Rosseland Centre for Solar Physics

Multispectral Observations of the Sun: Infrared to Millimeter Wavelengths

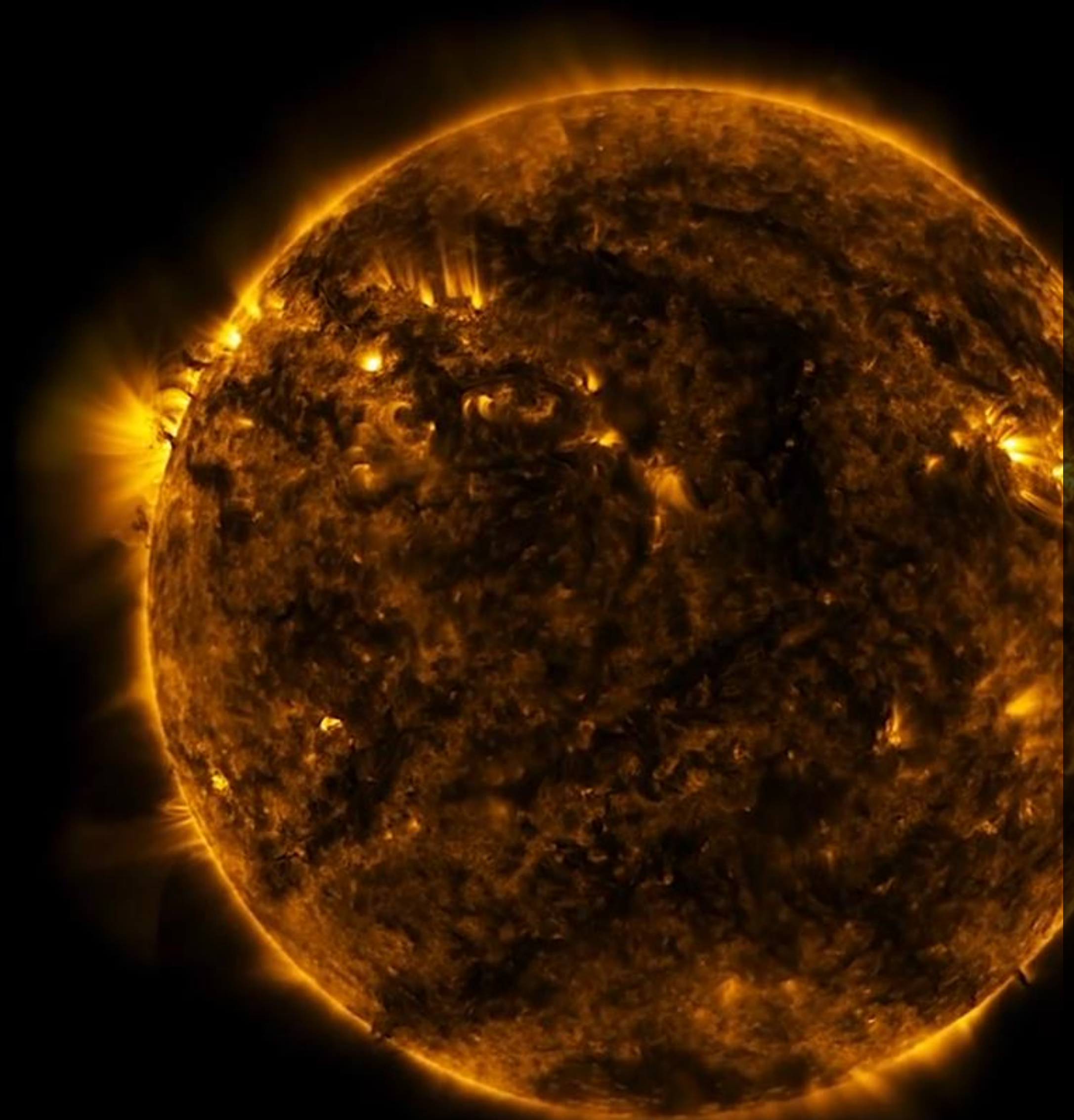
Sven Wedemeyer

Rosseland Centre for Solar Physics, Institute of Theoretical Astrophysics
University of Oslo, Norway

Presented at
Future Role of FIR-Submm Space Observations Defining
Urgent Science and Instrumentation, Leiden, 2025

ALMA, SDO/NASA

Introduction



Solar Dynamics Observatory SDO/NASA

- The solar atmosphere:
  - Stratified, varies with height
  - Highly dynamic
  - Intermittent
  - Dynamically coupled
- Structured on a large range of spatial scales
  (even below current limit of ~0.1″)
- Plethora of processes.
- The Sun is dynamic on **short timescales.**

➢ Observations different than for many other astronomical objects.

➢ Can create challenges when using general purpose instruments

Solar Science Cases

UNIV. OF OSLO
SVEN WEDEMEYER

R C S

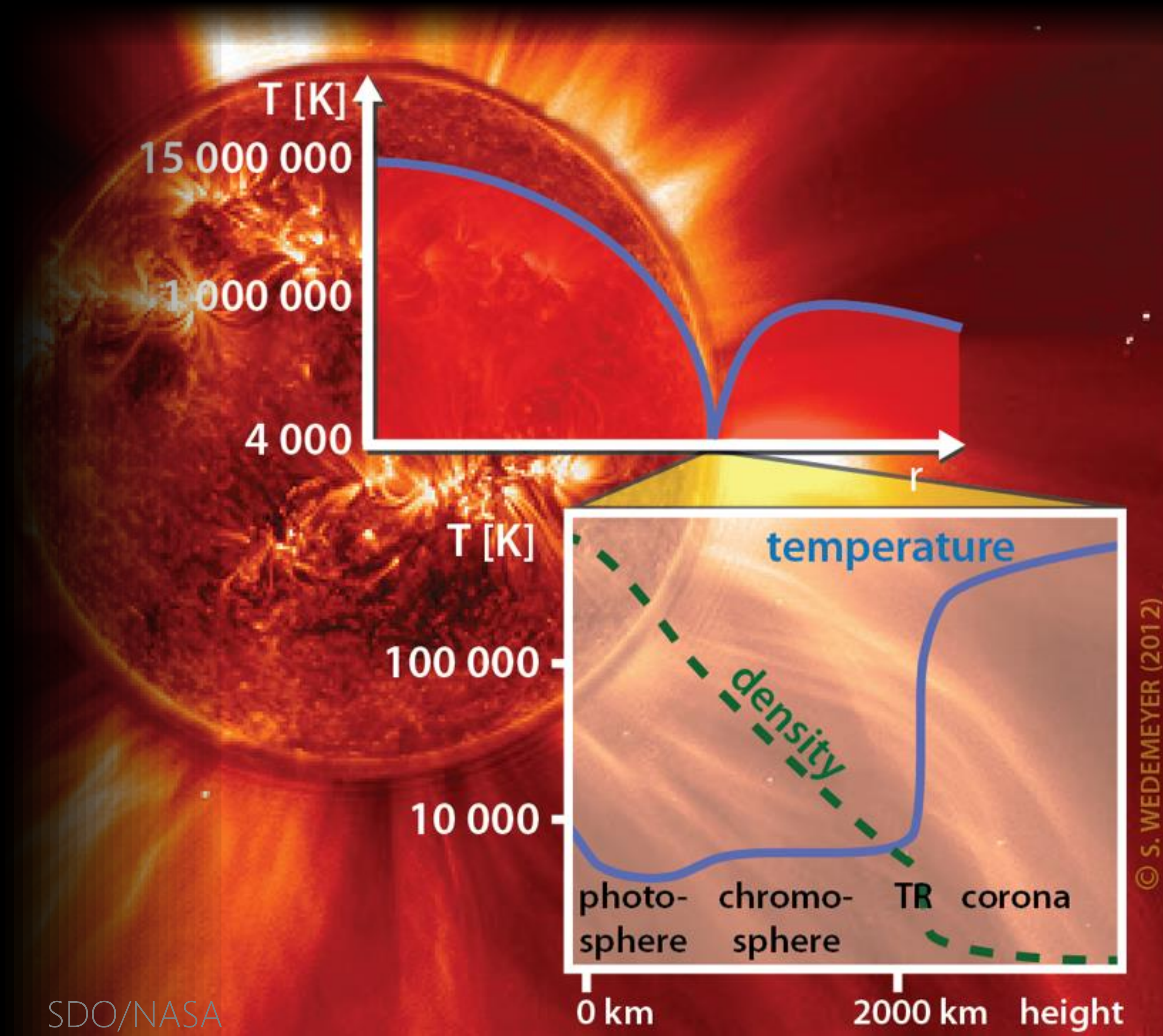
Wedemeyer et al. 2016, Space Reviews, 200, 1Science

- Essential for the Sun’s atmosphere as a complex and dynamic object: **3D time-dependent thermal, kinetic and magnetic structure**
- **Coronal/chromospheric heating problem:** Why are the outer layers of the Sun so hot? (T > 10^6 K!)

- A long-standing central problem in solar / stellar astrophysics (known and unsolved for > 80 yr)

➢ How are the outer layers heated?

➢ Applies to (solar-like) stars in general

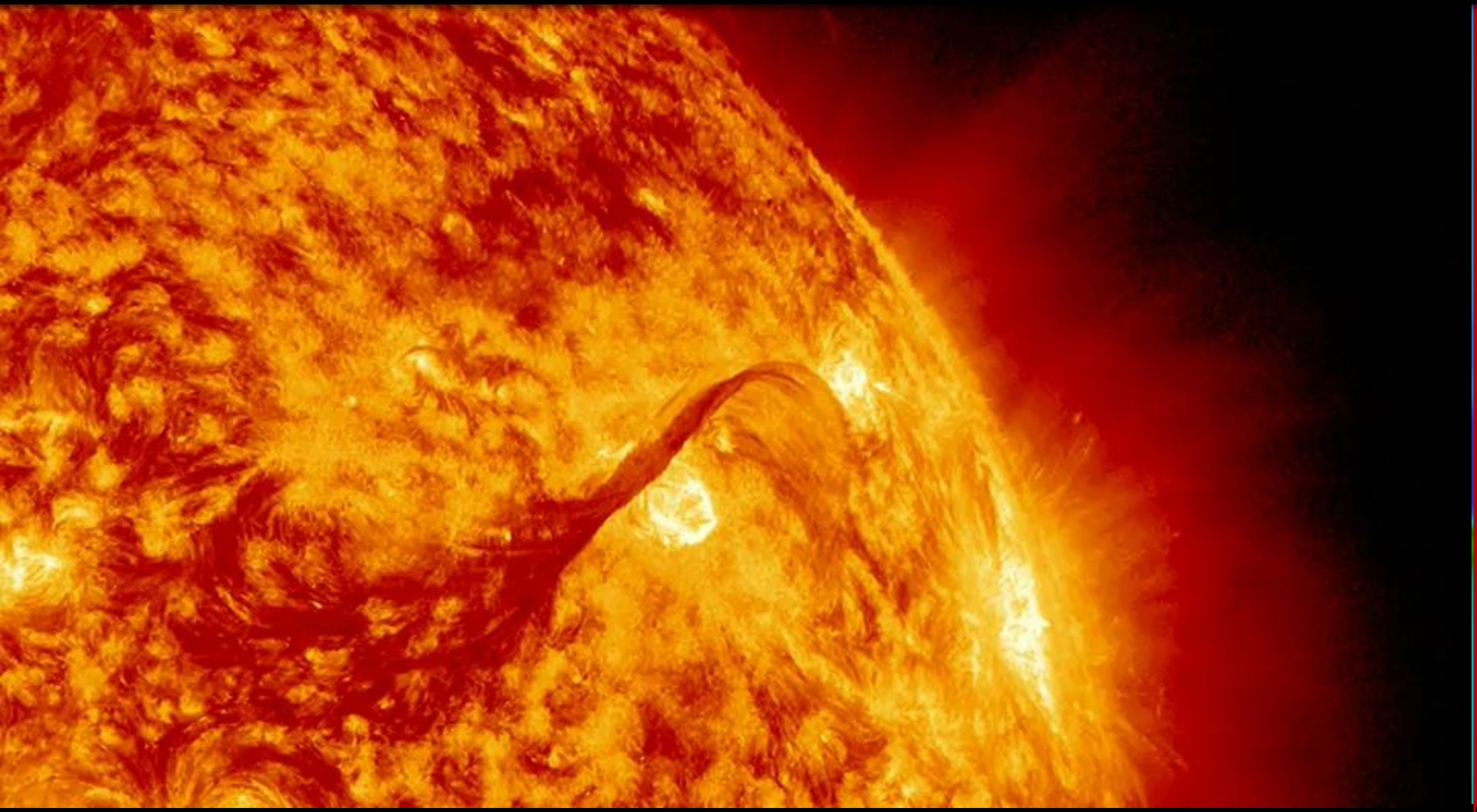


Solar Science Cases

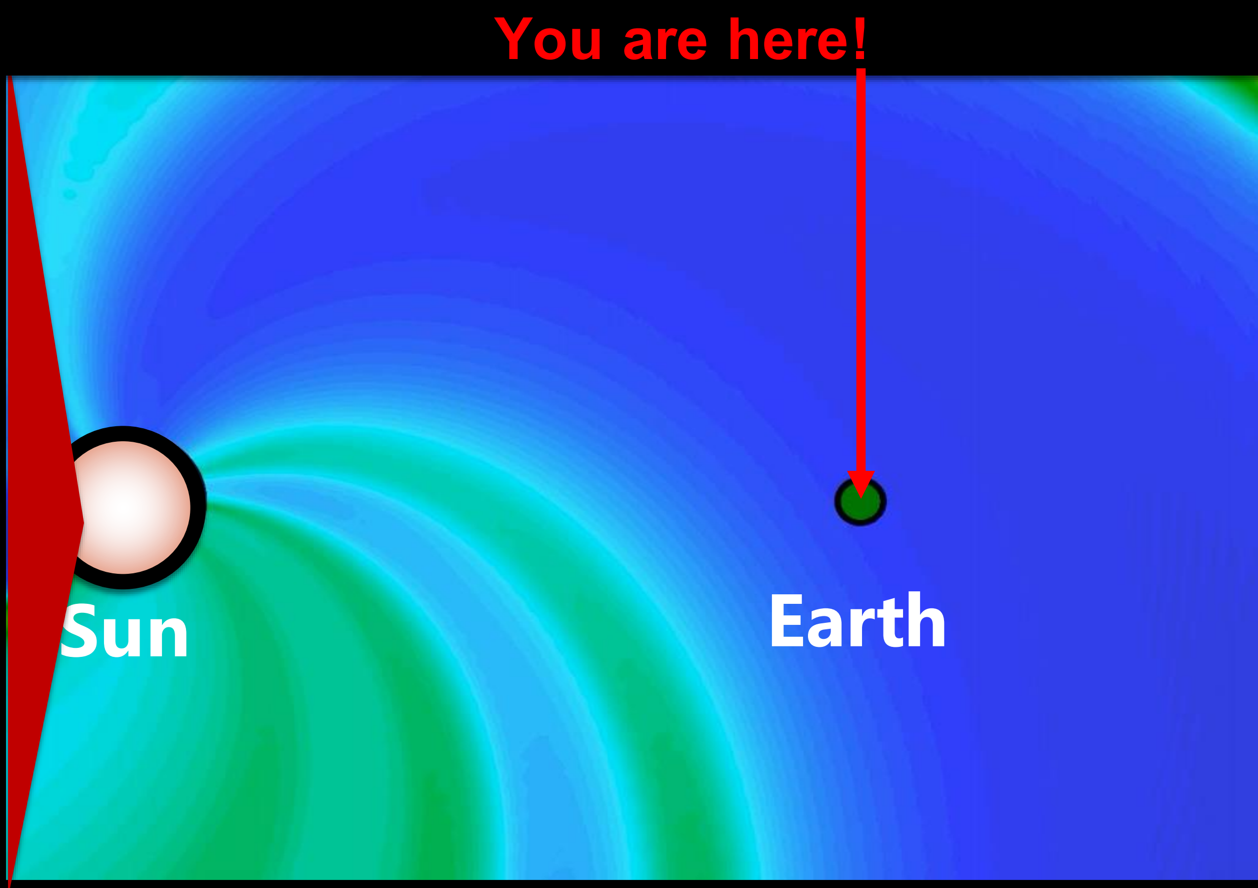
UNIV. OF OSLO
SVEN WEDEMEYER

R C S

- Energetic events – The Sun as the source and driver of space weather
- Solar flares, coronal mass ejections, solar wind
- Impact on technological infrastructure (power grids, satellites etc)
- Input from the Sun poorly understood, making current forecasting unreliable
- ➢ Implications for other stars, exoplanet habitability



SDO/NASA

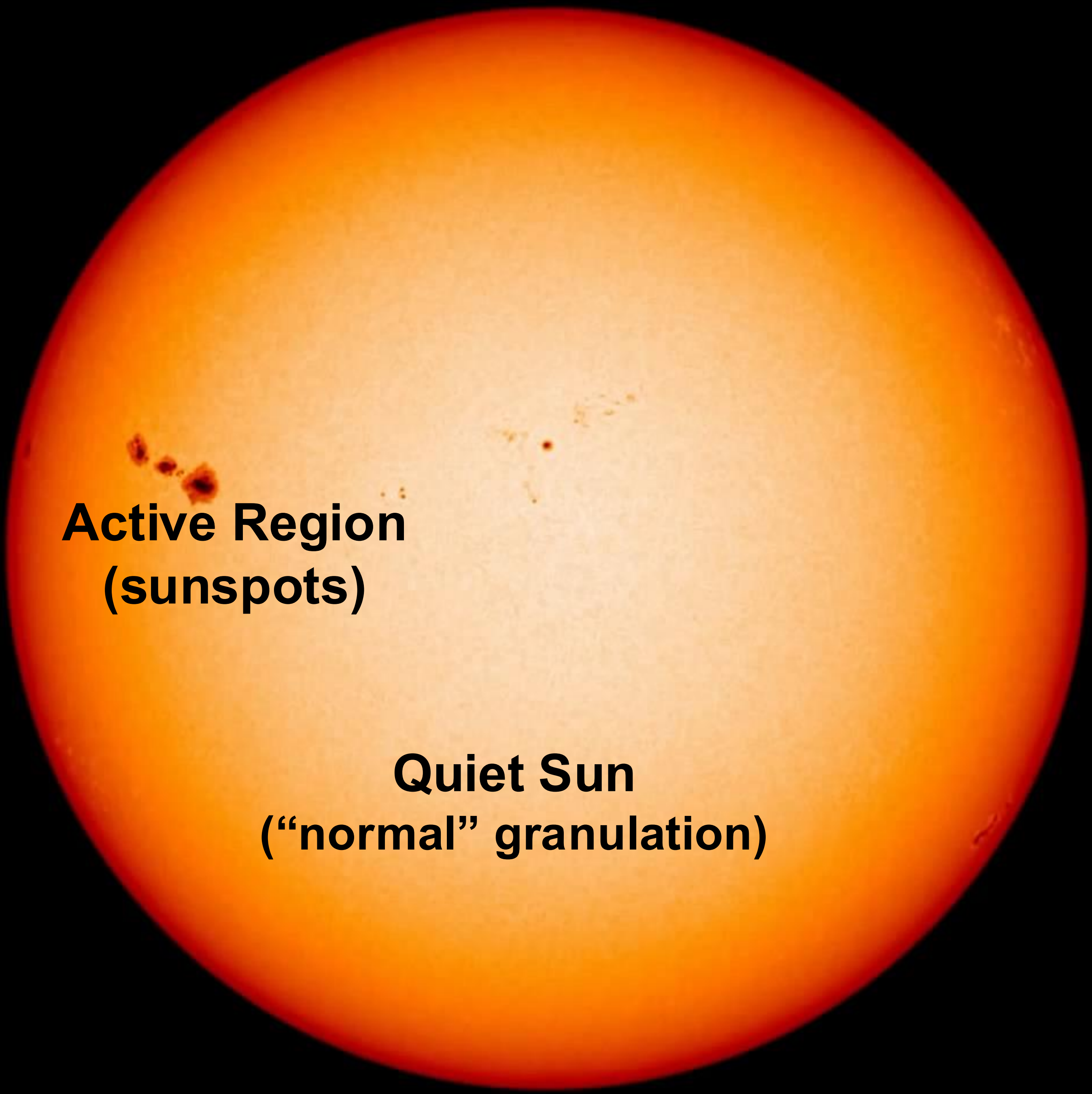


WSA-Enlil advanced forecast model,
NWS Space Weather Prediction Center

Instrumental requirements

How to observe the Sun?

- Different continua and spectral lines probe different plasma properties in different domains/layers
- Multi-wavelength co-ordinated space-borne/ground-based campaigns as standard in modern solar physics

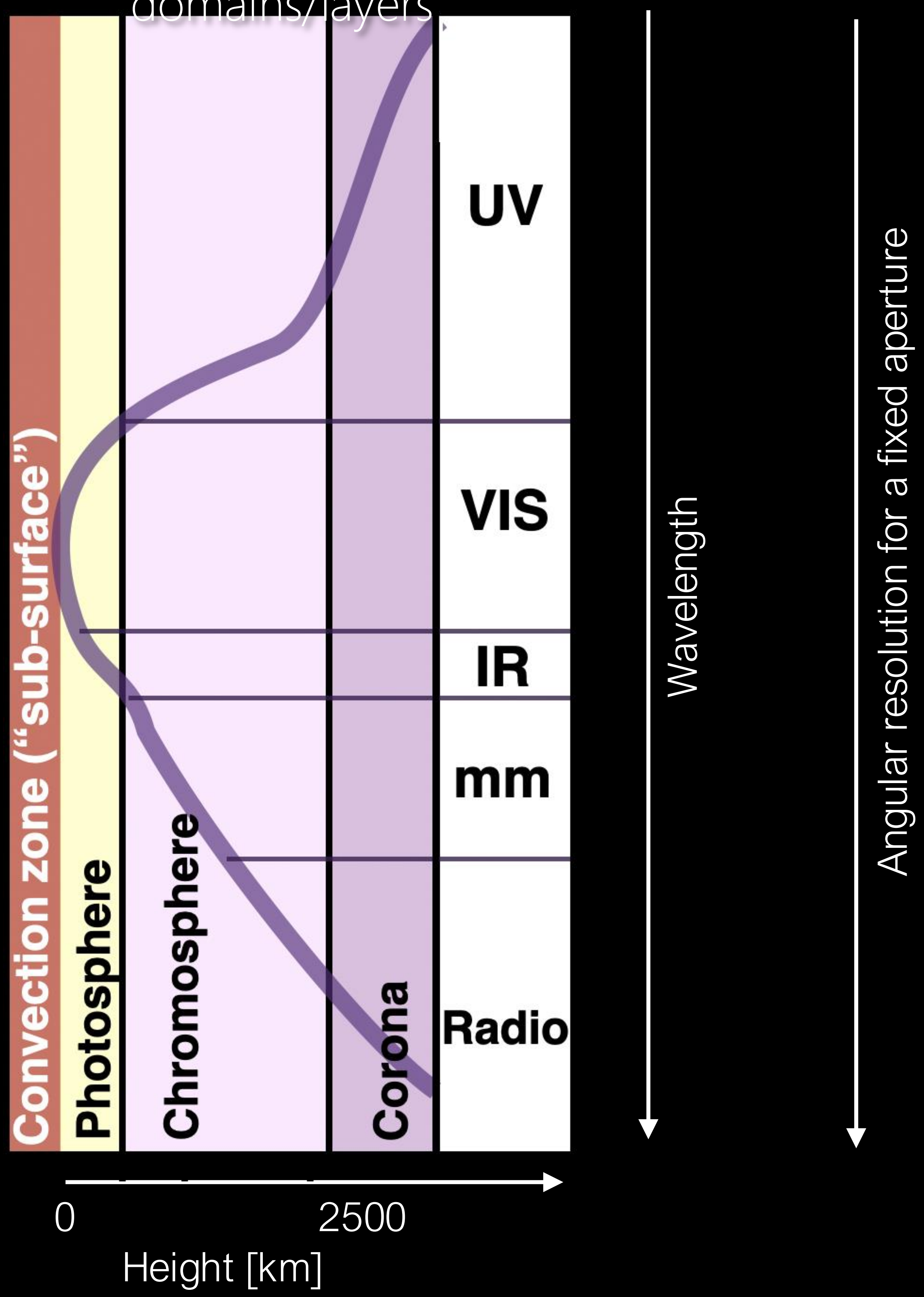


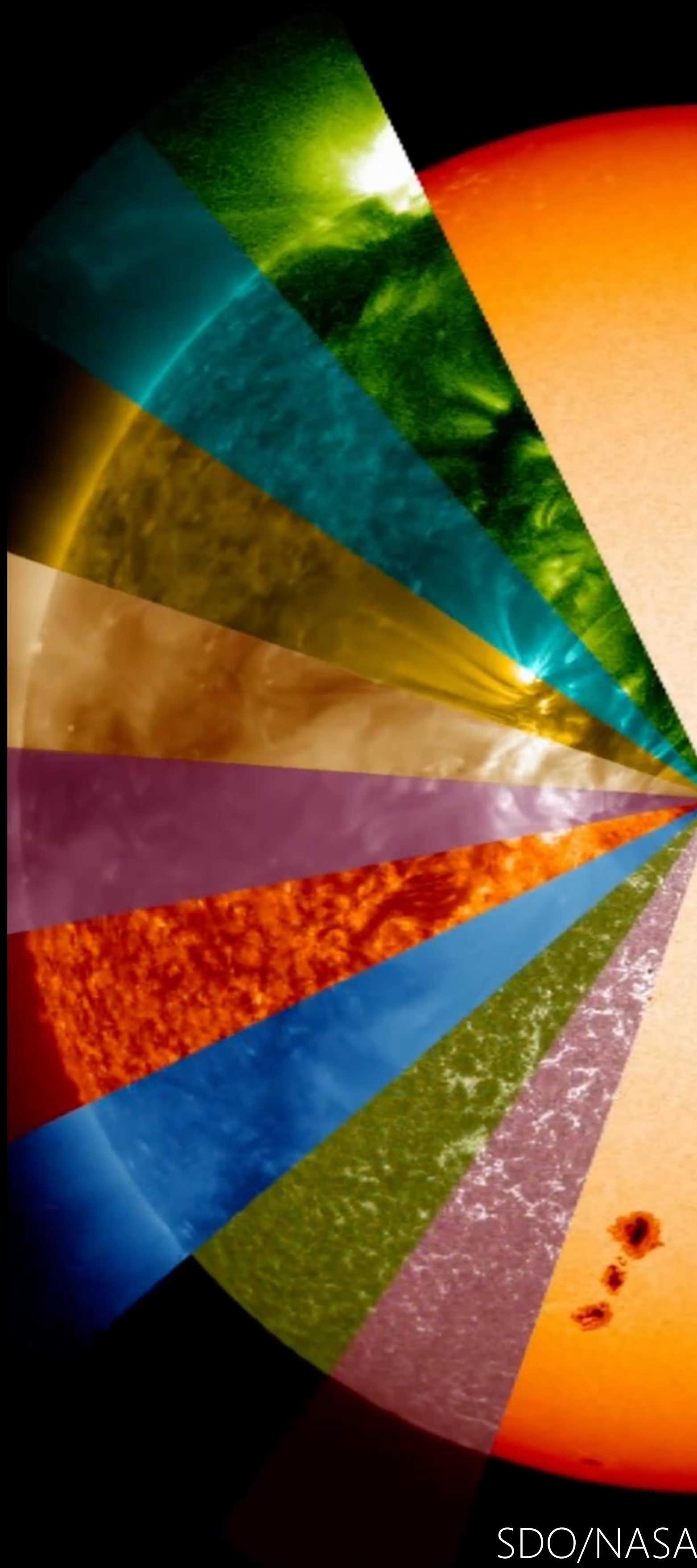
Solar Dynamics Observatory SDO/NASA

How to observe the Sun?

UNIV. OF OSLO
SVEN WEDEMEYER

- Different continua and spectral lines probe different plasma properties in different domains/layers

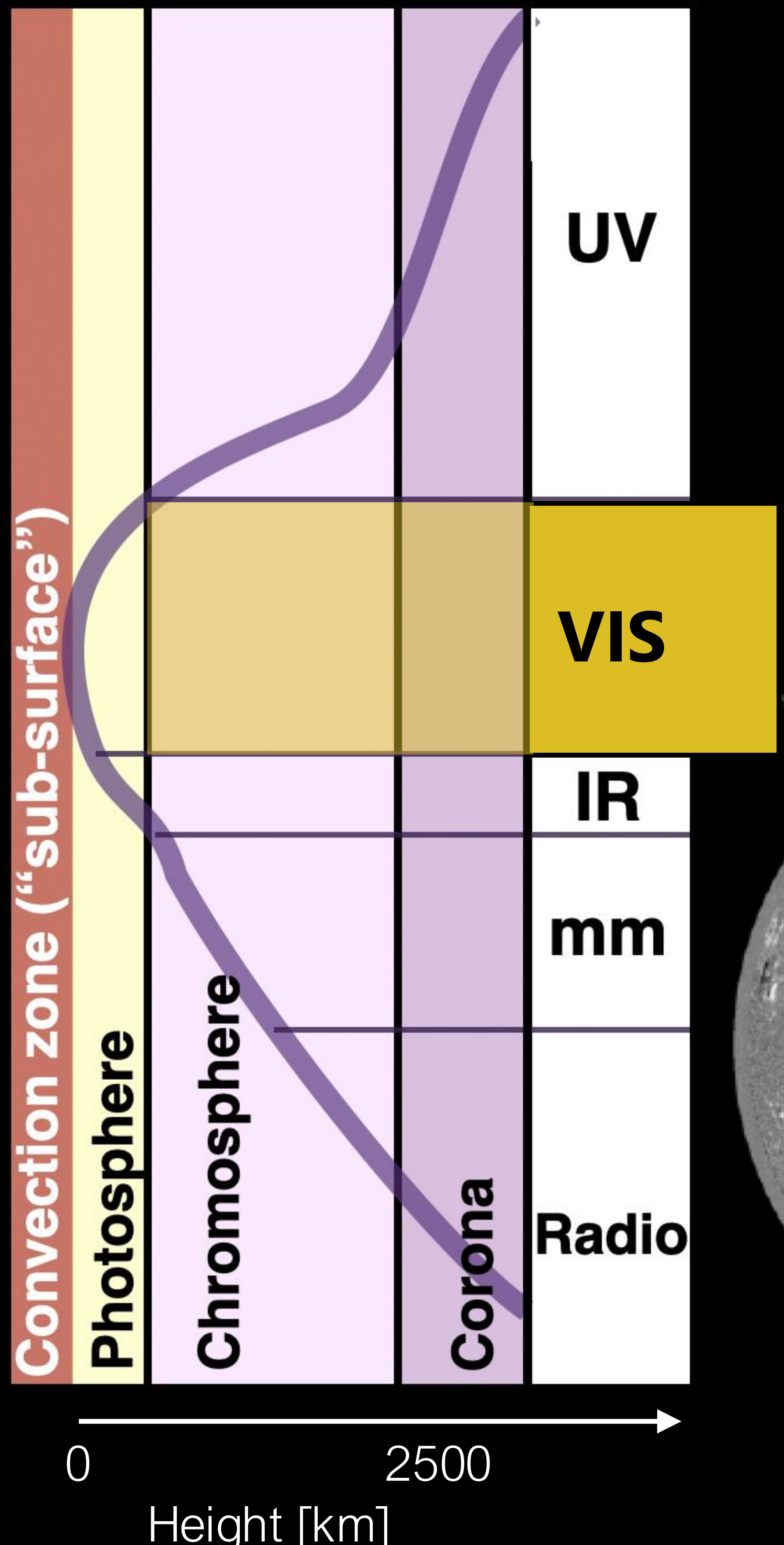


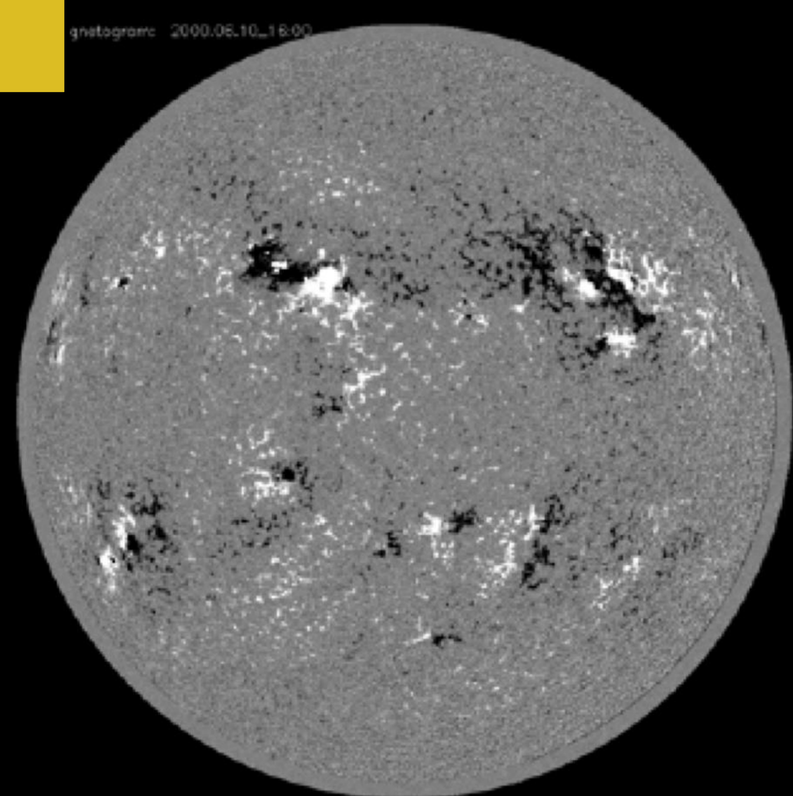


How to observe the Sun?

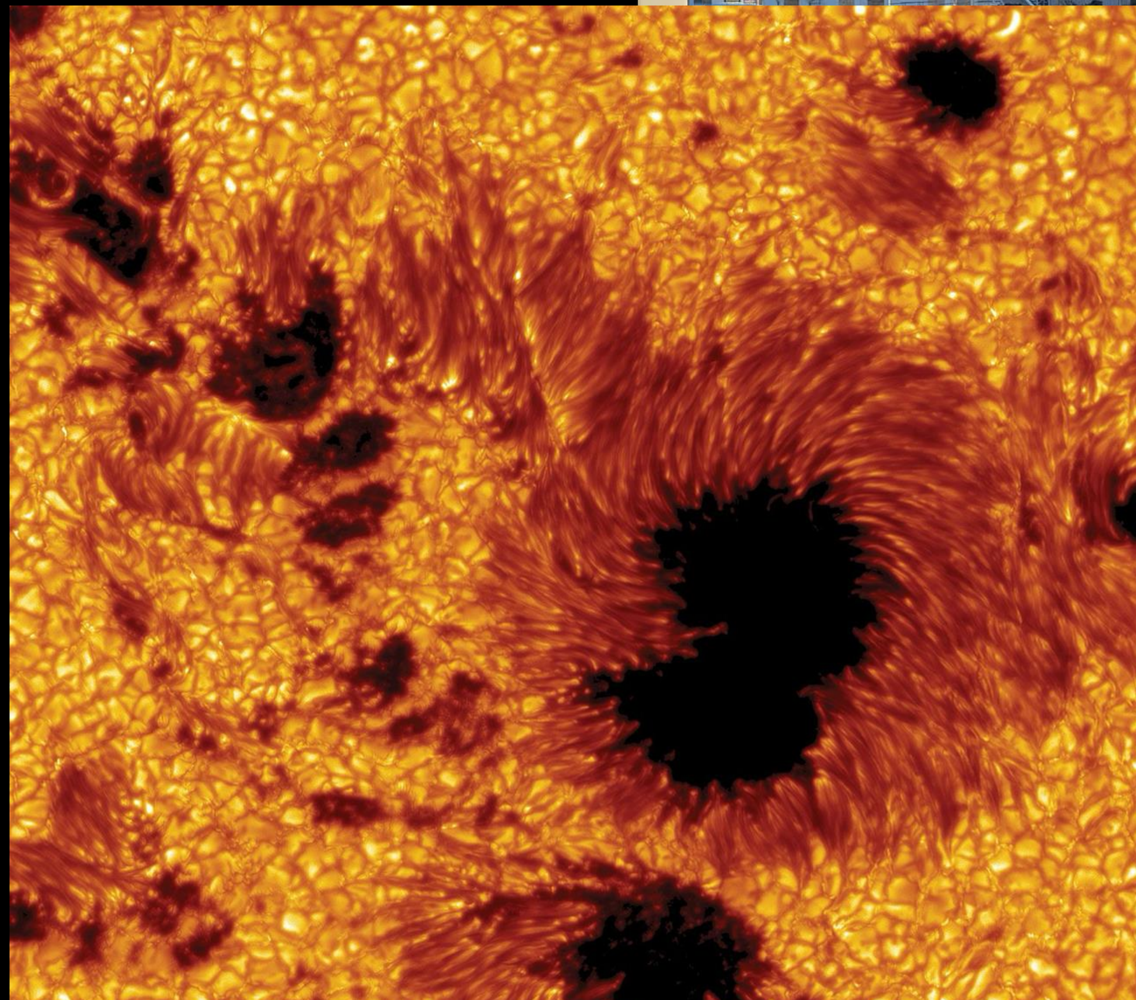
Visible

- Covered well with ground-based and space-borne instruments
- Continuum, spectral lines, magnetograms
- 4m-class telescopes:
  - DKIST (Hawaii, first light in 2019)
  - European Solar Telescope (proposed)
- 24/7 monitoring from space



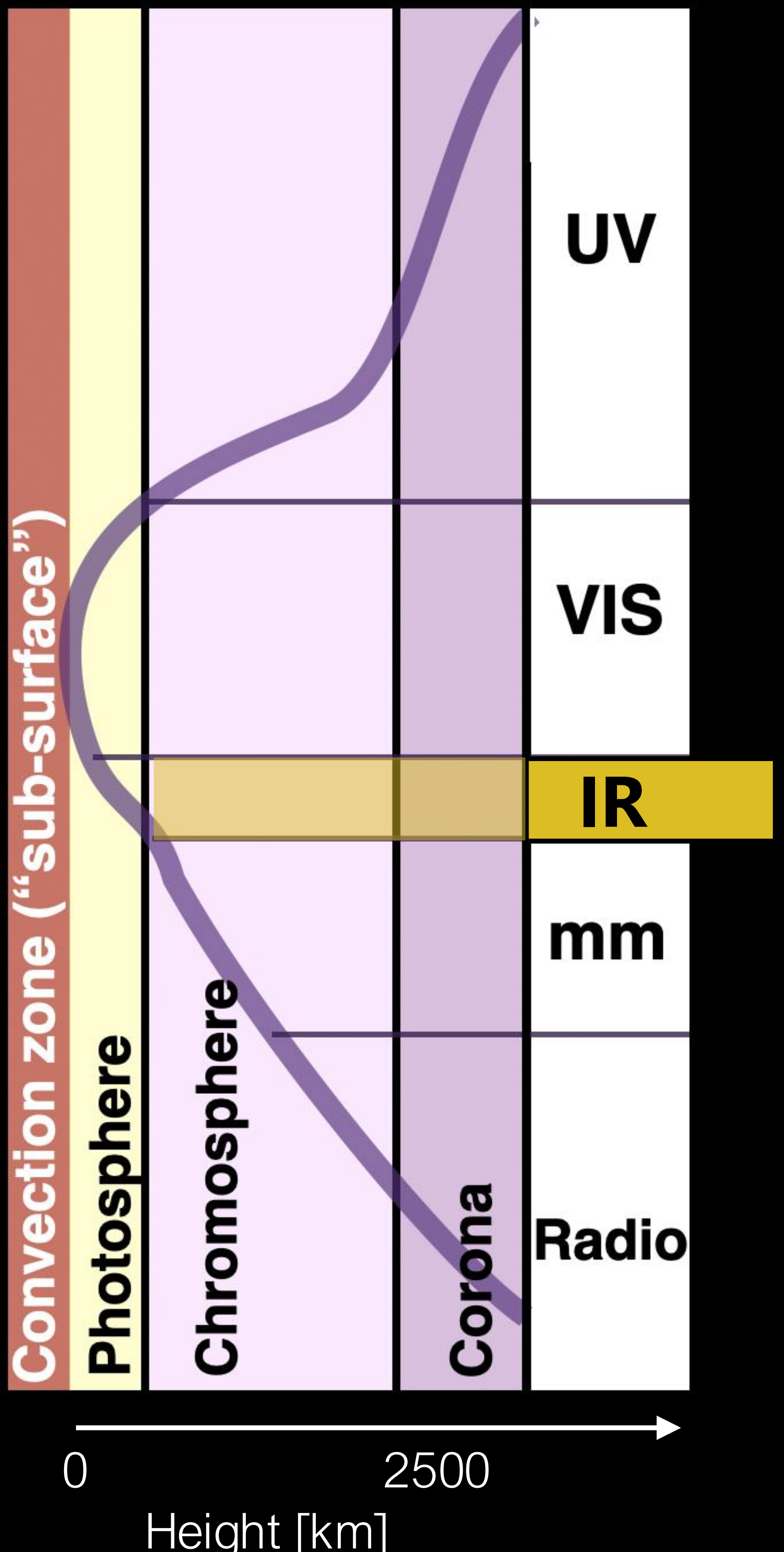


Magnetogram – SDO



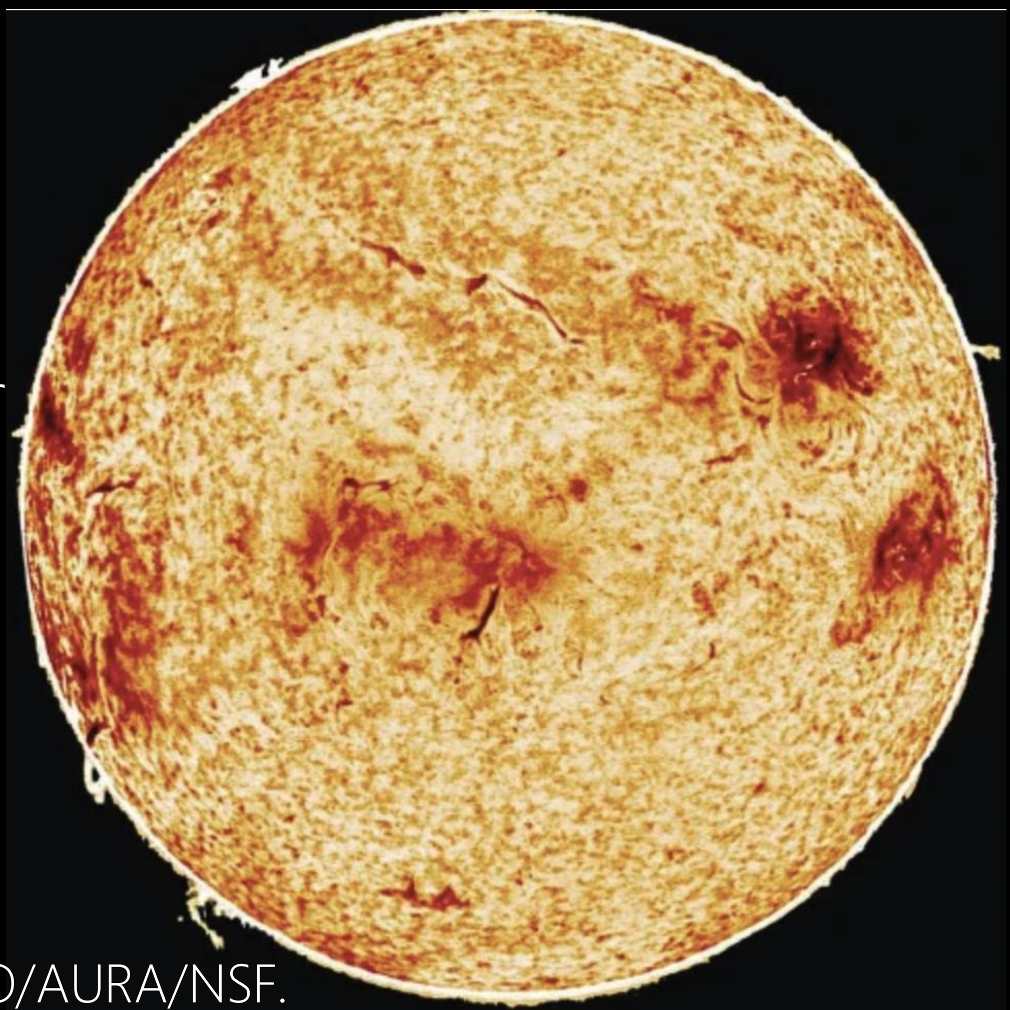
How to observe the Sun?

Infrared



- Ground-based telescopes
- Typically only up to a few micron (except for, previously: McMathPierce telescope up to 21 micron)
- CO lines – temperature constraints
- Helium 10830 Å – magnetic field in the upper atmosphere
- Maps the middle photosphere, convective overshooting dying off with height
- 10-300 micron maps upper photosphere:
  - ➢ Less structure
  - ➢ Less scientifically interesting

Helium 10830 Å



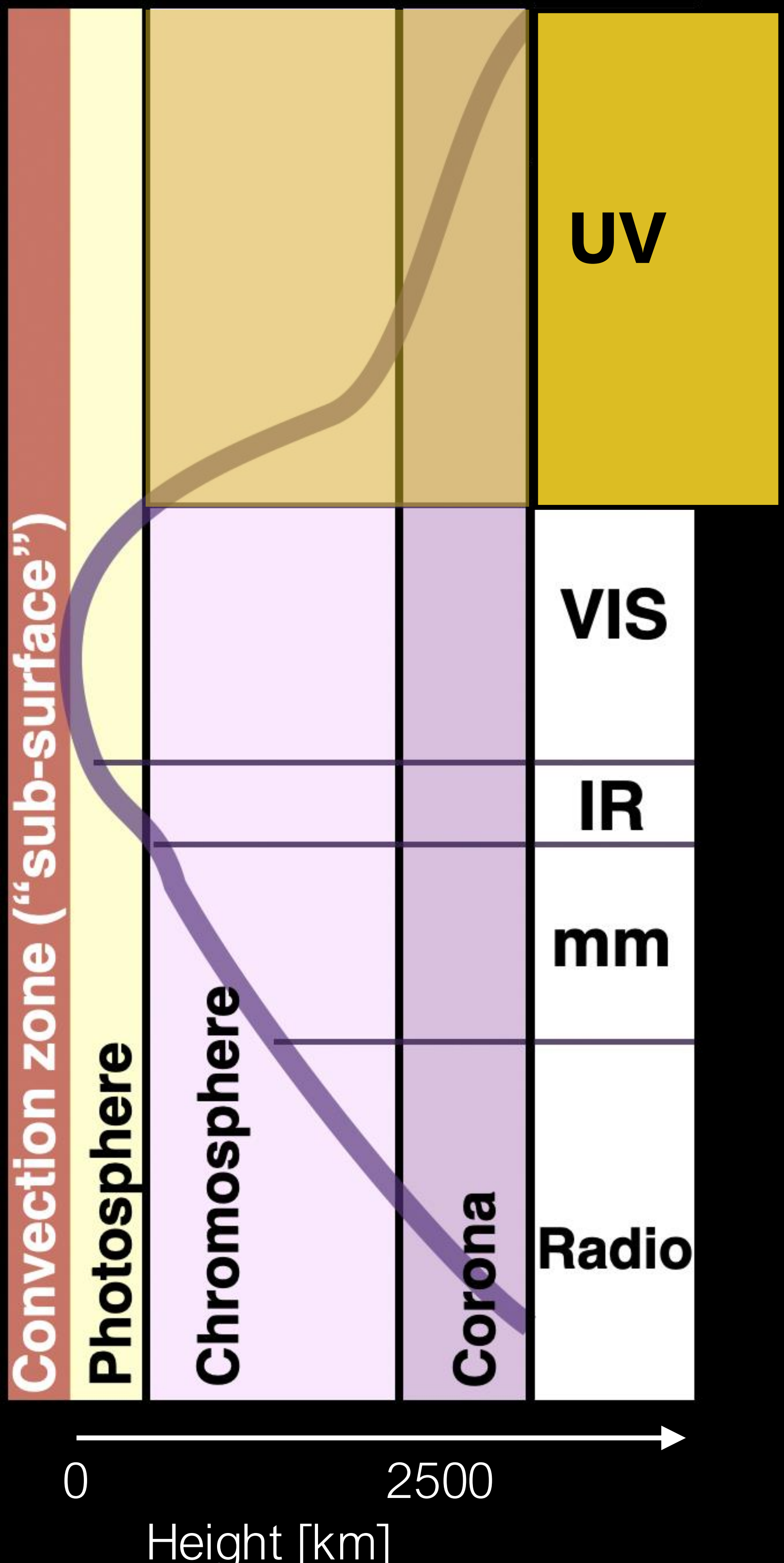
Credits: NSO/AURA/NSF.

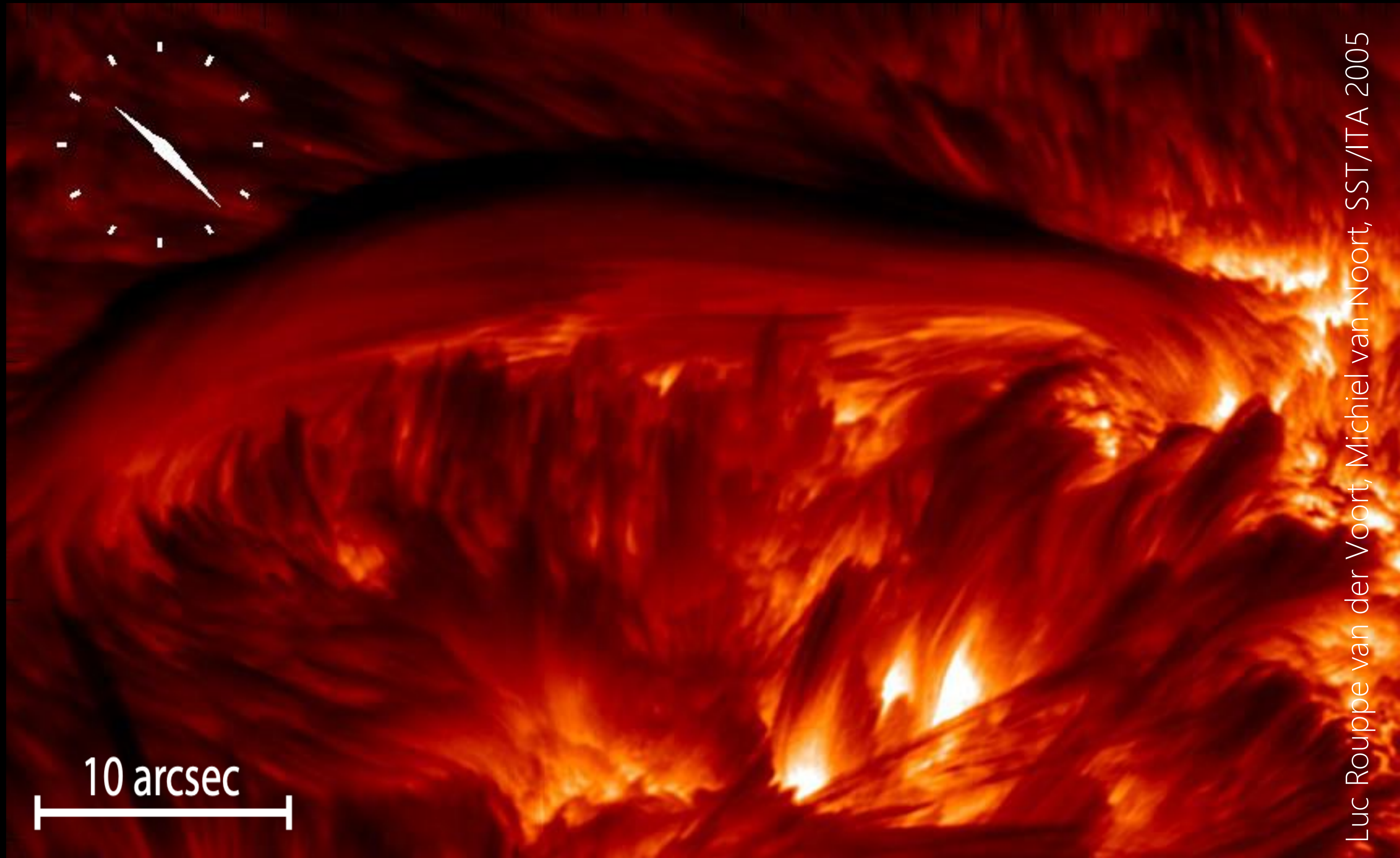
How to observe the Sun?

UNIV. OF OSLO
SVEN WEDEMEYER
R C S

Ultraviolet - continuum and spectral lines

- Few suitable diagnostics for the chromosphere
- Space-borne telescopes – limits aperture and thus resolution
- Complicated formation mechanisms and non-equilibrium effects (e.g., ionisation, non-LTE)
- ➢ Uncertainties for the derived chromospheric plasma properties (like temperatures)!
- ➢ Interpretation difficult.

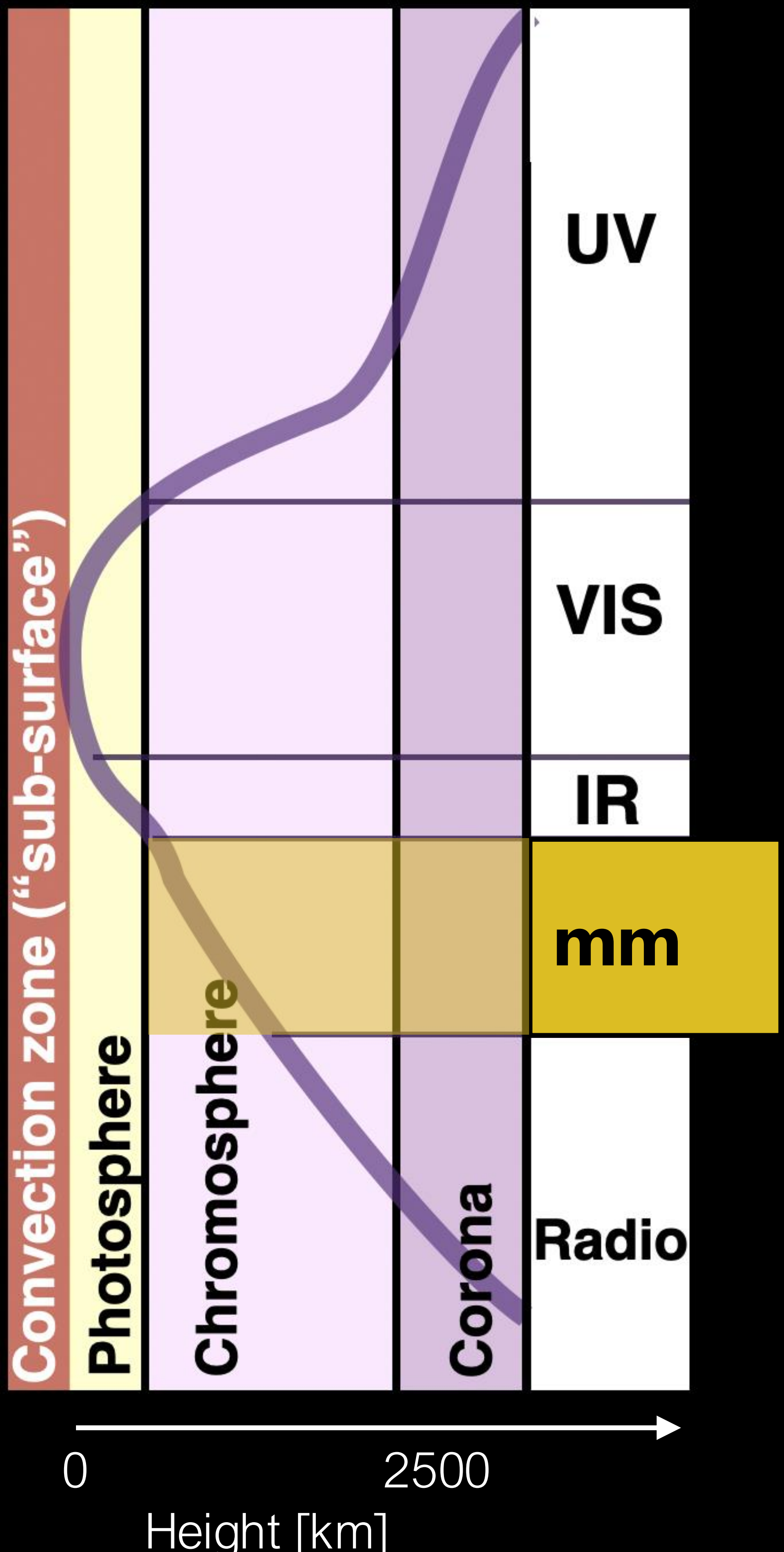




How to observe the Sun?

UNIV. OF OSLO
SVEN WEDEMEYER

R C S



mm wavelengths

- mm continuum as chromospheric diagnostic at high cadence (1s) and (relatively) high angular resolution
- Measured brightness temperature closely related to the (electron) temperature in the continuum-forming layer
  - Formation height increases with wavelength
- High spatial + temporal + spectral resolution = big leap!
- Polarisation: Local magnetic field (offered for Band 3, first regular observ. in 2024)

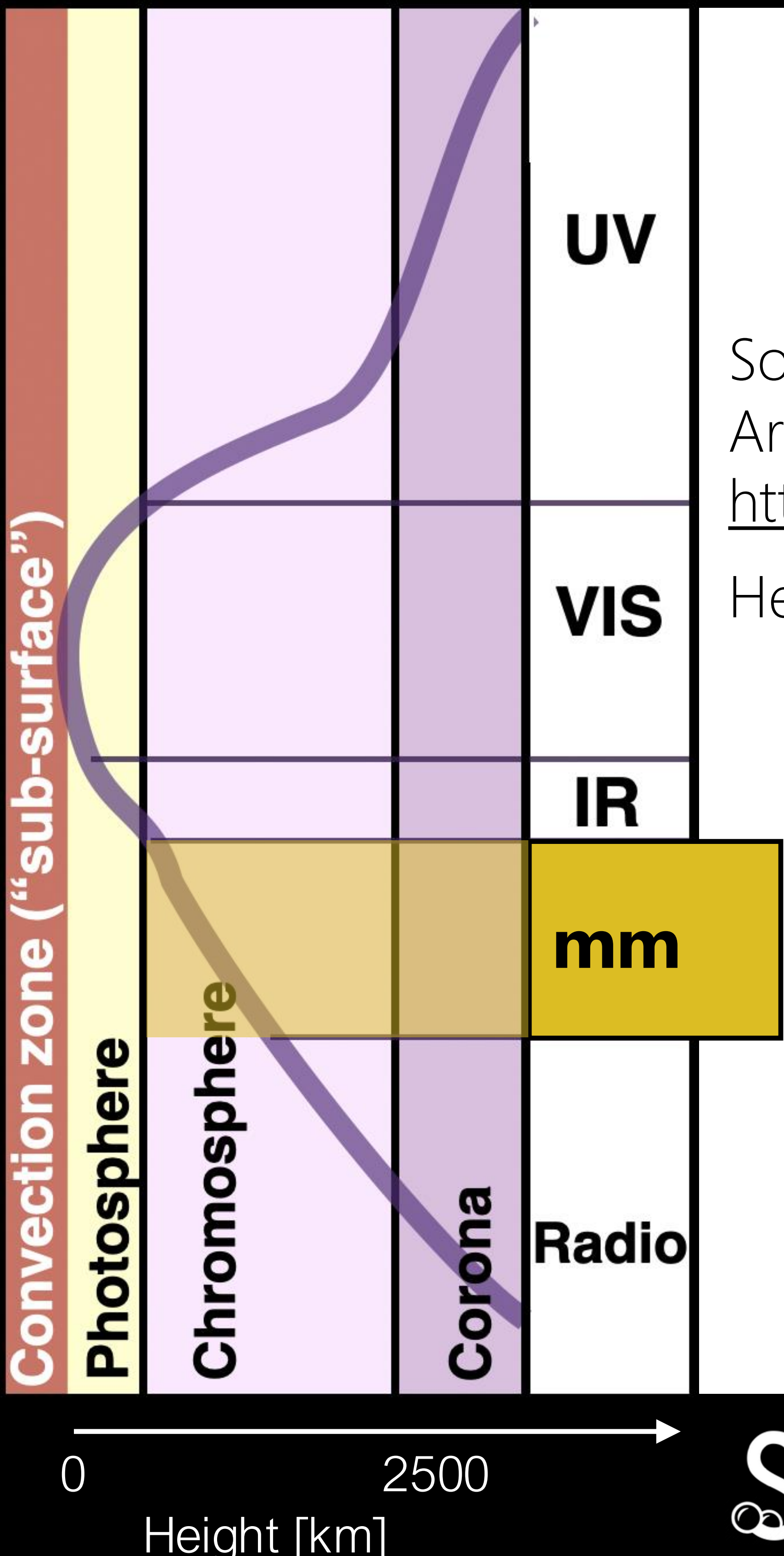
- Remaining challenges:
  - Absolute brightness temperatures (TP calibration)
  - Sparse uv coverage for snapshot imaging (target changes fast!)
  - Only one receiver band at a time (small height range!)
  - Too little observing time ...

UNIV. OF OSLO
SVEN WEDEMEYER

R C S

How to observe the Sun?

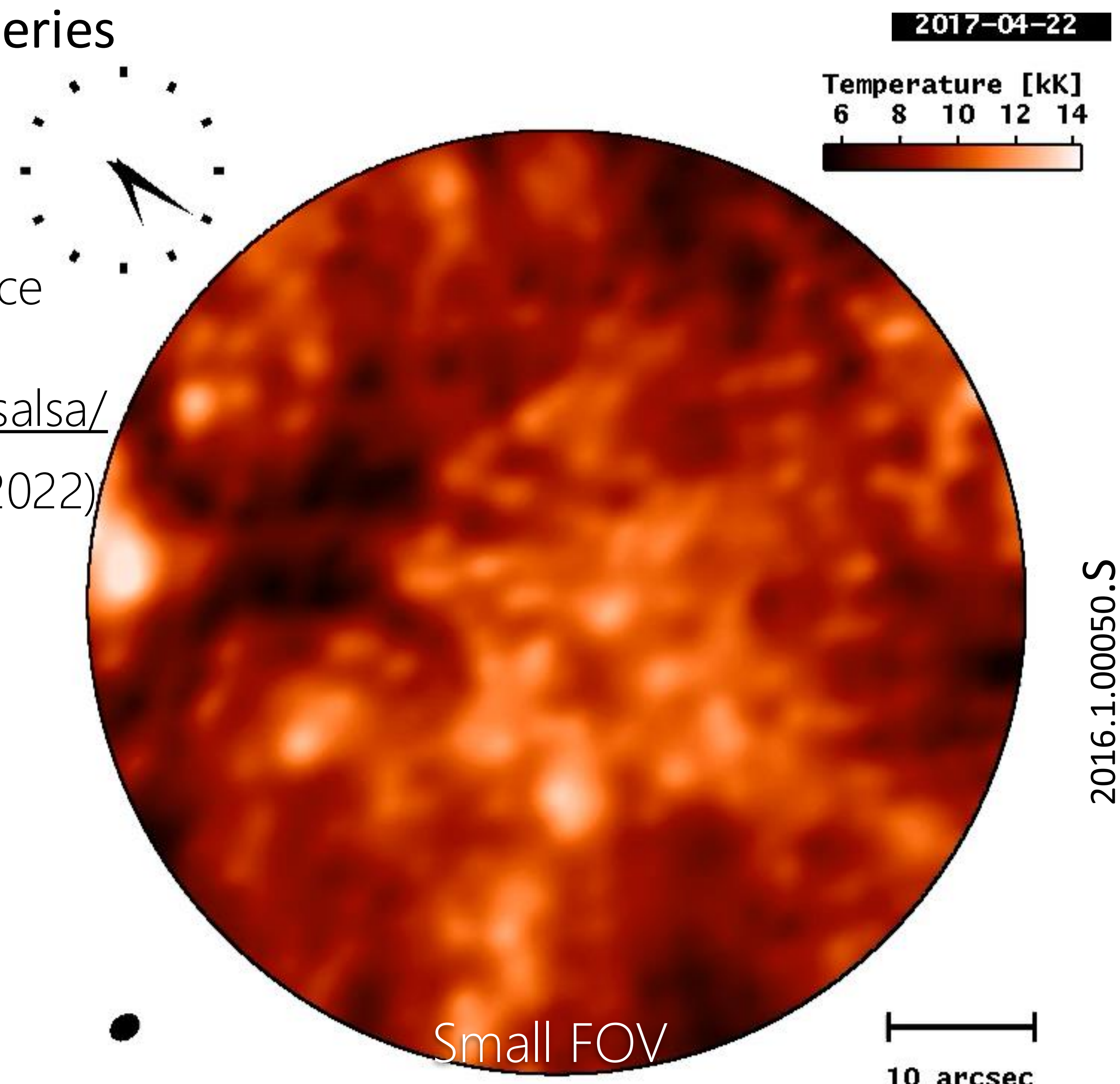
mm wavelengths



Band 3 time series

Solar ALMA Science Archive
http://sdc.uio.no/salsa/

Henriques et al. (2022)



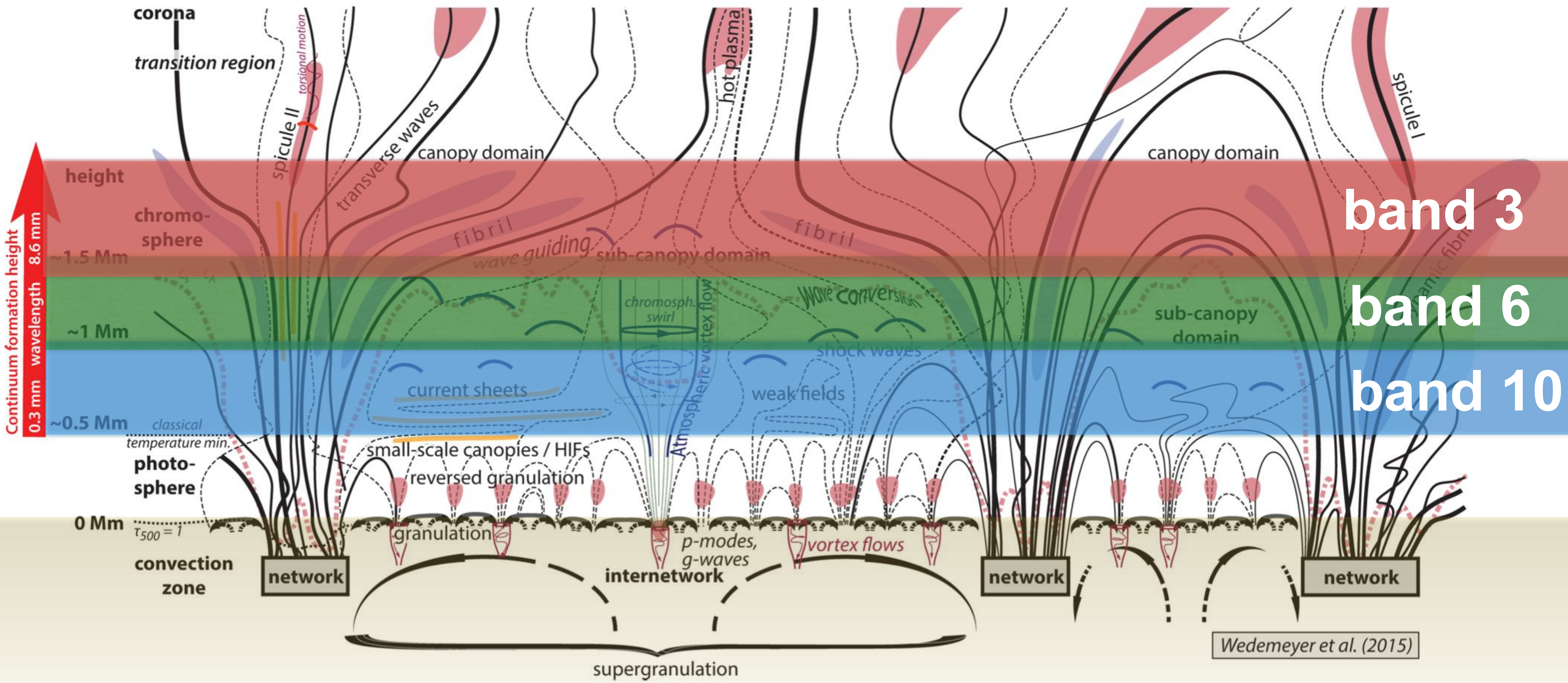
Small FOV
Not the whole Sun!

This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 682462).

wavelengths

- Multi-band observations for atmospheric tomography
  - ➢ Time-dependent 3D thermal structure of the atmosphere
  - ➢ How can this be achieved?

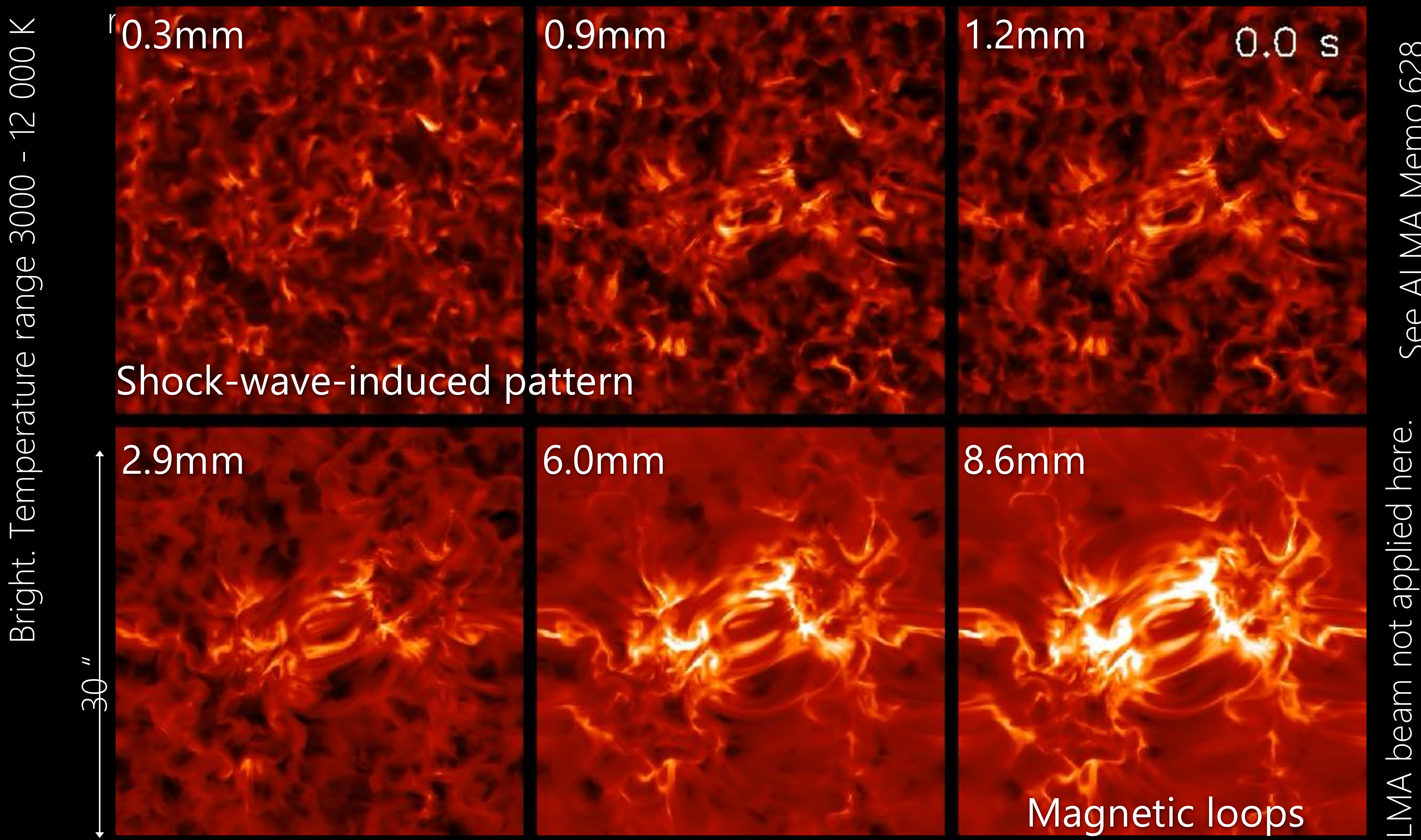
Probed atmospheric height increases with wavelength



- **Fast cycling** through up to 3 ready receiver bands (currently not possible with ALMA
  - ➢ Mapping different layers in the chromosphere quasi-simultaneously

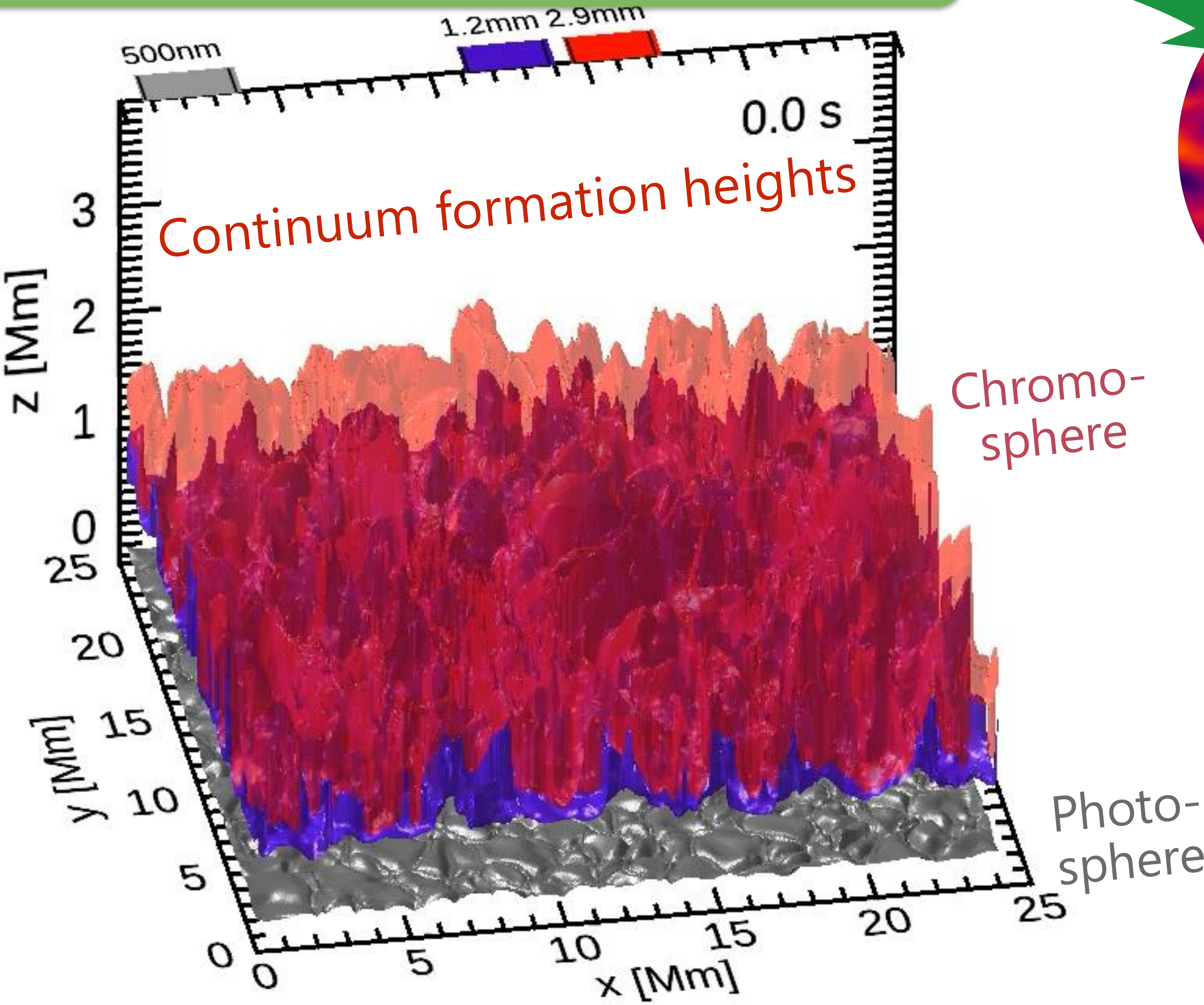
Numerical simulations

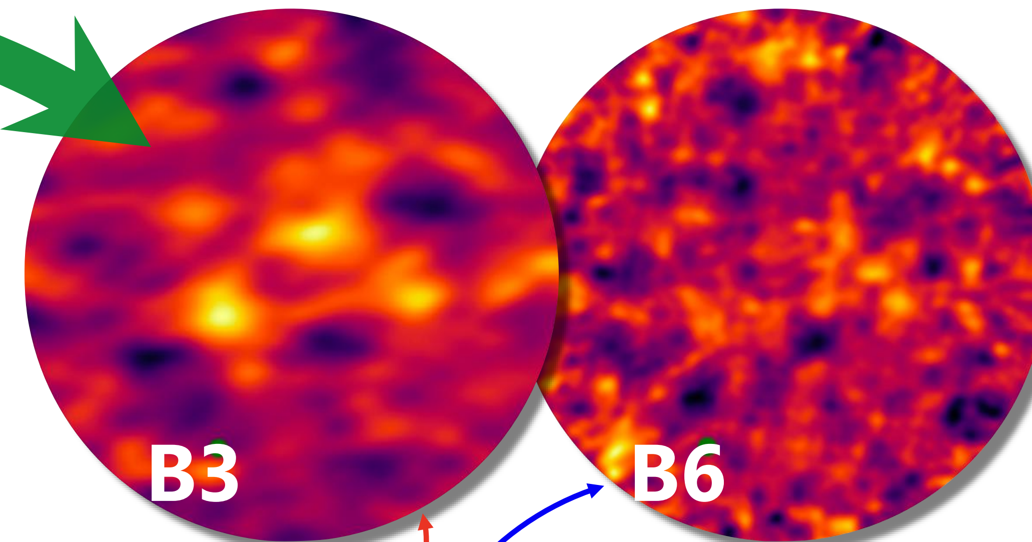
- Detailed simulations of the Sun and ALMA to suggest and develop observing modes
- Strictly simultaneous observations across a very extended wavelength / frequency r

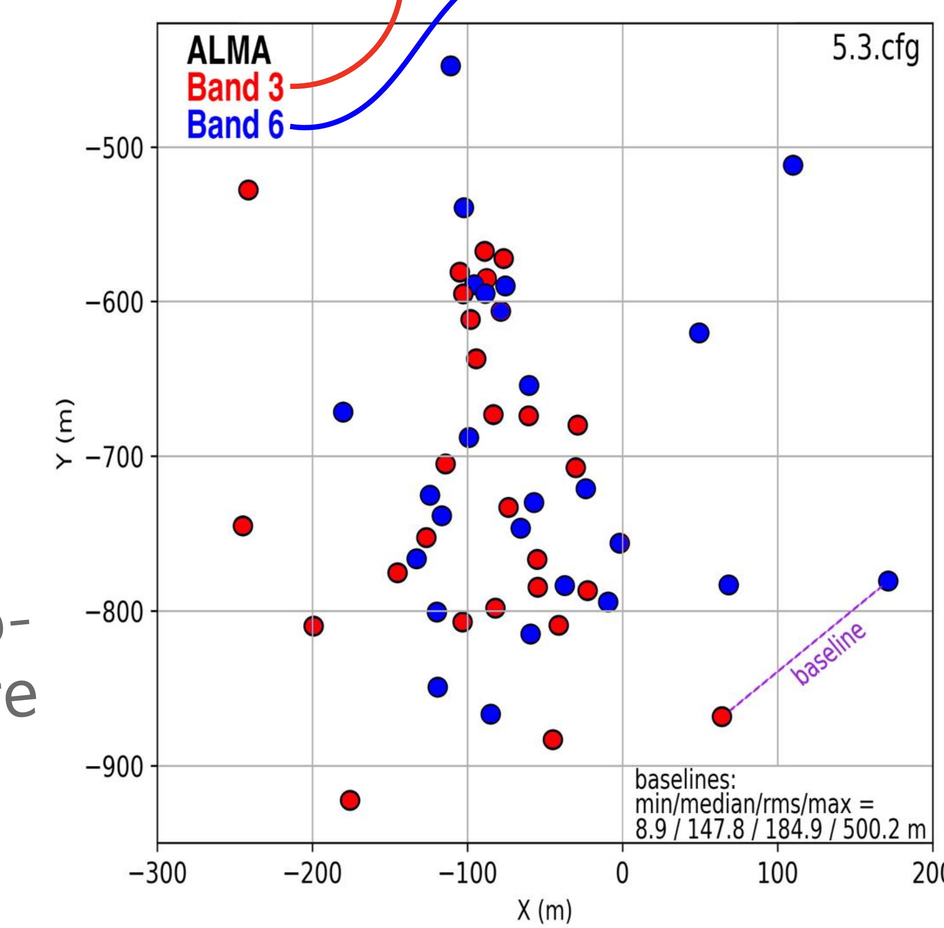


Sub-Arrays — Dual-band observations

- Wanted: **Wide-frequency range <u>simultaneously</u>**
- Simulations with SASim: 1 sub-array @ Band 3 + 1 sub-array @ Band 6. (M.Sc. thesis project of E. Martaillé Richard, UiO, 2024)
  - ➢ Decent imaging seems possible







Future ALMA upgrades

ALMA WSU

- Extended bandwidth and combined receiver bands!
  - Slope across receiver band as proxy for temperature gradient in the mapped (chromospheric) layer
  - Extended multi-frequency synthesis for improved data quality (uv coverage limited for snapshot imaging!)

ALMA 2040

- Better uv coverage (more antennae)
- Strictly simultaneous observing in very broad frequency range

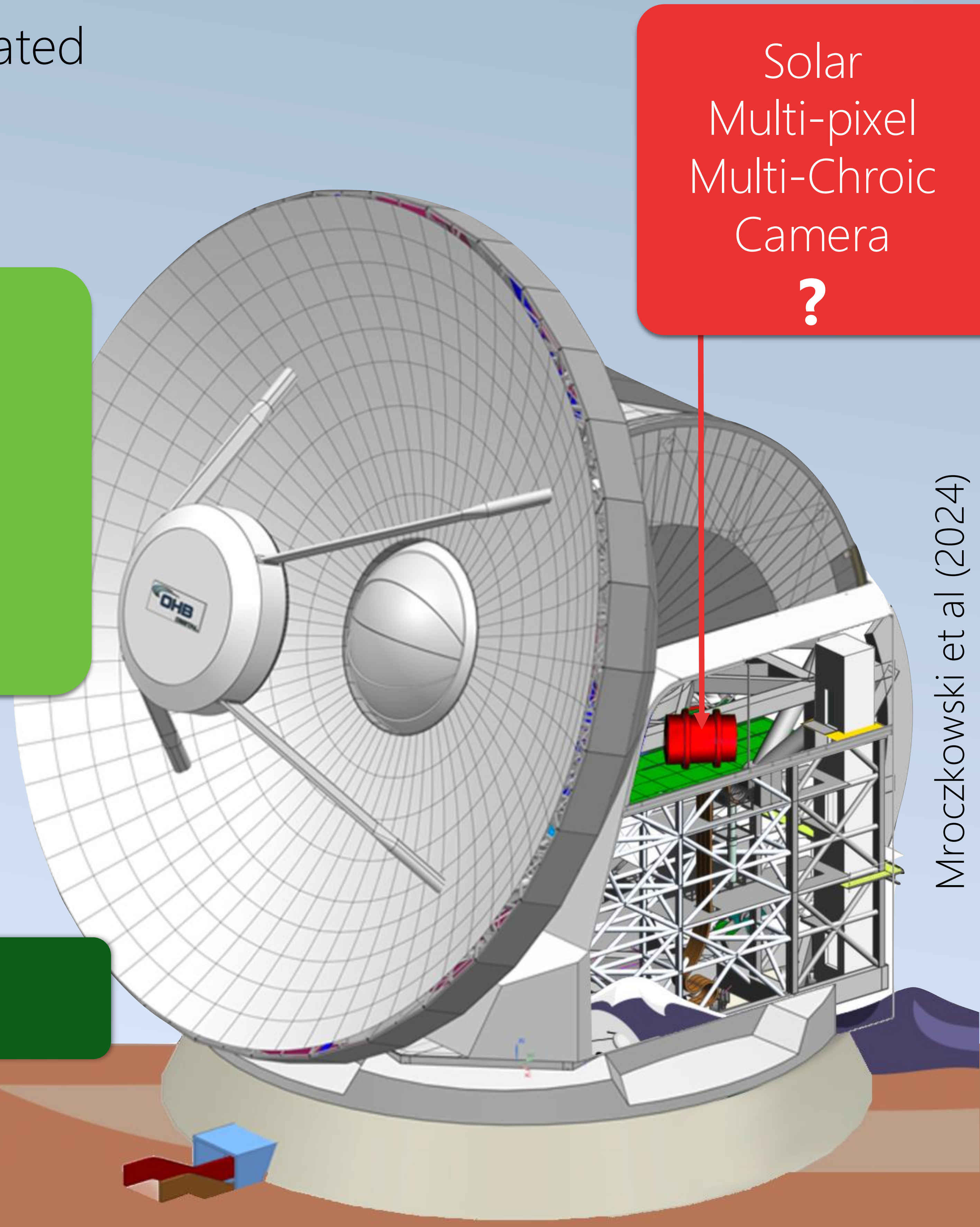
Solar observing with AtLAST

UNIV. OF OSLO
SVEN WEDEMEYER

- **50m single-dish** antenna to be located at the ALMA site
- **Solar science cases for AtLAST** (Wedemeyer et al. ORE 2024)

➢ **Wanted capabilities**
- Camera with >50 000 “pixels”
- Fast scanning
- Continuum observations for at least 6 frequencies across ~90 — 700 GHz simultaneously

- Complementary to ALMA

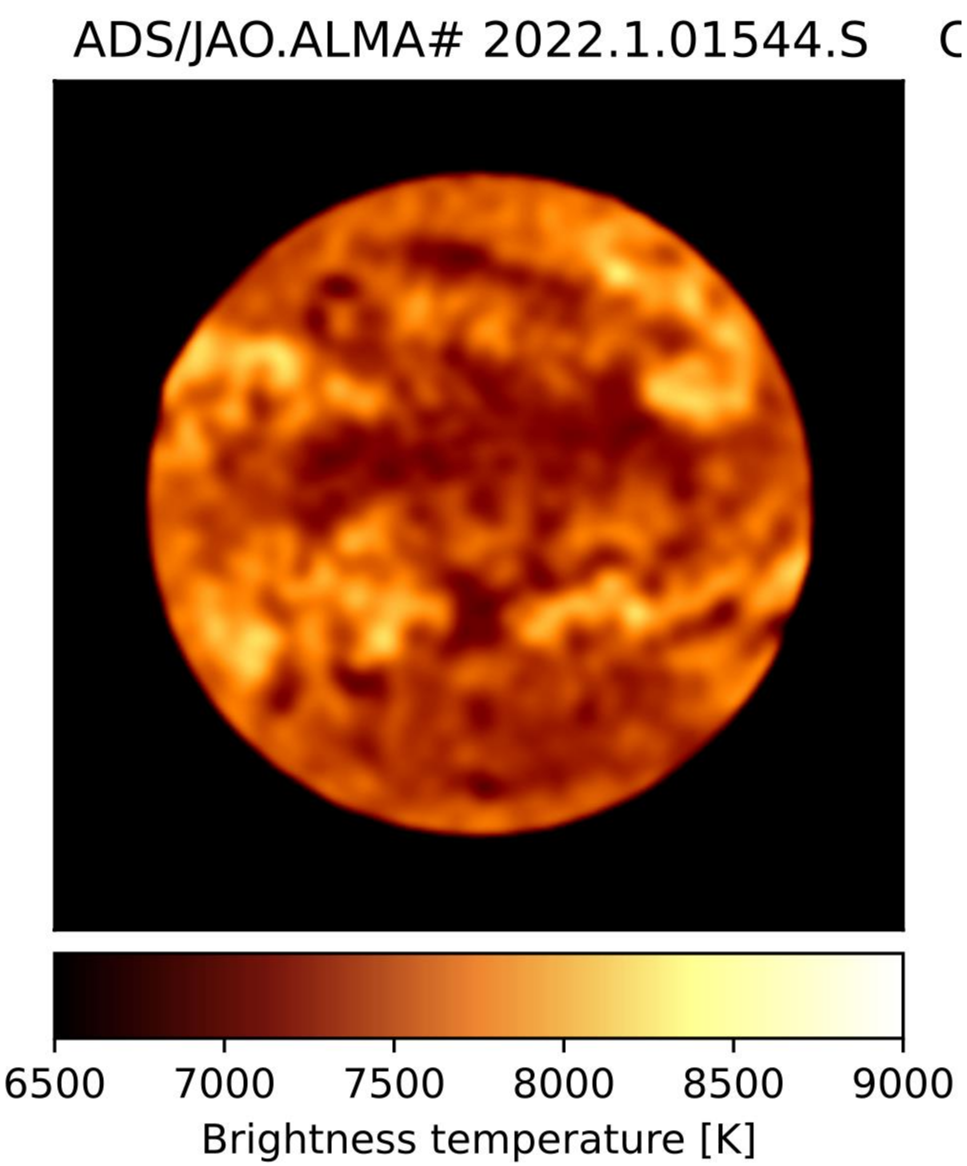


Mroczkowski et al (2024)

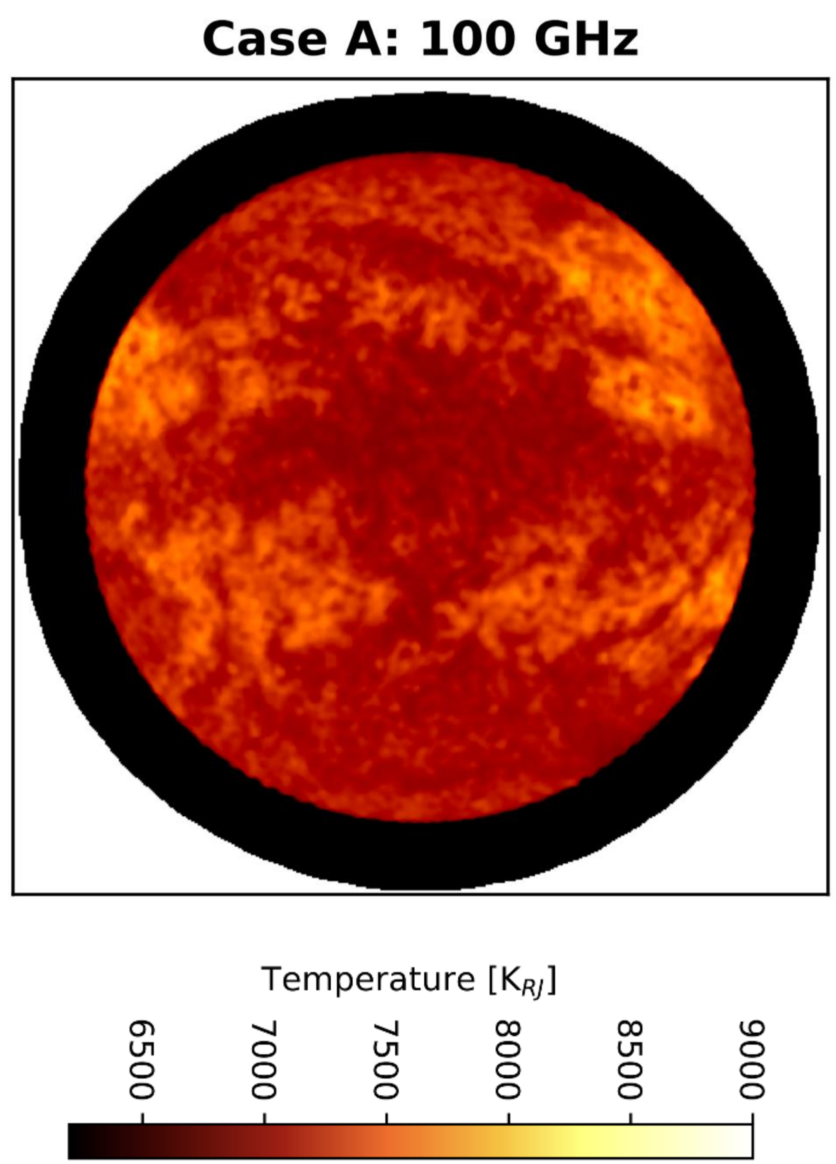
Solar observing with AtLAST

- Simulations with maria – Kirkaune et al (submitted):
  - Scanning **the whole disk** of the Sun at **high cadence**
  - **Cadence down to ~30s for a 1st generation instrument with poossibly 4-8 continuum channels**
  - 2nd generation instruments even faster

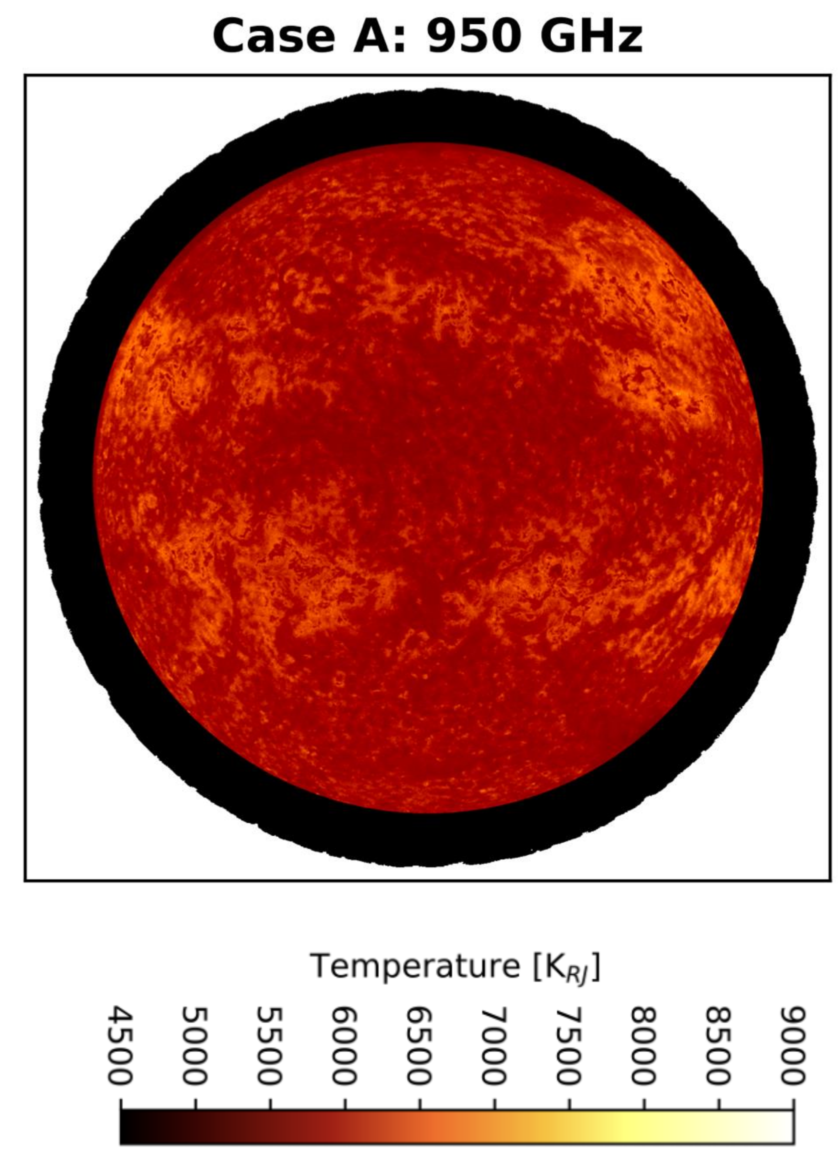
ALMA TP Band 3



AtLAST Band 3

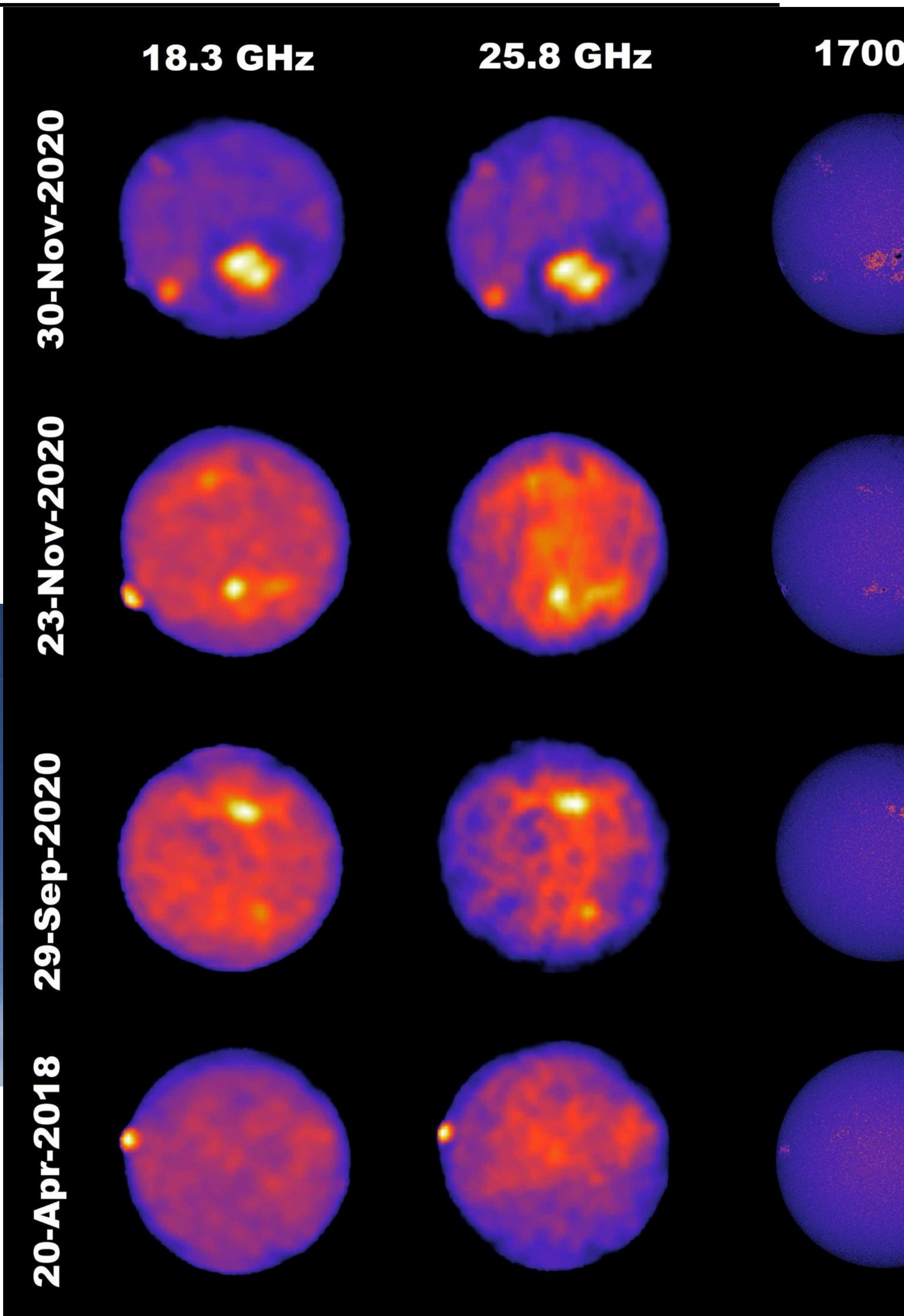


AtLAST Band 10



Solar monitoring with Solaris

- Aim: 24/7 365 days monitoring of the Sun at mm wavelengths
  - Input for space weather forecasting
- Italian-led consortium (Pellizzoni, Potenza et al.)
- Stations Antarctica and Alpes active
- To follow: Station in Arctic



SUMMARY & OUTLOOK

Rosseland Centre for Solar Physics

Credit: CC-BY - ALMA (ESO/NAOJ/NRAO)

- **The wider the frequency range, the better** the structure of the solar atmosphere can be reconstructed
  - Coordinated observations + data inversion
  - Full polarisation observations for magnetic field measurements
  - High-cadence and **strictly simultaneous** (1 second)
  - ➢ **Enables high-impact science (atmospheric heating, solar/stellar activity, space weather)**