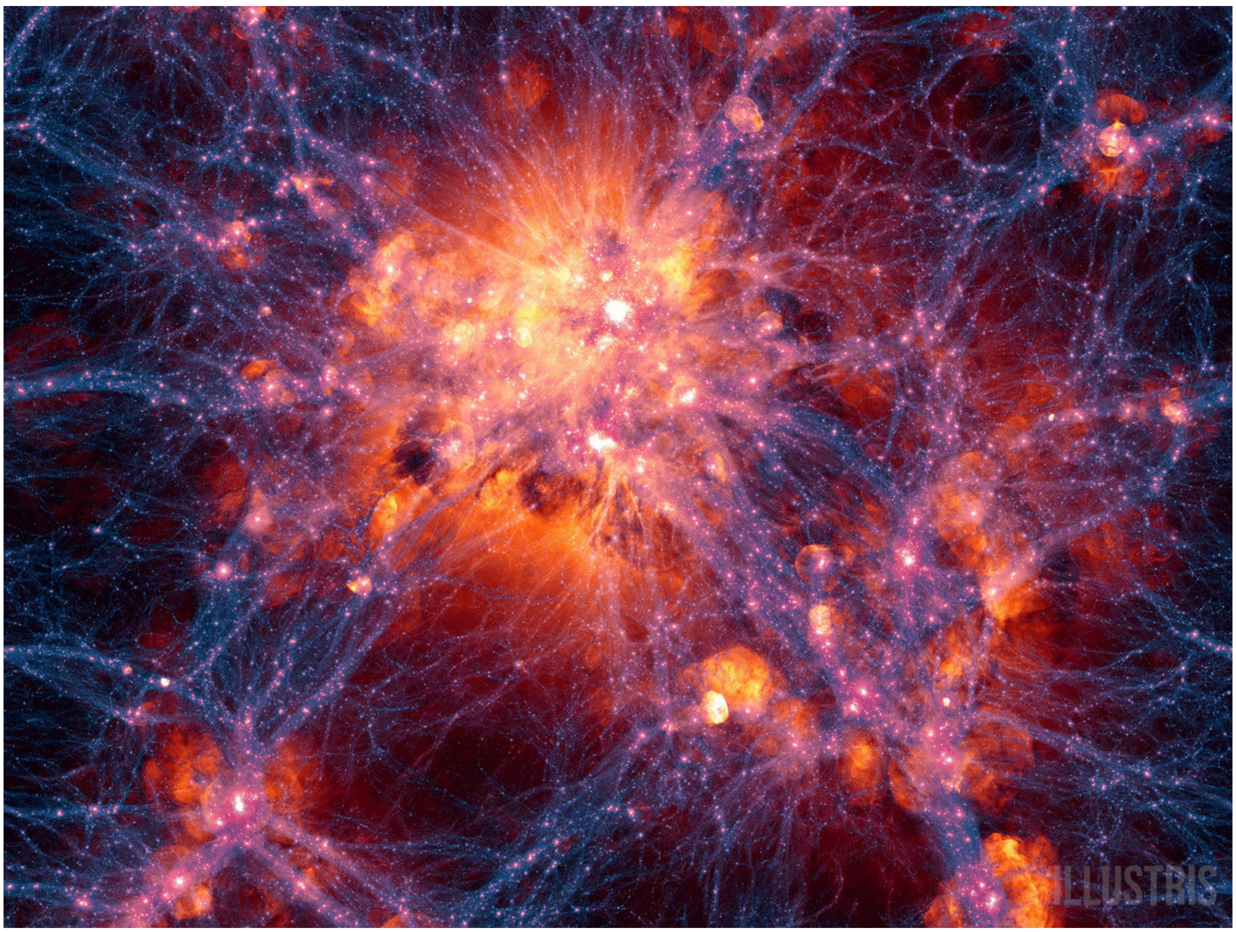
A quantum leap toward expanding the search for dark matter

September 25 2018, by Glenn Roberts Jr



A visualization of a massive galaxy cluster that shows dark matter density (purple filaments) overlaid with the gas velocity field. Credit: Illustris Collaboration

Figuring out how to extend the search for dark matter particles – dark matter describes the stuff that makes up an estimated 85 percent of the total mass of the universe yet so far has only been measured by its gravitational effects – is a bit like building a better mousetrap… that is, a mousetrap for a mouse you've never seen, will never see directly, may be joined by an odd assortment of other mice, or may not be a mouse after all.

Now, through a new research program supported by the U.S. Department of Energy's Office of High Energy Physics (HEP), a consortium of researchers from the DOE's Lawrence Berkeley National Laboratory (Berkeley Lab), UC Berkeley, and the University of Massachusetts Amherst will develop sensors that enlist the seemingly weird properties of quantum physics to probe for dark matter particles in new ways, with increased sensitivity, and in uncharted regions. Maurice Garcia-Sciveres, a Berkeley Lab physicist, is leading this Quantum Sensors HEP-Quantum Information Science (QIS) Consortium.

Quantum technologies are emerging as promising alternatives to the more conventional "mousetraps" that researchers have previously used to track down elusive particles. And the DOE, through the same HEP office, is also supporting a collection of other research efforts led by Berkeley Lab scientists that tap into quantum theory, properties, and technologies in the QIS field.

These efforts include:

- Unraveling the Quantum Structure of Quantum Chromodynamics in Parton Shower Monte Carlo Generators – This effort will develop computer programs that test the interactions between fundamental particles in extreme detail. Current computer simulations are limited by classical algorithms, though quantum algorithms could more accurately model these interactions and could provide a better way to compare with and understand particle events measured at CERN's Large Hadron Collider, the world's most powerful particle collider. Berkeley Lab's Christian Bauer, a senior research scientist, will lead this effort.

- Quantum Pattern Recognition (QPR) for High-Energy Physics –Increasingly powerful particle accelerators require vastly faster computer algorithms to monitor and sort through billions of particle events per second, and this effort will develop and study the potential of quantum-based algorithms for pattern recognition to reconstruct charged particles. Such algorithms have the potential for significant speed improvements and increased precision. Led by Berkeley Lab physicist and Divisional Fellow Heather Gray, this effort will involve high-energy physics and high-performance computing expertise in Berkeley Lab's Physics Division and at the Lab's National Energy Research Scientific Computing Center, a DOE Office of Science User Facility, and also at UC Berkeley.
- Skipper-CCD, a New Single-Photon Sensor for Quantum Imaging – For the past six years, Berkeley Lab and Fermi National Accelerator Laboratory (Fermilab) have been collaborating in the development of a detector for astrophysics experiments that can detect the smallest individual unit of light, known as a photon. This Skipper-CCD detector was successfully demonstrated in the summer of 2017 with an incredibly low noise that allowed the detection of even individual electrons. As a next step, this Fermilab-led effort will seek to image pairs of photons that exist in a state of quantum entanglement, meaning their properties are inherently related – even over long distances – such that the measurement of one of the particles necessarily defines the properties of the other. Steve Holland, a senior scientist and engineer at Berkeley Lab who is a pioneer in the development of high-performance silicon detectors for a range of

uses, is leading Berkeley Lab's participation in this project.

- Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology –This effort will develop quantum algorithms and simulations for properties, including error correction and information scrambling, that are relevant to black hole theories and to quantum computing involving highly connected arrays of superconducting qubits – the basic units of a quantum computer. Researchers will also compare these with more classical methods. UC Berkeley is heading up this research program, and Irfan Siddiqi, a scientist in Berkeley Lab's Materials Sciences Division and founding director of the Center for Quantum Coherent Science at UC Berkeley, is leading Berkeley Lab's involvement.
- Siddiqi is also leading a separate research program, Field Programmable Gate Array-based Quantum Control for High-Energy Physics Simulations with Qutrits, that will develop specialized tools and logic families for high-energy-physics-focused quantum computing. This effort involves Berkeley Lab's Accelerator Technology and Applied Physics Division.

These projects are also part of Berkeley Quantum, a partnership that harnesses the expertise and facilities of Berkeley Lab and UC Berkeley to advance U.S. quantum capabilities by conducting basic research, fabricating and testing quantum-based devices and technologies, and educating the next generation of researchers.

Also, across several of its offices, the DOE has announced support for a wave of other R&D efforts that will foster collaborative innovation in quantum information science at Berkeley Lab, at other national labs, and at partner institutions.

At Berkeley Lab, the largest HEP-funded QIS-related undertaking will include a multidisciplinary team in the development and demonstration of quantum sensors to look for very-low-mass dark matter particles – so-called "light dark matter" – by instrumenting two different detectors.

One of these detectors will use liquid helium at a very low temperature where otherwise familiar phenomena such as heat and thermal conductivity display quantum behavior. The other detector will use specially fabricated crystals of gallium arsenide (see a related article), also chilled to cryogenic temperatures. The ideas for how these experiments can search for very light dark matter sprang from theory work at Berkeley Lab.

"There's a lot of unexplored territory in low-mass dark matter," said Natalie Roe, director of the Physics Division at Berkeley Lab and the principal investigator for the Lab's HEP-related quantum efforts. "We have all the pieces to pull this together: in theory, experiments, and detectors."

Garcia-Sciveres, who is leading the effort in applying quantum sensors to the low-mass dark matter search, noted that other major efforts – such as the Berkeley Lab-led LUX-ZEPLIN (LZ) experiment that is taking shape in South Dakota – will help root out whether dark matter particles known as WIMPs (weakly interacting massive particles) exist with masses comparable to that of atoms. But LZ and similar experiments are not designed to detect dark matter particles of much lower masses.

"The traditional WIMP dark matter experiments haven't found anything yet," he said. "And there is a lot of theoretical work on models that favor particles of a lower mass than experiments like LZ can measure," he added. "This has motivated people to really look hard at how you can detect very-low-mass particles. It's not so easy. It's a very small signal that has to be detected without any background noise."

Researchers hope to develop quantum sensors that are better at filtering out the noise of unwanted signals. While a traditional WIMP experiment is designed to sense the recoil of an entire atomic nucleus after it is "kicked" by a dark matter particle, very-low-mass dark matter particles will bounce right off nuclei without affecting them, like a flea bouncing off an elephant.

The goal of the new effort is to sense the low-mass particles via their energy transfer in the form of very feeble quantum vibrations, which go by names like "phonons" or "rotons," for example, Garcia-Sciveres said.

"You would never be able to tell that an invisible flea hits an elephant by watching the elephant. But what if every time an invisible flea hits an elephant at one end of the herd, a visible flea is flung away from an elephant at the other end of the herd?" he said.

"You could use these sensors to watch for such slight signals in a very cold crystal or superfluid helium, where an incoming dark matter particle is like the invisible flea, and the outgoing visible flea is a quantum vibration that must be detected."

The particle physics community has held some workshops to brainstorm the possibilities for low-mass dark matter detection. "This is a new regime. This is an area where there aren't even any measurements yet. There is a promise that QIS techniques can help give us more sensitivity to the small signals we're looking for," Garcia-Sciveres added. "Let's see if that's true."

The demonstration detectors will each have about 1 cubic centimeter of detector material. Dan McKinsey, a Berkeley Lab faculty senior scientist and UC Berkeley physics professor who is responsible for the development of the liquid helium detector, said that the detectors will be constructed on the UC Berkeley campus. Both are designed to be sensitive to particles with a mass lighter than protons – the positively charged particles that reside in atomic nuclei.

The superfluid helium detector will make use of a process called "quantum evaporation," in which rotons and phonons cause individual helium atoms to be evaporated from the surface of superfluid helium.

Kathryn Zurek, a Berkeley Lab physicist and pioneering theorist in the search for very-low-mass dark matter particles who is working on the quantum sensor project, said the technology to detect such "whispers" of dark matter didn't exist just a decade ago but "has made major gains in the last few years." She also noted, "There had been a fair amount of skepticism about how realistic it would be to look for this light-mass dark matter, but the community has moved more broadly in that direction."

There are many synergies in the expertise and capabilities that have developed both at Berkeley Lab and on the UC Berkeley campus that make it a good time – and the right place – to develop and apply quantum technologies to the hunt for dark matter, Zurek said.

Theories developed at Berkeley Lab suggest that certain exotic materials exhibit quantum states or "modes" that low-mass dark matter particles can couple with, which would make the particles detectable – like the "visible flea" referenced above.

"These ideas are the motivation for building these experiments to search for light dark matter," Zurek said. "This is a broad and multipronged approached, and the idea is that it will be a stepping stone to a larger effort."

The new project will draw from a deep experience in building other types of particle detectors, and R&D in ultrasensitive sensors that operate at the threshold where an electrically conducting material becomes a superconductor – the "tipping point" that is sensitive to the slightest fluctuations. Versions of these sensors are already used to search for slight temperature variations in the relic microwave light that spans the universe.

At the end of the three-year demonstration, researchers could perhaps turn their sights to more exotic types of detector materials in larger volumes.

"I'm excited to see this program move forward, and I think it will become a significant research direction in the Physics Division at Berkeley Lab," she said, adding that the program could also demonstrate ultrasensitive detectors that have applications in other fields of science.

Provided by Lawrence Berkeley National Laboratory

Citation: A quantum leap toward expanding the search for dark matter (2018, September 25) retrieved 28 April 2024 from https://phys.org/news/2018-09-quantum-dark.html