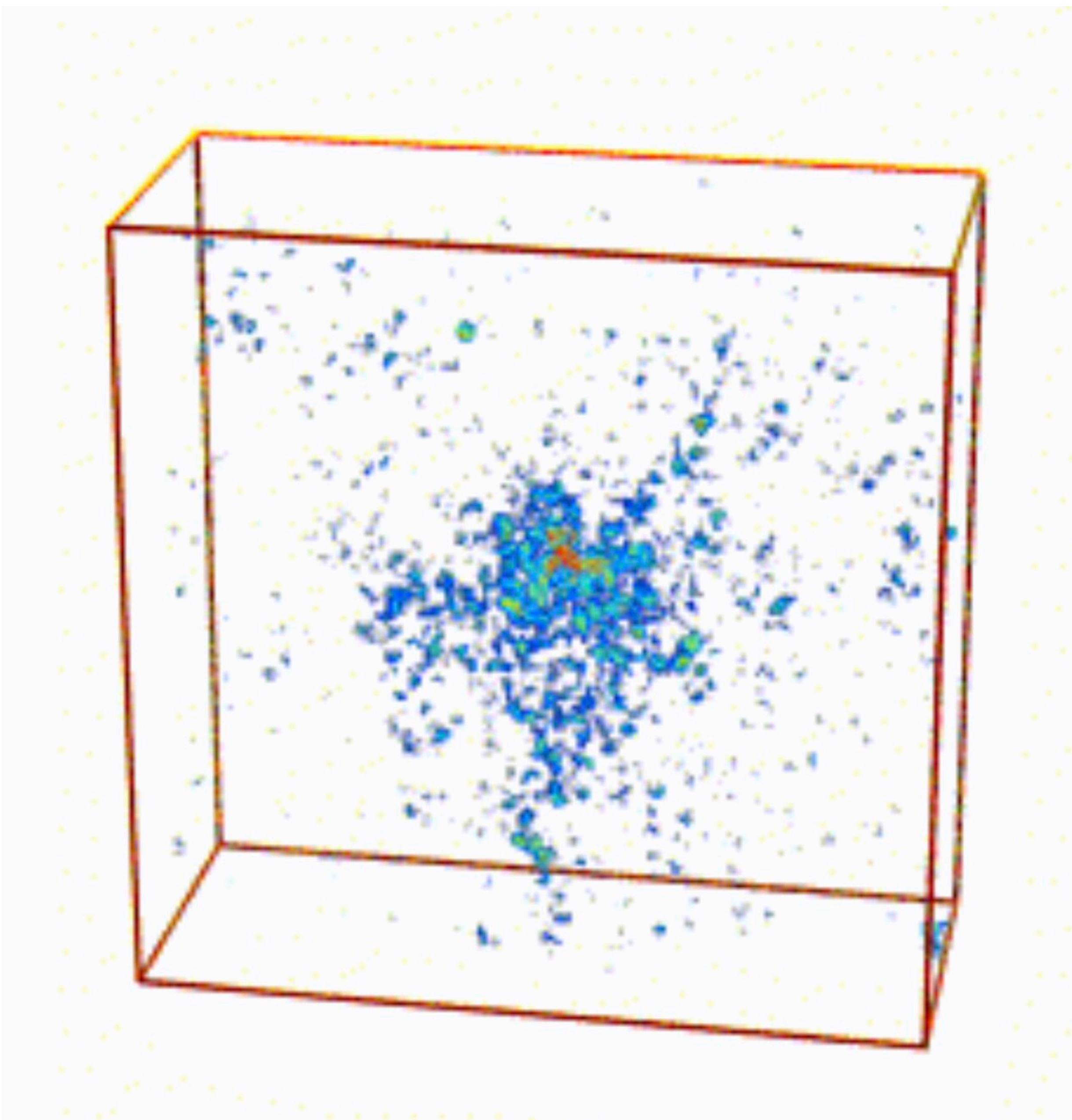
Simulations reveal Anderson transition for light in 3D disordered systems

February 14 2025, by Ingrid Fadelli



Visualization of a localized state of light found in the team's simulations. Credit: Yamilov et al.

The Anderson transition is a phase transition that occurs in disordered systems, which entails a shift from a diffusive state (i.e., in which waves or particles are spread out) to a localized state, in which they are trapped in specific regions. This state was first studied by physicist Philip W. Anderson, who examined the arrangement of electrons in disordered solids, yet it was later found to also apply to the propagation of light and other waves.

Researchers at Missouri University of Science & Technology, Yale University, and Grenoble Alpes University in France recently set out to further explore the Anderson transition for light (i.e., electromagnetic waves) in 3D disordered systems.

Their paper, published in *Physical Review Letters*, outlines the simulation of light wave transport in an arrangement of perfect-electric-conducting (PEC) spheres, materials that reflect electromagnetic waves.

"This paper builds on our earlier publication in *Nature Physics*, which demonstrated Anderson localization (AL) of light in 3D random media but didn't study how the transition from diffusion to localization unfolds," Alexey Yamilov, first author of the paper, told Phys.org.

"Previous studies of Anderson transition include model numerical calculations for electrons in disordered solids, vibrations in mechanical systems, as well as experiments with ultrasound and matter waves in cold-atom systems. They demonstrated the universality of the transition by establishing that certain quantities behave the same, whatever the physical nature of the studied physical system."

Building on their previous research, Yamilov and his colleagues, Hui Cao and Sergey Skipetrov, set out to demonstrate that the Anderson transition for light is the exact same as that observed for other types of waves. To do this, they first set out to determine whether the cross-over from diffusion to localization in the medium they examined represents a true Anderson transition.

In addition, they wished to probe the existence of a critical frequency separating the two regimes (i.e., diffusion and localization), which is referred to as a sharp mobility edge.

Finally, they explored the extent to which the Anderson transition exhibits the universal scaling behavior predicted by localization theory, to ultimately determine the universality of the transition.

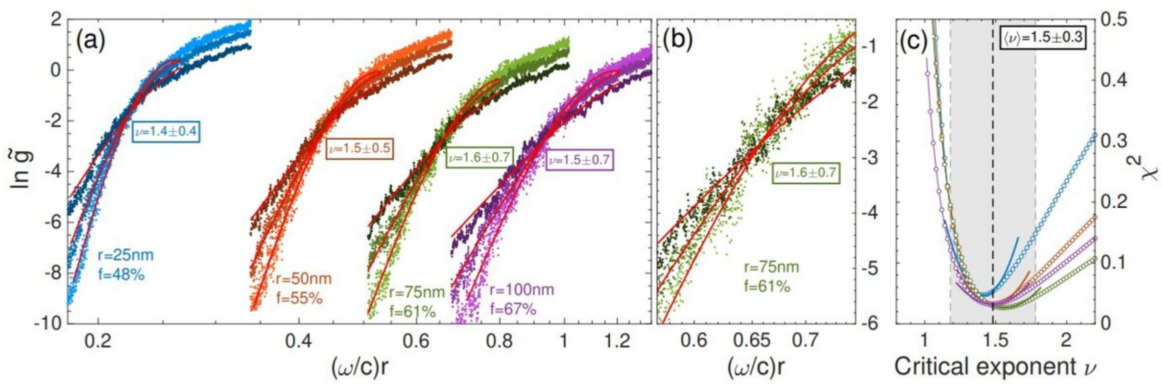
"Since observation of the AL of light evaded scientists for almost 40 years, our Nature Physics paper made these questions highly pertinent," explained Skipetrov.

"Study of Anderson transition presents the same fundamental difficulty as the study of any phase transition: it only takes place in a system of infinite extent, which is never the case in experiments or numerical simulations. In a system of finite size, the abrupt transition is replaced by a continuous crossover."

To overcome the challenges encountered in previous studies studying phase transitions, the researchers employed a finite-size scaling approach. This approach allowed them to examine the crossover between diffusion and localization as the size of a 3D system increases.

"Standard methods of statistical physics developed to study phase transitions allow for determining transition parameters that would be observed in an infinite system, from the obtained size-dependence," said Yamilov.

"Although very powerful, this approach still requires being able to simulate light scattering in samples of large (though not infinite) size, which was made possible by the revolutionary software Tidy3D, developed by FlexCompute, Inc."



Transition from diffusion to localization in random ensembles of overlapping spheres. Credit: Alexey Yamilov et al

Using Tidy3D, a software platform that can be used to simulate the behavior of electromagnetic waves, the researchers set out to study how the transmission of light varies along with the size of a 3D metallic system at different frequencies near the Anderson transition point.

In their simulations, they sent light pulses through the metallic structures and measured the extent to which light passed through. This allowed them to determine the exact frequency at which the transition from diffusion to localization occurs, which is known as the critical point.

"At this special point, transmission curves for different system sizes all cross each other," said Yamilov.

"The key was, of course, to start with a system which does exhibit Anderson localization of light, as we reported in our previous publication. Then, using modern computational methods, we simulated large enough systems to definitively show that this is a true phase transition, similar to what happens with electrons in disordered metals."

The simulations performed by Yamilov and his colleagues showed that the transition for light in 3D disordered systems they simulated belongs to the same universality class as other Anderson transitions. This means that even if they are more complex than electronic waves, electromagnetic waves exhibit the same fundamental behavior when they become localized.

"Until recently, 3D systems of size, sufficient to observe [the] AL of light and to systematically study it, could not be simulated due to computational constraints," said Yamilov.

"Recent advances in Finite Difference Time Domain (FDTD) algorithms, pioneered by FlexCompute Inc, finally enabled such simulations. Now, this can be done by anyone! In fact, our code is openly available to the public and FlexCompute Inc has offered access for anyone to scrutinize our results free of charge."

Symmetry is a fundamental concept in physics, with countless past studies demonstrating that some specific properties of physical systems directly follow from their symmetries, such as the time-reversal or spin-rotation symmetries, and can thus be easily predicted. The findings gathered by Yamilov and his colleagues offer a further, striking example of the importance of symmetries.

"The fact that the considered optical system possesses the time-reversal symmetry and that the only broken symmetry is the translational one (because of disorder), imposes Anderson transition to fall in the so-called orthogonal universality class, the same as for electrons in disordered metals or vibrations in solids," explained Skipetrov.

"More precisely, our quantitative analysis of the scaling behavior in the vicinity of the critical point led to the first estimate of the critical exponent ≈1.5. Its value indicates that this transition belongs to the orthogonal universality class, revealing a deep connection between light localization and other wave phenomena, e.g. electrons or sound, in disordered systems."

This recent study could soon open new possibilities for research focusing on the control of light in 3D. The ability to confine light in random structures, as demonstrated in the team's simulations, could, for instance, enable the development of new technologies, including optical devices, sensors and lasers, which could be based on nanoporous metals.

"The most pressing direction is experimental verification of Anderson localization of light in 3D metallic systems, but optical absorption of metals poses a challenge," added Cao.

"Moving to near-IR and microwave frequencies will reduce the absorption. We are looking into extending the numerical analysis to systems with controlled absorption to understand how it affects the transition. This bridges our idealized simulations with real materials and could guide experimental design."

In their next studies, the researchers plan to continue investigating the Anderson localization of light in 3D metallic systems. They also plan to explore this transition's real-world applications, specifically focusing on how the localization of light in nanoporous metals could be leveraged to enhance light-matter interactions, which could advance photocatalysts and sensing devices.

More information: Alexey Yamilov et al, Anderson Transition for Light in a Three-Dimensional Random Medium, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.134.046302. On *arXiv*: DOI: 10.48550/arxiv.2408.04853

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