A revolutionizing new view of our Sun with ALMA

Sven Wedemeyer

(University of Oslo, Norway)

in cooperation with

the North American and European ALMA Solar Development Teams

and the Solar Simulations for the Atacama Large Millimeter Observatory Network

The solar atmosphere

Height in atmosphere
(Distance from solar centre)

Corona

Transition region

Chromosphere

Photosphere (*visible "surface"*)

Interior

Chromosphere:

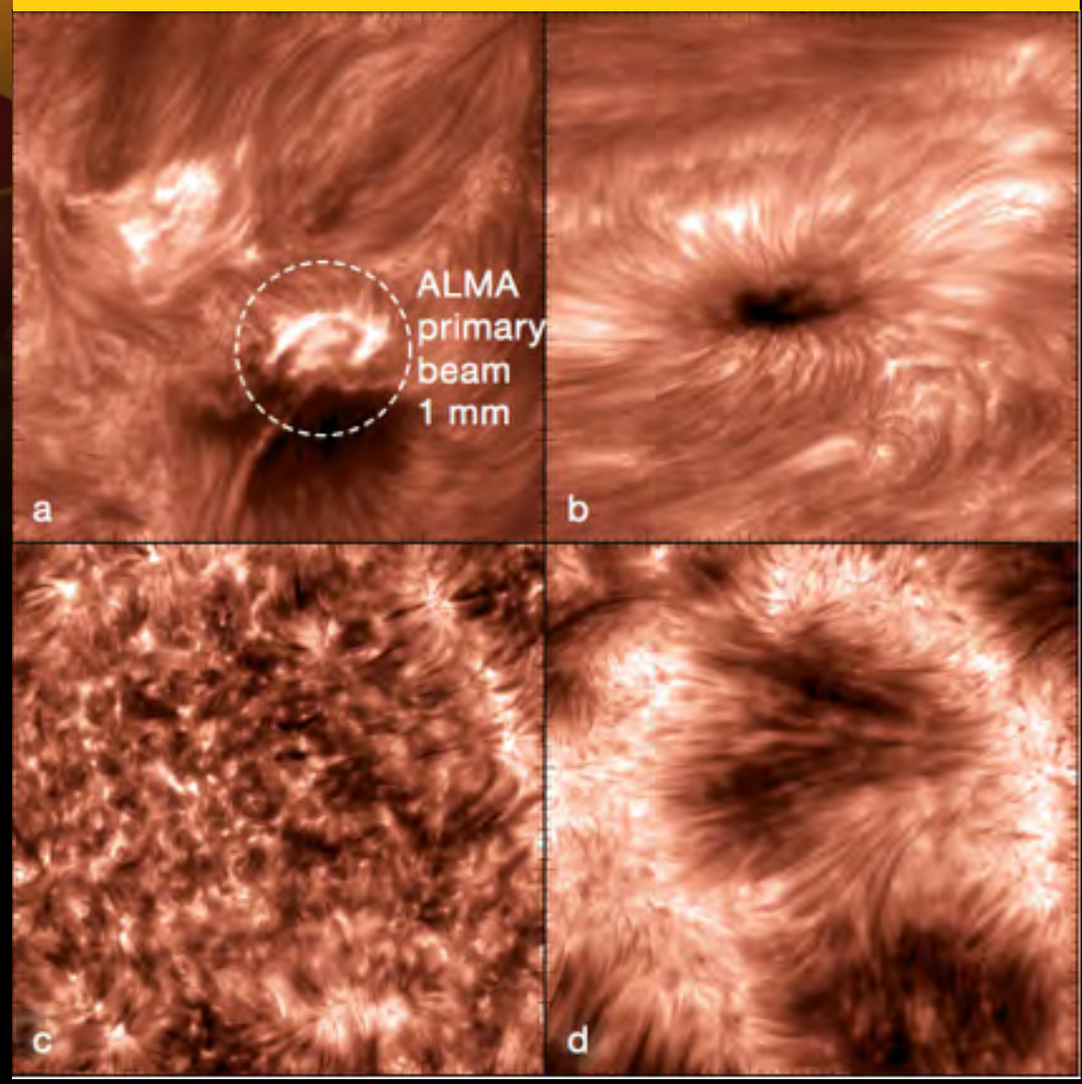
- Thin but important region between photosphere and corona

  ➡ All energy and mass must pass through

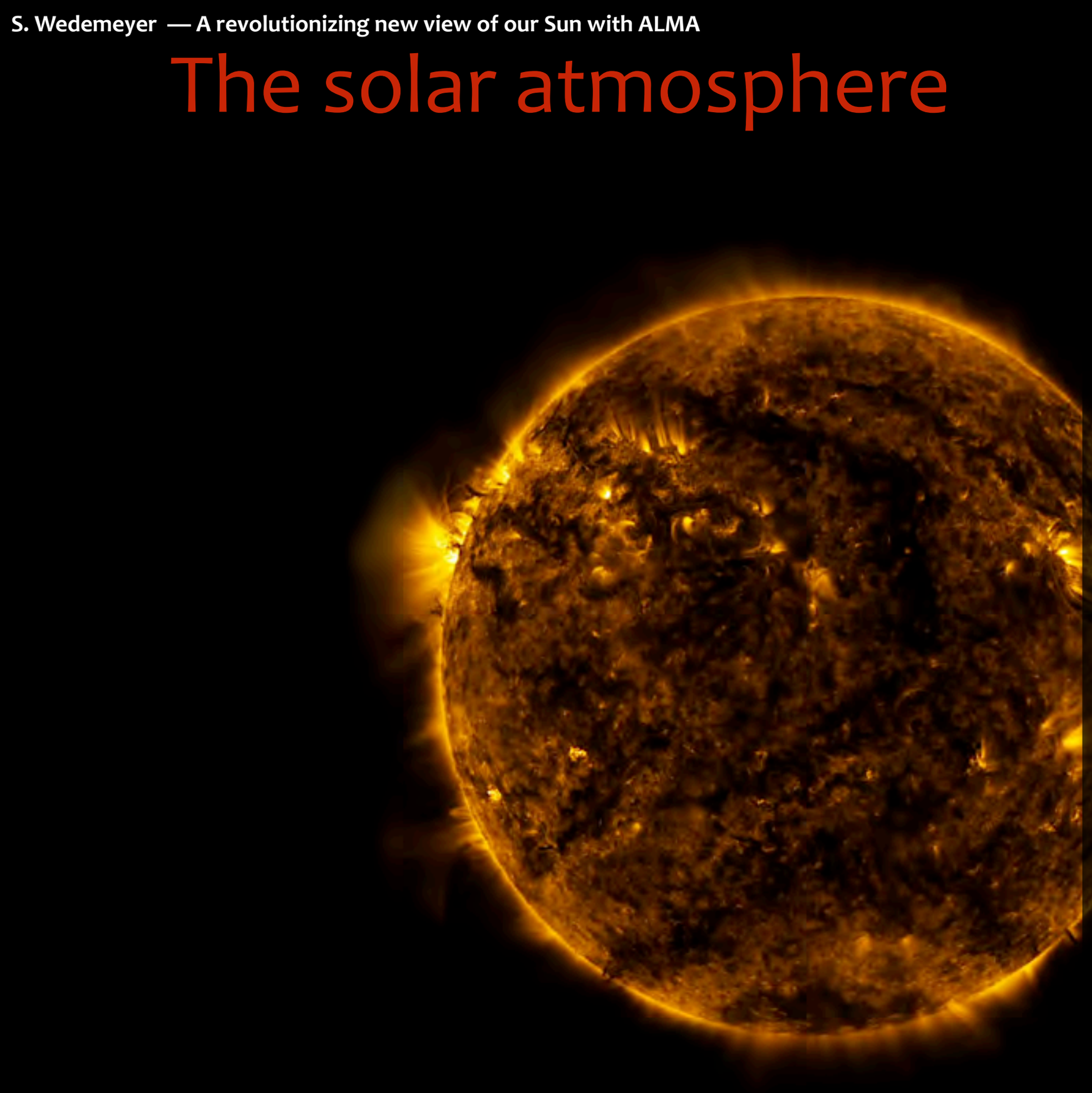
- Highly dynamic and intermittent

- Still elusive despite many decades of research

Chromosphere - Layer mapped by ALMA



The solar atmosphere



Solar Dynamics Observatory SDO/NASA

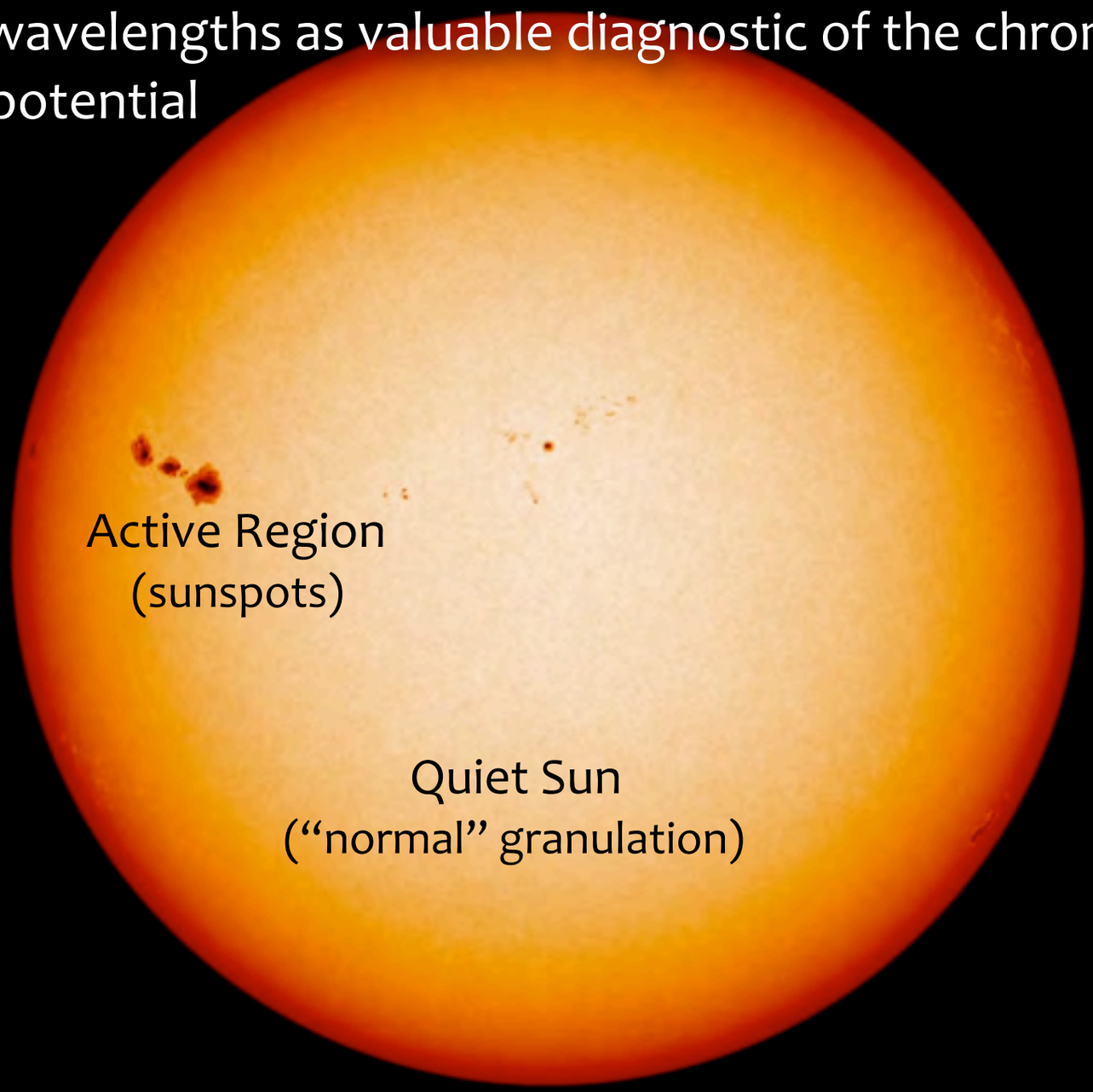
- Not a static stack of isolated layers
- Compound of domains
  - highly dynamic
  - intermittent
  - dynamically coupled
- Structured on a large range of spatial scales, spatially resolvable.
- Plethora of processes.
- Dynamic timescales from days to seconds.
- Observations different than for many other astronomical objects.

How to observe the Sun?

- Continua and spectral lines probe different plasma properties in different layers

➡ Modern solar physics: Multi-wavelength co-ordinated space-borne/ground-based campaigns

➡ Radiation at mm wavelengths as valuable diagnostic of the chromosphere with ground-breaking potential



Solar Dynamics Observatory SDO/NASA

The solar atmosphere in 3D - Scanning in height

Observations with the SST (Swedish 1-m Solar Telescope)

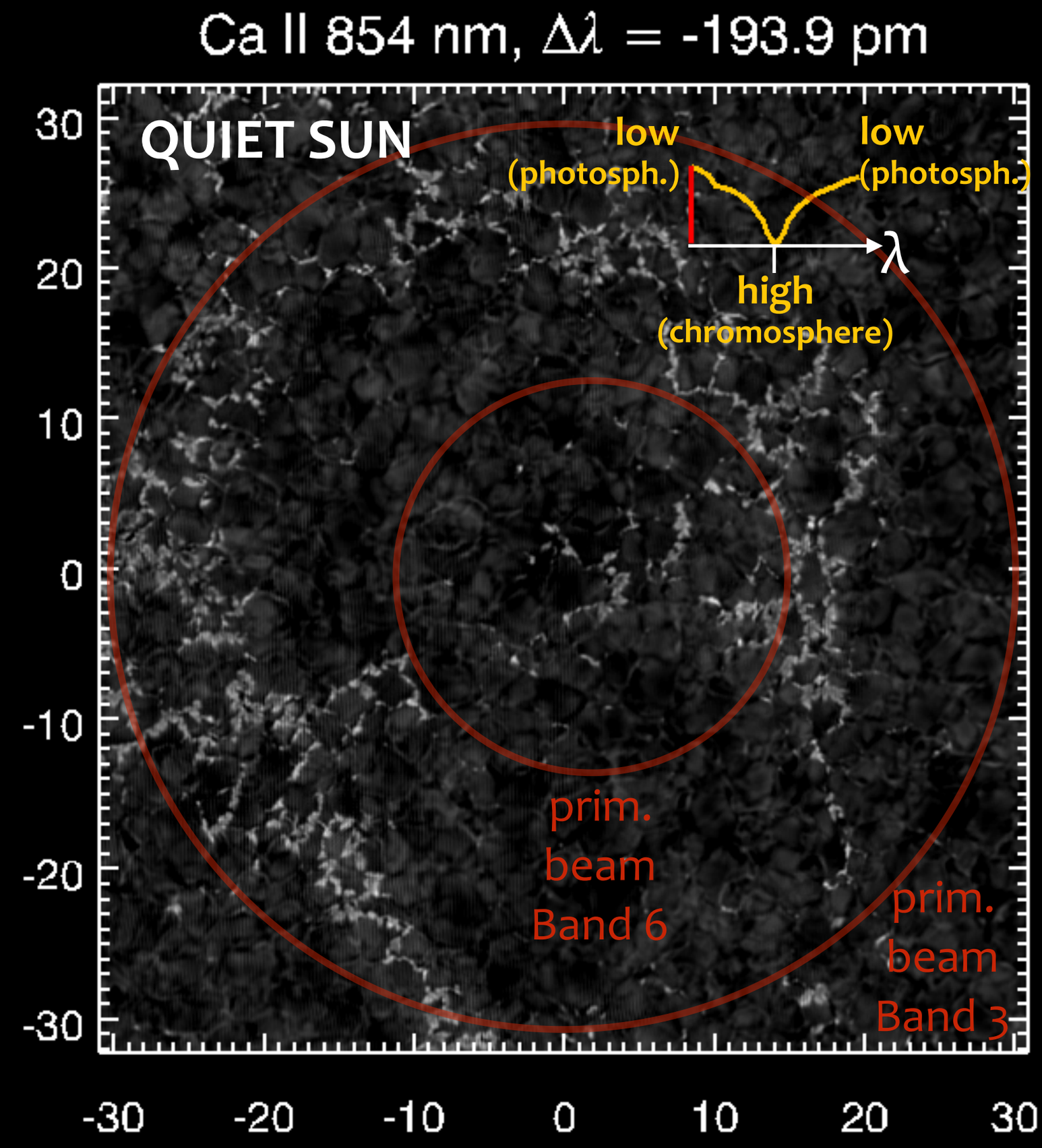
Scan in wavelength through Ca II 854 nm line

- line wings formed in the photosphere
- line core formed in the chromosphere

➡ sampling different layers

➡ atmospheric stratification, 3D structure (qualitatively)

- spatial resolution ~0.1 arcsec



The diagnostic problem

- Existing diagnostics for the chromosphere in the UV/visible/IR:
  - Few suitable diagnostics accessible
  - Complicated formation mechanisms and non-equilibrium effects (e.g., ionisation, non-LTE *(non-thermal thermodynamic equilibrium)*)

➡ Non-linear relation between observables and plasma properties

➡ Uncertainties for the derived chromospheric plasma properties!

➡ Interpretation difficult.

ALMA as true game changer

Remarkable diagnostic capabilities for the Sun:

✓1. Linear thermometer - direct determination of local gas temperatures

✓2. Measurements of the magnetic field

✓3. Probed atmospheric height selectable *(increases with wavelength)*

✓4. High temporal resolution *(Cycle 4: 2s)*

✓5. High spatial resolution

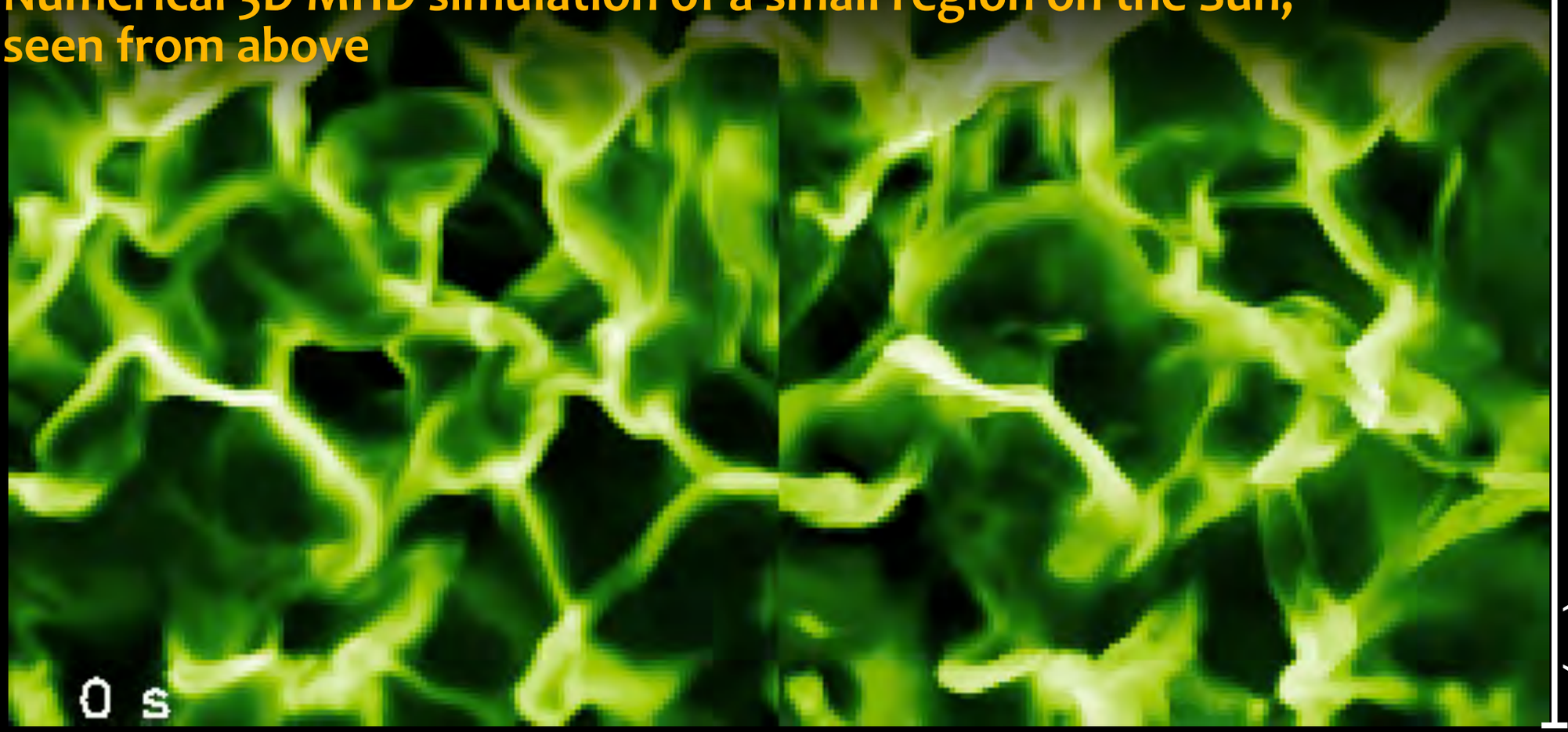
✓6. High spectral resolution

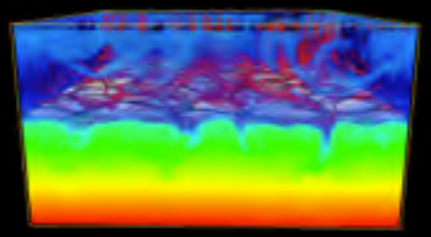
➡ **Perfect for the solar chromosphere**

➡ **A new view of our Sun with important results to be expected**

1. ALMA as linear thermometer

Numerical 3D MHD simulation of a small region on the Sun, seen from above





Horizontal cut through the model chromosphere

3D model and corresponding artificial mm observation
gas temperature and continuum intensity (brightness temperature)

What is what?

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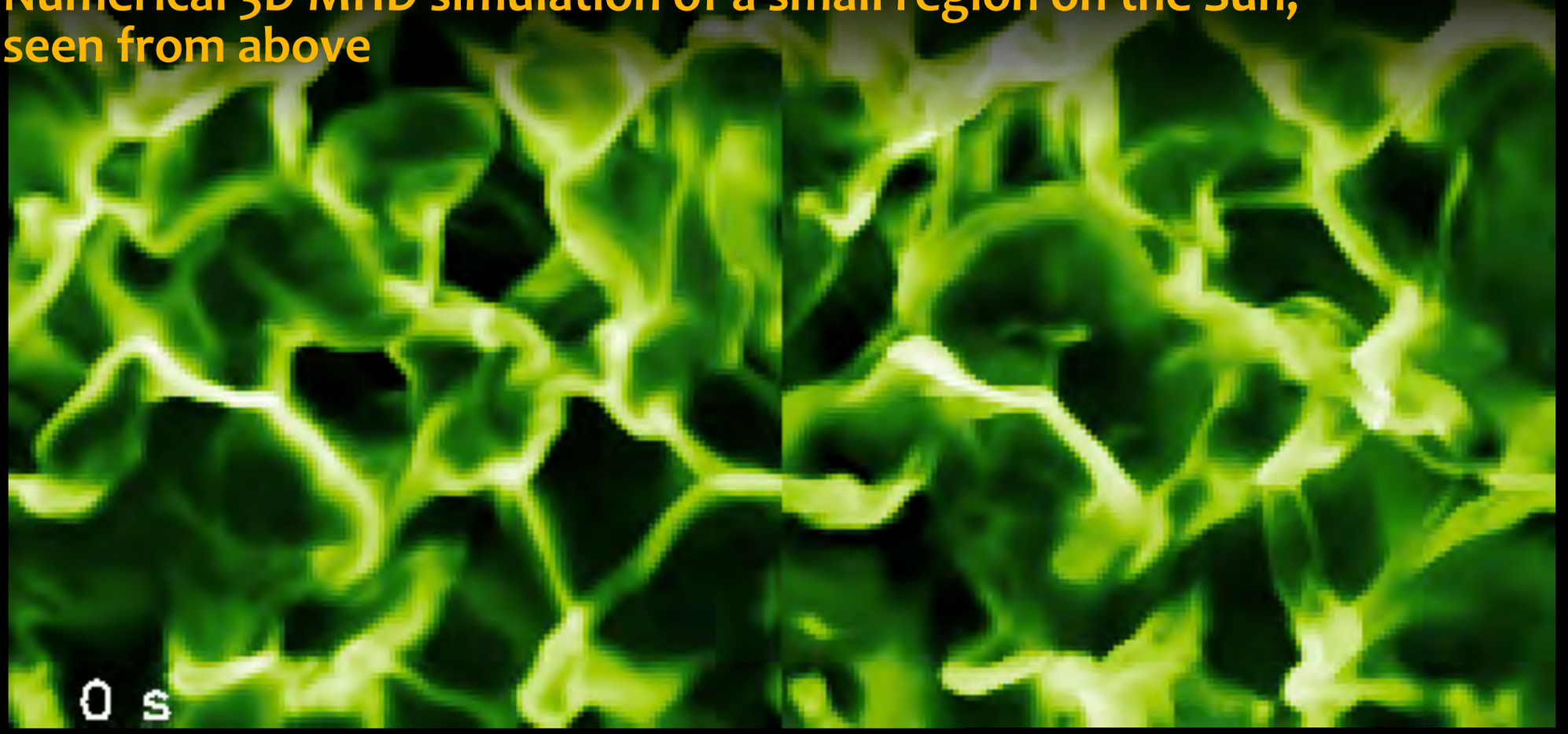
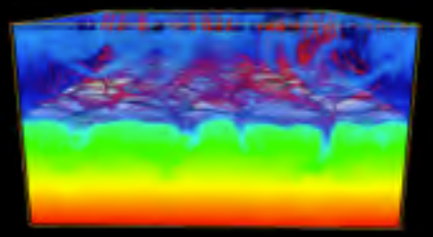
Numerical 3D MHD simulation of a small region on the Sun, seen from above



gas temperature
at z=1000km

continuum intensity at
λ=1mm



Horizontal cut through the model chromosphere

6 Mm (8")

- local gas temperatures closely mapped (2000 K - 8000K, avg. ~ 4700 K)
- same spatial scales (1-2 arcsec, comparable to solar granulation)
- same time scales (few seconds, pattern evolution time scale ~20-30 s)

2. Magnetic field

- Demonstrated by *Loukitcheva, Fleishman et al. (2015)* based on a Bifrost model:

- **Polarisation** of the continuum intensity

➡ longitudinal magnetic field component *(Bogod & Gelfreikh 1980; Grebinskij et al. 2000)*

➡ for different heights

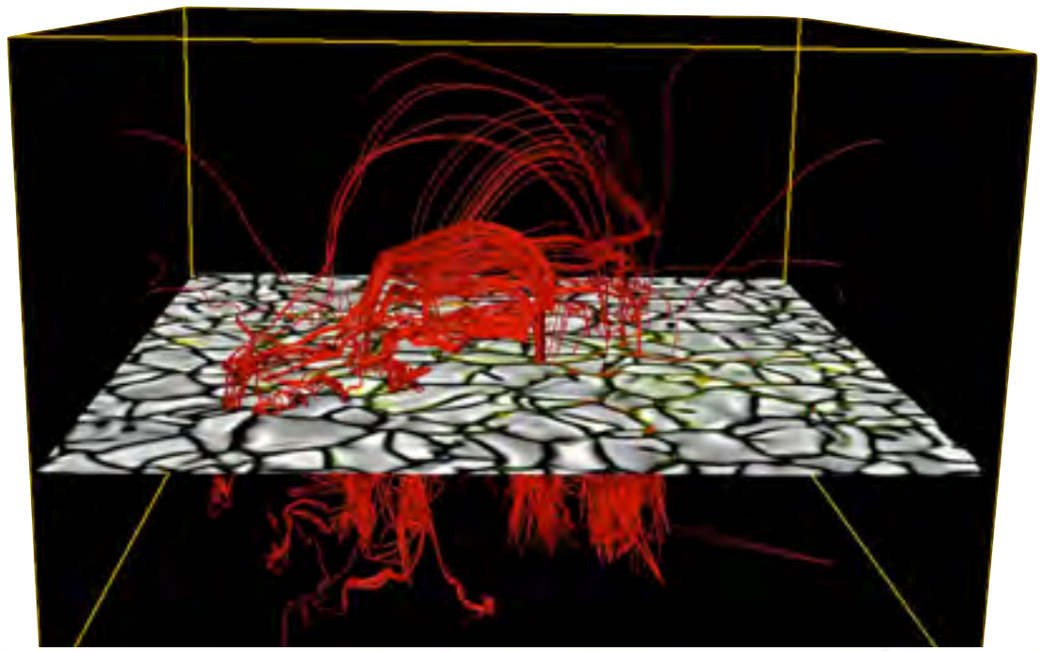
➡ Constraints for the **3D** **magnetic field topology**

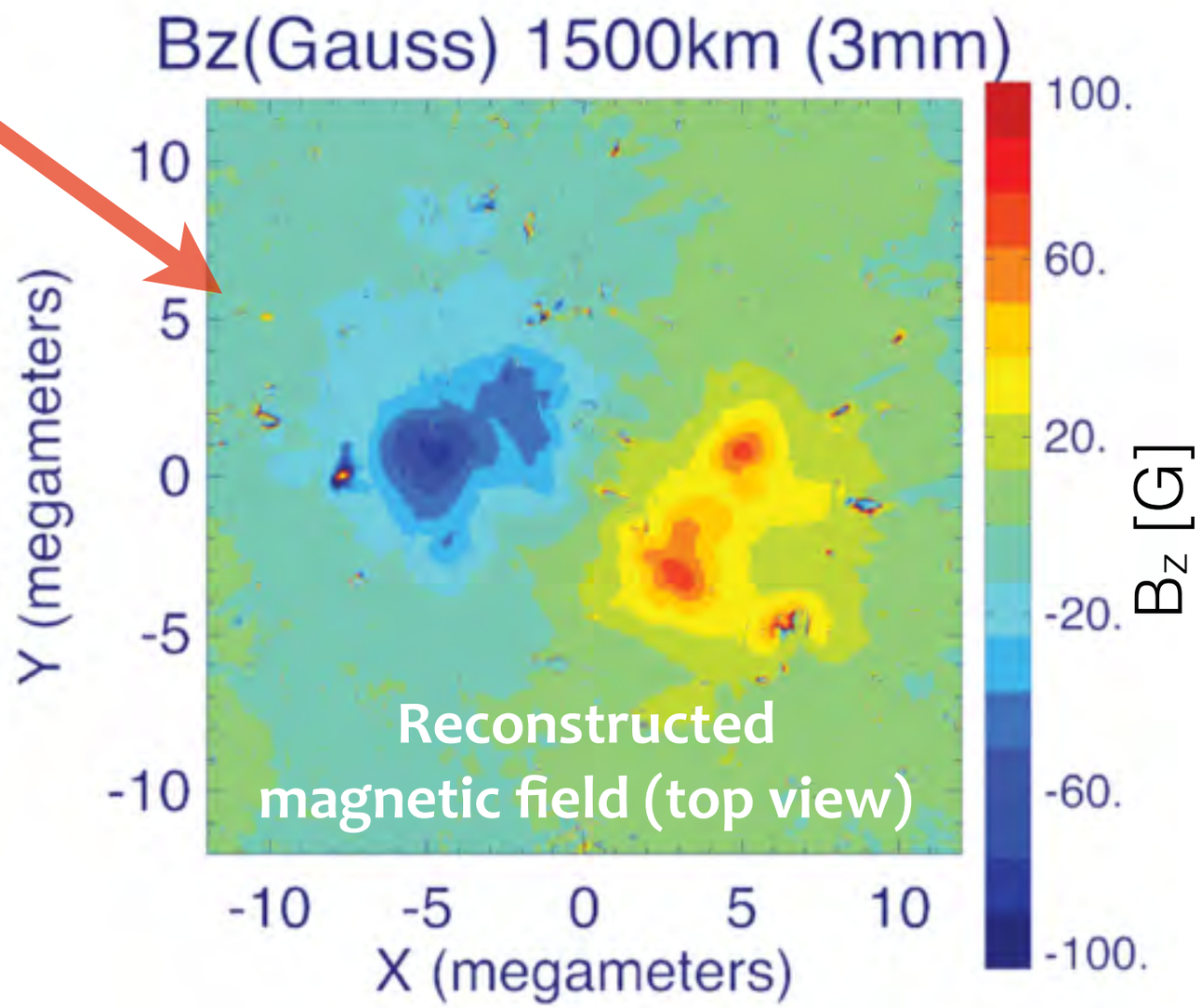
- Polarisation signal
  - Active Regions: few %
  - Quiet Sun: few 0.1%

➡ Should be measurable with ALMA.

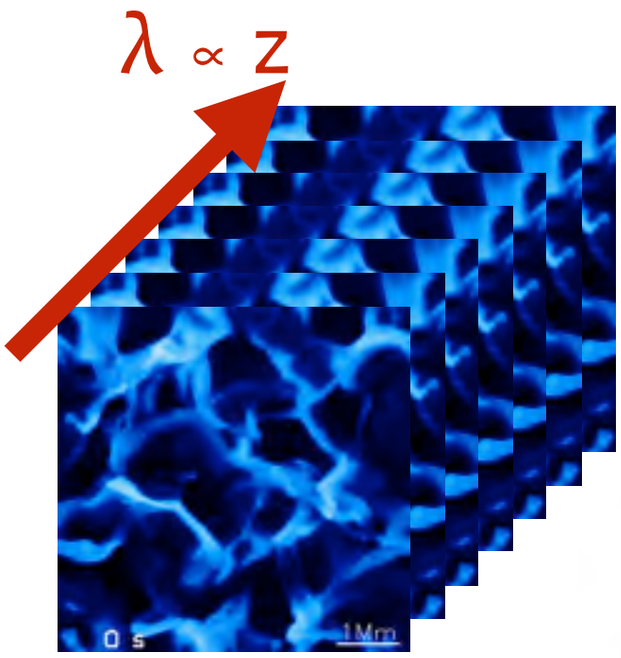
- Not in Cycle 4.

3D Bifrost model (Carlsson et al. 2016)



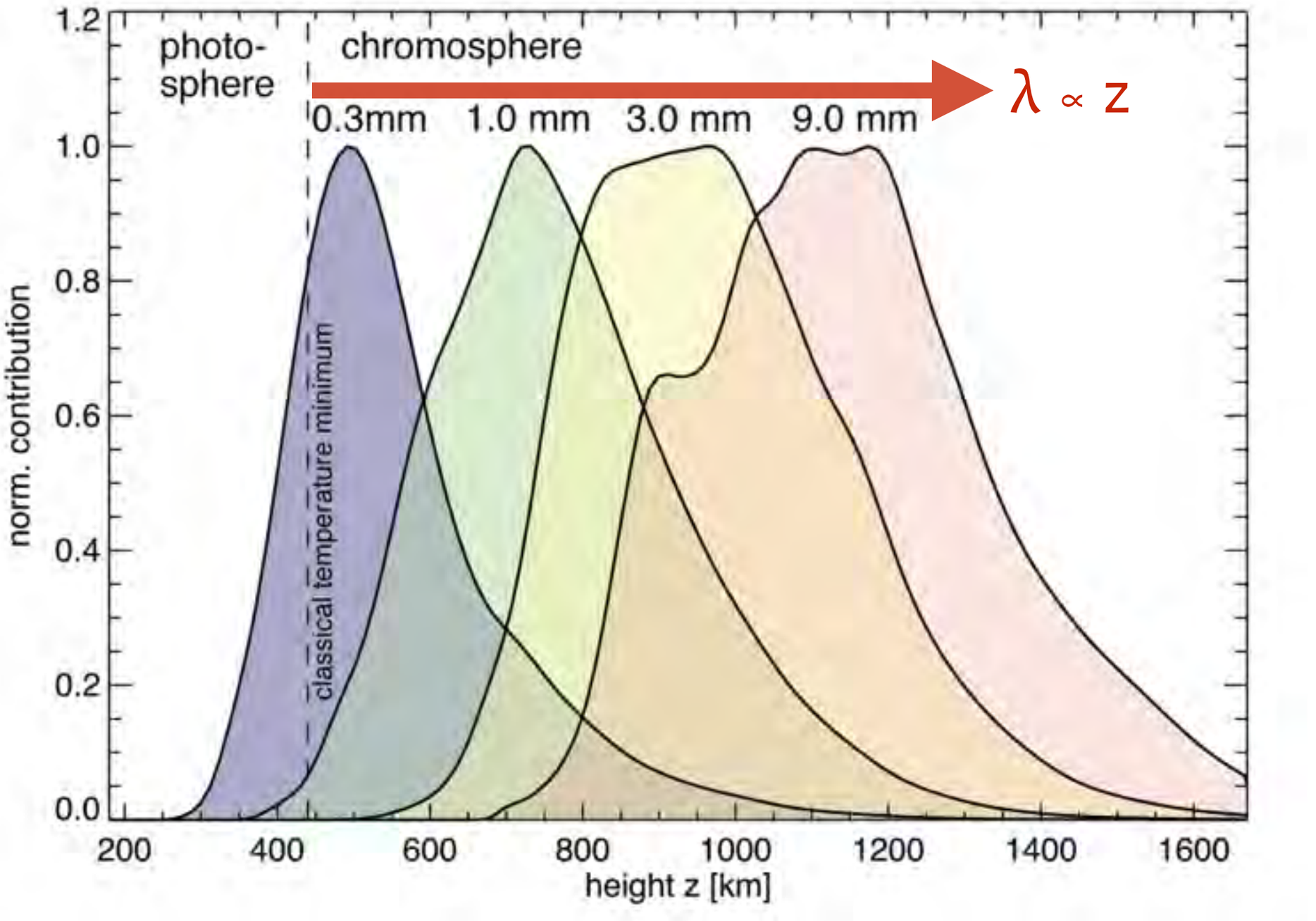


3. Scanning in height



Continuum formation heights

➡Height range probed at certain wavelength



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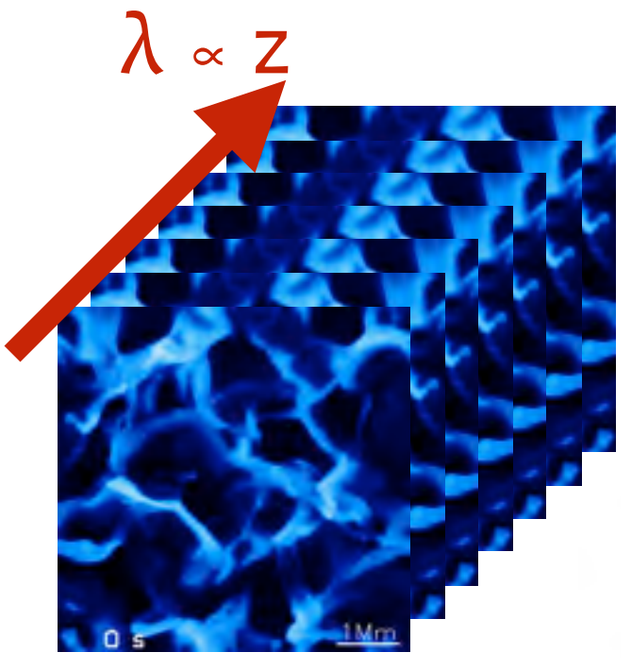

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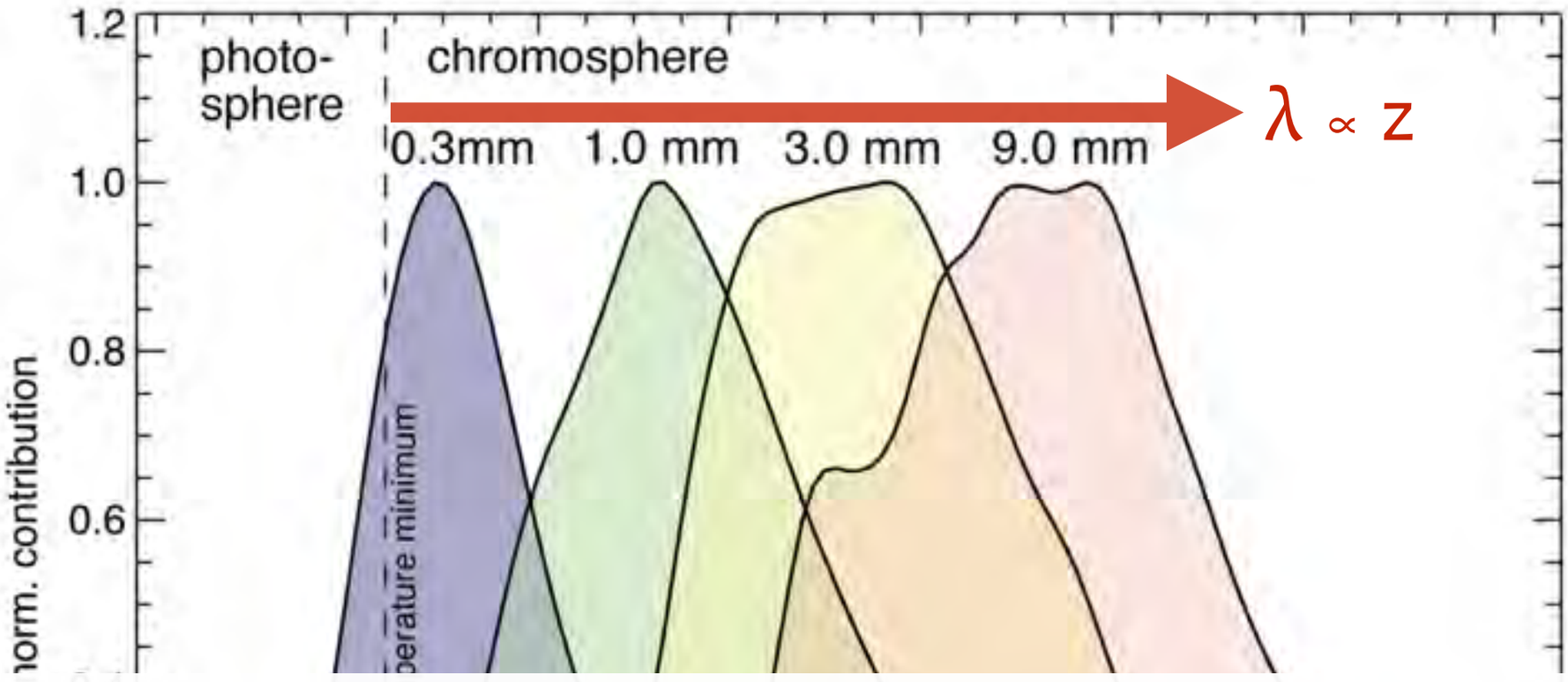


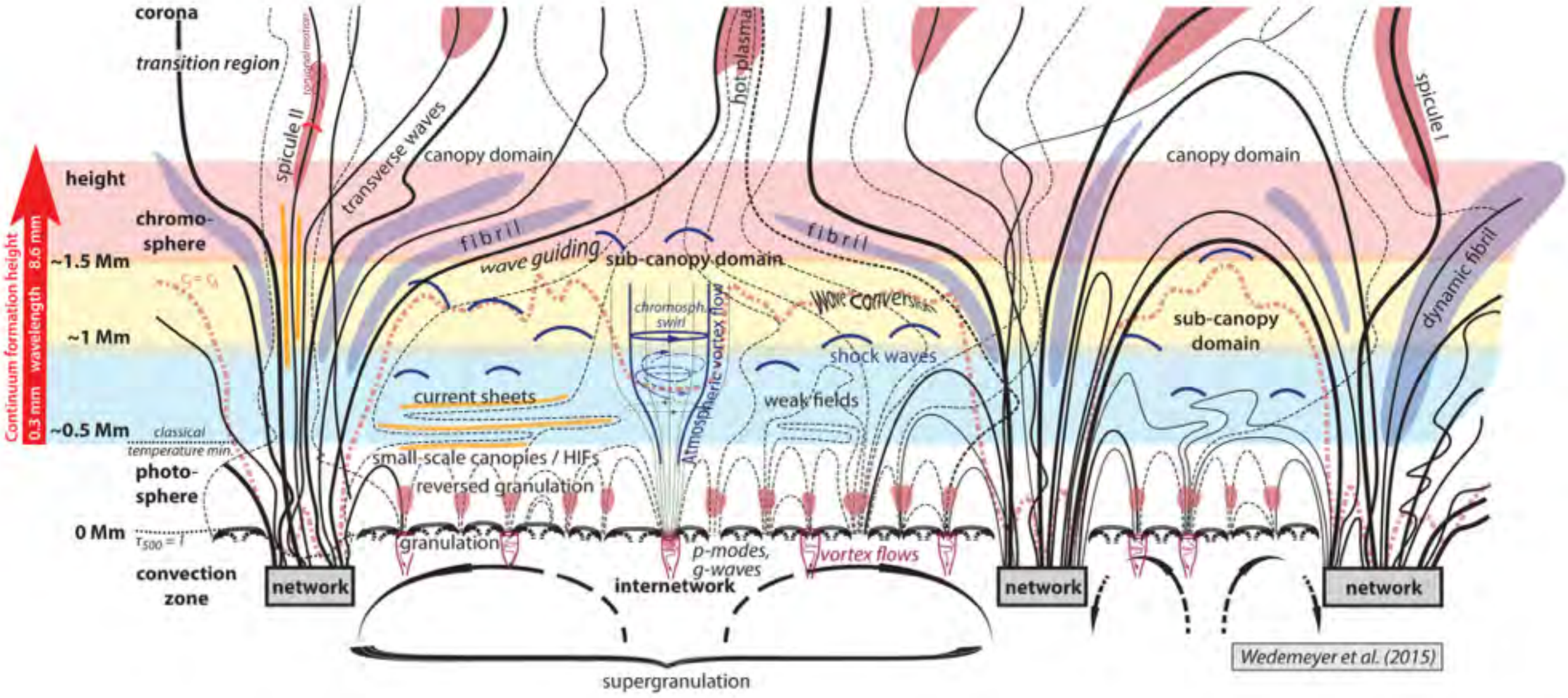
- Could multi-band observations be used for an atmospheric tomography?

➡ Time-dependent 3D thermal structure of the atmosphere?

➡ Unprecedented observations with large scientific impact!

3. Scanning in height

- Quiet Sun regions: Sampled layer increases with wavelength
  - shortest : low chromosphere, maybe upper photosphere
  - longest: high chromosphere, maybe transition region



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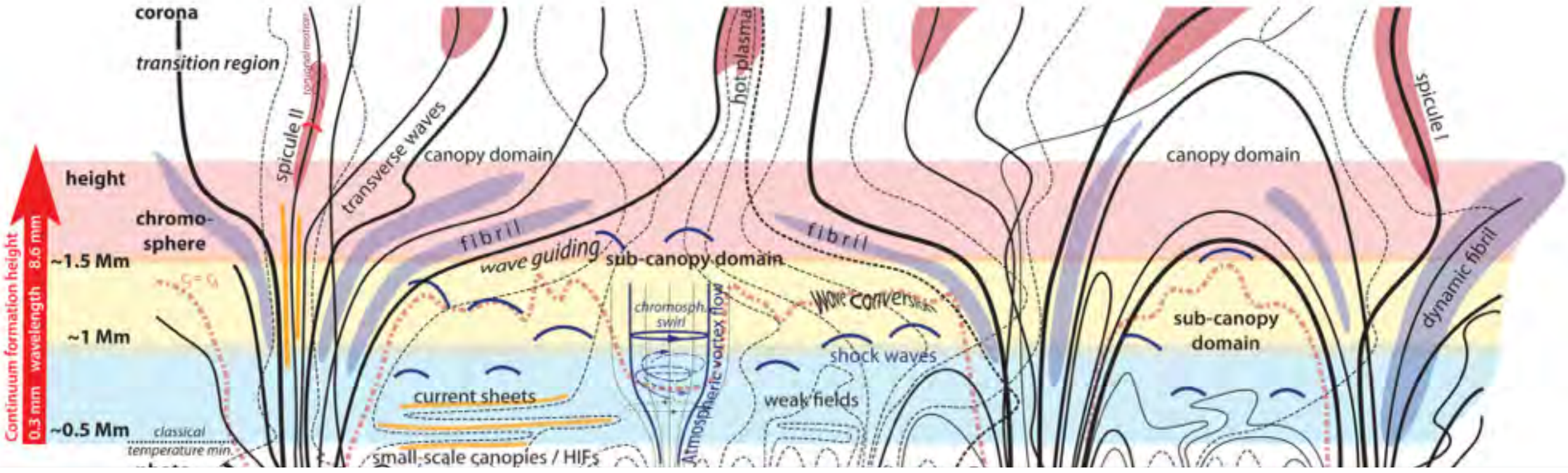
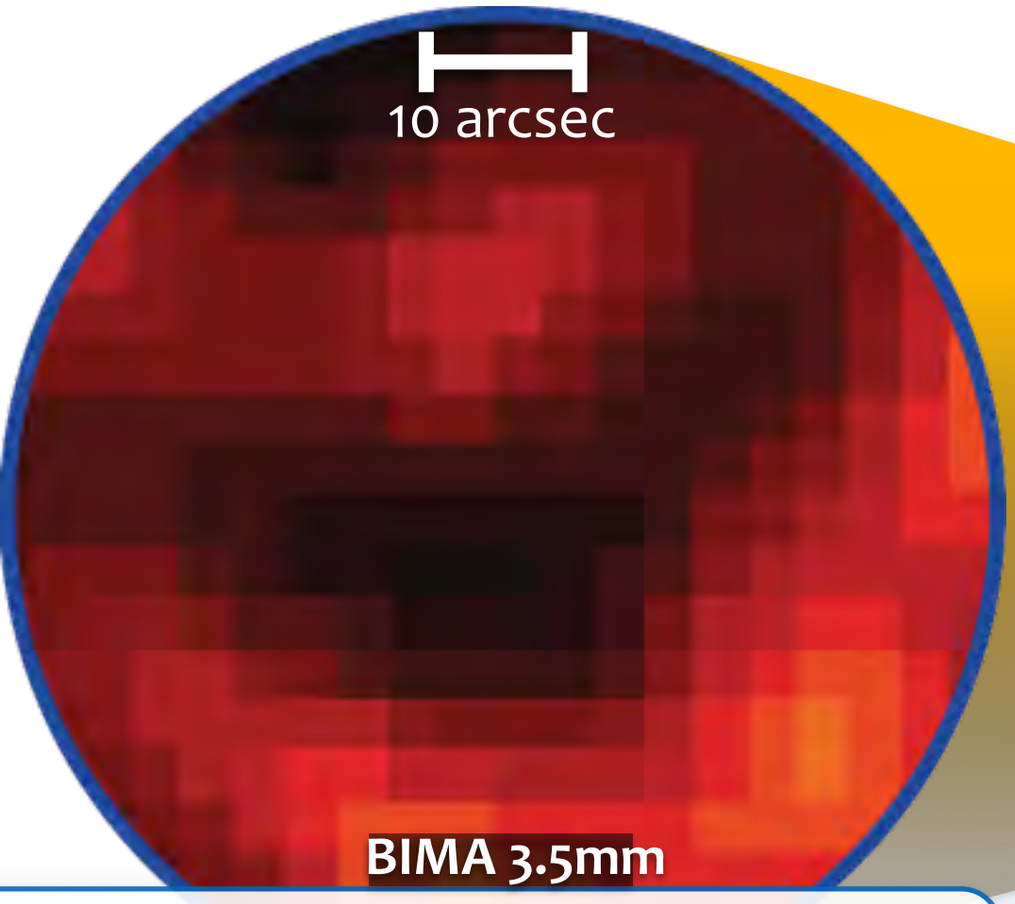


- Wanted: Fast cycling through 2-3 ready receiver bands

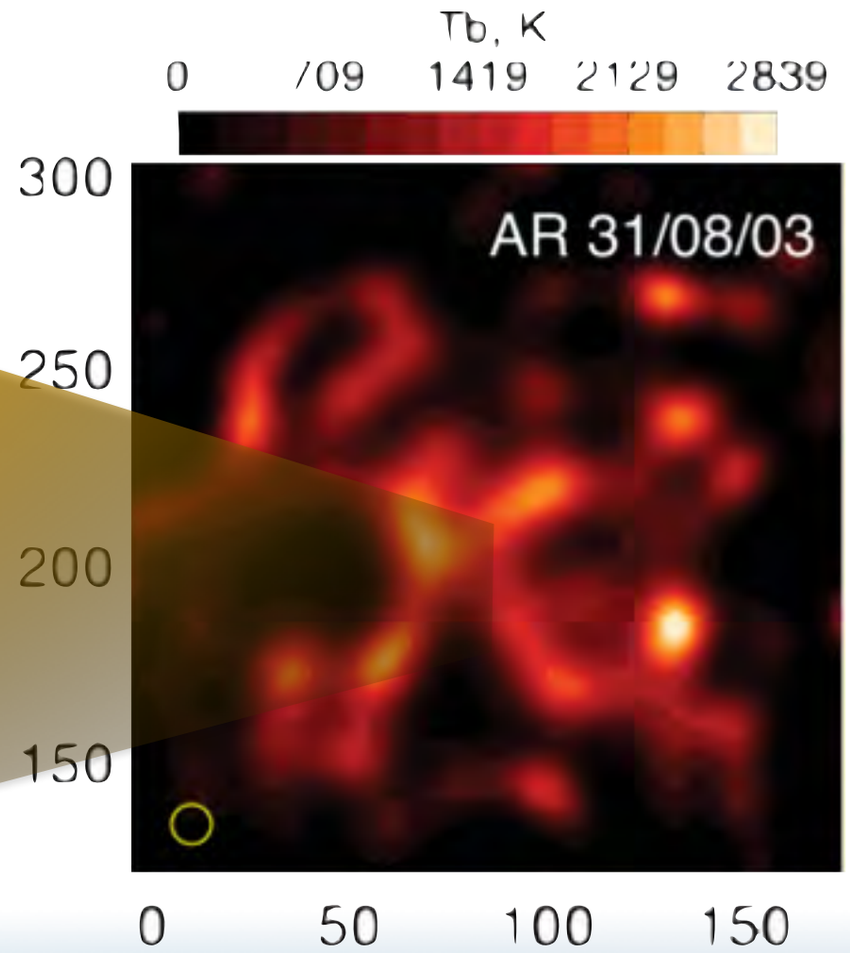
➡"Quasi-simultaneous" mapping of different layers in the chromosphere (not in Cycle 4)

➡Tracking of propagating waves/seismology ➤ 3D atmospheric structure

5. High spatial resolution



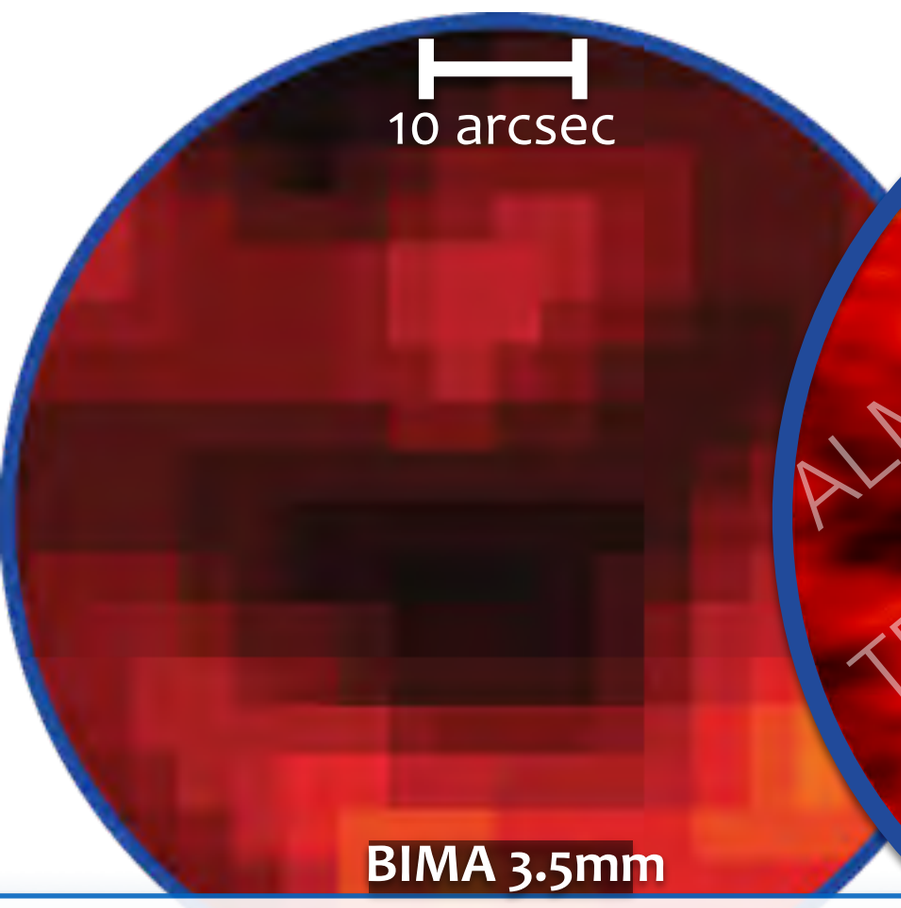
Berkeley-Illinois-Maryland Array (BIMA, 2004), λ = 3.5 mm:
resolution 10 arcsec



Loukitcheva et al. (2014)

5. High spatial resolution

IRIS 140 nm image
Interface Region Imaging Spectrograph (NASA)



BIMA 3.5mm

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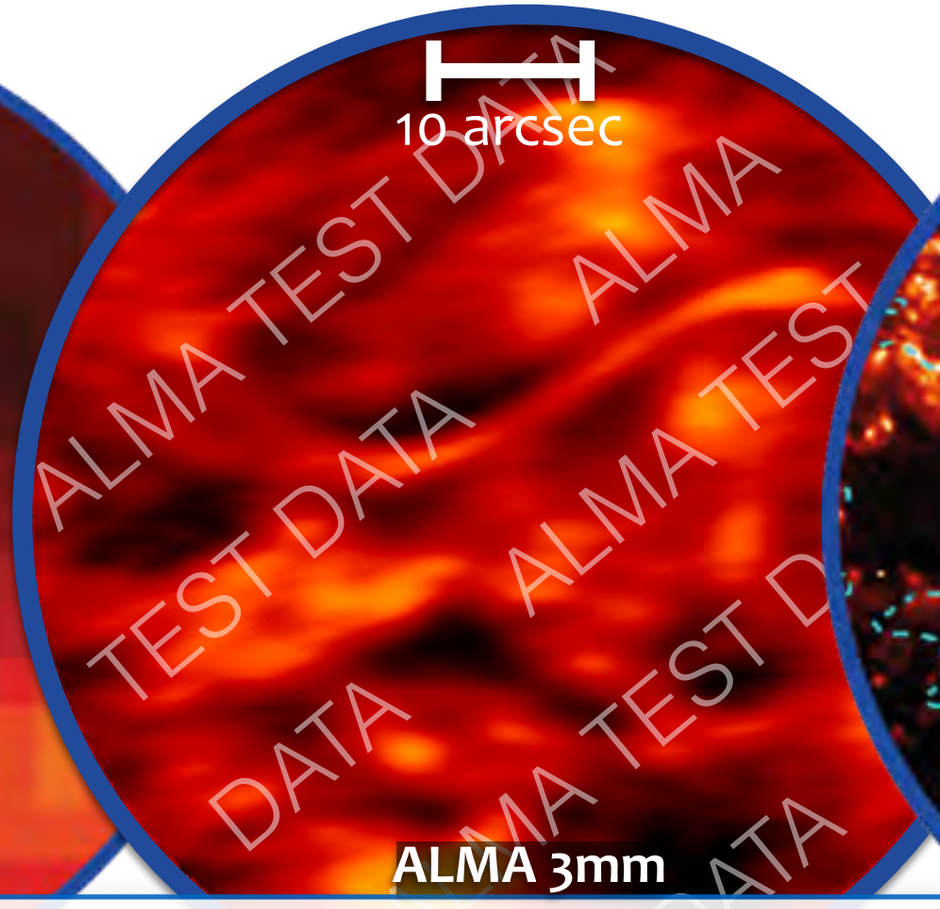
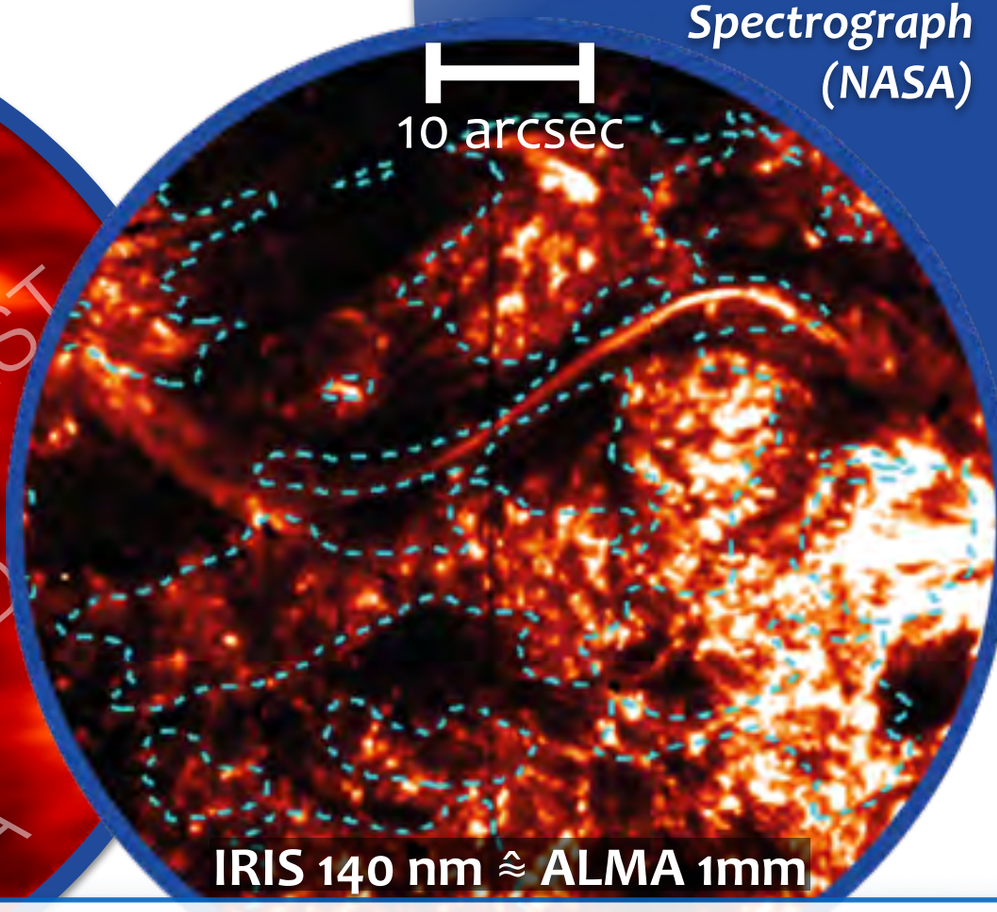


ALMA 3mm

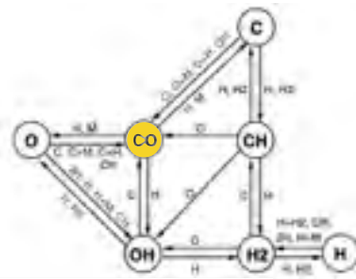
ALMA, successful test 2014,
interferometry, λ = 3.0 mm:
resolution < 1 arcsec !
(but integrated over 40min)



IRIS 140 nm ≋ ALMA 1mm

further improvements
ALMA , whole array
0.3 arcsec × λ /1mm

6. Spectral capabilities



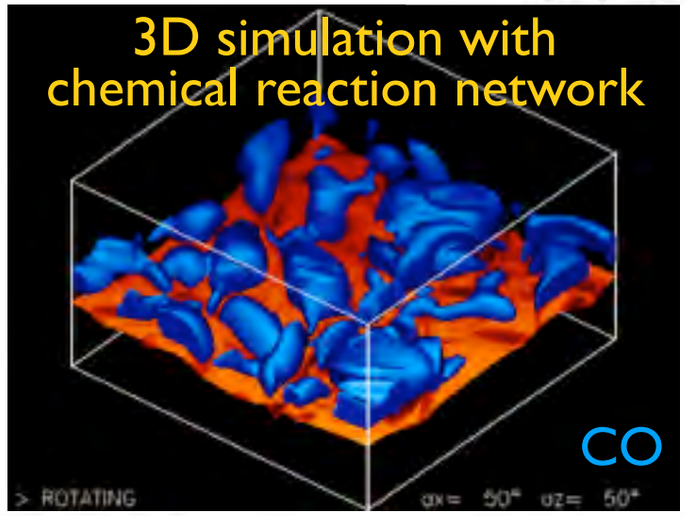
- Spectral information on chromospheric gas:
  - (wavelength) slope of continuum
  - radio recombinations lines
  - molecular lines (e.g., CO)
  - Some lines originate in corona!

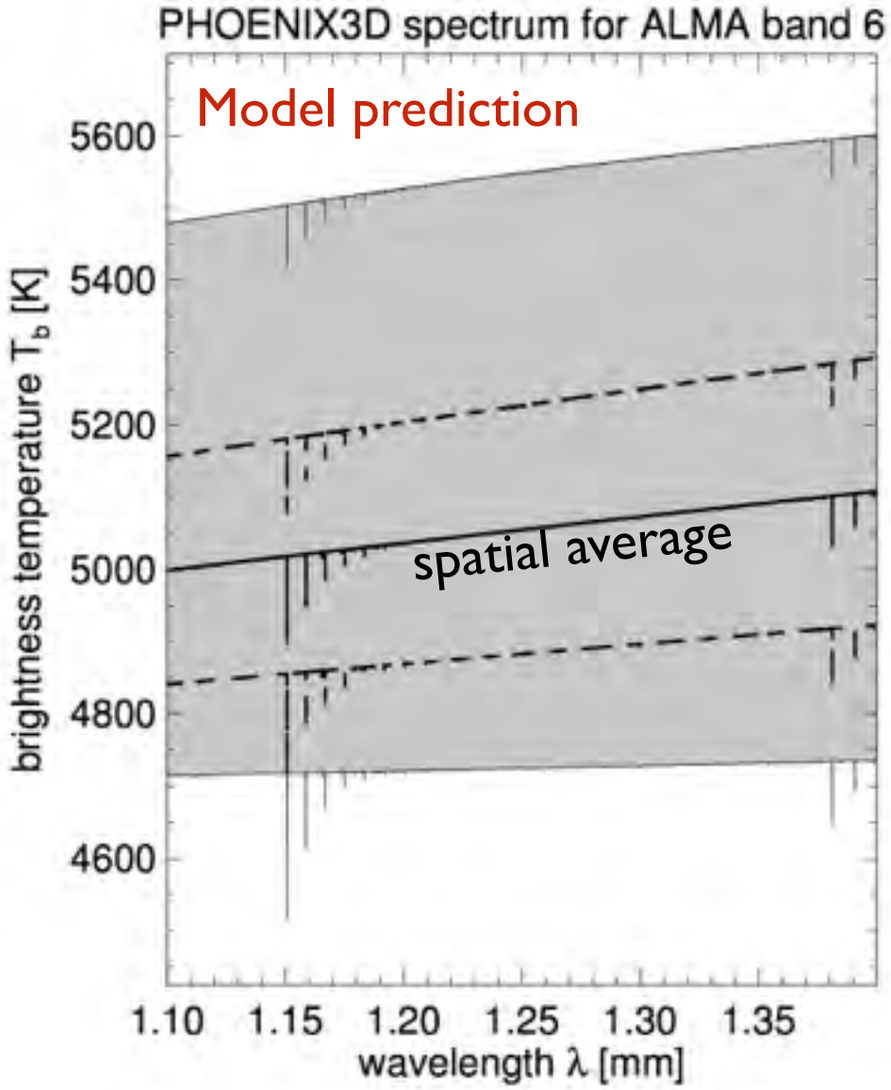
- Dynamic, intermittent chromosphere
  - ➡ Line profiles easily "smeared out" when resolution insufficient, shallow profiles, not much known

- ALMA has now (soon) the needed resolution

➡ **Set of complementary thermal, kinetic and magnetic diagnostics!**

- **Still little known, a lot to develop, and a lot of diagnostic potential!**



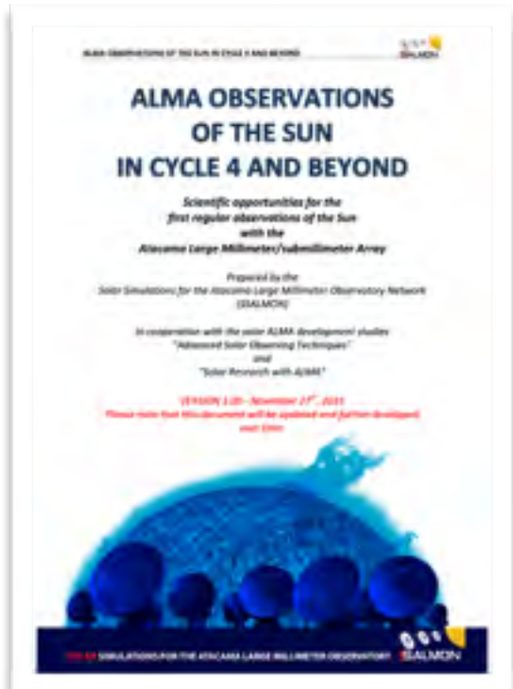


SOLAR SIMULATIONS FOR THE ATACAMA LARGE MILLIMETER OBSERVATORY NETWORK

SALMON

- International network (since 9/2014)
- Simulations in support of ALMA in order to better plan, optimize and analyze solar observations.
- 83 network members from 18 countries (+ESO, ESA)
- Open for everybody with professional interest in solar ALMA science.

- Solar ALMA review paper - Space Science Reviews 200, 1 (2016)
- White Paper for Cycle 4
- Solar-stellar ALMA session at Cool Stars 19



- SSALMON web pages at http://ssalmon.uio.no

Solar science with ALMA

ALMA overview paper: Wedemeyer et al. SSRv 200, 1 (2016)

Central questions in solar physics to be addressed with ALMA

Solar science with ALMA

ALMA overview paper: Wedemeyer et al. SSRv 200, 1 (2016)

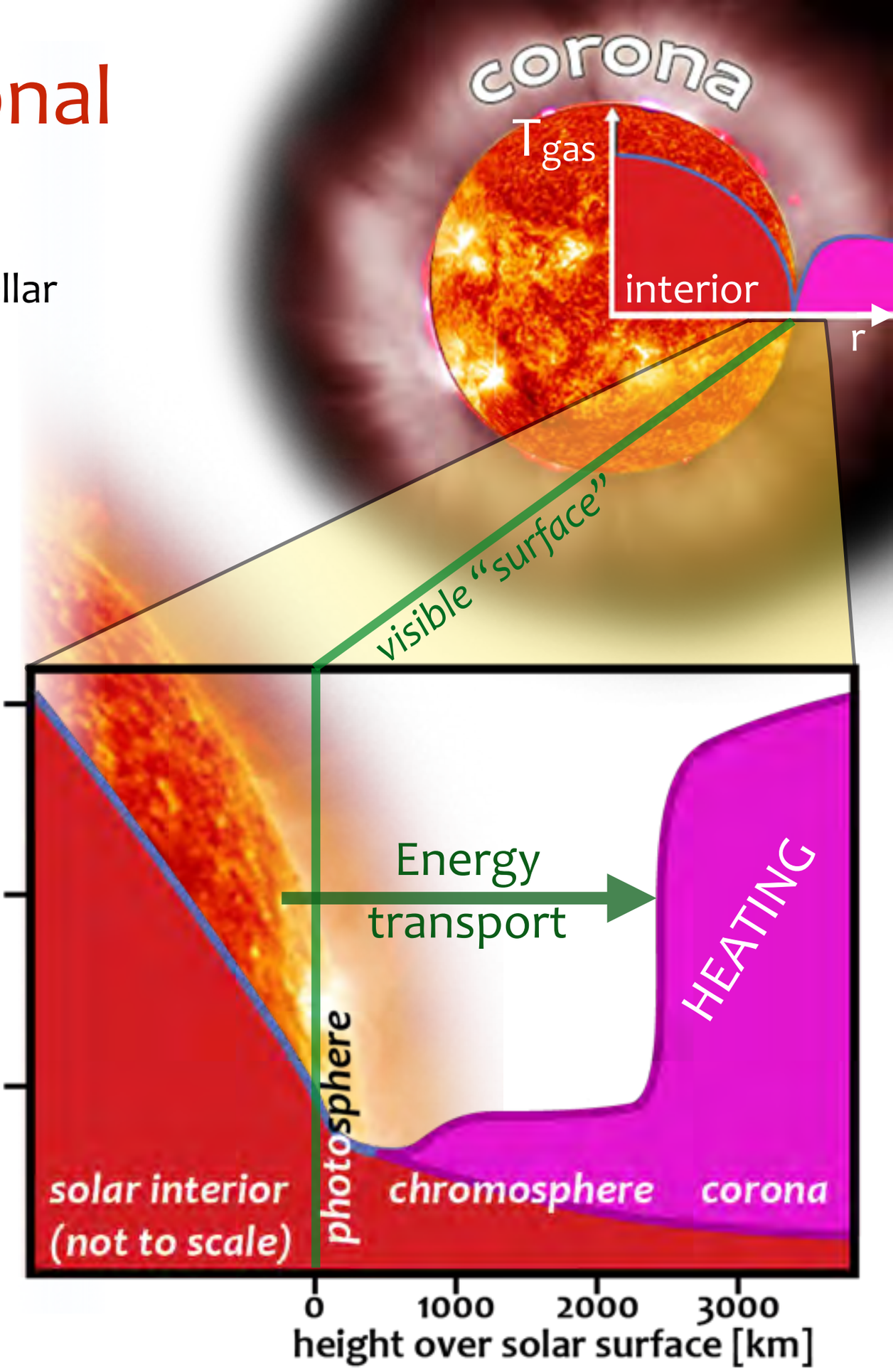
The chromospheric/coronal heating problem

- A long-standing central problem in solar / stellar astrophysics!
- Known and unsolved for ~75 years *(Grotrian 1939, Edlén 1940)*:
- **Gas temperature > 1 000 000 K** in the outer layers of the Sun.

➡ **Outer layers heated!**

➡ **Open question:**

HOW?



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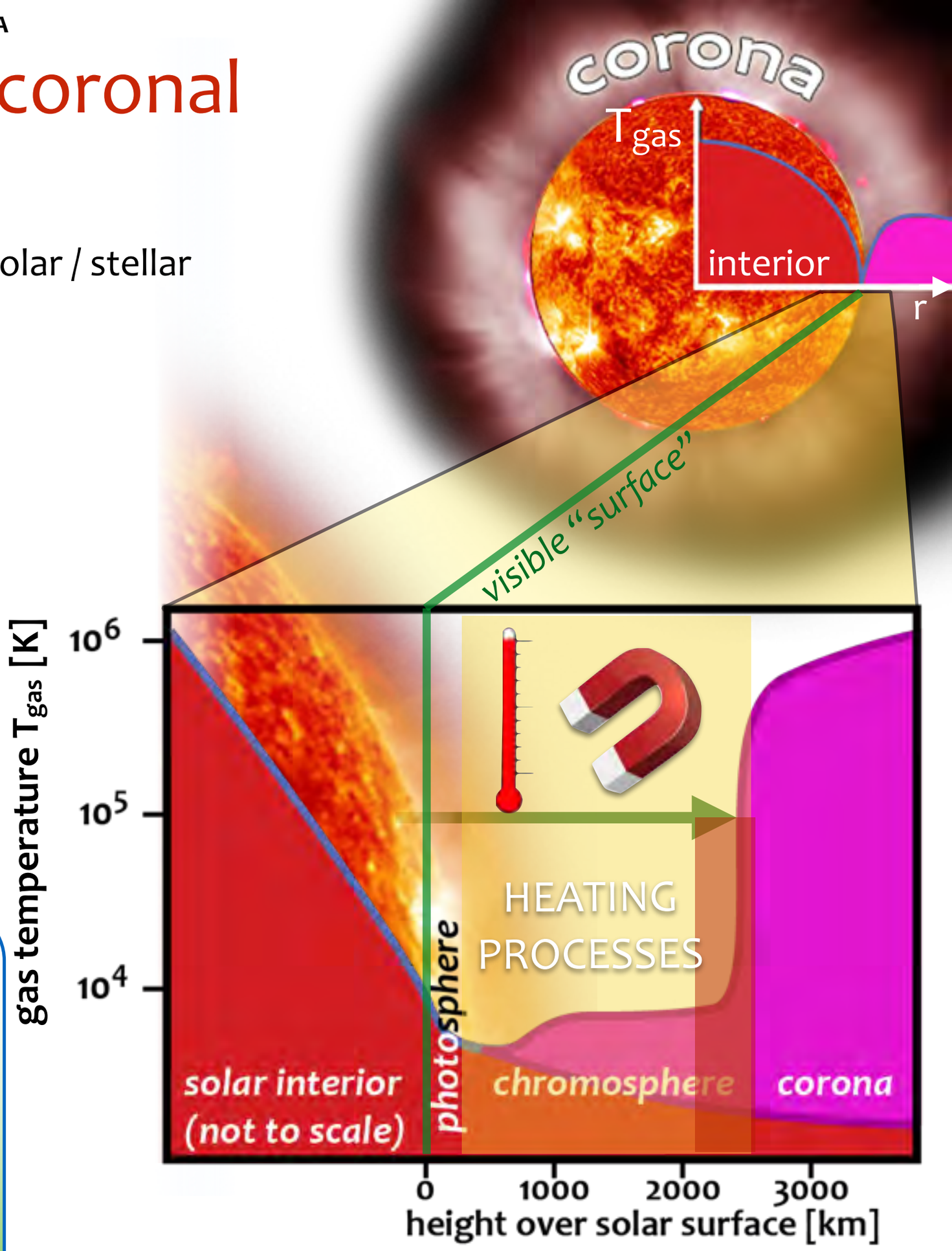
- **ALMA = solution:**
  Measuring the 3D thermal and magnetic structure of the chromosphere
  - ➡ sinks and sources of energy
  - ➡ signatures of heating processes



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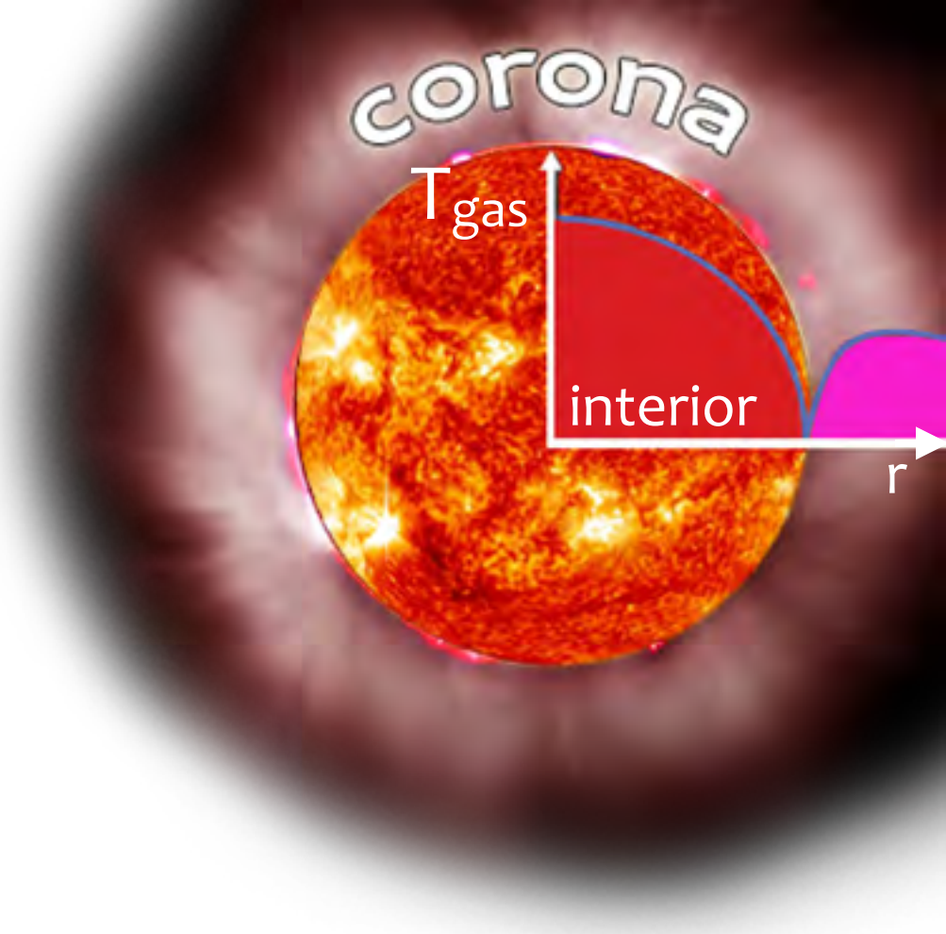

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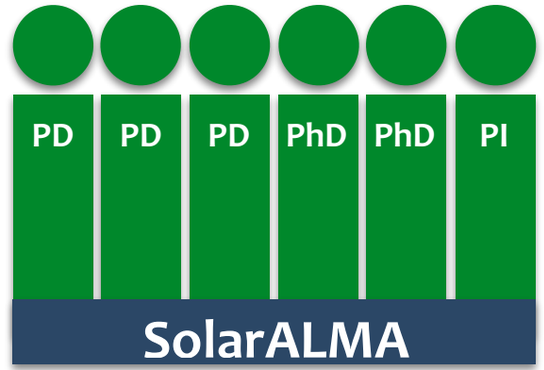
- **SolarALMA project@University of Oslo**
- **ERC Consolidator Grant**
- **2016 - 2021, 2 MEUR, team of 5+**



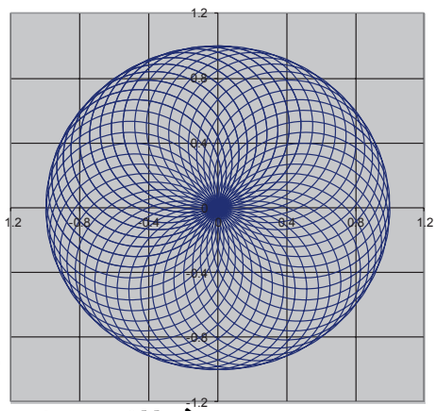
Recommendations for future development

"Basic" capabilities

- **Continuous observing** (sequences of 1-2 hours, in one band)
  - *Cycle 4: blocks of 10 min interrupted by 3 min of calibration*
  - *Wanted: NO (or minimal) interruption due to calibration*

	30 min	*10 min*	*3 min*	*10 min*	*3 min*
Cycle 4	initial calibration	**science**	calibration	**science**	calibration
wanted	initial calibration	**science**	*No interruptions: Possible? (Self-)Calibration?*		

- **Complementary single-dish fast scanning** (context+imaging)
  - *Cycle 4: only full-disk scans (~7-10 min per scan)*
  - *wanted: smaller FOVs with accordingly higher cadence*

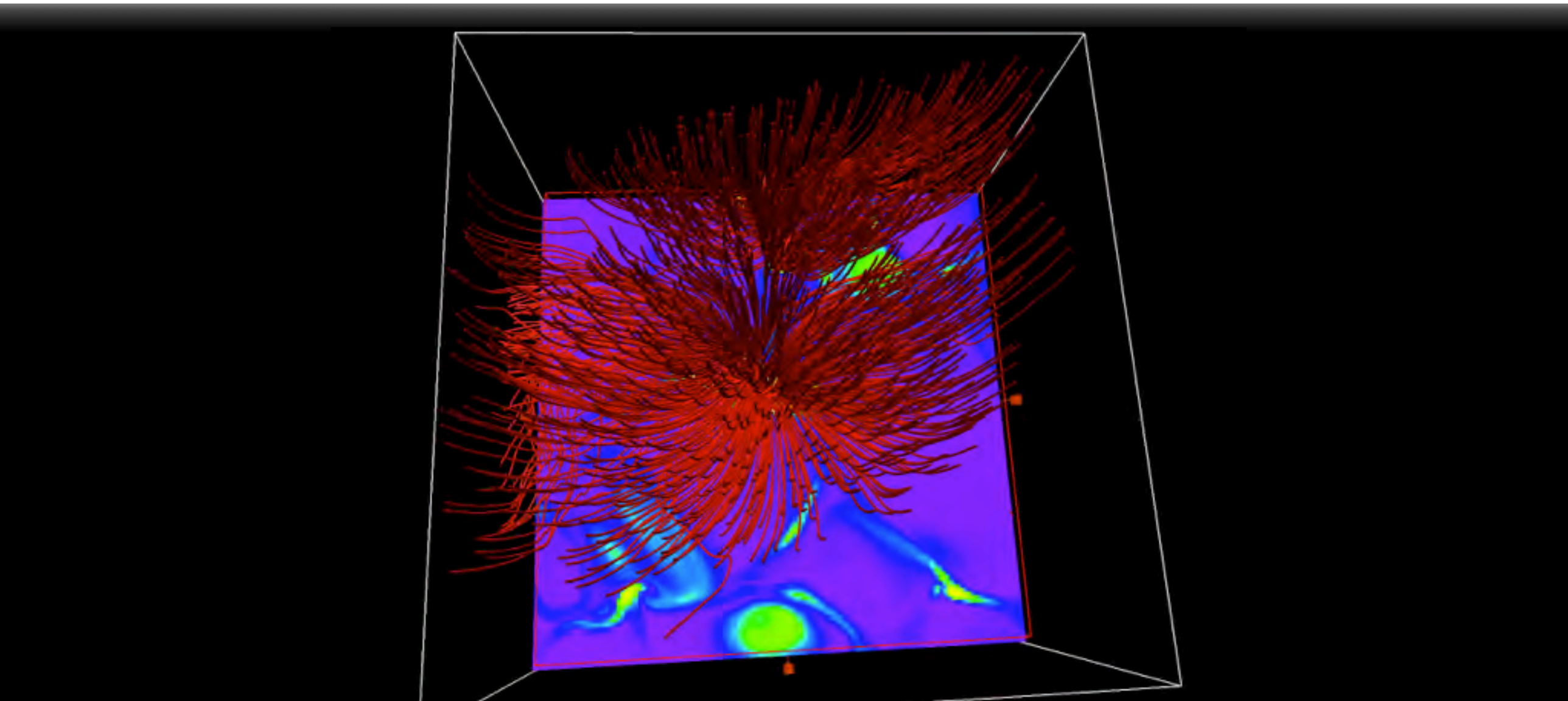


scan pattern (Hudson & Hills)

Recommendations for future development

Advanced capabilities with potentially large scientific impact

- **Polarization capabilities**
  - ➡ Chromospheric magnetic field measurements extremely important.
  - ➡ A “hot topic”!
  - ➡ Chromospheric 3D field topology never directly measured before



Recommendations for future development

Advanced capabilities with potentially large scientific impact

- **Fast receiver band switching** (tomography)
  - *rapid (or "quasi-simultaneous") mapping of a large frequency range and thus large atmospheric height range*
    - *Time for band switching of 1 min or less. Possible?*
  - *Additionally/alternatively: "multi-band receivers" covering large frequency range (?)*

- **Full spectral capability**
  - *Cycle 4: 4 x 128 continuum channels*
  - *Wanted: More channels, high spectral resolution*

➡ *novel plasma probes*

➡ *Discoveries ahead!*

Recommendations for future development

Alternative/additional capabilities

- **Sub-arrays** - as solution to enable:
  - Simultaneous multi-band observations

	30 min	*10 min*	*3 min*	*10 min*	*3 min*
Sub-array 1	initial calibration	**science, band 3**	calibration	**science, band 3**	calibration
Sub-array 2	initial calibration	**science, band 6**	calibration	**science, band 6**	calibration

  - Continuous single-band observing

	30 min	*10 min*	*10 min*	*10 min*	*10 min*
Sub-array 1	initial calibration	**science, band 3**	calibration (3 min)	**science, band 3**	calibration (3 min)
Sub-array 2	initial calibration	wait	**science, band 3**	calibration (3 min)	**science, band 3**

- **Multi-frequency synthesis** for improved imaging

Recommendations for future development

NextGen post-processing pipeline - Data "afterburners"

- **Increasing the scientific content of solar ALMA data to unprecedented levels**
- Development started, could be ready soon *(part of ERC-funded SolarALMA project)*

INPUT

ALMA DATA

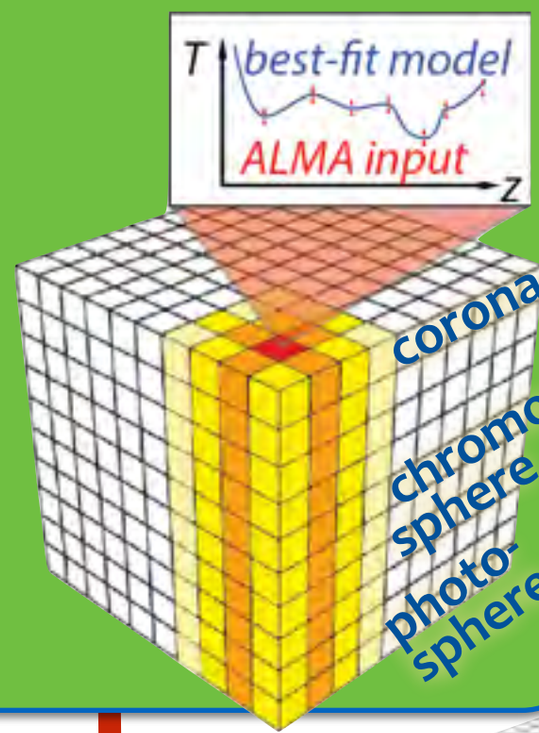
preferably:

- *multi-band*
- *sequences with high cadence*

DATA INVERSION CODE

Fitting time series of 3D model atmospheres to input data:

many nodes, spatially and temporally coupled, handles even sparse data



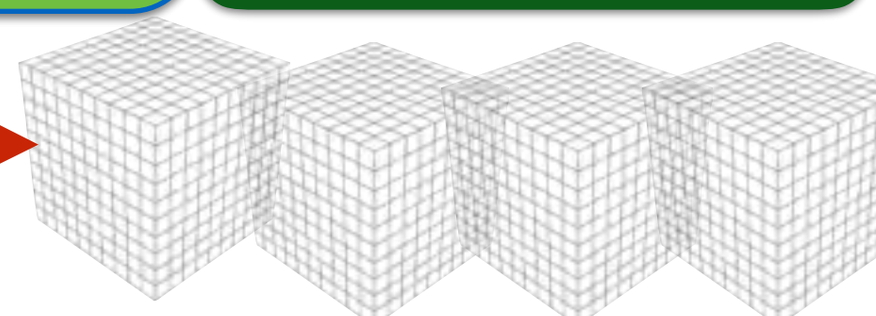
Model constraints:
Magnetohydrodynamics, Equation of state, Continuity, …

Radiative transfer
Synthetic observables

Instrumental effects:
Array, receivers, …

➡ **OUTPUT**

complete 3D, time-dependent thermal, magnetic and kinetic state of the chromospheric plasma



Conclusion:

Solar ALMA observations promise many exciting and important results!

3D MHD simulation + rad. transfer (Bifrost, M. Carlsson, University of Oslo)