Future prospects with ALMA

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University of Oslo

Overview

- What is ALMA? A short overview.
- Radiation at millimeter wavelengths
- Technical capabilities for solar observations
- SSALMONetwork and future activities
- Prospects for coronal rain observations

"ALMA provides the necessary spatial, temporal and spectral resolution to explore central questions in modern solar physics with implications for stellar atmospheres and plasma physics."

Atacama Large Millimeter/submillimeter Array

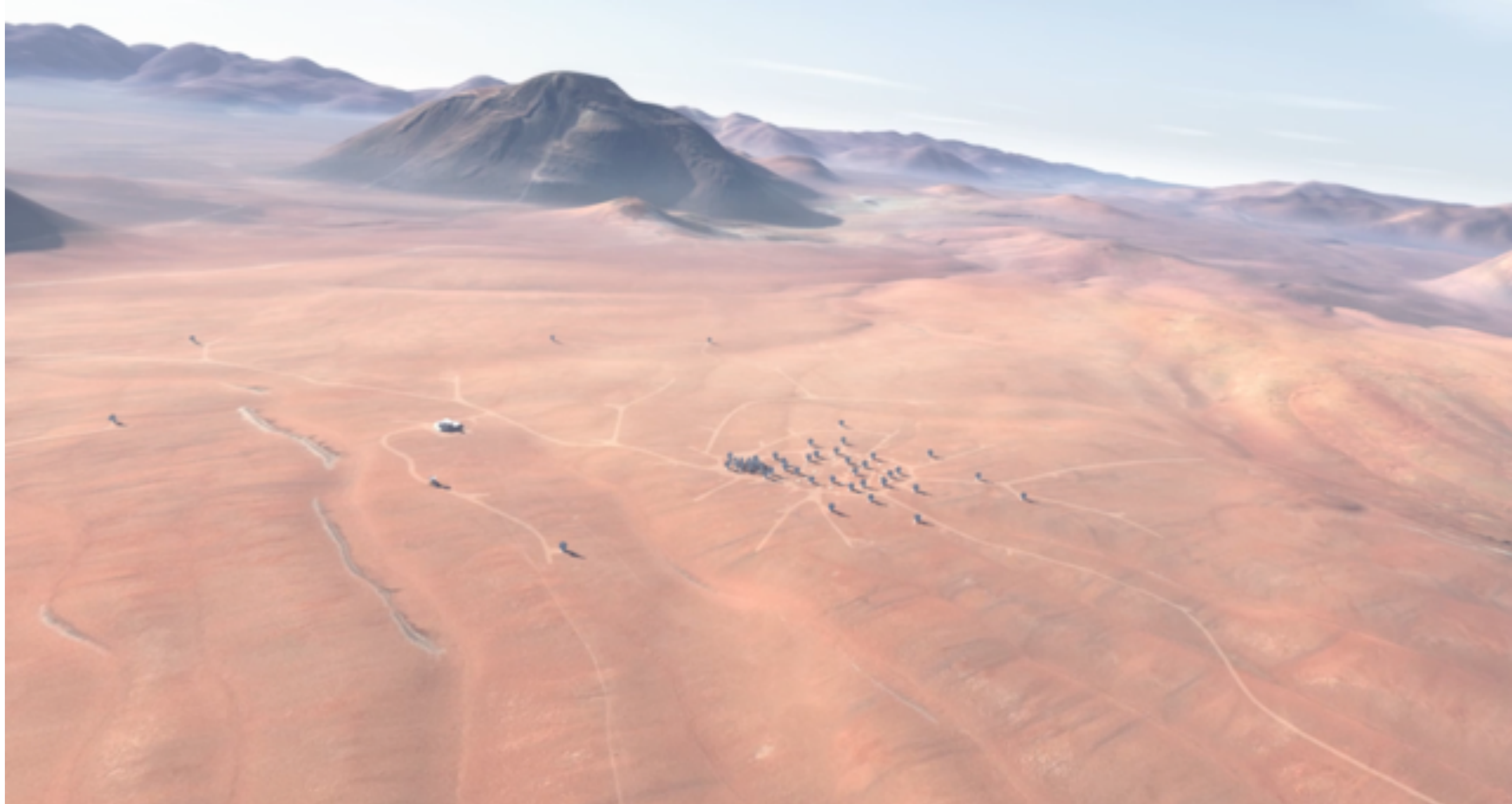
- International partnership between Europe (ESO), North America (NRAO), and East Asia (NAOJ) in cooperation with the Republic of Chile

➡ Aim: build and operate a millimetre/submillimeter interferometer on the Chajnantor plateau in the Chilean Andes at an altitude of 5000 m.

- Wavelength range:
    - final: 0.3 mm - 8.6 mm (35 GHz to 950 GHz)
    - receivers for longest wavelengths yet to be installed

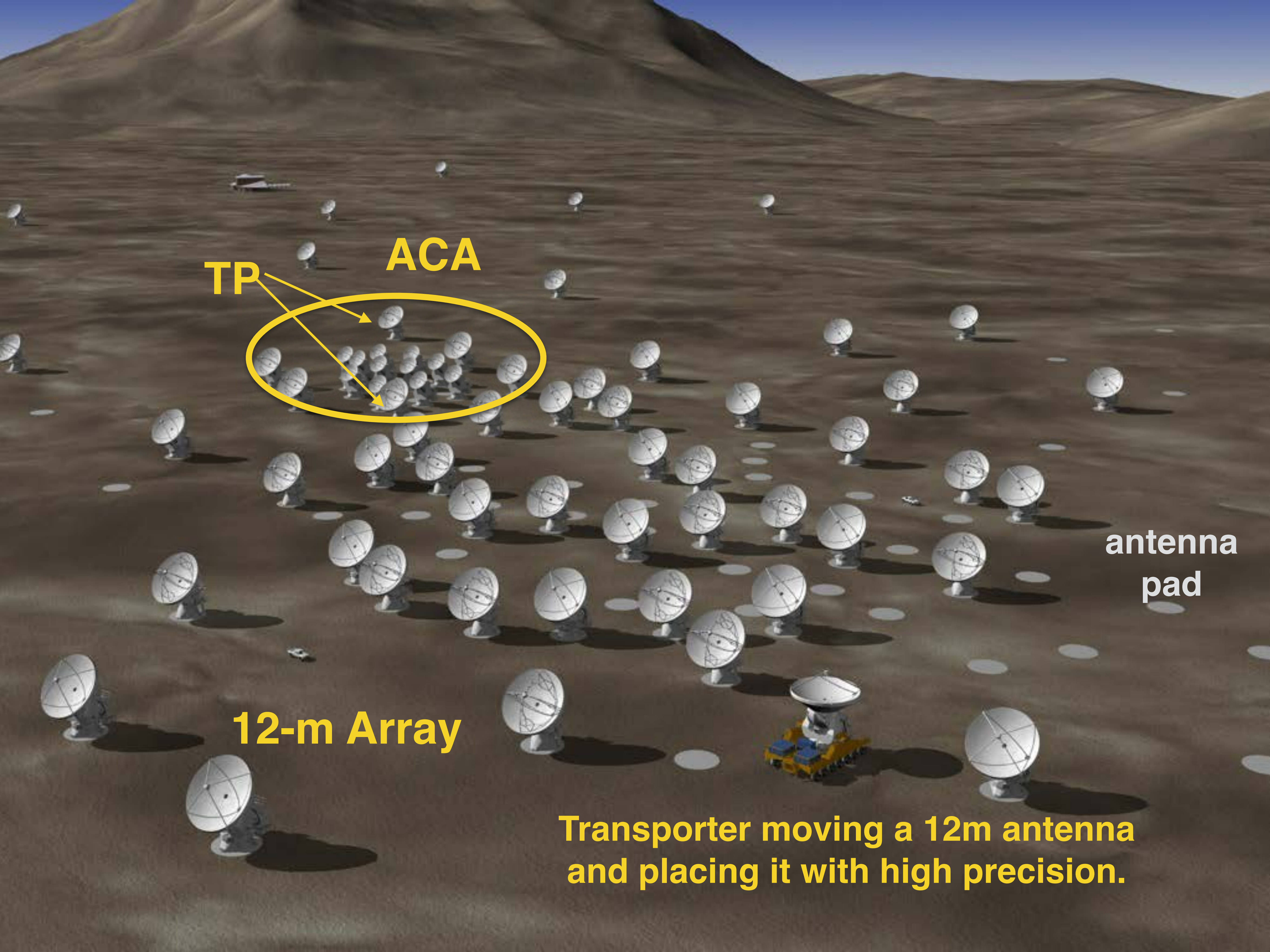
- Early science phase (since 2013) with first results

- Solar observations still in commissioning phase.



Atacama Large Millimeter/submillimeter Array

- ALMA with in total **66 antennas**, arranged in two arrays:
  - The **12-m Array**: 50 movable antennas with 12m diameter
  - Can be rearranged to form compact or more widely spread configurations with baselines, i.e. distances between the individual antennas, of up to 16 km.
  - **Atacama Compact Array** (ACA aka “Morita Array”):
    - installed in a very compact fixed configuration
    - 7-m Array: 12 antennas with 7m diameter for interferometry
    - Total Power (TP) Array: 4 antennas with 12m diameter for single dish observations (surrounding the 7-m Array).

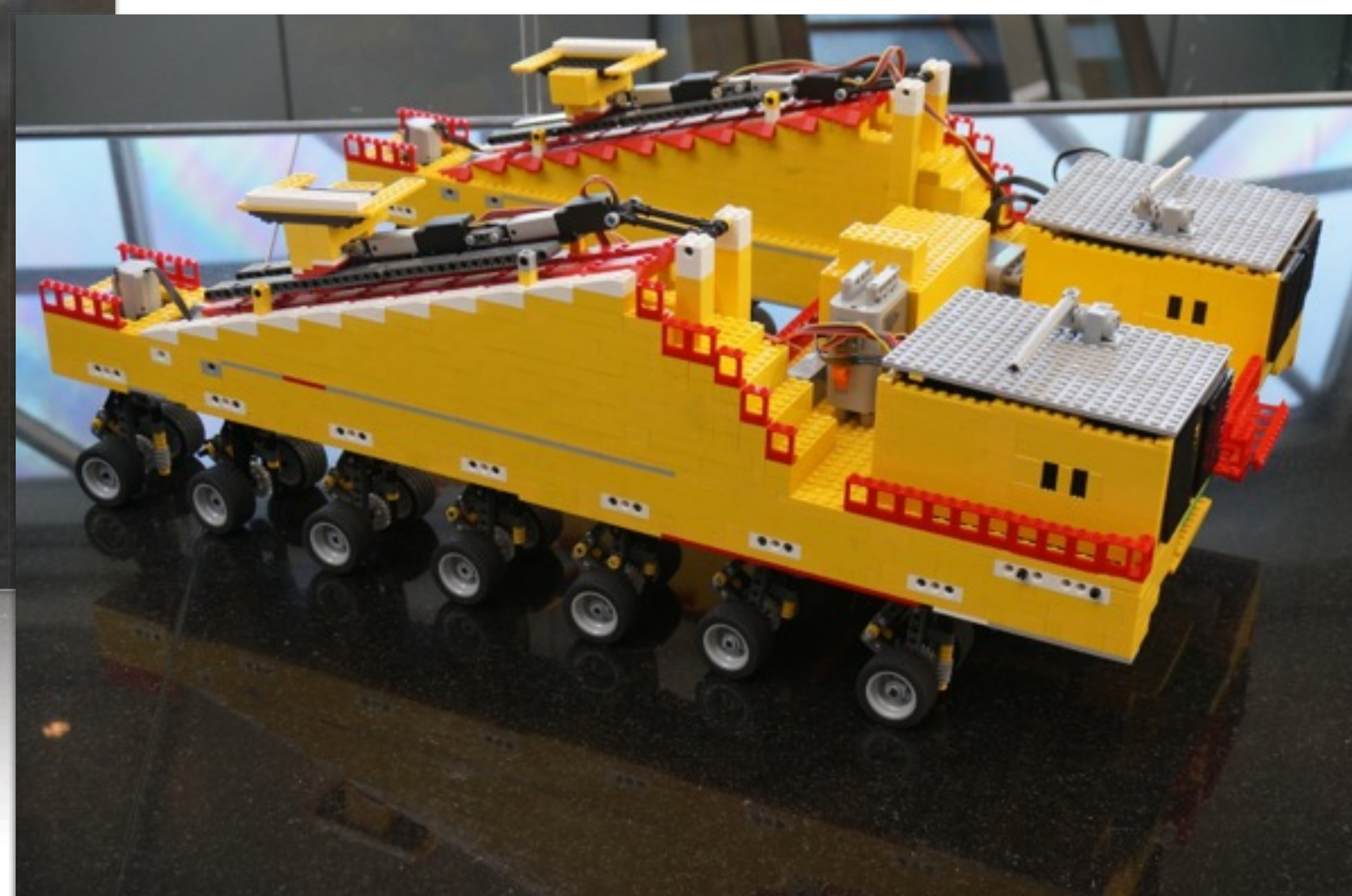

ACA
TP
antenna
pad
12-m Array
Transporter moving a 12m antenna
and placing it with high precision.

Array reconfiguration

Real antenna weighs 115t;
12 m dish diameter

Antenna transporter

- 10 m wide, 20 m long and 6 m high, 130t
- twin turbocharged 500 kW Diesel engines (=1360 PS)



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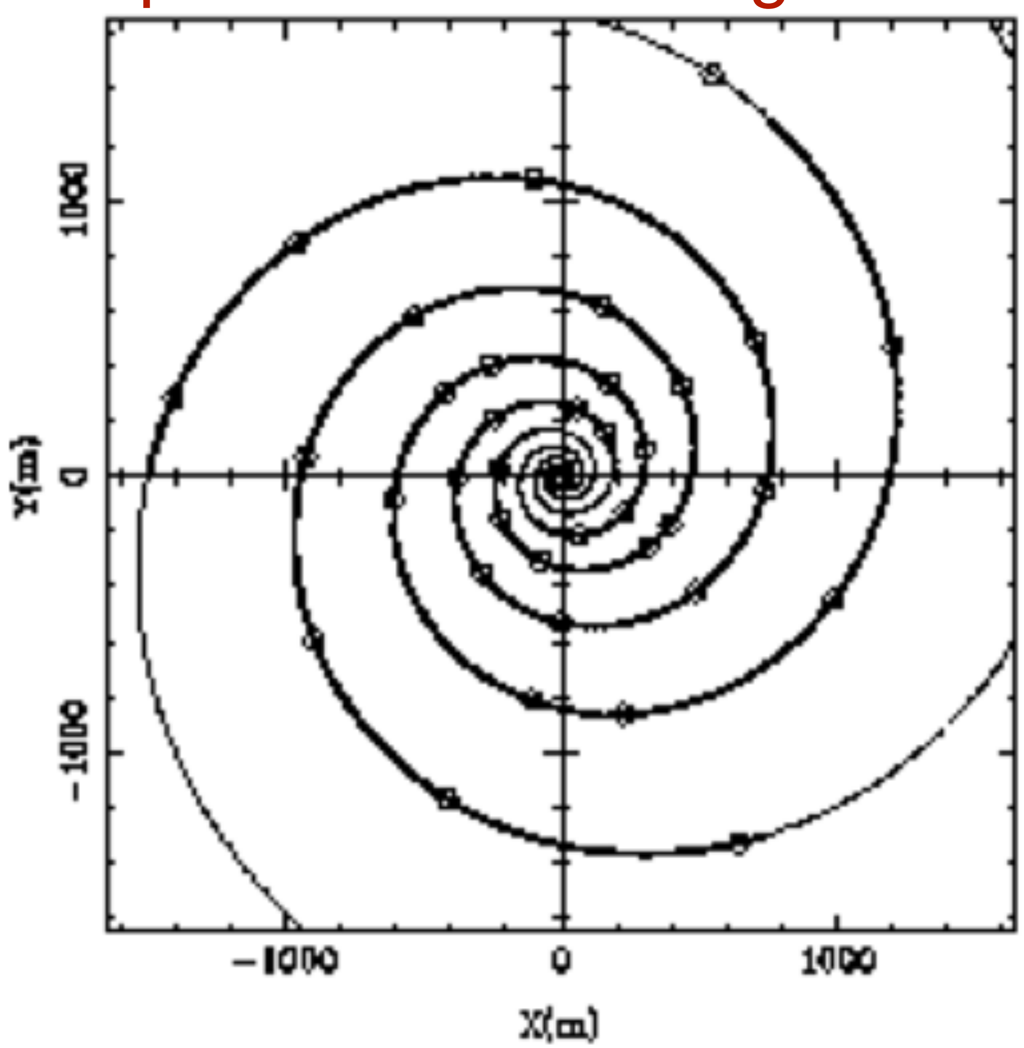
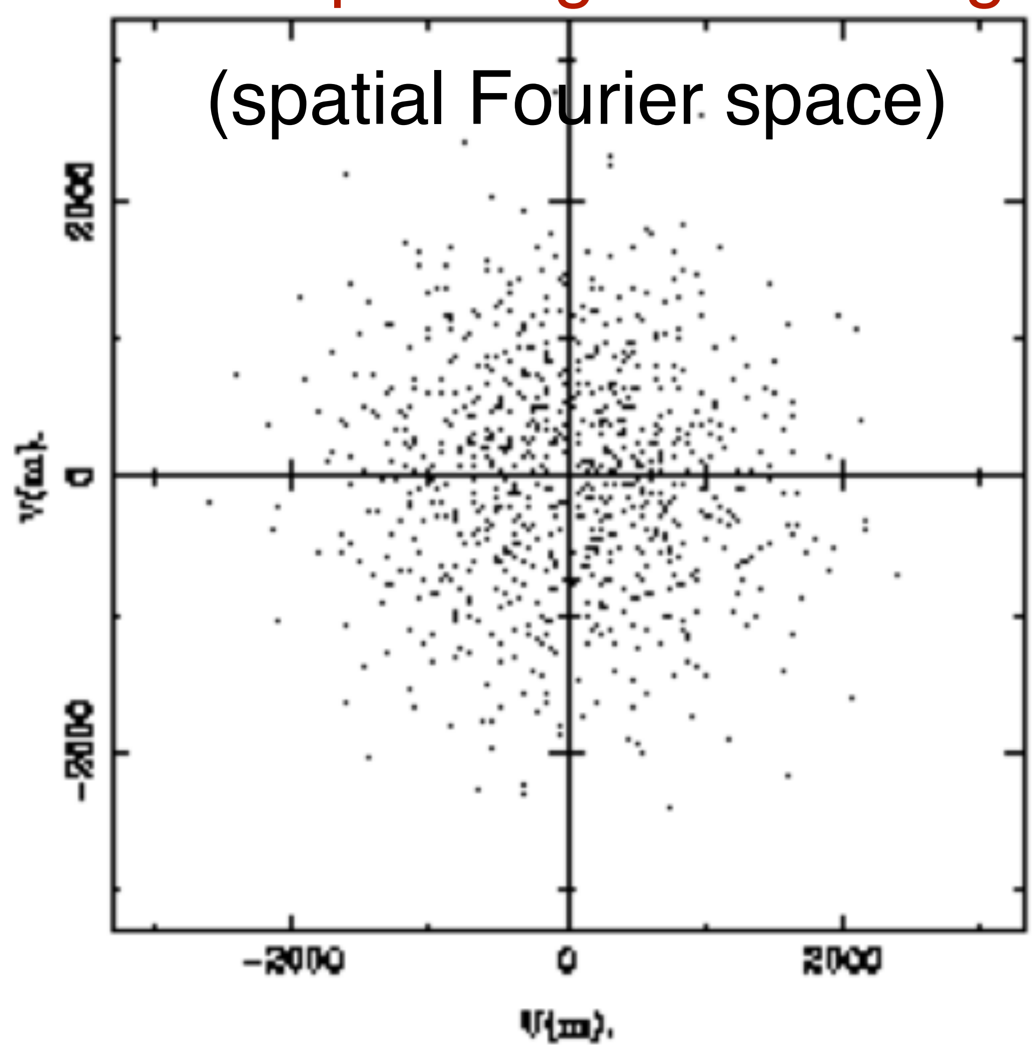
ALMA

- Array configuration can be changed by redistributing antennas on fixed stations (“pads”)
- Maximum baseline = 16km

Spiral antenna configuration



Corresponding u-v coverage



Antenna properties

- **FOV** given by the FWHM of the primary antenna beam

$$\theta \approx 1.13 \times \frac{\lambda}{D} \approx 19'' \times \frac{\lambda}{1\,\mathrm{mm}} \quad \text{for } D = 12\,\mathrm{m}.$$

λ [mm]	0.3	1.0	3.0	9.0
FOV [arcsec]	6	19	58	175

- FOV can be increased by mosaicing (multiple pointings)

Antenna properties

- Angular resolution given by the longest distance d between two antennas:

$\Delta\alpha \propto \lambda / d$

λ [mm]	0.3	1.0	3.0	9.0
Δα [milliarcsec]	4	13	40	350

- BUT: Refers to the separations of two point sources!

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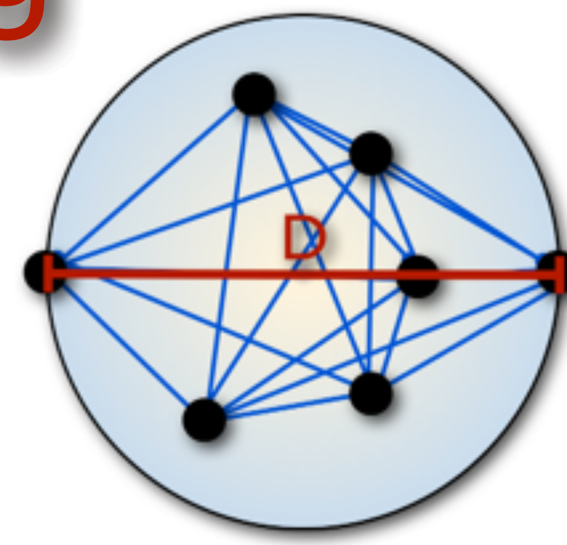
Interferometric imaging



- The Sun is an extended area source!

➡ PSF and image reconstruction

➡ ALMA as **aperture synthesis** telescope:

- Longest baseline determines the diameter of the synthesised aperture, i.e. of the "equivalent telescope size"

- Each baseline has a length and a direction

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

- For N_a antennas ➡ baselines $$N_b = \frac{N_a\,(N_a - 1)}{2}$$

  - $N_a=50$ ➡ $N_b = 1225$

    ➡ 1225 baselines / "visibilities" / points in u-v space

    ➡ Sampling of the PSF of the large synthesised aperture

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Interferometric imaging

ALMA CFG 10

300 GHz

rms: ~2%

Inner sidelobes:

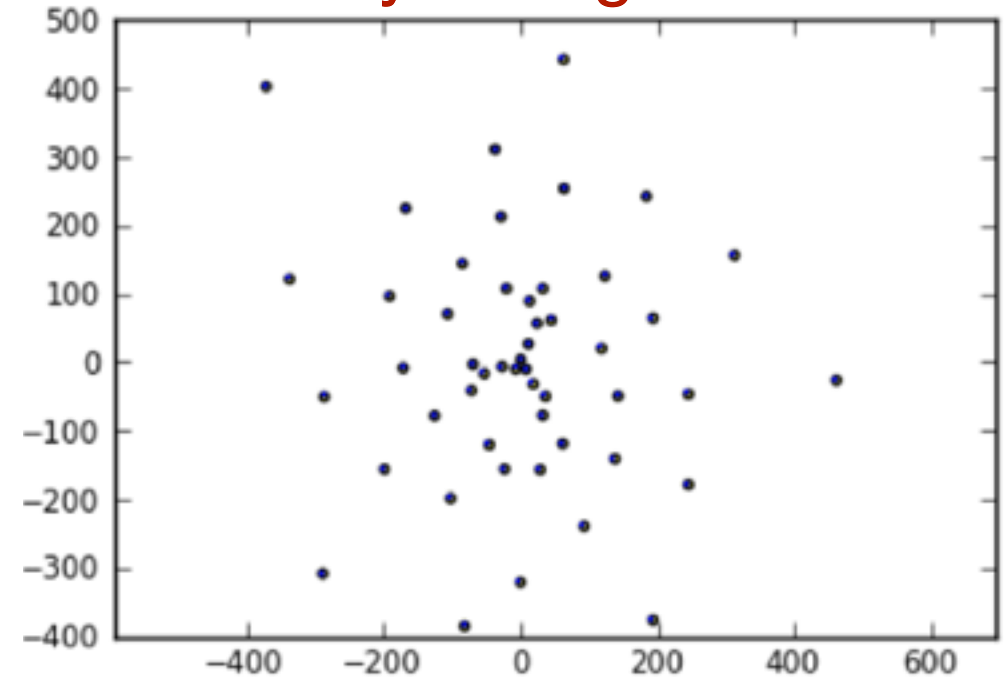
-2.5% to 7.7%

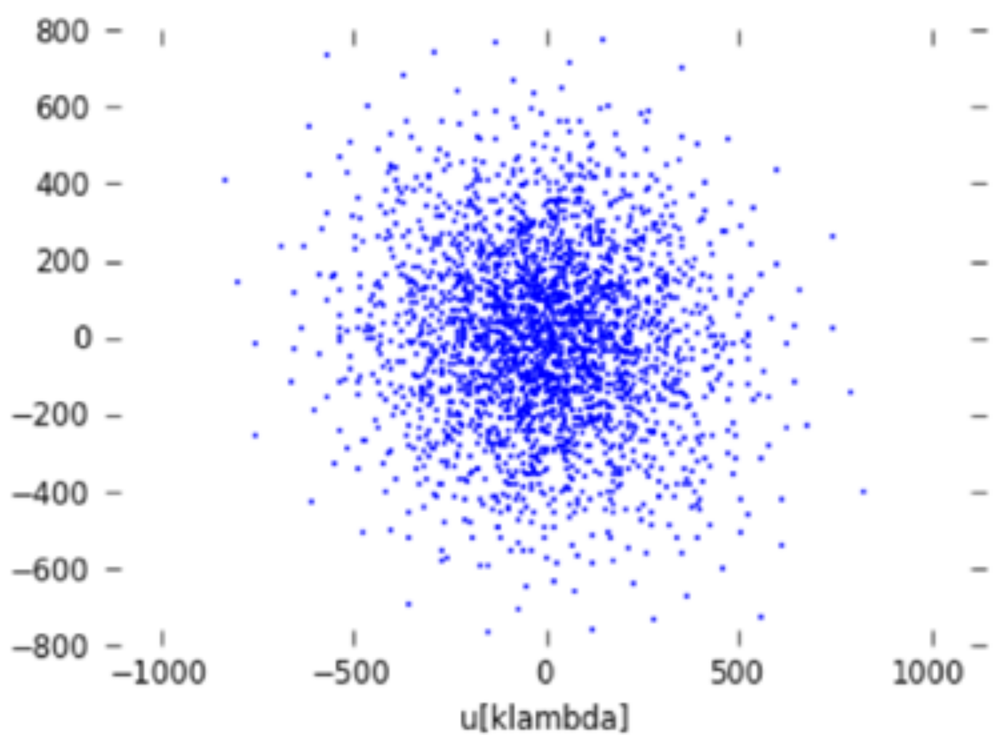
Outer sidelobes

-4% to 16%

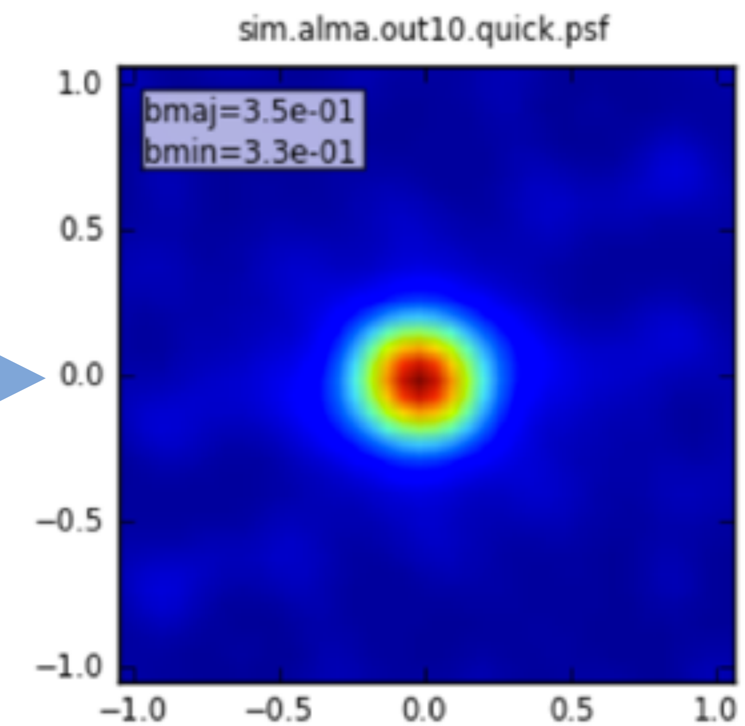
Quasi-random

Array configuration





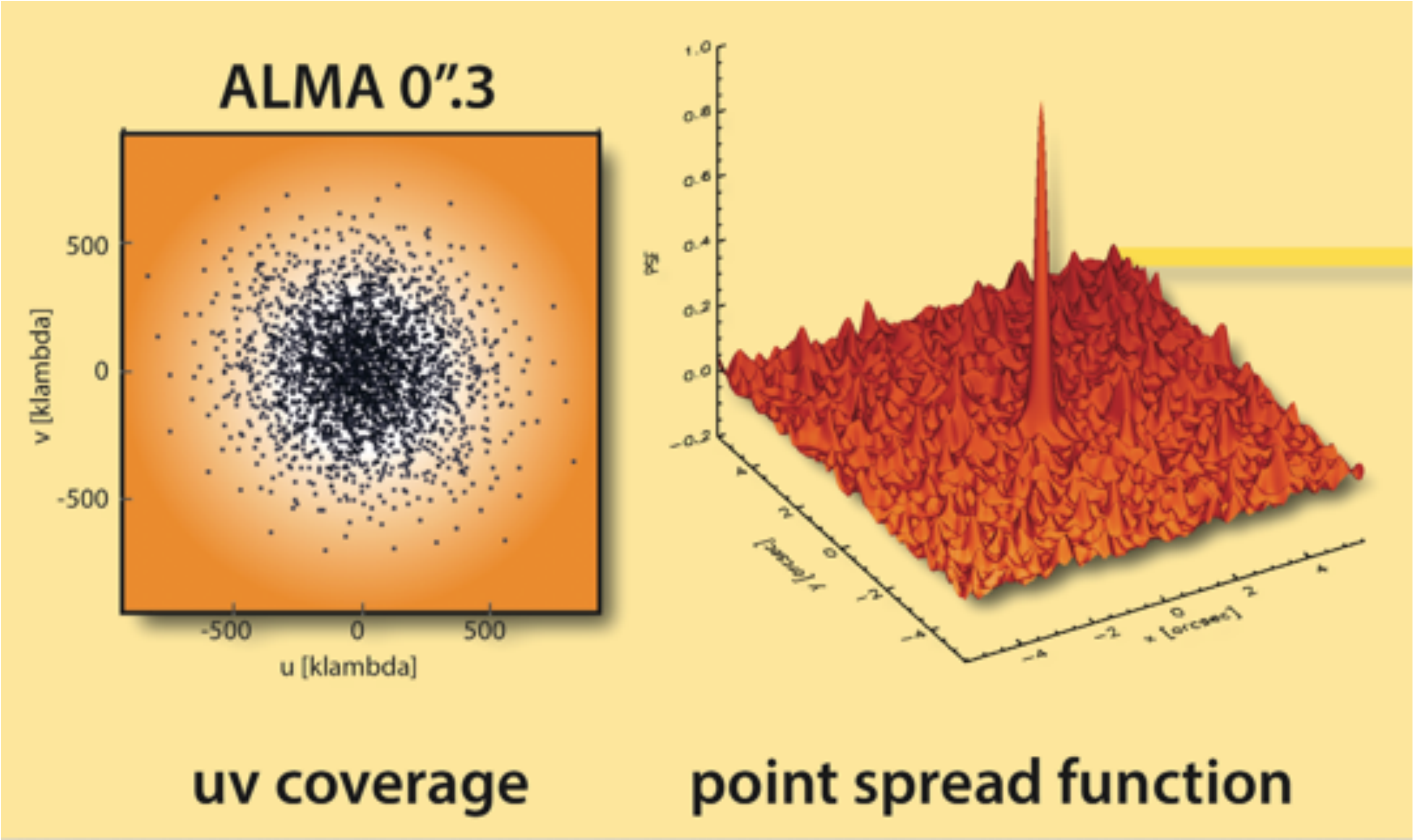
u-v coverage

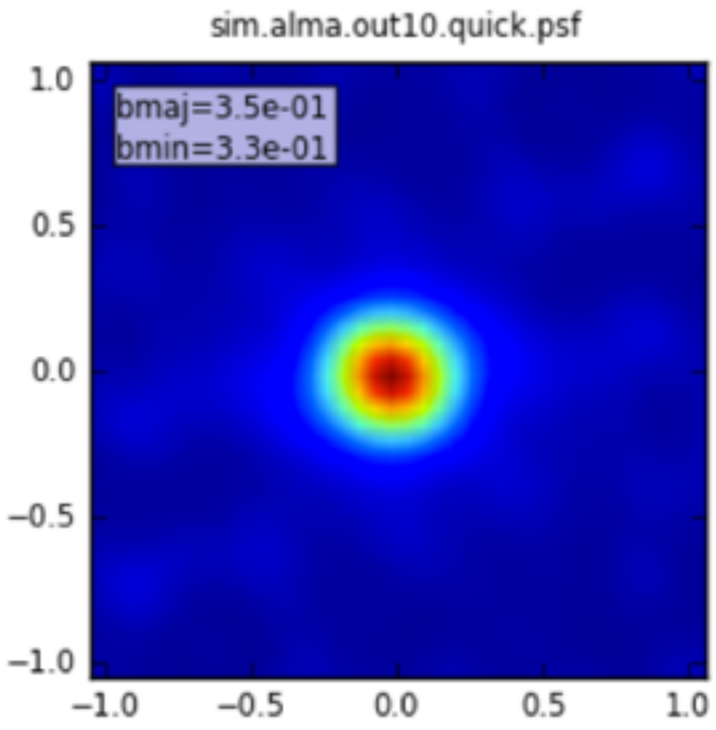


PSF

Interferometric imaging

- “Funny fact”: Antenna size limits the minimum separation (baseline)
- ➡ 0-component in u-v space not sampled
- ➡ Reconstructed PSF would have a “hole” in the middle.
- ➡ Therefore combination with ACA and in particular TP antennas!





➡ Effective spatial resolution of the reconstructed images probably ~0.3” at 1mm - Yet to be seen based on real observations.

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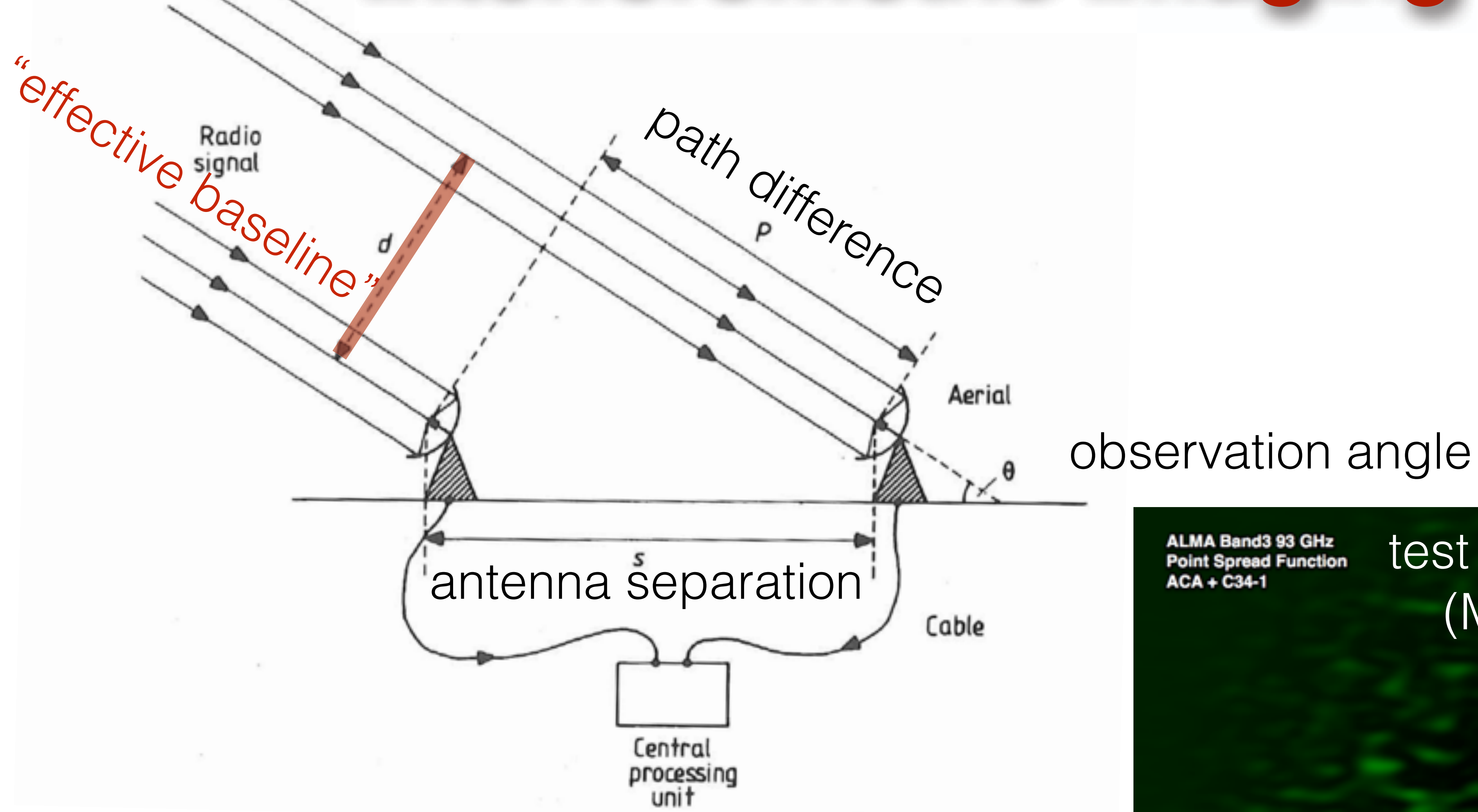
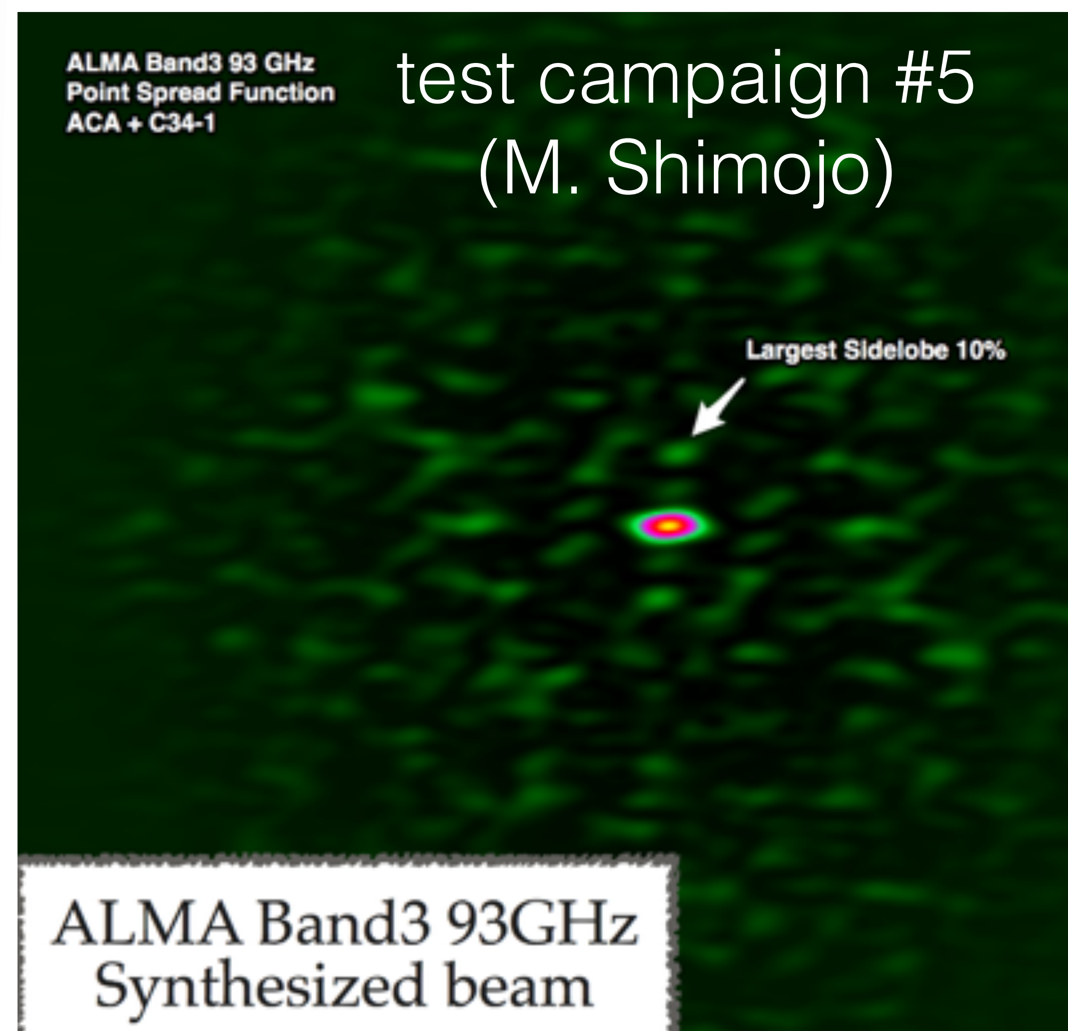
Interferometric imaging



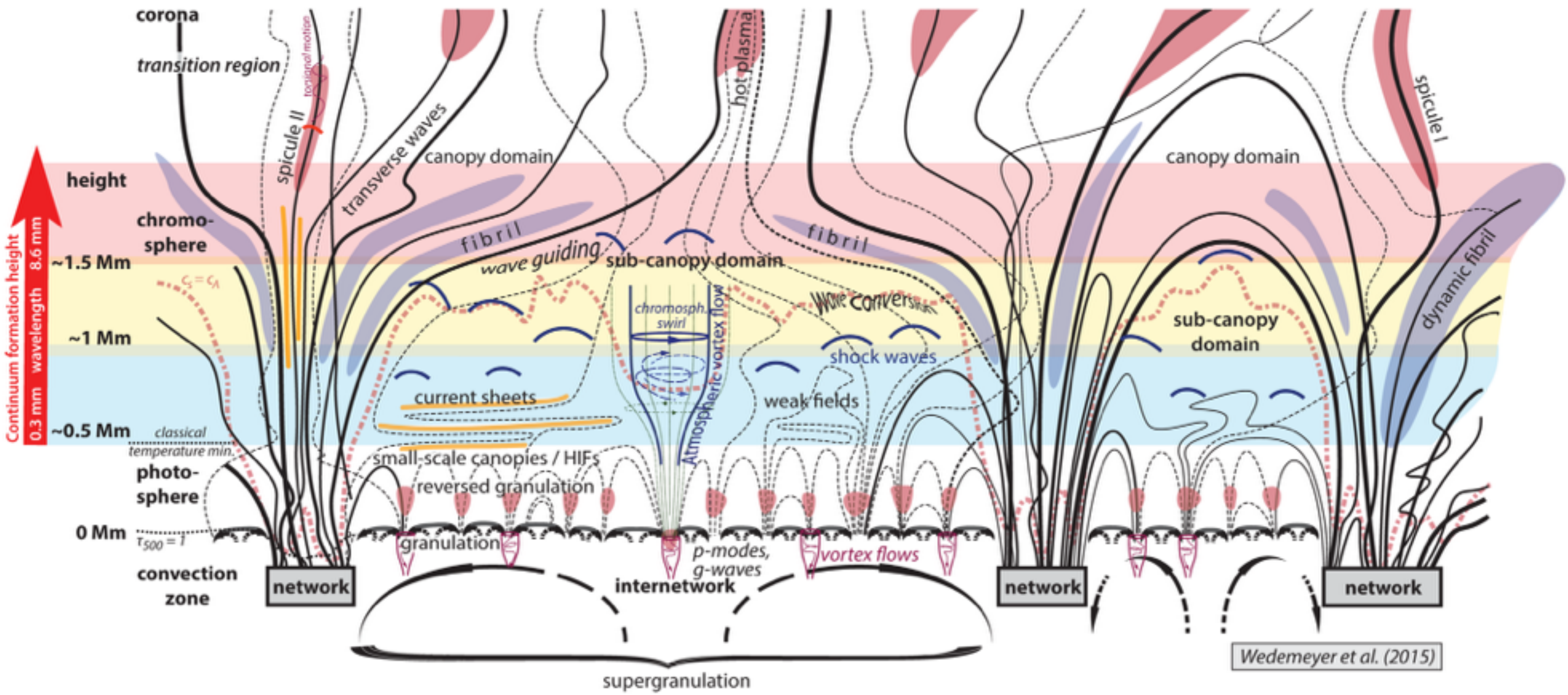
- Source not in zenith

➡ PSF non-symmetric



What will ALMA observe?

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

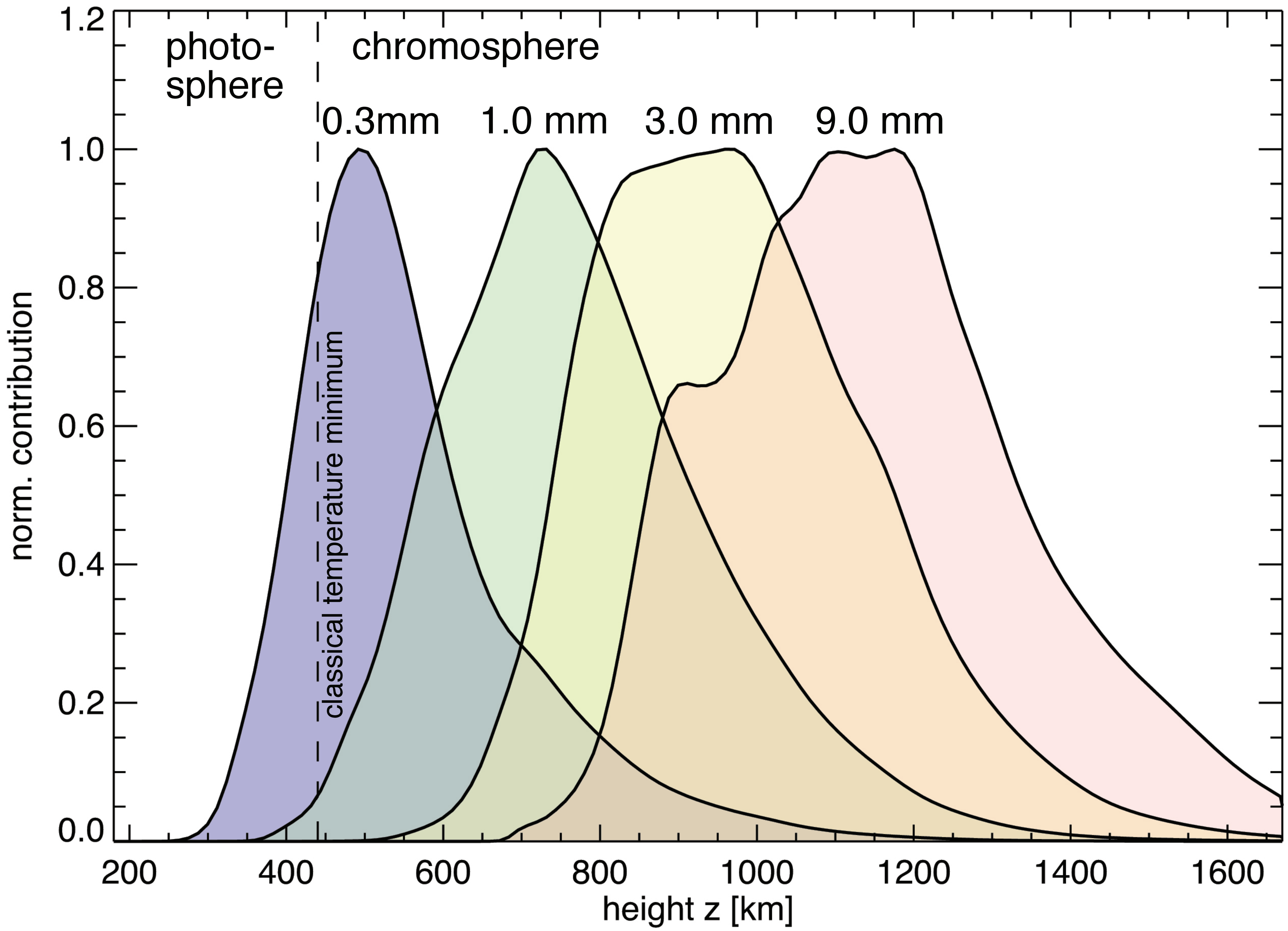


Millimeter radiation

- **Opacity sources:**
  - inverse thermal bremsstrahlung (main)
  - H^- free-free absorption (smaller contribution)
  - non-thermal gyrosynchrotron emission due to high-energy electrons (in particular during flares)
- **Source function**
  - Long wavelength
  - ➡ Rayleigh-Jeans limit
  - ➡ Planckian source function, linear dependence on gas temperature
  - ➡ Resulting intensity linearly related to atmospheric gas temperature *(integrated along the line of sight)*
  - ➡ **ALMA serves as linear thermometer of the chromospheric plasma!**
  - Brightness temperatures used instead of intensity.

Millimeter radiation

- Continuum intensity formed over a relatively narrow height range

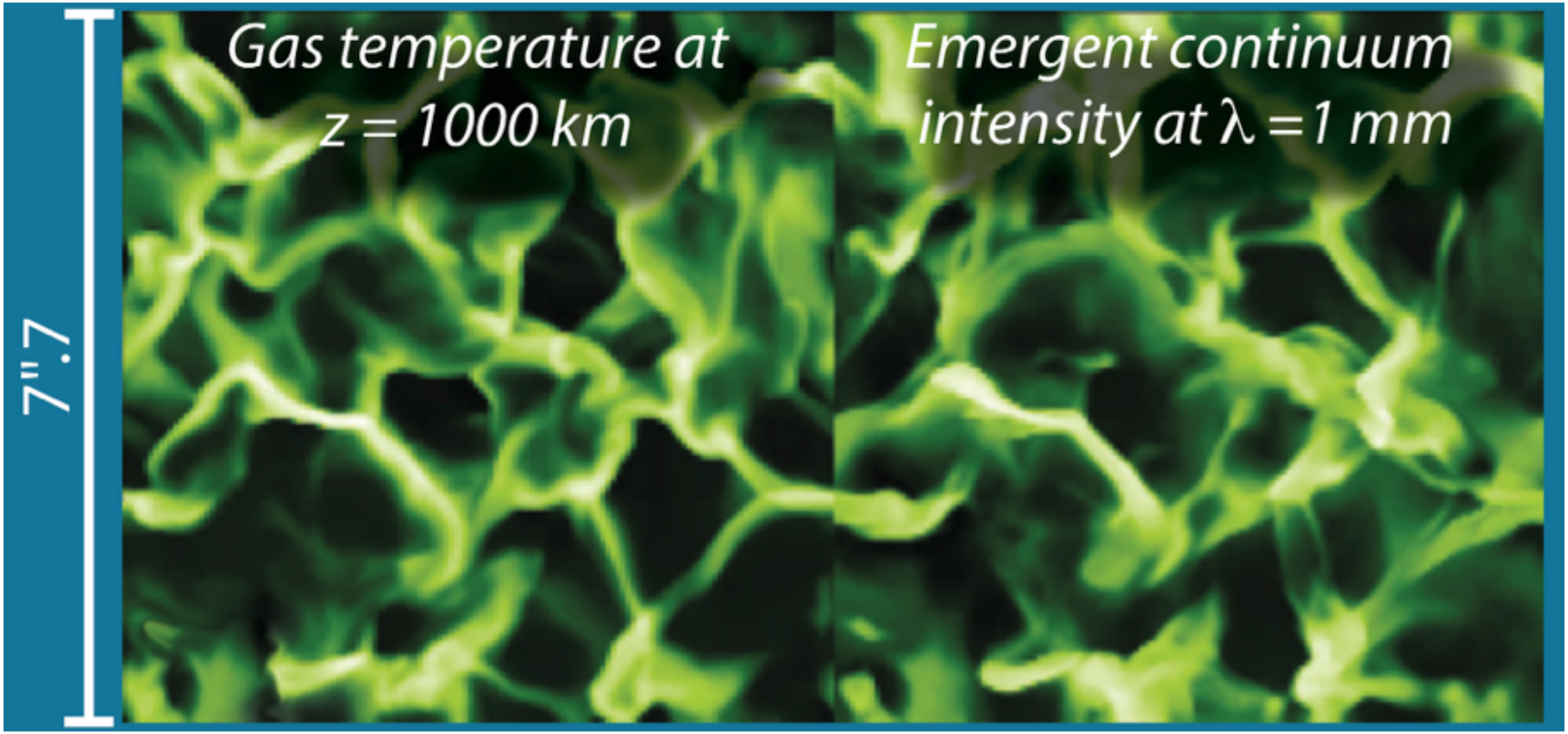


Contribution functions based on 3D simulation (Wedemeyer-Böhm et al. 2007)

Radiation continuum

- 3D models show: Brightness temperature of emergent radiation closely related to original (local) gas temperature!

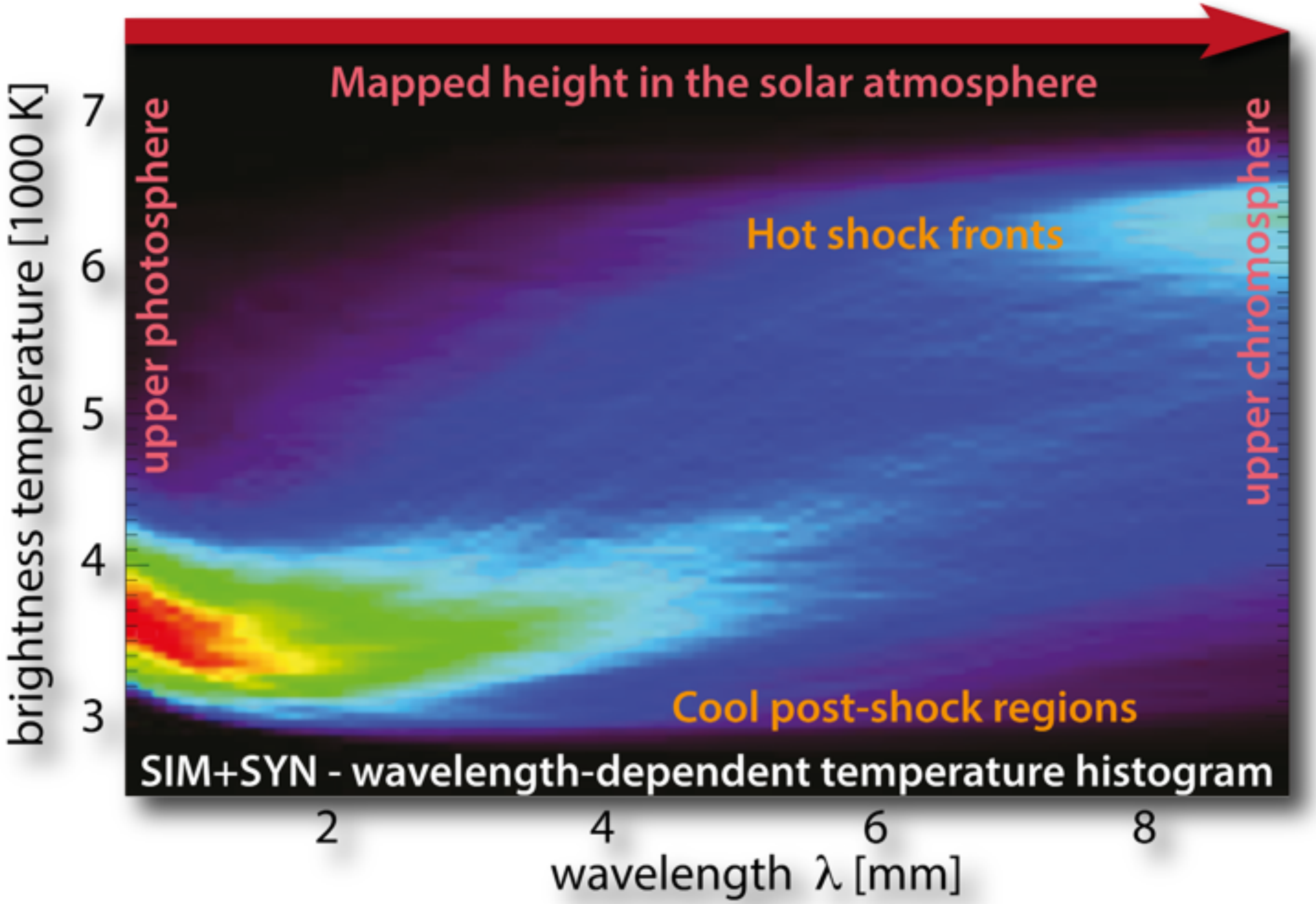
➡ Amazing thermal diagnostic!



(Wedemeyer-Böhm et al. 2007)

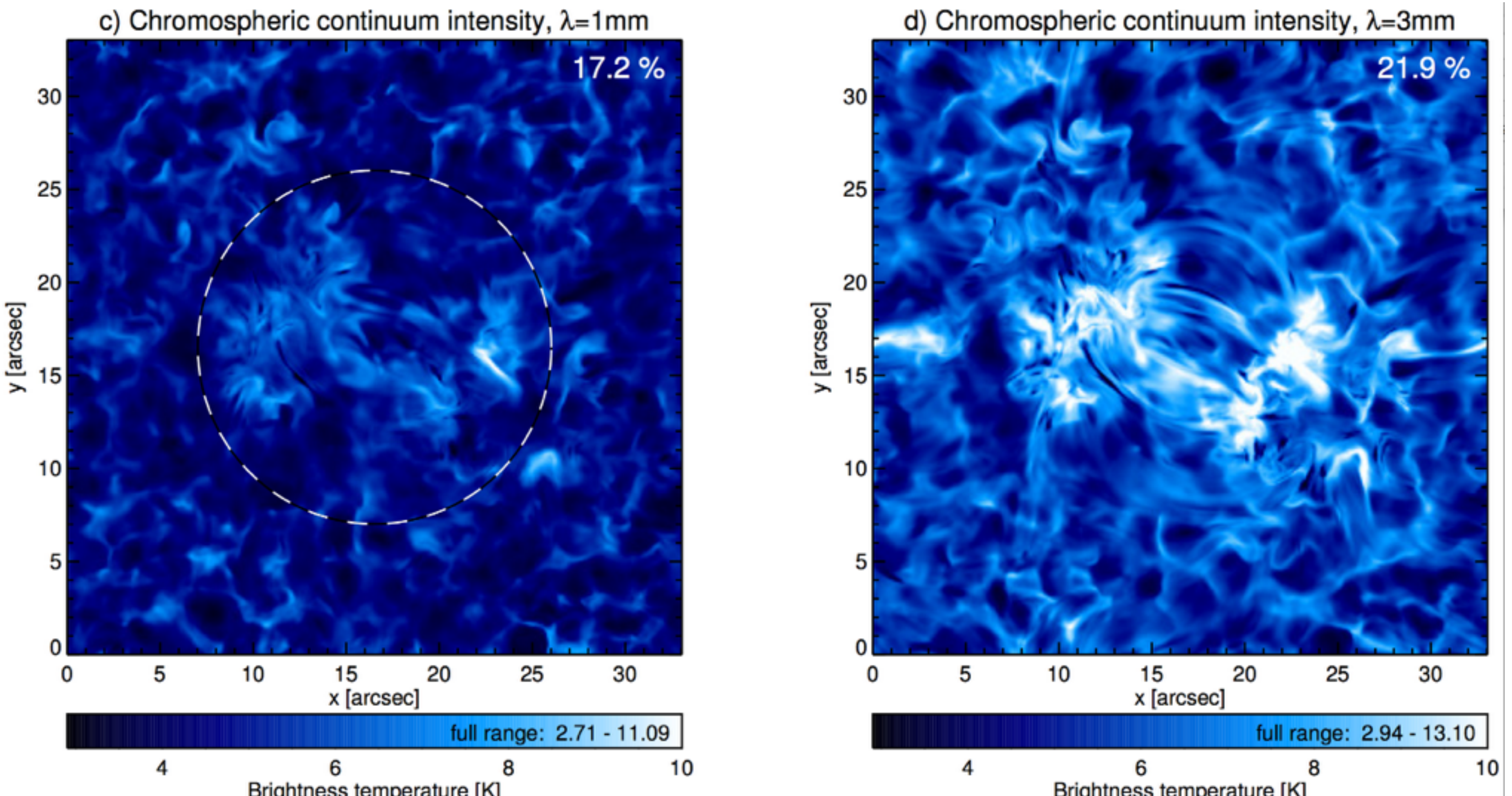
Radiation continuum

- Scanning through wavelength
- ➡ Scanning through height in the chromosphere
- ➡ (statistical) 3D thermal structure (tomography)



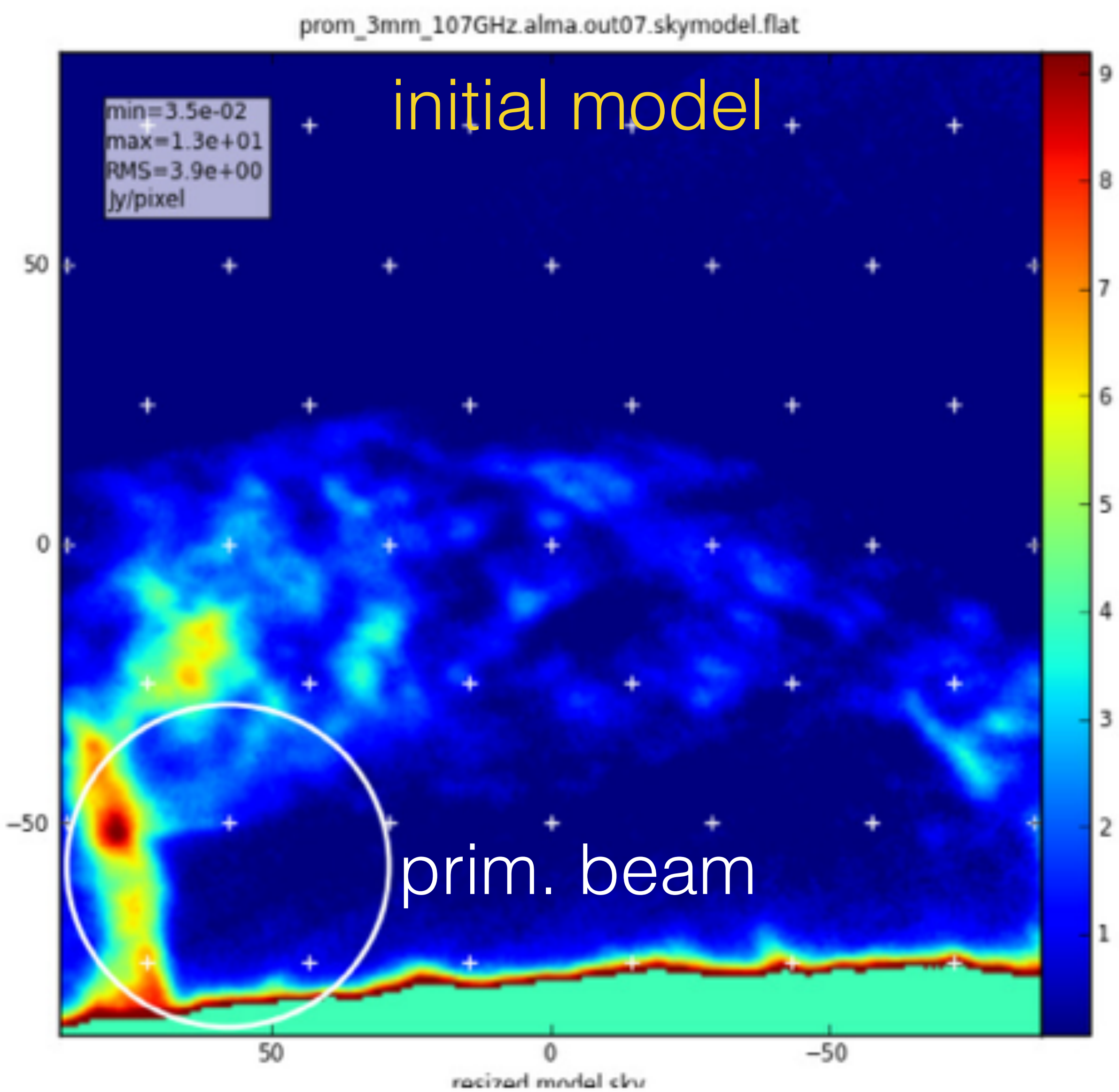
Millimeter radiation

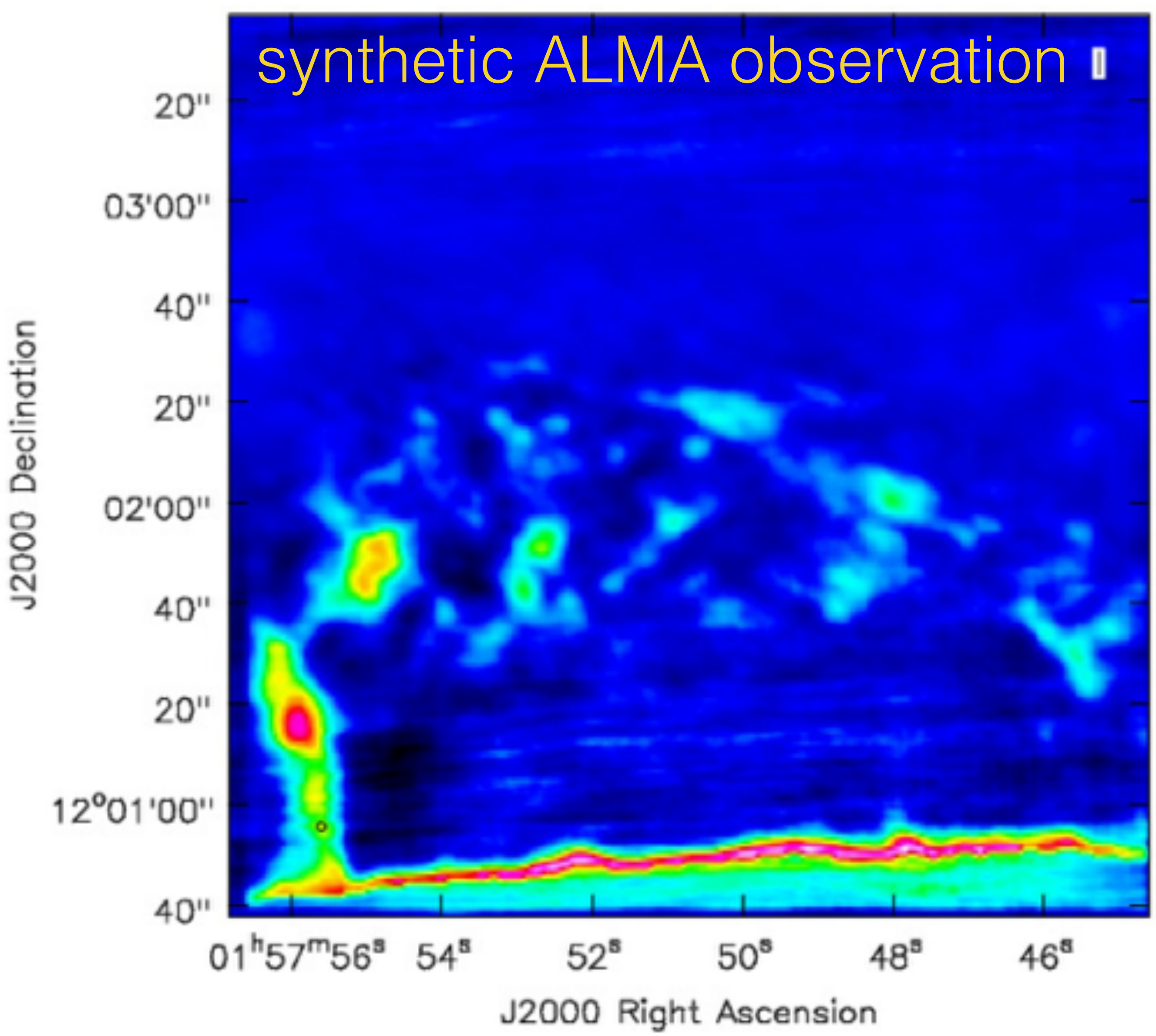
- Bifrost simulation of enhanced network with coronal loops
- ➡ Imprint of loops different at different wavelengths and thus layers
- ➡ Constraints for the 3D magnetic field topology



Millimeter radiation

- Simulations for a prominence observations with a large FOV through mosaicing (3 mm, 180” x 180”)





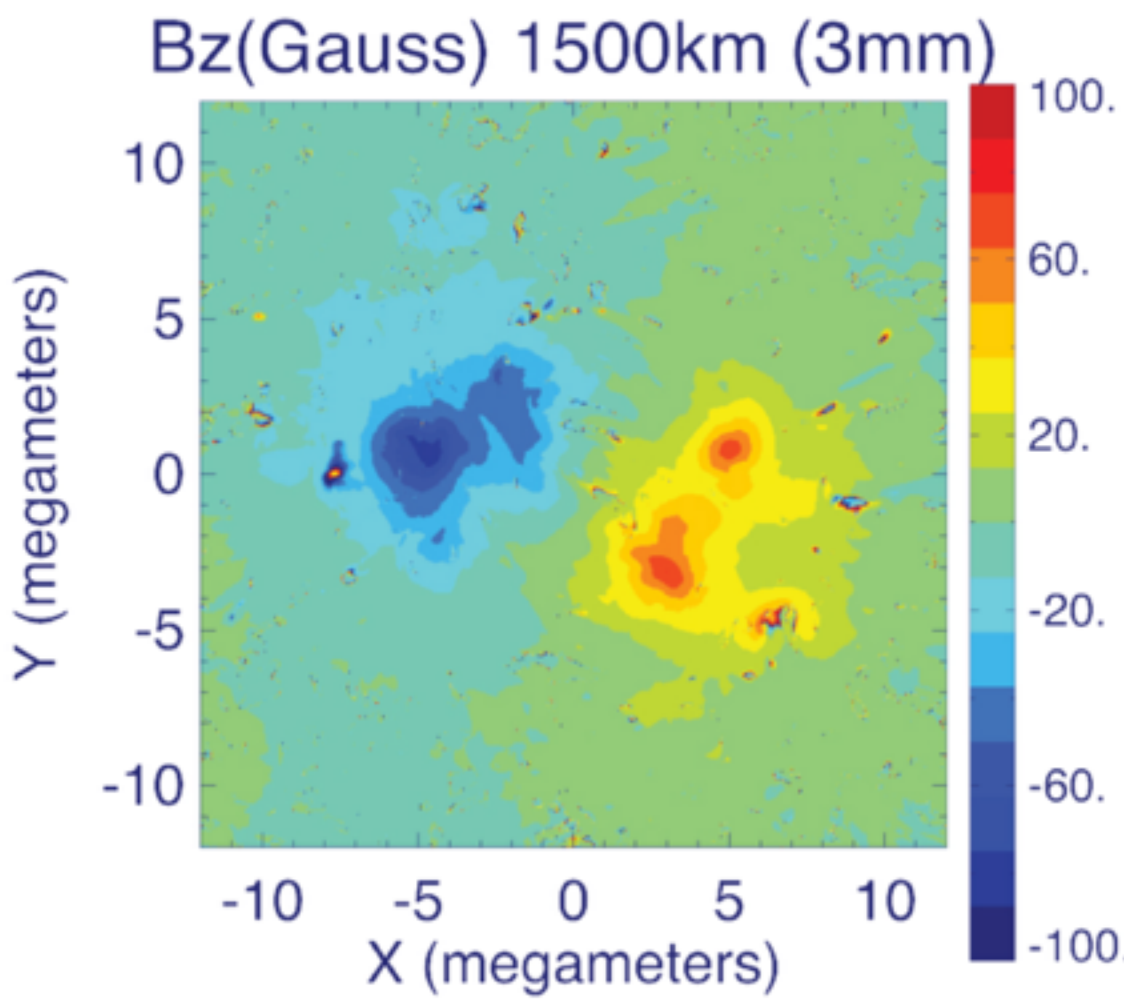
Heinzel et al. (2014)

Magnetic field measurements

- Free-free opacity depends on the local magnetic field strength.
- ALMA measures the polarisation!
- Polarisation of the continuum intensity can be used to derive the longitudinal magnetic field component
(Bogod & Gelfreikh 1980; Grebinskij et al. 2000; Loukitcheva, Fleishman et al. 2015)
- Scan through wavelength and thus height

➡ Constraints for the 3D magnetic field topology

- Method very likely to work for active regions and sunspots; has to be tested for weaker field



Bifrost model; Loukitcheva et al. (2015)

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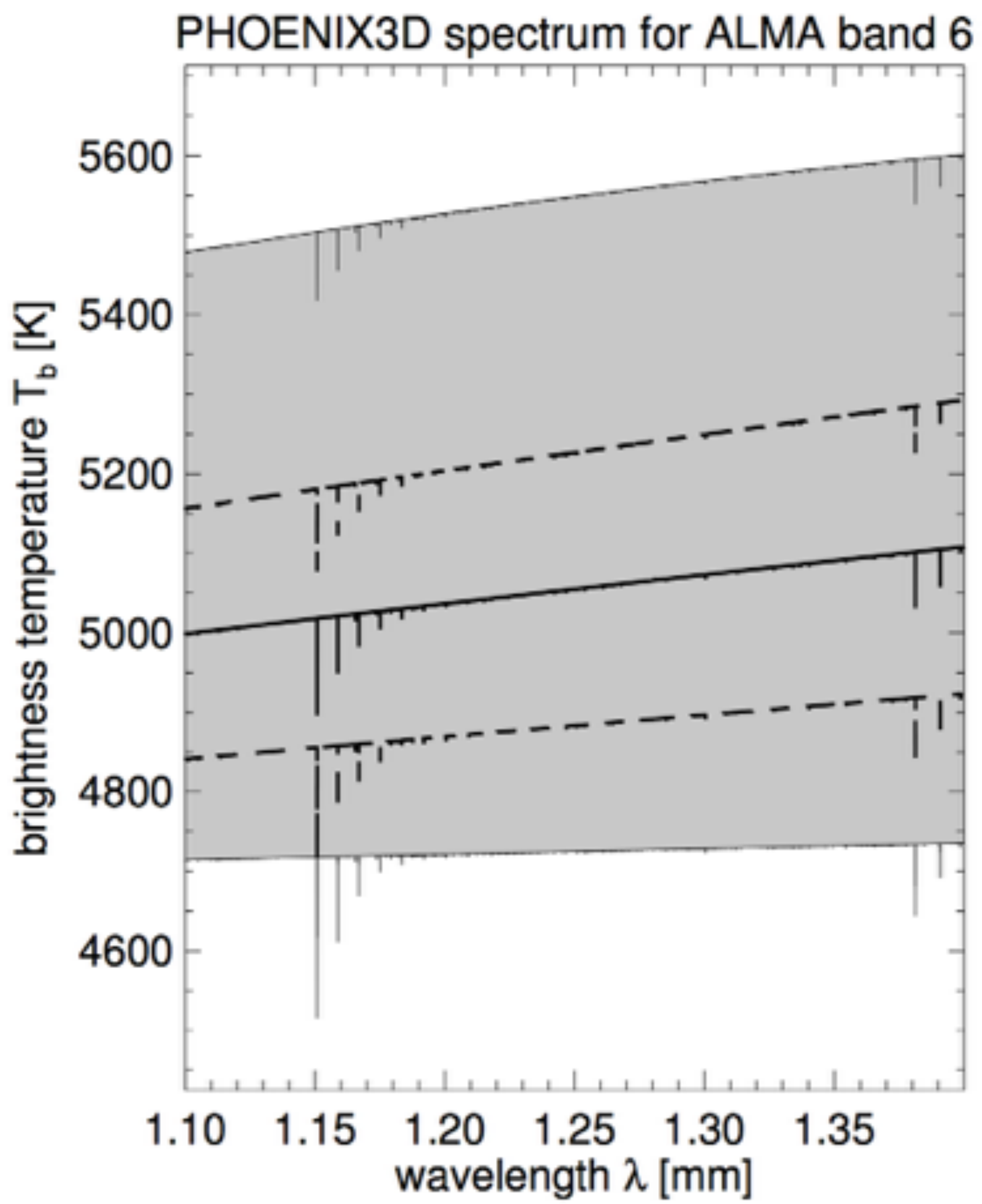
Spectral capabilities

- 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 (different modes, very flexible)
- Example: Velocity resolution of 0.02 km s^{-1} at λ = 2.73 mm
- 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 potential!

Temporal resolution

- The Sun is a bright mm source.
- ALMA quite sensitive with high SNR

➡ Short integration times and on-the-fly observing (antenna move continuously)

- Three receiver bands are “warm” at the same time.

➡ Sequences cycling through three bands possible.

- Time for changing theoretically only a few sec but currently a few min. May improve in the future.

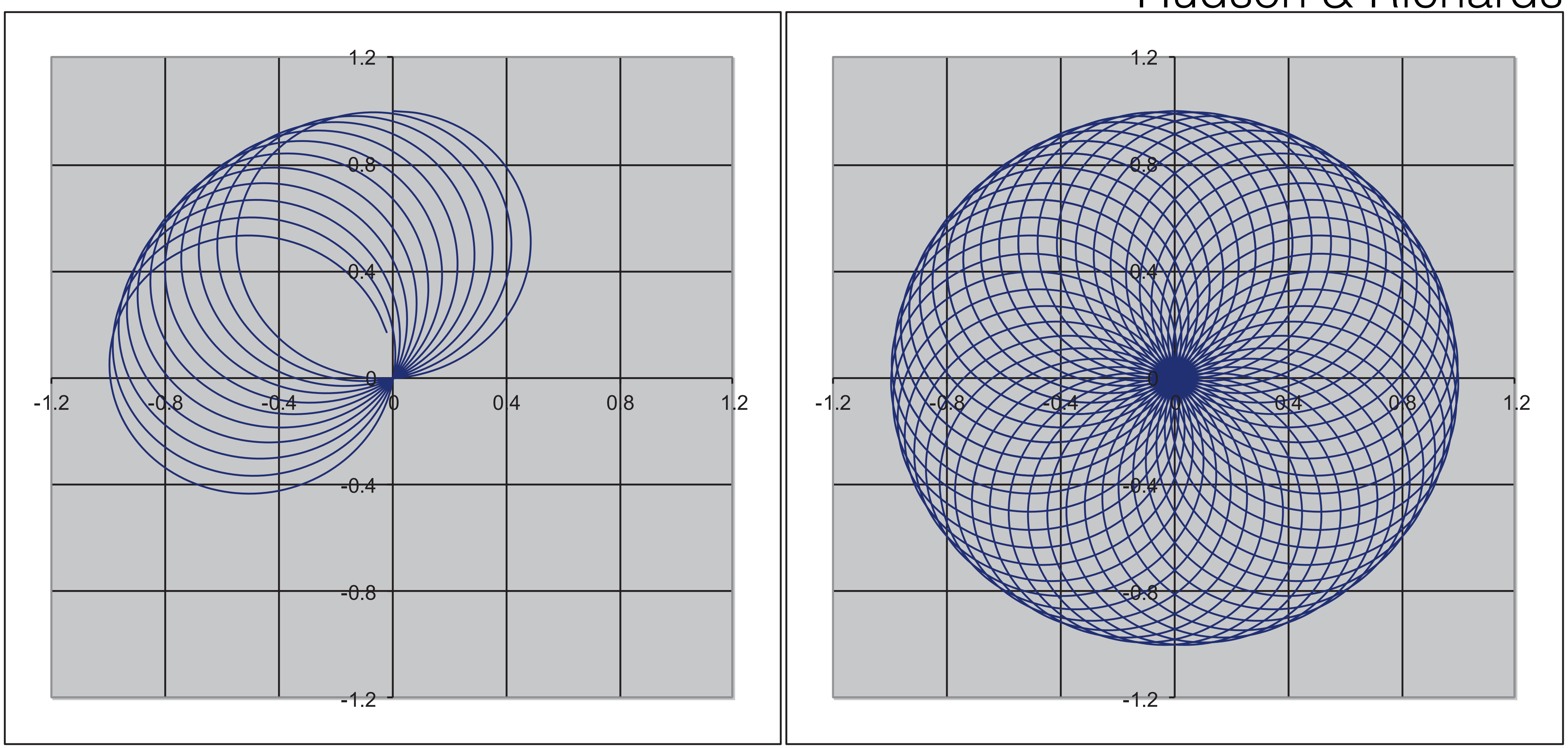
On-the-fly single-dish observations

- Different full-disk scan pattern (e.g., Lissajous), here: double-circle pattern with the functions in a 2:1 amplitude ratio

- Precise tracking corrections ➡ Antennas driven at freq. ~1 Hz,
- Excellent SNR ➡ sampling times of msec.

➡ Whole disk scanned within 1 - few min.

Hudson & Richards



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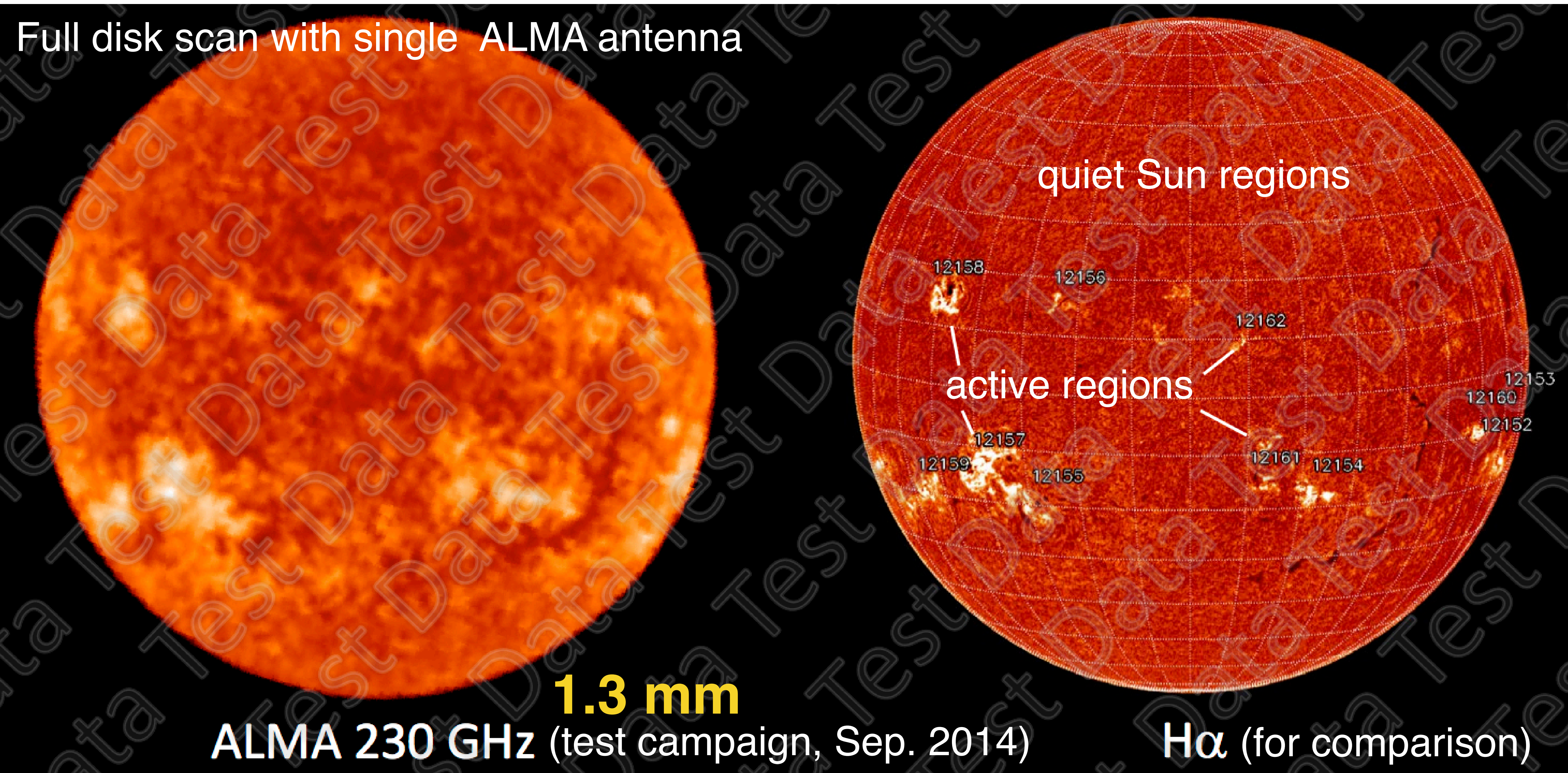
On-the-fly single-dish observations

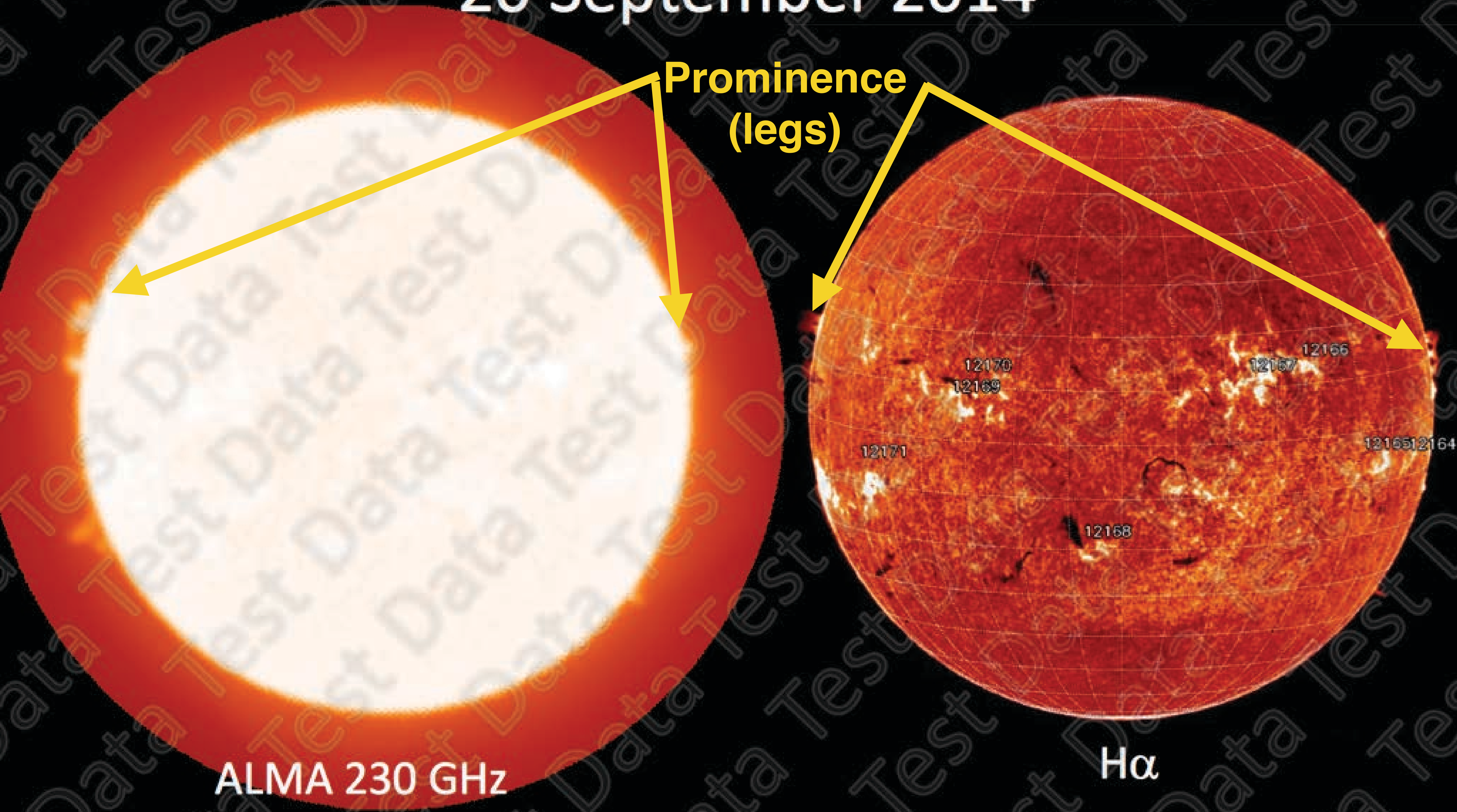
Phillips et al. (2015)

- Preliminary results (non-public commissioning data) for test campaign #4 (September 2014)



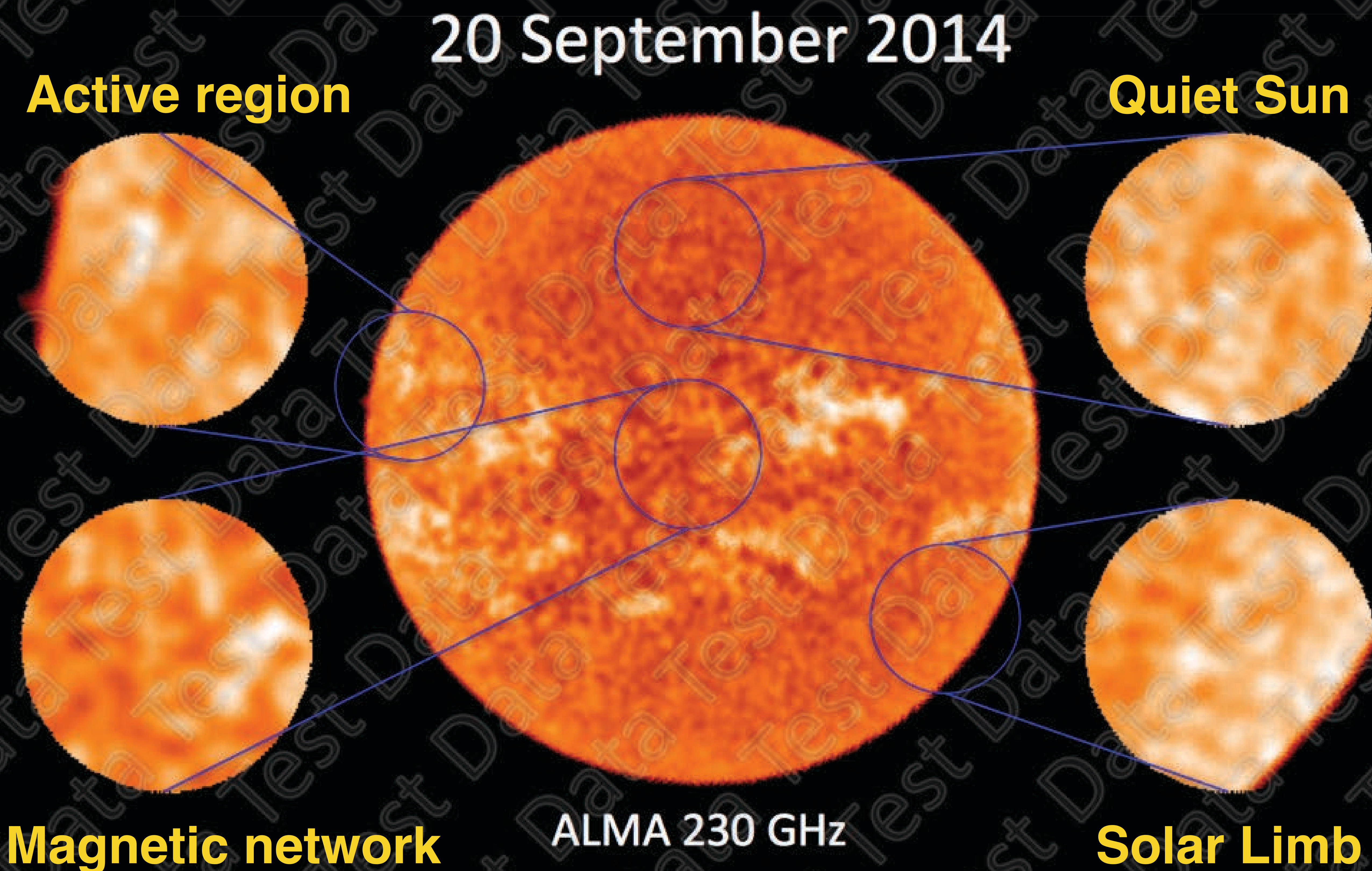
Phillips et al. (2015)

20 September 2014



Data range chosen to make features at limb visible.

Phillips et al. (2015)



Solar test campaigns

ALMA development studies

- **“Advanced Solar Observing Techniques"**
  A project within the North American Study Plan for Development Upgrades of the ALMA
  (PI: T. Bastian, National Radio Astronomy Observatory (NRAO), USA).

- **"Solar Research with ALMA"**
  A project carried out at the Czech ARC node of European ALMA Regional Center (EU ARC at Ondrejov, Czech Republic) in the frame of the ESO program "Enhancement of ALMA Capabilities/EoC”
  (PI: Roman Brajsa, Hvar Observatory, Croatia).

- These studies aim at the successful implementation of solar observing modes that are scientifically useful.

SOLAR SIMULATIONS FOR THE ATACAMA LARGE MILLIMETER OBSERVATORY NETWORK

SSALMON

◉ International network

- Focus on numerical simulations and modelling related to solar ALMA science (i.e., the solar chromosphere at (sub-)millimeter wavelengths)

◉ 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.

SSALMON - Network growth

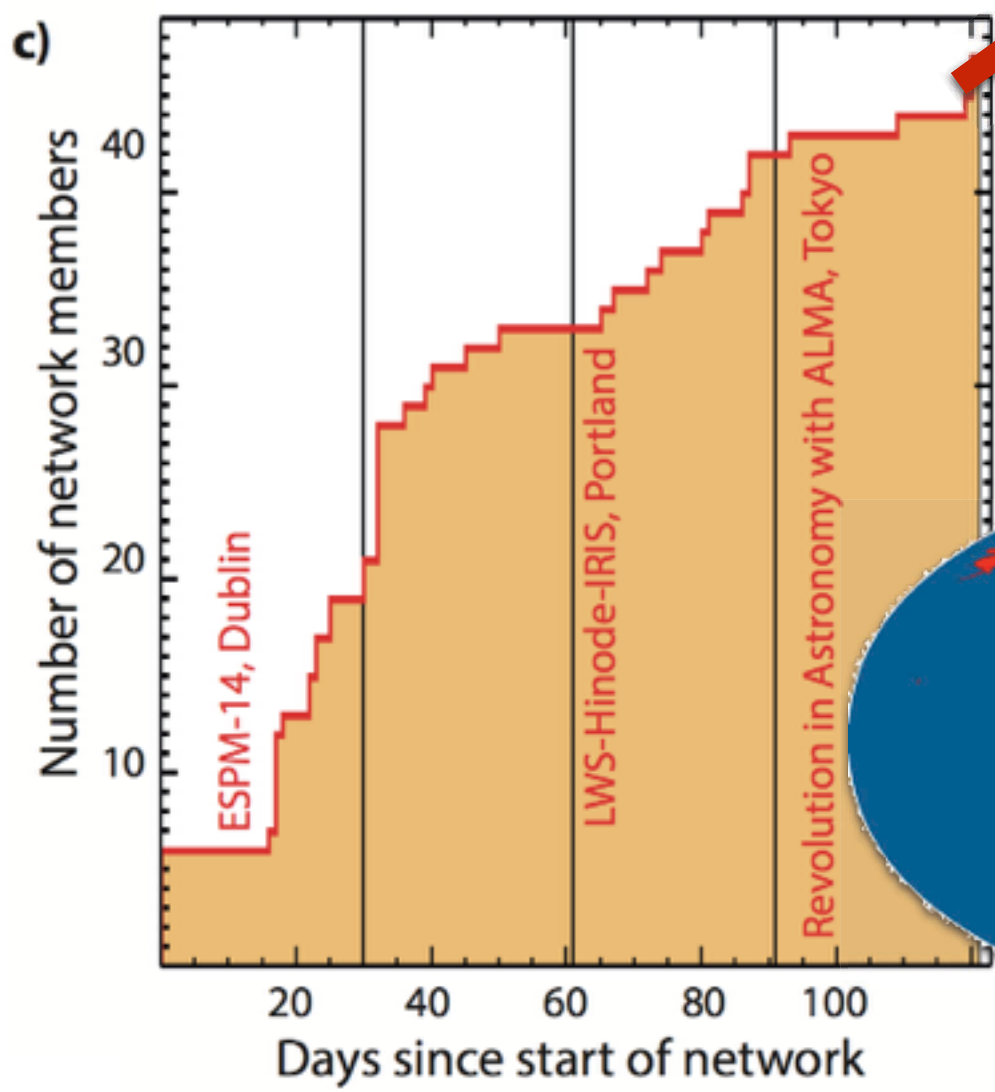
- Now: 54 network members from 15 countries (+ESO, ESA)

Members sorted by region

Europe	37
North America	14
East Asia	3

Sorted by members per country*:

USA:	14
Germany:	7
Norway:	6
Czech Republic:	5
United Kingdom:	4
Japan:	3
Spain:	3
Austria:	2
Greece:	2
Belgium:	1



Recent activities

- 1st September 2014: Official start date of network
- Sep. - Dec., 2014 : Presentation at various conferences
  - ESPM/Dublin, Ireland (9/2014)
  - LWS-Hinode-IRIS/Portland, USA (11/2014)
  - Revolution in Astronomy with ALMA - The 3rd year / Tokyo, Japan (12/2014)
- Regular newsletter (every 3 months)
- 5 proceedings articles (submitted) and a long review on solar ALMA science (38 authors, ~70 pages, to be submitted soon)

SSALMON publications so far

SSALMON - The Solar Simulations for the Atacama Large Millimeter Observatory Network
Wedemeyer, S.; Bastian, T.; Brajsa, R.; Barta, M.; Hudson, H.; Fleishman, G.; Loukitcheva, M.; Fleck, B.; Kontar, E.; De Pontieu, B.; and 20 coauthors (incl. Patrick)
2015arXiv150205601W (ESPM proceedings)

Solar ALMA Observations - A new view of our host star
Wedemeyer, Sven; Bastian, Tim; Brajsa, Roman; Barta, Miroslav; Shimojo, Masumi; Hales, Antonio; Yagoubov, Pavel; Hudson, Hugh
2015arXiv150206397W (Tokyo proceedings)

Solar Simulations for the Atacama Large Millimeter Observatory Network
Wedemeyer, Sven; Bastian, Tim; Brajsa, Roman; Barta, Miroslav; Shimojo, Masumi
2015arXiv150206379W (Tokyo proceedings)

Fast single-dish scans of the Sun using ALMA
Phillips, Neil; Hills, Richard; Bastian, Tim; Hudson, Hugh; Marson, Ralph; Wedemeyer, Sven
2015arXiv150206122P (Tokyo proceedings)

ALMA's high-cadence imaging capabilities for solar observations
Wedemeyer, S.; Parmer, A.
2015arXiv150203580W (Tokyo proceedings)

Current activities

- **Call for expert teams** to work on individual topic:

A Numerical models of the solar atmosphere
B Radiative transfer and brightness temperature synthesis
C Simulating instrumental effects for ALMA (incl. interferometric imaging)
D Spectral lines in the millimeter range as new diagnostic tools
E Emission mechanisms at millimeter wavelengths
F Magnetic field measurements
G Oscillations and waves
H Solar flares
I Prominences
J Chromospheric and coronal heating
K Quiet Sun regions
L Active regions and sunspots
M Magnetic loops in the upper atmosphere
N Space weather
O Implications for stellar physics - The solar-stellar connection
P Limb-brightening studies

- First deadline to register active participation: March 15th, 2015

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Potential for coronal rain studies

Based on Patrick's words…

- ALMA - temperature maps at high spatial and temporal resolution
- Coordinated observation campaigns with space-based instruments such as IRIS probing different temperature ranges.

★ Determining the size distribution of fundamental substructure and its role in the chromosphere-corona mass cycle.

★ How such is degree of complexity achieved?

★ Differentiating mechanisms of substructure generation in flux tubes (incl. Kelvin-Helmholtz instability vortices as strand-like or thread-like structure along the coronal or prominence loops)

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Potential for coronal rain studies

Questions for the experts

- How would ALMA measurements of the chromospheric magnetic field contribute to studies of coronal rain?
- Potentially useful spectral lines / spectral features which should be looked at with ALMA?
- What cadence is desirable?
- Or more important to cycle through different wavelength bands?

Patrick's words…

Field tracing
Alfvénic waves

Wave energy

seismology

field topology

turbulence

Scales
transverse **longitudinal**

0.2" → 60"

clump width | shower width | clump length | shower length

Transversal Field length?

Longitudinal Field length?

magnetic strands?

KHI?

tangential discontinuities?

Pinching?

PCTR

Flare ribbons?

Dynamics
transverse **longitudinal**

transverse oscillations

longitudinal oscillations

drifts?

Low acceleration

flocculent flows

solitons

transverse MHD waves

pressure restructuring?

magnetic pinching (sausage waves)?

slow modes

Mass cycle
chromosphere-corona mass cycle

Occurrence frequency
Loop EUV variability

multi-thermality

redshifts above sunspots

stellar connection

impacts on lower atmosphere

Plasma state
Optical thickness

partial ionisation effects

2-step cooling