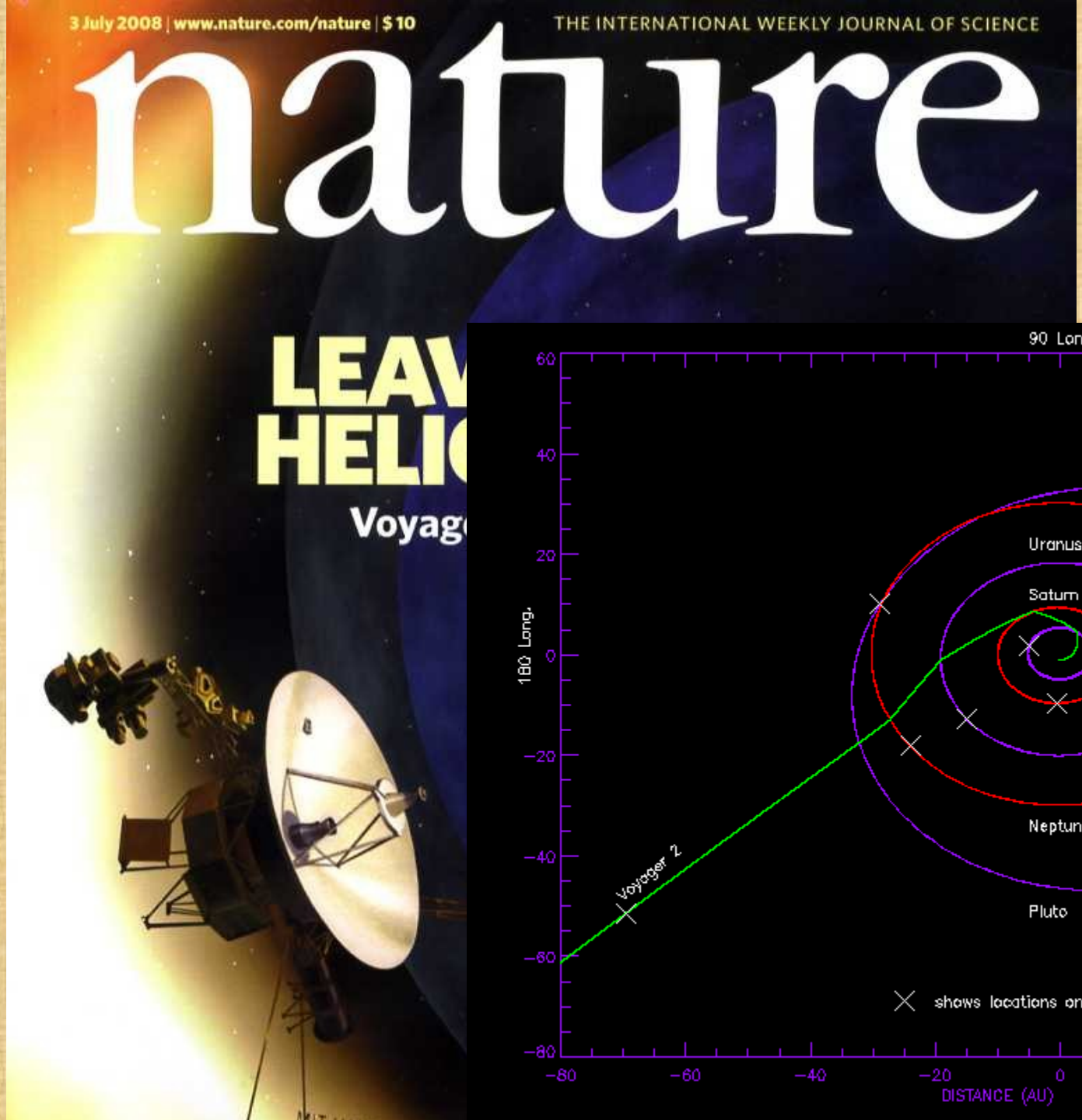


Passage of comet ISON

The limits of heliosphere

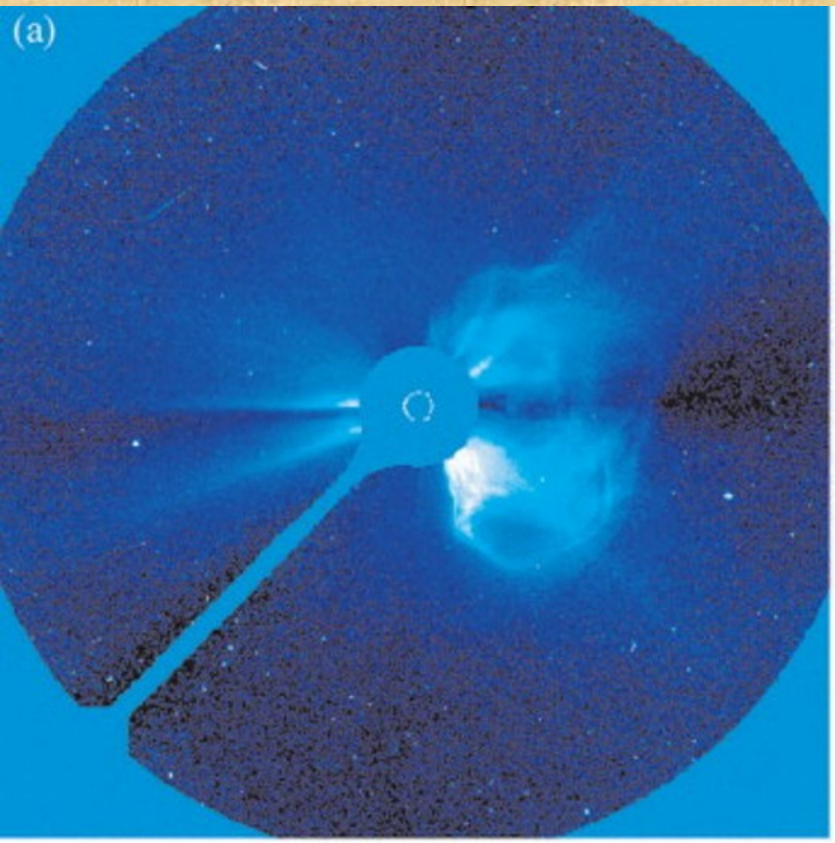
- The boundary lies where interstellar winds become about as strong as the solar wind (pressure equilibrium)
- Inner heliosphere – lies inside the orbit of the Earth
- Outer heliosphere – the rest

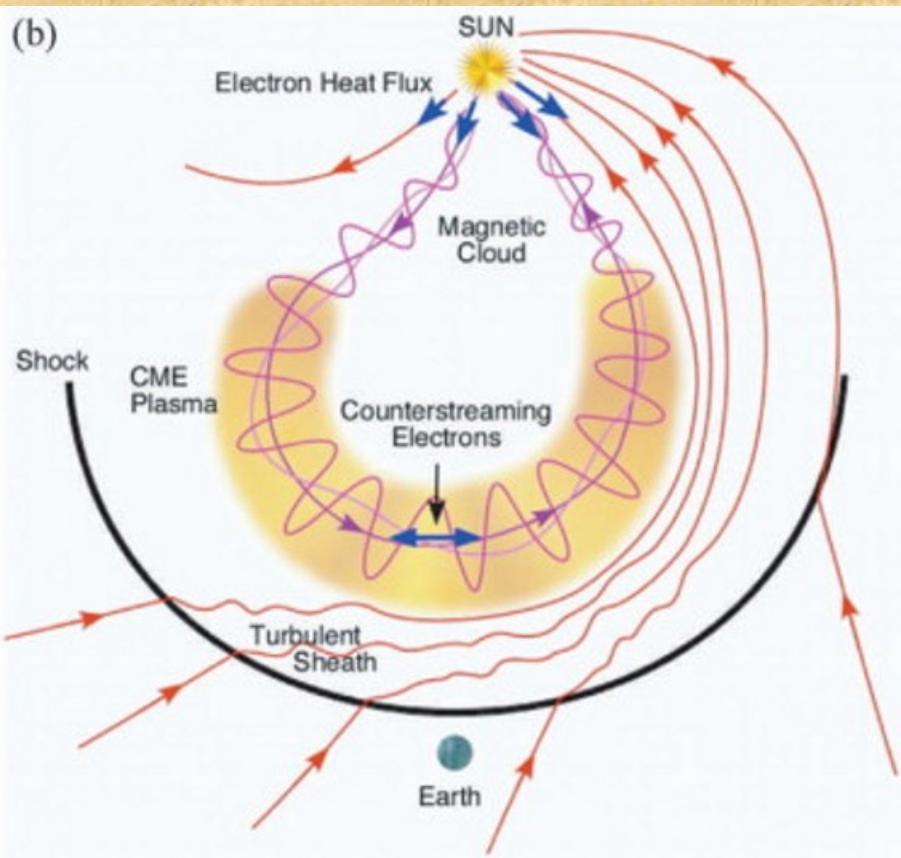



3 July 2008 | www.nature.com/nature | $10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
LEAV
HELIC
Voyag

90 Long.
180 Long.
0 Long.
Uranus
Saturn
Neptune
Pluto
Voyager 2
shows locations on 7/ 17/ 2008
DISTANCE (AU)
60
40
20
0
-20
-40
-60
-80
-60
-40
-20
0
20
40
60

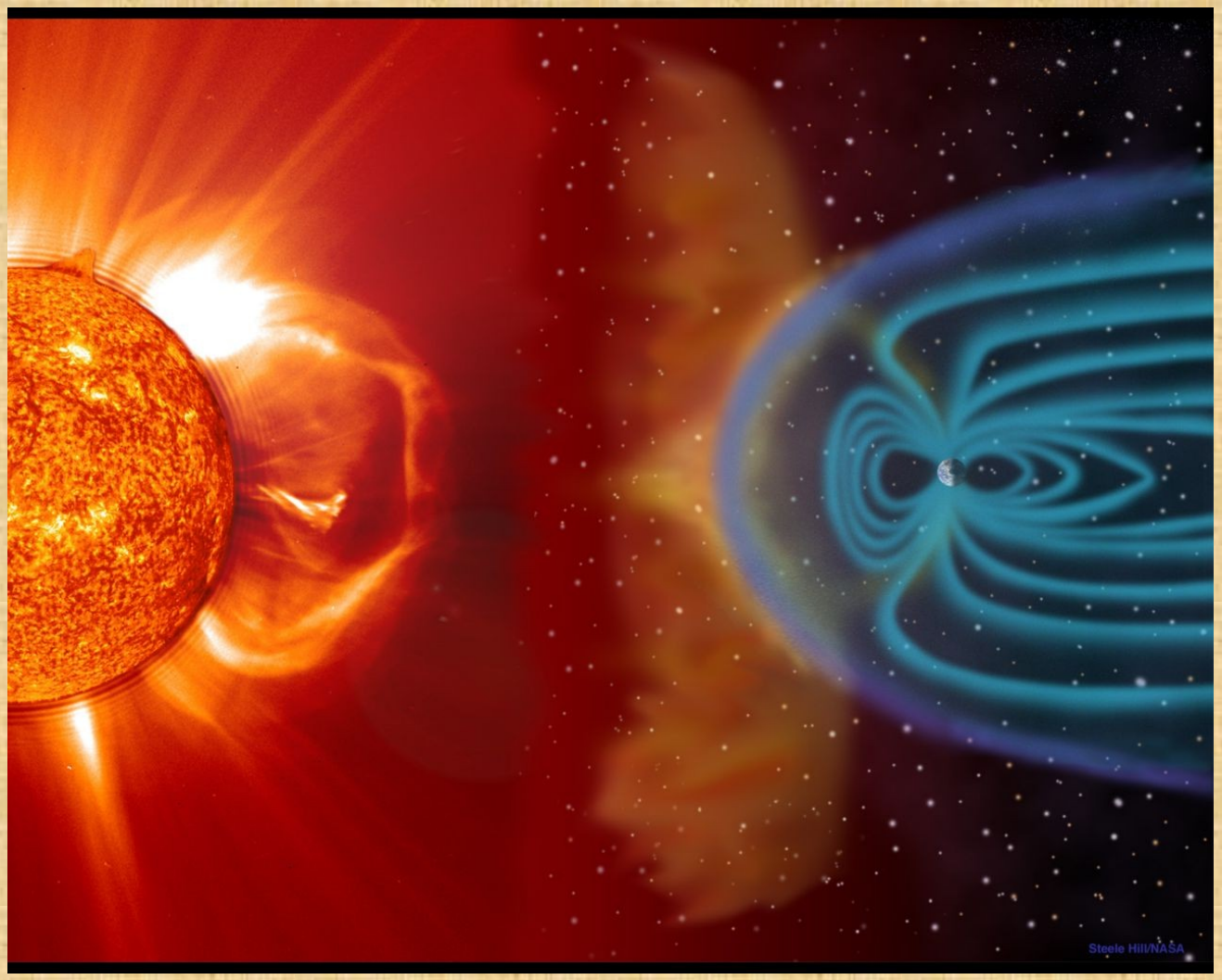
Coronal Mass Ejections

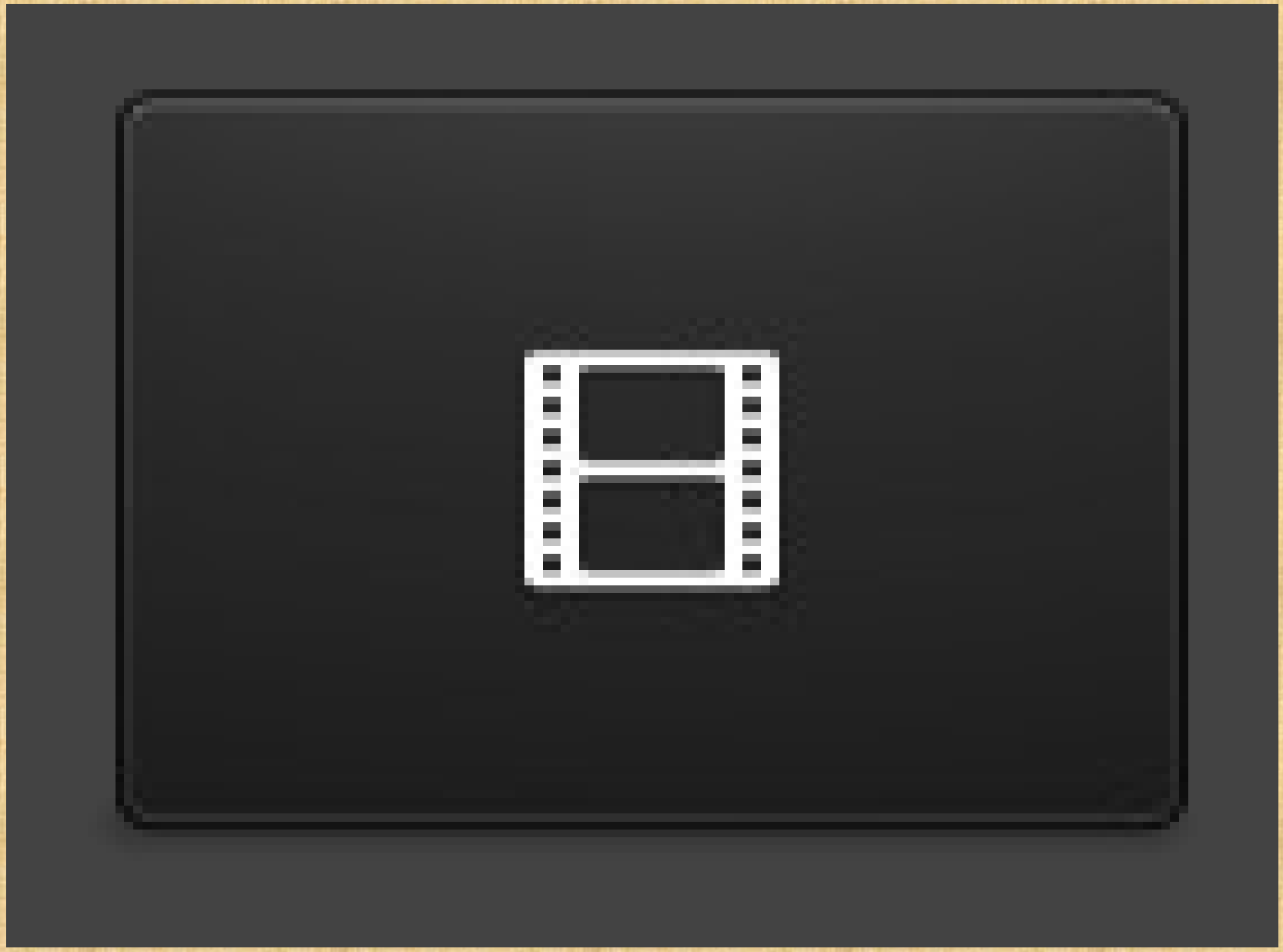




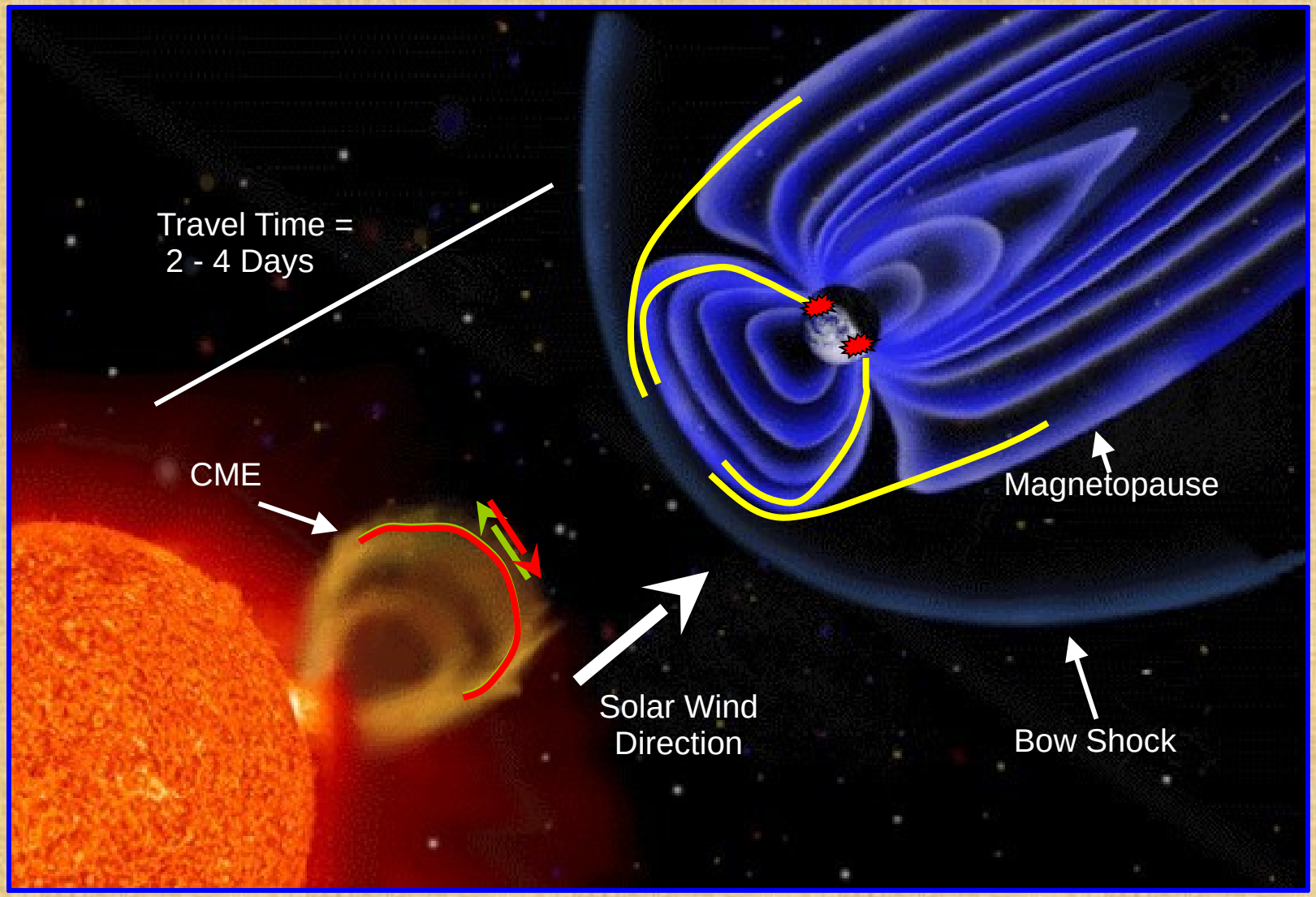
Masson et al., 2013

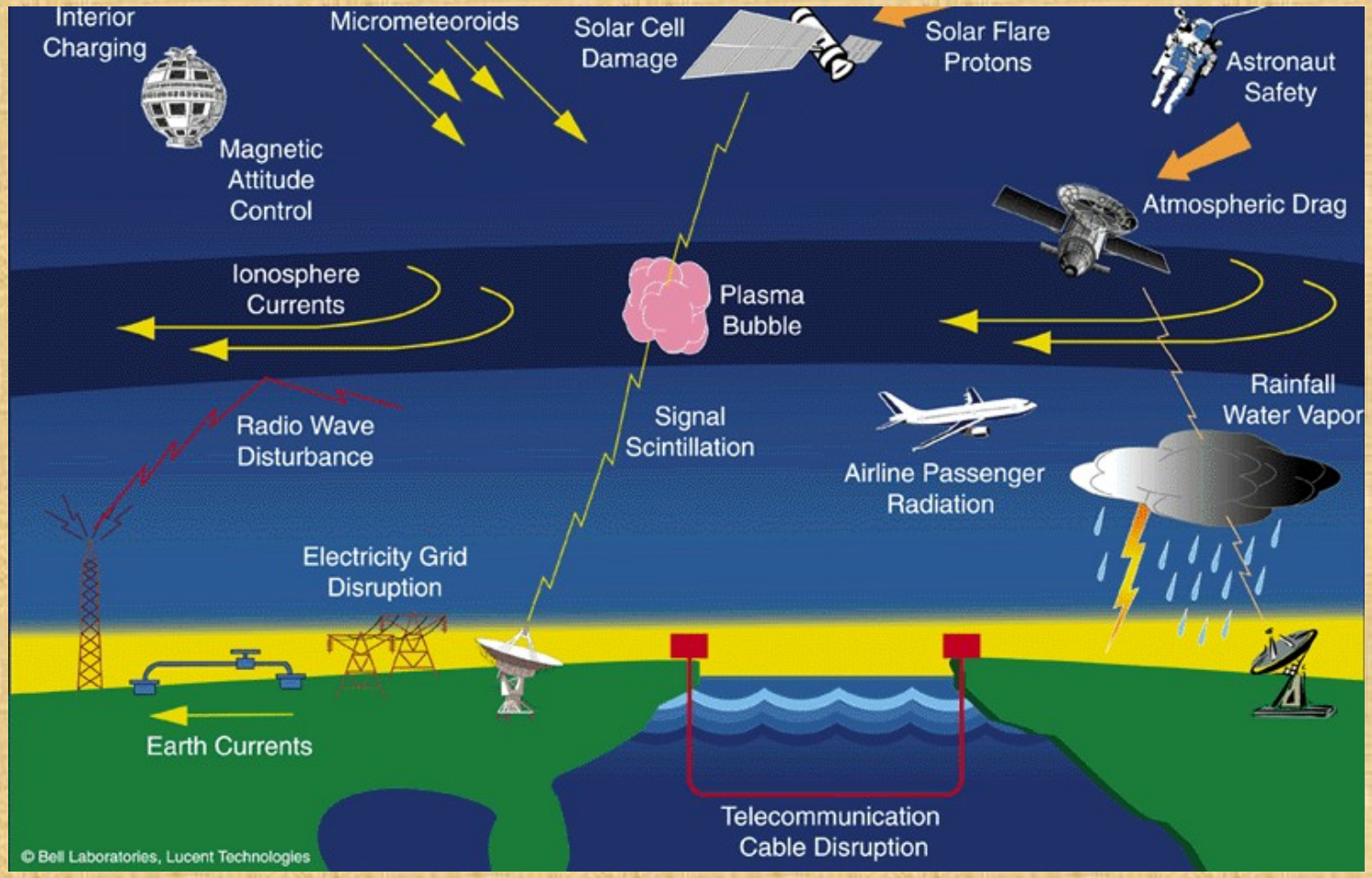
CMEs and Space Weather





The Sun-Earth Connection





Significant disruption for our technology reliant society

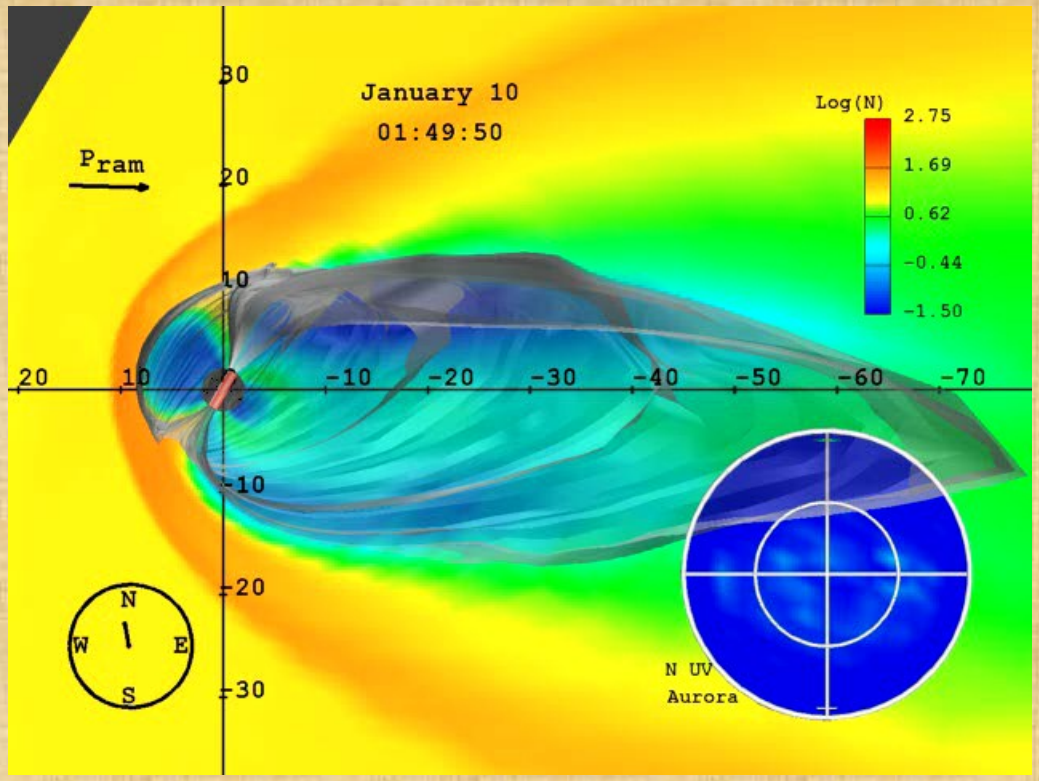
Radiation Hazards

Damage to Satellites

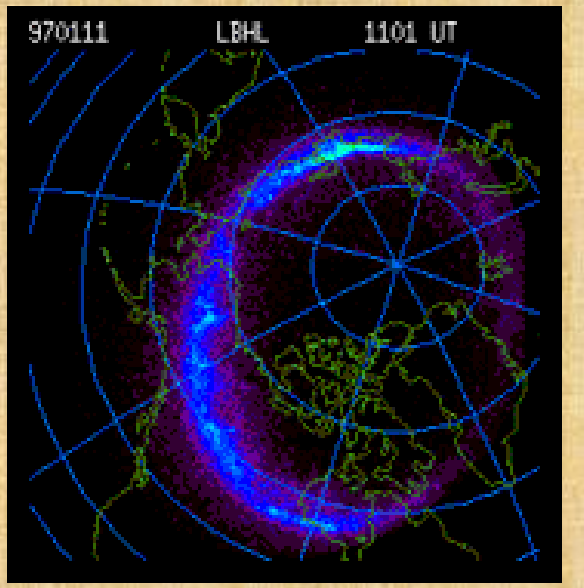
Communications Failures

GPS Navigation Problems

Geomagnetic Storms

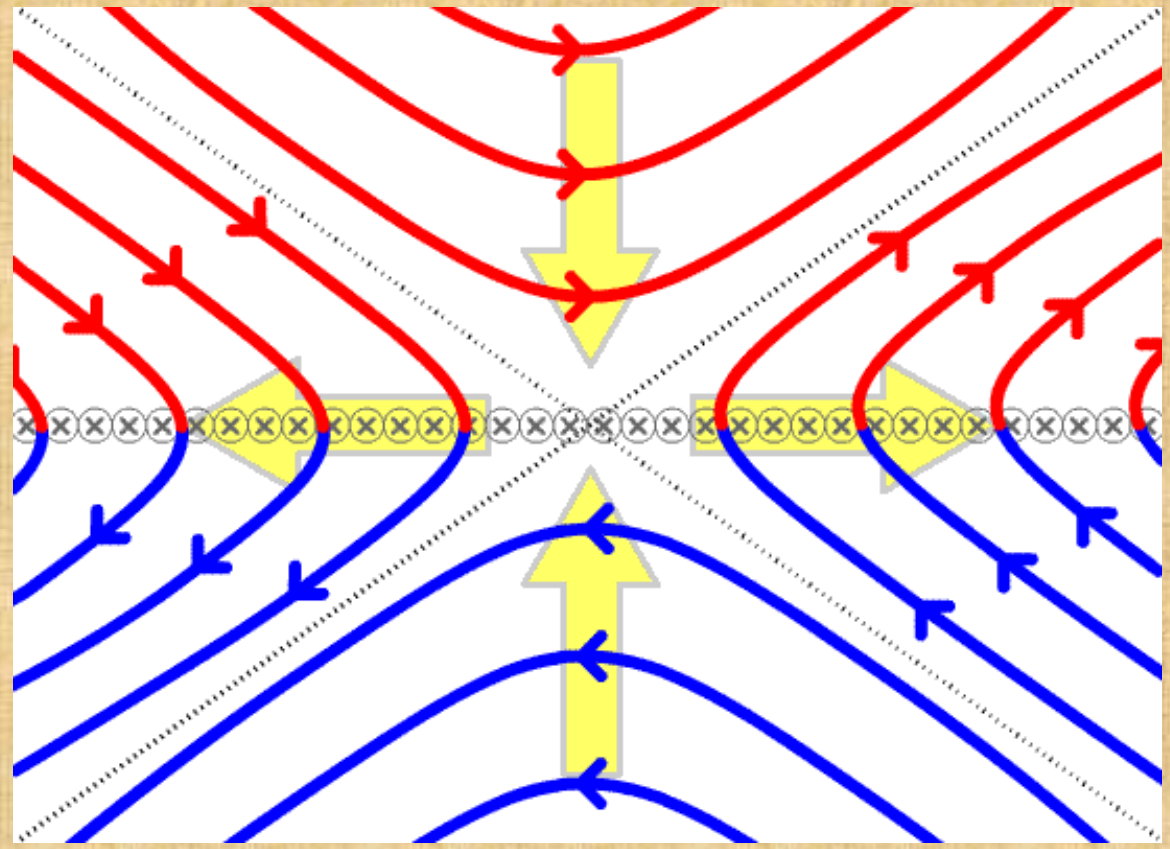


Magnetospheric Response



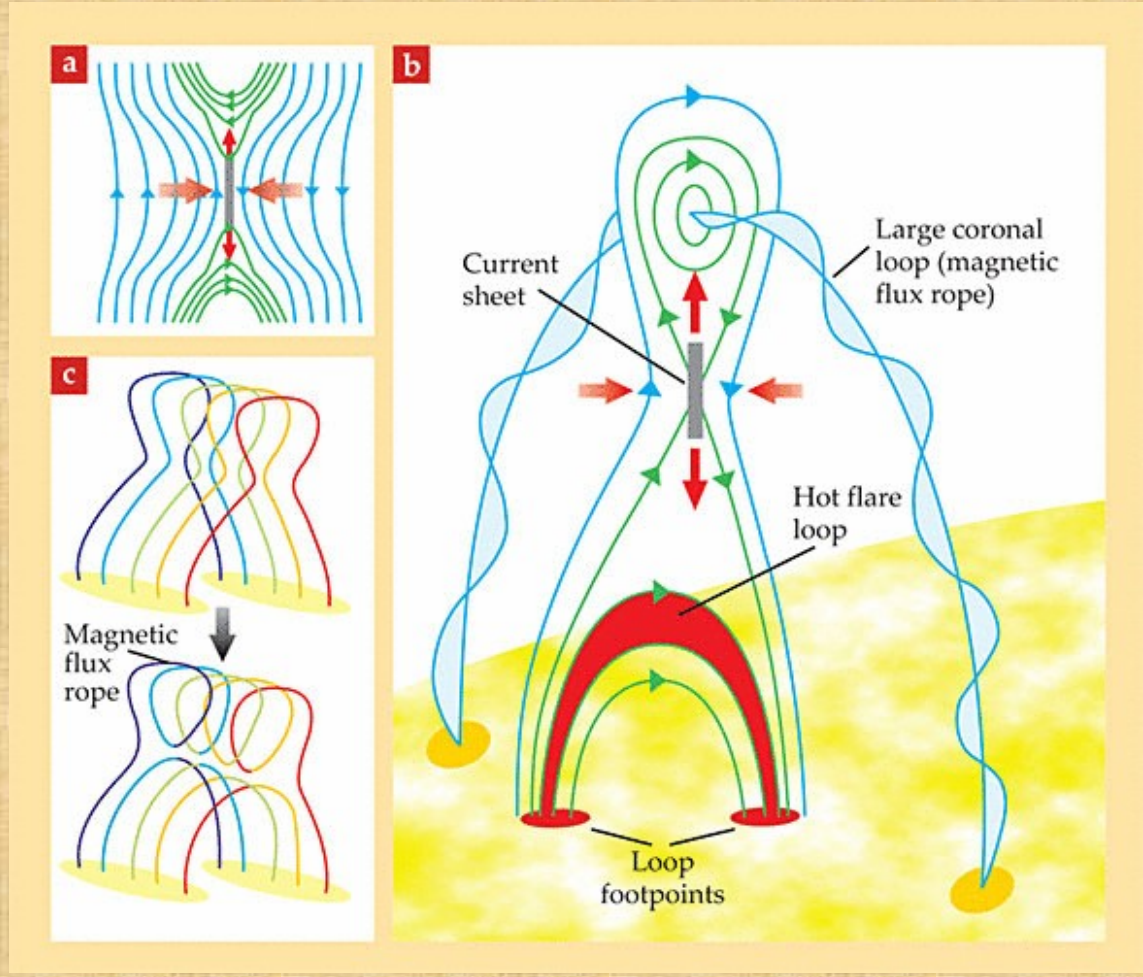
Atmospheric Response

Magnetic reconnection



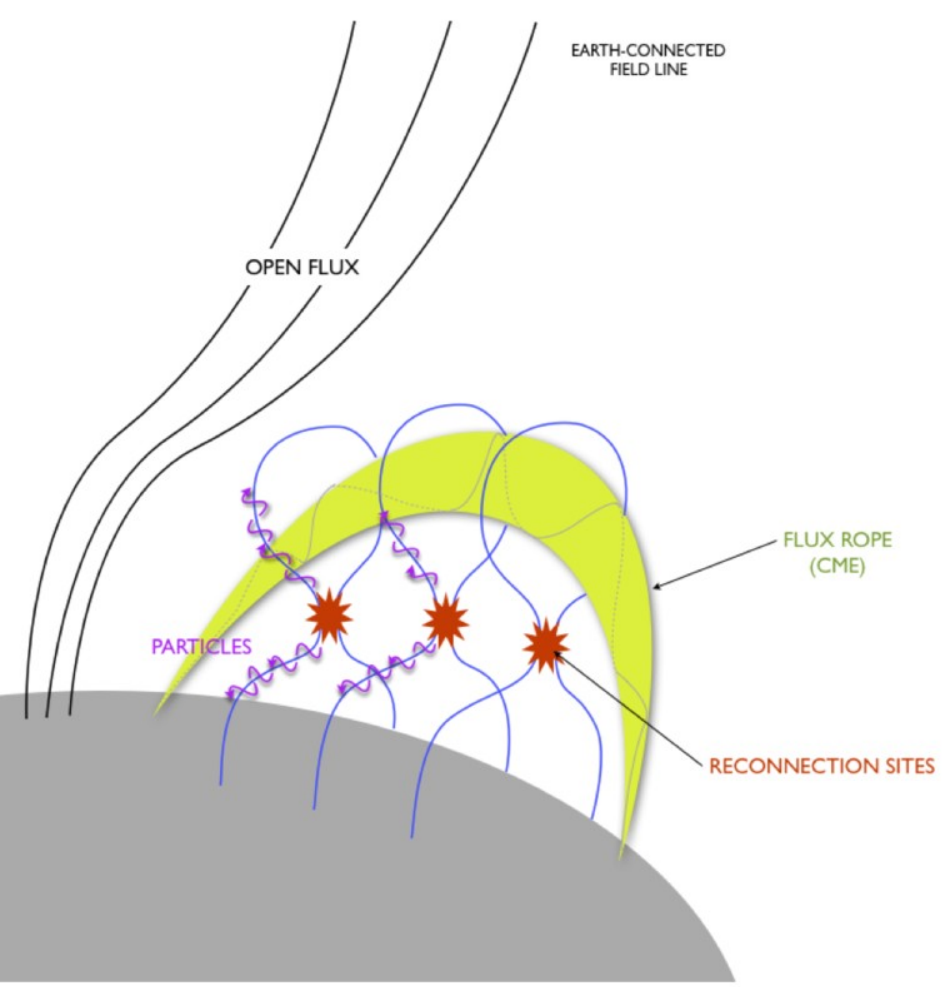
Wikipedia Commons

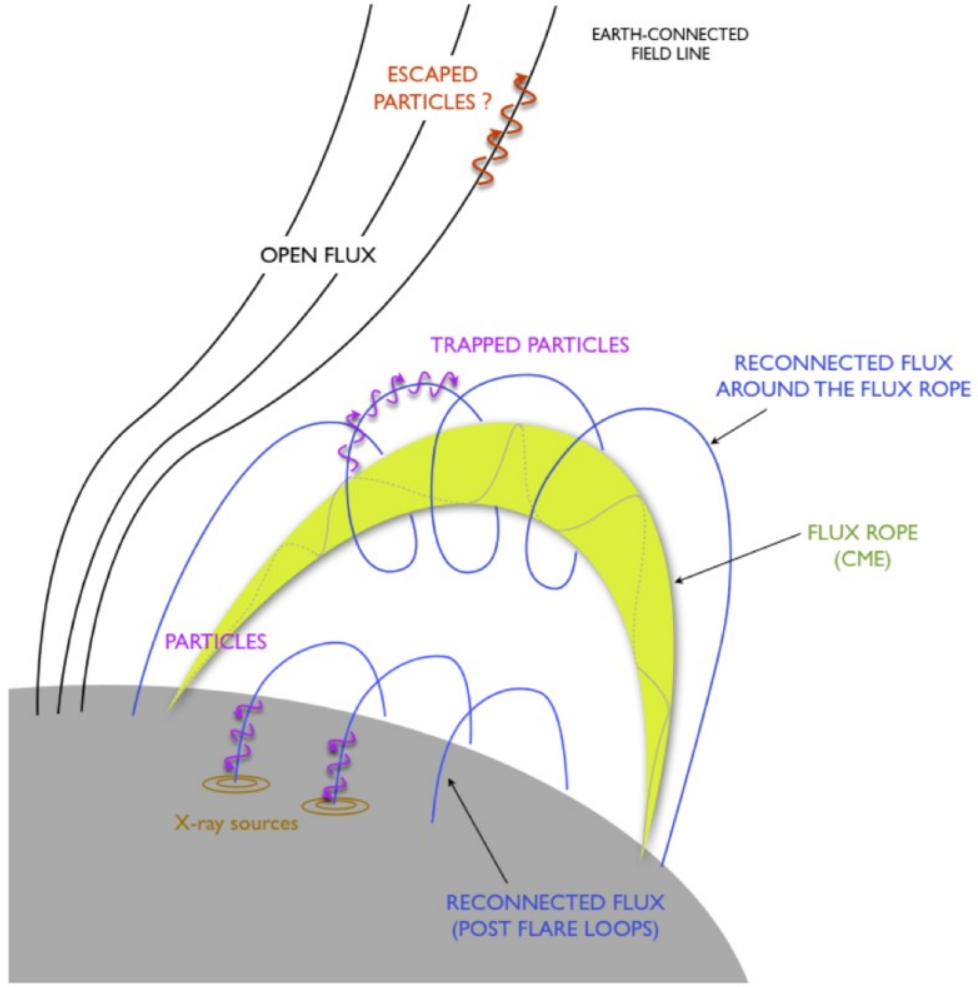
Magnetic Reconnection – CMEs



Holman, 2013

Magnetic Reconnection – CMEs

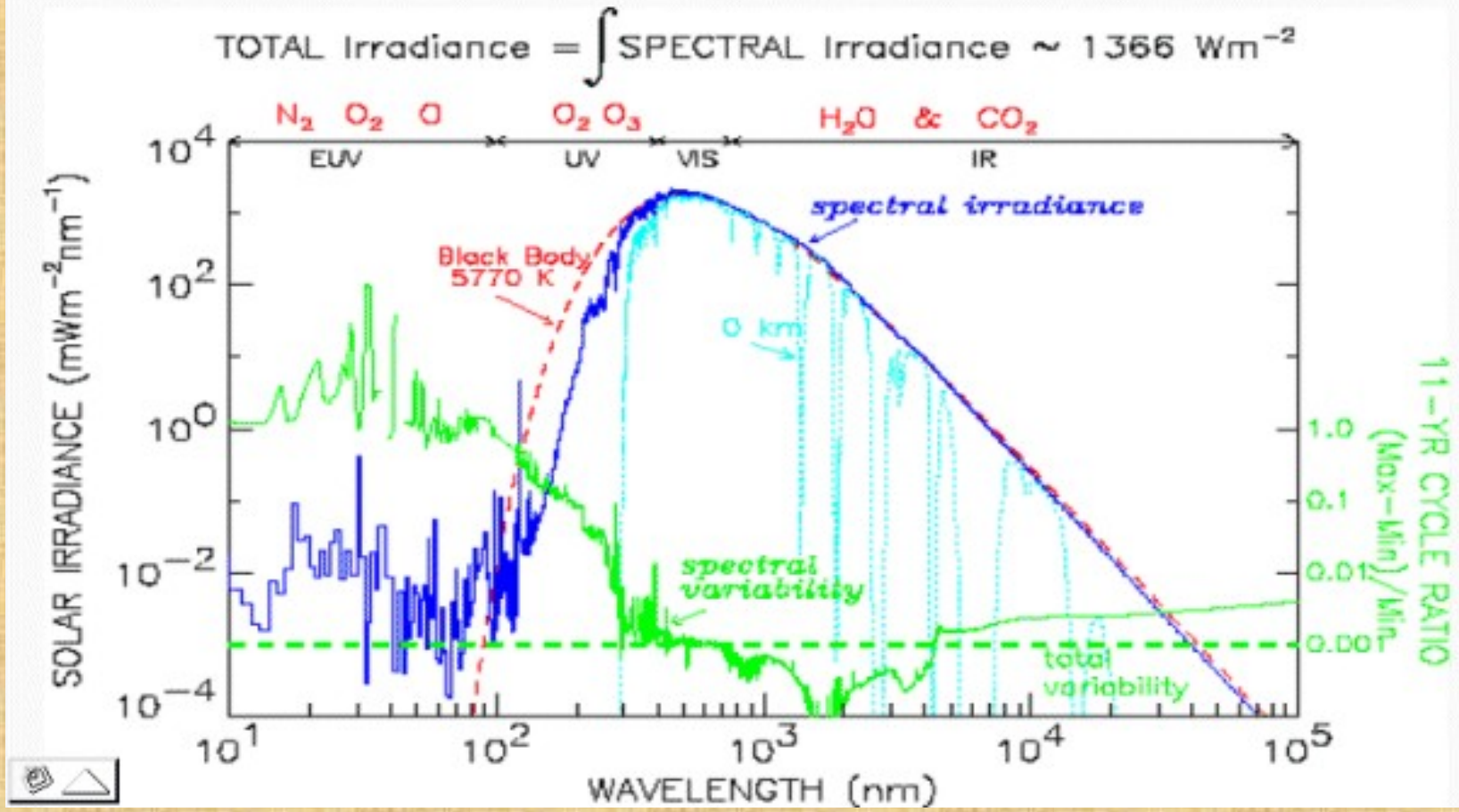




Masson et al., 2013

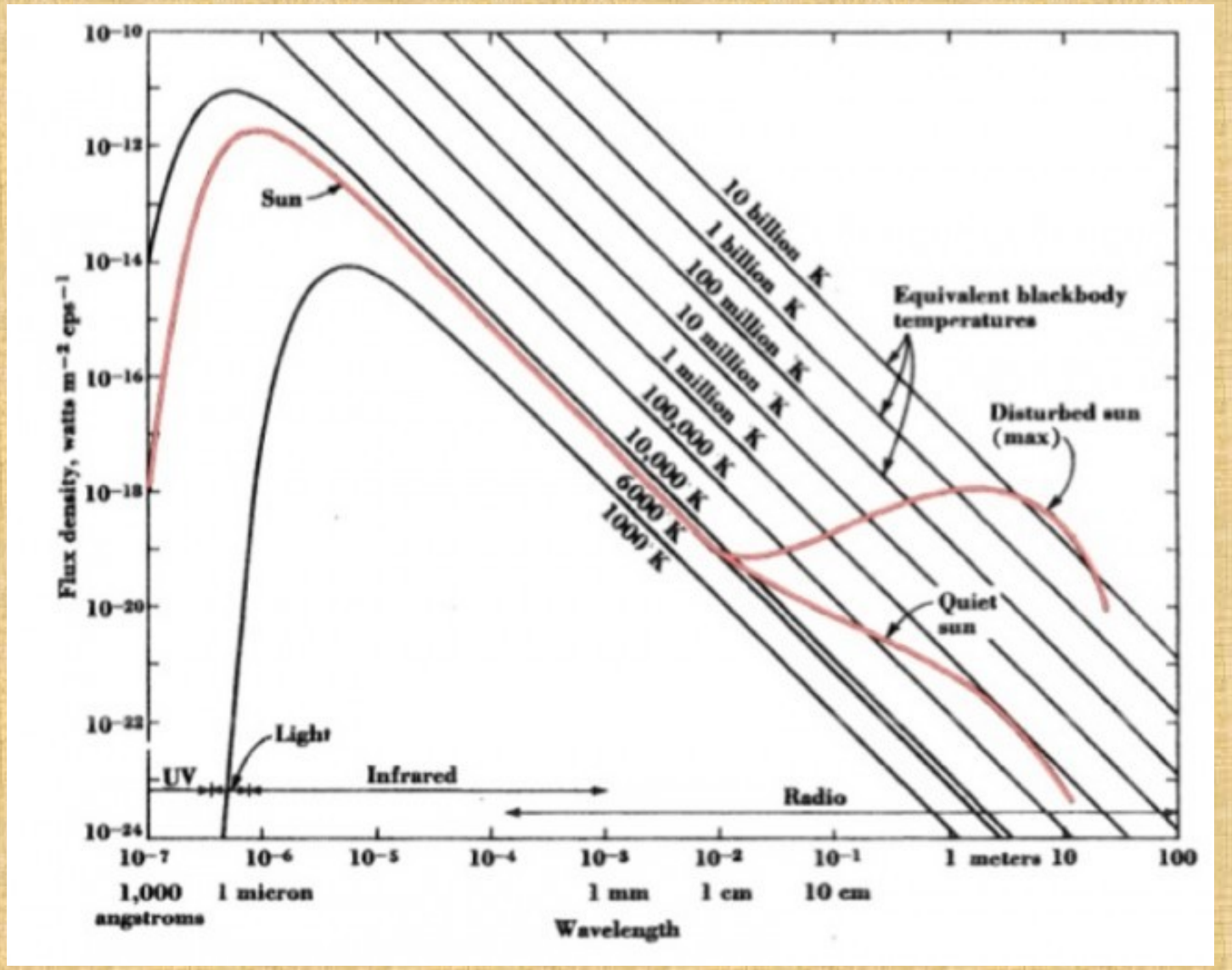
The Radio Sun

SOLAR SPECTRUM, VARIABILITY and ATMOSPHERIC ABSORPTION

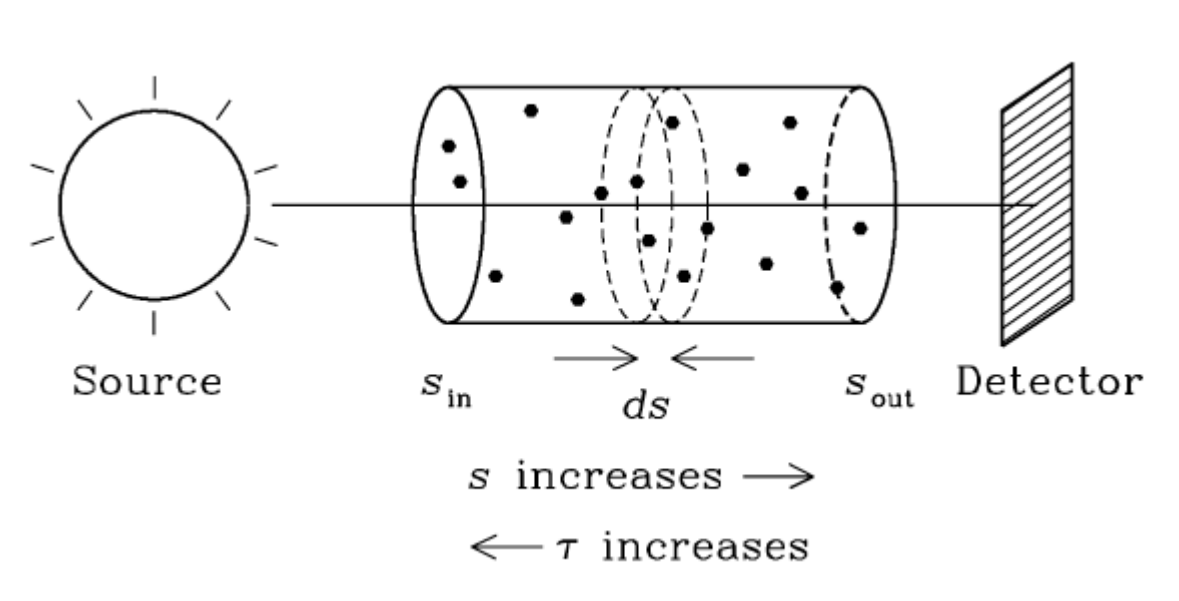


Lean, J. (US NRL)

Solar spectrum



Radiative Transfer



$$T_0 = T_0 e^{-\tau} + T_{Medium}(1 - e^{-\tau})$$

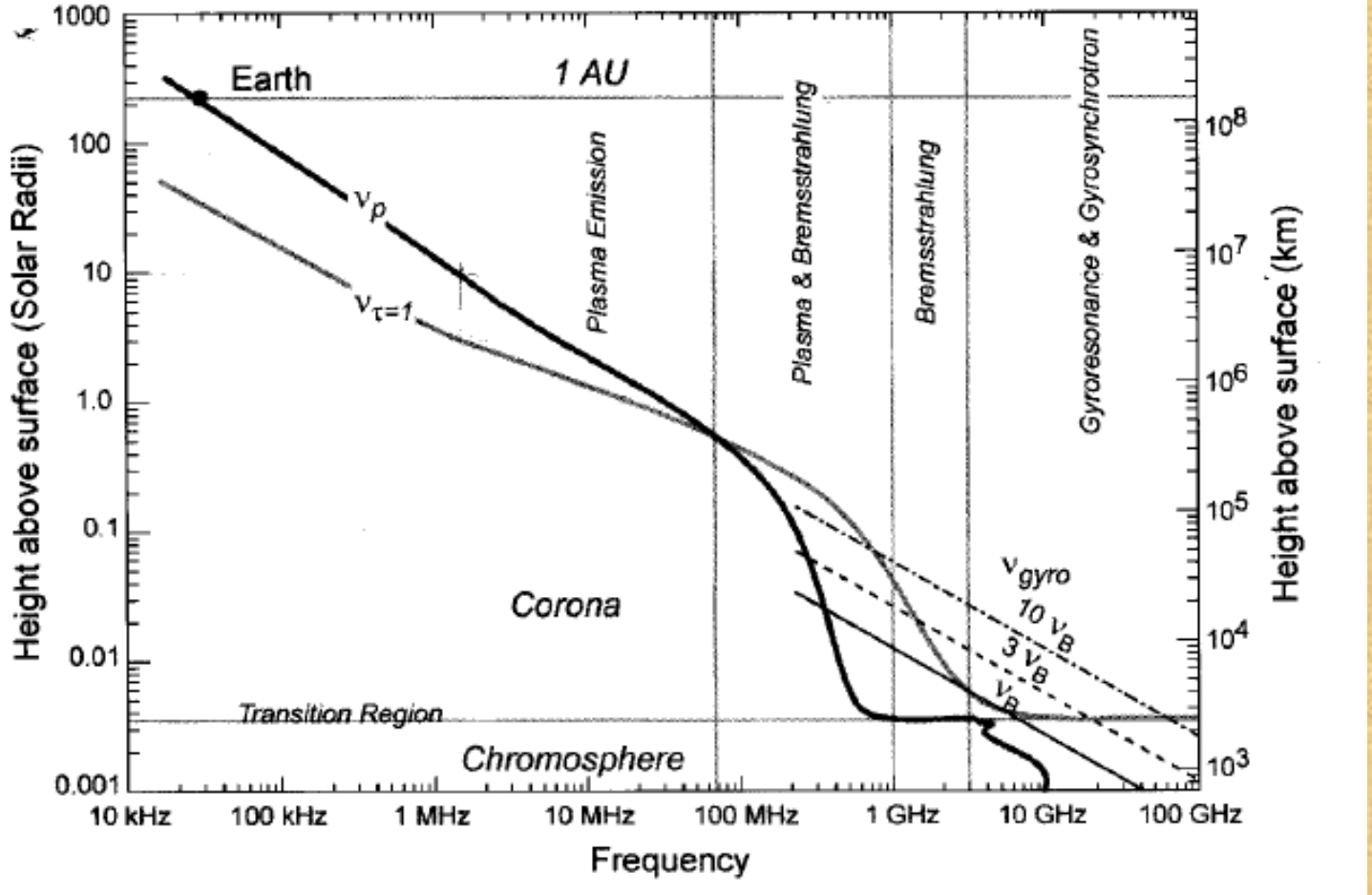
Radiative Transfer in the Corona

- $T_B = T_{Chr}\exp(-\tau_{Cor}) + T_{Cor}(1 - \exp(-\tau_{Cor}))$
- $T_{Chr} \approx 10^4$ K; $T_{Cor} \approx 10^6$ K

$$\tau = \int_0^s k \, \mathrm{d}s \; ; \quad \kappa = \frac{0.2 N_e^{\,2}}{n T^{1.5} f^2} \; ; \quad n^2 = 1 - \frac{f_{cr}^{\,2}}{f^2}$$

@ 100 MHz, 10^6 K, typical Coronal conditions

Characteristic frequencies and emission mechanisms



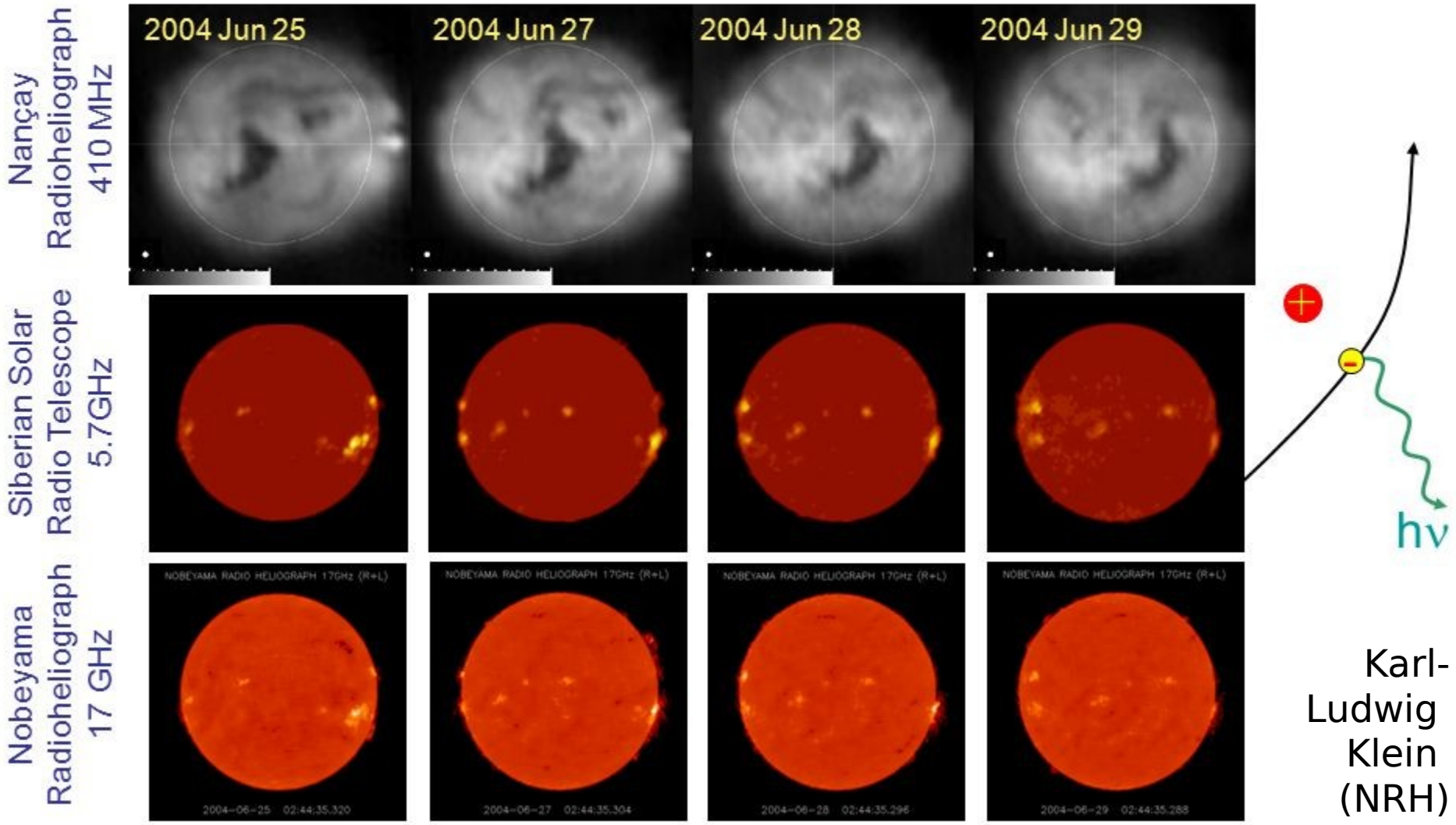
Plasma freq.
$\nu_p \approx 9 \times 10^3$ $N_e^{1/2}$

Free-free emission
$\nu(\tau_{ff} = 1) \approx$ $0.5\ N_e\ T_e^{-3/4}$ $L^{1/2}$

e gyro freq
$\nu_B \approx 2.8 \times 10^6$ B

Gary and Hudson, 2007

A multi frequency view of the radio Sun

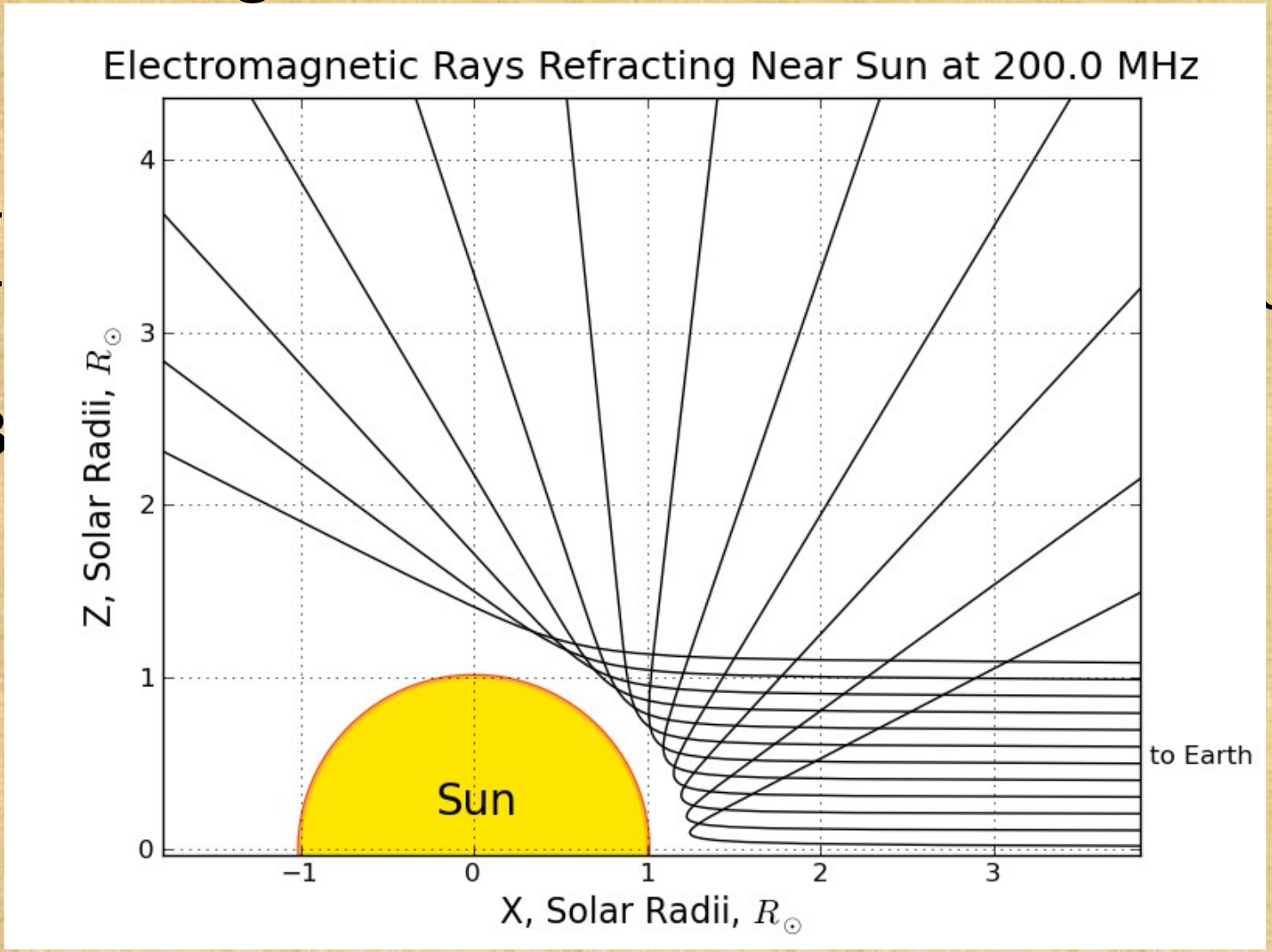


Karl-Ludwig Klein (NRH)

Different structures at ≠ ν: active regions (GHz), coronal holes

Background Thermal Emission

- L
  -
  -
- B

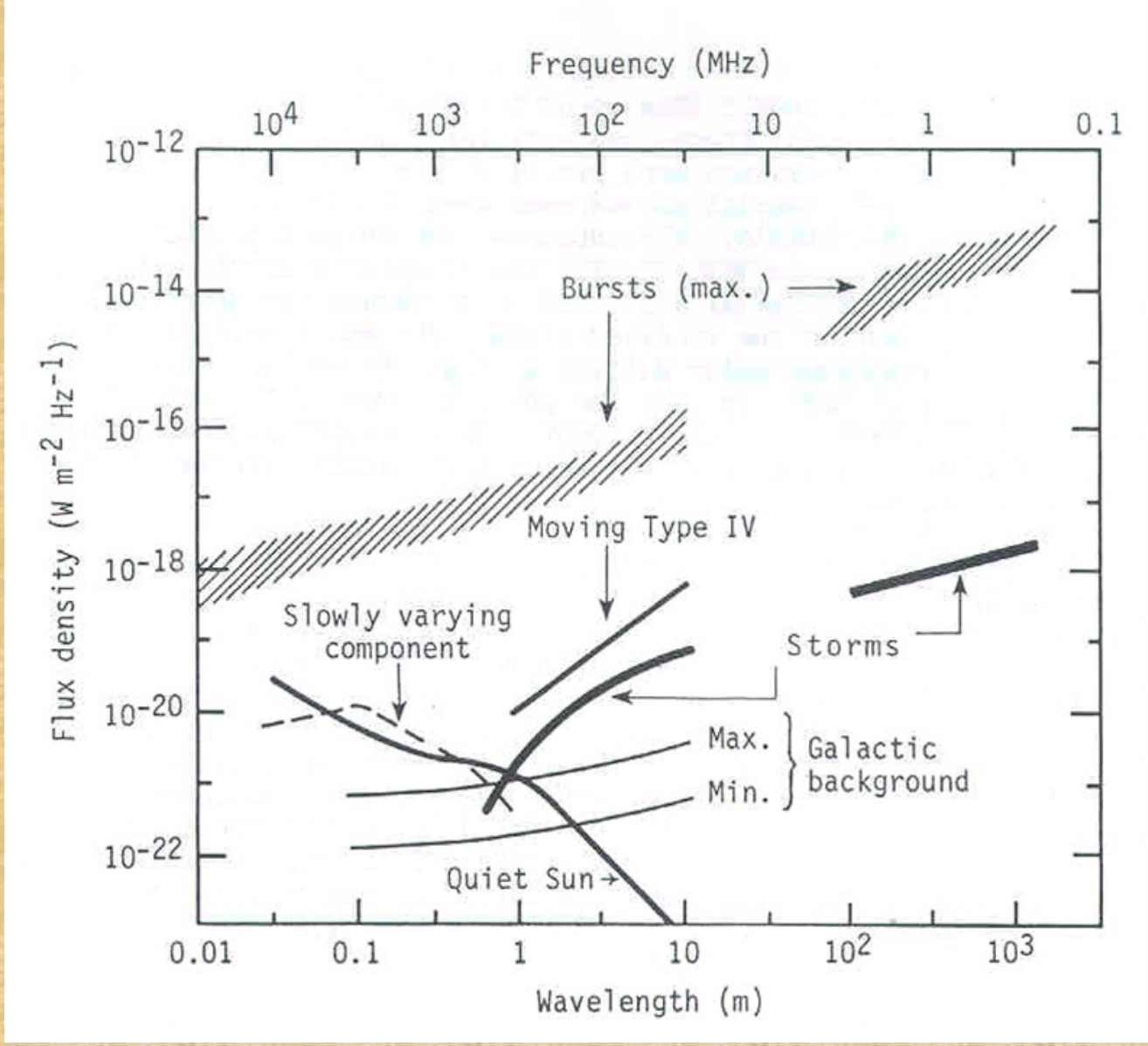


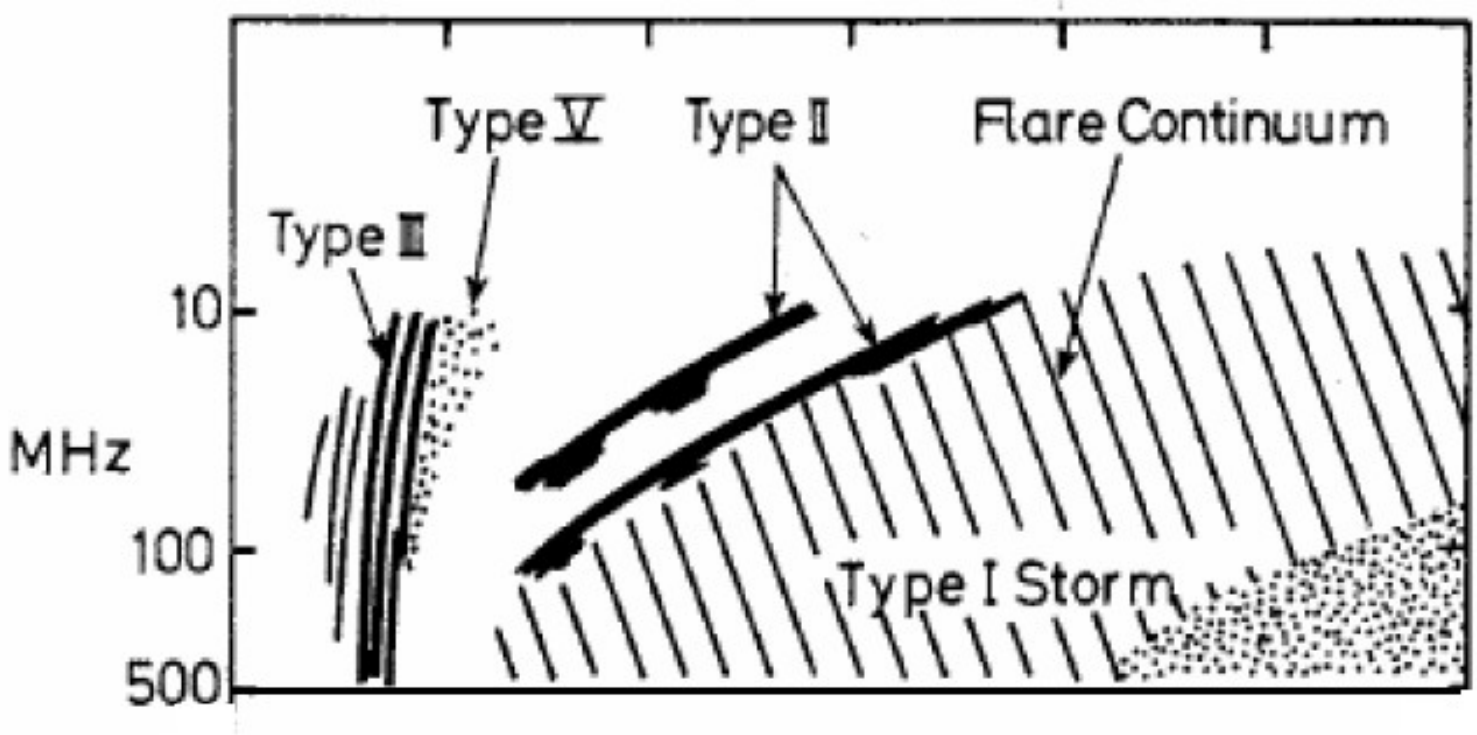
JV,

For the Active Sun

- Incoherent emission mechanisms
  - Free-free thermal emission, Gyrosynchroton
  - T_B contains all the physics (N_e, T_e, B field)
- Coherent emission mechanisms
  - Plasma emission (at fundamental and harmonic)
  - T_B – rate of growth of the instability
  - Properties in the freq-time plane, polarisation and morphology provide the physics

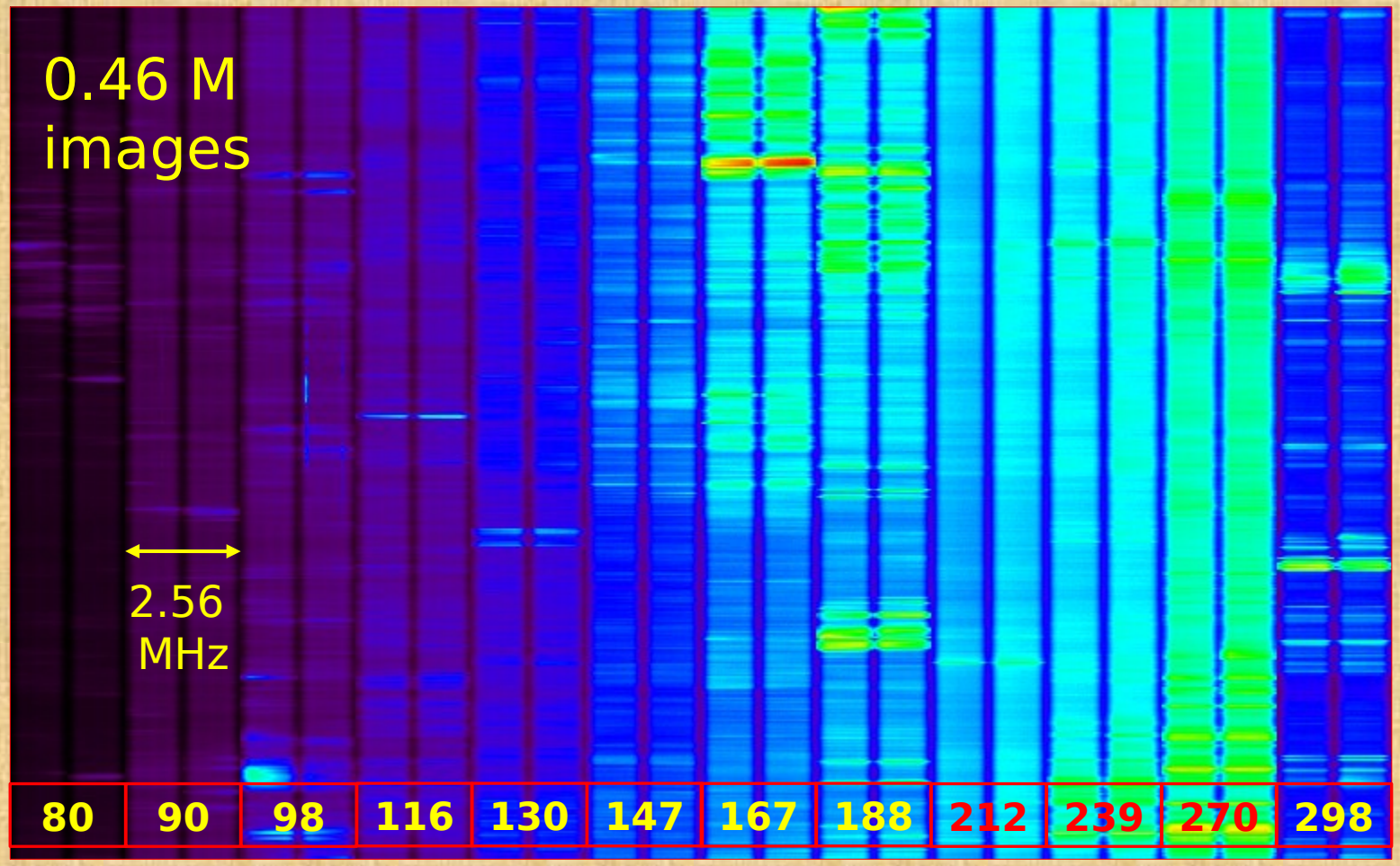
Solar Radio Emissions





"Classical" radio bursts

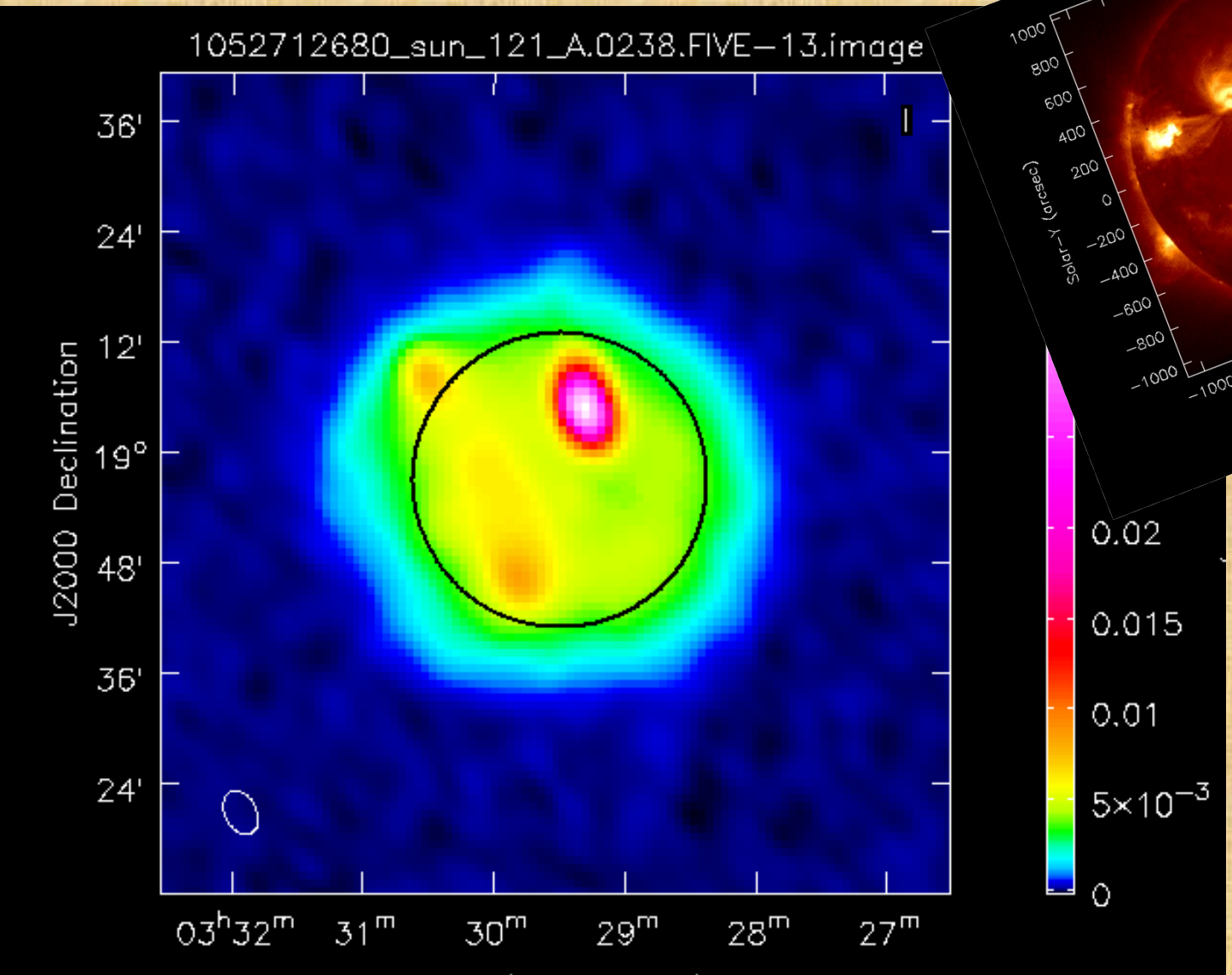
Sample MWA Dynamic Spectrum

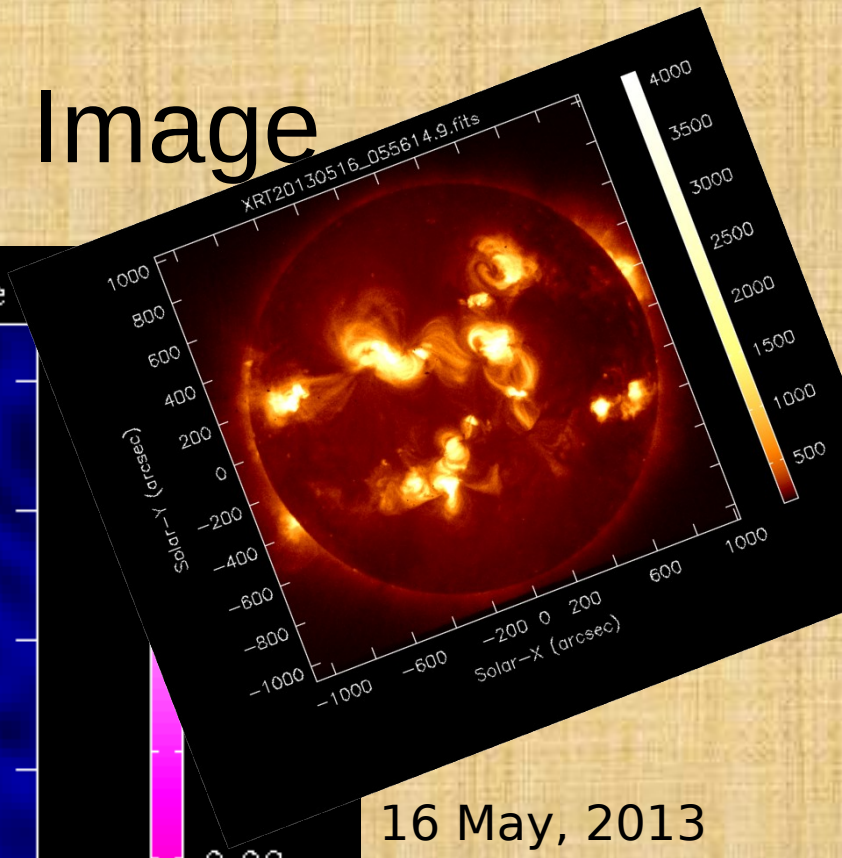


Time (5 min)

Frequency
(12 log-spaced groups of 2.56 MHz spanning 80 – 300 MHz)

An Example Image





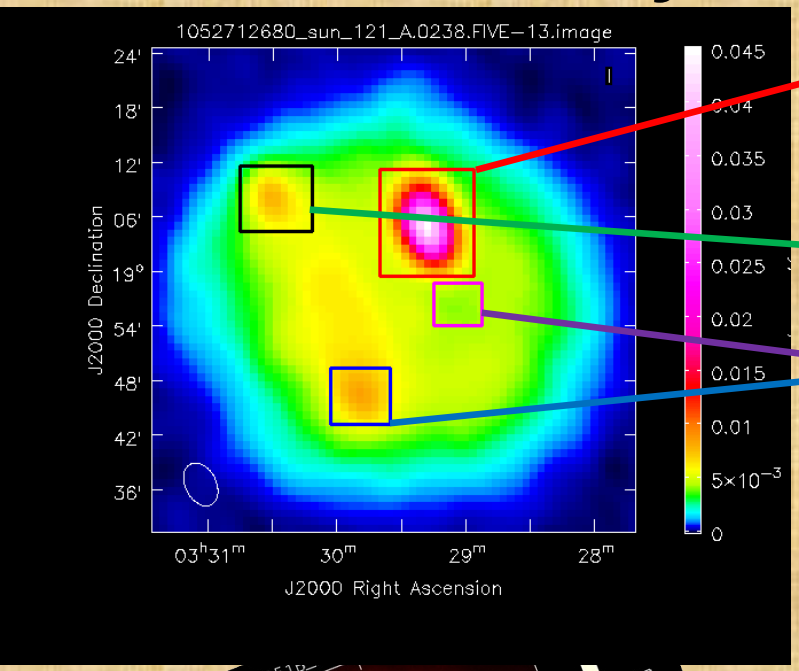
16 May, 2013
04:15:02 UT

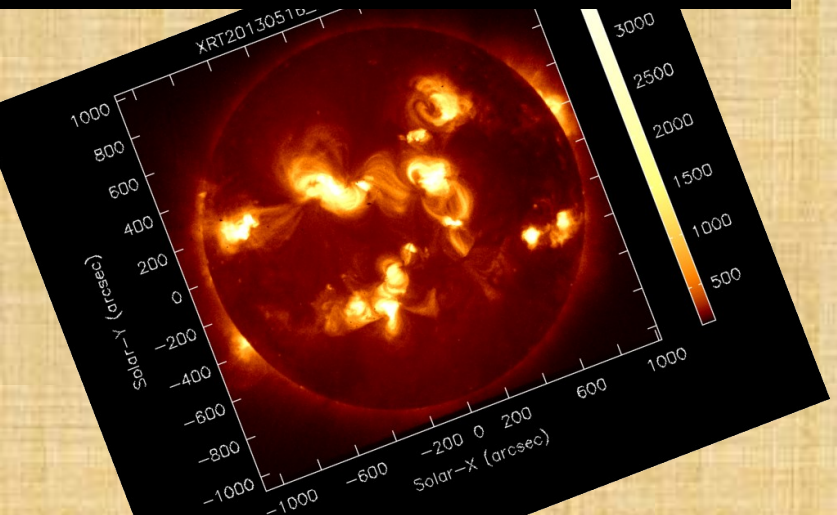
ν_0=153.905 MHz
$\Delta\nu$=640 kHz

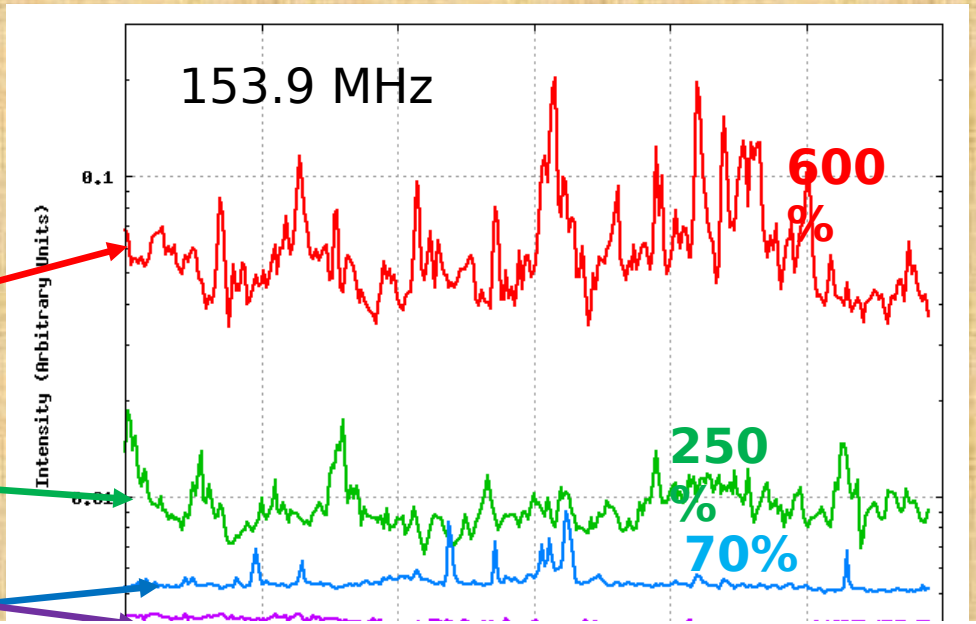
Δt=1 second

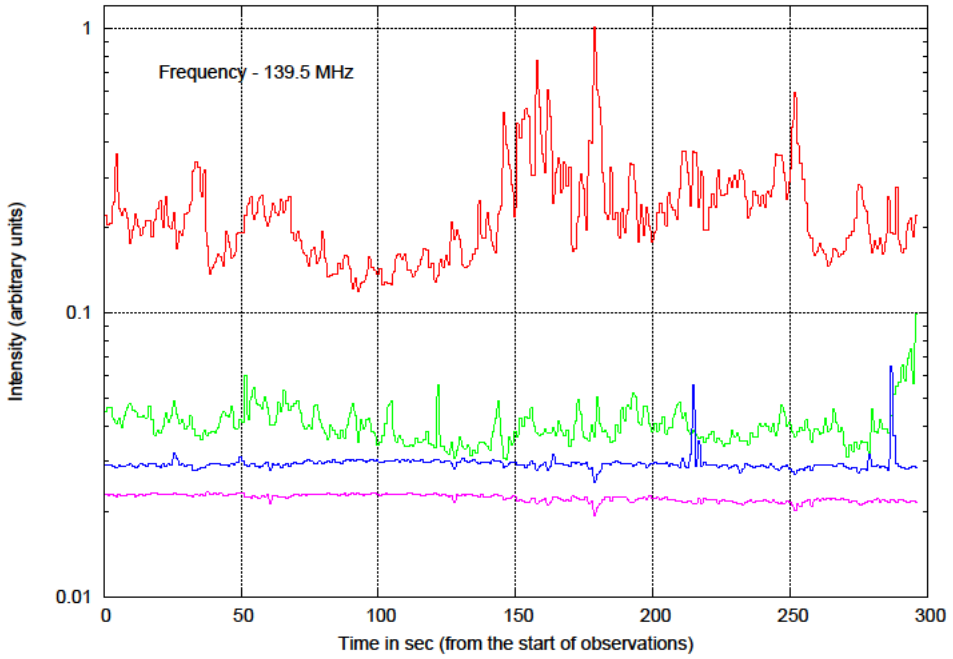
Imaging
Dynamic Range

Spatial Variability

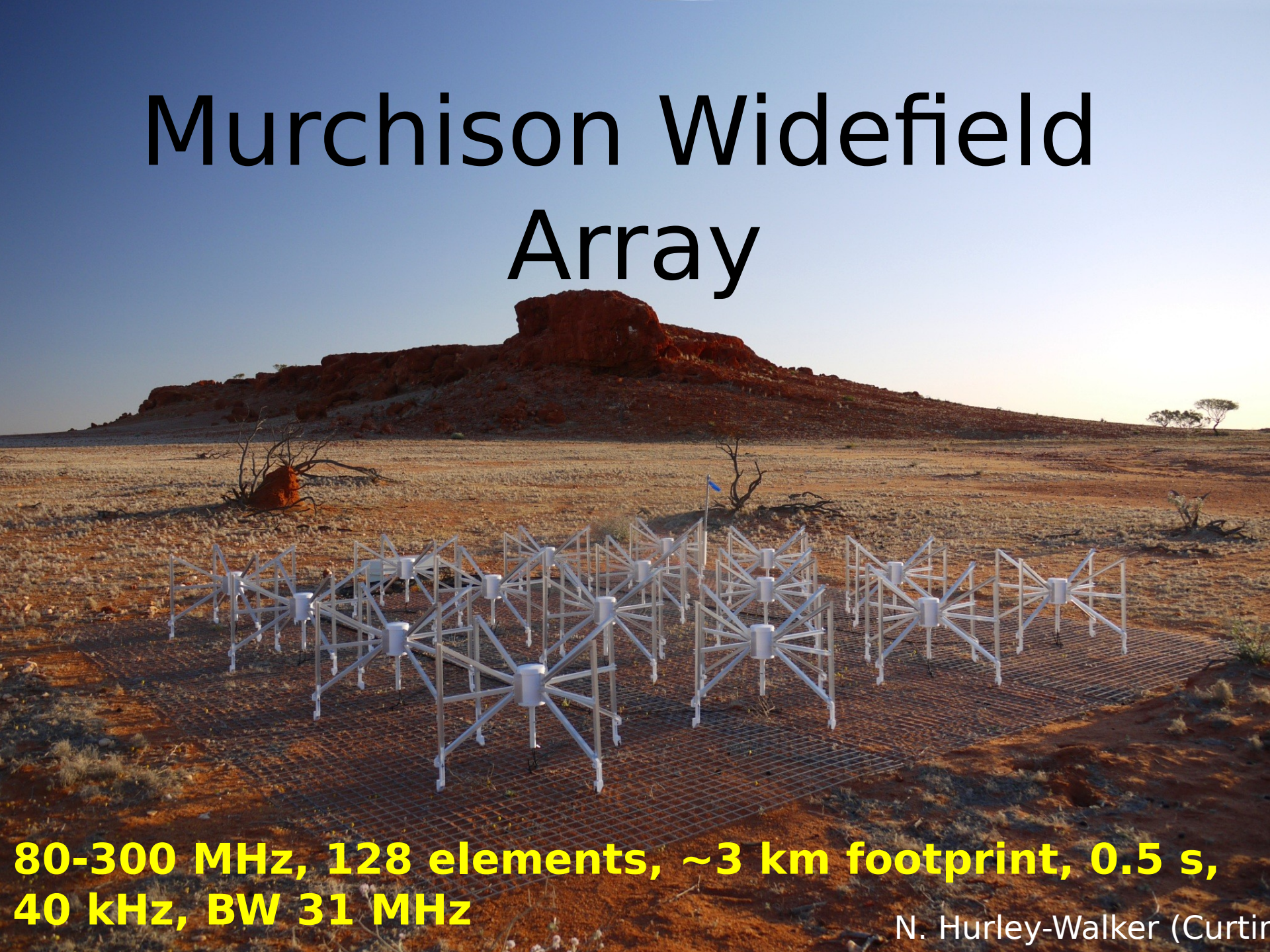








Murchison Widefield Array



80-300 MHz, 128 elements, ~3 km footprint, 0.5 s, 40 kHz, BW 31 MHz

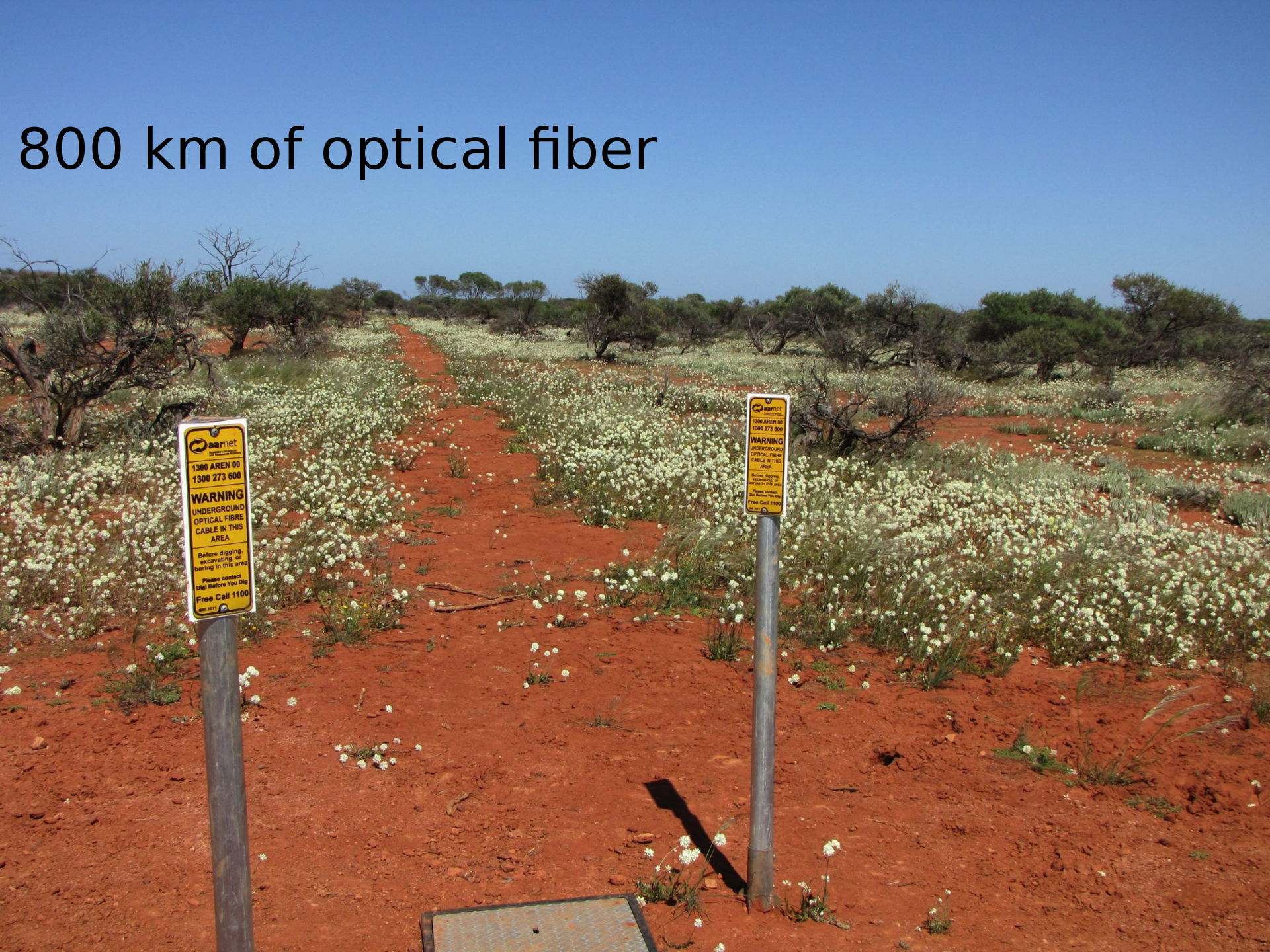
N. Hurley-Walker (Curtin

Antennas

Receivers

Central Signal Processing

800 km of optical fiber

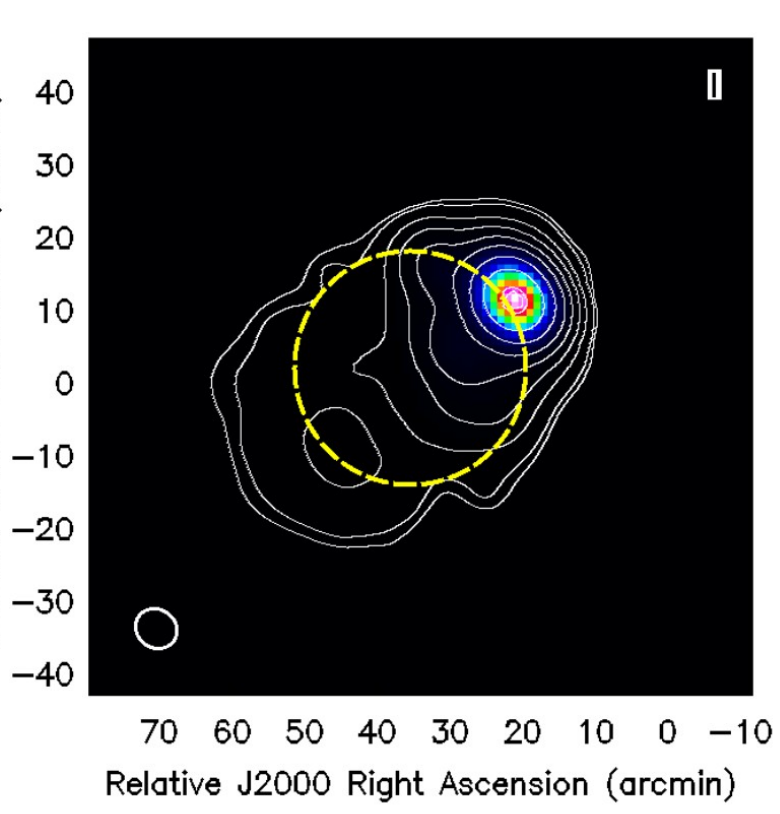


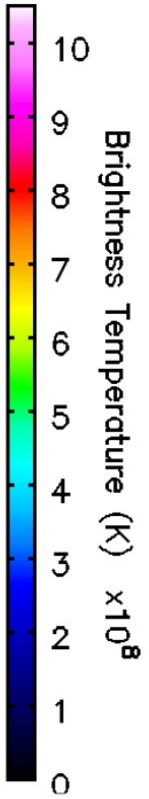
Pawsey Centre

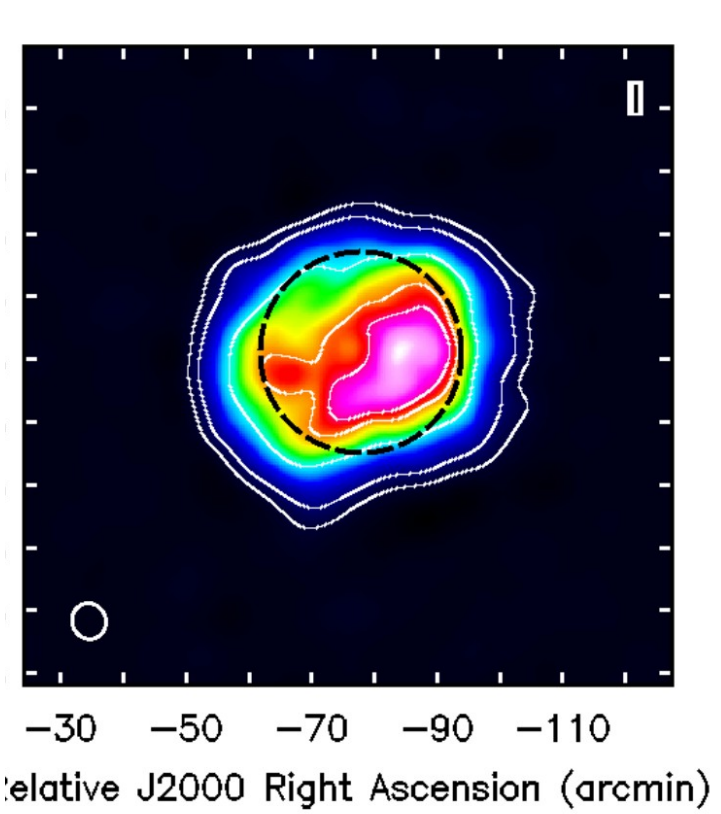
Solar Imaging Requirements

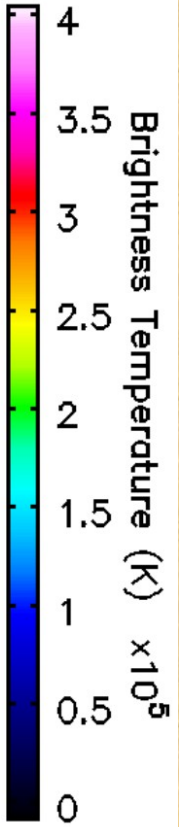
- Extreme time variability ⇒ no synthesis in time
- Spectral features over small fractional bandwidths ⇒ no meaningful frequency synthesis
- Emission scales – resolution/scattering limit to ~45’
- Dynamic range requirements $\geq 10^5$
- ***High dynamic range, high fidelity imaging capability with monochromatic, snapshot data over a wide band.***

Automated Imaging Pipeline







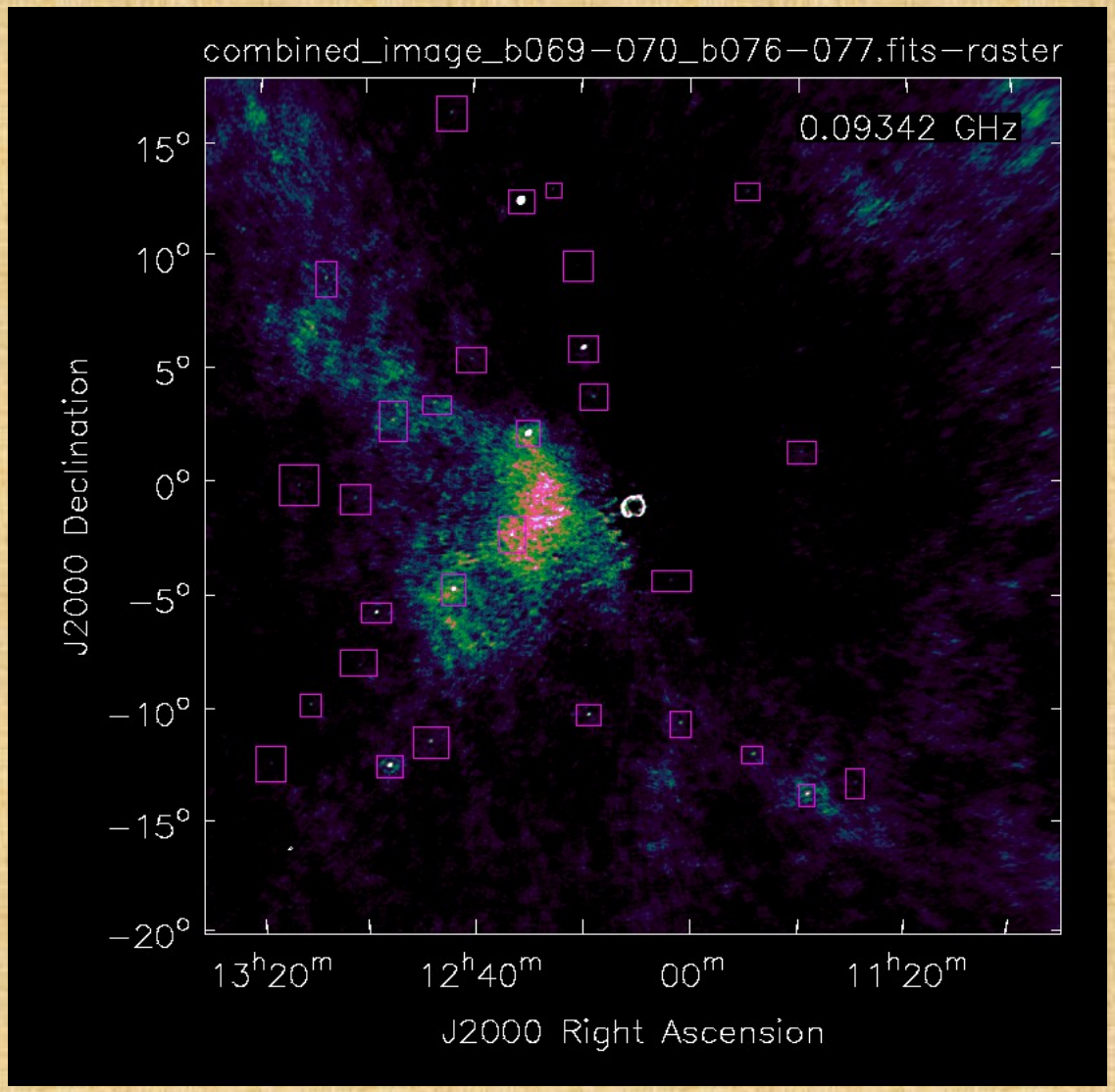


Contour levels: (0.0007, 0.002, 0.02, 0.2,0.4,0.8) X 10^9 K
144.32 MHz; 40 kHz; 0.5 s
Imaging dynamic range: >10^5

Contour levels: (0.03, 0.09, 0.4, 0.7, 0.8) x 4x10^5 K
239.10 MHz; 160 kHz; 0.5 s
Imaging dynamic range: ~1000

Mondal et al., 2019

Stars in daytime!



- Boxes - detected sources with a counterpart in the TGSS 150 MHz survey.
- Sun imaged (0.5 s; 160 kHz) using AIRCARS.
- The model subtracted from the visibilities and the residual visibilities from about 350 such frames were combined.
- Able to detect sources <10Jy with >5σ confidence.
- The bright annular region at the center of the image is the unmodeled contribution from the Sun.

Data/Computation Challenges

- Data volumes
  - raw data ~1 TB/hr (~3 PB in the archive)
- Computational burden
  - 5min - 1hr/image (4 min of data, ~23,000 images, ~12+ days on a dedicated 36 core machine)
- Reduced data ~1 TB/hr
- Bandwidth requirements
  - Data archived at the Pawsey Centre in Perth, Australia
- What will we do once we make these millions of images!

Conclusions

- Metrewave radio observations probe coronal regions
- With the availability of new instruments, this region is very promising for investigations of:
  - Coronal heating related studies – looking for signatures of very weak nonthermal emissions which are not measurable at higher energies
  - Space weather studies – by providing measurements of magnetic fields of CMEs and the quiescent corona
- Very exciting time to study the Sun at low radio frequencies