Graphene induced exotic time crystalline phases of hybrid nano-mechanical resonator modes

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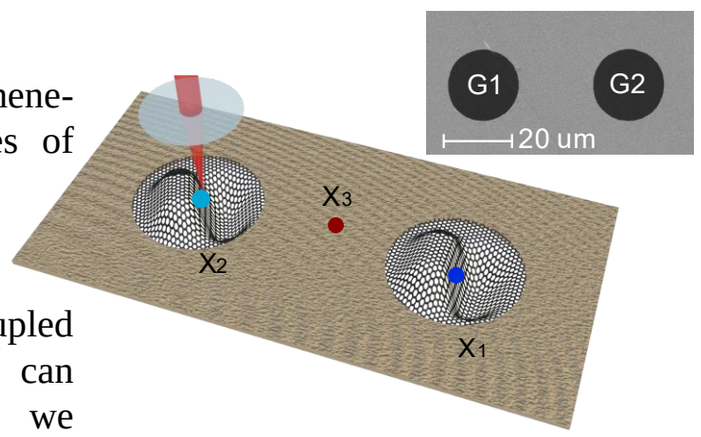
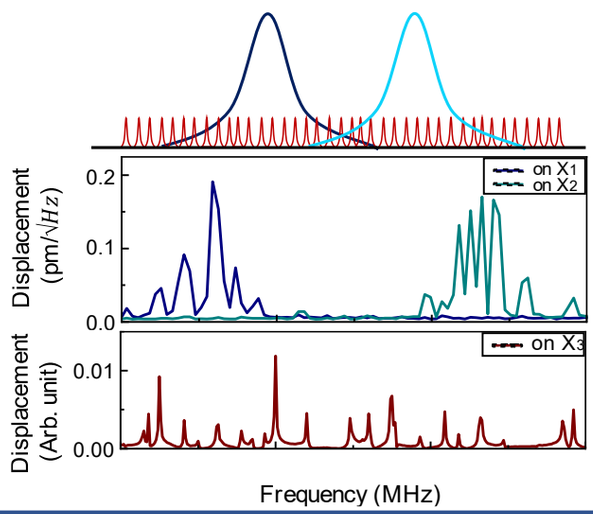
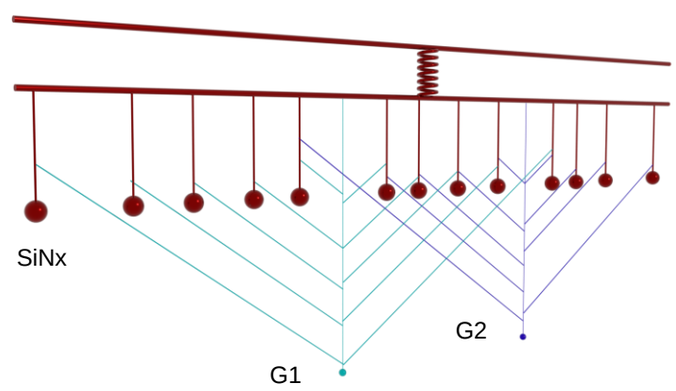
Device and model:

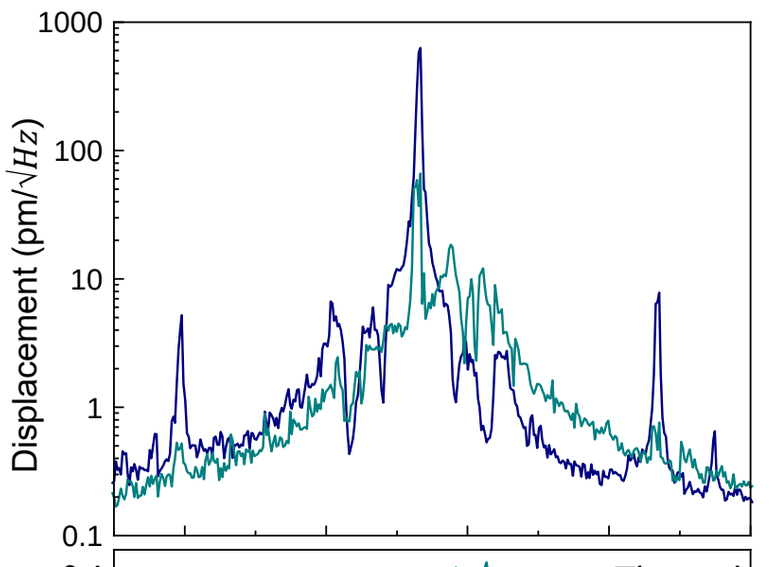
Experiment is done on a Graphene-SiNx hybrid resonator. Modes of SiNx membrane interact with fundamental modes graphene drums. We can think of a model of many coupled oscillator system which can describe essential features we observe experimentally.

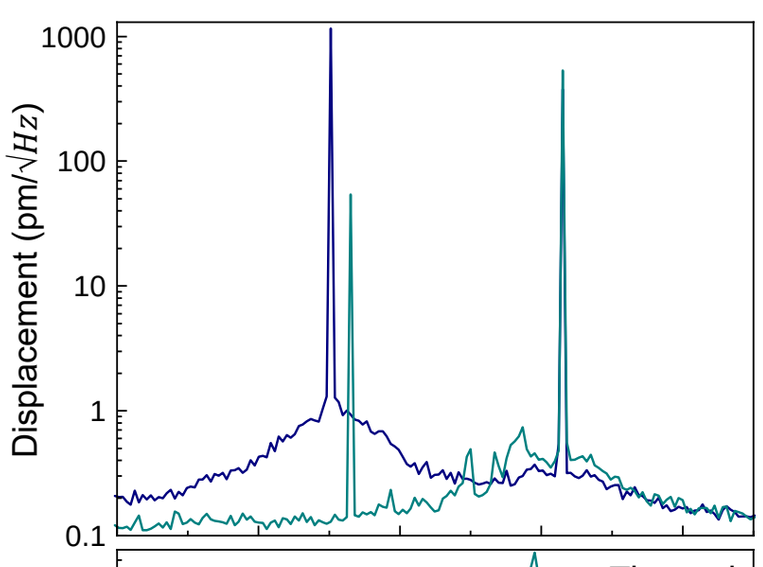


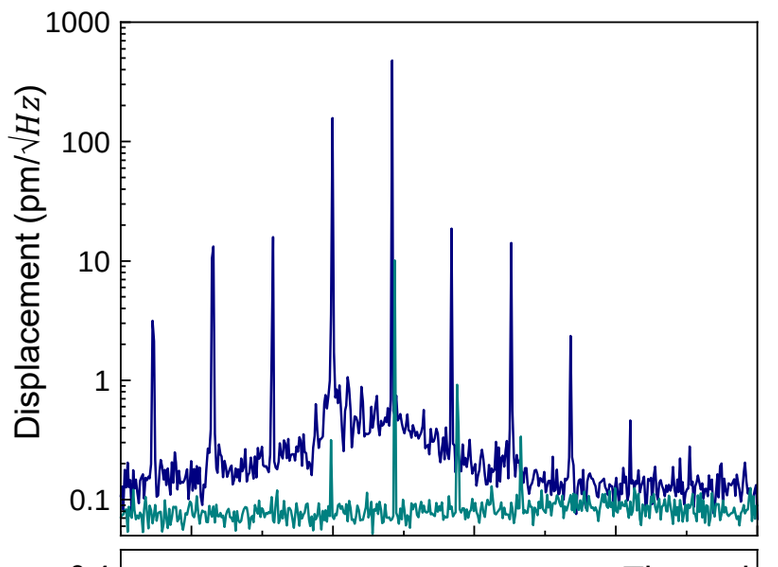




Time Crystalline Phases: Sub-harmonic, An-harmonic and Bi-harmonic:



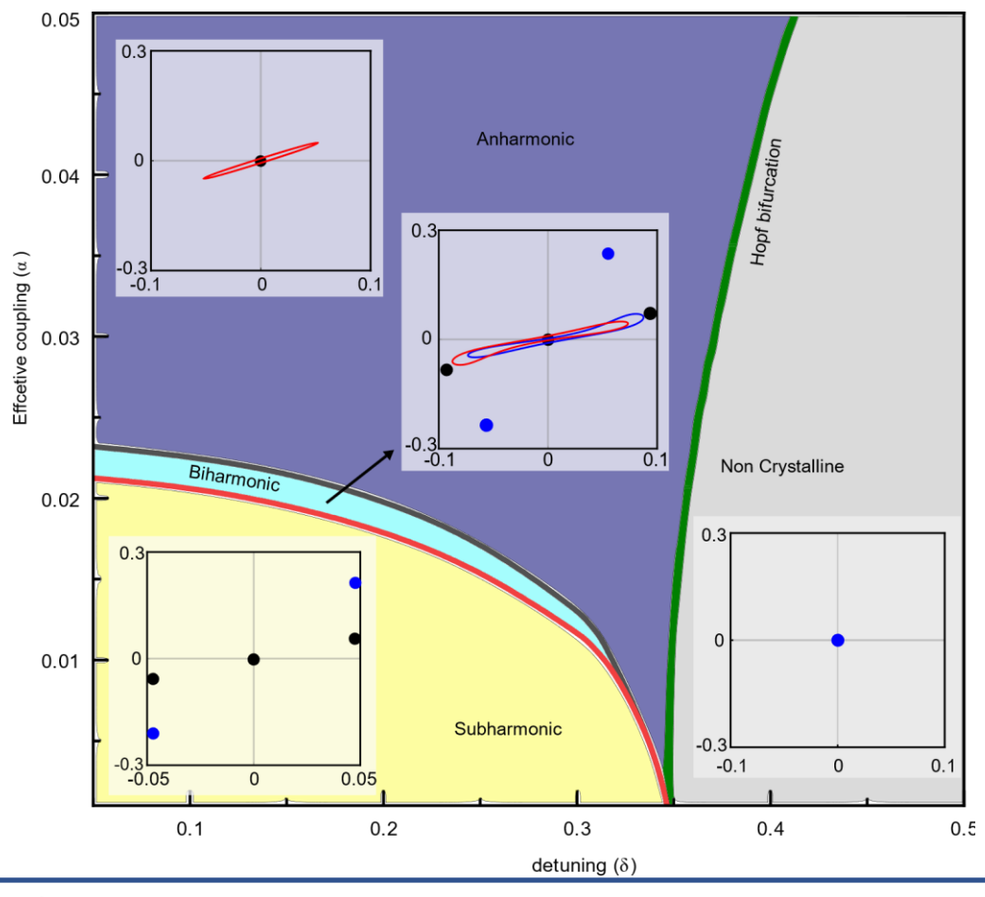




Mean field model equation:

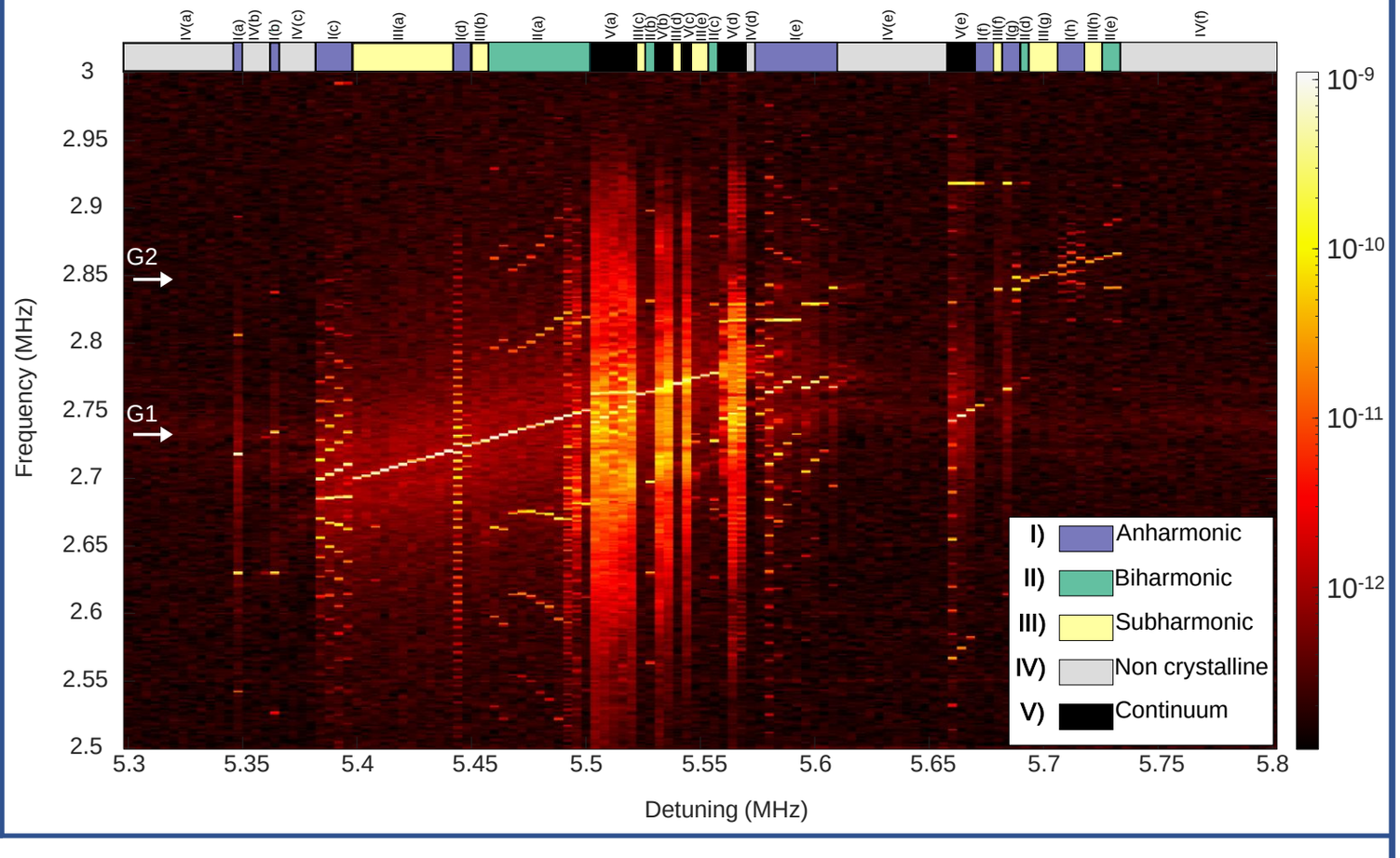
$$\ddot{x} = -\gamma\dot{x} - \frac{\eta}{m_g}x^2\dot{x} - \left\{\left(\omega - \frac{\Delta}{2}\right)^2 + \frac{h}{m_g}\cos(2\omega t + \chi_x)\right\}x - \frac{\beta}{m_g}x^3 + \frac{\alpha}{m_g}y$$

$$\ddot{y} = -\gamma\dot{y} - \frac{\eta}{m_g}y^2\dot{y} - \left\{\left(\omega + \frac{\Delta}{2}\right)^2 + \frac{h}{m_g}\cos(2\omega t + \chi_y)\right\}y - \frac{\beta}{m_g}y^3 + \frac{\alpha}{m_g}x$$



Observation of time crystalline phases with drive frequency detuning:

Depending on coupling, detuning, drive strength and drive frequency, system response changes from one phase to other as shown in phase diagram. Experimental plot shows more exotic behaviour than the phase diagram we get from two mode theory. Experimentally we can't tune coupling and detuning independently. We observe different phases at different frequency detuning because of change in coupling detuning and number of modes together.



References :

1) R. Singh, R. J. T. Nicholl, K. I. Bolotin, and S. Ghosh, Motion transduction with thermo-mechanically squeezed graphene resonator modes, Nano Letters 18, 6719 (2018).
2) R. Singh, A. Sarkar, C. Guria, R. J. Nicholl, S. Chakraborty, K. I. Bolotin, and S. Ghosh, Giant tunable mechanical nonlinearity in graphene silicon nitride hybrid resonator, Nano Letters 20, 4659 (2020), pMID: 32437616, https://doi.org/10.1021/acs.nanolett.0c01586.