

# Confining classical and quantum waves with crystals

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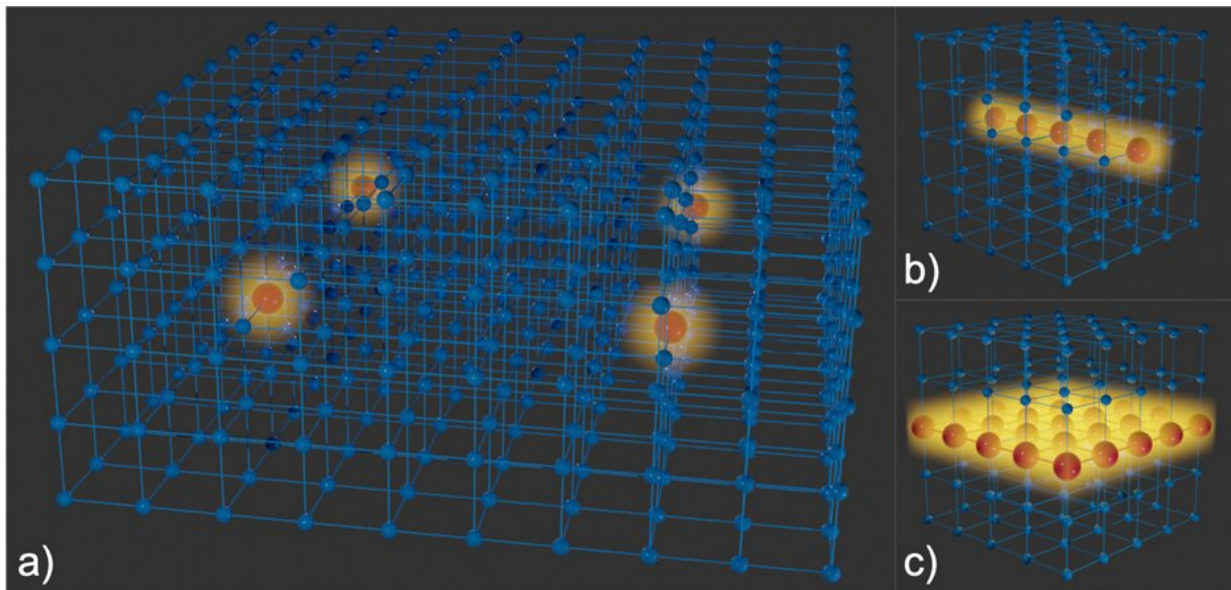


Figure 1: Illustration of a 3-dimensional crystal with various types of confining centres. Blue spheres represent unmodified unit cells, and red spheres are confining centres. (a) Crystal with four confining centres, each trapping waves (yellow) in all three dimensions ( $c=3$ ) simultaneously. (b) Crystal with a linear confining centre where waves can propagate in 1 dimension, analogous to an optical fibre ( $c=2$ ). (c) Crystal with a planar confining centre where waves can propagate in 2 dimensions, analogous to a 2D electron gas ( $c=1$ ). Credit: University of Twente

In the journal *Physical Review Letters*, a team of researchers from the

University of Twente describes how any kind of wave, whether quantum or classical, is confined in any kind of crystal. The results will notably boost efficient new integrated circuits that steer information encoded in tiny light pulses through smart cities.

Waves represent an inseparable part of our everyday life, whether we listen to music, observe our reflection in a mirror, or experience the ocean rocking a sailing ship. A central challenge in manipulating waves for applications requires the ability to confine the waves in small regions in space.

Scientists already know that it's possible by deliberately introducing tailored deviations from perfect periodicity into the crystal. But how exactly are the waves locked up? Are they confined in all dimensions simultaneously, or do they retain the freedom to move along a line or in a plane? Remarkably, the key step from having the crystal's structure to predicting the confinement of waves had not been taken until now.

You might be familiar with crystals formed by minerals in nature. Such crystals can be used to confine quantum-mechanical electronic waves. Man-made crystals of silicon have led to the discovery of electronic transistors, the basis for the ongoing digital revolution. We now know that there are other types of crystals, that are able to confine and manipulate different types of waves like light, sound, and potentially even earthquakes.

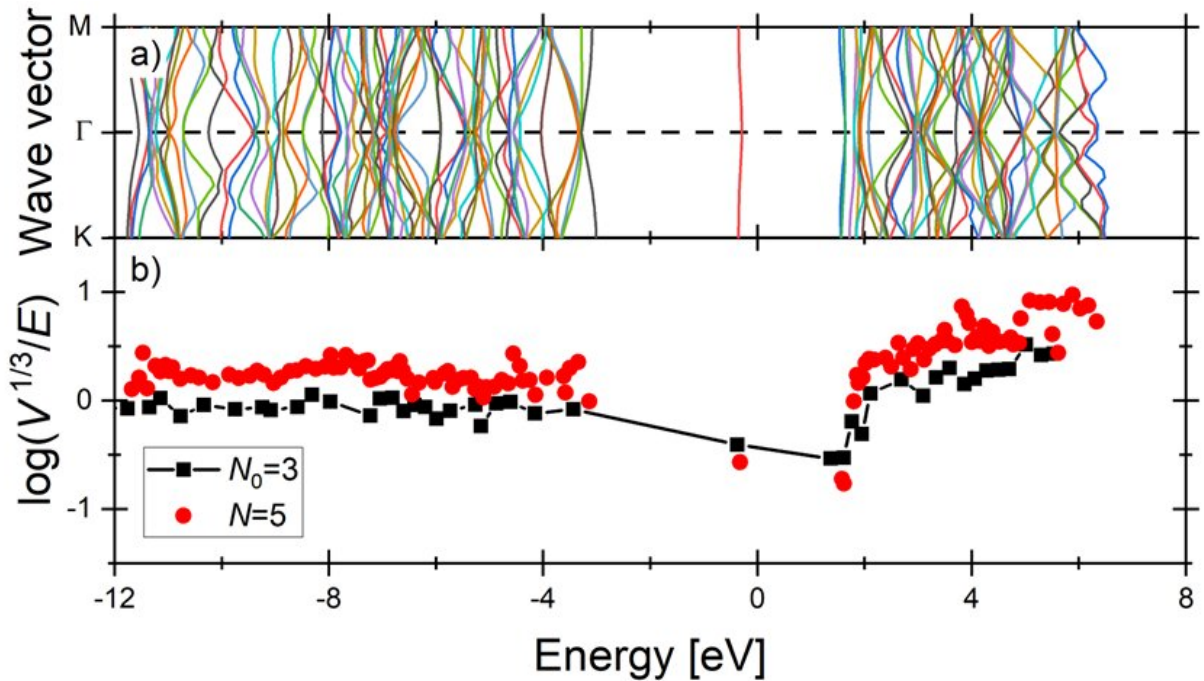


Figure 2: Confinement analysis of a 2-dimensional quantum crystal for electrons in the semiconductor hexagonal boron-nitride with a nitrogen vacancy. (a) Dispersion relations of the crystal. (b) Ratio of the confinement volume to confinement energy computed for each propagating band of waves. Red points correspond to bands in the crystal with size  $N = 5$ , and black points represent the smaller reference  $N_0 = 3$  crystal. With the increased size, bands with  $c=2$  confinement move down and bands with  $c=0$  move up in the graph and are thus clearly distinguished. Due to the wave confinement geometry, it turns out there are no  $c=1$  bands. Credit: University of Twente

Having a crystal at hand is not enough to confine waves. The internal structure of the crystal must specifically suit the desired application. To make matters more complicated, there are infinite possibilities for this structure, considering all conceivable building blocks and their arrangements in the crystal. Until now, scientists and engineers trying to confine waves had to rely on their intuition, guesswork, and costly trial-and-error experiments.

In their *Physical Review Letters* paper, the Twente researchers present a robust analysis tool that predicts how waves are confined within a crystal, using only the crystal's structure as input. First author and Ph.D. student Marek Kozon MSc explains, "A central parameter in our analysis is a 'confinement dimensionality' that we have invented. It describes the confinement for each possible wave."

COPS group leaders Prof. Dr. Willem Vos and Prof. Dr. Ad Lagendijk add enthusiastically: "We got excited when we realized from discussions with Marek that our method pertains to not only to classical waves such as sound and light but also to quantum [waves](#) such as electrons in tiny nanostructures."

Based on the new know-how, the designers of [crystals](#) can now benefit from new "rules of thumb" for specific applications, resulting in highly simplified and thus efficient design processes. MACS group leaders Dr. Matthias Schlottbom and Prof. Dr. Jaap van der Vegt add: "Our results are relevant for efficient information processing in new photonic and electronic chips that will populate future smart cities."

**More information:** Marek Kozon et al, Scaling Theory of Wave Confinement in Classical and Quantum Periodic Systems, *Physical Review Letters* (2022). [DOI: 10.1103/PhysRevLett.129.176401](https://doi.org/10.1103/PhysRevLett.129.176401)

Provided by University of Twente

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