Spatial structure of resonance cavities in sunspots

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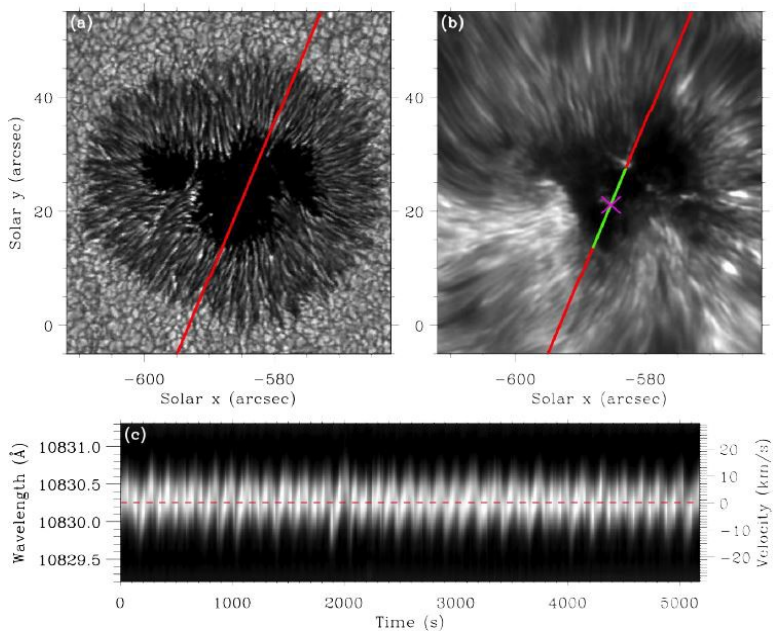
Content of the work

- **Purpose:** Study oscillations in the sunspots with establish 3D structure of waveguides and resonant cavities previously found in **Jess et al., 2020** from spectropolarimetric observations. In these regions an amplification of oscillations with formation a fine structure of harmonics in sunspot spectra is assumed.

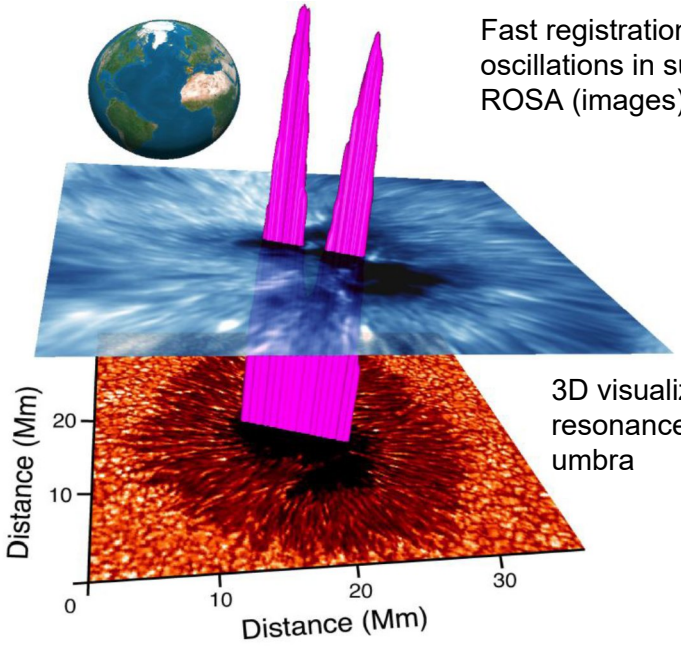
- **Data observations:** Investigation of wave processes in the sunspot active regions NOAA 11131 (10 December 2010) and NOAA 12565 (14 July 2016) observed by the SDO/AIA spacecraft at set of UV spectral lines 1600A, 304A and 171A

- **Methods:** We applied spectral data processing using Pixel Wavelet Filtering (PWF analysis) and Pixelized Mode Decomposition (PMD analysis) digital techniques for 2D and 3D preparation and visualisation of oscillation sources.

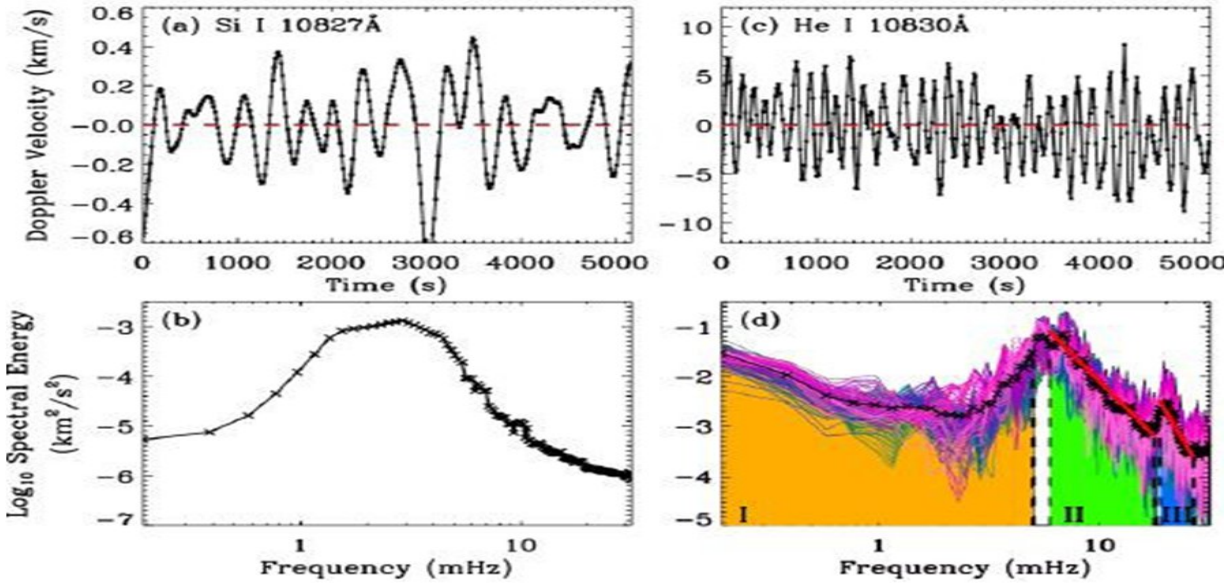
1D spectroscopic observations of resonance cavities



Fast registrations of Doppler velocity oscillations in sunspot 14.07.2016 ROSA (images) and IBIS (spectra)



3D visualization of geometry of resonance cavities above sunspot umbra



❑ Spectropolarimetric observations with the Dunne Solar Telescope show a **temperature stratification** with **increasing Doppler velocity** oscillations at high frequency (> 5.2 mHz) and **their penetration into the upper layers** of sunspot atmosphere.

❑ The **theory predicts** the existence of selected **acoustic resonators** created by large **temperature gradients** in sunspot atmosphere.

❑ Using total **FFT spectra** of each point on the umbra spectral slit, **three regions increasing** of umbra oscillations are found as **resonance cavities**: low-frequency regions below **5 mHz**, **6-17 mHz** with a peak at 3 minutes, and high-frequency with **18-27 mHz**.

Jess D. et al., Nature Astronomy, 2020

Possible evidence of the presence resonant cavities

High-frequency periodicity

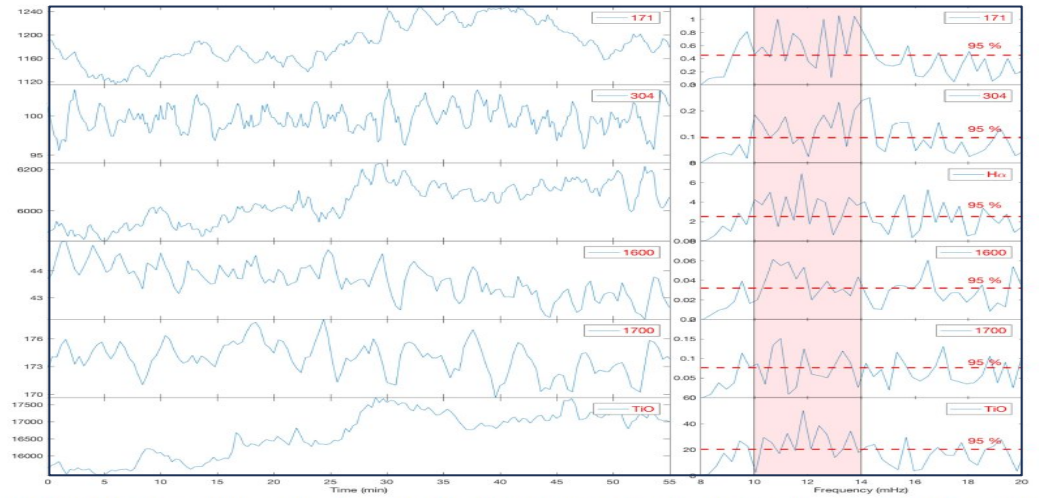
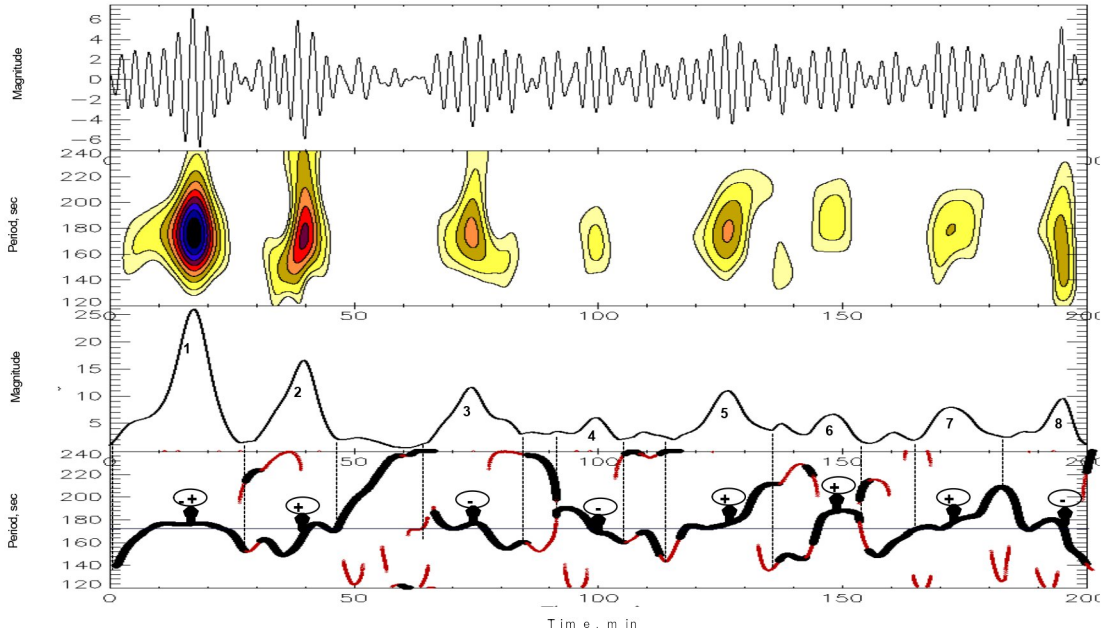


Figure 3. Left column: intensity curves averaged over the entire umbra region in different channels. Right column: the corresponding Fourier spectra of the de-trended curves. Red dashed curves denote the 95% confidence levels. The shaded regions denotes the frequency range of interest in this work.

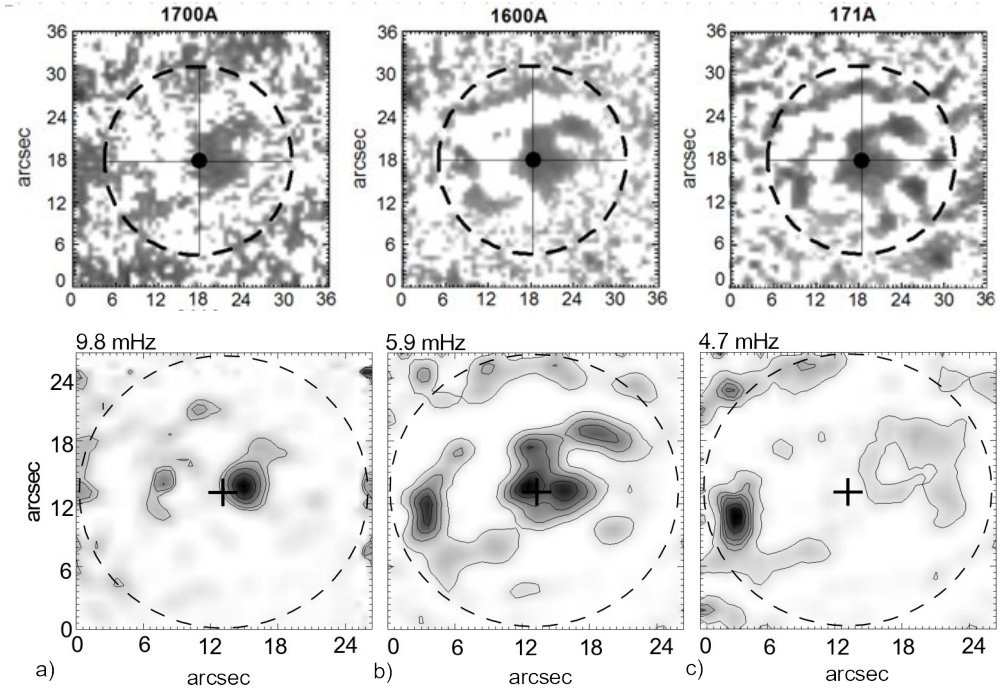
Feng Wang et al., The ApJL, 856:L16 , 2018

Frequency drifts of 3-min oscillations

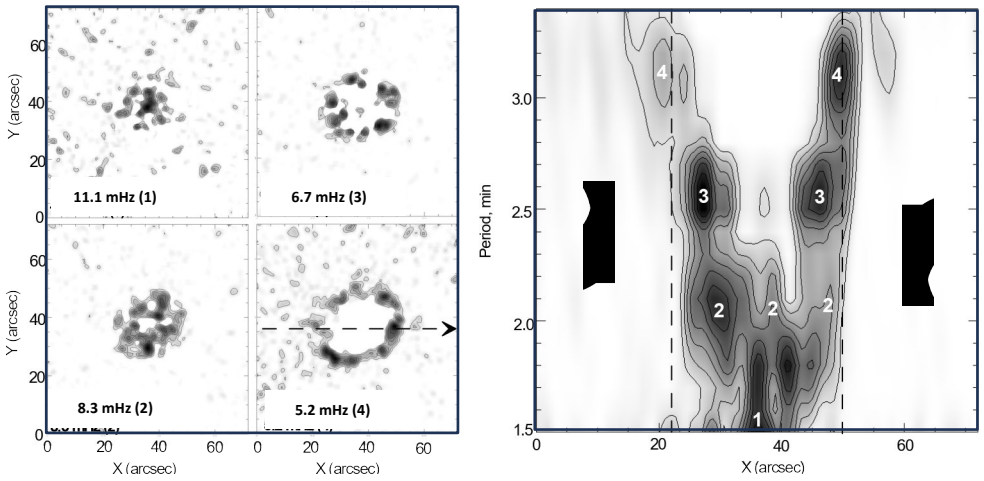


Sych R. et al., A&A, 539, A23, 2012

Spirality of wave fronts

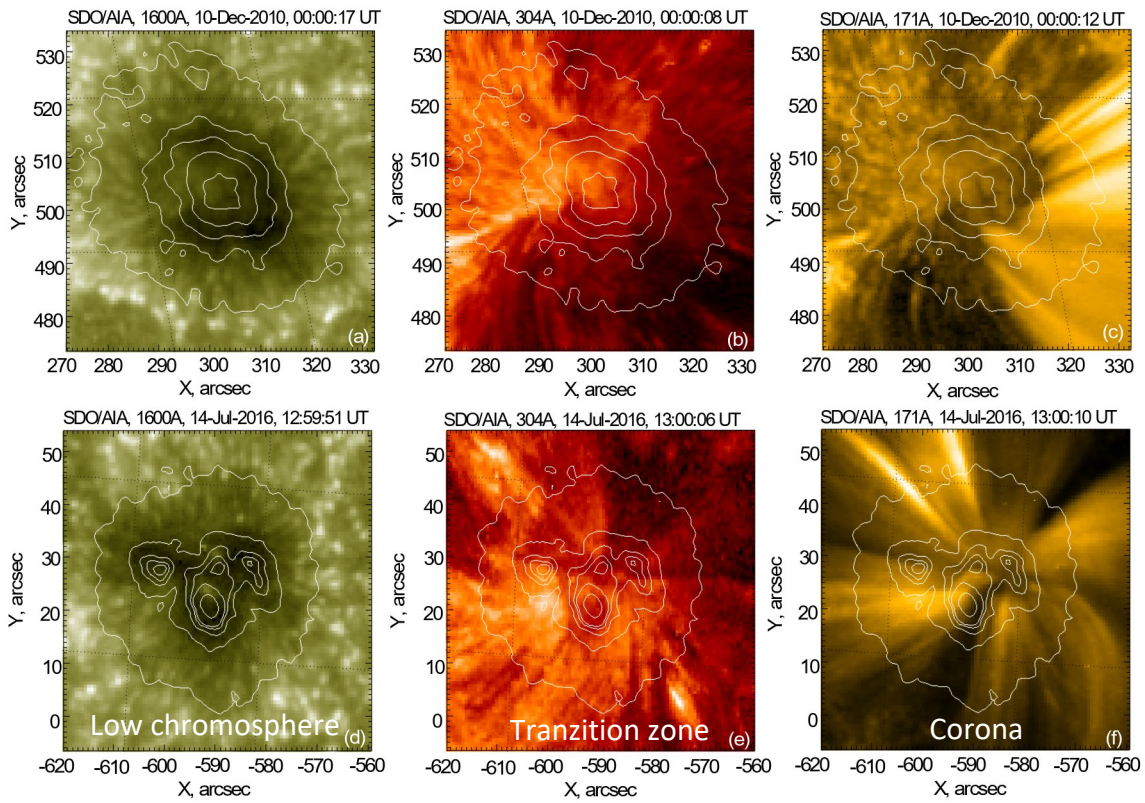


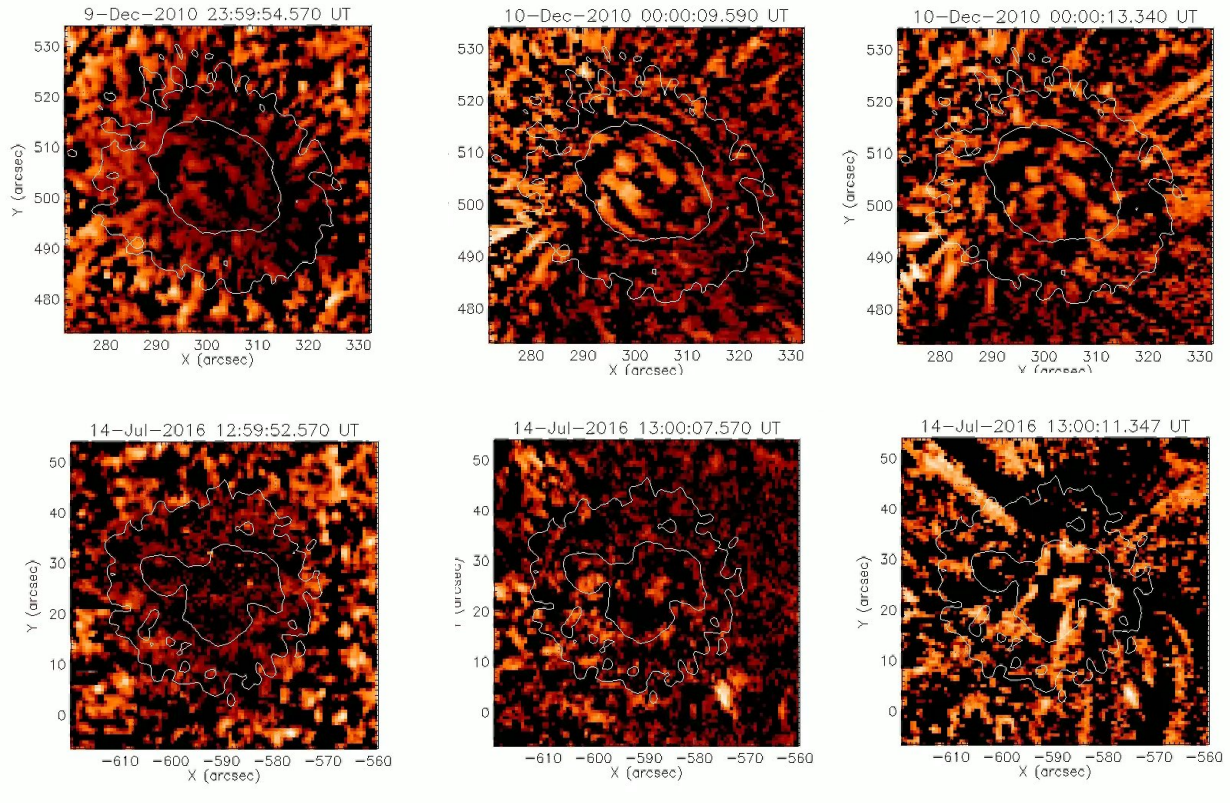
Structure of oscillation sources



Sych R. and Nakariakov V. ApJ, 569, 2014

Sunspot oscillations at different SDO/AIA wavelengths





- NOAA 11131 and NOAA 12565 have **different spatial structure** maxima **position and them number**;
- On different EUV/UV wavelengths images shown **symmetric and asymmetric** structure of magnetic loops;
- For NOAA 11131 low and high loops closing on the **trailing part** of the group and **background regions**;
- For NOAA 12565 prevail set of **symmetric** high loops anchored in different parts of sunspot umbra;
- For spectral analyze of oscillations at different SDO/AIA channels we used **PWF and PMD techniques**.

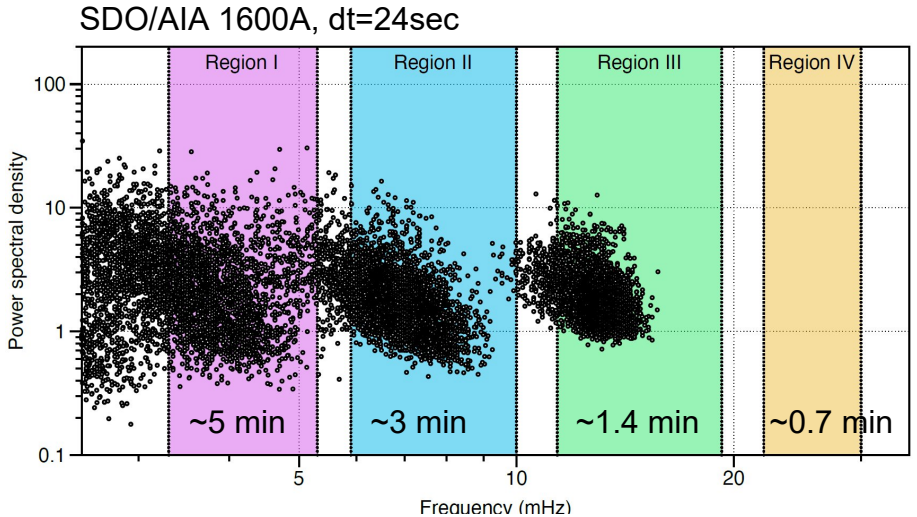
Sych et al, 2014;
Zhugzhda et al., 2014

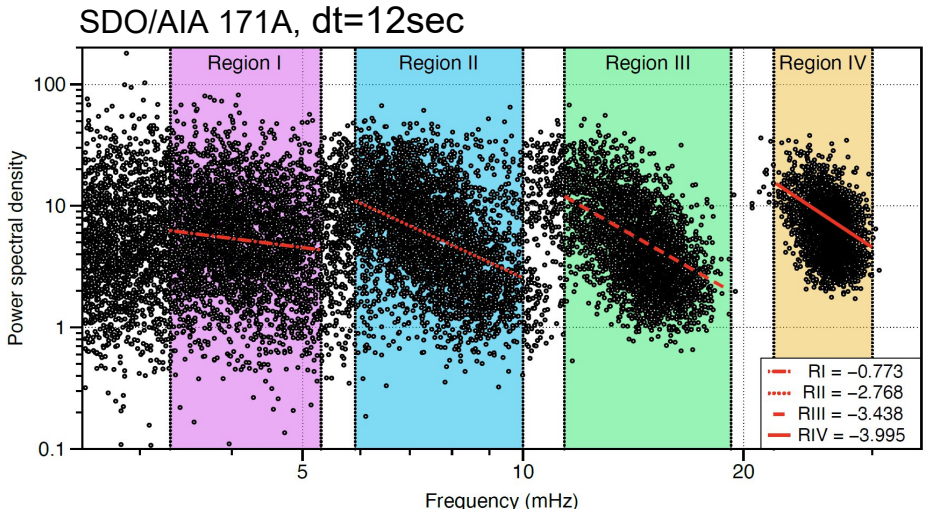
NOAA 11131 (December 10, 2010)

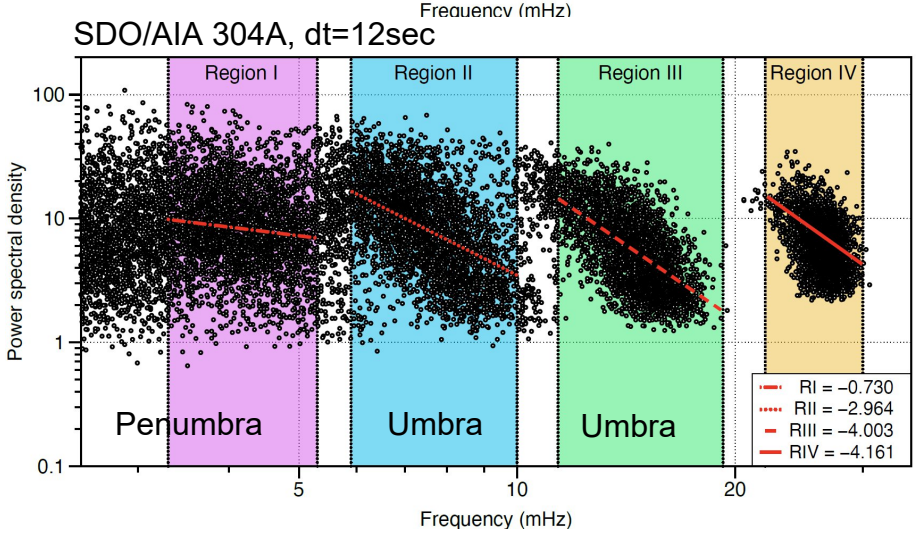
Jess et al., 2020

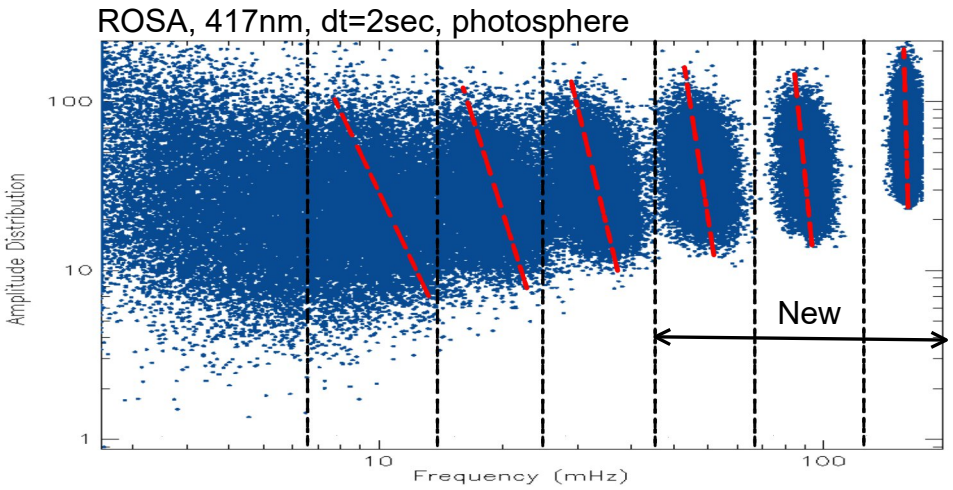
NOAA 12565 (July 14, 2016)

PMD spectra of oscillations in NOAA 11131



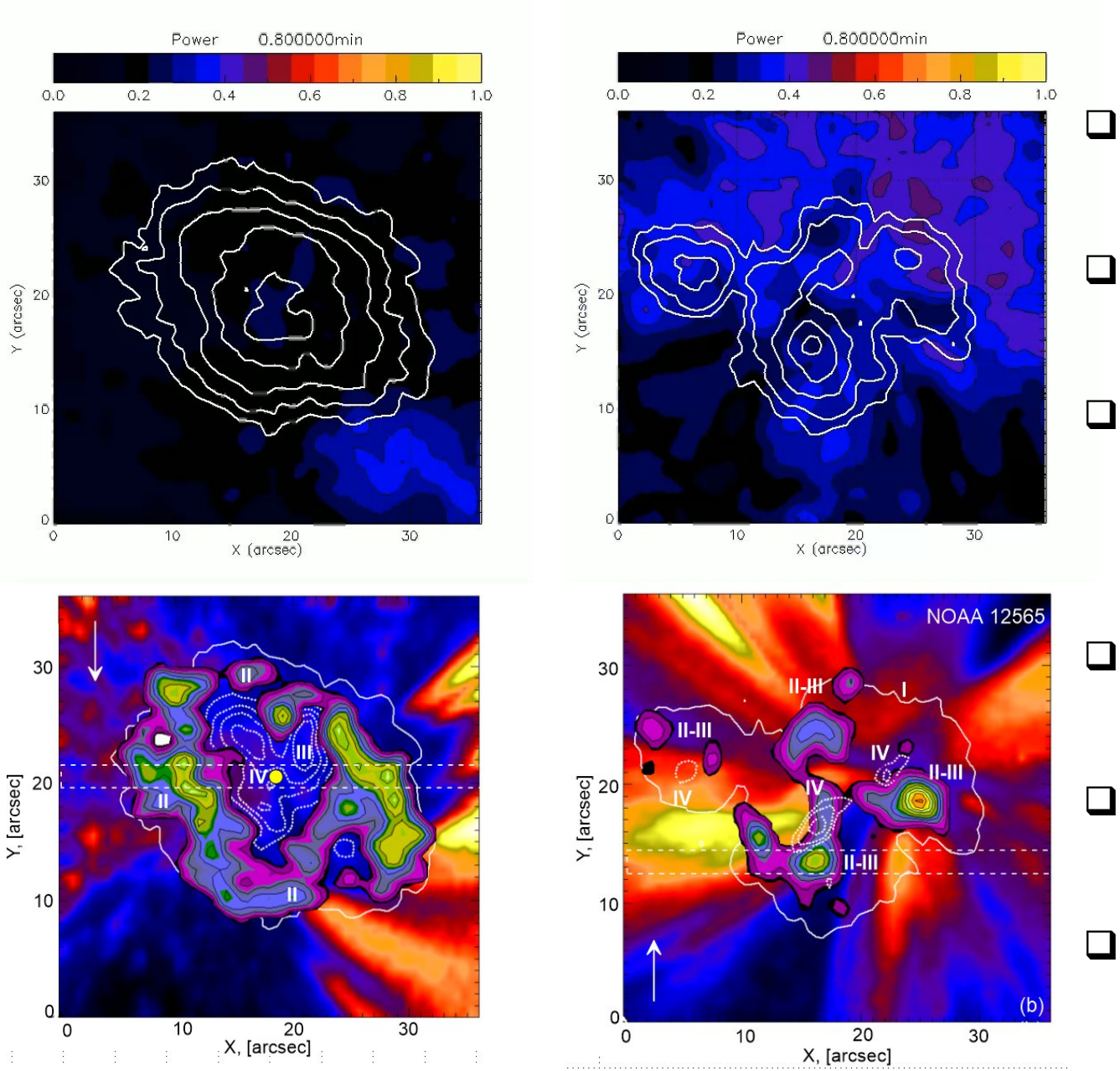






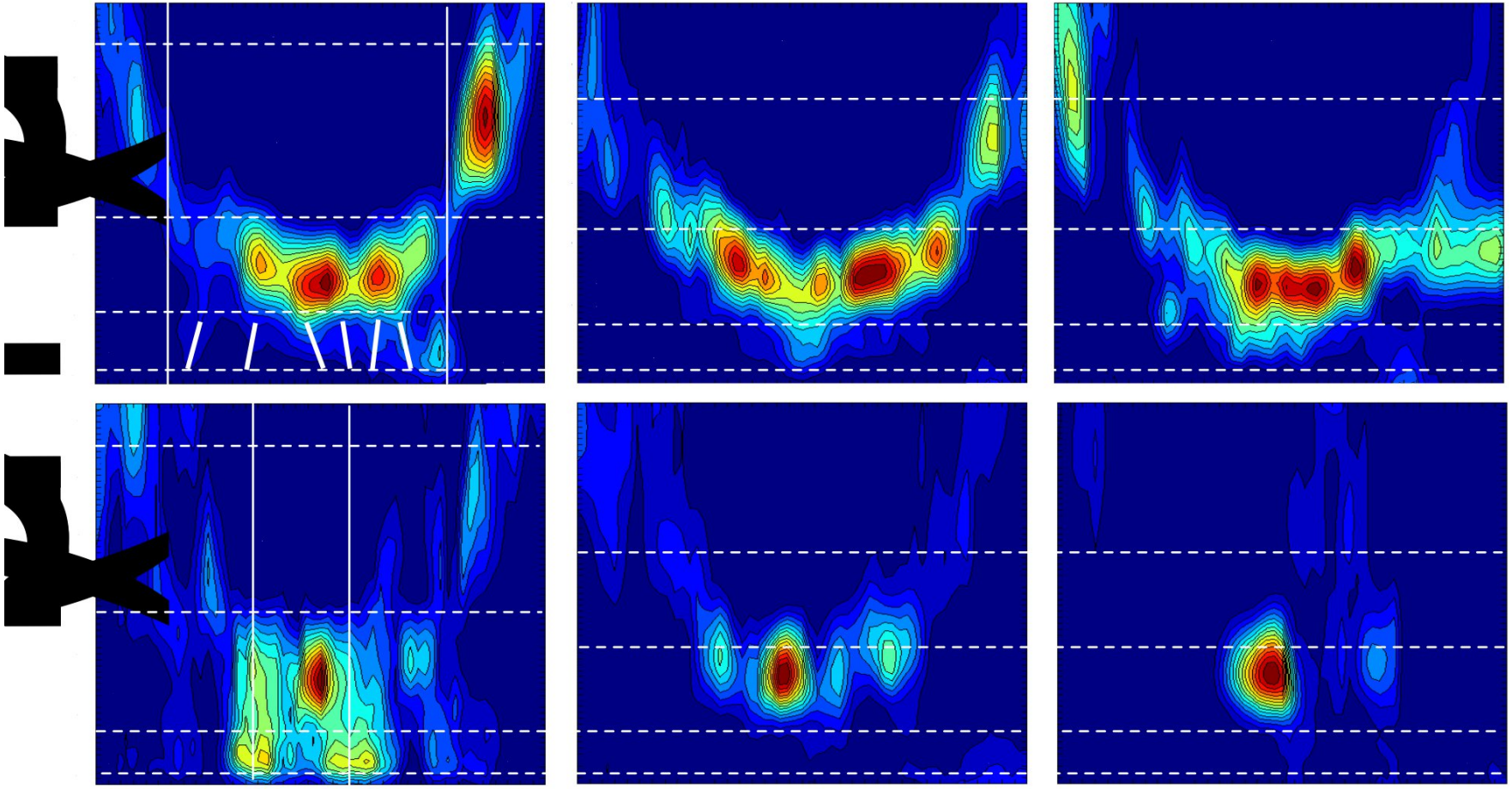
- Pixelized Mode Decomposition (PMD) analysis allowed to obtain **fine energy distributions** in the oscillation spectra
- We detected **set of spectral bands:** IV (23-32 mHz), III (12-18 mHz), II (5.8-10 mHz) и I (2-5.2 mHz);
- The **multiplicity** of period values suggests that these are likely to **be even harmonics of the global p-mode.**
- **The slopes** become **steeper** for increasing spectral windows.

PWF narrowband images of resonance cavities



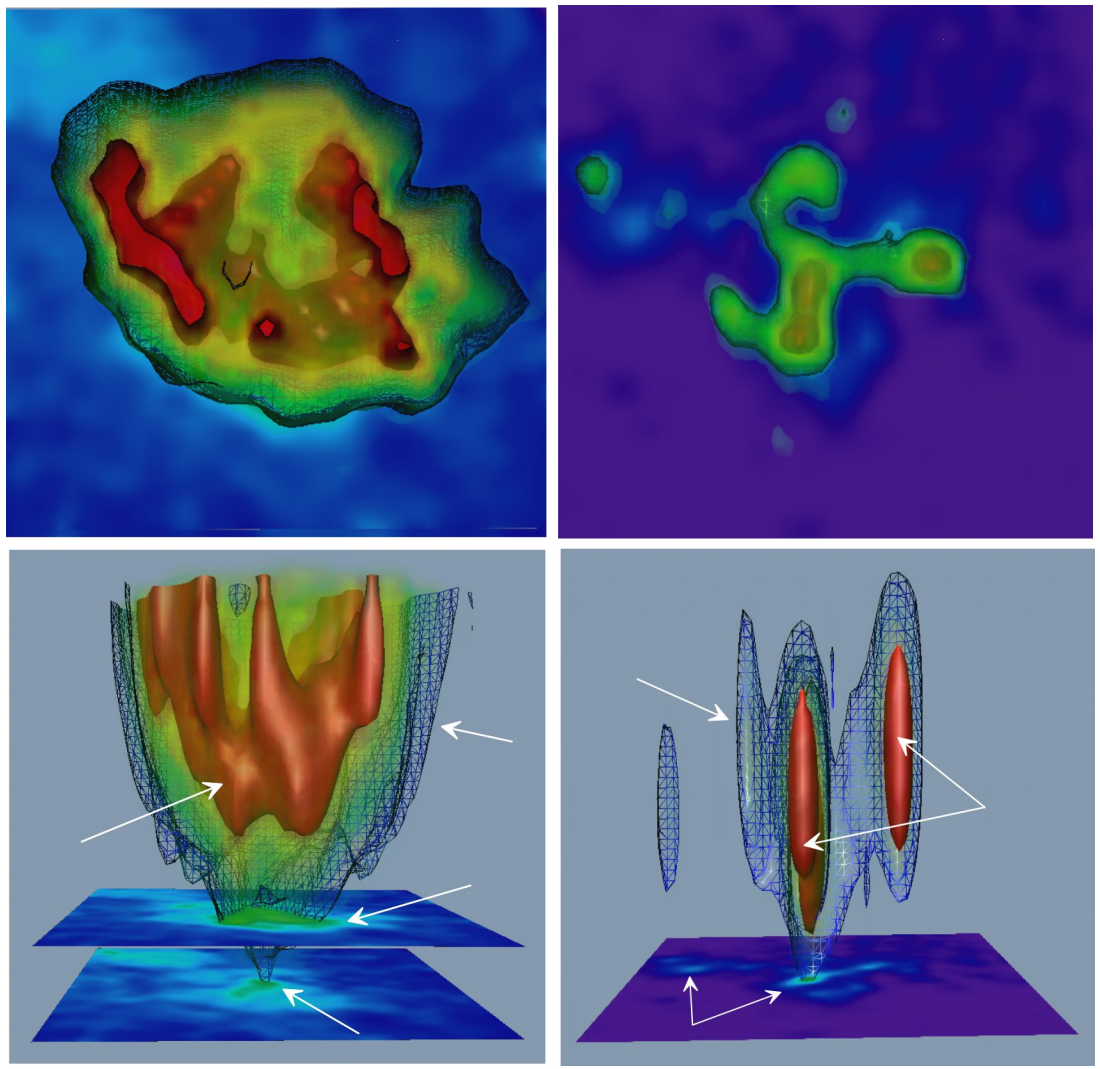
- **Four spectral regions** of the sunspot oscillations at 304A can separate using **PWF analysis;**
- Each period region is associated with a **selected** oscillations **source;**
- The high frequency part **(IV region)** is connect with **footpoint of magnetic bundle.** The source of **III region** is occupies part of bundle with divergence of magnetic field lines;
- **3-min oscillations (II region)** are localized in separate magnetic **waveguides** within umbra;
- Found frequency bands as resonance **cavities are discrete and do not overlap**.
- There is difference between spatial structure of **magnetic configuration in** two sunspots.

1D distribution of amplitude oscillations on selected frequencies



- We obtained **coordinate-period diagrams** of sunspot atmosphere use 1D slices at 1600A, 304A, 171A wavelengths.
- For the high frequency **III region** sources **show the convergence of filamentous discrete structures** towards the central part of the umbra at **1600A** with the formation of a **thick vertical magnetic bundle at 304A**. At **171A** it expands and the **bundle disintegrates** into individual **thin magnetic tubes.**
- For low-frequency oscillations in **regions I and II**, smoothed V-shaped structures consist of **discrete components** whose localisation depends on frequency and distance from the centre of the umbra.

3D distribution of resonant cavities in sunspot atmosphere



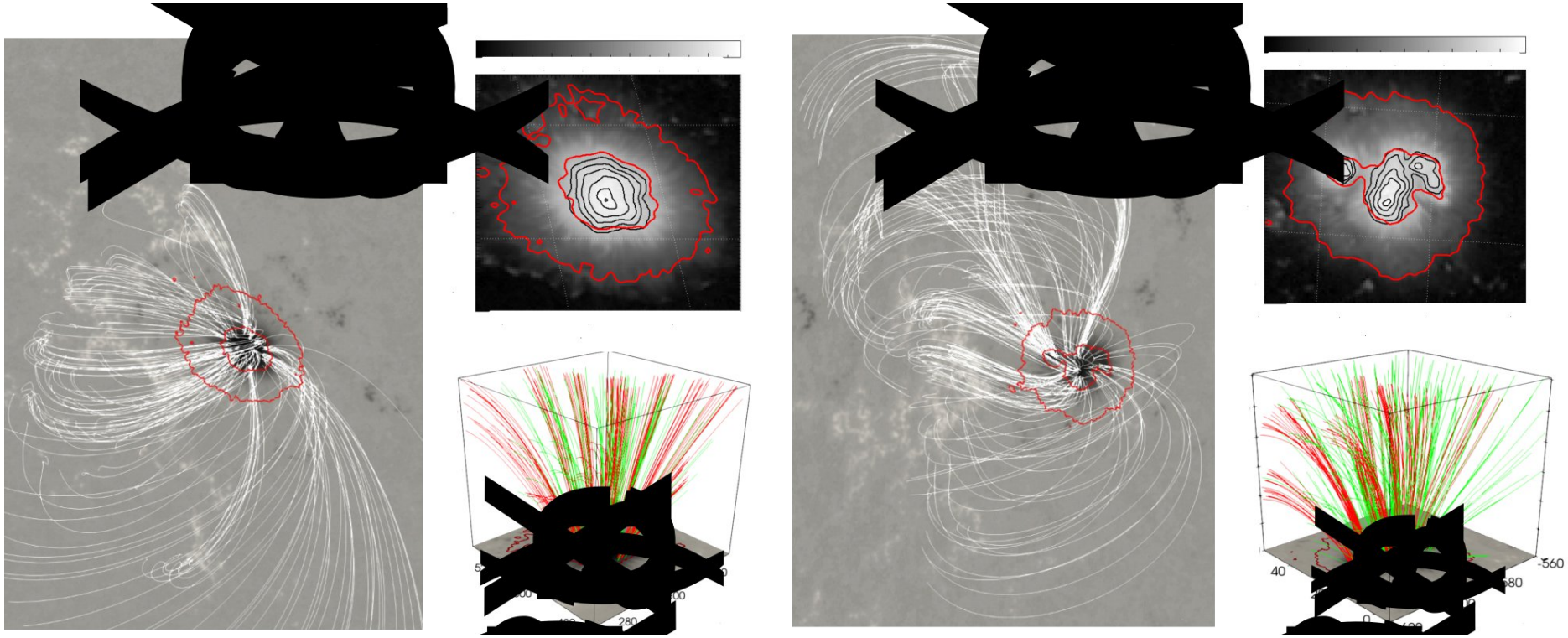
3D spatial-periodic localization of oscillation sources in the sunspot umbra at 304A. The left panels (a and b) correspond to sunspot A, the right panels (c and d) to sunspot B with top and side views of the narrowband data. The period range is from 0.8 min (~20 mHz) to 7 min (~2.3 mHz).

- Use the PWF analysis we obtained the **3D localization of spectral regions** where the amplification of oscillations in sunspot is observed. We suppose that these regions are **associated with resonance cavities** found earlier in Jess et al, 2020 by spectropolarimetric observations.

- High-frequency resonant cavity with frequencies of **~20 mHz** is associated with oscillations in the **footpoints** of magnetic bundles. The **~13 mHz** harmonic occupies the **part of the bundles**, without significant divergence of magnetic field lines. Harmonics **~6 mHz** (3-min oscillations) are localized in separated **waveguides** inside umbra. Low frequencies > **3 mHz** are located in the **penumbra** region as common **envelope.**

- The **structure** of the resonant cavities **varies** depending on the **magnetic configuration** of active region.

Structure of sunspot magnetic field with NLFF extrapolation



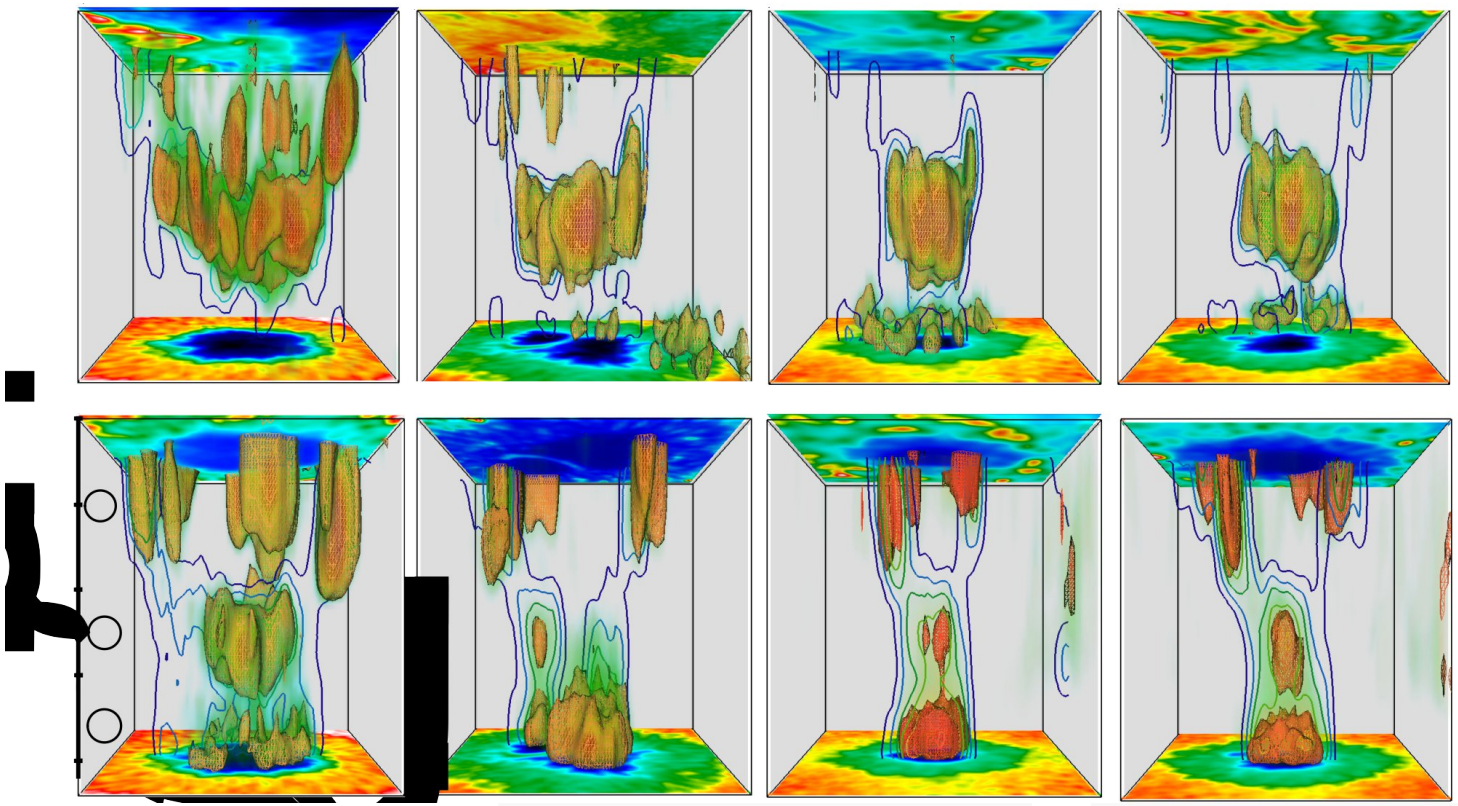
Structure of the magnetic field of the two active groups NOAA 11 131 (sunspot A, left panels) and NOAA 12 565 (sunspot B, right panels) from the SDO/HMI magnetogram. Panels a and d show the interpolated field lines for each group. Panels b and e show the field strength in kG of sunspots with umbra structure detailed by contours. Panels c and f show the zoomed view of the footpoints of extrapolated field lines.

- The **3D structure of the magnetic field** obtained from the distribution of oscillations on sunspots shows **good agreement** with the structure of the **Nonlinear Force Free (NLFF) extrapolated magnetic field**. The **footpoints** of the magnetic **bundles** and **maxima** of sunspot **oscillations coincid**e with the footpoints of the coronal loops visible in the 171 Å temperature channel.
- The magnetic **field strength is maximal** in these places

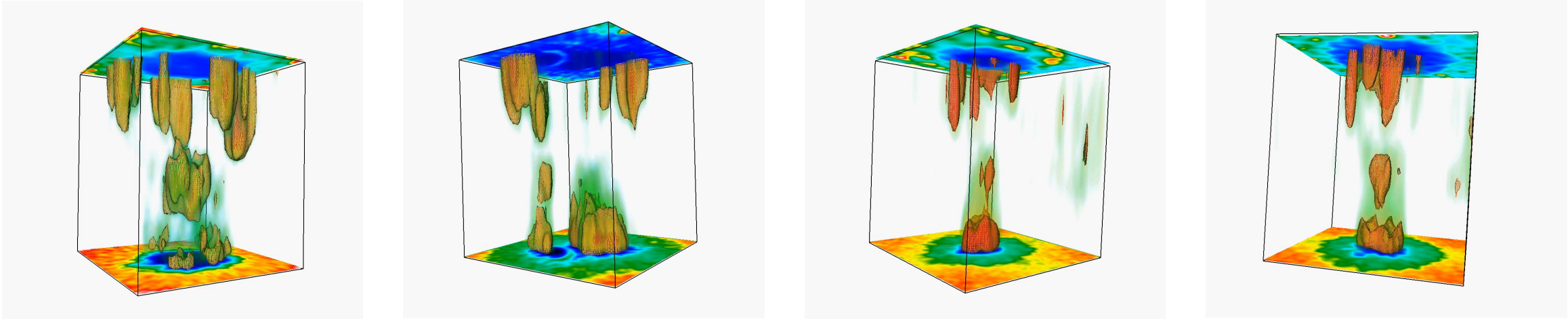
3D structure of photosphere and chromosphere resonators

304A

1700A



- There are **many separated waveguides** with **isolated resonators** at selected frequencies;
- Spatial **structure** of magnetic tubes is individual with **special properties** in photosphere and chromosphere levels;
- There is a **convergence at high frequencies** (III region) of thin magnetic tubes into a thick bundle;
- The magnetic **structures is various** for different active regions.



Results

- For the first time the presence of number discrete sunspot regions (resonance cavities) in the wide range of oscillations is shown.
- These regions occupy the selected parts of the waveguides in sunspot atmosphere and do not overlap with each other.
- It is assumed that in these regions the amplification of oscillations on multiple harmonics of the fundamental P-mode occurs with formation of fine structure harmonics in spectra.
- The correspondence between the shape of the sources and the structure of the magnetic field is found.
- We plan to use different ARs, wavelengths, cadence, spatial and time resolution to obtain height structure of waveguides in future.

Thank you
for your attention !