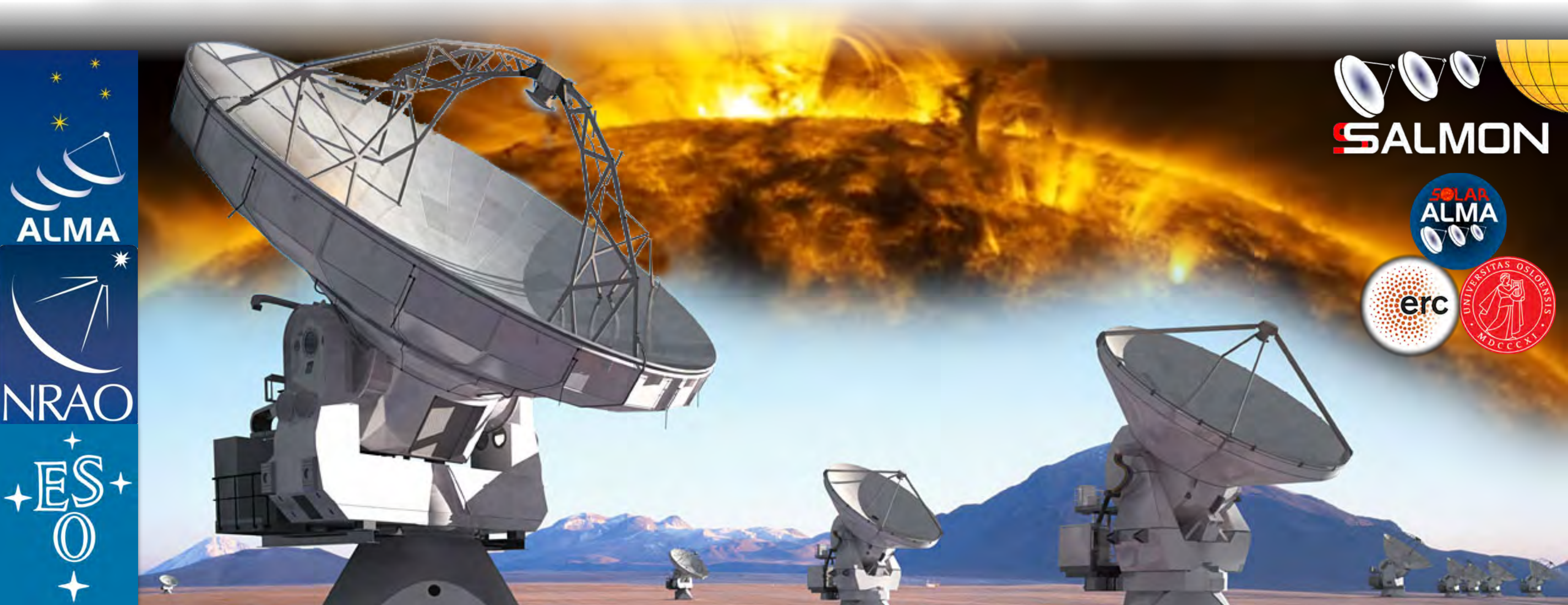
A new perspective on the Sun with ALMA

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



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ALMA's potential for the Sun

- Continuum radiation at mm wavelengths:
  - Thermal component *(electron-ion free-free + H^{-} free-free)*
  - Non-thermal component (*gyroresonance/-synchrotron*) in presence of strong magnetic fields and flares

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ALMA's potential for the Sun

- Maps the solar chromosphere
  - at high spatial resolution
  - at high temporal resolution *(possibly < 1s)*
  - at high spectral resolution
    (in the end up to 10 receiver bands, each with up to thousands of channels)
- Acts as linear thermometer of the solar plasma
  (long wavelengths ➡ Rayleigh-Jeans limit of the Planckian source function)
- Measures the polarisation *(the magnetic field can be determined)*

ALMA's potential for the Sun

- Diagnostics
  - continuum intensity / brightness temperature T_b [x,y,t,λ]
  - polarization/chromospheric magnetic field measurements
  - radio recombination lines (some originating in the corona) *(?)*
  - molecular lines (e.g., CO)

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ALMA's potential for the Sun

➡ **Important results and advances in solar physics to be expected!**

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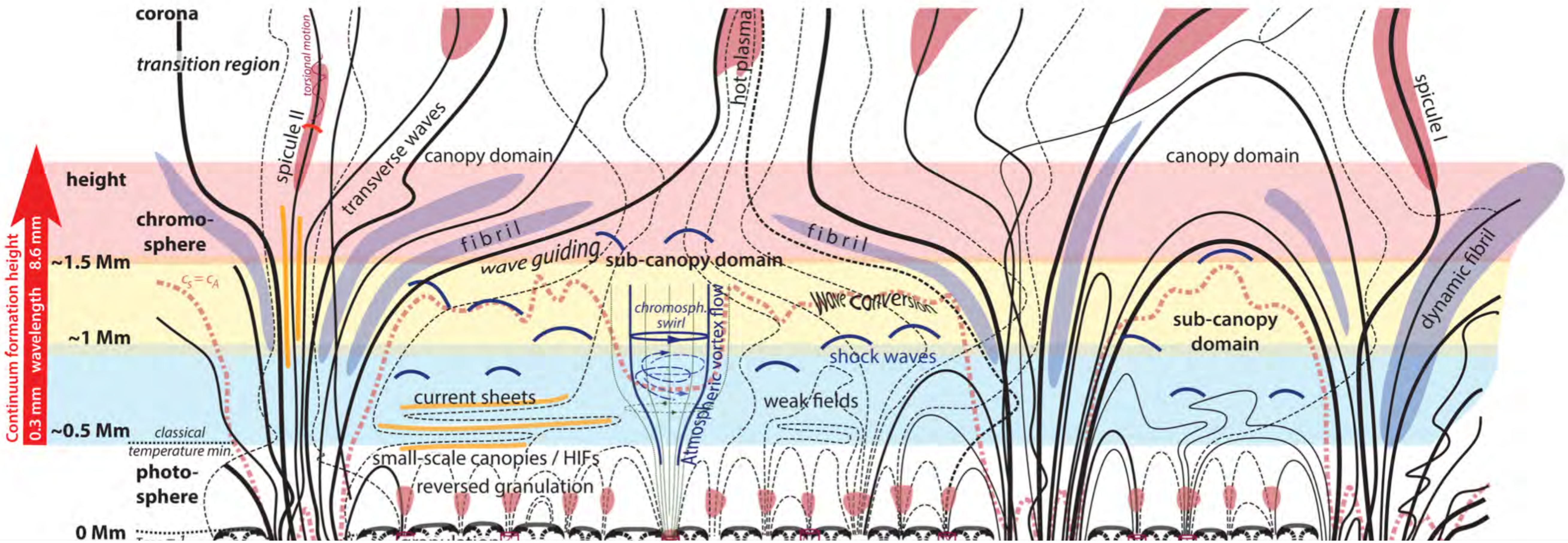
ALMA's potential for the Sun

- Height of mapped layer increases with wavelength
- Could multi-band observations be used for an atmospheric tomography?
- Time-dependent 3D thermal structure of the atmosphere?

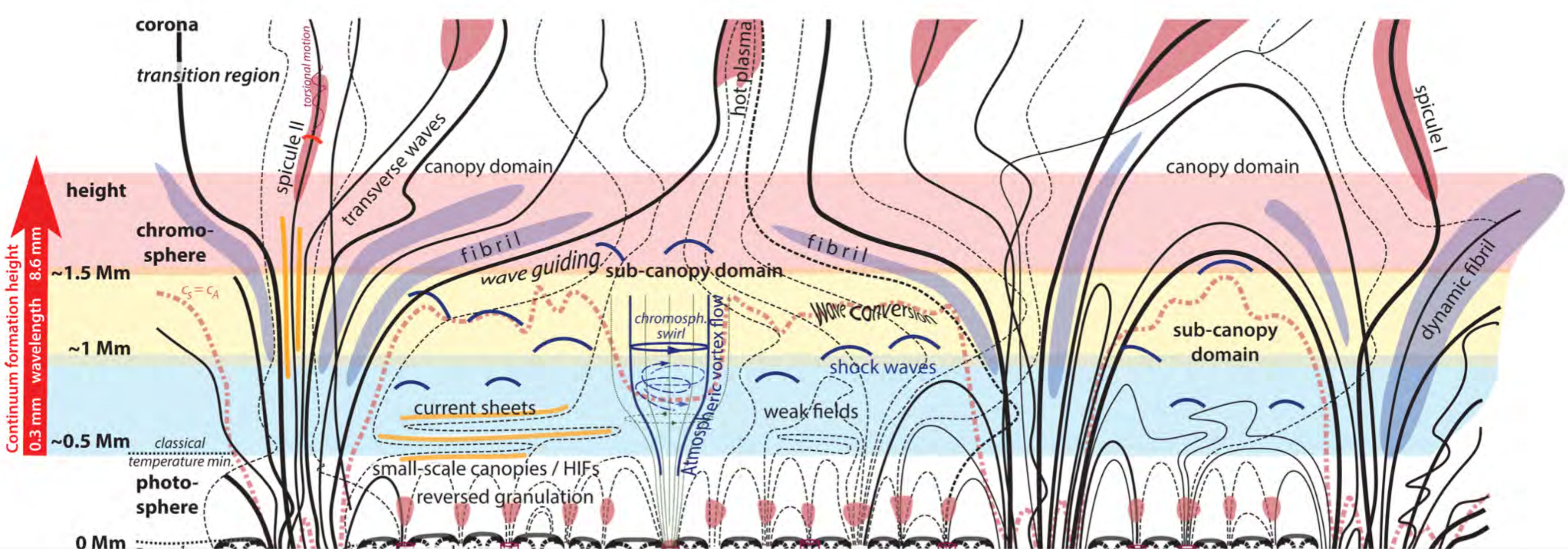


- Cycling through up to 3 ready receiver bands

➡ Mapping different layers in the chromosphere

ALMA's potential for the Sun

- Height of mapped layer increases with wavelength
- Could multi-band observations be used for an atmospheric tomography?
- Time-dependent 3D thermal structure of the atmosphere?



- Not offered in Cycle 4 (i.e. 10/2016-19/7) but hopefully soon

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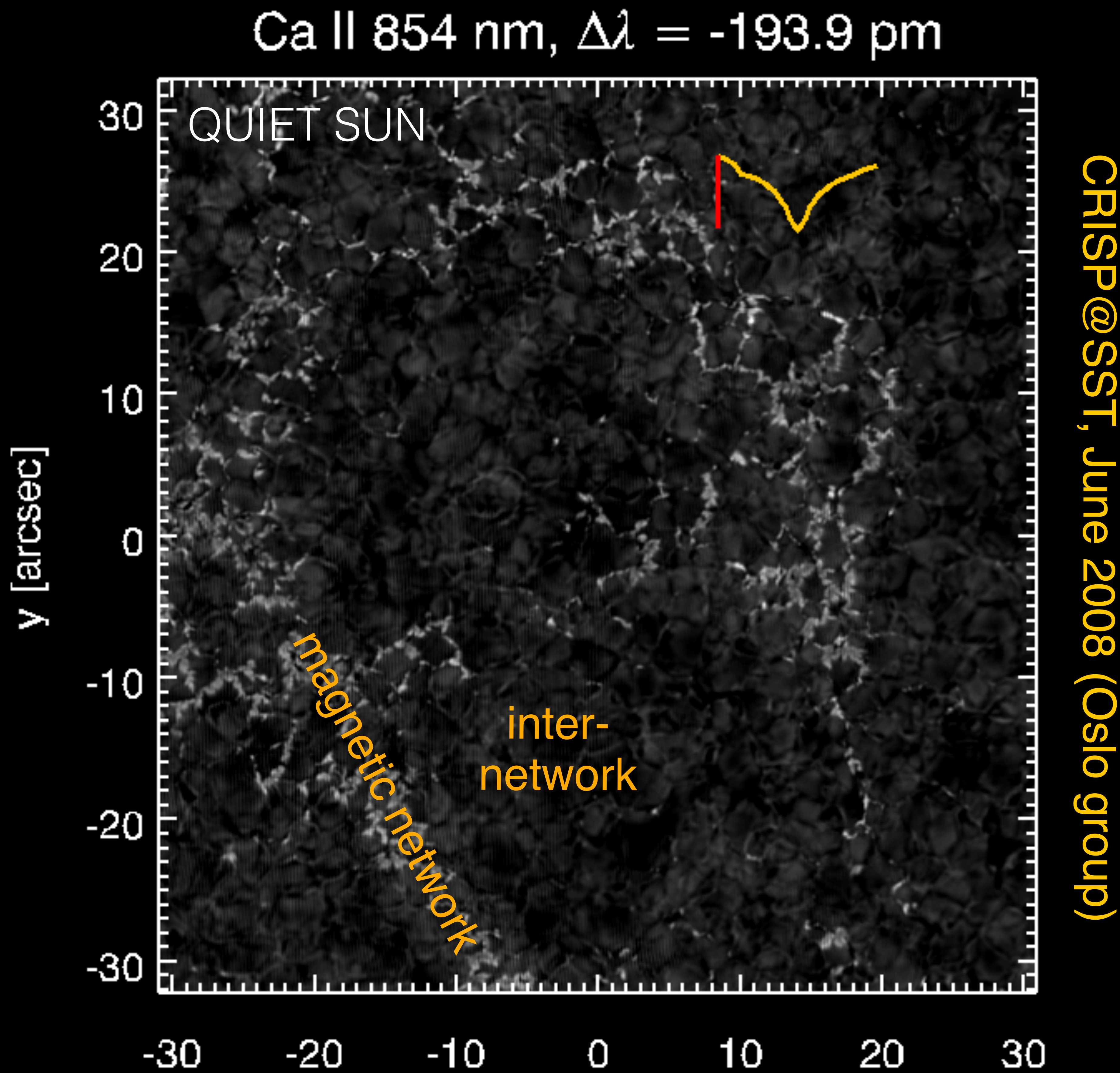
What will ALMA see?

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

Scan through Ca II 854 nm line

- wings formed in the photosphere
- core formed in the chromosphere
- sampling different layers
- atmospheric stratification (qualitatively)
- spatial resolution ~0.1 arcsec



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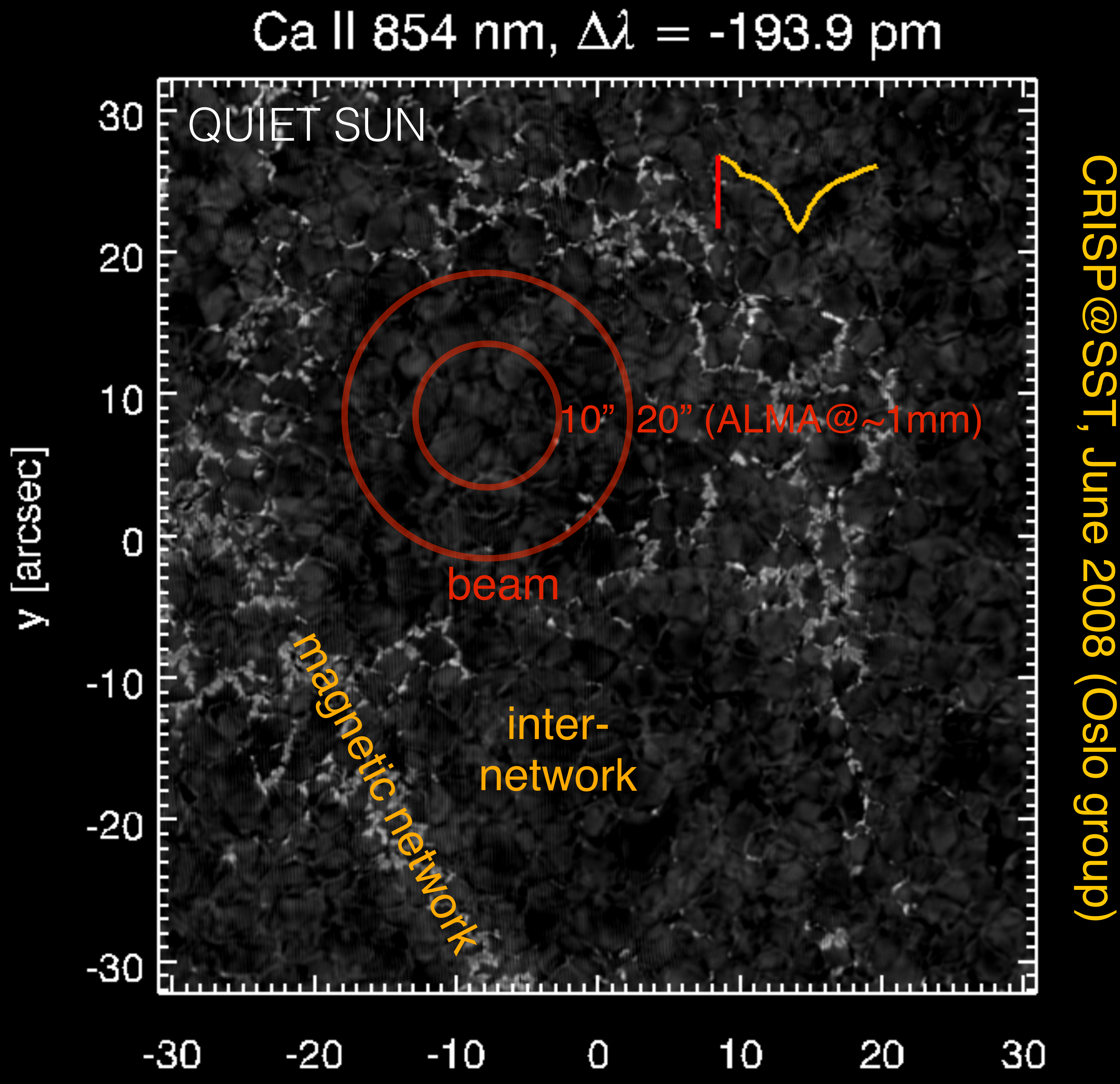
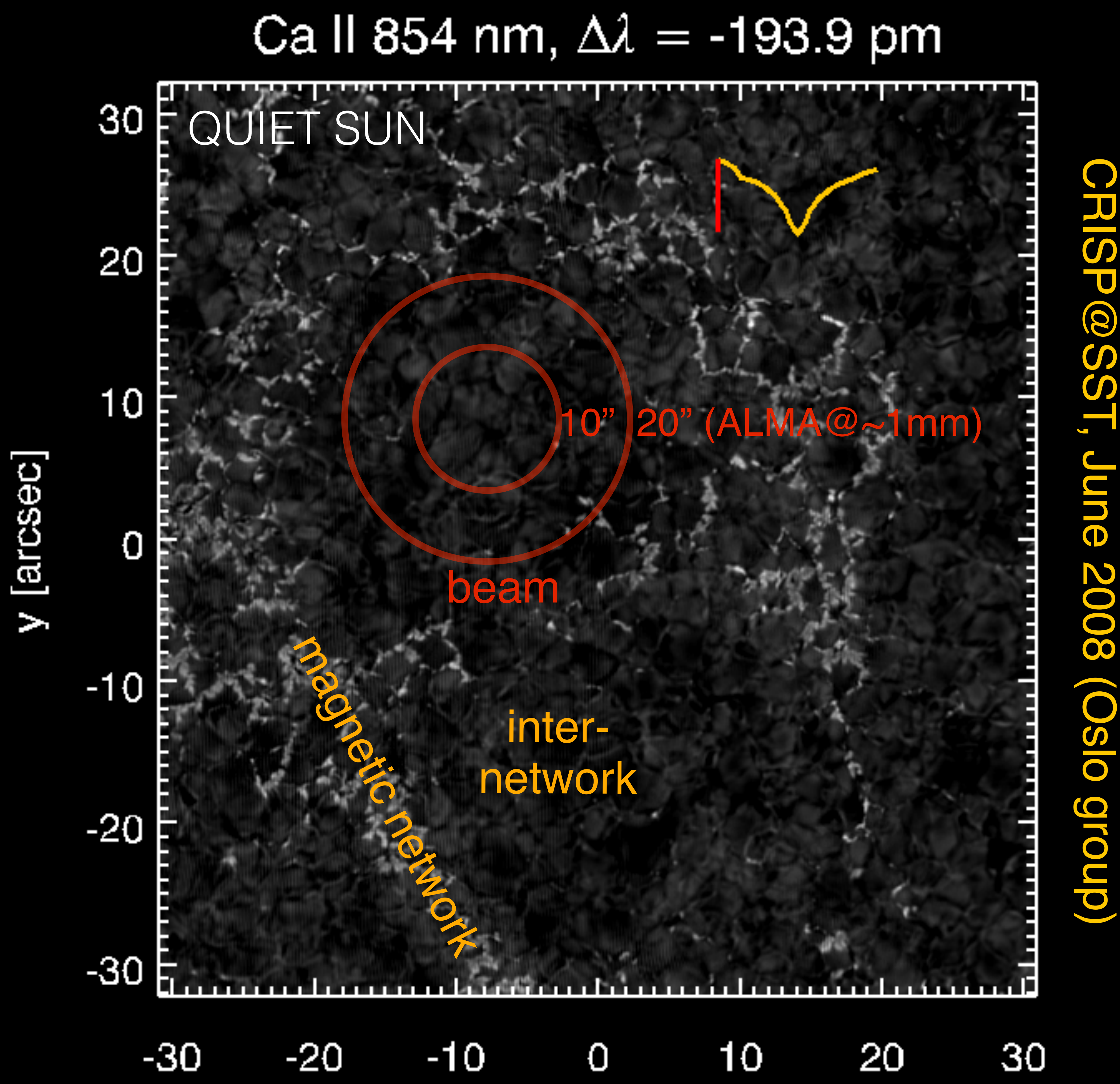
What will ALMA see?

- ➡ BUT: Images from currently available diagnostics are difficult to interpret (complicated line formation, non-equilibrium effects etc.)
- ➡ Continuum intensity at mm wavelengths easier to interpret



- ALMA has now the required spatial resolution

What will ALMA see?



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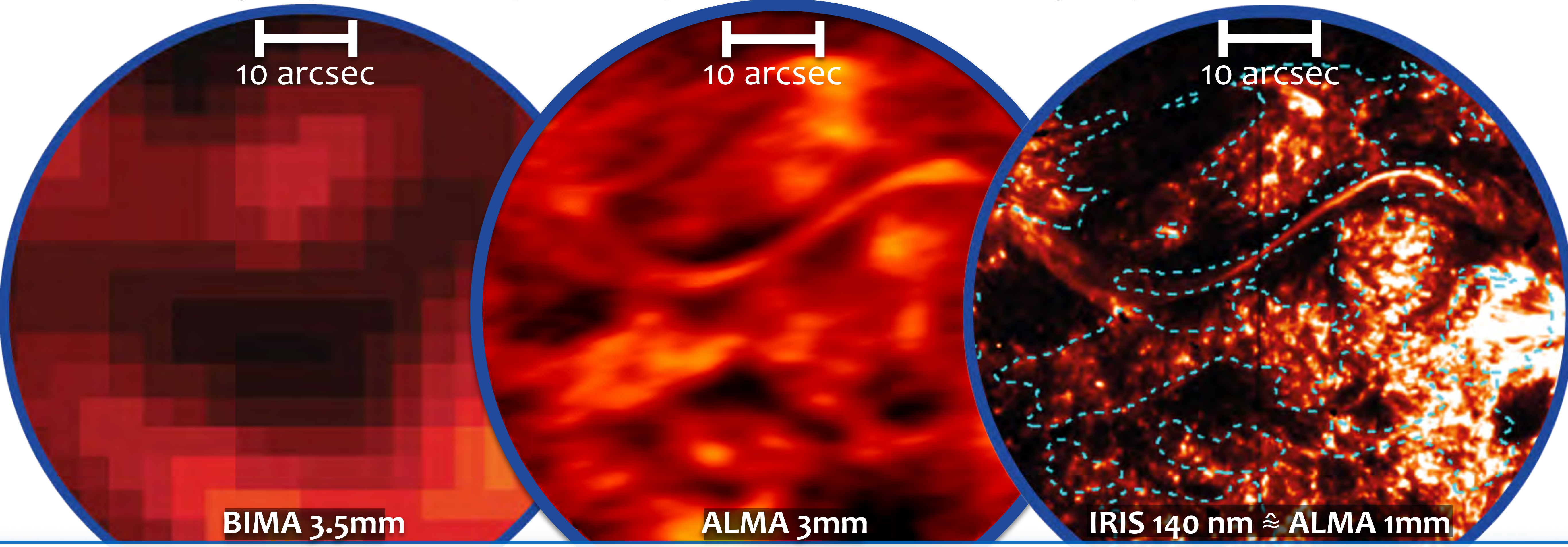
ALMA as a true game changer

High spatial + temporal + spectral resolution = big leap!



Berkeley-Illinois-Maryland Array (BIMA, 2004), λ = 3.5 mm:
resolution 10 arcsec
(cf. Loukitcheva et al. 2008)

ALMA, successful test 2014,
interferometry, λ = 3.0 mm:
resolution < 1 arcsec !

further improvements
full array ALMA
0.3 arcsec x λ /1mm

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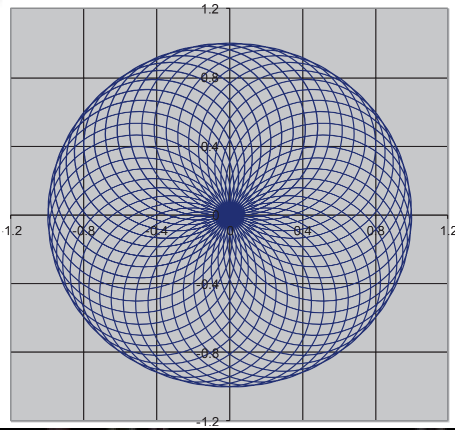
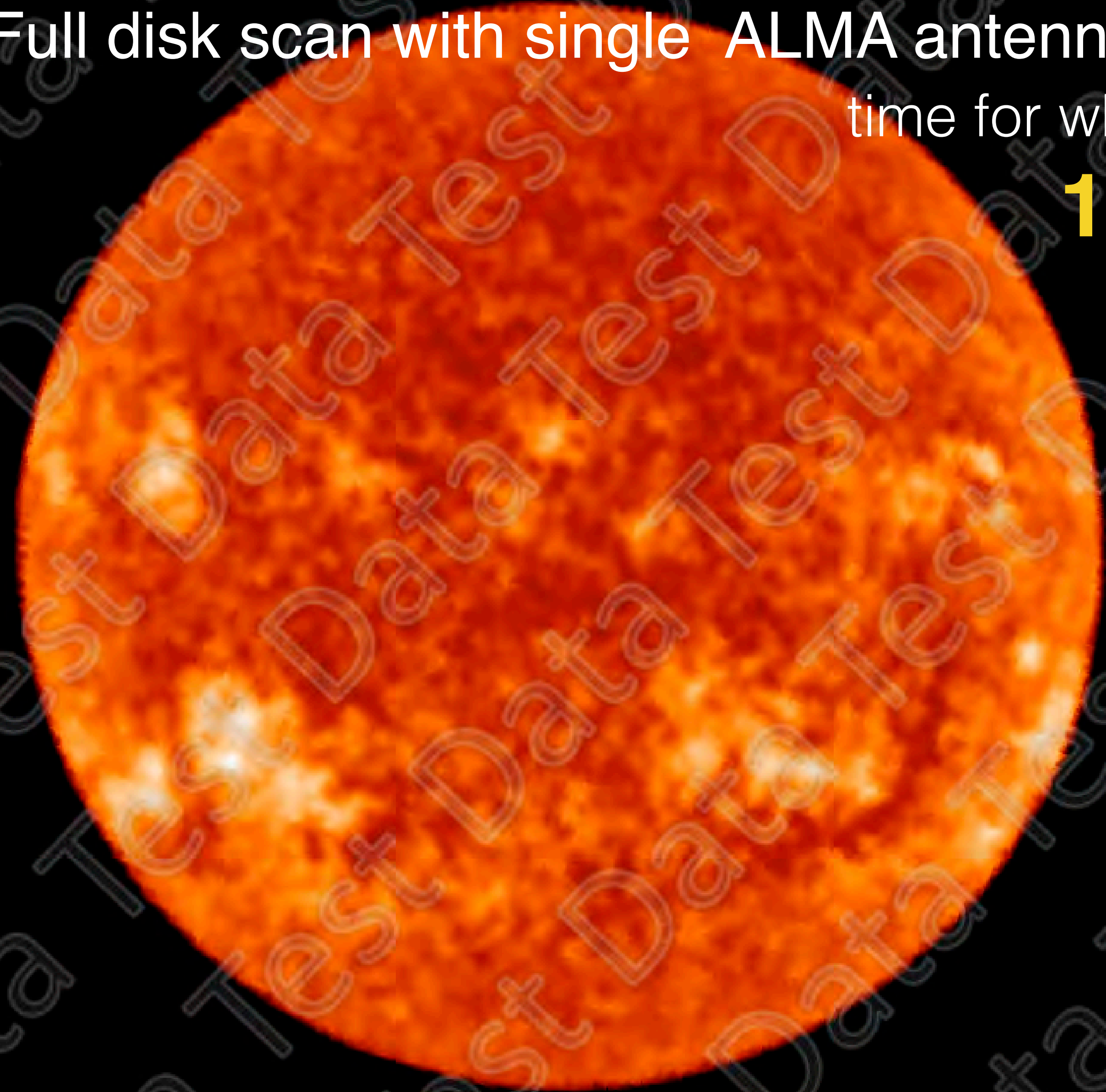
On-the-fly single-dish observations

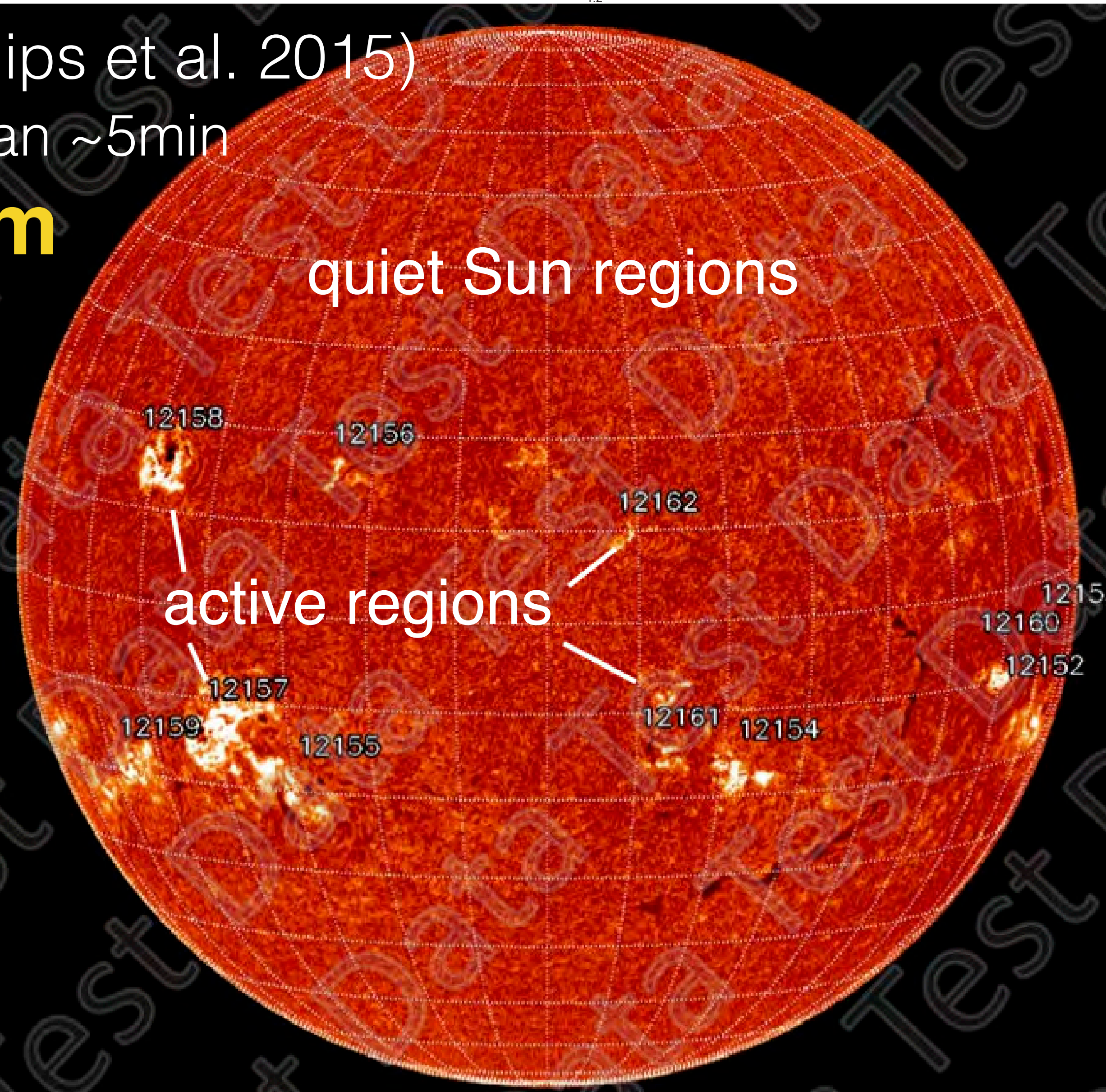
- Using fast scanning with the TP antennas
  (most likely offered simultaneous to interferometry in Cycle 4)
- Preliminary results from CSV campaign #4 (9/2014)
  (non-public commissioning data)



scan pattern (Hudson & Hills)



ALMA 230 GHz (test campaign, Sep. 2014)



Hα (for comparison)

SOLAR SIMULATIONS FOR THE ATACAMA LARGE MILLIMETER OBSERVATORY NETWORK

SSALMON

◉ International network

- Initiated in 9/2014 in connection with development teams
- Focus on numerical simulations and modelling related to solar ALMA science (i.e., the solar chromosphere at (sub-)millimeter wavelengths)
- Now: 78 network members from 18 countries (+ESO, ESA)

◉ Key goals

1. Raising awareness of science opportunities with ALMA.
2. Clear visibility of solar science within the ALMA community.
3. Constrain ALMA observing modes in order to better plan, optimize and analyze solar observations.

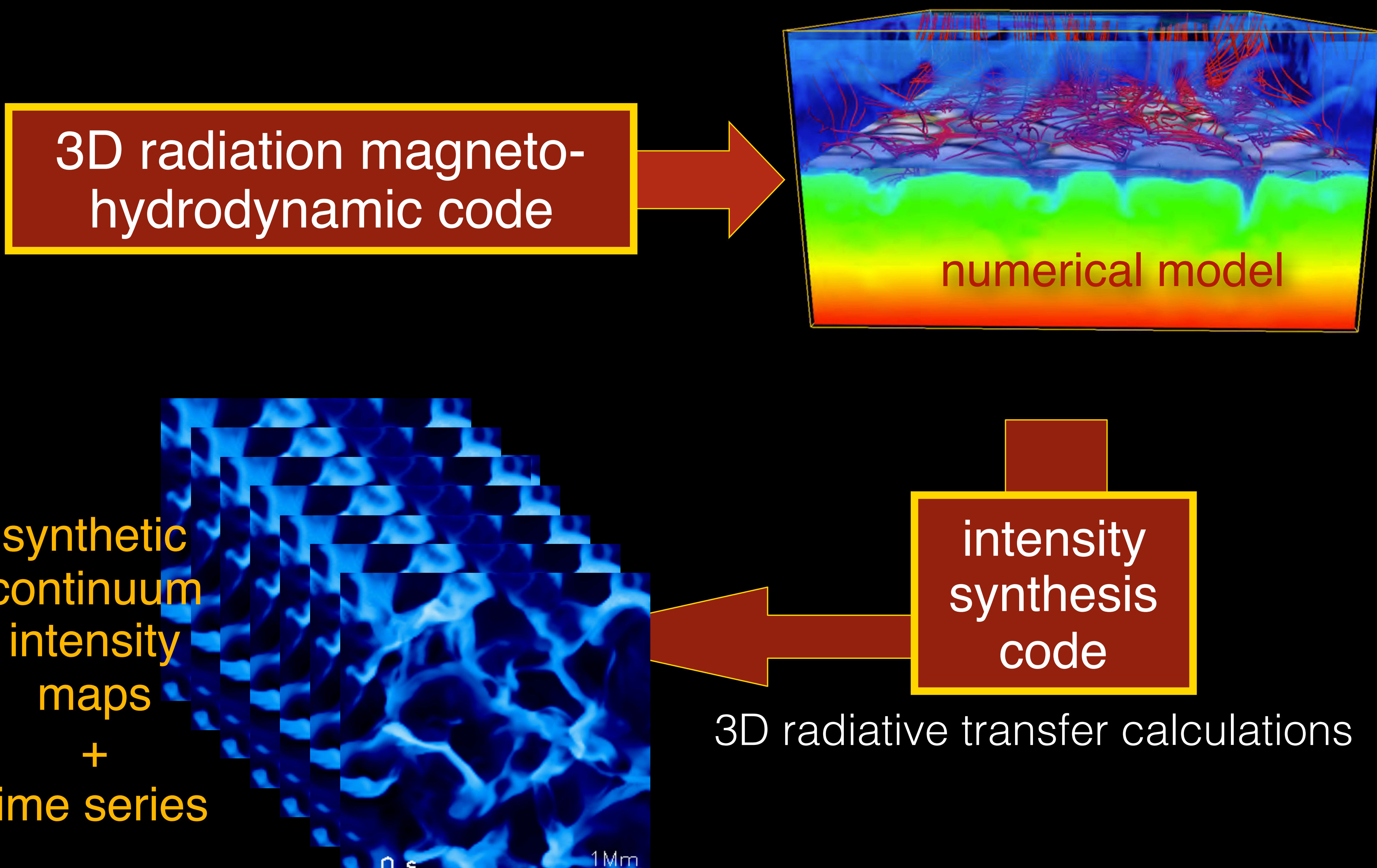
◉ SSALMON web pages at http://ssalmon.uio.no.

◉ Open for everybody with professional interest in solar ALMA science.

Quiet Sun regions

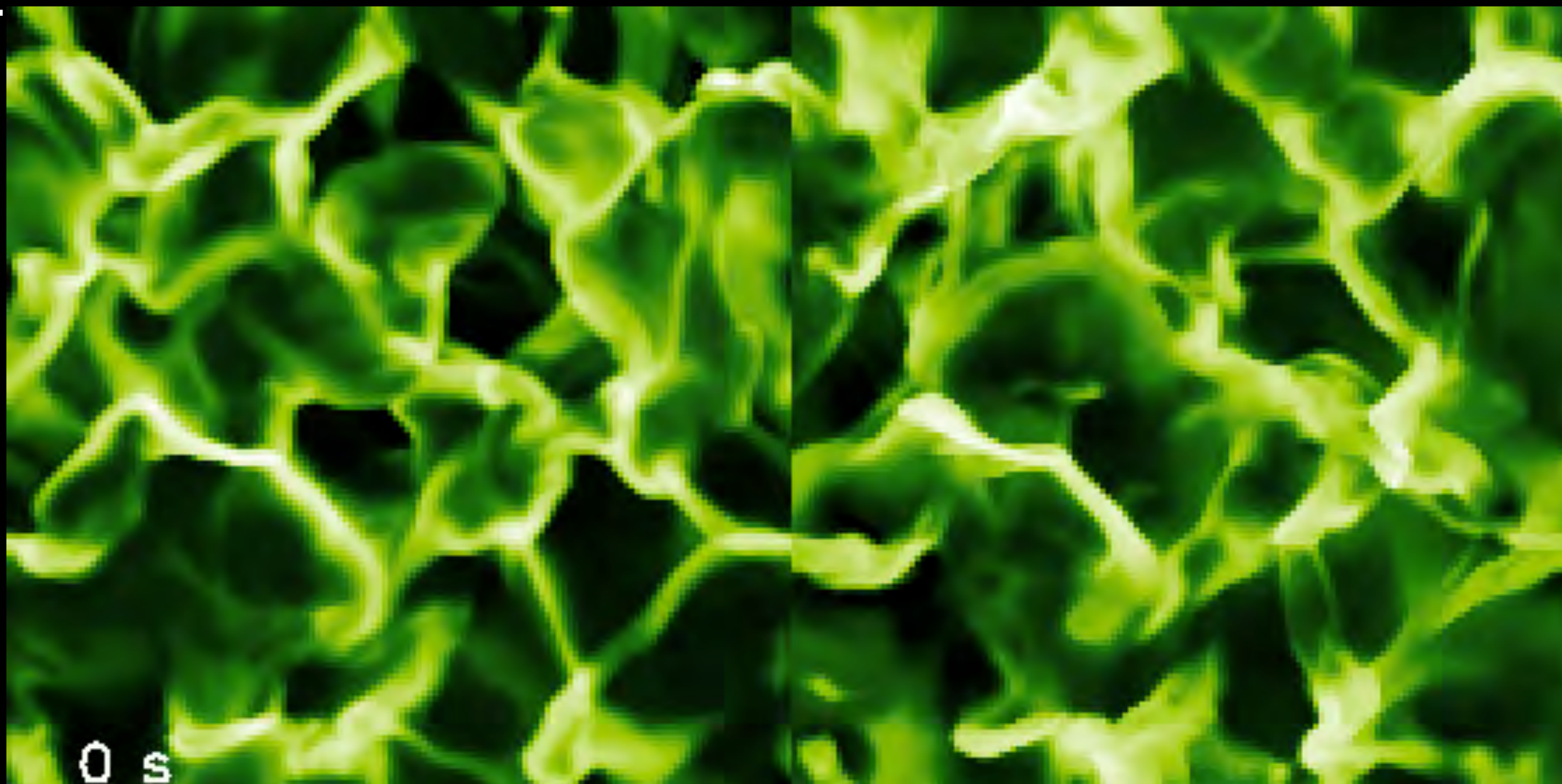
What can we expect to see?

- Predictions by means of synthetic intensity maps calculated from 3D radiation magnetohydrodynamic simulations



Quiet Sun chromosphere

6 Mm (8”)



Wedemeyer-B. et al. (2007)

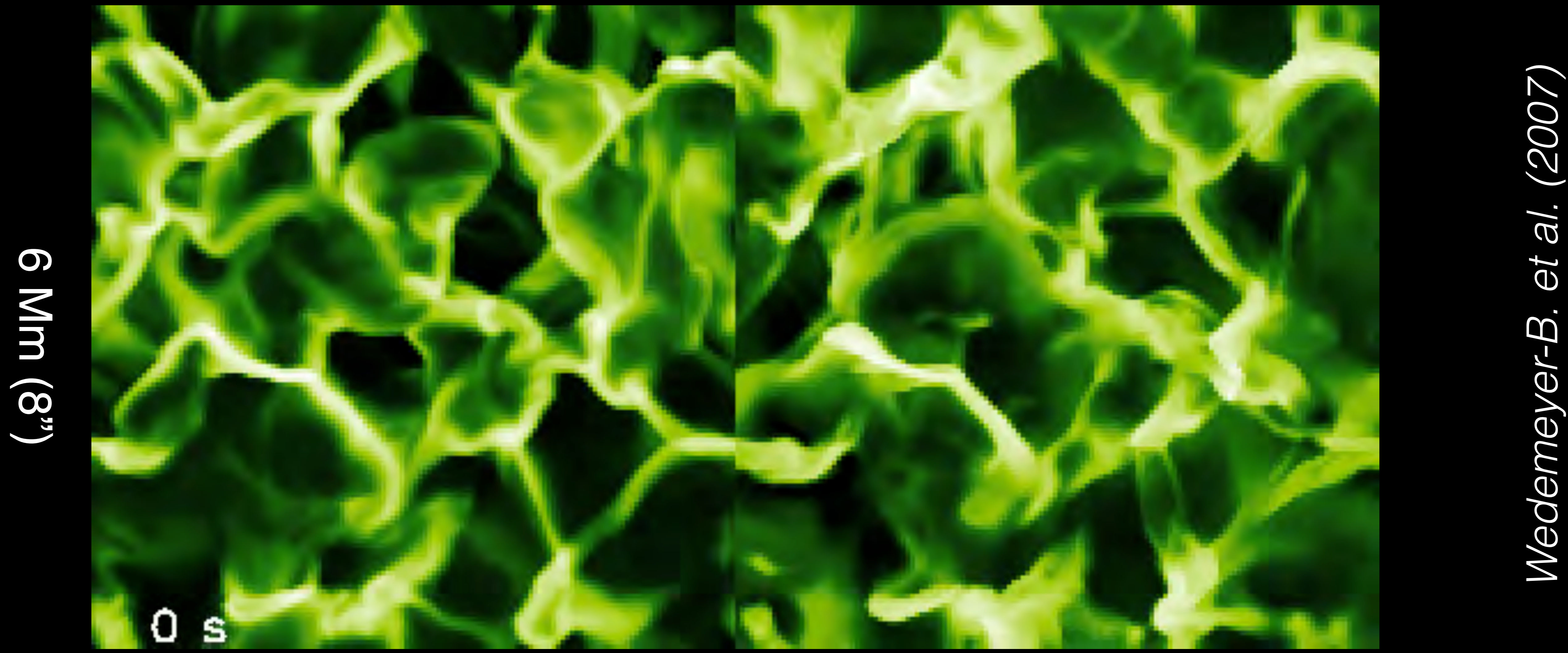
What is what?

gas temperature
at z=1000km

continuum intensity at
λ=1mm

3D hydrodynamical model
pattern produced by
the interaction of
propagating shock waves

Quiet Sun chromosphere



gas temperature at z=1000km

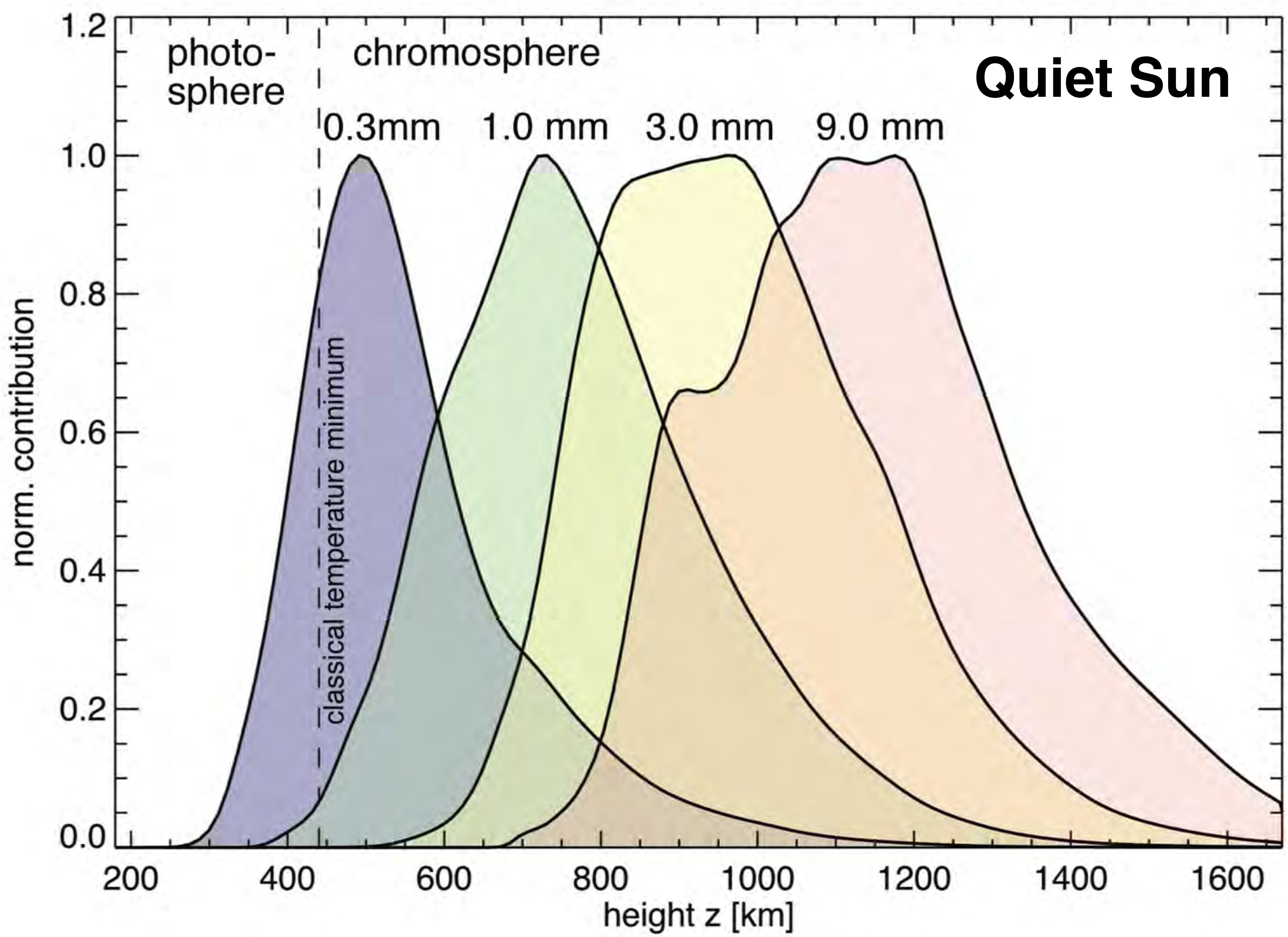
continuum intensity at λ=1mm

ALMA as linear thermometer for the chromospheric plasma!

➡ Gas temperature in chromosphere closely mapped

Continuum formation heights

- Could multi-band observations be used for an atmospheric tomography?
- Time-dependent 3D thermal structure of the atmosphere?



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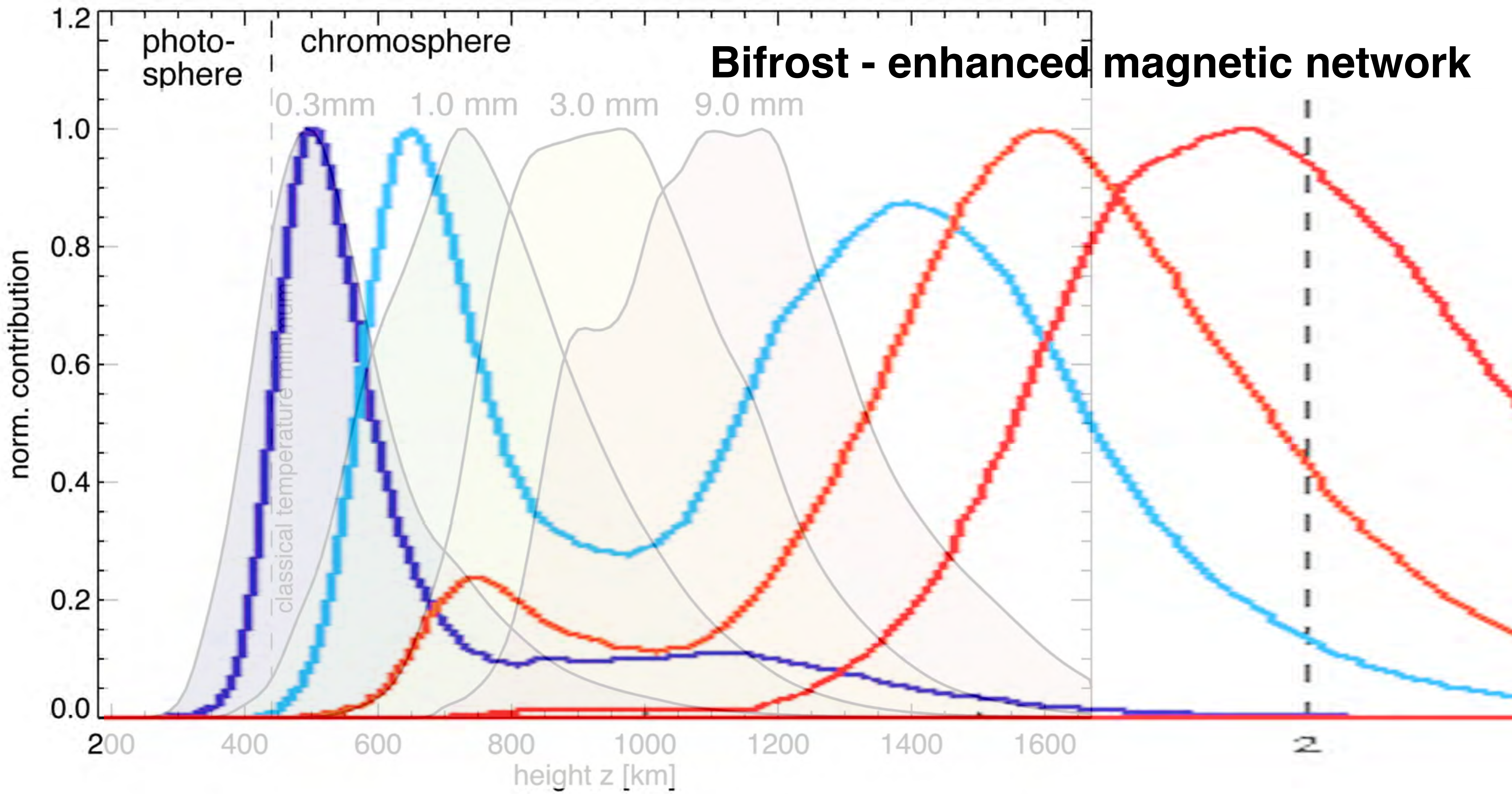

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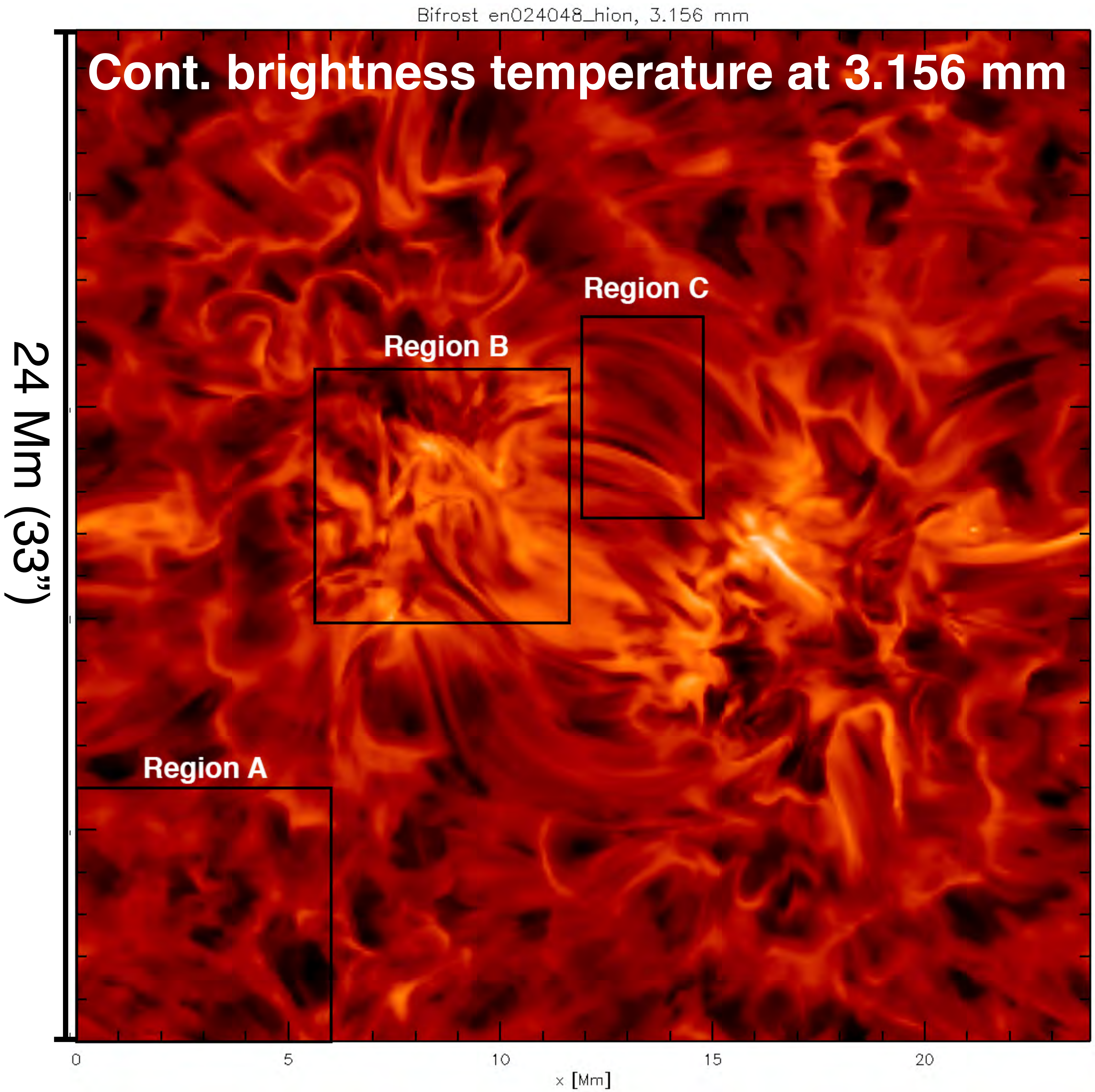
Continuum formation heights

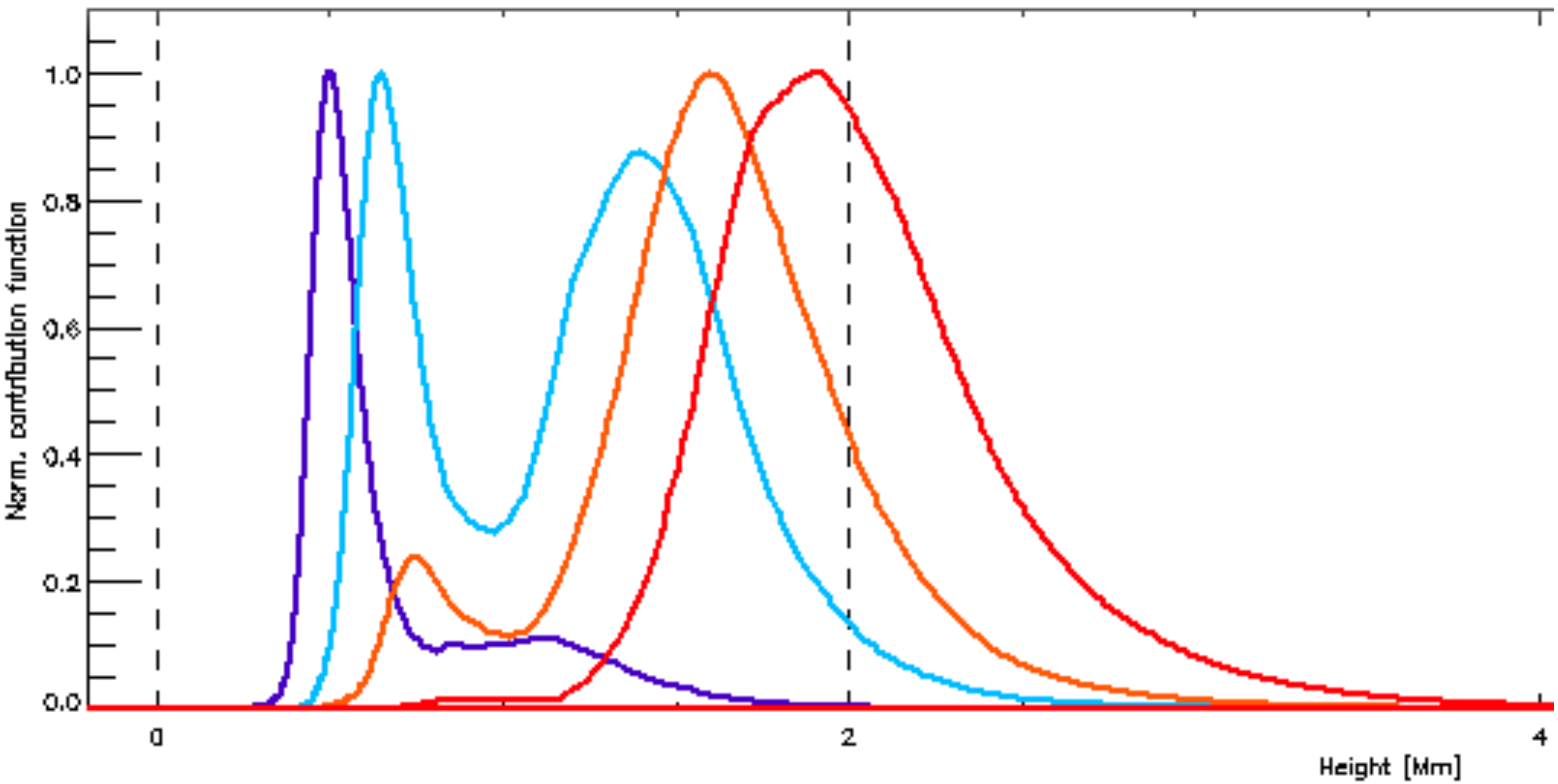


- **Bifrost snapshot** (Carlsson et al. 2016; cf. Loukitcheva et al. 2015)
- **Enhanced magnetic network:** patches of opposite polarity, coronal loops
- Used as benchmark for RT code comparison by SSALMON team B

A. "Quiet Sun"
B. Above magnetic field concentration
C. Coronal loops

Continuum formation heights

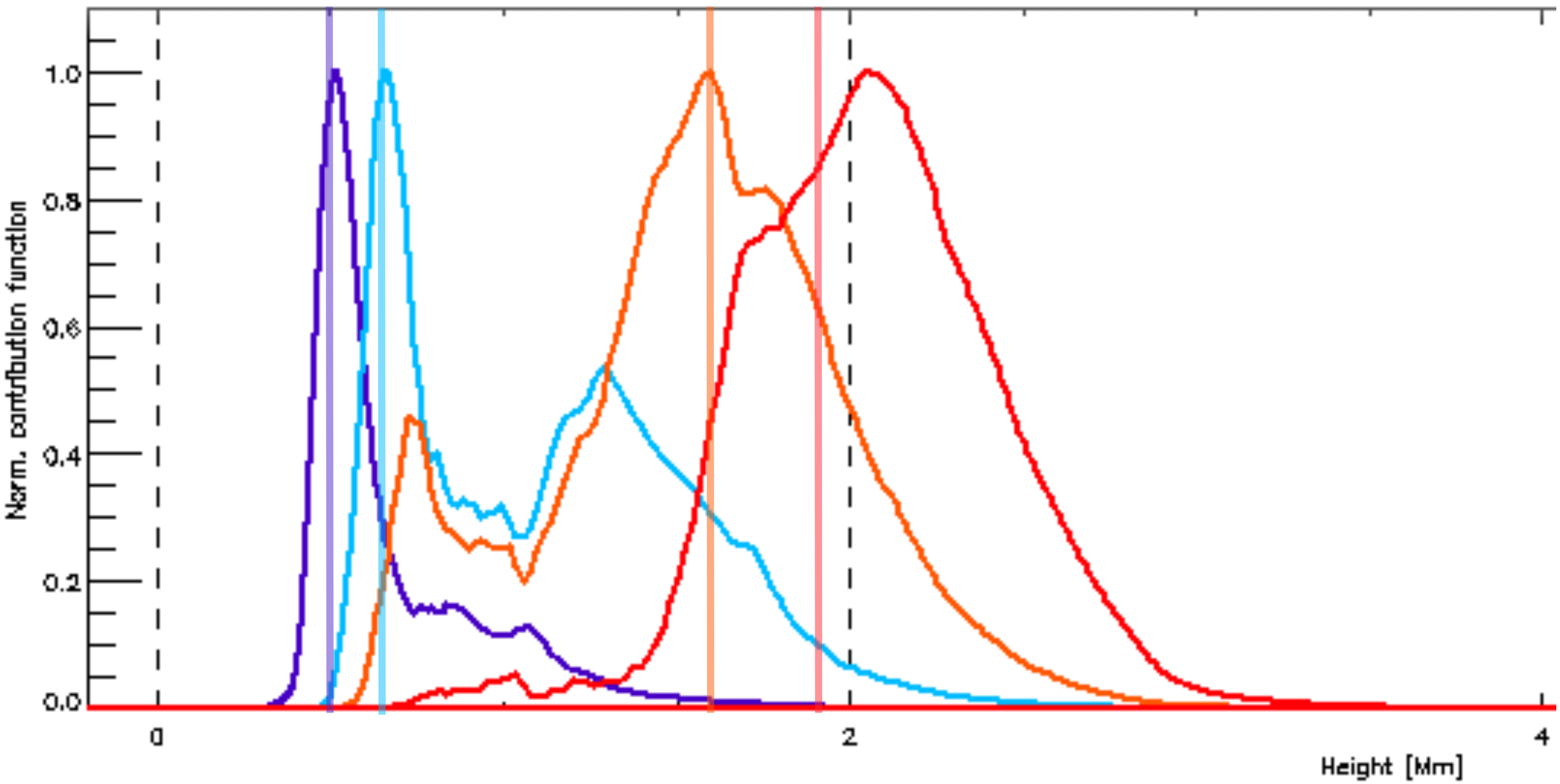
Whole computational box



0.316 mm 1.292 mm 3.156 mm 9.671 mm

Continuum formation heights

A: "Quiet Sun"



0.316 mm 1.292 mm 3.156 mm 9.671 mm

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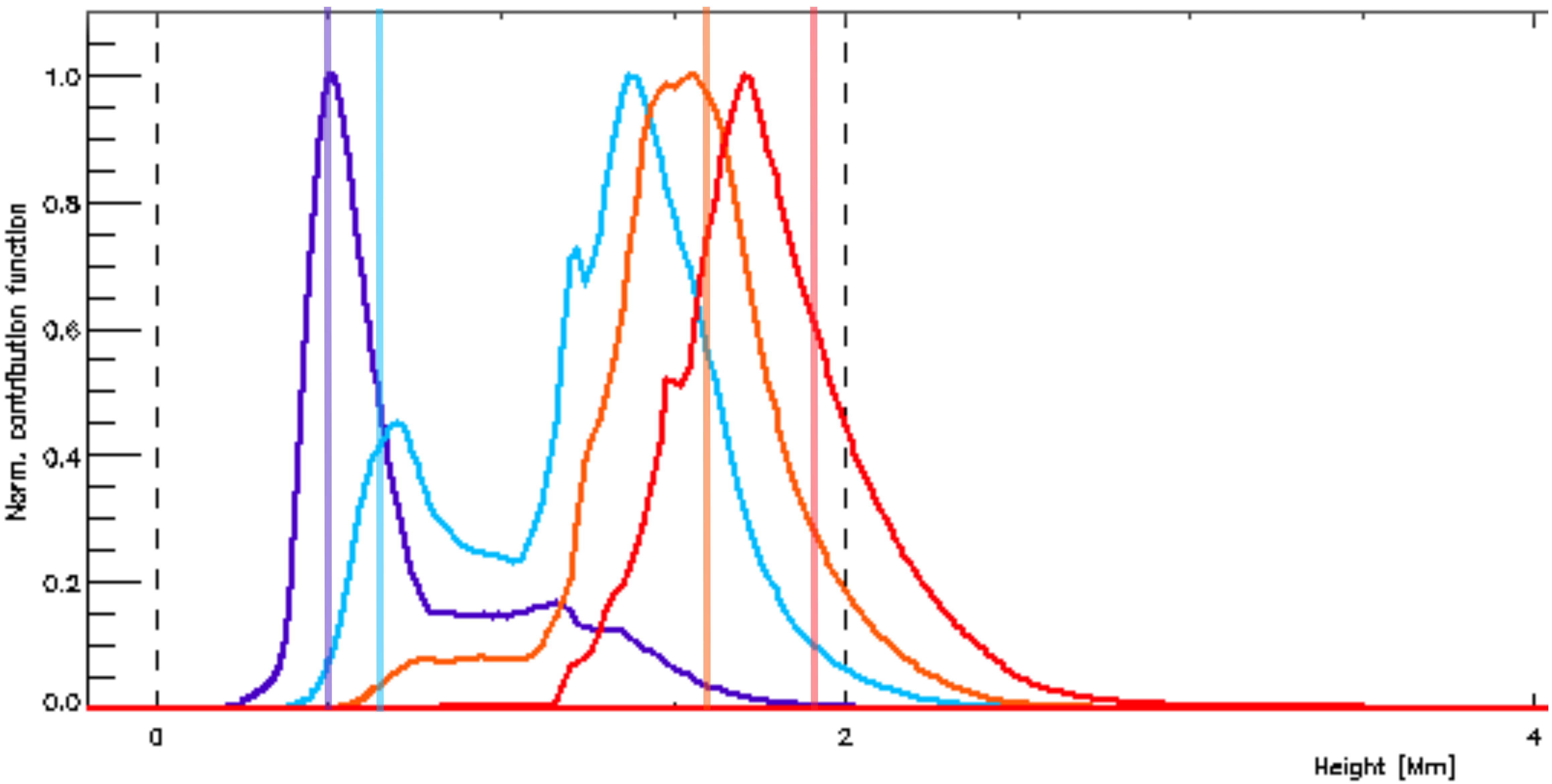
Continuum formation heights

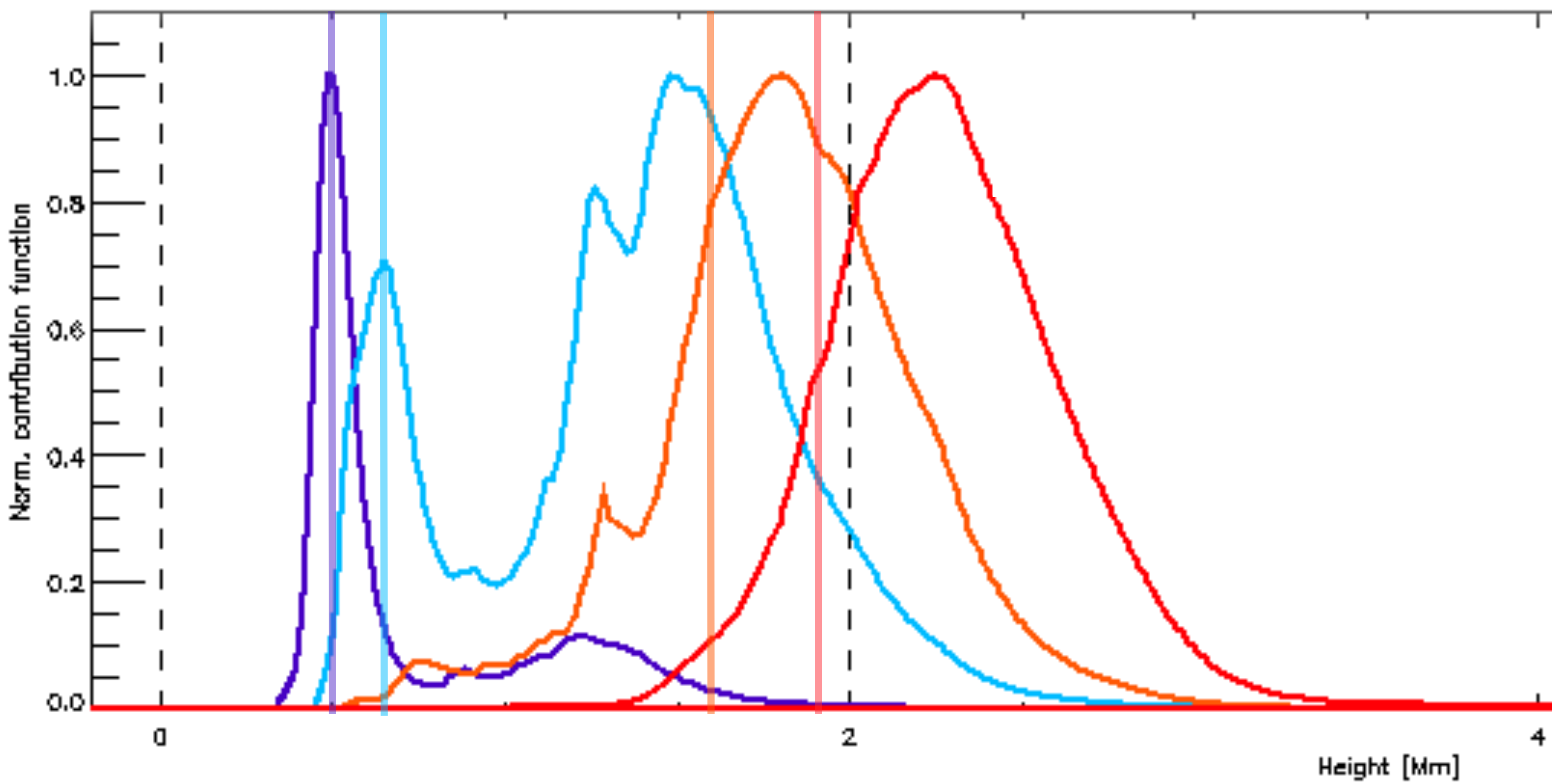
B: Above magnetic field concentration



0.316 mm **1.292 mm** **3.156 mm** **9.671 mm**

Continuum formation heights

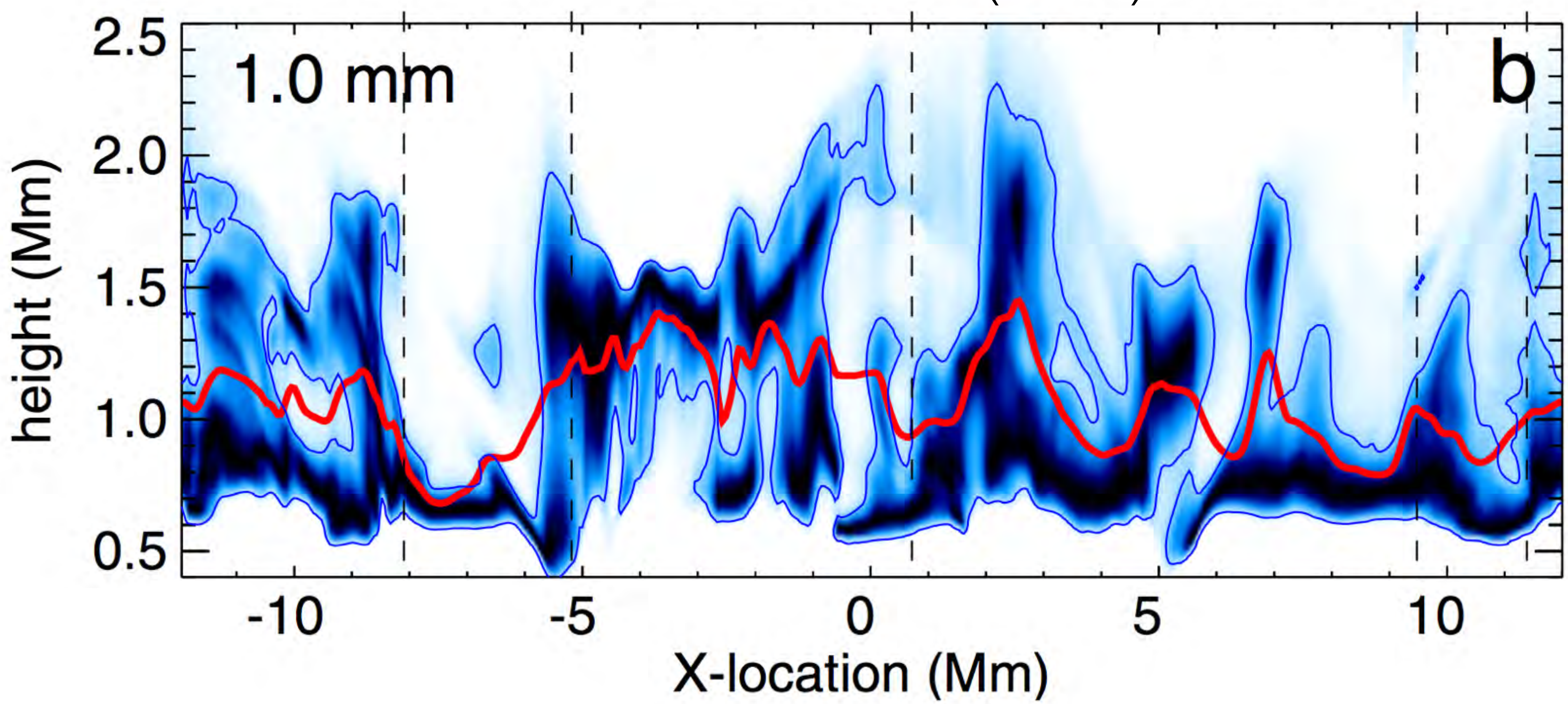
C: Coronal loops



0.316 mm　1.292 mm　3.156 mm　9.671 mm

Continuum formation heights

Loukitcheva et al. (2015)



- Taking into account non-equilibrium hydrogen ionisation reduces spread in height

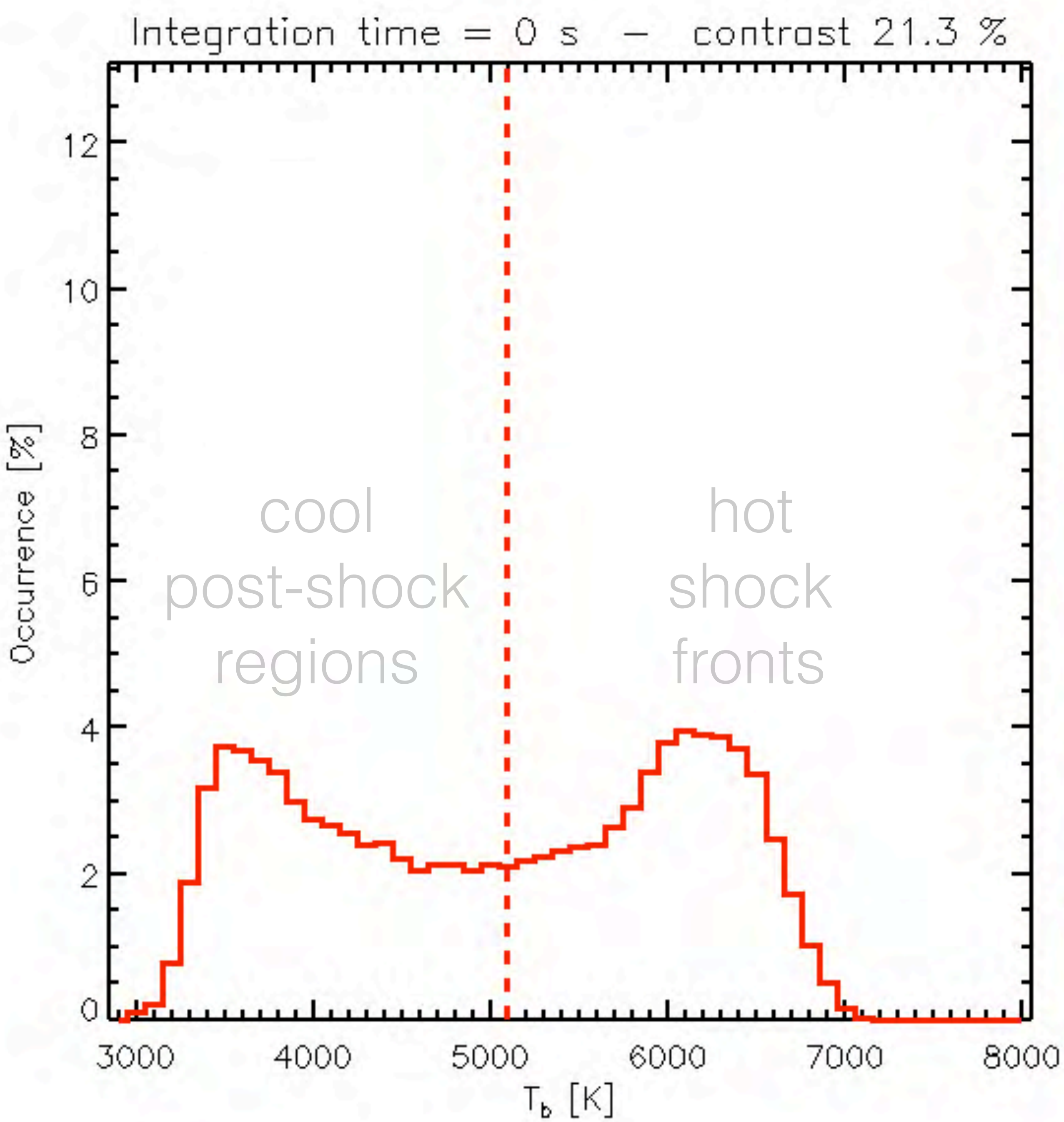
Upshot:

- Formation heights different for different types of regions/situations
- Formation heights vary from position to position

➡ Further studies based on numerical models needed.

➡ Ongoing SSALMON activities.

Integration time



Brightness temperature @ 1 mm

8 Mm (11”)
(very) quiet Sun model

- Double-peaked nature already lost after 30s

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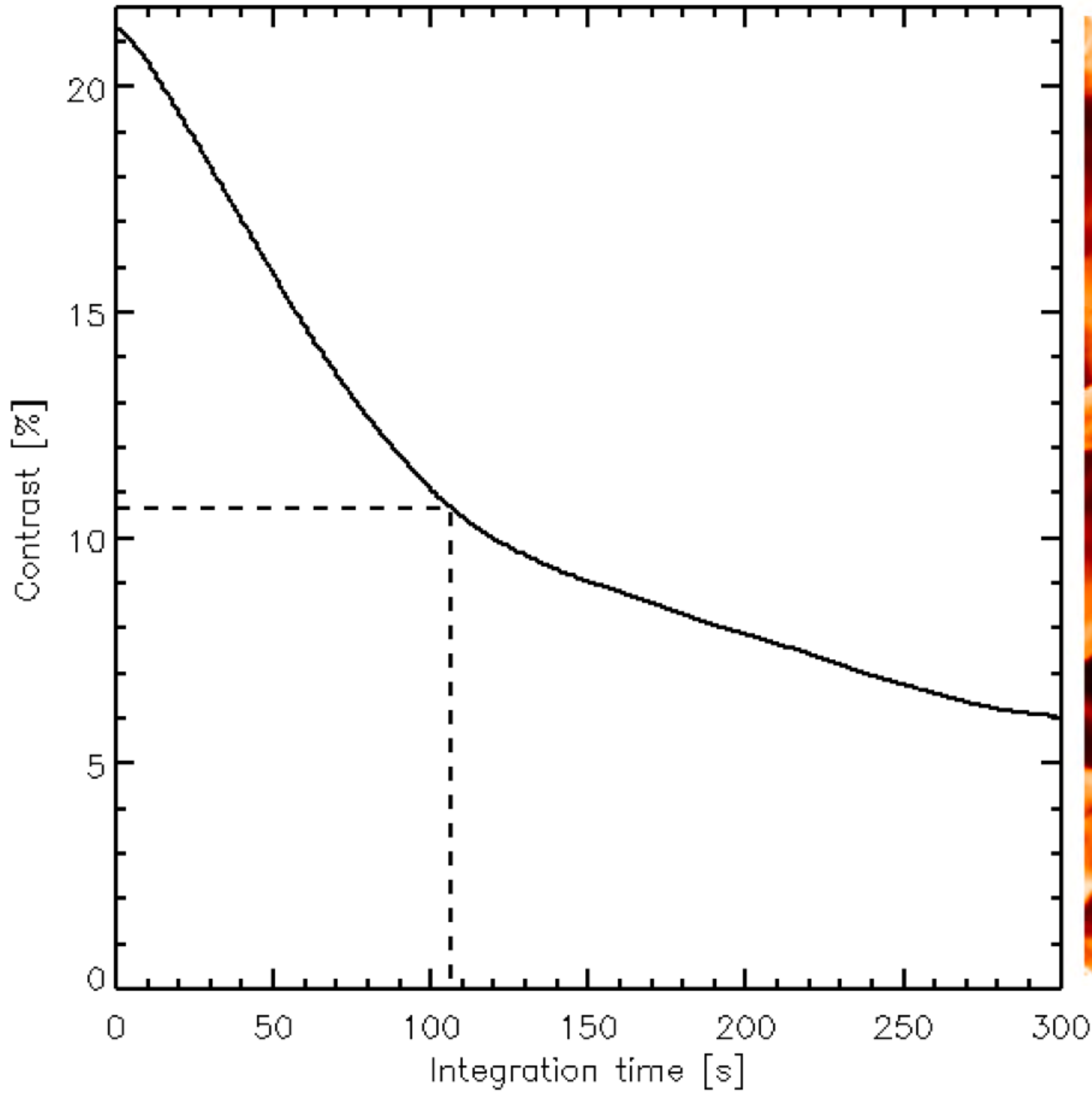
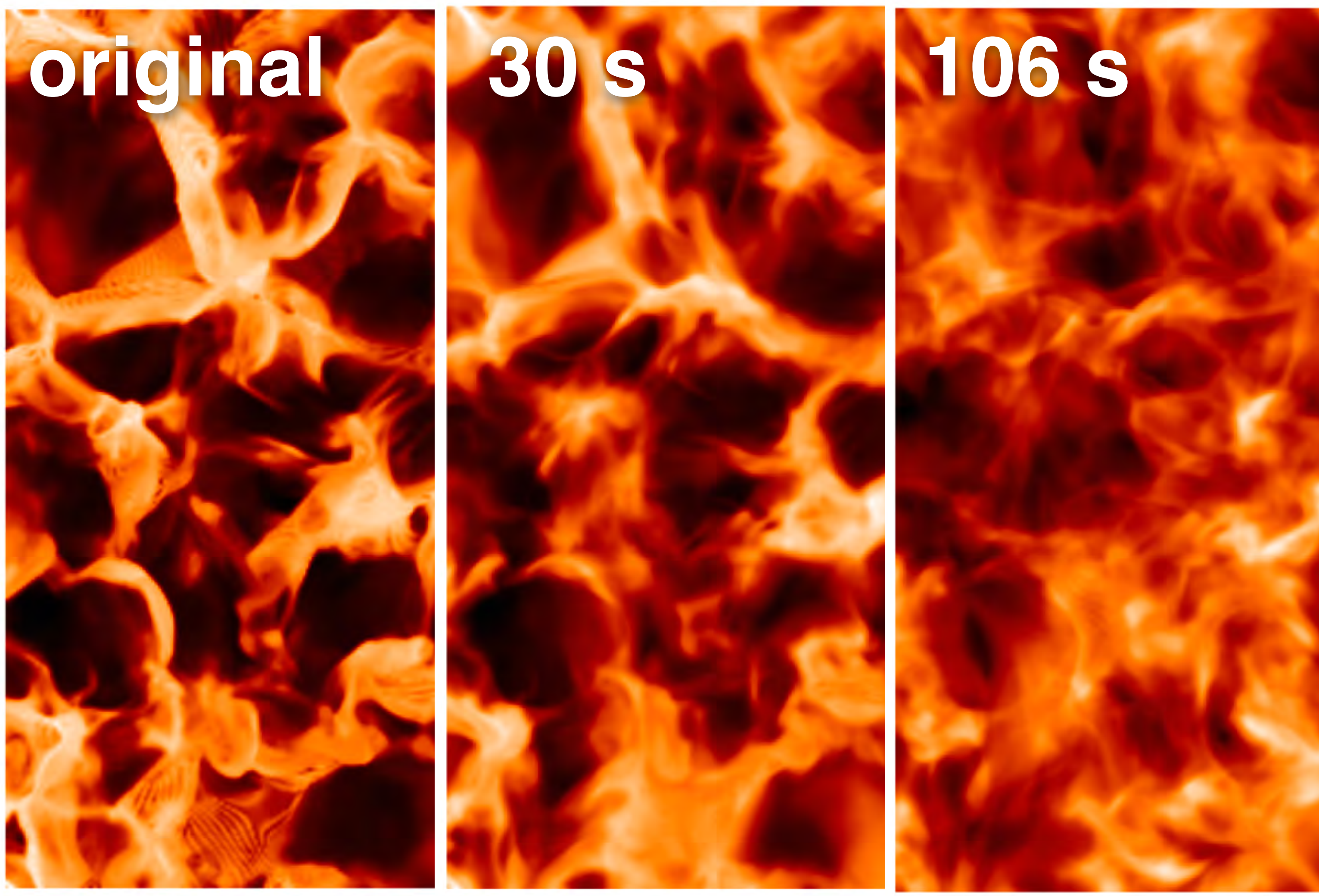
Integration time

Contrast of brightness temperature maps



Brightness temperature @ 1 mm



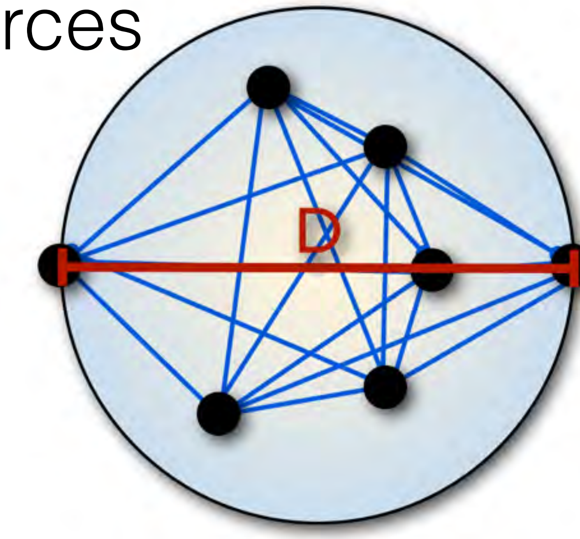
- Half contrast after 106 s; many details lost already at shorter times.

➡ High-cadence important for capturing chromospheric dynamics on small scale

Interferometric imaging

- Max. angular resolution ∝ λ / D for resolving 2 point sources
  λ = 0.3 mm and D = 16 km ➡ 4mas!
- BUT: The Sun is an extended area source.

➡ ALMA as **aperture synthesis** telescope



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- BUT: The Sun is an extended area source.

➡ ALMA as **aperture synthesis** telescope

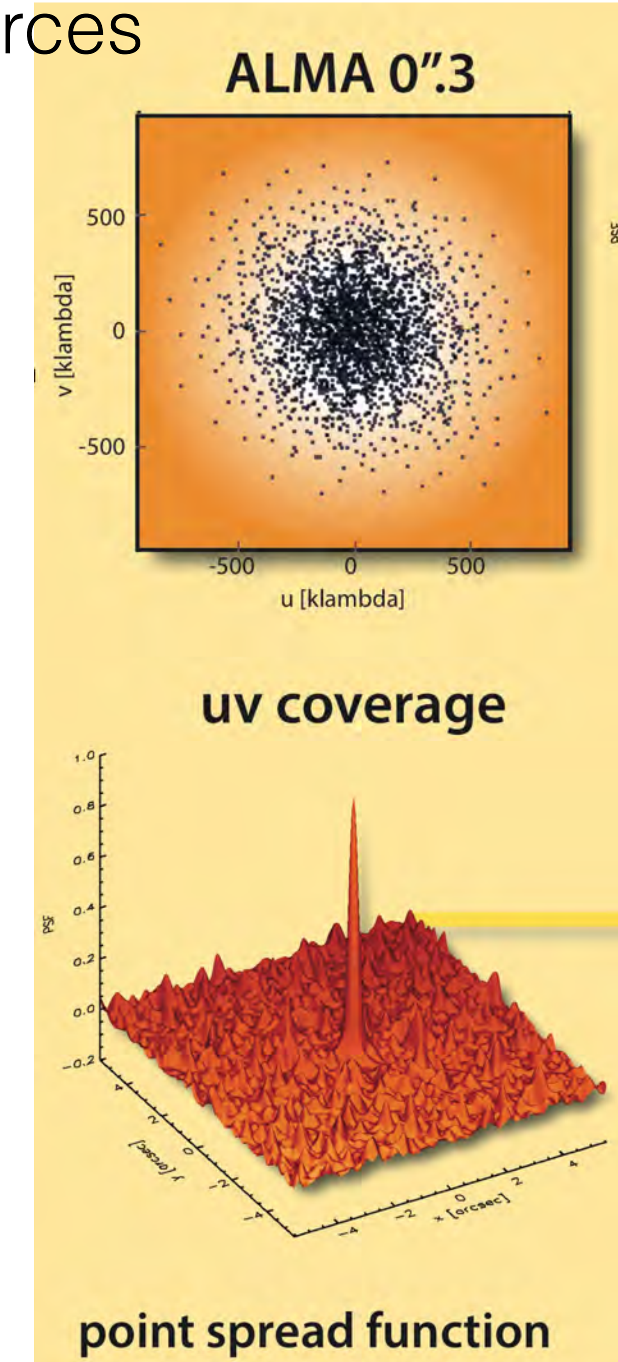
- Longest baseline determines the diameter of the **synthesised aperture** *("equivalent telescope size")*

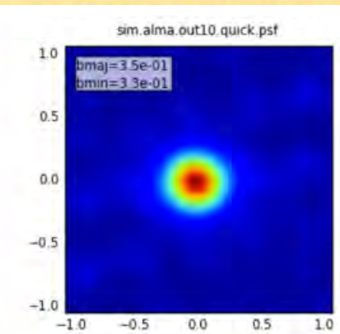
- Each baseline has a length and a direction

➡ one component in spatial Fourier space, i.e. u-v component

➡ Sampling of the point spread function (PSF) of the <u>large synthesised aperture</u>

➡ Reconstruction of the mm image





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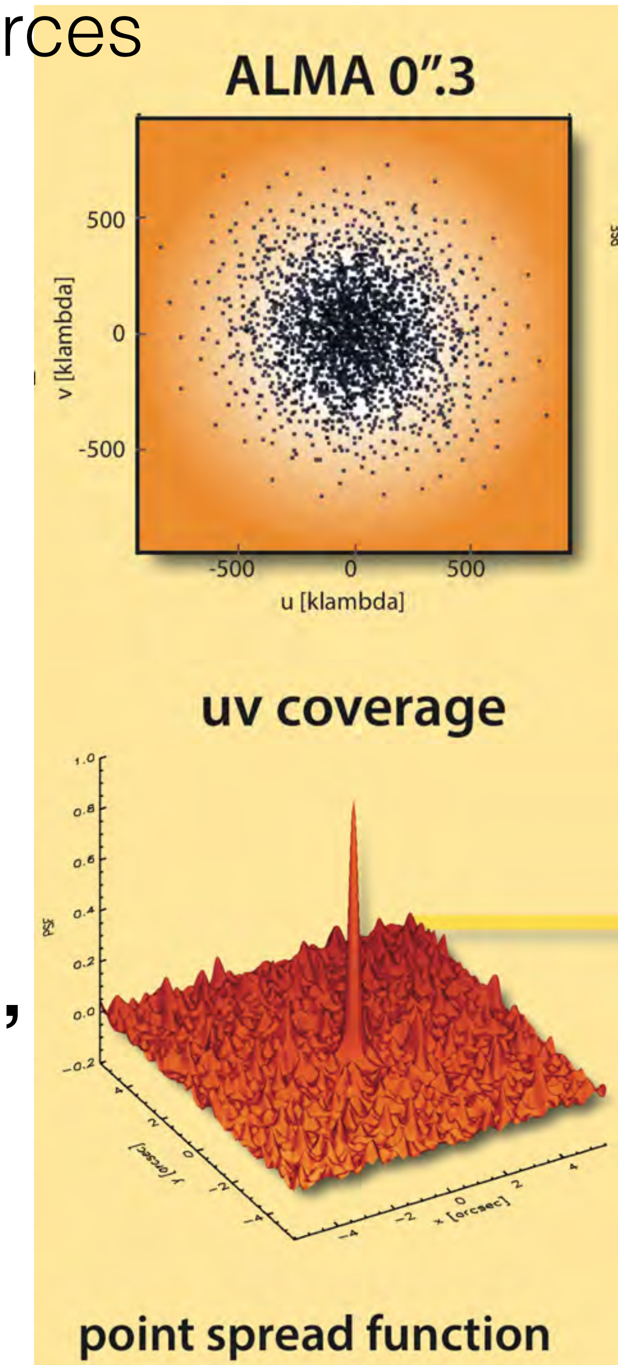
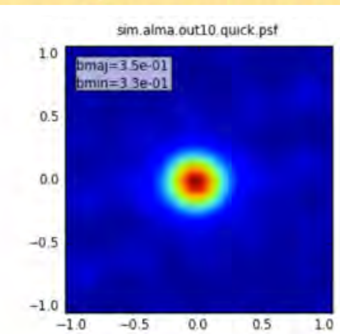


➡ **Anticipated image resolution 0.3 - 0.4 arcsec at 1 mm, possibly down to 0.1 arcsec at the shortest wavelengths**

- Spatial resolution gets *close to* what is possible with current optical instruments



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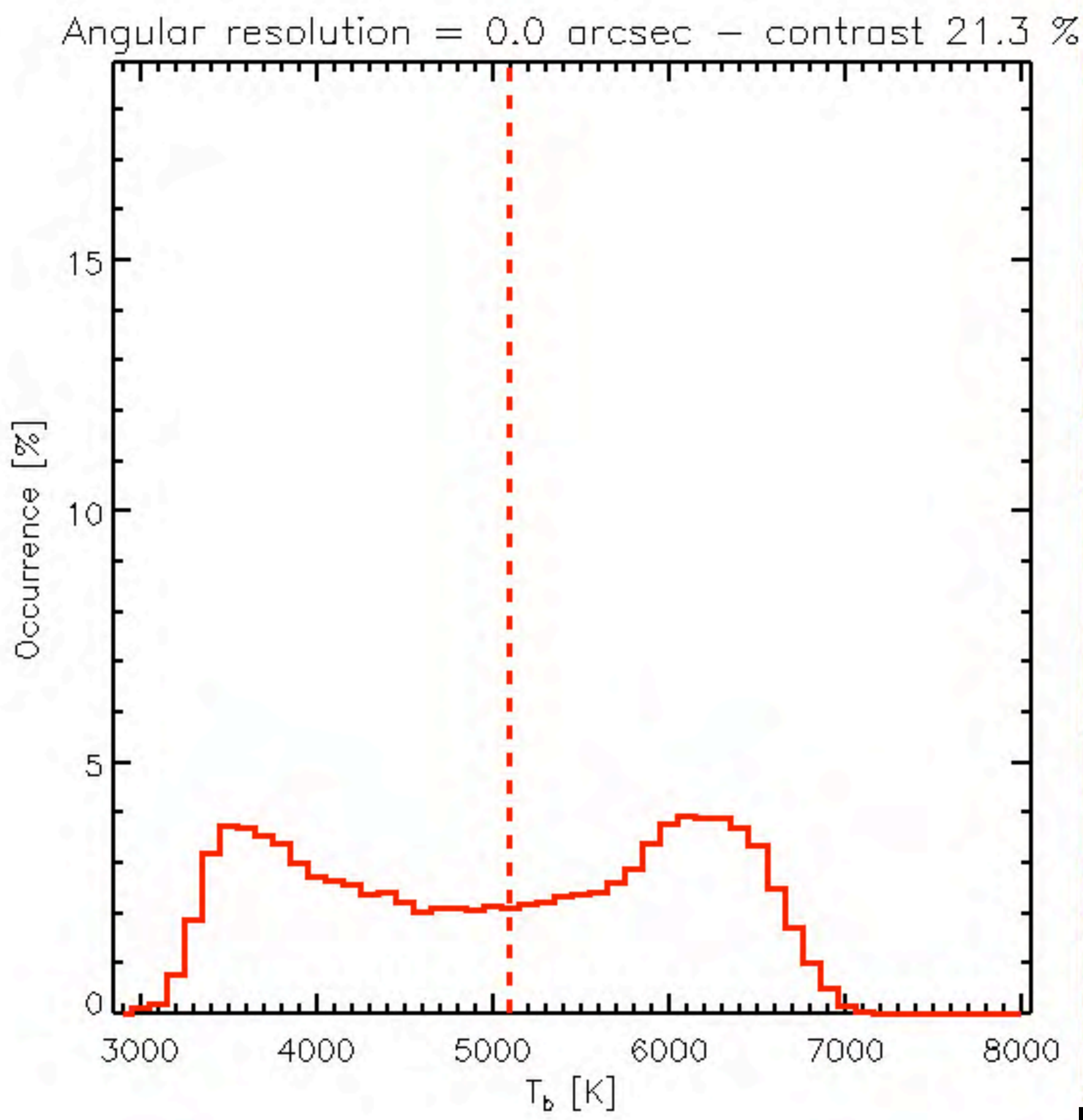
Angular resolution



Brightness temperature @ 1 mm

8 Mm (11")
(very) quiet Sun model

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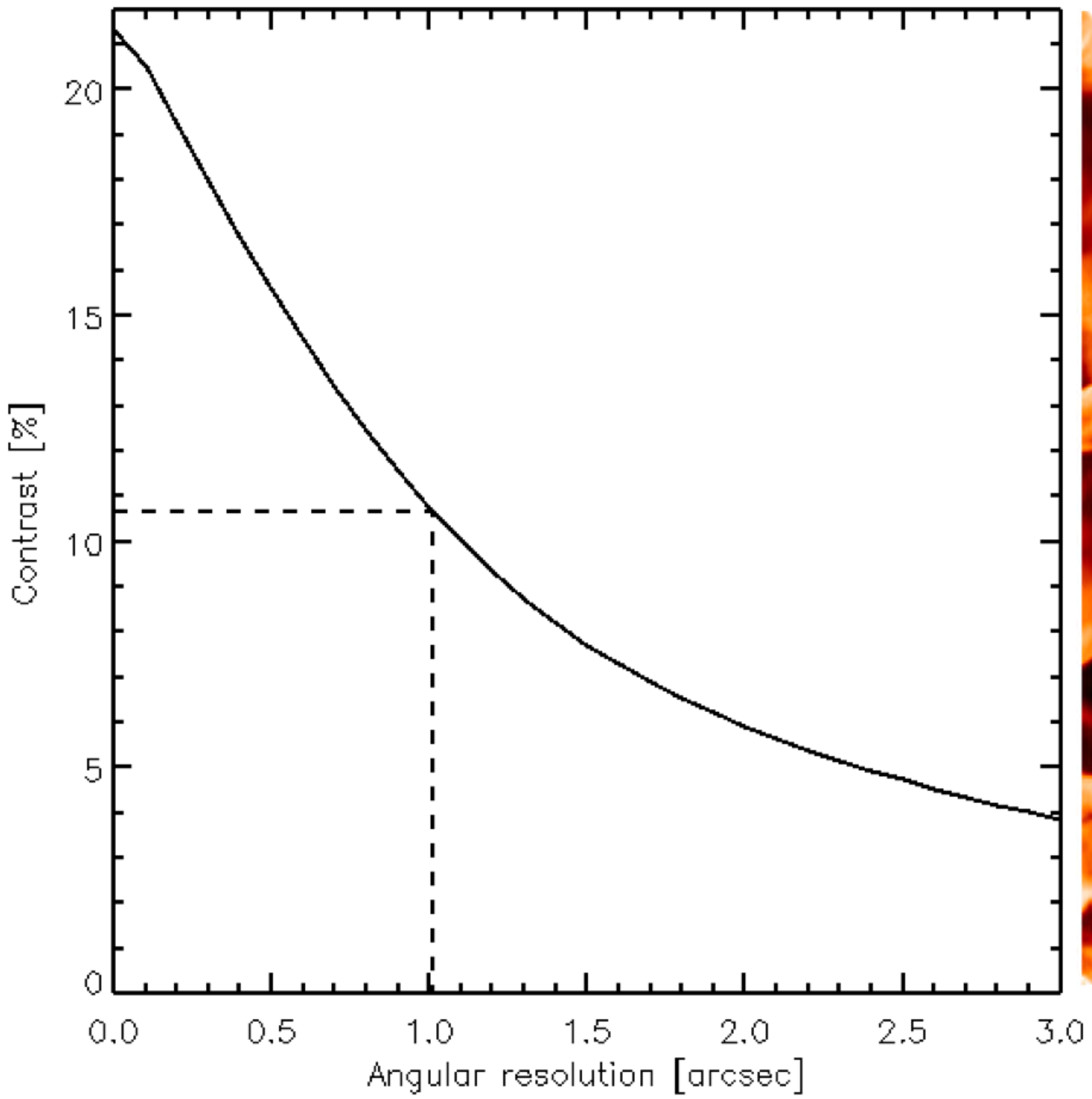
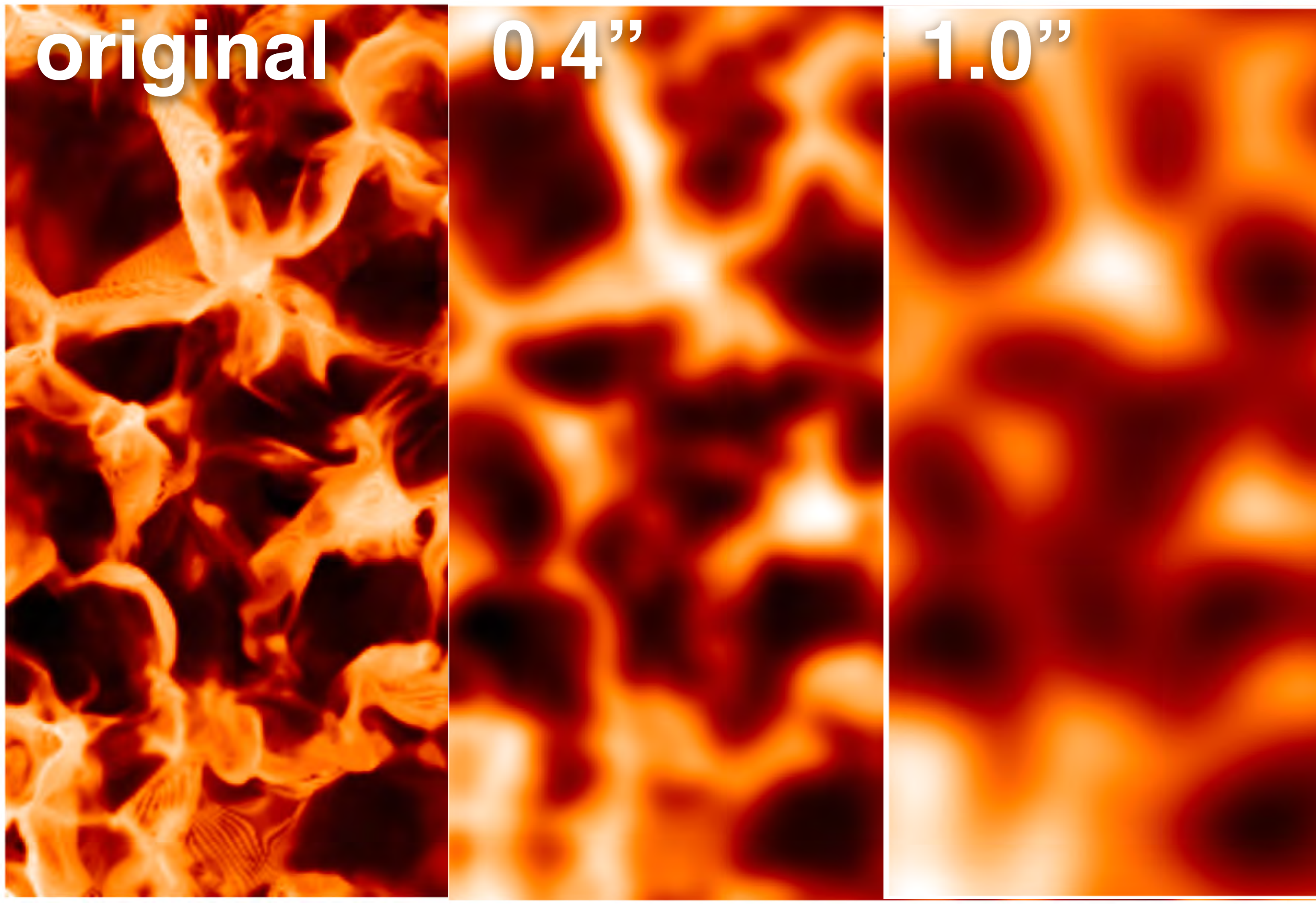
Angular resolution

Contrast of brightness temperature maps



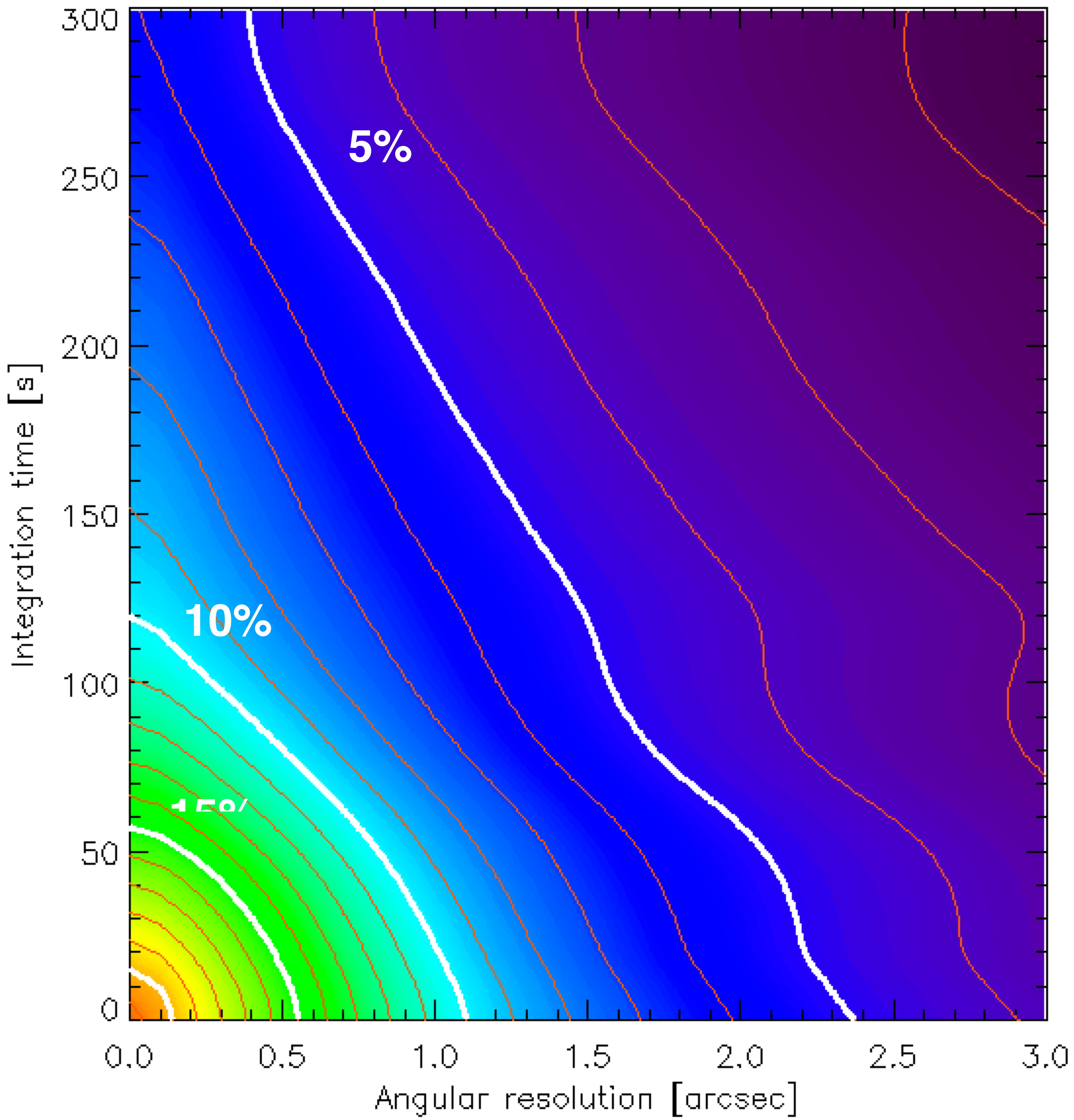
Brightness temperature @ 1 mm



- High spatial resolution needed for observing the fine-scale structure of the chromosphere

Temporal-spatial resolution

Contrast of brightness temperature maps @1mm



- Small spatial scales connected to short temporal scales
- Compromises unavoidable!
- Depends on priorities of individual science cases
- Simulations can help to make smart choices.

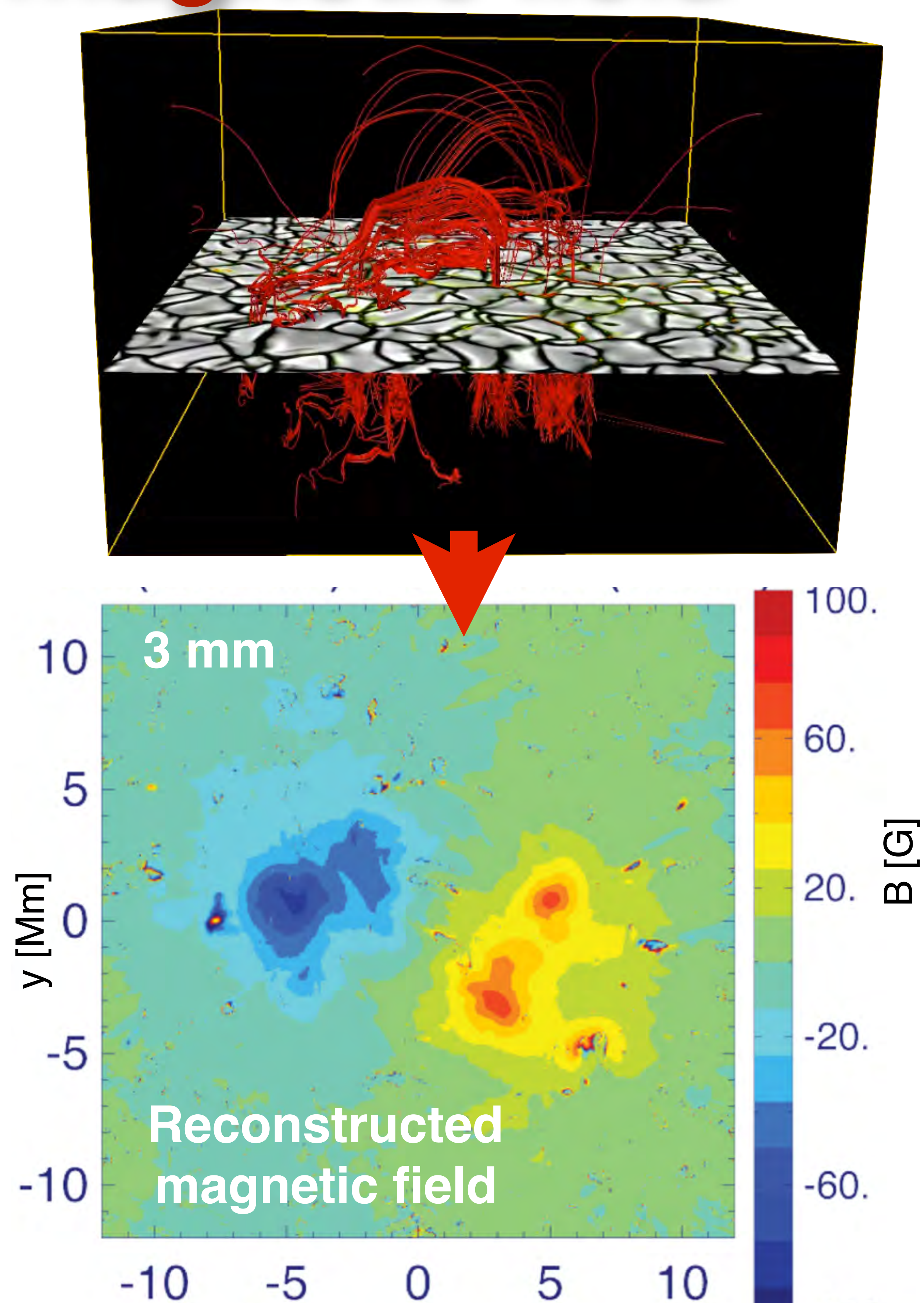
Chromospheric magnetic field

- Polarisation of the continuum intensity allows to derive the longitudinal magnetic field component
  (Bogod & Gelfreikh 1980; Grebinskij et al. 2000)

➡ Demonstrated by Loukitcheva et al. (2016), Fleishman et al. (2015)

- Larger 3D simulation *(Bifrost) (Carlsson et al. 2016):* enhanced magnetic network
- Polarisation ±0.5 % at 3 mm

➡ Chromospheric magnetic field with ±100 G in layer mapped at 3 mm successfully reconstructed



Chromospheric magnetic field

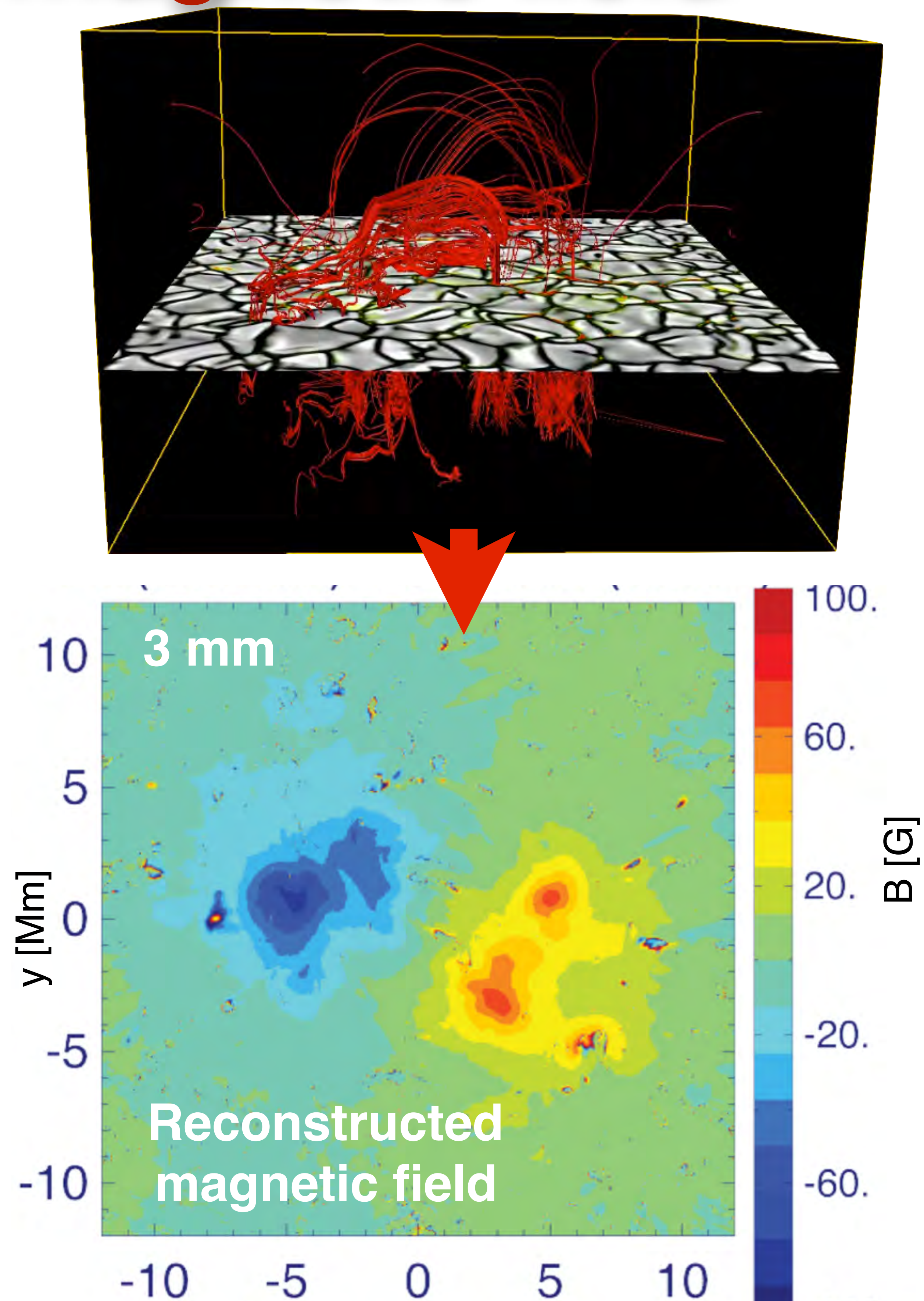
- Like for continuum intensity: Scanning in height by changing observing wavelength
- Constraints for the magnetic field topology in many layers

➡ 3D magnetic structure!?

- Polarisation signal even in Quiet Sun regions of a few 0.1%

➡ Should be measurable with ALMA.

◉ Not offered in Cycle 4 but hopefully soon.



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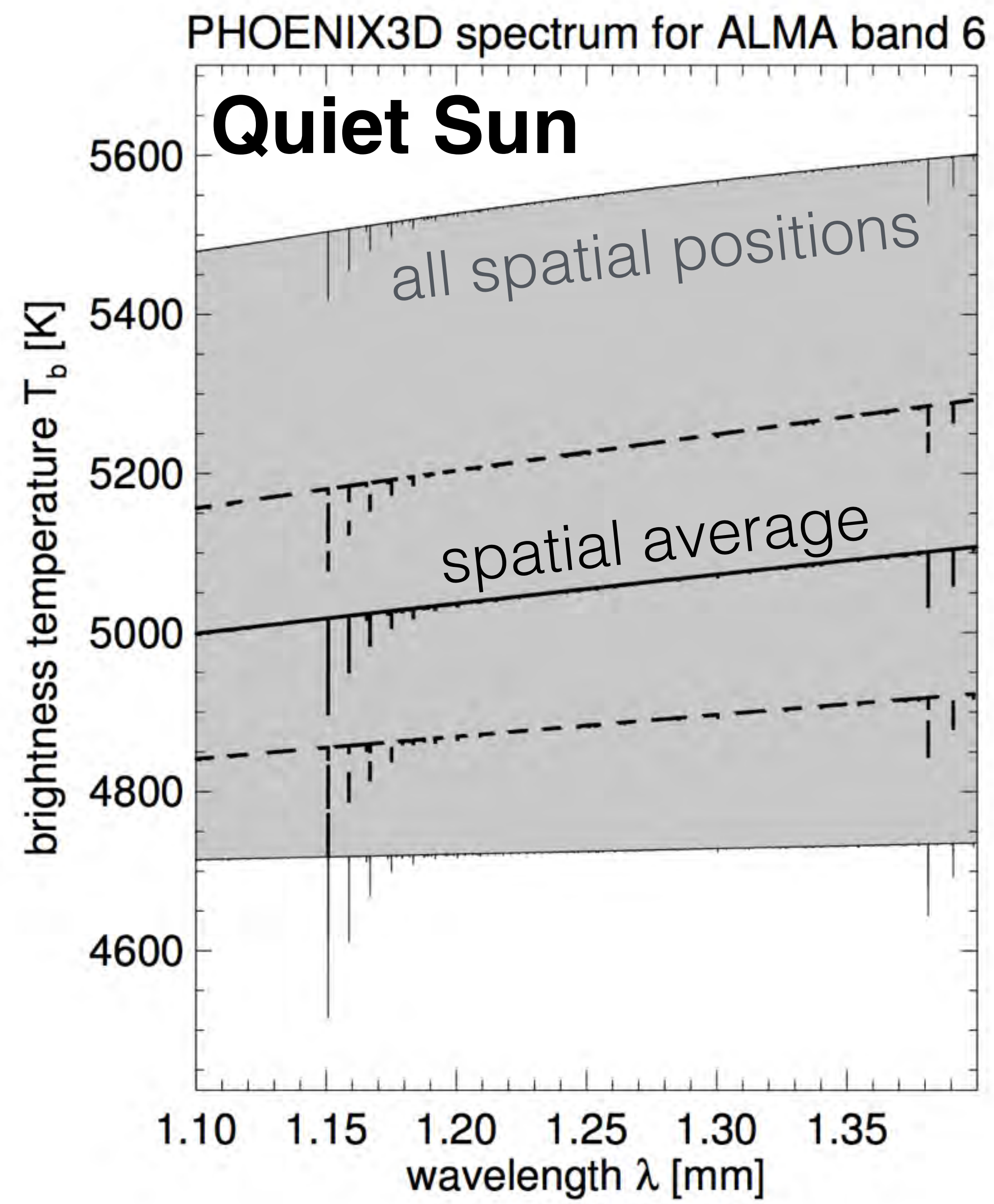
Spectral capabilities

- Each ALMA antenna has (in the end) 10 receiver bands (covering a freq./ wavelength range each)
- Each band with up to a few 1000 channels
- Whole spectral cube simultaneous!
- Slope of continuum, radio recombinations lines, molecular lines (e.g., CO) as complementary thermal, kinetic and magnetic diagnostic
- Some recomb. lines originate in corona



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

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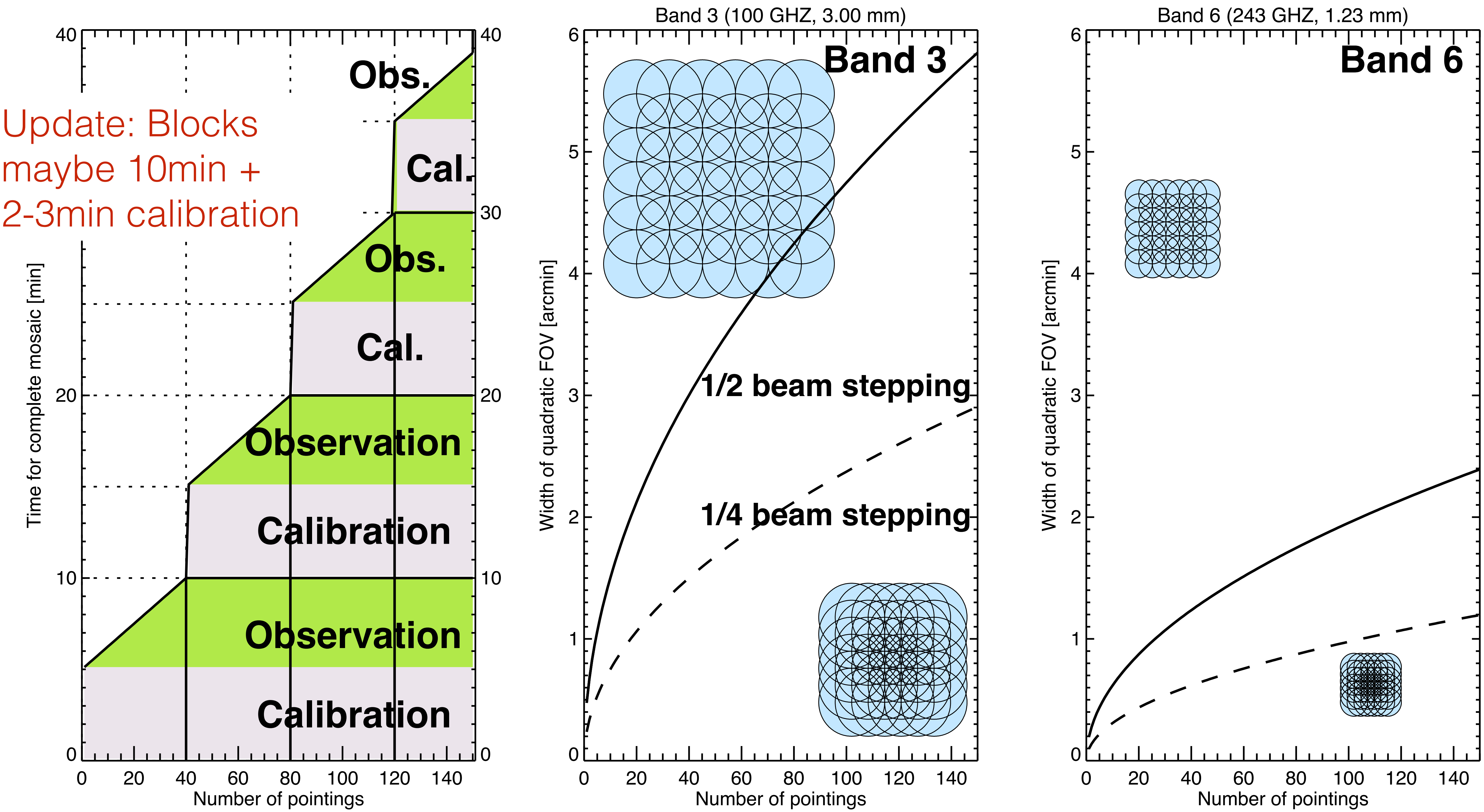
Mosaicking

- ALMA's FOV small: ~58"@3mm, ~ 21" @1mm down to ~7" @0.3mm

➡ Mosaicking for larger targets (but then with lower cadence)

★ Up to 150 pointings (with ~40min cadence)

Update: Blocks maybe 10min + 2-3min calibration



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Co-observations with ALMA

- Context data and complementary diagnostics probing different plasma properties and atmospheric layers
- Potential challenges:
  - Different locations and thus time differences
  - Overlap due to small FOVs

✦ Many more observations in other wavelength domains inc. radio

✦ Co-observations with space-borne observatories (e.g., SDO, IRIS, Hinode, RHESSI…

ALMA Cycle 4

(10/2016 - 9/2017)

- Interferometric observations with simultaneous TP fast scanning of whole solar disk
- Band 3 (84 - 116 GHz, 3.6 - 2.6 mm)
- Band 6 (211 - 275 GHz, 1.4 - 1.1mm)
  - with 4 sub-bands each
    (4 x 128 channels for interferometry, 4 averaged channels for TP)
- >10 7m- and >40 12m-antennas.
- Compact antenna configurations with max. baseline of a few 100 m.
- Min. integration time = 2s
- Interferometric observations in 5min blocks with 3-5min calibration breaks
  - No polarisation capability yet.
  - No full spectral capability yet.

Solar science cases for ALMA

- Which scientific questions can be addressed with ALMA?

- **Solar ALMA overview paper by SSALMON,**
  Solar science with the Atacama Large Millimeter/submillimeter Array – A new view of our Sun
  Wedemeyer, S.; Bastian, T.; Brajša, R.; Hudson, H.; Fleishman, G.; Loukitcheva, M.; Fleck, B.; Kontar, E. P.; De Pontieu, B.; Yagoubov, P.; Tiwari, S. K.; Soler, R.; Black, J. H.; Antolin, P.; Scullion, E.; Gunár, S.; Labrosse, N.; Ludwig, H.-G.; Benz, A. O.; White, S. M.; Hauschildt, P.; Doyle, J. G.; Nakariakov, V. M.; Ayres, T.; Heinzel, P.; Karlicky, M.; Van Doorsselaere, T.; Gary, D.; Alissandrakis, C. E.; Nindos, A.; Solanki, S. K.; Rouppe van der Voort, L.; Shimojo, M.; Kato, Y.; Zaqarashvili, T.; Perez, E.; Selhorst, C. L.; Barta, M.
  (published online first, 73 pages, 38 authors)
  Space Science Reviews (2015)

- ***ESO Messenger article "New eyes on our Sun - Solar science with ALMA"***
  March 2016

Solar science cases for ALMA

Central questions in solar physics to be addressed with ALMA

- Quiet Sun
- Active Regions
- Limb studies
- …

SSALMON White Paper

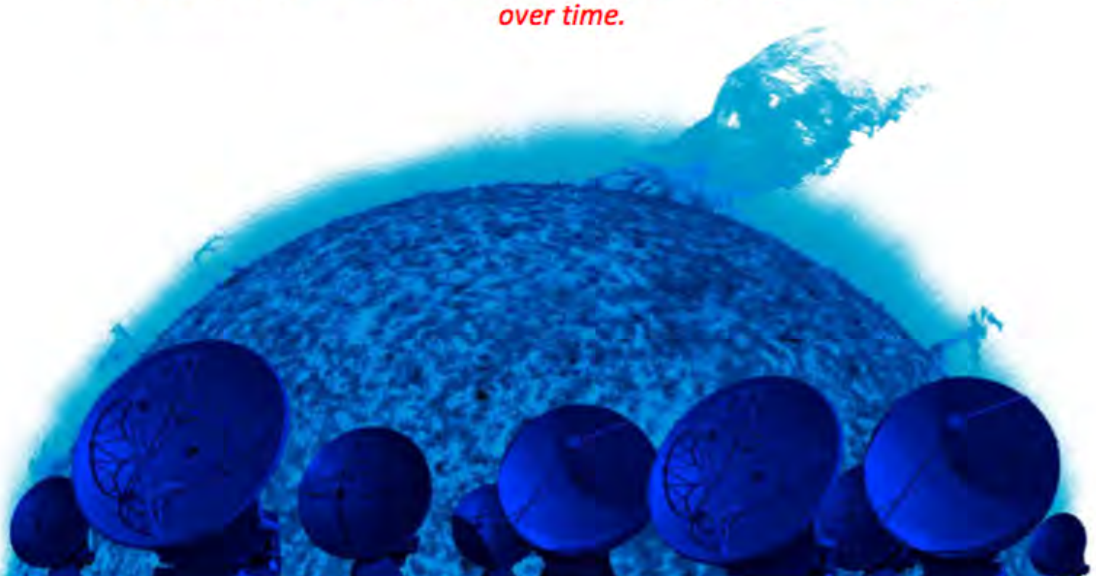
ALMA OBSERVATIONS OF THE SUN IN CYCLE 4 AND BEYOND

Scientific opportunities for the first regular observations of the Sun with the Atacama Large Millimeter/submillimeter Array

Prepared by the
Solar Simulations for the Atacama Large Millimeter Observatory Network (SSALMON)

In cooperation with the solar ALMA development studies "Advanced Solar Observing Techniques" and "Solar Research with ALMA"

VERSION 1.1 - January 6th, 2016
Please note that this document will be updated and further developed over time.



SOLAR SIMULATIONS FOR THE ATACAMA LARGE MILLIMETER OBSERVATORY SSALMON

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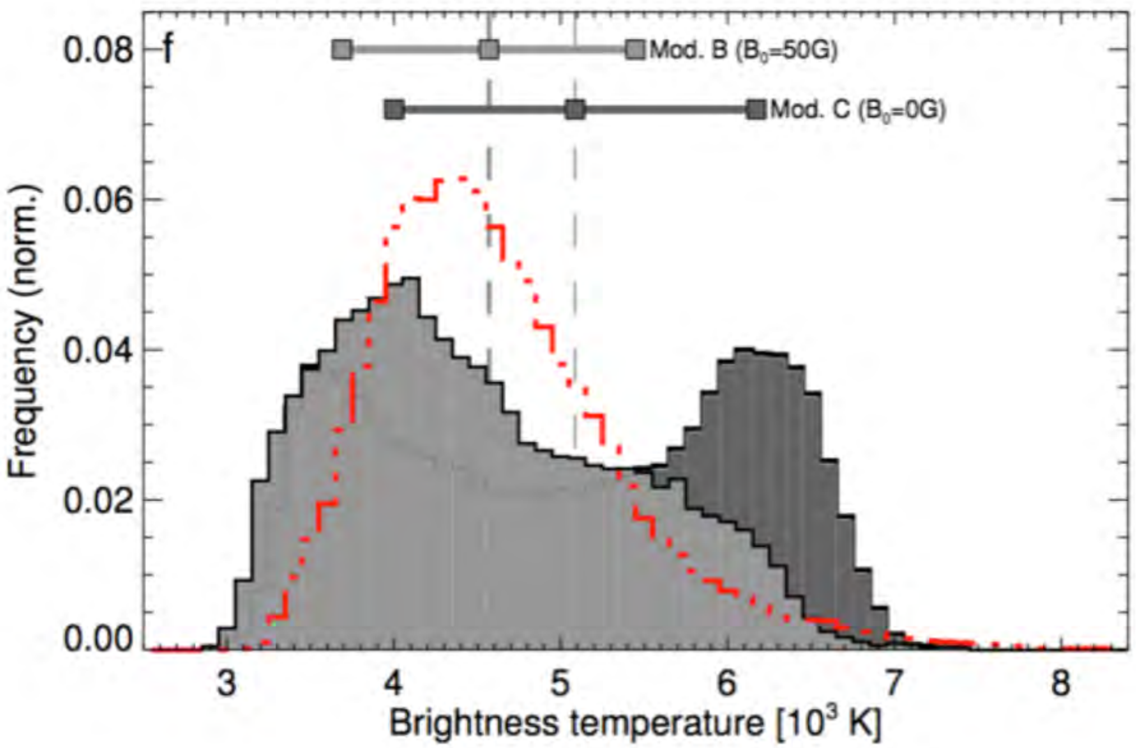
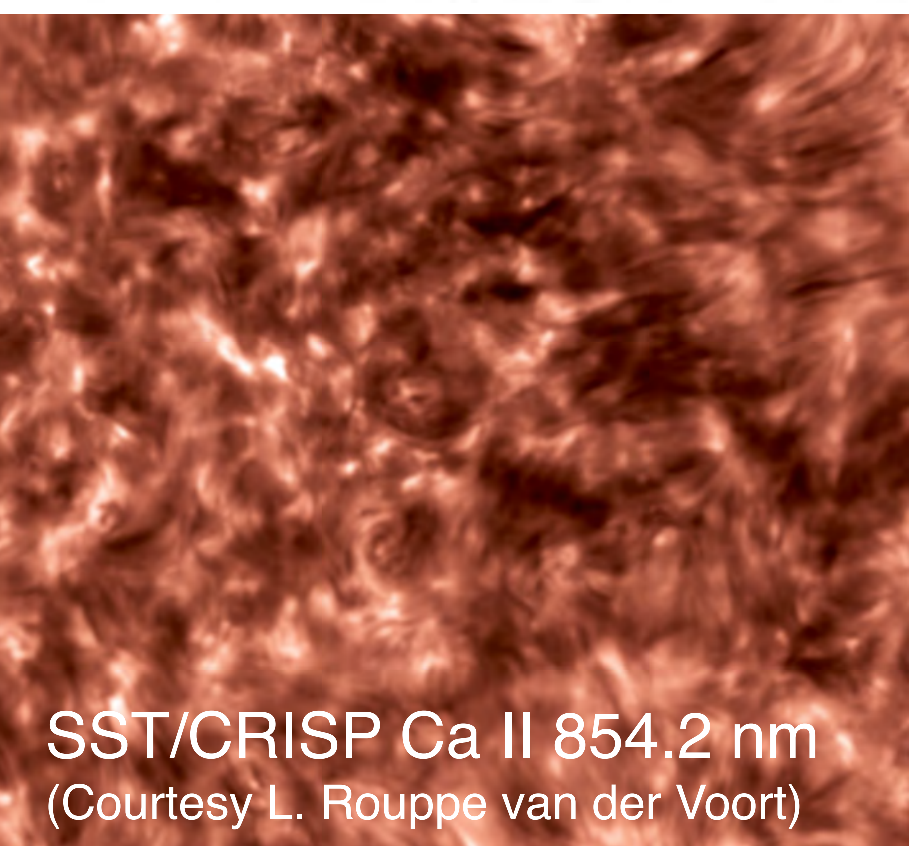
Quiet Sun

Some key questions for Cycle 4





SST/CRISP Ca II 854.2 nm
(Courtesy L. Rouppe van der Voort)

- What are the **statistical characteristics** of the brightness temperature distribution in quiet Sun regions?

➡ Could it be used to **calibrate** future ALMA data?

- How does the brightness temperature distribution depend on the observation angle *(and thus radial distance from the solar disk center and thus sampled height)* ?

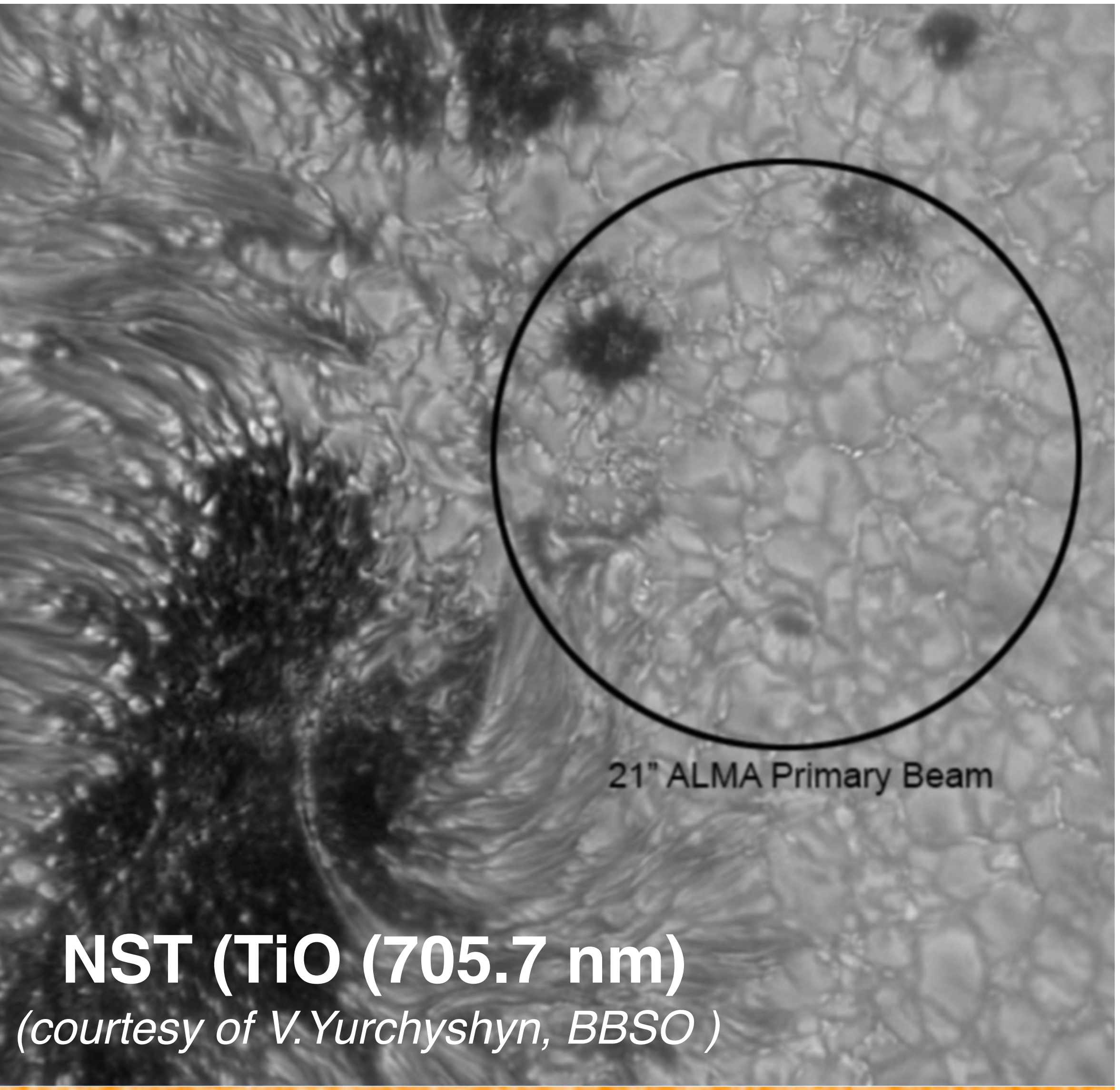
- Local slope of the brightness temperature spectrum as function of observing frequency and thus sampled atmospheric height?

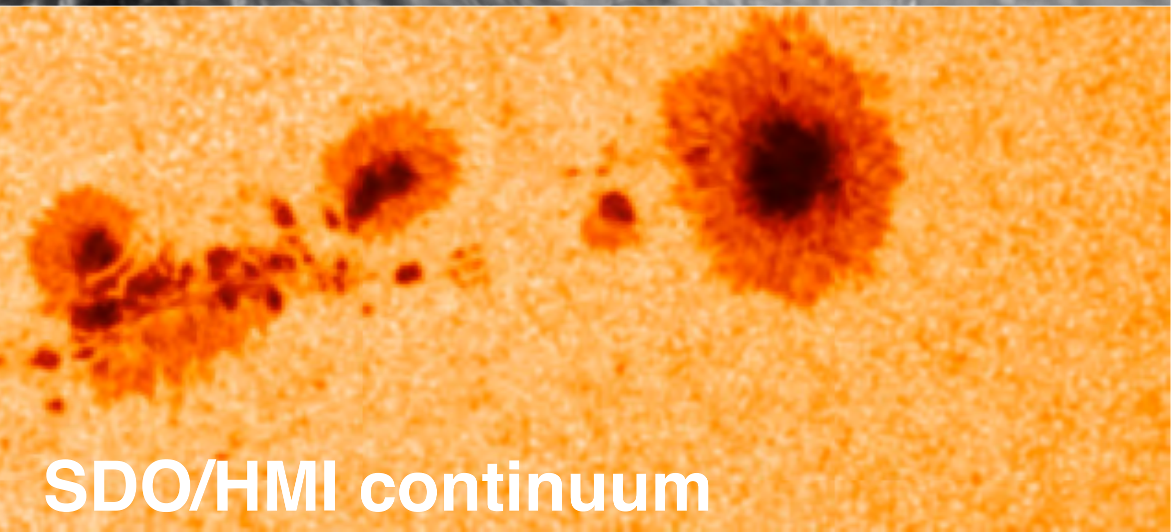
➡ **Thermal structure of the chromosphere.**

- Horizontal velocity spectrum?
  Wave propagation? *(Poster by B. Fleck)*

Active Regions and Flares

Some key questions for Cycle 4

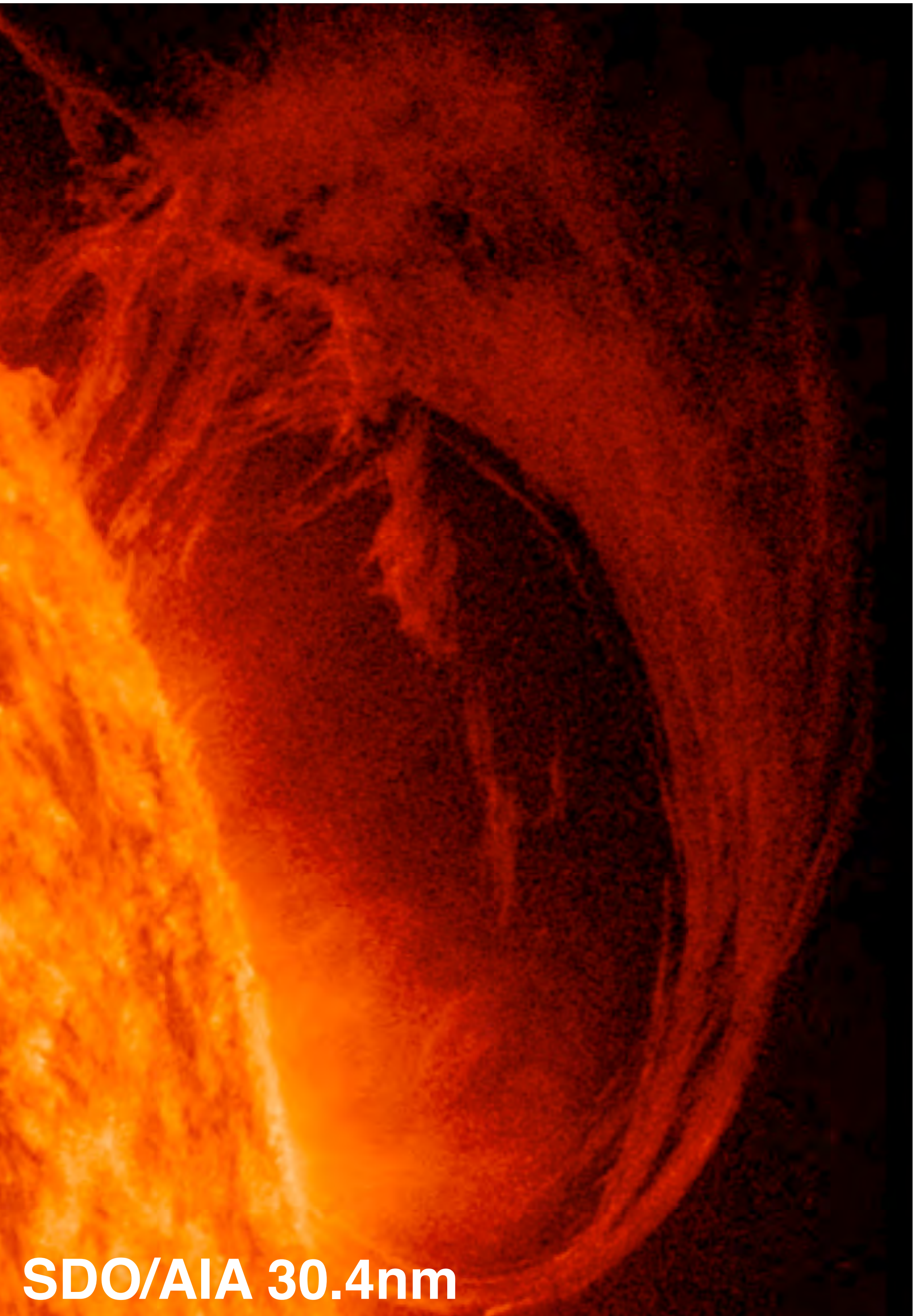




- Brightness temperature distribution and local slope of spectra in ARs/sunspots and its wavelength-depend?
- ➡ **Constraints on the thermal** *(and indirectly magnetic?)* **structure** of ARs?!
- Statistical characteristics of the brightness temp. distribution in **flare-productive vs non-flaring ARs?**
- Dependence on the underlying photospheric magnetic field?
- Shape of (coarse) spectra during flares?
- What is the (spatial) origin, morphology and temporal evolution of solar flare emission at ALMA wavelengths?

Prominences/Filaments

Some key questions for Cycle 4



- **Fine-scale thermal structure** at high spatial resolution in their main body and in the prominence-corona transition region (PCTR)?
- How does the prominence plasma react to various **heating processes**?
- How is the **dynamics** of the plasma related on small scales and on large scales to the thermal structure?
- How is the fine-scale structure shaped by the **magnetic field**?
- How do Active Region and Quiet Sun prominences differ at millimeter wavelengths?

➡ *Talk by N. Labrosse*

- ★ **ALMA promises interesting results for a large range of topics in solar physics, in particular for the chromosphere,** mapped at high spatial + temporal + spectral resolution
- Acts as linear thermometer of the solar plasma
- More information: **SSALMON website:** http://ssalmon.uio.no
    - ALMA overview SSRv paper