Rosseland Centre for Solar Physics

Five years observing the solar chromosphere with ALMA

First results and future opportunities

Sven Wedemeyer

M. Szydlarski, S. Jafarzadeh, V. Henriques,
H. Eklund, J. Guevara Gómez, A. Mohan, S. Pandit, M. Saberi, M. G. Barrios Sazo

Rosseland Centre for Solar Physics, Univ Oslo

ESPM-16, 7 September 2021

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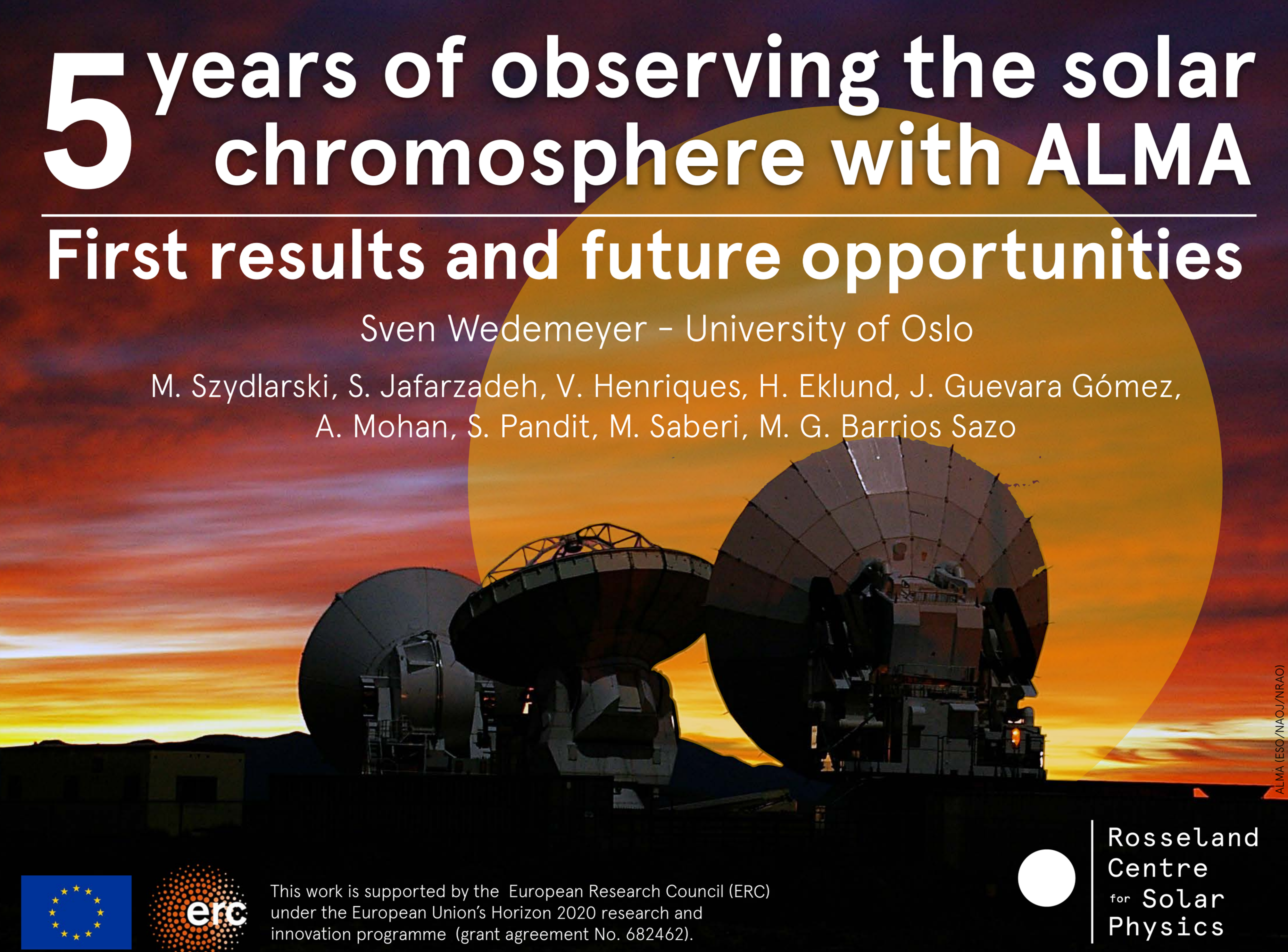

ALMA (ESO/NAOJ/NRAO)

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).

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Observing at millimetre wavelengths

- Millimetre continuum as complementary chromospheric diagnostic
  - Measured brightness temperature closely related to temperature in continuum-forming layer
  - Different wavelengths sample different layers in the chromosphere

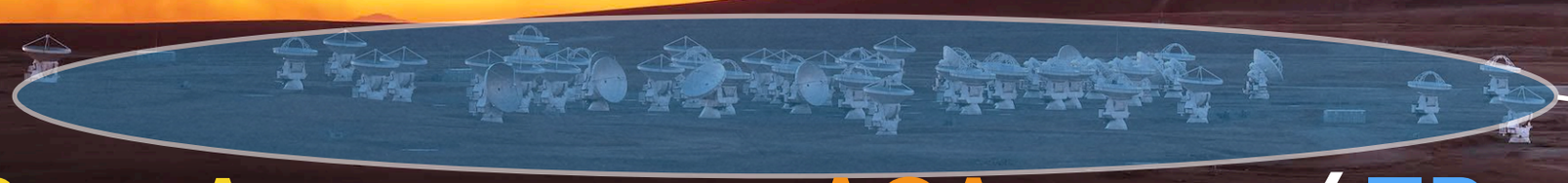
Observing at millimetre wavelengths

- Millimetre continuum as complementary chromospheric diagnostic
  - Measured brightness temperature closely related to temperature in continuum-forming layer
  - Different wavelengths sample different layers in the chromosphere
- BUT: Long wavelengths need large apertures for decent angular resolution
- Solution:
  - ➡ Interferometry and **aperture synthesis**
  - ➡ Sampling a "synthetic aperture" at discrete points
  - ➡ **Antennas together act as a giant telescope.**

synthetic aperture

Atacama Large Millimeter/submillimeter Array

- Up to 66 antennas (most 12m diameter) with distances of up to 780m (for solar observing)
- Signals from all antenna pairs brought together in the correlator
- Regular observations of the Sun since 2016
- Still new and a lot to develop



12-m Array 50 x 12-m + ACA 12 x 7-m / TP 4 x 12-m Correlator

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Current capabilities

INTEFEROMETRIC

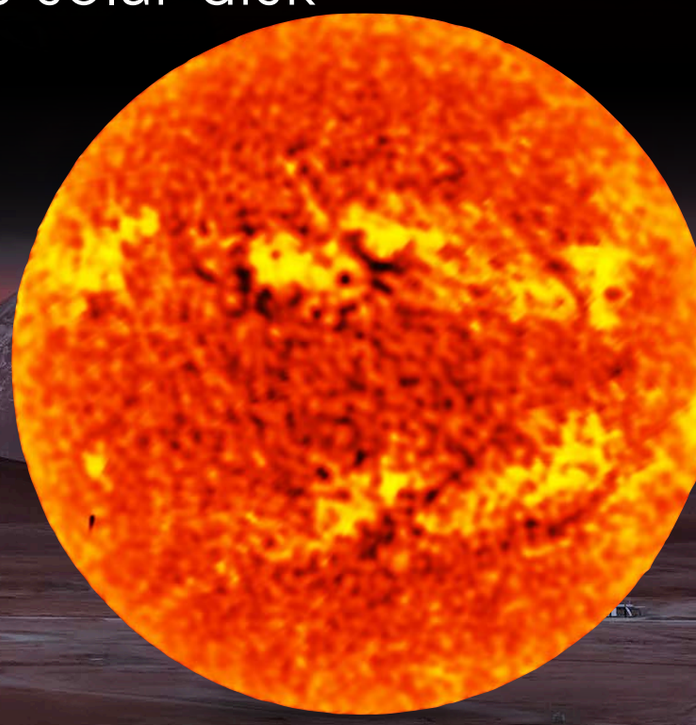
- Wavelengths ~1 – 3mm (Band 3, 5, 6, 7)
- Single pointing time series at **1s cadence**
  - Scan duration max. 10min (3-4 scans, 2-3min breaks)
  - FOV (primary beam): 60″ (Band 3) to 25″ (Band 6)
  - Resolution: 1.4″-2.5″ (Band 3) down to **~0.6″** (Band 6/7)
- Mosaics up to 149 points

Shimojo et al. (2017)

TP

- Simultaneous Total Power (TP) fast scans of whole solar disk
- Temperature offset for interferometric data

White et al. (2017)



Band 3 (ESO)

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Imaging + processing

- ALMA delivers calibrated measurement sets but no science-ready data!

➡ PI needs to do the image reconstruction

➡ Post-processing (imaging) non-trivial

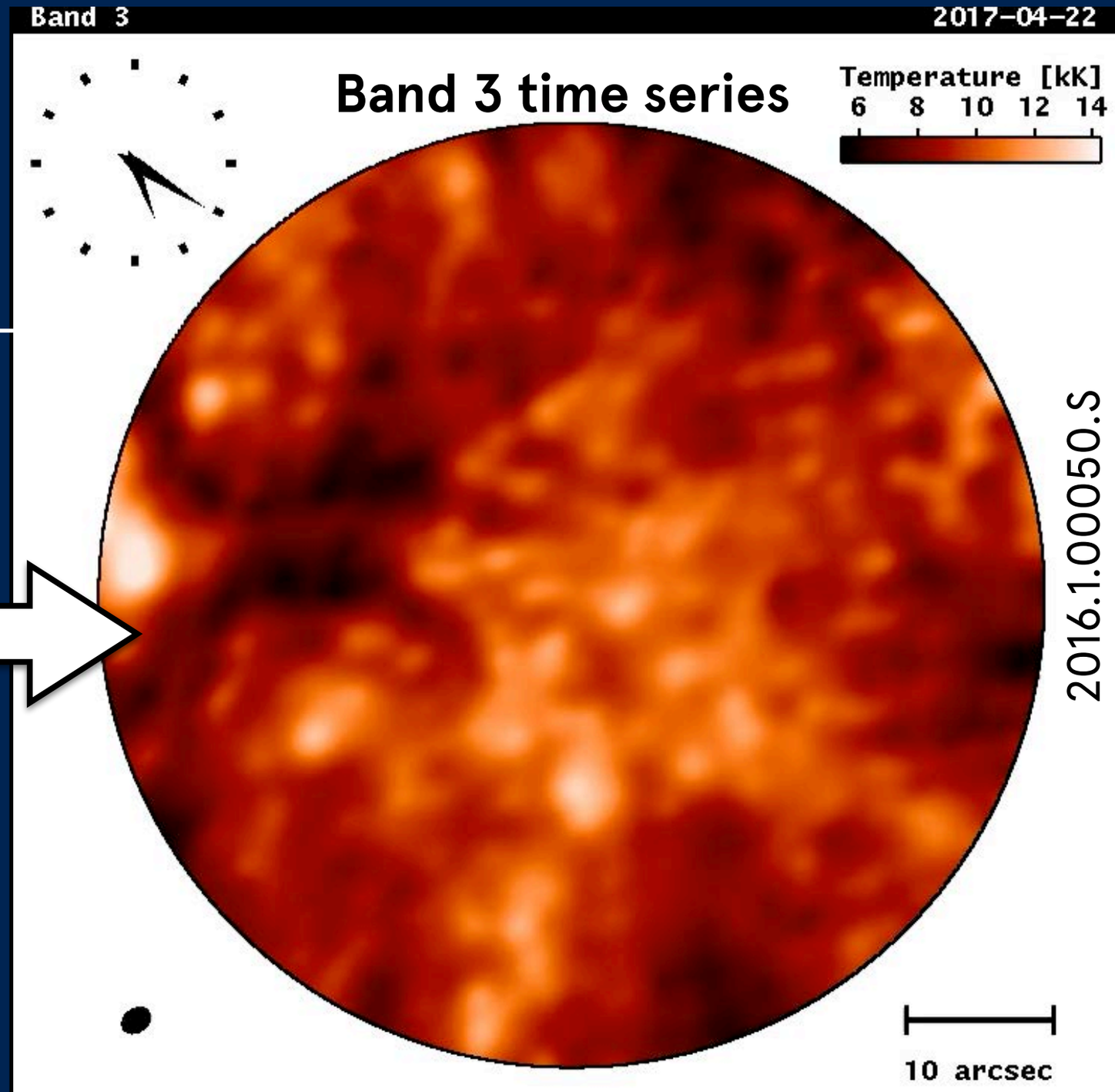
SoAP

Solar ALMA Pipeline

➡ Development of the processing pipeline started in 2016 in Oslo

➡ Since 2019 routinely used

➡ 2021: Built up a data base



12-m + 7-m together (mosaic mode) + TP

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SALSA – Public database

- Major result of 5 years SolarALMA project: Database of **science-ready** ALMA time series
- Webpage provides
  - Data FITS files
  - Links to co-observations

http://sdc.uio.no/salsa/

See also: Henriques et al. 2021arXiv210902374H

UiO

Solar ALMA Science Archive (SALSA)

NOTE

The Solar ALMA Library of Auxiliary Tools (SALAT) enables easy loading and initial visualisation/exploration of **SALSA** data products in both IDL and Python. **Click here** for more information, downloads and documentation.

REFERENCE

Detailed information about the SALSA datacubes (i.e., their structures, extensions, headers, and their brief overviews and references), as well as an introduction to SALAT, are described in **this preprint** (to be soon published).

Show 10 entries

Search ....

Data	Date	Project ID	Band / λ	Cad.	Obs. Time (UTC)	(x,y)	μ	T_{mean} (K)	bmin / bmaj	Time Series	Datacube	Co-Obs	Thumbnail	SD Thumbnail
D01	2016-12-22	2016.1.00423.S	3 / 3 mm	2 sec	14:19:31-15:07:07	0,0	0.99	7387 ± 519	1.37 / 2.10	▷ MOVIE	⭳ DOWNLOAD	SDO		
D02	2017-04-22	2016.1.00050.S	3 / 3 mm	2 sec	17:20:13-17:42:37	-249,267	0.92	9317 ± 1229	1.69 / 2.21	▷ MOVIE	⭳ DOWNLOAD	SDO IRIS		
D03	2017-04-23	2016.1.01129.S	3 / 3 mm	2 sec	17:19:19-18:52:54	-54,251	0.96	7161 ± 1817	1.92 / 2.30	▷ MOVIE	⭳ DOWNLOAD	SDO IRIS		
D04	2017-04-27	2016.1.01532.S	3 / 3 mm	2 sec	14:19:52-15:31:17	520,272	0.78	7974 ± 1145	1.74 / 2.23	▷ MOVIE	⭳ DOWNLOAD	SDO IRIS		
D05	2017-04-27	2016.1.00202.S	3 / 3 mm	2 sec	16:00:30-16:43:56	172,-207	0.96	7287 ± 1297	1.77 / 1.88	▷ MOVIE	⭳ DOWNLOAD	SDO IRIS		
D06	2018-04-12	2017.1.00653.S	3 / 3 mm	1 sec	15:52:28-16:24:41	-128,400	0.90	7586 ± 661	1.77 / 2.55	▷ MOVIE	⭳ DOWNLOAD	SDO IRIS		
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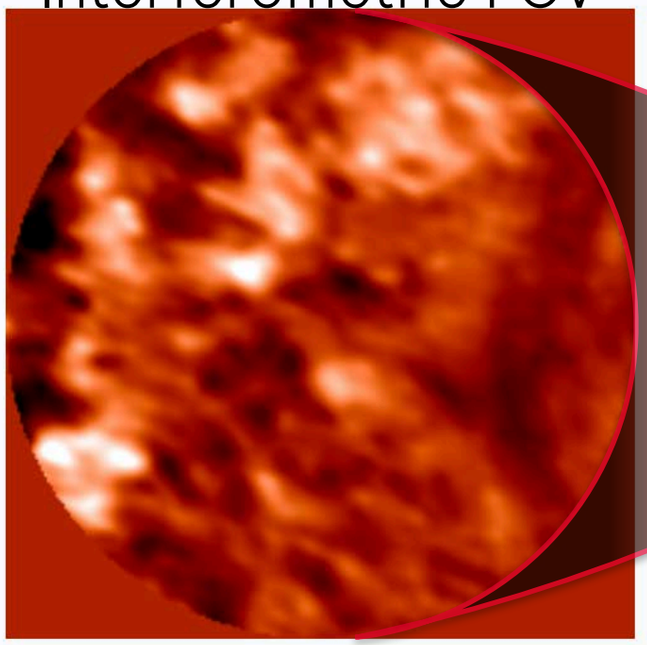
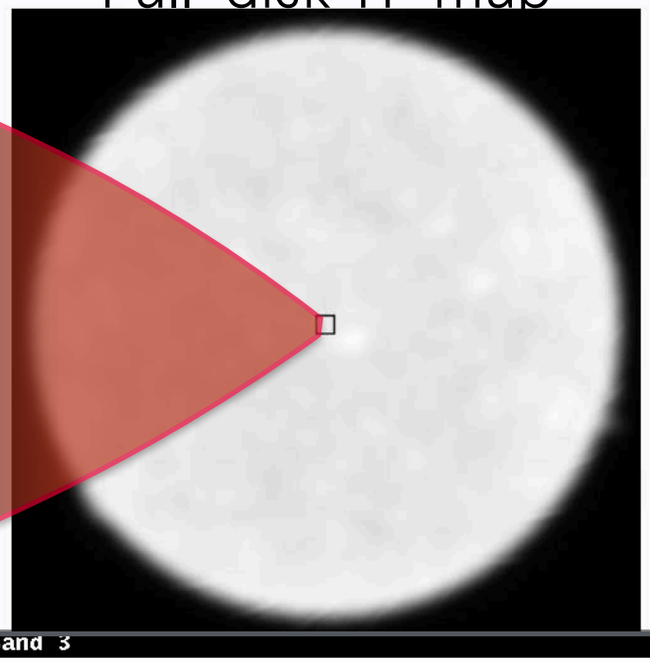
SALSA – Public database

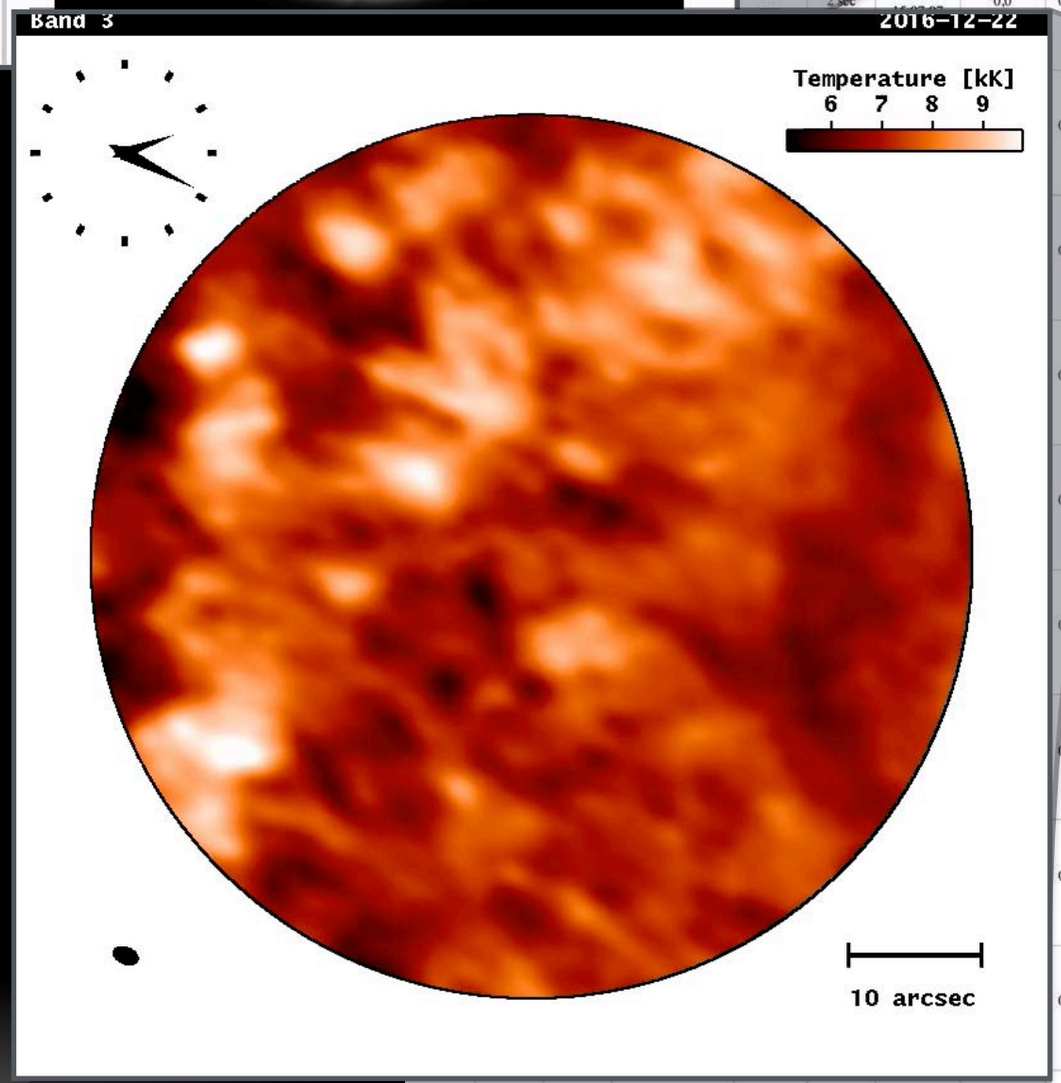
Interferometric FOV



Full-disk TP map



- First release with 26 data sets
- Preview movie
- Context full-disk map



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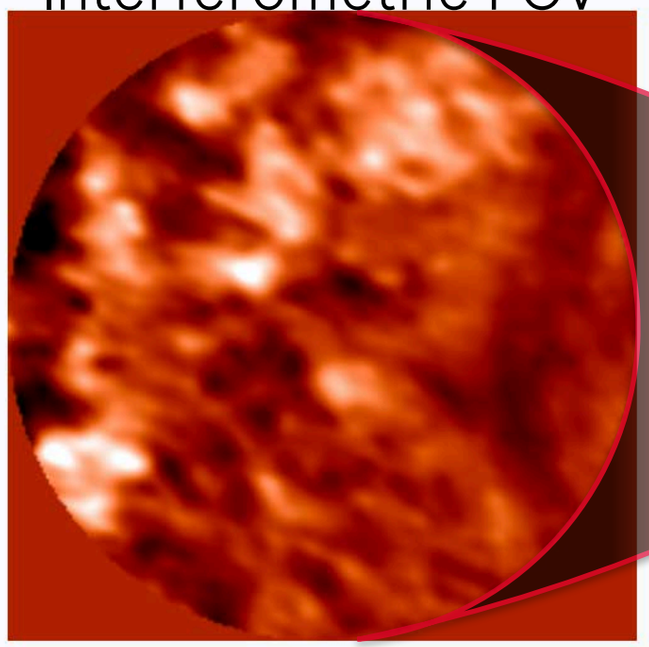

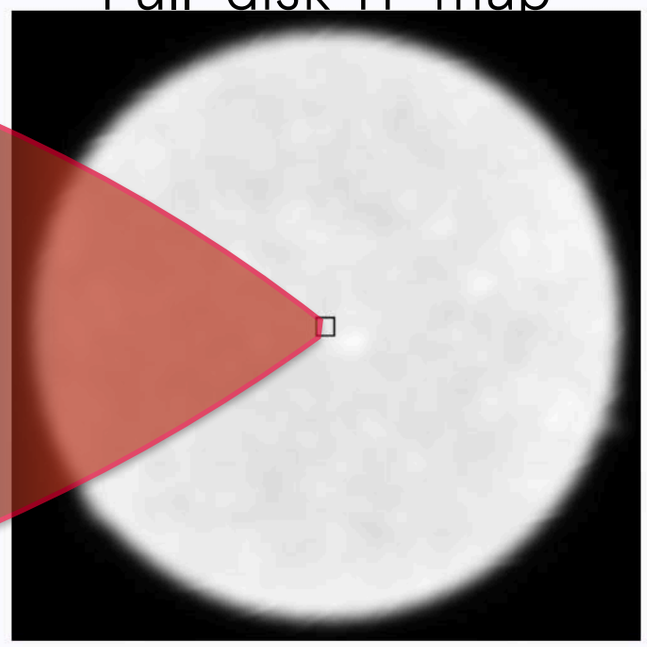

- SALAT (Solar ALMA Library of Auxiliary Tools)
- Easy loading of SALSA data
- Overview and quick view

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First results

The number of published ALMA results is finally growing more rapidly.

See the appendix of this presentation for examples.

- **Structure and dynamics of the chromosphere as observed with ALMA**
  - Alissandrakis et al. (2017), Bastian et al. (2017), Shimojo et al. (2017b), Brajša et al. (2018), Nindos et al. (2018), Yokoyama et al. (2018), Jafarzadeh et al. (2019), Loukitcheva et al. (2019), Molnar et al. (2019), Rodger et al. (2019), Selhorst et al. (2019), Martínez-Sykora et al. (2020), Patsourakos et al. (2020), da Silva Santos et al. (2020), Nindos et al. (2020), Wedemeyer et al (2020), Chintzoglou et al. (2021)...
- **Understanding ALMA's diagnostic potential**
  - da Silva Santos et al (2020): Potential of ALMA as additional input for improved NLTE inversions of the solar chromosphere (especially IRIS+ALMA)
  - Molnar et al. (2019): relation Hα – ALMA T_b
- Studies of **propagating waves and oscillations**:
  - Nindos et al. (2020), Patsourakos et al. (2020), Guevara Gómez et al. (2020), Eklund et al. (2020), Jafarzadeh et al. (2020), Molnar et al. (2021), Nindos et al. (2021) ...

Future opportunities

ALMA (ESO/NAOJ/NRAO)

Capabilities will be gradually expanded

- More receiver bands
  - Additional wavelengths ranges and thus mapped height ranges

- Polarimetry (full Stokes – LOS magnetic field measurements, testing in progress, to be developed during the next few years)

- Regional mapping (larger FOV)

- Larger array configurations (higher angular resolution, new ESO development study to start soon, lead: M. Barta)

- Simultaneous sub-arrays (later – tbd)
  (several bands at same time, large coverage of atmospheric heights)

Future development

ALMA (ESO/NAOJ/NRAO)

Second International Workshop
on Solar Imaging with ALMA

ALMA-SOL-IMG2

Time: Nov. 3, 2021–Nov. 5, 2021

Registration deadline October 15

Primarily for whoever wants to get involved in ALMA data processing

https://www.mn.uio.no/rocs/english/news-and-events/events/2021/alma-sol-img2-2021.html

ALMA Data Analysis Workshop
Maybe to be organised in 2022
TBD

SALSA!

http://sdc.uio.no/salsa/

See also: Henriques et al.
2021arXiv210902374H

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).

Bonus material

First results

- The following pages contain examples of studies that focus on the small-scale structure and dynamics of the solar chromosphere as seen with ALMA.

➡ Such studies can be carried out with SALSA data!

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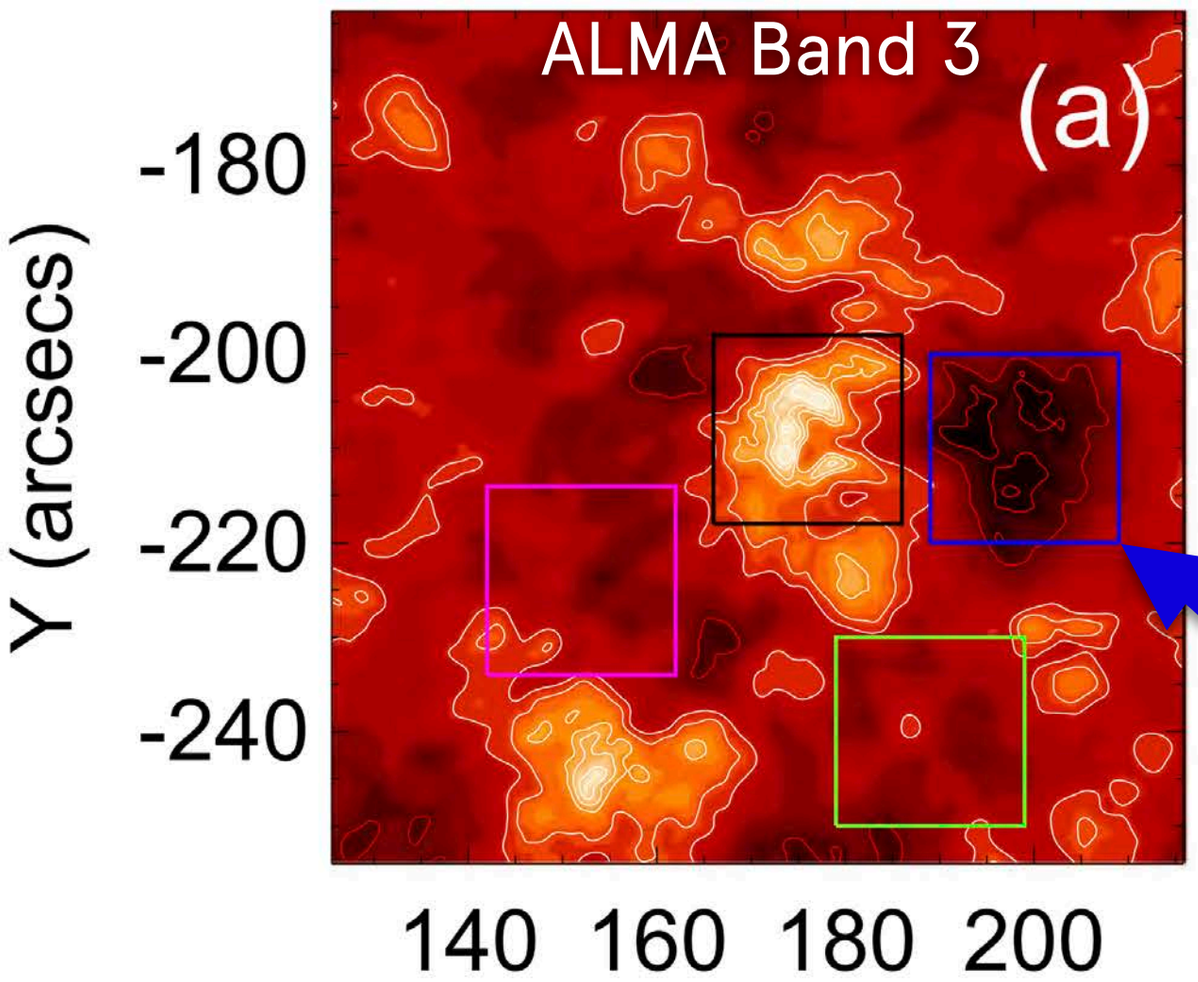
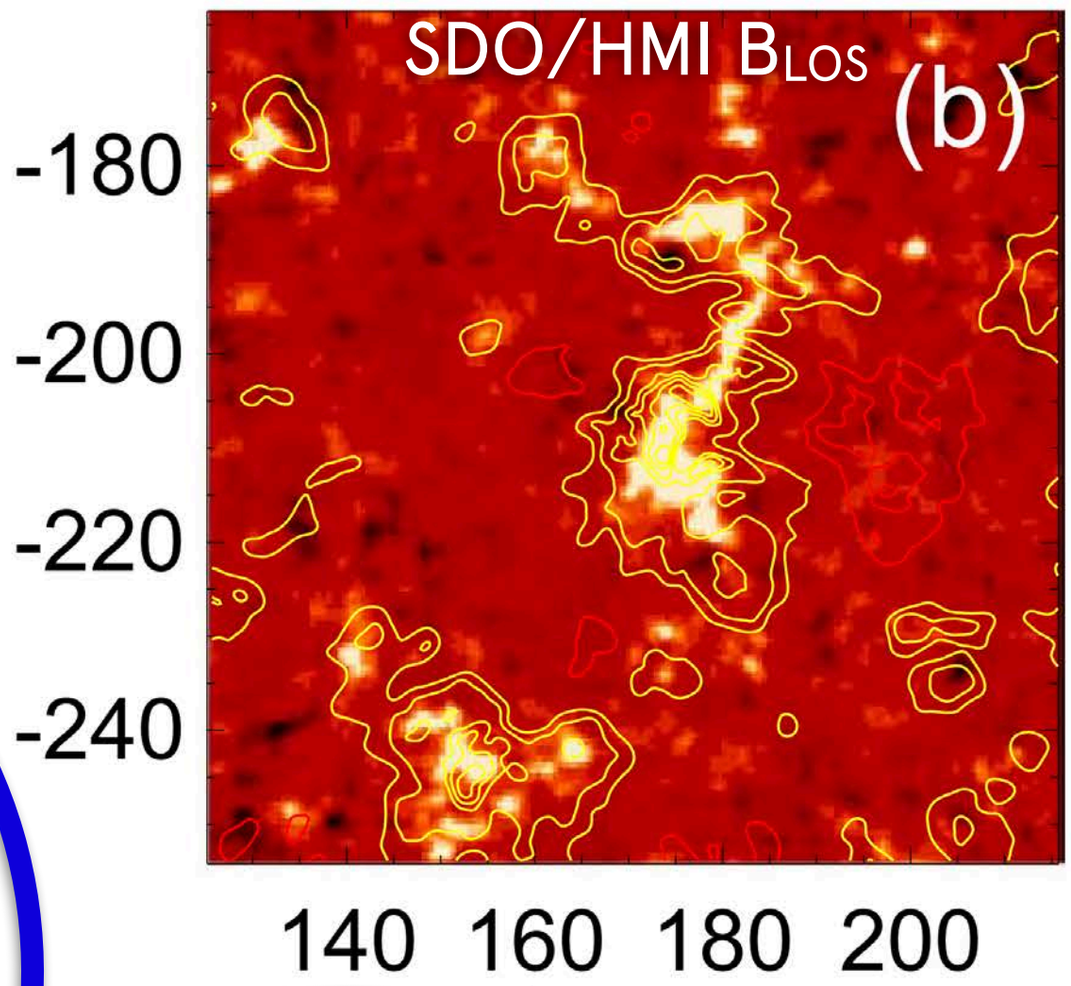
First results



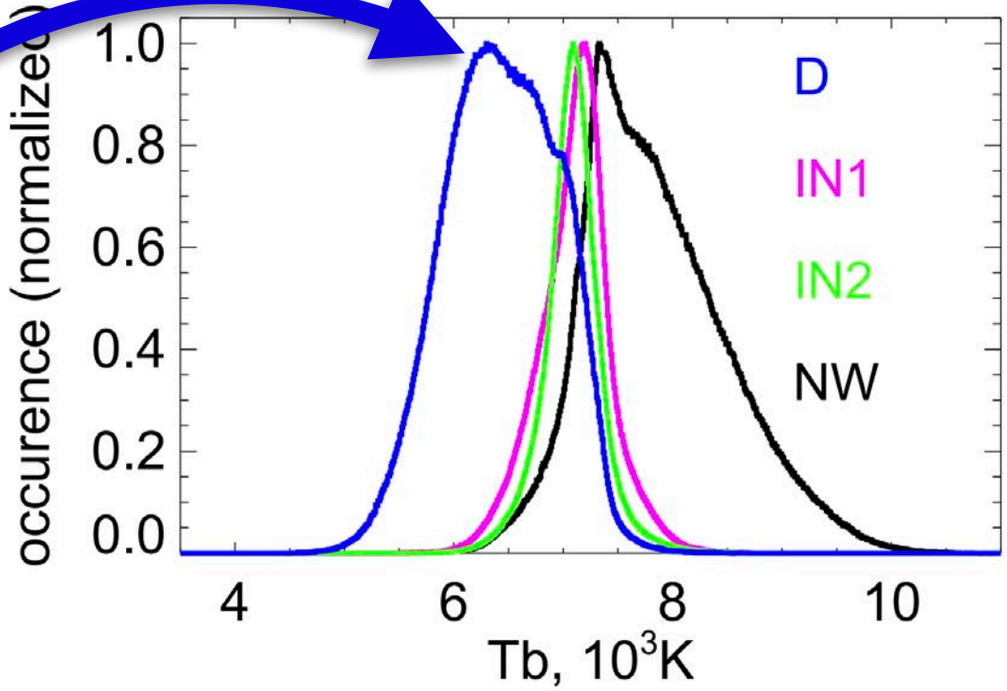


2016.1.00202.S. ALMA

"Chromospheric ALMA Holes (ChAH)"

- Loukitcheva et al (2019), Band 3, 4/2017
- Cool region 15-20" wide w. T_b < 6500K
- Min. T_b =4370 K

➡ ~3000K lower than avg. QS value



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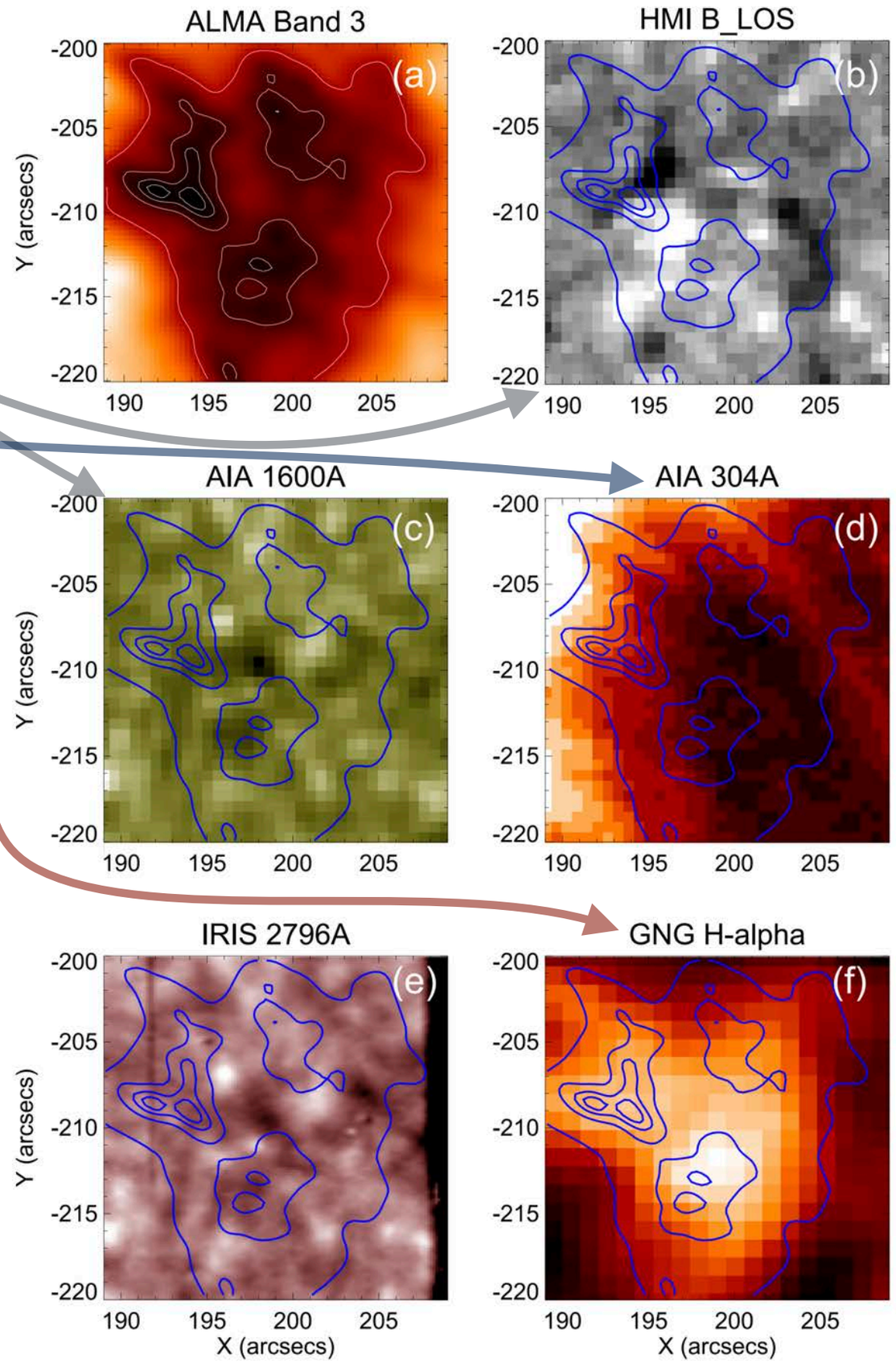
First results

"Chromospheric ALMA Holes (ChAH)"
(Loukitcheva et al 2019)

- Nothing "special" in lower atmosphere, (very) Quiet Sun
- **Dark in SDO/AIA 304**
- **Bright in Hα**

Conclusions

- Physical explanation for cool region in upper chromosphere not yet given
- Hα and ALMA Band 3 probe different layers of the chromosphere.
- Understanding formation heights is essential.



2016.1.00202.S. ALMA

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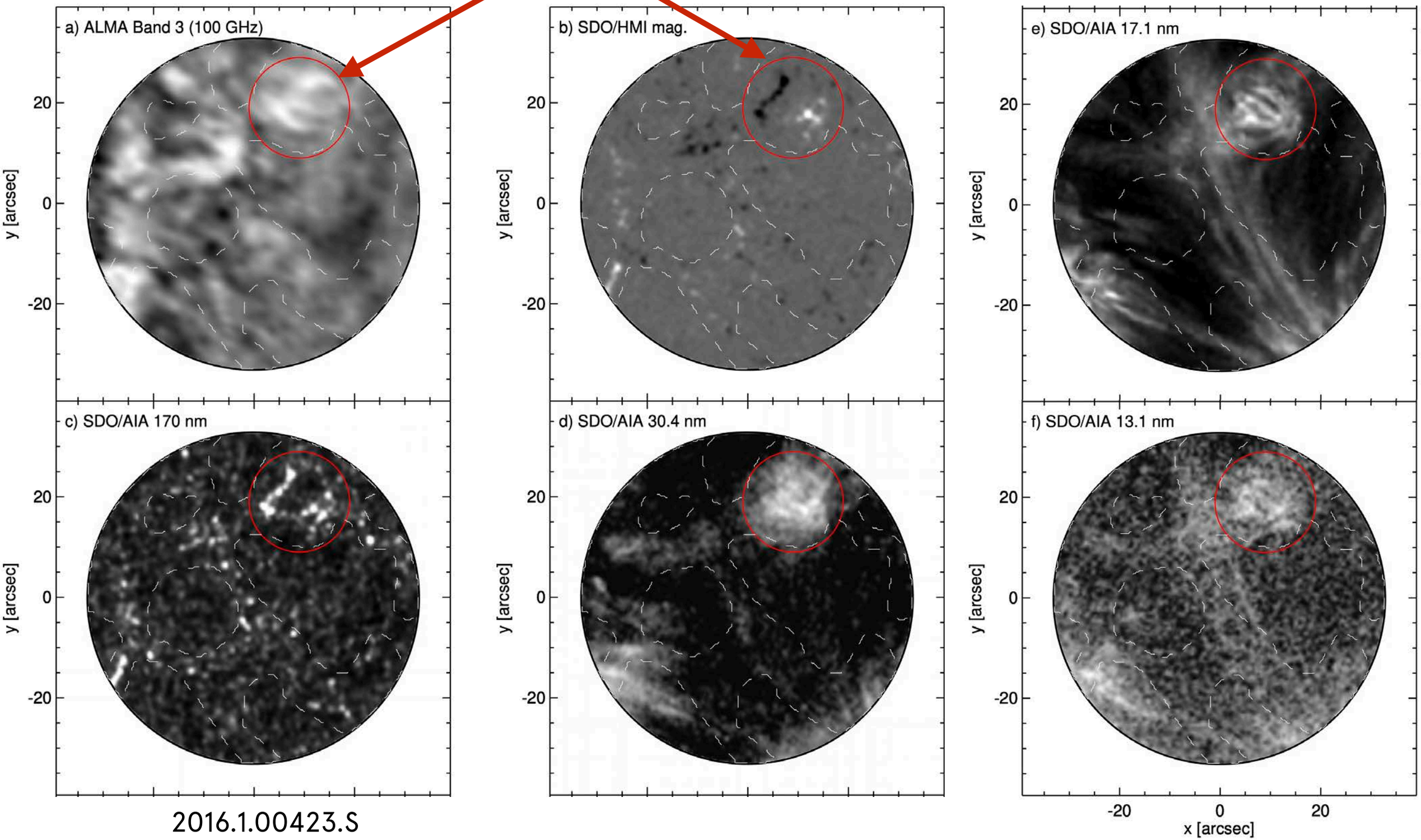
First results

Quiet Sun – Region with "compact" magnetic loops *(Wedemeyer et al 2020)*



2016.1.00423.S

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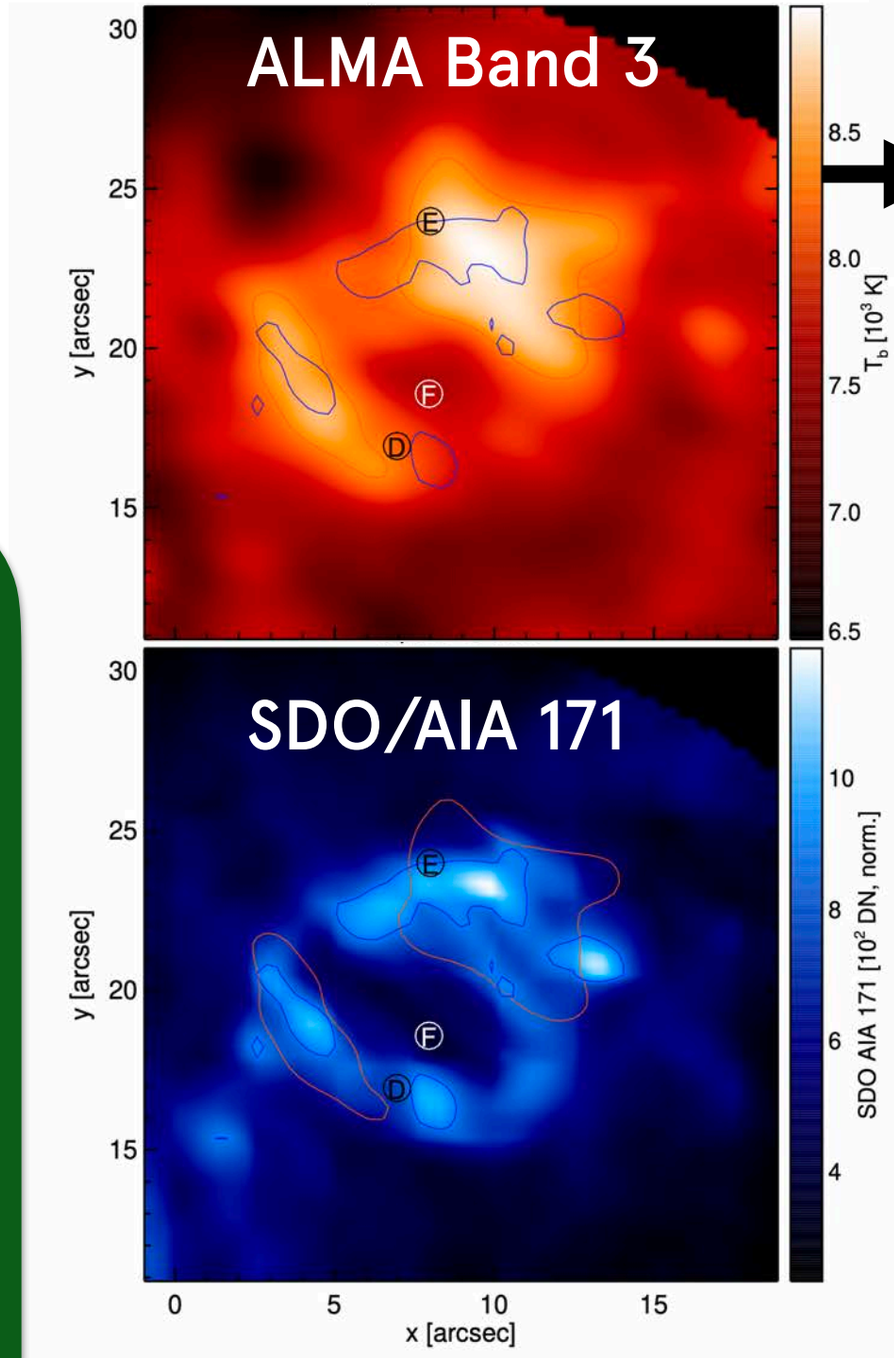
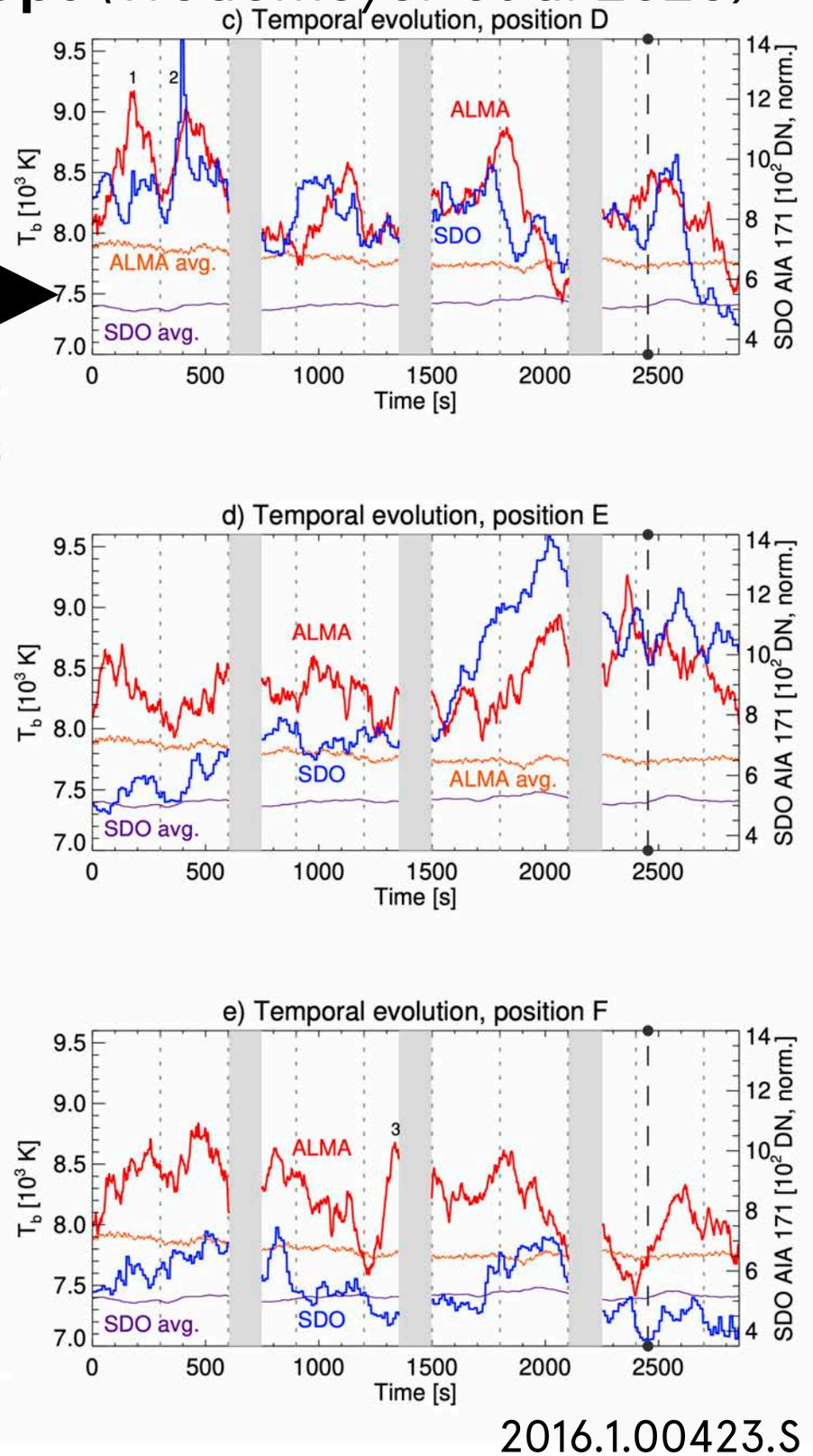
First results

Quiet Sun – Region with "compact" magnetic loops *(Wedemeyer et al 2020)*

- ALMA provides (brightness) temperatures in the hot loop tops and their variation with time





Conclusions

- ALMA has large potential as a novel complementary tool for studying the structure and dynamics of the solar chromosphere

2016.1.00423.S

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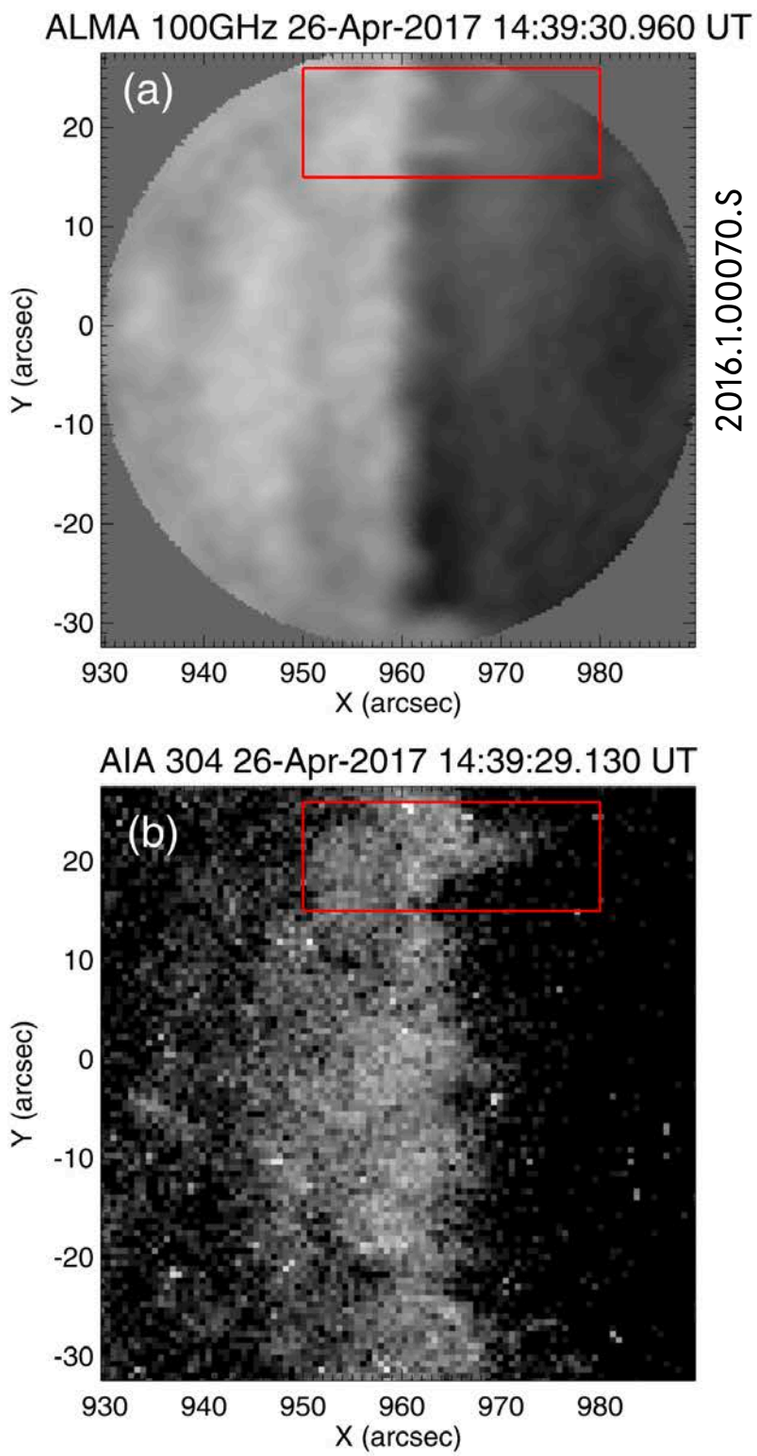
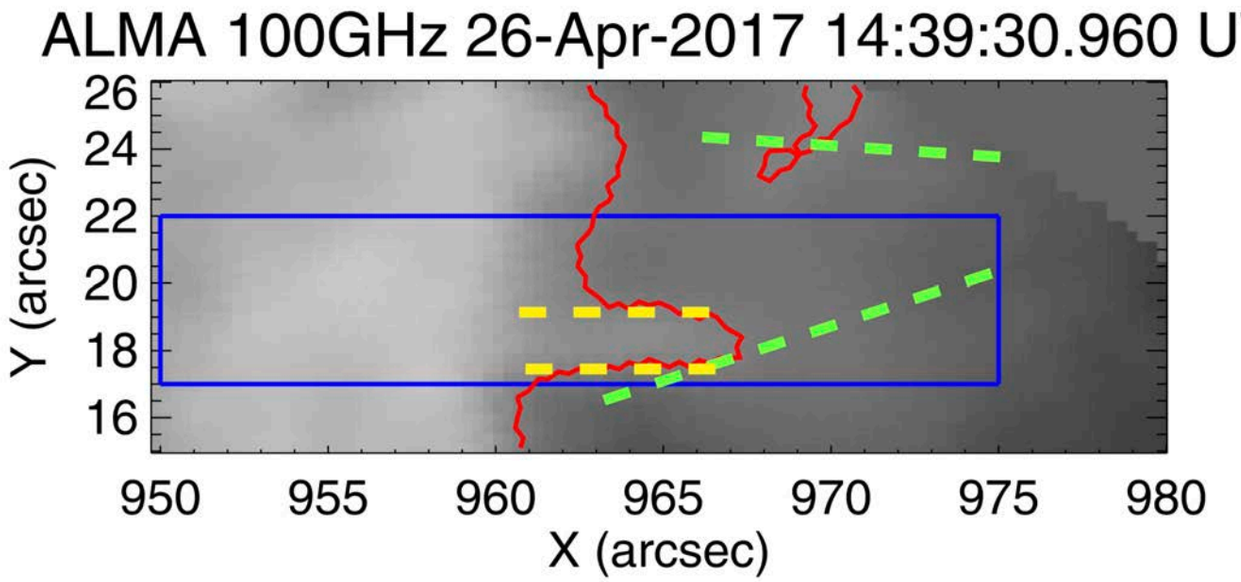
First results

(Macro)Spicule (Shimojo et al. 2019)

- Band 3, limb observation
- Detection of a (macro)spicule
- Estimates of physical properties:
  - (Kinetic) temperature ~6800 K
  - Number density of ionized hydrogen: 2.2×10^{10} cm^{-3}
- Example of IRIS-ALMA(-SDO) co-observation





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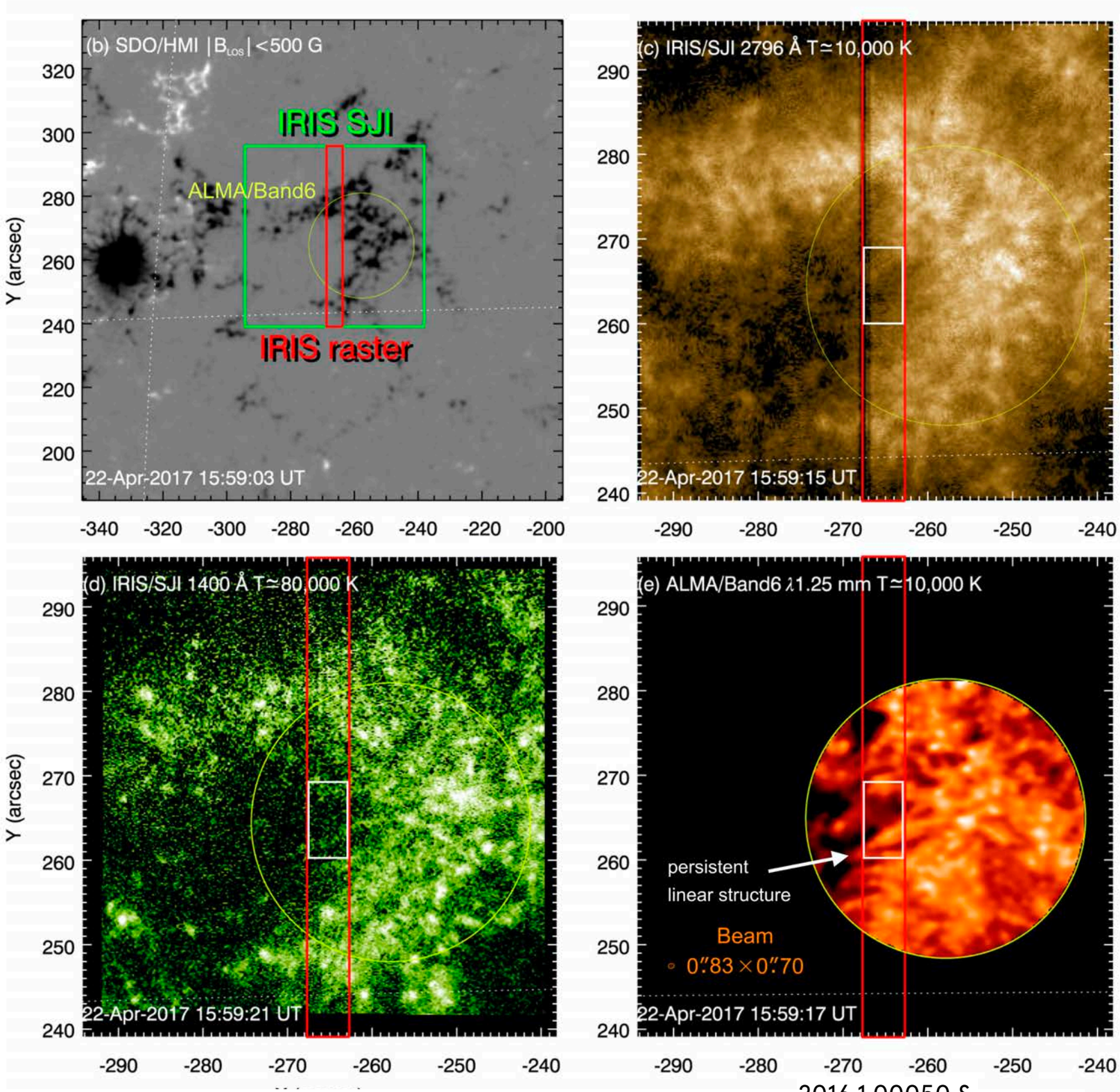
First results

On-Disk Type II Spicule (Chintzoglou et al. 2021)

- Band 6, chromospheric plage region
- Detection of a dynamic linear structure captured in IRIS and ALMA/Band6

➡ On-disk spicule (type II)

- First analysis of its multi-thermal nature and temporal evolution
- Example of possible IRIS-ALMA(-SDO) co-observation



2016.1.00050.S

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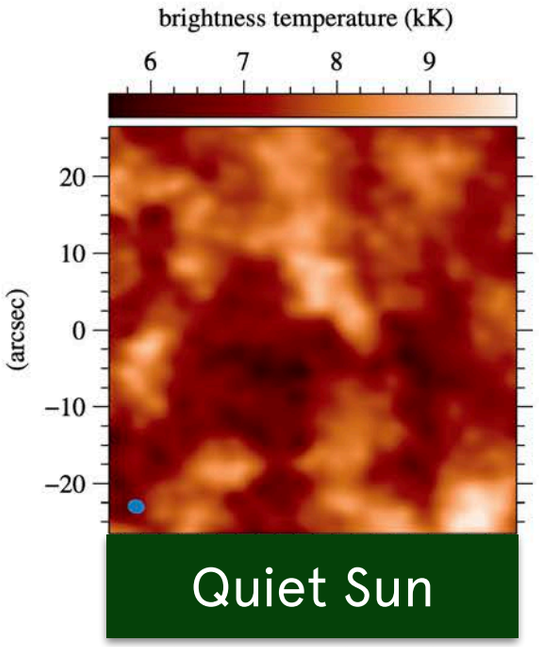
First results

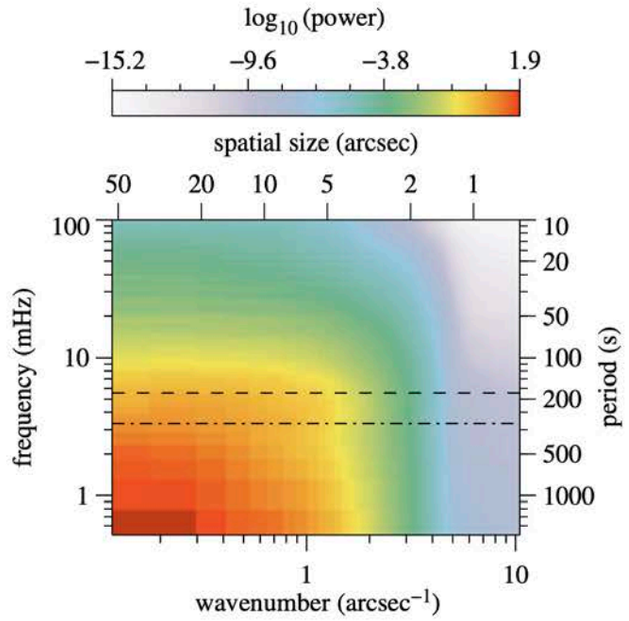
An overall view of temperature oscillations in the solar chromosphere with ALMA (Jafarzadeh et al 2020)

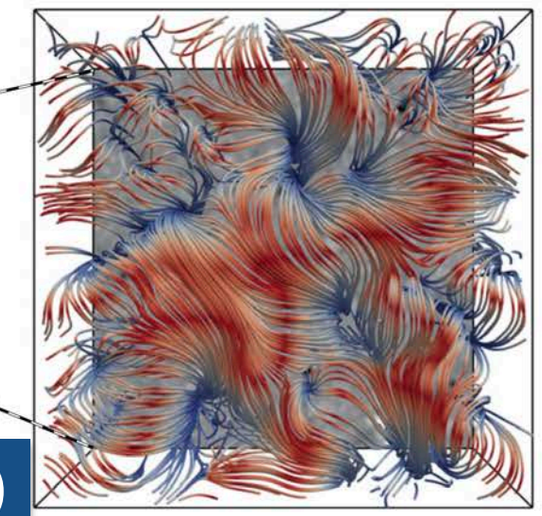
- 10 datasets of regions with different levels of magnetic flux
- Fourier and Lomb–Scargle transforms
- Spatial structuring of dominant frequencies and average global frequency distributions of oscillations

➡ Observed frequencies significantly vary from one dataset to another,

➡ **Enhanced power in 3–5mHz range for most magnetically quiescent datasets**







Band 3 (D6, 2017.1.00653.S)

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First results

An overall view of temperature oscillations in the solar chromosphere with ALMA (Jafarzadeh et al 2020)

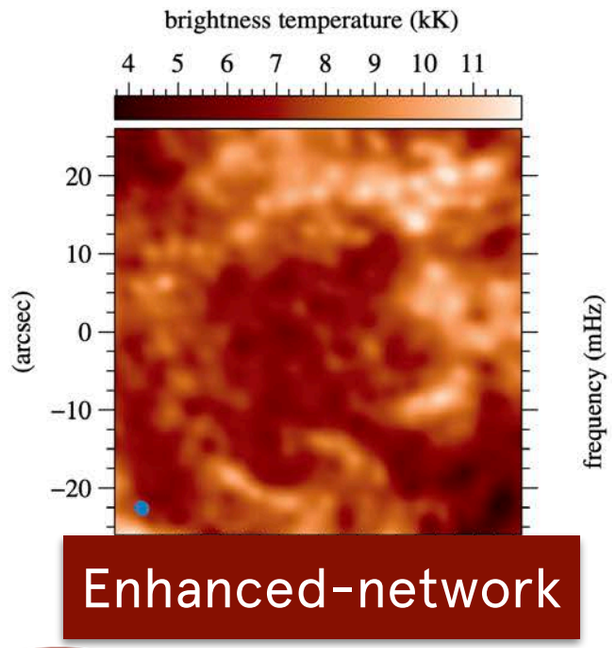
- Lower frequencies dominate in regions with strong underlying magnetic field concentrations

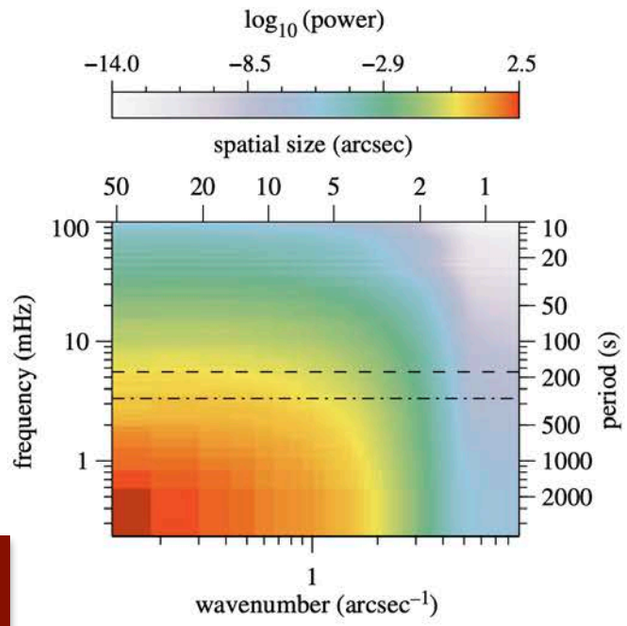
➡ **Power suppression at ~ 5.5 mHz**

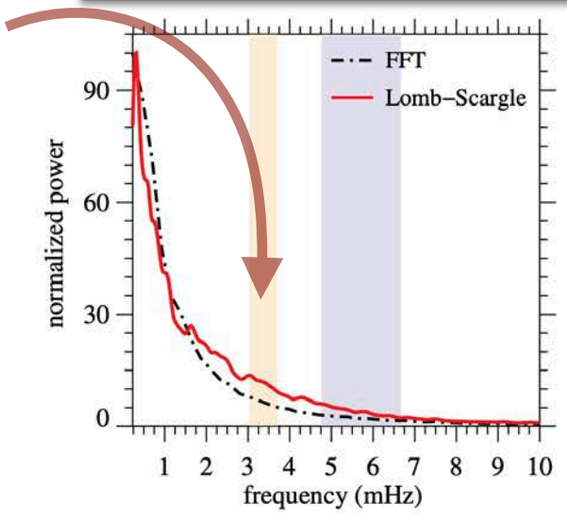
➡ **In contrast to other chromospheric diagnostics**
(except forHα line-core)

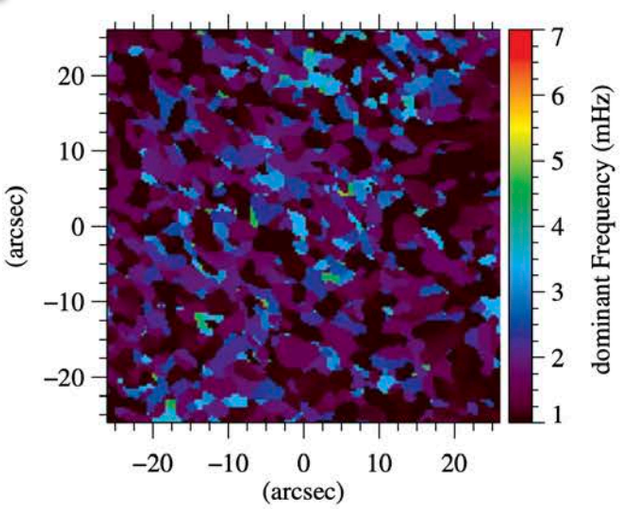
Conclusions

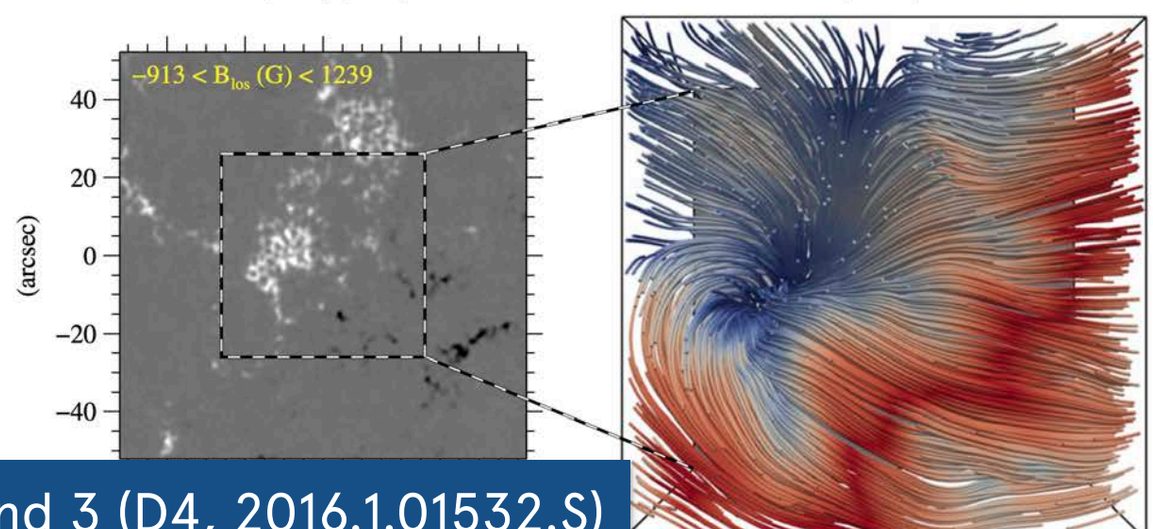
- Large potential for studying oscillations due to high cadence
- Formation heights / contributions from different (chromospheric) layers must be understood











Band 3 (D4, 2016.1.01532.S)

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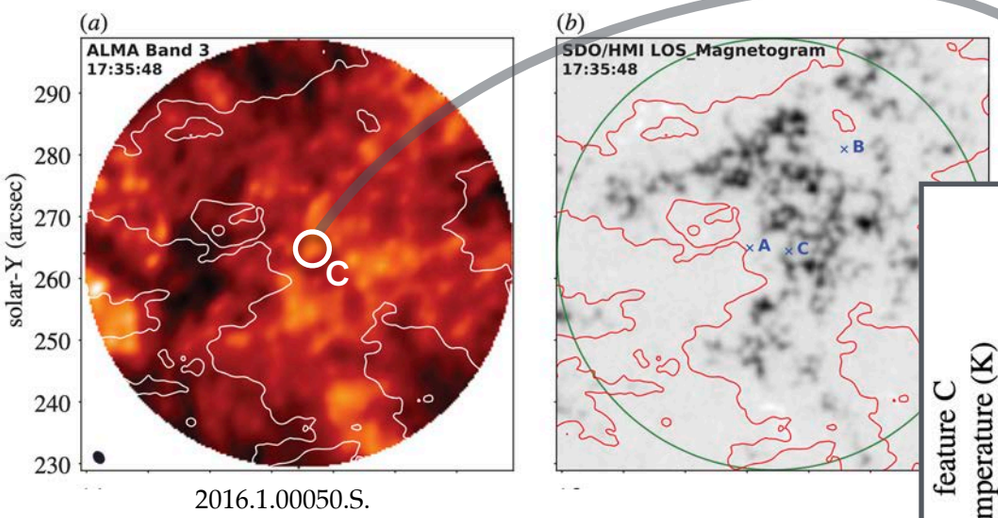
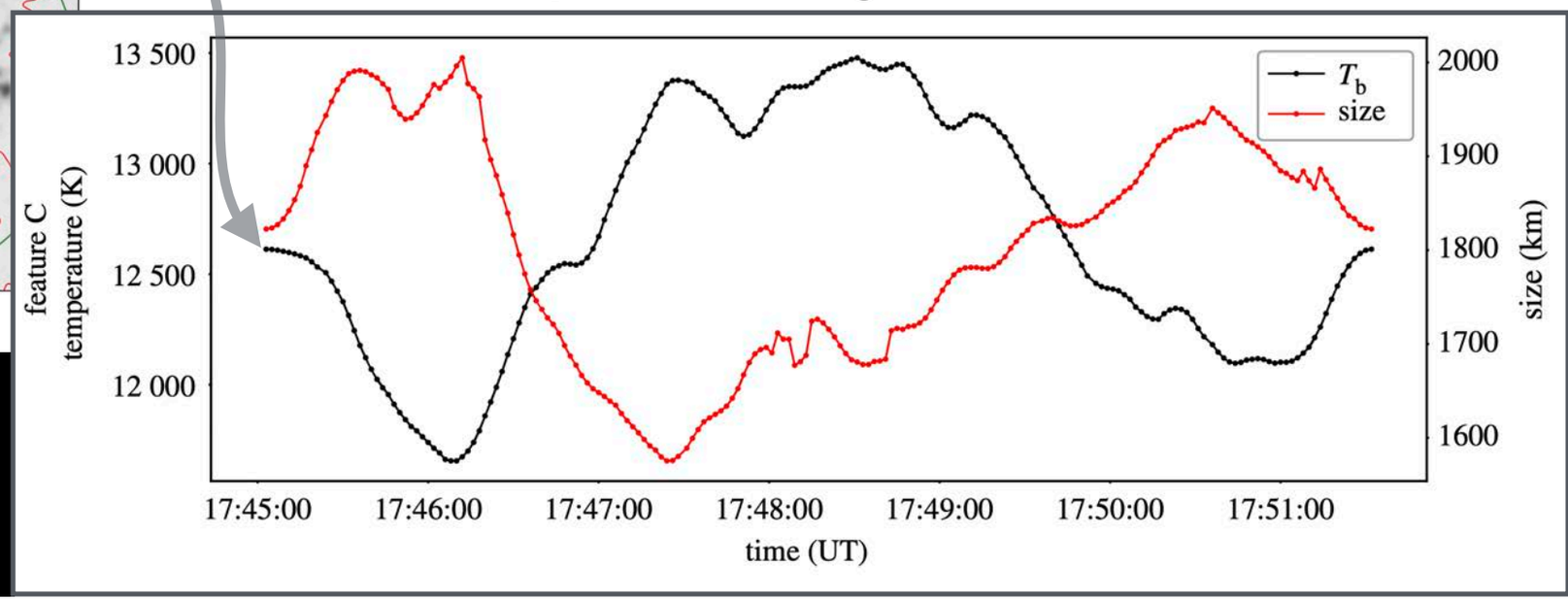
First results



Guevara Gómez et al. (2020)

High-frequency oscillations in small chromospheric bright features



- ALMA Band 3: three small bright features in the chromosphere of a plage/ enhanced-network region
- **Oscillations** in brightness temperature, size and horizontal velocity
  - Periods in the range ~60s - 120s
  - Anti-correlations between brightness, temperature and size

  ➡ Fast sausage-mode waves
- Additional transverse oscillations may indicate kink waves.

Conclusion: Large potential for studying oscillations due to high cadence

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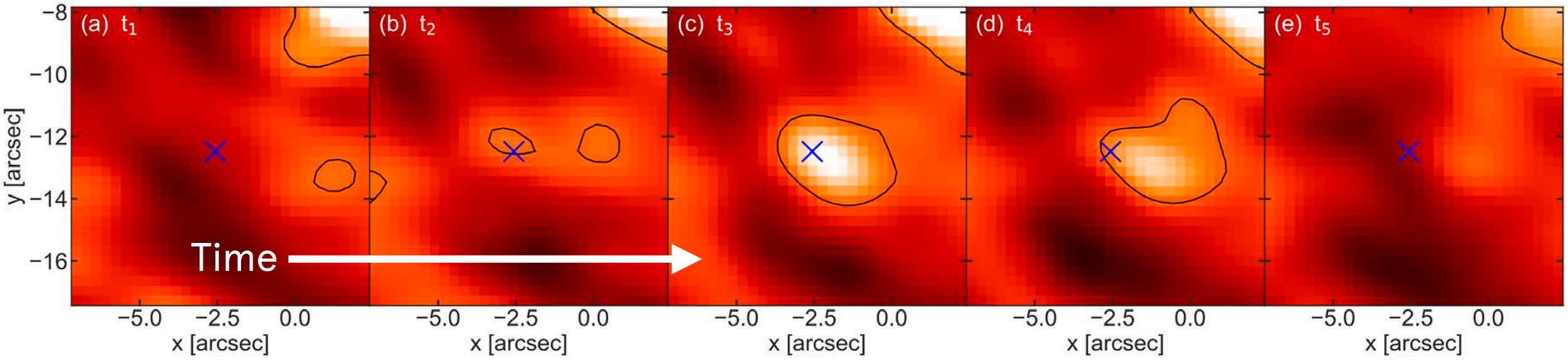
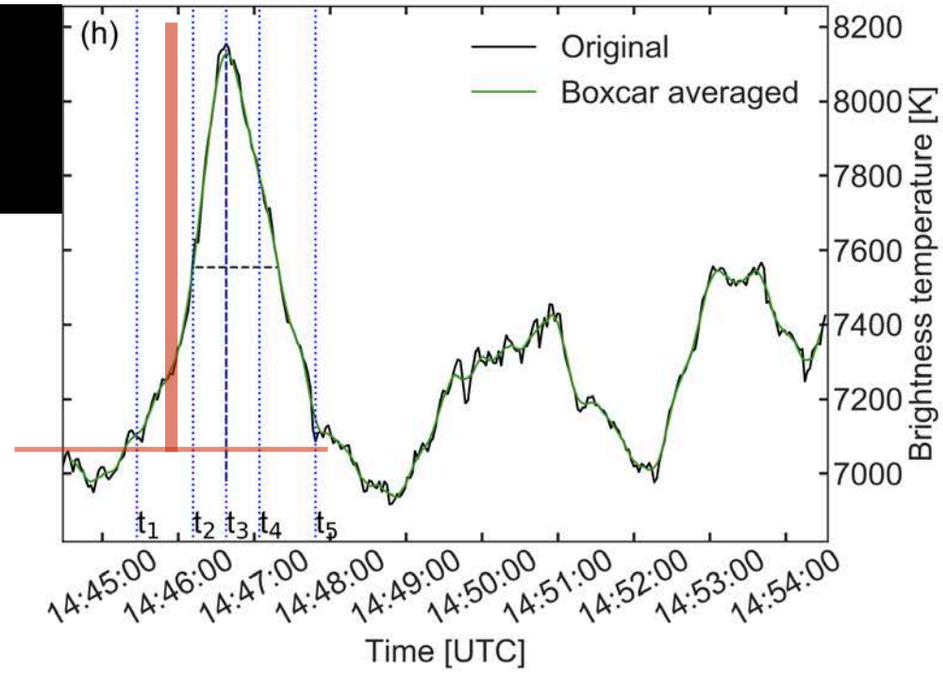
First results



Small-scale dynamic events in ALMA **Band 3** (Eklund et al. 2020)

- 552 events with ΔT_b excess ≥400 K (wrt to local base temperature)
- Amplitude ΔT_b up to ~1200K (typically ~450–750K)
- Lifetimes typically ~55 and 125 s.



Conclusions

- Most likely signatures of **propagating shock waves**
- In line with predictions from simulations when taking into account instrumental effects (**angular resolution**! Eklund et al., submitted)