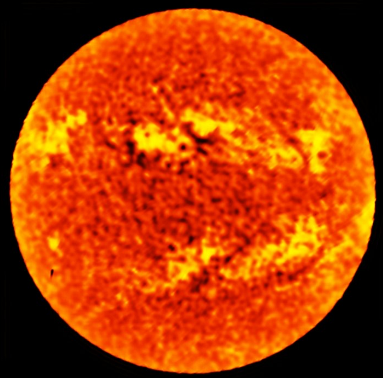
Science with LLAMA 2022 @ Salta

Single-dish observation of the Sun at millimeter/submillimeter range



Kazumasa Iwai

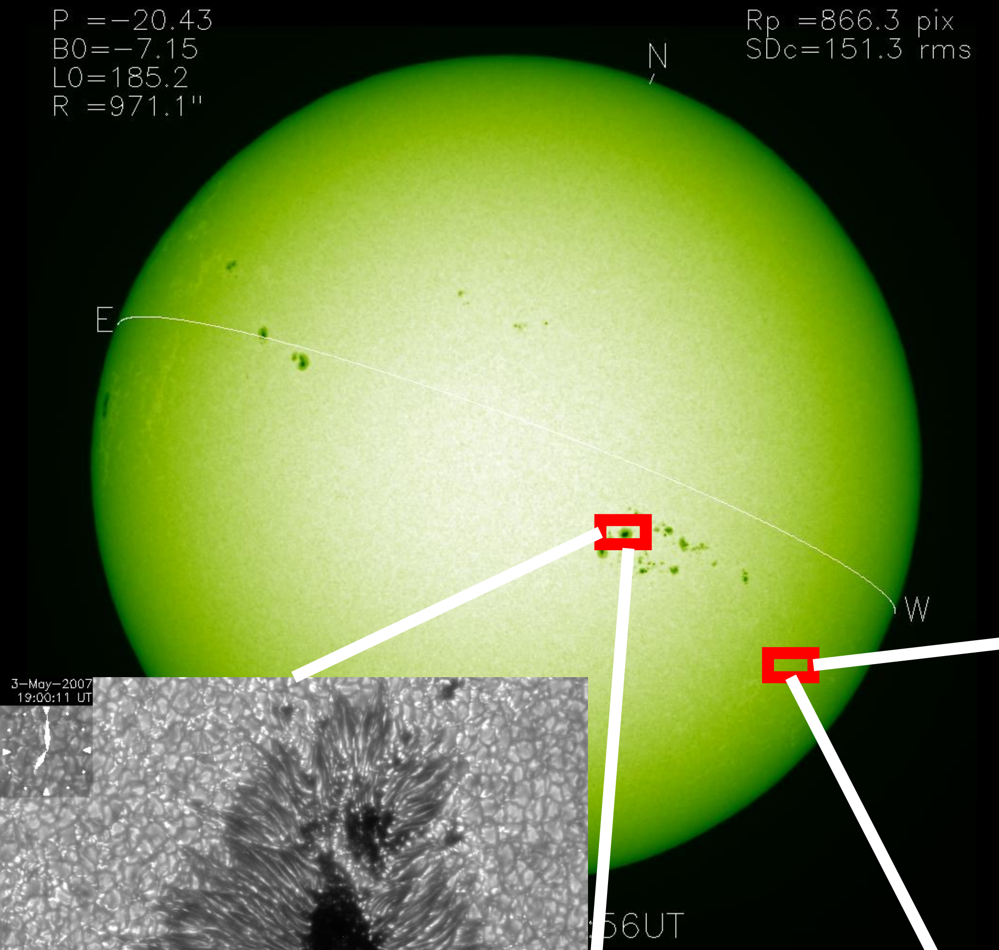
ISEE, Nagoya University

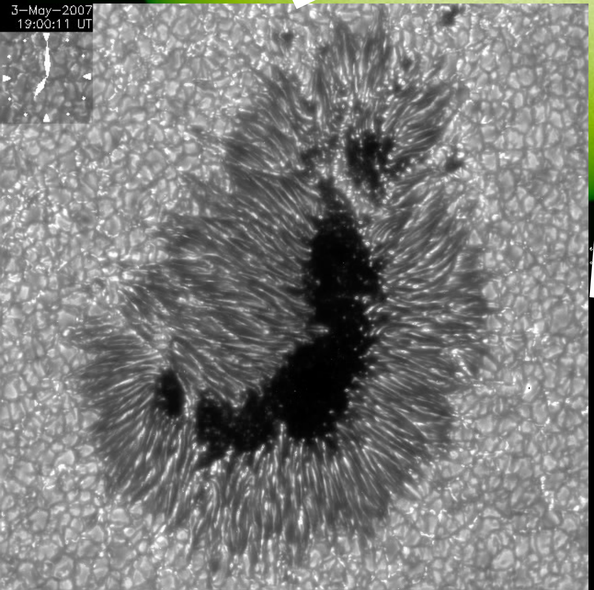
Nagoya University Institute for Space–Earth Environmental Research

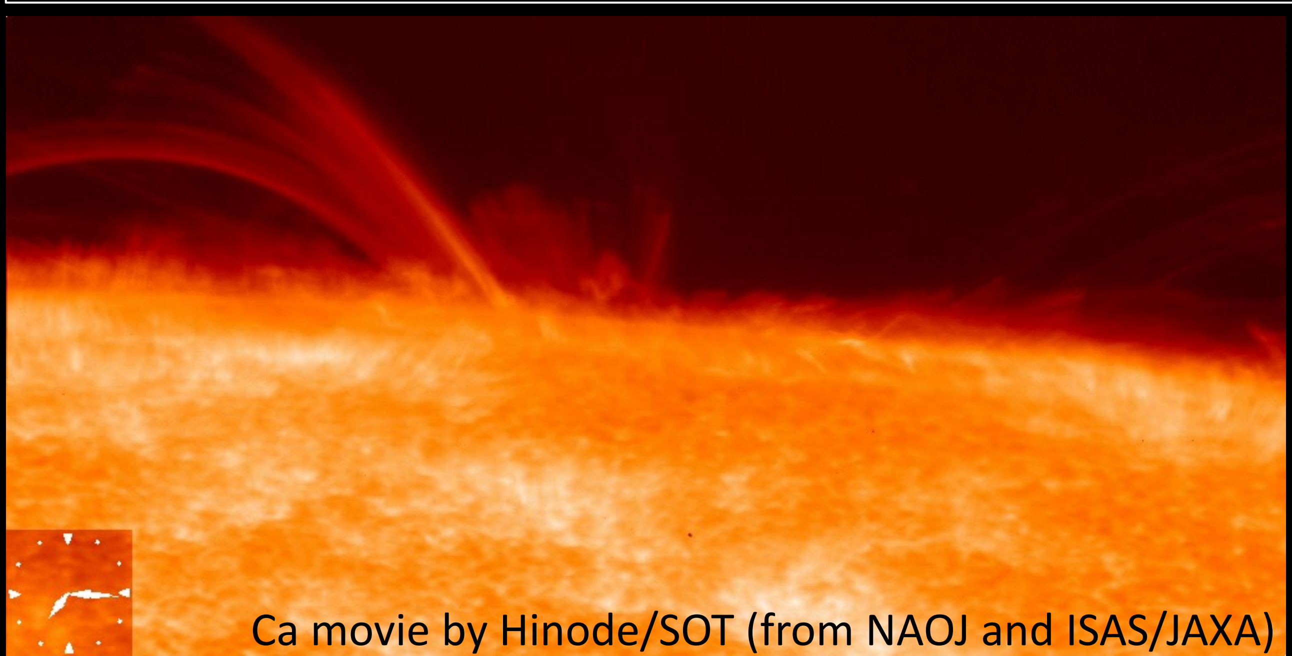
Why the Sun is so interesting?

The Sun and its activity

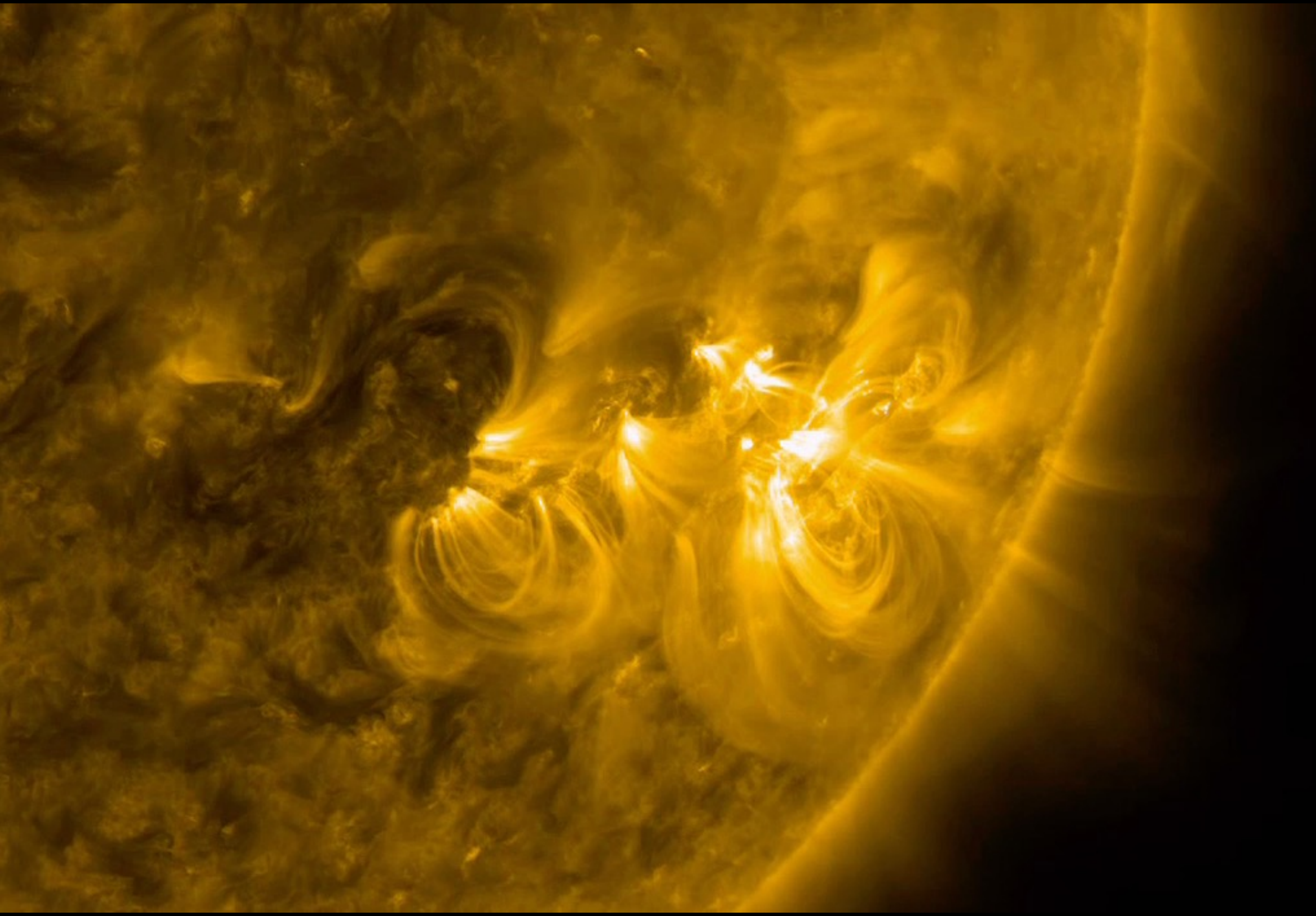
The solar atmosphere is filled with various structures with a wide range of spatial scale.
Such structures are made by magnetic fields, and they generate various eruptive phenomena.





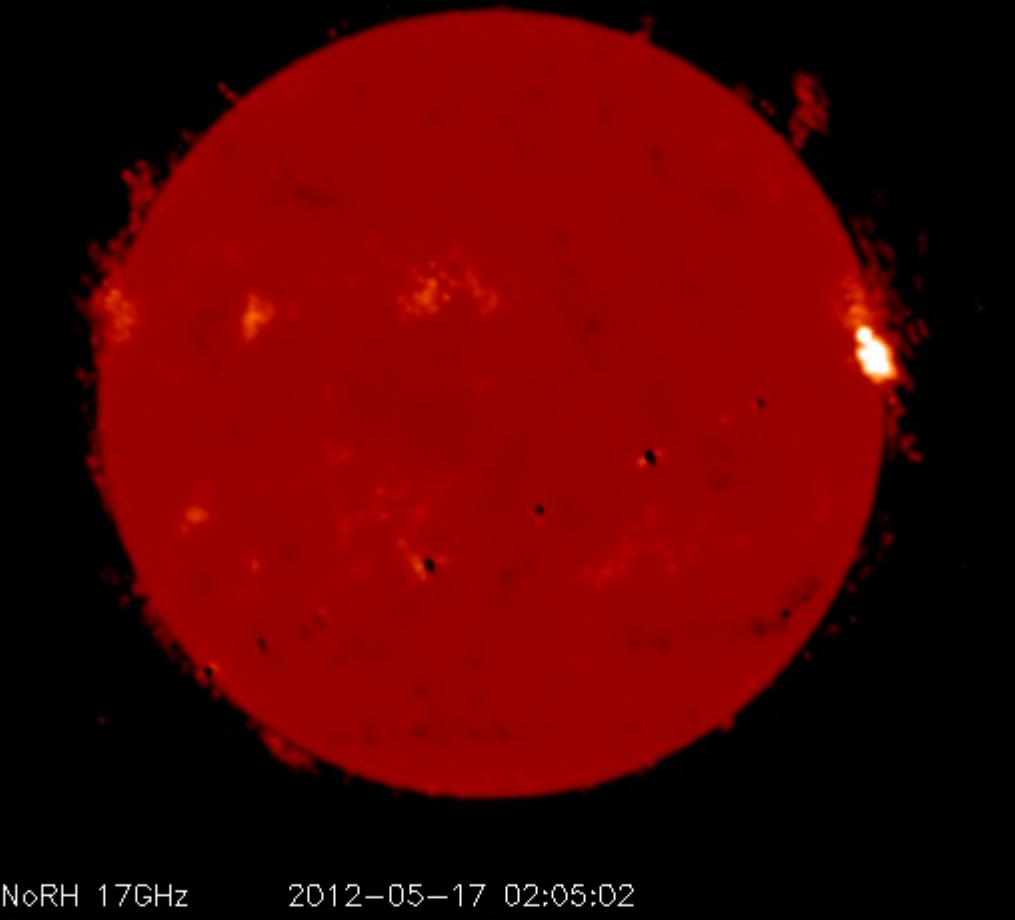


Solar flare



© NASA

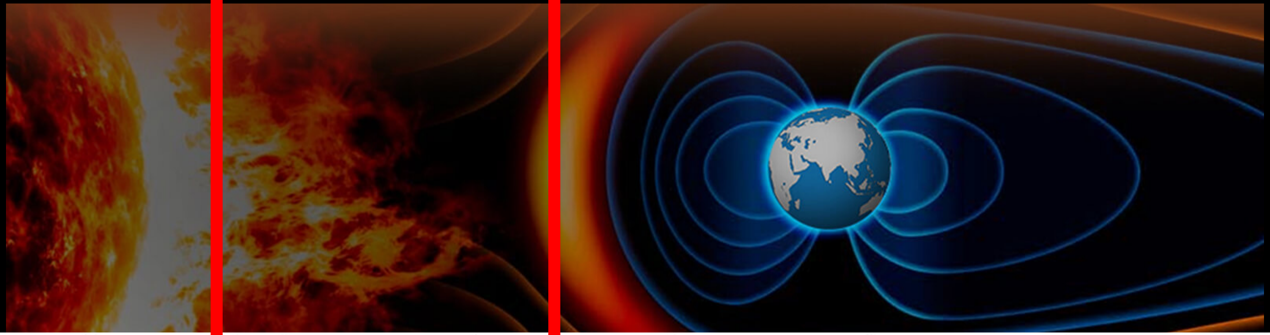
The solar flare is an explosion of the magnetic field energy.

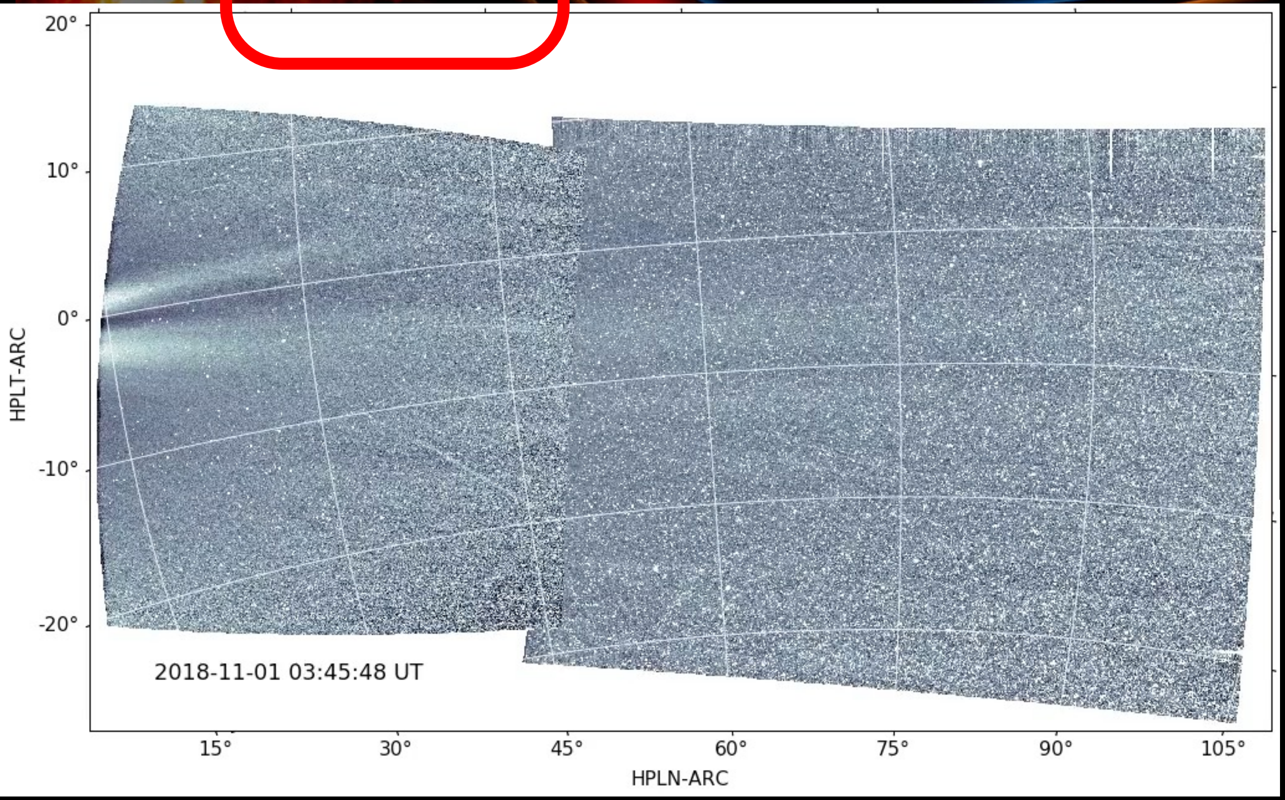


Solar disc at radio wavelength (17GHz) observed by the Nobeyama Radioheliograph

The solar flare generates high energy particles that generate strong radio emission called solar radio burst.

Solar wind and CMEs





Solar wind observed by the white light imager of PSP (Howard+2019)

Solar wind:

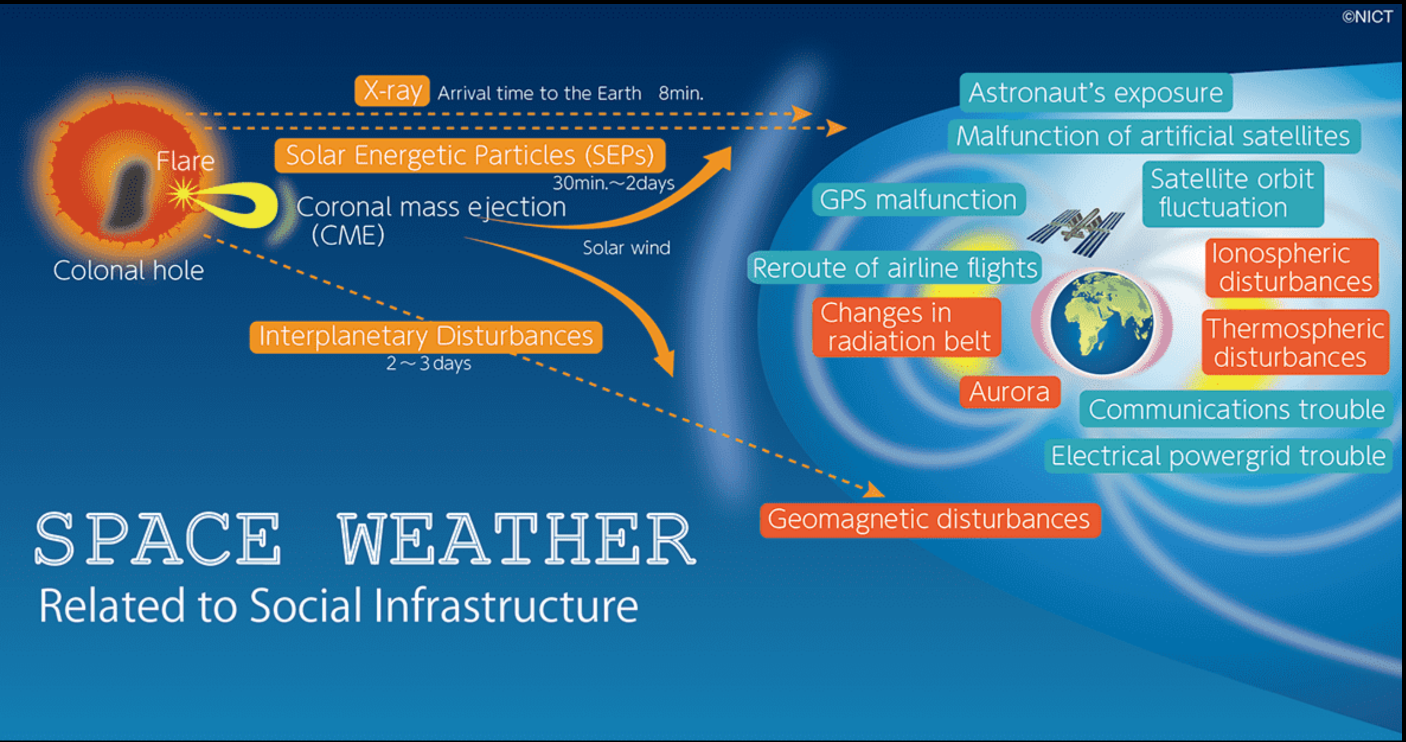
- a thin stream of electrically charged gas from the Sun
- about 300 km/s (slow wind) ~ 800 km/s (fast wind)

Coronal Mass Ejection (CME):

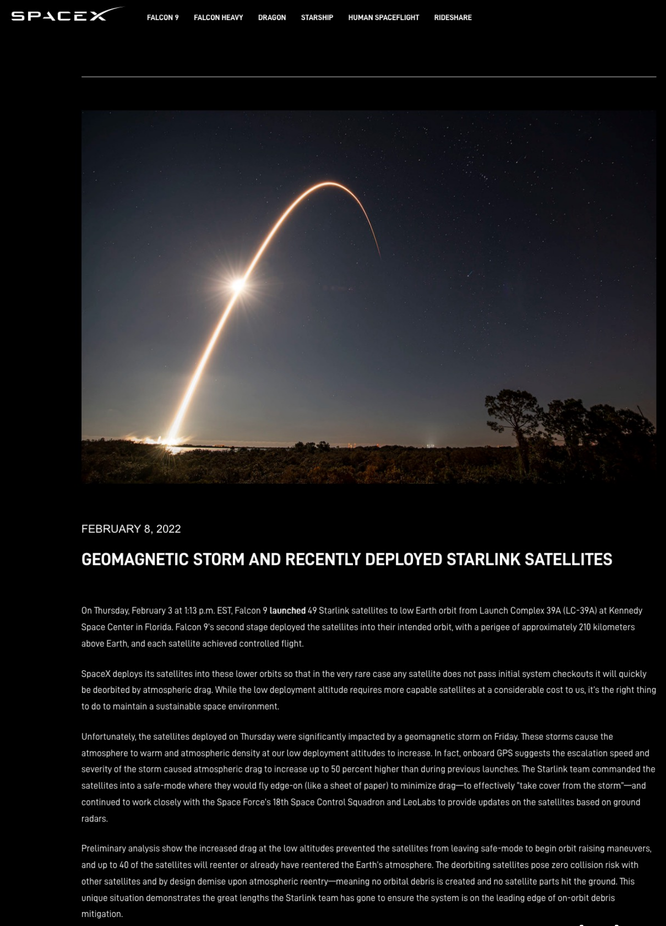
- Eruptions of magnetized plasma structures generated by solar eruptive phenomena

Solar wind/CMEs cause various disturbances of the space environment around the Earth

Sun and space weather



(C)NICT



FEBRUARY 8, 2022

GEOMAGNETIC STORM AND RECENTLY DEPLOYED STARLINK SATELLITES

On Thursday, February 3 at 1:13 p.m. EST, Falcon 9 **launched** 49 Starlink satellites to low Earth orbit from Launch Complex 39A (LC-39A) at Kennedy Space Center in Florida. Falcon 9's second stage deployed the satellites into their intended orbit, with a perigee of approximately 210 kilometers above Earth, and each satellite achieved controlled flight.

SpaceX deploys its satellites into these lower orbits so that in the very rare case any satellite does not pass initial system checkouts it will quickly be deorbited by atmospheric drag. While the low deployment altitude requires more capable satellites at a considerable cost to us, it's the right thing to do to maintain a sustainable space environment.

Unfortunately, the satellites deployed on Thursday were significantly impacted by a geomagnetic storm on Friday. These storms cause the atmosphere to warm and atmospheric density at our low deployment altitudes to increase. In fact, onboard GPS suggests the escalation speed and severity of the storm caused atmospheric drag to increase up to 50 percent higher than during previous launches. The Starlink team commanded the satellites into a safe-mode where they would fly edge-on (like a sheet of paper) to minimize drag—to effectively "take cover from the storm"—and continued to work closely with the Space Force's 18th Space Control Squadron and LeoLabs to provide updates on the satellites based on ground radars.

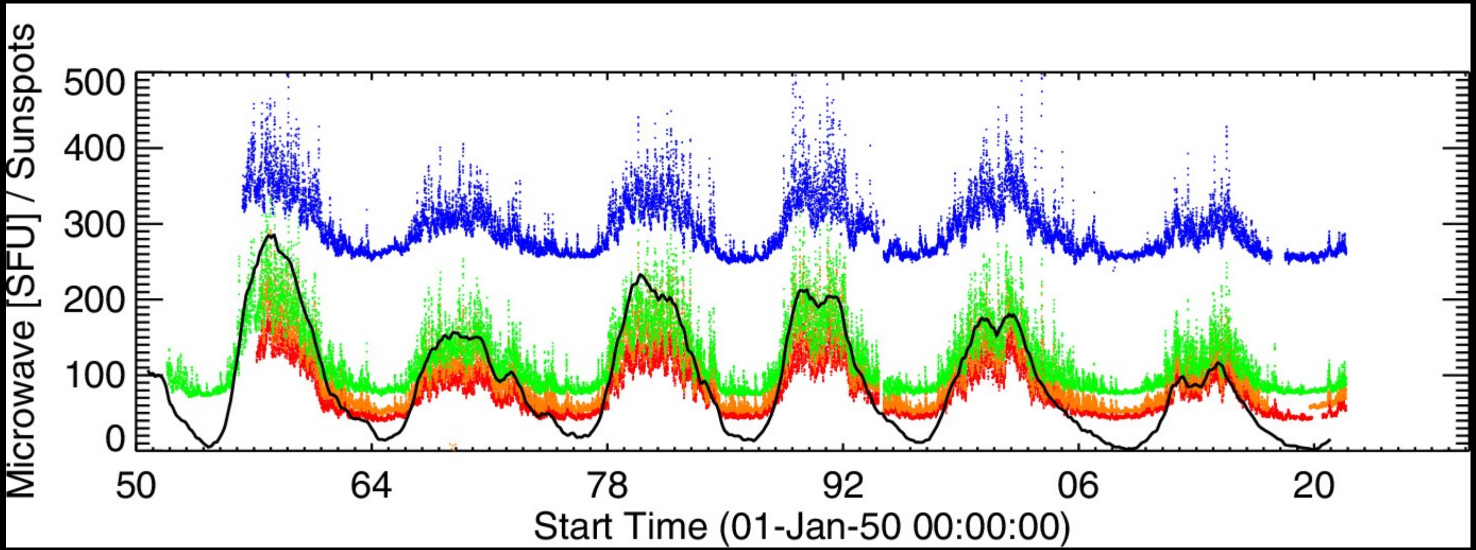
Preliminary analysis show the increased drag at the low altitudes prevented the satellites from leaving safe-mode to begin orbit raising maneuvers, and up to 40 of the satellites will reenter or already have reentered the Earth's atmosphere. The deorbiting satellites pose zero collision risk with other satellites and by design demise upon atmospheric reentry—meaning no orbital debris is created and no satellite parts hit the ground. This unique situation demonstrates the great lengths the Starlink team has gone to ensure the system is on the leading edge of on-orbit debris mitigation.

(C) Space X

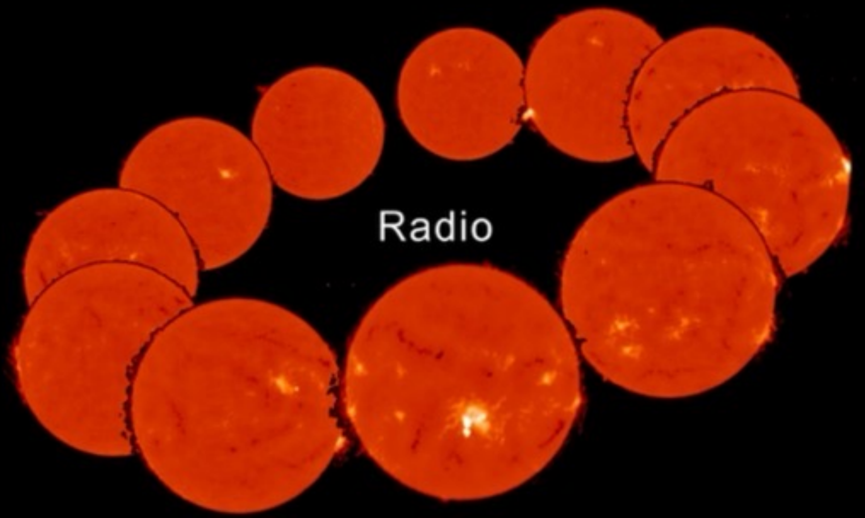
Solar phenomena occasionally reach the Earth and cause various disturbances of the space environment, where a vast amount of social infrastructure is in operation.
e.g., telecommunication satellites, humans,

2022, Feb.: 40 of microsats are lost by the CME driven disturbance.

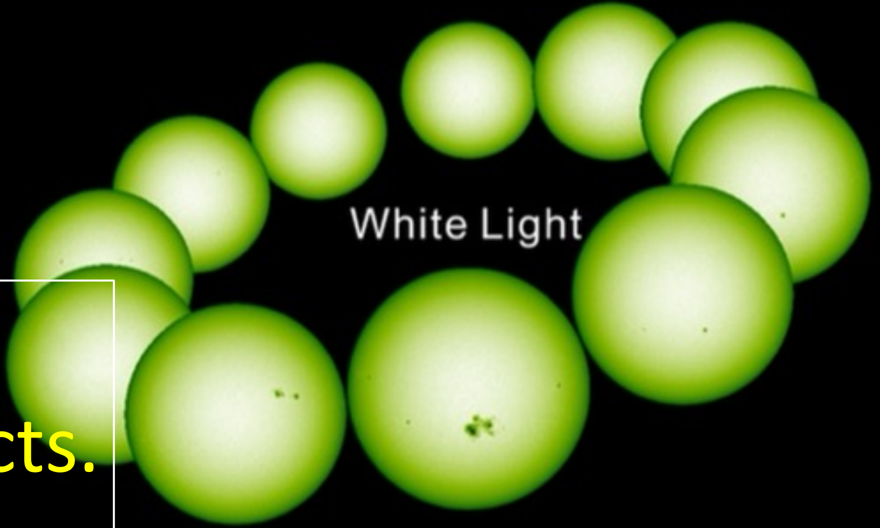
Solar cycle



Long-term variations of microwave fluxes and sunspots from the 1950s to December 2021 by NoRP. Red: 1 GHz, orange: 2 GHz, green: 3.75 GHz, blue: 9.4 GHz, and black: 13-month smoothed sunspot number. Shimojo and Iwai, 2022.



Solar cycle variation of the Sun at 17 GHz by NoRH



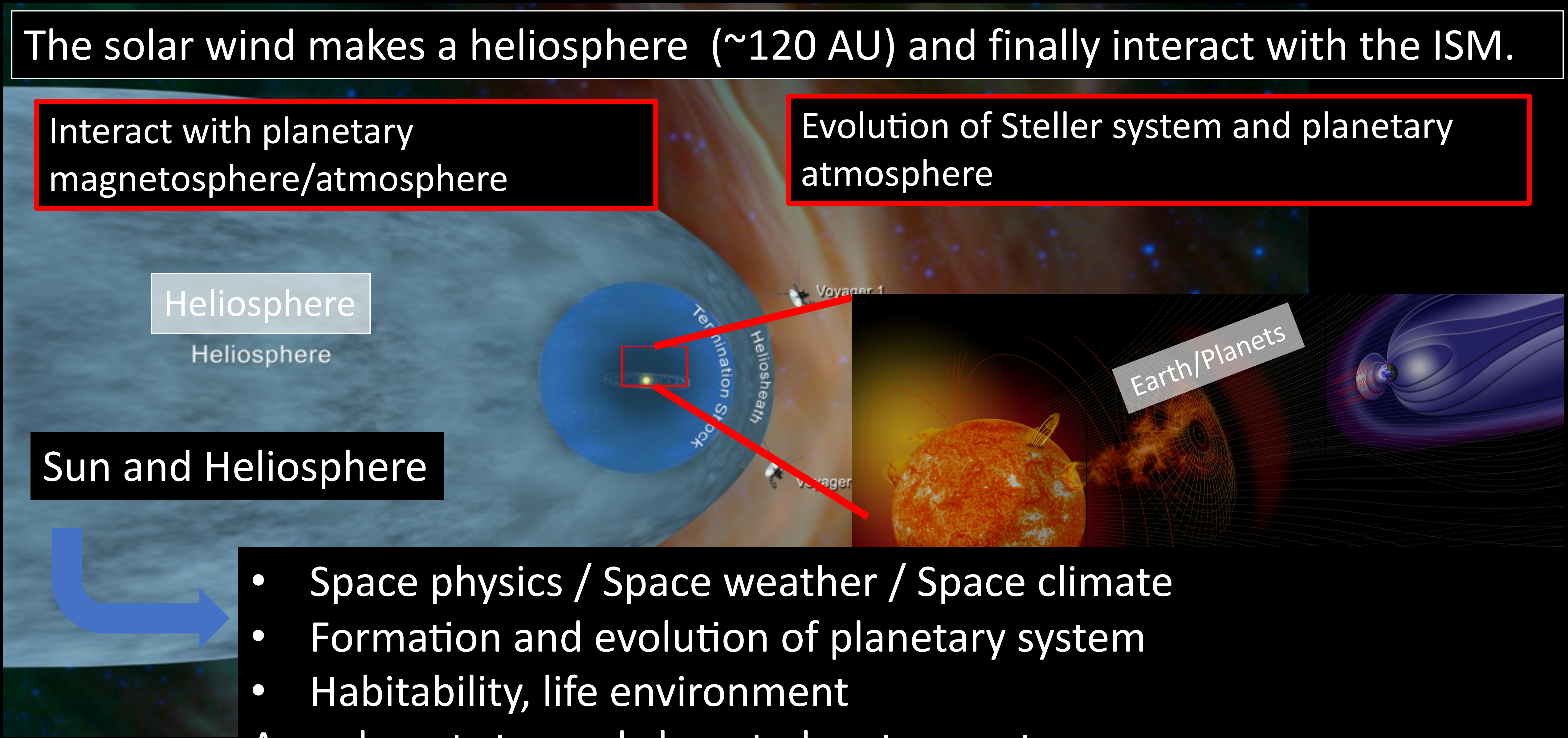
Solar activity shows about 11-years cycle.
The activity often modulated by unknow effects.
Solar radio emission has been an important index of the solar activity.

Sun and heliosphere; as an astrophysics

The solar wind makes a heliosphere (~120 AU) and finally interact with the ISM.

Interact with planetary magnetosphere/atmosphere

Evolution of Steller system and planetary atmosphere



Sun and Heliosphere

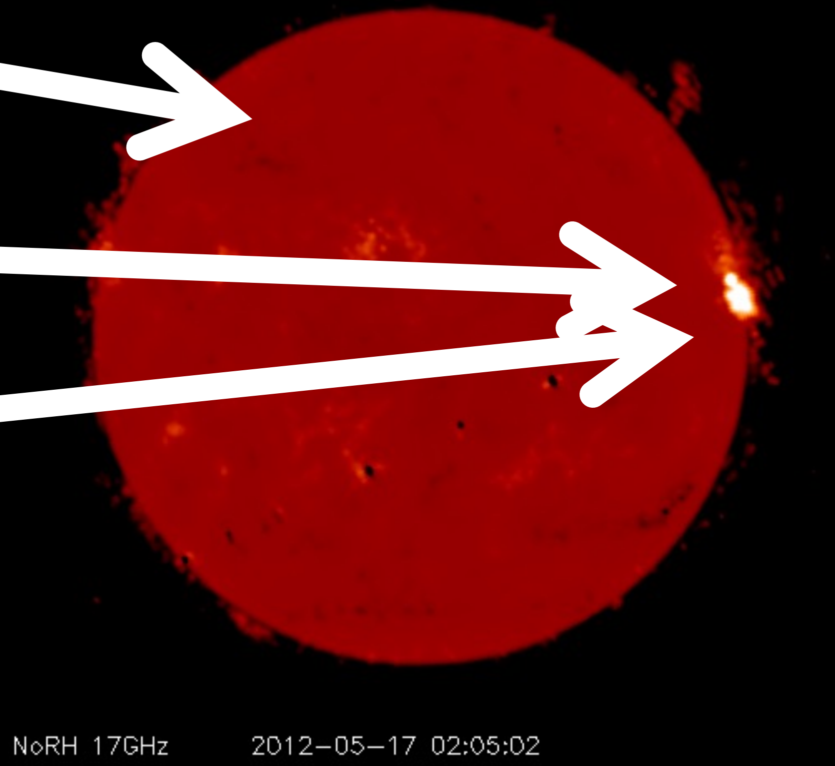
- Space physics / Space weather / Space climate
- Formation and evolution of planetary system
- Habitability, life environment

As a closest star and closest planetary system.

Basics of the solar radio emission

Radio emission from the Sun

- Thermal free-free
  - Main component of the solar disk
- Gyro-resonance
  - Electrons in a strong magnetic field
- Non-thermal
  - High-energy particles generated from flares
  - Gyro-synchrotron emission
  - Plasma emission
- Molecular lines (minor comp.)
  - Recombination line of H



Solar disk at 17 GHz observed by Nobeyama Radioheliograph (NoRH)

Thermal emission from the Sun

Upper atmosphere

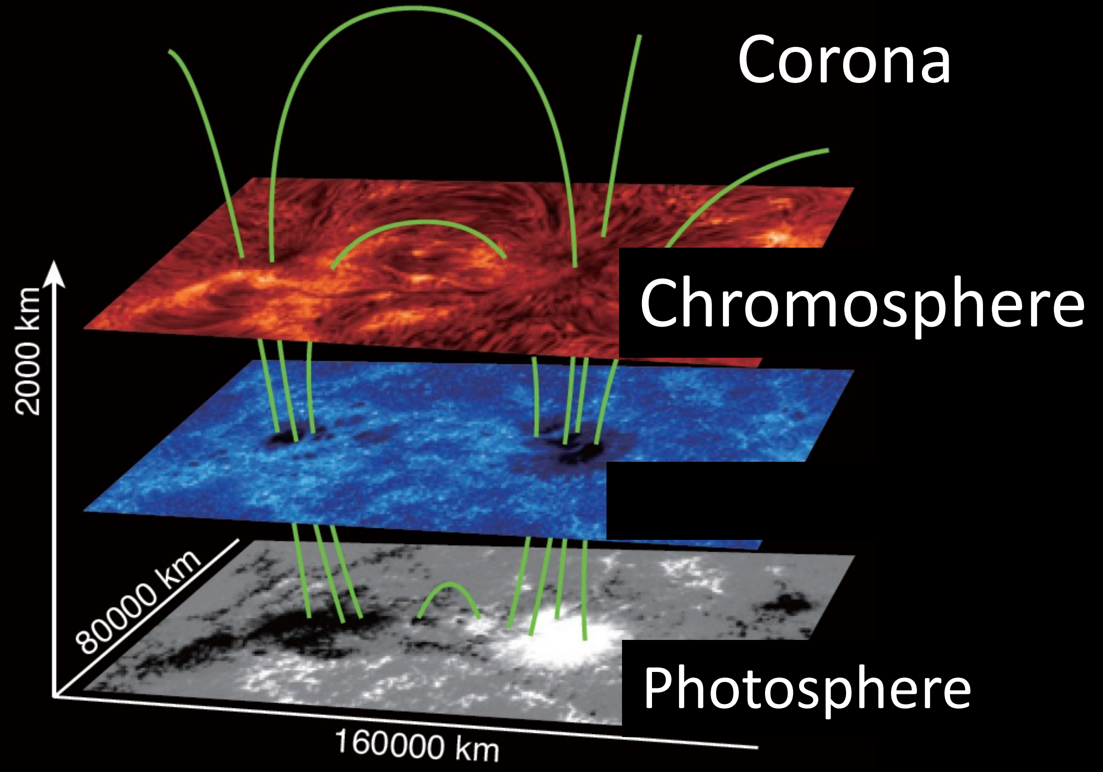
Radio emission Optical depth $\propto \dfrac{EM}{T^{\frac{3}{2}}}$

Metric wave (0.1 GHz)
Corona (MK)

Microwave (10 GHz)
Transition region (10,000 K)

mm/sub-mm
Chromosphere (7000 K)

Photosphere



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Non-thermal emission from the Sun

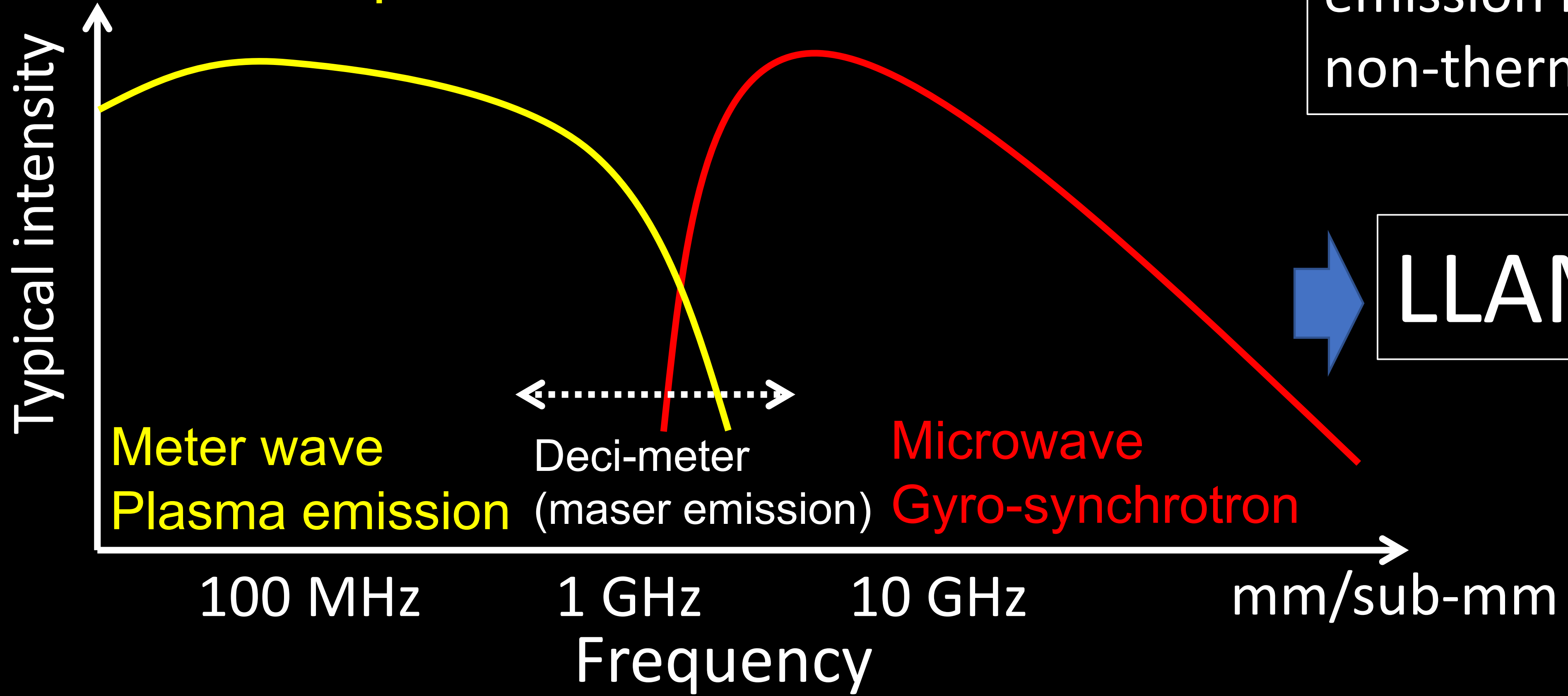
- Plasma emission : fp
- Gyro-synchrotron emission
- (Cyclotron maser emission : fc)

Continuum emission

For mm/submm; Gyro-synchrotron emission is a dominant non-thermal emission

Plasma frequency of the solar atmosphere < GHz

Optical depth of GS=1 at ~ 10 GHz



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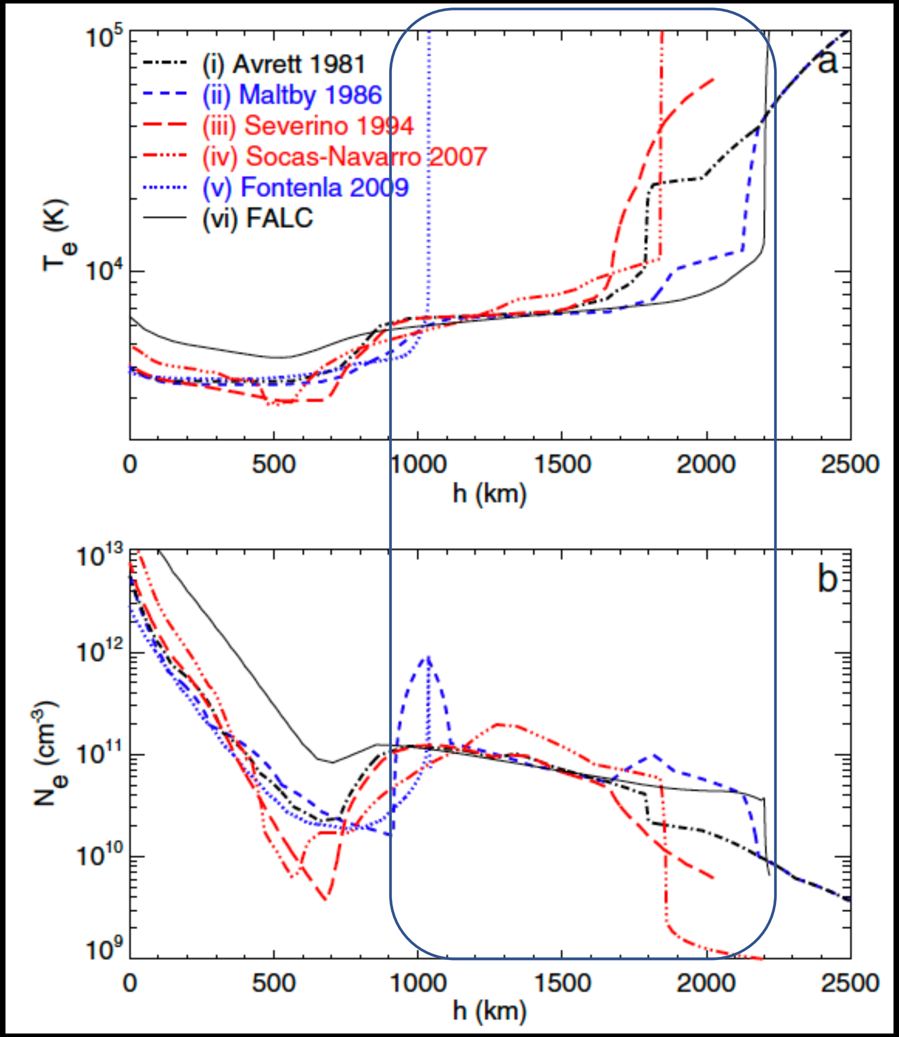
New Solar physics by mm/sub-mm radio observation

1: Thermal free-free emission and atmosphere

Vertical structure of the Sun is still an unknown issue at the chromosphere!

There have been many such models, and most of these are based on strong atomic lines in the ultraviolet (UV) and infrared range.
These lines are thought to be formed under non-local thermodynamic equilibrium (non-LTE) conditions. Hence, the observational results require non-LTE radiative-transfer simulations to facilitate their interpretation.



Various atmospheric models (Loukitcheva+2014)

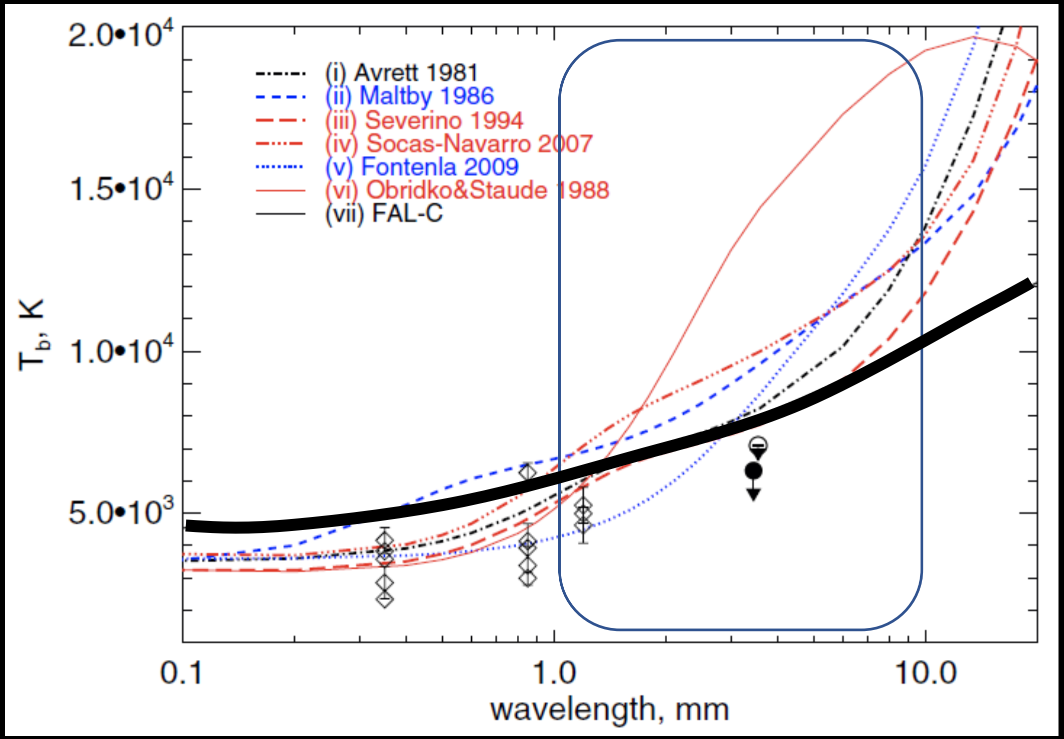
Thermal free-free emission and atmosphere

Thermal free-free emission

Optical depth $\propto \dfrac{EM}{T^{\frac{3}{2}}}$

- the Rayleigh–Jeans law
- LTE conditions

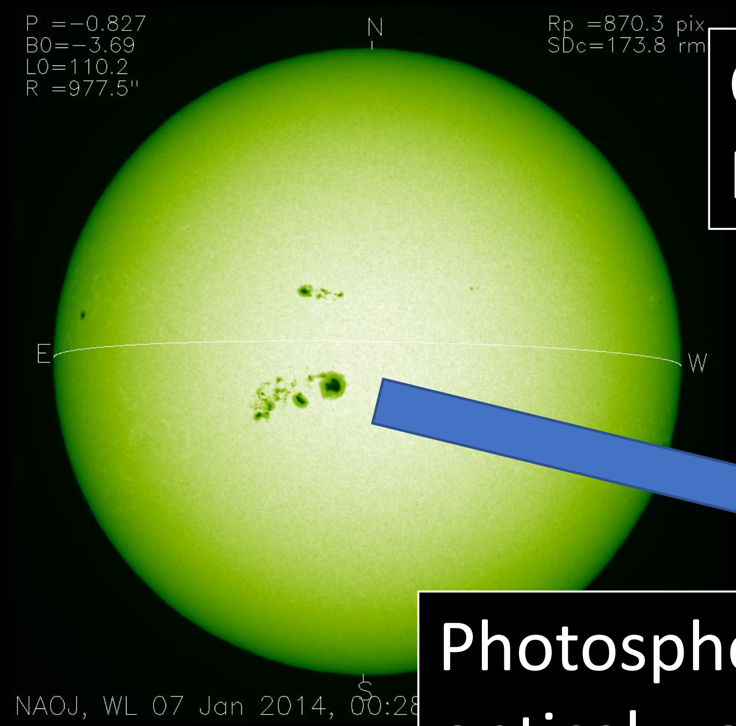
We can derive radio brightness from atmospheric models

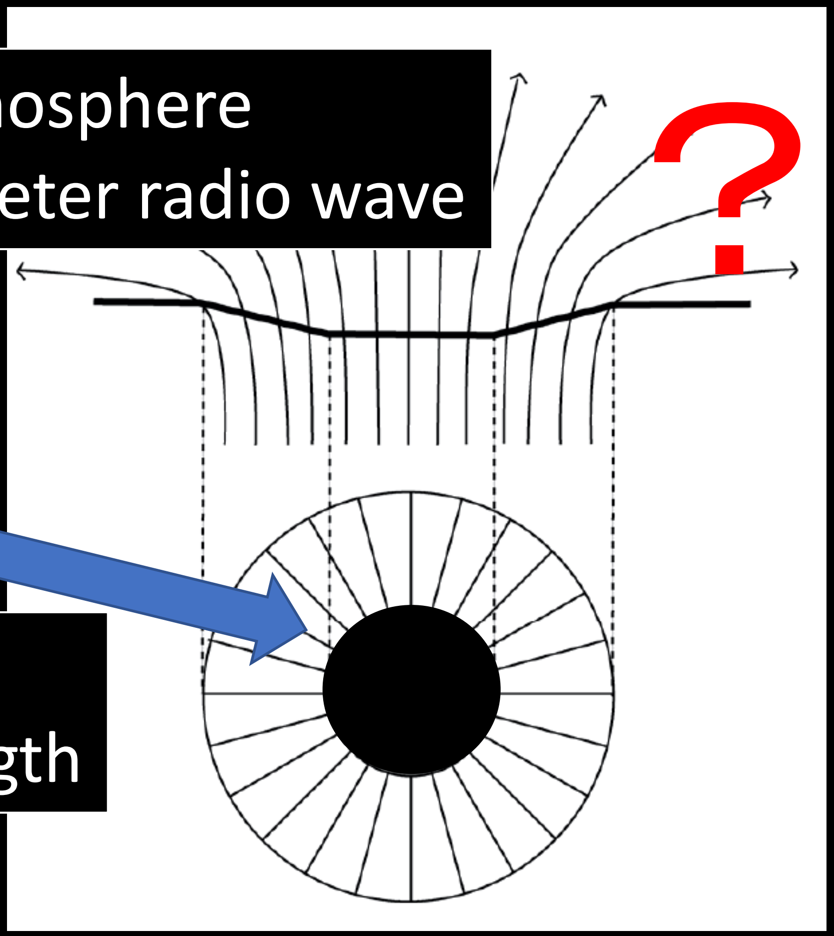


Radio brightness temperature estimated from various atmospheric models (Loukitcheva+2014)

Validation of the atmospheric models of the chromosphere

Sunspots; as an example of mm solar radio study





Chromosphere
Millimeter radio wave

Photosphere
optical wavelength

Sunspot

- Photosphere＝dark
- Chromosphere ＝？？？

Is the sunspot dark or bright?

The Nobeyama 45m radio telescope

45m telescope:

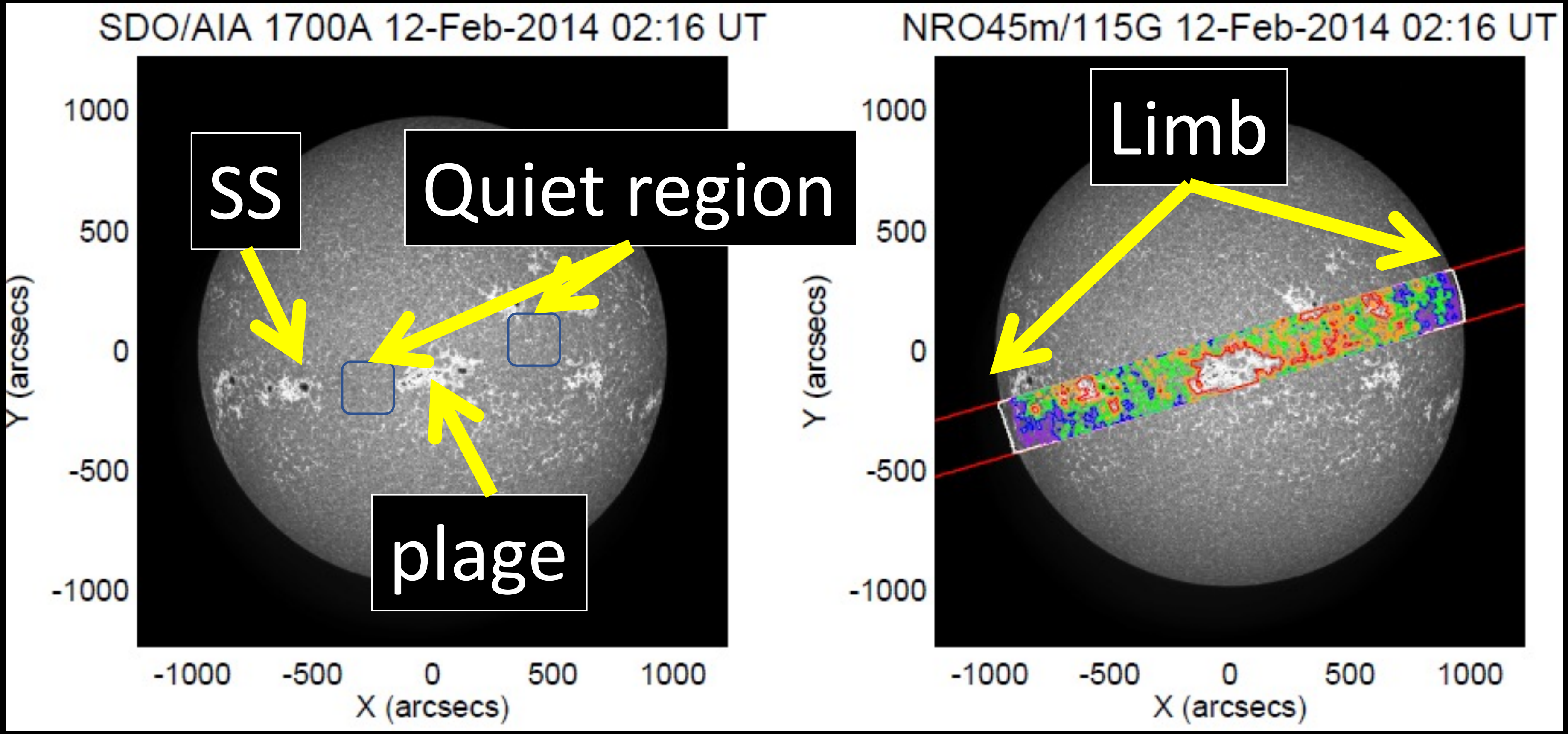
- Frequency: ~115GHz
- Spatial resolution: ~15″
- Solar observation

Note; There have been solar mm/sub-mm observations by JCMT, CSO, NRO45, and ALMA. Many mm/sub-mm (non-solar dedicated) telescopes can observe the Sun.
Don't be afraid!

Technical demonstration experiment for the solar observation of ALMA.

A sunspot observation at 3 mm band with sufficient spatial resolution for resolving the sunspot umbra.

Results



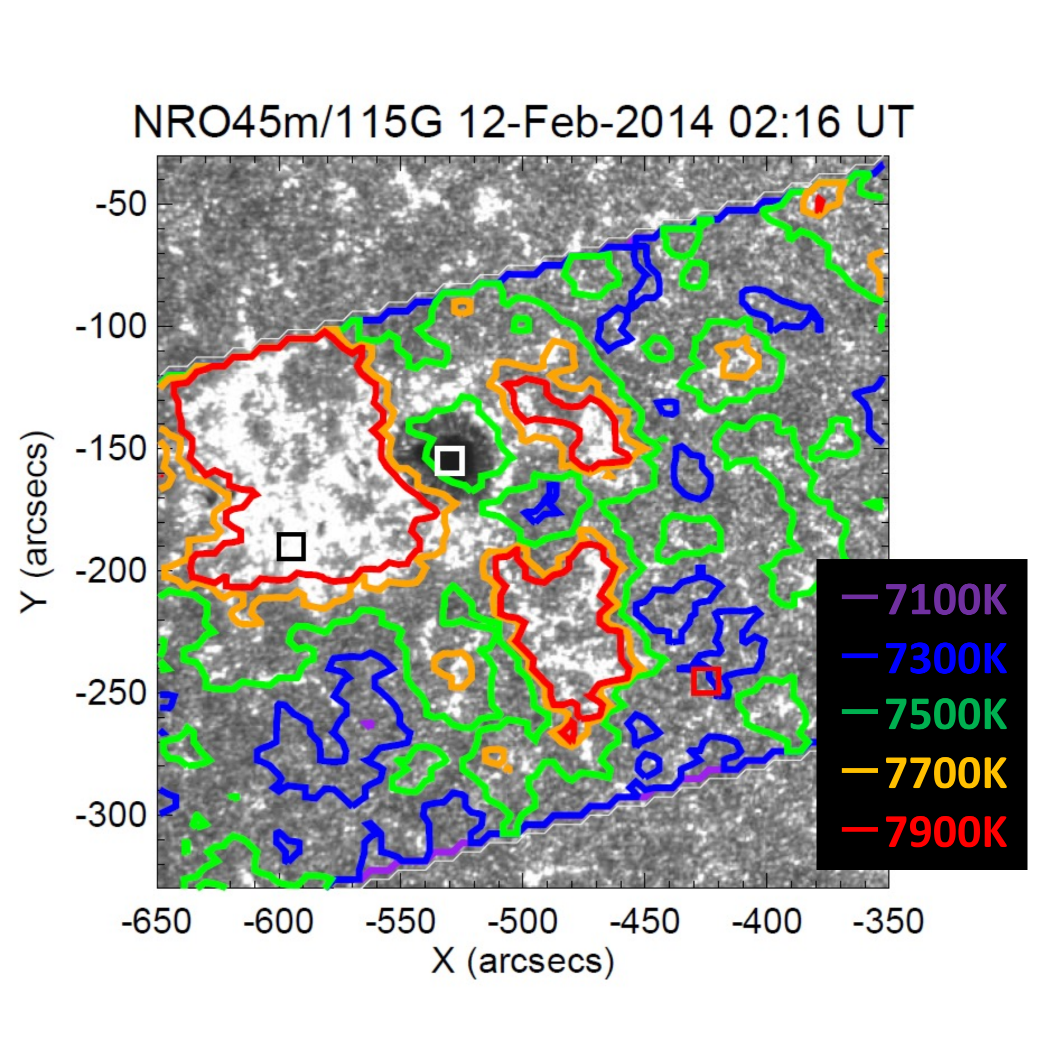
Iwai and Shimojo 2015, ApJL
Iwai et al 2017, ApJ

The Sun observed by SDO/AIA at 1700 A (12-Feb-2014)

Color contour: Radio brightness at 115GHz

Brightness temperature of Sunspot @115G

Center of the sunspot ＝ not bright



Iwa&Shimojo 2015

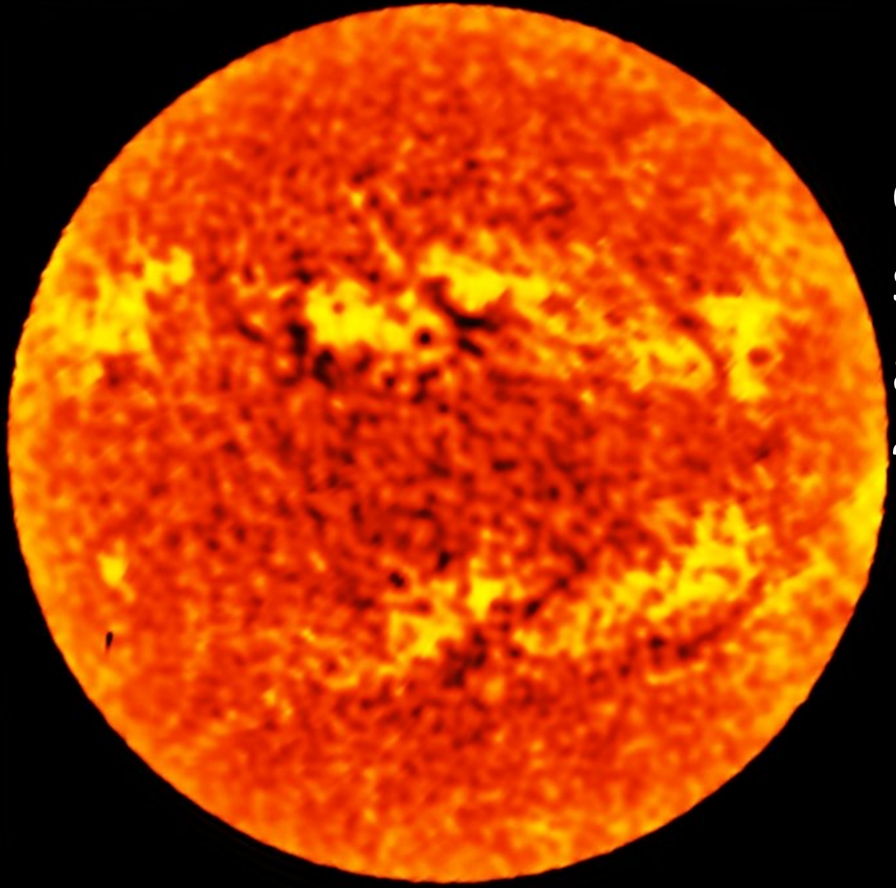
The brightness temperature distribution at millimeter range strongly corresponds to the UV emission at 1700 Å

Quiet region:
7,340～ 7,460K

Sunspot: ～7,410K

ALMA Solar Observation

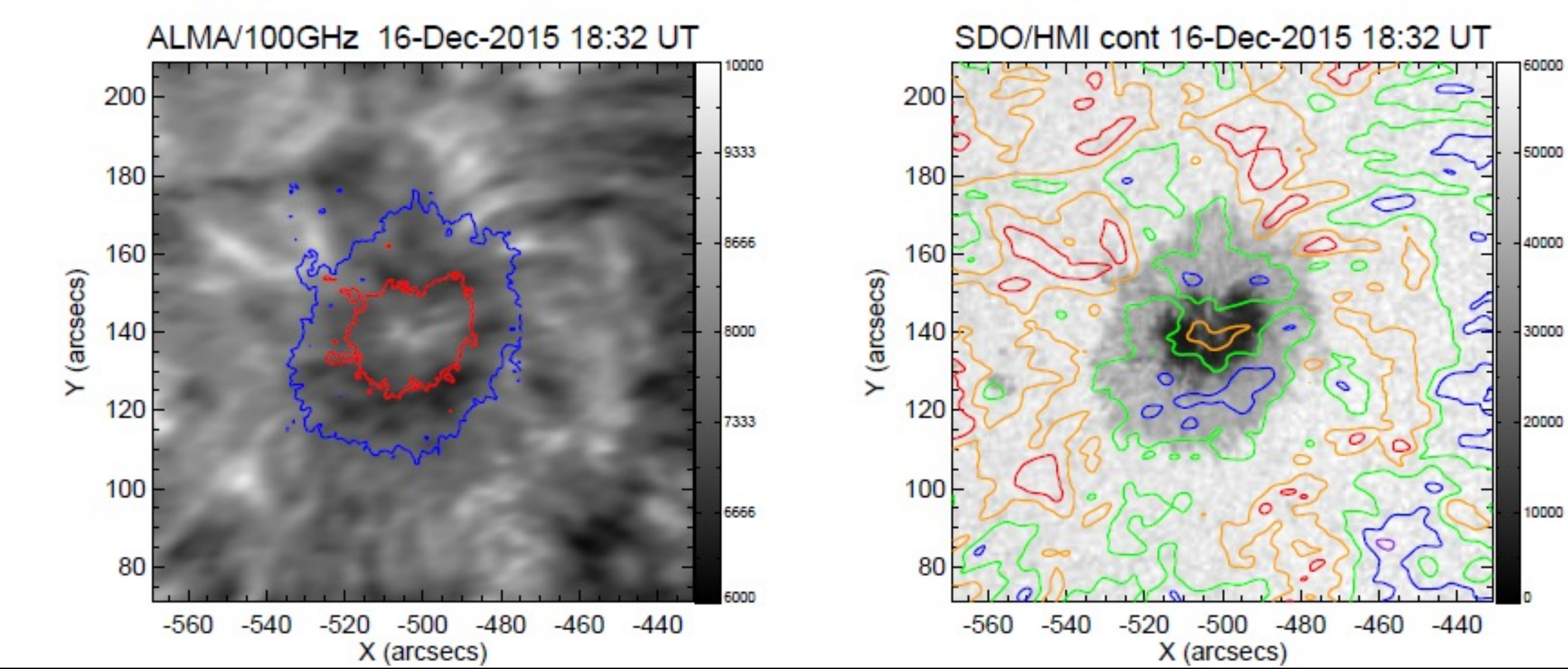
ALMA © JAO



Full solar disc observed by ALMA single dish antenna at band 6
~24”

The highest spatial-resolution map of an entire sunspot in this frequency range

ALMA observation @ 3mm

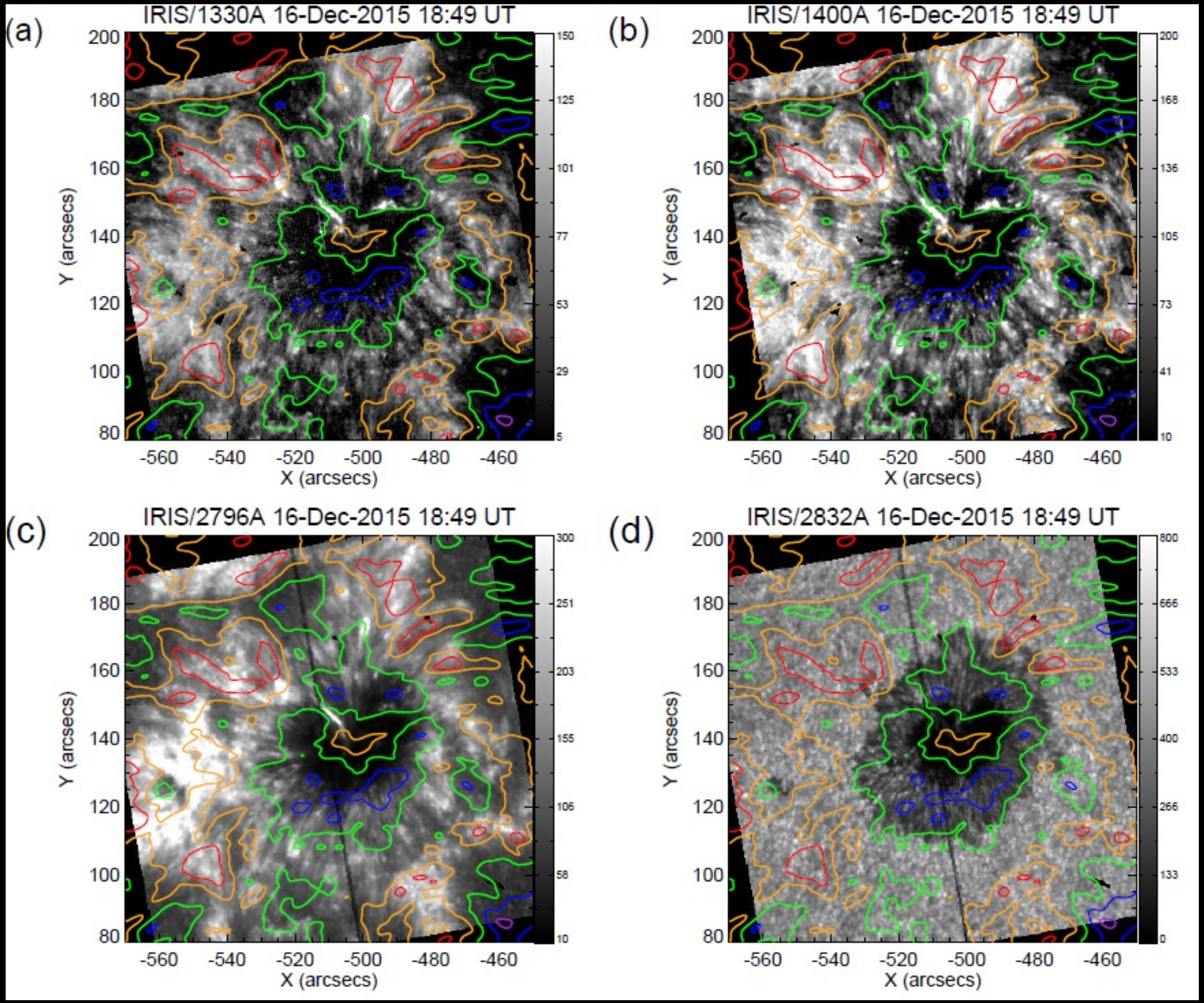


Note; This image is derived form both interferometer data and single dish data.
The single-dish and interferometric data were combined in the UV plane (feathering) to derive the absolute brightness temperature of the interferometric maps.

There is a bright spot at the center of the umbra

ALMA 3mm and IRIS (UV obs.)

Iwai et al, 2017



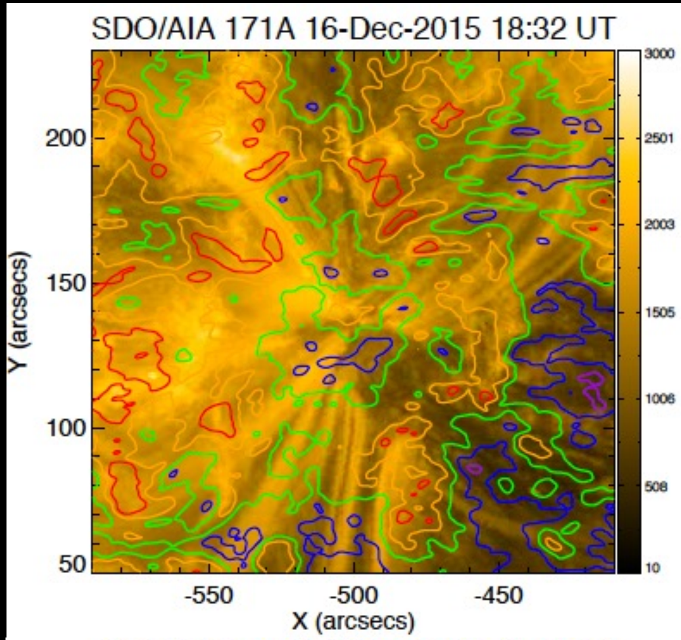
Weak enhancements at 1330A and 1400A images

No counterparts at 2796A and 2832A images

3mm Radio enhancement = Upper chromophore (consistent with the typical 3mm contribution function.)

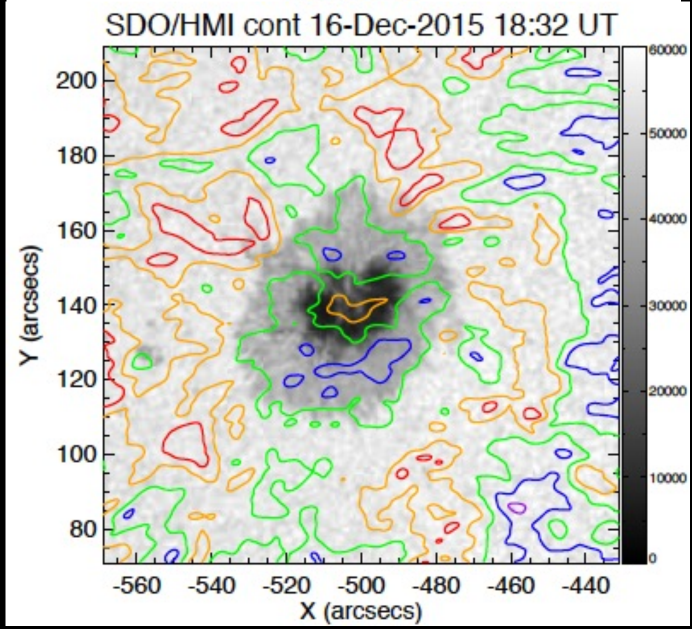
Discussion

Iwai et al, 2017



Radio coronal plume?

Bright region corresponds to footpoints of coronal loops at 171 Å

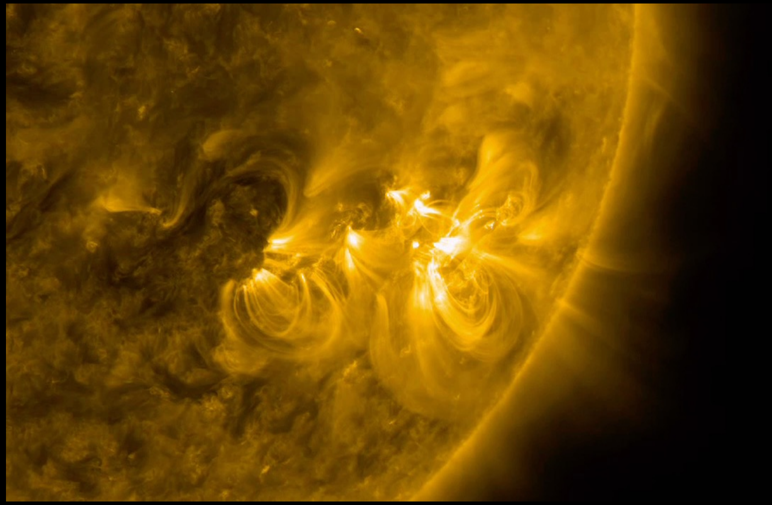


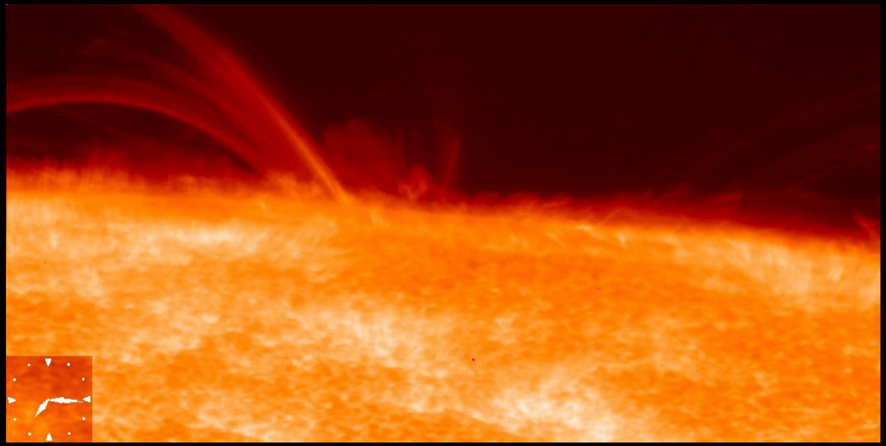
Three-minute oscillations?

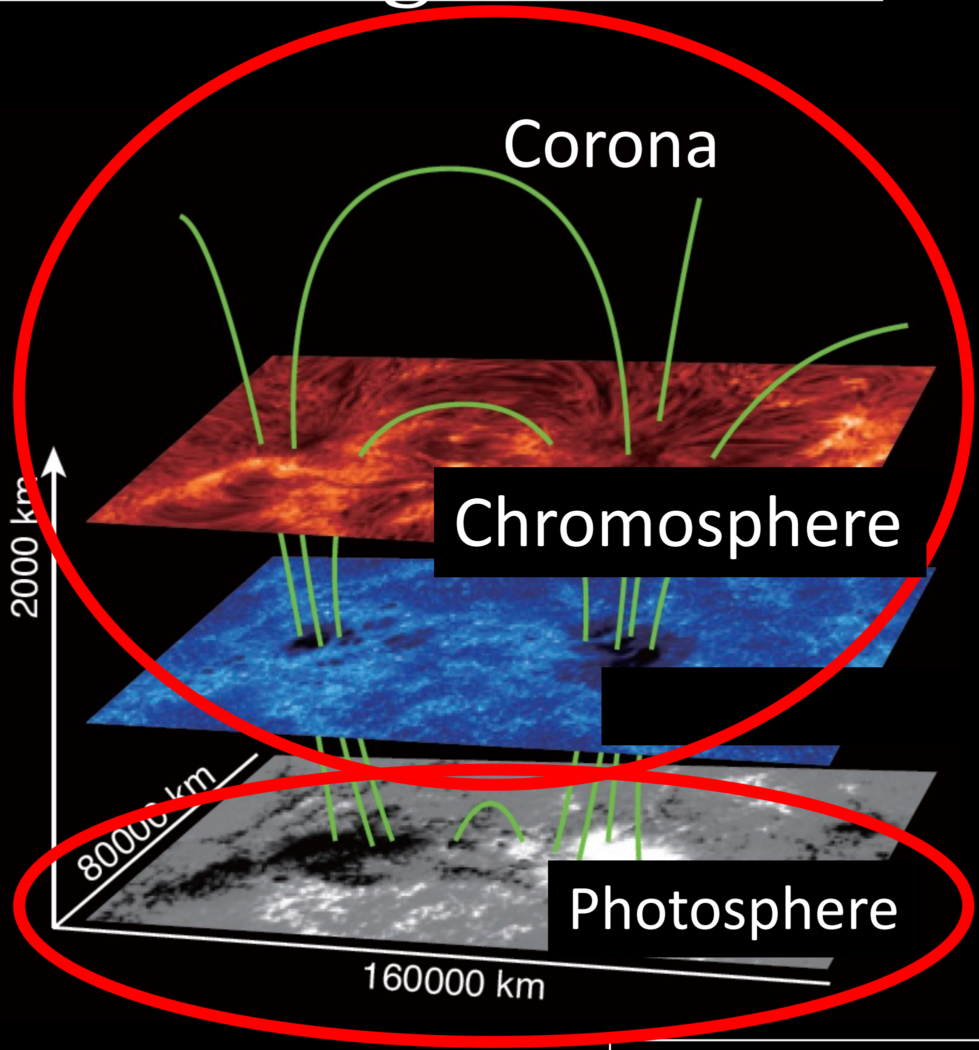
Plasma compression can cause the radio enhancement

(time variation, radio spectral observation)

2: Polarization and Magnetic field







difficult

possible

Optical spectroscopy

Zeeman effect

[Magnetic field]

Key parameter of the solar physics

Polarization at the chromosphere

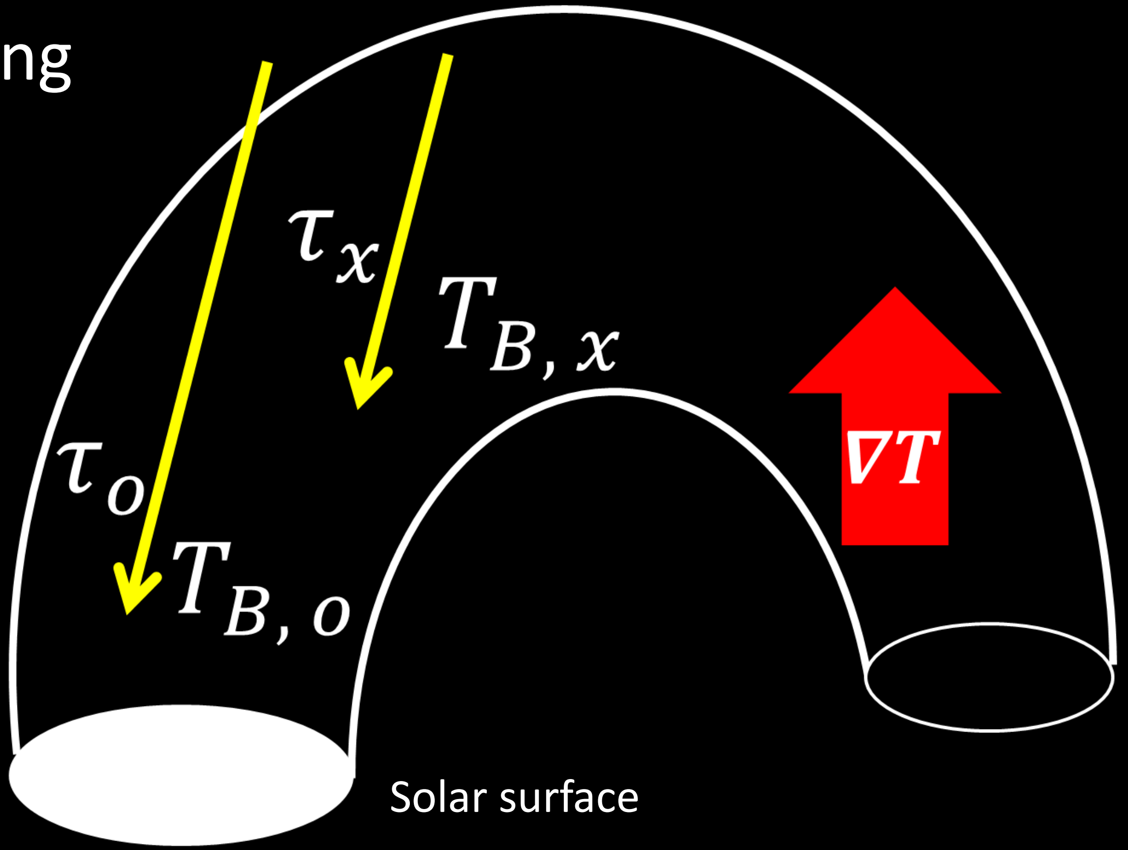
Thermal bremsstrahlung
(Free-free emission)
at microwave range

At the chromosphere
$\tau \approx 1$

Magnetic field
$\tau_o \neq \tau_x$

penetrate into different layers

Temperature gradient
$T_{B,o} \neq T_{B,x}$



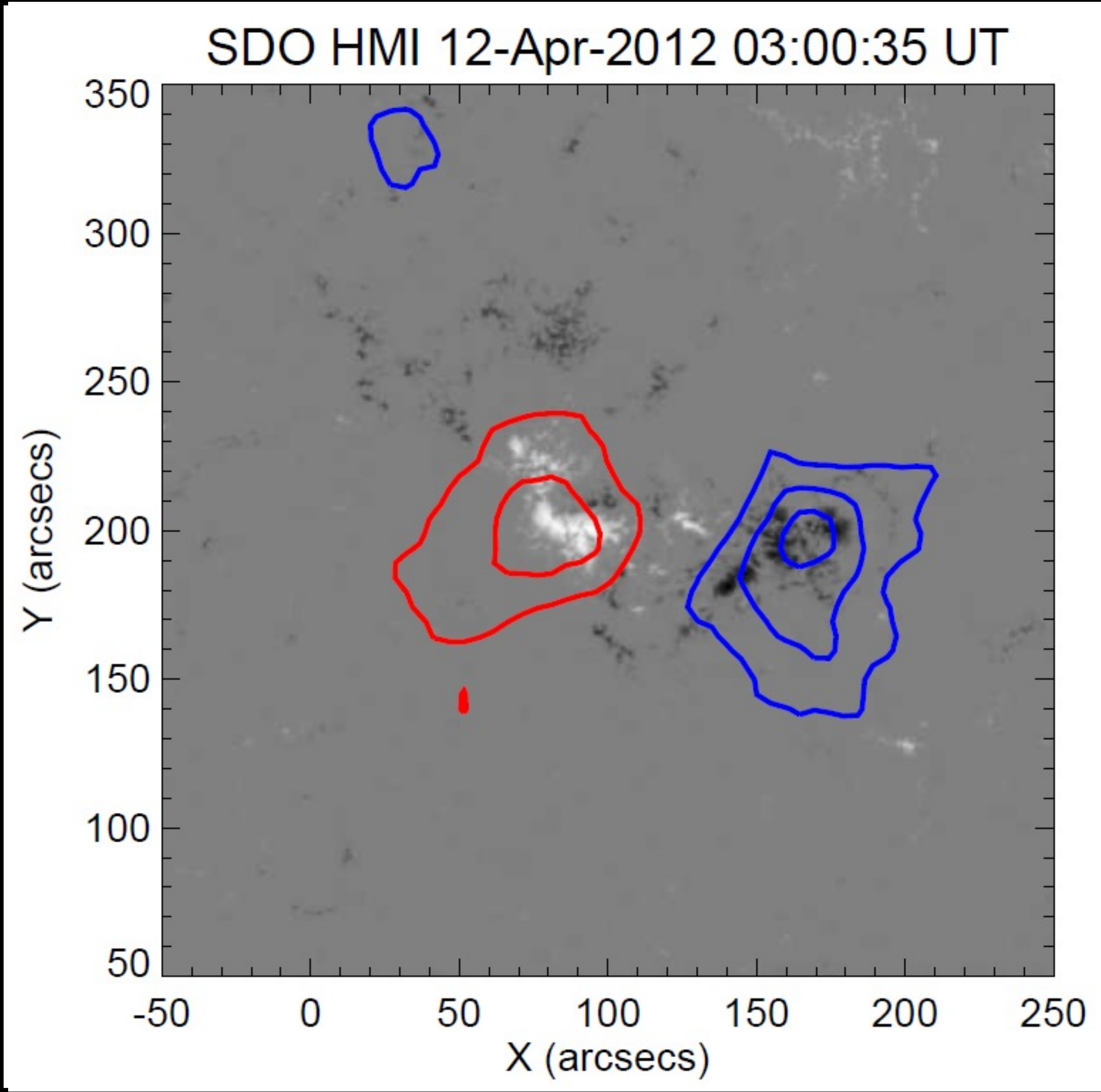
Note; Polarized molecular lines at mm/submm ranges have not been discovered on the Sun. The line survey will be another interesting work.

$$P = \frac{\left(T_{B,x} - T_{B,o}\right)}{\left(T_{B,x} + T_{B,o}\right)}$$

Polarization

Observation: circular polarization

Iwai and Shibasaki, 2013

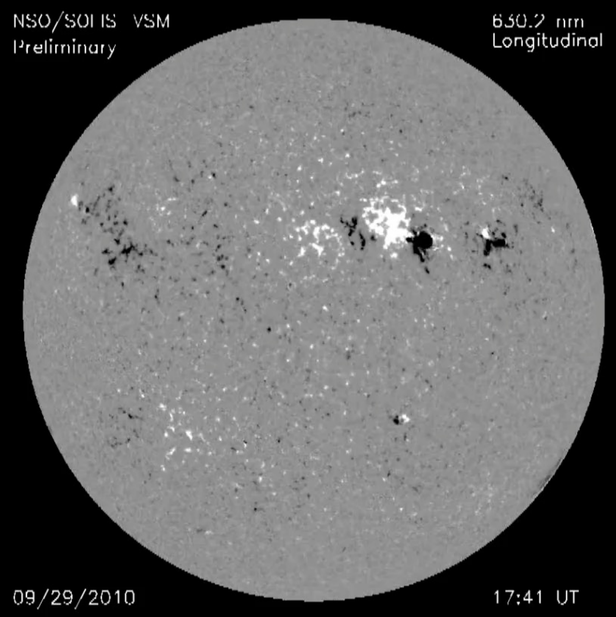


polarization is corresponds to the Chromospheric and the Coronal magnetic field

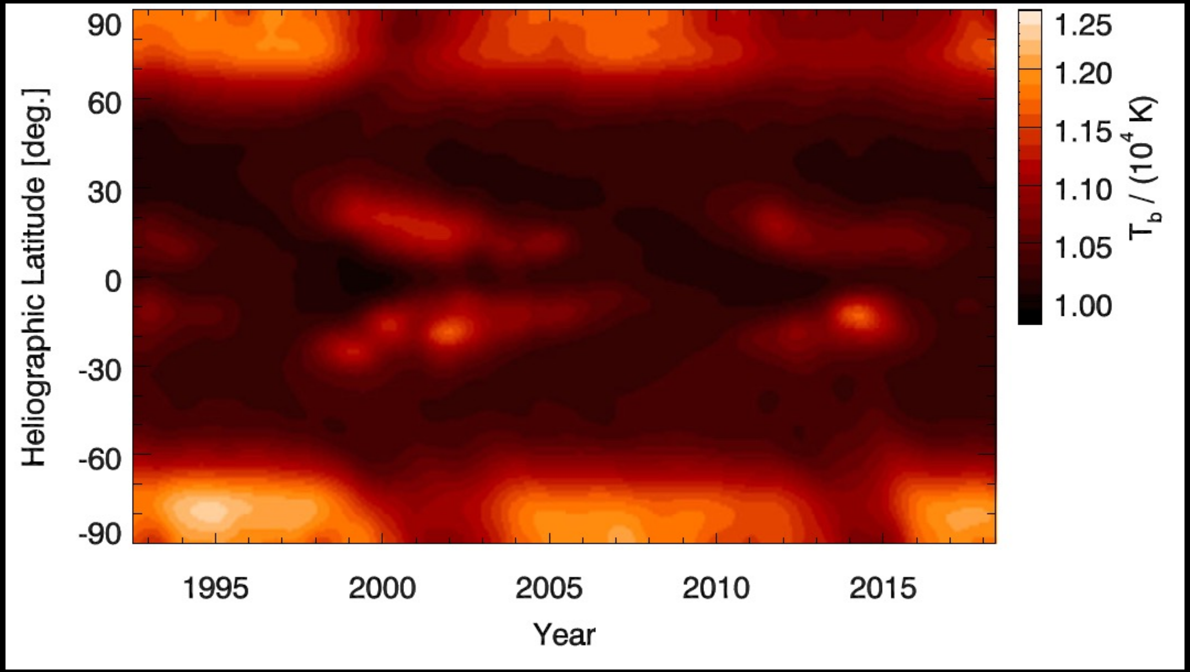
Red : Radio pol (+)
0.5 1.0 %
Blue : Radio pol (-)
-0.5 -1.0 -1.5%

Solar polarization observation test at mm/submm range is now going on in the ALMA team.

3: Synoptic observation and Polar brightening



How to make a synoptic map. Credit: National Solar Observatory (NSO)



Synoptic map of the Sun at 17 GHz. Fujiki, KI+ 2018

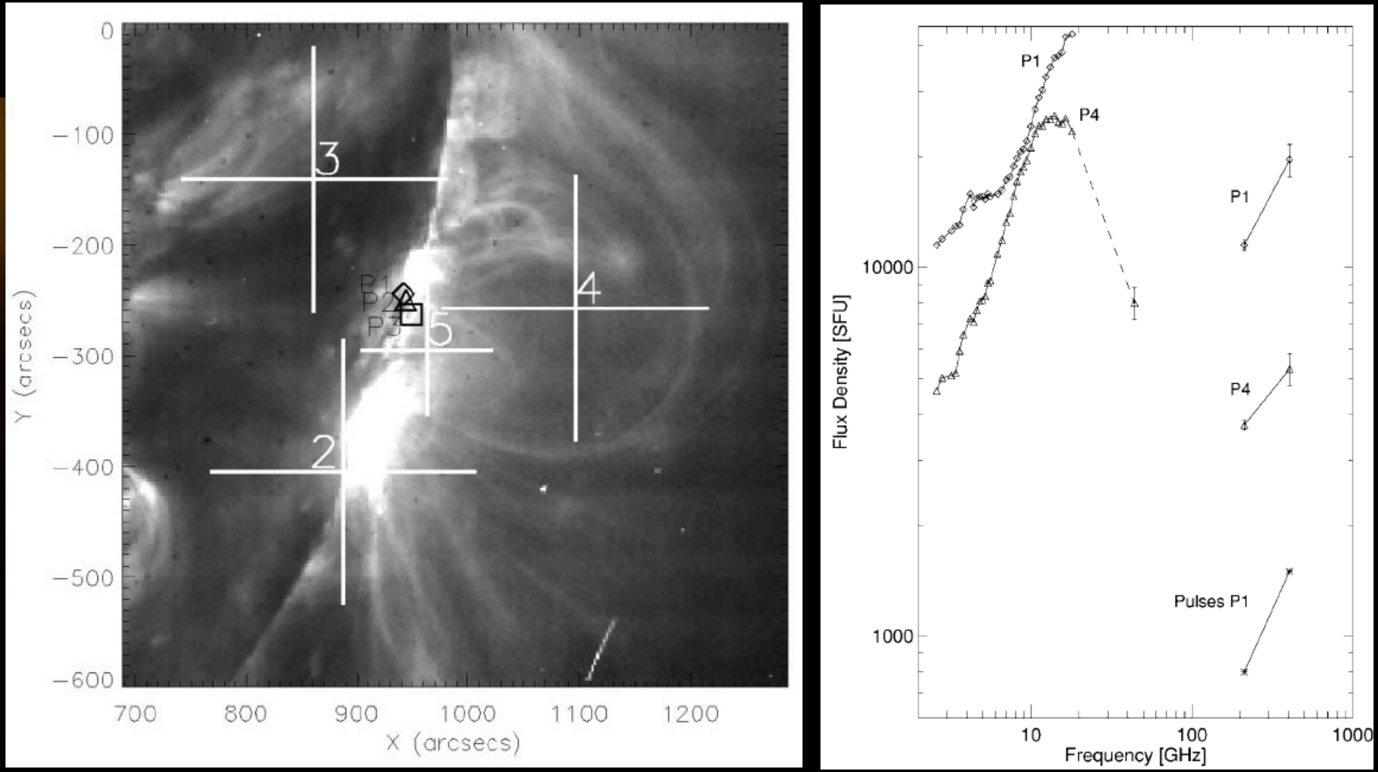
Polar regions become brighter at the solar minimum that corresponds to the polar magnetic field.

Continuous observation of the Sun enables us make a synoptic map.

Even 1 full disc image / week will be a big science result.

4: Solar flare

- Microwave radio spectra of the gyro-synchrotron emission gives energy spectra of the non-thermal particles generated by the flare.
- There might be other processes at the higher frequency.



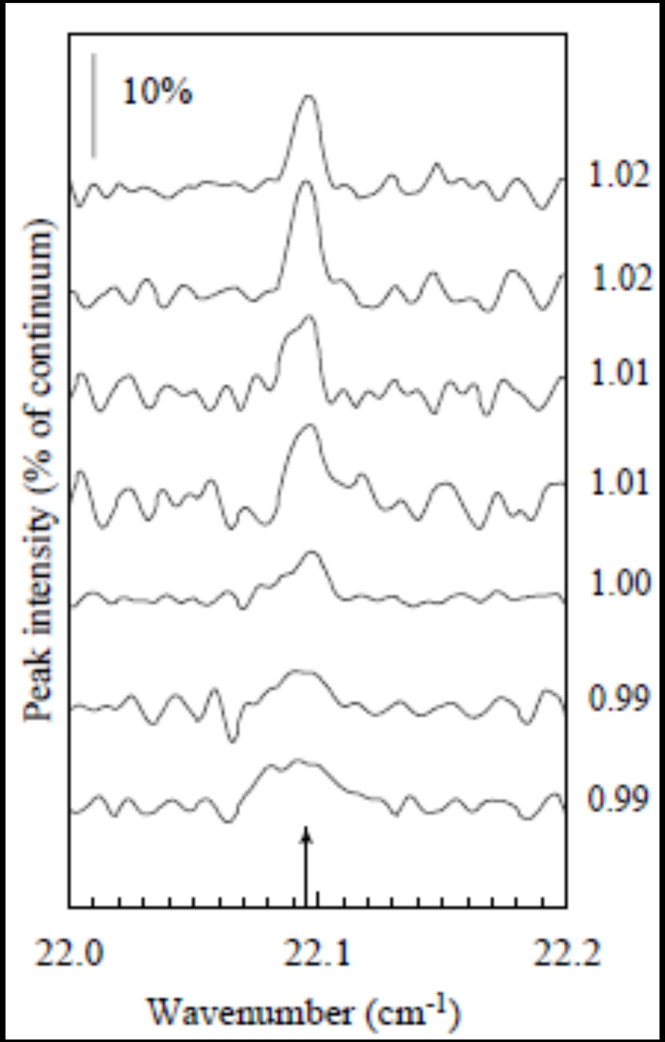
Note; There have been significant contributions of SST for the solar flare studies on mm/submm ranges. That should be given in later in this session.

An example of radio spectra by SST. (Kaufmann+2004)

5. Molecular lines

H recombination line
H_I n=22–21 (JCMT/FTS)
(Clark+2000, A&A)

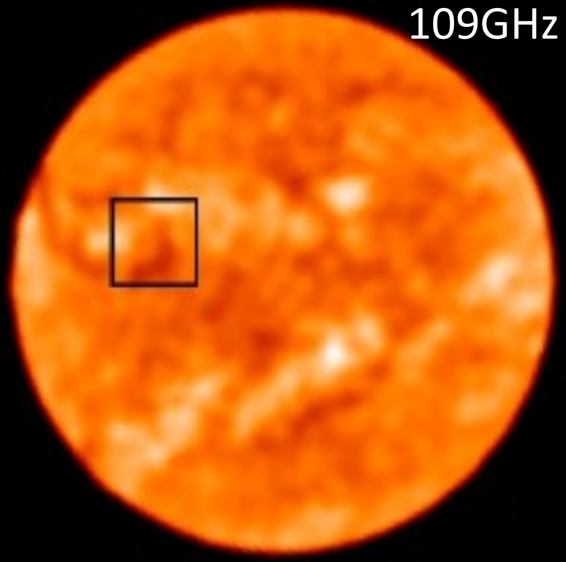
- Post flare loop
- Off limb observation
- Very rare

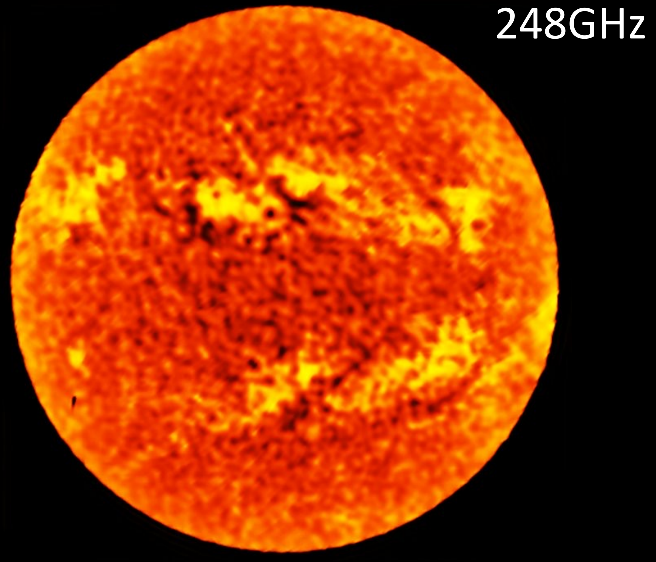


660 663GHz 666

There might be other lines (e.g. CO)

Synergy with ALMA



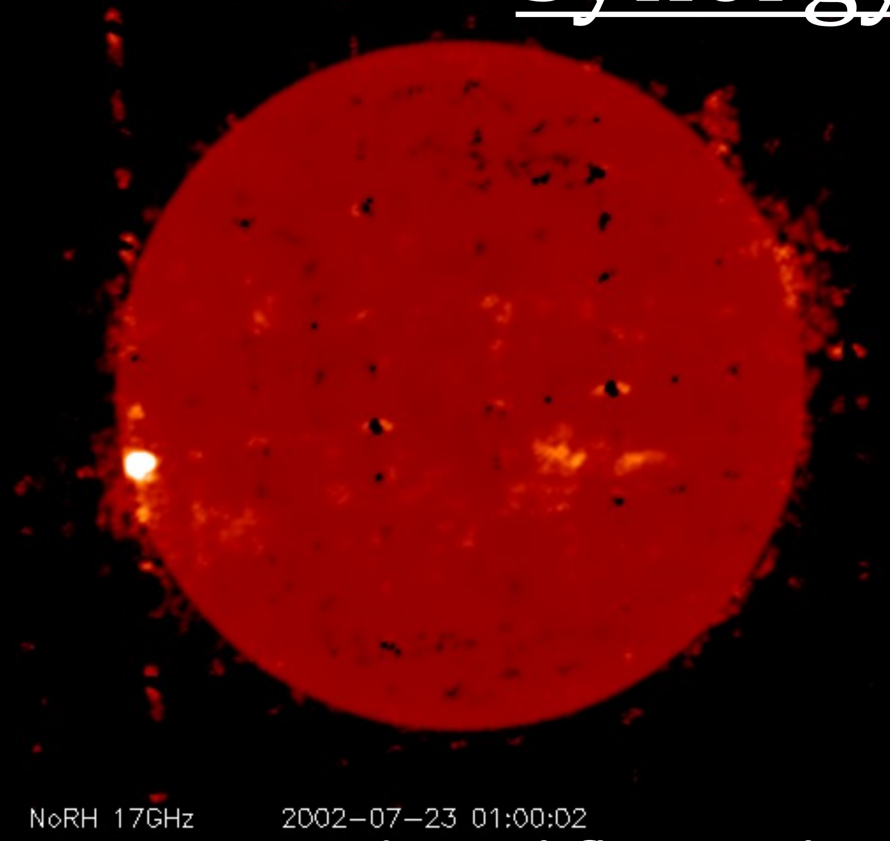


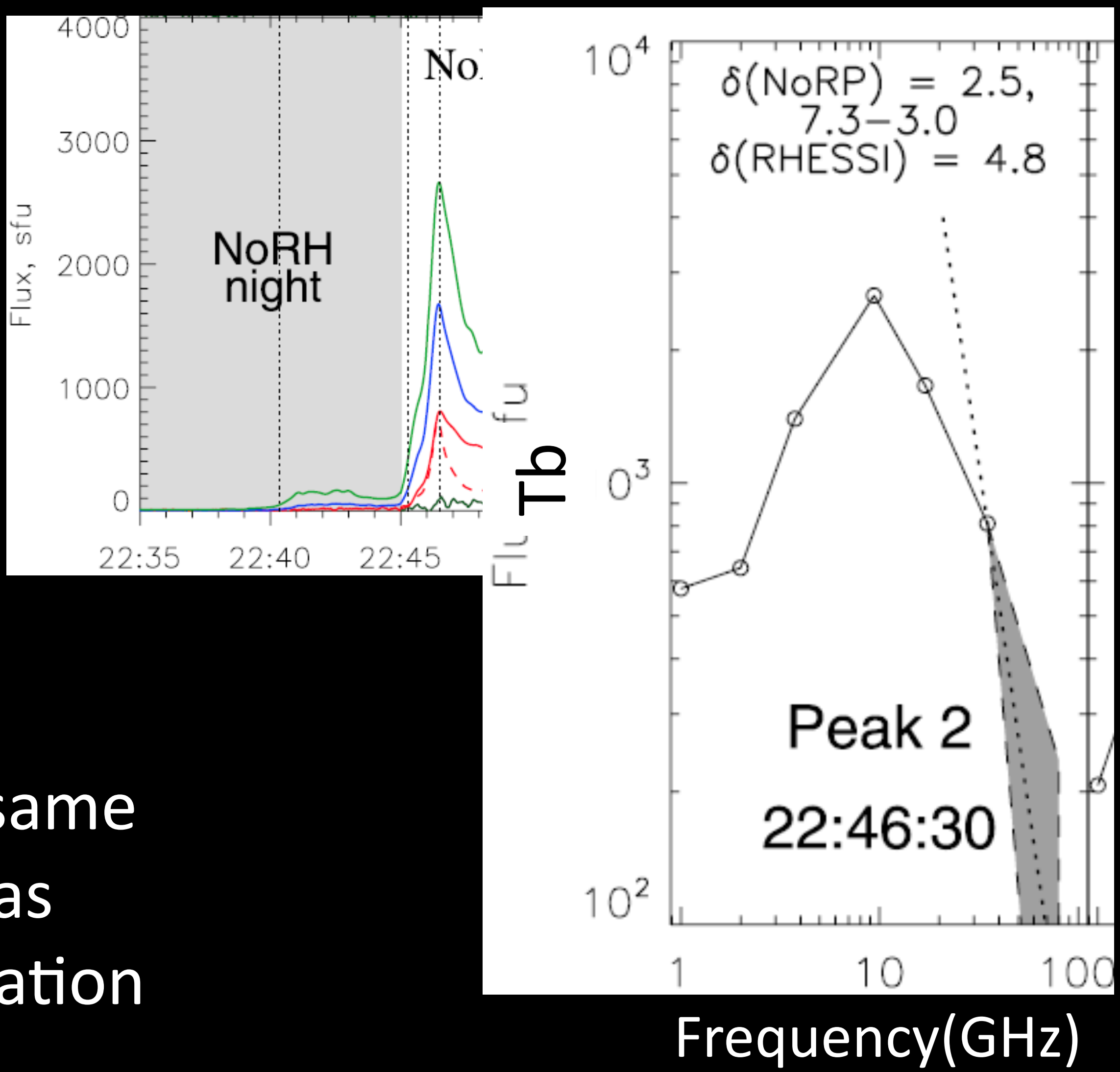
Solar full disc image taken by ALMA PM antenna at band 3 (left) and 6 (right).

ALMA can observe the Sun.
The single dish images are taken by PM antenna.
The sub-array is not available that means the spectra is usually unavailable that is a significant issue for solar physics because the Sun has significant time variations.

Observe the Sun simultaneously with ALMA with Different band is a simple but VERY strong strategy that gives the mm/sub-mm spectra of the Sun.

Synergy with SST





- Full disc imaging and total flux at the same time and location (NoRP and NoRH) has been an strong tool to derive both location and energy spectra of the particle acceleration.

Kundu et al, 2009

Some experiences from the single dish commissioning works for solar observation

Iwai et al, 2017

Detuning of SIS devices

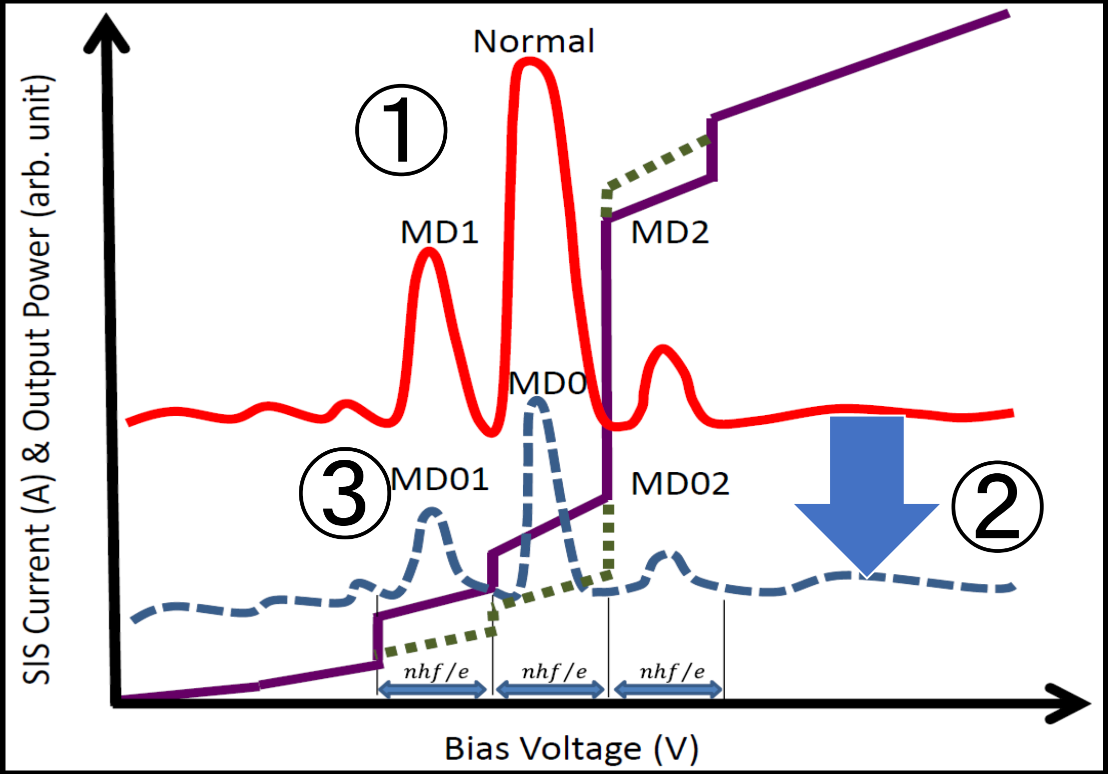


Figure 1 Schematic image of the bias voltage and output diagram of an SIS mixer and its detuning modes.

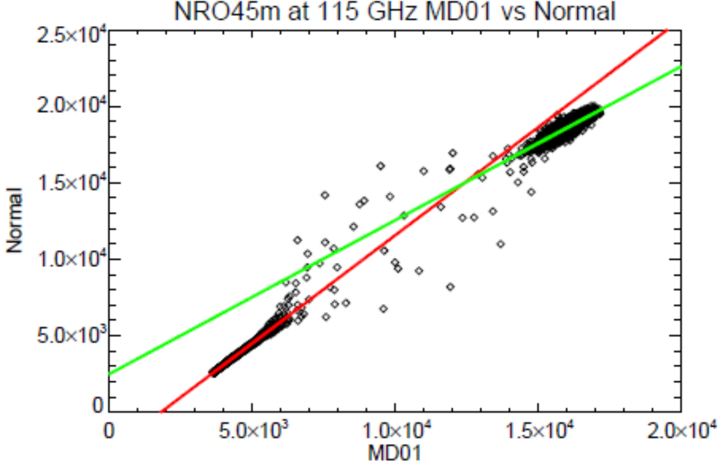
How to reduce the input power?

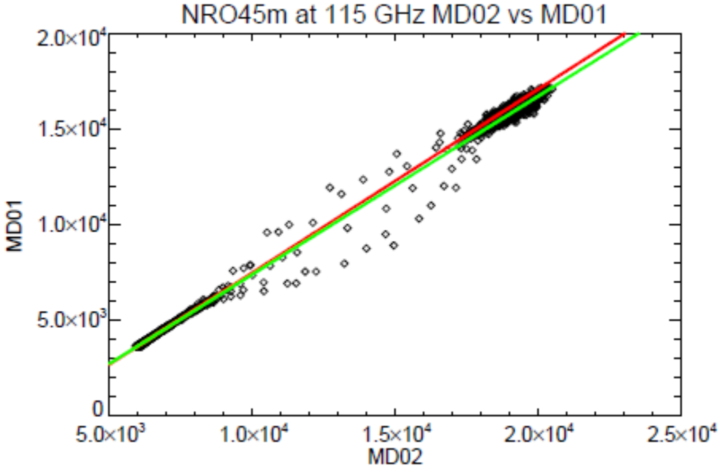
We examined several “SIS-detuning” techniques,

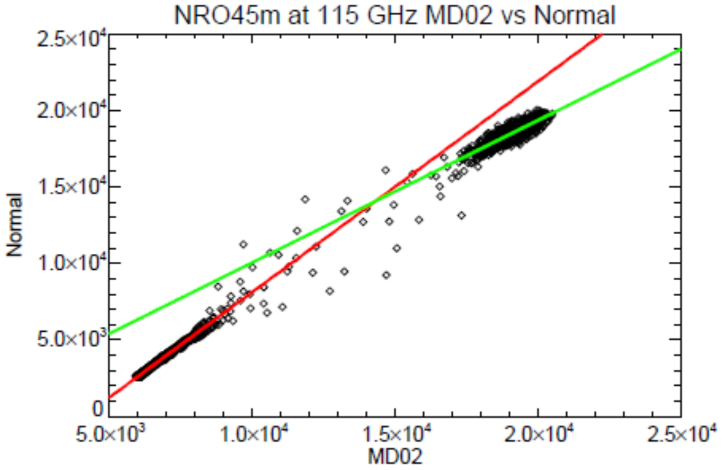
① induce a bias voltage nhf/e lower/higher than the best point (MD1/2)

②induce a weaker local signal (MD0)

③Combination between ① and ② (MD01/02).







Linearity check

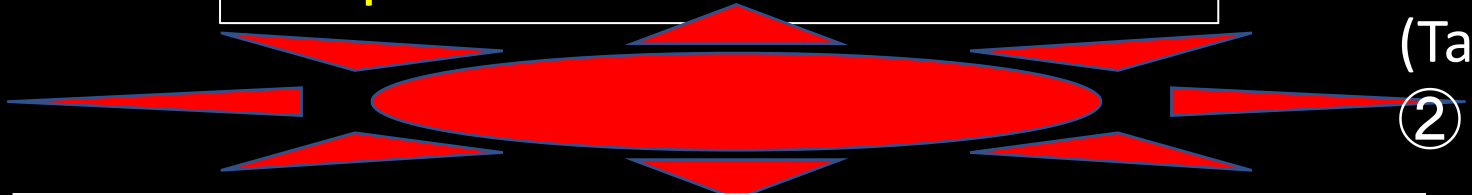
How to check the linearity of the strongest input?

Observe the Sun using different tuning conditions and made a scatter plots.

- Non-linearity between the Normal/MD01 modes: Saturation of the SIS device.
- Linearity between the MD01/MD02 modes: Neither the MD01 nor the MD02 mode is saturated.

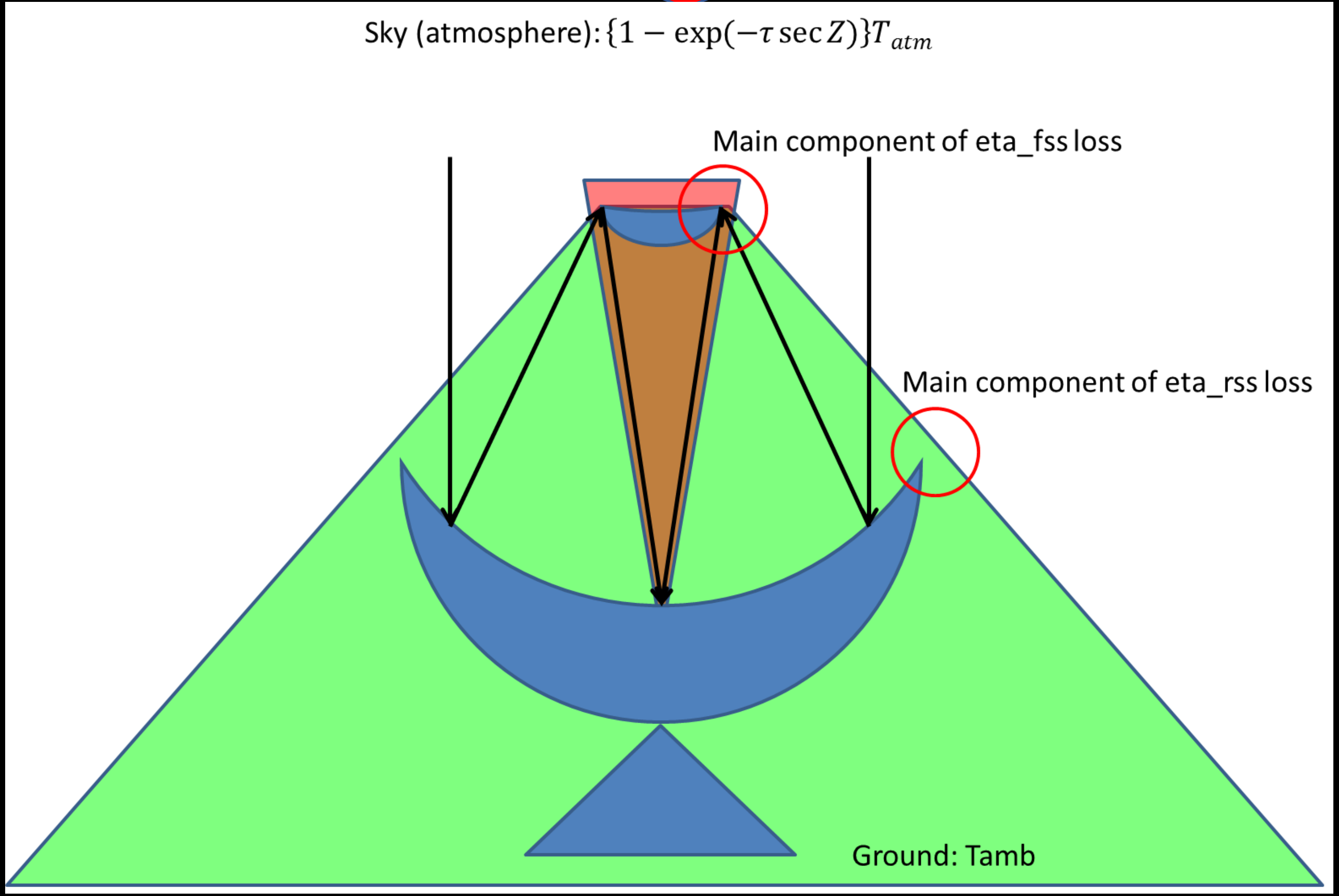
Absolute Calibration

How to derive the brightness temperature?



① Derive the antenna temp. (Ta*) by 1 load calibration

② Ta* → absolute Tb

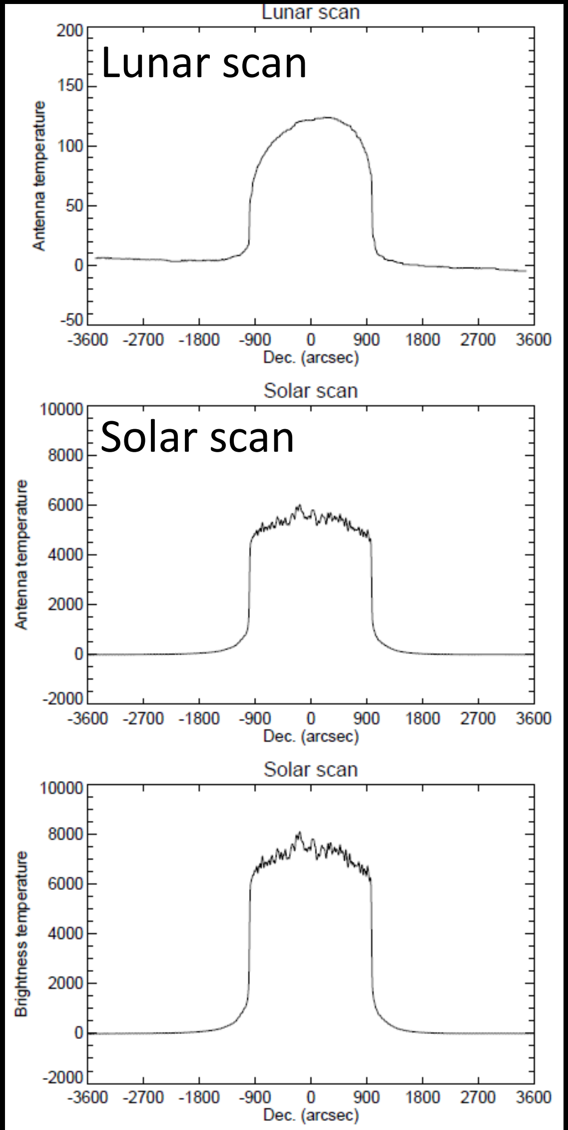


Most side lobes are terminated to the Sun

$$T_B \neq T_a^*$$

$$\boxed{T_B = \frac{T_a^*}{\eta}}$$

New Moon Calibration



$$\eta_{\mathrm{moon}} = \frac{T^*_{AM}}{T_m},$$

Ratio between lunar Ta*and actual lunar temperature (model)

$$T_{\mathrm{BS}} = \frac{T^*_{AS}}{\eta_{moon}}.$$

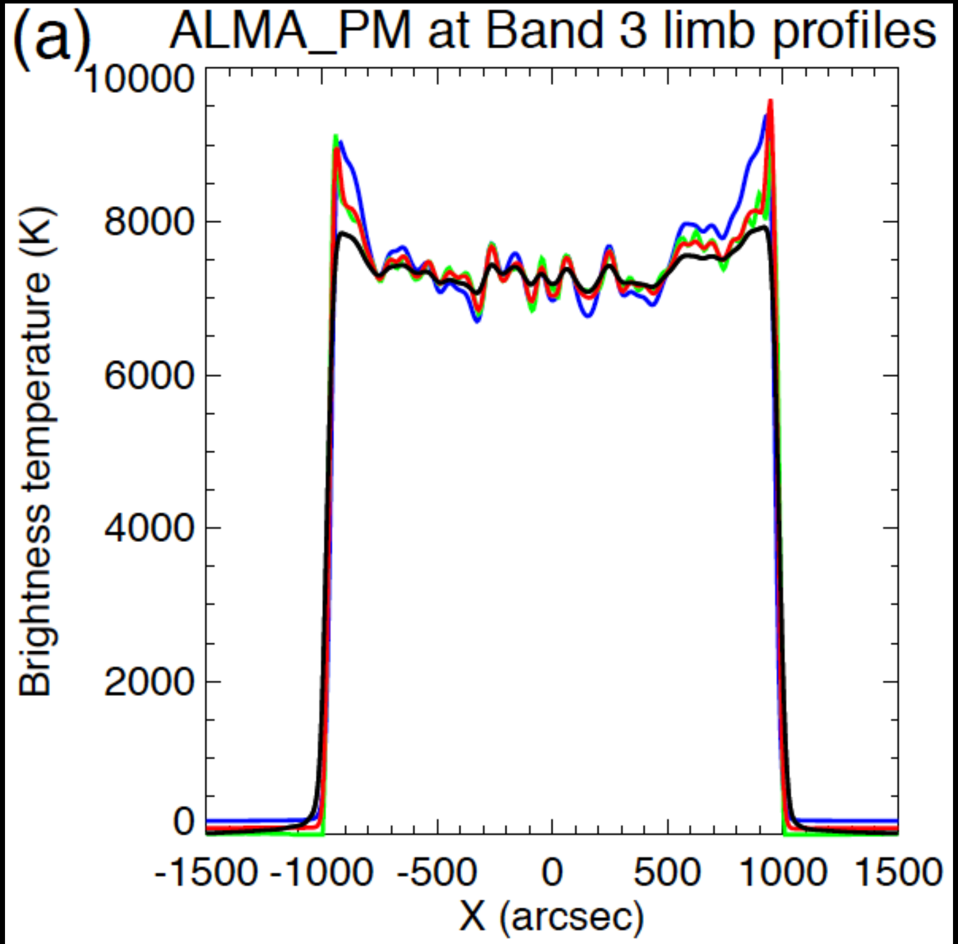
η_{moon} can be used to derive the absolute solar brightness temperature

Note; We do not use the Moon calibration for the ALMA TP antenna although it is recommended to the solar observation. Details are given in White et al, 2017.

η_{moon} at 115 GHz: 0.74 ±0.08 (2015)
(it was 0.69 on 2003's full Moon test)

The Sun at 115 GHz: 7700 ± 310 K

“True” feature of the Sun by the side lobe deconvolution

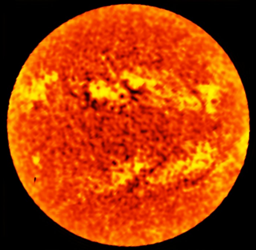


(black) observed solar disc profile.
(red) after the deconvolution of the side lobe

The deconvolution-map became more vivid. (around the sunspot region)

Far side lobes have little influence on the non-solar maps, but it is better to check if there are bright (>10dB) and broad (>> beam size) sources in the map.

Center-to-limb variation and solar radius is sometimes used to investigate the atmosphere. Such studies can be improved by this deconvolution.



Summary

- The Sun is an exiting science target that is filled with magnetic activities and eruptions.
- The solar physics at mm/sub-mm range can investigate the solar atmosphre, magnetic field, and high-energy particles.
- The LLAMA has a large potential for solar physics.
- The solar commissioning works will be required. But it helps us to understand the telescope.

Observing the Sun with LLAMA will be an interesting project!