Comparison of Local Dynamic Response of MEMS Nanostructures Using Ultrasonic Force Microscopy and Laser Doppler Vibrometry

[1]**M. Mucientes**, [2] R. McNair, [2] A. Peasey, [2] S. Shao, [2] J. Wengraf, [1]K.J. Lulla, [1]B.J. Robinson and [1]O.V. Kolosov
[1] Physics Department, Lancaster University, LA1 4YB, UK
[2] National Graphene Institute, The University of Manchester, M13 9PL, UK
m.sanjuanmucientes@lancaster.ac.uk

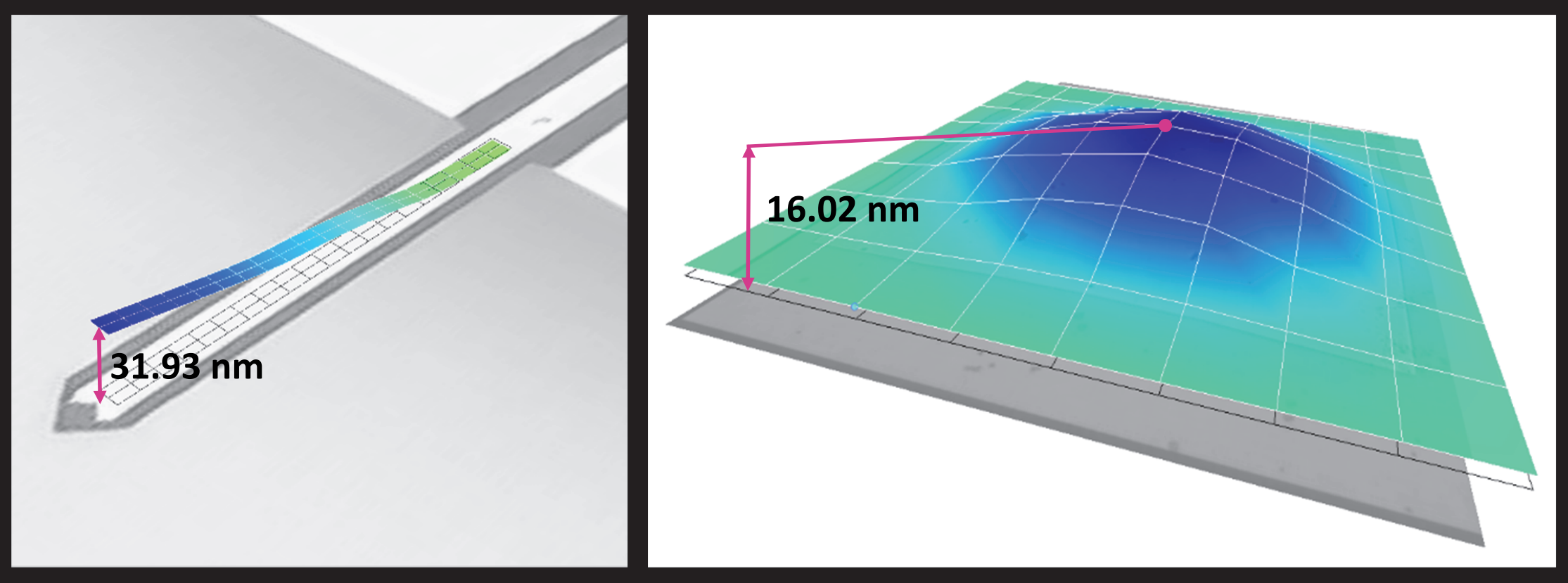
The development of **two dimensional (2D) materials micro-** and **nano-electromechanical systems (MEMS/NEMS)** demands special characterization methods with nanoscale lateral resolution, high frequency (HF) response and high sensitivity to out-of-plane displacements. In the particular case of mapping the distribution of vibrational modes of a mechanical resonators - like thin film membranes - optical methods, such as the **Laser Doppler Vibrometry (LDV),** offer high sensitivity in the vertical axis, however they are spatially limited by the wavelength of the light. For this reason, it is tempting to use **Scanning Probe Microscopy (SPM),** such as the **Atomic Force Microscopy (AFM),** which offers nanoscale spatial resolution as well as the capacity for HF excitation and detection in the linear and nonlinear regimes.

Probing MEMS with Laser Doppler Vibrometry (LDV)

The LDV is highly sensitive allowing us to study excitation of cantilevers and membranes due to purely thermally excited vibrations linking the thermal (E_{Th}) and the harmonic oscillator (E_{Os}) energies.

$$E_{Th} = \frac{k_B \cdot T}{2} = E_{Os} = \frac{k \cdot x^2}{2} \rightarrow x = \sqrt{\frac{k_B \cdot T}{k}}$$

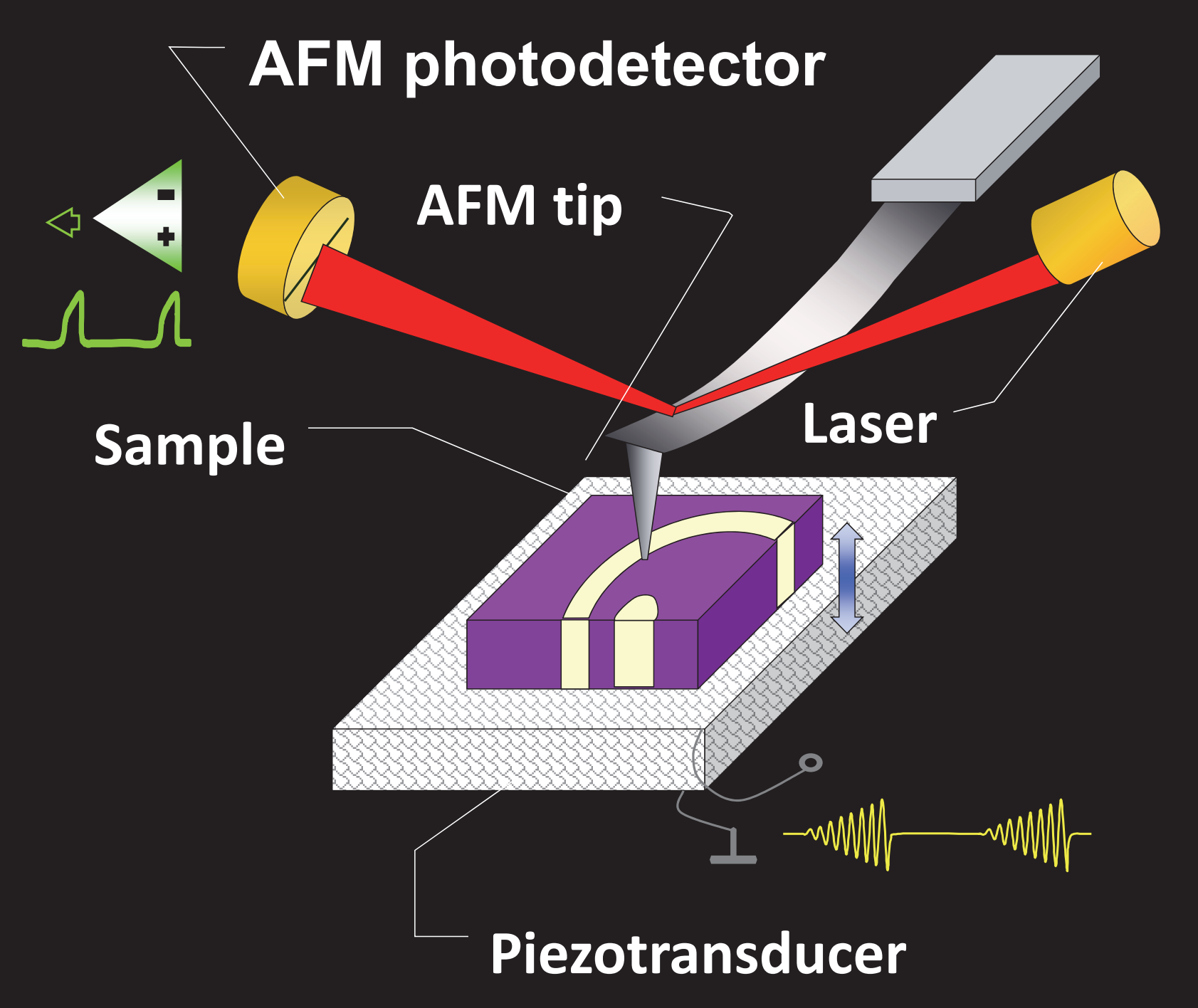
LDV can sense from *nm* down to *10s* of *pm* range vibration amplitudes.



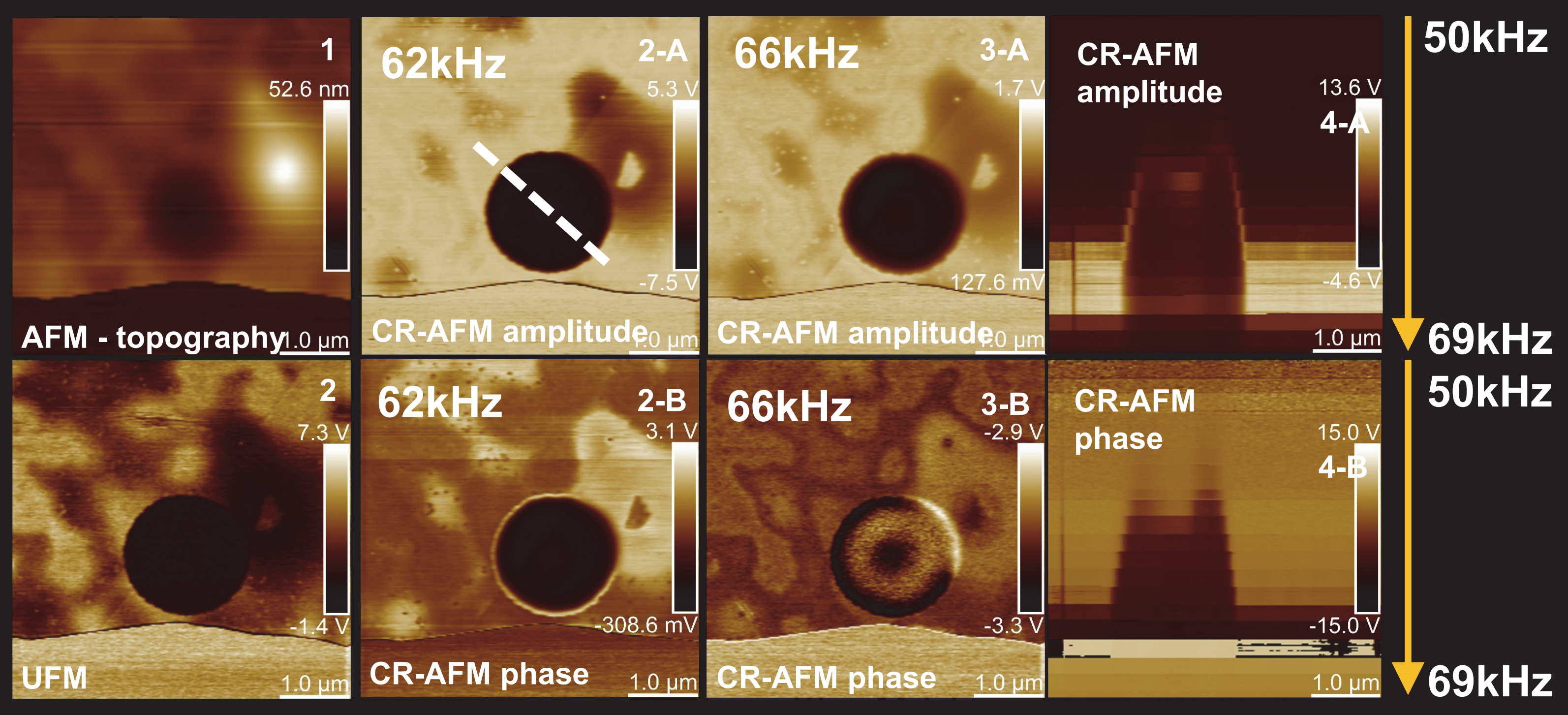
The ultra-high frequency (UHF) LDV, coupled with piezo-excitation of vibrations, can map the spatial distribution of the oscillation modes in the MEMS/NEMS devices.

SPM with ultrasonic excitation

- Force Modulation Microscopy (FMM)
- Contact Resonance AFM (CR-AFM) [1]
- Ultrasonic Force Microscopy (UFM)
- Modulation UFM **(M-UFM)**

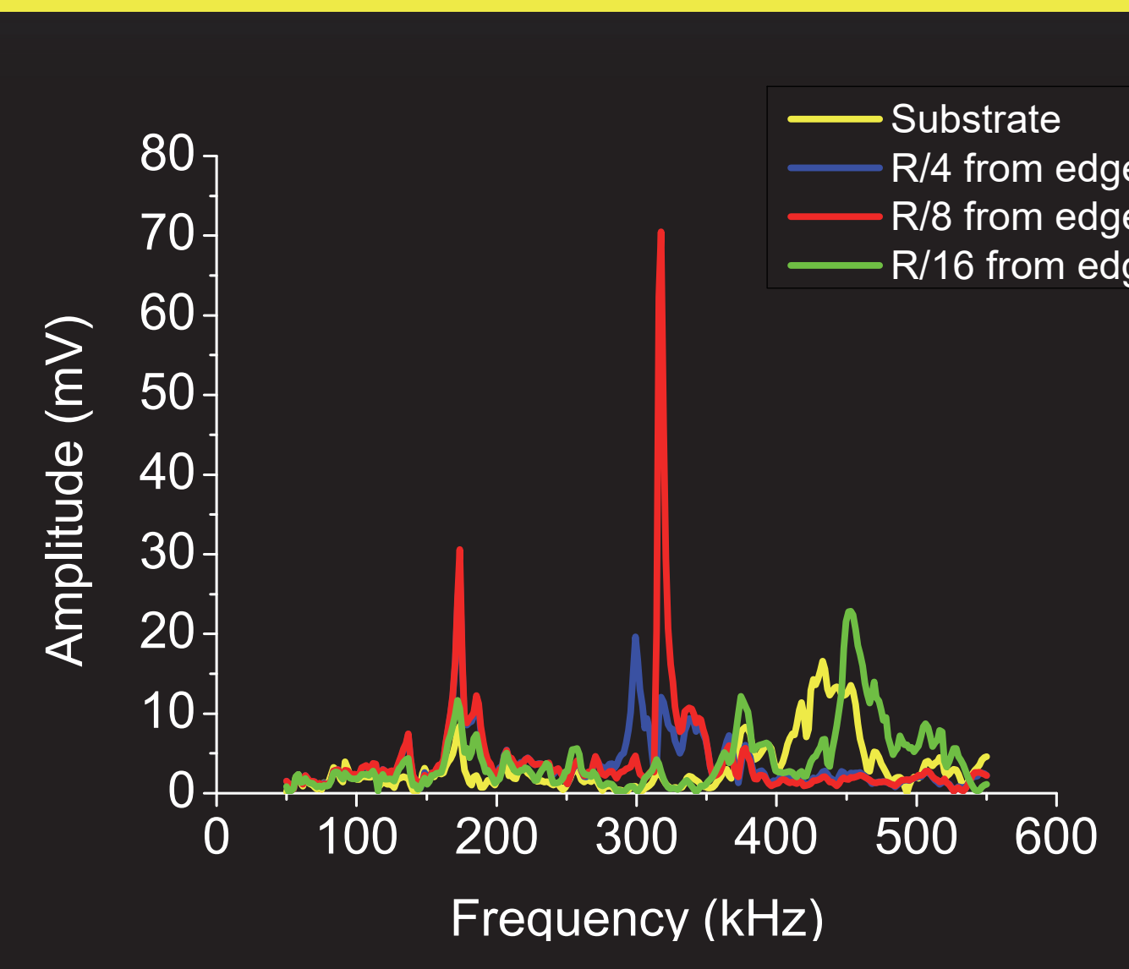


CR-AFM of a multilayer graphene drum



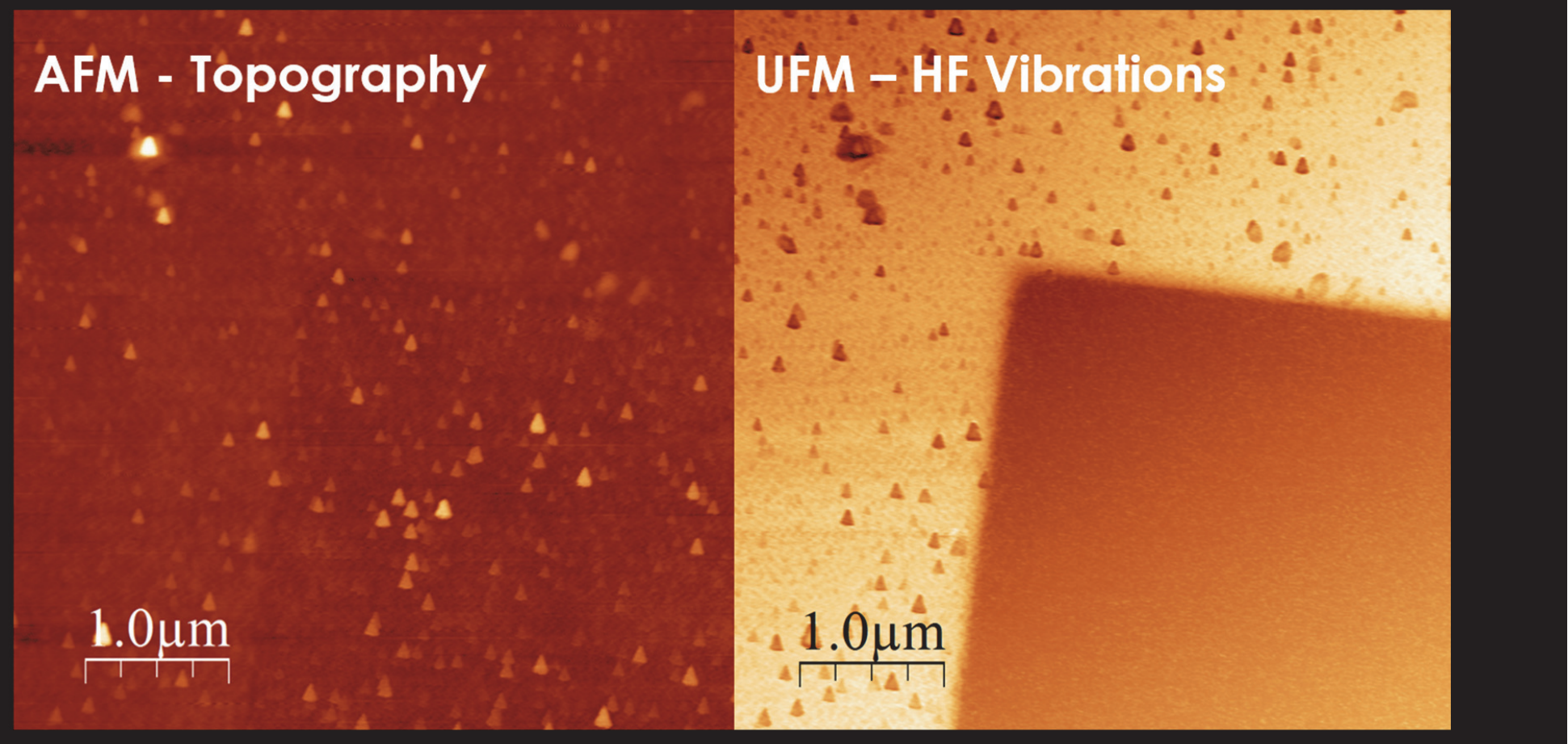
The linear detection method **CR-AFM** allows the observation of hidden features under the flake. Sweeping the excitation frequency simultaneously with the scan along one line across the drum it is possible to identify the coupled resonances: cantilever + graphene drum.

SPM detection of vibrations with nm spatial resolution

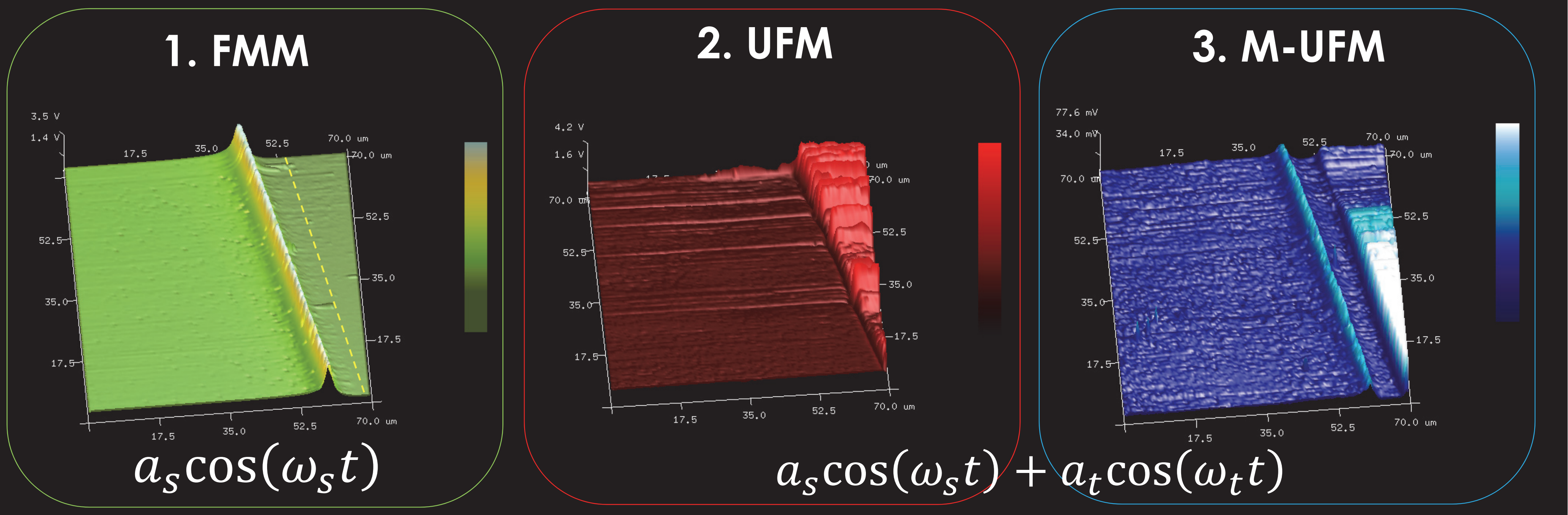


The resonance frequencies of the **membrane + cantilever system** are identified by the probing of the tip during contact with the sample using a simultaneous frequency sweep of the piezo drive excitation. The ultrasonic vibration can be **linearly** detected via Force Modulation Microscopy (FMM) at the excitation frequency [2]

…or nonlinearly – at the modulation frequency via Ultrasonic Force Microscopy (UFM) principle. UFM can detect subsurface features, like the edge of a tensioned Si_3N_4 membrane (right), not seen in AFM topography (left).



Comparison of different SPM modes - Si_3N_4 membrane



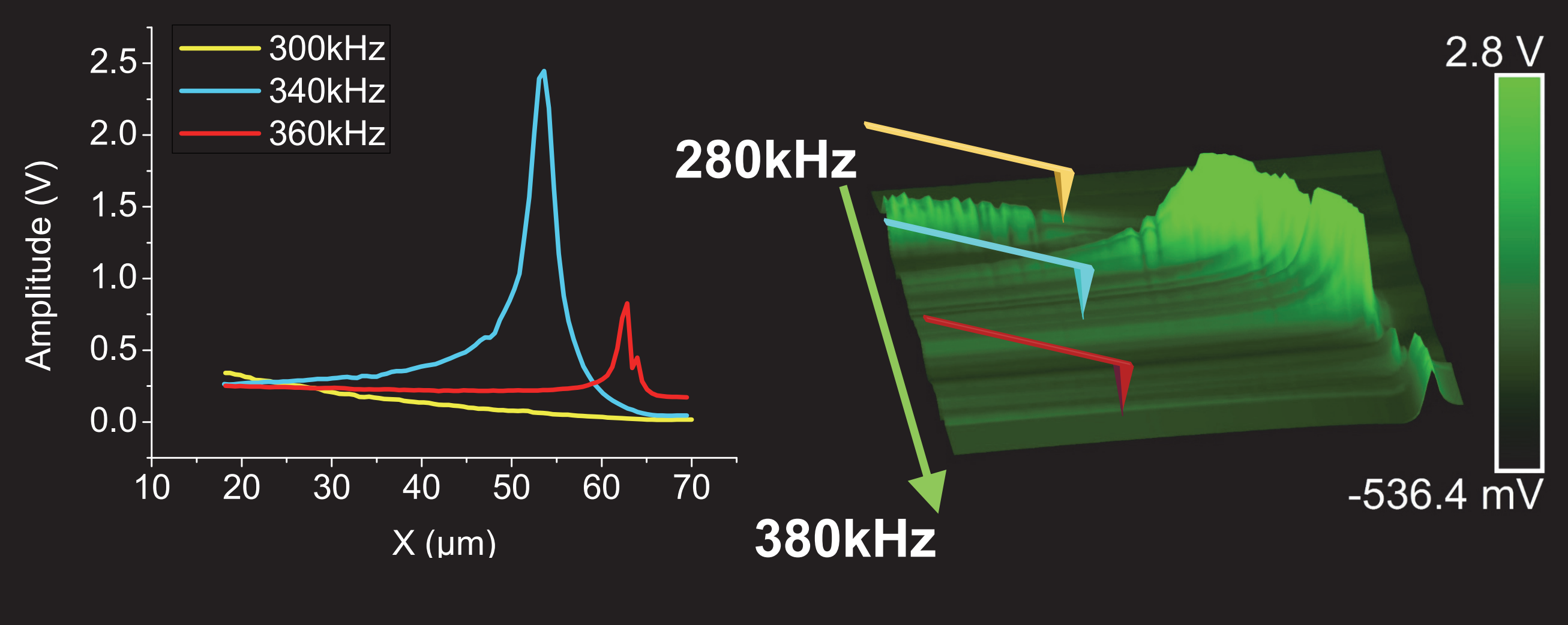
$$a_s\cos(\omega_s t)$$

$$a_s\cos(\omega_s t) + a_t\cos(\omega_t t)$$

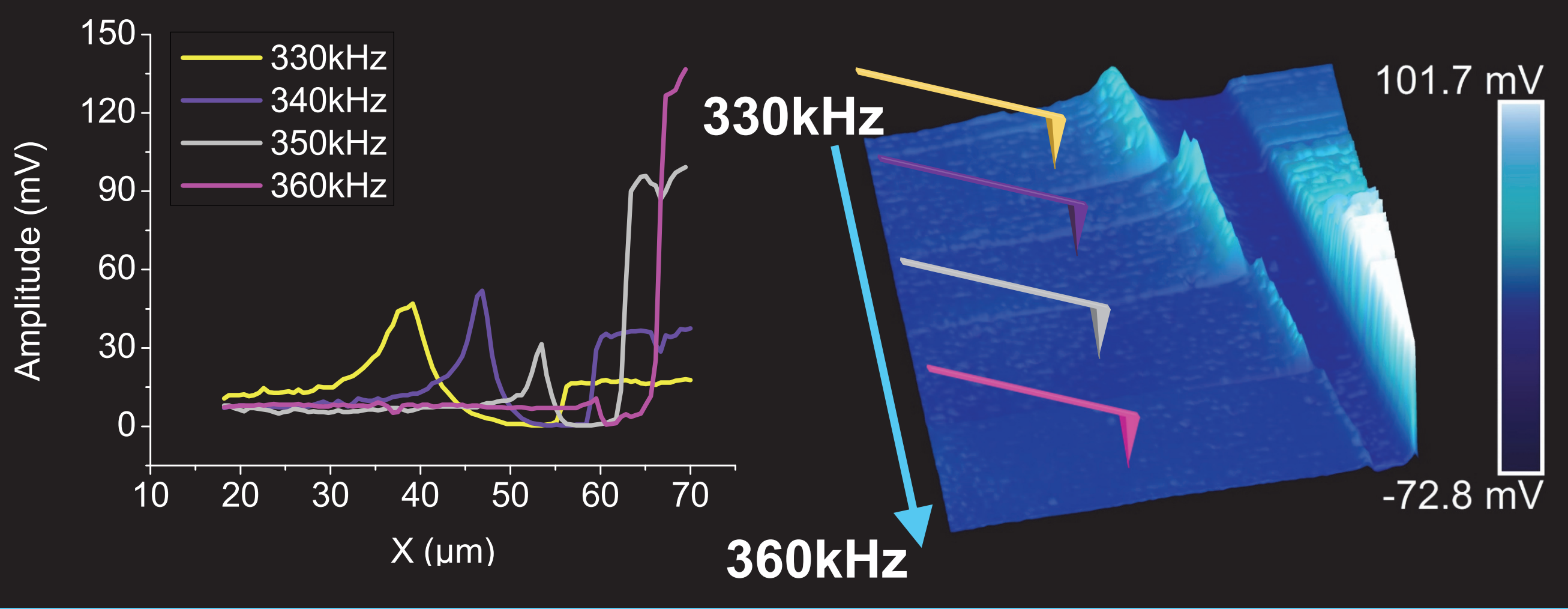
$$a_s^2\frac{1}{2}[1+\cos(2\omega_s t)] + a_t^2\frac{1}{2}[1+\cos(2\omega_t t)] - a_s\, a_t\big[\cos((\omega_s-\omega_s)t)+\cos((\omega_s+\omega_s)t)\big]$$

1. **FMM** detects vibrations directly localizing the resonance peak.
2. **UFM** images show the membrane edge, but not the vibration modes.
3. **M-UFM** allows to study the spatial distribution of the vibrational modes as well as subsurface structure of the sample.

Probing of the vibrational modes distribution



FMM probes vibrational modes of membrane + cantilever system excited as a whole. The amplitude and frequency of the mode depend on the position of the tip and the excitation frequency.



M-UFM measurements excite the vibration locally at the tip point and show how the distribution of the vibrational modes along the membrane depend of the excitation frequency.

CONCLUSIONS:

- SPMs and LDV allow the measurement of *sub-nm* MEMS/NEMS vibration amplitudes, with *µm* (LDV) and *nm* (SPM) lateral resolution.
- The SPM measurements of vibrations are in a good correlation with the LDV data.
- The optimal SPM tip position for the observation of vibrational modes should be close to the membrane edge.
- To detect high frequency modes nonlinearly, M-UFM is used, providing the broadest frequency range for modulation frequencies.
- Graphene membranes stiffness can be studied using CR-AFM methods providing good quality of data.

References:

[1] C. Ma et al., Journal of Applied Physics, 121 (2017) 154301.
[2] M.T. Cuberes et al., Journal of Physics D-Applied Physics, 33 (2000) 2347-2355.

Acknowledgements:

Lancaster University, Graphene NowNano and EPSRC.