Solar Astrophysics with ALMA

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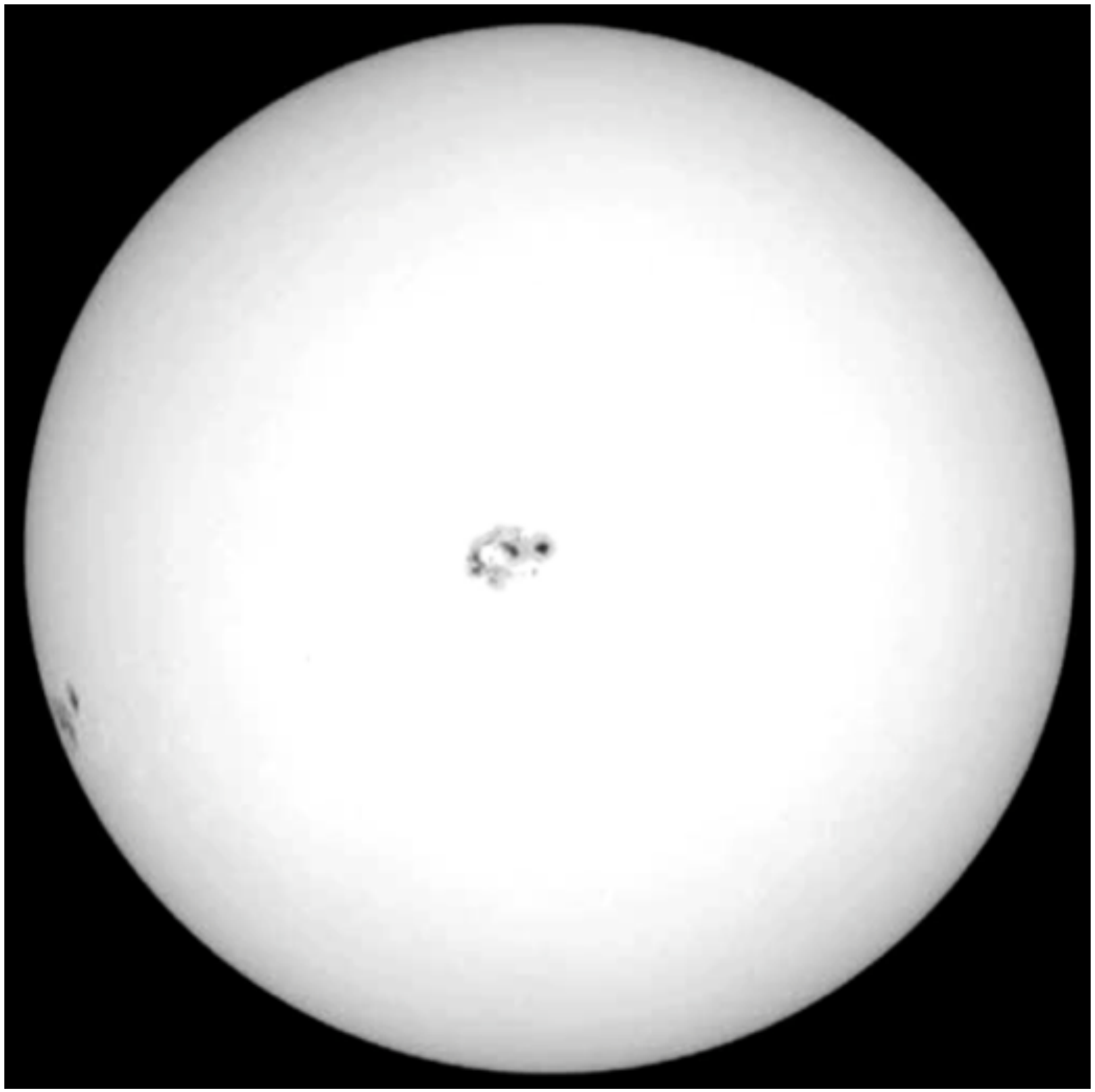
Contents

1. The Sun



Space-born observations from photosphere to corona
& Animation presenting Flare/CME/High energy particle events

- Dynamic star governs our solar system.
- Closest star that allow us to study various phenomena.
- Exciting plasma physics laboratory.
- Major source of space weather effect

Solar observations

- Progress in solar observations by development of instruments

New Solar Telescope (NST), 1.6m, ~ 0.06 arcsec ~ 40 km (Goode Solar Telescope)

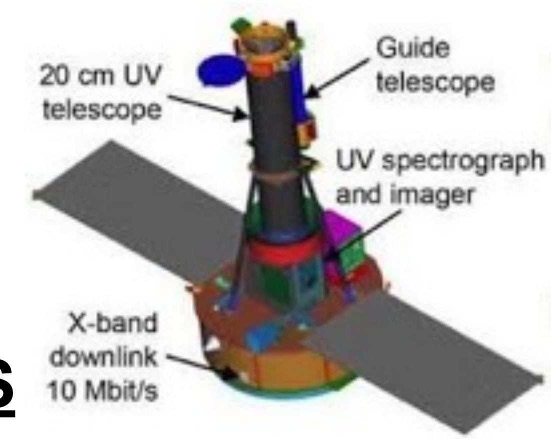
Swedish Solar Telescope (SST), 1m, ~ 0.1 arcsec ~ 70 km

Solar Dynamics Observatory(SDO), EUV/UV/magnetogram, 0.5”, 2sec, full-sun

Hinode, X-ray/Optical/vector magnetogram, 0.2”, partial of the sun

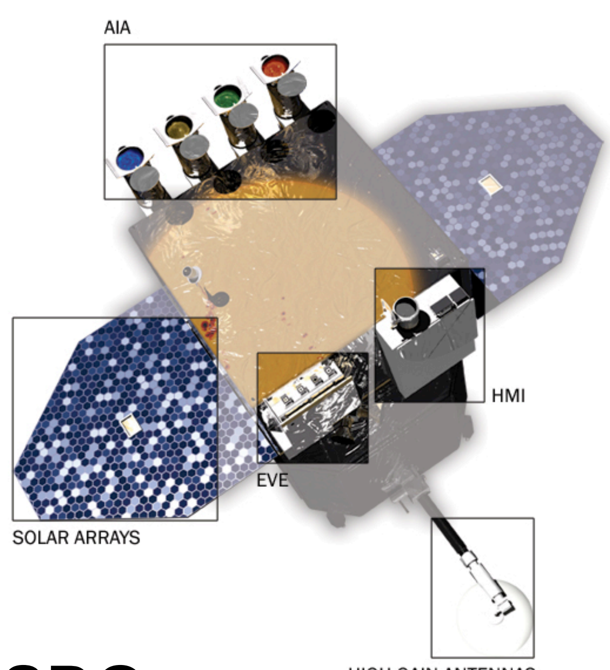
IRIS, UV spectrum, imaging spectrograph, partial of the sun

RHESSI, Hard X-rays imaging/spectrum

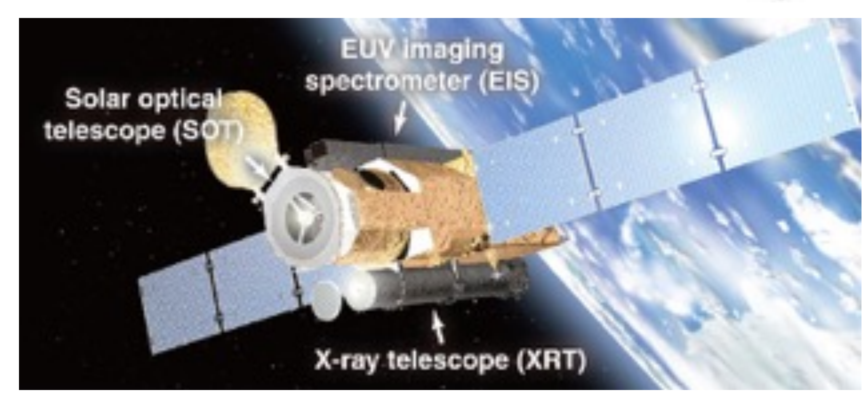


IRIS

NST



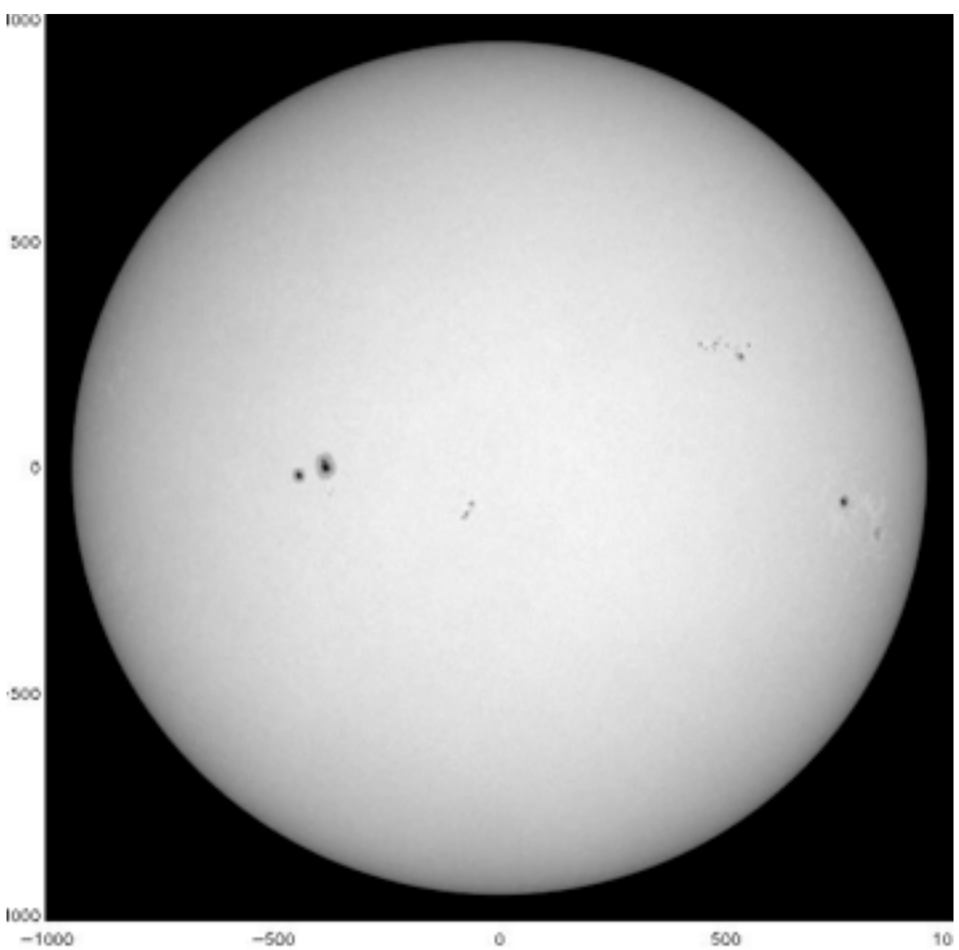
SDO



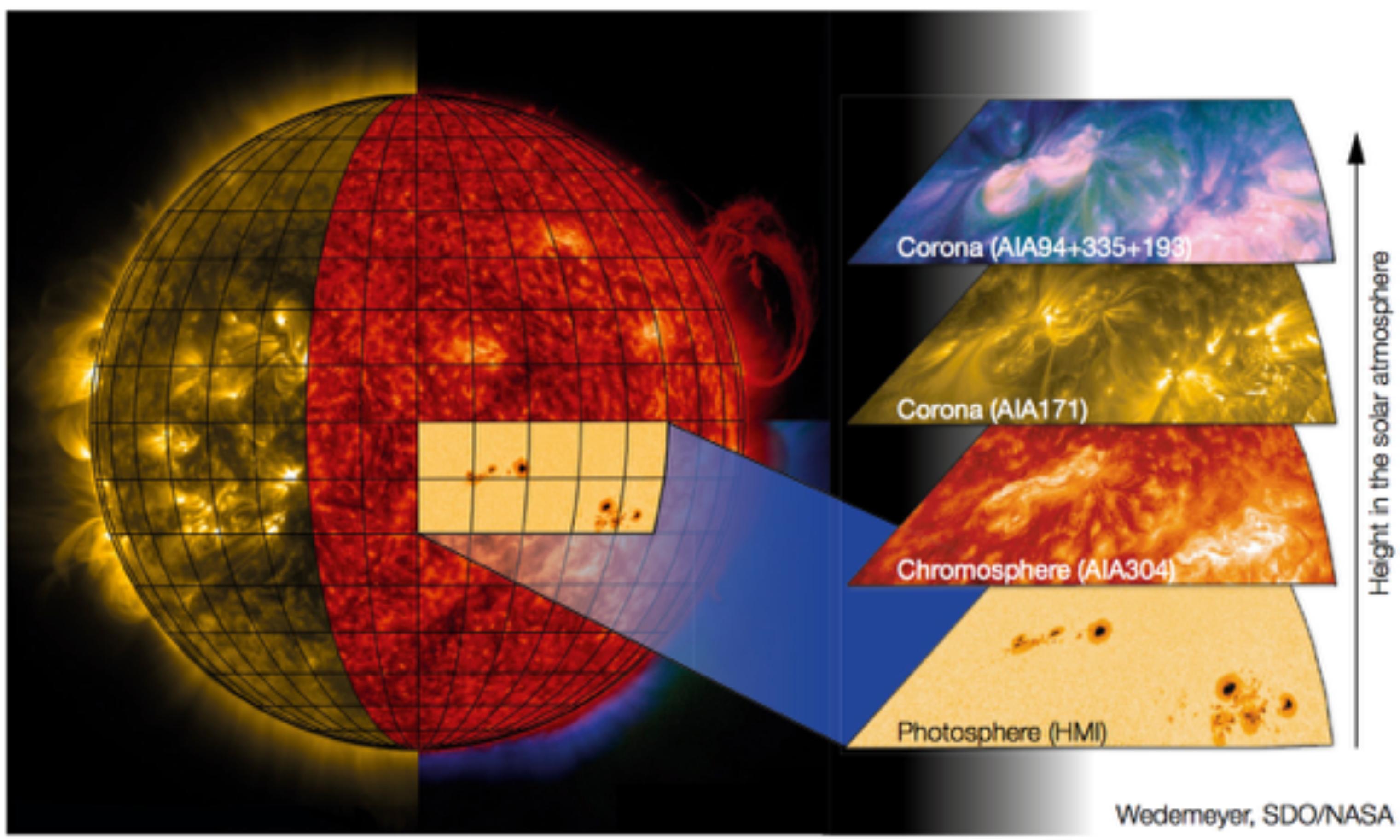
Hinode

Solar observations

- Progress in observations by development of instruments
  - High spatial and temporal resolution, < 75 km and < 2 seconds
  - Multi-wavelength Imaging/Spectrum
  - Coordinated campaign observation with ground-based and space-borne observatory



Ground-based observation

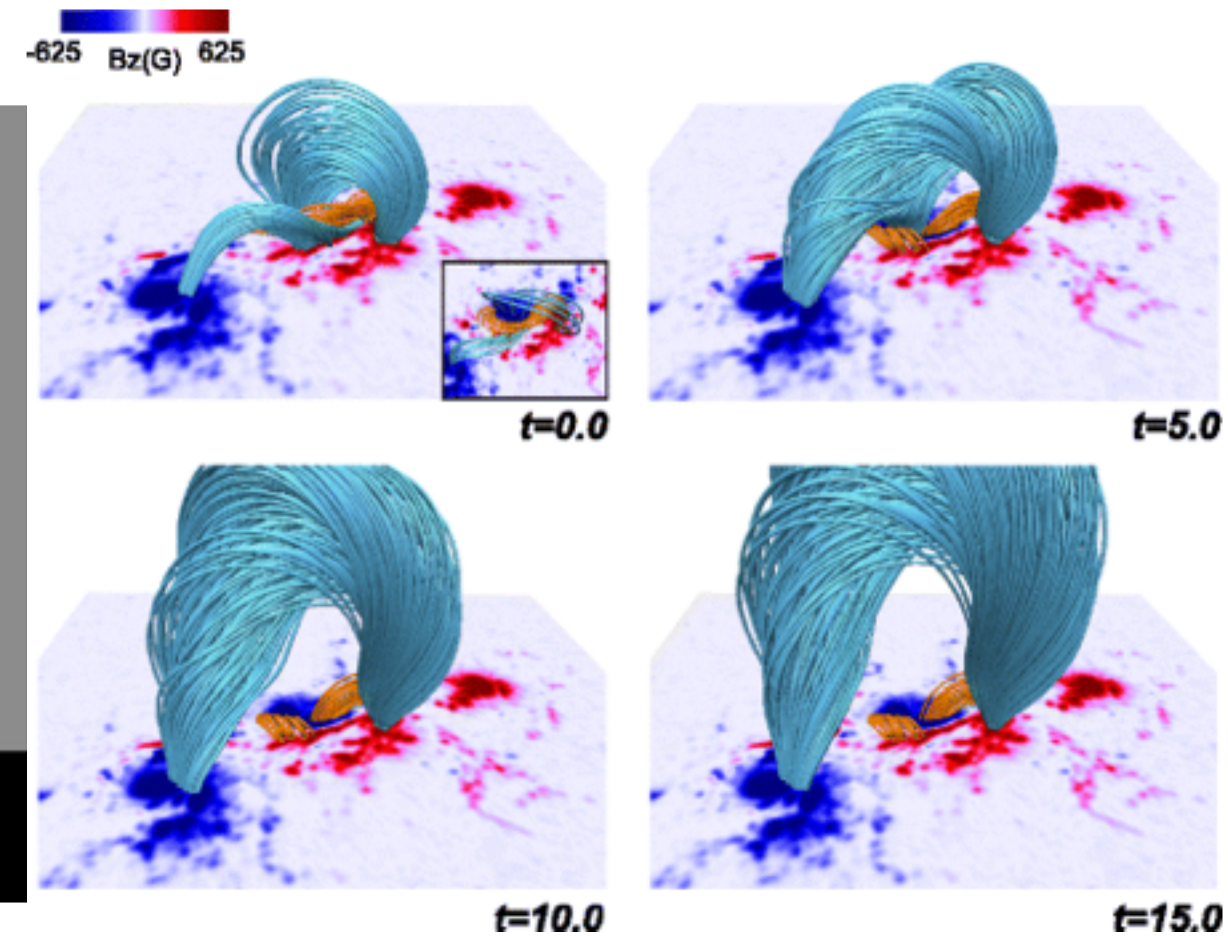


SDO multi-wavelength EUV images

Numerical modelling

- Numerical modelling

Radiative MHD simulation for Active Region formation
(Cheng et al. 2010)



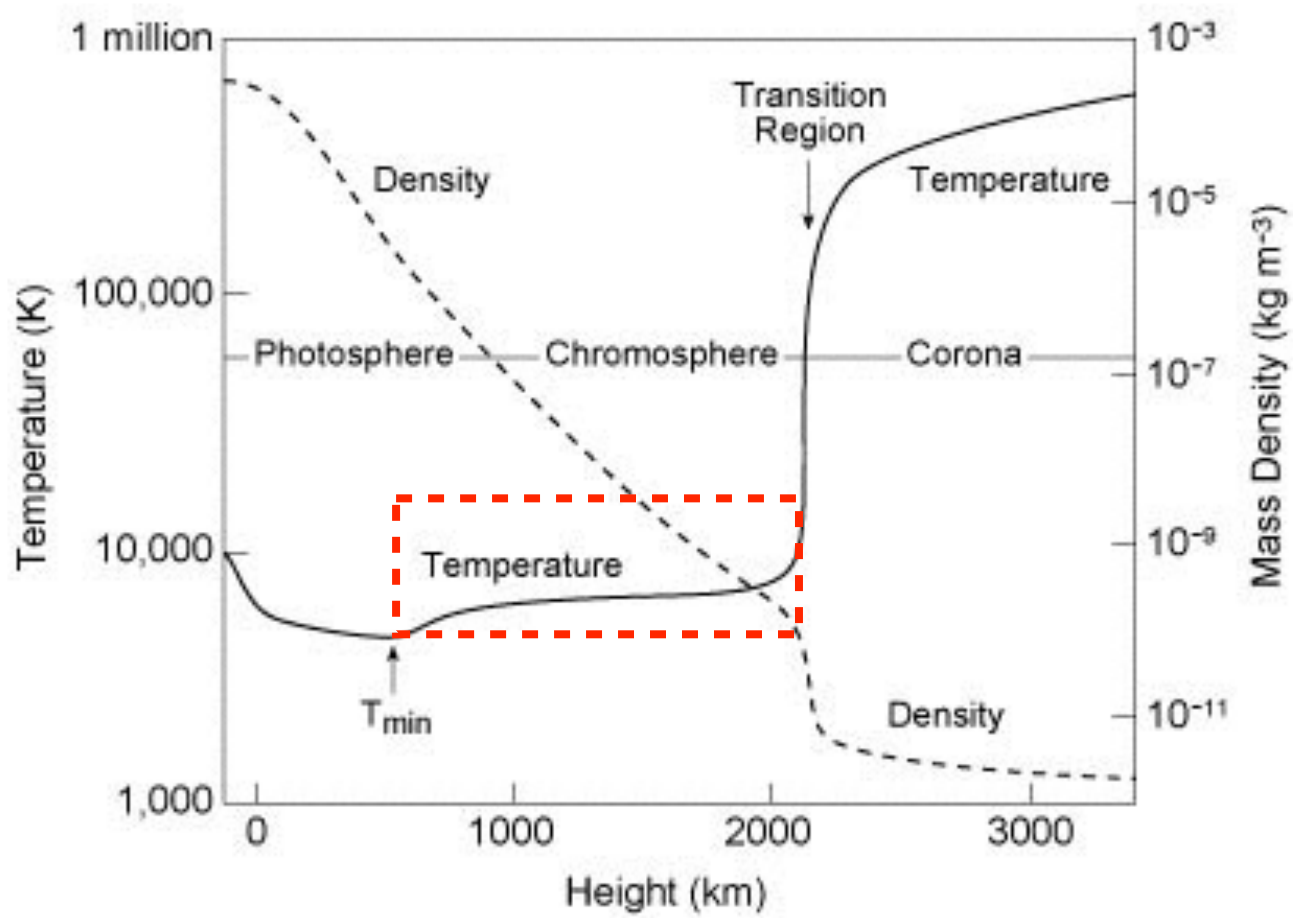
3D dynamics of the flux tube during an X2.2-class flare reproduced by MHD simulation
(Inoue et al. 2010)

- We still do not fully understand
  - **- Chromospheric and Coronal heating**
  - - Flare: Magnetic reconnection process and particle acceleration
  - - Chrom. phenomena (ex. prominence): Magnetic nature and cause of eruption

Solar Atmosphere

- One of key questions: Atmospheric heating in chromosphere and corona.
- **Chromosphere** is a quite complicated layer which is difficult to diagnose its plasma conditions.

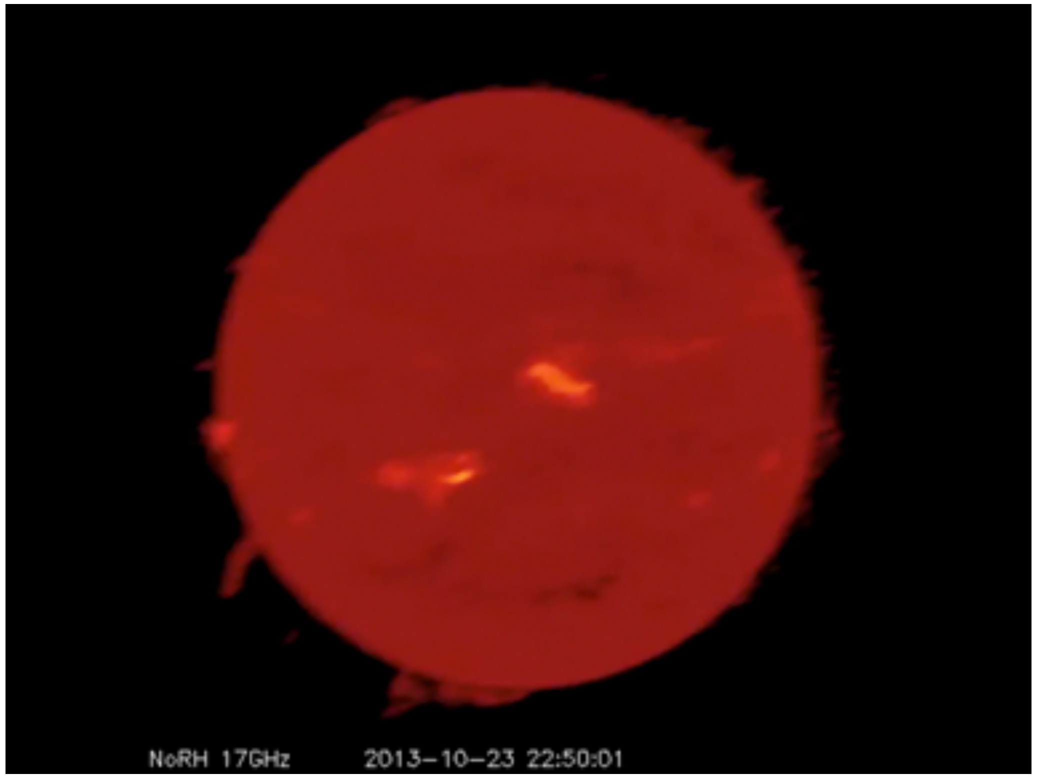
  - non-equilibrium conditions: ionising the gas by continuous activities but recombination does not occur instantaneously due to rarer density.



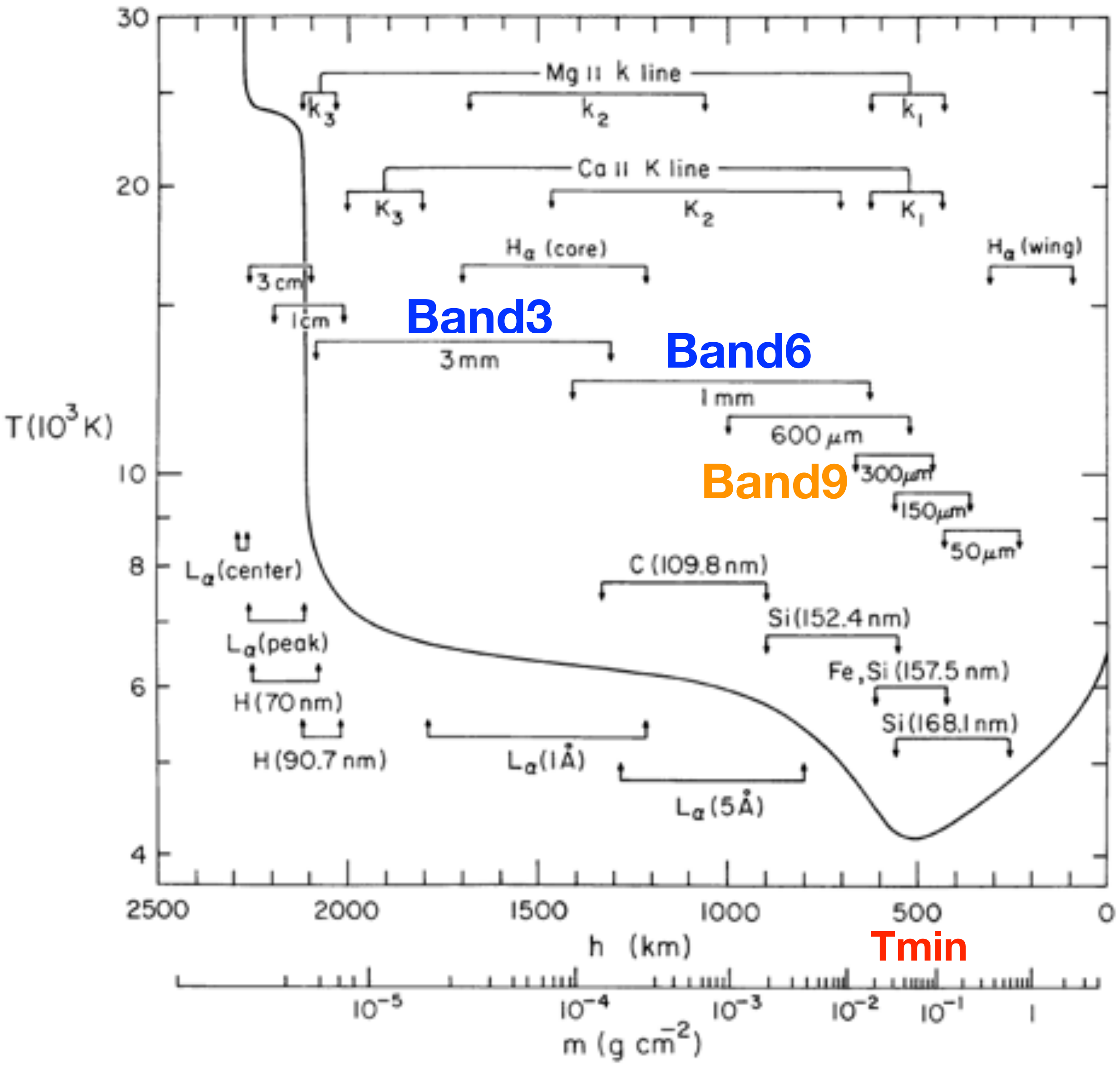
Temperature and Mass density profile of solar atmosphere from photosphere to corona [NASA's Cosmos]

2. ALMA science targets

- Chromosphere
  - Emission at the mm/sub-mm satisfies LTE condition in Chromosphere.
  - ➔ Thermal f-f emission at $\tau \sim 1$, $T_B = T_{eff}$
  - **> Thermometer of chromosphere**
  - **> Chromospheric tomography (multi-Band observation)**



17 GHz images, ~ 10,000 K for quiet sun from Nobeyama Radioheliograph
R~10 arcsec. 1 seconds



Vernazza, Avrett & Loeser, 1981

Chromosphere

- Chromosphere above sunspots has been investigated by
  - ➤ Caltech sub-mm Obs., Bastian et al. (1993)
  - ➤ James Clerk Maxwell telescope, Lindsey & Kopp (1995)
  - ➤ Berkeley-Illinois-Maryland Array Interferometer, White et al. (2006)
  - ➤ Nobeyama 45m telescope, Iwai & Shimojo (2015)
  - ➤ Nobeyama Radioheliograph at 8.8mm, Iwai et al. (2016)

: the limit of those observations was that the **beam size larger than 10 arcsec** seems average existing fine scale structure within the beam size.

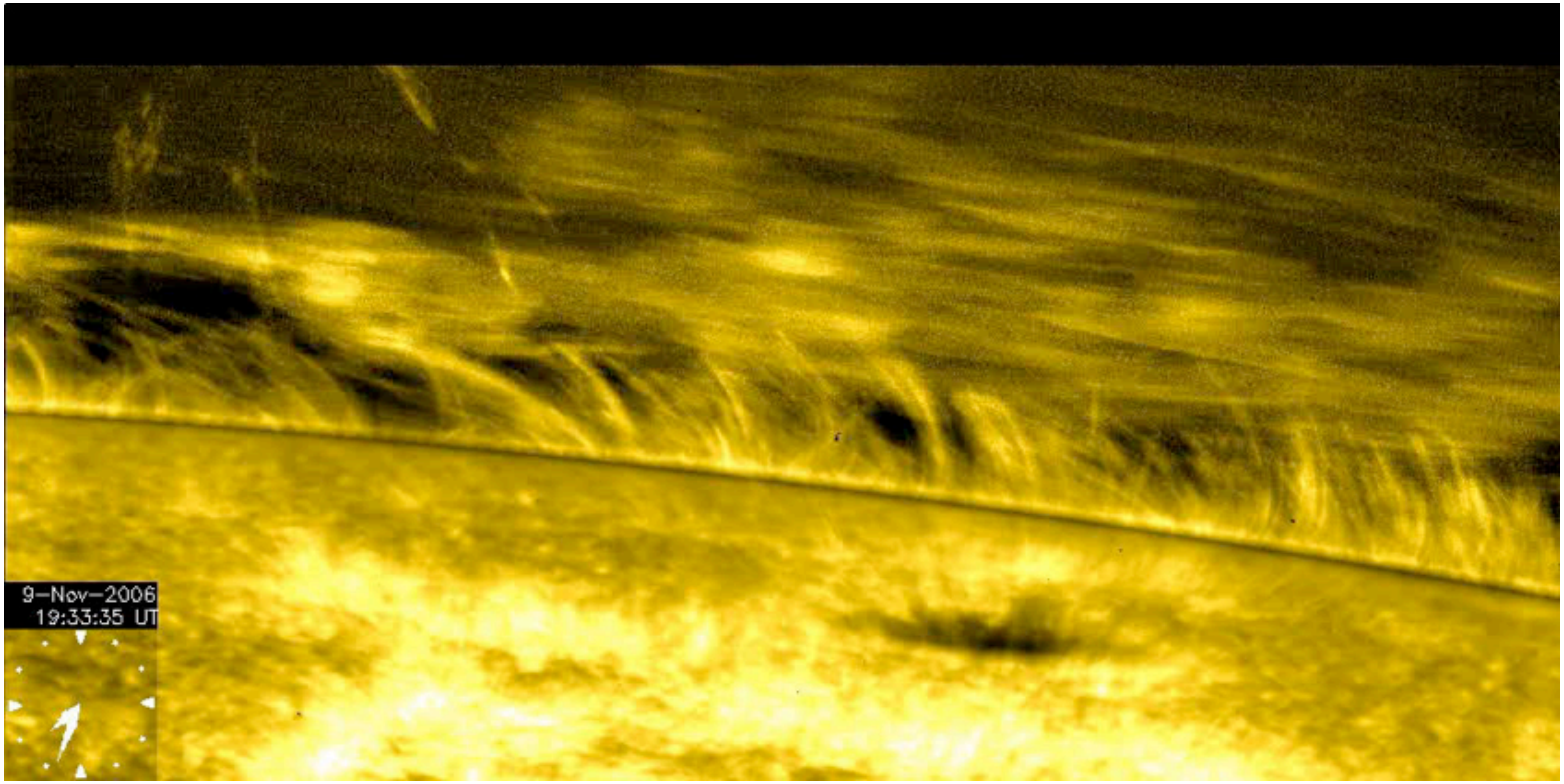
➔ ALMA spacial **R. 1.4” at 3 mm and 0.5” at 1.3 mm**

(Iwai et al. 2017, Loukitcheva et al. 2017 reported the new finding)

- energy transport in chromosphere
- nature of chromospheric features: spicules, prominence
- temperature observed by ALMA improves the atmospheric models

Chromospheric features

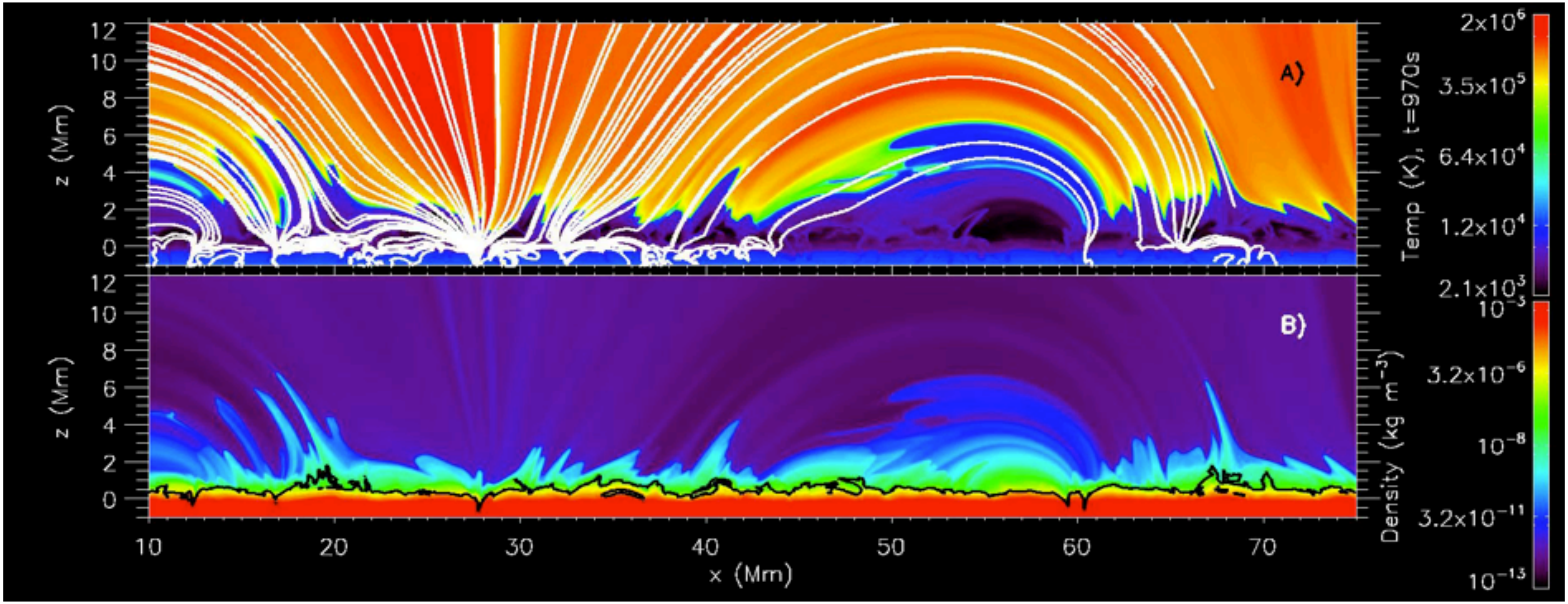
- Spicules
  - MHD waves responsible for the heating and the spicule formation (Avrett 1981)



Hinode Ca II observation (Okamoto et al. 2007)

Chromospheric features

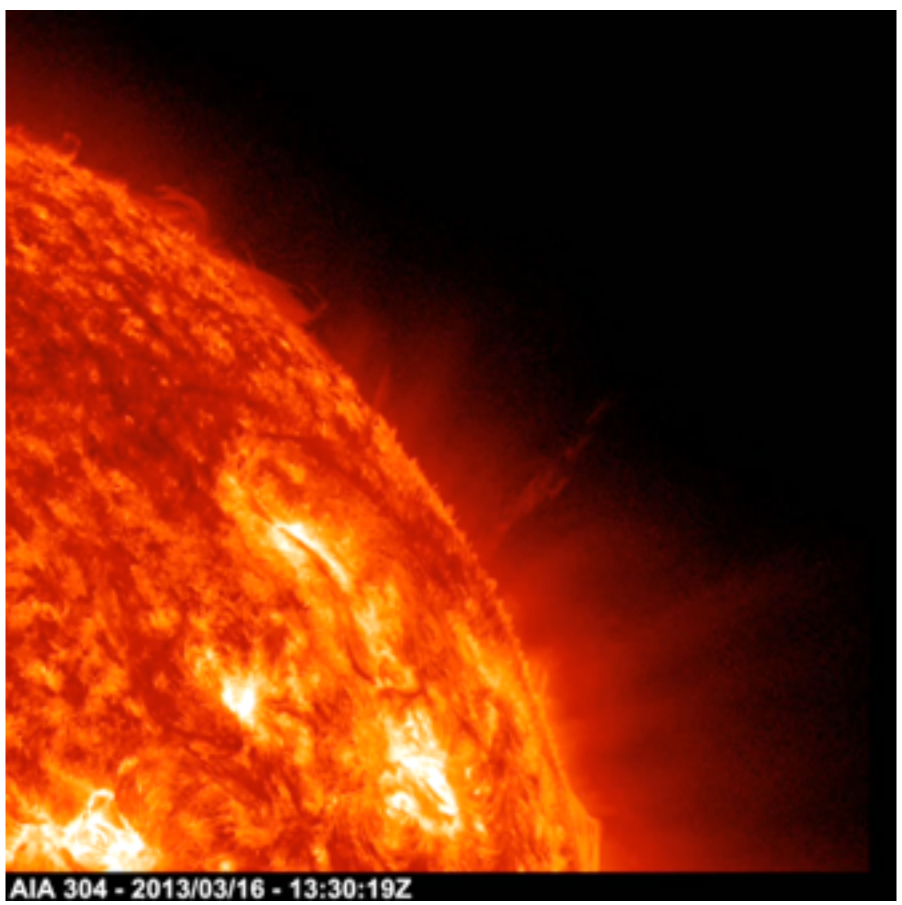
- Spicules
  - MHD waves responsible for the heating and the spicule formation (Avrett 1981)



Radiative MHD simulation for spicules
Martínez-Sykora et al. 2017 Science

Chromospheric features

- Prominence (Filament)
  - lasts hours to days
  - finally erupt or disrupt
  - magnetic nature and cause of instability leading eruption are not clear.



Prominence eruption [SDO/304 filergram]

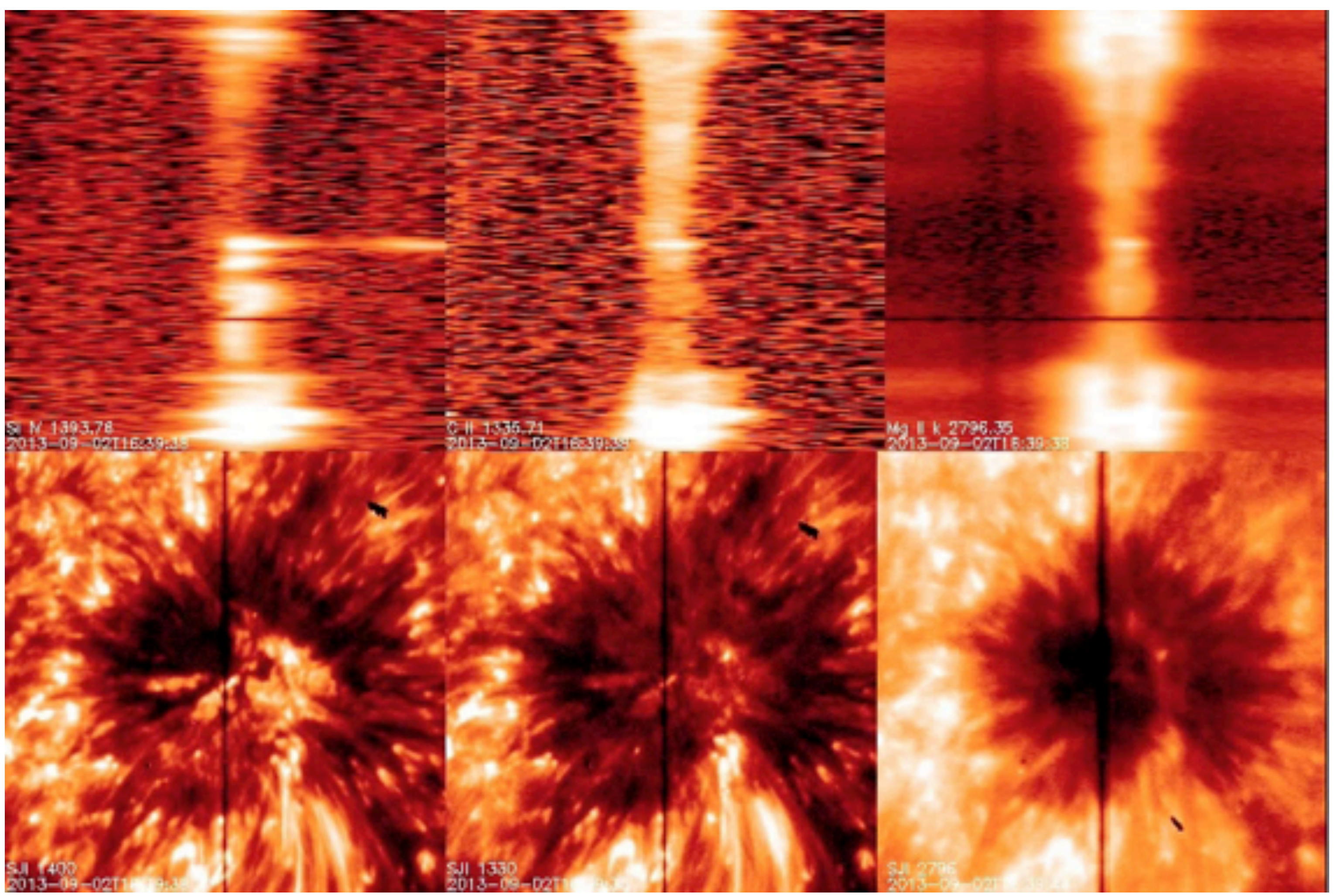
6562.5 A [H alpha]

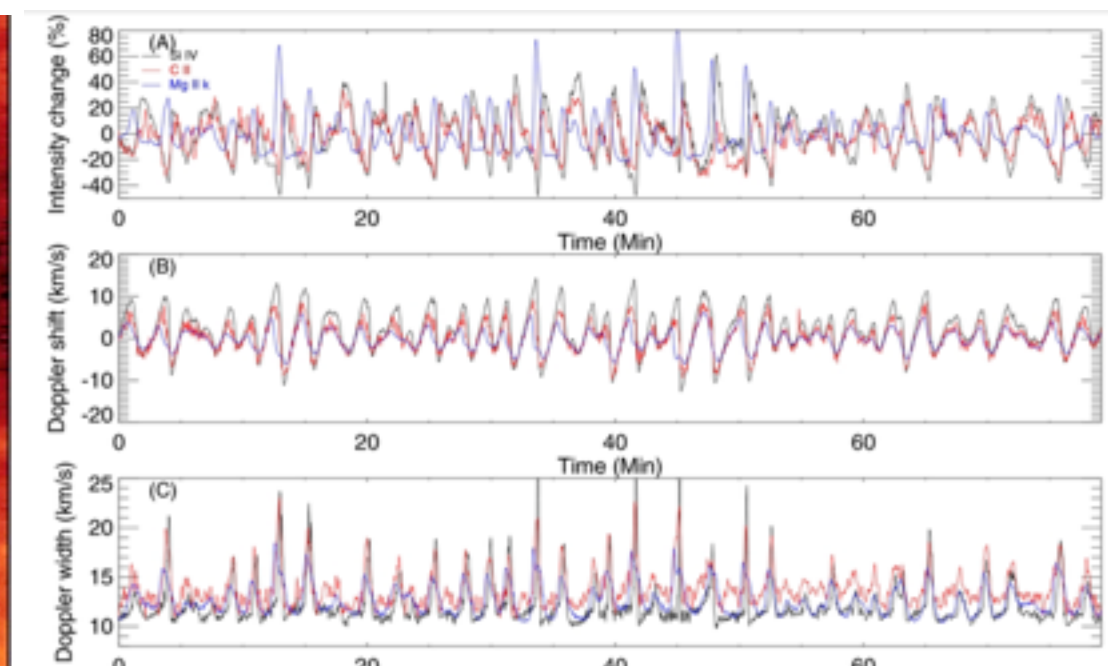
Oscillations

- Oscillation in chromosphere

  - Chromosphere is the passage of energy transportation and **a layer of shock formation by waves from photosphere**.

  - Oscillations is great tool to find waves and diagnose MHD wave mode (slow, fast, Alfvenic) and the physical conditions.

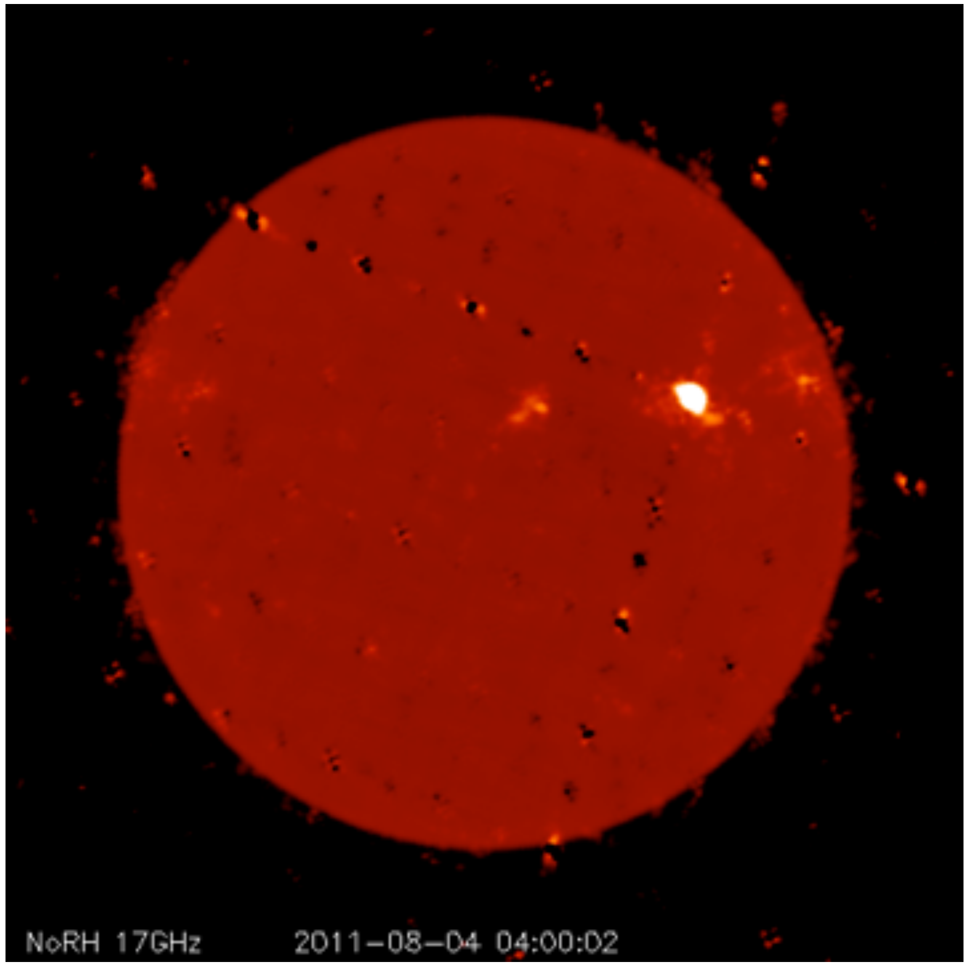




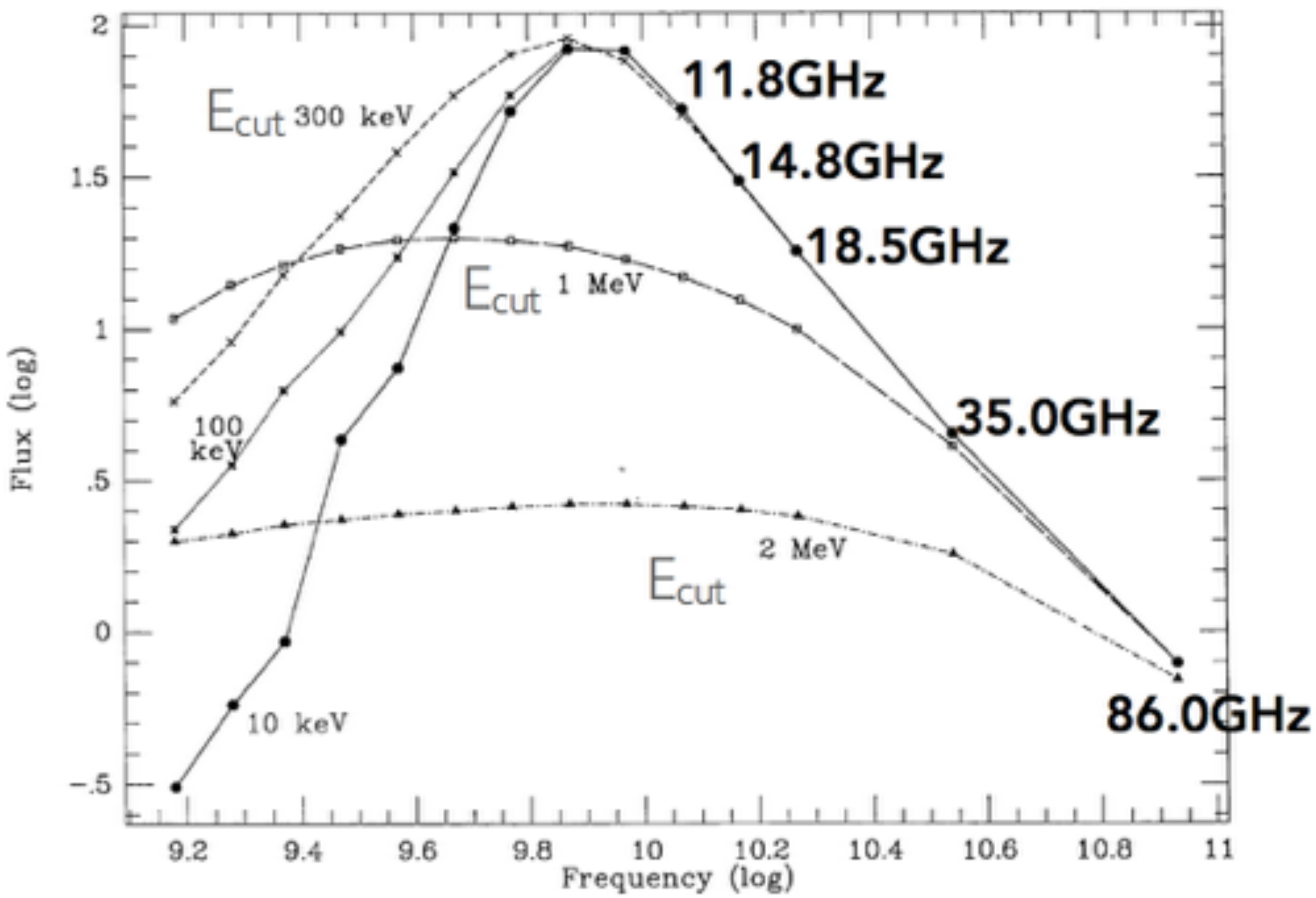
IRIS satellite observation of sunspot 3 minutes oscillation with **Si IV(left), C II (center), Mg II K (right) spectral line**: Upward propagating magneto-acoustic shock waves
Tian et al. 2017

Flares

- Non-thermal emission from MeV electrons
  - Gyrated electrons in magnetic fields emit electromagnetic wave
    : Gyrated thermal electrons -> Gyro-resonance, Freq.
    : Gyrated non-thermal electrons ==> Gyro-synchrotron



M-class flare observed by
17 GHz Nobeyama Radioheliograph



Observed Spectrum and fitting results with
different energy of electrons

3. ALMA Capability for solar observations

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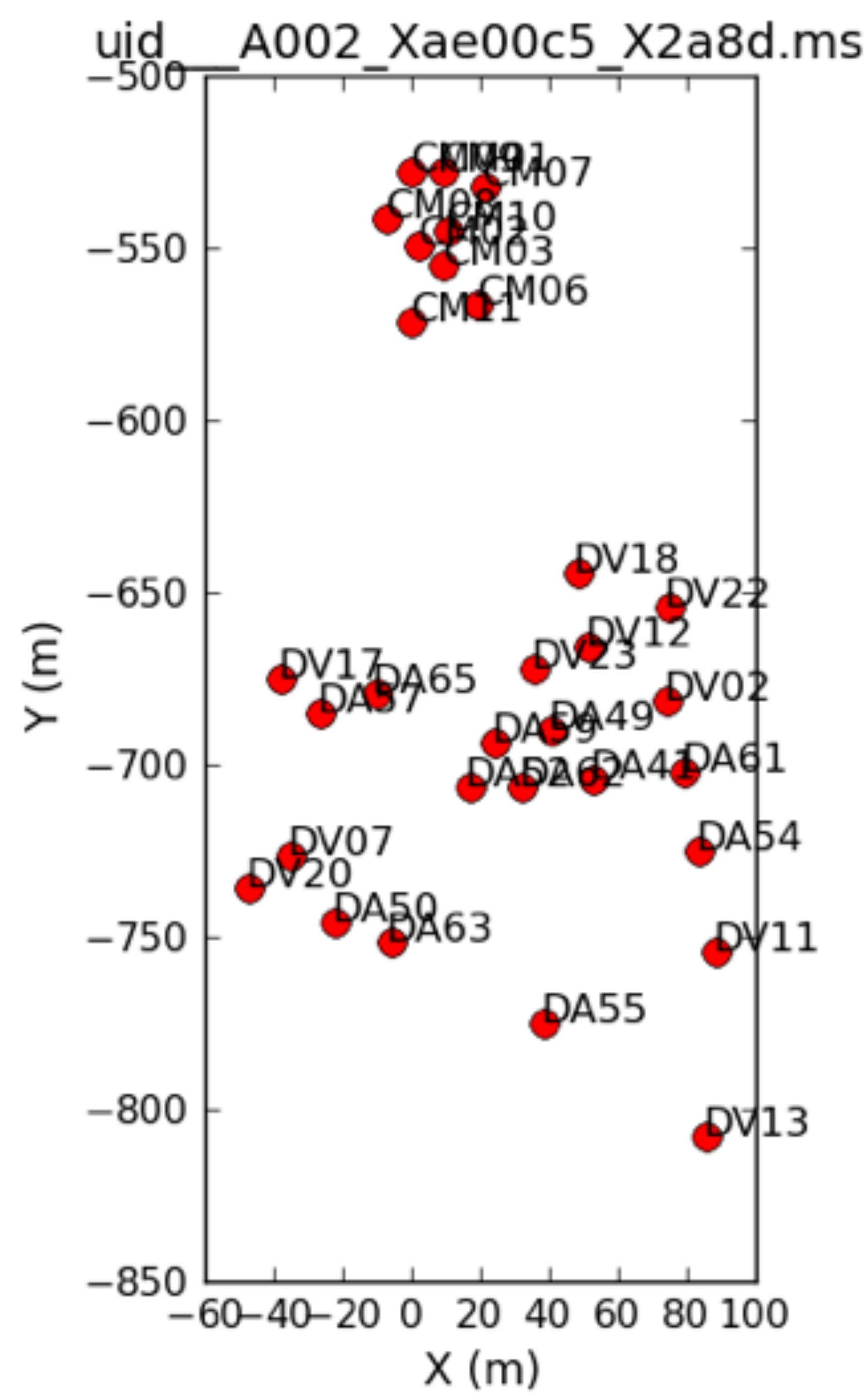
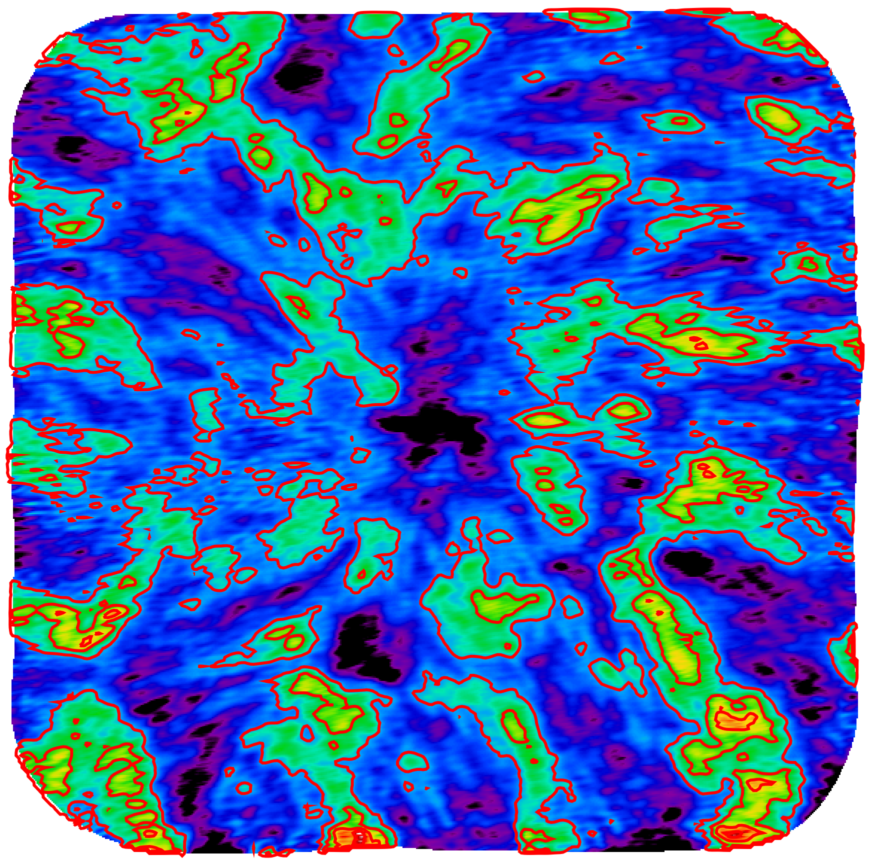
- Scanning full-sun

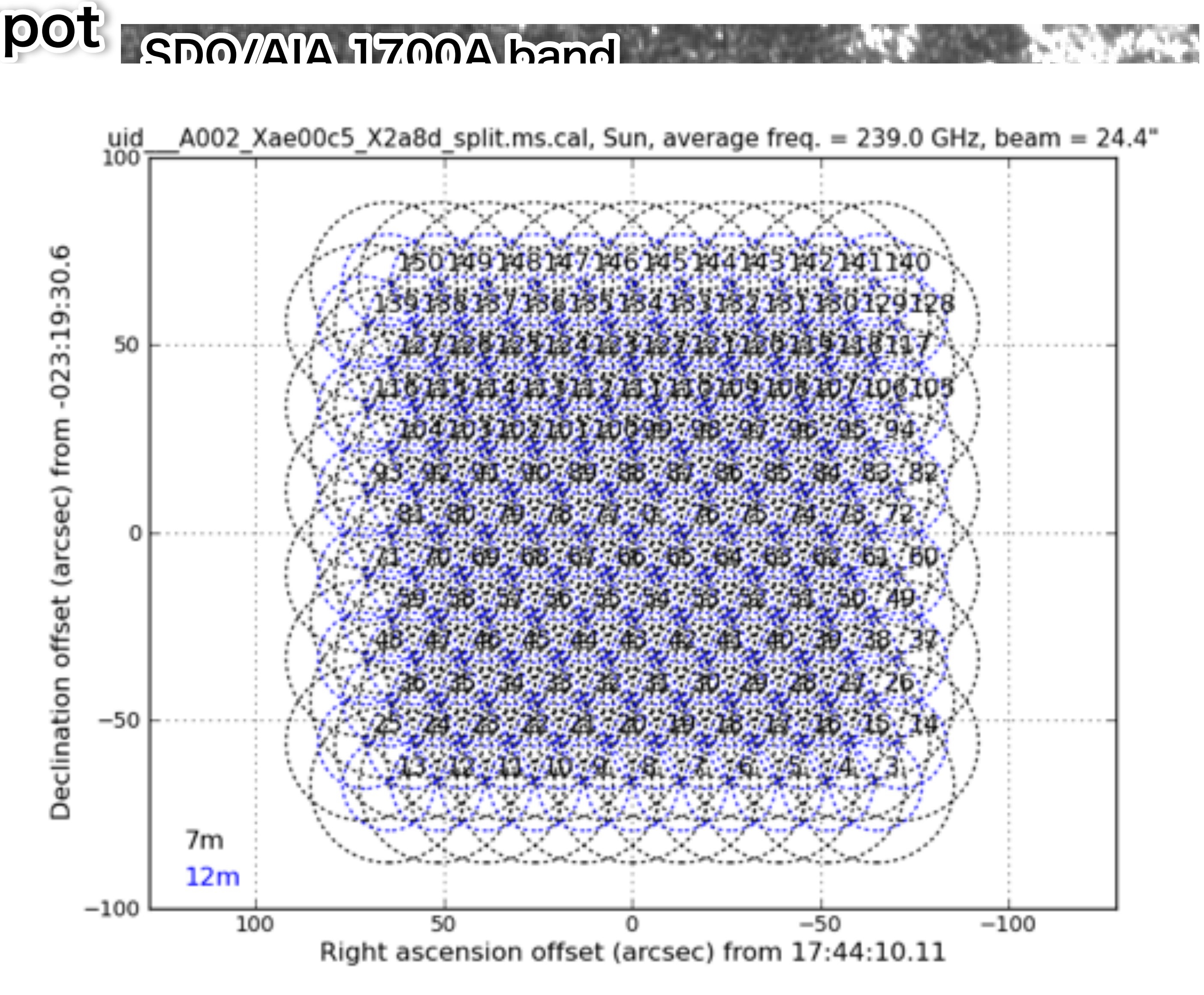


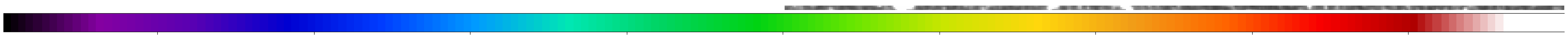
Interferometric obs. Mosaic Mode

ALMA 150pts-Mosaic Image
NOAA 12470 Preceding Sunspot
2015-12-18 19:39 -- 20:03UT



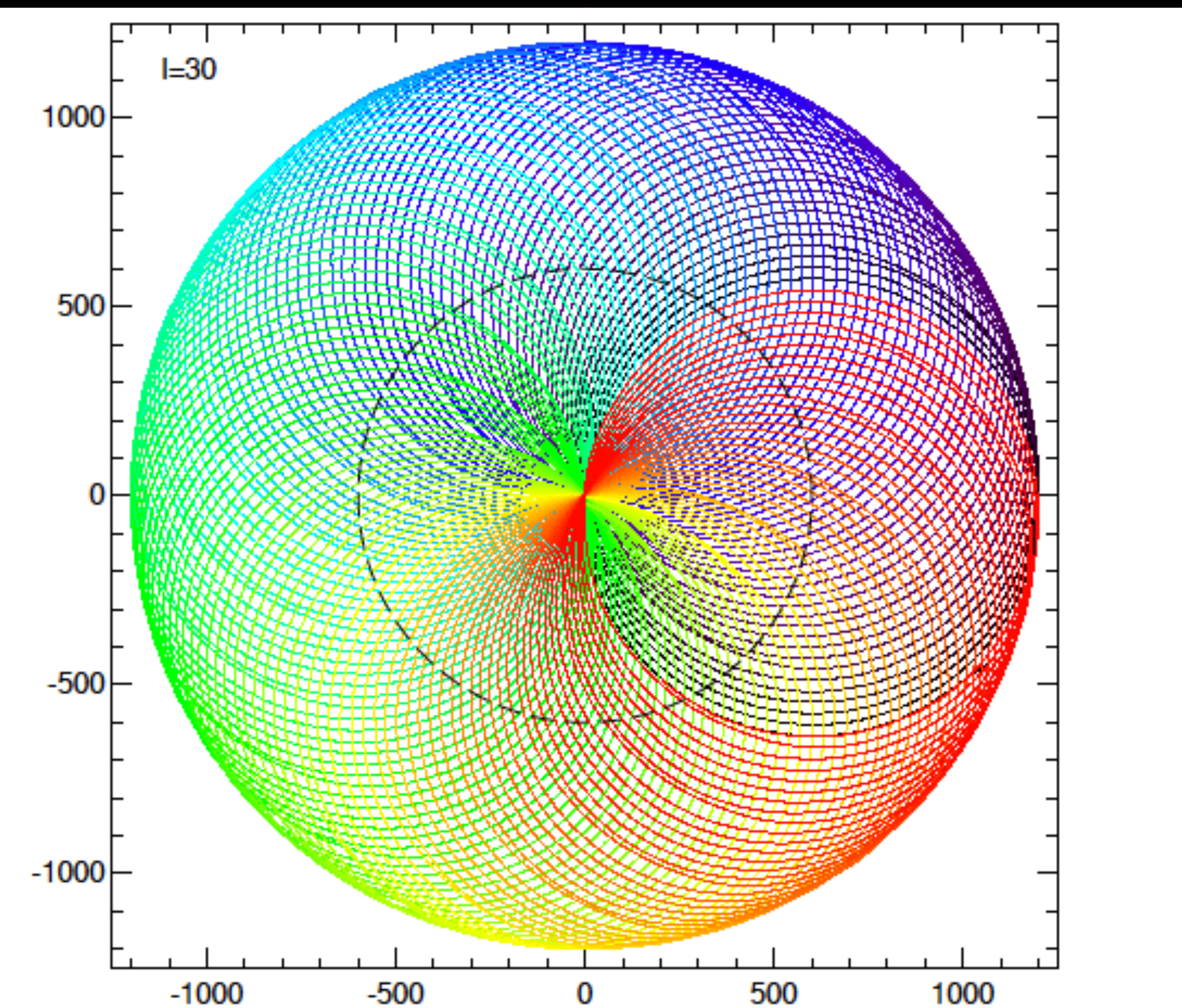
Band6 230 GHz (Synth. Beam 2.6" x (

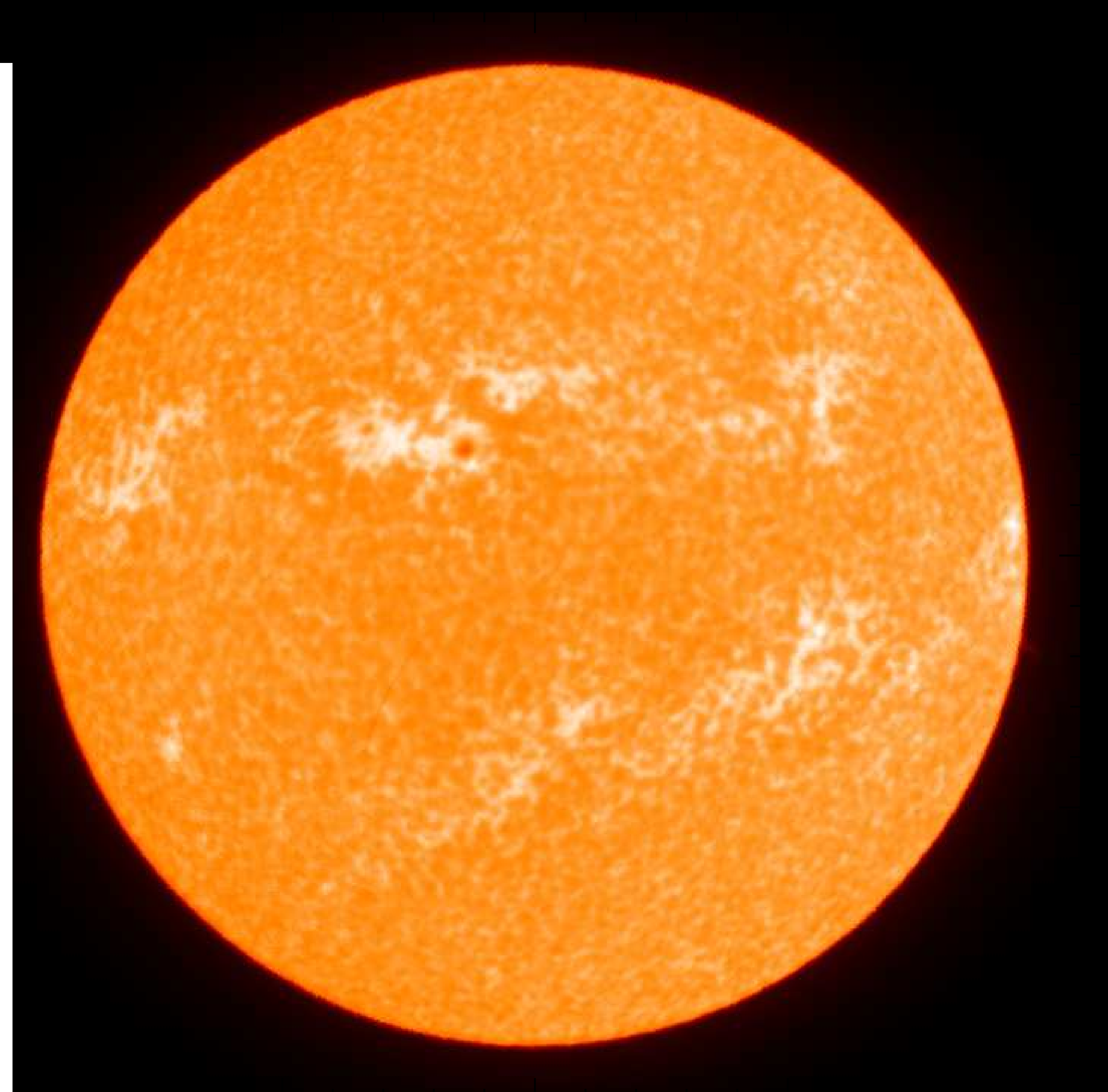




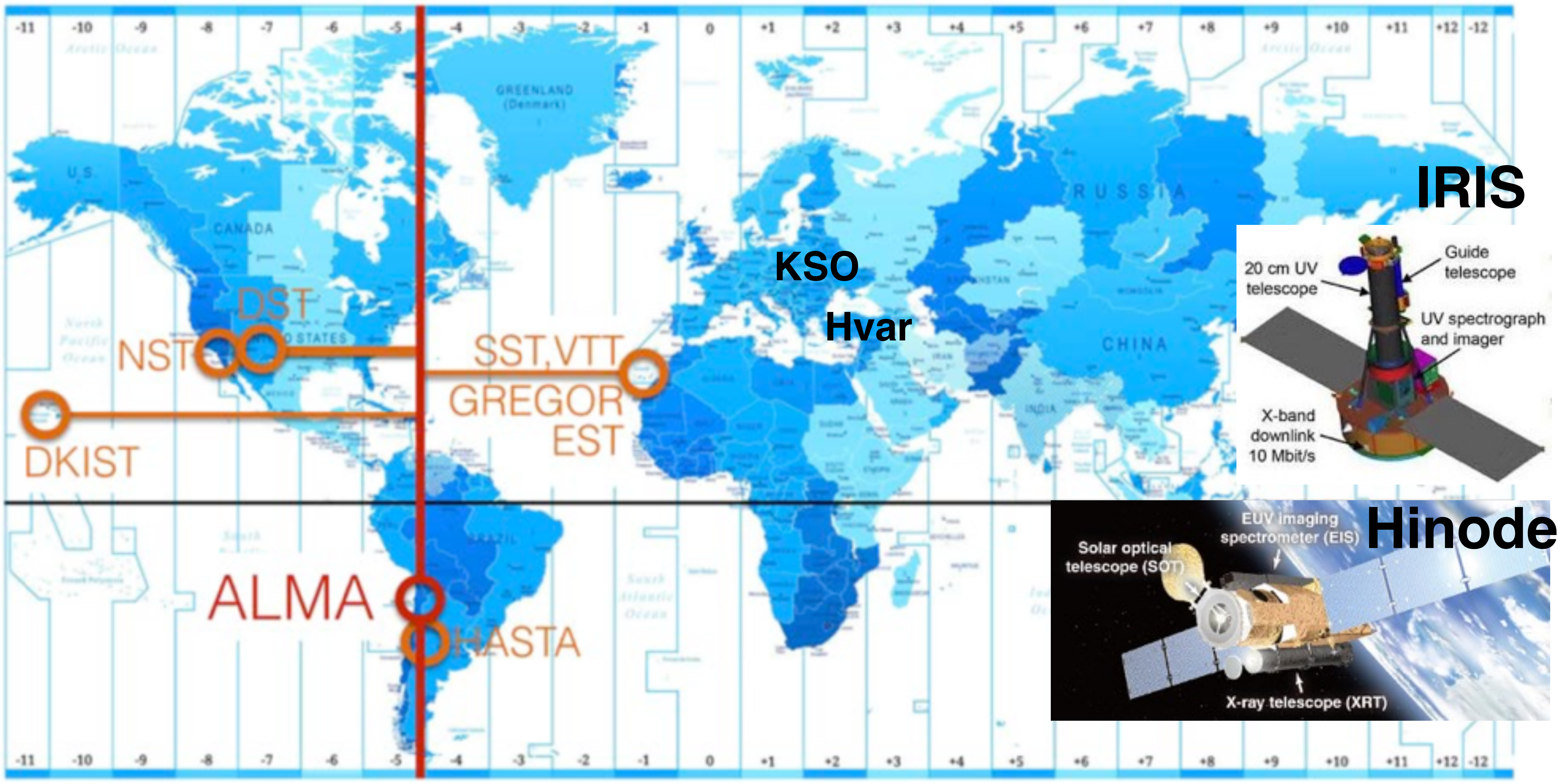
Red Contours : ALMA 230GHz

Single-Dish obs. (Band9)





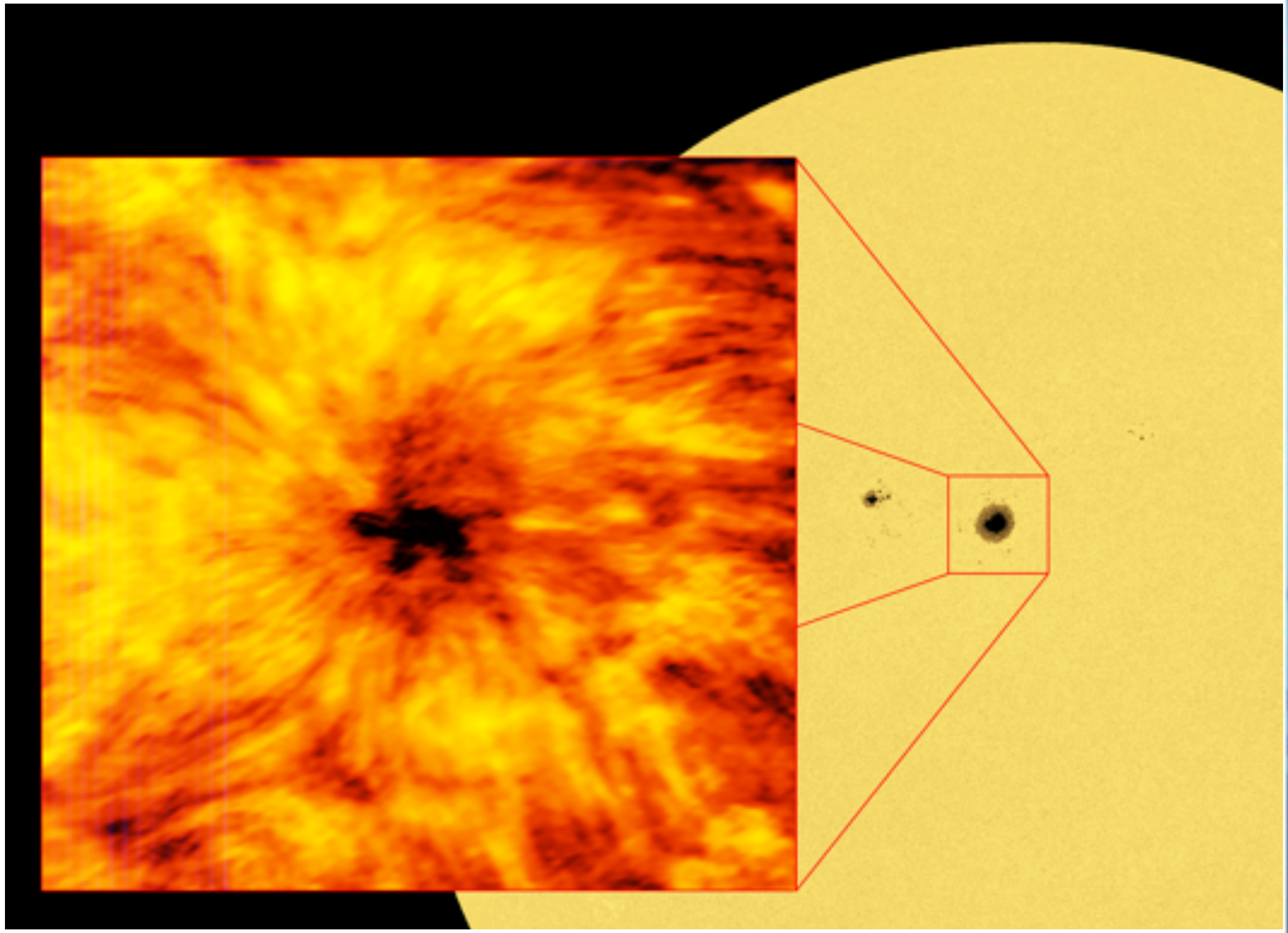
Coordinate observation



4. Recent results with ALMA

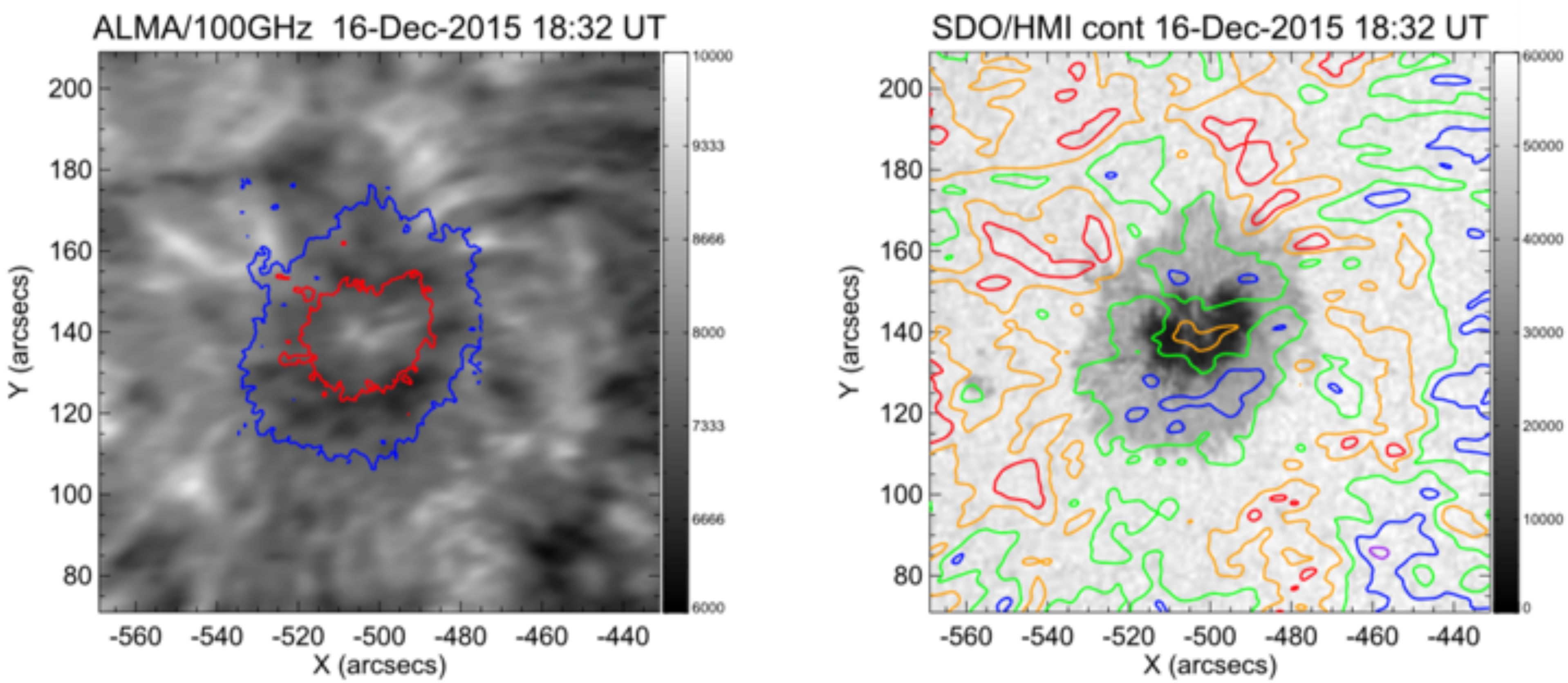
- Science verification campaign observation in 2015 Dec.
- SV data released on 18 Jan. 2017
  https://almascience.nao.ac.jp/alma-data/science-verification

- Sunspot observation



1) Umbral brightening at 3mm

- Iwai et al. (2017) investigated chromospheric temperature above the sunspot using ALMA Band3 (100 GHz) and found the enhancement of brightness which is close to bright structure (plage) near the sunspot.
- It is first observation in mm wavelength only available by ALMA with high spatial resolution (beam size: 4.9” × 2.2”)



[ALMA 100 GHz mosaic image (left) and SDO continuum image (right)]

Iwai et al. (2017), The Astrophysical Journal Letters, 841:L20

1) Umbral brightening at 3mm

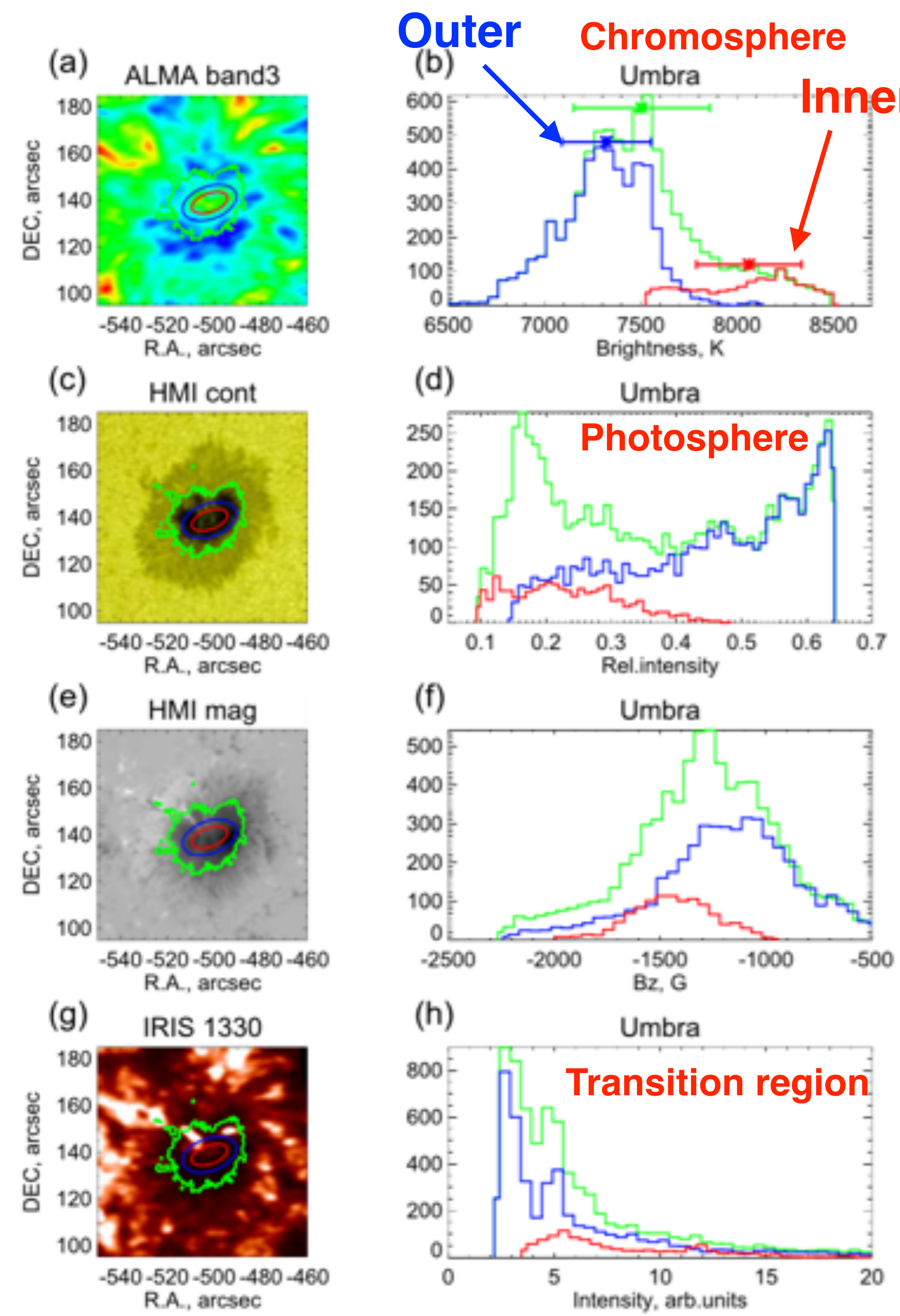
- Umbral brightening at 3mm

  - Multi-wavelength data obtained by coordinated observation

  - Umbral brightening was suggested by several models (ex. Loukitcheva et al. 2014).

  - Thus the discovery of this observation would be penumbral darkening.

  - This result can be used to constrain the model for atmosphere above the active region.



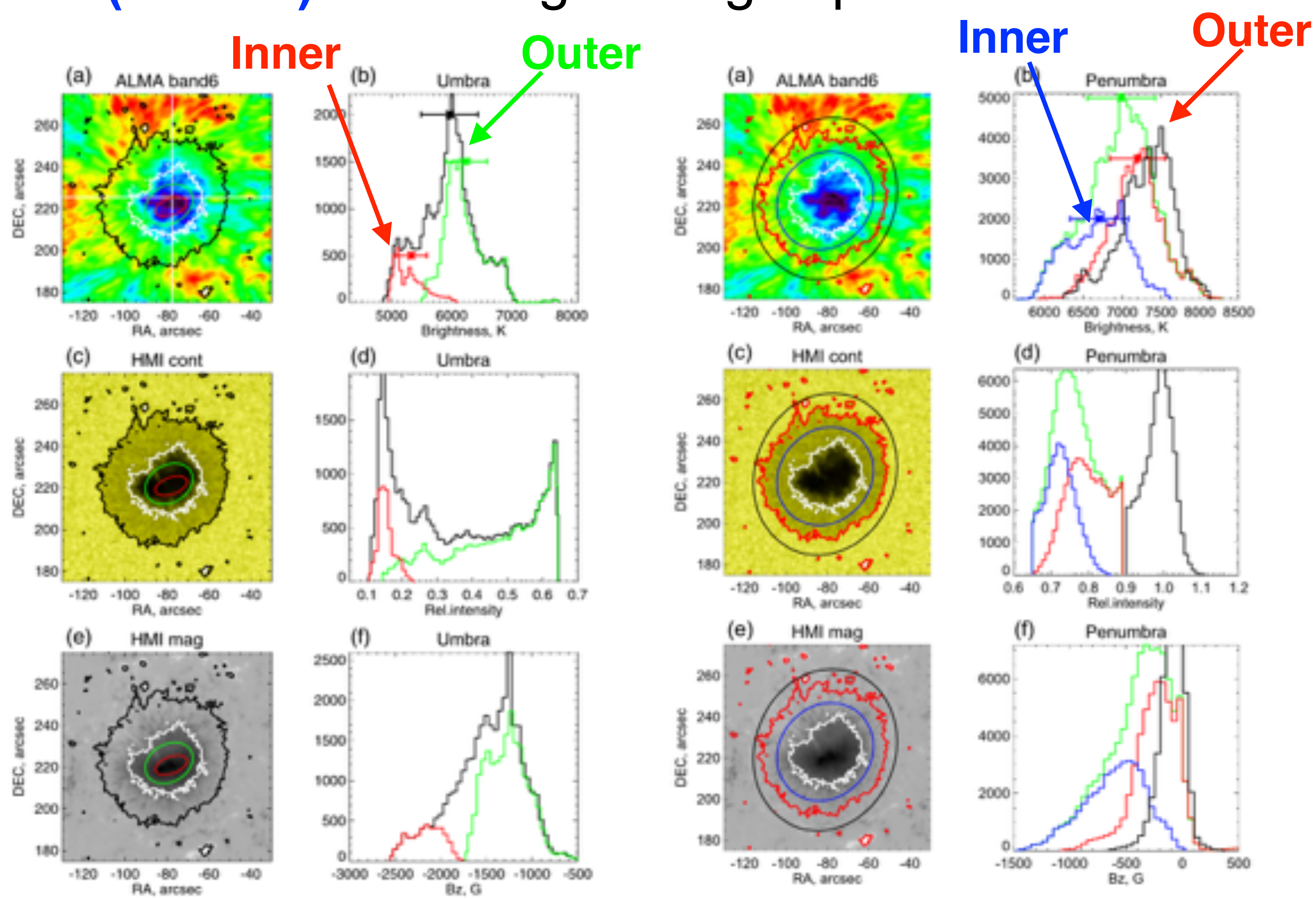
[ALMA 100 GHz mosaic, SDO continuum and magnetogram, and IRIS 1330 A image from the top]

Iwai et al. (2017), The Astrophysical Journal Letters, 841:L20

2) Umbra and penumbra brightness

- Umbra and penumbra brightness at 3 mm and 1.3 mm :constraining the chromosphere model above sunspot

  - Loukitcheva et al.(2017) presented a **darkening in umbra at 1.3 mm (Badn6) unlikely at 3 mm (Band6)** while brightening in penumbra at 1.3 mm and 3 mm.



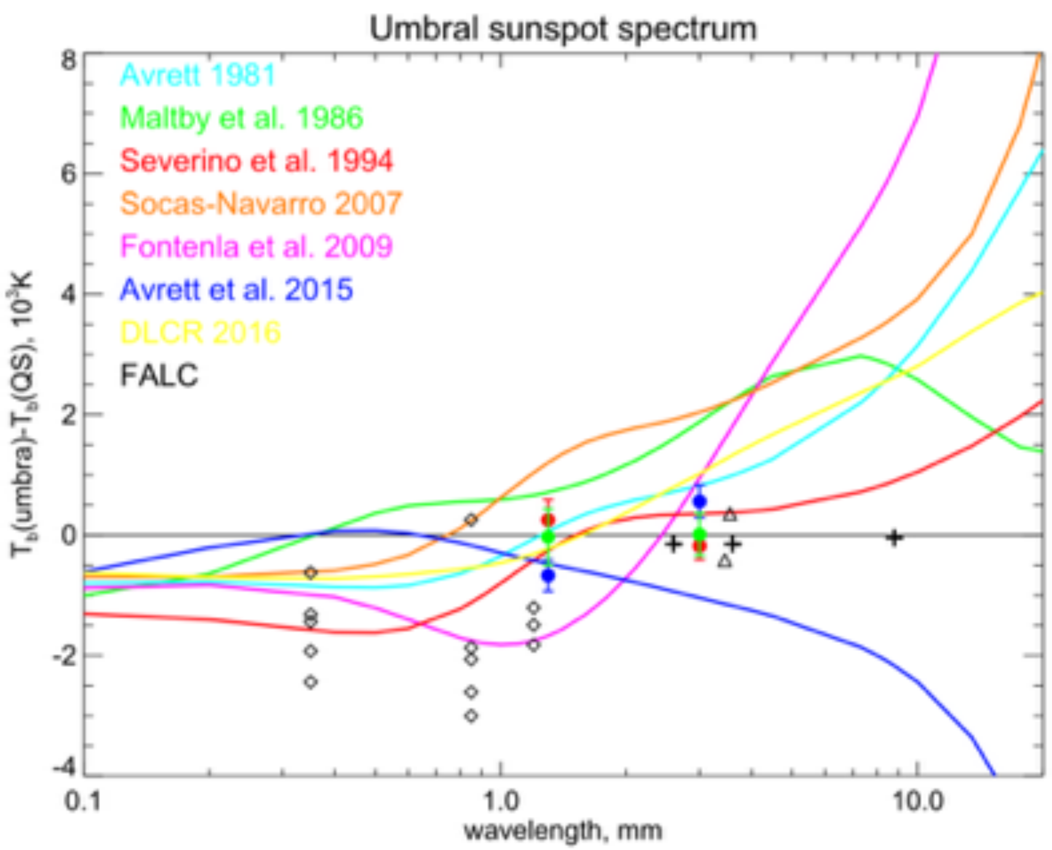
[ALMA 230 GHz mosaic, SDO continuum and magnetogram image from the top]

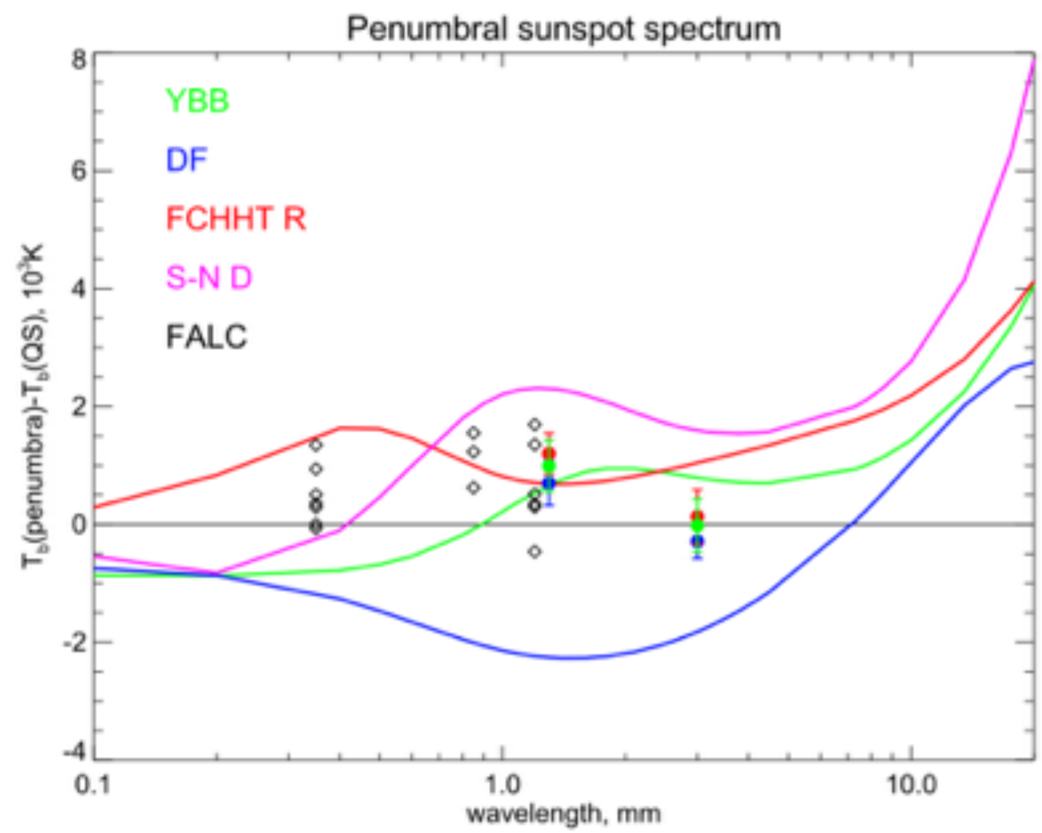
Loukitcheva et al. (2017), The Astrophysical Journal, 850:35

2) Umbra and penumbra brightness

- Umbra and penumbra brightness at 3 mm and 1.3 mm : constraining the chromosphere model above sunspot

  - Atmospheric model above the umbra has well fitted to ALAM observation, but not for the model above the penumbra.



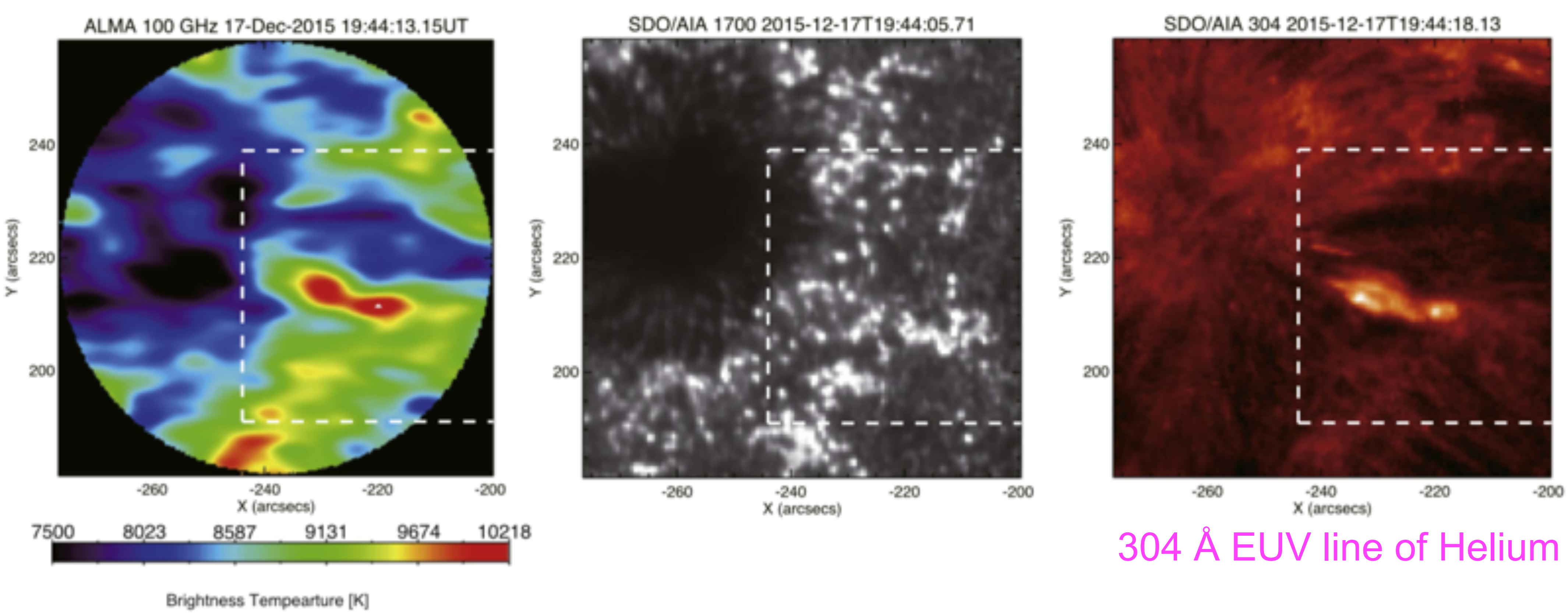


Loukitcheva et al. (2017), The Astrophysical Journal, 850:35

3) Plasmoid ejection

- Solar plasmoid ejection from X-ray bright point

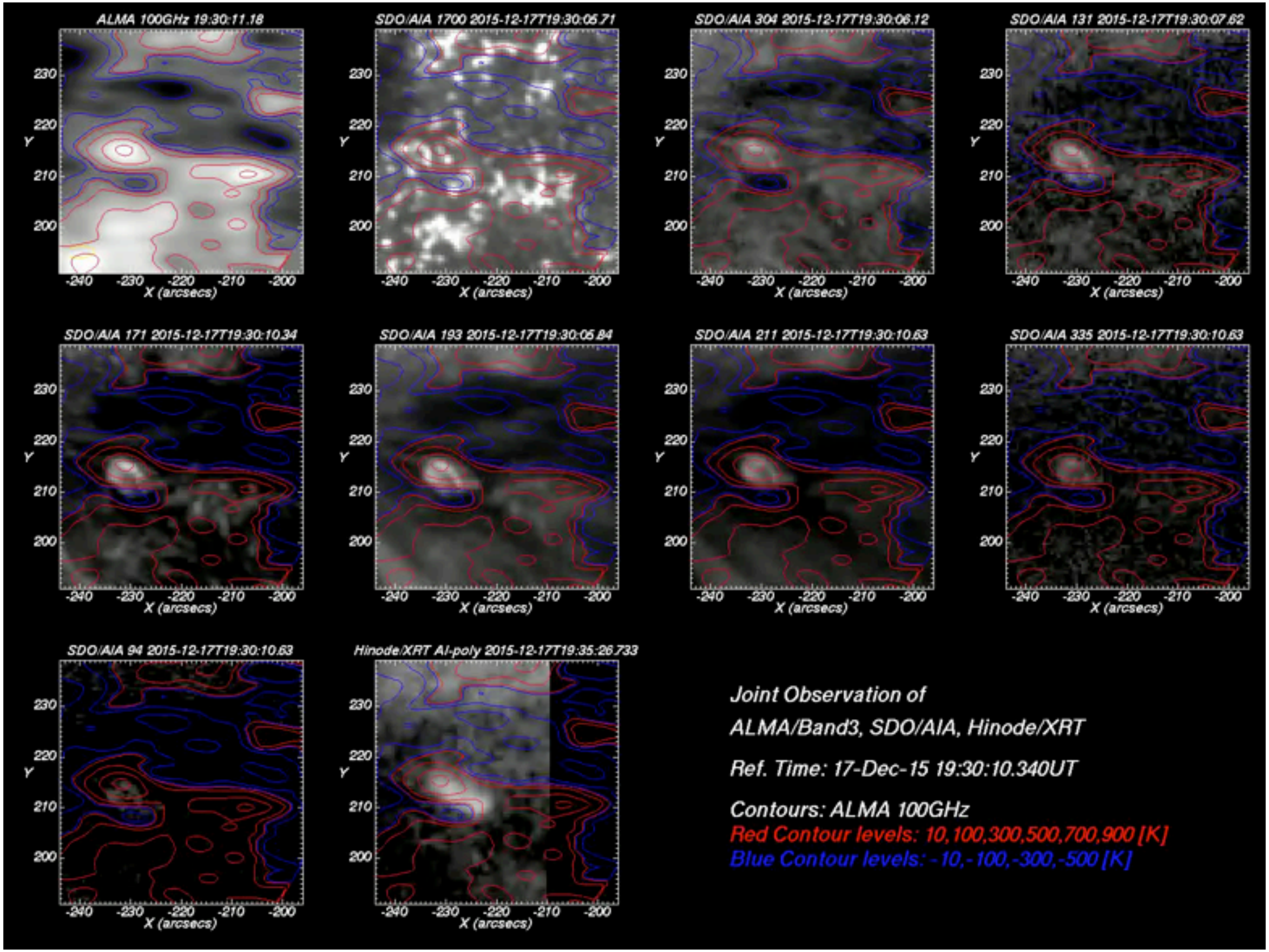
  - Shimojo et al. (2017) reported the physical parameters of the plasmoid determined by combining ALMA 100 GHz, EUV, and X-ray data.
  - As a results, they concluded that the plasmoid can consist either of isothermal ~ 10^5 K plasma that is optically thin at 100 GHz, or a ~ 10^4 K core with a hot envelope.



304 Å EUV line of Helium ~ 10^5 K

Shimojo et al. (2017), The Astrophysical Journal Letters, 841:L5

3) Plasmoid ejection



Shimojo et al. (2017), The Astrophysical Journal Letters, 841:L5

Summary

- The ALMA SV data has proved that the ALMA show us the new view of the solar chromosphere and dynamics.

- Several investigations for the chromosphere and chromospheric features using ALMA SV data are underway together with numerical modelling.

- The ALMA has a high potential for future science with new functions for the solar observation:
  ✓ Band7 and Band9, and fast band switching
  : Tomography of the chromosphere
  ✓ Polarimetry: Magnetic field of the chromosphere
  ✓ Spectral line: Radio recombination line, ex. CO

Thank you for your attention

Cycle5 selection statistics: Sun

Table 3. Number of proposals and Grade A & B projects by proposal type

Proposal Tye	Number Submitted	Number Grade A & B	Acceptance Rate (%)
All	1661	433	26
ACA (Standalone or with 12-m Array)	347	80	23
ACA Standalone	61	16	26
Large Programs	22	4	18
Polarization	100	30	30
Solar	36	16	44
Solar System	42	16	38
Target of Opportunity	22	11	50
VLBI	15	10	67